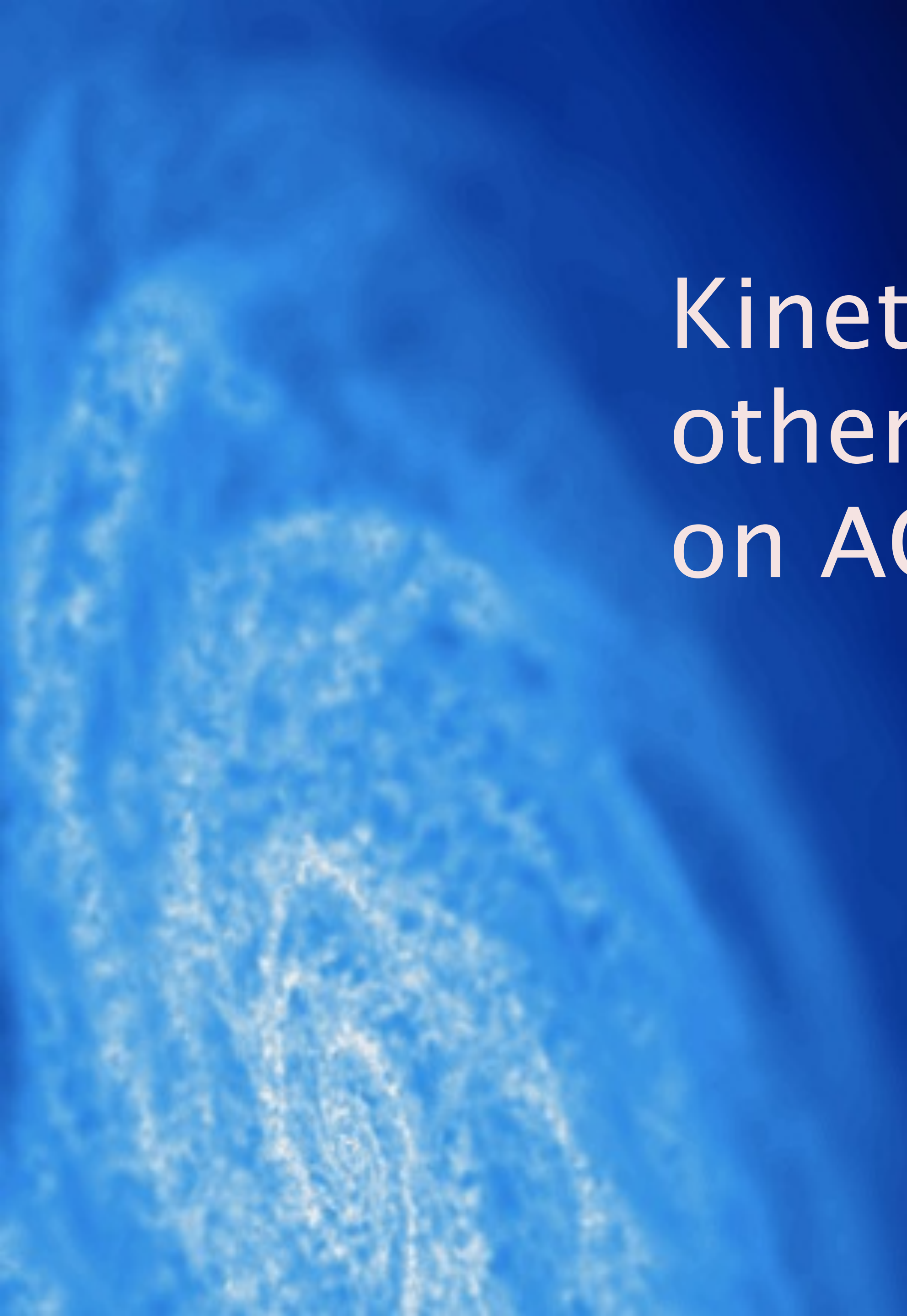


Kinetic SN Feedback & other UNLV efforts on AGORA

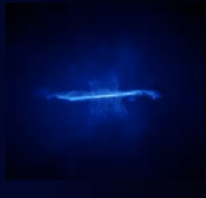
Ken Nagamine (Osaka / UNLV)

Keita Todoroki (UNLV / Kansas)

Robert Thompson (Cape Town)

Junhwan Choi (UT Austin)

Jason Jaacks (UT Austin)



Outline

I. Motivation
   - Role of feedback mechanisms

II. Modeling & Setup
   - Type II SN & Sedov-Taylor solution
   - Computational methods

III. Simulation Results

IV. Grackle Implementation

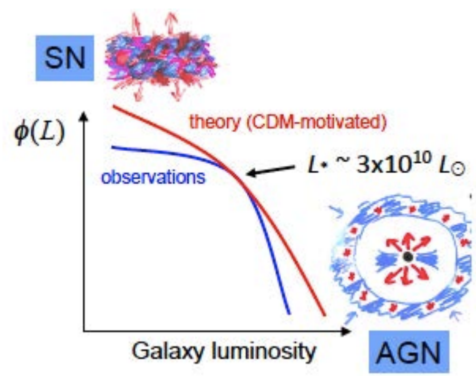
V. Future work

Discrepancies with observations

Some of the major issues:

- **Overcooling problem**
  - Simulations with no / weak feedback tend to over-predict the cosmic SF history with excessive amount of stars produced
    - (e.g. Katz, Weinberg & Hernquist 1996; Somerville & Primack 1999; Springel & Hernquist 2003; Kereš et al. 2009)
- **Luminosity function**
  - Simulations without feedback tend to make the lower and higher-mass ends steeper

    (e.g. Review by Silk 2013)



(Silk & Mamon 2012)

- **Missing satellites problem**
  - Simulations tend to over-predict

  number of small satellites for MW-type of galaxies

    (e.g. Klypin et al. 1999; Moore et al. 1999)

Indispensable role of feedback

- Chemical enrichment of the ISM and IGM
- Multi-phase nature of the ISM
- Evolution of galaxy morphologies
- Explaining observed galaxy properties

it is essential to integrate accurately modeled feedback mechanisms into galaxy formation simulations to better understand the structure formation.

e.g., Springel '05; Oppenheimer & Davè '06; Vecchia & Schaye '08 & '12; Choi & KN '10; Durier & Vecchia '11 & '12; Hopkins+ '12; Agertz+ '13; Aumer+ '13; + more

Problems w/ Previous models

- Resolution limits
- Phenomenological models w/ approx.

Involves turning off
(1) Cooling, or
(2) Star formation, or
(3) Hydrodynamic interactions
by hand for certain period of time

e.g. for SPH
- **Constant wind model (Springel & Hernquist '03)**
- **Kinetic SN feedback (Dalla Vecchia & Schaye '12)**
- **Stellar feedback (w/ SN) (Stinson+ '13)**

- **Models for cosmological box runs uses global galactic quantities (e.g. $M_\star$, σ, SFR)**

→ **Can & should build a better model based on local physical quantities**

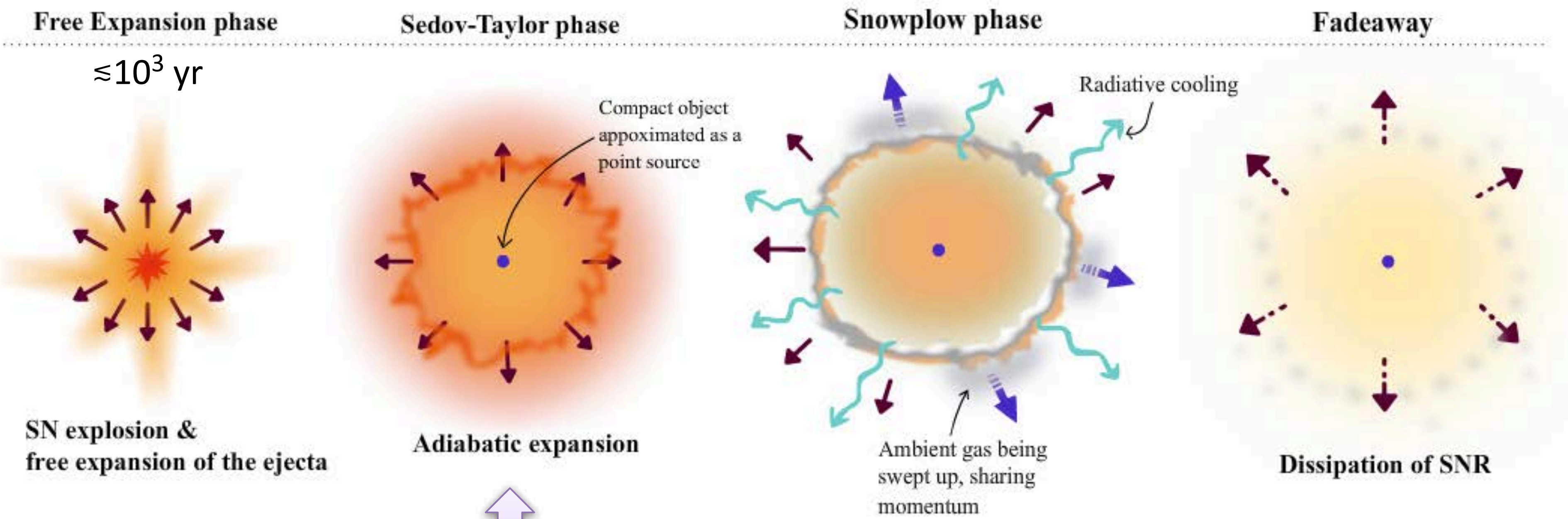
III. Our Modeling & Setup

- SN-II feedback model
  - SNR evolutionary phases
    - Sedov-Taylor solution
    - Gas & metal recycling
  - Stellar feedback

(Keita Todoroki's Master's thesis @ UNLV)

(paper in prep.)

SNR evolutionary phases



$\lesssim 10^3$ yr

$M_{ej} \approx 1 M_\odot$

$v_{ej} \approx 10^4\,\mathrm{kms}^{-1}$

$E_0 \approx 10^{51}$ erg

Radiative loss is negligible

Radiative cooling become non-negligible

Continuous expansion with decreasing speed & pressure

(e.g. Cox '93; Draine '11)

Sedov–Taylor solution

- **Shock vel, shock radius, time-scales are computed based on SN energy and gas density**

shock vel.
$$v_s = 188 \left(\frac{E_k}{n_0^2}\right)^{0.07} [\mathrm{km\ s^{-1}}]$$

shock radius
$$R_s = R_{SNR} = 23.7\, E_0{}^{0.29} n_0^{-0.42}\ [\mathrm{pc}]$$

End of ST-phase
$$t_{End\ of\ ST phase} = 49.3 \times 10^3\ E_0^{0.22} n_0^{-0.55} [\mathrm{yr}]$$

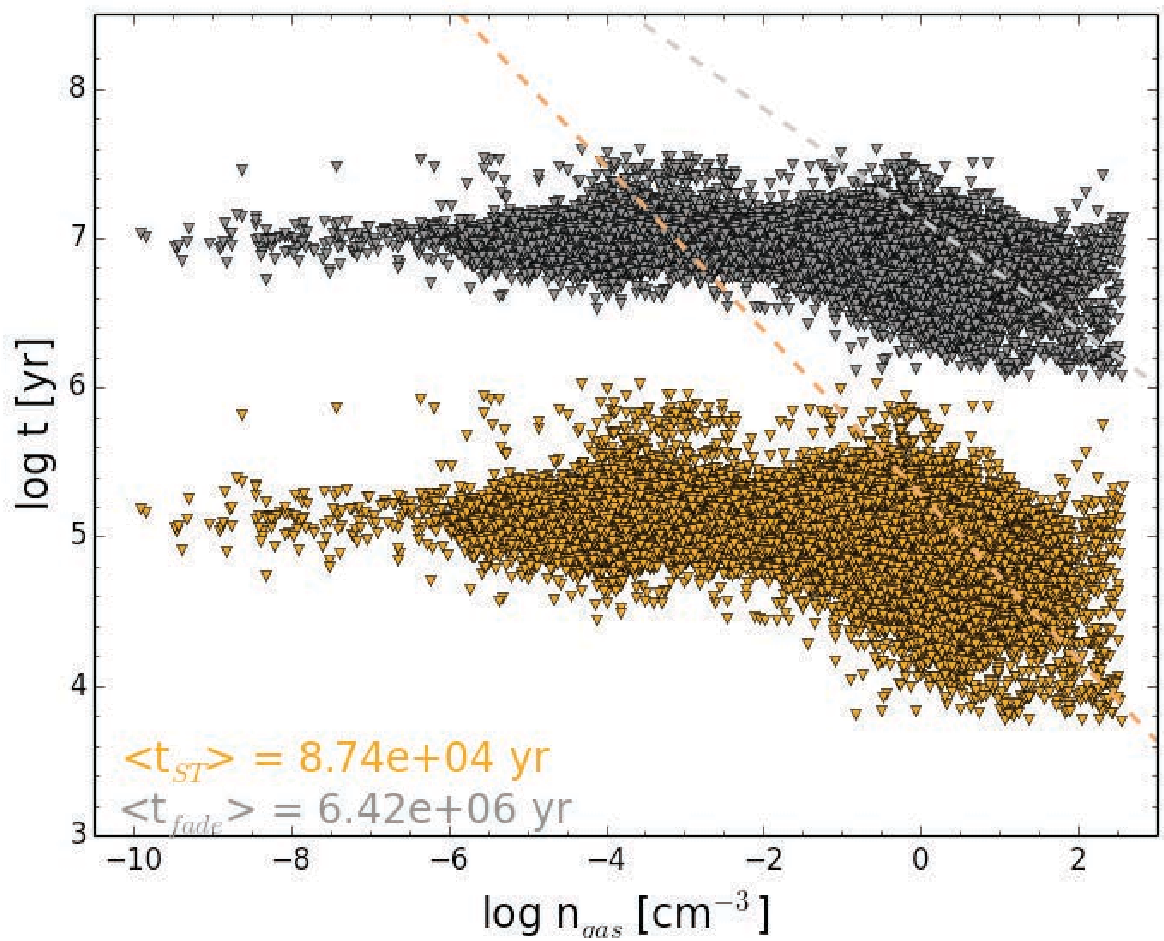
(Draine 2011)

E_0 = total SN energy of 10^{51} erg / SN
n_0 = ambient gas density in cm^{-3}

The denser the ambient gas
(1) the smaller the shock velocity
(2) the smaller the size of the SNR

Reduces the # of params compared to previous models (e.g. constant Vw model of SH03)

Time-scales of SN-II FB model



`Fade-out' time-scale "t_{Fade}"

`End-of-ST-phase' time-scale "t_{ST}"

Note: SN-II model turns off cooling for t_{ST} to mimic its adiabatic expansion phase.
(Stinson et al. '13 and some other models turns off cooling for a fixed time of 30 Myr)

Gas & Metal Recycling

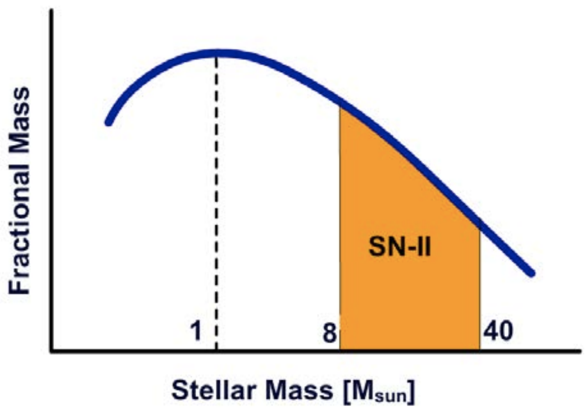
Following the AGORA prescription (Kim+ ’14):

Recycling fraction:

$$R = \int_{8M_\odot}^{40M_\odot} (m - w_m)\phi(m)\, dm \quad \text{with} \quad \phi(m) = dn/dm \propto m^{-2.3}$$

for a Chabrier IMF

where $w_m = 1.4\ M_\odot$ that is left behind as a remnant.



Metal production by SN-II

$$M_Z = 2.09 M_O + 1.06 M_{Fe}$$

(Kim et al. 2014)

→ Corresponding fractional masses: $0.0133 / M_\odot$ (O) and $0.011 / M_\odot$ (Fe)

Stellar Feedback (SFB)

Primary function:

- *Thermalizing* and *homogenizing* the ambient gas for 4 Myr after star formation. (pure thermal feedback)

Model:

- Follow the approach by Stinson+ ’13; but we *don’t* turn off cooling by hand
- Distributes 2 x 10^{50} erg / $M_\odot$ over 4 Myr

$$\Delta E_{th} = \epsilon_{SFB}\, E_0 \,\frac{t - t_{deposited}}{t_{explode}}$$

Summary of our FB model

Star formation

Time →

4 Myr

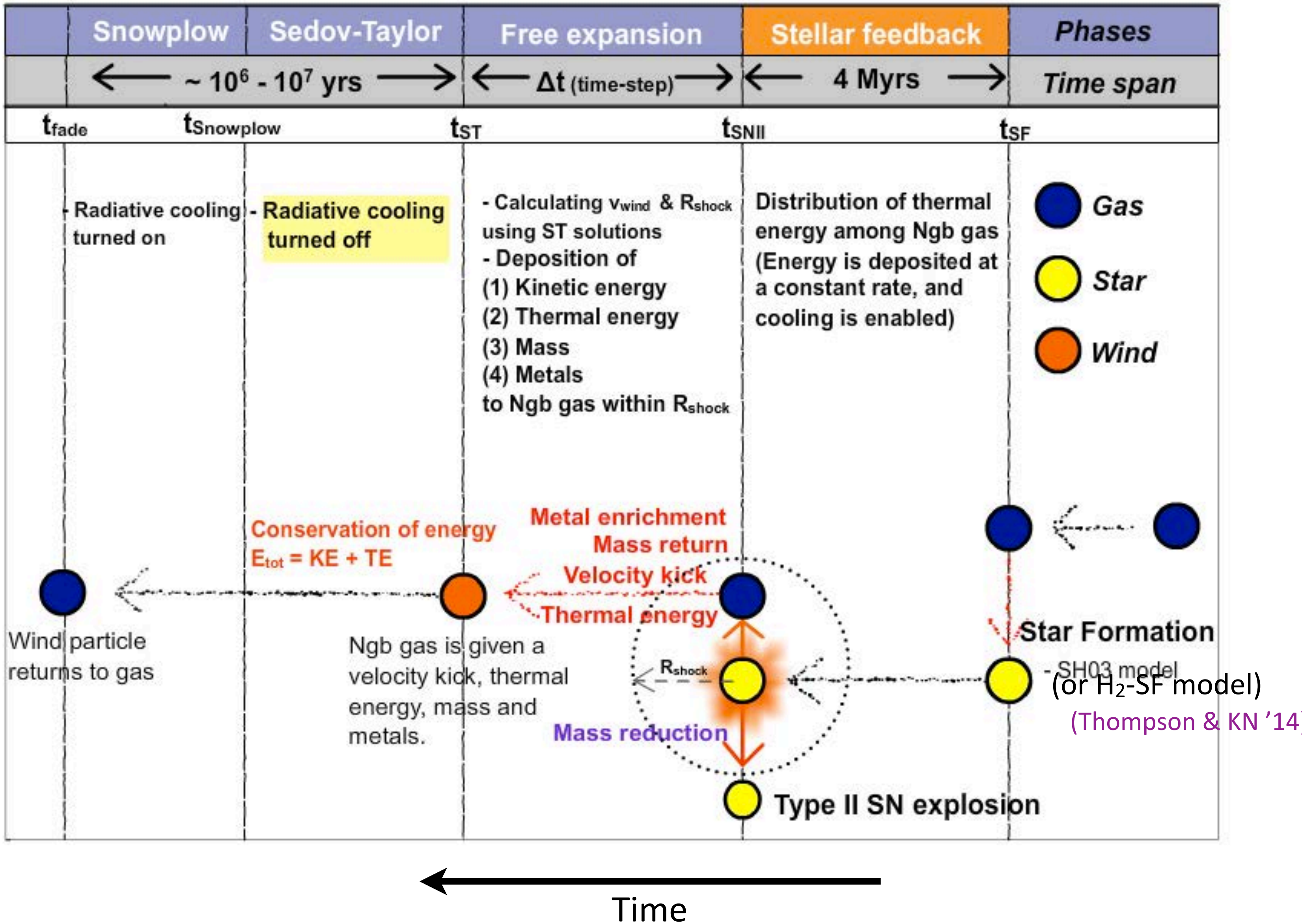
Stellar feedback (**SFB**)

- Depositing thermal energy into the surrounding medium at a constant rate

SN-II explosion (**SNII**) 10^{51} erg /SN

- Energy deposited as in (1) Kinetic (2) thermal forms (use Sedov-Taylor solution)
- Mass return & metal production and distribution
- Turn off cooling for Sedov-Taylor phase

Schematics of the model



Simulation setup

Code: **GADGET-3 SPH** (Springel '05 + modifications by our group)

Code utilizes:

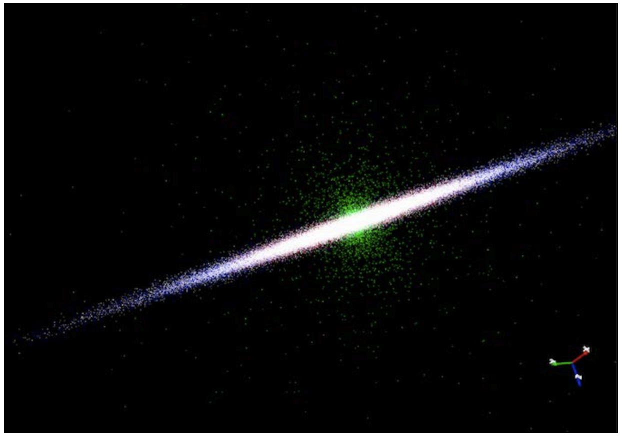
- Lagrangian formulation to track evolution of mass elements
- Tree-PM (particle-mesh) for gravity solver

Our code includes:

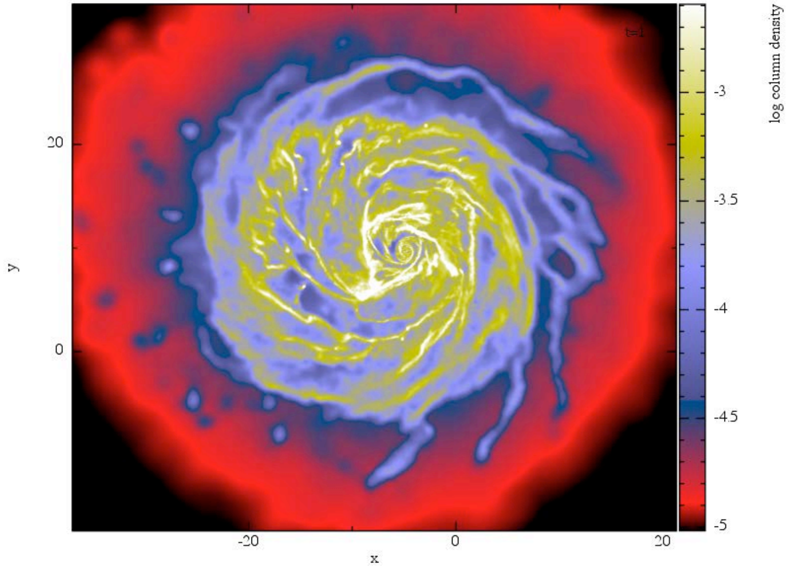
- **Metal cooling** by H & He (Choi & KN '09)
- heating by a **UV background** (Katz+ '96; Dave; Faucher-Giguere)
- **star formation** (SH03+variations) & SN feedback (this work)
- density independent SPH (Hopkins '13; Saitoh & Makino '13)
- a time-step limiter (Saitoh & Makino '09)
- quintic spline kernel (Morris '96)
- ……

<u>Isolated galaxy simulations</u>: (PAPER 3+4 of AGORA)

- A single galaxy resides in a single DM halo
- IC composed of gas, bulge, disk and DM (`MakeDisk' code, Springel)
- Decoupled from the Hubble expansion or linear growth
- No merger history
- Finer resolution can be achievable even compared with zoom-in
  - e.g. we tested with **80 pc & 30 pc** cases



MW-typed isolated disk IC:
Bulge (green), disk (white), gas (blue & red)
DM halo not shown.

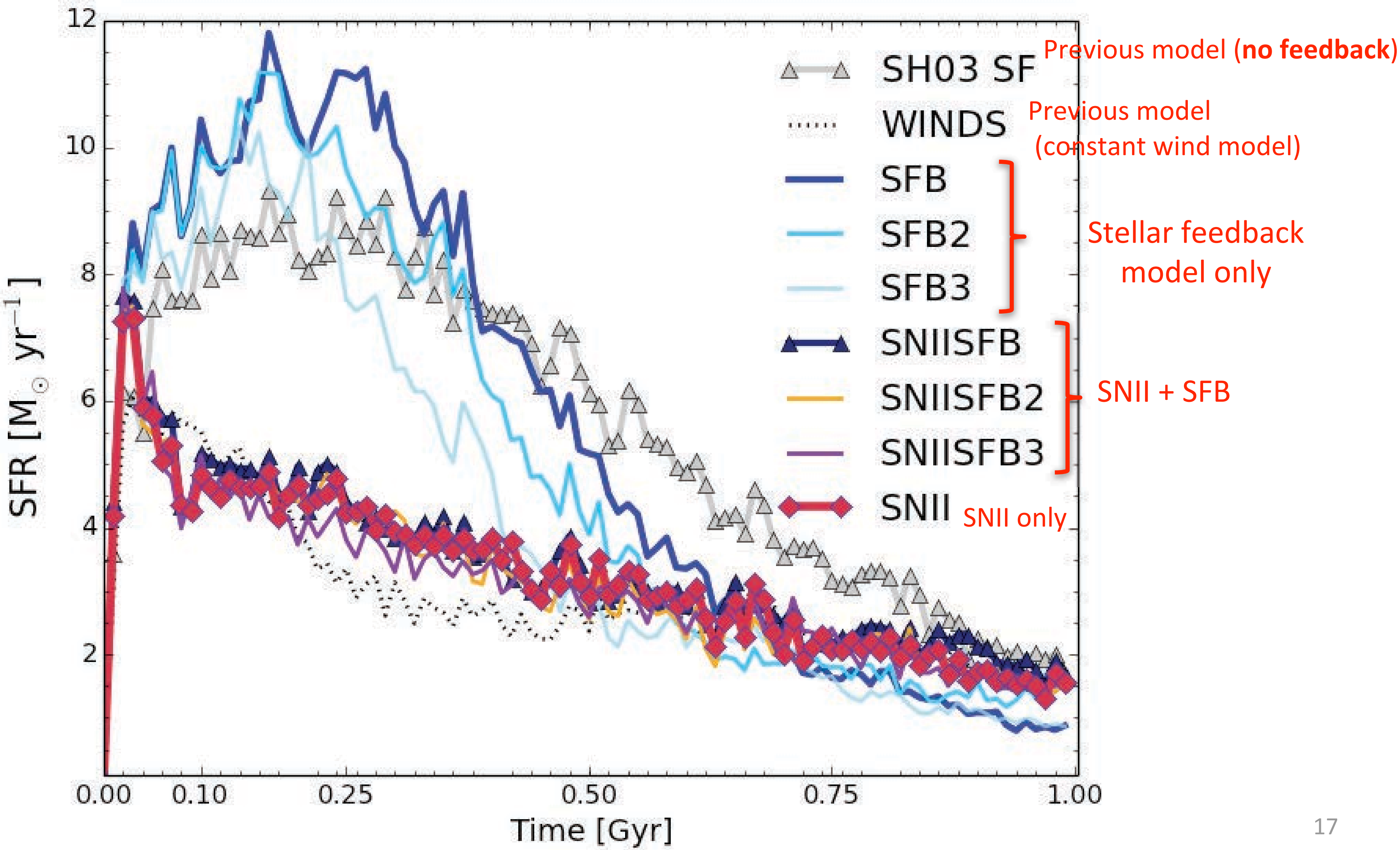


Parameters used for idealized MW-type isolated galaxy simulations

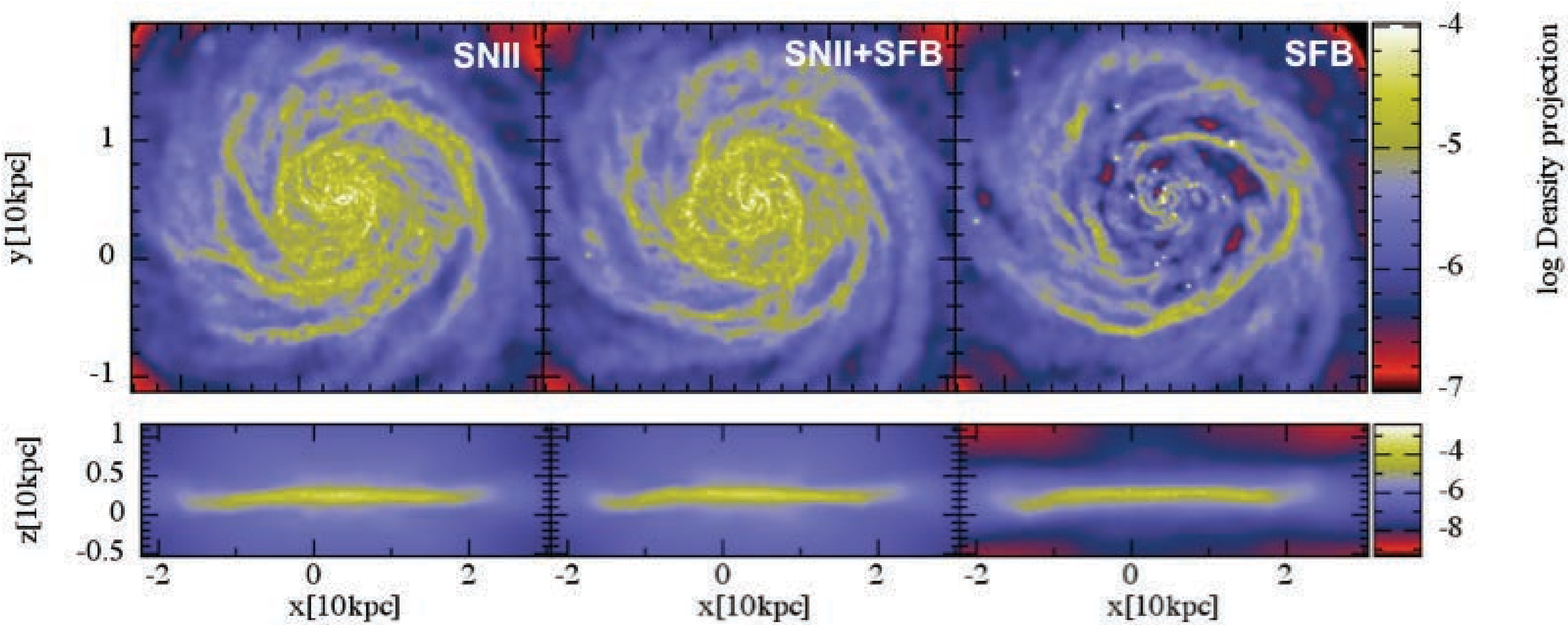
Param Name	Symbol	Value
Disk mass	M_{disk}	4.3×10^{10} $M_\odot$
Gas mass	M_{gas}	8.6×10^{9} $M_\odot$
R_{200} mass	M_{200}	1.07×10^{12} $M_\odot$
Total mass	M_{tot}	1.3×10^{12} $M_\odot$
R_{200}	R_{200}	205 kpc
Scale length	r_{disk}	3.43 kpc
Scale height	h_{disk}	0.343 kpc
Number of gas particle	N_{gas}	1×10^{5}
Number of dark matter particle	N_{DM}	1×10^{5}
Number of disk particle	N_{disk}	1×10^{5}
Number of bulge particle	N_{bulge}	1250
Gas particle mass	m_{gas}	8.59×10^{4} $M_\odot$
Dark matter particle mass	m_{DM}	1.25×10^{7} $M_\odot$
Disk particle mass	m_{disk}	3.44×10^{5} $M_\odot$
Bulge particle mass	m_{bulge}	3.44×10^{5} $M_\odot$
Softening length	for all particle types	80 pc

(AGORA project)

Star Formation History



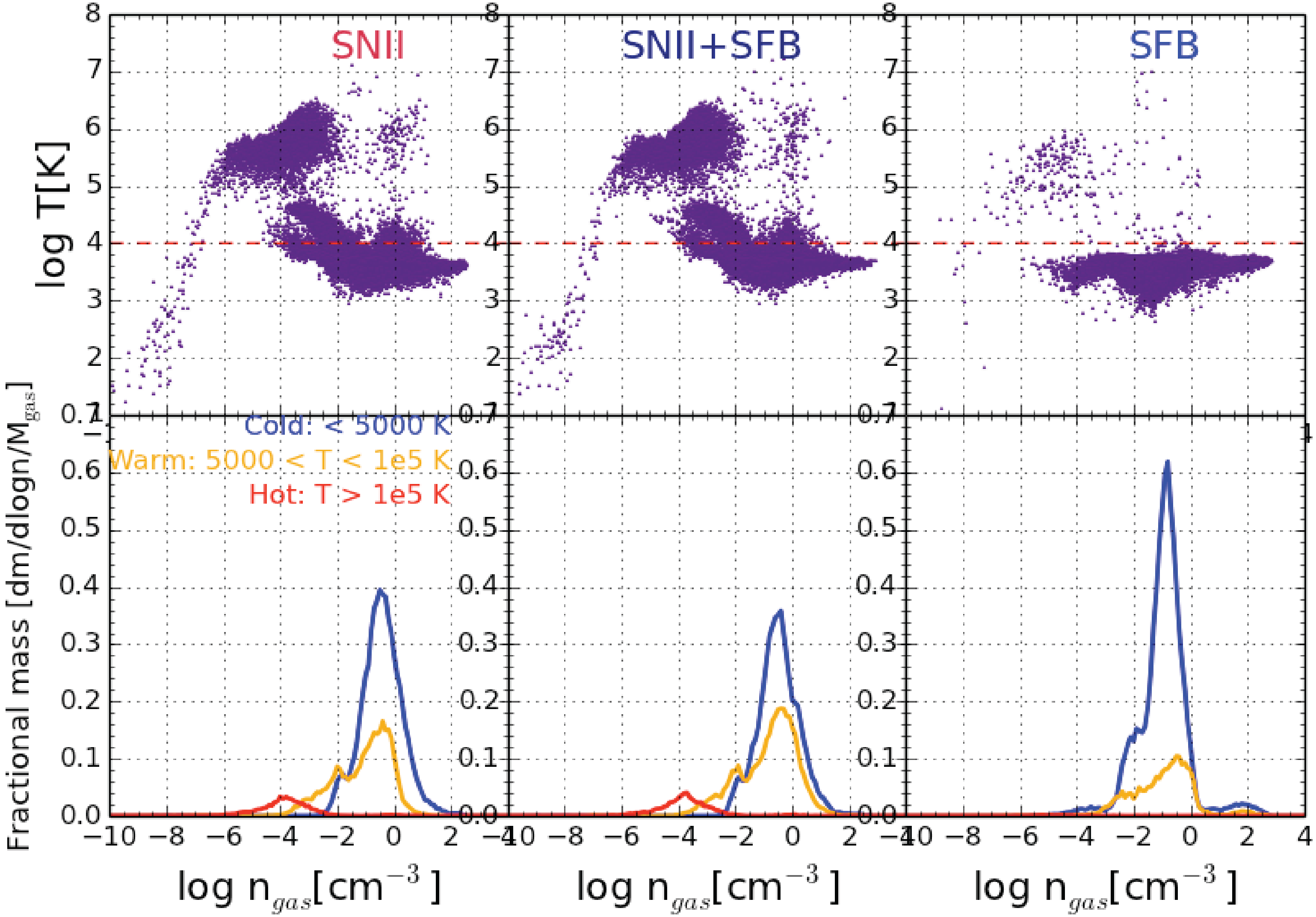
Face-on Disks



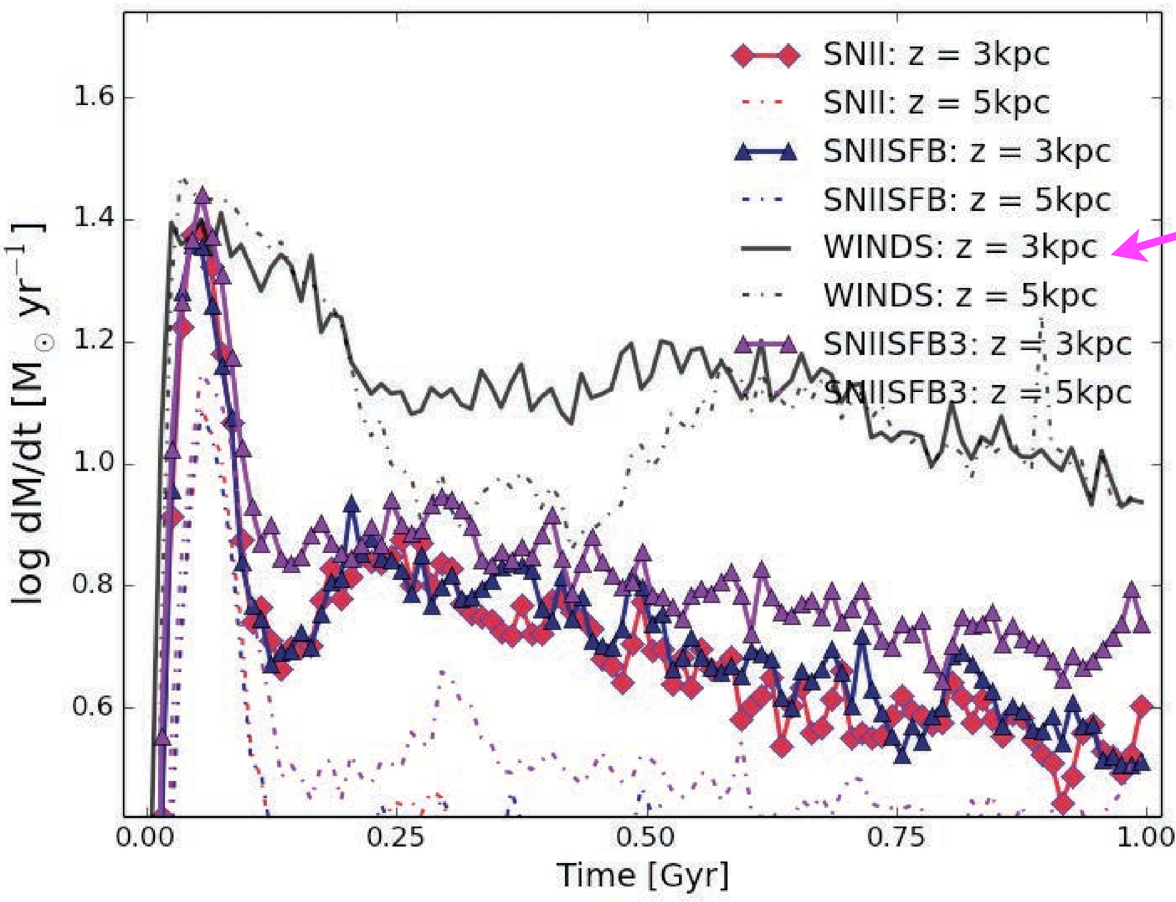
- excessive SF in high-density knots, large low-density regions

Nice, smooth, extended spiral arms

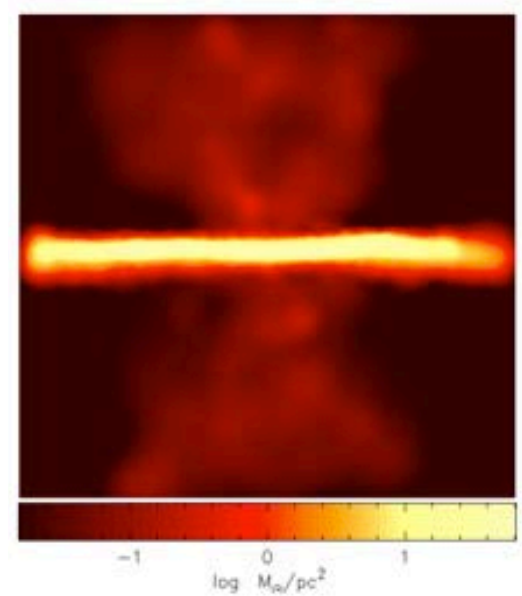
Phase Diagram



Outflow rates



WINDS = previous model (constant wind; SH03)
- turns off hydrodynamical interactions by hand



Tests with
Cosmological zoom-in simulations

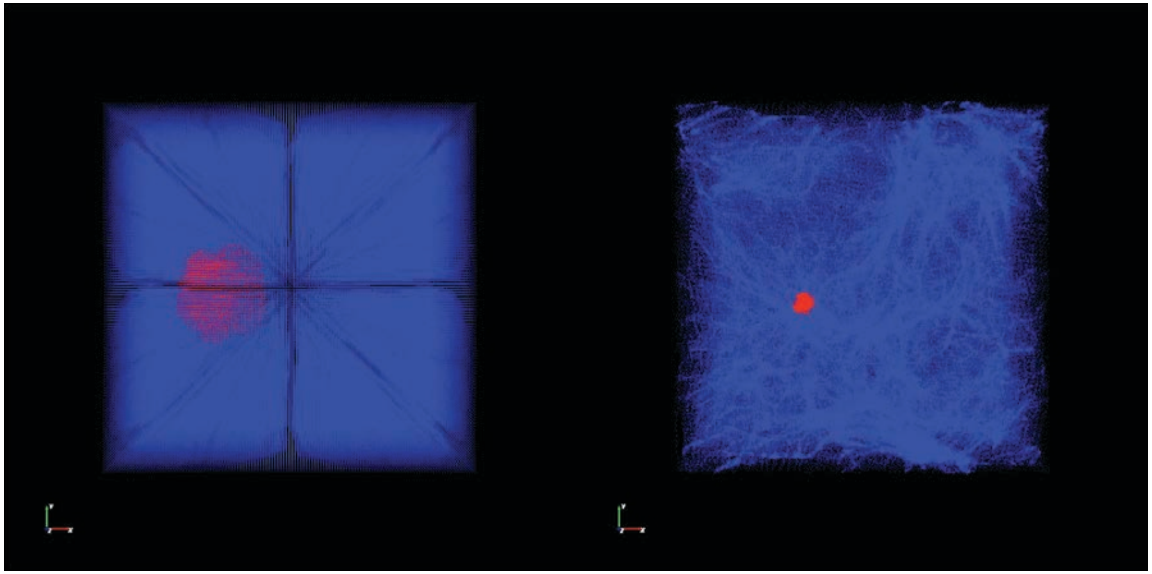
Key things to address:

- Does the **stellar-to-halo mass ratio** agree with observations?
- Does SN-II feedback model resolve the **missing satellites problem**?

(This is also tied with the overcooling problem)

Setup: Cosmological **zoom-in** simulations

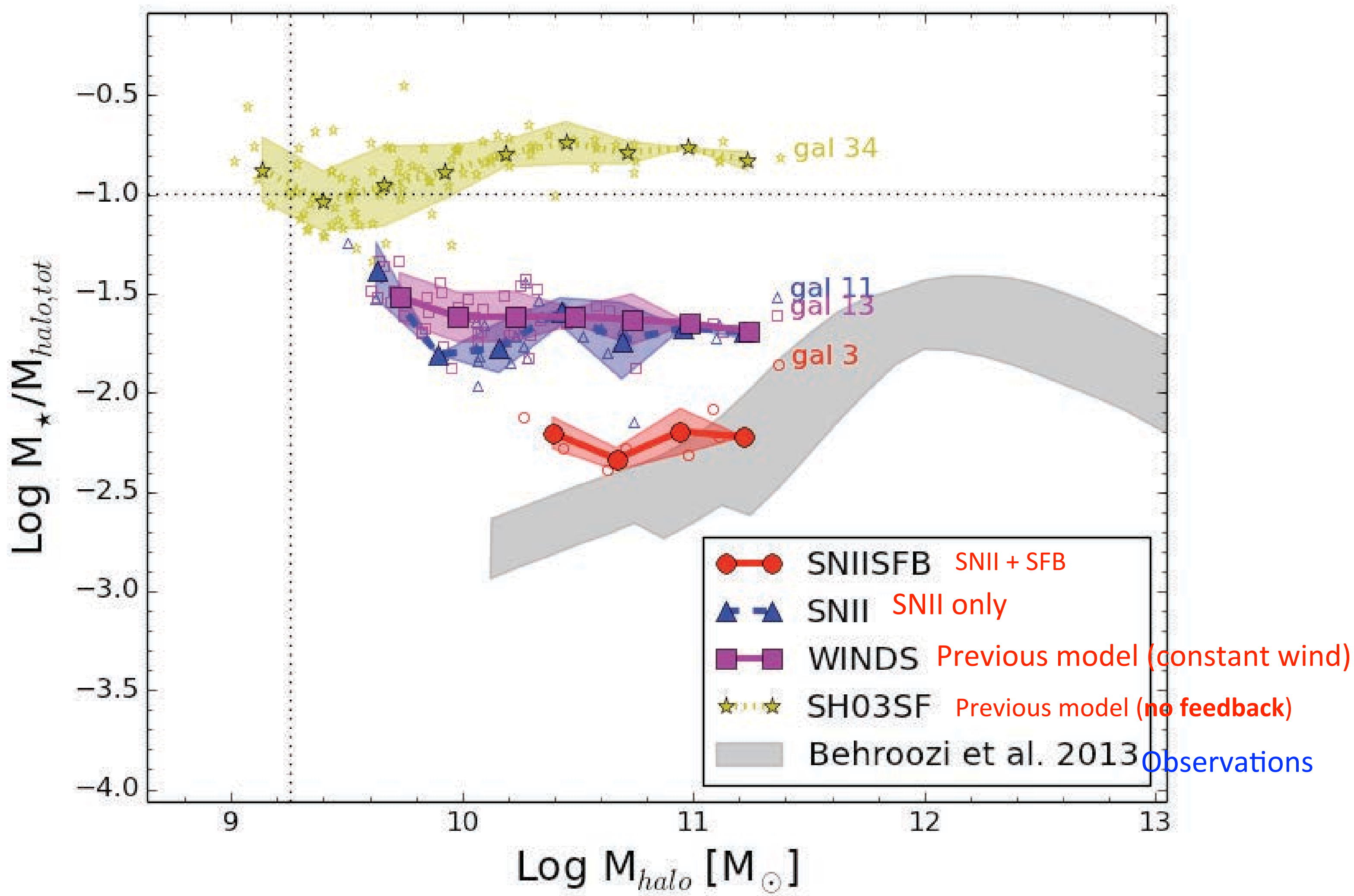
(1) Run a simulation with a cosmological initial condition (from z = 99 to z = 0)
(2) Identify a DM halo of interest in a Lagrangian volume at z = 0
(3) Rerun the simulation by feeding them back in with higher resolution DM particles and *baryons*



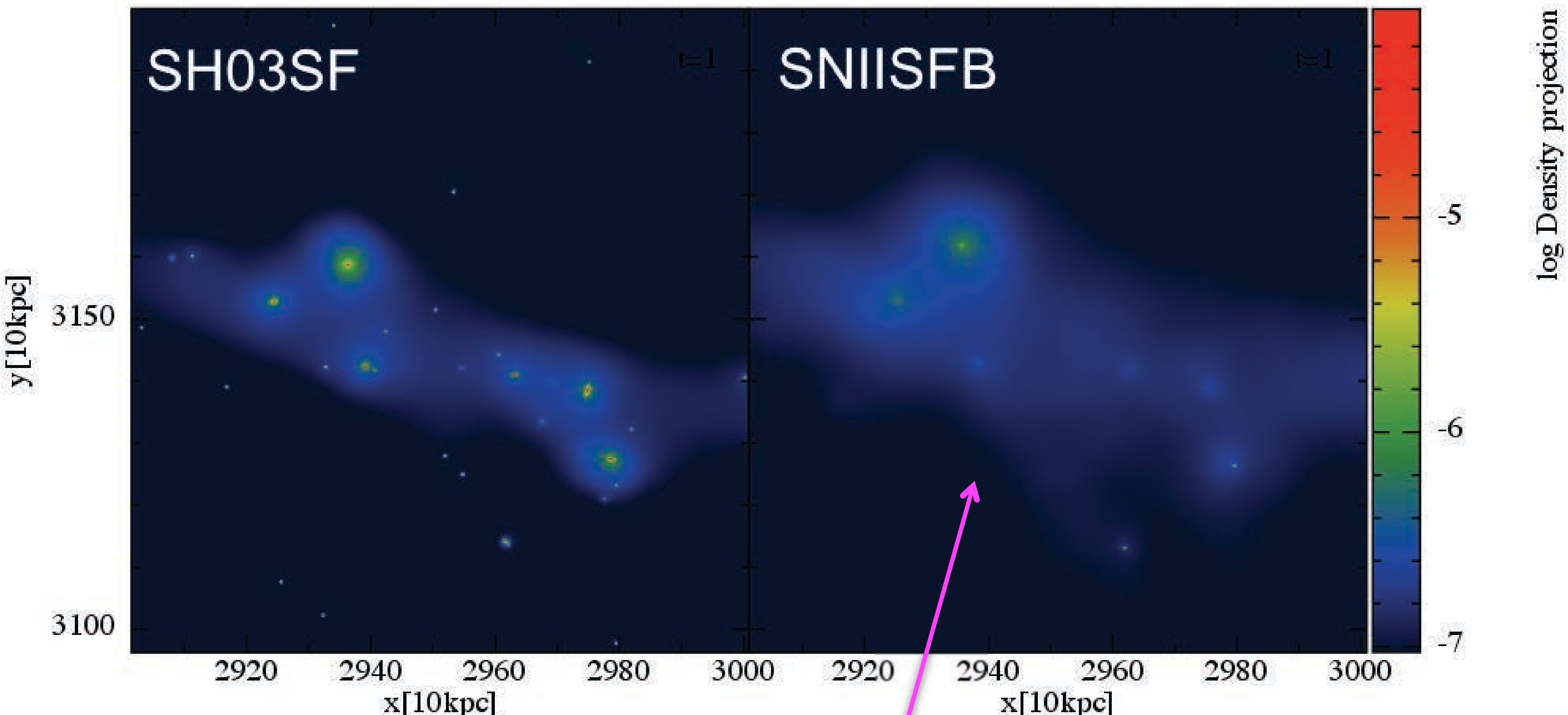
Note: The IC can be created by MUSIC code (Hahn & Abel 2011)

- AGORA IC used in Kim et al. '14 with *lower resolution* (spatial resolution of **586 pc** in **60 *h*$^{-1}$ Mpc** comoving box)
  - forms a galactic halo of 10^{11} $M_{\odot}$ with quiescent merger history at the center of the box

Stellar-to-halo mass ratio



Less Substructures



SNIISFB creates a lot less small satellites and gas is distributed more diffusively

Conclusions

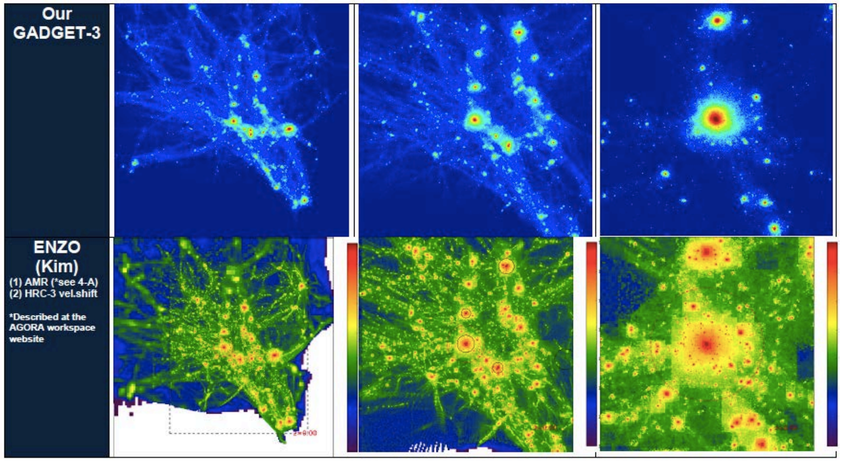
- More physical approach on modeling a SN-II feedback using the **Sedov-Taylor solution**
  - reduces the free parameters & artificial adjustments

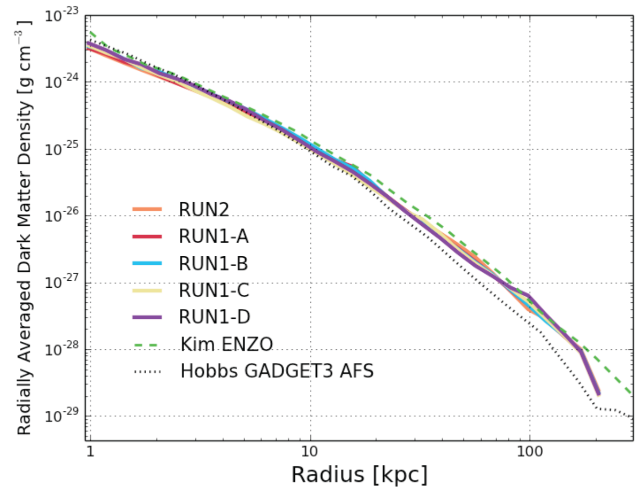
Key findings:

- SN-II is good; +Stellar FB helps also.
- Without turning off hydro, SN-II produces outflows and suppresses SFRs
  - thereby resolving the **over-cooling problem.** ✔
- SNII+SFB model successfully reduces the number of satellites
  - alleviating the **missing satellites problem.** ✔

Ongoing participation in the AGORA project

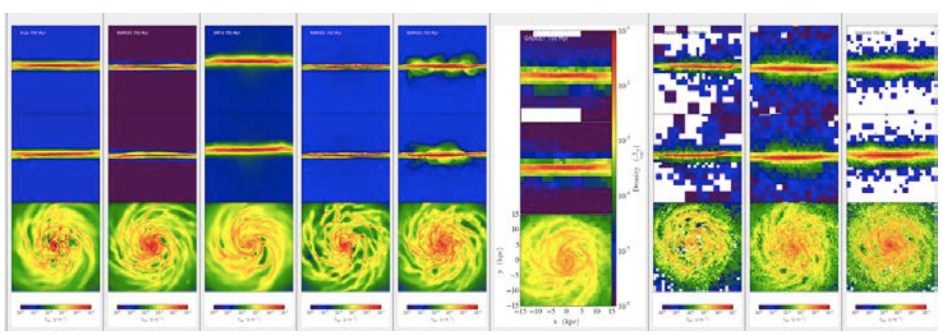
(Papers 1, 2 w/ Dark Matter-only runs)





Comparison among different codes on dark matter-only simulations with common ICs.

Collaboration with AGORA project on `yt` common analysis tools for improvements in SPH data handling.



Last

JHC's Grackle Implementation

(Jun-Hwan Choi)

in UNLV version of Gadget-3

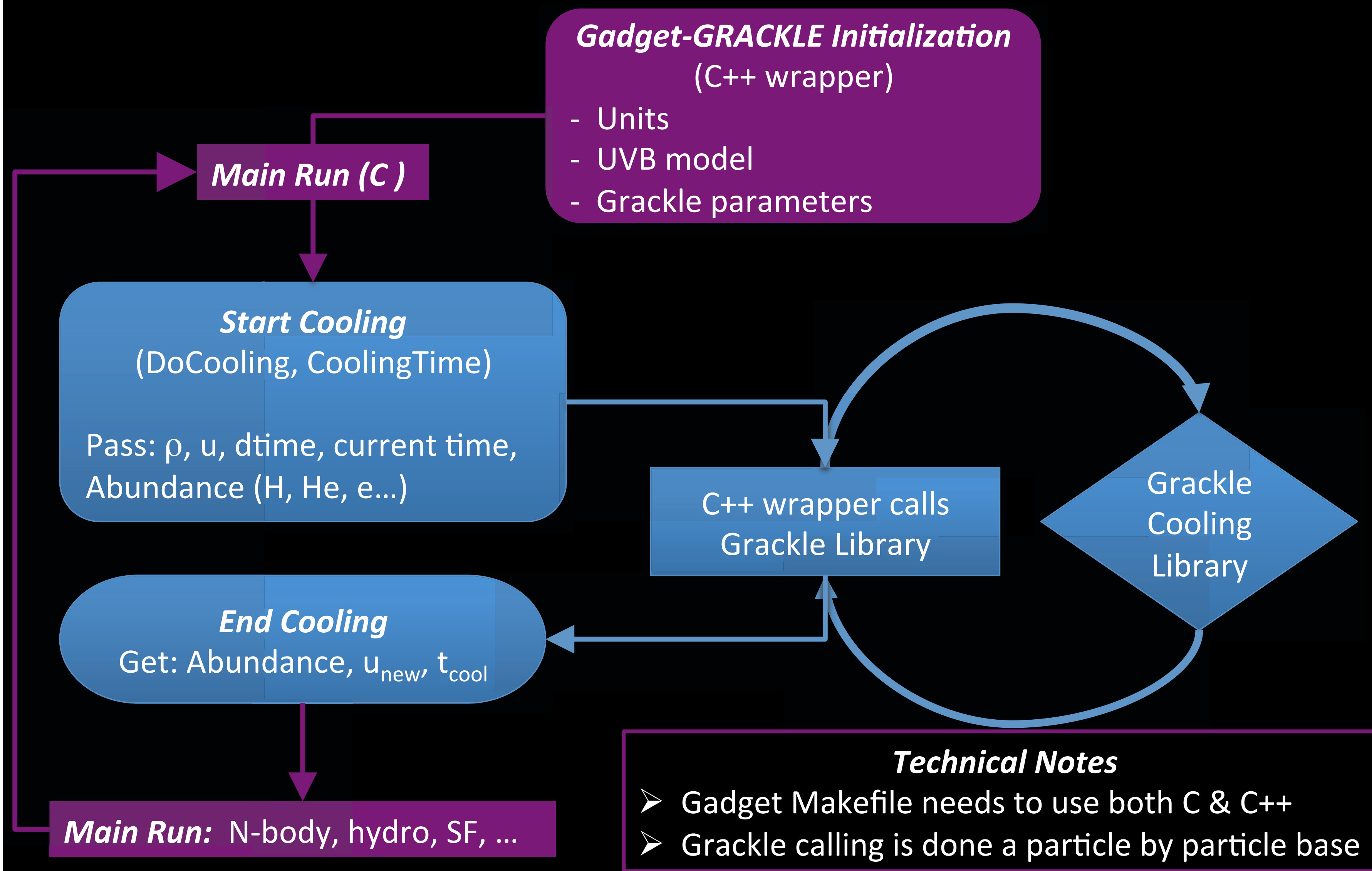
GRACKLE

(Britton Smith)

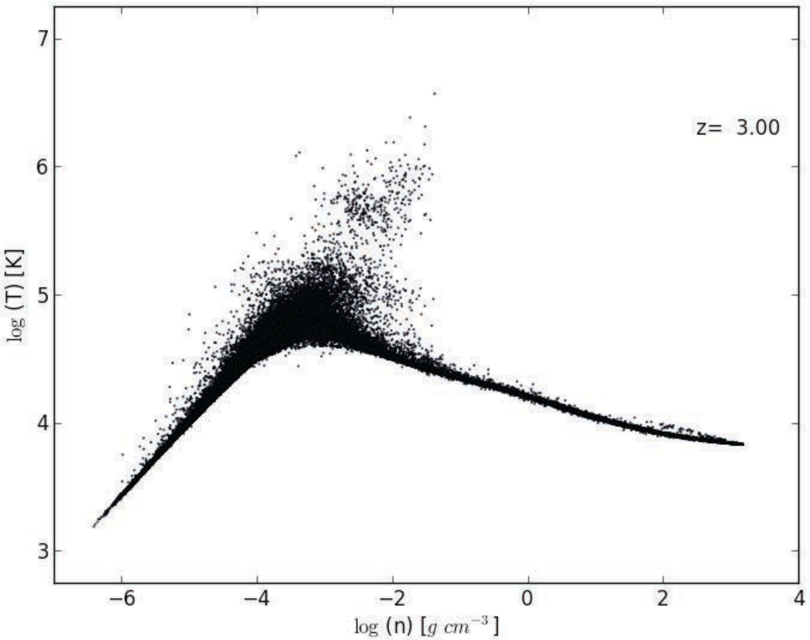
https://grackle.readthedocs.org/en/latest/

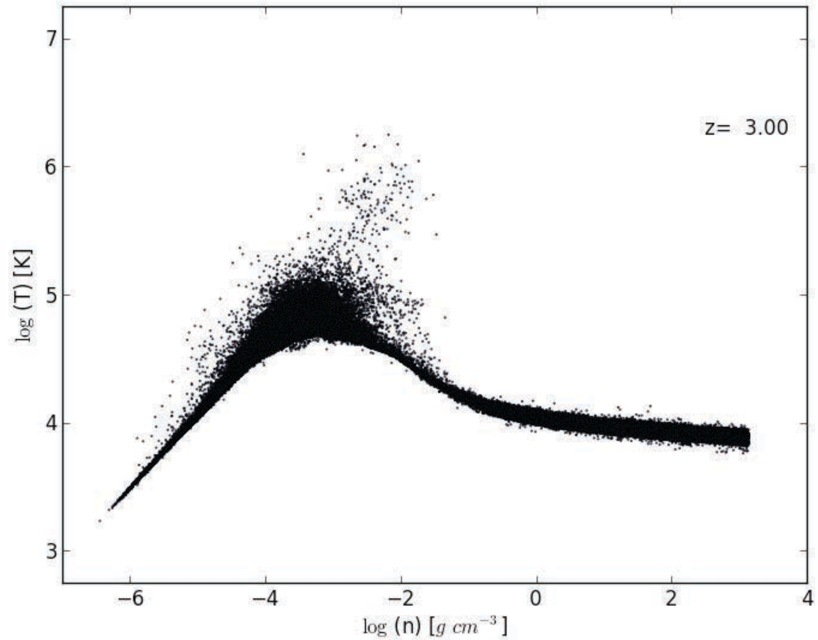
- Grackle is a chemistry and radiative cooling library for astrophysical simulations.
- Language: C++ code calls Fortran numerical module
  - Need a C++ wrapper to from from Gadget (written in C)
  - Pure C version released recently.
- Chemistry
  - Cloudy cooling
  - Non-equil. primordial chem. network (~10% speed decrease)
- UVB
  - Faucher-Giguere et al. 2009 (Updated in 2011)
  - Haardt & Madau 2012

Gadget-GRACKLE interface



Comparing with original gadget cooling





Gadget Cooling **(Katz+ '96; Springel '05)**
UVB : FG2011

Grackle cooling (i.e. CLOUDY)
UVB : FG2011

Overall agreement; seems to be working.

End