SPH Simulations of Clustered Star Formation with Dust and Gas Energetics

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Modeling Clustered Star Formation (i. e. Clump)

- Turbulence
- Hydrodynamics
- Gravity
- Magnetic Fields
- Dust Temperature
  - Radiative Heating from Stars
  - Gas-Dust collisional coupling
  - Dust Formation, Evolution, and Destruction - Composition
- Gas Temperature
  - Molecular Cooling Functions
  - Gas-Dust collisional coupling
  - Gas Formation, Evolution, and Destruction - Chemistry
- Stellar Feedback
  - Radiation
  - Stellar Winds & Outflows
  - Ionization

Early Simulations of Clustered Star Formation

- Isothermal - Klessen et al. (1998), Martel et al. (2006), + many others.
- Barotropic - Bate et al. (2003), more realistic Equation of State, but actual star formation feedback not included
- Radiative Transfer - Krumholz et al. (2007)
  - FLD - approximates treatment of dust (opaque), but in 3D
  - assumes $T_{Dust} = T_{Gas}$, true in dense regions only.
  - Focus on single massive star formation

Our Model…

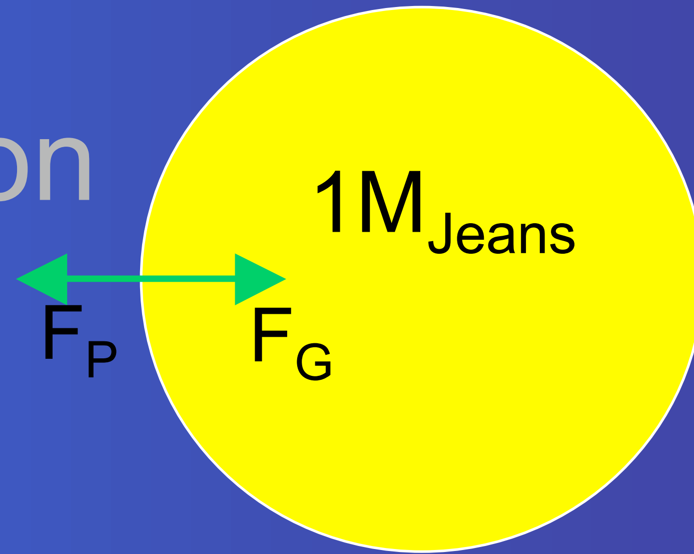
Cluster Formation - IMF

- SPH with Particle Splitting.
- More accurate treatment of dust properties and response to radiation field.
- Calculate Gas Temperature via Energy Balance.

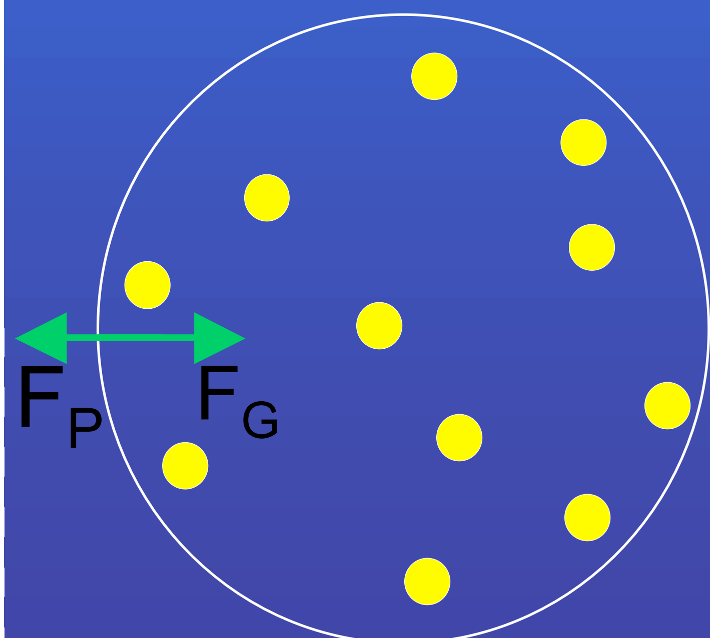
SPH with Particle Splitting

- Developed by Kitsionas & Whitworth (2002)
  - Applied to clustered star formation by Martel et al. (2006)
- Prevents artificial fragmentation

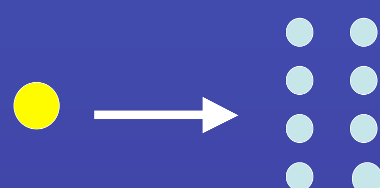
Artificial Fragmentation

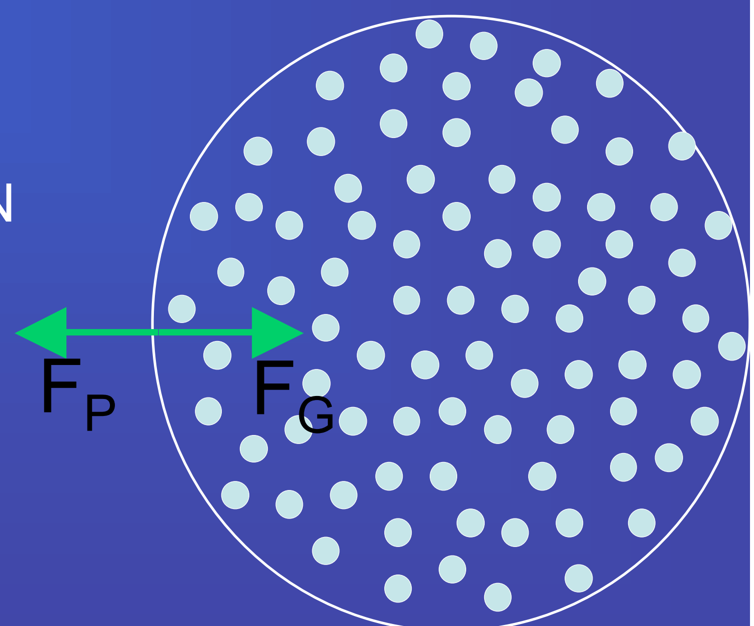


- Jeans Criterion - minimum number of particles needed to resolve Jeans Mass.
    - Bate & Burkert (1997)
    - Truelove et al. (1997)



- ARTIFICIAL FRAGMENTATION or Particle Splitting





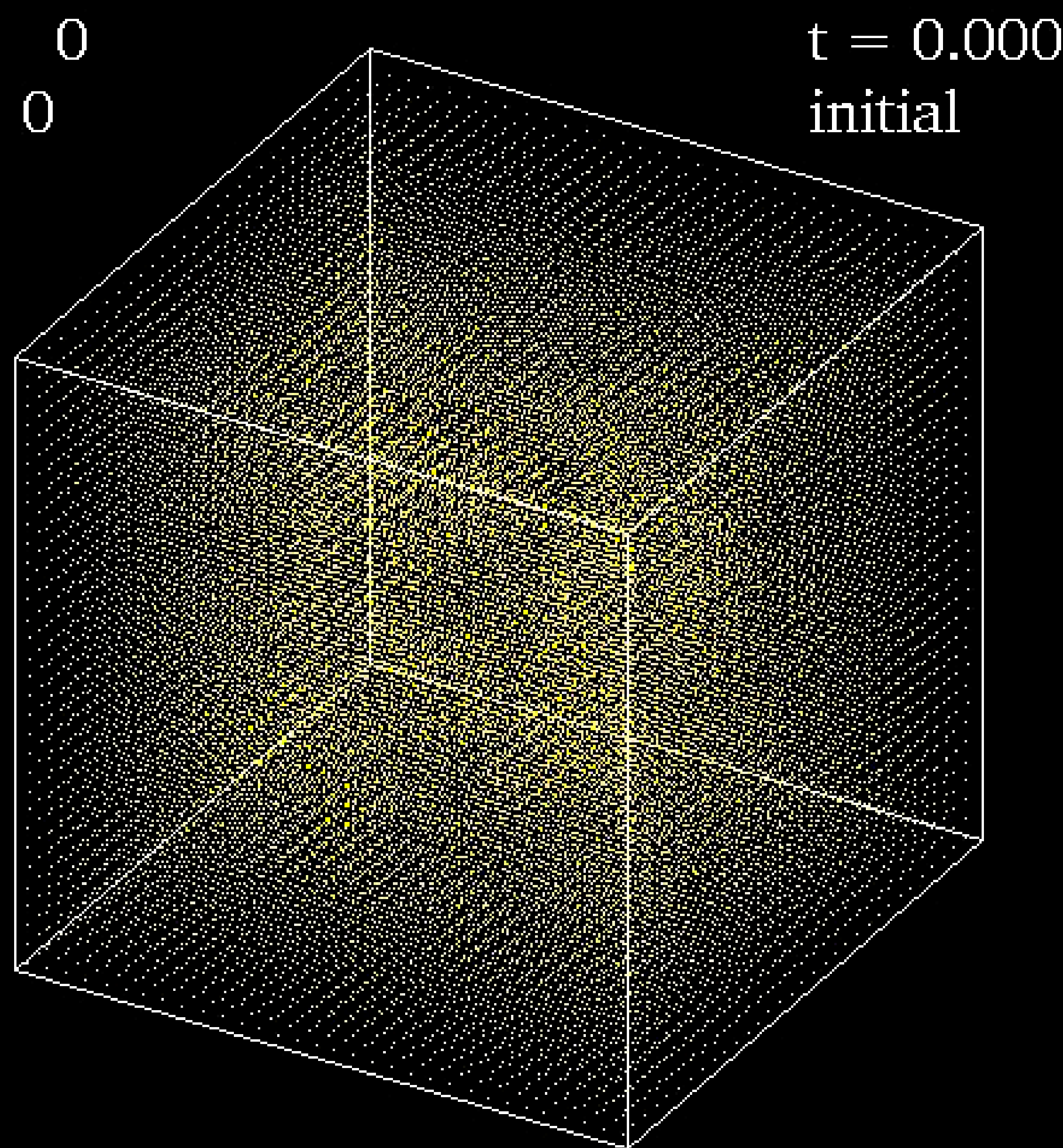
0th Generation

1st Generation

2nd Generation

Sink Particles

(initial) ~0.1Msun



Martel, Evans, & Shapiro 2006

- Closed system – periodic boundary conditions
- T=10K
- n_{avg} = 10^5
- total mass $3.2 \times 10^2\ M_\odot$
- length of box =0.38 pc
- time 2×10^5 yr

Modeling Cluster Formation

- $M = 1300\ M_{sun}$
- $L_{box} = .6$ pc
- $n_{initial} = 10^5\ cm^{-3}$
- $n_{sink} = 6 \times 10^8\ cm^{-3}$
- $N_{Gen} = 2$
- $N_{Particles} = 64^3 = 260{,}000$
- $N_{effective} = 256^3 = 17$ million

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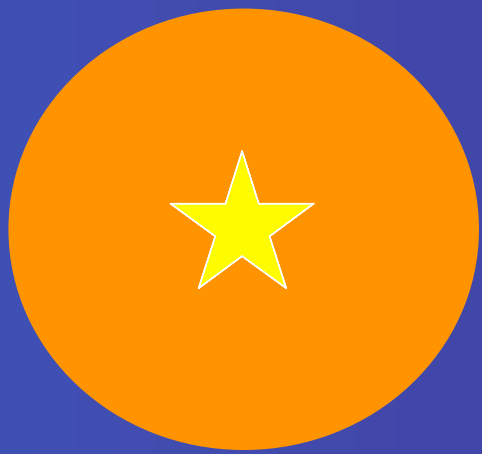
- Calculate Gas Temperature via Energy Balance.

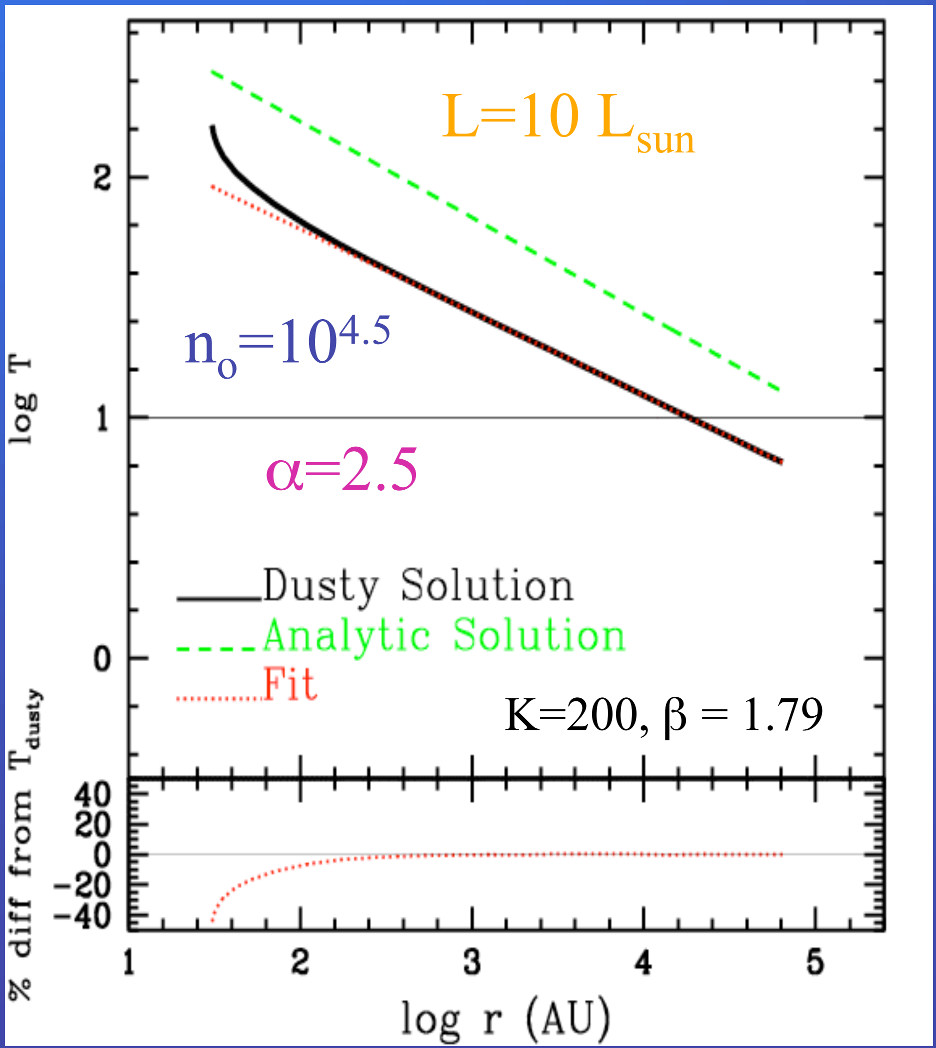
Dust Temperature

- Create a grid of models → Look up Table
  - Spherical, radiative transfer code, DUSTY (Ivezić, et al. 1997)
  - Dust properties: OH5 dust (Ossenkopf & Henning 1994)
  - Density profile - $n=n_o(r/1000AU)^{-\alpha}$
  - Range of Luminosities: 10^{-2} - 10^{6} L_{sun}
    - 10,000K black body
  - Dust temperature profile approximation



$$T_{dust}(r) = K\left(L/r^2\right)^{\frac{1}{4+\beta}}$$

Dust Temperature



$$n = n_o (r/1000AU)^{-\alpha}$$

$$T_{dust}(r) = K\left(L/r^2\right)^{\frac{1}{4+\beta}}$$

Our Model…

Cluster Formation - IMF

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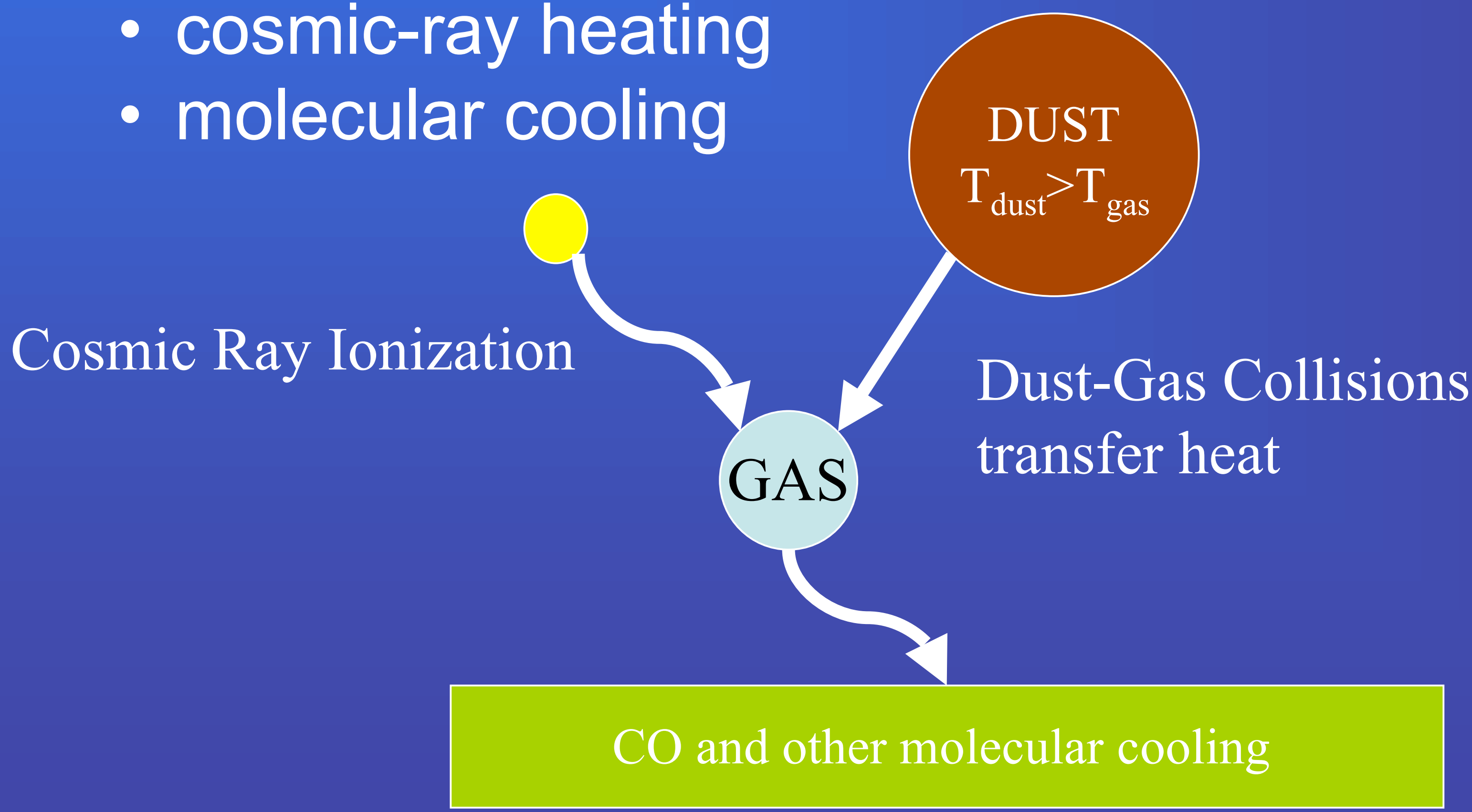
Gas Temperature

- Energy rate balance code

Doty & Neufeld 1997
Young et al. 2004

  - gas-dust collisional temperature coupling
  - cosmic-ray heating
  - molecular cooling



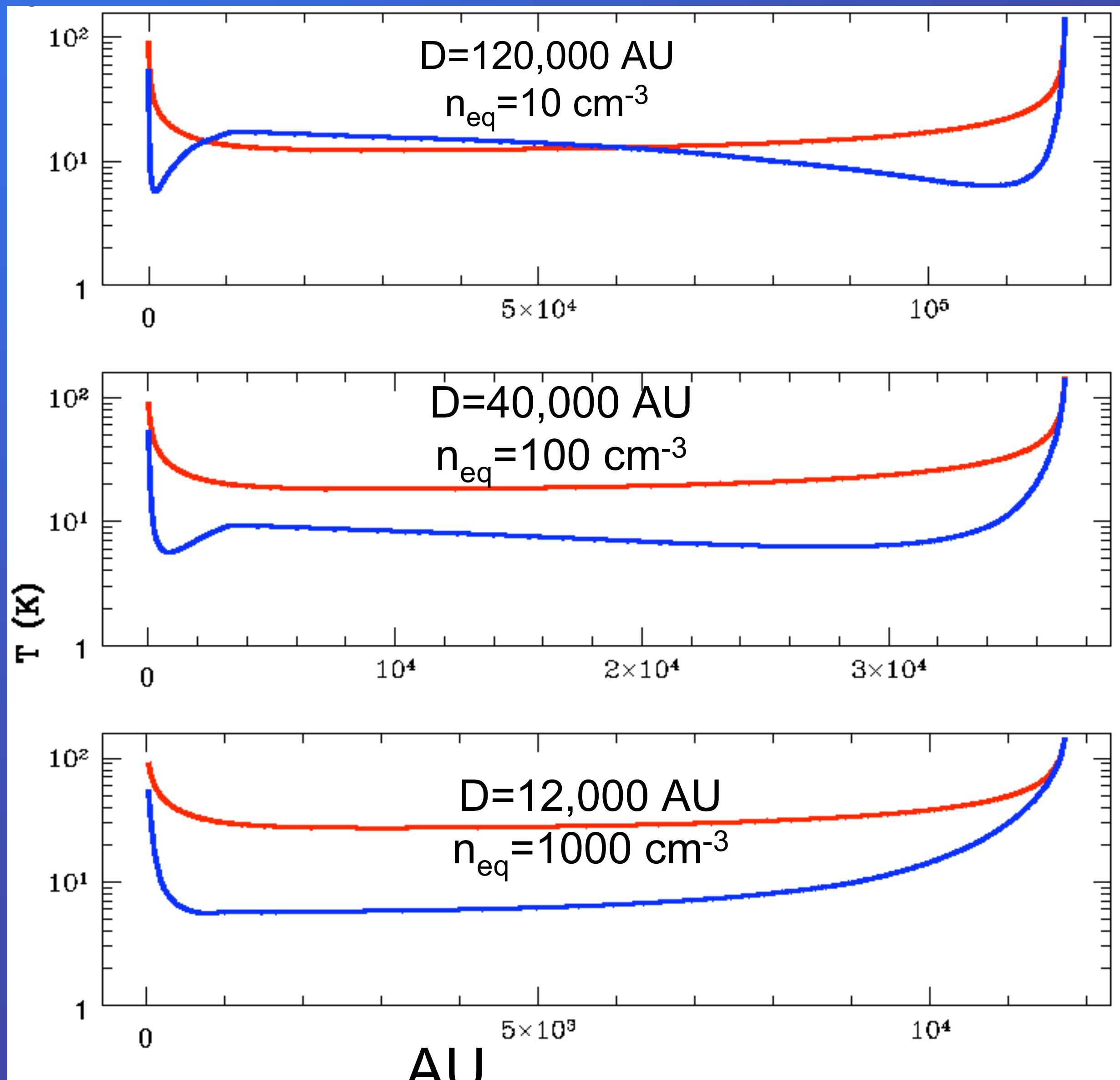
$$n = 10^3 (r/1000\,AU)^{-2}$$

T_{DUST}

T_{GAS}

$$n = 10^5 (r/1000\,AU)^{-2}$$

1 L_{sun}



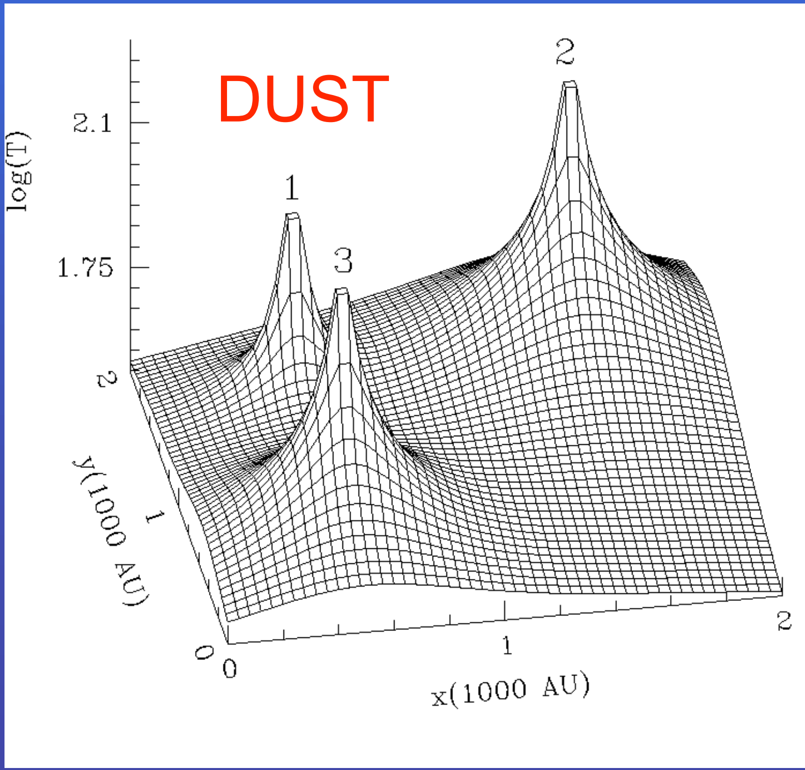
100 L_{sun}

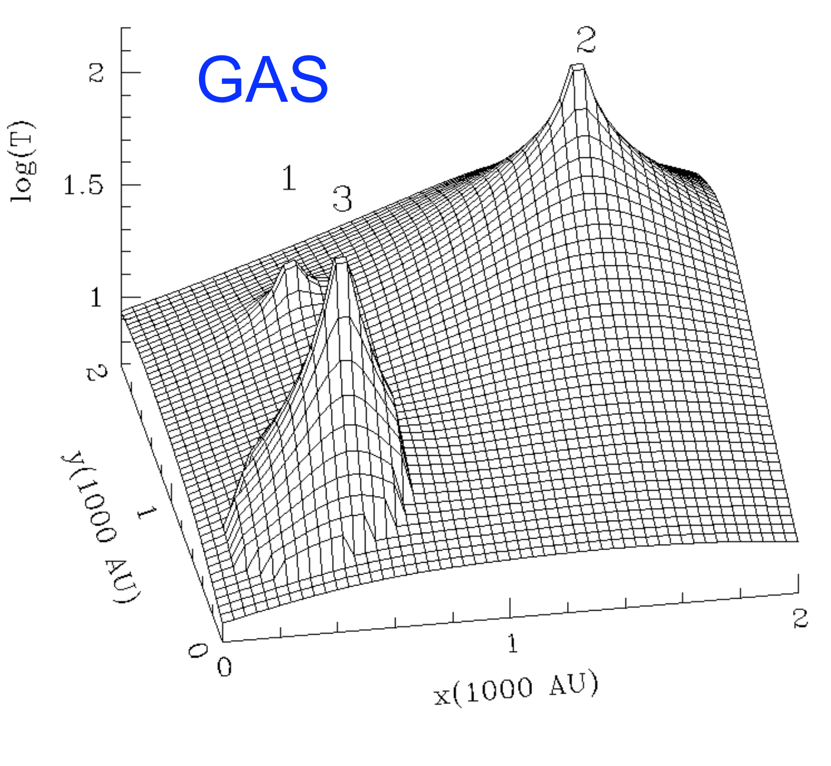
Three Sources

Source	Luminosity ($L_\odot$)	n_o(cm^{-3})	α	r_{out} (pc)
1	1	10^3	2	0.1
2	100	10^5	2	0.1
3	10	10^4	2	0.1

– T_{Gas} drops more quickly than T_{dust}

– Source 1 still visible





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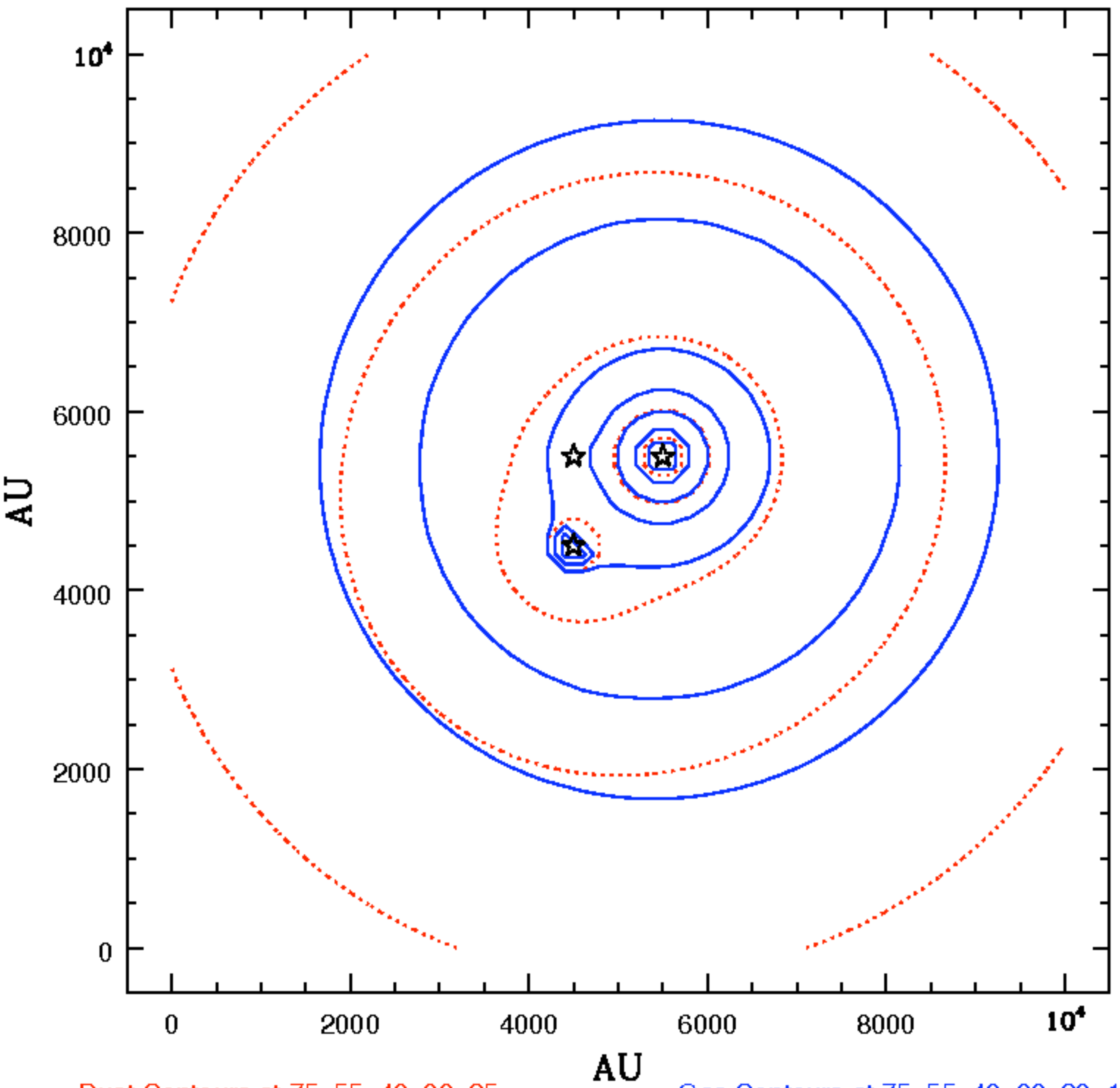
DUST

GAS



.....Dust Contours at 75, 55, 40, 30, 25

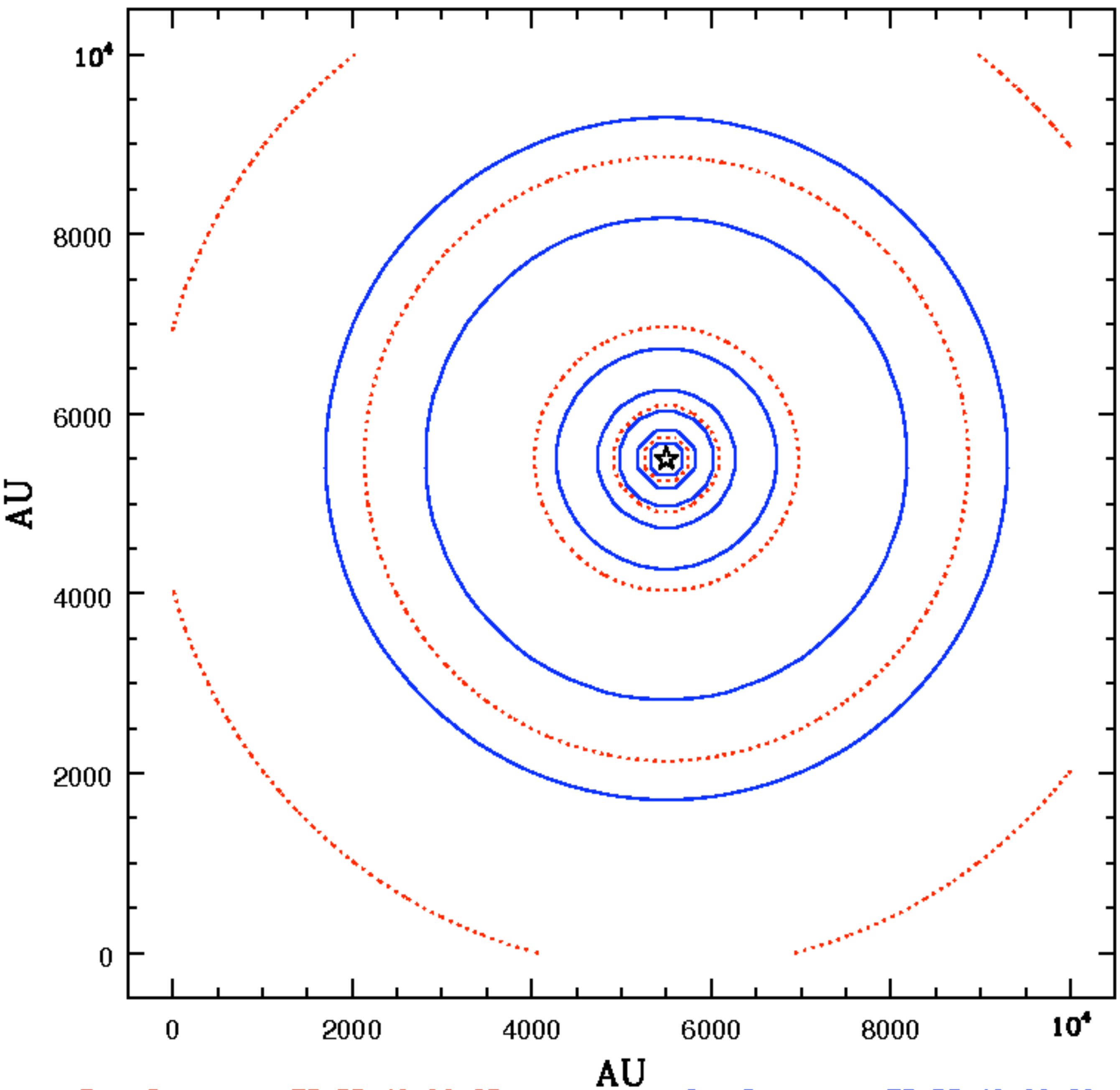
__Gas Contours at 75, 55, 40, 30, 20, 10, 8

1

130 L_{sun}

DUST

GAS



.....Dust Contours at 75, 55, 40, 30, 25

—Gas Contours at 75, 55, 40, 30, 20, 10, 8

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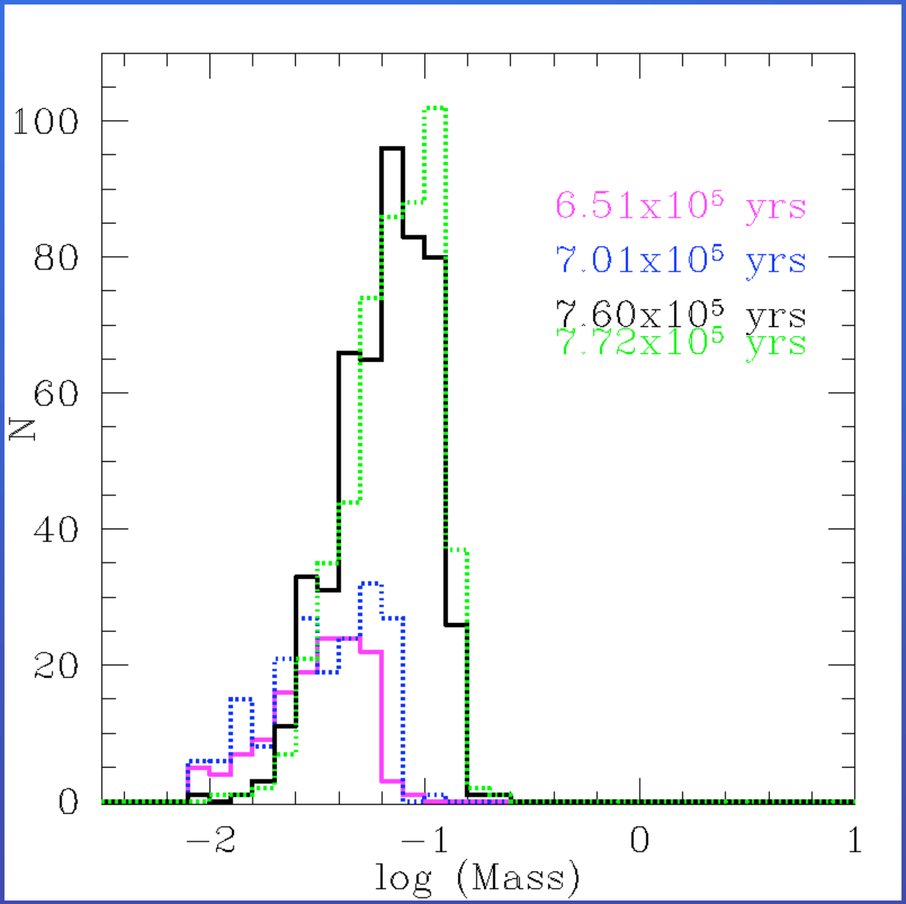
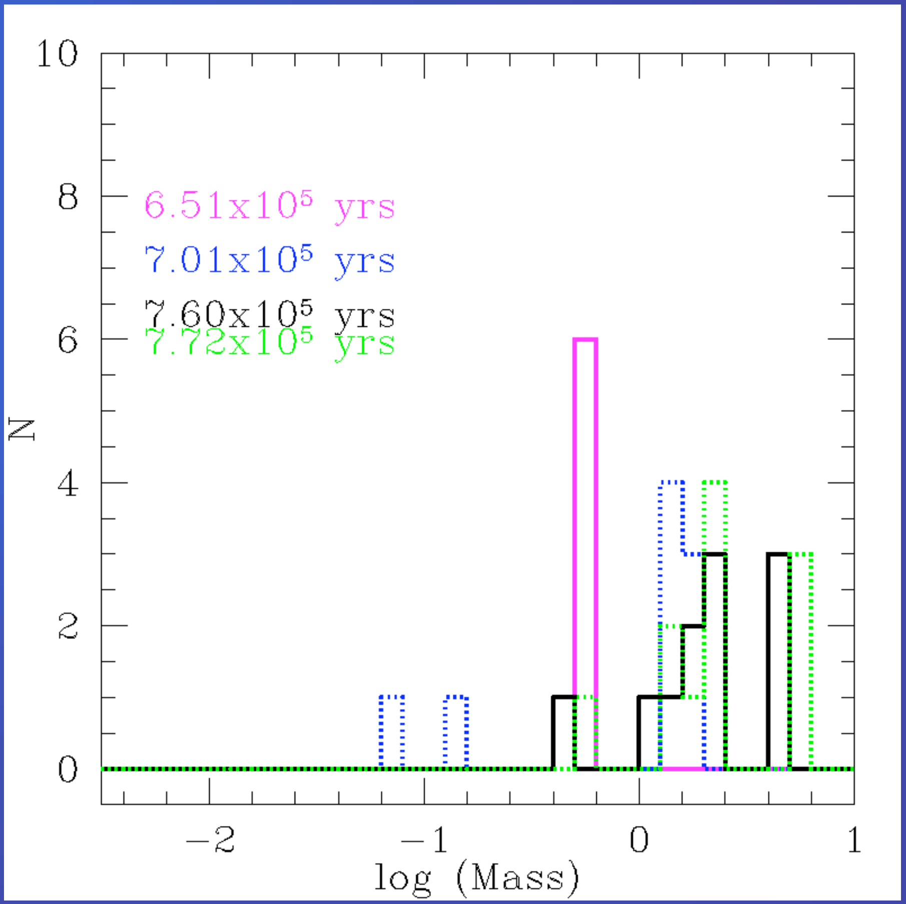
Preliminary Results

Isothermal $N_{Gen} = 1$ $T_{dust} = T_{gas}$





Same density resolution, smaller mass/size

$M=162\ M_{sun}$, $L_{box} = 0.3$ pc

Conclusion

- Using three methods
  - SPH with particle splitting
  - Dust Energetics
  - Gas Energetics
- Still to come
  - Put everything together.

We can get one step closer to understanding clustered star formation.