MSc Astrophysics Research Project

Numerical Modeling of Internal Radiative Feedback from Accreting Protostars in Moving-Mesh Code AREPO

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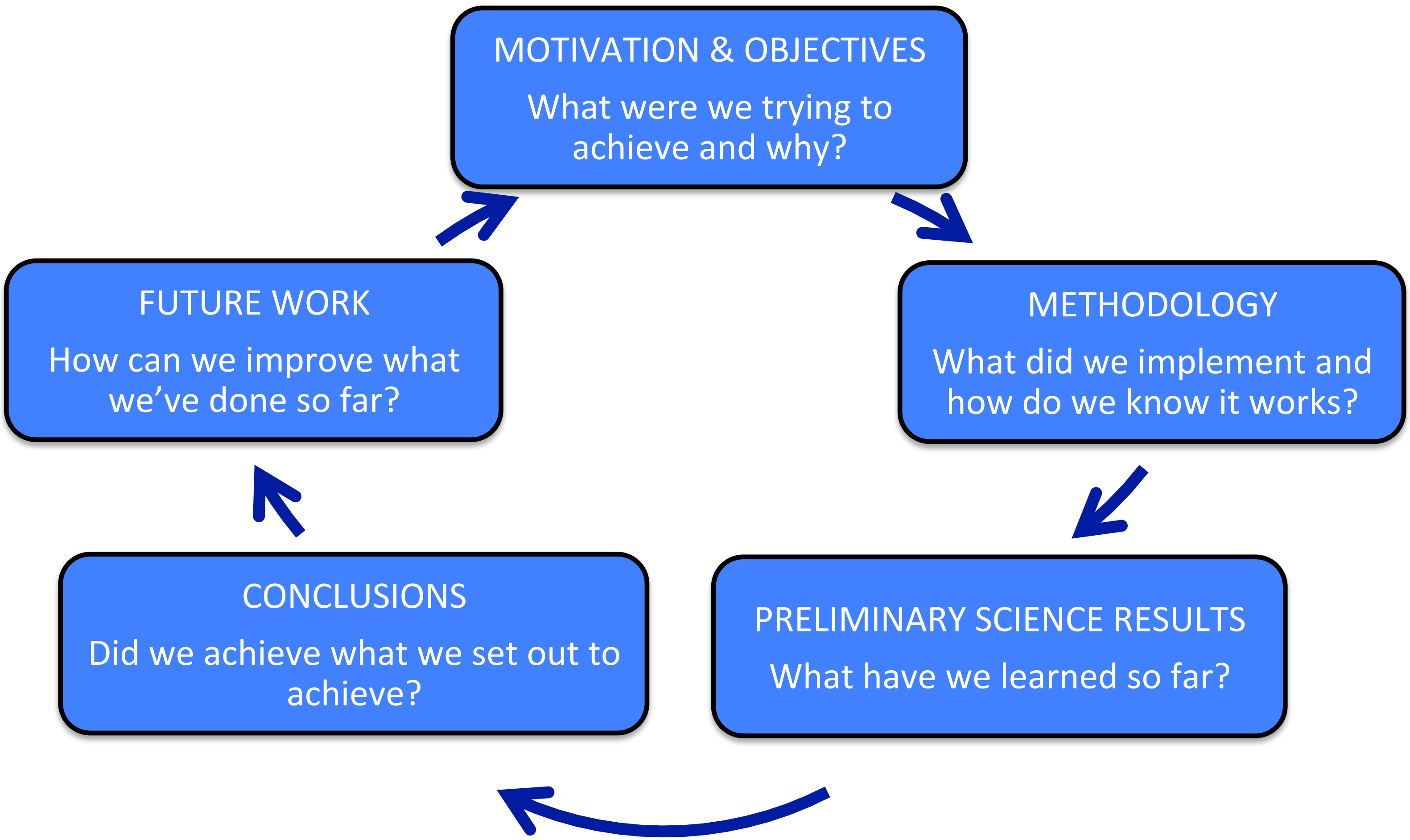
Presentation Structure

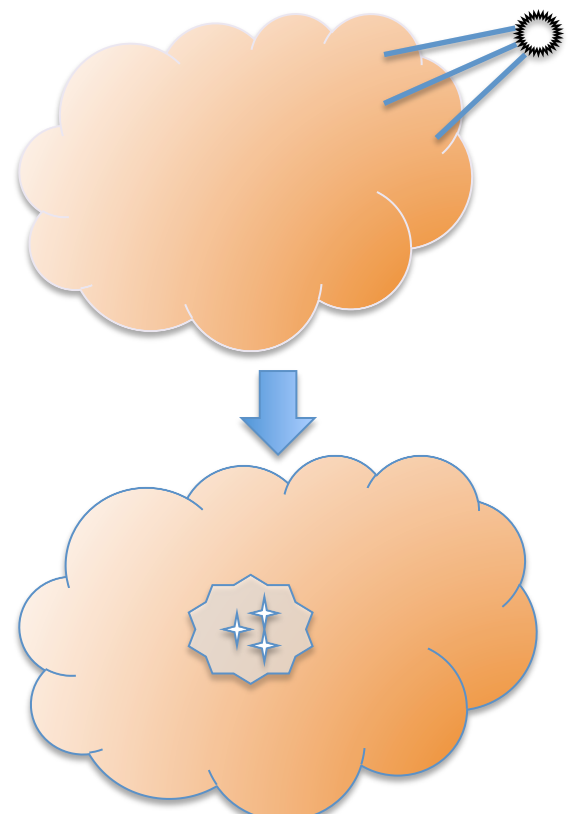


Project Motivation I

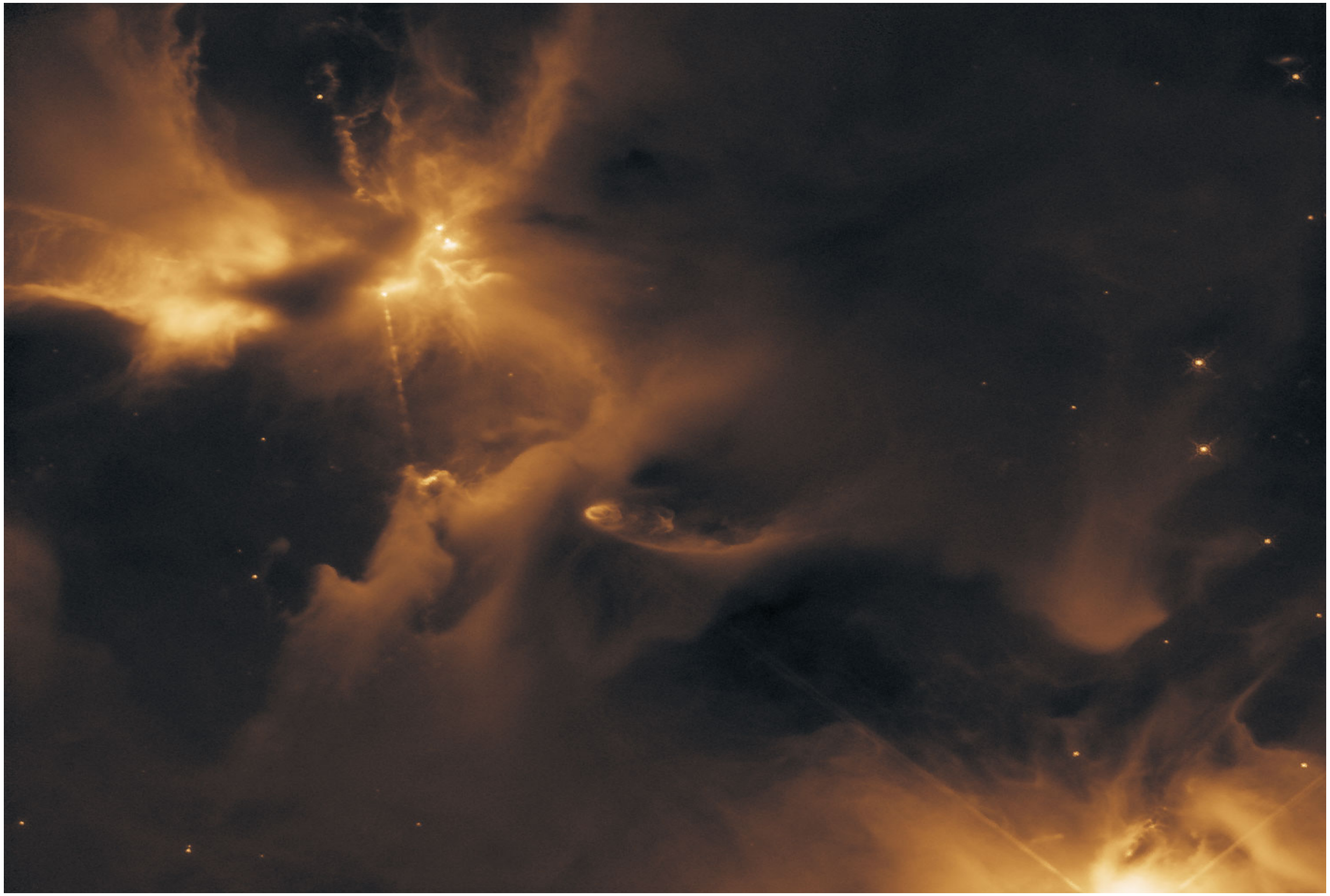
- Feedback is an essential ingredient of star formation models that manage to reproduce observed stellar populations (Dale, 2015)

- Most models of the impact of radiative feedback on molecular cloud evolution based on imposed or ‘external’ sources, typically OB *stars*

- A more sophisticated model would feature ‘internal’ feedback from an array of stellar objects generated by the model itself and evolving in situ



Project Motivation I



HST image of young stellar objects in the Orion B molecular cloud complex (https://apod.nasa.gov)

Project Motivation II

- Moving-mesh hydrodynamic codes (AREPO) offer a 'best of both worlds' numerical modelling approach compared to traditional particle or grid codes...
- ... yet only limited feedback modelling has been performed using AREPO, and no 'internal' feedback modelling.

Project Objectives

1. Address the key research question:
   - Can we implement an effective <u>internal</u> radiative feedback model in <u>AREPO</u> within the constraints set by the existing coding architecture?
   - How do we demonstrate the validity of the model/algorithm?
2. Conduct <u>preliminary</u> science investigations
   - First phase of a wider research plan

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MOTIVATION & OBJECTIVES
What were we trying to achieve and why?

METHODOLOGY
What did we implement and how do we know it works?

PRELIMINARY SCIENCE RESULTS
What have we learned so far?

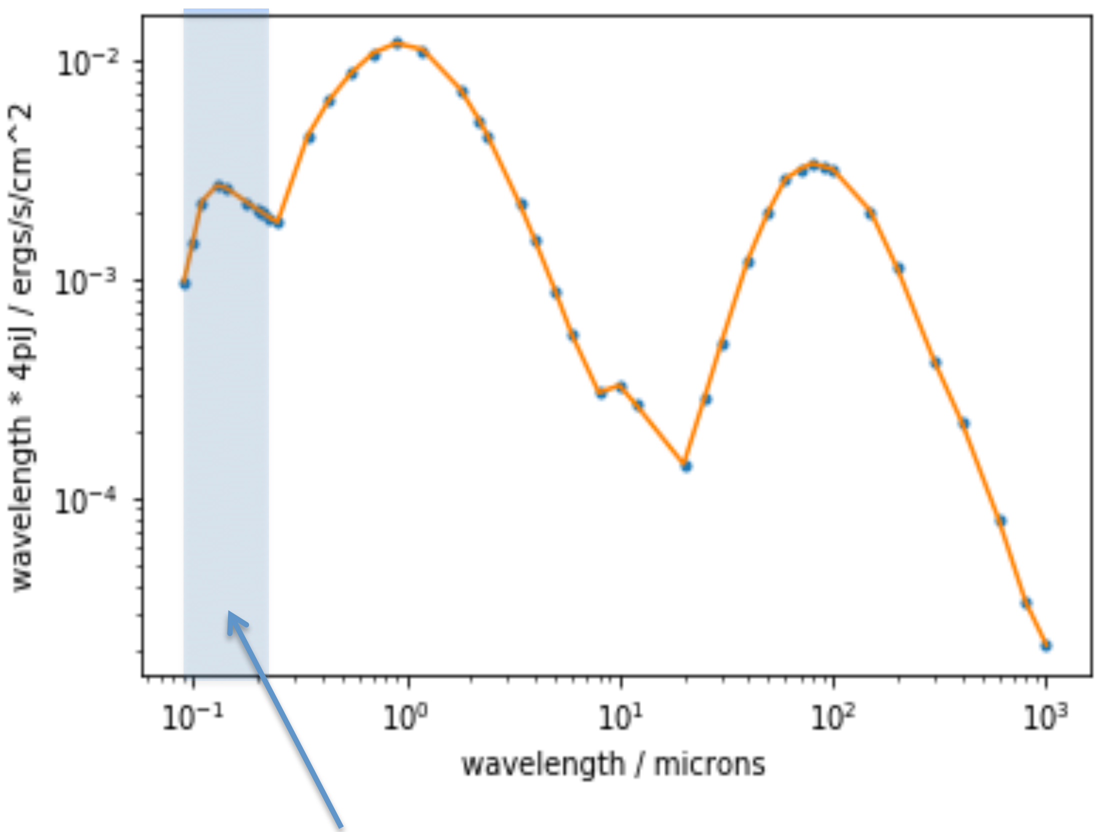
CONCLUSIONS
Did we achieve what we set out to achieve?

FUTURE WORK
How can we improve what we've done so far?

Methodology: Base Case

- Spherical overdensity of 200,000 cells with radius ≈ 1.6 pc
- Mass 1,000 $M_\odot$ at 10 K: Jean’s radius ≈ 48 pc
- Mathis (1983) ambient interstellar radiation field (‘ISRF’)
  - Modelled as acting isotropically around any particle
- ‘TreeCol’ radiative transfer algorithm (Clark et al. 2012)
  - Sphere of 48 column density ‘pixels’ around each cell
  - Attenuation of isotropic ISRF from mean column density
- ‘Sink’ particles form at $\rho > 4\times10^{-17}$g cm-3
  - Have mass and position only once formed

Mathis ISRF & G_0

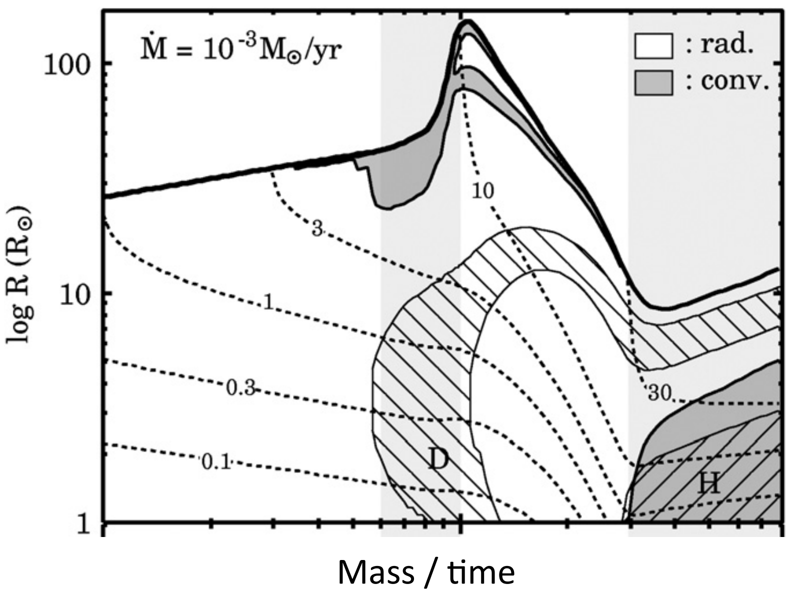


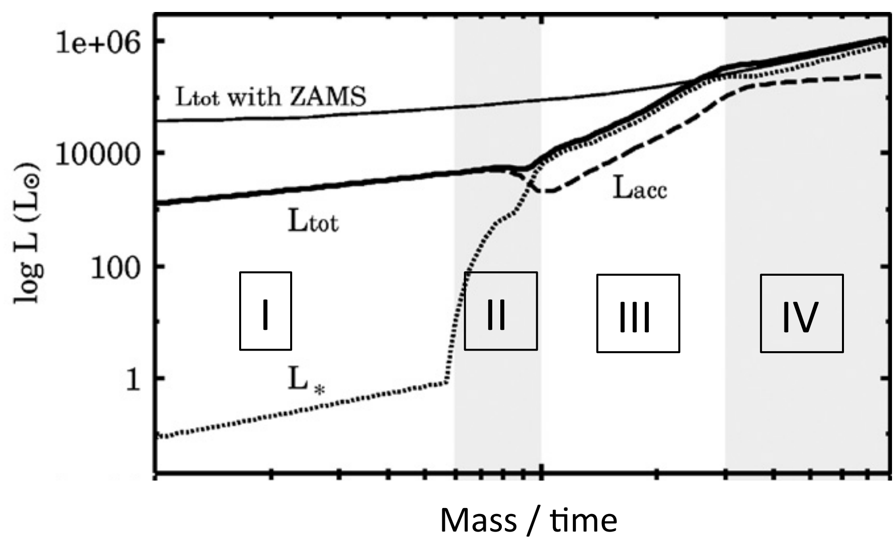
$$G_0 = \frac{u(6-13.6\ \mathrm{eV})}{5.29\times10^{-14}\ \mathrm{erg\ cm^{-3}}} = 1.15$$

Methodology: Feedback Case

- Sink particles assumed to be accreting protostars and given appropriate luminosity

Evolution of Accreting Protostars





Ref: Hosokawa & Omukai (2009)

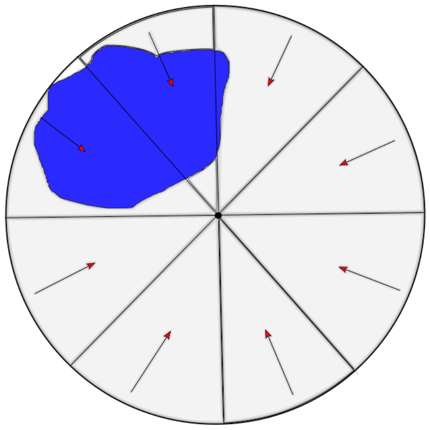
I: Adiabatic accretion
II: Swelling
III: Kelvin-Helmholtz contraction
IV: Main sequence

Methodology: Feedback Case

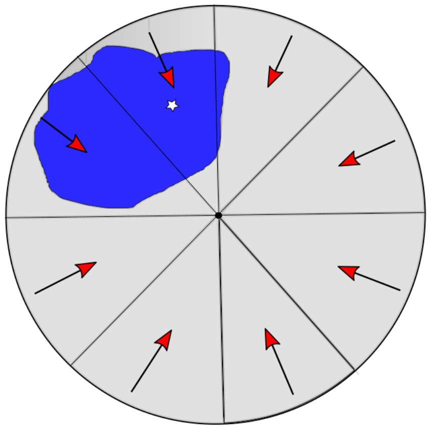
- Sink particles assumed to be accreting protostars and given appropriate luminosity
- Isotropic radiation field maintained but with specific intensity determined by G_0 amplification factor
- Directionality of sources dealt with through mean column density and associated attenuation in TreeCol

Radiative Transfer Algorithms

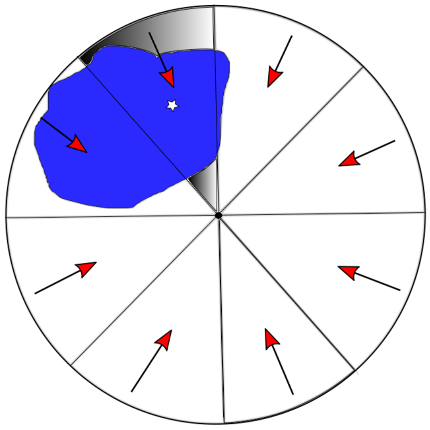
2D analogue of 3D TreeCol 48 pixel spheres



Base Case:
Isotropic Mathis ISRF only; mean attenuation calculated from equally weighted column density pixels

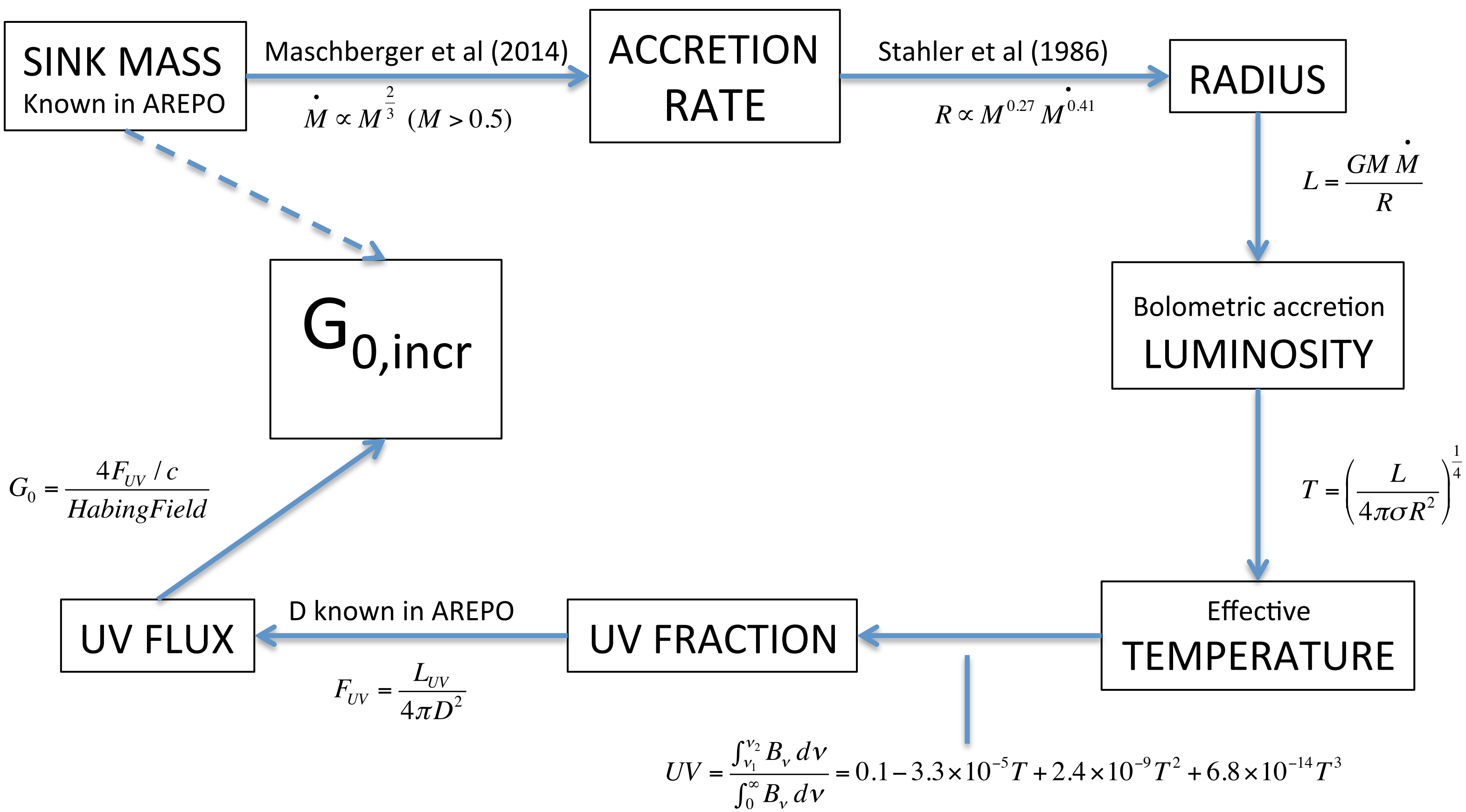


Isotropic Model:
G_0 enhanced by contribution from sink; but mean attenuation still calculated from equally weighted pixels

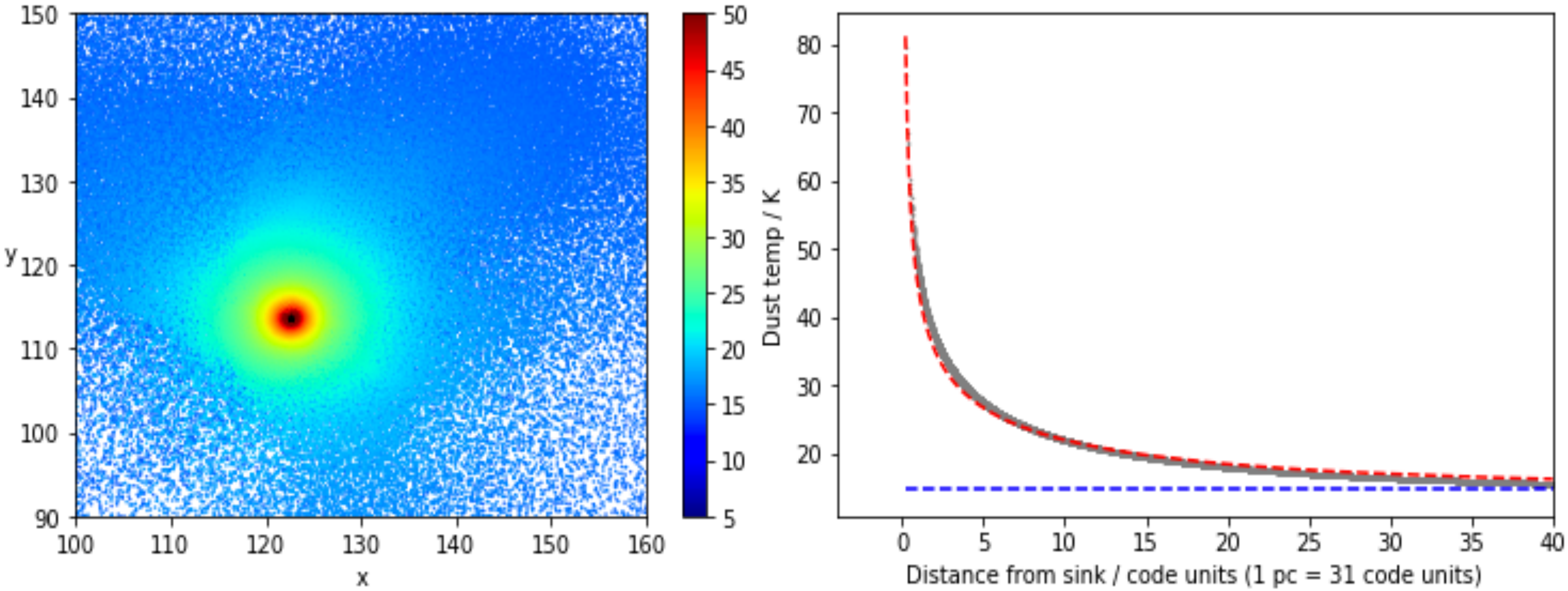


Anisotropic Model:
G_0 enhanced by contribution from sink; mean attenuation now calculated from pixels weighted according to G_0 contribution

Incremental G_0 Algorithm



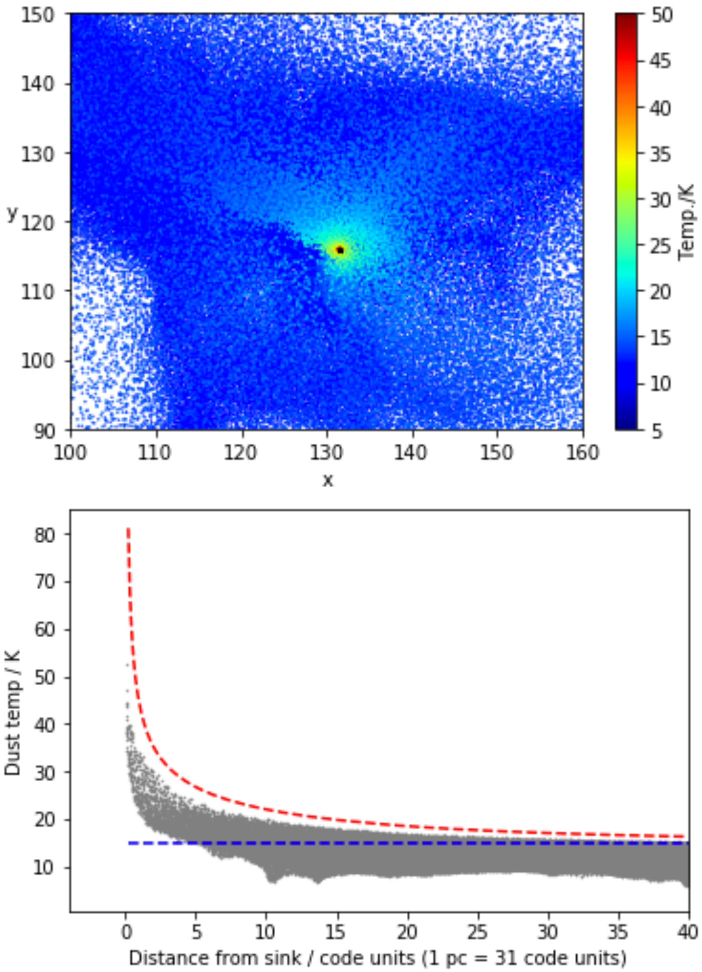
Single Sink Dust Temperature



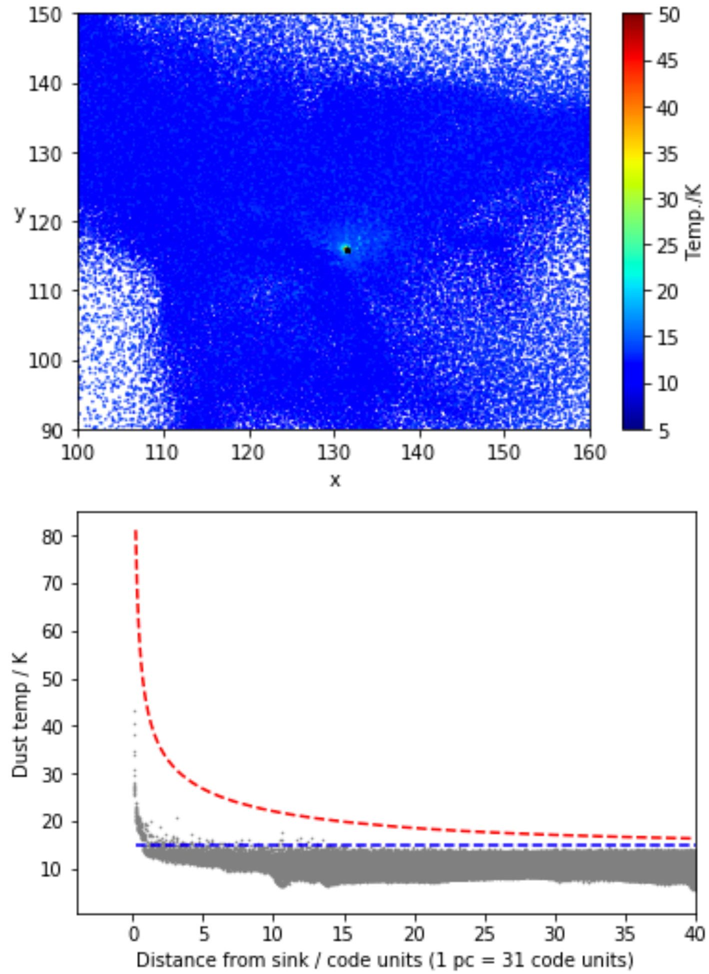
Unattenuated isotropic feedback from 5 $M_{\odot}$ protostar

Single Sink Dust Temperature

Attenuated isotropic feedback



Attenuated anisotropic feedback



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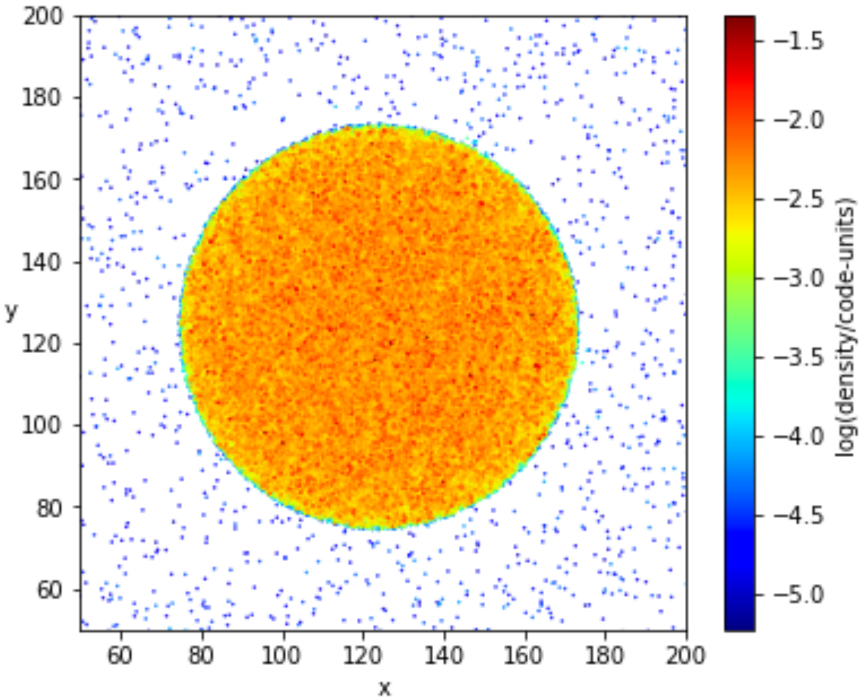
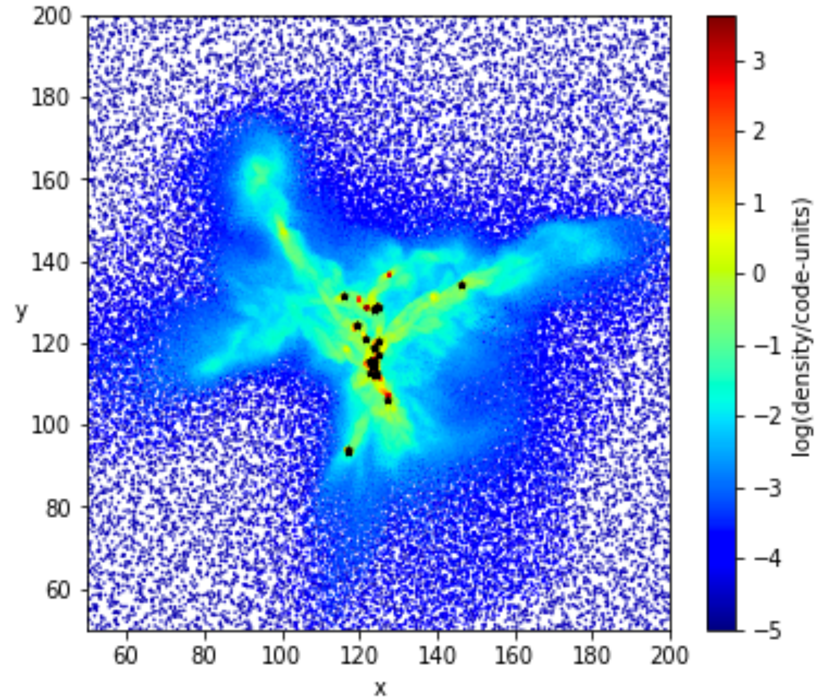
Preliminary Results: Density

Density Evolution after ~ 1.1 Myrs



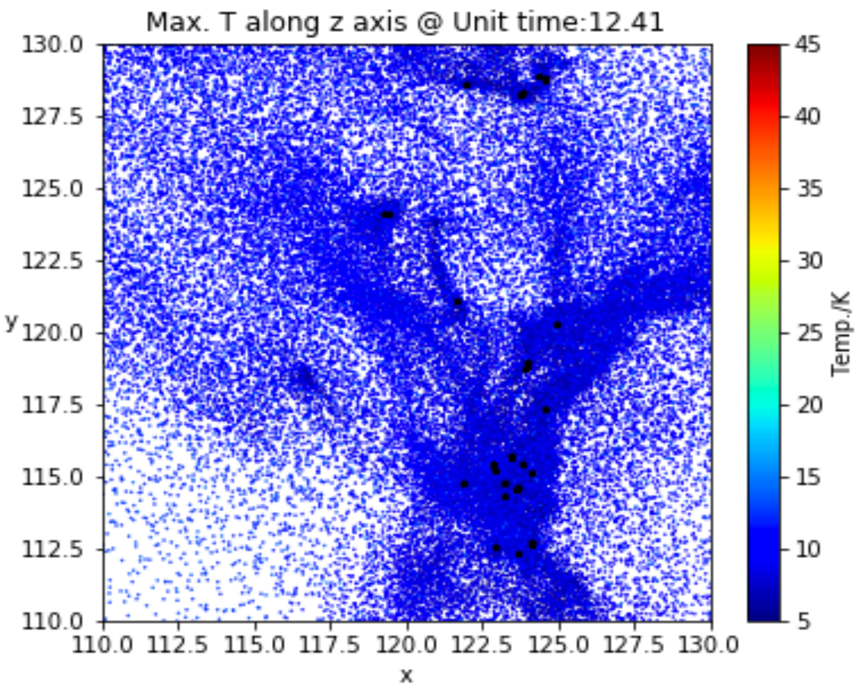


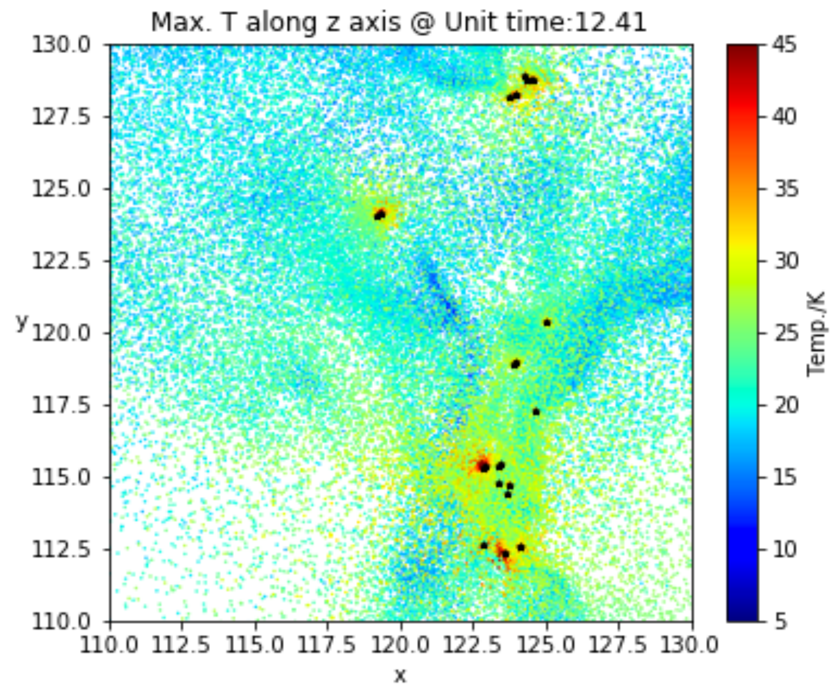
Preliminary Results: Dust Temperature

Dust Temperature Evolution after ~ 1.1 Myrs

No feedback

Isotropic feedback

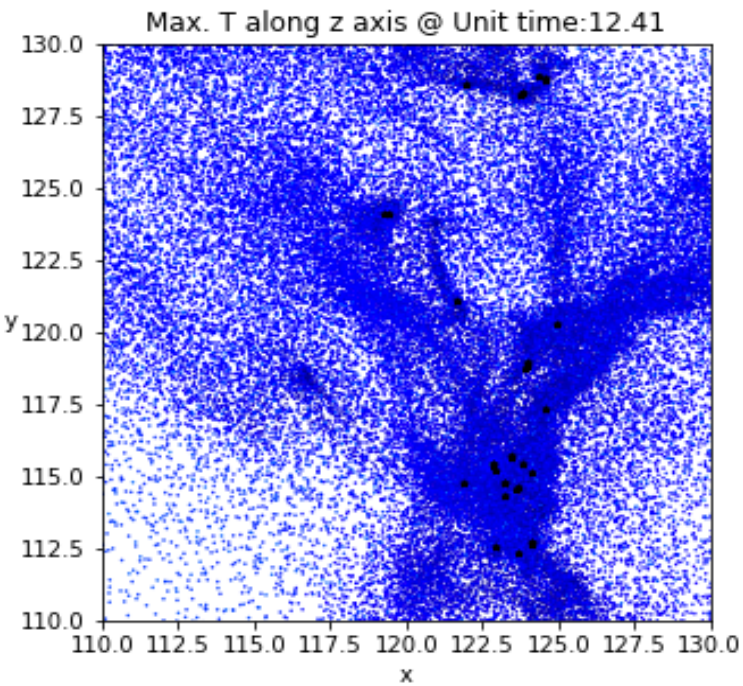




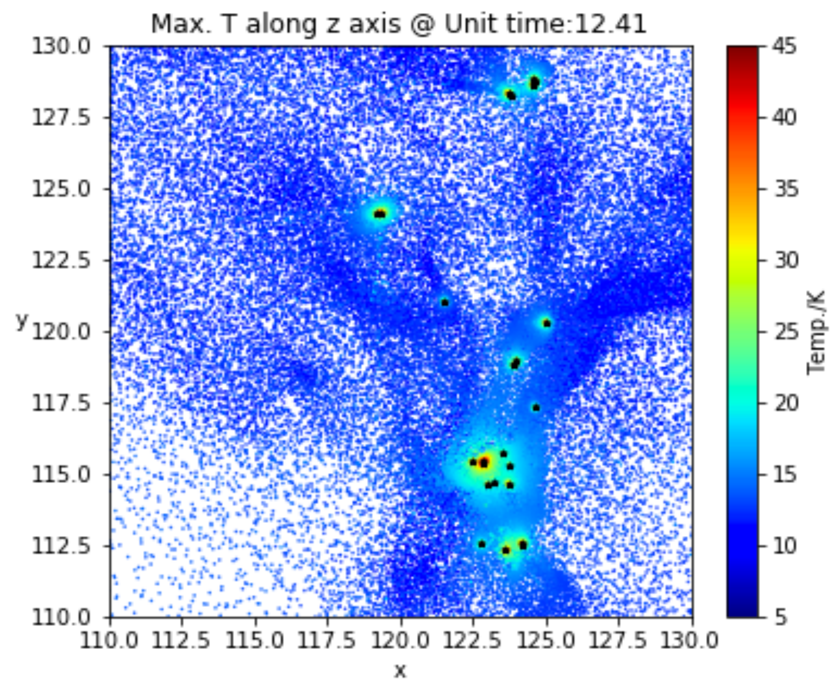
Preliminary Results: Dust Temperature

Dust Temperature Evolution after ~ 1.1 Myrs

No feedback

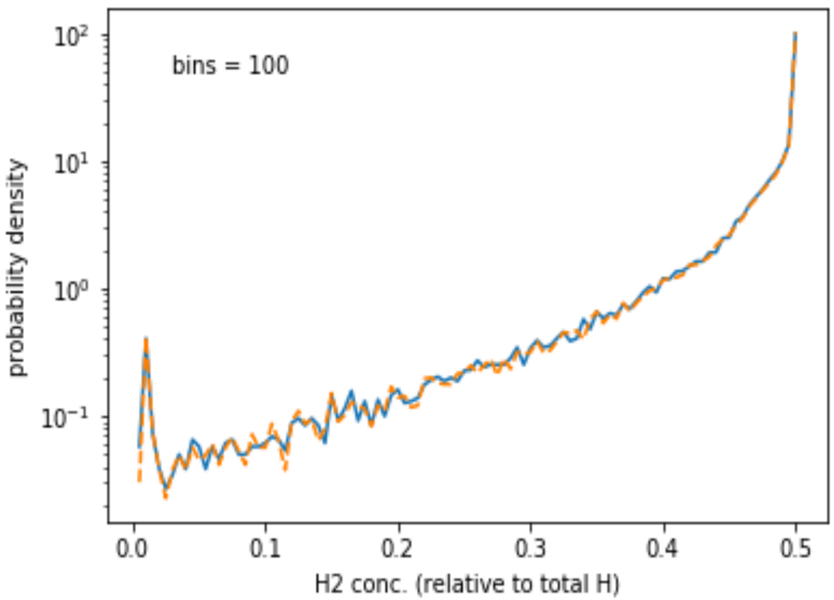


Anisotropic feedback

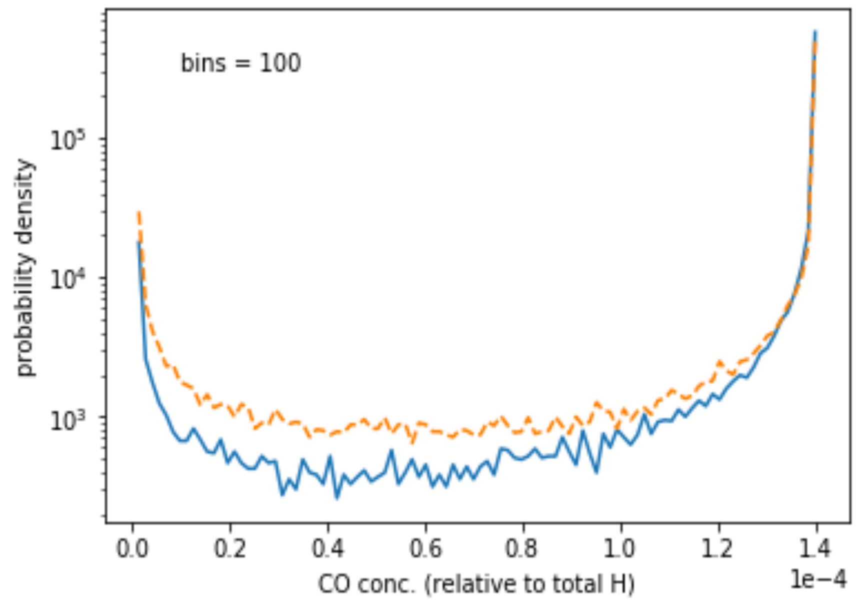


Preliminary Results: Chemistry

H2 concentration



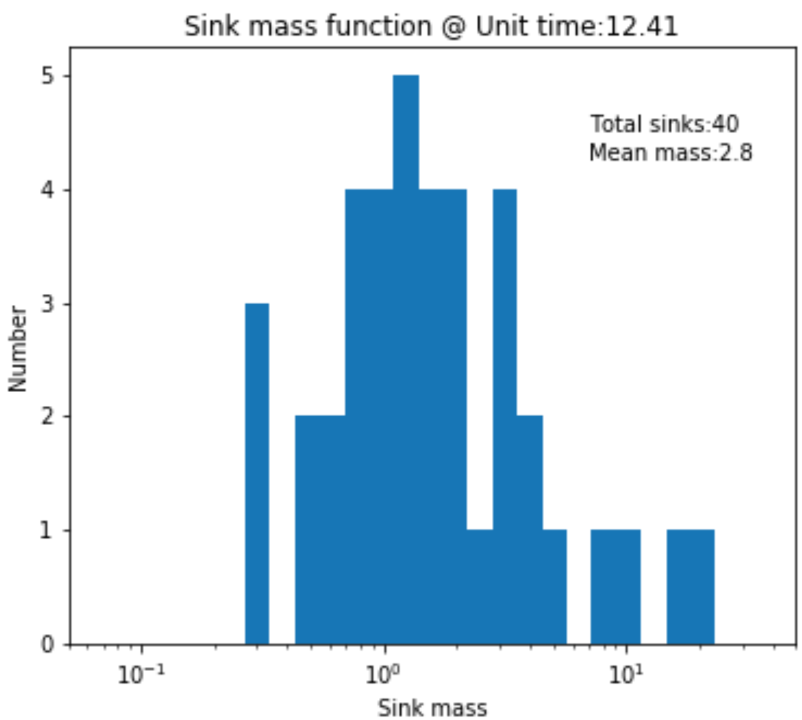
CO concentration

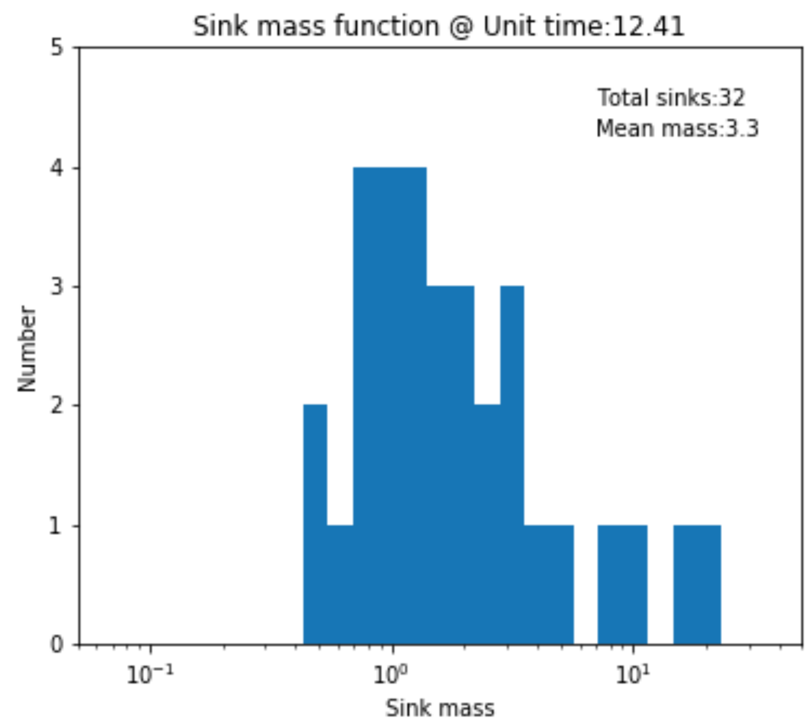


Mean = 0.466 (with and without feedback)

Mean = 1.30×10-4 (without feedback - blue)
Mean = 1.22×10-4 (with feedback – orange dash)

Preliminary Results: Mass Function





No feedback:
Total sinks = 40
Mean mass = 2.8 $M_\odot$

With feedback:
Total sinks = 32
Mean mass = 3.3 $M_\odot$

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General Conclusions

1. An effective anisotropic feedback algorithm can be implemented within existing AREPO coding architecture – key research question.

2. Comparison with analytical calculation of dust temperature suggests the feedback algorithm gives reliable results

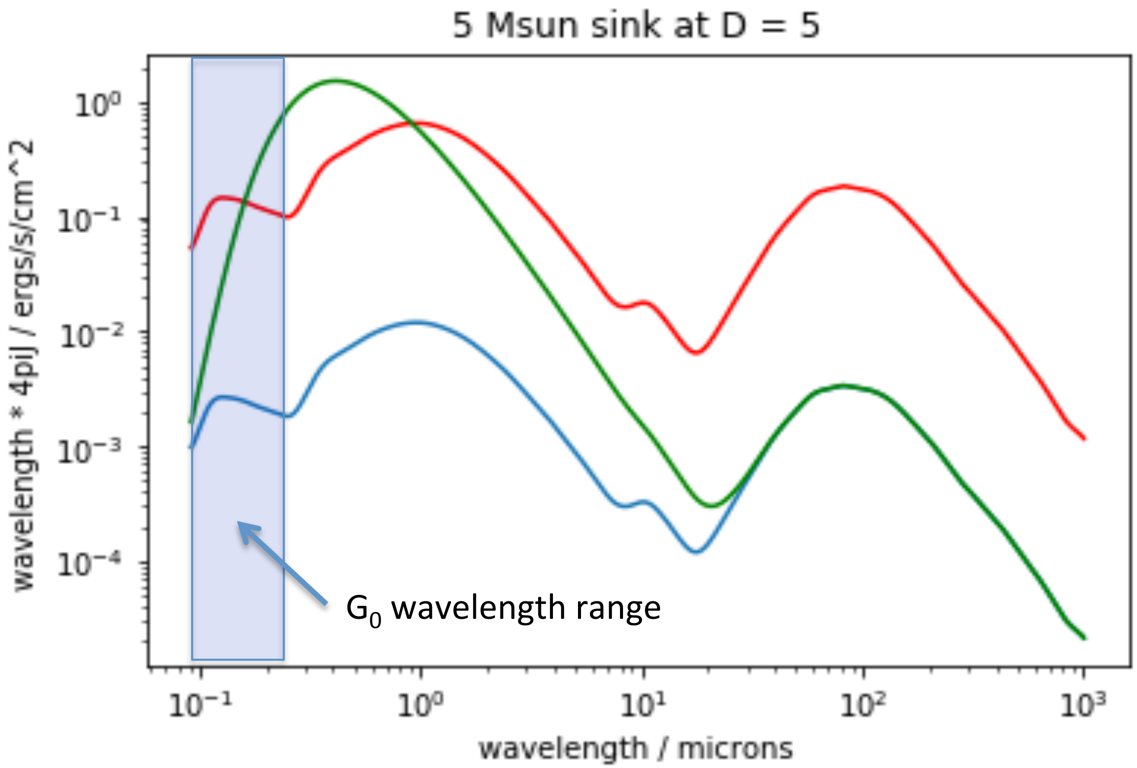
3. Preliminary science results (secondary objective) indicate reduction in star formation efficiency results from radiative feedback – confirming previous work

4. More rigorous science results and novel insights will require further model sophistication in a second phase of the project.

Suggested Further Work: Phase II

1. Improve intensity enhancement model across the spectrum

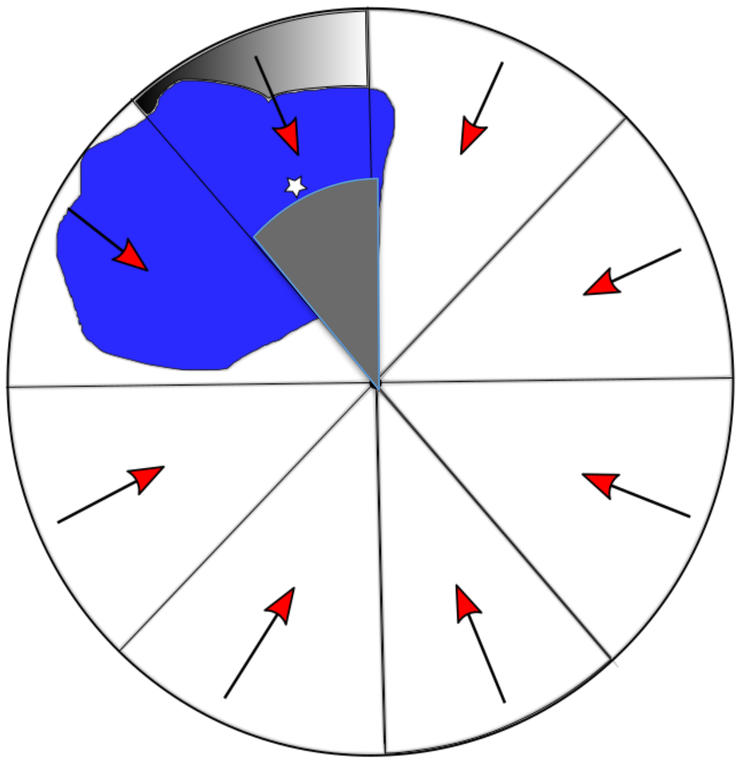
Further Work: Incremental Intensity



Suggested Further Work: Phase II

1. Improve intensity enhancement model across the spectrum
2. Limit column density used for radiative transfer to sink location

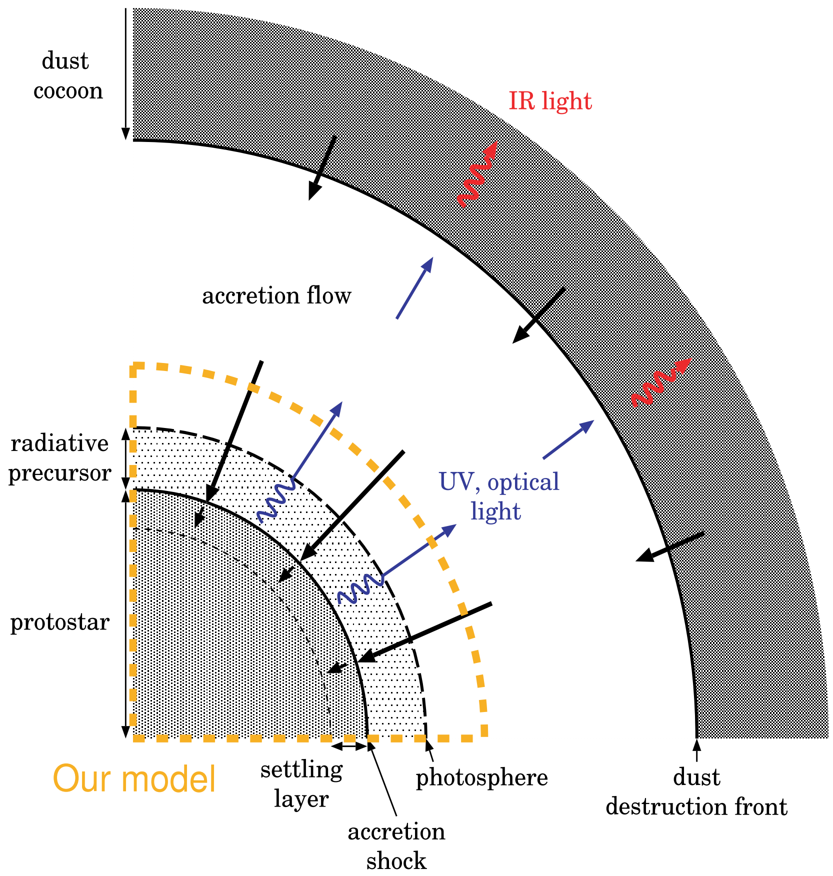
Further Work: Column Density



Suggested Further Work: Phase II

1. Improve intensity enhancement model across the spectrum
2. Limit column density used for radiative transfer to sink location
3. Increase the sophistication of the accretion luminosity model
    - Spherical v disc accretion
    - Location of photosphere
    - Effect of dust cocoon

Accretion Luminosity



Ref: Hosokawa & Omukai (2009)

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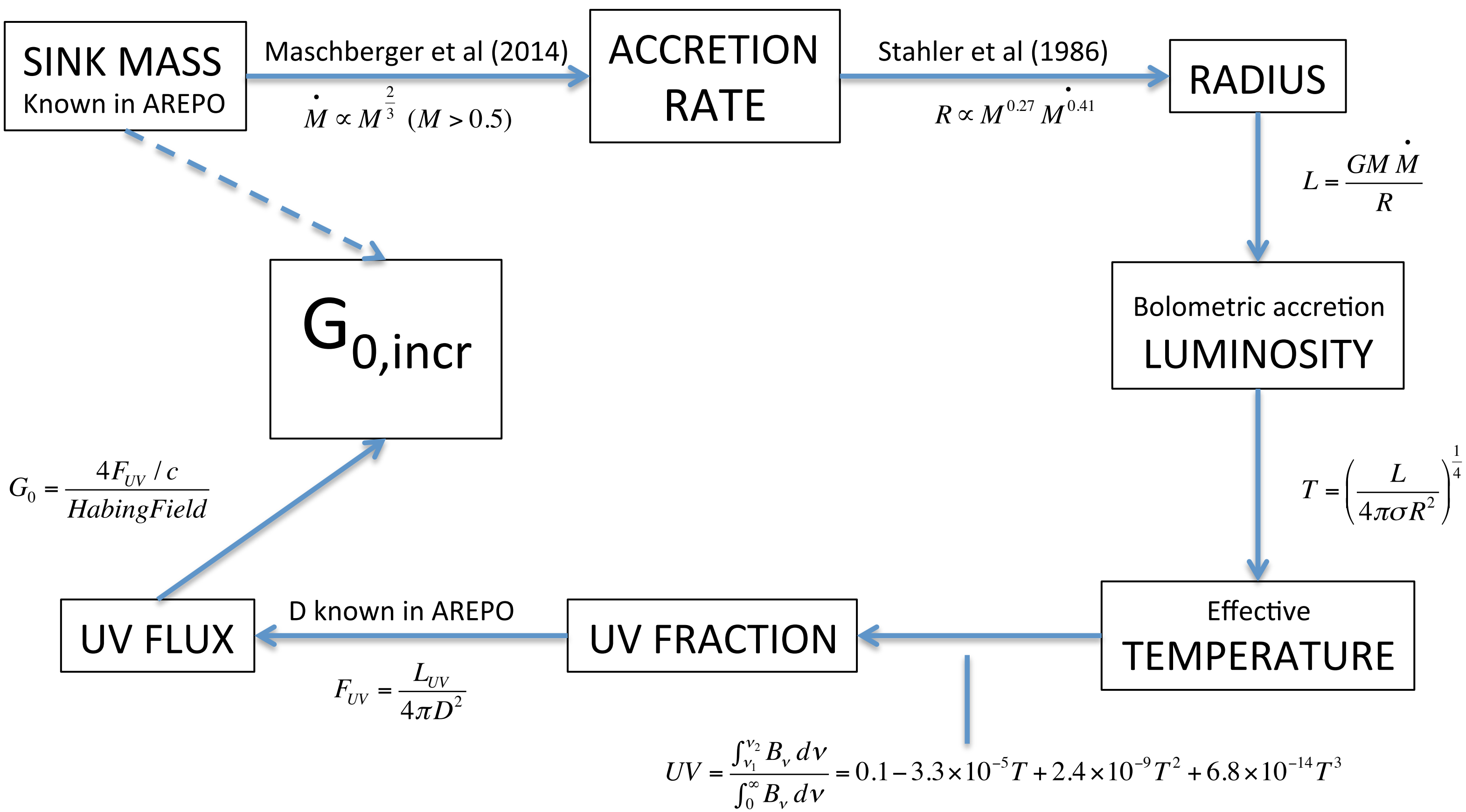
    - Effect of dust cocoon
4. Utilise intrinsic accretion rate

Incremental G_0 Algorithm



Suggested Further Work: Phase II

1. Improve intensity enhancement model across the spectrum
2. Limit column density used for radiative transfer to sink location
3. Utilise intrinsic accretion rate
4. Increase the sophistication of the accretion luminosity model
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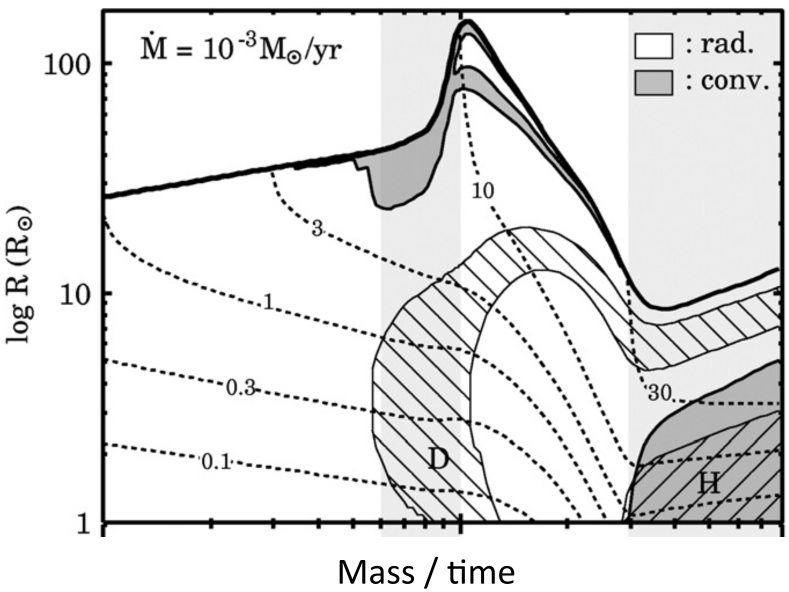
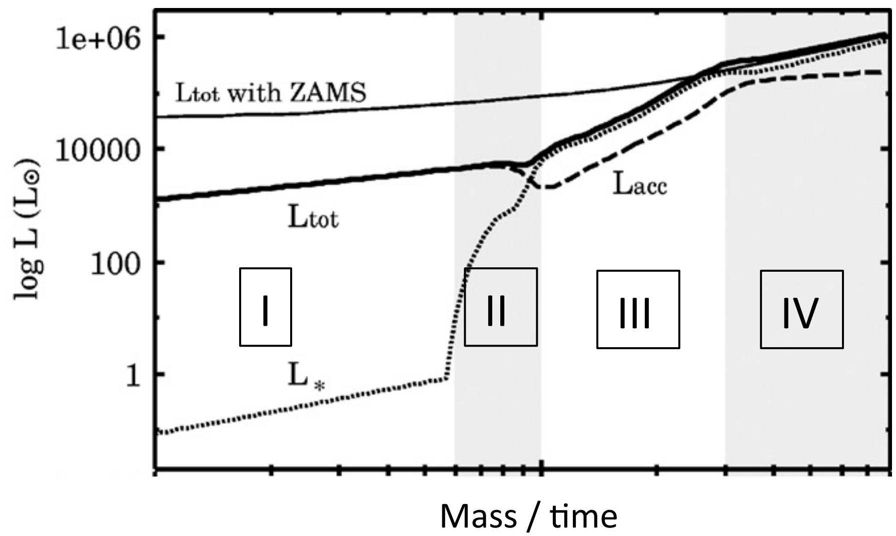
   - Location of photosphere
   - Effect of dust cocoon
5. Track protostellar evolution and calculate luminosity accordingly

Evolution of Accreting Protostars





Ref: Hosokawa & Omukai (2009)

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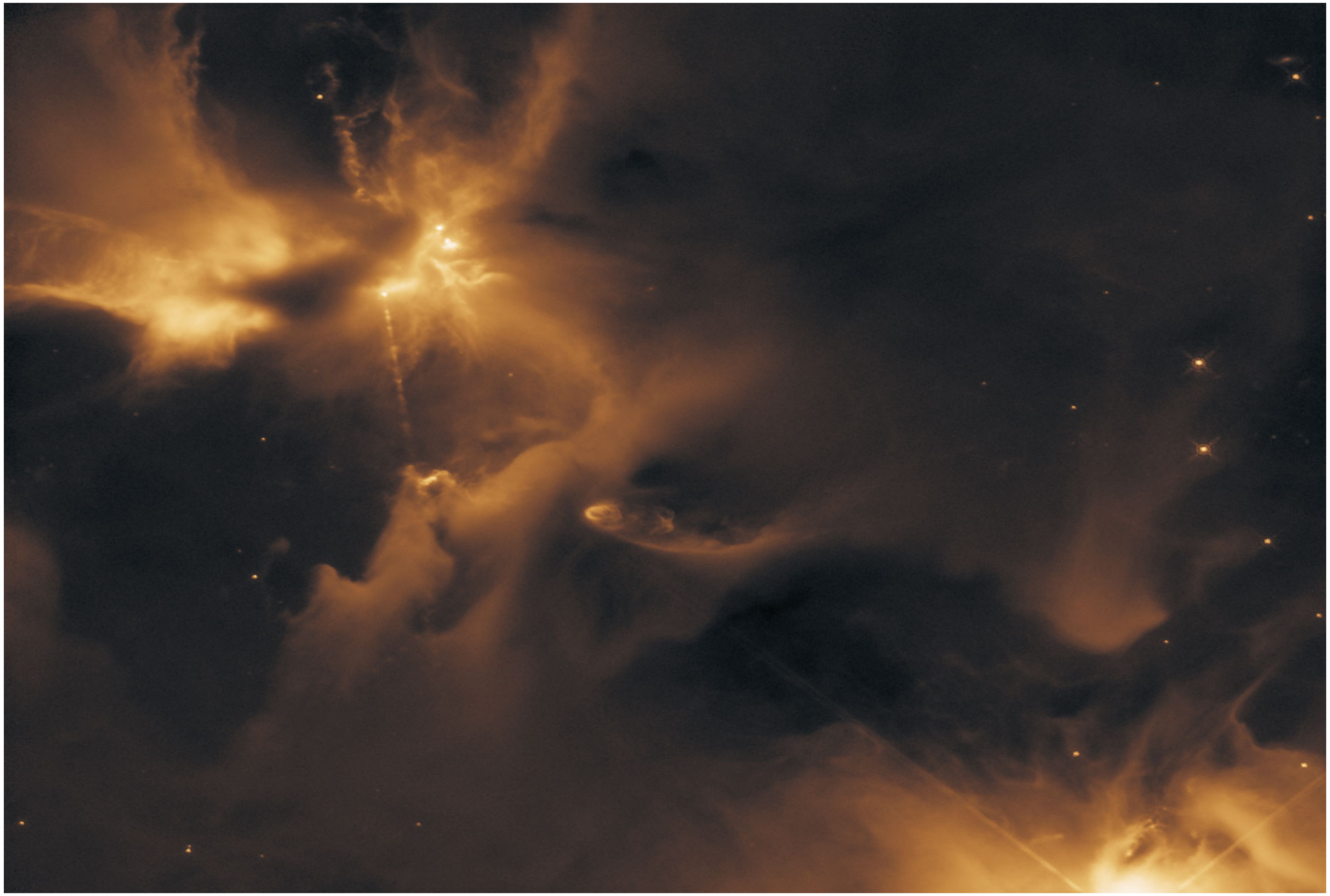
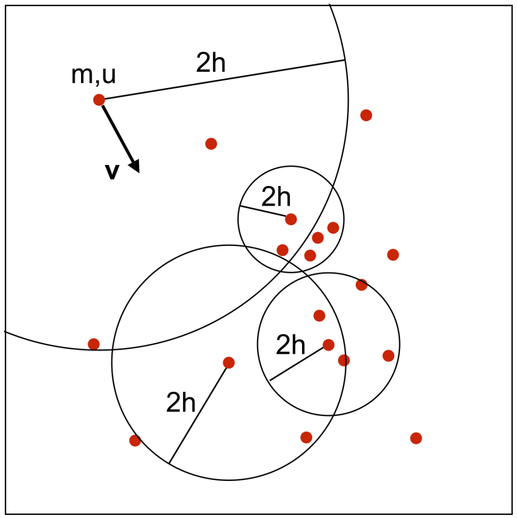
Questions

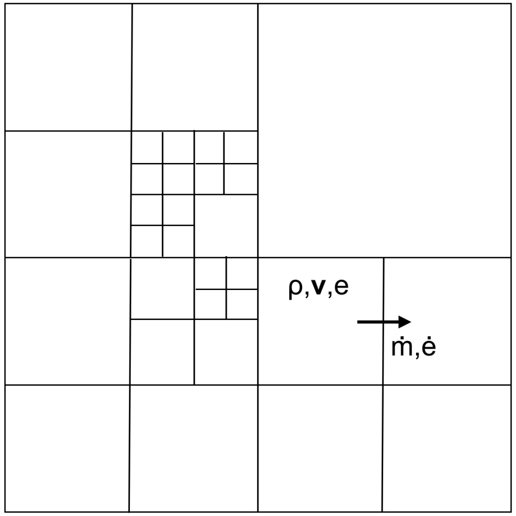


HST image of young stellar objects in the Orion B molecular cloud complex (https://apod.nasa.gov)

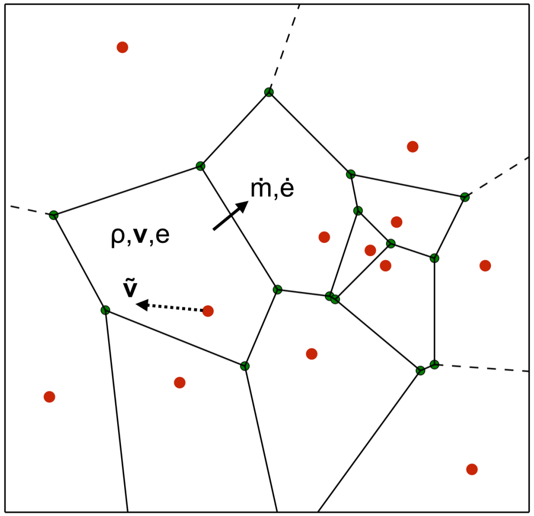
Hydrodynamic Simulation Codes



(a) SPH



(b) AMR

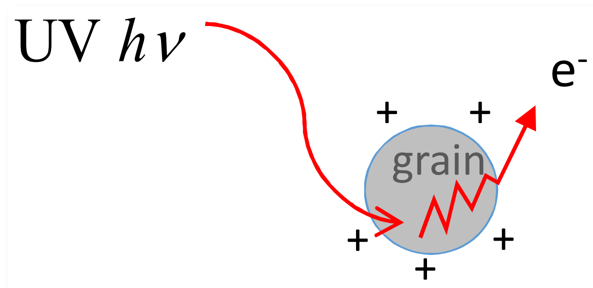


(c) Moving mesh

Ref: Dale (2015)

Dust Temperature

- Key radiative feedback interaction is with dust grains
- Photo-ionisation of dust by UV photons is dominant gas heating mechanism



- Gas cooling capacity dependent on concentration of molecular species (particularly CO / C+); equilibrium between:
  - Destructive photodissociation and ionisation processes
  - Constructive dust surface catalysis processes: a function of dust temperature