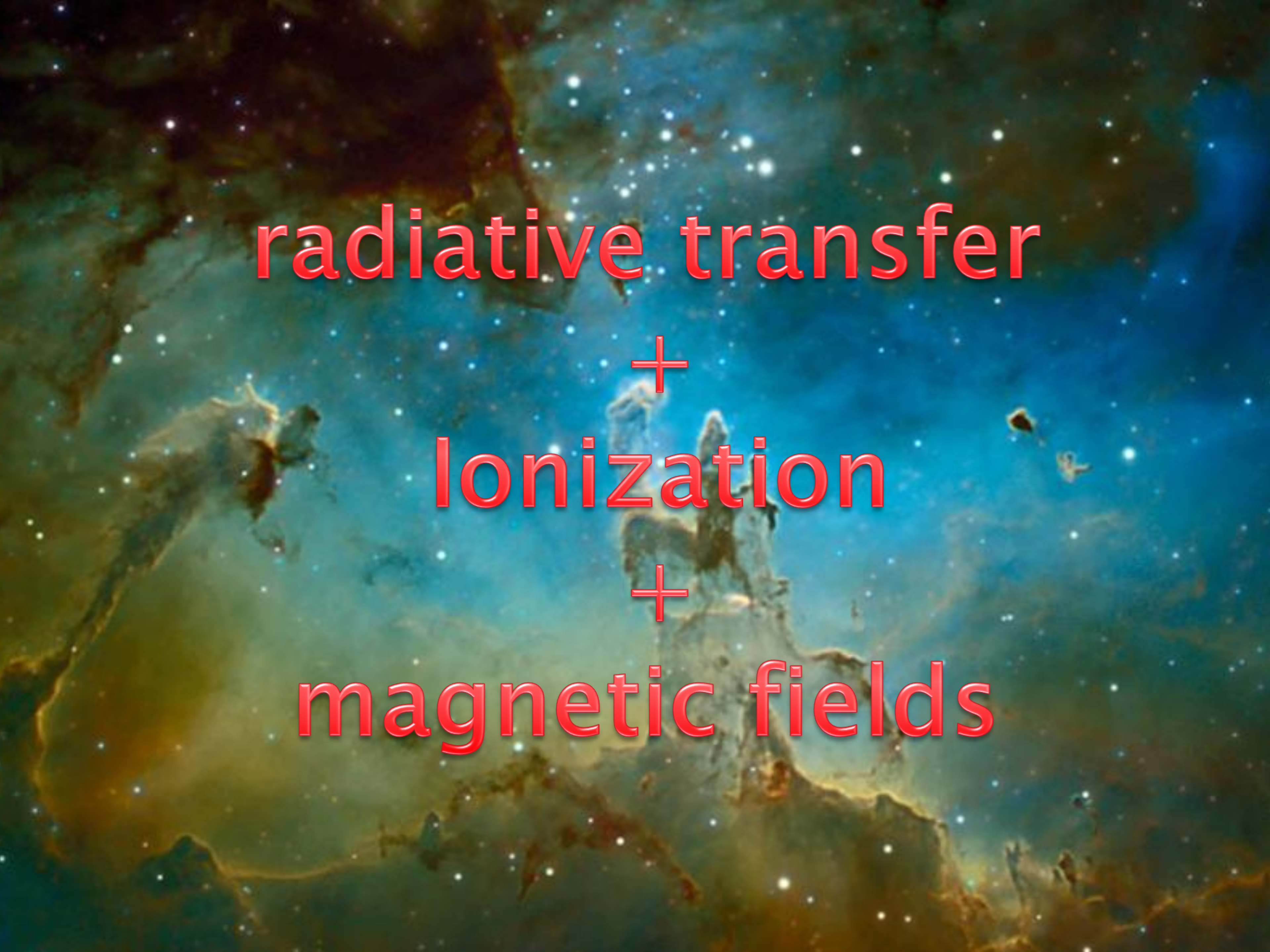
Enzo Lectures

Mike Norman, Matt Turk

Laboratory for Computational Astrophysics
UC San Diego

	Morning	Afternoon
Mon.	Introduction to Enzo	
Tue.	1. Setting Up and Running Enzo 2. Enzo Projects	Introduction to YT
Wed.	Enzo Algorithms	Lab session
Thu.	Applications to First Stars, First Galaxies, and Reionization	Lab session
Fri.	What's New in Enzo 2.0?	Q & A



radiative transfer

+

Ionization

+

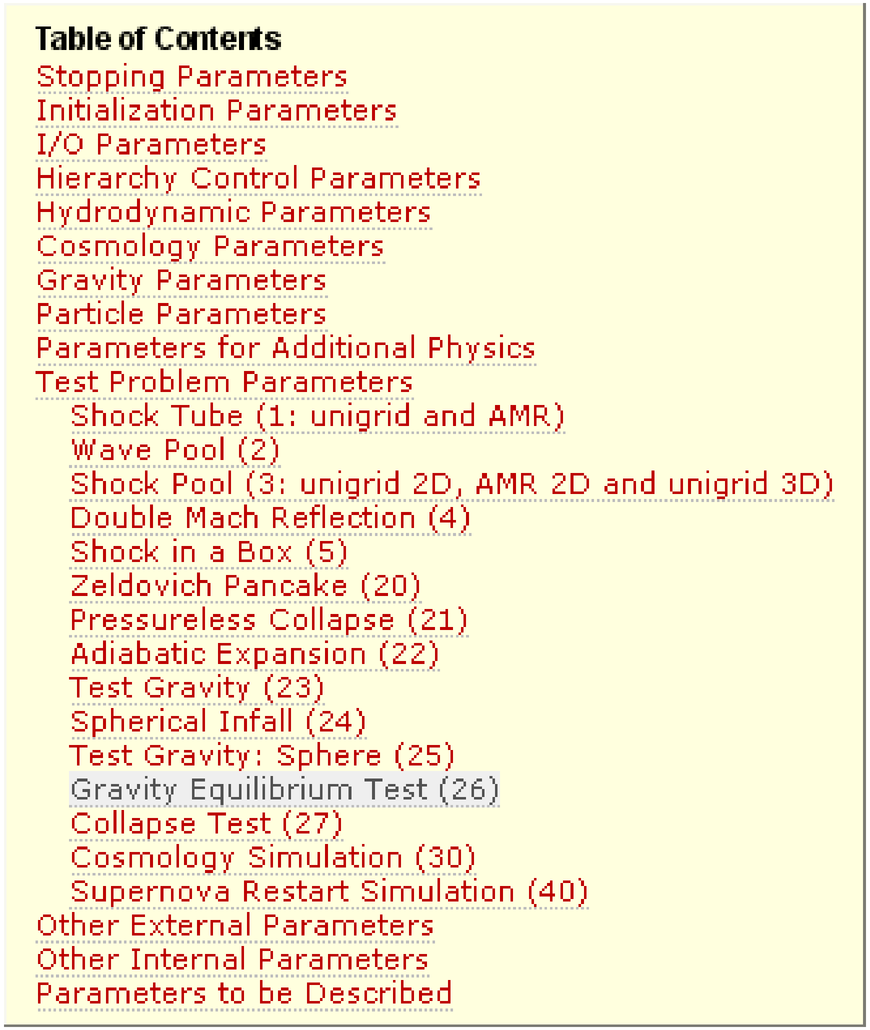
magnetic fields

New Features in Enzo 2.0

Feature	Authors
physics	
star particle class	John Wise, Ji-hoon Kim
adaptive ray tracing radiative transfer	John Wise, Tom Abel
flux limited diffusion radiative transfer	Dan Reynolds
Runge-Kutta2 MHD	Tom Abel, Peng Wang
CUDA MHD	Tom Abel, Peng Wang
high-density primordial chemistry	Matt Turk
CLOUDY cooling	Britton Smith
sink particles	John Wise, Peng Wang, Tom Abel

New Features in Enzo 2.0

Feature	Authors
numerics	
particle splitting	Ji-hoon Kim
shearing box boundary conditions	Tom Abel, Fen Zhao
inline Friends-Of-Friends	John Wise
mpgraphic initial conditions	John Wise
non-blocking communication	John Wise, Greg Bryan
AMR checkpoint dumps	Matt Turk
r16 Positioning	Matt Turk
Python embedding	Matt Turk
LCA-perf	James Bordner
New Streaming Format	John Wise, Tom Abel



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- Stopping Parameters
- Initialization Parameters
- I/O Parameters
- Hierarchy Control Parameters
- Hydrodynamic Parameters
- Cosmology Parameters
- Gravity Parameters
- Particle Parameters
- Parameters for Additional Physics
- Test Problem Parameters
  - Shock Tube (1: unigrid and AMR)
  - Wave Pool (2)
  - Shock Pool (3: unigrid 2D, AMR 2D and unigrid 3D)
  - Double Mach Reflection (4)
  - Shock in a Box (5)
  - Zeldovich Pancake (20)
  - Pressureless Collapse (21)
  - Adiabatic Expansion (22)
  - Test Gravity (23)
  - Spherical Infall (24)
  - Test Gravity: Sphere (25)
  - Gravity Equilibrium Test (26)
  - Collapse Test (27)
  - Cosmology Simulation (30)
  - Supernova Restart Simulation (40)
- Other External Parameters
- Other Internal Parameters
- Parameters to be Described

V1.5

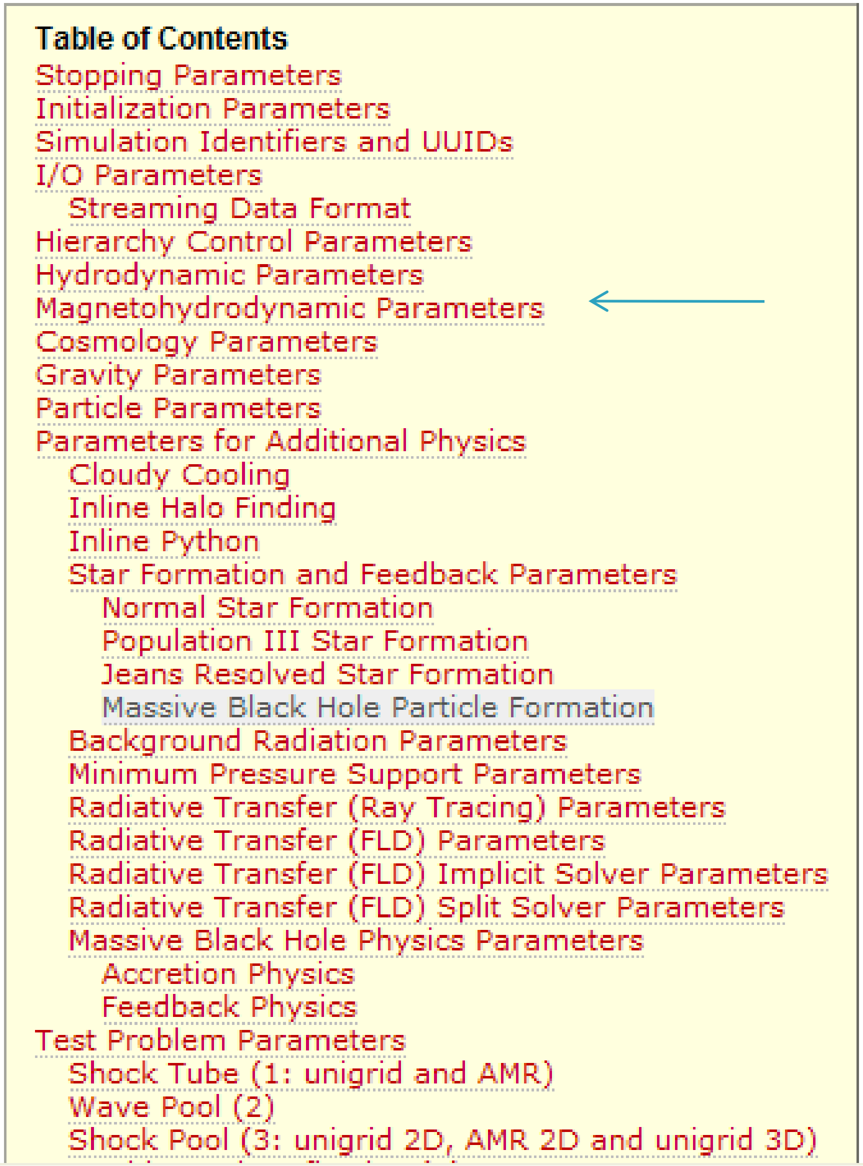

Table of Contents

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- Initialization Parameters
- Simulation Identifiers and UUIDs
- I/O Parameters
  - Streaming Data Format
- Hierarchy Control Parameters
- Hydrodynamic Parameters
- Magnetohydrodynamic Parameters
- Cosmology Parameters
- Gravity Parameters
- Particle Parameters
- Parameters for Additional Physics
  - Cloudy Cooling
  - Inline Halo Finding
  - Inline Python
  - Star Formation and Feedback Parameters
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    - Population III Star Formation
    - Jeans Resolved Star Formation
    - Massive Black Hole Particle Formation
  - Background Radiation Parameters
  - Minimum Pressure Support Parameters
  - Radiative Transfer (Ray Tracing) Parameters
  - Radiative Transfer (FLD) Parameters
  - Radiative Transfer (FLD) Implicit Solver Parameters
  - Radiative Transfer (FLD) Split Solver Parameters
  - Massive Black Hole Physics Parameters
    - Accretion Physics
    - Feedback Physics
- Test Problem Parameters
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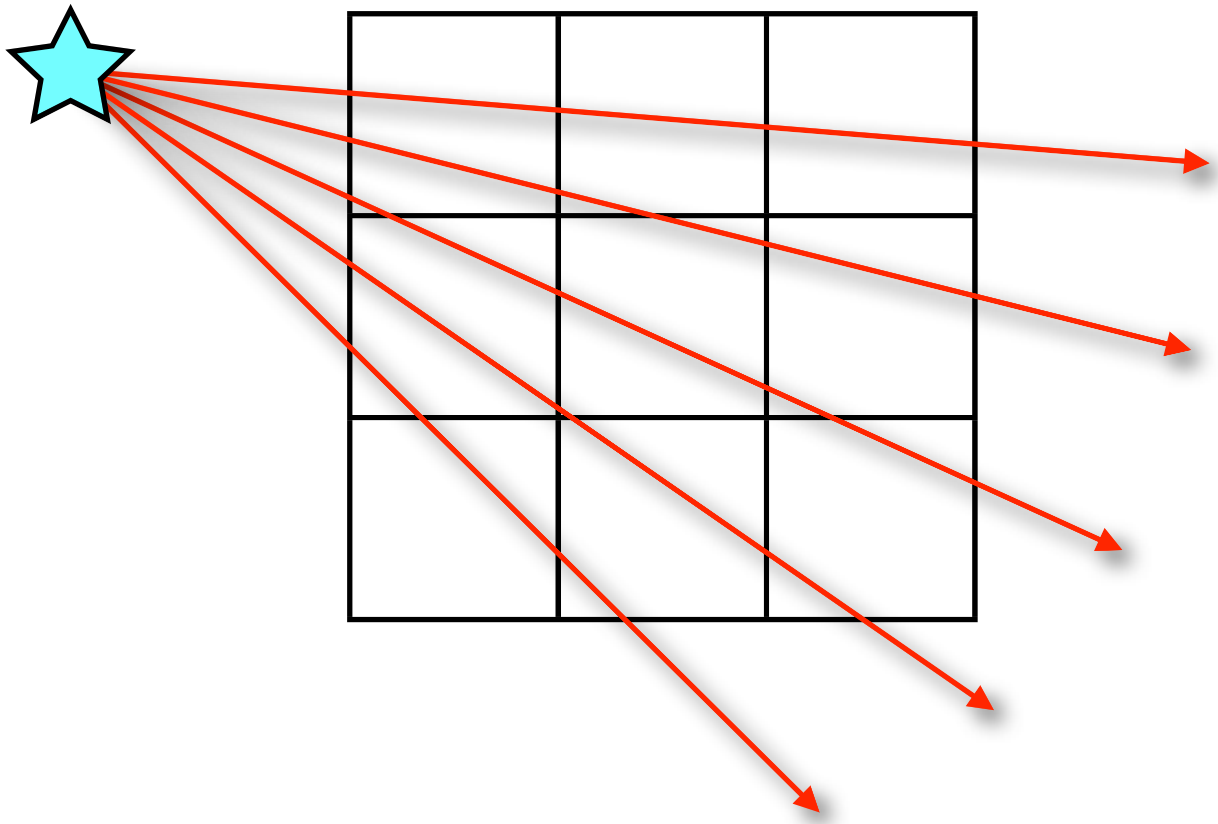
  - Wave Pool (2)
  - Shock Pool (3: unigrid 2D, AMR 2D and unigrid 3D)

V2.0

I. Radiative Transfer with Ray Tracing
II. Radiating "Star" Particles

John Wise (Princeton)
Enzo Workshop
UCSD – 29 Jun 2010



Cosmological Radiative Transfer Equation

$$I_\nu \equiv I(\nu, \mathbf{x}, \Omega, t)$$

n := normal vector
a := scale factor
ā := a/a$_{em}$
H := Hubble factor
ν := frequency

$$\frac{1}{c}\ \frac{\partial I_\nu}{\partial t} + \frac{\hat{n} \cdot \nabla I_\nu}{\bar{a}} - \frac{H}{c}\ \left(\nu \frac{\partial I_\nu}{\partial \nu} - 3 I_\nu\right) = -\kappa_\nu I_\nu + j_\nu$$

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Propagation &
Cosmic Expansion

Redshifting

Cosmological Dilution

Absorption

Emission

Simplifications – “Local” Approximation

1. Short timesteps (**ā** = 1)
2. Ignore cosmological redshift and dilution (may become important >50 Mpc)

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Propagation & Cosmic Expansion

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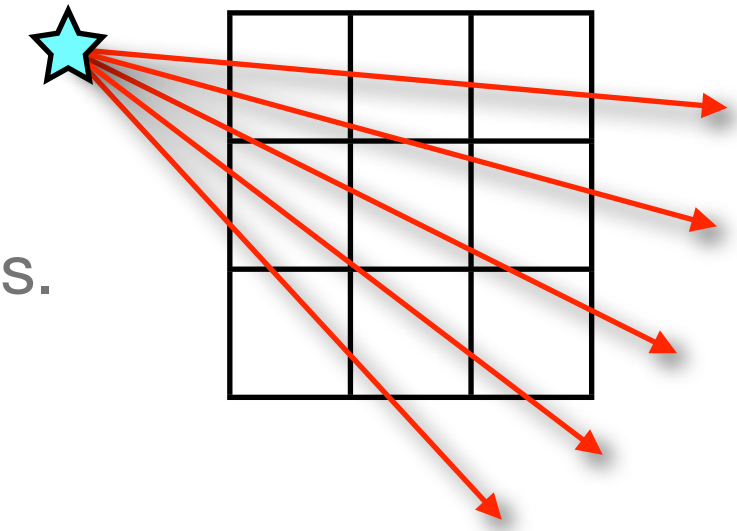
RT Equation along a Ray



- Consider point sources of radiation

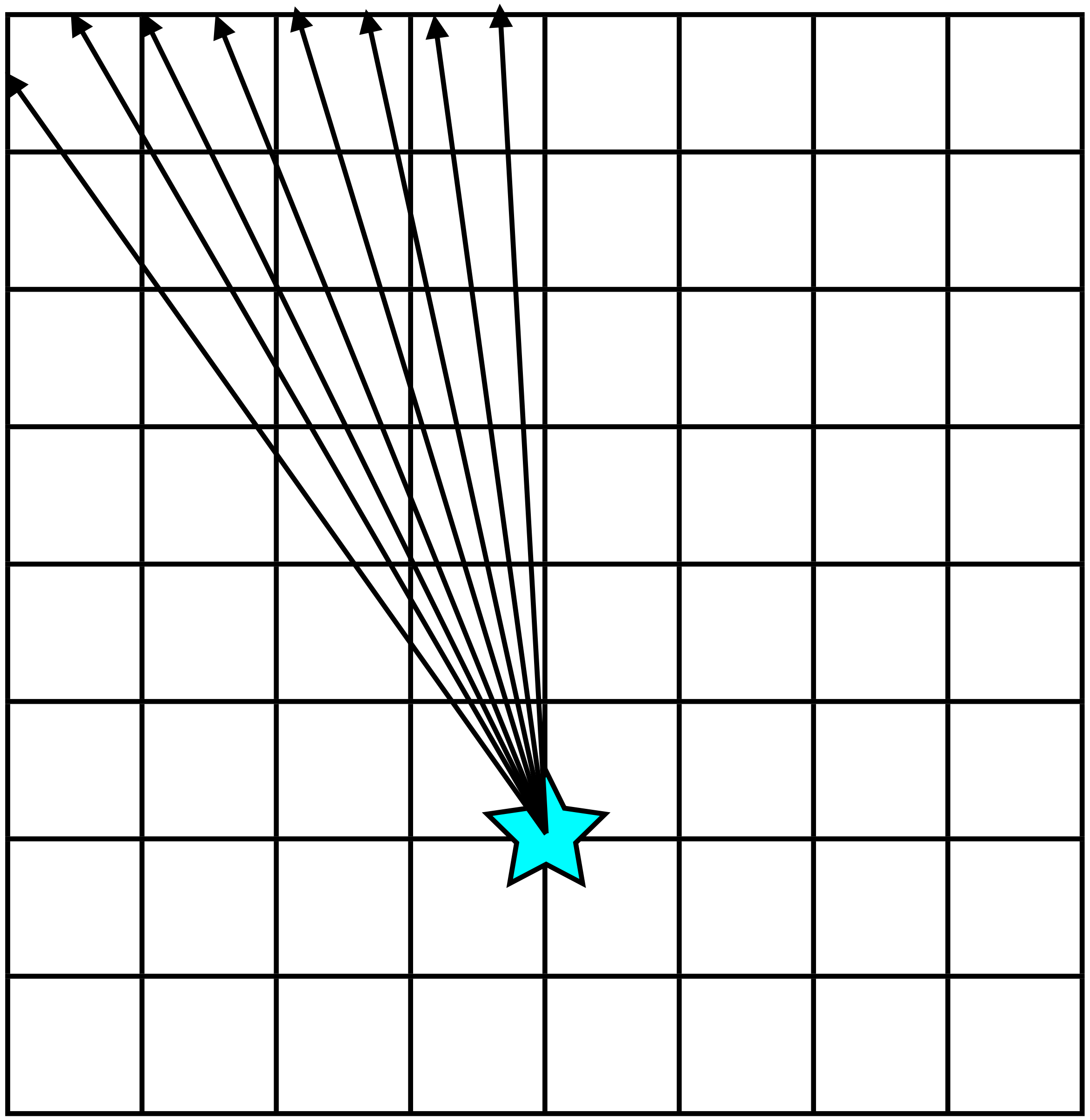
- Initially, the radiation flux is split equally among all rays.

$$\frac{1}{c}\frac{\partial P}{\partial t} + \frac{\partial P}{\partial r} = -\kappa P$$

- P := photon flux in the ray

Adaptive Ray Tracing

Abel & Wandelt (2002)



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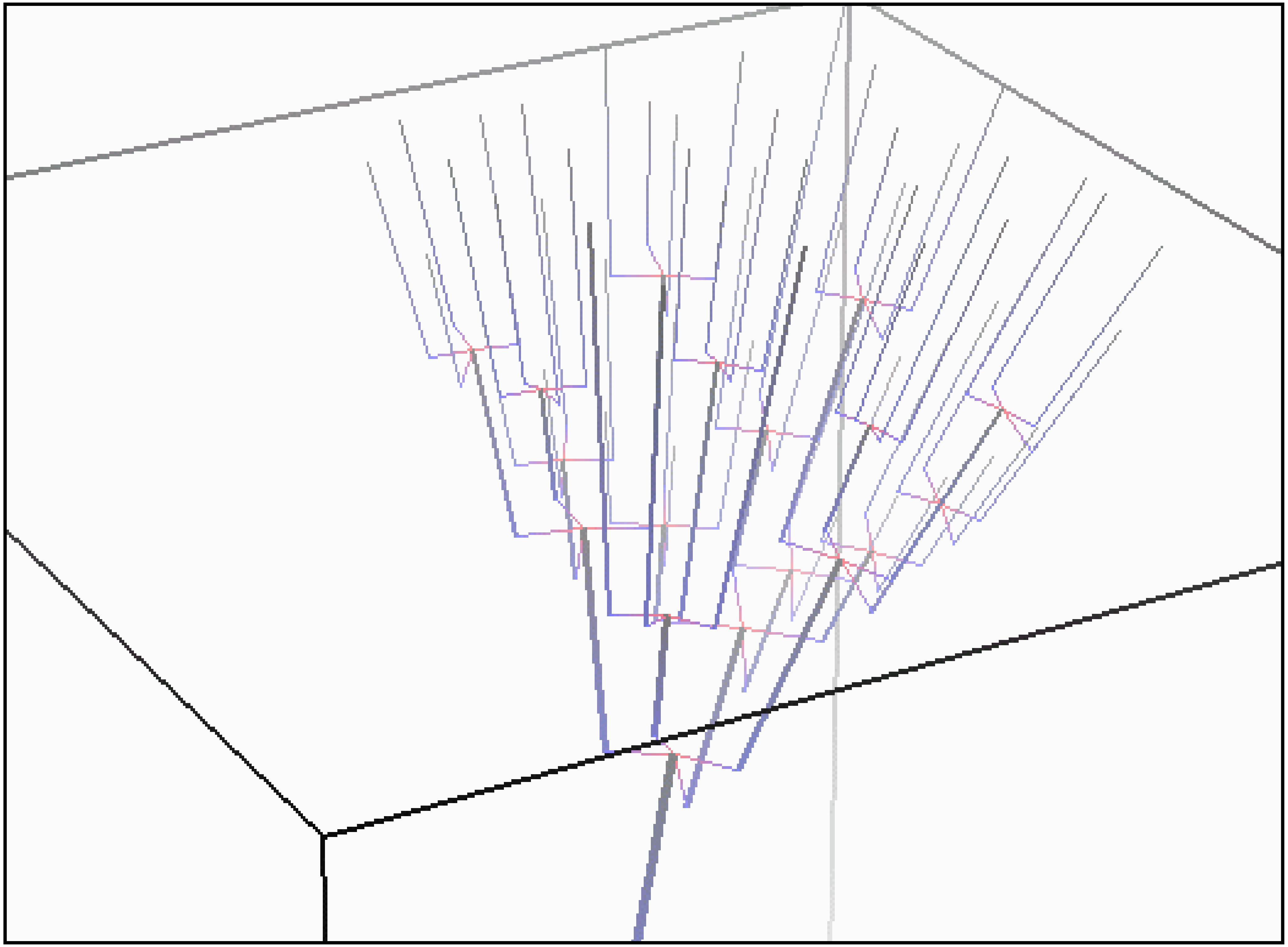
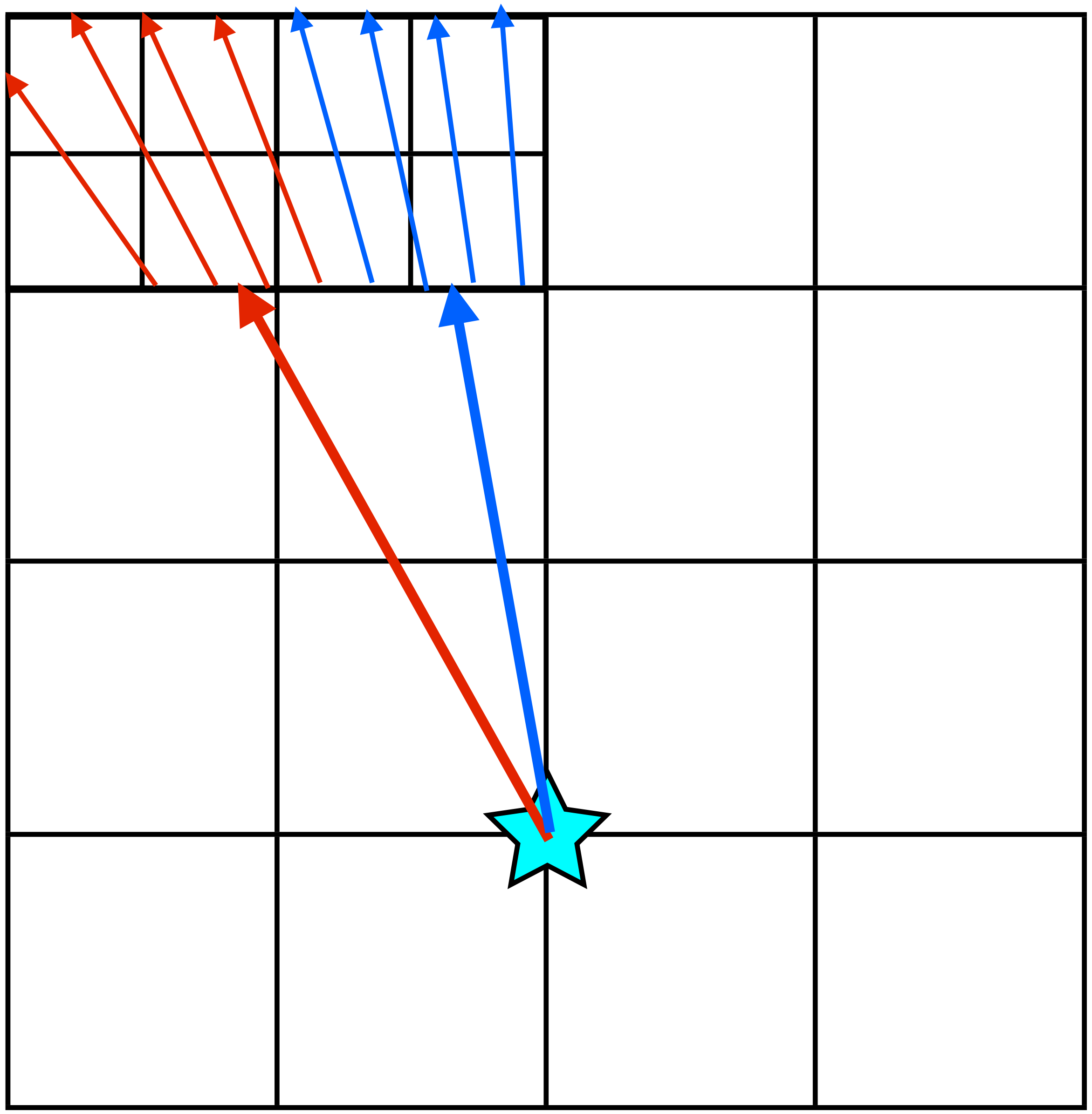
Abel & Wandelt (2002)



Adaptive Ray Tracing

Abel & Wandelt (2002)

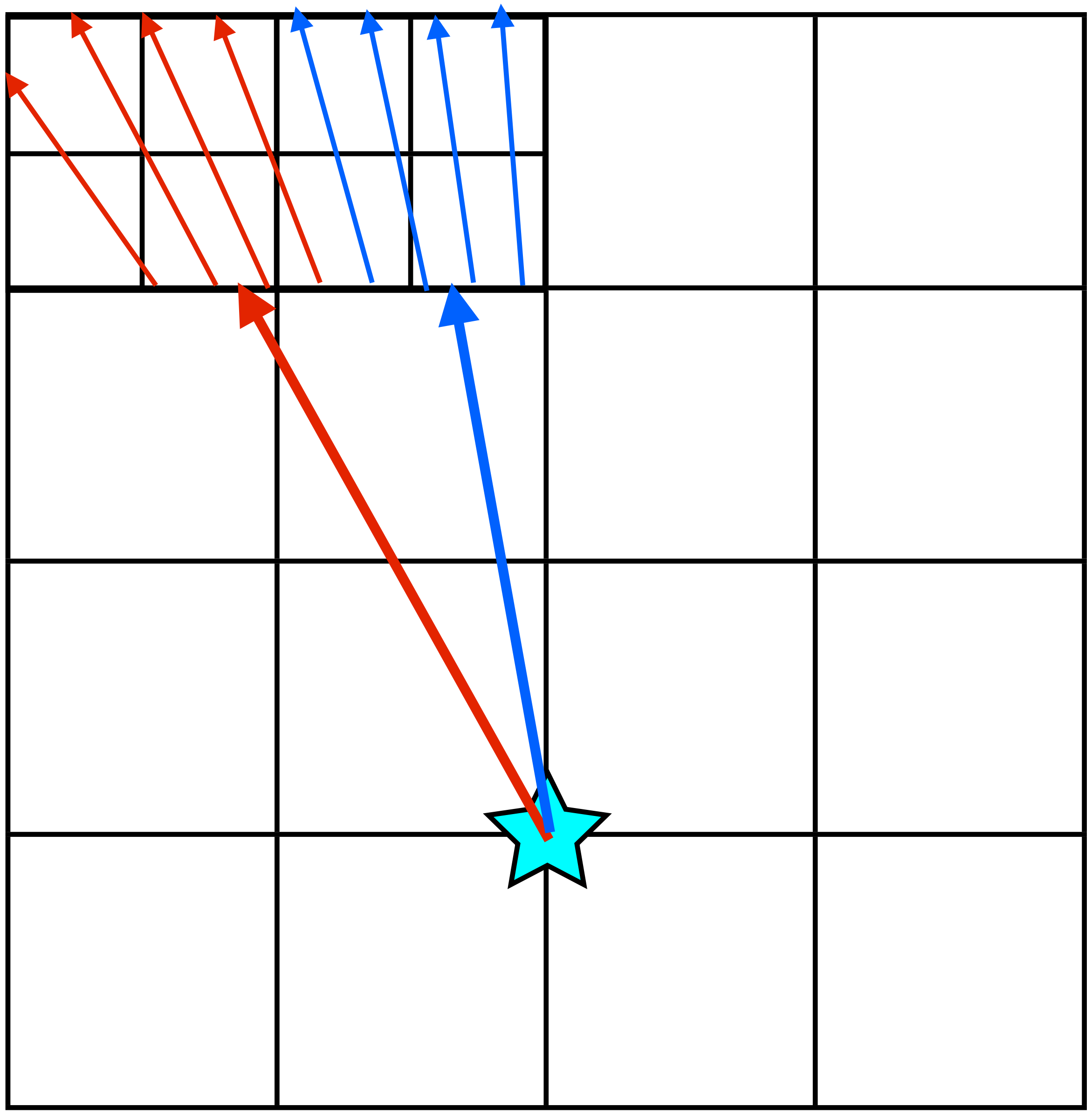
- Ray directions and splitting based on HEALPix (Gorski et al. 2005)
- Rays are split into 4 child rays when the solid angle is large compared to the cell face area
- Well-suited for AMR
- Fully coupled to the chemistry and energy solvers in Enzo, i.e. **radiation hydrodynamics**!



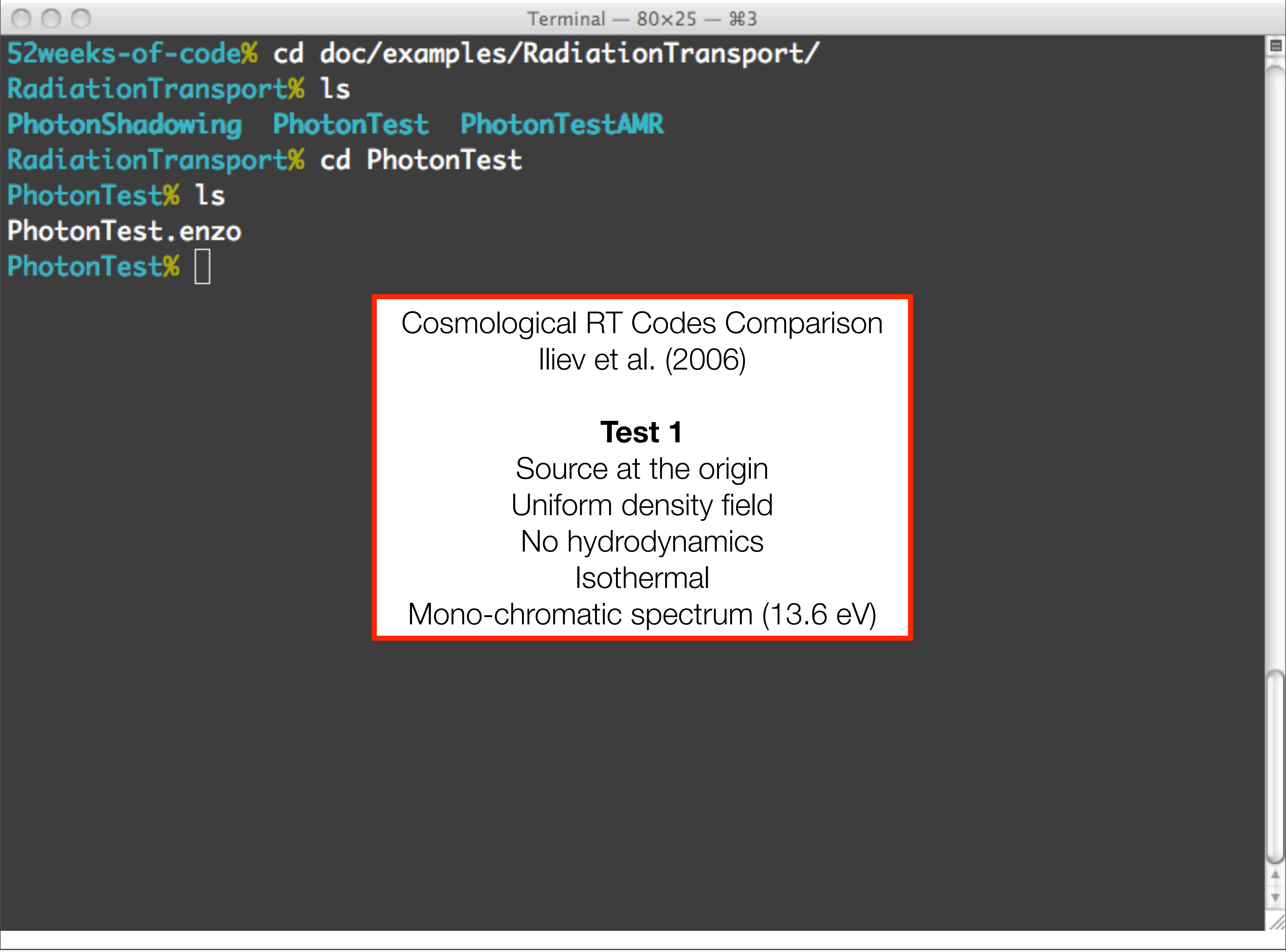
Adaptive Ray Tracing

Abel & Wandelt (2002)

- Each ray is mono-chromatic
- Hydrogen ionizing (E > 13.6 eV)
- Helium singly ionizing (E > 24.6 eV)
- Helium doubly ionizing (E > 54.4 eV)
- X-rays
    - hydrogen ionizations
    - secondary ionizations
    - helium ionizations
    - reduced photo-heating
- H_2 dissociating (Lyman-Werner)



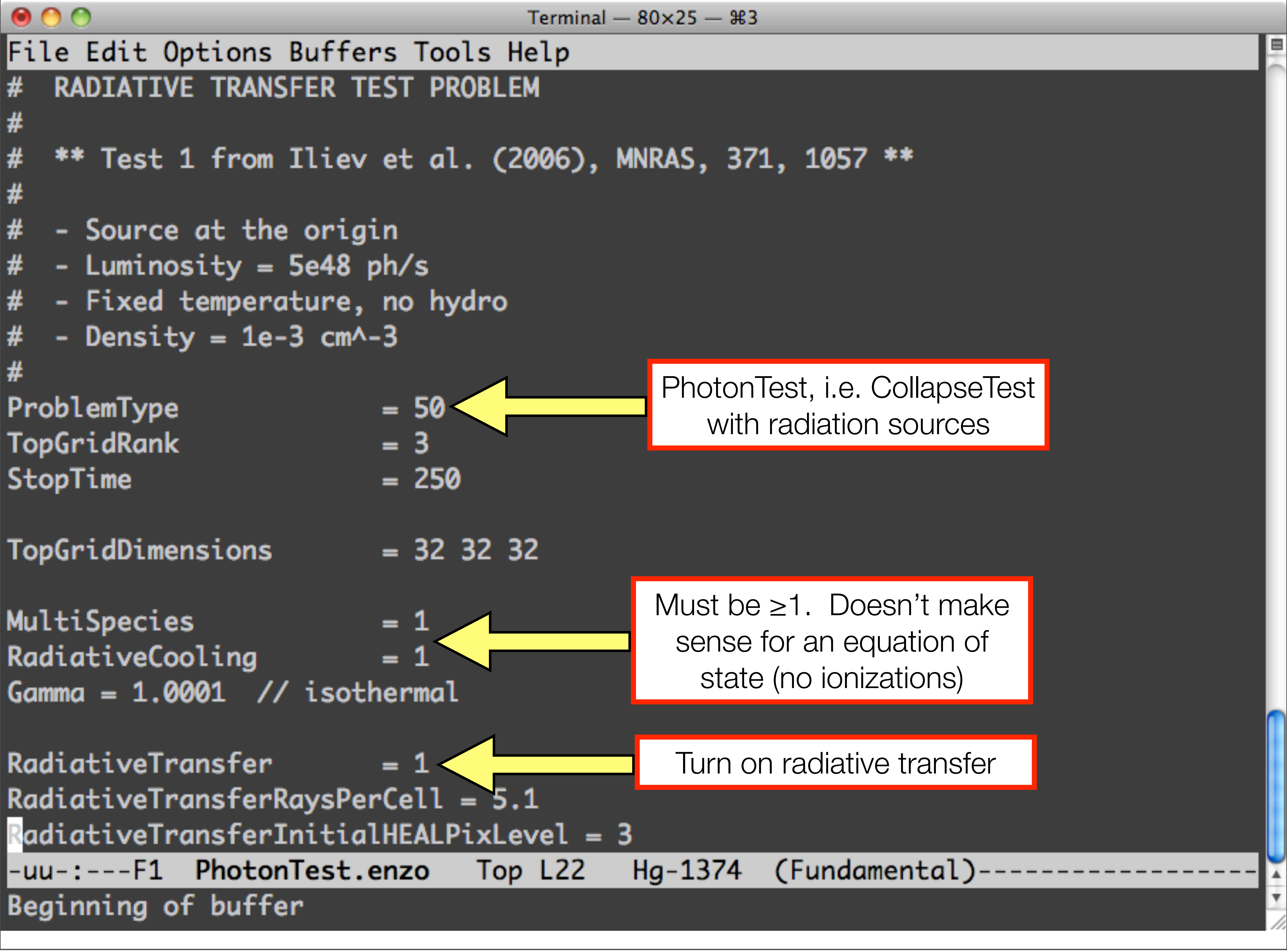
Time for an **example**!



```
52weeks-of-code% cd doc/examples/RadiationTransport/
RadiationTransport% ls
PhotonShadowing  PhotonTest  PhotonTestAMR
RadiationTransport% cd PhotonTest
PhotonTest% ls
PhotonTest.enzo
PhotonTest% 
```

Cosmological RT Codes Comparison
Iliev et al. (2006)

Test 1
Source at the origin
Uniform density field
No hydrodynamics
Isothermal
Mono-chromatic spectrum (13.6 eV)



```
#  RADIATIVE TRANSFER TEST PROBLEM
#
#  ** Test 1 from Iliev et al. (2006), MNRAS, 371, 1057 **
#
#  - Source at the origin
#  - Luminosity = 5e48 ph/s
#  - Fixed temperature, no hydro
#  - Density = 1e-3 cm^-3
#
ProblemType               = 50
TopGridRank               = 3
StopTime                  = 250

TopGridDimensions         = 32 32 32

MultiSpecies              = 1
RadiativeCooling          = 1
Gamma = 1.0001  // isothermal

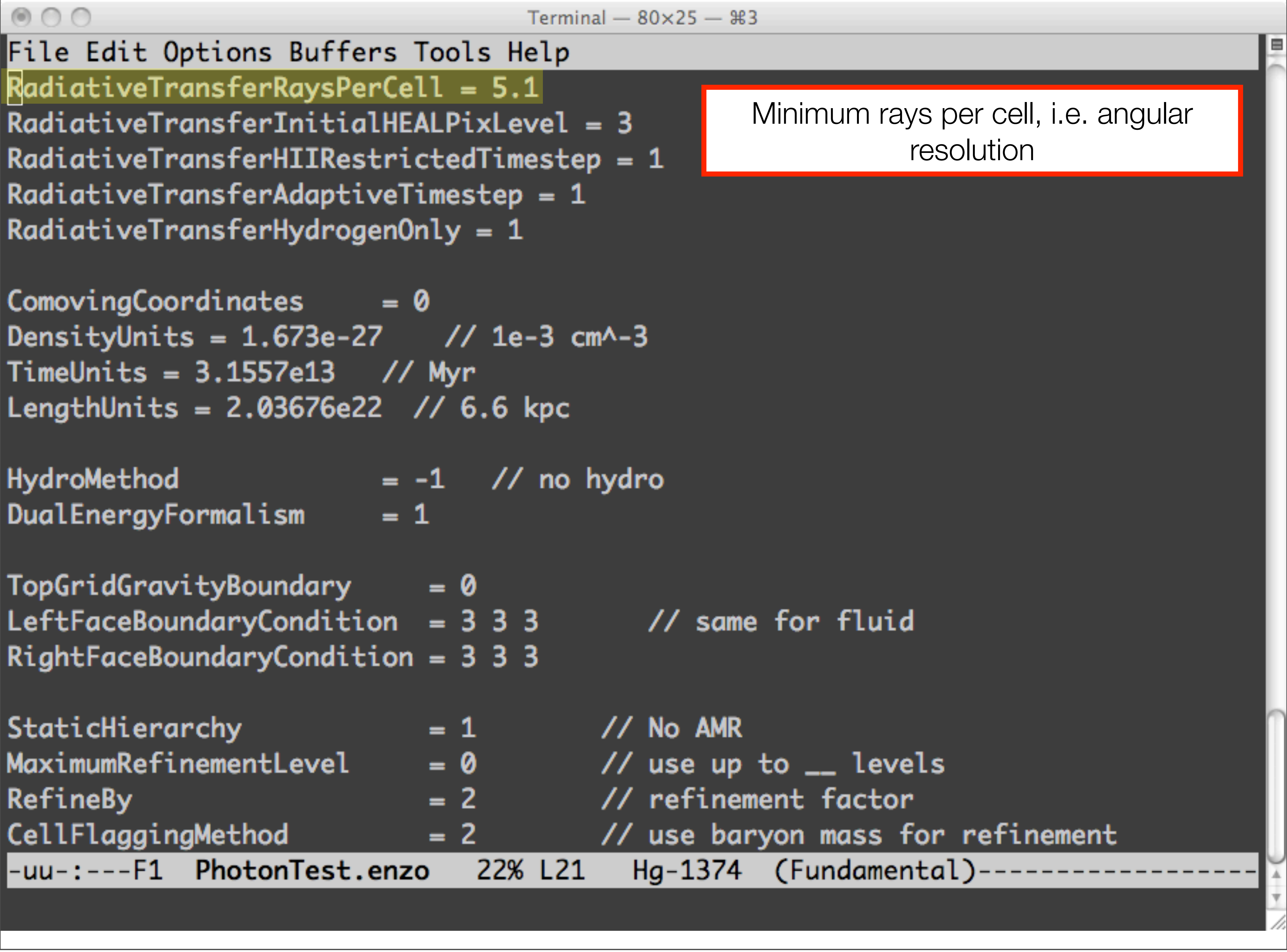
RadiativeTransfer         = 1
RadiativeTransferRaysPerCell = 5.1
RadiativeTransferInitialHEALPixLevel = 3
-uu-:---F1  PhotonTest.enzo    Top L22    Hg-1374  (Fundamental)----------------
Beginning of buffer
```

PhotonTest, i.e. CollapseTest with radiation sources

Must be ≥1. Doesn't make sense for an equation of state (no ionizations)

Turn on radiative transfer

Tuesday, 29 June 2010



```
RadiativeTransferRaysPerCell = 5.1
RadiativeTransferInitialHEALPixLevel = 3
RadiativeTransferHIIRestrictedTimestep = 1
RadiativeTransferAdaptiveTimestep = 1
RadiativeTransferHydrogenOnly = 1

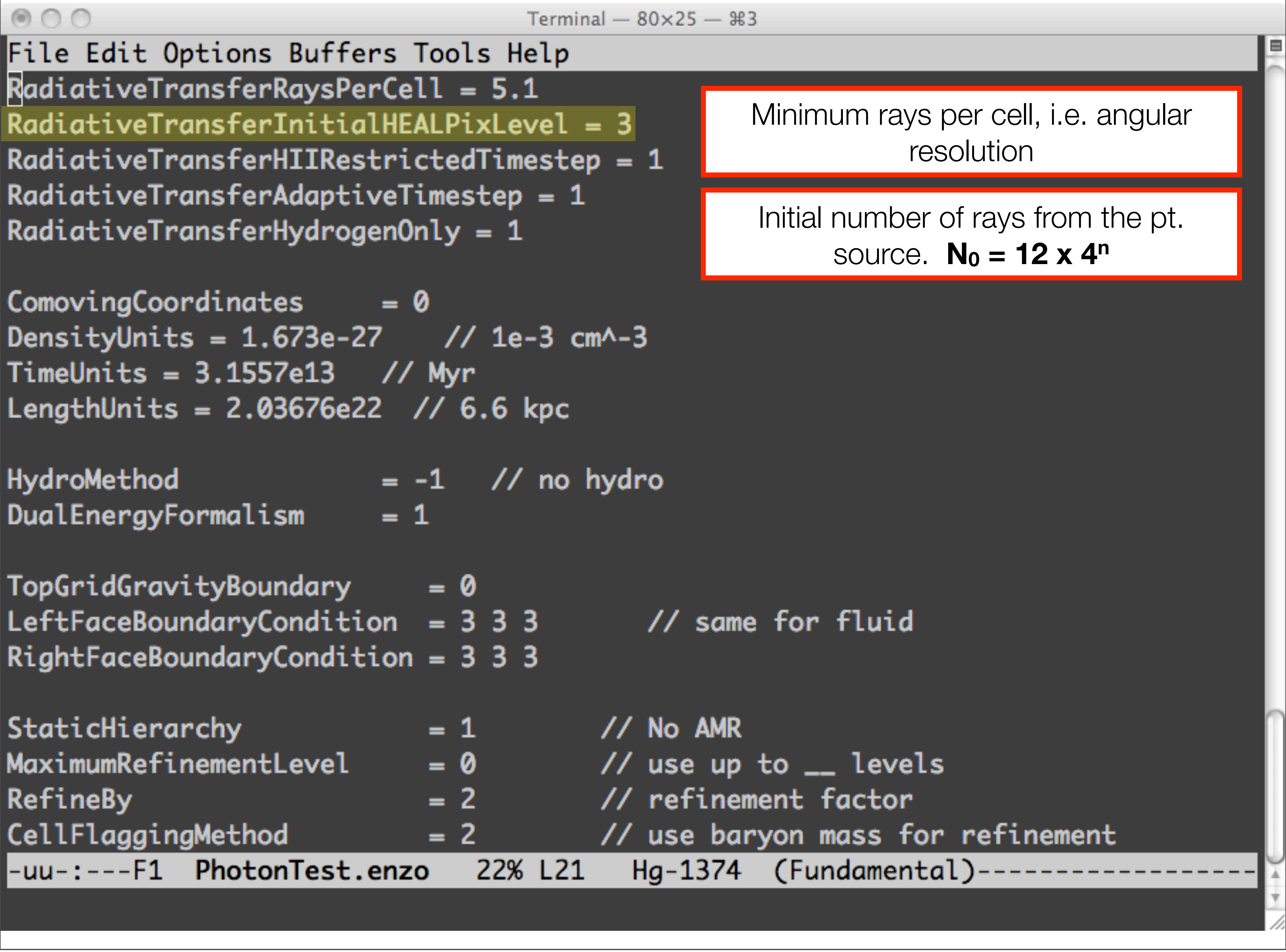
ComovingCoordinates      = 0
DensityUnits = 1.673e-27    // 1e-3 cm^-3
TimeUnits = 3.1557e13   // Myr
LengthUnits = 2.03676e22  // 6.6 kpc

HydroMethod             = -1   // no hydro
DualEnergyFormalism     = 1

TopGridGravityBoundary     = 0
LeftFaceBoundaryCondition  = 3 3 3       // same for fluid
RightFaceBoundaryCondition = 3 3 3

StaticHierarchy            = 1         // No AMR
MaximumRefinementLevel     = 0         // use up to __ levels
RefineBy                   = 2         // refinement factor
CellFlaggingMethod         = 2         // use baryon mass for refinement
-uu-:---F1  PhotonTest.enzo   22% L21   Hg-1374  (Fundamental)----------------
```

Minimum rays per cell, i.e. angular resolution



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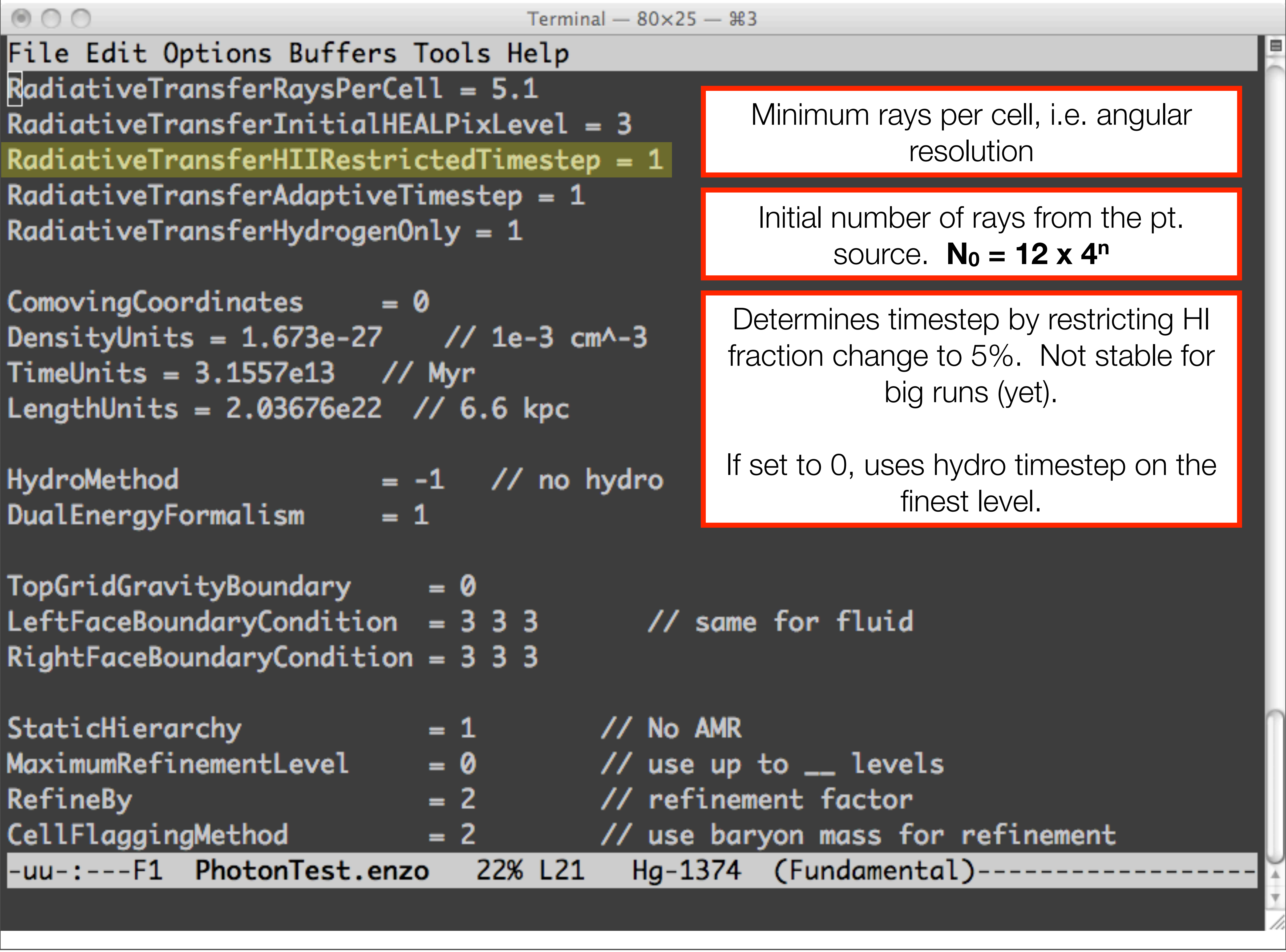
```

Minimum rays per cell, i.e. angular resolution

Initial number of rays from the pt. source. **$N_0 = 12 \times 4^n$**



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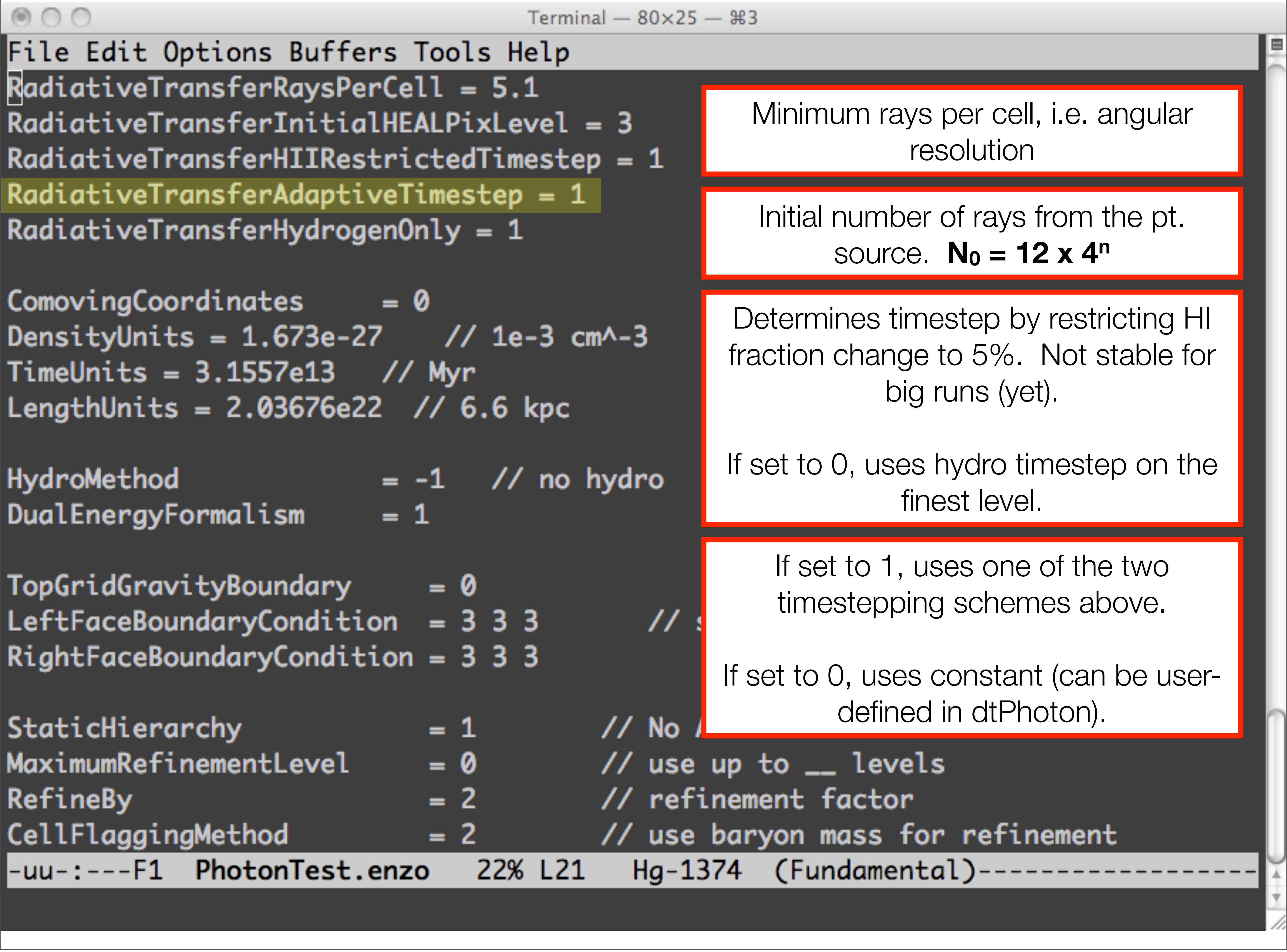
Minimum rays per cell, i.e. angular resolution

Initial number of rays from the pt. source. **$N_0 = 12 \times 4^n$**

Determines timestep by restricting HI fraction change to 5%. Not stable for big runs (yet).

If set to 0, uses hydro timestep on the finest level.



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Minimum rays per cell, i.e. angular resolution

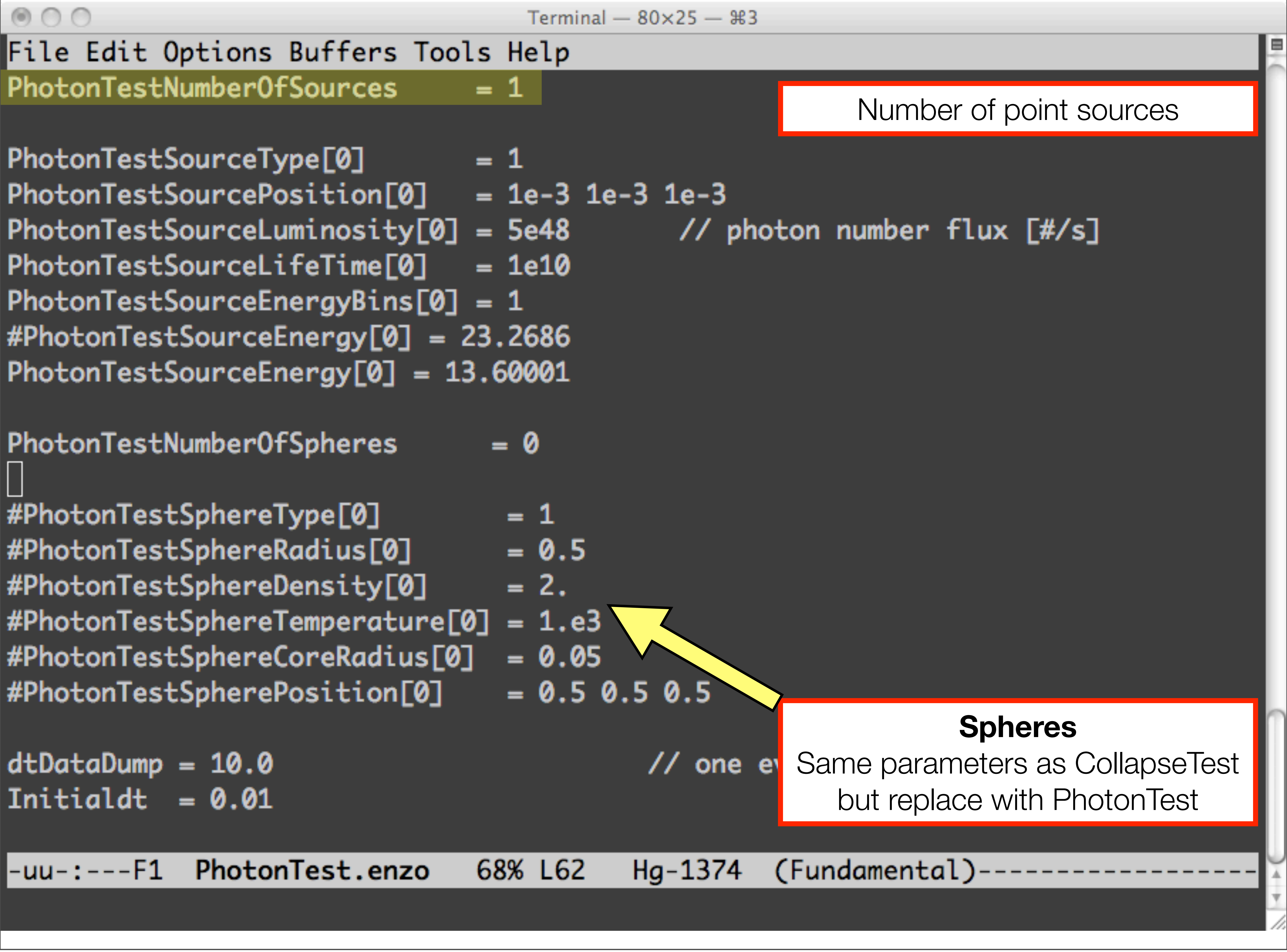
Initial number of rays from the pt. source. $\mathbf{N_0 = 12 \times 4^n}$

Determines timestep by restricting HI fraction change to 5%. Not stable for big runs (yet).

If set to 0, uses hydro timestep on the finest level.

If set to 1, uses one of the two timestepping schemes above.

If set to 0, uses constant (can be user-defined in dtPhoton).



```
PhotonTestNumberOfSources     = 1

PhotonTestSourceType[0]       = 1
PhotonTestSourcePosition[0]   = 1e-3 1e-3 1e-3
PhotonTestSourceLuminosity[0] = 5e48       // photon number flux [#/s]
PhotonTestSourceLifeTime[0]   = 1e10
PhotonTestSourceEnergyBins[0] = 1
#PhotonTestSourceEnergy[0] = 23.2686
PhotonTestSourceEnergy[0] = 13.60001

PhotonTestNumberOfSpheres      = 0

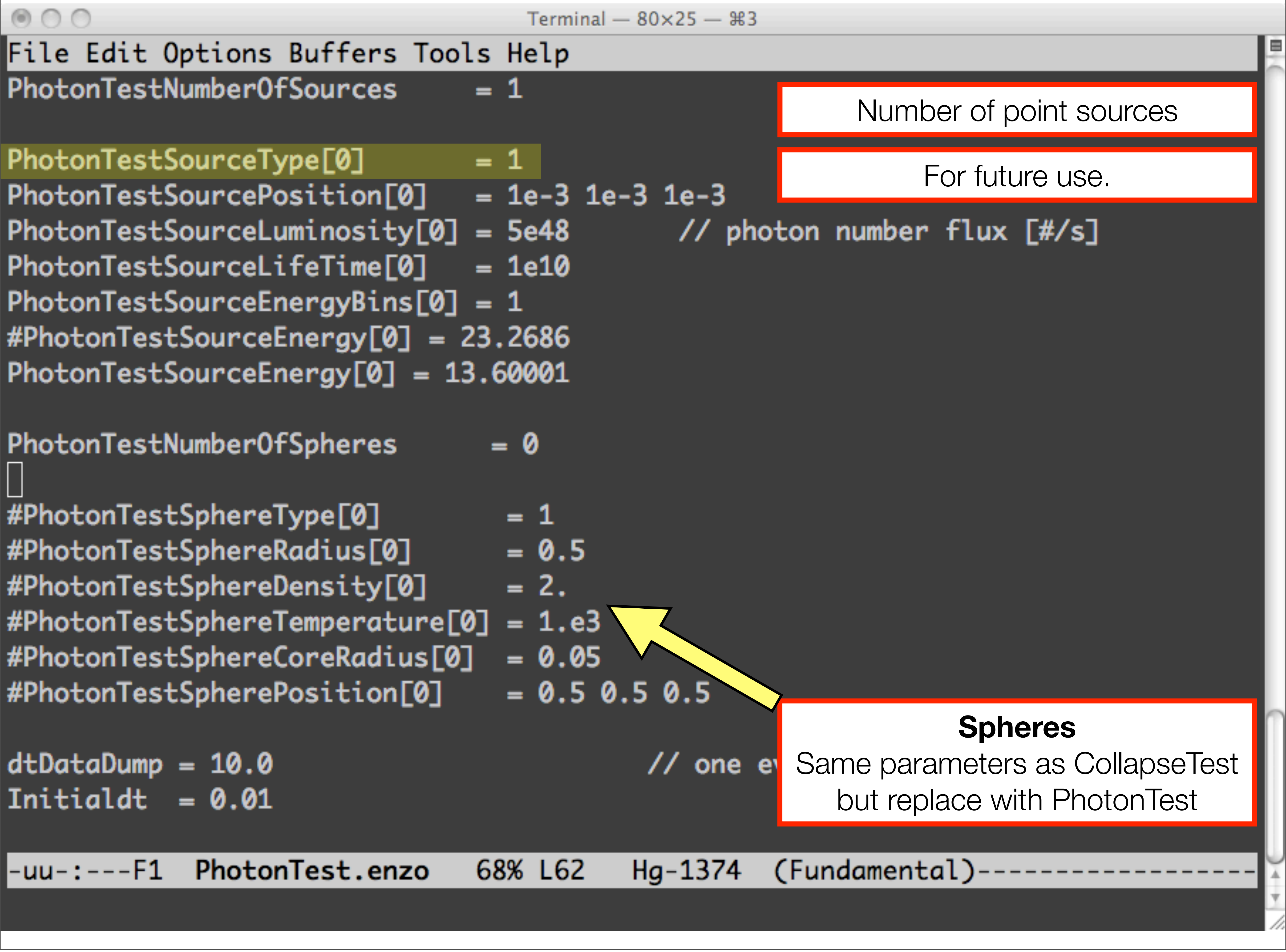
#PhotonTestSphereType[0]        = 1
#PhotonTestSphereRadius[0]      = 0.5
#PhotonTestSphereDensity[0]     = 2.
#PhotonTestSphereTemperature[0] = 1.e3
#PhotonTestSphereCoreRadius[0]  = 0.05
#PhotonTestSpherePosition[0]    = 0.5 0.5 0.5

dtDataDump = 10.0                        // one e
Initialdt  = 0.01

-uu-:---F1  PhotonTest.enzo   68% L62   Hg-1374  (Fundamental)-----------------
```

Number of point sources

Spheres
Same parameters as CollapseTest
but replace with PhotonTest



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-uu-:---F1  PhotonTest.enzo    68% L62    Hg-1374   (Fundamental)----------------
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Number of point sources

For future use.

Spheres
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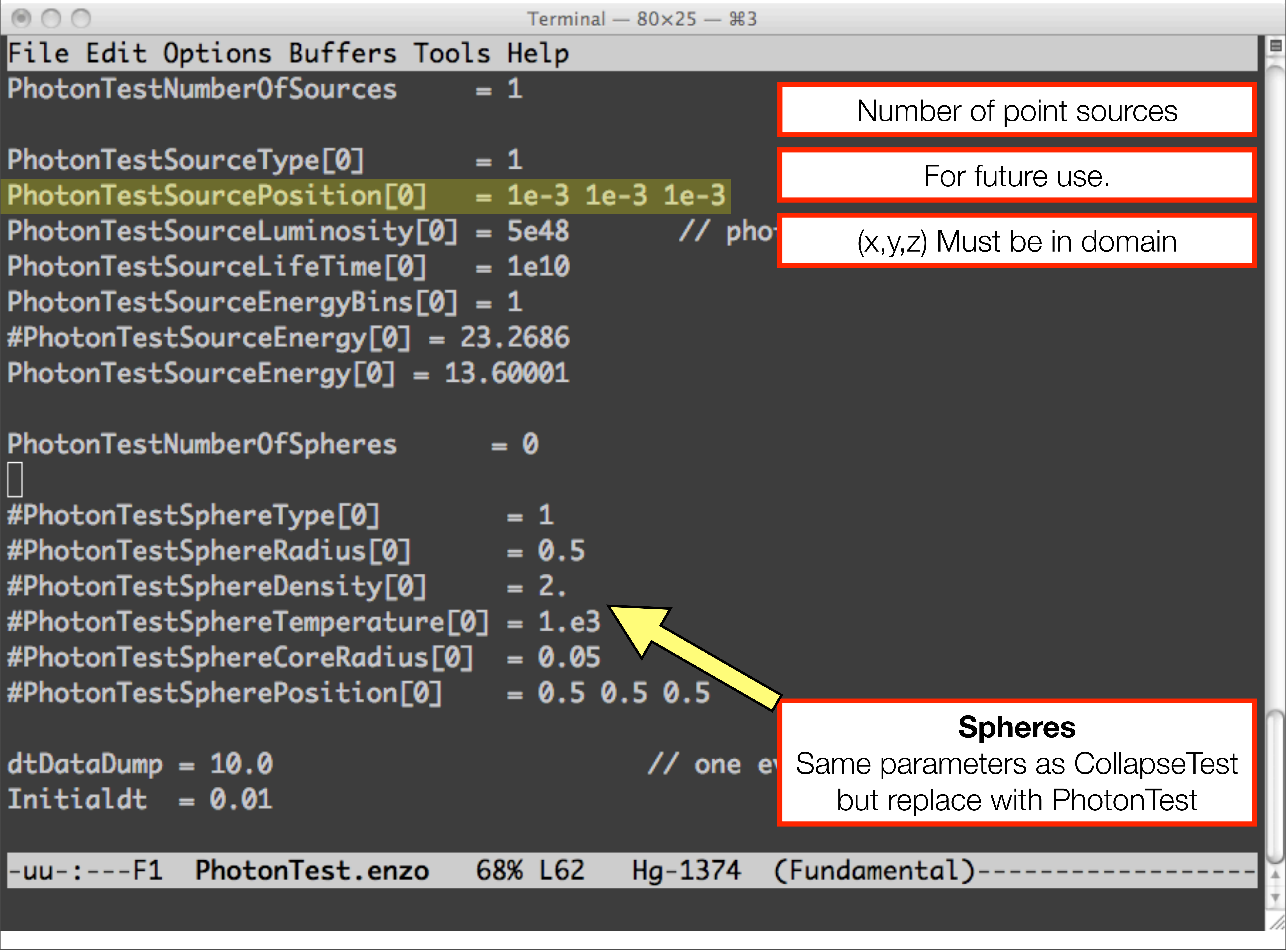

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Number of point sources

For future use.

(x,y,z) Must be in domain

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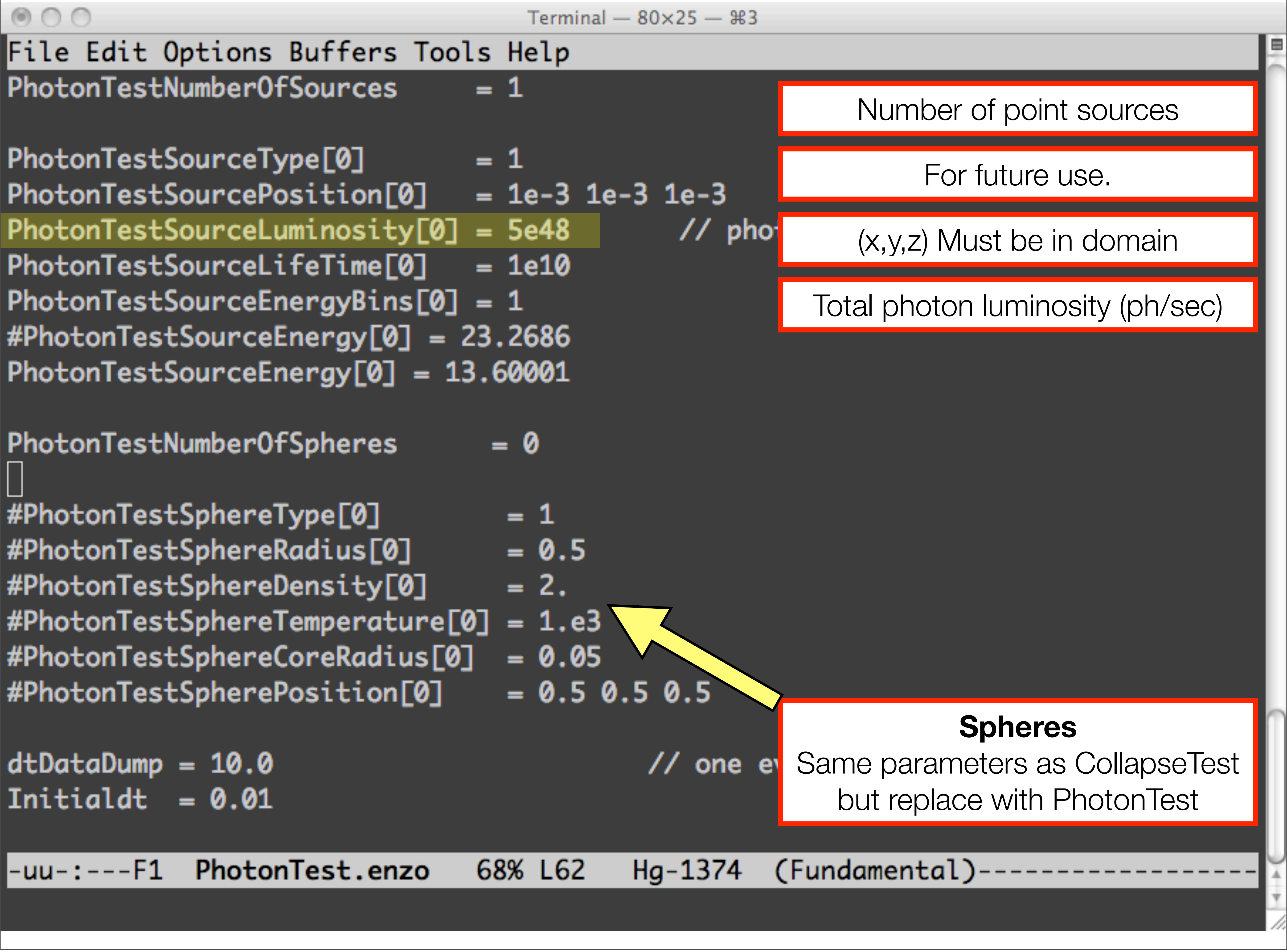

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-uu-:---F1  PhotonTest.enzo    68% L62    Hg-1374  (Fundamental)-----------------
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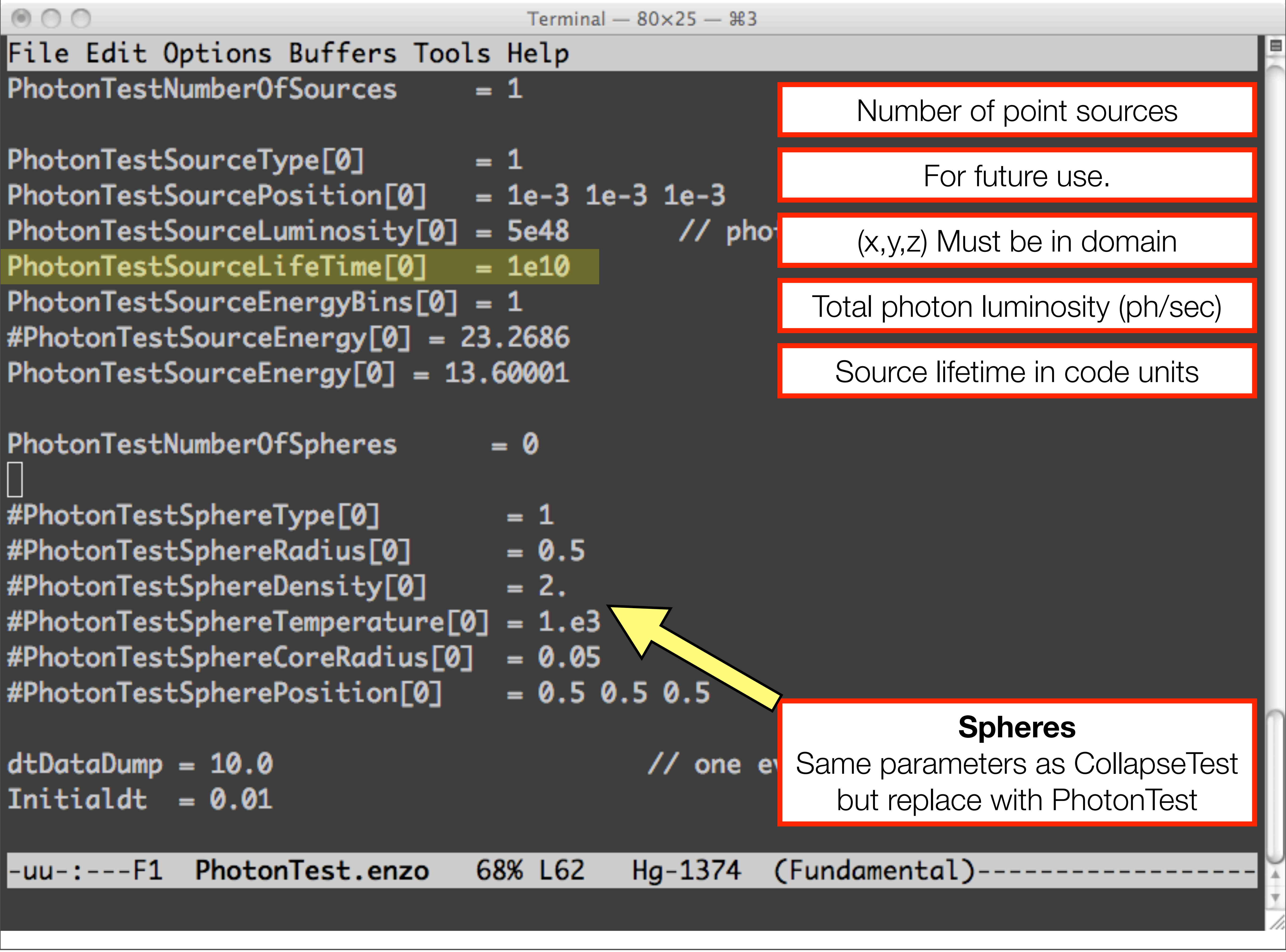
Number of point sources

For future use.

(x,y,z) Must be in domain

Total photon luminosity (ph/sec)

Spheres
Same parameters as CollapseTest
but replace with PhotonTest



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-uu-:---F1  PhotonTest.enzo    68% L62    Hg-1374  (Fundamental)-----------------
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Number of point sources

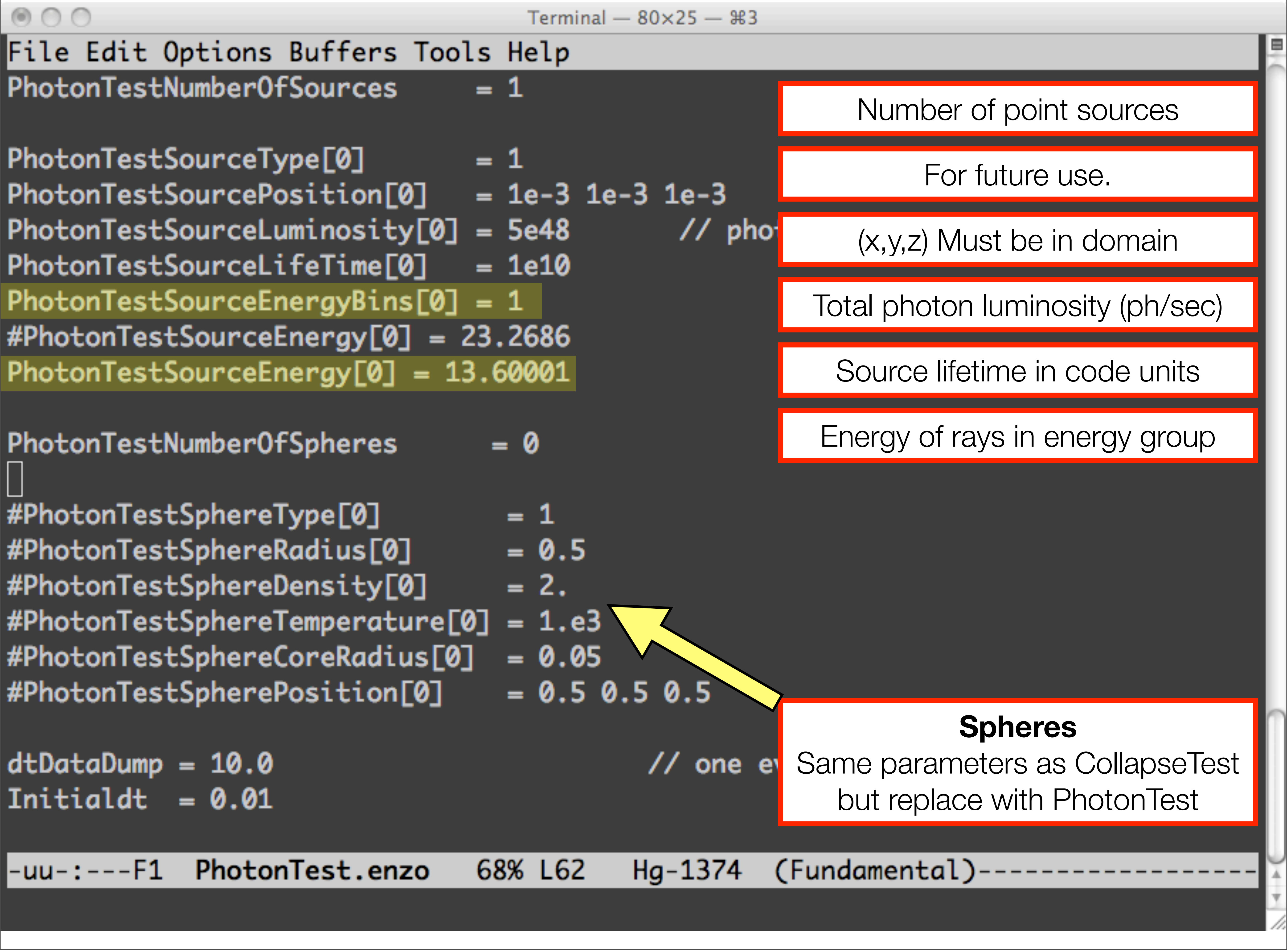
For future use.

(x,y,z) Must be in domain

Total photon luminosity (ph/sec)

Source lifetime in code units

Spheres
Same parameters as CollapseTest
but replace with PhotonTest



```
File Edit Options Buffers Tools Help
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#PhotonTestSphereType[0]          = 1
#PhotonTestSphereRadius[0]        = 0.5
#PhotonTestSphereDensity[0]       = 2.
#PhotonTestSphereTemperature[0] = 1.e3
#PhotonTestSphereCoreRadius[0]  = 0.05
#PhotonTestSpherePosition[0]    = 0.5 0.5 0.5

dtDataDump = 10.0                         // one e
Initialdt  = 0.01

-uu-:---F1  PhotonTest.enzo    68% L62    Hg-1374   (Fundamental)-----------------
```

Number of point sources

For future use.

(x,y,z) Must be in domain

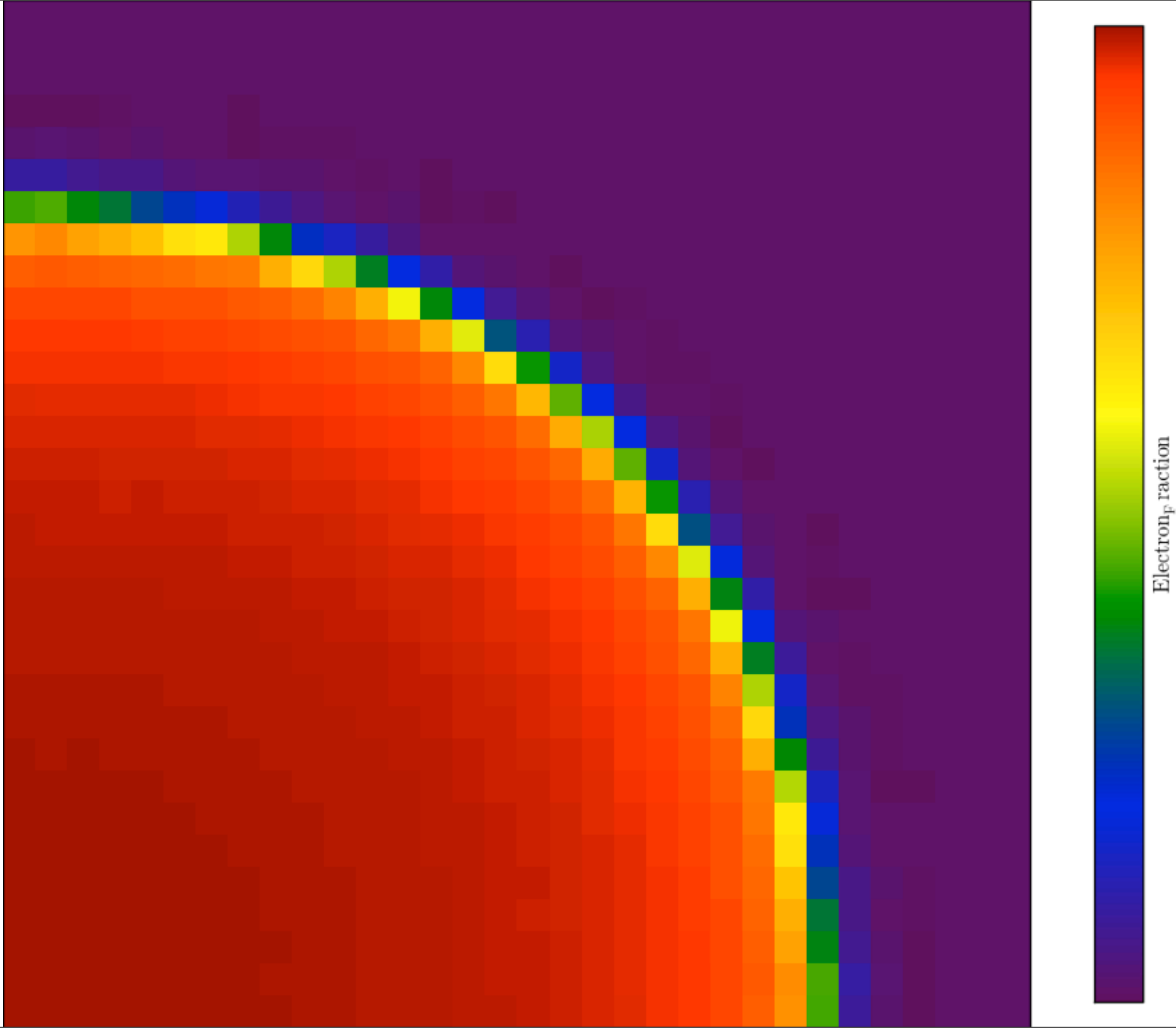
Total photon luminosity (ph/sec)

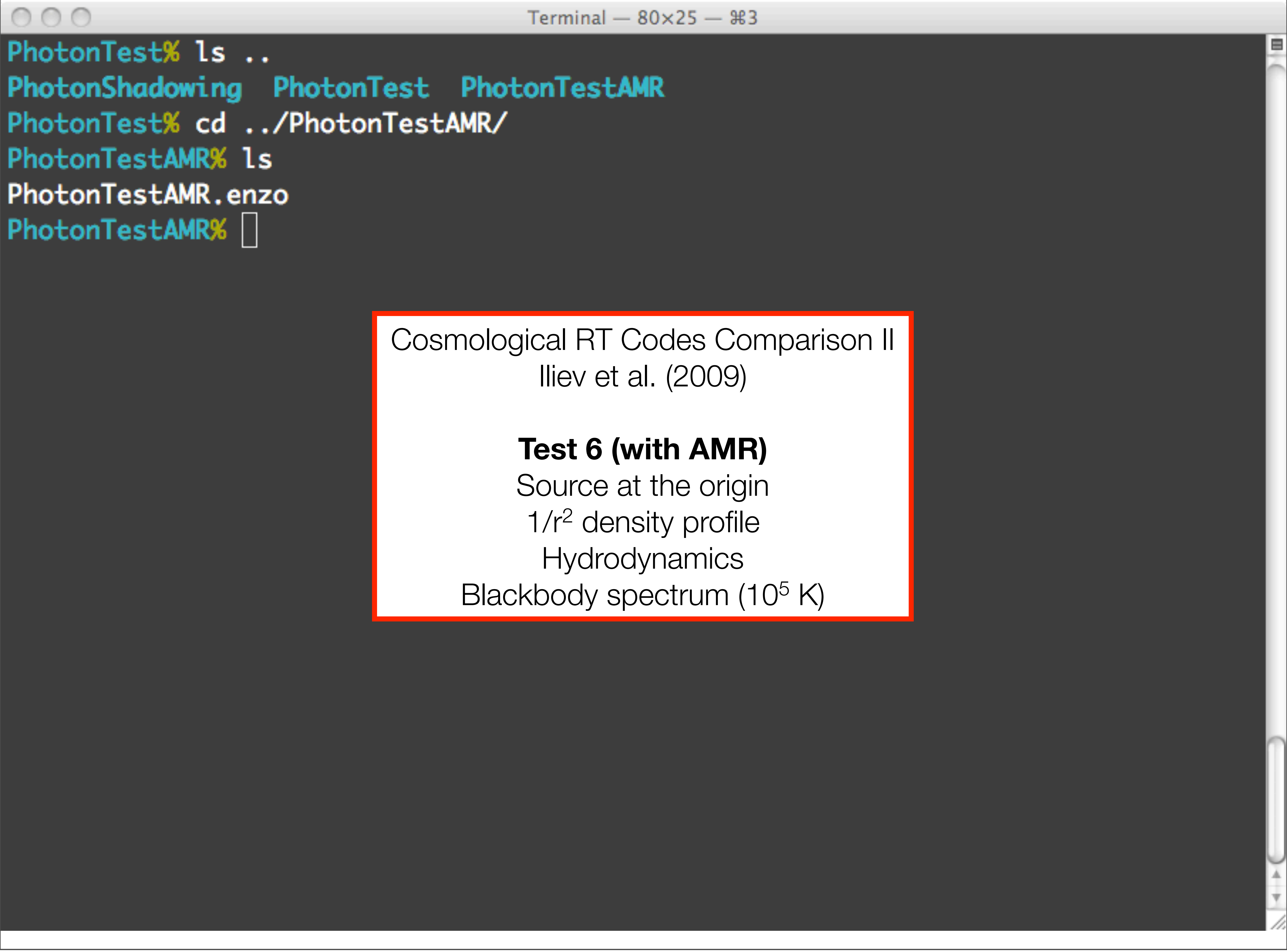
Source lifetime in code units

Energy of rays in energy group

Spheres

Same parameters as CollapseTest but replace with PhotonTest

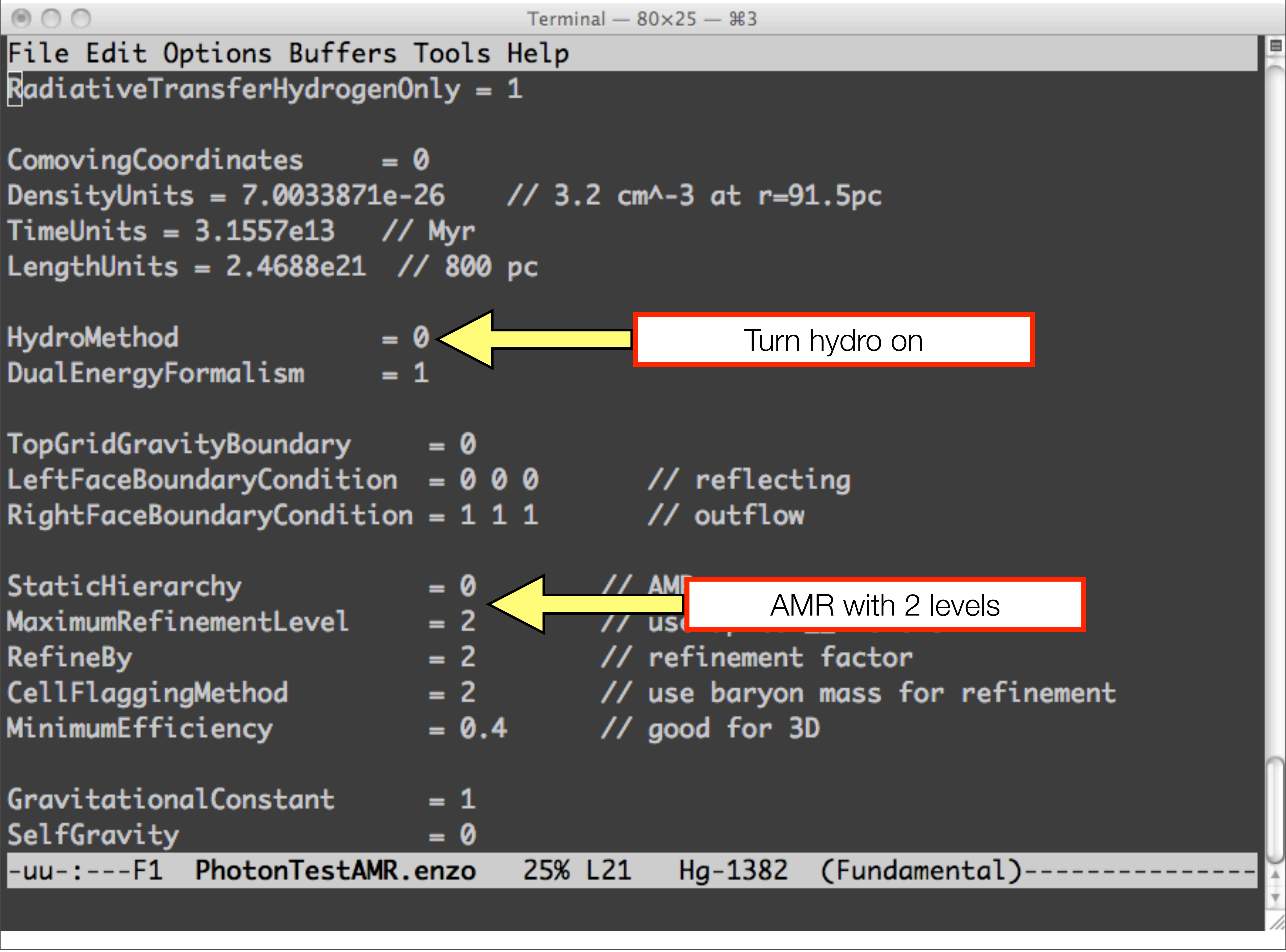

Electron$_F$ raction



```
PhotonTest% ls ..
PhotonShadowing  PhotonTest  PhotonTestAMR
PhotonTest% cd ../PhotonTestAMR/
PhotonTestAMR% ls
PhotonTestAMR.enzo
PhotonTestAMR% 
```

Cosmological RT Codes Comparison II
Iliev et al. (2009)

Test 6 (with AMR)
Source at the origin
$1/r^2$ density profile
Hydrodynamics
Blackbody spectrum (10^5 K)



```
RadiativeTransferHydrogenOnly = 1

ComovingCoordinates       = 0
DensityUnits = 7.0033871e-26    // 3.2 cm^-3 at r=91.5pc
TimeUnits = 3.1557e13    // Myr
LengthUnits = 2.4688e21  // 800 pc

HydroMethod               = 0
DualEnergyFormalism       = 1

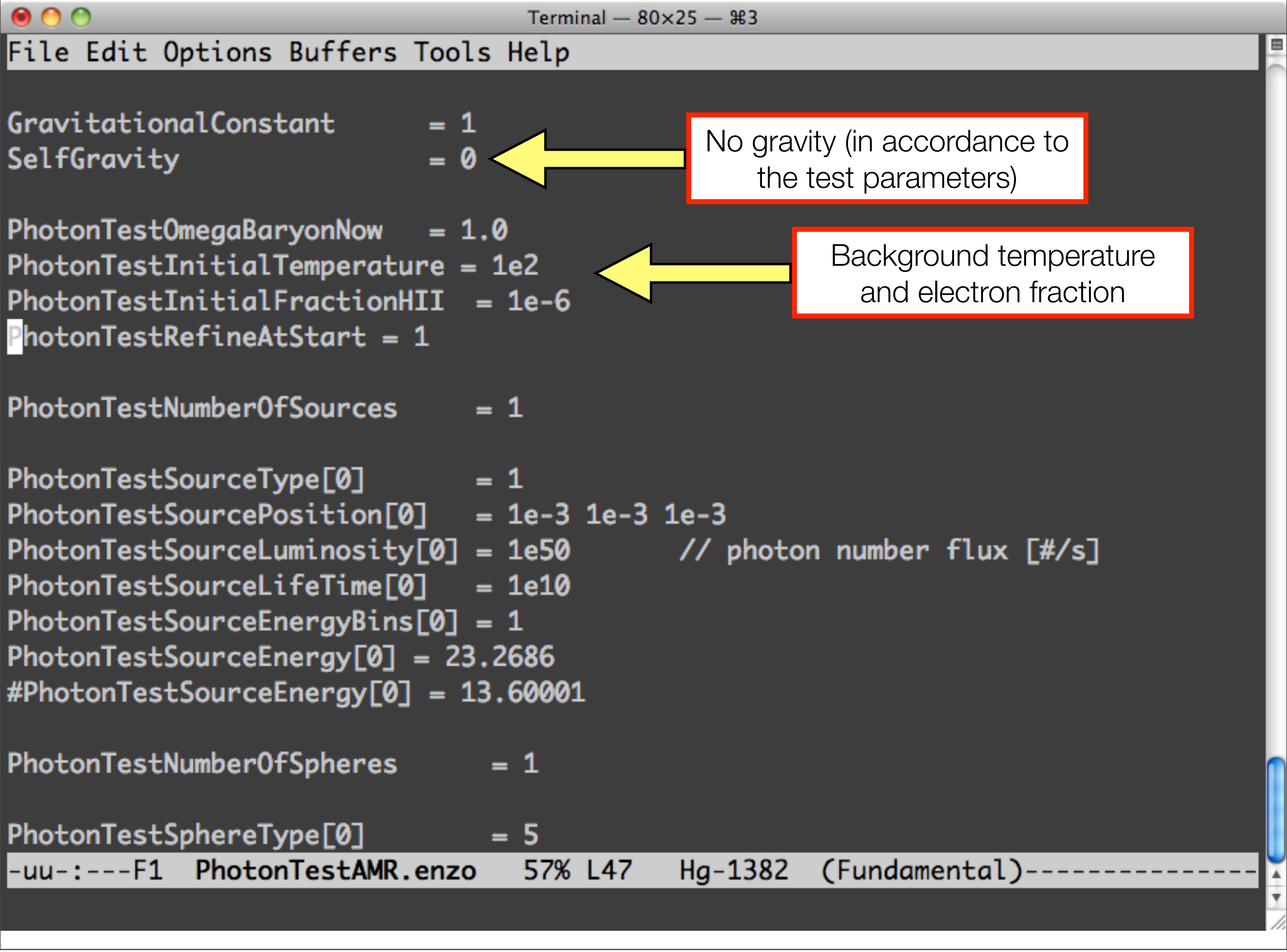
TopGridGravityBoundary       = 0
LeftFaceBoundaryCondition  = 0 0 0       // reflecting
RightFaceBoundaryCondition = 1 1 1       // outflow

StaticHierarchy              = 0       // AM
MaximumRefinementLevel       = 2       // us
RefineBy                     = 2       // refinement factor
CellFlaggingMethod           = 2       // use baryon mass for refinement
MinimumEfficiency            = 0.4     // good for 3D

GravitationalConstant        = 1
SelfGravity                  = 0
-uu-:---F1  PhotonTestAMR.enzo    25% L21    Hg-1382  (Fundamental)--------------
```

Turn hydro on

AMR with 2 levels



```

GravitationalConstant       = 1
SelfGravity                 = 0

PhotonTestOmegaBaryonNow    = 1.0
PhotonTestInitialTemperature = 1e2
PhotonTestInitialFractionHII   = 1e-6
PhotonTestRefineAtStart = 1

PhotonTestNumberOfSources      = 1

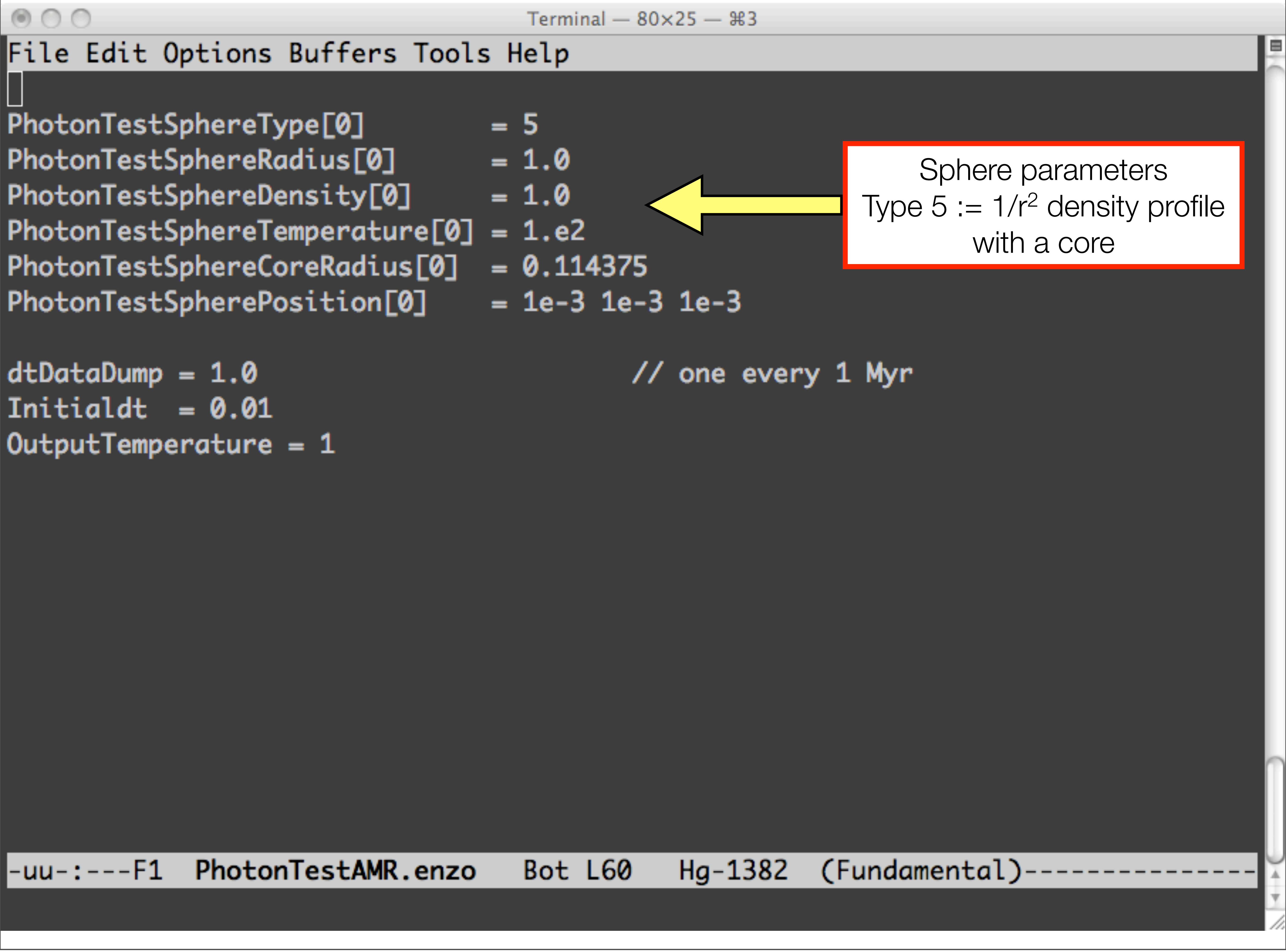
PhotonTestSourceType[0]        = 1
PhotonTestSourcePosition[0]    = 1e-3 1e-3 1e-3
PhotonTestSourceLuminosity[0] = 1e50       // photon number flux [#/s]
PhotonTestSourceLifeTime[0]    = 1e10
PhotonTestSourceEnergyBins[0] = 1
PhotonTestSourceEnergy[0] = 23.2686
#PhotonTestSourceEnergy[0] = 13.60001

PhotonTestNumberOfSpheres       = 1

PhotonTestSphereType[0]         = 5
-uu-:---F1  PhotonTestAMR.enzo   57% L47   Hg-1382  (Fundamental)--------------
```

No gravity (in accordance to the test parameters)

Background temperature and electron fraction

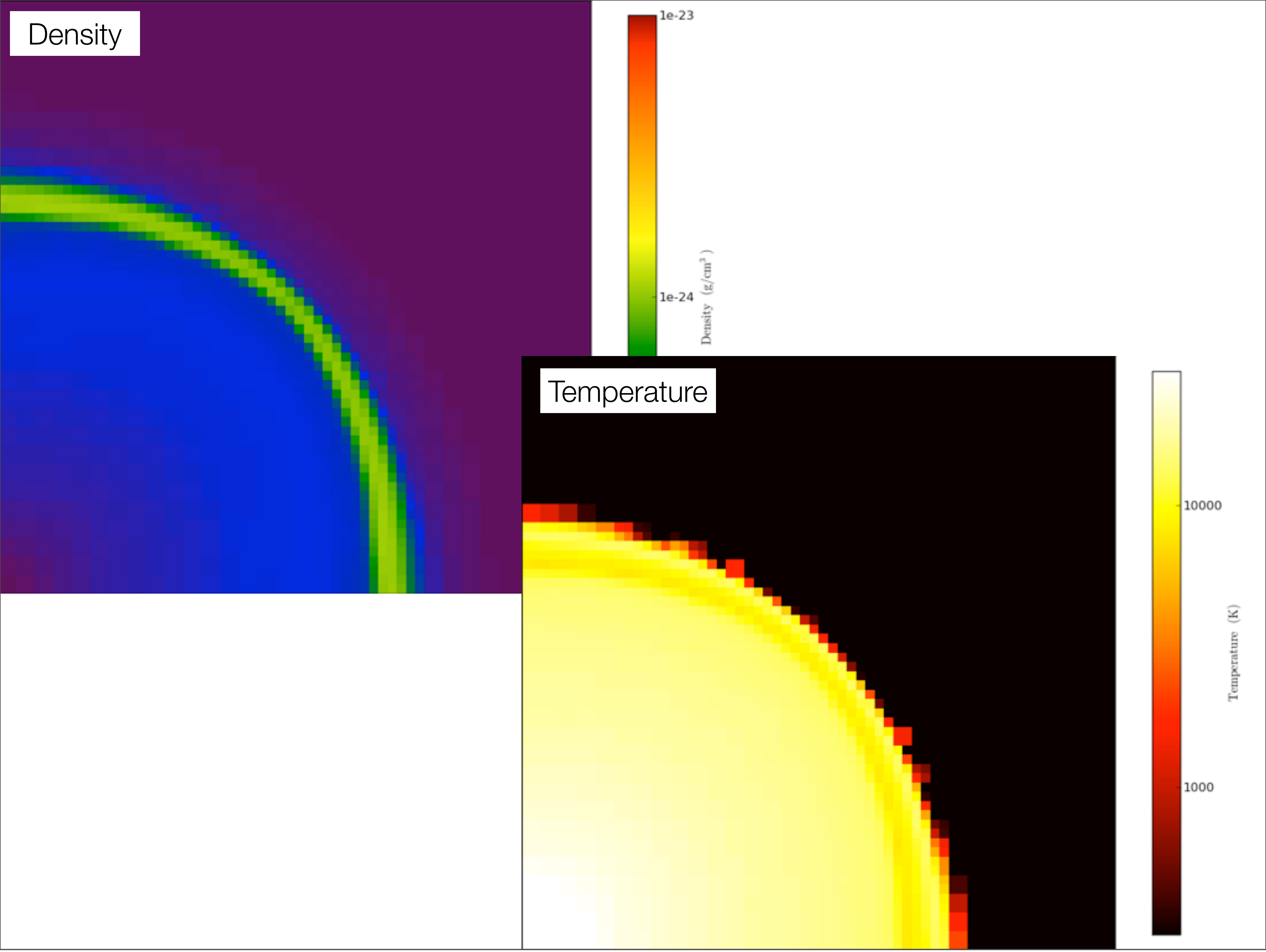


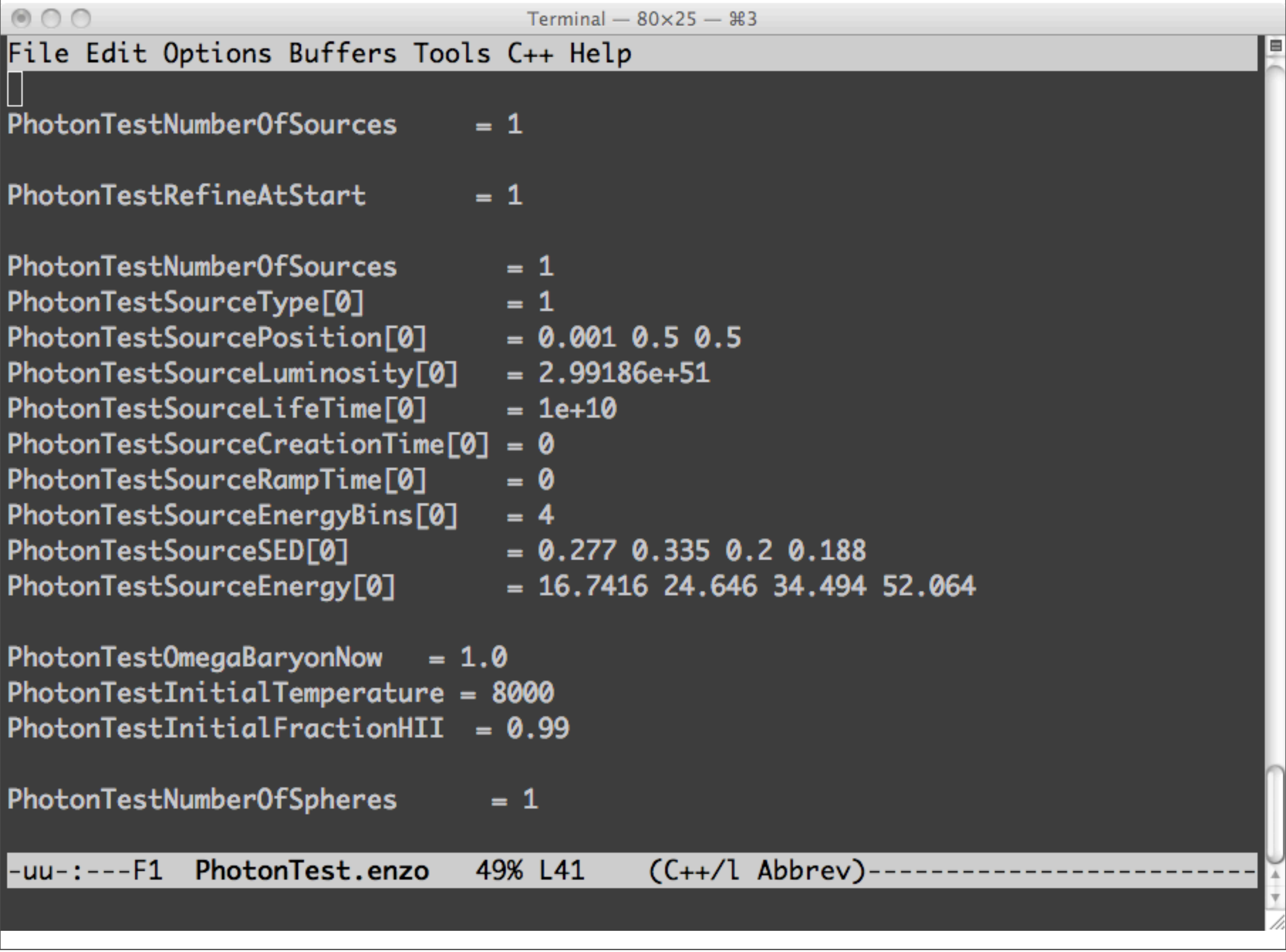
```
PhotonTestSphereType[0]        = 5
PhotonTestSphereRadius[0]      = 1.0
PhotonTestSphereDensity[0]     = 1.0
PhotonTestSphereTemperature[0] = 1.e2
PhotonTestSphereCoreRadius[0]  = 0.114375
PhotonTestSpherePosition[0]    = 1e-3 1e-3 1e-3

dtDataDump = 1.0                        // one every 1 Myr
Initialdt  = 0.01
OutputTemperature = 1
```

```
-uu-:---F1  PhotonTestAMR.enzo   Bot L60   Hg-1382  (Fundamental)-------------
```

Sphere parameters
Type 5 := $1/r^2$ density profile
with a core


Density
1e-23
1e-24
Density (g/cm^3)
Temperature
10000
1000
Temperature (K)



```

PhotonTestNumberOfSources     = 1

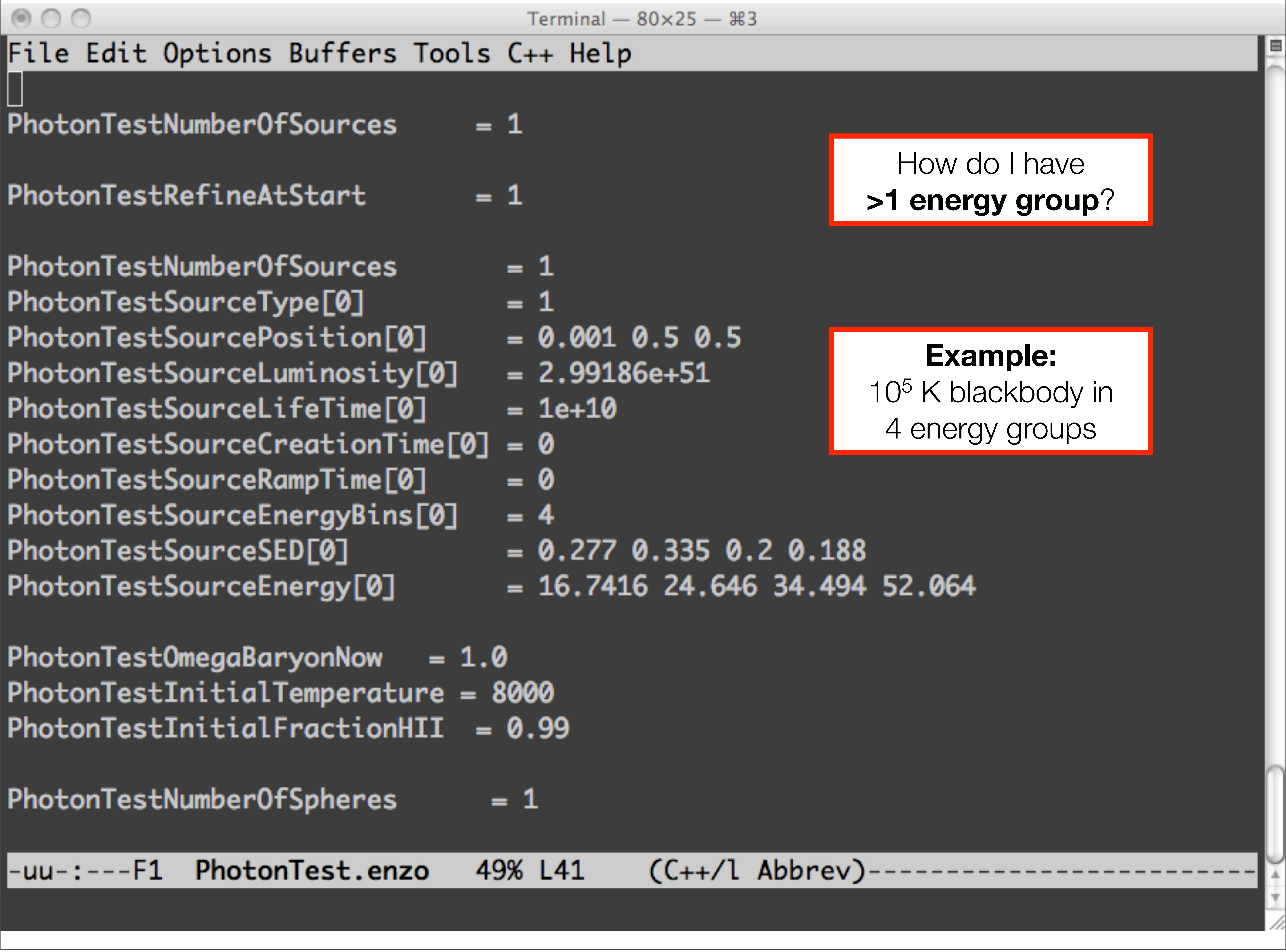
PhotonTestRefineAtStart       = 1

PhotonTestNumberOfSources       = 1
PhotonTestSourceType[0]         = 1
PhotonTestSourcePosition[0]     = 0.001 0.5 0.5
PhotonTestSourceLuminosity[0]   = 2.99186e+51
PhotonTestSourceLifeTime[0]     = 1e+10
PhotonTestSourceCreationTime[0] = 0
PhotonTestSourceRampTime[0]     = 0
PhotonTestSourceEnergyBins[0]   = 4
PhotonTestSourceSED[0]          = 0.277 0.335 0.2 0.188
PhotonTestSourceEnergy[0]       = 16.7416 24.646 34.494 52.064

PhotonTestOmegaBaryonNow   = 1.0
PhotonTestInitialTemperature = 8000
PhotonTestInitialFractionHII  = 0.99

PhotonTestNumberOfSpheres      = 1

```



```
PhotonTestNumberOfSources      = 1

PhotonTestRefineAtStart        = 1

PhotonTestNumberOfSources        = 1
PhotonTestSourceType[0]          = 1
PhotonTestSourcePosition[0]      = 0.001 0.5 0.5
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PhotonTestSourceSED[0]           = 0.277 0.335 0.2 0.188
PhotonTestSourceEnergy[0]        = 16.7416 24.646 34.494 52.064

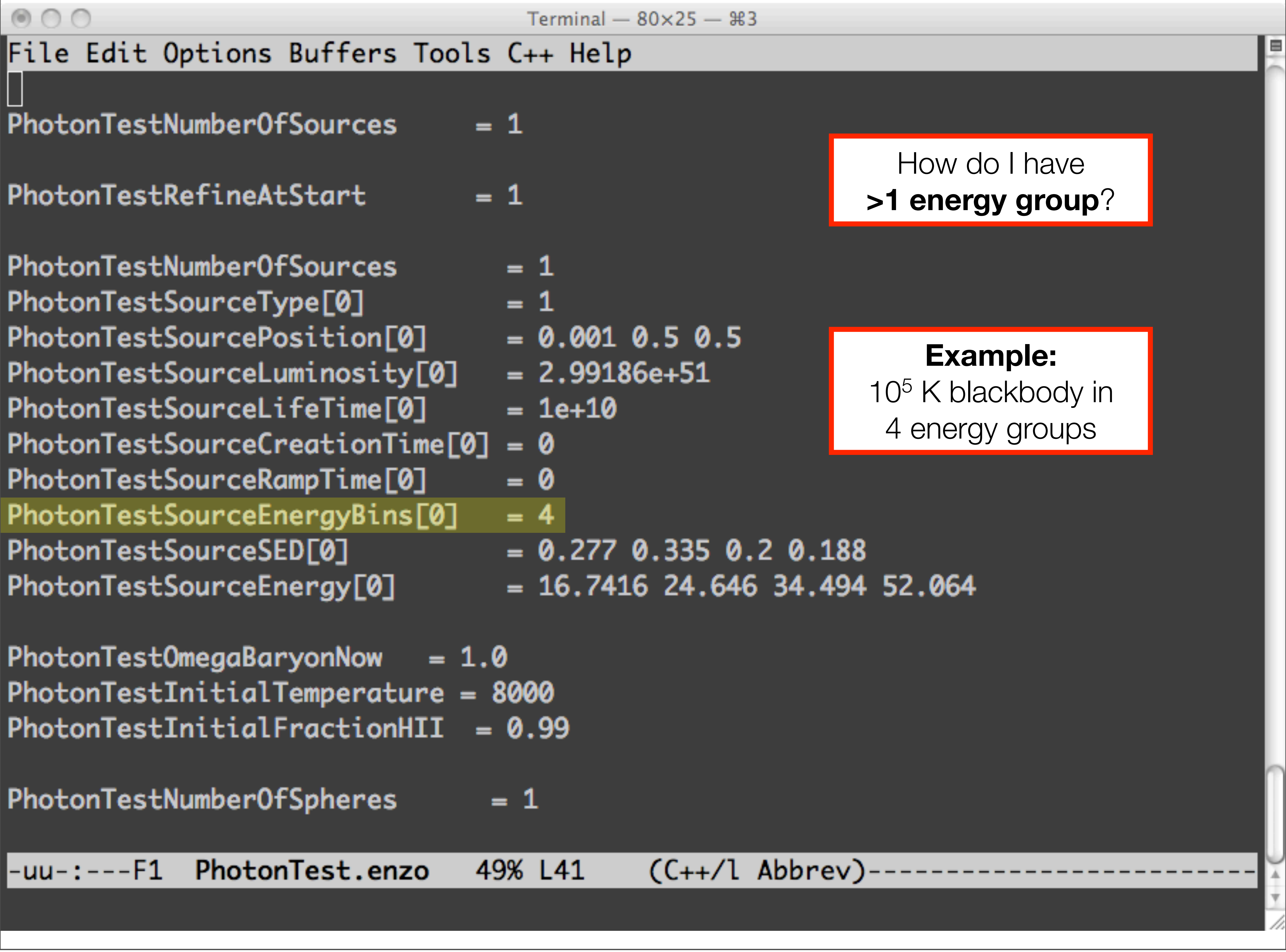
PhotonTestOmegaBaryonNow    = 1.0
PhotonTestInitialTemperature = 8000
PhotonTestInitialFractionHII  = 0.99

PhotonTestNumberOfSpheres       = 1

-uu-:---F1  PhotonTest.enzo    49% L41     (C++/l Abbrev)------------------------
```

How do I have
>1 energy group?

Example:
10^5 K blackbody in
4 energy groups



```
PhotonTestNumberOfSources      = 1

PhotonTestRefineAtStart        = 1

PhotonTestNumberOfSources        = 1
PhotonTestSourceType[0]          = 1
PhotonTestSourcePosition[0]      = 0.001 0.5 0.5
PhotonTestSourceLuminosity[0]    = 2.99186e+51
PhotonTestSourceLifeTime[0]      = 1e+10
PhotonTestSourceCreationTime[0]  = 0
PhotonTestSourceRampTime[0]      = 0
PhotonTestSourceEnergyBins[0]    = 4
PhotonTestSourceSED[0]           = 0.277 0.335 0.2 0.188
PhotonTestSourceEnergy[0]        = 16.7416 24.646 34.494 52.064

PhotonTestOmegaBaryonNow    = 1.0
PhotonTestInitialTemperature = 8000
PhotonTestInitialFractionHII  = 0.99

PhotonTestNumberOfSpheres       = 1

-uu-:---F1  PhotonTest.enzo    49% L41    (C++/l Abbrev)--------------------------
```

How do I have
>1 energy group?

Example:
10^5 K blackbody in
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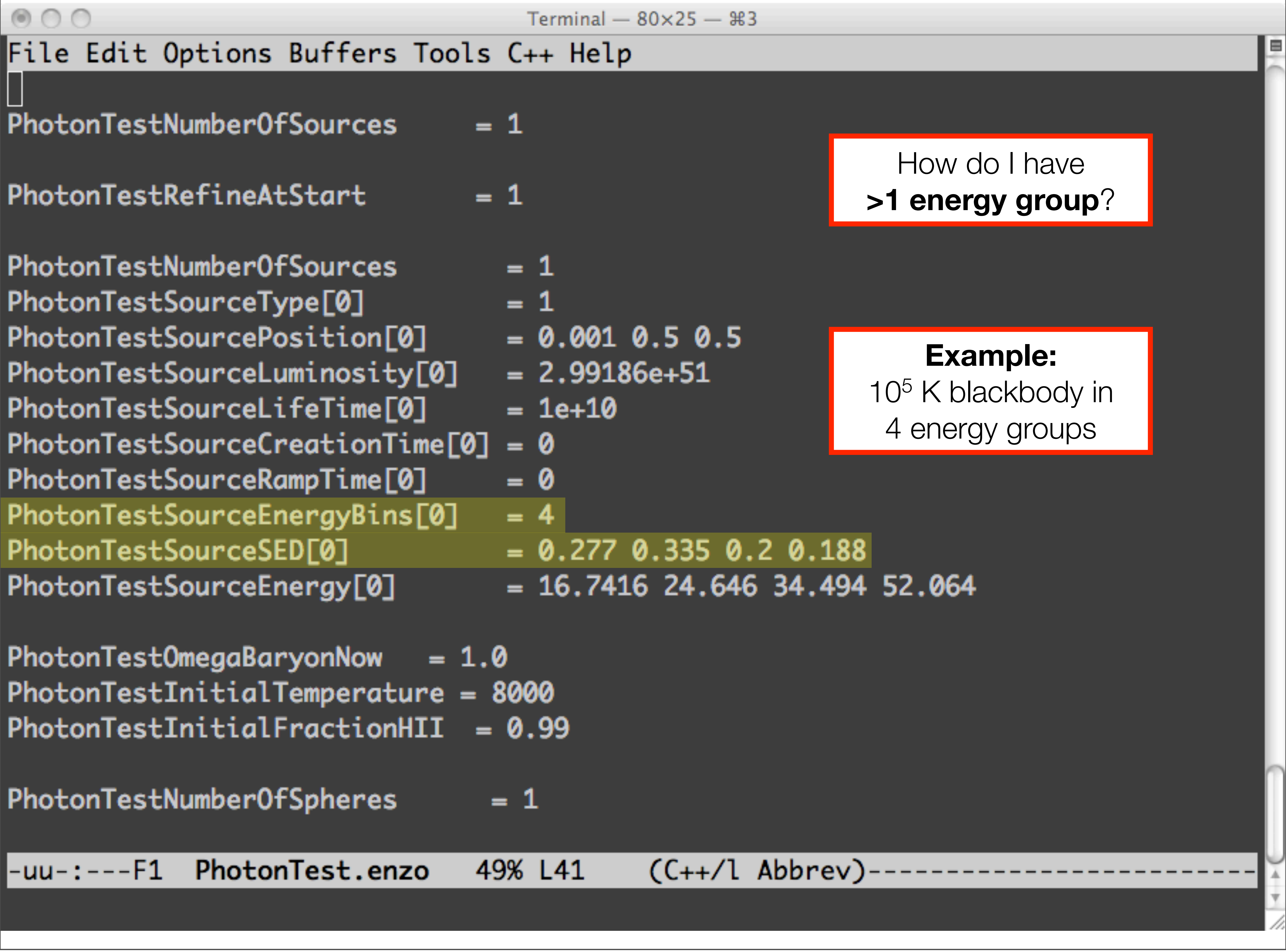


```
PhotonTestNumberOfSources      = 1

PhotonTestRefineAtStart        = 1

PhotonTestNumberOfSources         = 1
PhotonTestSourceType[0]           = 1
PhotonTestSourcePosition[0]       = 0.001 0.5 0.5
PhotonTestSourceLuminosity[0]     = 2.99186e+51
PhotonTestSourceLifeTime[0]       = 1e+10
PhotonTestSourceCreationTime[0]   = 0
PhotonTestSourceRampTime[0]       = 0
PhotonTestSourceEnergyBins[0]     = 4
PhotonTestSourceSED[0]            = 0.277 0.335 0.2 0.188
PhotonTestSourceEnergy[0]         = 16.7416 24.646 34.494 52.064

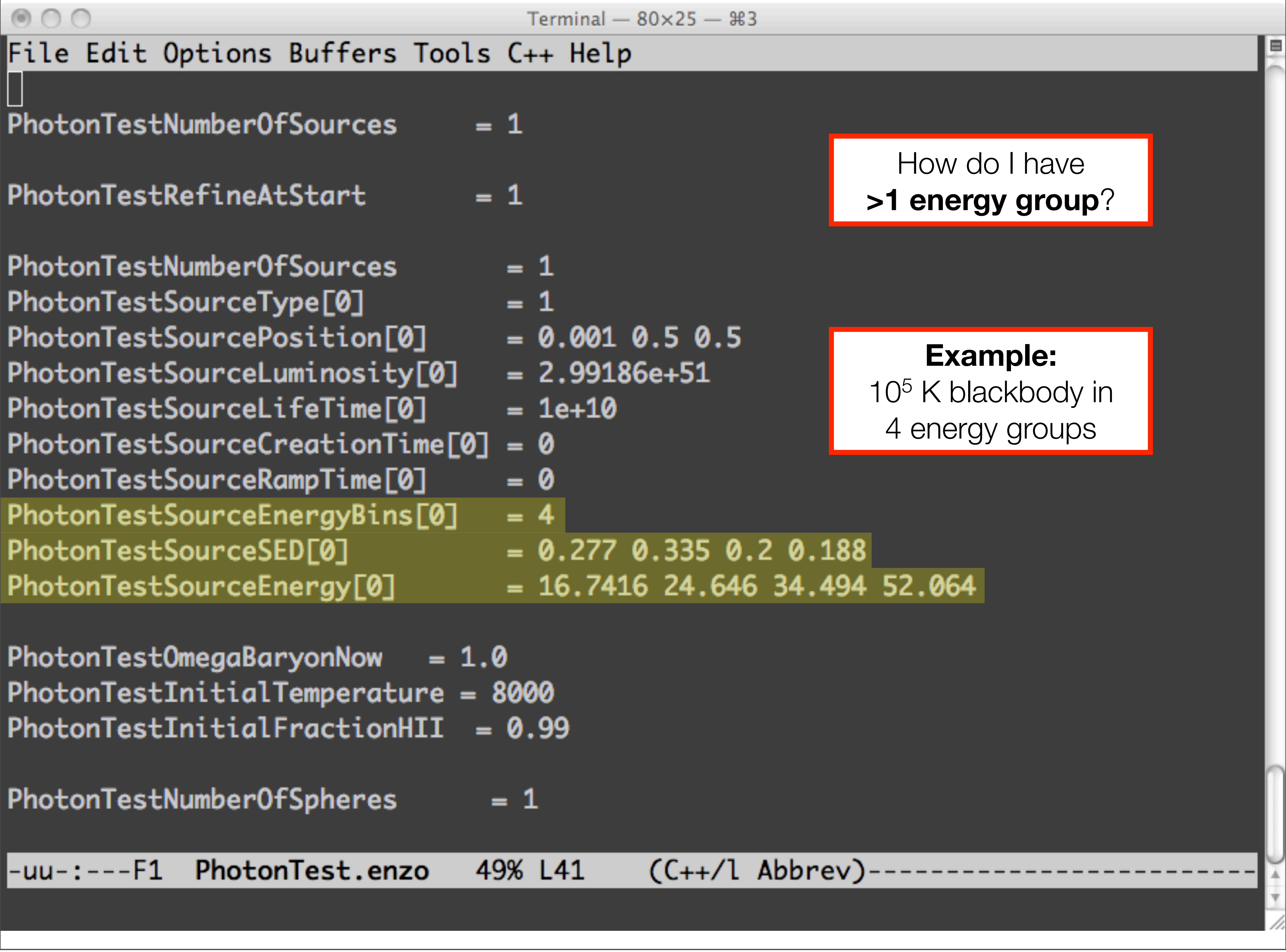
PhotonTestOmegaBaryonNow     = 1.0
PhotonTestInitialTemperature = 8000
PhotonTestInitialFractionHII   = 0.99

PhotonTestNumberOfSpheres        = 1

-uu-:---F1  PhotonTest.enzo    49% L41    (C++/l Abbrev)------------------------
```

How do I have
>1 energy group?

Example:
10^5 K blackbody in
4 energy groups



```
PhotonTestNumberOfSources      = 1

PhotonTestRefineAtStart        = 1

PhotonTestNumberOfSources         = 1
PhotonTestSourceType[0]           = 1
PhotonTestSourcePosition[0]       = 0.001 0.5 0.5
PhotonTestSourceLuminosity[0]     = 2.99186e+51
PhotonTestSourceLifeTime[0]       = 1e+10
PhotonTestSourceCreationTime[0]   = 0
PhotonTestSourceRampTime[0]       = 0
PhotonTestSourceEnergyBins[0]     = 4
PhotonTestSourceSED[0]            = 0.277 0.335 0.2 0.188
PhotonTestSourceEnergy[0]         = 16.7416 24.646 34.494 52.064

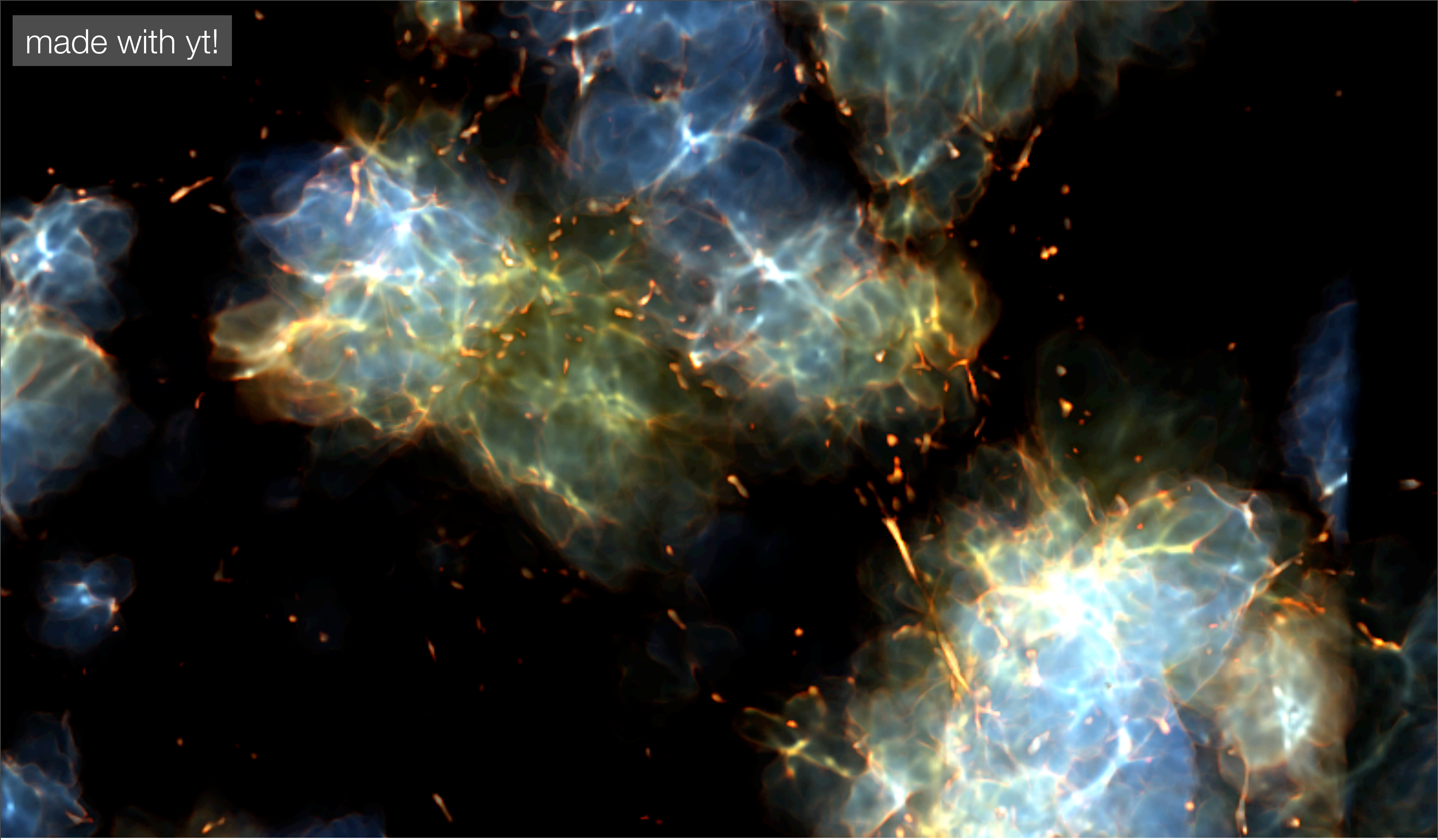
PhotonTestOmegaBaryonNow     = 1.0
PhotonTestInitialTemperature = 8000
PhotonTestInitialFractionHII  = 0.99

PhotonTestNumberOfSpheres        = 1


-uu-:---F1  PhotonTest.enzo    49% L41    (C++/l Abbrev)------------------------
```

How do I have
>1 energy group?

Example:
10^5 K blackbody in
4 energy groups



Radiative “Star” Particles

Complex behavior encouraged!

Star particle overview

- Two types of star particles: (1) **Normal** and (2) **Radiative**
- Normal star particles are similar to DM particles but have particle attributes
  - Creation time
  - Dynamical time (or lifetime)
  - Metallicity
- Normal star particles only interact with local grid cells.
- Feedback is accomplished through energy injection

Star class

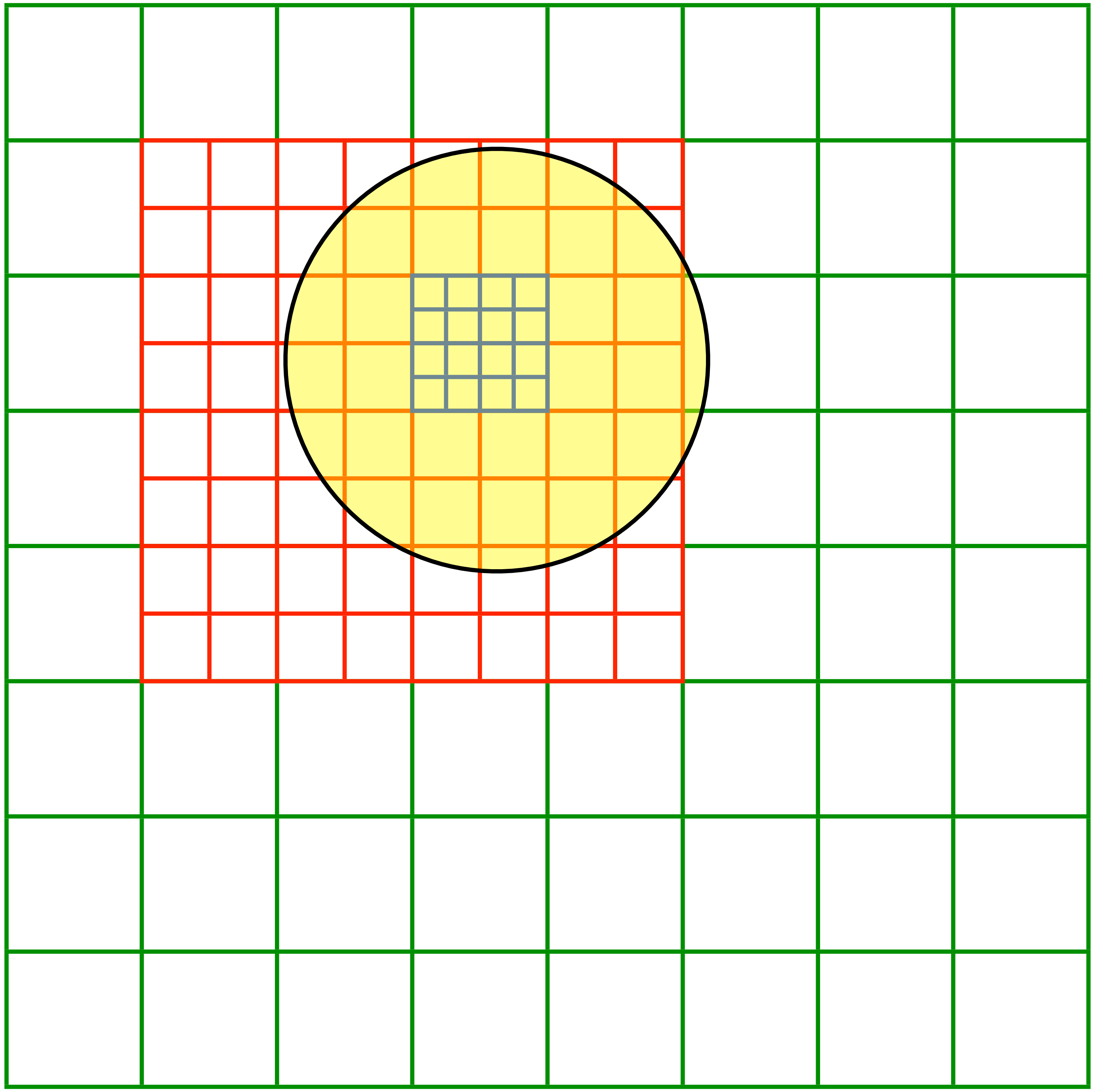
- To mirror nature better, star particles needed more flexibility.

```
class Star {};
```

- The class is an **additional layer** on top of the normal star particle, so it is included in the gravity solver and refinement criteria.

- **Main advantage:** greater interactivity between the stars and grid
  - Able to change cells on multiple grids and levels

Feedback spheres



Star class

- Different types of feedback modes (all operate in spheres of any radius)
  - Star formation – instantaneous accretion
  - Supernova feedback – thermal energy injection
  - Strömgren sphere – radial profile taken from Whalen et al. (2004)
  - Color field – Marks sphere with a color

Star class

- Can represent a single star, star cluster, black hole, neutron star, etc.

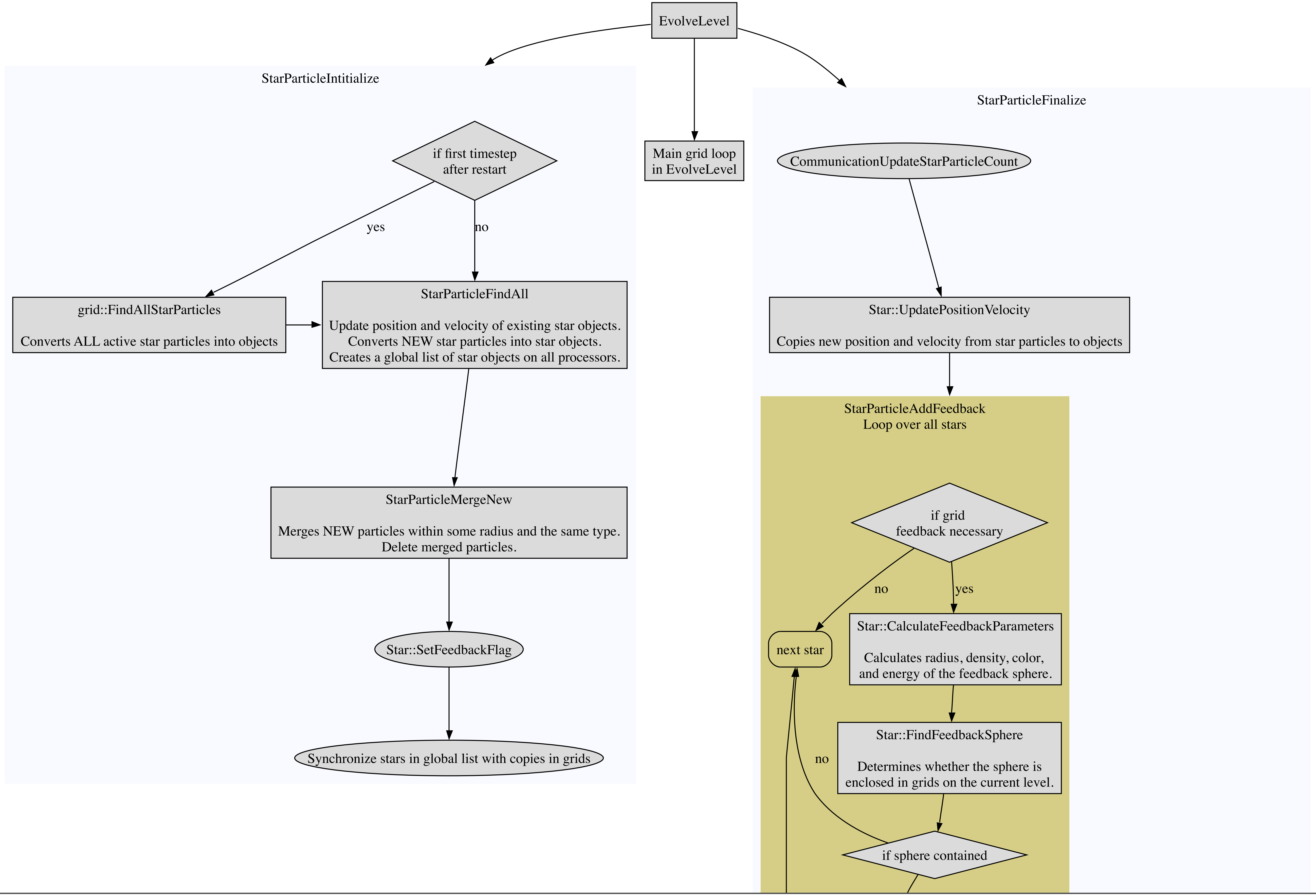
- Can grow from a pre-determined accretion rate “future”.

- Easy to merge.

```
if (Star1->Mergable(Star2)) {
   Star1 += Star2;
   Star2->DisableParticle(LevelArray);
}
```

- Doesn’t necessarily creates radiation. This is determined in `Star_IsARadiationSource.C`.

http://lca.ucsd.edu/projects/enzo/wiki/Tutorials/StarParticleClass



EvolveLevel

Main grid loop
in EvolveLevel

StarParticleIntitialize

if first timestep
after restart

yes

no

grid::FindAllStarParticles

Converts ALL active star particles into objects

StarParticleFindAll

Update position and velocity of existing star objects.
Converts NEW star particles into star objects.
Creates a global list of star objects on all processors.

StarParticleMergeNew

Merges NEW particles within some radius and the same type.
Delete merged particles.

Star::SetFeedbackFlag

Synchronize stars in global list with copies in grids

StarParticleFinalize

CommunicationUpdateStarParticleCount

Star::UpdatePositionVelocity

Copies new position and velocity from star particles to objects

StarParticleAddFeedback
Loop over all stars

if grid
feedback necessary

no

yes

next star

Star::CalculateFeedbackParameters

Calculates radius, density, color,
and energy of the feedback sphere.

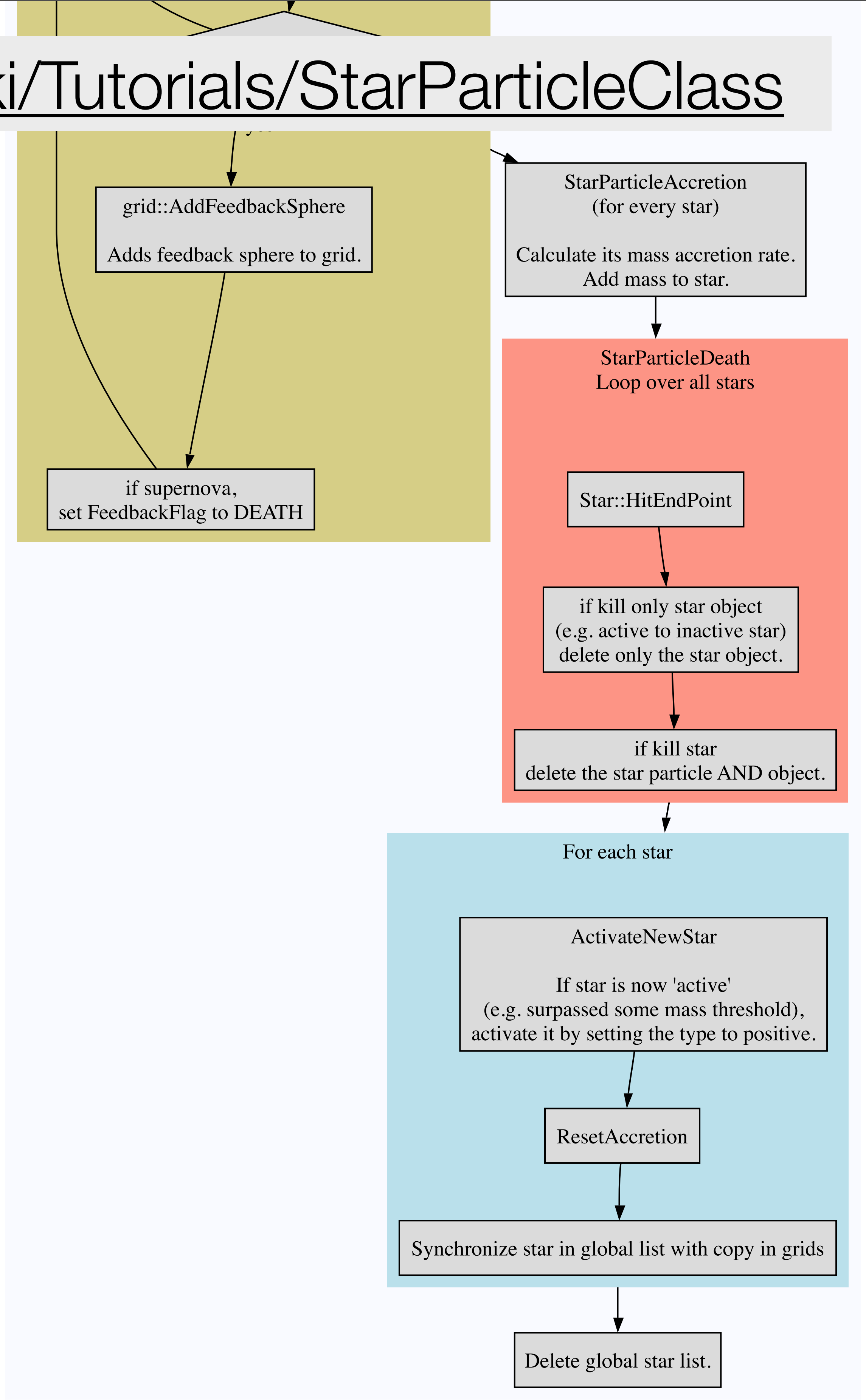
Star::FindFeedbackSphere

Determines whether the sphere is
enclosed in grids on the current level.

no

if sphere contained

http://lca.ucsd.edu/projects/enzo/wiki/Tutorials/StarParticleClass



grid::AddFeedbackSphere

Adds feedback sphere to grid.

if supernova,
set FeedbackFlag to DEATH

StarParticleAccretion
(for every star)

Calculate its mass accretion rate.
Add mass to star.

StarParticleDeath
Loop over all stars

Star::HitEndPoint

if kill only star object
(e.g. active to inactive star)
delete only the star object.

if kill star
delete the star particle AND object.

For each star

ActivateNewStar

If star is now 'active'
(e.g. surpassed some mass threshold),
activate it by setting the type to positive.

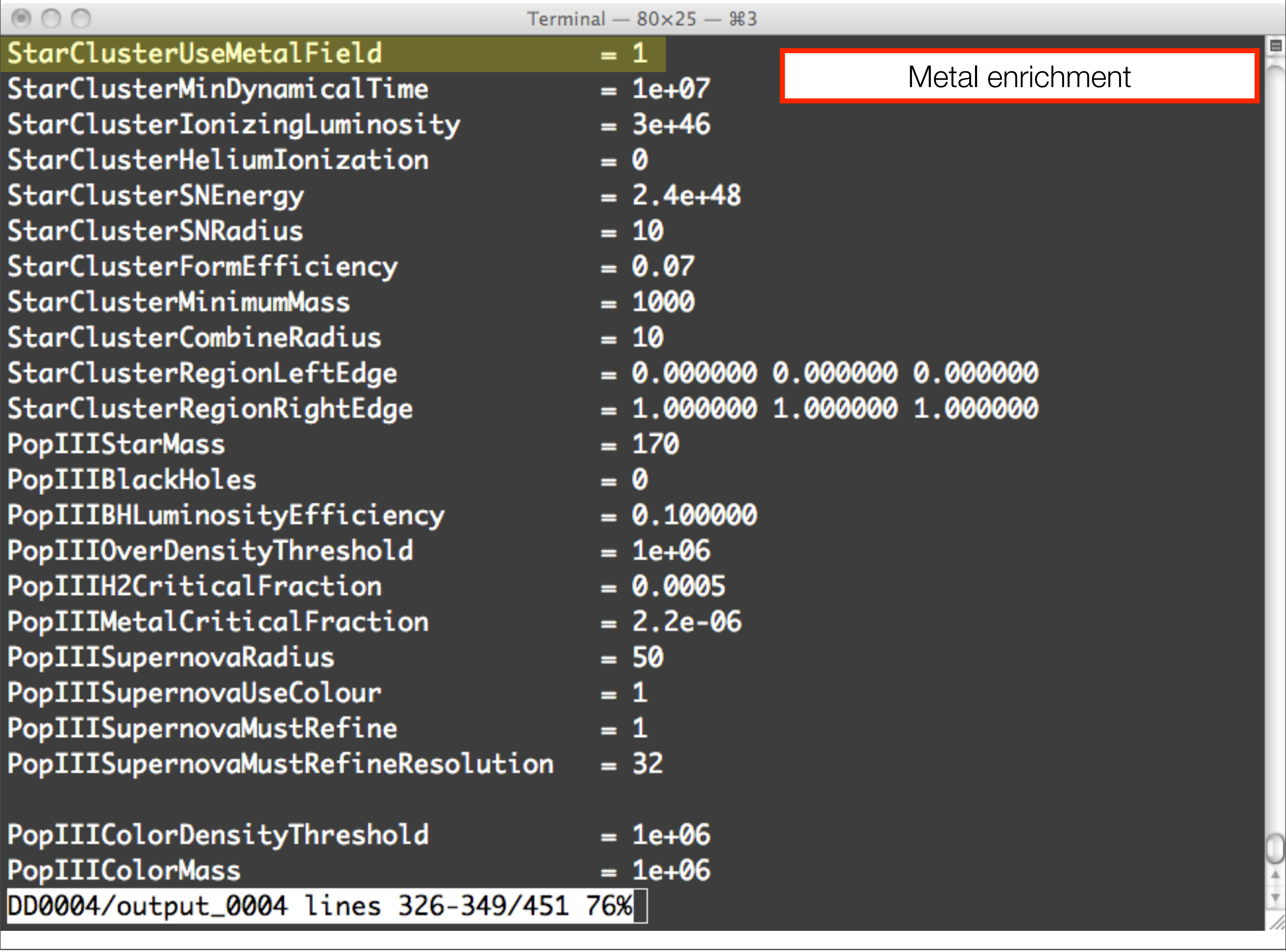
ResetAccretion

Synchronize star in global list with copy in grids

Delete global star list.

Radiative Star Particles

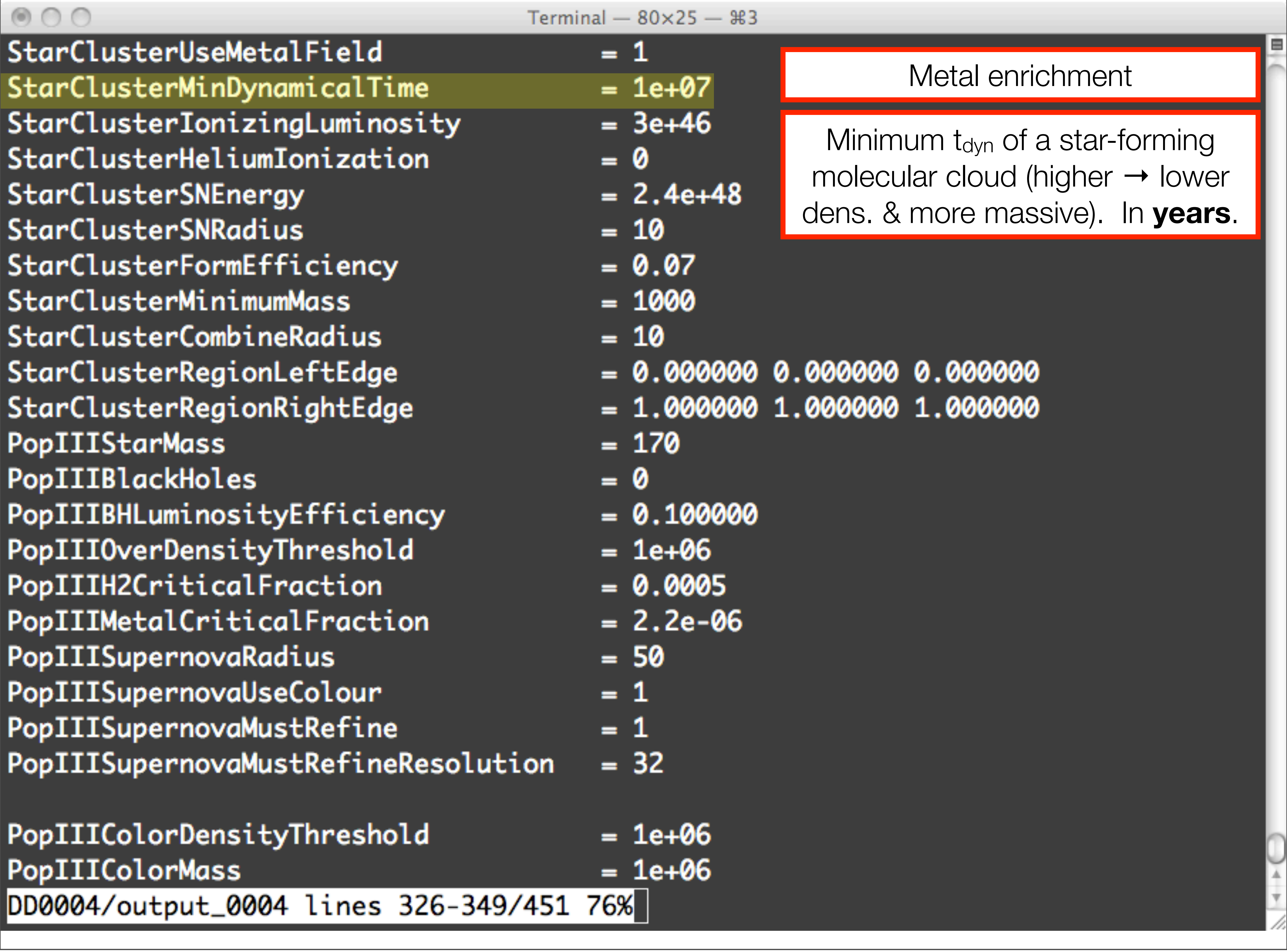
- **Population III stars** – method 3. Represent single Pop III stars. Luminosity, lifetime, and endpoint determined from `PopIIIStarMass`
- **"Star cluster" particles** – method 5. Represents a star cluster or galaxy (depending on resolution).
- In Enzo 2.0, multiple star formation routines may be used.
  - Specified in a bitwise fashion.
  - Method 3 → $2^3 = 8$
  - Method 4 → $2^4 = 16$
  - Method 3 & 5 → $2^3 + 2^5 = 40$
- **Black hole particles** – `PopIIIBlackHoles = 1`



Metal enrichment

```
StarClusterUseMetalField              = 1
StarClusterMinDynamicalTime           = 1e+07
StarClusterIonizingLuminosity         = 3e+46
StarClusterHeliumIonization           = 0
StarClusterSNEnergy                   = 2.4e+48
StarClusterSNRadius                   = 10
StarClusterFormEfficiency             = 0.07
StarClusterMinimumMass                = 1000
StarClusterCombineRadius              = 10
StarClusterRegionLeftEdge             = 0.000000 0.000000 0.000000
StarClusterRegionRightEdge            = 1.000000 1.000000 1.000000
PopIIIStarMass                        = 170
PopIIIBlackHoles                      = 0
PopIIIBHLuminosityEfficiency          = 0.100000
PopIIIOverDensityThreshold            = 1e+06
PopIIIH2CriticalFraction              = 0.0005
PopIIIMetalCriticalFraction           = 2.2e-06
PopIIISupernovaRadius                 = 50
PopIIISupernovaUseColour              = 1
PopIIISupernovaMustRefine             = 1
PopIIISupernovaMustRefineResolution   = 32

PopIIIColorDensityThreshold           = 1e+06
PopIIIColorMass                       = 1e+06
DD0004/output_0004 lines 326-349/451 76%
```



```
StarClusterUseMetalField              = 1
StarClusterMinDynamicalTime           = 1e+07
StarClusterIonizingLuminosity         = 3e+46
StarClusterHeliumIonization           = 0
StarClusterSNEnergy                   = 2.4e+48
StarClusterSNRadius                   = 10
StarClusterFormEfficiency             = 0.07
StarClusterMinimumMass                = 1000
StarClusterCombineRadius              = 10
StarClusterRegionLeftEdge             = 0.000000 0.000000 0.000000
StarClusterRegionRightEdge            = 1.000000 1.000000 1.000000
PopIIIStarMass                        = 170
PopIIIBlackHoles                      = 0
PopIIIBHLuminosityEfficiency          = 0.100000
PopIIIOverDensityThreshold            = 1e+06
PopIIIH2CriticalFraction              = 0.0005
PopIIIMetalCriticalFraction           = 2.2e-06
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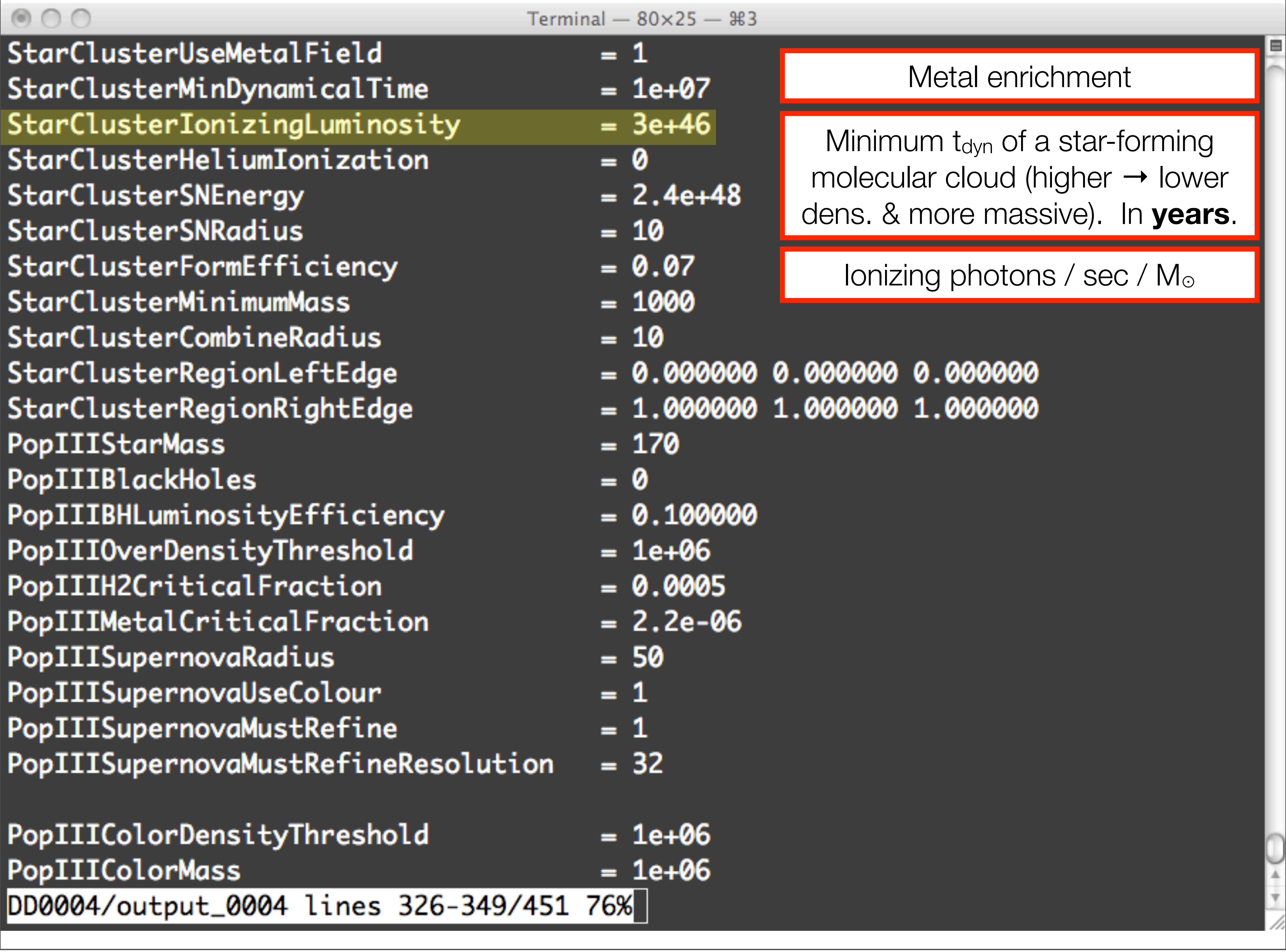
PopIIISupernovaMustRefine             = 1
PopIIISupernovaMustRefineResolution   = 32

PopIIIColorDensityThreshold           = 1e+06
PopIIIColorMass                       = 1e+06
DD0004/output_0004 lines 326-349/451 76%
```

Metal enrichment

Minimum t_{dyn} of a star-forming molecular cloud (higher → lower dens. & more massive). In **years**.



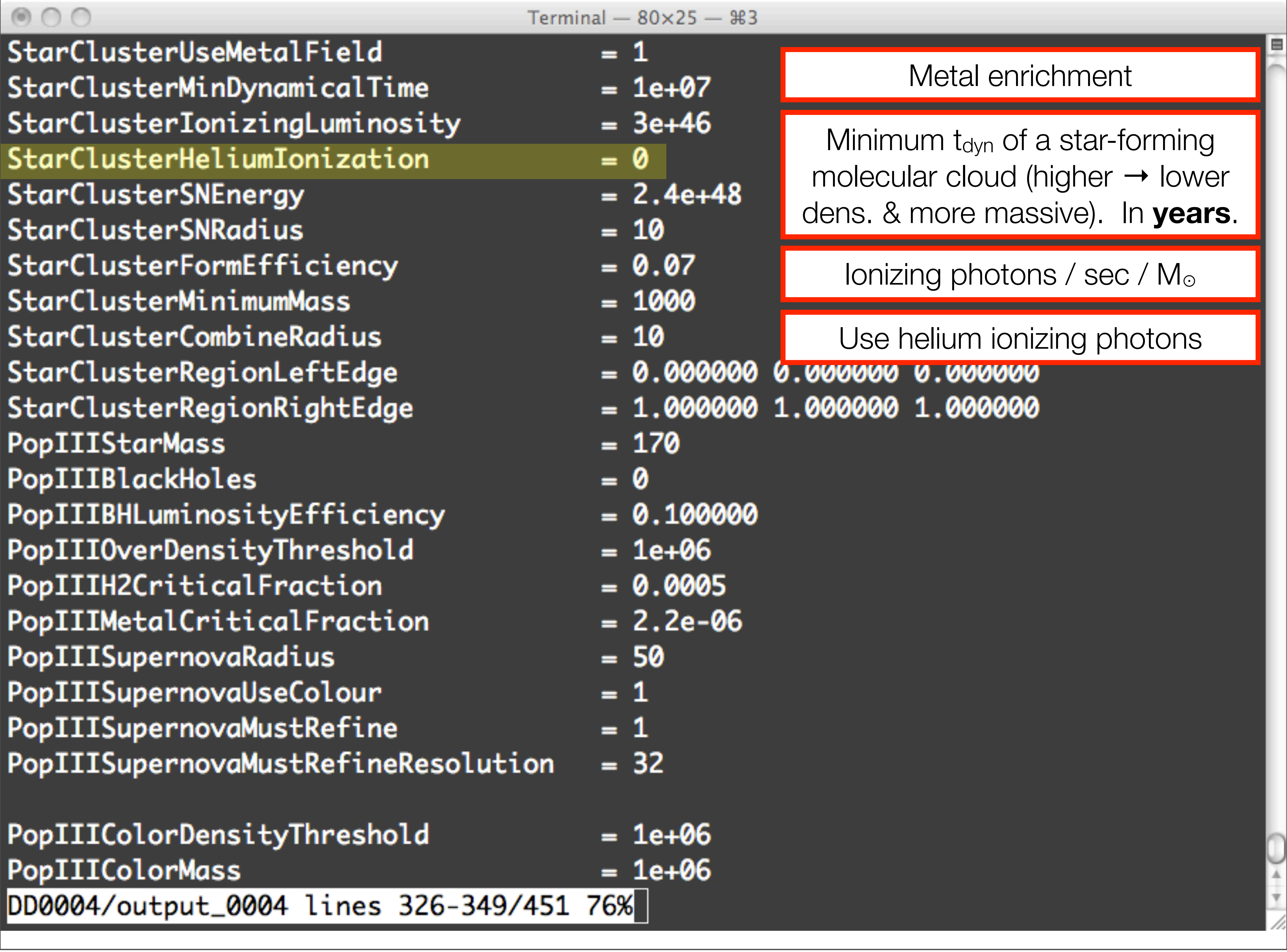
```
StarClusterUseMetalField                = 1
StarClusterMinDynamicalTime             = 1e+07
StarClusterIonizingLuminosity           = 3e+46
StarClusterHeliumIonization             = 0
StarClusterSNEnergy                     = 2.4e+48
StarClusterSNRadius                     = 10
StarClusterFormEfficiency               = 0.07
StarClusterMinimumMass                  = 1000
StarClusterCombineRadius                = 10
StarClusterRegionLeftEdge               = 0.000000 0.000000 0.000000
StarClusterRegionRightEdge              = 1.000000 1.000000 1.000000
PopIIIStarMass                          = 170
PopIIIBlackHoles                        = 0
PopIIIBHLuminosityEfficiency            = 0.100000
PopIIIOverDensityThreshold              = 1e+06
PopIIIH2CriticalFraction                = 0.0005
PopIIIMetalCriticalFraction             = 2.2e-06
PopIIISupernovaRadius                   = 50
PopIIISupernovaUseColour                = 1
PopIIISupernovaMustRefine               = 1
PopIIISupernovaMustRefineResolution     = 32

PopIIIColorDensityThreshold             = 1e+06
PopIIIColorMass                         = 1e+06
DD0004/output_0004 lines 326-349/451 76%
```

Metal enrichment

Minimum t_{dyn} of a star-forming molecular cloud (higher → lower dens. & more massive). In **years**.

Ionizing photons / sec / $M_\odot$



```
StarClusterUseMetalField              = 1
StarClusterMinDynamicalTime           = 1e+07
StarClusterIonizingLuminosity         = 3e+46
StarClusterHeliumIonization           = 0
StarClusterSNEnergy                   = 2.4e+48
StarClusterSNRadius                   = 10
StarClusterFormEfficiency             = 0.07
StarClusterMinimumMass                = 1000
StarClusterCombineRadius              = 10
StarClusterRegionLeftEdge             = 0.000000 0.000000 0.000000
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PopIIIStarMass                        = 170
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PopIIIBHLuminosityEfficiency          = 0.100000
PopIIIOverDensityThreshold            = 1e+06
PopIIIH2CriticalFraction              = 0.0005
PopIIIMetalCriticalFraction           = 2.2e-06
PopIIISupernovaRadius                 = 50
PopIIISupernovaUseColour              = 1
PopIIISupernovaMustRefine             = 1
PopIIISupernovaMustRefineResolution   = 32

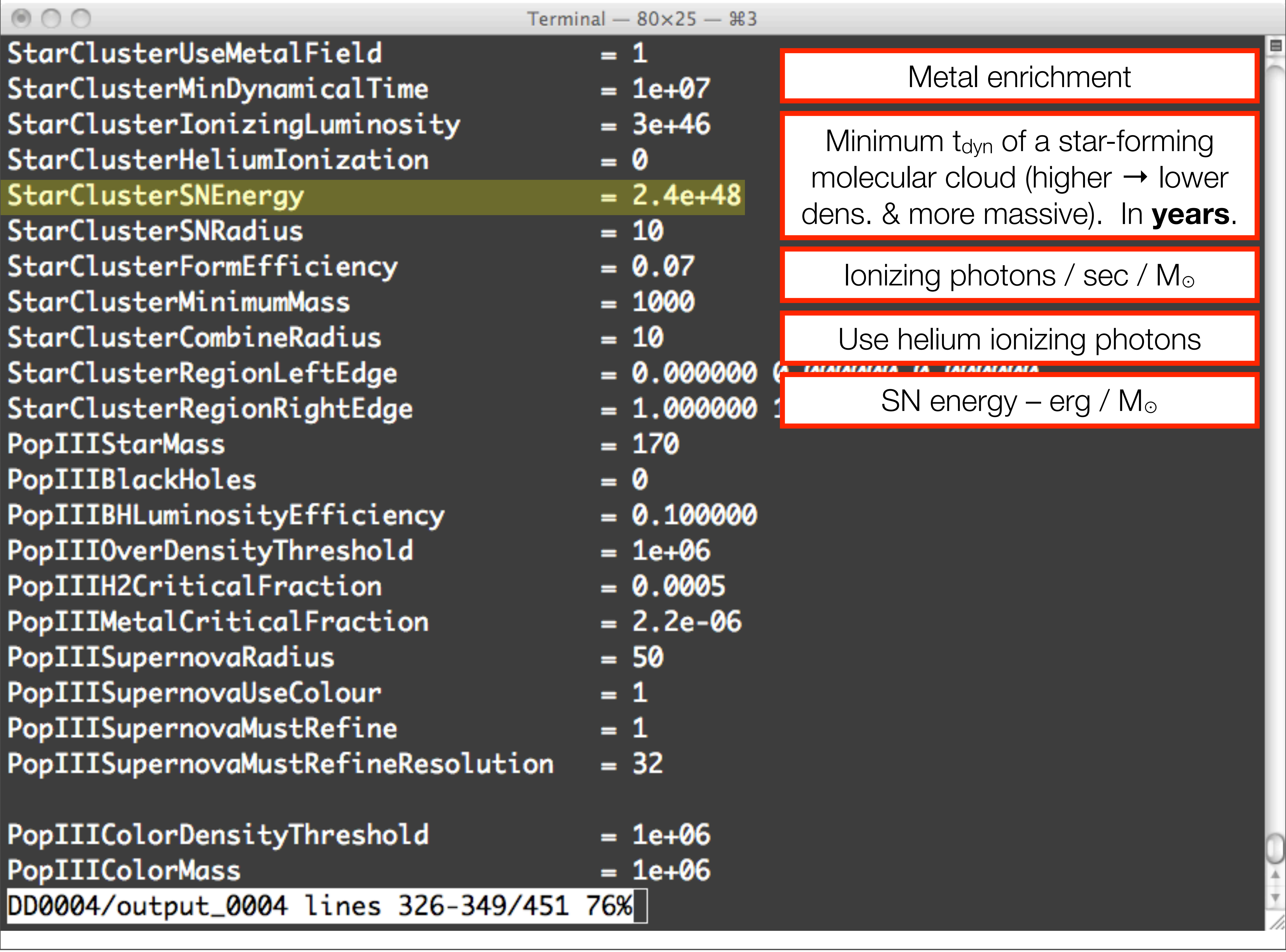
PopIIIColorDensityThreshold           = 1e+06
PopIIIColorMass                       = 1e+06
DD0004/output_0004 lines 326-349/451 76%
```

Metal enrichment

Minimum t_{dyn} of a star-forming molecular cloud (higher → lower dens. & more massive). In **years**.

Ionizing photons / sec / $M_\odot$

Use helium ionizing photons



```
StarClusterUseMetalField               = 1
StarClusterMinDynamicalTime            = 1e+07
StarClusterIonizingLuminosity          = 3e+46
StarClusterHeliumIonization            = 0
StarClusterSNEnergy                    = 2.4e+48
StarClusterSNRadius                    = 10
StarClusterFormEfficiency              = 0.07
StarClusterMinimumMass                 = 1000
StarClusterCombineRadius               = 10
StarClusterRegionLeftEdge              = 0.000000 0
StarClusterRegionRightEdge             = 1.000000 1
PopIIIStarMass                         = 170
PopIIIBlackHoles                       = 0
PopIIIBHLuminosityEfficiency           = 0.100000
PopIIIOverDensityThreshold             = 1e+06
PopIIIH2CriticalFraction               = 0.0005
PopIIIMetalCriticalFraction            = 2.2e-06
PopIIISupernovaRadius                  = 50
PopIIISupernovaUseColour               = 1
PopIIISupernovaMustRefine              = 1
PopIIISupernovaMustRefineResolution    = 32

PopIIIColorDensityThreshold            = 1e+06
PopIIIColorMass                        = 1e+06
DD0004/output_0004 lines 326-349/451 76%
```

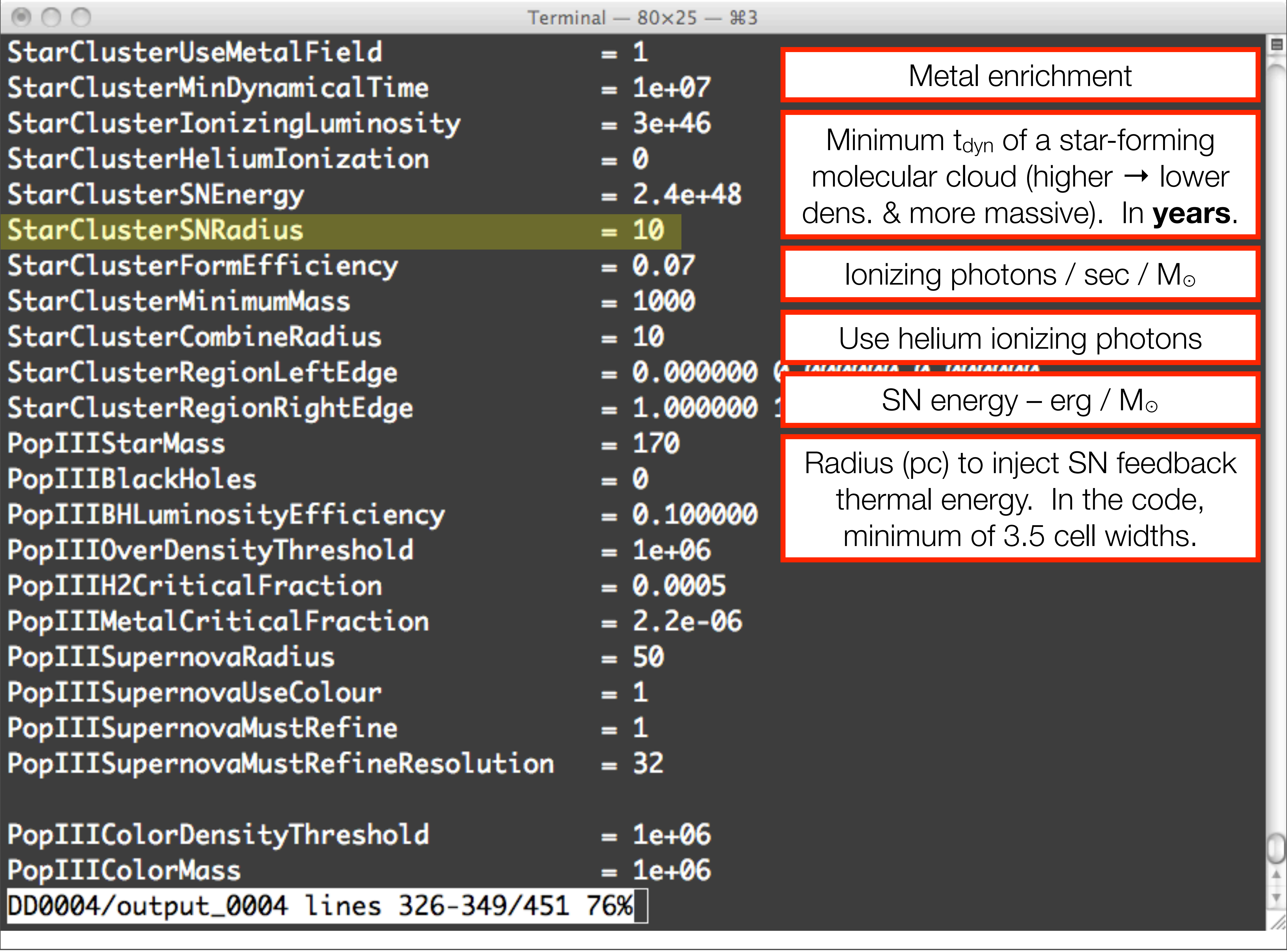
Metal enrichment

Minimum t_{dyn} of a star-forming molecular cloud (higher → lower dens. & more massive). In **years**.

Ionizing photons / sec / $M_\odot$

Use helium ionizing photons

SN energy – erg / $M_\odot$



```
StarClusterUseMetalField                = 1
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StarClusterIonizingLuminosity           = 3e+46
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PopIIIBHLuminosityEfficiency            = 0.100000
PopIIIOverDensityThreshold              = 1e+06
PopIIIH2CriticalFraction                = 0.0005
PopIIIMetalCriticalFraction             = 2.2e-06
PopIIISupernovaRadius                   = 50
PopIIISupernovaUseColour                = 1
PopIIISupernovaMustRefine               = 1
PopIIISupernovaMustRefineResolution     = 32

PopIIIColorDensityThreshold             = 1e+06
PopIIIColorMass                         = 1e+06
DD0004/output_0004 lines 326-349/451 76%
```

Metal enrichment

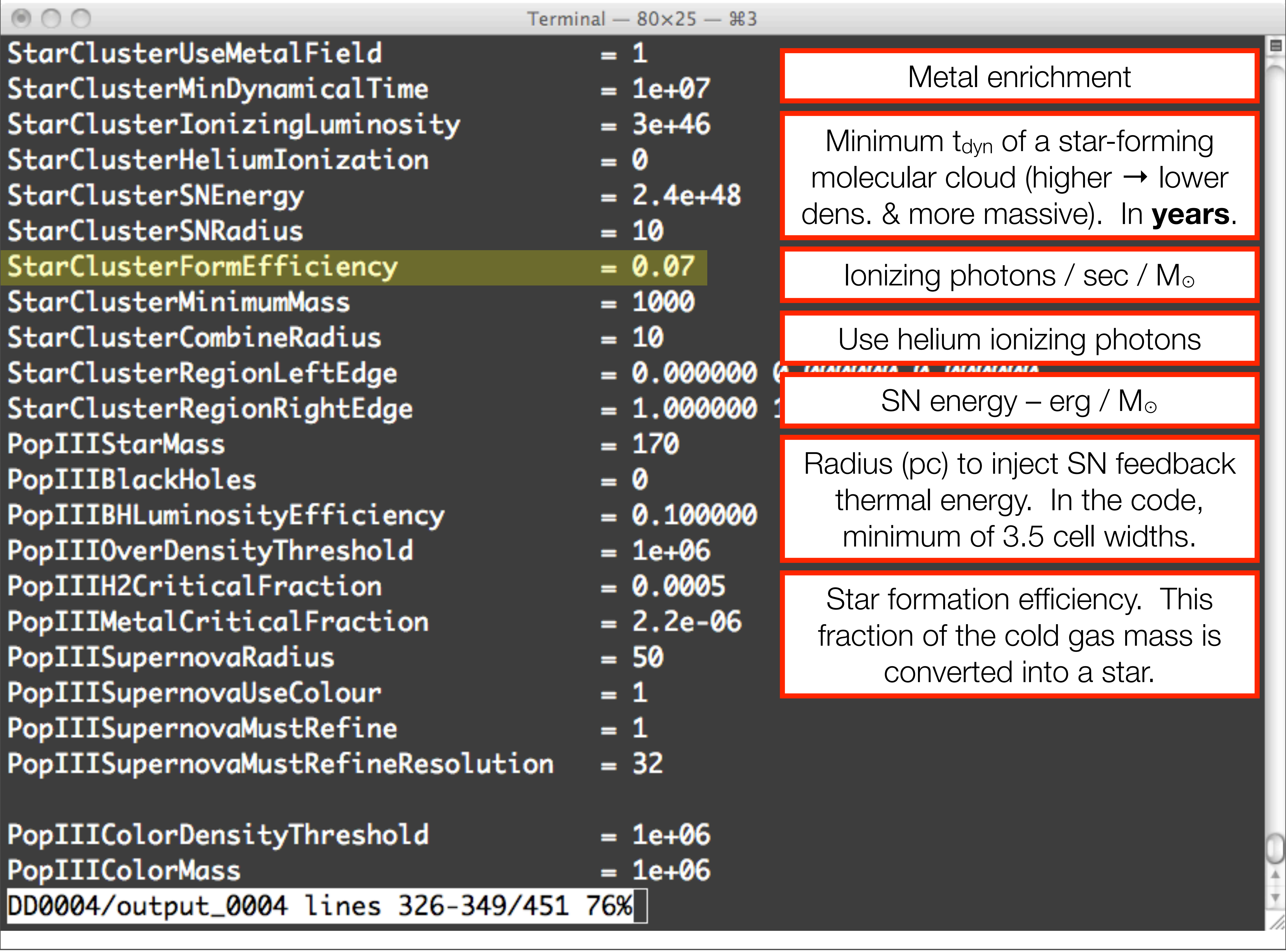
Minimum t_{dyn} of a star-forming molecular cloud (higher → lower dens. & more massive). In **years**.

Ionizing photons / sec / $M_\odot$

Use helium ionizing photons

SN energy – erg / $M_\odot$

Radius (pc) to inject SN feedback thermal energy. In the code, minimum of 3.5 cell widths.



```
StarClusterUseMetalField                = 1
StarClusterMinDynamicalTime             = 1e+07
StarClusterIonizingLuminosity           = 3e+46
StarClusterHeliumIonization             = 0
StarClusterSNEnergy                     = 2.4e+48
StarClusterSNRadius                     = 10
StarClusterFormEfficiency               = 0.07
StarClusterMinimumMass                  = 1000
StarClusterCombineRadius                = 10
StarClusterRegionLeftEdge               = 0.000000
StarClusterRegionRightEdge              = 1.000000
PopIIIStarMass                          = 170
PopIIIBlackHoles                        = 0
PopIIIBHLuminosityEfficiency            = 0.100000
PopIIIOverDensityThreshold              = 1e+06
PopIIIH2CriticalFraction                = 0.0005
PopIIIMetalCriticalFraction             = 2.2e-06
PopIIISupernovaRadius                   = 50
PopIIISupernovaUseColour                = 1
PopIIISupernovaMustRefine               = 1
PopIIISupernovaMustRefineResolution     = 32

PopIIIColorDensityThreshold             = 1e+06
PopIIIColorMass                         = 1e+06
DD0004/output_0004 lines 326-349/451 76%
```

Metal enrichment

Minimum t_{dyn} of a star-forming molecular cloud (higher → lower dens. & more massive). In **years**.

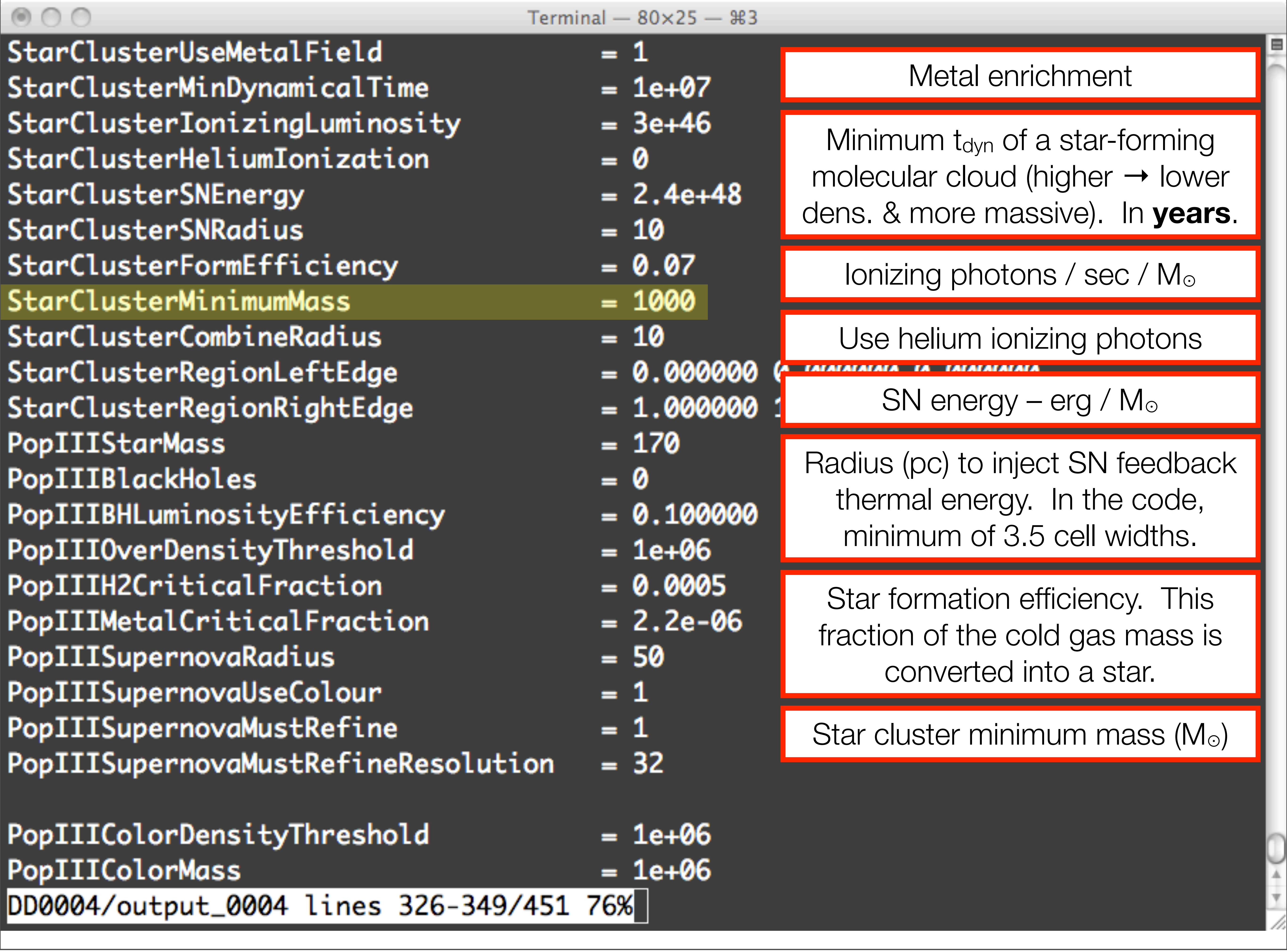
Ionizing photons / sec / $M_\odot$

Use helium ionizing photons

SN energy – erg / $M_\odot$

Radius (pc) to inject SN feedback thermal energy. In the code, minimum of 3.5 cell widths.

Star formation efficiency. This fraction of the cold gas mass is converted into a star.



```
StarClusterUseMetalField              = 1
StarClusterMinDynamicalTime           = 1e+07
StarClusterIonizingLuminosity         = 3e+46
StarClusterHeliumIonization           = 0
StarClusterSNEnergy                   = 2.4e+48
StarClusterSNRadius                   = 10
StarClusterFormEfficiency             = 0.07
StarClusterMinimumMass                = 1000
StarClusterCombineRadius              = 10
StarClusterRegionLeftEdge             = 0.000000
StarClusterRegionRightEdge            = 1.000000
PopIIIStarMass                        = 170
PopIIIBlackHoles                      = 0
PopIIIBHLuminosityEfficiency          = 0.100000
PopIIIOverDensityThreshold            = 1e+06
PopIIIH2CriticalFraction              = 0.0005
PopIIIMetalCriticalFraction           = 2.2e-06
PopIIISupernovaRadius                 = 50
PopIIISupernovaUseColour              = 1
PopIIISupernovaMustRefine             = 1
PopIIISupernovaMustRefineResolution   = 32

PopIIIColorDensityThreshold           = 1e+06
PopIIIColorMass                       = 1e+06
DD0004/output_0004 lines 326-349/451 76%
```

Metal enrichment

Minimum t_{dyn} of a star-forming molecular cloud (higher → lower dens. & more massive). In **years**.

Ionizing photons / sec / $M_\odot$

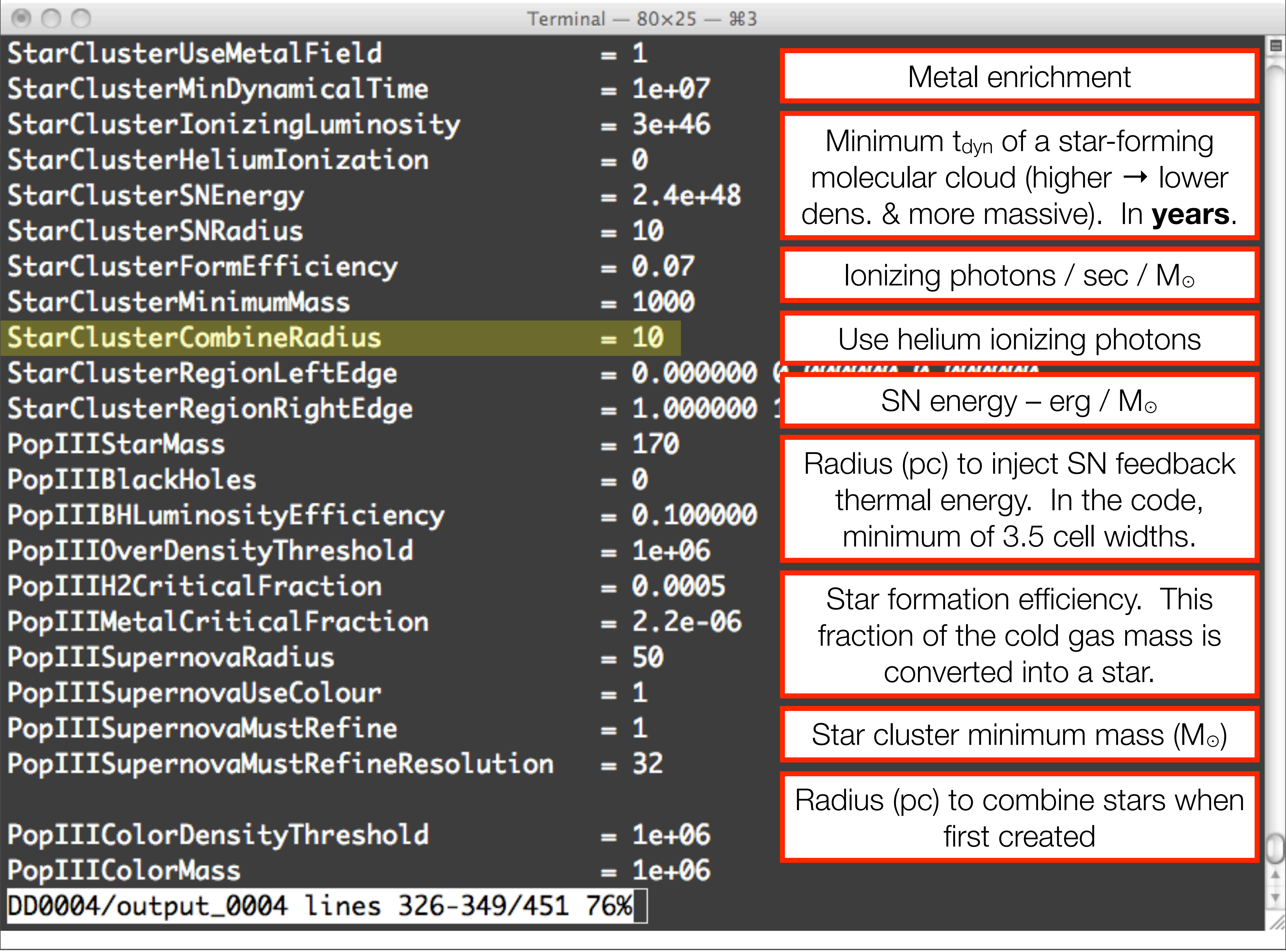
Use helium ionizing photons

SN energy – erg / $M_\odot$

Radius (pc) to inject SN feedback thermal energy. In the code, minimum of 3.5 cell widths.

Star formation efficiency. This fraction of the cold gas mass is converted into a star.

Star cluster minimum mass ($M_\odot$)



```
StarClusterUseMetalField               = 1
StarClusterMinDynamicalTime            = 1e+07
StarClusterIonizingLuminosity          = 3e+46
StarClusterHeliumIonization            = 0
StarClusterSNEnergy                    = 2.4e+48
StarClusterSNRadius                    = 10
StarClusterFormEfficiency              = 0.07
StarClusterMinimumMass                 = 1000
StarClusterCombineRadius               = 10
StarClusterRegionLeftEdge              = 0.000000 0
StarClusterRegionRightEdge             = 1.000000 1
PopIIIStarMass                         = 170
PopIIIBlackHoles                       = 0
PopIIIBHLuminosityEfficiency           = 0.100000
PopIIIOverDensityThreshold             = 1e+06
PopIIIH2CriticalFraction               = 0.0005
PopIIIMetalCriticalFraction            = 2.2e-06
PopIIISupernovaRadius                  = 50
PopIIISupernovaUseColour               = 1
PopIIISupernovaMustRefine              = 1
PopIIISupernovaMustRefineResolution    = 32

PopIIIColorDensityThreshold            = 1e+06
PopIIIColorMass                        = 1e+06
DD0004/output_0004 lines 326-349/451 76%
```

Metal enrichment

Minimum t_{dyn} of a star-forming molecular cloud (higher → lower dens. & more massive). In **years**.

Ionizing photons / sec / $M_\odot$

Use helium ionizing photons

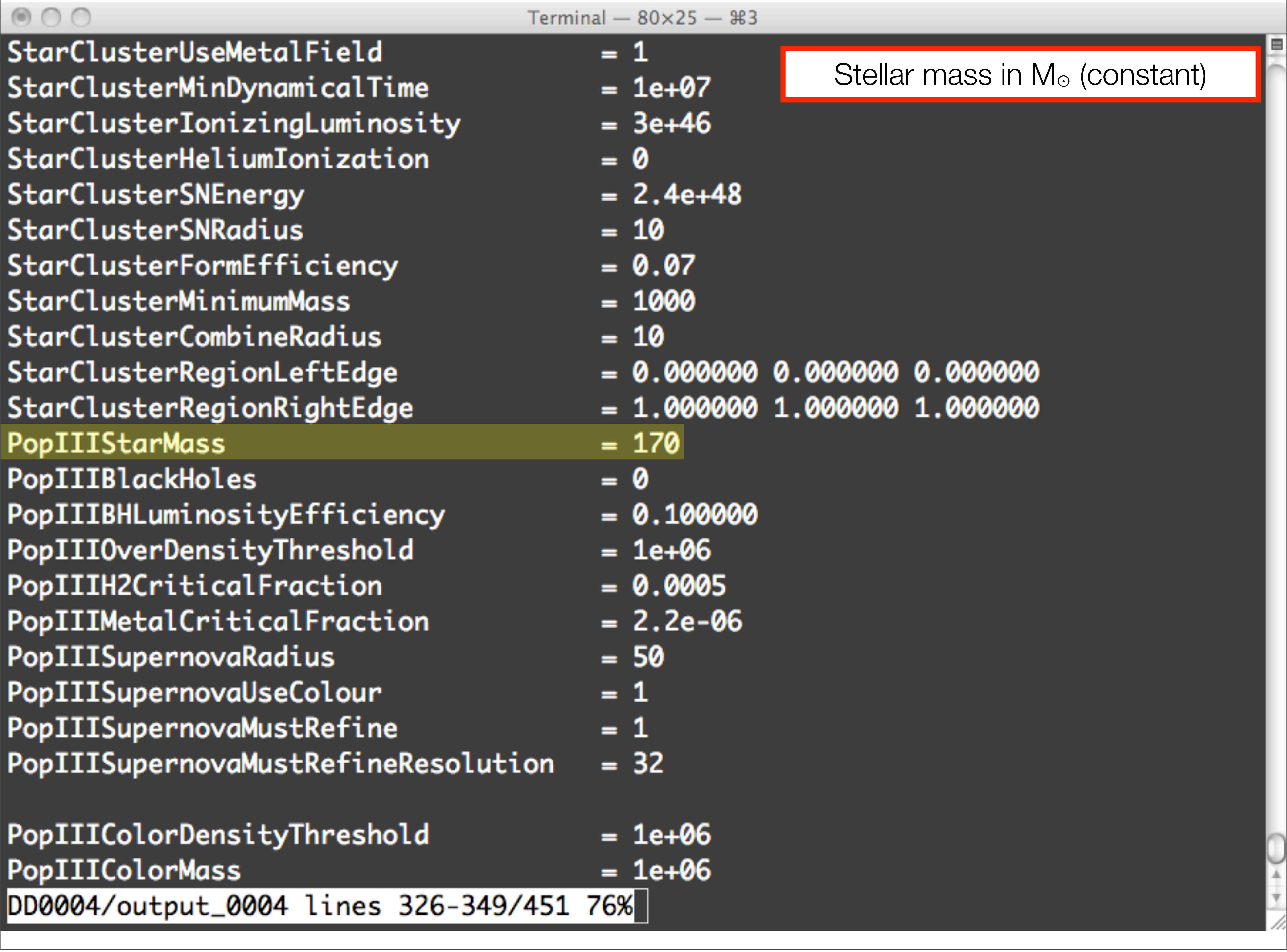
SN energy – erg / $M_\odot$

Radius (pc) to inject SN feedback thermal energy. In the code, minimum of 3.5 cell widths.

Star formation efficiency. This fraction of the cold gas mass is converted into a star.

Star cluster minimum mass ($M_\odot$)

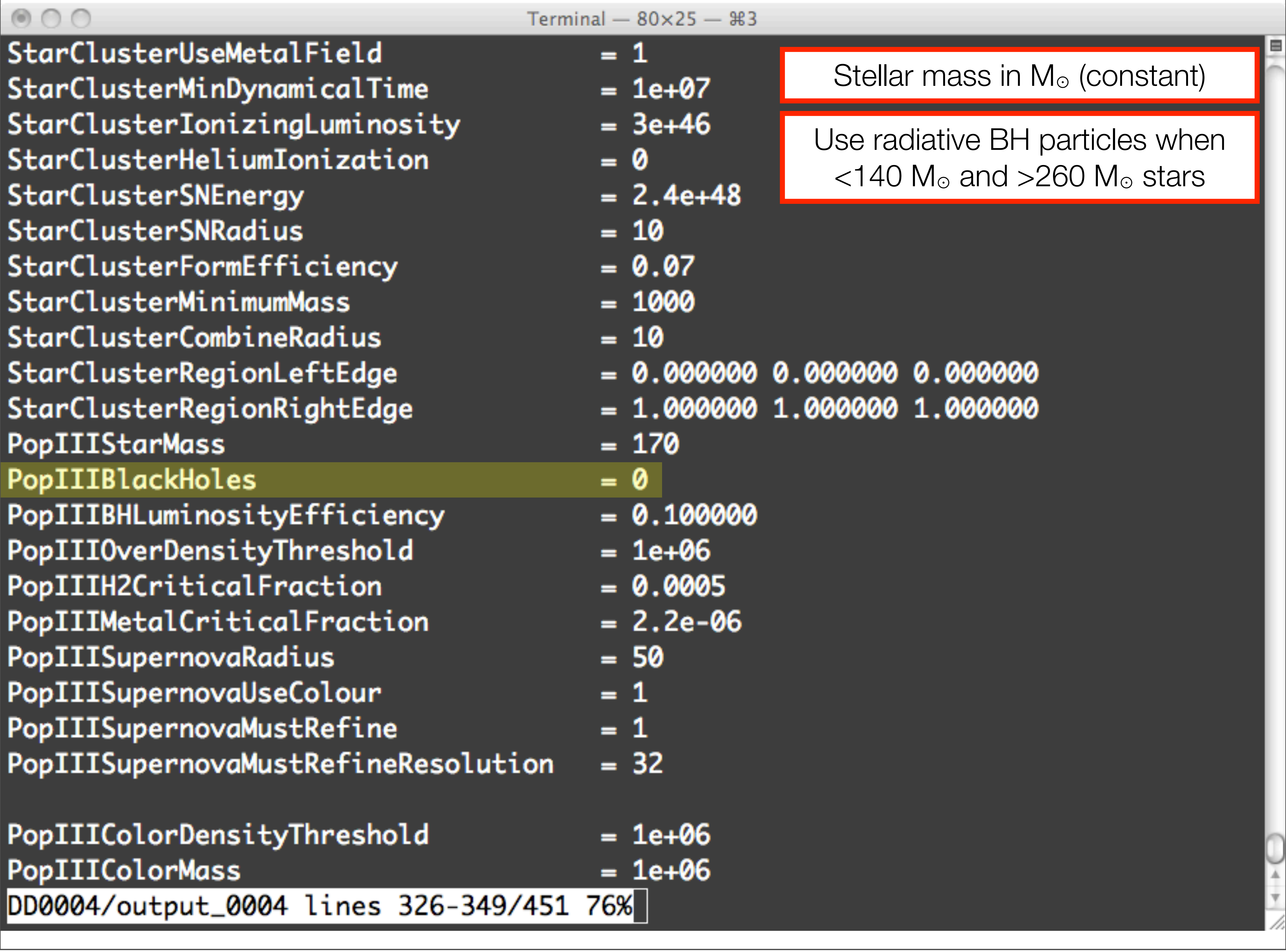
Radius (pc) to combine stars when first created



Stellar mass in M☉ (constant)

```
StarClusterUseMetalField              = 1
StarClusterMinDynamicalTime           = 1e+07
StarClusterIonizingLuminosity         = 3e+46
StarClusterHeliumIonization           = 0
StarClusterSNEnergy                   = 2.4e+48
StarClusterSNRadius                   = 10
StarClusterFormEfficiency             = 0.07
StarClusterMinimumMass                = 1000
StarClusterCombineRadius              = 10
StarClusterRegionLeftEdge             = 0.000000 0.000000 0.000000
StarClusterRegionRightEdge            = 1.000000 1.000000 1.000000
PopIIIStarMass                        = 170
PopIIIBlackHoles                      = 0
PopIIIBHLuminosityEfficiency          = 0.100000
PopIIIOverDensityThreshold            = 1e+06
PopIIIH2CriticalFraction              = 0.0005
PopIIIMetalCriticalFraction           = 2.2e-06
PopIIISupernovaRadius                 = 50
PopIIISupernovaUseColour              = 1
PopIIISupernovaMustRefine             = 1
PopIIISupernovaMustRefineResolution   = 32

PopIIIColorDensityThreshold           = 1e+06
PopIIIColorMass                       = 1e+06
DD0004/output_0004 lines 326-349/451 76%
```

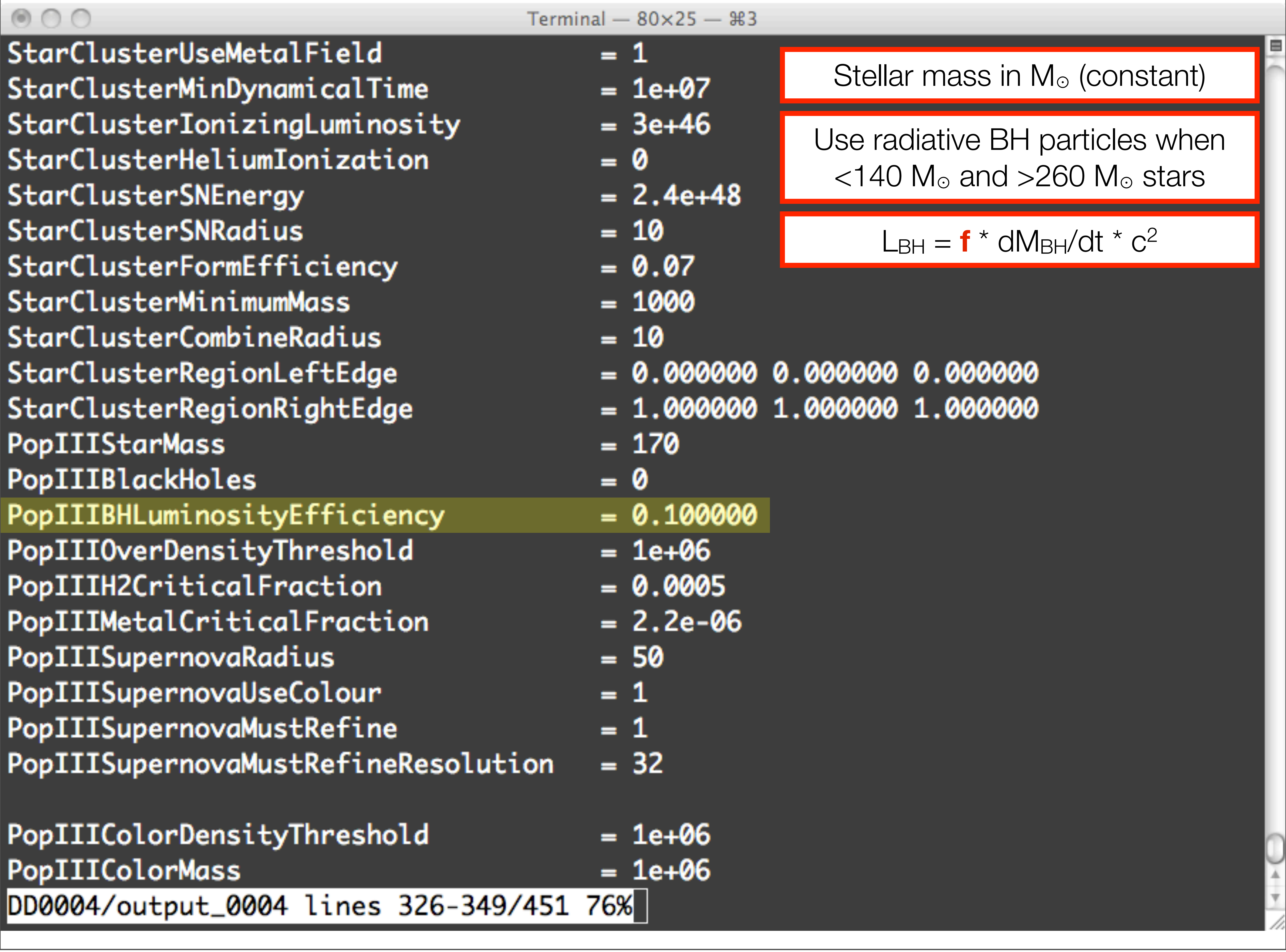


```
StarClusterUseMetalField              = 1
StarClusterMinDynamicalTime           = 1e+07
StarClusterIonizingLuminosity         = 3e+46
StarClusterHeliumIonization           = 0
StarClusterSNEnergy                   = 2.4e+48
StarClusterSNRadius                   = 10
StarClusterFormEfficiency             = 0.07
StarClusterMinimumMass                = 1000
StarClusterCombineRadius              = 10
StarClusterRegionLeftEdge             = 0.000000 0.000000 0.000000
StarClusterRegionRightEdge            = 1.000000 1.000000 1.000000
PopIIIStarMass                        = 170
PopIIIBlackHoles                      = 0
PopIIIBHLuminosityEfficiency          = 0.100000
PopIIIOverDensityThreshold            = 1e+06
PopIIIH2CriticalFraction              = 0.0005
PopIIIMetalCriticalFraction           = 2.2e-06
PopIIISupernovaRadius                 = 50
PopIIISupernovaUseColour              = 1
PopIIISupernovaMustRefine             = 1
PopIIISupernovaMustRefineResolution   = 32

PopIIIColorDensityThreshold           = 1e+06
PopIIIColorMass                       = 1e+06
DD0004/output_0004 lines 326-349/451 76%
```

Stellar mass in M☉ (constant)

Use radiative BH particles when <140 M☉ and >260 M☉ stars



```
StarClusterUseMetalField              = 1
StarClusterMinDynamicalTime           = 1e+07
StarClusterIonizingLuminosity         = 3e+46
StarClusterHeliumIonization           = 0
StarClusterSNEnergy                   = 2.4e+48
StarClusterSNRadius                   = 10
StarClusterFormEfficiency             = 0.07
StarClusterMinimumMass                = 1000
StarClusterCombineRadius              = 10
StarClusterRegionLeftEdge             = 0.000000 0.000000 0.000000
StarClusterRegionRightEdge            = 1.000000 1.000000 1.000000
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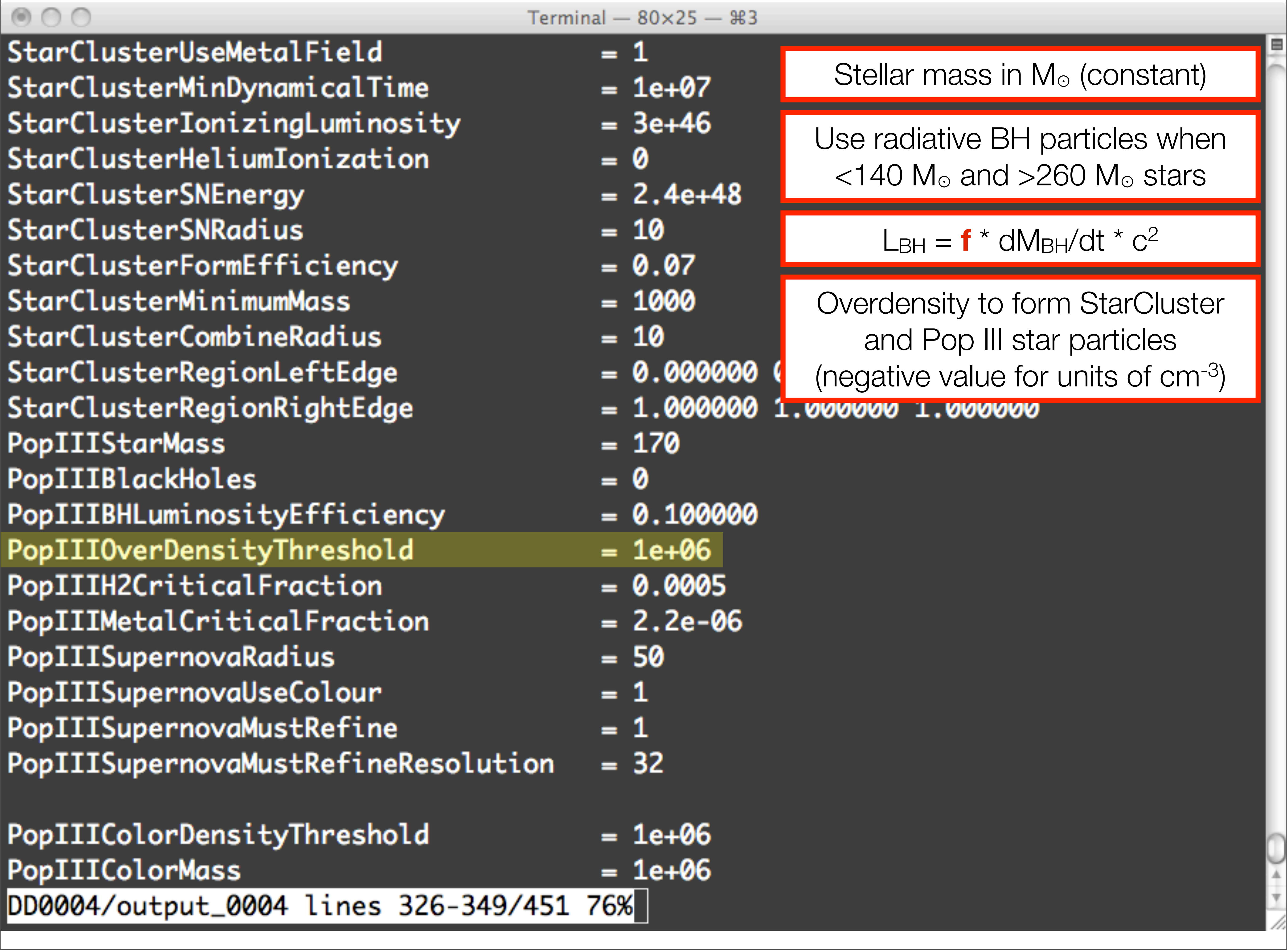
PopIIIBlackHoles                      = 0
PopIIIBHLuminosityEfficiency          = 0.100000
PopIIIOverDensityThreshold            = 1e+06
PopIIIH2CriticalFraction              = 0.0005
PopIIIMetalCriticalFraction           = 2.2e-06
PopIIISupernovaRadius                 = 50
PopIIISupernovaUseColour              = 1
PopIIISupernovaMustRefine             = 1
PopIIISupernovaMustRefineResolution   = 32

PopIIIColorDensityThreshold           = 1e+06
PopIIIColorMass                       = 1e+06
DD0004/output_0004 lines 326-349/451 76%
```

Stellar mass in $M_\odot$ (constant)

Use radiative BH particles when $<140\ M_\odot$ and $>260\ M_\odot$ stars

$L_{BH} = \mathbf{f} * dM_{BH}/dt * c^2$



```
StarClusterUseMetalField               = 1
StarClusterMinDynamicalTime            = 1e+07
StarClusterIonizingLuminosity          = 3e+46
StarClusterHeliumIonization            = 0
StarClusterSNEnergy                    = 2.4e+48
StarClusterSNRadius                    = 10
StarClusterFormEfficiency              = 0.07
StarClusterMinimumMass                 = 1000
StarClusterCombineRadius               = 10
StarClusterRegionLeftEdge              = 0.000000
StarClusterRegionRightEdge             = 1.000000 1.000000 1.000000
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PopIIIBHLuminosityEfficiency           = 0.100000
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PopIIIH2CriticalFraction               = 0.0005
PopIIIMetalCriticalFraction            = 2.2e-06
PopIIISupernovaRadius                  = 50
PopIIISupernovaUseColour               = 1
PopIIISupernovaMustRefine              = 1
PopIIISupernovaMustRefineResolution    = 32

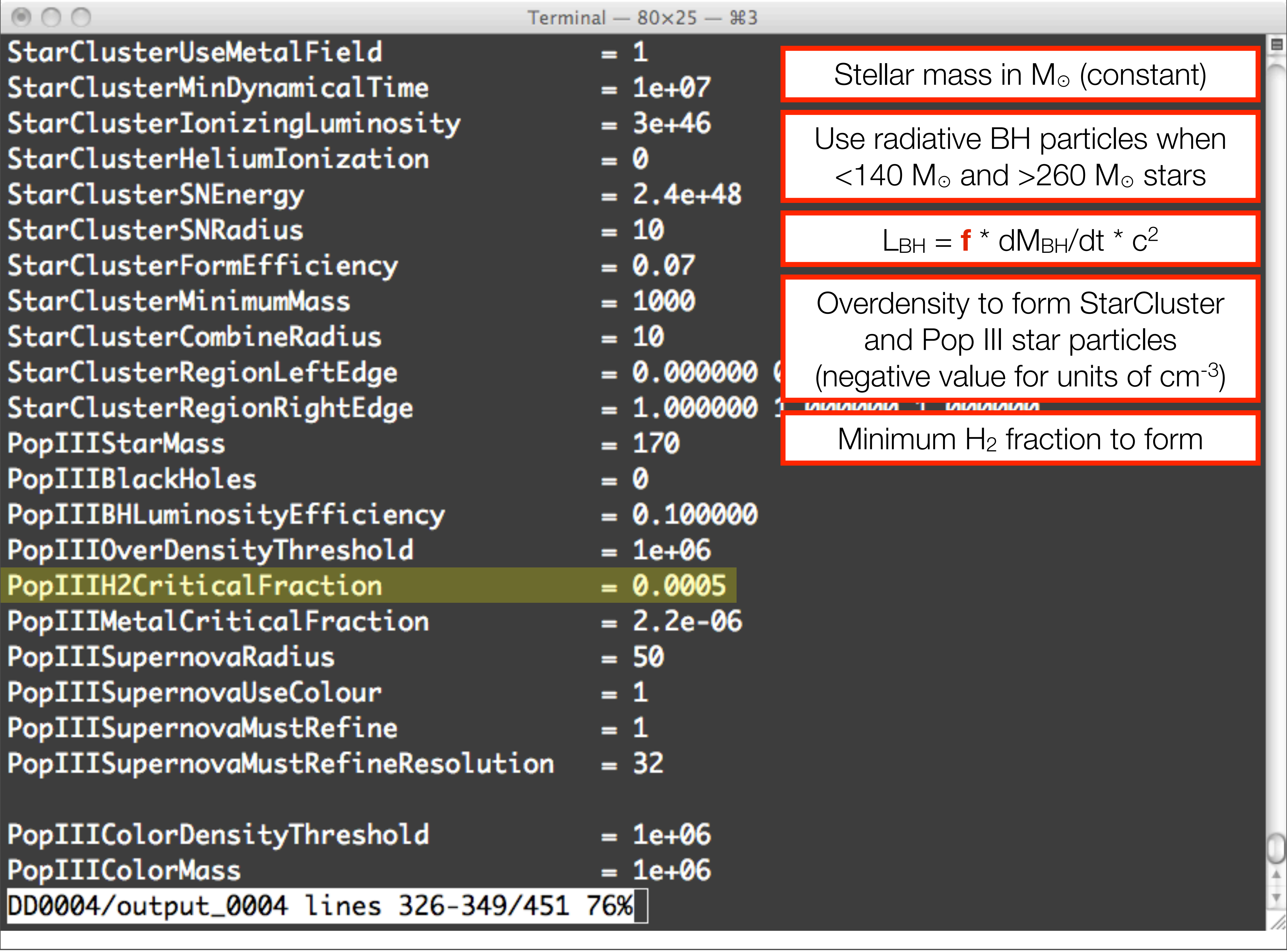
PopIIIColorDensityThreshold            = 1e+06
PopIIIColorMass                        = 1e+06
DD0004/output_0004 lines 326-349/451 76%
```

Stellar mass in $M_\odot$ (constant)

Use radiative BH particles when <140 $M_\odot$ and >260 $M_\odot$ stars

$L_{BH} = \mathbf{f} * dM_{BH}/dt * c^2$

Overdensity to form StarCluster and Pop III star particles (negative value for units of cm^{-3})



```
StarClusterUseMetalField                = 1
StarClusterMinDynamicalTime             = 1e+07
StarClusterIonizingLuminosity           = 3e+46
StarClusterHeliumIonization             = 0
StarClusterSNEnergy                     = 2.4e+48
StarClusterSNRadius                     = 10
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StarClusterRegionLeftEdge               = 0.000000
StarClusterRegionRightEdge              = 1.000000
PopIIIStarMass                          = 170
PopIIIBlackHoles                        = 0
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PopIIIOverDensityThreshold              = 1e+06
PopIIIH2CriticalFraction                = 0.0005
PopIIIMetalCriticalFraction             = 2.2e-06
PopIIISupernovaRadius                   = 50
PopIIISupernovaUseColour                = 1
PopIIISupernovaMustRefine               = 1
PopIIISupernovaMustRefineResolution     = 32

PopIIIColorDensityThreshold             = 1e+06
PopIIIColorMass                         = 1e+06
DD0004/output_0004 lines 326-349/451 76%
```

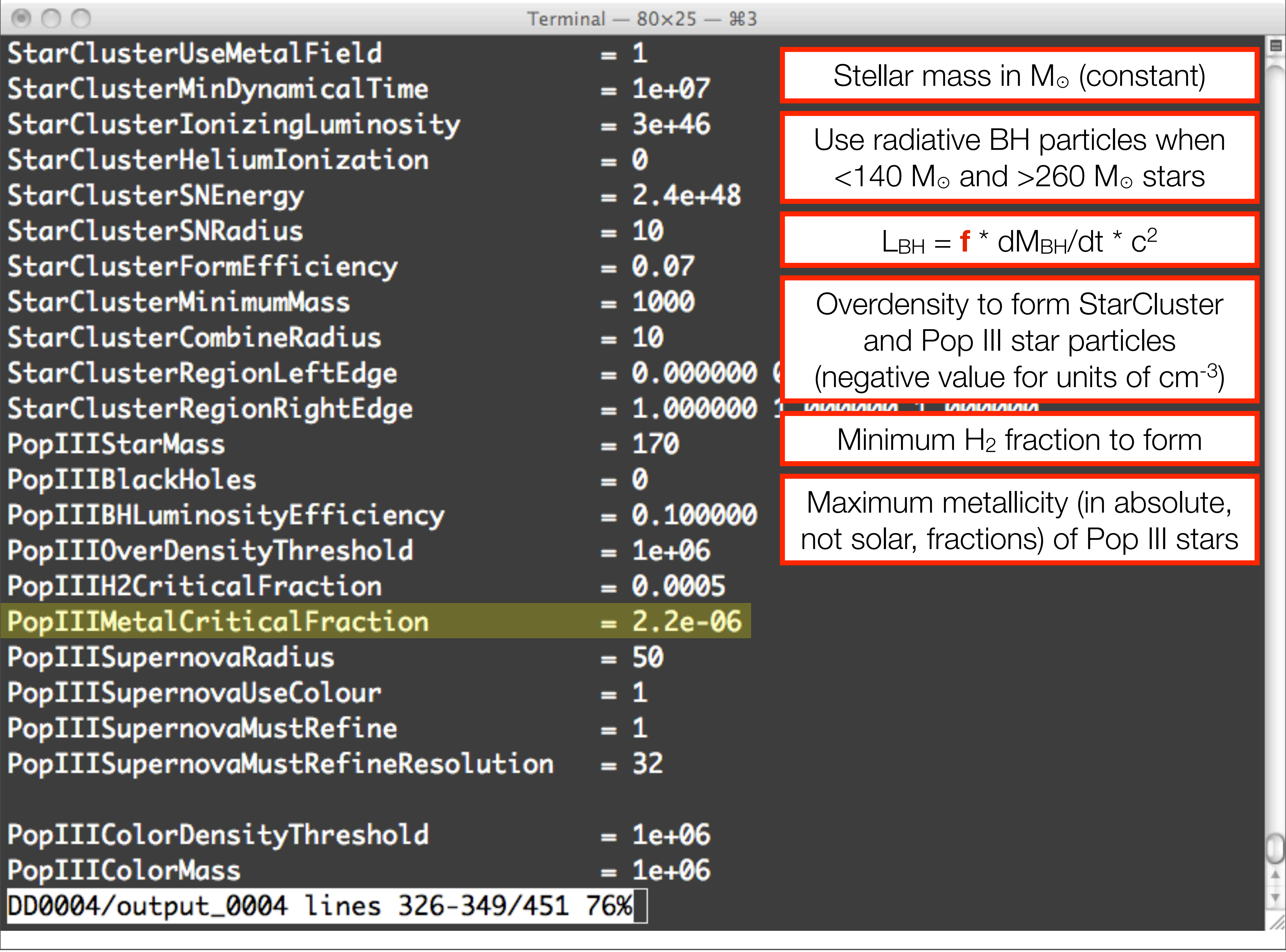
Stellar mass in $M_\odot$ (constant)

Use radiative BH particles when $<140\ M_\odot$ and $>260\ M_\odot$ stars

$L_{BH} = \mathbf{f} * dM_{BH}/dt * c^2$

Overdensity to form StarCluster and Pop III star particles (negative value for units of cm^{-3})

Minimum H_2 fraction to form



```
StarClusterUseMetalField              = 1
StarClusterMinDynamicalTime           = 1e+07
StarClusterIonizingLuminosity         = 3e+46
StarClusterHeliumIonization           = 0
StarClusterSNEnergy                   = 2.4e+48
StarClusterSNRadius                   = 10
StarClusterFormEfficiency             = 0.07
StarClusterMinimumMass                = 1000
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StarClusterRegionRightEdge            = 1.000000
PopIIIStarMass                        = 170
PopIIIBlackHoles                      = 0
PopIIIBHLuminosityEfficiency          = 0.100000
PopIIIOverDensityThreshold            = 1e+06
PopIIIH2CriticalFraction              = 0.0005
PopIIIMetalCriticalFraction           = 2.2e-06
PopIIISupernovaRadius                 = 50
PopIIISupernovaUseColour              = 1
PopIIISupernovaMustRefine             = 1
PopIIISupernovaMustRefineResolution   = 32

PopIIIColorDensityThreshold           = 1e+06
PopIIIColorMass                       = 1e+06
DD0004/output_0004 lines 326-349/451 76%
```

Stellar mass in $M_\odot$ (constant)

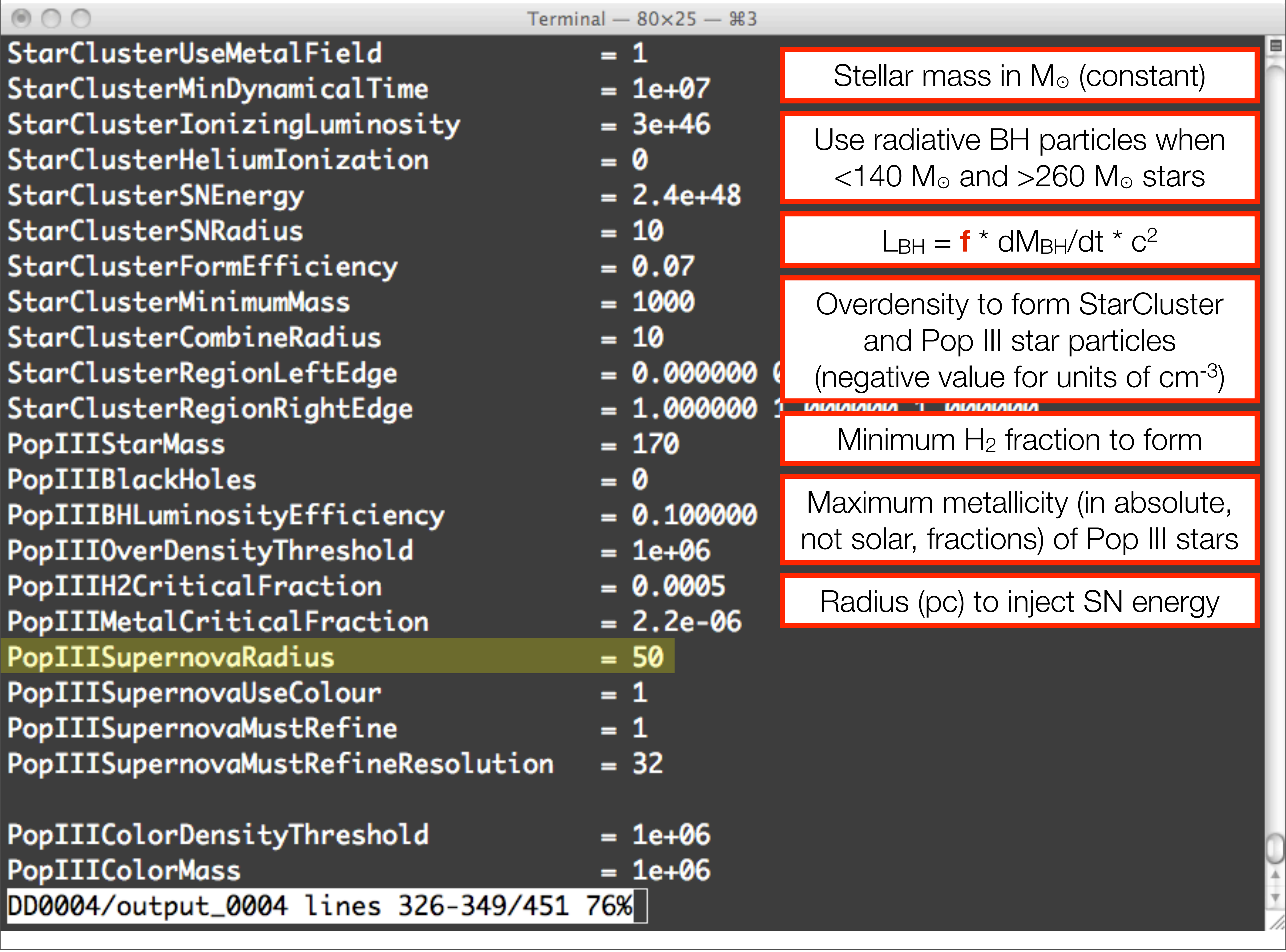
Use radiative BH particles when $<140\ M_\odot$ and $>260\ M_\odot$ stars

$L_{BH} = \mathbf{f} * dM_{BH}/dt * c^2$

Overdensity to form StarCluster and Pop III star particles (negative value for units of cm^{-3})

Minimum H_2 fraction to form

Maximum metallicity (in absolute, not solar, fractions) of Pop III stars



```
StarClusterUseMetalField           = 1
StarClusterMinDynamicalTime        = 1e+07
StarClusterIonizingLuminosity      = 3e+46
StarClusterHeliumIonization        = 0
StarClusterSNEnergy                = 2.4e+48
StarClusterSNRadius                = 10
StarClusterFormEfficiency          = 0.07
StarClusterMinimumMass             = 1000
StarClusterCombineRadius           = 10
StarClusterRegionLeftEdge          = 0.000000 0
StarClusterRegionRightEdge         = 1.000000 1
PopIIIStarMass                     = 170
PopIIIBlackHoles                   = 0
PopIIIBHLuminosityEfficiency       = 0.100000
PopIIIOverDensityThreshold         = 1e+06
PopIIIH2CriticalFraction           = 0.0005
PopIIIMetalCriticalFraction        = 2.2e-06
PopIIISupernovaRadius              = 50
PopIIISupernovaUseColour           = 1
PopIIISupernovaMustRefine          = 1
PopIIISupernovaMustRefineResolution = 32

PopIIIColorDensityThreshold        = 1e+06
PopIIIColorMass                    = 1e+06
DD0004/output_0004 lines 326-349/451 76%
```

Stellar mass in $M_\odot$ (constant)

Use radiative BH particles when $<140\ M_\odot$ and $>260\ M_\odot$ stars

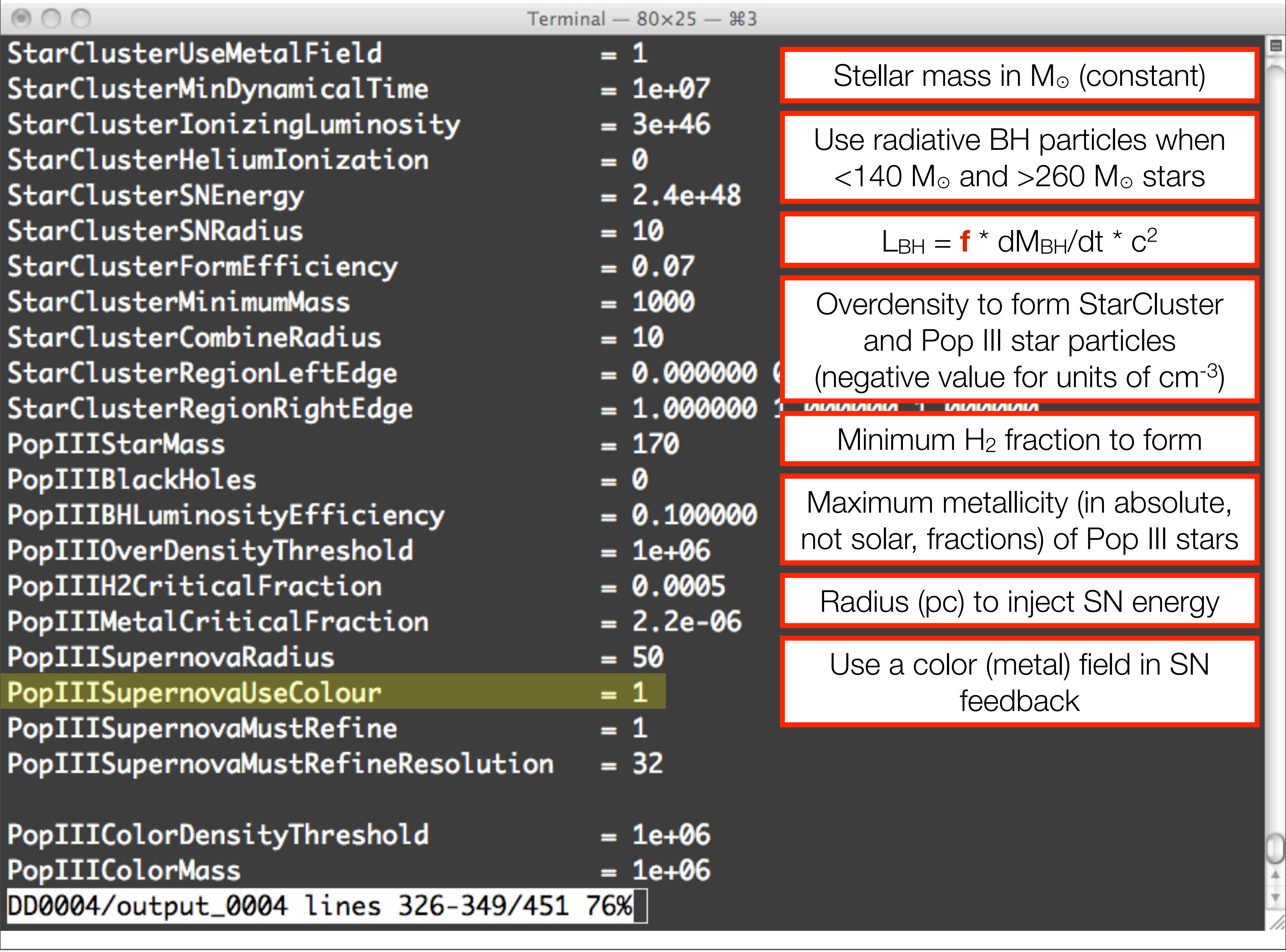
$L_{BH} = \mathbf{f} * dM_{BH}/dt * c^2$

Overdensity to form StarCluster and Pop III star particles (negative value for units of cm^{-3})

Minimum H_2 fraction to form

Maximum metallicity (in absolute, not solar, fractions) of Pop III stars

Radius (pc) to inject SN energy



```
StarClusterUseMetalField                = 1
StarClusterMinDynamicalTime             = 1e+07
StarClusterIonizingLuminosity           = 3e+46
StarClusterHeliumIonization             = 0
StarClusterSNEnergy                     = 2.4e+48
StarClusterSNRadius                     = 10
StarClusterFormEfficiency               = 0.07
StarClusterMinimumMass                  = 1000
StarClusterCombineRadius                = 10
StarClusterRegionLeftEdge               = 0.000000
StarClusterRegionRightEdge              = 1.000000
PopIIIStarMass                          = 170
PopIIIBlackHoles                        = 0
PopIIIBHLuminosityEfficiency            = 0.100000
PopIIIOverDensityThreshold              = 1e+06
PopIIIH2CriticalFraction                = 0.0005
PopIIIMetalCriticalFraction             = 2.2e-06
PopIIISupernovaRadius                   = 50
PopIIISupernovaUseColour                = 1
PopIIISupernovaMustRefine               = 1
PopIIISupernovaMustRefineResolution     = 32

PopIIIColorDensityThreshold             = 1e+06
PopIIIColorMass                         = 1e+06
DD0004/output_0004 lines 326-349/451 76%
```

Stellar mass in $M_\odot$ (constant)

Use radiative BH particles when $<140\ M_\odot$ and $>260\ M_\odot$ stars

$L_{BH} = \mathbf{f} * dM_{BH}/dt * c^2$

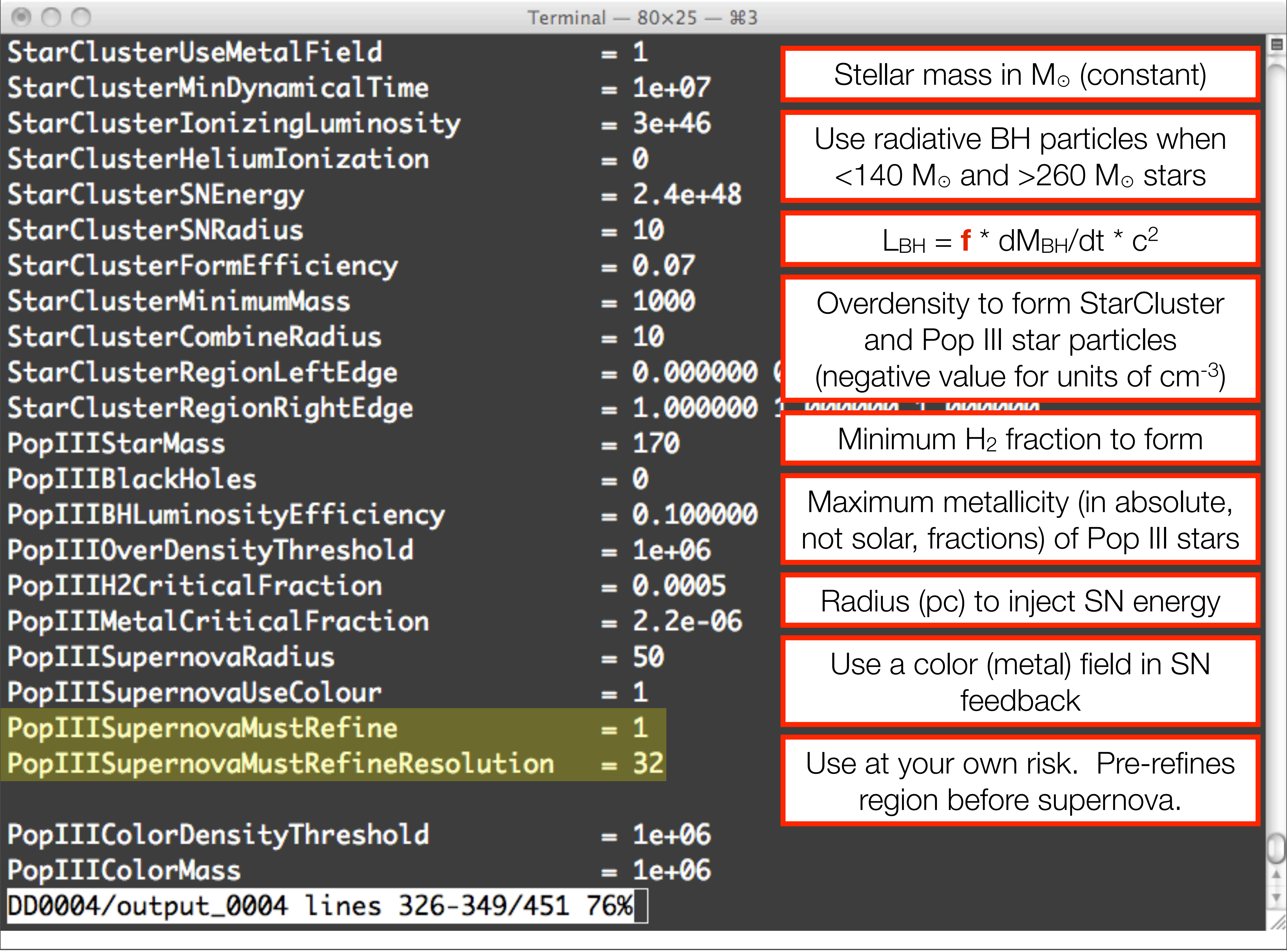
Overdensity to form StarCluster and Pop III star particles (negative value for units of cm^{-3})

Minimum H_2 fraction to form

Maximum metallicity (in absolute, not solar, fractions) of Pop III stars

Radius (pc) to inject SN energy

Use a color (metal) field in SN feedback



```
StarClusterUseMetalField                 = 1
StarClusterMinDynamicalTime              = 1e+07
StarClusterIonizingLuminosity            = 3e+46
StarClusterHeliumIonization              = 0
StarClusterSNEnergy                      = 2.4e+48
StarClusterSNRadius                      = 10
StarClusterFormEfficiency                = 0.07
StarClusterMinimumMass                   = 1000
StarClusterCombineRadius                 = 10
StarClusterRegionLeftEdge                = 0.000000
StarClusterRegionRightEdge               = 1.000000
PopIIIStarMass                           = 170
PopIIIBlackHoles                         = 0
PopIIIBHLuminosityEfficiency             = 0.100000
PopIIIOverDensityThreshold               = 1e+06
PopIIIH2CriticalFraction                 = 0.0005
PopIIIMetalCriticalFraction              = 2.2e-06
PopIIISupernovaRadius                    = 50
PopIIISupernovaUseColour                 = 1
PopIIISupernovaMustRefine                = 1
PopIIISupernovaMustRefineResolution      = 32

PopIIIColorDensityThreshold              = 1e+06
PopIIIColorMass                          = 1e+06
DD0004/output_0004 lines 326-349/451 76%
```

Stellar mass in $M_\odot$ (constant)

Use radiative BH particles when <140 $M_\odot$ and >260 $M_\odot$ stars

$L_{BH} = \mathbf{f} * dM_{BH}/dt * c^2$

Overdensity to form StarCluster and Pop III star particles (negative value for units of cm^{-3})

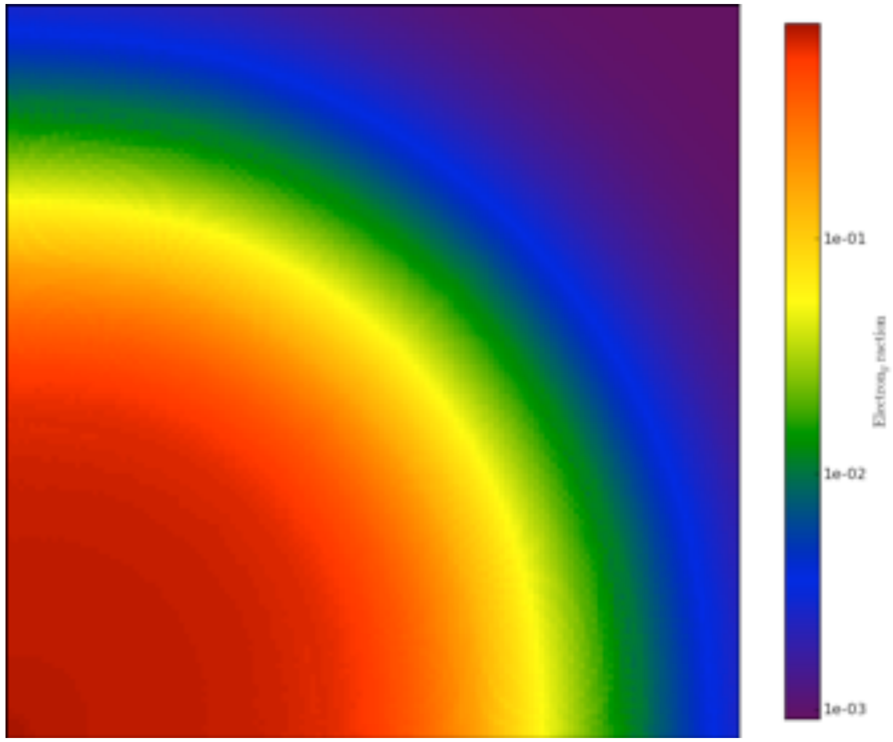
Minimum H_2 fraction to form

Maximum metallicity (in absolute, not solar, fractions) of Pop III stars

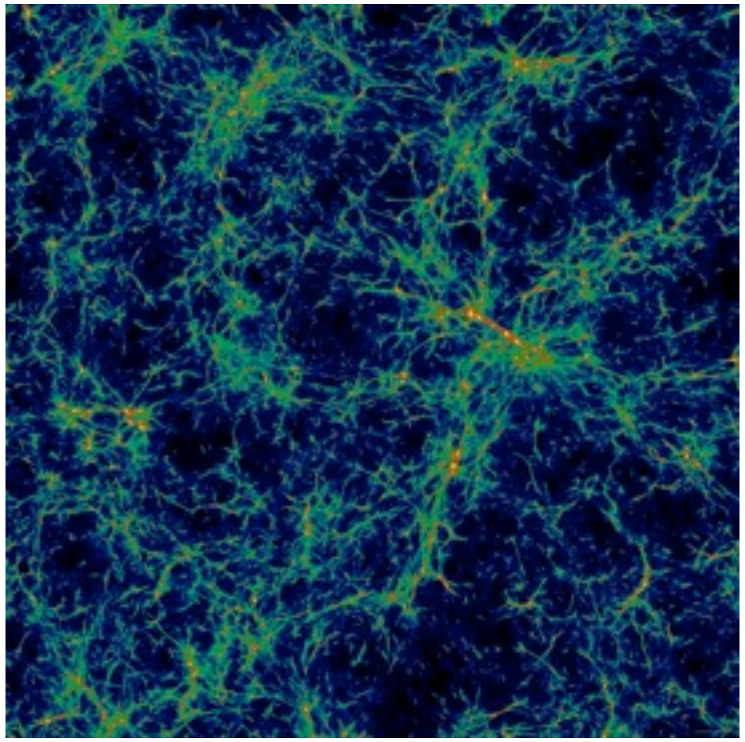
Radius (pc) to inject SN energy

Use a color (metal) field in SN feedback

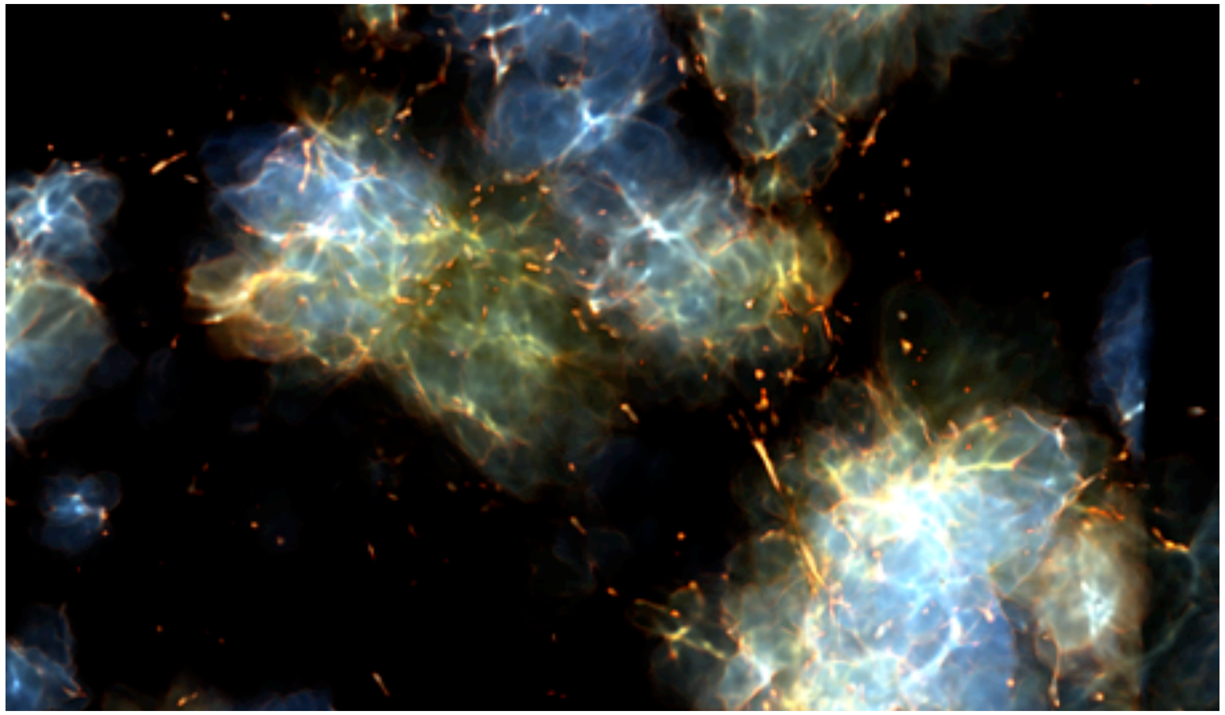
Use at your own risk. Pre-refines region before supernova.



+

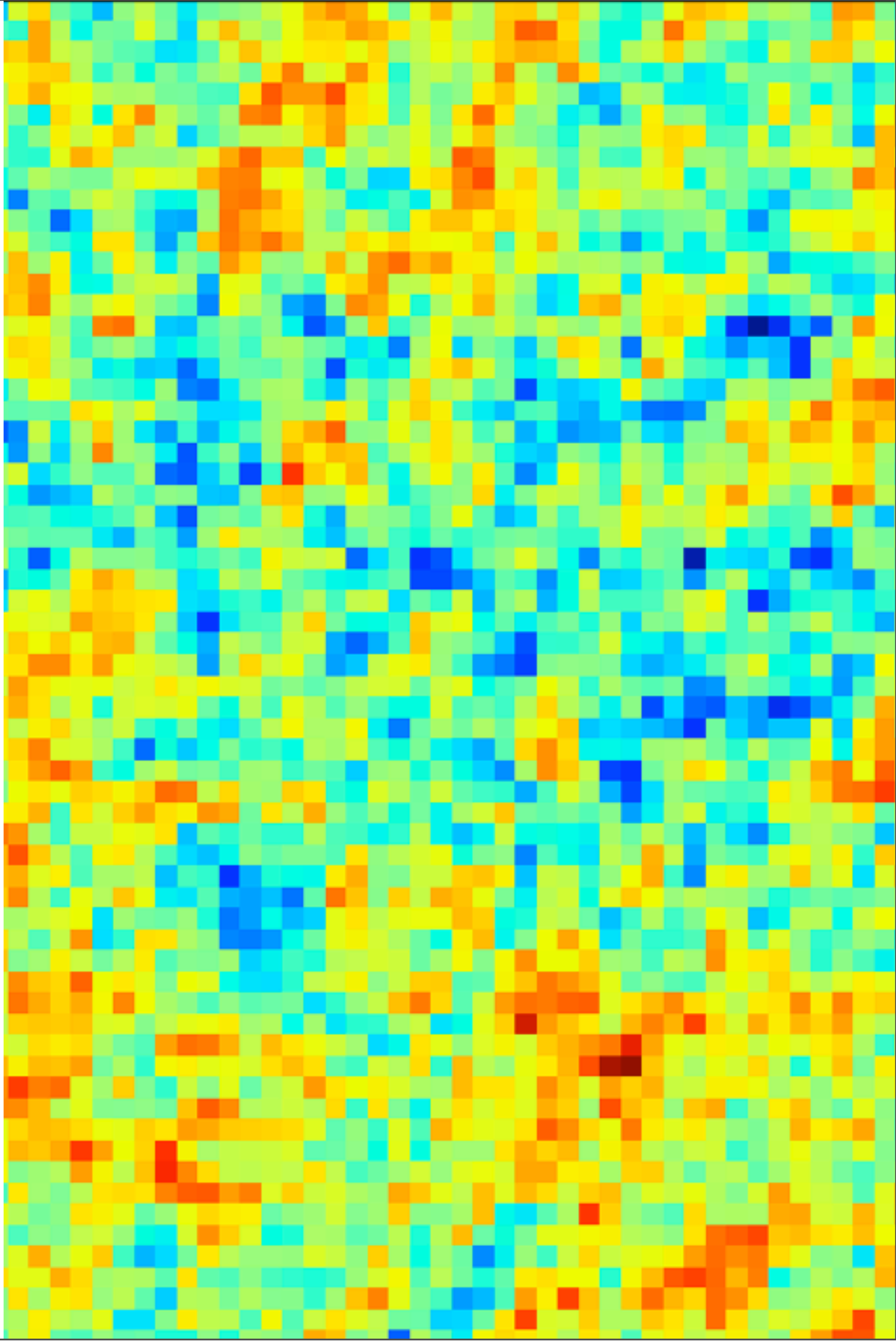


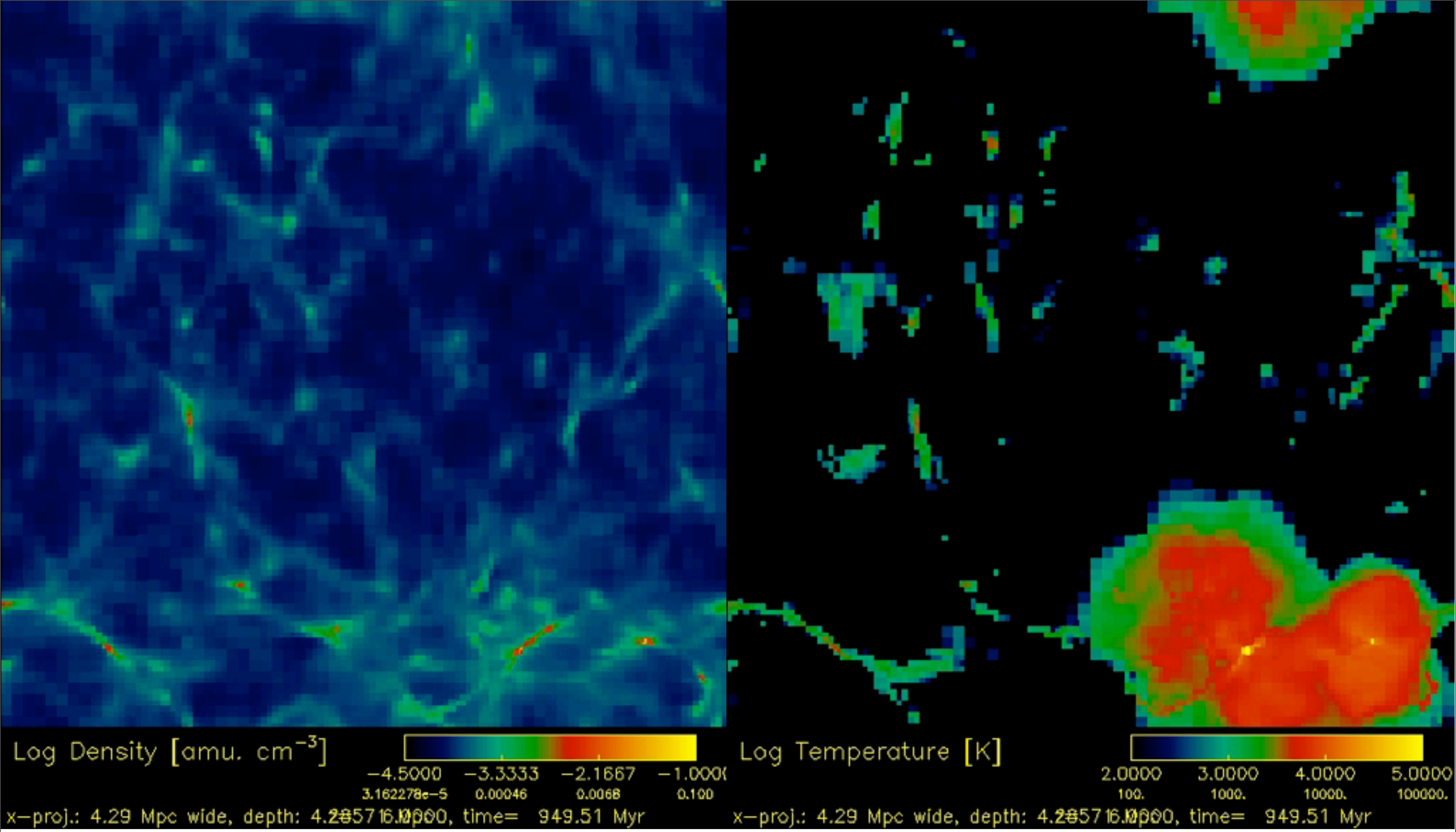
Let’s put them **together**.



Toy Reionization Simulation

- 30 Mpc, 64^3 resolution
- AMR with 8 levels
- Maximal spatial resolution of 1.8 comoving kpc
- $4 \times 10^9 \, M_\odot$ DM mass resolution
- Hydrogen ionization only
- Star cluster particles with metal enrichment
- Stop at $z = 6$

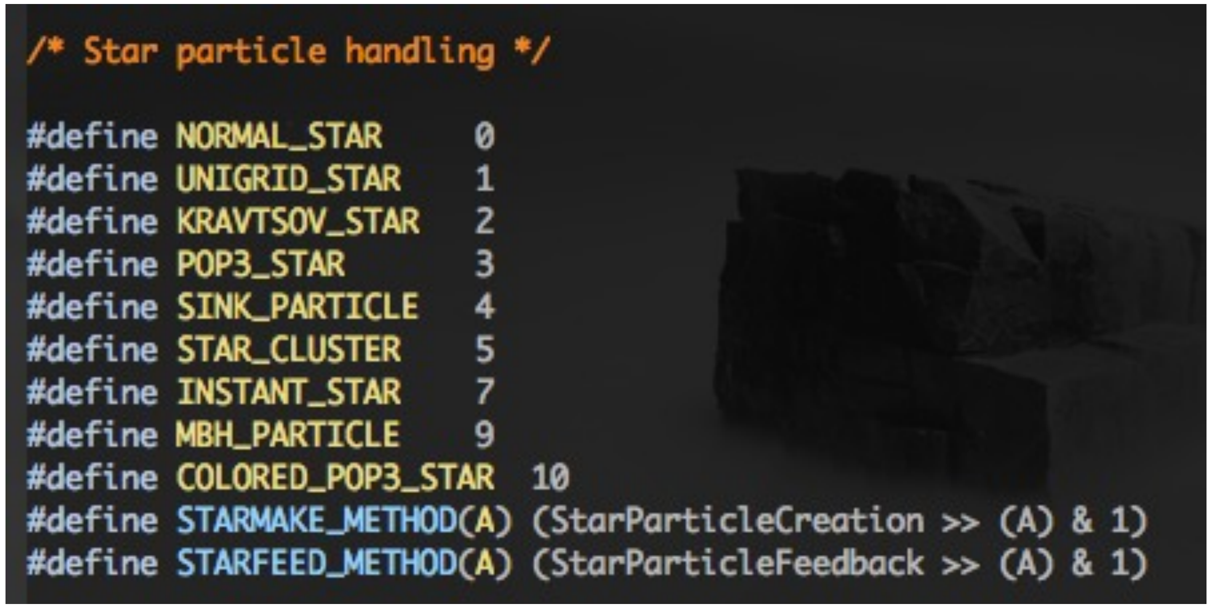




No full reionization because of mass resolution (i.e. we miss all of the low-luminosity dwarfs)

Create your own star particle type

1. In `macros_and_parameters.h`, add your particle type macro.



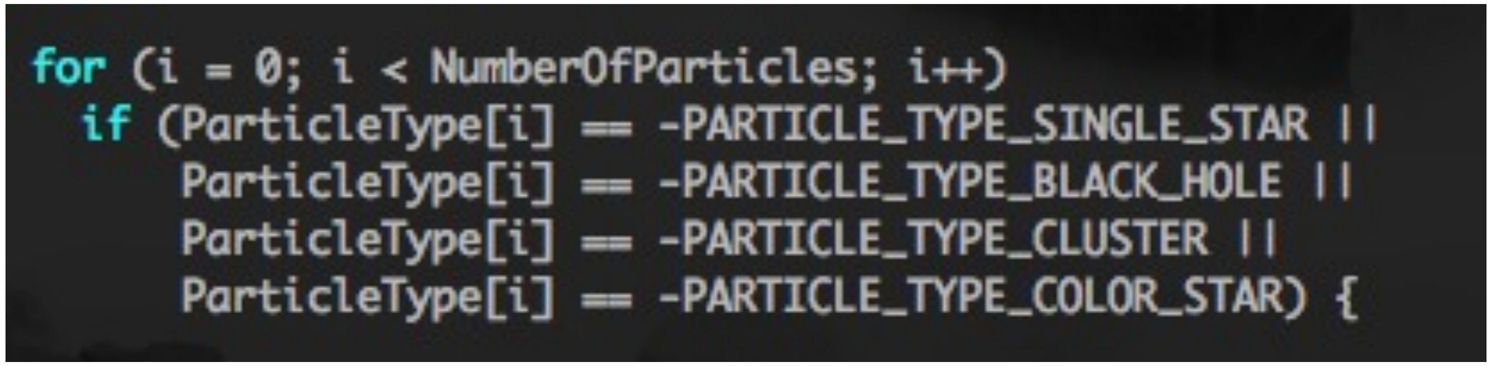
```
/* Star particle handling */

#define NORMAL_STAR     0
#define UNIGRID_STAR    1
#define KRAVTSOV_STAR   2
#define POP3_STAR       3
#define SINK_PARTICLE   4
#define STAR_CLUSTER    5
#define INSTANT_STAR    7
#define MBH_PARTICLE    9
#define COLORED_POP3_STAR  10
#define STARMAKE_METHOD(A) (StarParticleCreation >> (A) & 1)
#define STARFEED_METHOD(A) (StarParticleFeedback >> (A) & 1)
```

2. Add a “`star_maker`” to `Grid_StarParticleHandler.C` or create your own routine that adds particles to the grid (e.g., only done in a restart).
    - Assign the new particles a particle type = –NEW_PARTICLE_TYPE, which tells the Star class routines to create a new Star object from this particle. It will be changed into a positive number when the Star object is created.

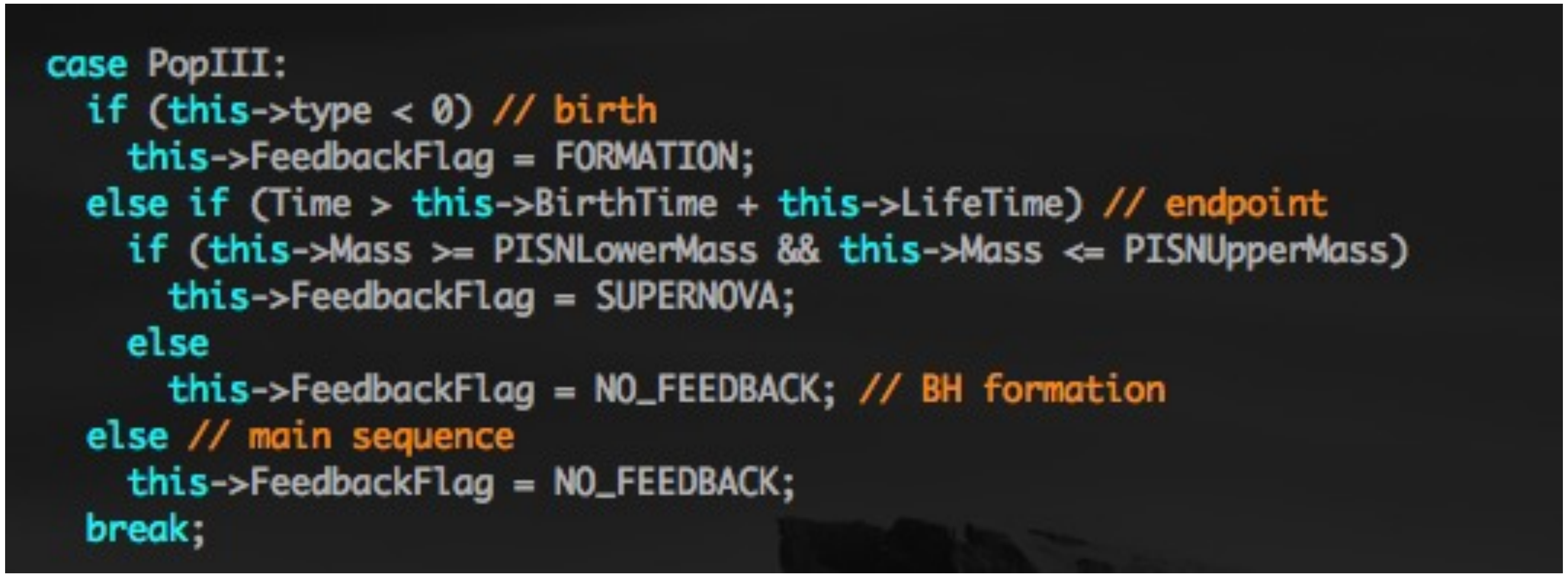
Create your own star particle type

3. Add your new star particle type to the if-statement in `Grid_FindNewStarParticles.C`



```
for (i = 0; i < NumberOfParticles; i++)
  if (ParticleType[i] == -PARTICLE_TYPE_SINGLE_STAR ||
      ParticleType[i] == -PARTICLE_TYPE_BLACK_HOLE ||
      ParticleType[i] == -PARTICLE_TYPE_CLUSTER ||
      ParticleType[i] == -PARTICLE_TYPE_COLOR_STAR) {
```

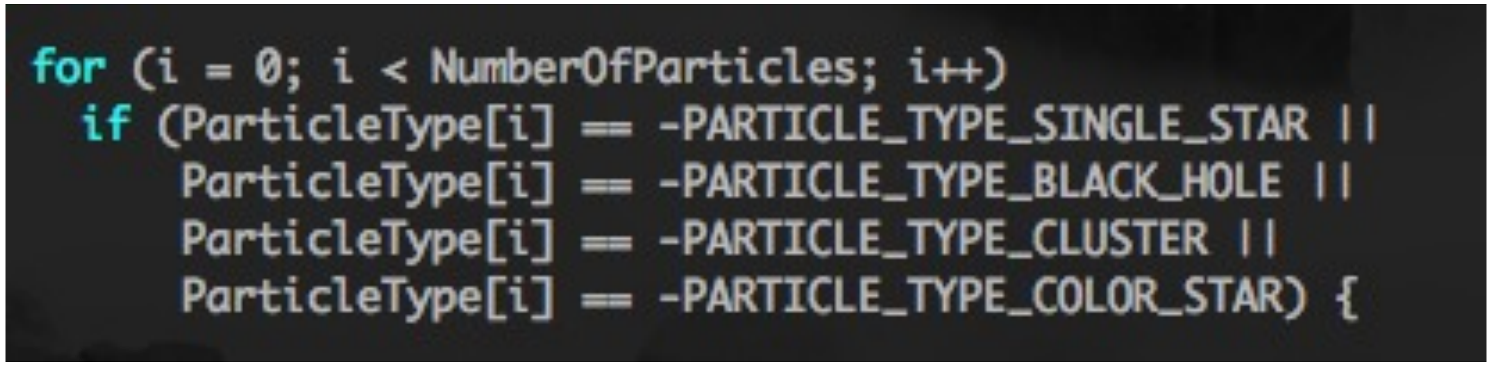
4. Add a case-statement to Star_SetFeedbackFlag



```
case PopIII:
  if (this->type < 0) // birth
    this->FeedbackFlag = FORMATION;
  else if (Time > this->BirthTime + this->LifeTime) // endpoint
    if (this->Mass >= PISNLowerMass && this->Mass <= PISNUpperMass)
      this->FeedbackFlag = SUPERNOVA;
    else
      this->FeedbackFlag = NO_FEEDBACK; // BH formation
  else // main sequence
    this->FeedbackFlag = NO_FEEDBACK;
  break;
```

Create your own star particle type

3. Add your new star particle type to the if-statement in `Grid_FindNewStarParticles.C`



```
for (i = 0; i < NumberOfParticles; i++)
  if (ParticleType[i] == -PARTICLE_TYPE_SINGLE_STAR ||
      ParticleType[i] == -PARTICLE_TYPE_BLACK_HOLE ||
      ParticleType[i] == -PARTICLE_TYPE_CLUSTER ||
      ParticleType[i] == -PARTICLE_TYPE_COLOR_STAR) {
```

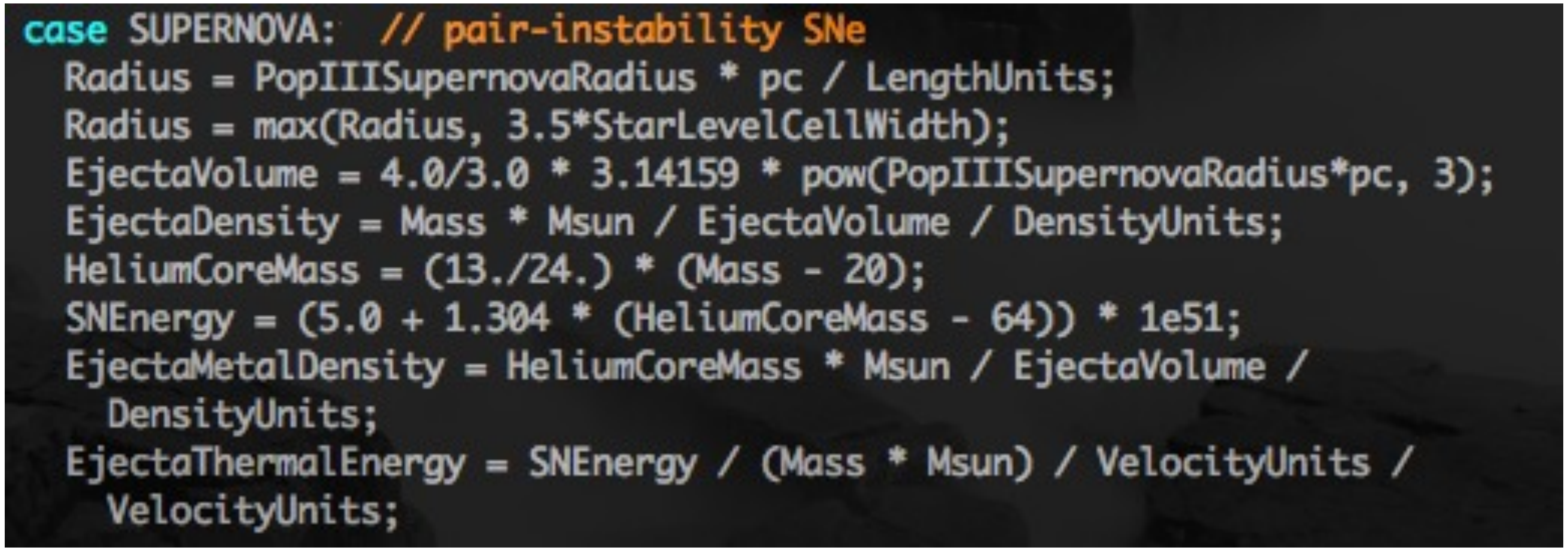
4. Add a case-statement to Star_SetFeedbackFlag

```
case BlackHole:
  this->FeedbackFlag = NO_FEEDBACK;
  break;
```

Create your own star particle type

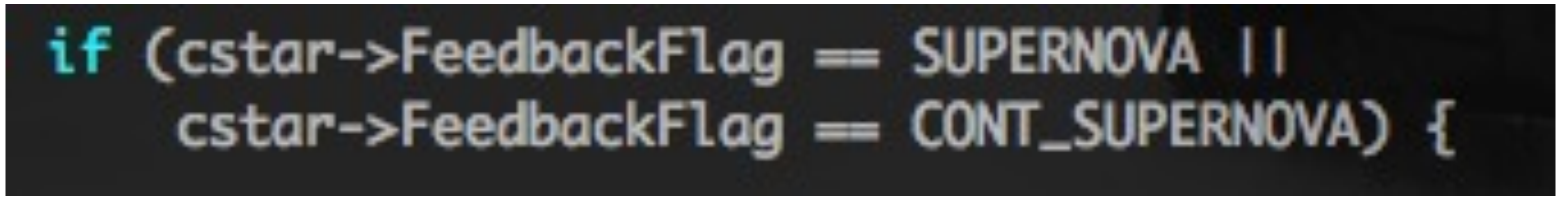
5. If adding a feedback sphere, you can customize your own sphere in

   `Star_CalculateFeedbackParameters.C`



```
case SUPERNOVA:  // pair-instability SNe
  Radius = PopIIISupernovaRadius * pc / LengthUnits;
  Radius = max(Radius, 3.5*StarLevelCellWidth);
  EjectaVolume = 4.0/3.0 * 3.14159 * pow(PopIIISupernovaRadius*pc, 3);
  EjectaDensity = Mass * Msun / EjectaVolume / DensityUnits;
  HeliumCoreMass = (13./24.) * (Mass - 20);
  SNEnergy = (5.0 + 1.304 * (HeliumCoreMass - 64)) * 1e51;
  EjectaMetalDensity = HeliumCoreMass * Msun / EjectaVolume /
    DensityUnits;
  EjectaThermalEnergy = SNEnergy / (Mass * Msun) / VelocityUnits /
    VelocityUnits;
```

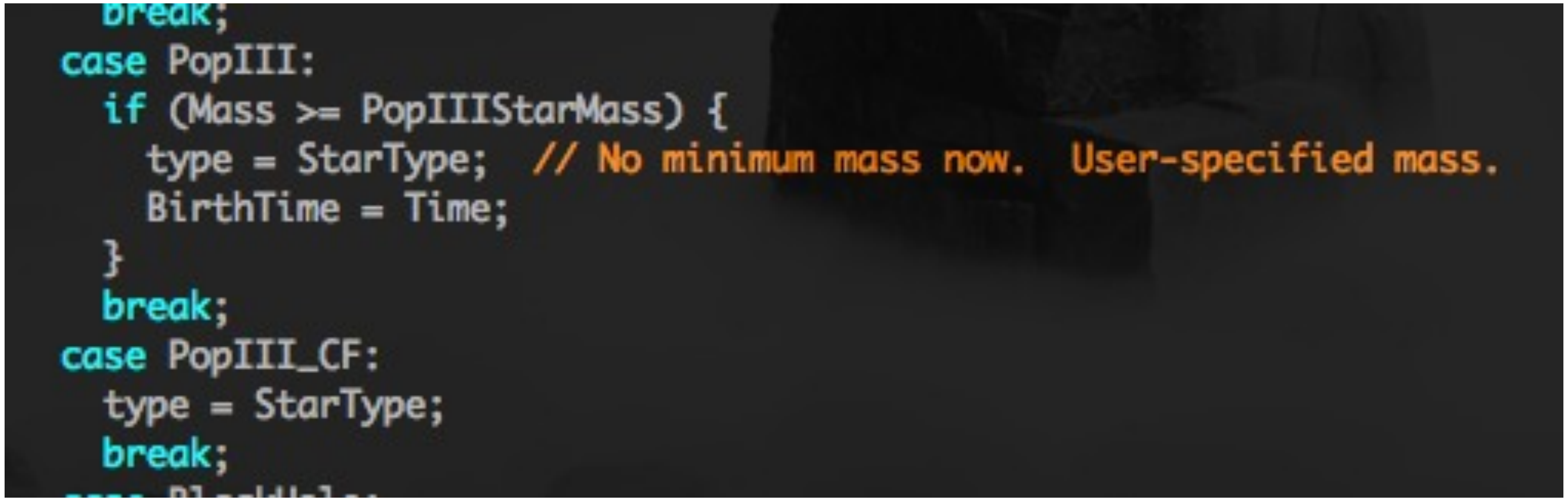
   `Grid_AddFeedbackSphere.C`.



```
if (cstar->FeedbackFlag == SUPERNOVA ||
    cstar->FeedbackFlag == CONT_SUPERNOVA) {
```

Create your own star particle type

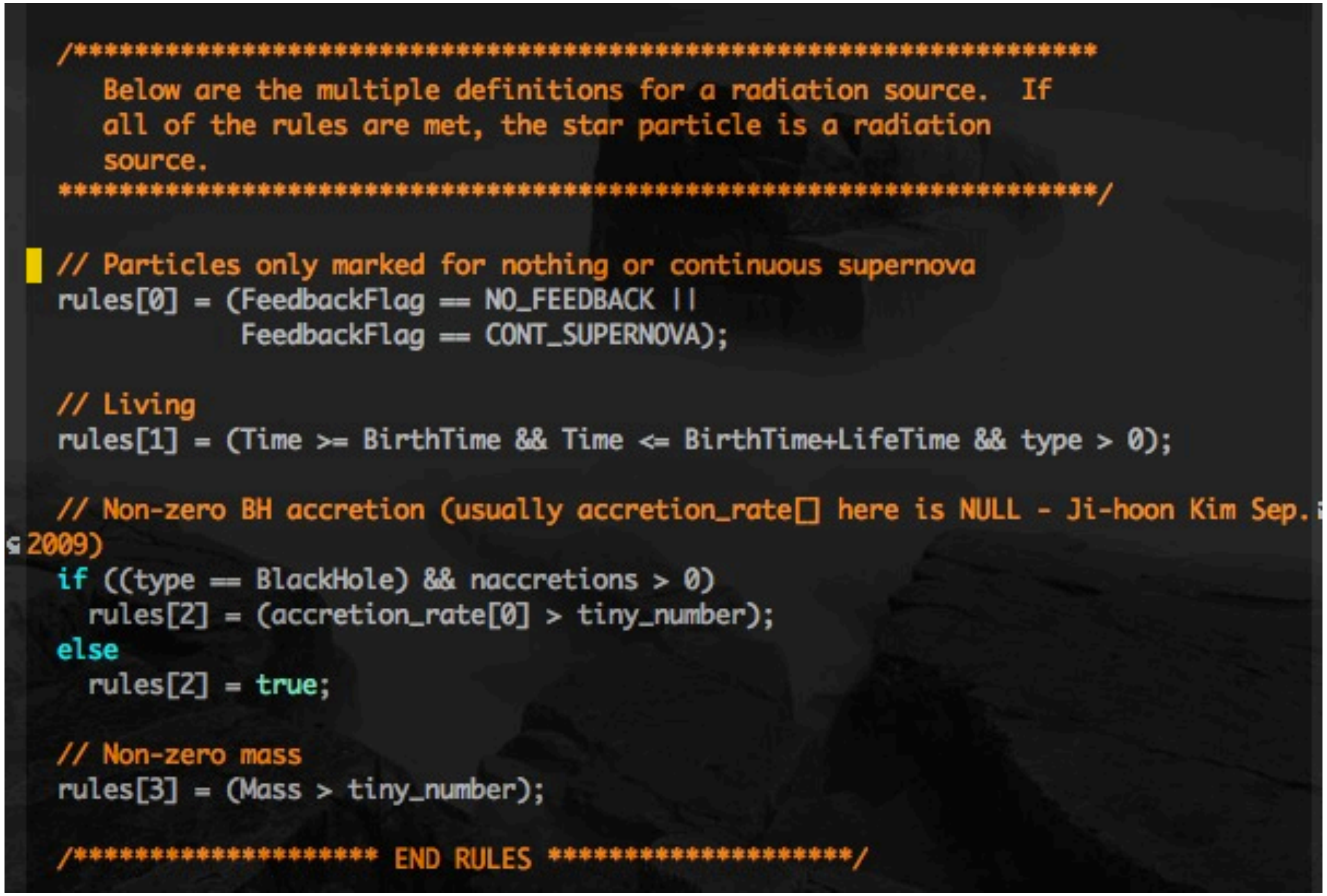
6. Add a case-statement to `Star_ActivateNewStar.C`



```
  break;
case PopIII:
  if (Mass >= PopIIIStarMass) {
    type = StarType;  // No minimum mass now.  User-specified mass.
    BirthTime = Time;
  }
  break;
case PopIII_CF:
  type = StarType;
  break;
```

Create your own star particle type

7. If you don’t want your new star particle type to be radiating (i.e. only add feedback spheres), add an additional logic check in `Star_IsARadiationSource.C`.



```
/*******************************************************************
   Below are the multiple definitions for a radiation source.  If
   all of the rules are met, the star particle is a radiation
   source.
*******************************************************************/

// Particles only marked for nothing or continuous supernova
rules[0] = (FeedbackFlag == NO_FEEDBACK ||
            FeedbackFlag == CONT_SUPERNOVA);

// Living
rules[1] = (Time >= BirthTime && Time <= BirthTime+LifeTime && type > 0);

// Non-zero BH accretion (usually accretion_rate[] here is NULL - Ji-hoon Kim Sep.
2009)
if ((type == BlackHole) && naccretions > 0)
  rules[2] = (accretion_rate[0] > tiny_number);
else
  rules[2] = true;

// Non-zero mass
rules[3] = (Mass > tiny_number);

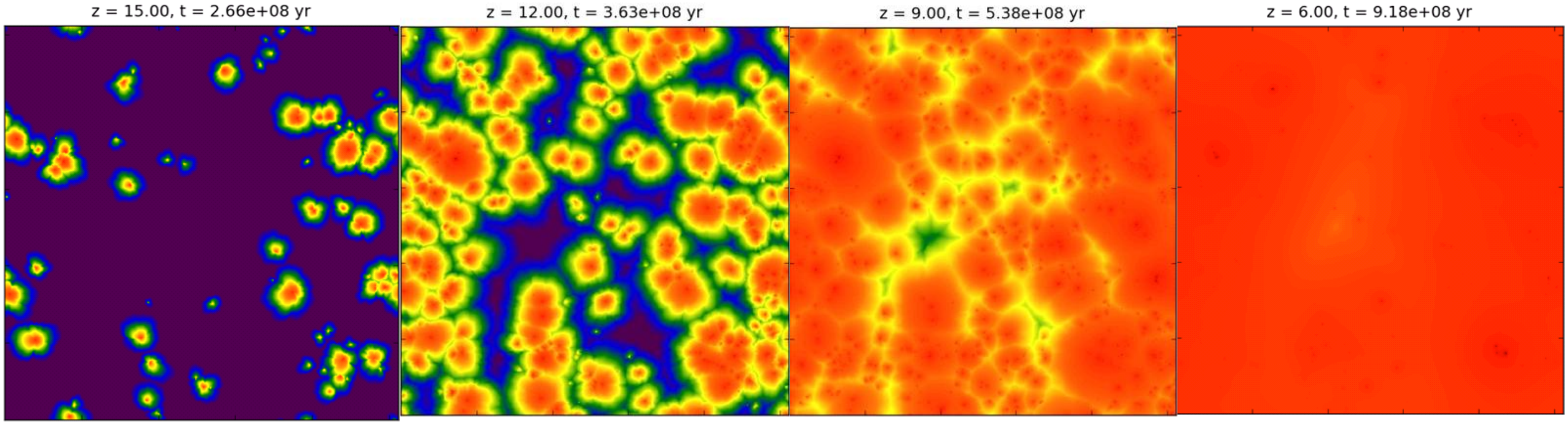
/******************** END RULES ********************/
```

Summary

- Run non-cosmological radiative hydrodynamics problems.
- New Star class
- New “star cluster” and Population III star particles.
- Run cosmological simulations with radiation transport from dynamically created star particles
- Create your own radiating “star” particle type.

Self-consistent Cosmological Radiation Hydrodynamics/Ionization

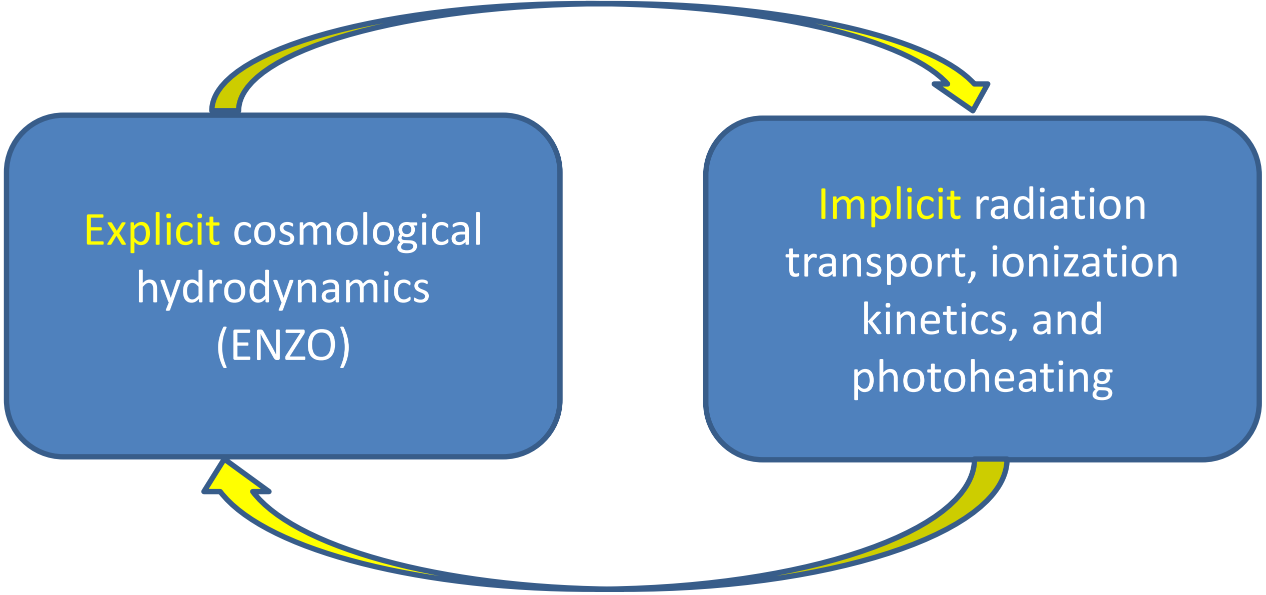
- implicit flux limited diffusion solver
- coupled to ionization kinetics and gas energy equation
- only for unigrid in 2.0 (AMR not supported yet)
- requires *hypre* library from LLNL



Self-consistent Cosmological Radiation Hydrodynamics/Ionization

Reynolds, Hayes, Paschos & MN (2009)

- Goal
  - Create a parallel scalable solver that couples cosmological hydrodynamics, radiation transport, chemical ionization, and gas photoheating self-consistently



Explicit cosmological hydrodynamics (ENZO)

Implicit radiation transport, ionization kinetics, and photoheating

Cosmological Radiative Transfer Equation

cosmological
redshift

cosmological
expansion

$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \frac{\hat{n}\cdot\nabla I_\nu}{a} - \frac{H(t)}{c}(\nu\frac{\partial I_\nu}{\partial \nu} - 3I_\nu) = \eta_\nu - \chi_\nu I_\nu$$

$$a(t) \equiv \frac{1}{1+z} \quad \text{cosmic scale factor}$$

$$E_\nu = \frac{1}{c}\oint I_\nu(\hat{n})d\Omega; \quad \vec{F}_\nu = \oint I_\nu(\hat{n})\hat{n}d\Omega$$

$$\frac{\partial E_\nu}{\partial t} + \frac{\nabla\cdot F_\nu}{a^2} - \frac{\dot{a}}{a}(\nu\frac{\partial E_\nu}{\partial \nu} - 3E_\nu) = 4\pi\eta_\nu - c\chi_\nu E_\nu$$

Spatial gradients WRT coordinates comoving with expanding universe

Flux-Limited Diffusion Radiation Transfer

We approximate the radiative flux as a function of the energy density gradient,

$$\mathbf{F}_\nu = -D\nabla E_\nu ,$$

where $D : \Omega \rightarrow \mathbb{R}^{3\times 3}$ is the *flux-limiter**, $D = D(e, E_\nu, \nabla E_\nu)$.

With this approximation, the radiation energy equation becomes

$$\partial_t E_\nu + \frac{1}{a}\nabla\cdot(E_\nu \mathbf{v}_b) - \frac{1}{a^2}\nabla\cdot(D\nabla E_\nu) - \frac{1}{ca^3}\xcancel{(\nabla(D\nabla E_\nu)) : (\nabla \mathbf{v}_b)}$$
$$= \nu\frac{\dot a}{a}\partial_\nu E_\nu - 3\frac{\dot a}{a}E_\nu + 4\pi\eta_\nu - ck_\nu E_\nu .$$

$$\boxed{\partial_t E_\nu + \frac{1}{a}\nabla\cdot(E_\nu \upsilon_b) = \frac{1}{a^2}\nabla\cdot(D\nabla E_\nu) + \frac{\dot a}{a}\left(\nu\partial_\nu E_\nu - 3E_\nu\right) + 4\pi\eta_\nu - c\kappa_\nu E_\nu}$$

Reduces to standard equation setting a=1

Spectral Modeling: 1-group Approximation

$$\boxed{E_\nu(\mathbf{x},t,\nu) = \tilde{E}(\mathbf{x},t)\,\chi_E(\nu)}$$

$$\chi_E(\nu) = \begin{cases} \delta(\nu - \nu_0) & \textit{monochromatic} \\ \mathrm{B}_\nu(T) & \textit{blackbody} \\ \chi_0(\nu/\nu_0)^\alpha & \textit{powerlaw} \end{cases}$$

Comoving radiation energy density

$$E(\mathbf{x},t) = \int_{\nu_0}^{\infty} E_\nu(\mathbf{x},t,\nu)\,d\nu = \tilde{E}(\mathbf{x},t)\int_{\nu_0}^{\infty} \chi_E(\nu)\,d\nu.$$

$$\boxed{\partial_t E + \frac{1}{a}\nabla\cdot(E\upsilon_b) = \frac{1}{a^2}\nabla\cdot(D\nabla E) + m\frac{\dot{a}}{a}E + 4\pi\eta - c\kappa E}$$

Why use FLD?

- Invented by my thesis adviser Jim Wilson
- Simple and easy (no formal solution needed)
- Correct behavior in limiting regimes
- Causal propagation of radiation energy
- I am interested in large volumes and many sources, where diffuse radiation backgrounds dominate local effects (i.e., shadows)
- SPD matrix➔efficient solution methods
- Extenstion to VTEF with analytic EFs straightforward

System of Equations

$$\partial_t \rho_b + \frac{1}{a}\mathbf{v}_b \cdot \nabla \rho_b = -\frac{1}{a}\rho_b \nabla \cdot \mathbf{v}_b, \tag{1}$$

$$\partial_t \mathbf{v}_b + \frac{1}{a}\left(\mathbf{v}_b \cdot \nabla\right)\mathbf{v}_b = -\frac{\dot{a}}{a}\mathbf{v}_b - \frac{1}{a\rho_b}\nabla p - \frac{1}{a}\nabla\phi, \tag{2}$$

$$\partial_t e + \frac{1}{a}\mathbf{v}_b \cdot \nabla e = -\frac{2\dot{a}}{a}e - \frac{1}{a\rho_b}\nabla \cdot (p\mathbf{v}_b) - \frac{1}{a}\mathbf{v}_b \cdot \nabla\phi + G - \Lambda \tag{3}$$

$$\partial_t \mathrm{n}_i + \frac{1}{a}\nabla \cdot (\mathrm{n}_i \mathbf{v}_b) = \alpha_{i,j}\mathrm{n}_e \mathrm{n}_j - \mathrm{n}_i \Gamma_i^{ph}, \qquad i = 1, \ldots, N_s \tag{4}$$

$$\partial_t E + \frac{1}{a}\nabla \cdot (E\mathbf{v}_b) = \nabla \cdot (D\nabla E) - m\frac{\dot{a}}{a}E + 4\pi\eta - c\kappa E. \tag{5}$$

$$\nabla^2\phi = \frac{4\pi g}{a}(\rho_b + \rho_{dm} - \langle\rho\rangle), \tag{6}$$

$$e = \frac{p}{\rho_b(\gamma - 1)} + \frac{1}{2}|\mathbf{v}_b|^2, \tag{7}$$

$$\Gamma_i^{ph} = \int_{\nu_i}^{\infty} c\,\sigma_{\mathrm{n}_i}(\nu)\,\frac{E_\nu}{h\nu}\,d\nu$$

Operator Splitting

let

$e = e_h + e_c$

where

e_h is gas energy due to hydrodynamic motions

e_c is energy correction due to coupling with radiation/ionization

Gas energy equation

$$\partial_t(e_h + e_c) + \frac{1}{a}\mathbf{v}_b \cdot \nabla(e_h + e_c) = \tag{13}$$

$$- \frac{2\dot{a}}{a}(e_h + e_c) - \frac{1}{a\rho_b}\nabla \cdot (p\mathbf{v}_b) - \frac{1}{a}\mathbf{v}_b \cdot \nabla\phi + G - \Lambda.$$

Explicit hydrodynamics

$$\partial_t \rho_b + \frac{1}{a}\mathbf{v}_b \cdot \nabla \rho_b = -\frac{1}{a}\rho_b \nabla \cdot \mathbf{v}_b, \tag{14}$$

$$\partial_t \mathbf{v}_b + \frac{1}{a}\left(\mathbf{v}_b \cdot \nabla\right)\mathbf{v}_b = -\frac{\dot{a}}{a}\mathbf{v}_b - \frac{1}{a\rho_b}\nabla p - \frac{1}{a}\nabla\phi, \tag{15}$$

$$\partial_t e_h + \frac{1}{a}\mathbf{v}_b \cdot \nabla e_h = -\frac{2\dot{a}}{a}e_h - \frac{1}{a\rho_b}\nabla \cdot \left(p\mathbf{v}_b\right) - \frac{1}{a}\mathbf{v}_b \cdot \nabla\phi \tag{16}$$

$$\partial_t \mathbf{n}_i + \frac{1}{a}\nabla \cdot \left(\mathbf{n}_i\mathbf{v}_b\right) = 0, \tag{17}$$

$$\partial_t E + \frac{1}{a}\nabla \cdot \left(E\mathbf{v}_b\right) = 0, \tag{18}$$

This is what ENZO already does

Implicit Coupled System

- non-equilibrium multispecies model

$$\partial_t e_c = -\frac{2\dot{a}}{a} e_c + G - \Lambda, \tag{19}$$

$$\partial_t \mathrm{n}_i = \alpha_{i,j} \mathrm{n}_e \mathrm{n}_j - \mathrm{n}_i \Gamma_i^{ph}, \tag{20}$$

$$\partial_t E = \nabla \cdot (D \nabla E) - m\frac{\dot{a}}{a} E + 4\pi\eta - c\kappa E, \tag{21}$$

- LTE (2 temperature) model

$$\partial_t e_c = -\frac{2\dot{a}}{a} e_c + G - \Lambda, \tag{19}$$

$$\partial_t E = \nabla \cdot (D \nabla E) - m\frac{\dot{a}}{a} E + 4\pi\eta - c\kappa E, \tag{21}$$

Temporal Discretization

Generalized Crank-Nicholson (theta scheme)

$$e_c^{n+1} + \Delta t\theta\mathcal{L}_e^{n+1} = e_c^n + \Delta t(\theta - 1)\mathcal{L}_e^n, \tag{22}$$

$$\mathrm{n}_i^{n+1} + \Delta t\theta\mathcal{L}_{\mathrm{n}_i}^{n+1} = \mathrm{n}_i^n + \Delta t(\theta - 1)\mathcal{L}_{\mathrm{n}_i}^n, \tag{23}$$

$$E^{n+1} + \Delta t\theta\left[\mathcal{D}_E^{n+1} + \mathcal{L}_E^{n+1}\right] = E^n + \Delta t(\theta - 1)\left[\mathcal{D}_E^n + \mathcal{L}_E^n\right]. \tag{24}$$

$$\mathcal{D}_E = \mathcal{D}_E(E, \mathrm{n}_i) \equiv -\nabla\cdot(D\nabla E), \tag{25}$$

and we have defined the local "reaction" operators as

$$\mathcal{L}_e = \mathcal{L}_e(e_c, E, \mathrm{n}_i) \equiv \frac{2\dot{a}}{a}e_c - G + \Lambda \tag{26}$$

$$\mathcal{L}_{\mathrm{n}_i} = \mathcal{L}_{\mathrm{n}_i}(\mathrm{n}_i, e_c, E) \equiv \mathrm{n}_i\Gamma_i^{ph} - \alpha_{i,j}\mathrm{n}_e\mathrm{n}_j \tag{27}$$

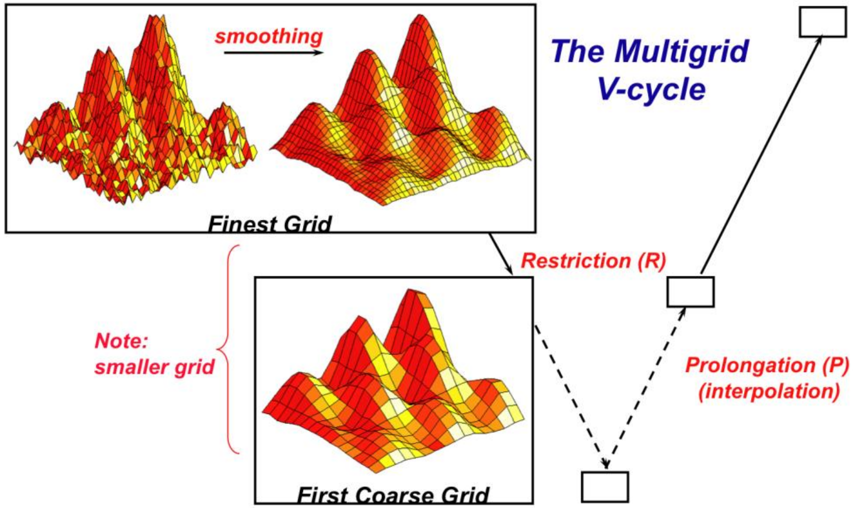
$$\mathcal{L}_E = \mathcal{L}_E(E, e_c, \mathrm{n}_i) \equiv m\frac{\dot{a}}{a}E - 4\pi\eta + ckE. \tag{28}$$

Multigrid-Preconditioned Conjugate Gradient

- The primary difficulty in solving these systems lies in the Schur complement system

$$(D - LM^{-1}U)\, x_E \;=\; b_E - LM^{-1}b_M$$

- Due to the diffusion approximation, and the spatial locality of M and L, this matrix is symmetric and positive definite.
- SPD systems are often solved using the *conjugate-gradient* method; a robust, low-memory Krylov iterative solver. Unfortunately, CG convergence rates depend on the eigenvalues of the matrix, which here spread rapidly with mesh refinement, resulting in slower convergence as the mesh is refined.
- We therefore *precondition* the CG solver, i.e. $Ax = b \;\rightarrow\; (P^{-1}AP^{-1})(Px) = P^{-1}b$, where the symmetric operator P^{-1} comes from a *geometric multigrid* (MG) solver.
- MG methods, while less robust, exhibit convergence rates that are independent of the matrix spectrum, resulting in near optimal log-linear algorithm complexity, and scalability to thousands of processors.
- This MG-CG combination results in a robust, scalable solver for the inner Schur systems.



HYPRE solver library, LLNL

Build Configuration

- To use any FLD solver module, Enzo must be configured with:
  - `gmake photon-yes` [enables all radiation solvers]
  - `gmake hypre-yes` [enables HYPRE solver interface]
  - `gmake use-mpi-yes` [enables MPI]
- Moreover, the machine Makefile must specify how to include and link with an available HYPRE library (version $\geq$ 2.4.0b).
- If you must compile HYPRE yourself, use the configuration option `--with-no-global-partition` for runs using over 1000 tasks.
- Optional/recommended Enzo configuration options include:
  - `gmake emissivity-yes` [enables coupling with star-maker]
  - `gmake precision-64` [the solvers prefer double precision]

Startup Parameters

The main problem parameter file must have the following parameters:

- `RadiativeTransferFLD` [0] – this must be 2.
- `ImplicitProblem` [0] – use 3 for `gFLDSplit`, 1 for `gFLDProblem`.
- `ProblemType` [0] – FLD-based solvers use values in the 400's.
- `RadHydroParamfile` [NULL] – the filename containing all FLD-specific solver parameters (next slide).
- `RadiativeTransferOpticallyThinH2` [1] – this must be 0.

- `RadiationFieldType` [0] – can be any value *except* 10 or 11.
- `RadiativeTransferFLDCallOnLevel` [0] – must currently be 0.
- `RadiativeTransfer` [0] – this must be be 0.
- `RadiativeCooling` [0] – must currently be 0.

FLD Solver Parameters (separate input file)

The following parameters control various aspects of `gFLDSplit`:

- `RadHydroESpectrum` [1] – form for radiation spectrum $\chi_E(\nu)$:
  - -1. is monochromatic at $h\nu = 13.6$ eV,
  - 0. is power law,
  - 1. is $T = 10^5$ blackbody.
- `RadHydroChemistry` [1] – controls whether to use $\mathtt{n}_{HI}$ (1 yes, 0 no)
- `RadHydroHFraction` [1] – controls the fraction of baryonic matter comprised of Hydrogen ($\mathtt{RadHydroHFraction} \in [0, 1]$).
- `RadHydroModel` [1] – determines which model for radiation-matter coupling we wish to use:
  1. Chemistry-dependent model with case B recombination coeff.
  4. Same as model 1, with an isothermal gas energy.
  10. Local thermodynamic equilibrium model (no $\mathtt{n}_{HI}$).

FLD Solver Parameters – continued

- `RadHydroMaxDt` [10^{20}] – sets Δt_{max} in scaled time units.
- `RadHydroMinDt` [0] – sets Δt_{min} in scaled time units.
- `RadHydroInitDt` [10^{20}] – sets the initial Δt_E in scaled time units.
- `RadHydroDtNorm` [2] – sets p in computing the time error estimate.
- `RadHydroDtRadFac`, `RadHydroDtGasFac`, `RadHydroDtChemFac` [10^{20}] – the values of $\tau_{i,\text{tol}}$ in computing Δt_E, Δt_e and Δt_{HI}.
- `RadiationScaling`, `EnergyCorrectionScaling`, `ChemistryScaling` [1.0] – the scaling factors s_E, s_e and s_{n}.
- `RadHydroTheta` [1.0] – the $\partial_t E$ discretization parameter, θ.
- `RadHydroSolTolerance` [10^{-8}] – linear solver tolerance δ.

FLD Solver Parameters – continued

- `RadiationBoundaryX0Faces`, `RadiationBoundaryX1Faces`, `RadiationBoundaryX2Faces` [0 0] – BC types at each face:
  0. periodic (must match on both faces in a given direction)
  1. Dirichlet
  2. Neumann
- `EnergyOpacityC0`-`EnergyOpacityC2` [1, 1, 0] – the opacity-defining constants C_0-C_2 for the LTE model.
- `RadHydroMaxMGIters` [50] – max number of MG-CG iterations.
- `RadHydroMGRelaxType` [1] - the MG relaxation method:
  0. Jacobi
  1. Weighted Jacobi
  2. Red/Black Gauss-Seidel (symmetric)
  3. Red/Black Gauss-Seidel (nonsymmetric)
- `RadHydroMGPreRelax` [1] – number of pre-relaxation MG sweeps.
- `RadHydroMGPostRelax` [1] – number of post-relaxation MG sweeps.

Customization

To set up a new FLD problem:

- Allocate a baryon field with `FieldType` set to `RadiationFreq0`.
- Set $\eta(\mathbf{x}, t)$ by either:
  - Edit `gFLDSplit_RadiationSource.src90` or `gFLDProblem_RadiationSource.src90`,
  - Fill in the baryon field `Emissivity0`, and edit logic in `gFLDSplit_Evolve.C` or `gFLDProblem_Evolve.C` to use that field (emulate logic for `StarMakerEmissivityField`).
- Edit `gFLDSplit_Initialize.C` or `gFLDProblem_Initialize.C` to call the problem initializer and set BCs.
- All other requirements for setting up a new ProblemType in Enzo are like normal (`InitializeNew.C`, problem initialization files, etc.).

Iliev Test 5 Example – Dynamic I-front Expansion

[on Triton: `/home/enzo-1/IlievEtAl5`]

Dynamic ionization test of an initially-neutral hydrogen region:

- Box size $L = 15$ kpc; Run time $T_f = 500$ Myr.
- $T = 10^5$ blackbody spectrum, at rate $\dot{N}_\gamma = 5 \cdot 10^{48}$ photon/s.
- Initial conditions: $n = 10^{-3}$ cm^{-3}, $T = 100$ K, $E = 10^{-30}\ \frac{\text{erg}}{\text{cm}^3}$.

No available analytical solution, but:

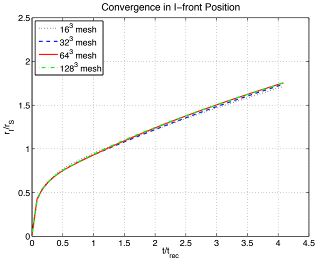
- Front transitions from R- to D-type as it reaches Strömgren radius,

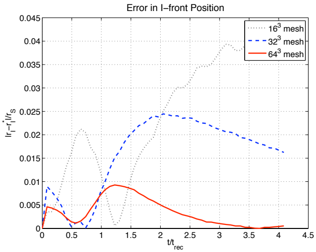
$$r_I^R = r_S \left[1 - e^{-t\alpha_B(T_i)n_H}\right]^{1/3}, \qquad r_I^D = r_S \left[1 + (7c_s t)/(4r_S)\right]^{4/7},$$

- Eventually stalls at $r_f = r_S \left(\frac{2T_i}{T_e}\right)^{2/3}$, where T_i and T_e are the temperatures behind and ahead of the I-front.

[Whalen & Norman, *ApJS*, 2006; Iliev et al., *MNRAS*, 2009]

Hydrodynamic Radiative Ionization Results



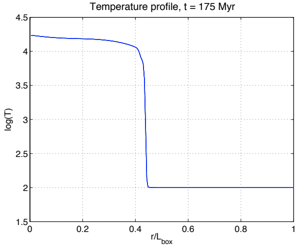


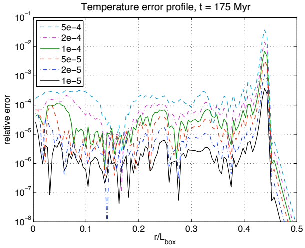
NW:
I-front position history

NE:
T profile (175 Myr)

SW:
r_I conv. wrt Δx

SE:
T convergence wrt Δt





Shapiro & Giroux [Isothermal, Static Cosmic Ionization]

[in enzo-2.0: `run/RadiationTransportFLD/SG_q5z4_sp`]
Repeat of previous test, but in a cosmologically expanding universe, with a static, isothermal gas, using a monochromatic radiation spectrum.

Four tests:

q_0	z_i	L_i [kpc]	$\rho_{b,i}$ [g cm^{-3}]	H_0	Ω_m	Ω_Λ	Ω_b
0.5	4	80	1.18e-28	0.5	1.0	0	0.2
0.05	4	60	2.35e-28	1.0	0.1	0	0.1
0.5	10	36	1.18e-28	0.5	1.0	0	0.2
0.05	10	27	2.35e-28	1.0	0.1	0	0.1

Analytical solution given by

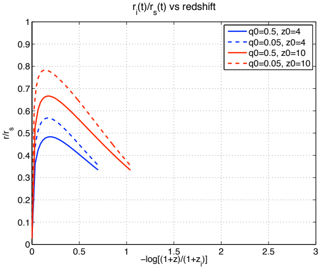
$$r_I(t) = r_{S,i}\left(\lambda e^{-\tau(t)}\int_1^{a(t)} e^{\tau(b)}\left[1-2q_0+2q_0(1+z_i)/b\right]^{-1/2}\mathrm{d}b\right)^{1/3},$$

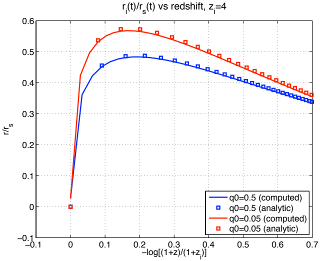
$$\tau(a) = \lambda\left[F(a)-F(1)\right]\left[6q_0^2(1+z_i)^2\right]^{-1}, \qquad \lambda = \frac{\alpha_B n_{H,i}}{H_0(1+z_i)},$$

$$F(a) = \left[2-4q_0-2q_0\frac{1+z_i}{a}\right]\left[1-2q_0+2q_0\frac{1+z_i}{a}\right]^{1/2}.$$

[Shapiro & Giroux, *ApJ*, 1987]

Cosmological Ionization Results





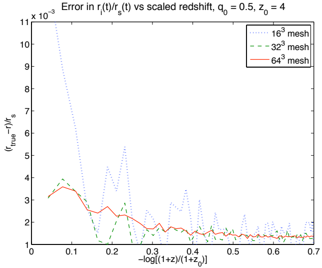
NW:
I-front radii vs scaled z

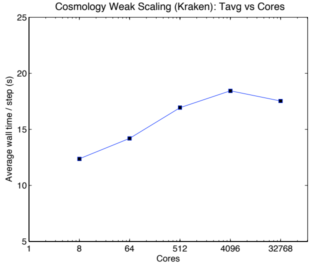
NE:
I-front error vs scaled z

SW:
I-front radii for $z_i = 4$.

SE:
Weak CPU scaling
$(N_{\text{src}} \propto N_{\text{CPU}})$

Kraken @ NICS:
$\mathcal{O}(N \log N)$ scaling





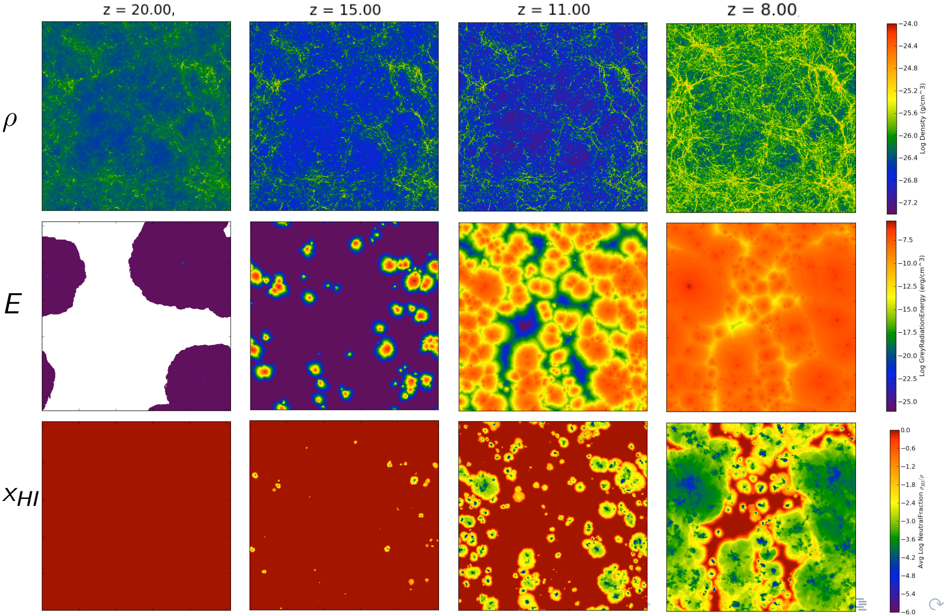
Reionization Simulations (FLD + StarMaker)

[in enzo-2.0: `run/RadiationTransportFLD/CosmologyFLD_RT`]

Geoffrey So has constructed an interface to StarMaker to seed $\eta(\mathbf{x}, t)$:

- Requires Enzo configuration with `EMISSIVITY` enabled,
- Adds `StarMakerEmissivityField=1` to main parameter file,
- The interface fills the `Emissivity0` baryon field based on emission from star particles; the FLD modules copy this field into $\eta(\mathbf{x}, t)$.
- Utilizes identical startup machinery as typical cosmology runs, via `CosmologySimulationInitialize.C` [ProblemType 30], with additional input file options to enable the FLD solver module.

Reionization Simulations (FLD + StarMaker)



Summary of Current Results

The `gFLDSplit` and `gFLDProblem` solver modules implement a grey, field-based, flux-limited diffusion radiation approximation for unigrid runs:

- Implicit MG-CG solvers enable scalable solution on many thousands of cores, *independently* of the number of ionization sources.
- Accurately solves couplings between radiation, ionization and gas energy, due to implicit formulation and coupled solvers.
- Split and implicit formulations allow for tradeoffs between robustness/efficiency and accuracy.

However, this approximation has its shortcomings:

- Single radiation field allows full absorption by hydrogen, even though higher-frequency radiation should pass through.
- Though better than simpler approximations, grey approach cannot accurately handle multi-species problems (hence H-only restriction).
- Currently limited to **unigrid** Enzo simulations.