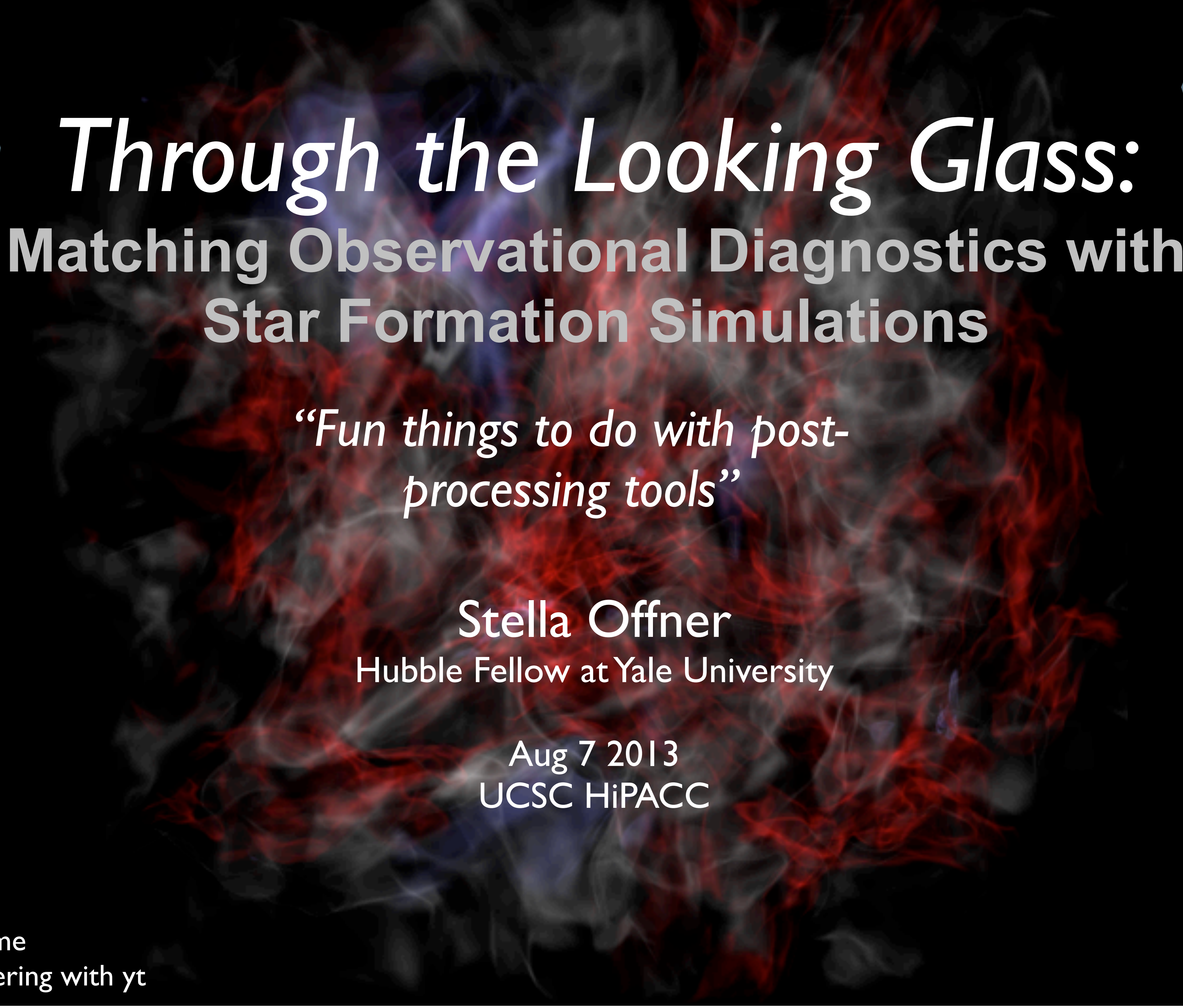


Through the Looking Glass:

Matching Observational Diagnostics with Star Formation Simulations

"Fun things to do with post-processing tools"

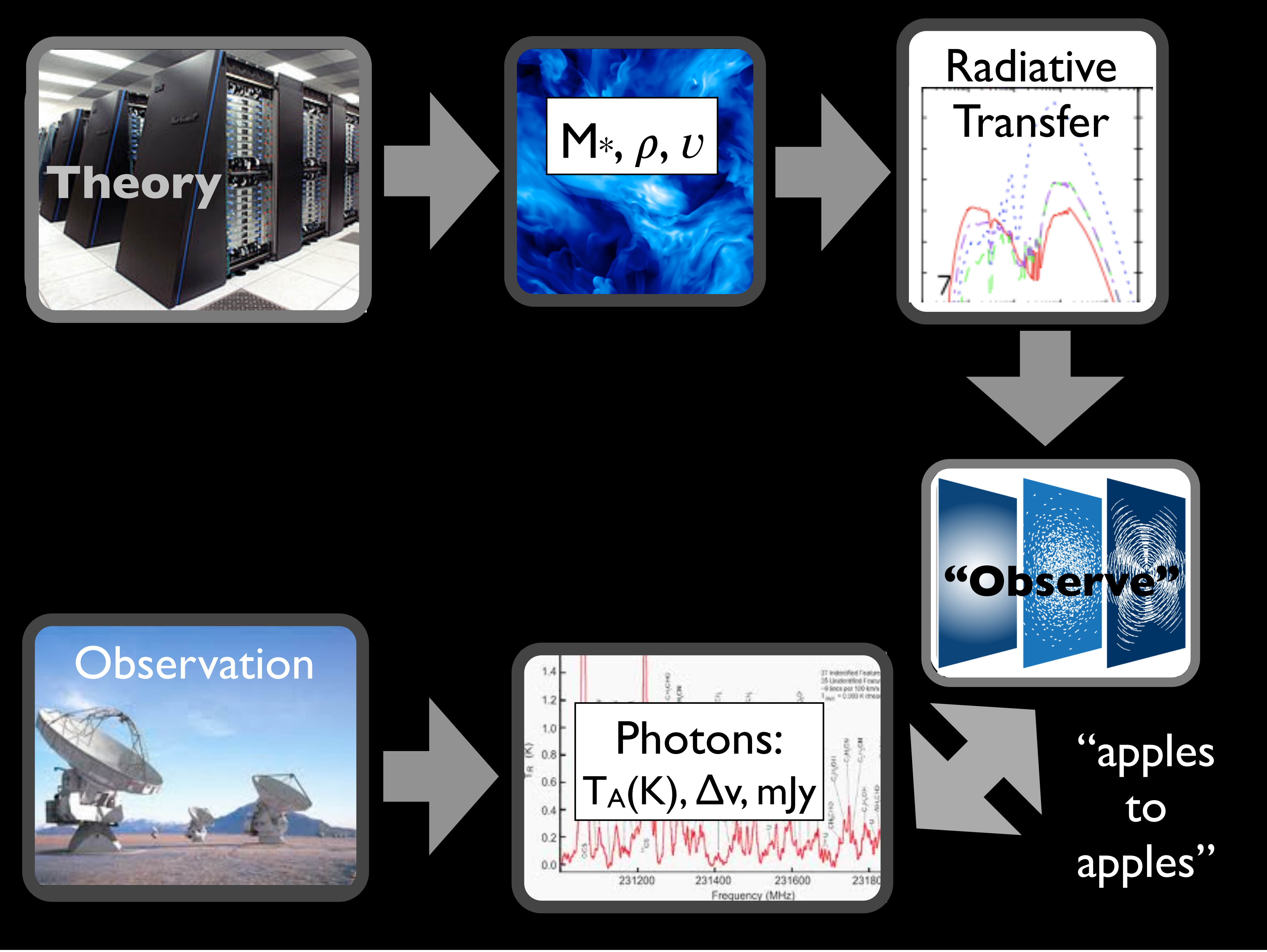
Stella Offner

Hubble Fellow at Yale University

Aug 7 2013

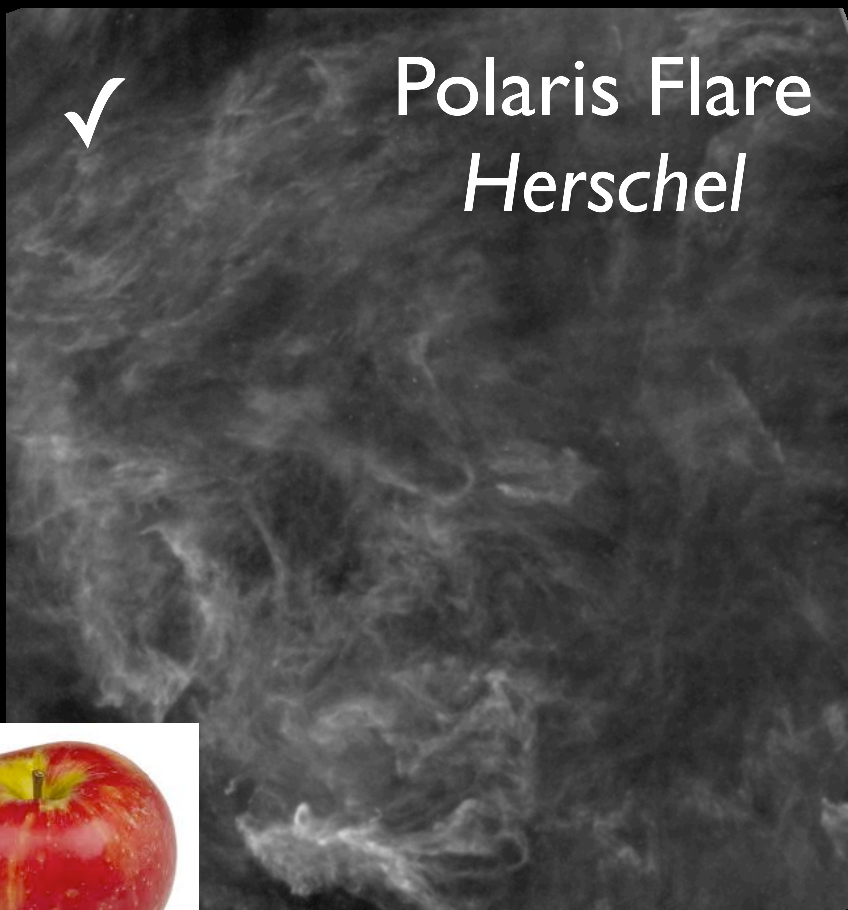
UCSC HiPACC

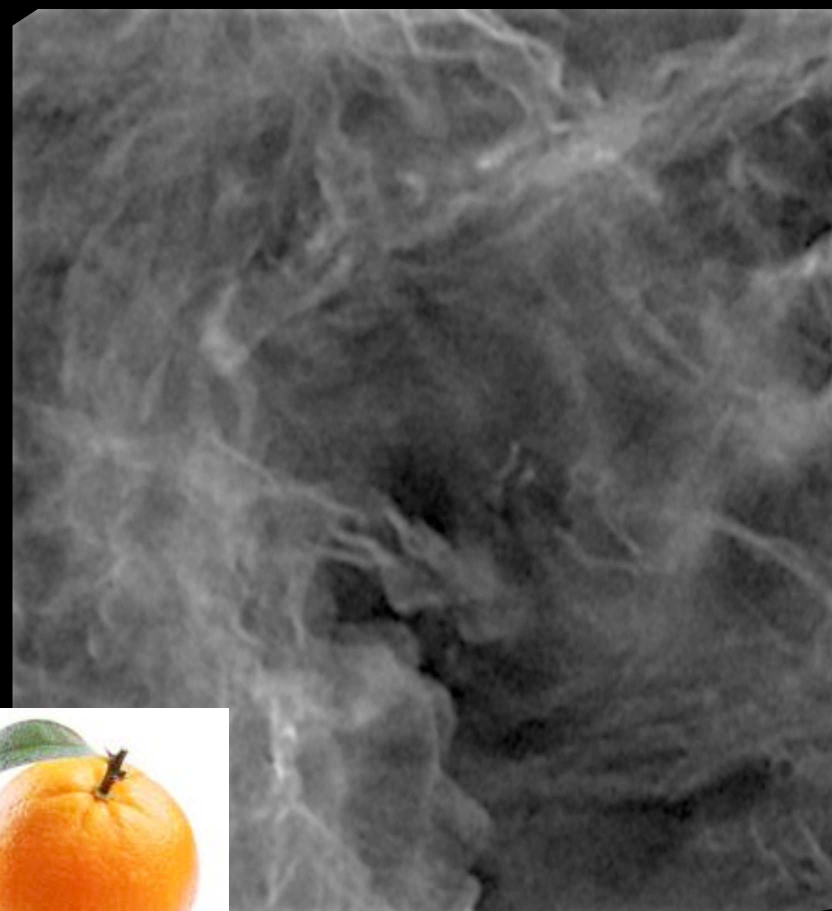
Volume rendering with yt


Theory
M*, ρ, υ
Radiative Transfer
"Observe"
Observation
Photons: TA(K), Δv, mJy
"apples to apples"
Frequency (MHz)

Pop Quiz

Simulation or Observation





Outline

1. Underlying numerical simulations

2. Fun with post-processing tools:

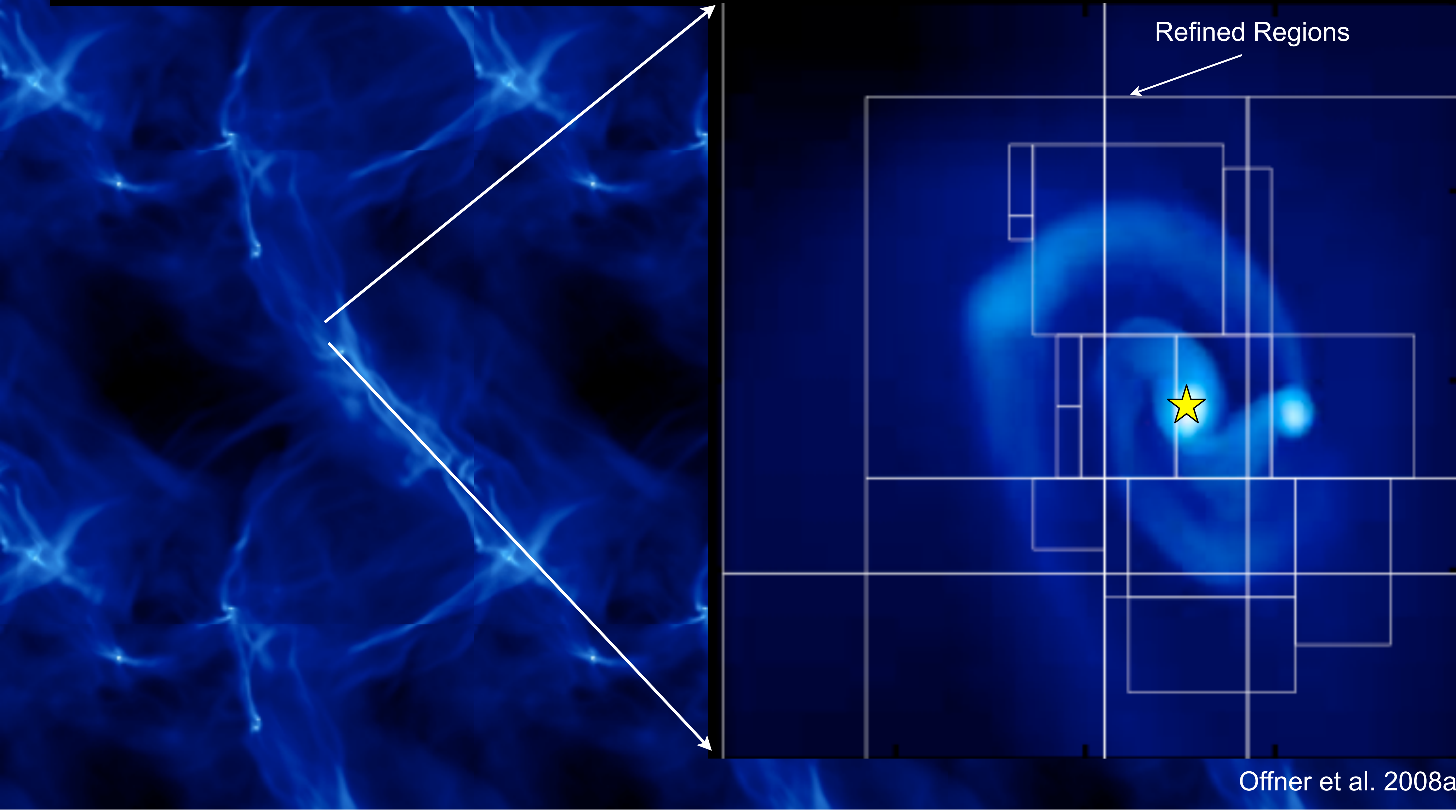
   - Protostellar evolution: synthetic continuum images/SEDs (Hyperion)

   - Binary formation: synthetic interferometry (CASA)

   - Cloud structure: synthetic molecular lines (RADMC)

Underlying numerical simulations

Adaptive Mesh Refinement



Offner et al. 2008a

Equations

ORION code

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0,$$

Conservation of Mass

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v}) = -\nabla P - \rho \nabla \phi,$$

Conservation of Momentum

$$\frac{\partial (\rho e)}{\partial t} + \nabla \cdot [(\rho e + P)\mathbf{v}] = \rho \mathbf{v} \nabla \phi$$

Conservation of Energy

$$\nabla^2 \phi = 4\pi G \left[\rho + \sum_n m_n \delta(\mathbf{x} - \mathbf{x}_n) \right]$$

Poisson Equation

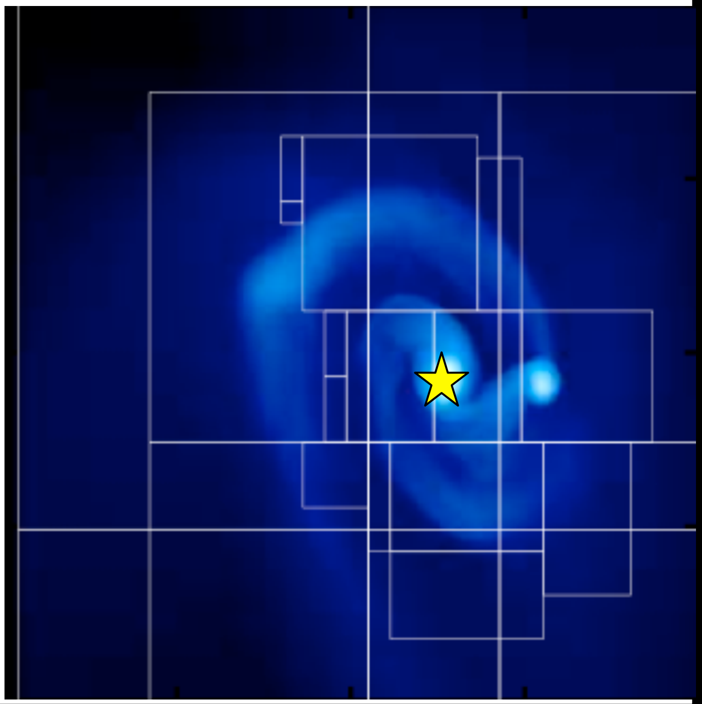
Equation of State:

$$P = \rho c_s^2 + \left(\frac{\rho}{\rho_c} \right)^{\gamma} \rho_c c_s^2$$

Adiabatic index (γ)

Critical density (ρ_c)

ρ	=	density
$\mathbf{v}$	=	velocity
P	=	pressure
ϕ	=	gravitational potential
e	=	energy density
m	=	star mass



Equations

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Conservation of Momentum

$$\frac{\partial (\rho e)}{\partial t} + \nabla \cdot [(\rho e + P)\mathbf{v}] = \rho \mathbf{v} \nabla \phi - \kappa_R \rho (4\pi B - cE)$$

Conservation of Energy

$$\nabla^2 \phi = 4\pi G \left[\rho + \sum_n m_n \delta(\mathbf{x} - \mathbf{x}_n) \right]$$

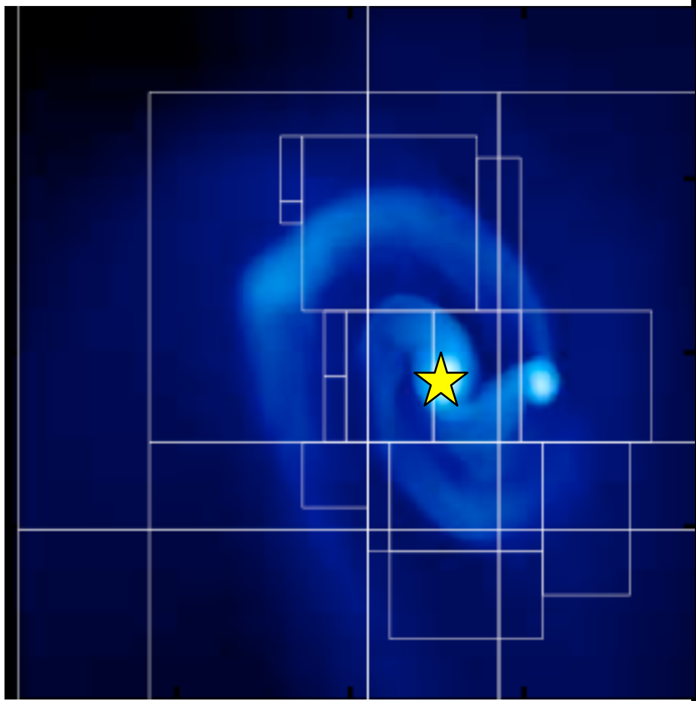
Poisson Equation

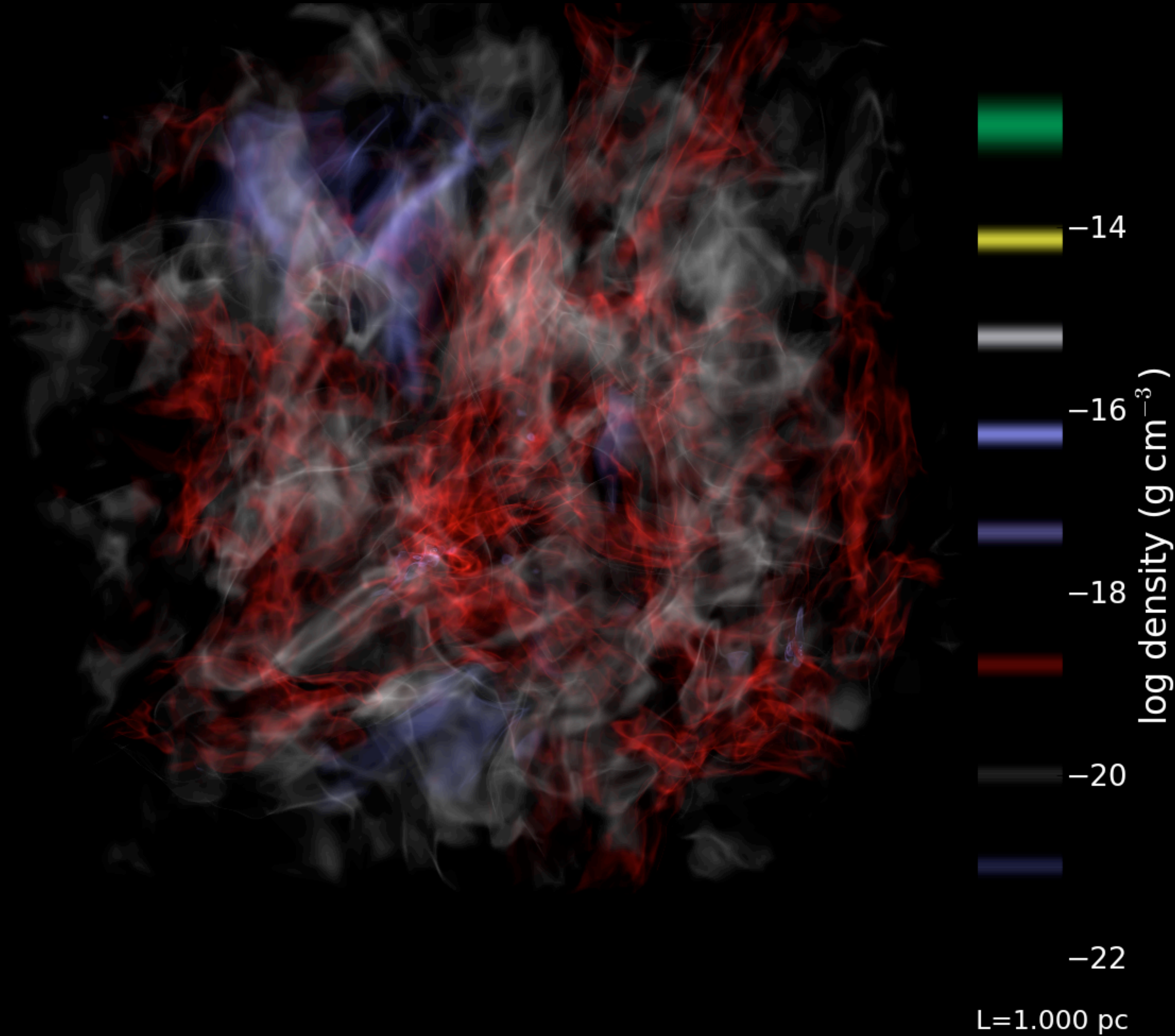
Radiation Diffusion Equation

Stellar Luminosities

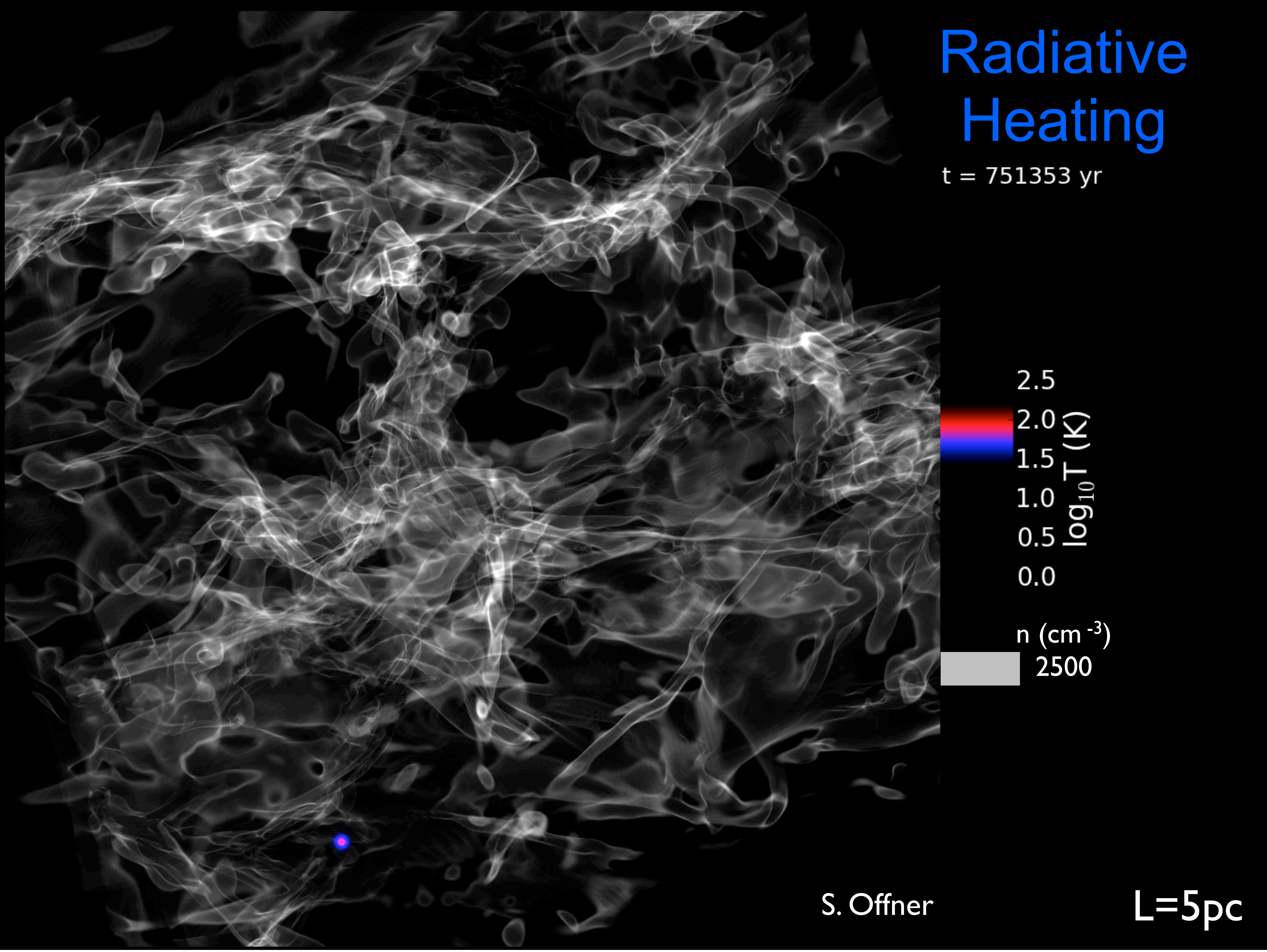
$$\frac{\partial E}{\partial t} - \nabla \cdot \left(\frac{c\lambda}{\kappa_R \rho} \nabla E \right) = \kappa_P \rho (4\pi B - cE) + \sum_n L_n W(\mathbf{x} - \mathbf{x}_n),$$

E	=	radiation energy density
κ	=	dust opacity
B	=	Planck function



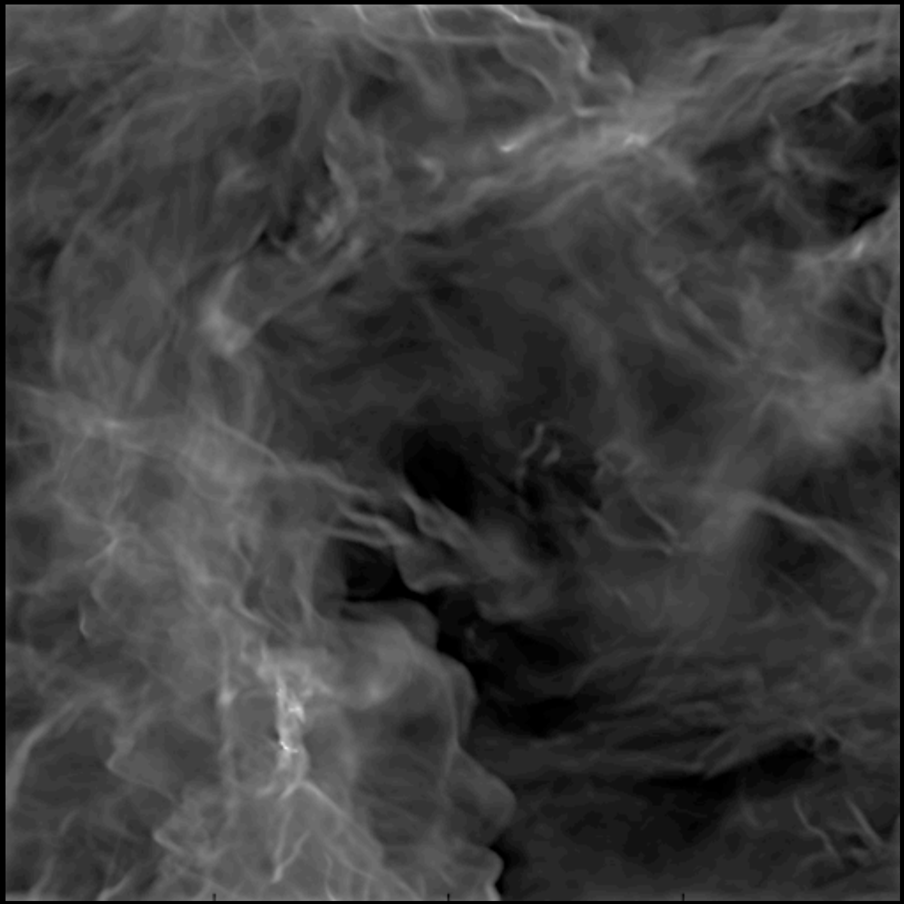


Offner et al. 2009, 2010


Radiative Heating
t = 751353 yr
2.5
2.0
1.5
1.0
0.5
0.0
$\log_{10}T$ (K)
n (cm^{-3})
2500
S. Offner
L=5pc

Simulations...

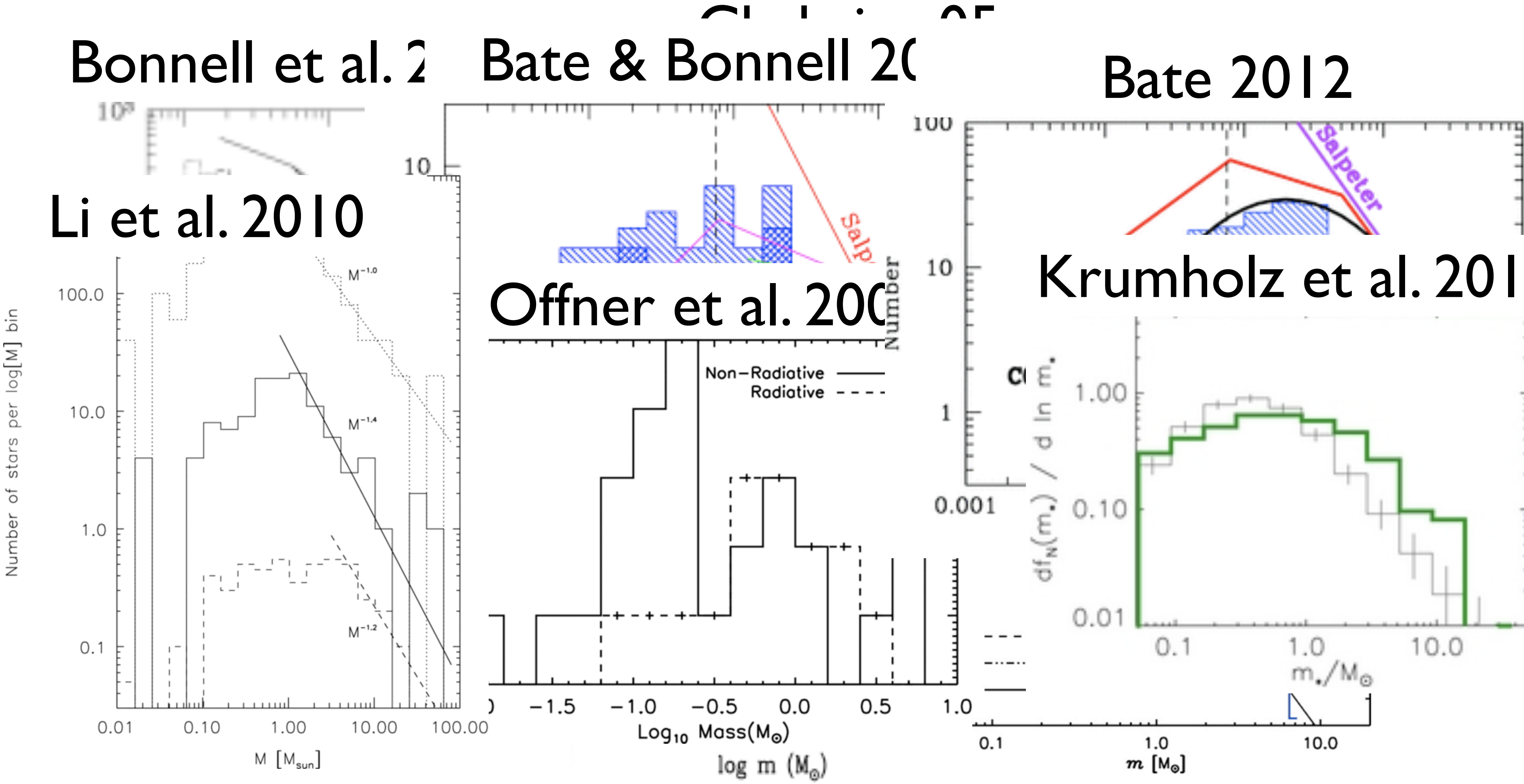
- ORION AMR
- Continuous, Large Scale Turbulence (k=1..2)
- Self-Gravity
- Virial Parameter ~ 1 (E_{grav}~E_{turb})
- Sink particles with sub-grid models for stellar evolution and outflows
- Equation of state or Grey Flux Limited Diffusion
- 256^3, 4-7 levels



Goal: use simulations to interpret observations and model reality

Problem: What diagnostics do we compare with?

Stellar Initial Mass Function (IMF)



The IMF is universal ...in simulations

Stellar Properties

- ~~IMF~~
- (Proto)stellar kinematics & distribution
- Protostellar luminosities
- Outflow properties and evolution

Gas Properties

- Molecular line profiles
- Core masses & shapes
- Cloud properties

Stellar Properties

- ~~IMF~~
- (Proto)stellar kinematics & distribution
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Gas Properties

- Molecular line profiles
- Core masses & shapes
- Cloud properties

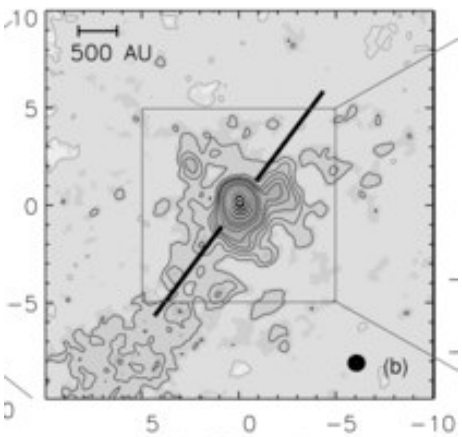
Hyperion & Protostellar Evolution

S. Offner, T. Robitaille, C. Hansen, C. McKee, R. Klein

Motivation

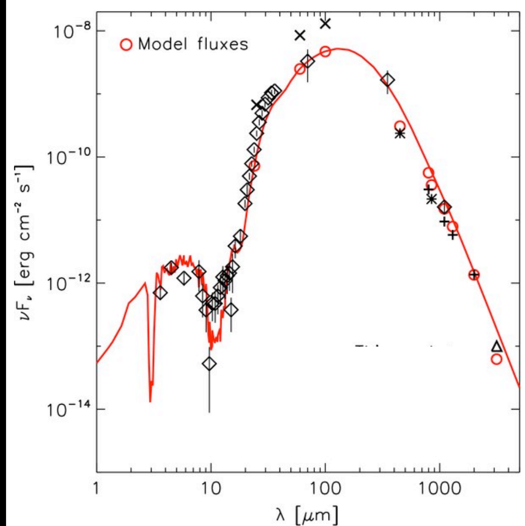
- How accurate are protostellar properties inferred from SEDs?
- How does viewing angle, multiplicity, or stage effect inferred properties?

Source

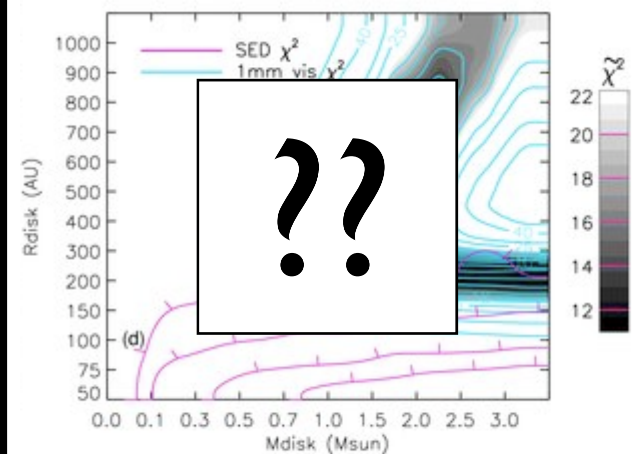


Enoch et al. 2009

SED



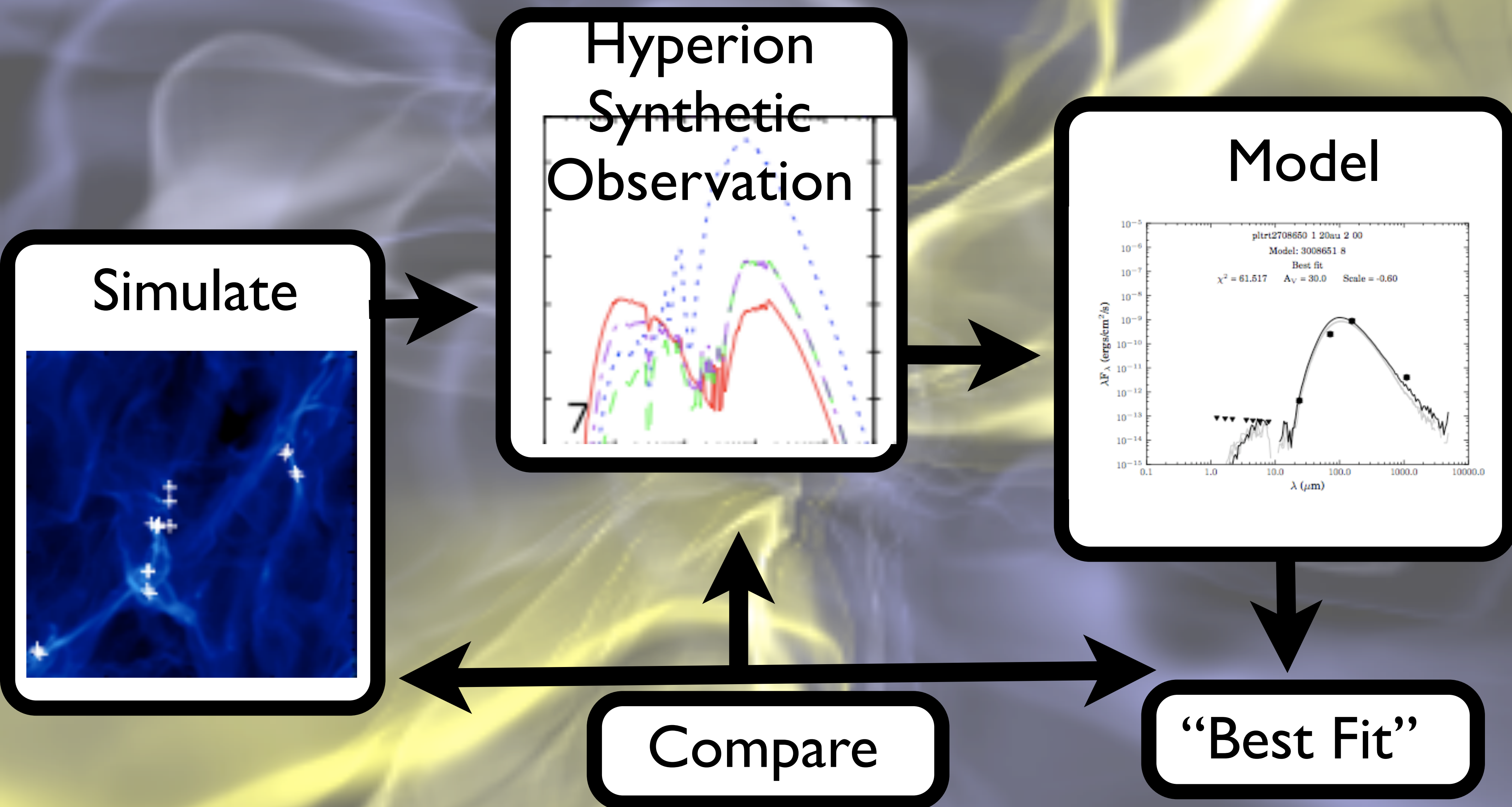
Models



“Best Fit”

age, inclination, star mass, disk mass, envelope mass, disk radius, outflow opening angle, accretion rate, density profile, disk radius, envelope radius, stellar radius...

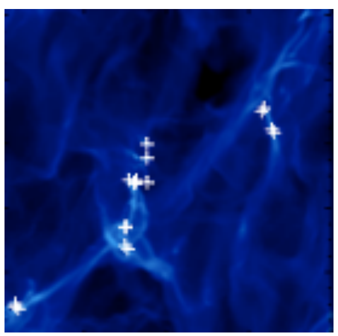
Synthetic Observations



Methods

- Adaptive Mesh Refinement (ORION)
- Turbulence
- Gravity
- Radiative Feedback (model for stellar evolution; Offner et al. 2009)
- Outflows use a model based upon Matzner & McKee 2000 (e.g. Cunningham et al. 2011, Offner et al. 2011)

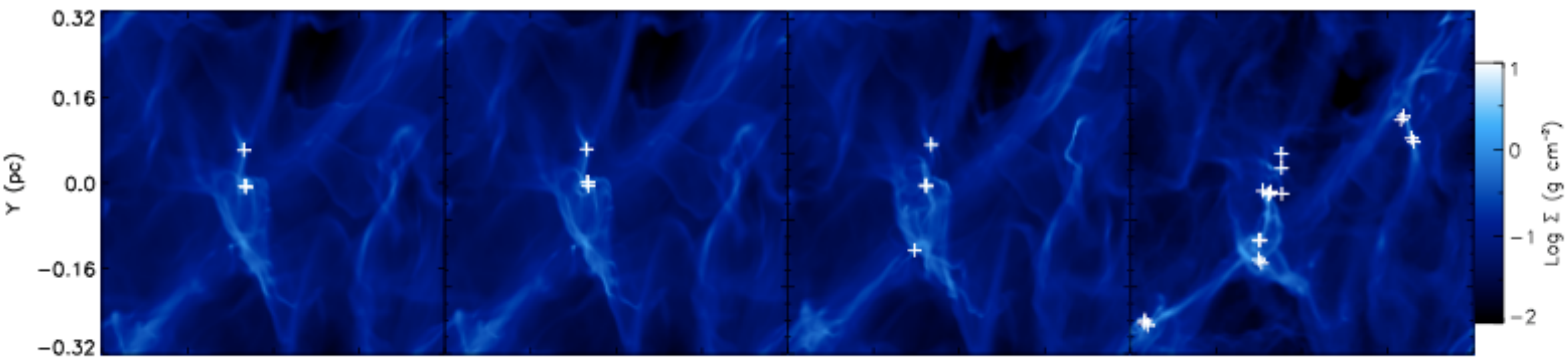
Simulate



Offner et al. 2012a

Zooming

- 1 Base Calculation
  - 1 freefall time
  - 130 AU resolution
- 4 Zooming Calculations
  - 4 AU resolution
  - "0", 15, 30, 60 kyr

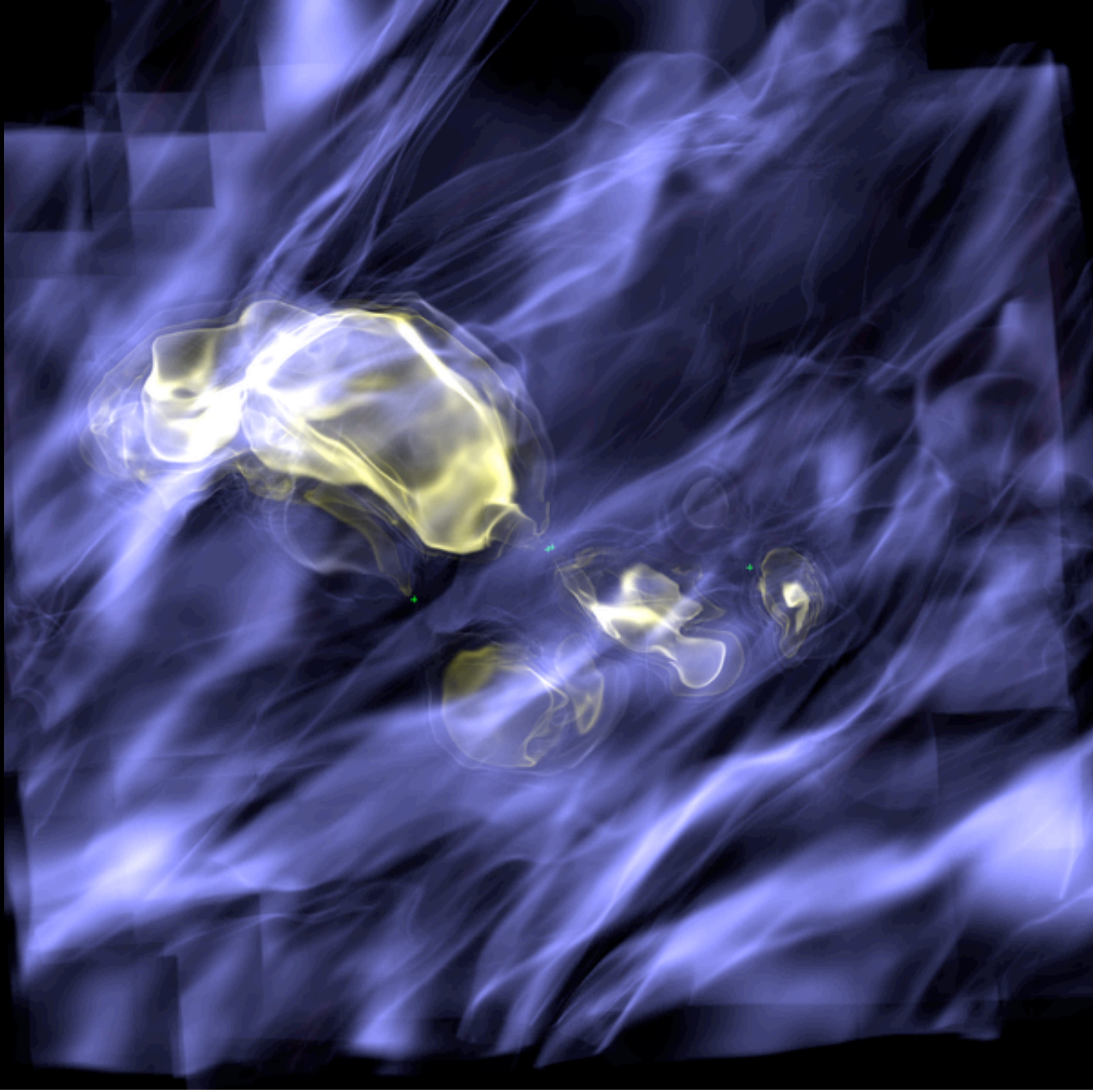


Log Column Density

Offner et al. 2012a

Gas Velocity

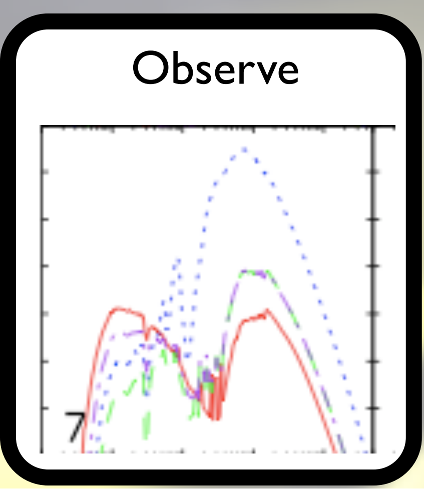
~1 km/s
~10 km/s



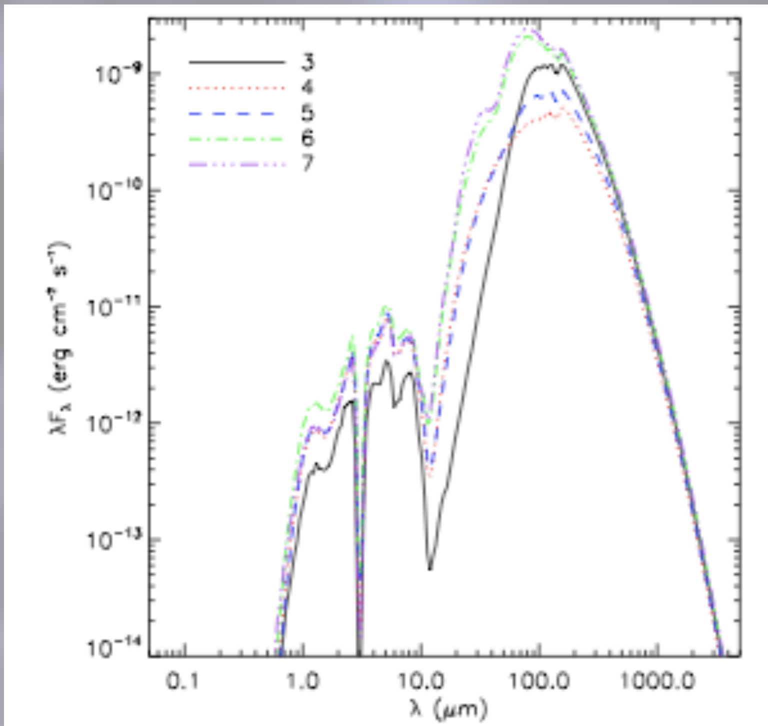
L=0.65 pc

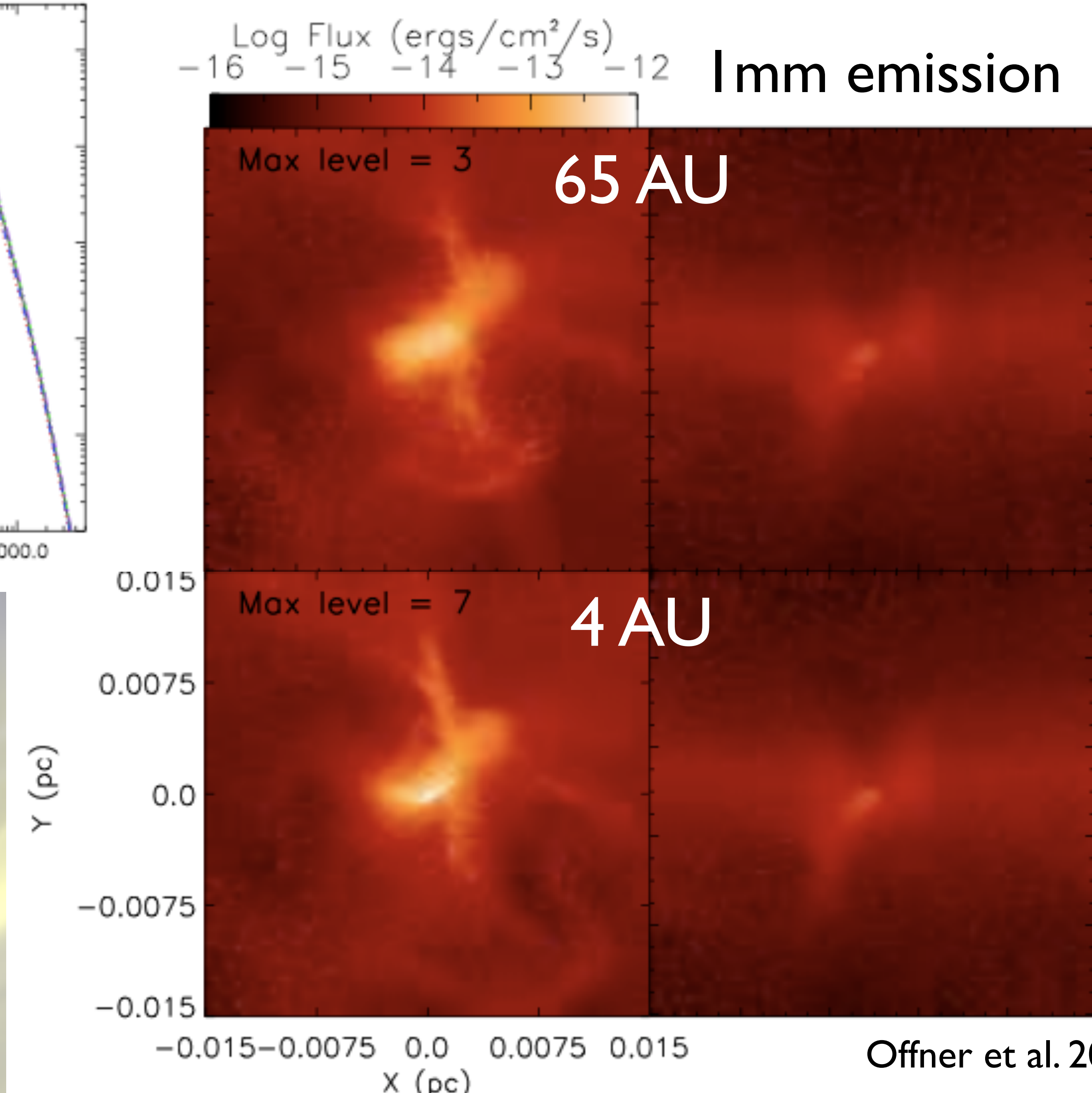
Post-Processing

- 10^7 photons
- 21 Protostars at final time (D burning)
- 200 Wavelengths (0.01 μm - 5000 μm)
- 20 Apertures (1,000-20,000 AU)
- 5 Resolutions (4-65 AU)
- 20 Viewing Angles



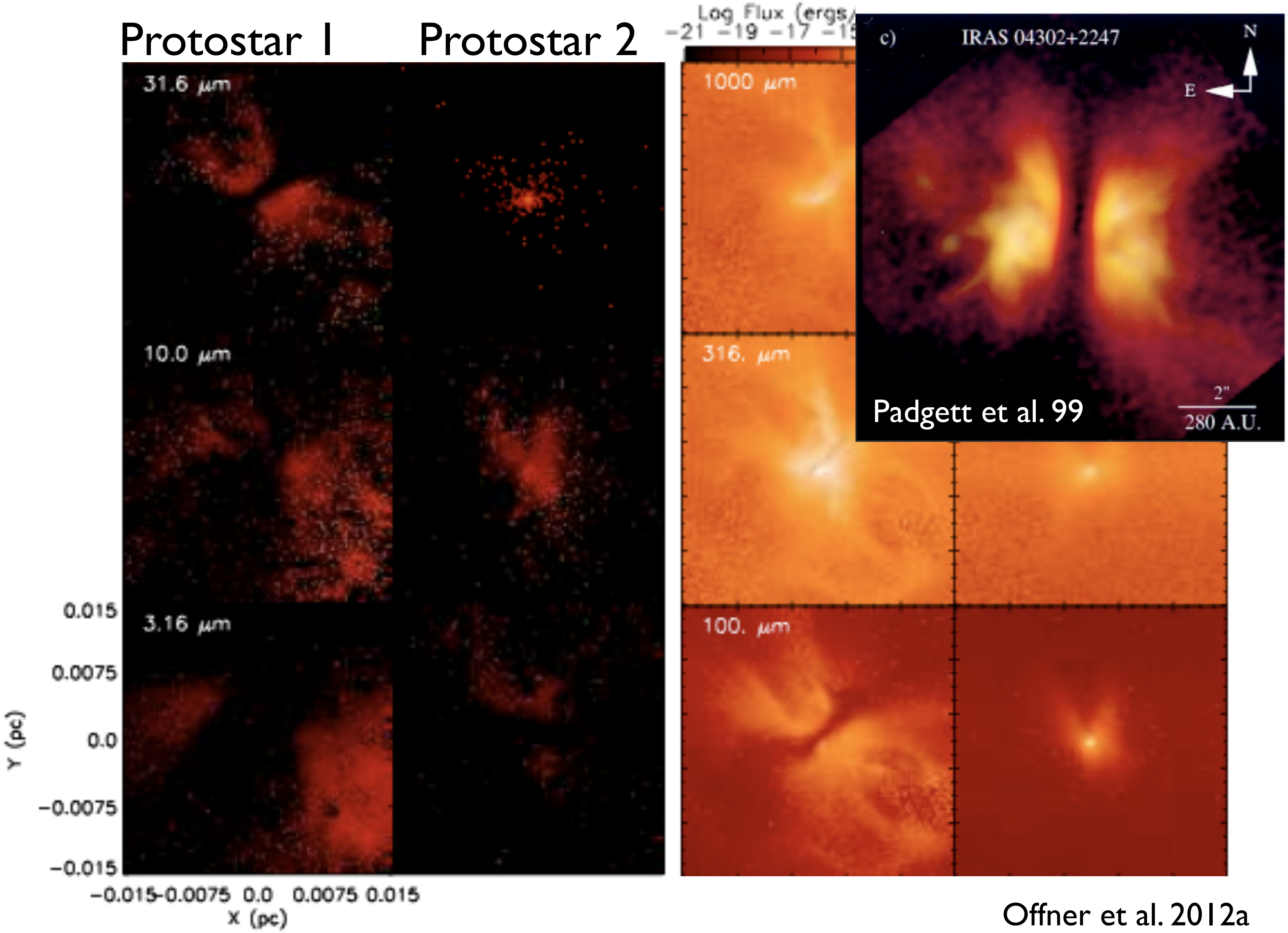
Resolution





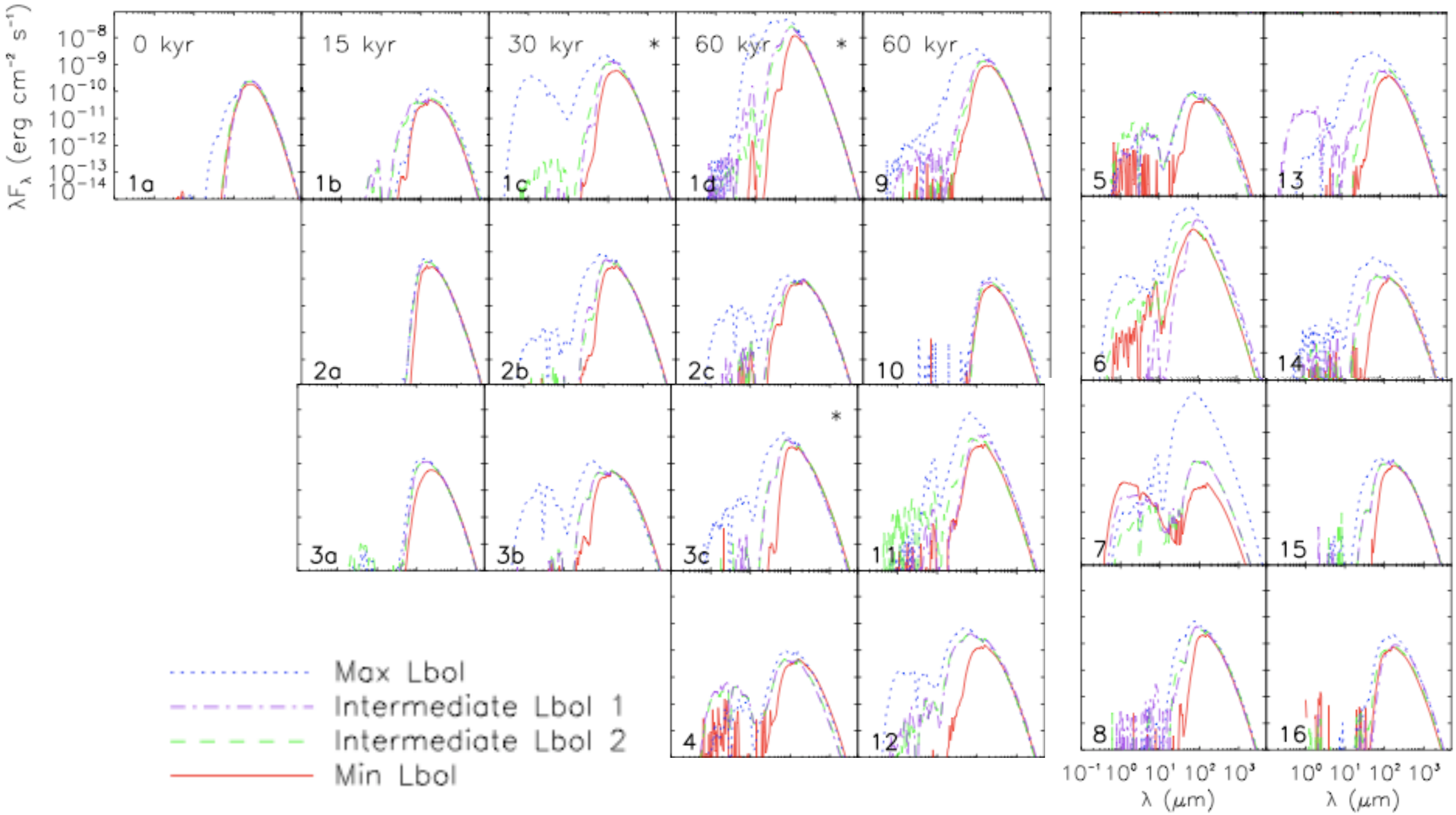
Offner et al. 2012a

Wavelength



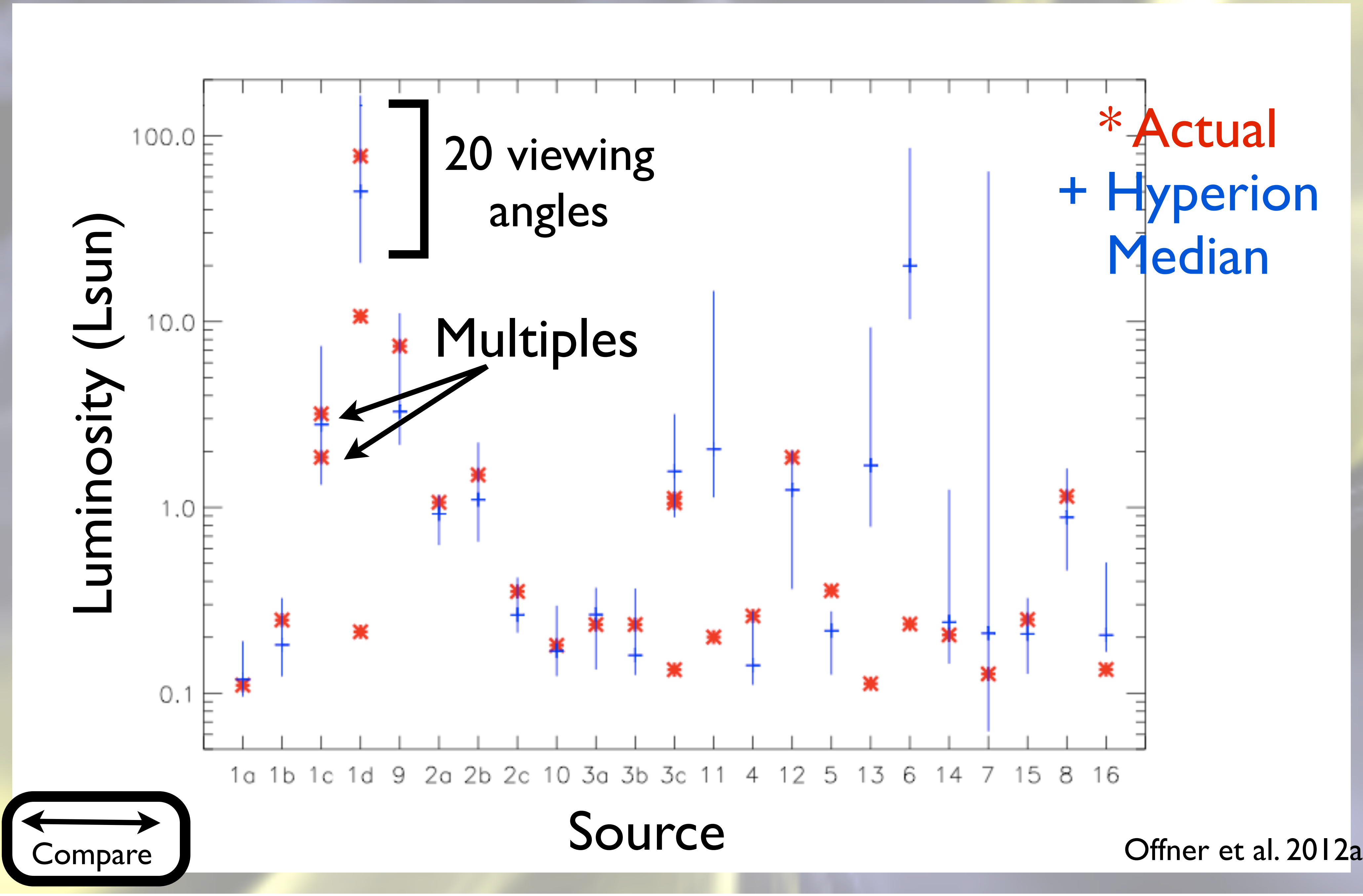
Offner et al. 2012a

SED Zoo

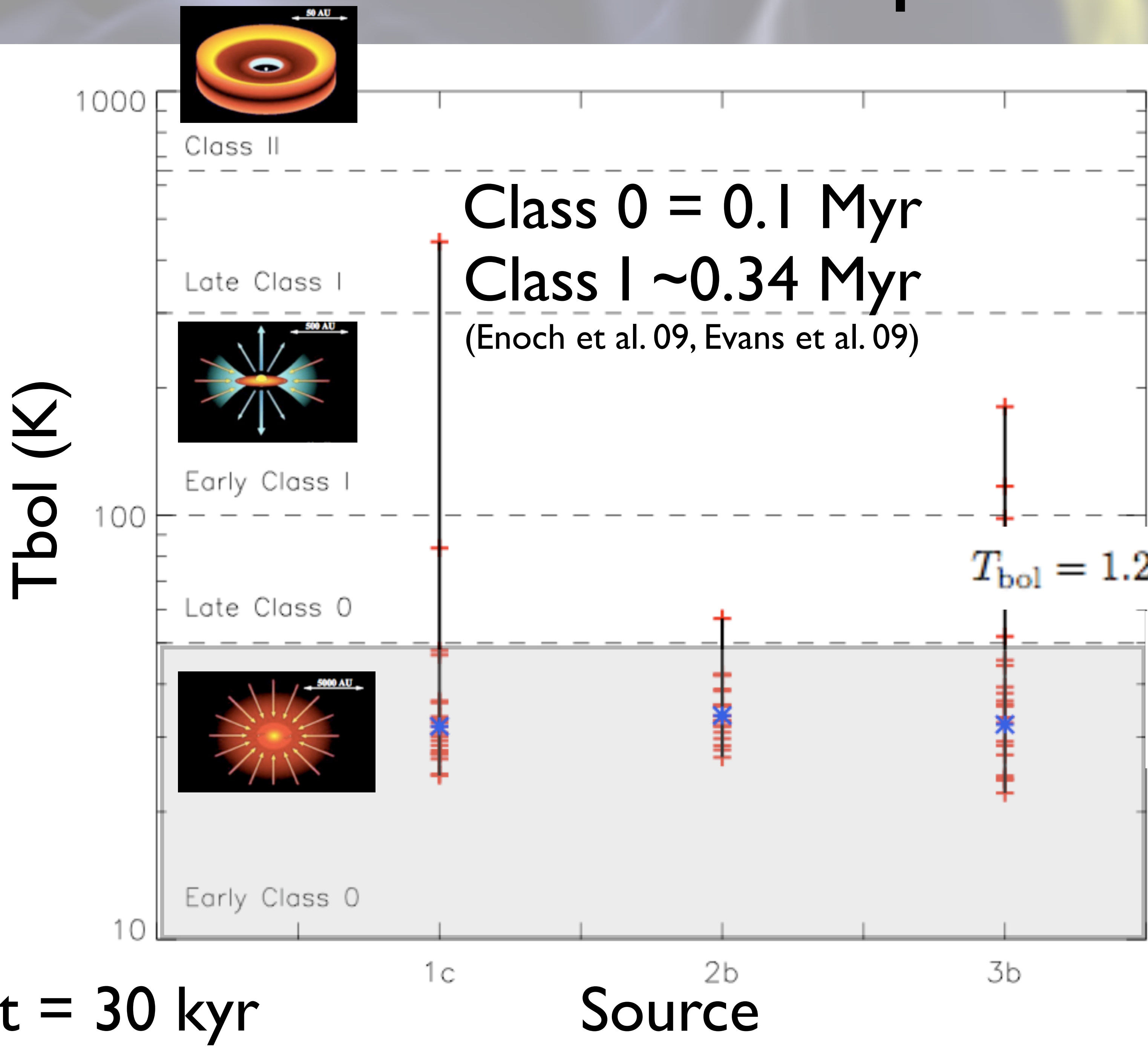


Offner et al. 2012a

Bolometric Luminosity



Bolometric Temperature



Class 0 = 0.1 Myr

Class I ~0.34 Myr

(Enoch et al. 09, Evans et al. 09)

\+ Different Views

\+ Median

$$T_{\rm bol} = 1.25 \times 10^{-11} < \nu > {\rm K}$$

$$< \nu > = \frac{\int \nu S_\nu d\nu}{\int S_\nu d\nu}$$

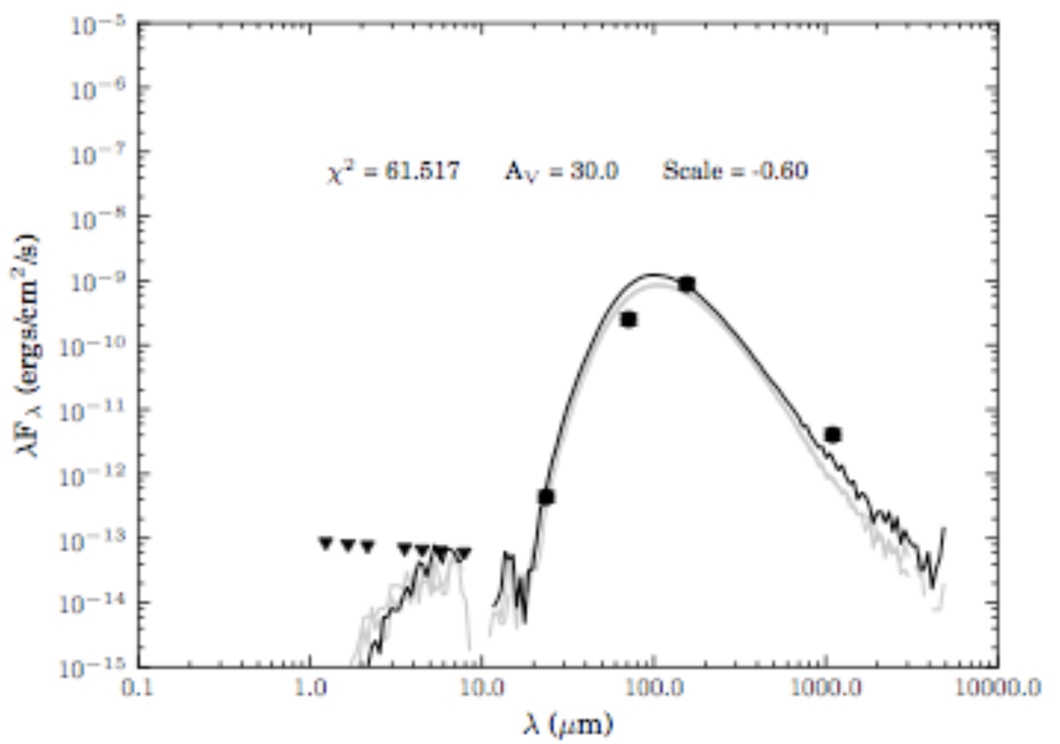
t = 30 kyr

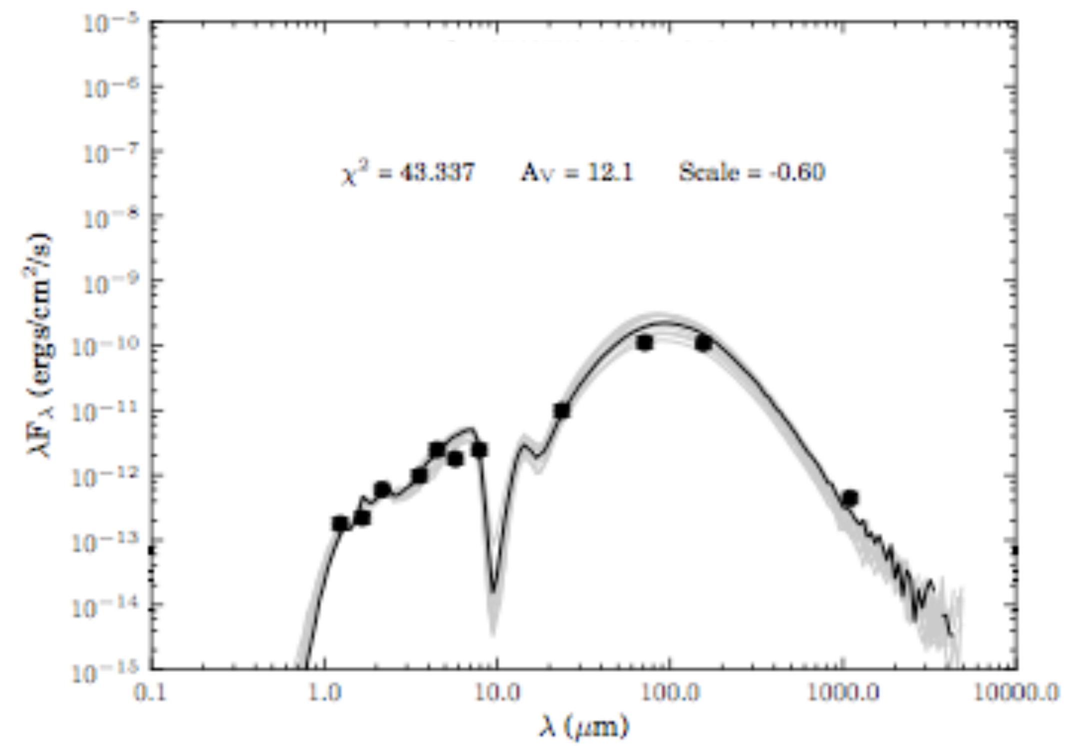
Offner et al. 2012a

Model Comparison

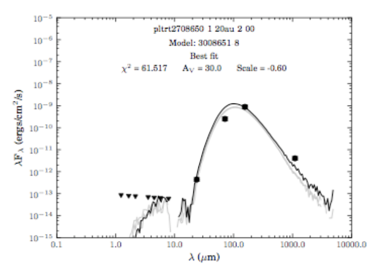
Compare with Robitaille et al. 2006: 200,000 model library

- ▪ “Observations” with 2MASS, MIPS, IRAC, Bolocam
- ∇ Upper limits
- ___ Best fit model
- ___ Good fit models ($\chi^2 < 3N$)



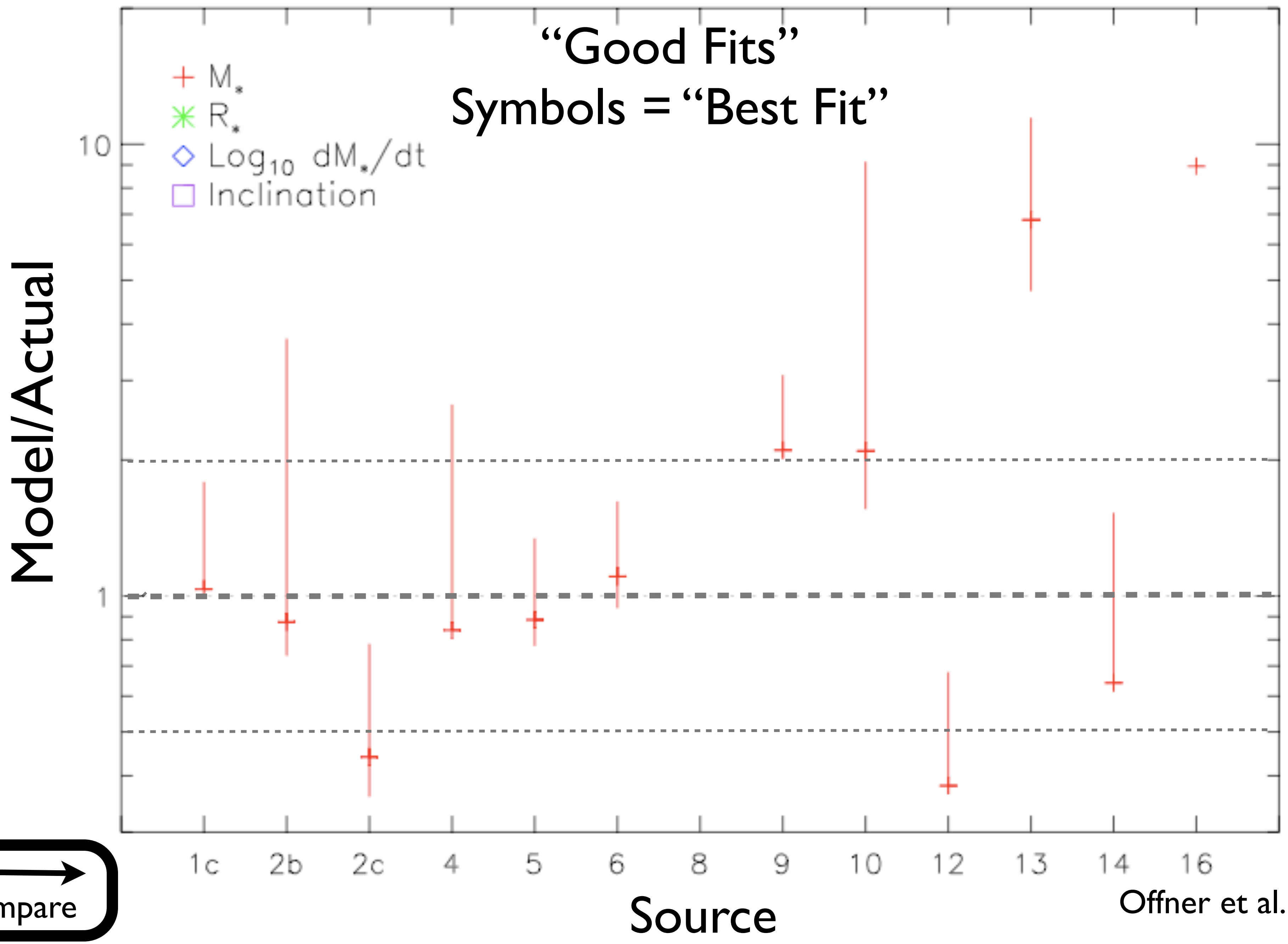


Model



Offner et al. 2012a

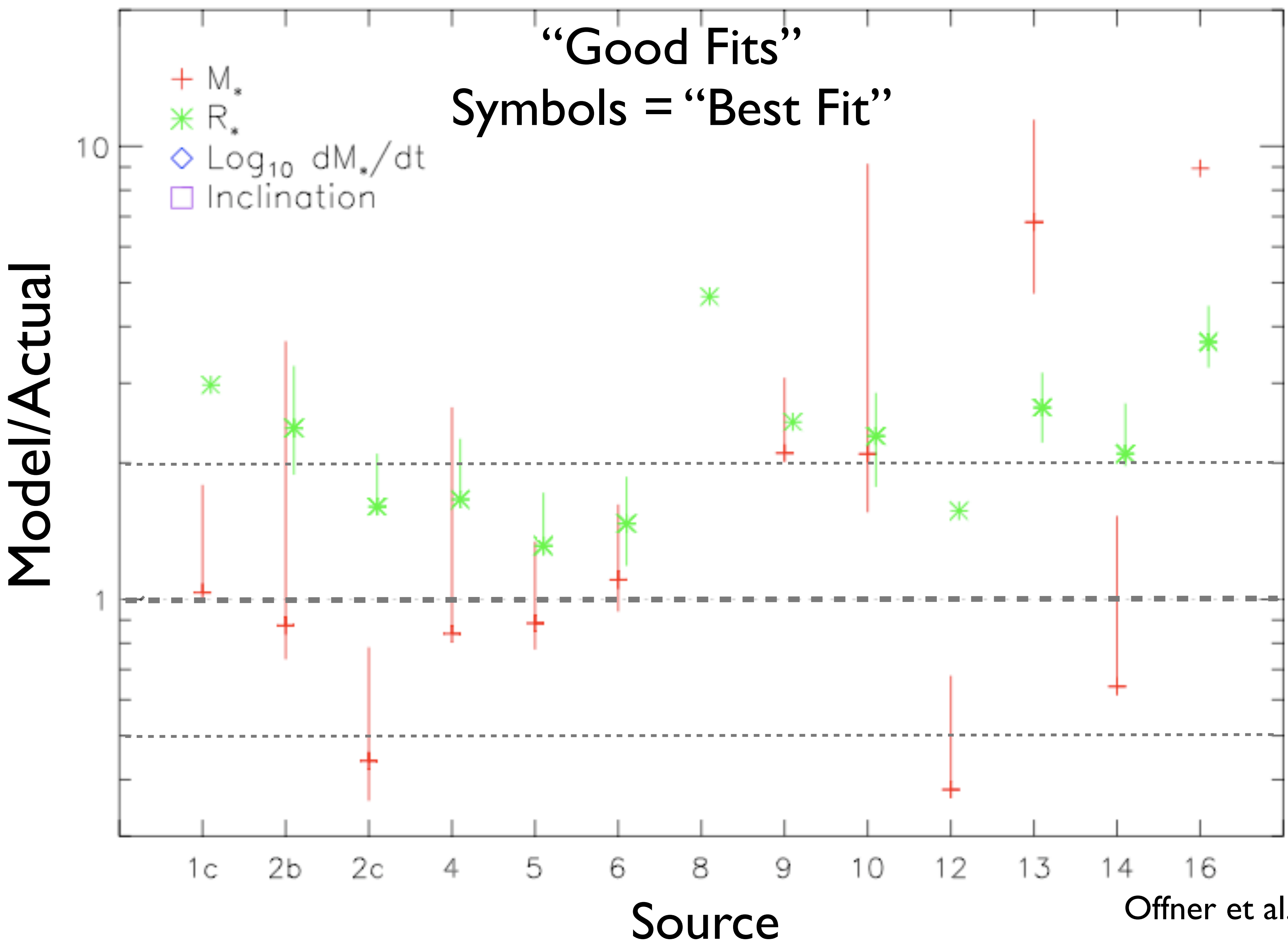
Model Comparison



Offner et al. 2012a

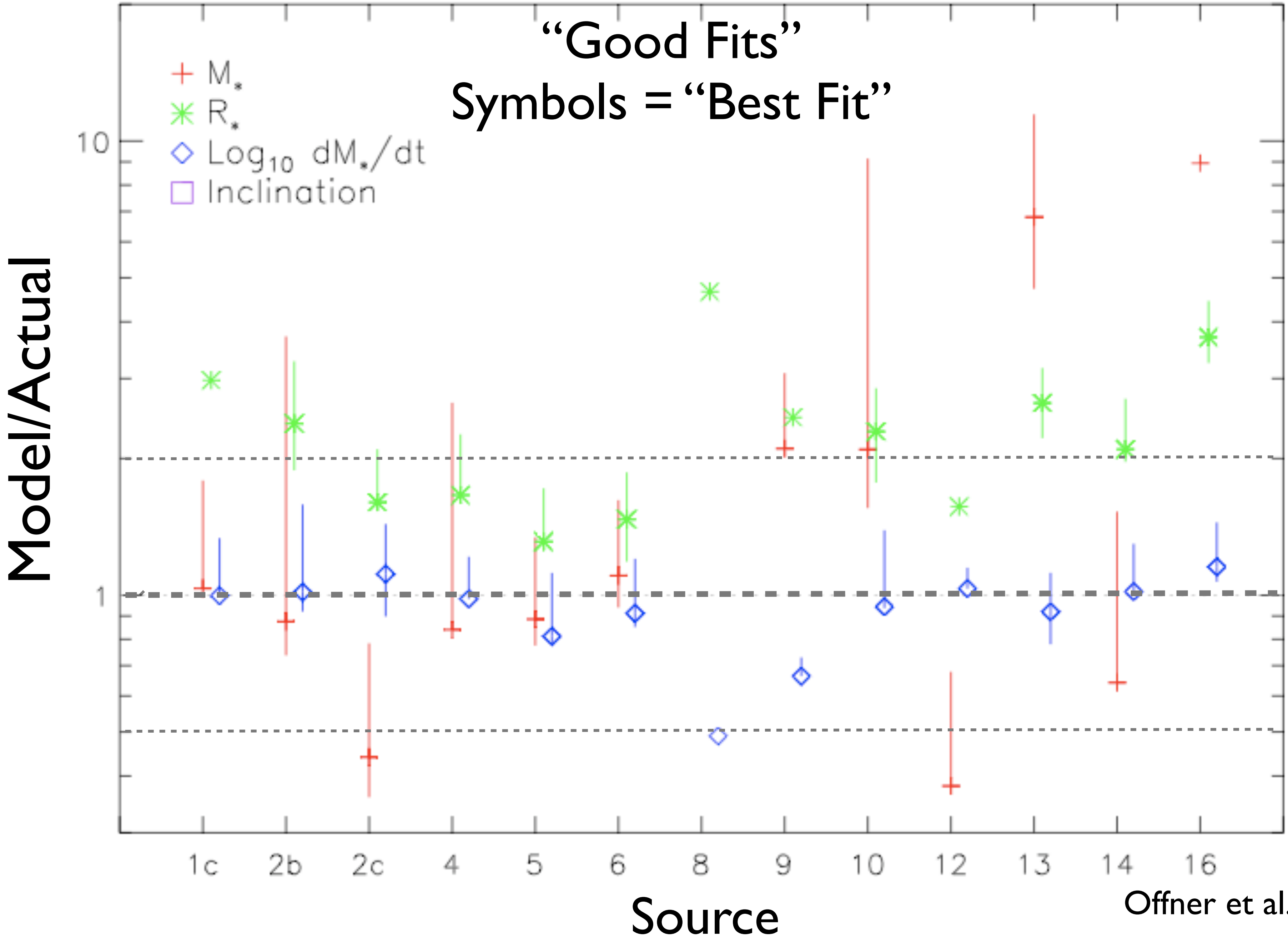
Compare

Model Comparison



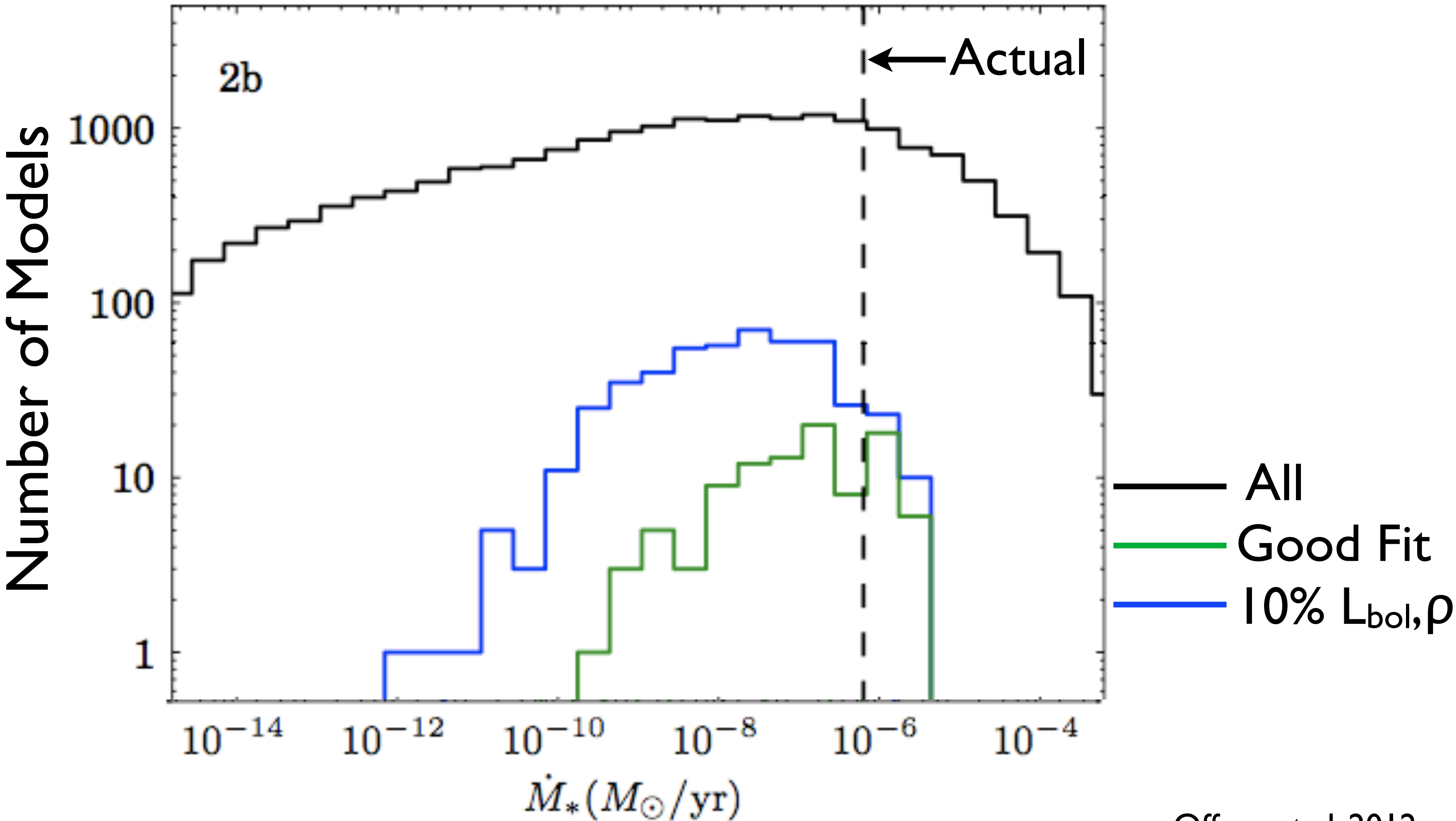
Offner et al. 2012a

Model Comparison



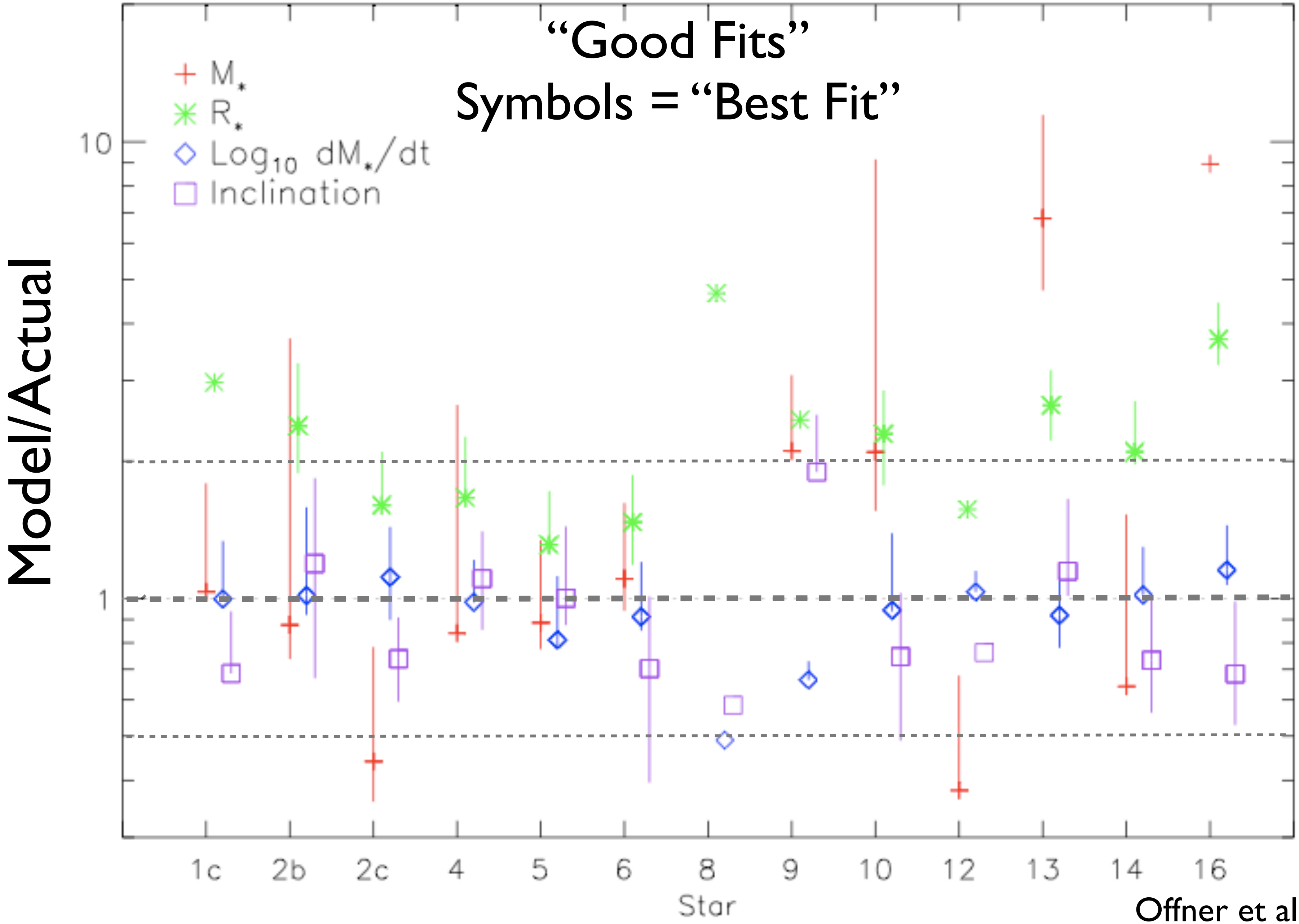
Offner et al. 2012a

Model Comparison



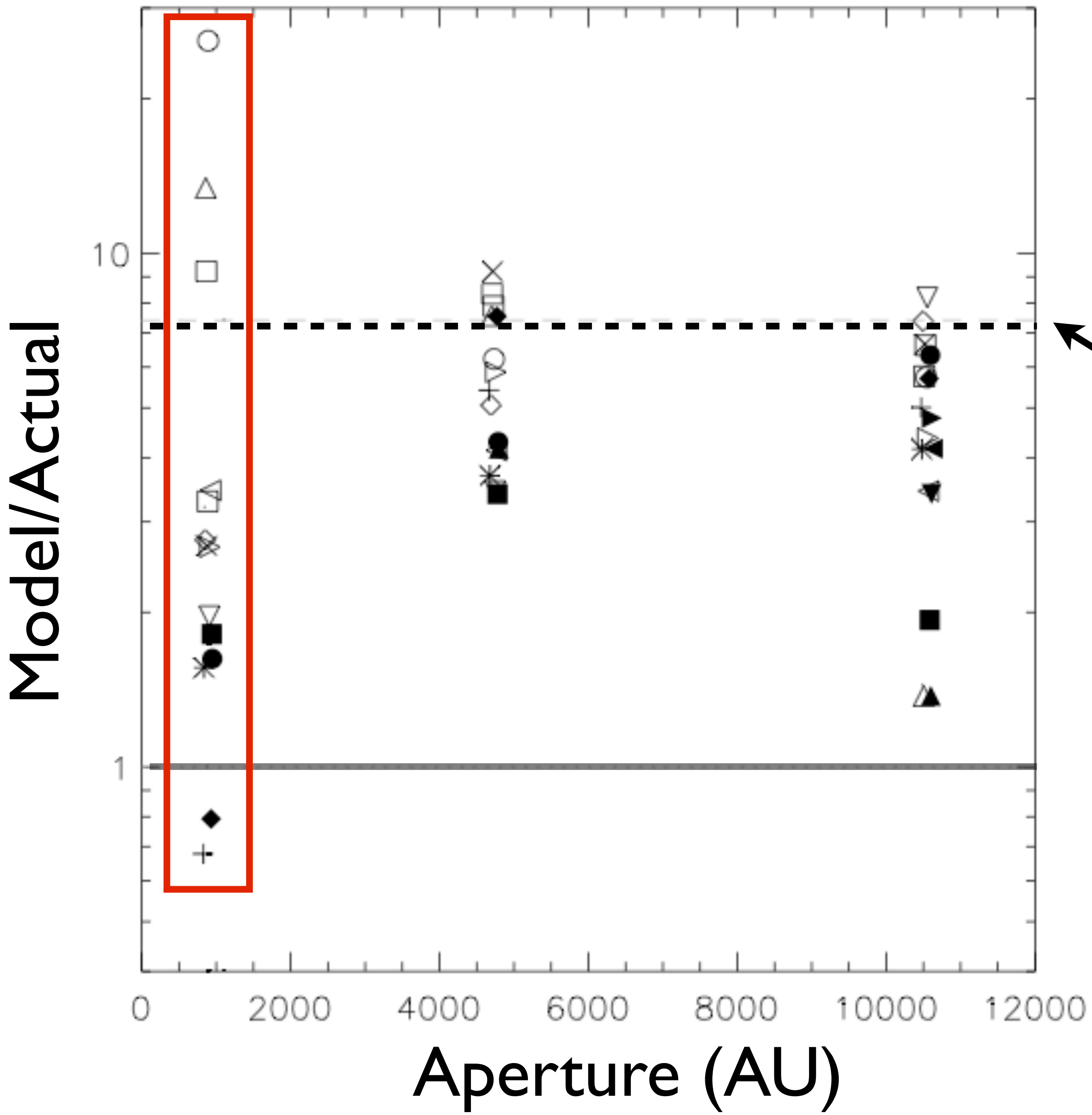
Offner et al. 2012a

Model Comparison



Offner et al. 2012a

Model Comparison



Envelope Mass

Expected based on opacity differences

Symbols = Different Sources

Offner et al. 2012a

Interferometric observations of dust continuum

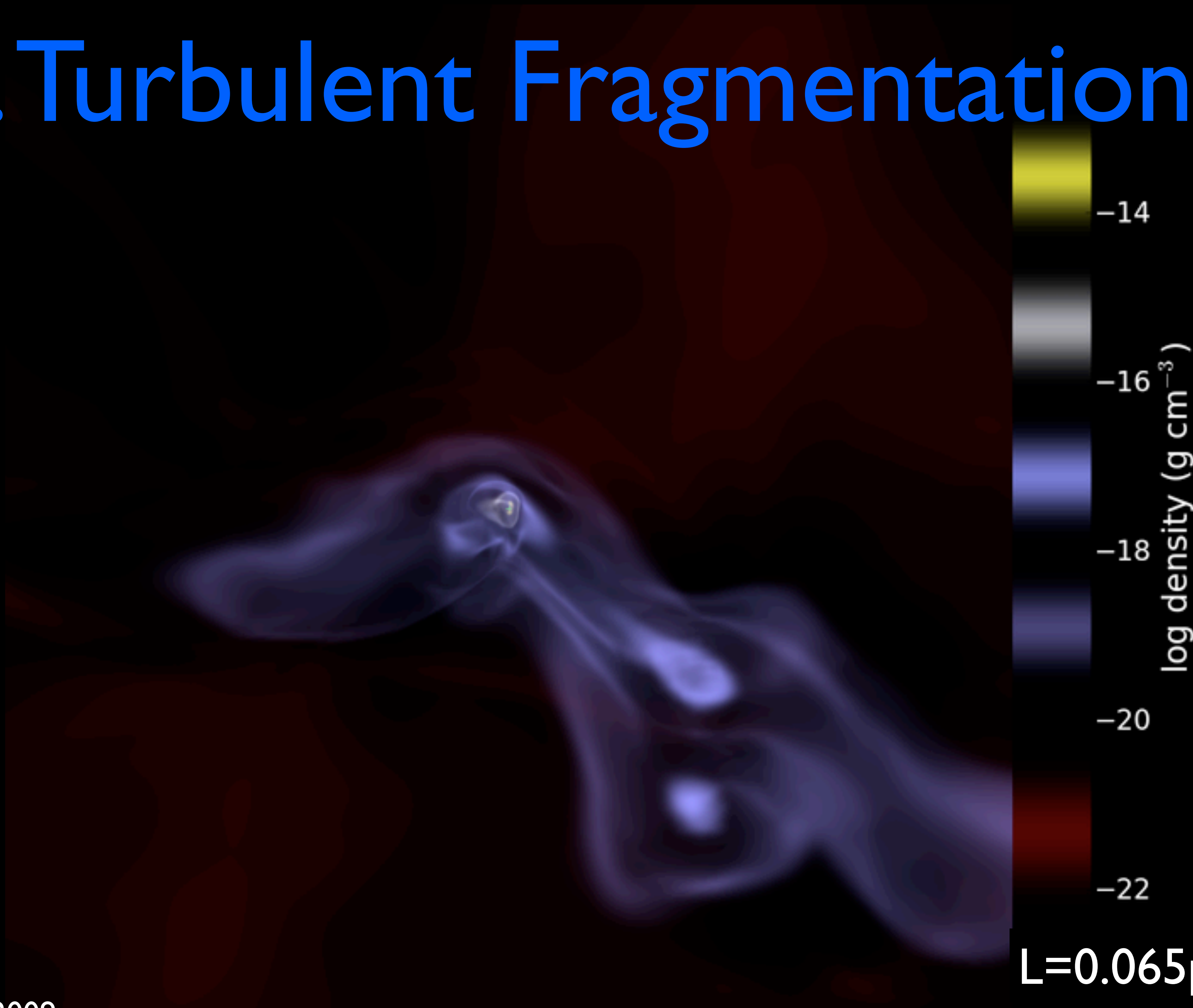
S. Offner, J. Capodilupo, S. Schnee, A. Goodman

Motivation

What is the initial stellar multiplicity?

- Deeply embedded
- Dynamical Interactions
- Resolution
- Boundedness

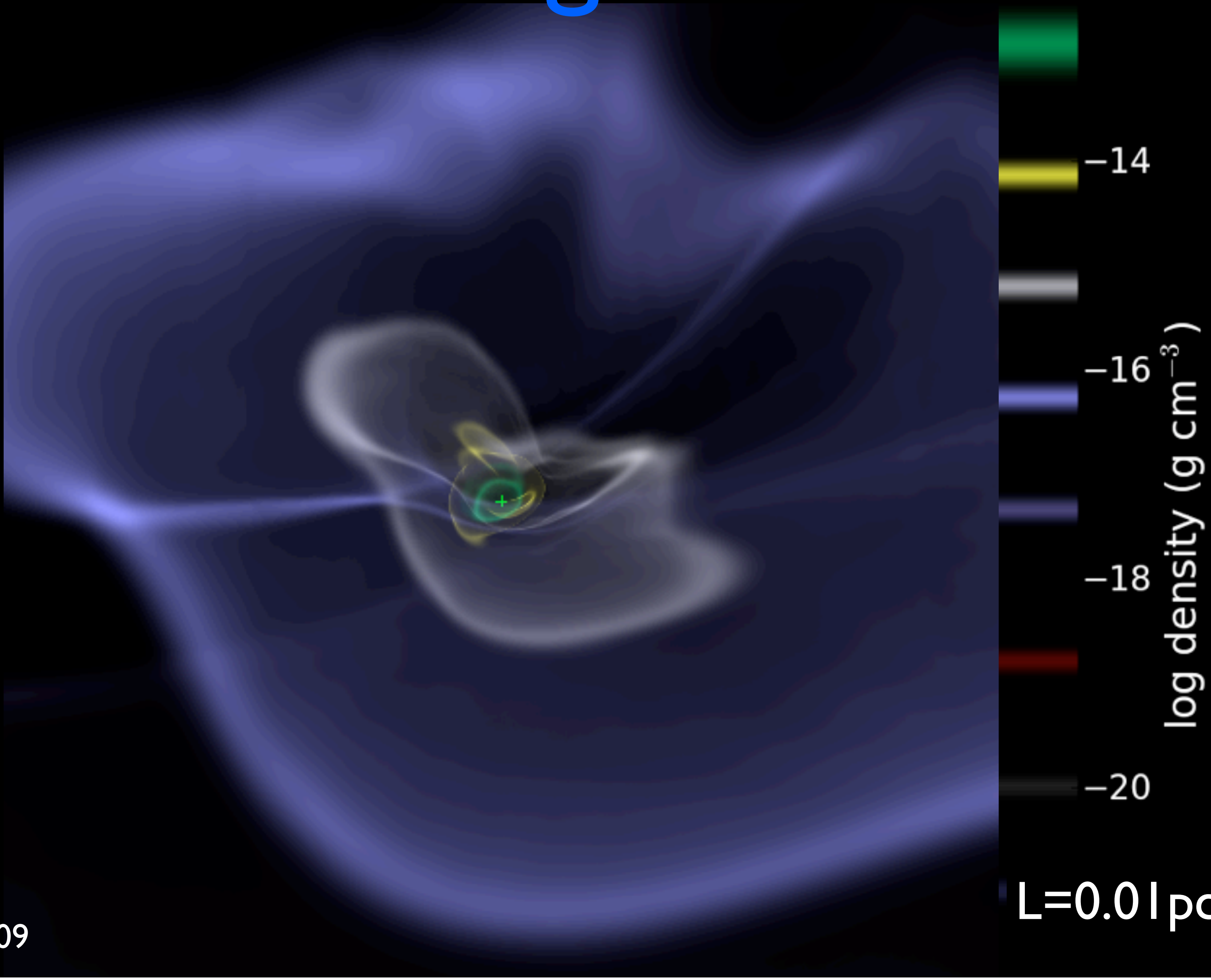
1. Turbulent Fragmentation



L=0.065pc

Offner et al. 2009

2. Disk Fragmentation



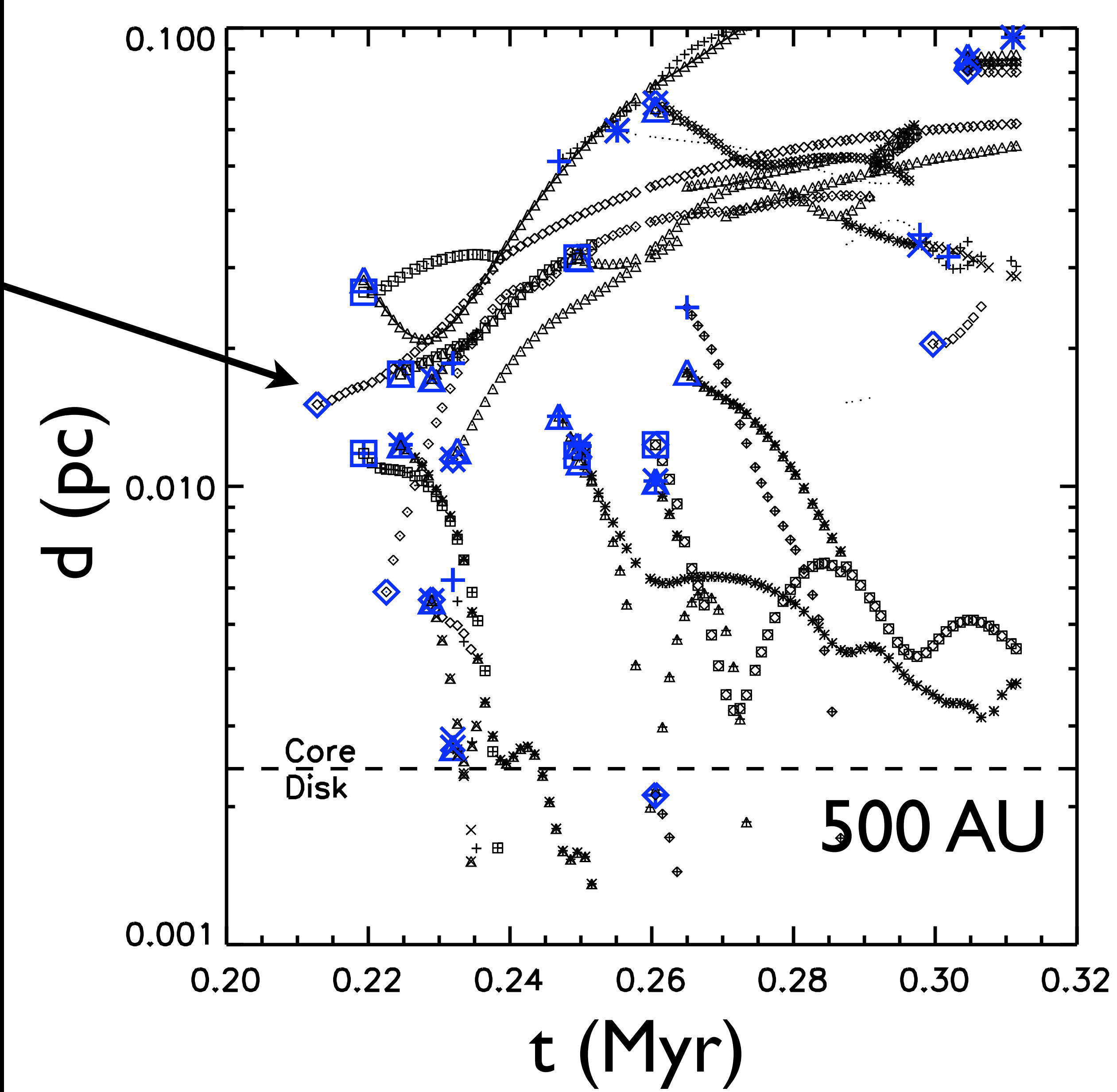
Offner et al. 2009

Including Radiation...

Offner et al. 2010

(For low-mass stars)

Look for these



See also:
Cai et al. 08, Bate 09, Kratter et al. 10

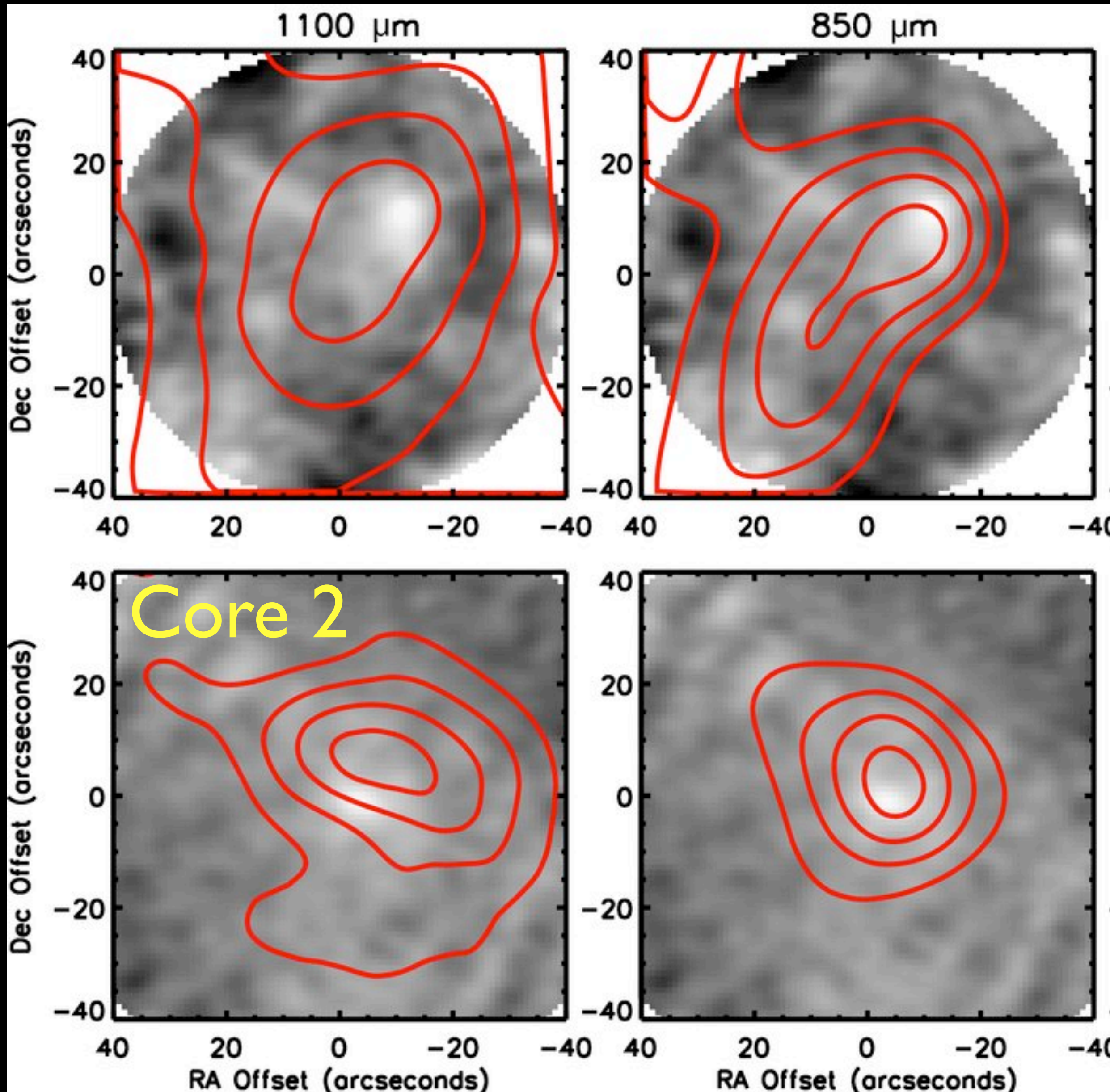
Somebody did look...

- 11 "starless" cores
- CARMA (3mm)
- Bolocam (1mm)
- SCUBA (0.85mm)

"An Observed Lack of Substructure in Starless Cores"

Core 1

Schnee et al. 10



Structure-less because?

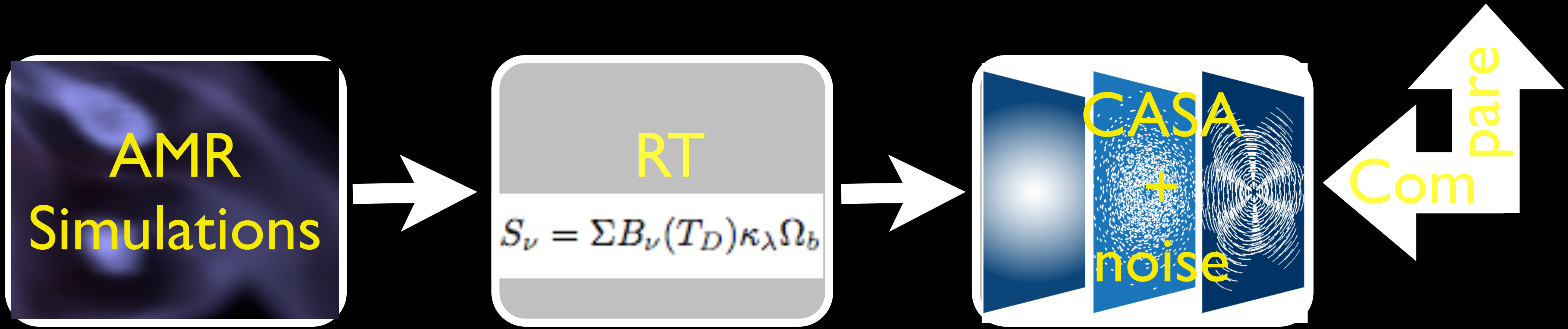
- No fragmentation?
- These will never form stars/binaries?
- Hard to really see -- even with CARMA ... or ALMA?

Predictions

- CASA software package
- mimic interferometry
- noise, beam resolution

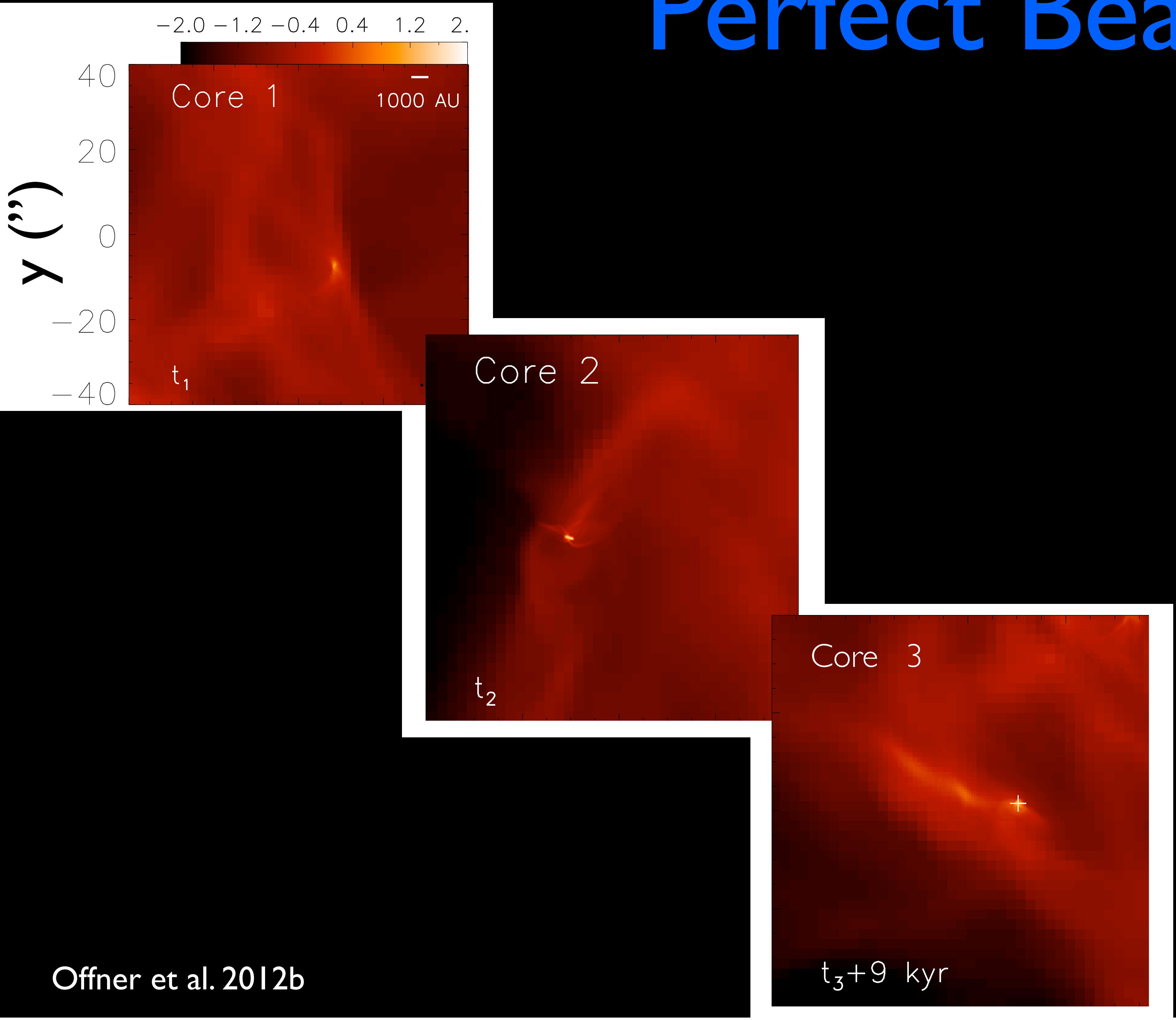
Predictions

- CASA software package
- mimic interferometry
- noise, beam resolution



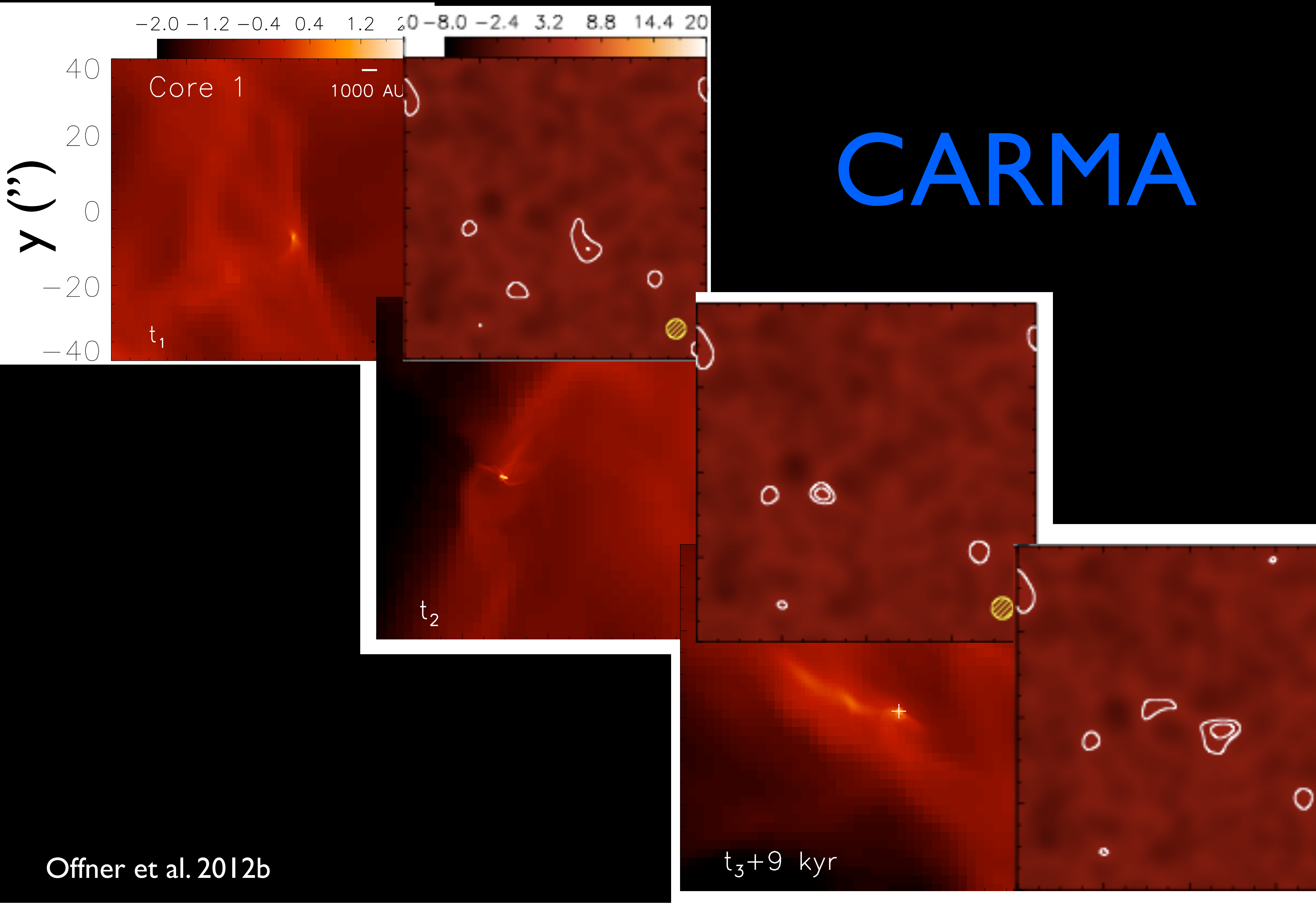
Perfect Beam

Log 1mm Flux (mJy)



Offner et al. 2012b

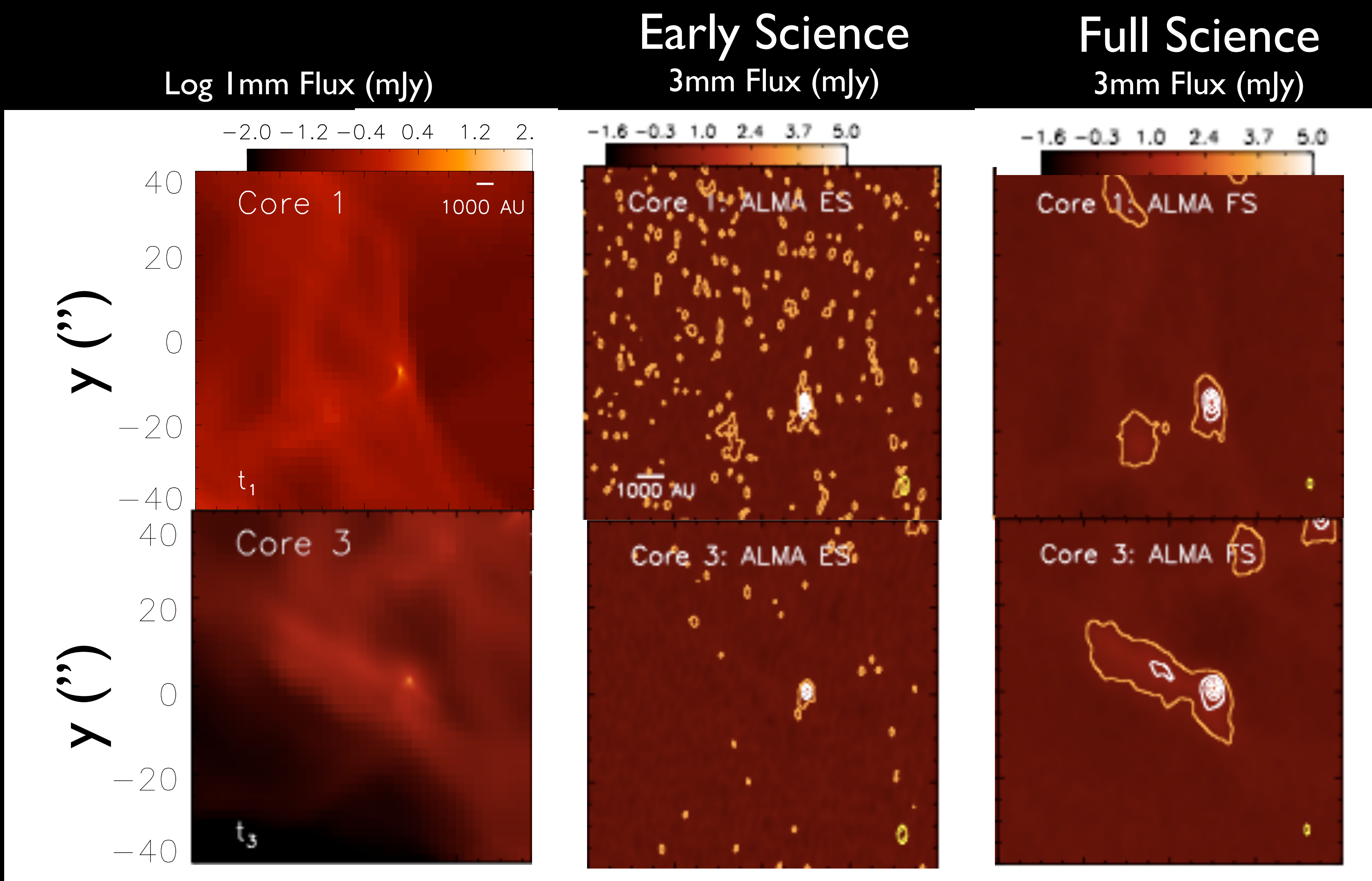
Log 1mm Flux (mJy)   3mm Flux (mJy)



CARMA

Offner et al. 2012b

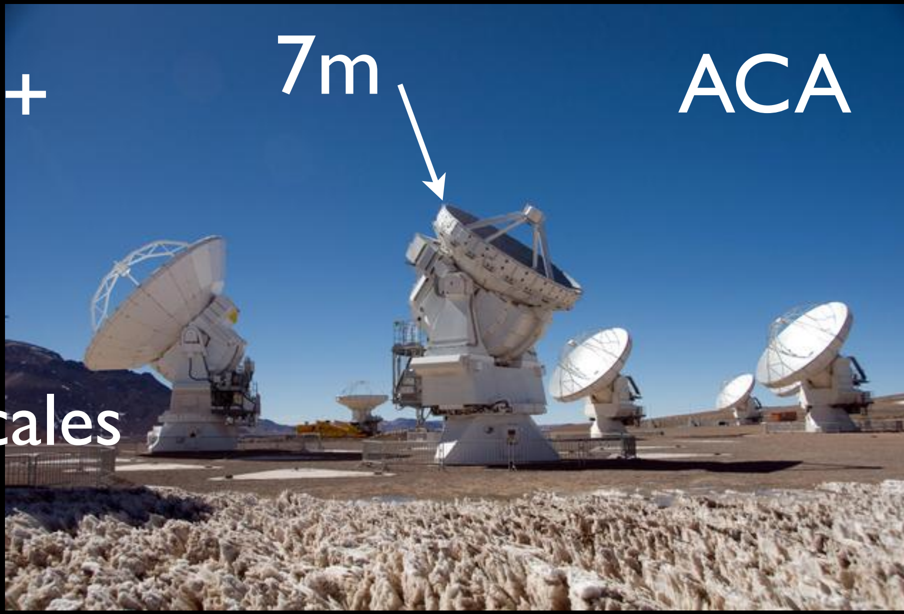
ALMA



Offner et al. 2012b

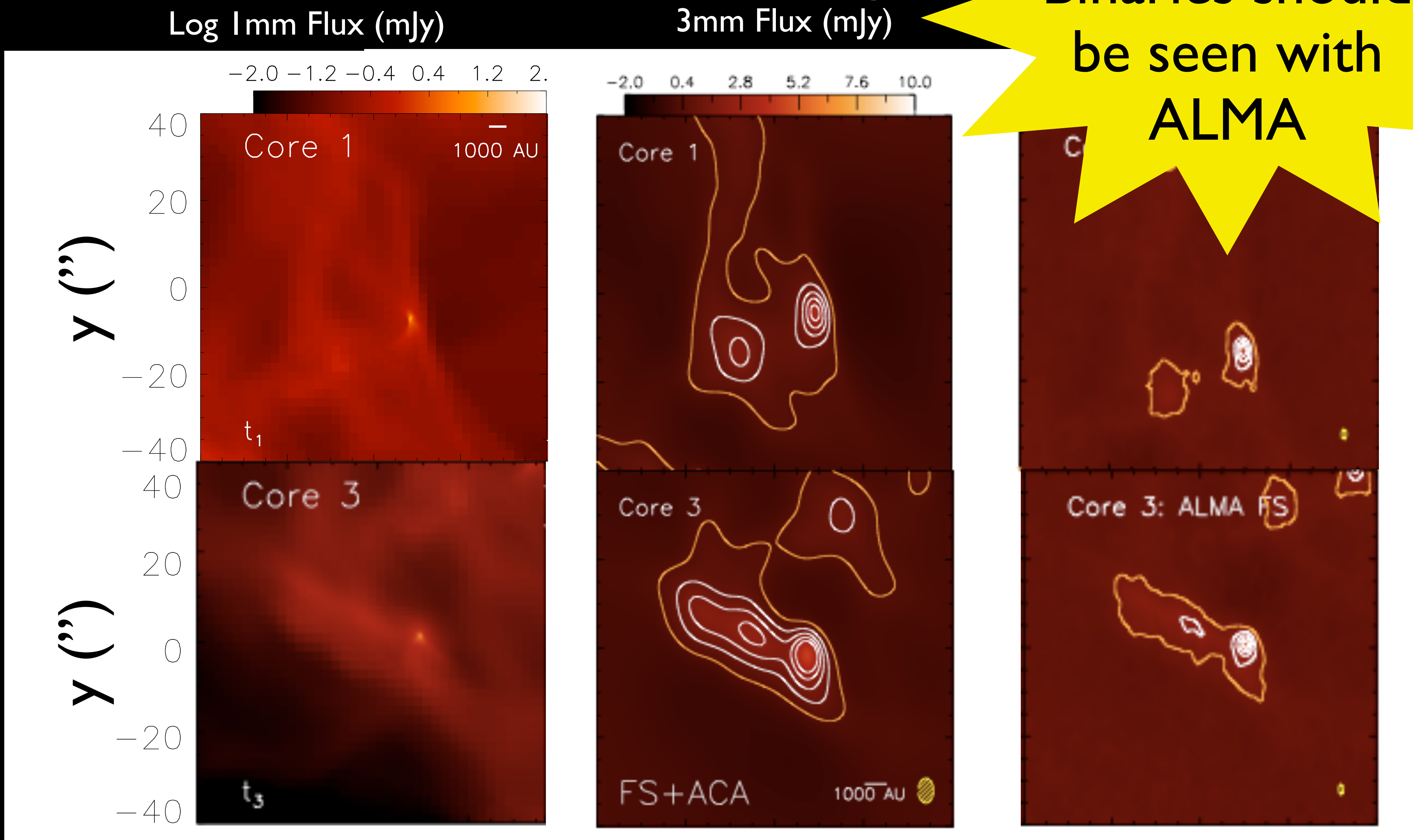
Atacama Compact Array

- Main array: 50 12m attennas
- Compact Array (ACA): 4 12m + 12 7m antennas
  - Allows antennas to be closer together: resolve larger spatial scales
  - Simultaneous observations



ALMA

Full Science+Compact Ar



Forming Binaries should be seen with ALMA

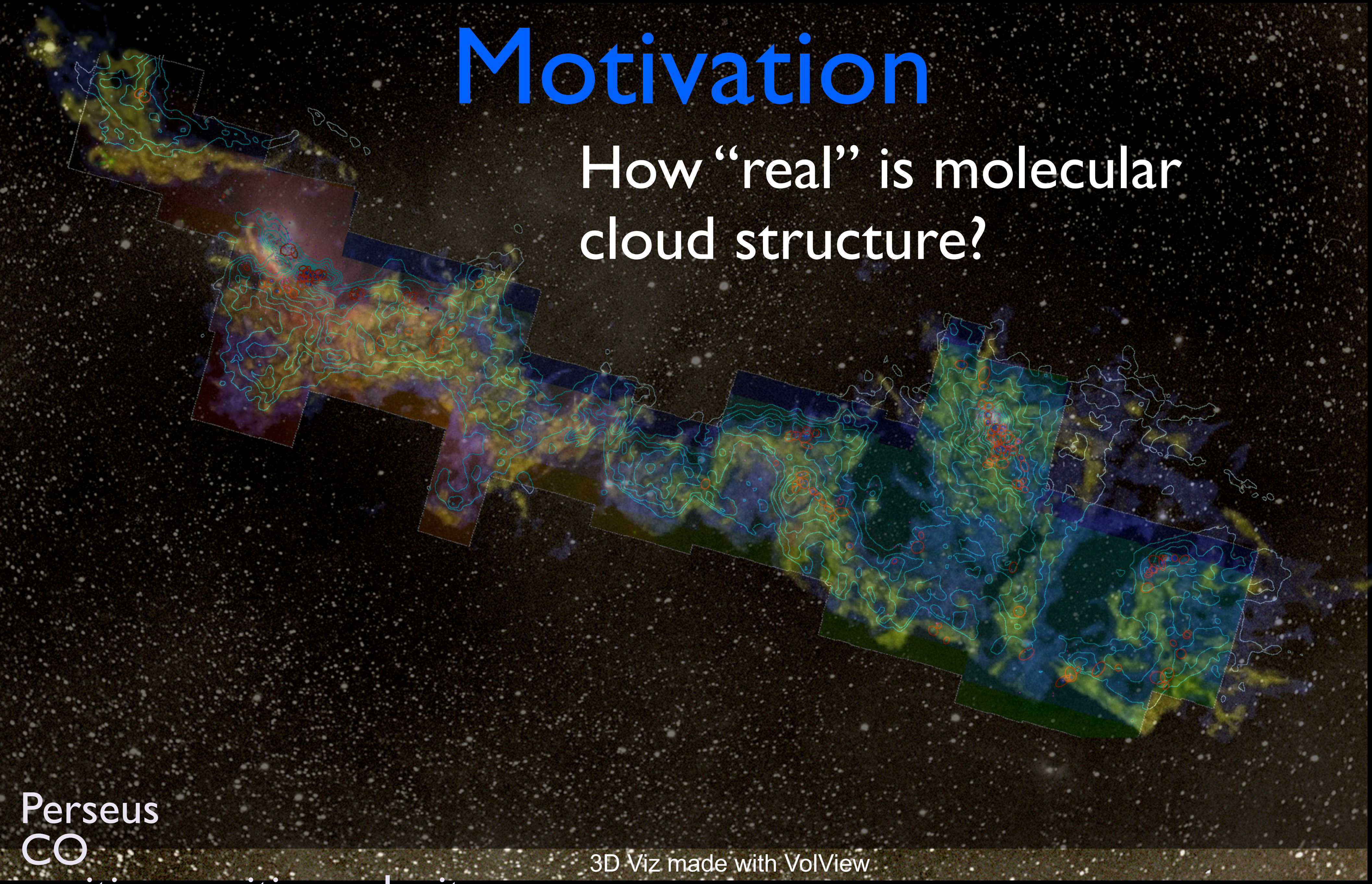
Offner et al. 2012b

Observations of molecular gas

C. Beaumont, S. Offner, R. Shetty, A. Goodman, S. Glover

Motivation

How “real” is molecular cloud structure?



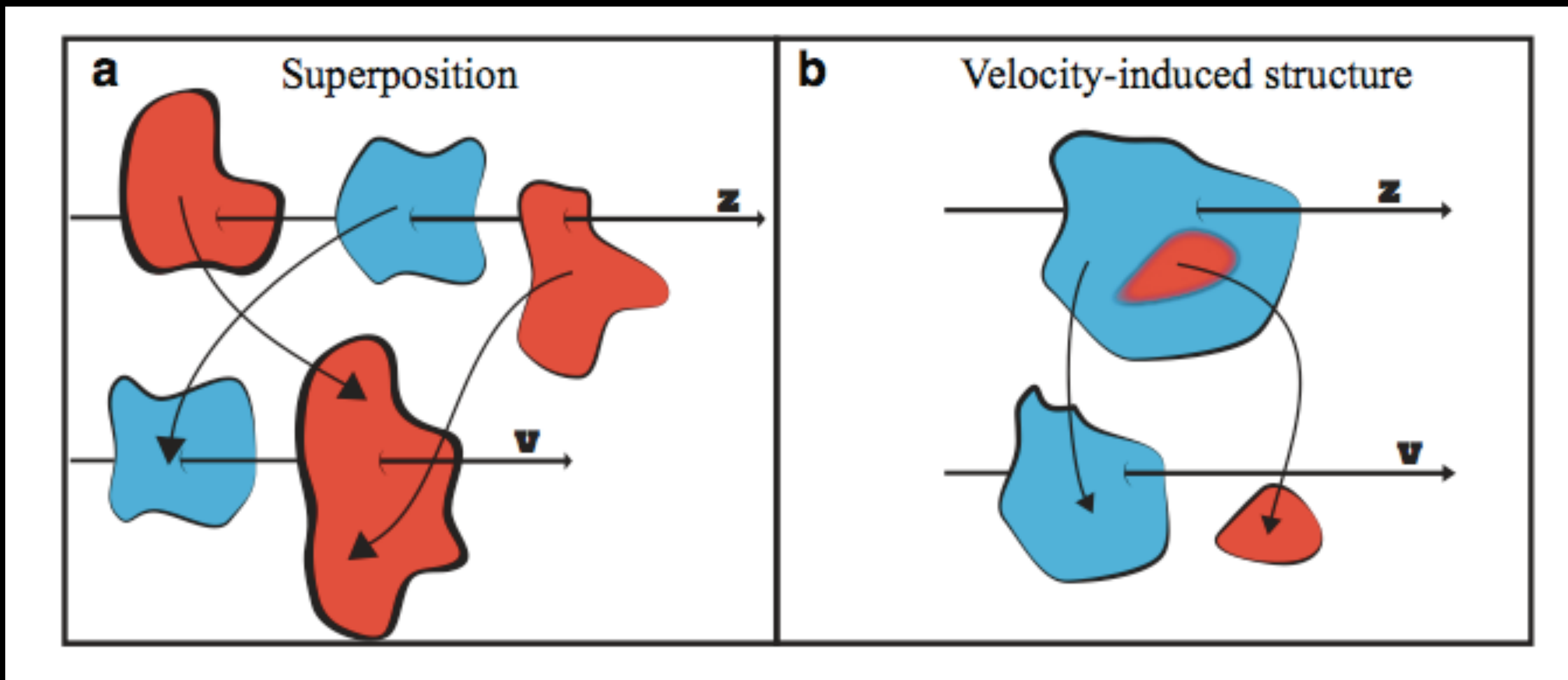
Perseus
CO
position-position-velocity

AstronomicalMedicine

COMPLETE

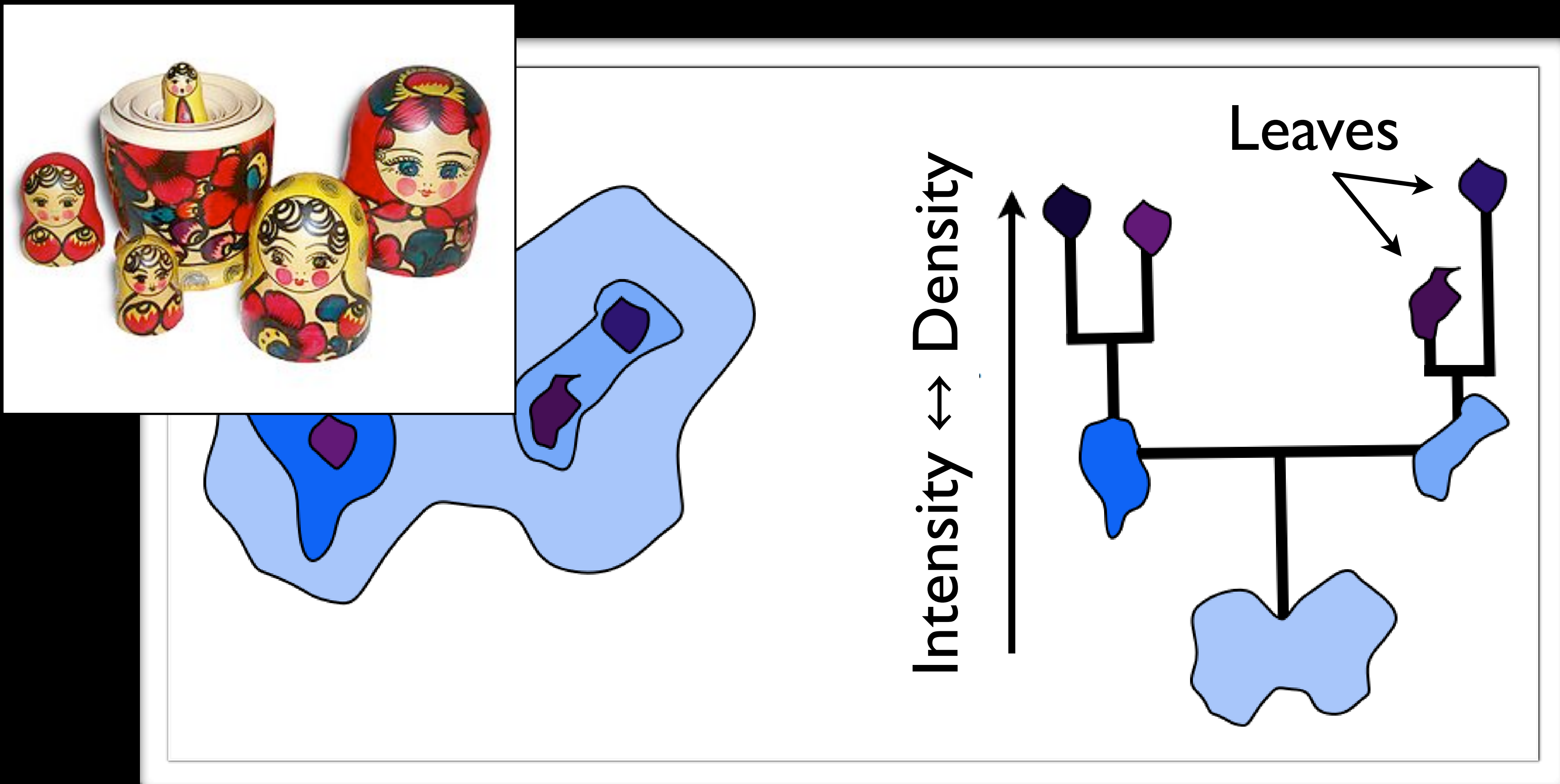
Mapping problems

Beaumont, Offner ea 2013



- Going from position-position-position (ppp, "real") space to position-position-velocity (ppv, "observed") space can be fraught

Dendrograms



Beaumont ea 2013

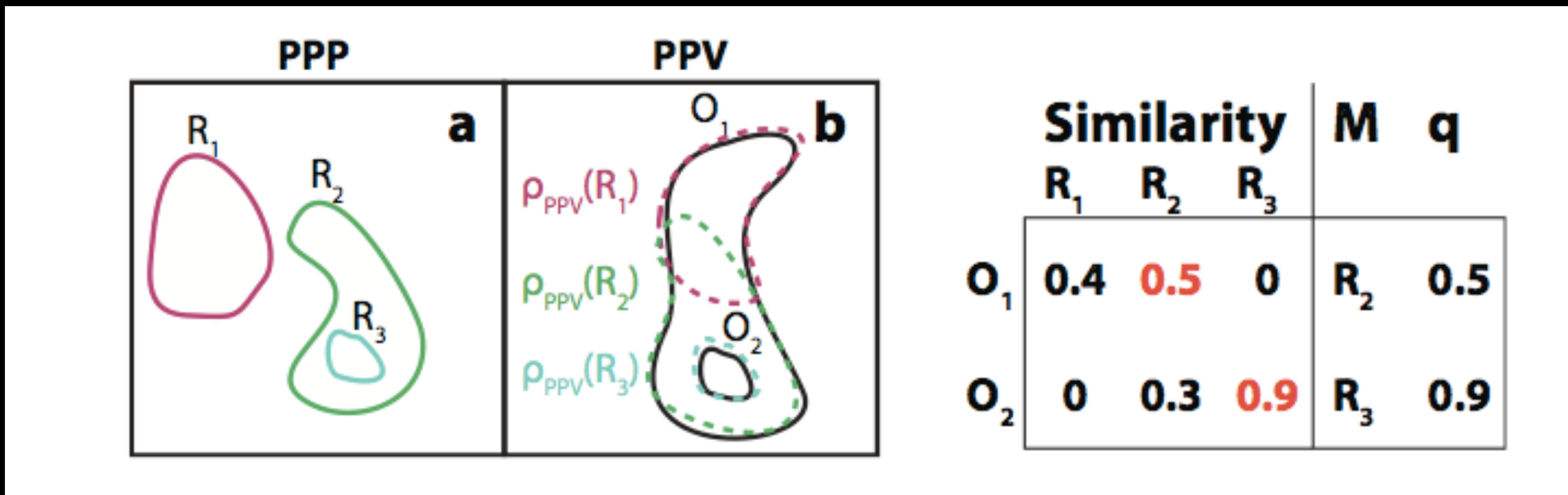
“Hierarchical Structure Trees”

2D or **3D**

e.g. Rosolowsky et al. 08

Similarity

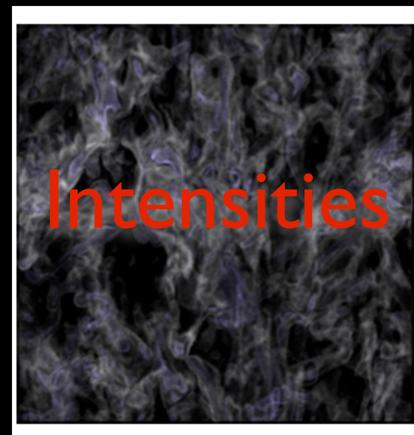
Beaumont ea 2013



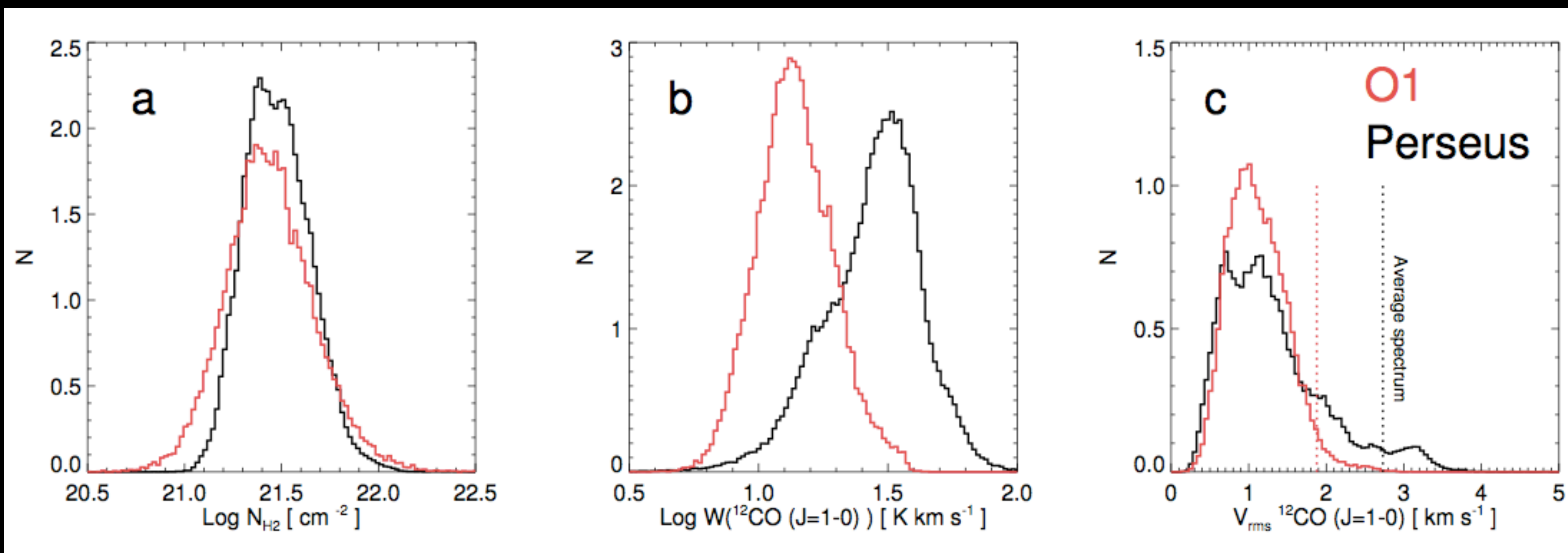
- Define q = how well a structure in ppv matches to a structure in ppp
- Define M = best matching structure in ppp

Matching Bulk Properties

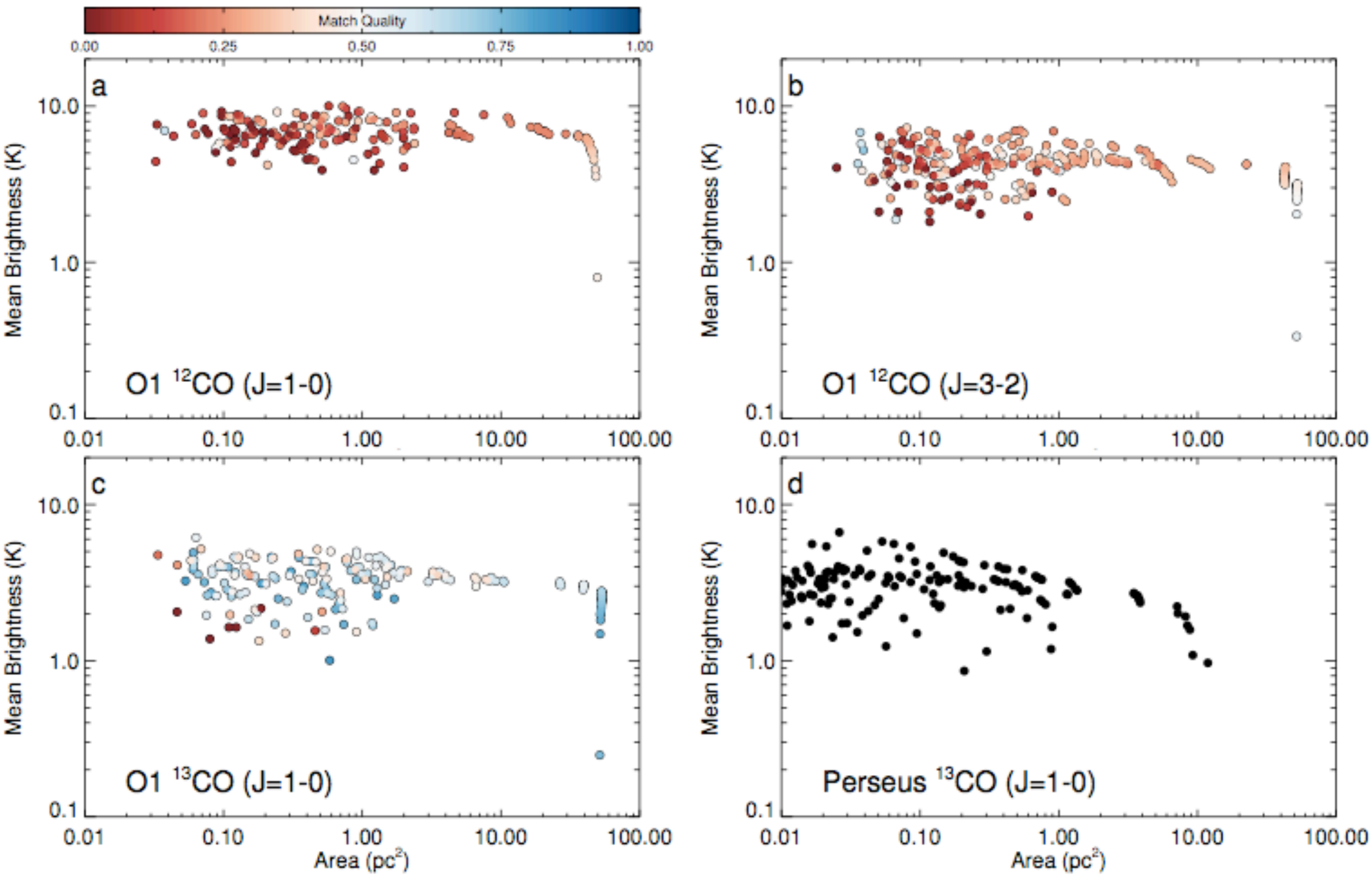
RADMC-3D
Dullemond 2012

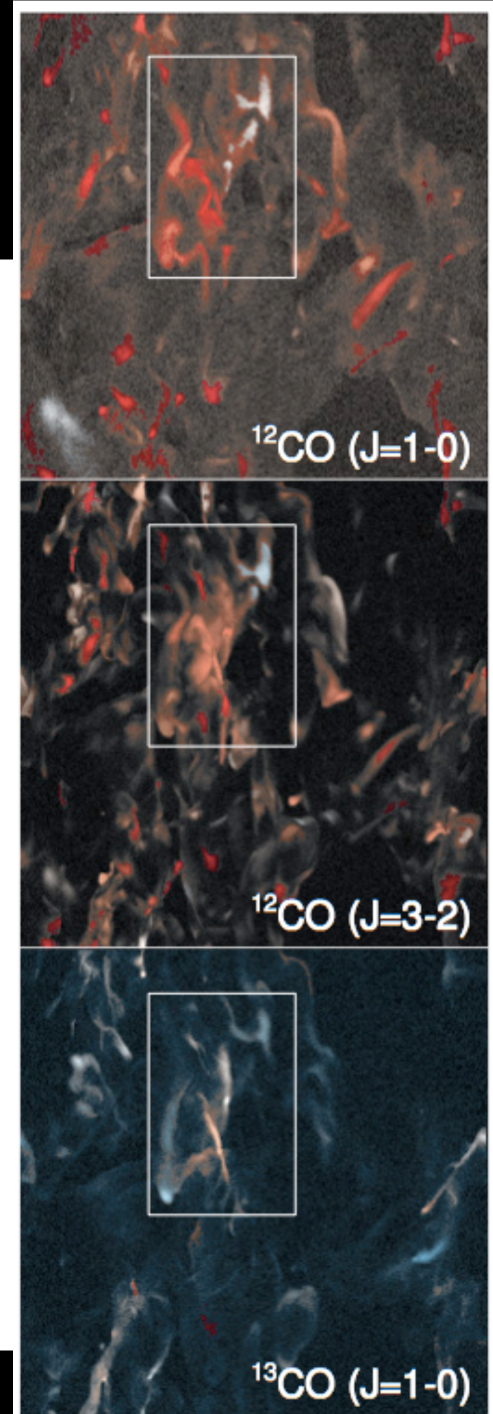


Beaumont ea 2013



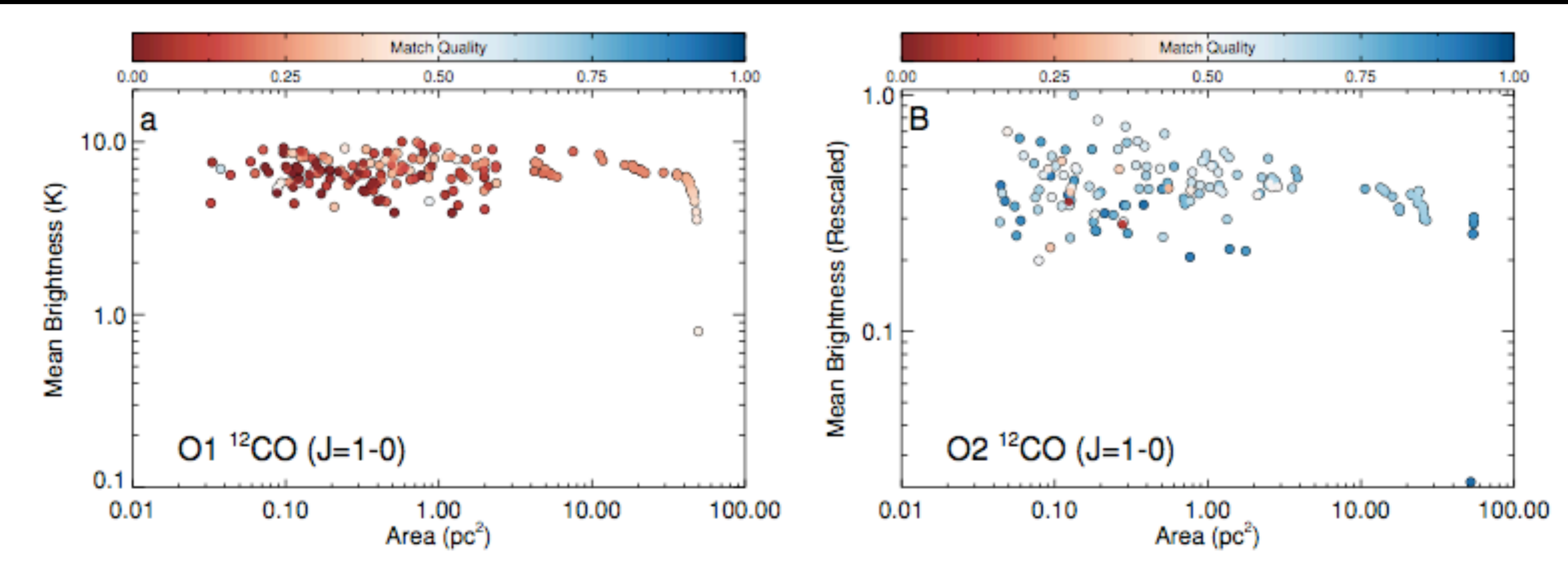
Match Quality





Beaumont ea 2013

Match Quality



- Opacity is disabled (i.e. gas is optically thin, so emission is linear)

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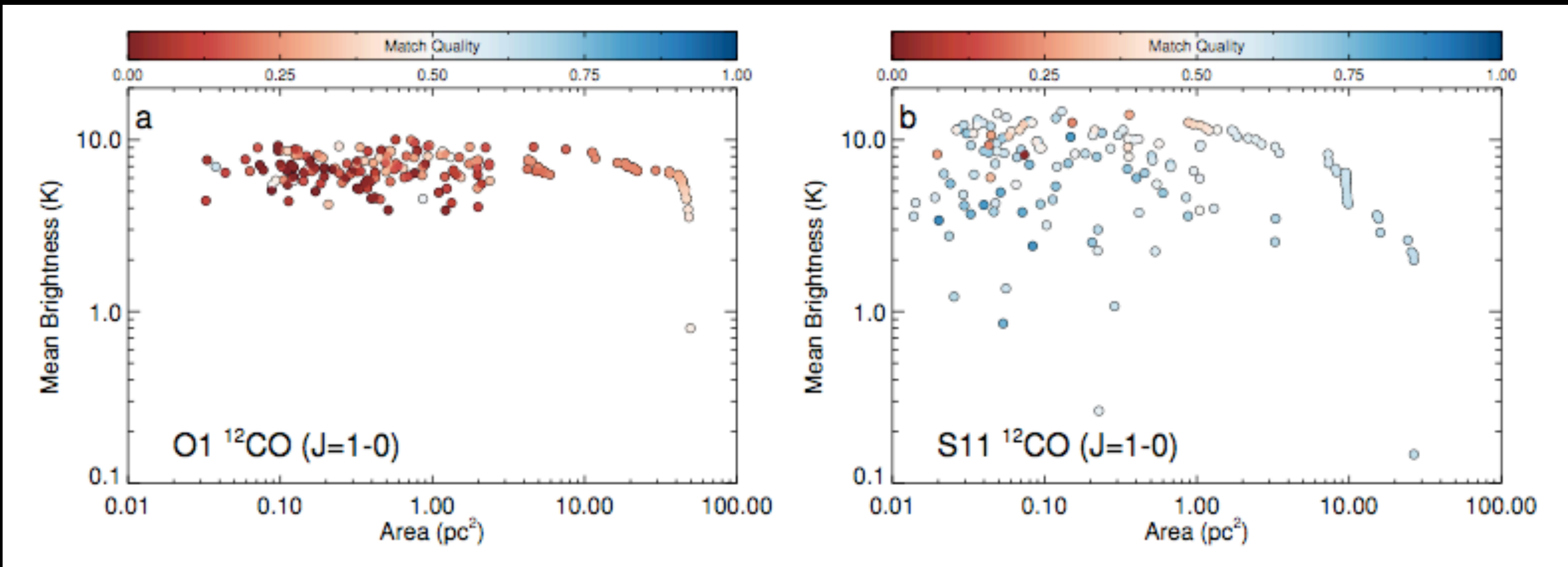
Match Quality



- Match quality is better when ^{12}CO abundance is determined with a reduced chemical network

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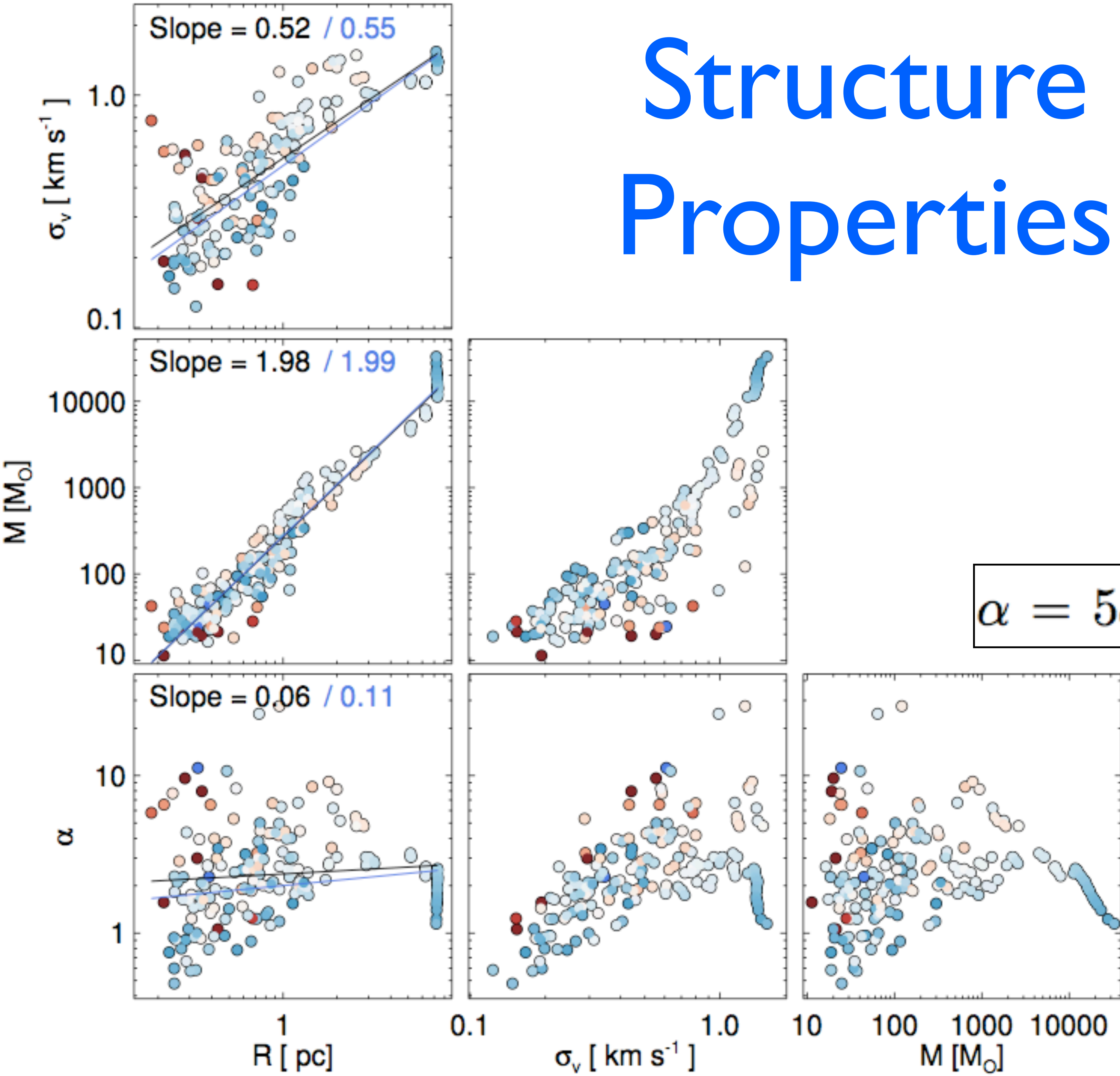
Structure Properties



$$\alpha = 5\sigma_v^2 R/GM$$

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Summary I

Synthetic observations are a powerful and necessary tool for studying star formation.

- SEDs and inferred properties are very sensitive to the viewing angle
  - Sources may span 2 classes even early on (ages over-estimated in 5-10%)

- Caution is necessary when extrapolating source parameters from SED models:
  - “Good” accretion rates may span 2 orders of magnitude, but usually centered close to actual
  - Envelope mass may be x2 (or more) too high

Summary II

Synthetic observations are a powerful and necessary tool for studying star formation.

- Observing turbulent fragmentation is hard
- .... Even with ALMA
- However, hope is not lost: ALMA + Compact Array

Summary III

Synthetic observations are a powerful and necessary tool for studying star formation.

- Cloud structure identified in ^{12}CO may not reflect real structure

- The problem is probably worse in regions with high-optical depth and strong clustering

- UV heating + chemistry helps by lowering optical depth, but may create artifical structure due to temperature and abundance varaition

- Structures in ^{13}CO are more likely to be “real”

Questions?