(THEORY OF)

RADIATIVE TRANSFER AND MOLECULAR EXCITATION

Christian Brinch
STARPLAN and Niels Bohr Institutet,
University of Copenhagen

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OUTLINE

- The radiative transfer problem in astronomy
- Available codes and the general model approach
- The LIME code
- Examples

DEFINITION

RT is important for astronomy

also atmospheric research, remote sensing, medical imaging, and nuclear weapons

Radiative transfer theory describ the propagation of light in a medium and its interaction with matter through emission, absorption, and scattering processes.

EQUATION OF RADIATIVE TRANSFE

Inhomogeneous first-order linear constant coefficient ordinary differential equation

$$\boxed{\frac{dI_\nu}{d\tau_\nu} = I_\nu - S(\tau_\nu)}$$

$$\tau_\nu = \int \alpha_\nu ds$$

$$S \equiv j_\nu/\alpha_\nu \, (+\sigma_\nu/\alpha_\nu)$$

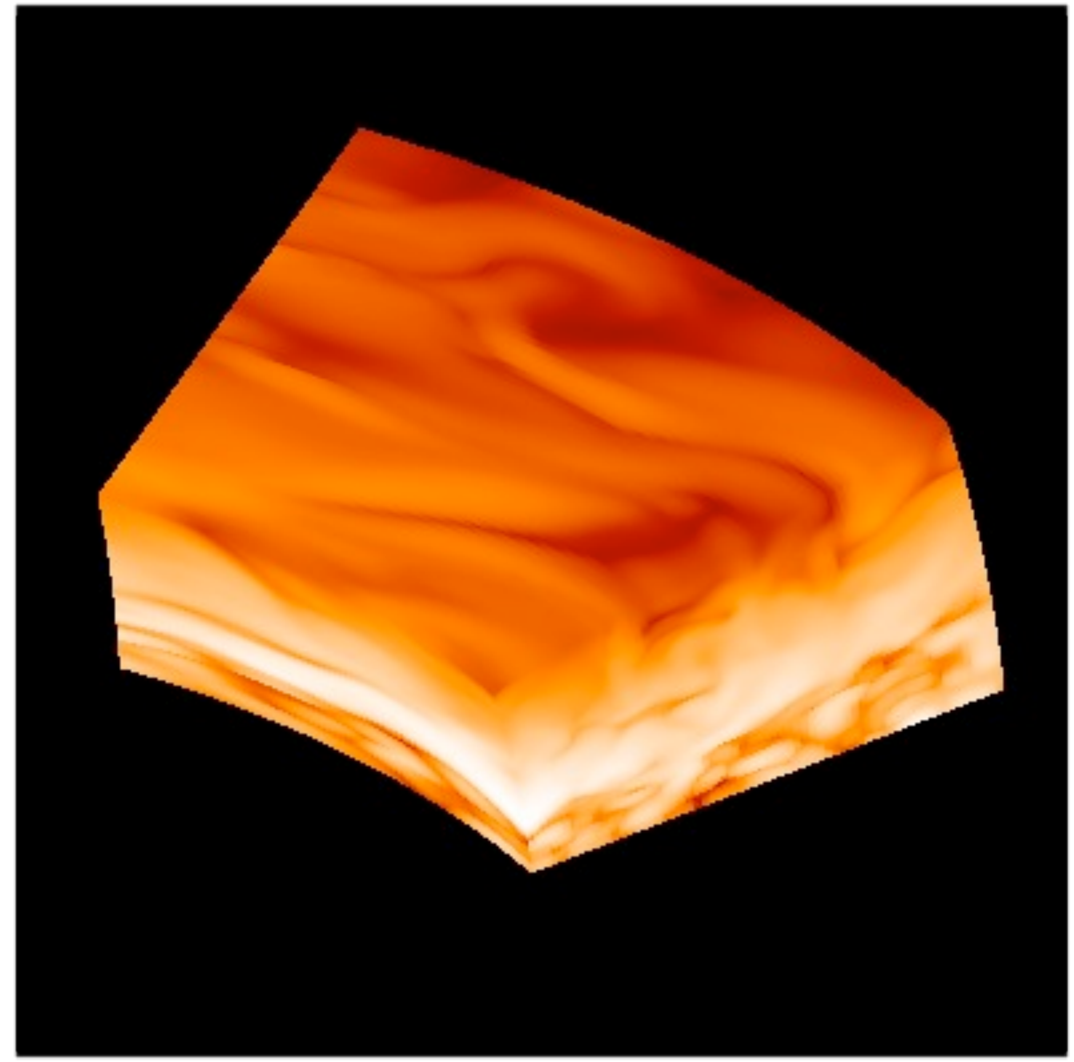
j_ν emission coefficient

α_ν absorption coefficient

$$\boxed{I_\nu(\tau_0) = I_\nu(\tau_1)e^{-(\tau_1-\tau_0)} + \int_{\tau_0}^{\tau_1} S(\tau_\nu)e^{-\tau_\nu} d\tau_\nu}$$

CONTINUUM RADIATIVE TRANSFER

$$j_\nu = \alpha_\nu B_\nu(T_{dust})$$
$$\alpha_\nu = \kappa_\nu \rho_{dust}$$



- popular codes include
  - radmc / radmc-3d (Dullemond)
  - Transphere (Dullemond)
  - DUSTY (Ivezic et al)
  - MC3D (Wolf)
  - HYPERION (Robitaille)

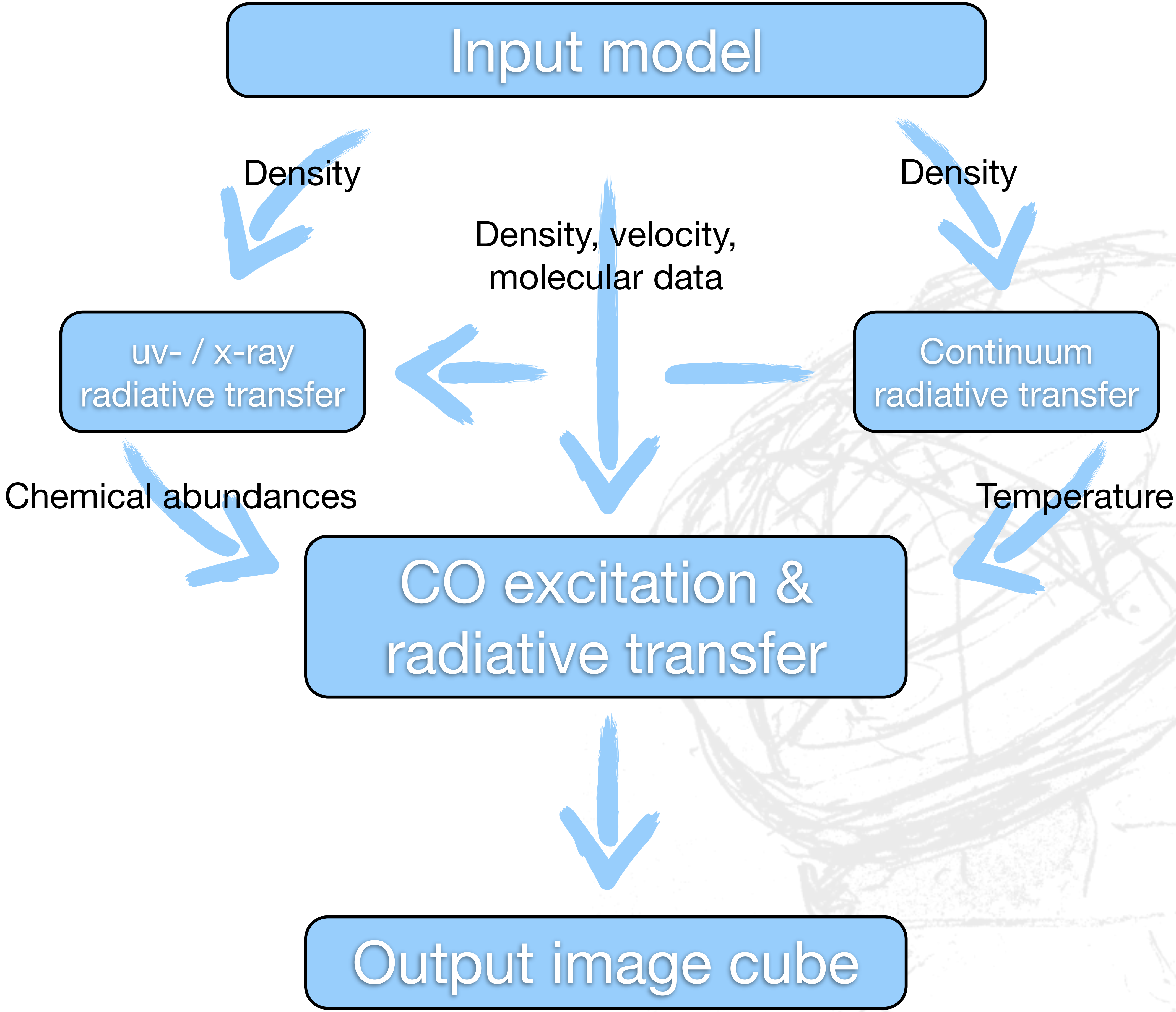
STATISTICAL EQUILIBRIUM

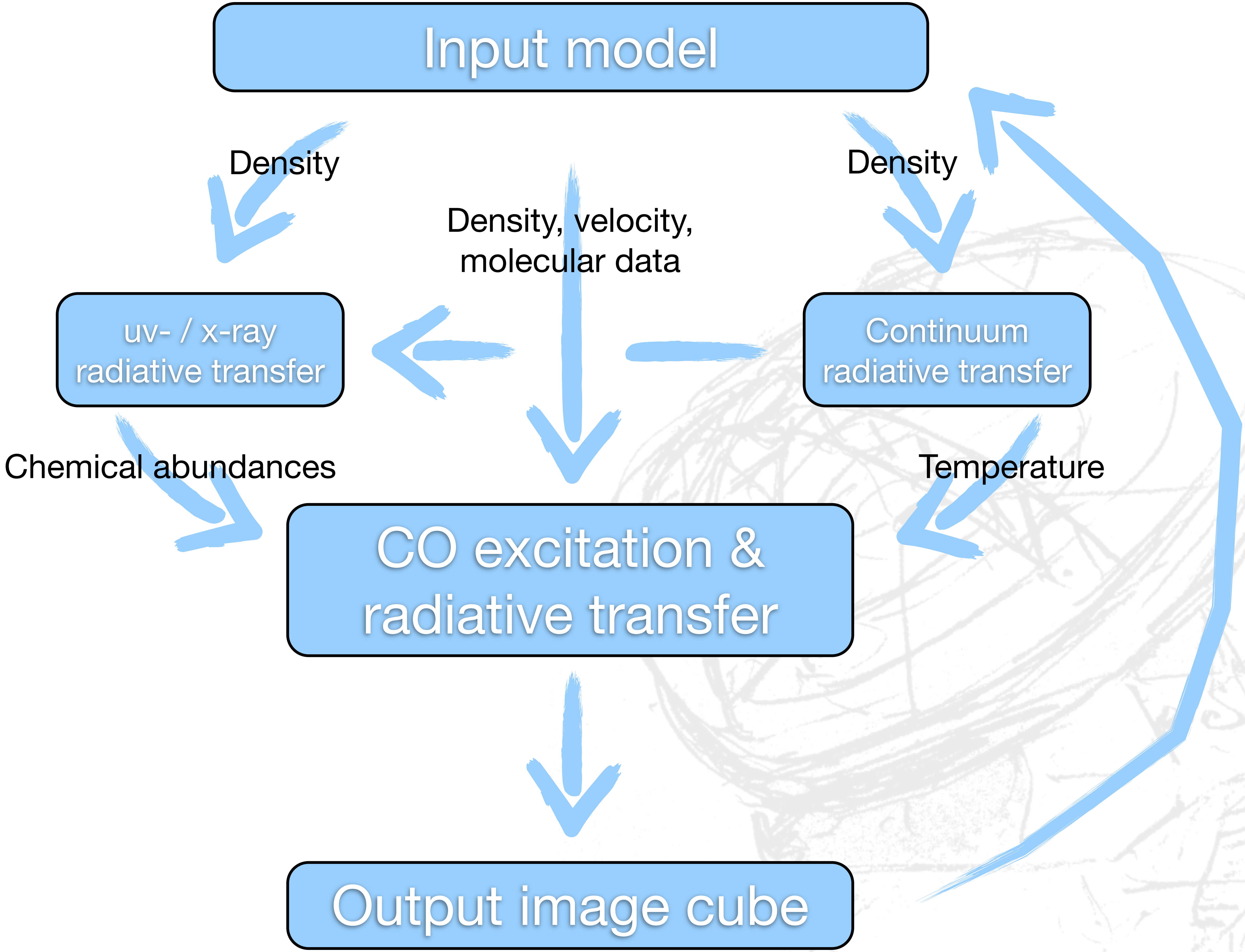
j_ν and α_ν are generally functions of density (ϱ), temperature (T), opacity ($\varkappa$), frequency (ν), doppler shifts (ϕ), Einstein coefficients (A_{21}, B_{21}, B_{12}), and quantum level population (n).

However,

n is a function of the intensity (I):

$$n_l \left[\sum_{k<l} A_{lk} + \sum_{k\neq l} (B_{lk} J_\nu + C_{lk})\right] = \sum_{k>l} n_k A_{kl} + \sum_{k\neq l} n_k (B_{kl} J_\nu + C_{kl}).$$


Input model
Density
Density, velocity,
molecular data
Density
uv- / x-ray
radiative transfer
Continuum
radiative transfer
Chemical abundances
Temperature
CO excitation &
radiative transfer
Output image cube



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uv- / x-ray radiative transfer
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WHY IS RADIATIVE TRANSFER HARD?

Simon Bruderer says:

```
Given
n cells (10000)
r lines (100)
s frequencies (100)
```

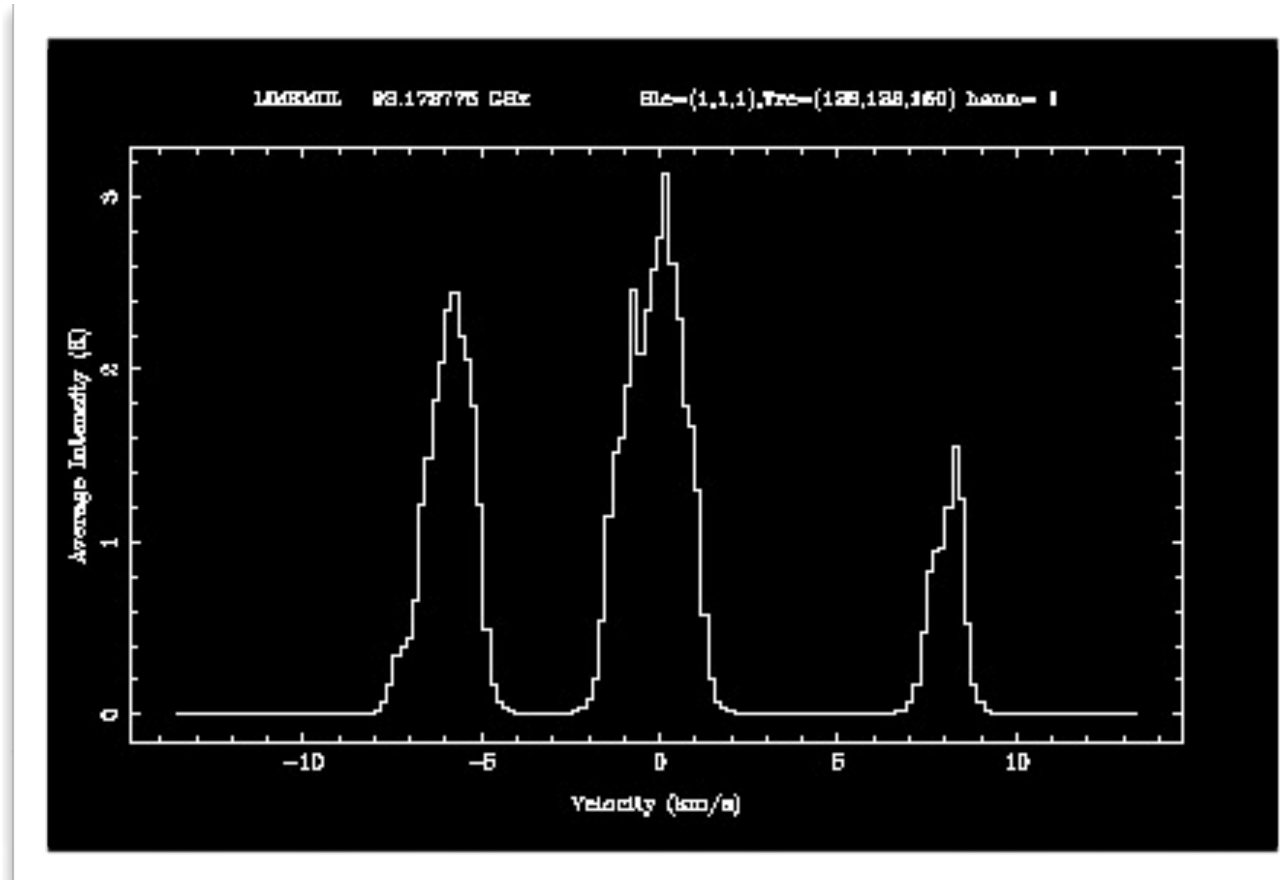
n^2 x r x s = 1e12 radiative connections

```
On one 2 GHz cpu, exp() takes of order ~ 30ish cycles
=> 5e7 exp()/second

1e12 exp()/iteration / 5e7 exp()/second = 20000 seconds
(or 6 hours) / iteration
```

MOLECULAR EXCITATION AND LINE RADIATIVE TRANSFER

- Exact methods
  - LI
  - ALI
  - MC
  - AMC
  - ...
- Approximations
  - LTE
  - Escape probability method
  - Large Velocity Gradient
  - ...



MOLECULAR EXCITATION AND LINE RADIATIVE TRANSFER

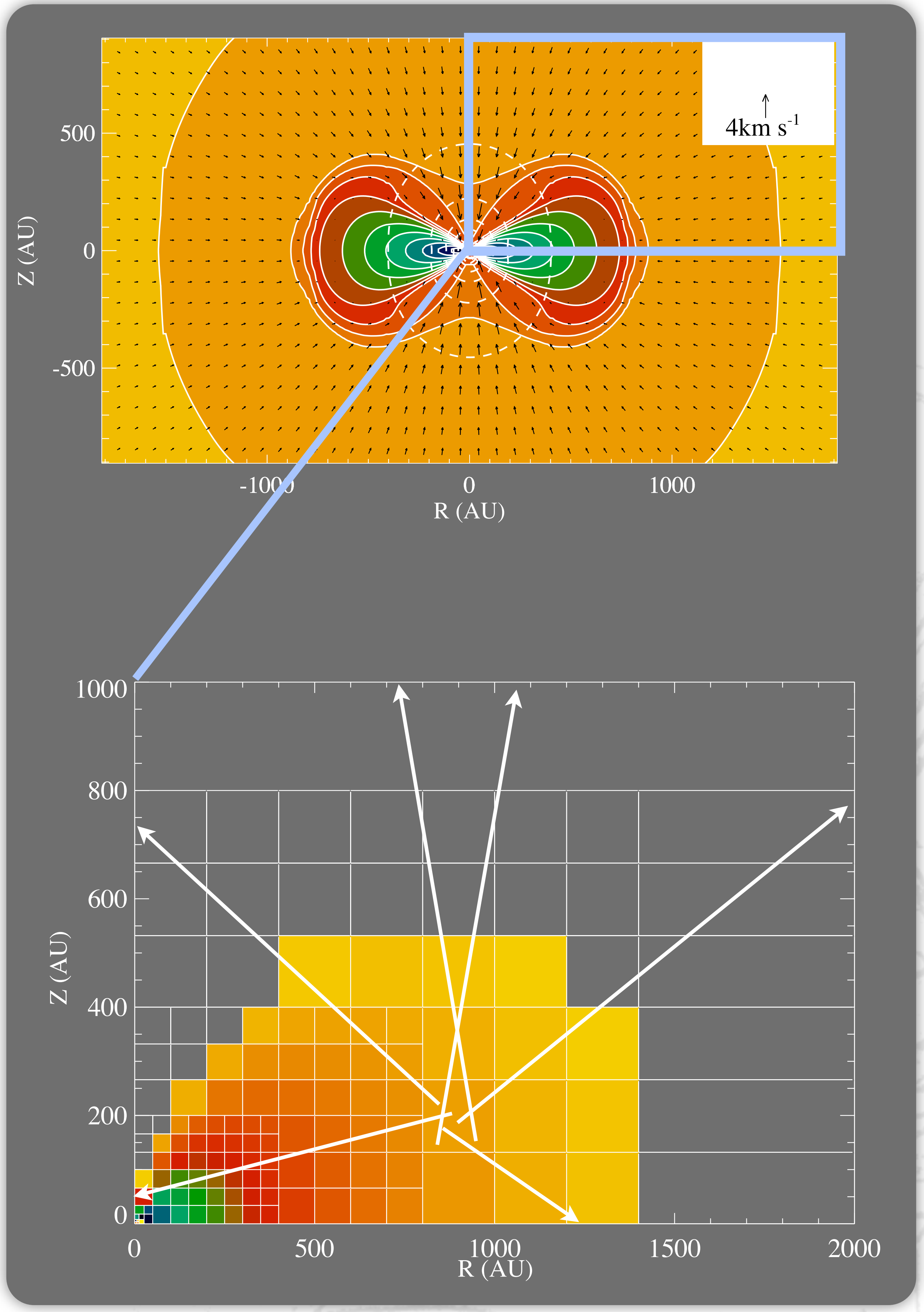
∀ cell:

trace n photon in random directions

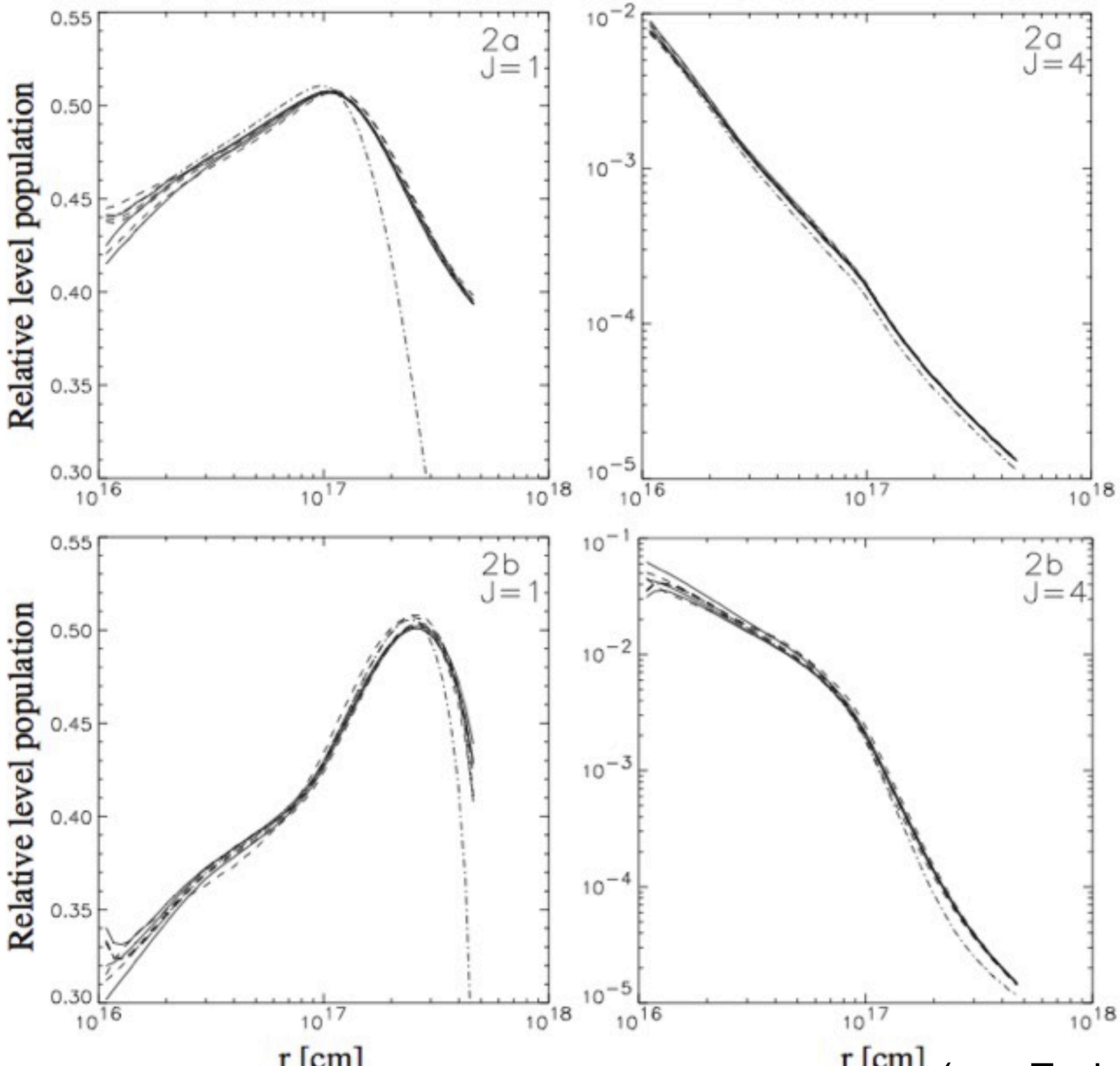
Calculate mean radiation field seen by cell

Construct rate matrix

Solve for populations



BENCHMARK

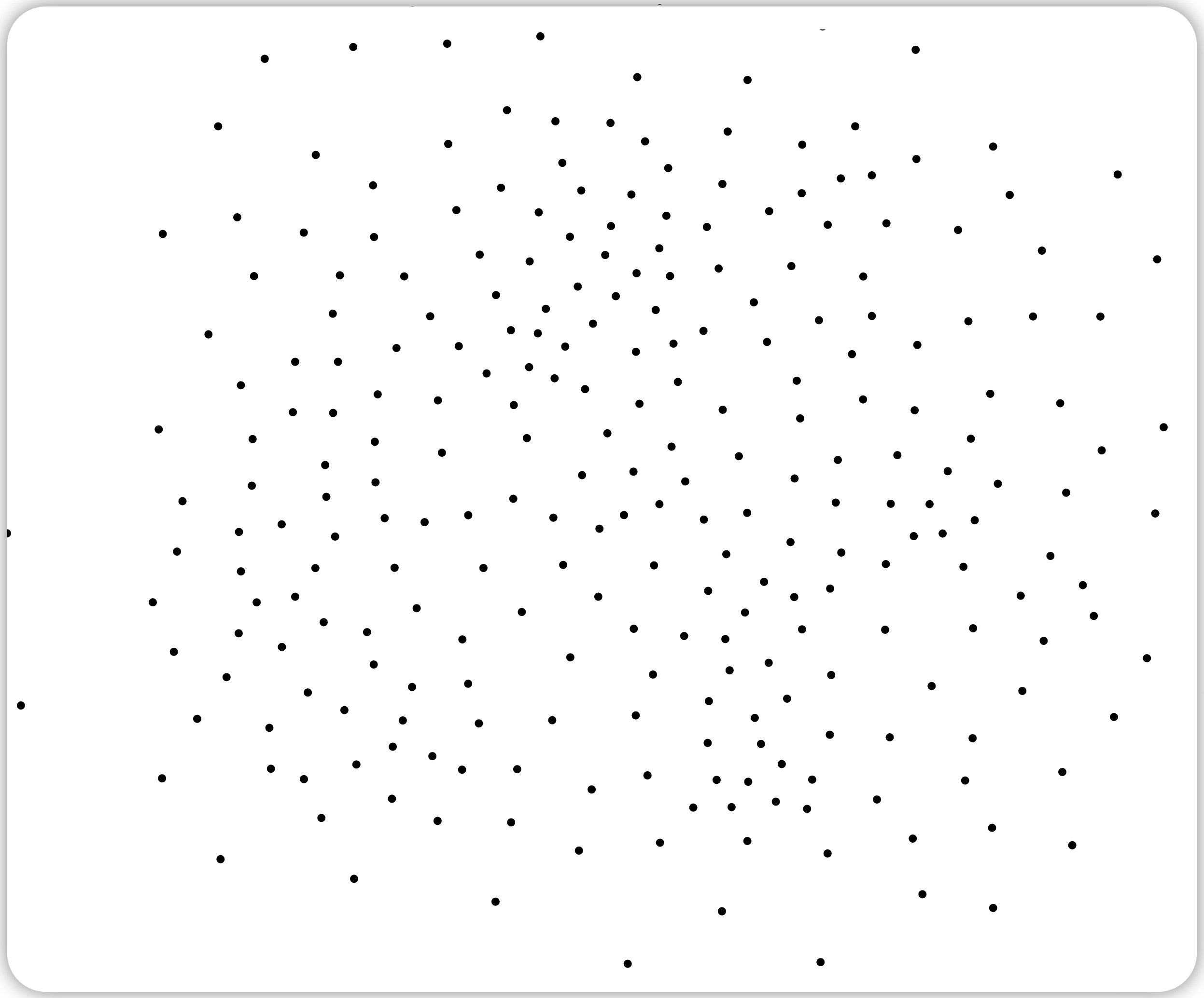


(van Zadelhoff et al., 2002)

PITFALLS

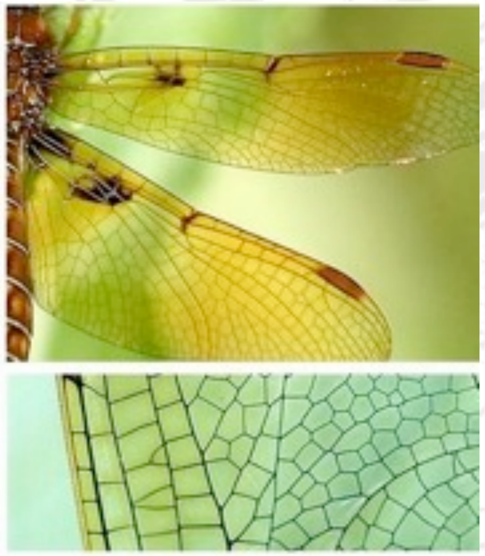
- Describing the model on a computational grid is (always!) difficult
- Convergence can be an issue
- The velocity field problem
- Parameters for imaging / ray-tracing need to be chosen carefully

LINE MODELING ENGINE (LIME)



- 3D line radiative transfer
- Random Delaunay grids for fast photon transfer
- Model properties are constant over a Voronoi volume (=> automatic mass conservation)

(Brinch and Hogerheijde, 2010)



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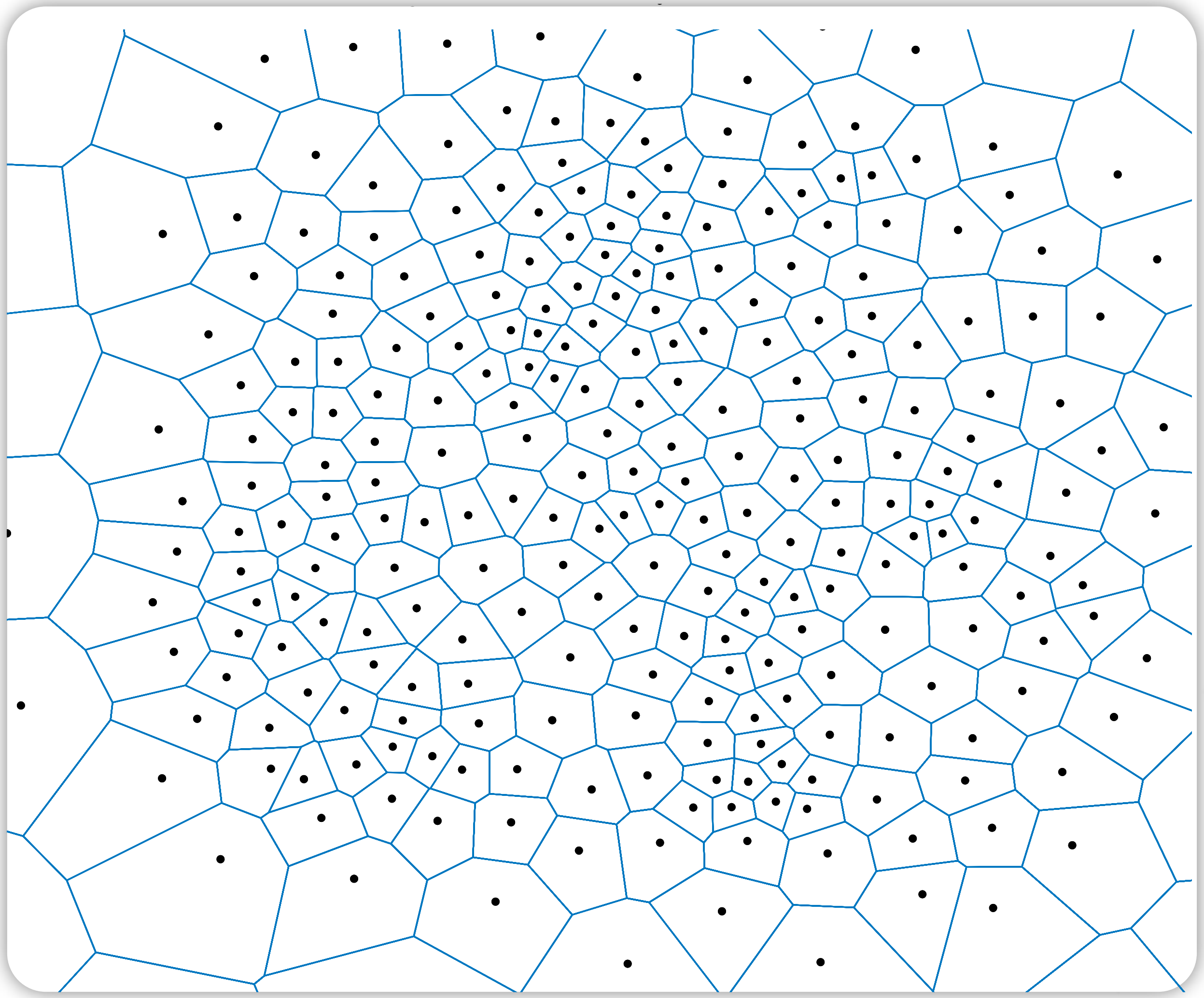

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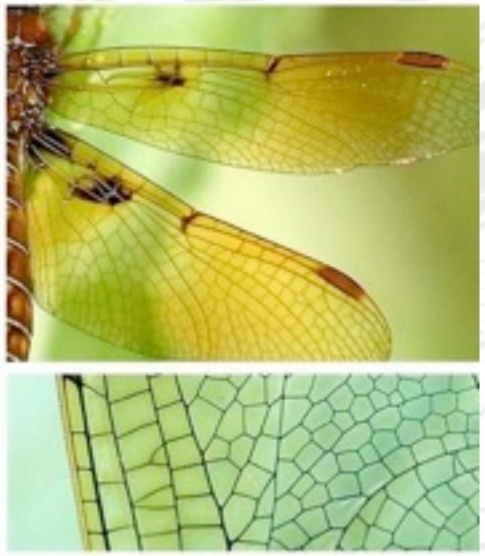

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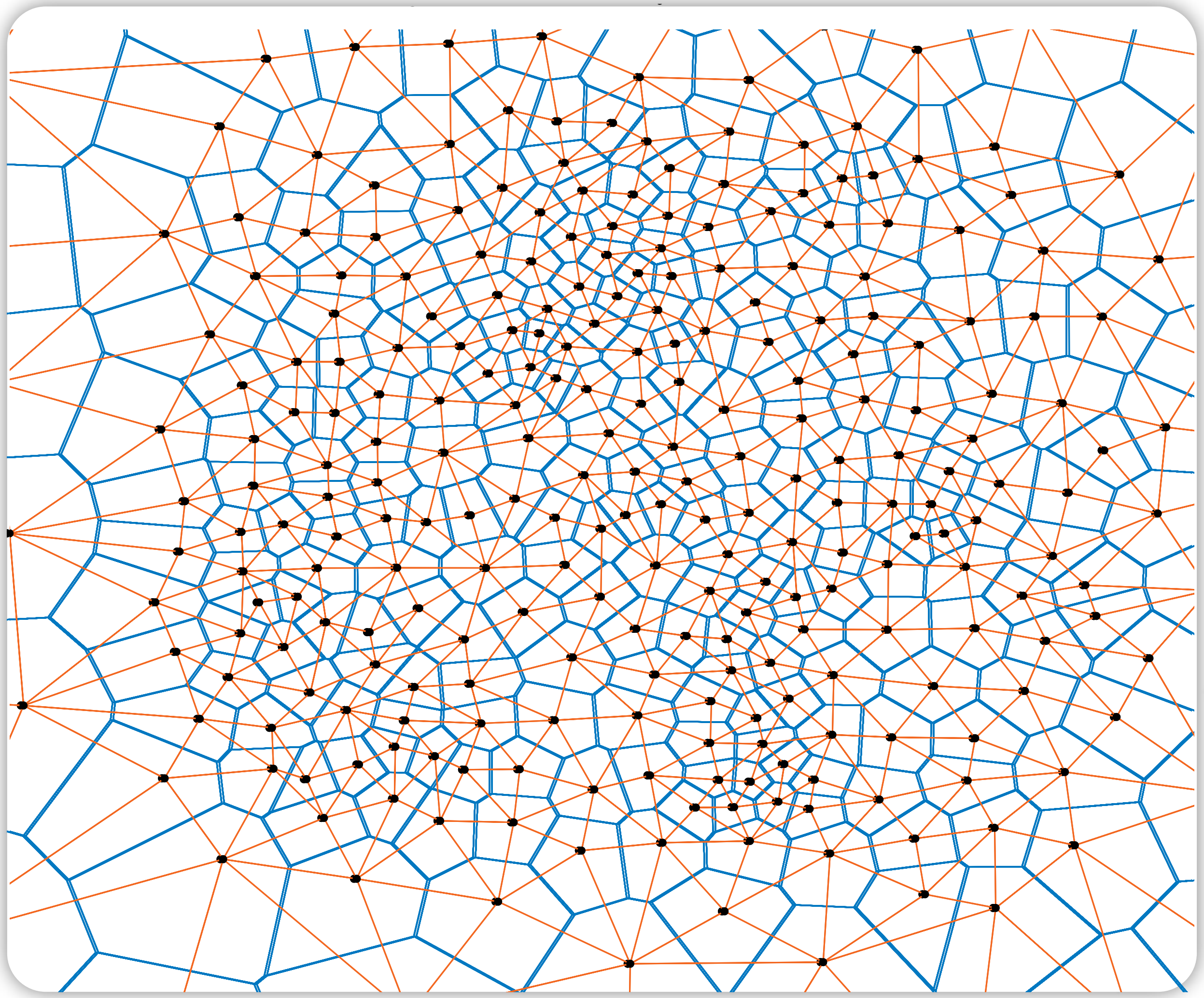

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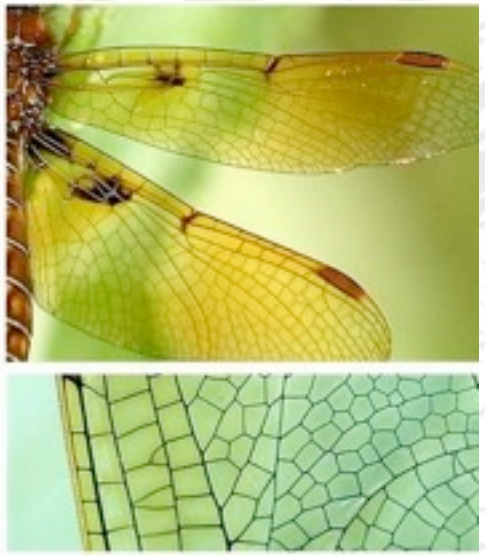

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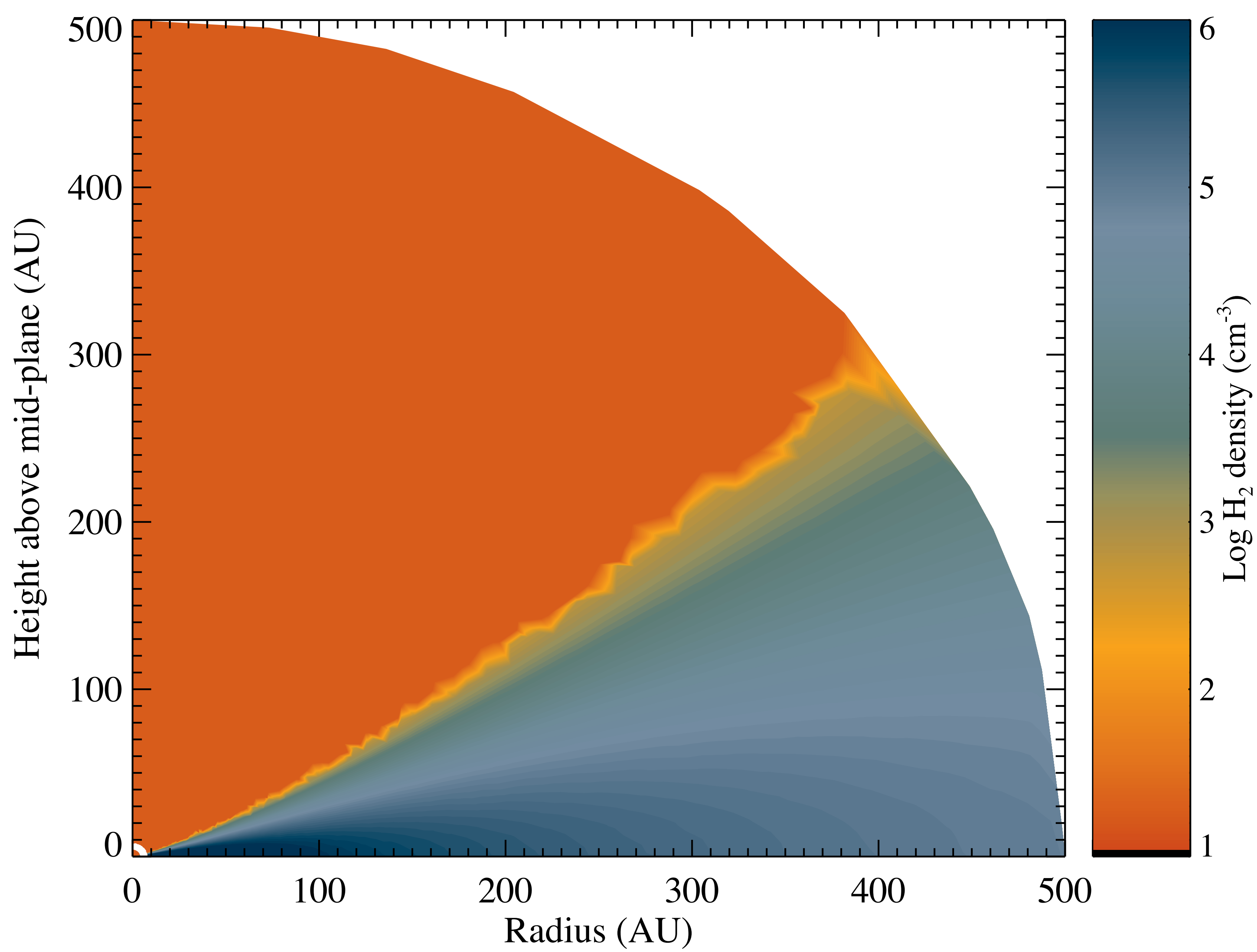

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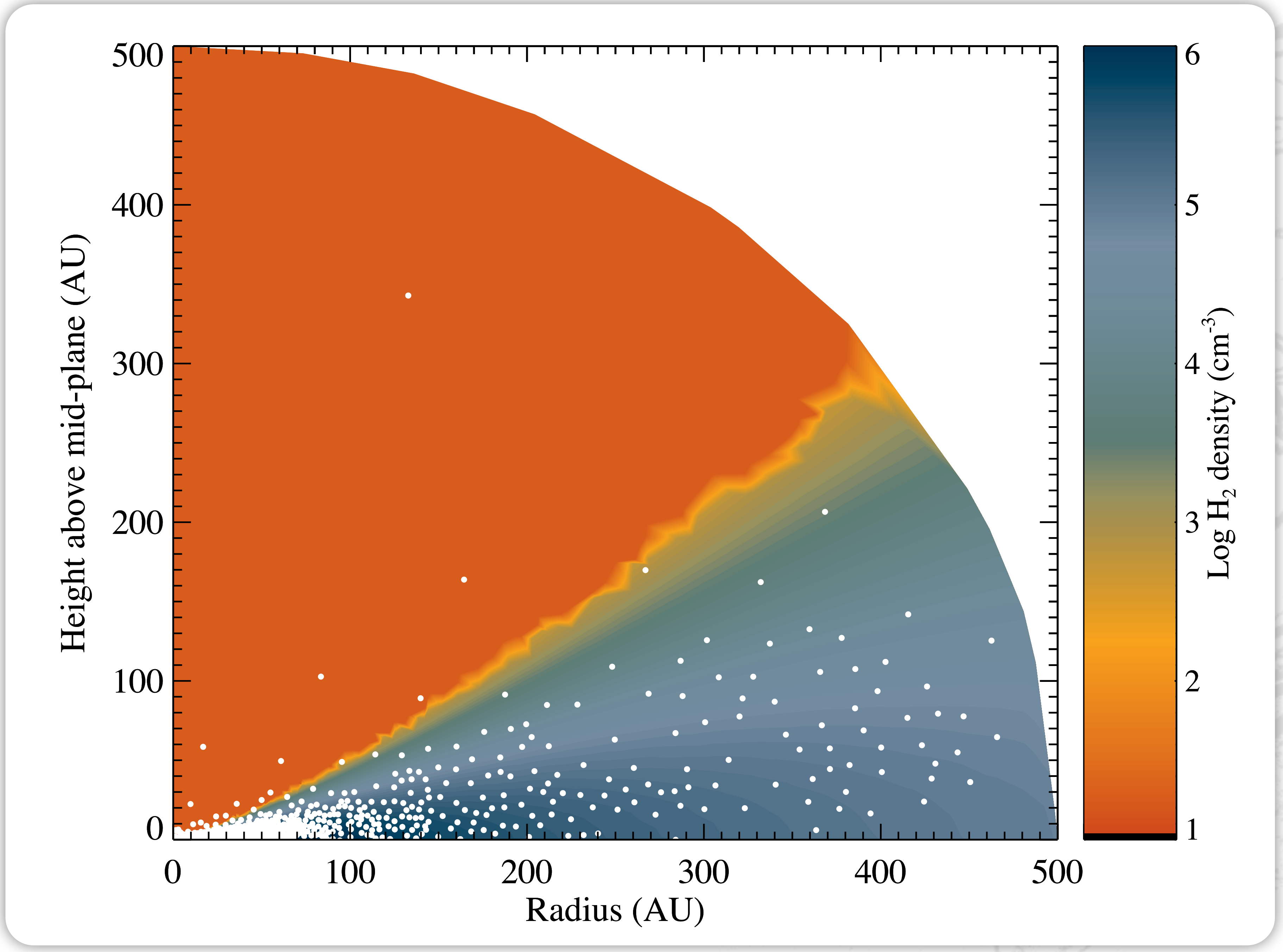

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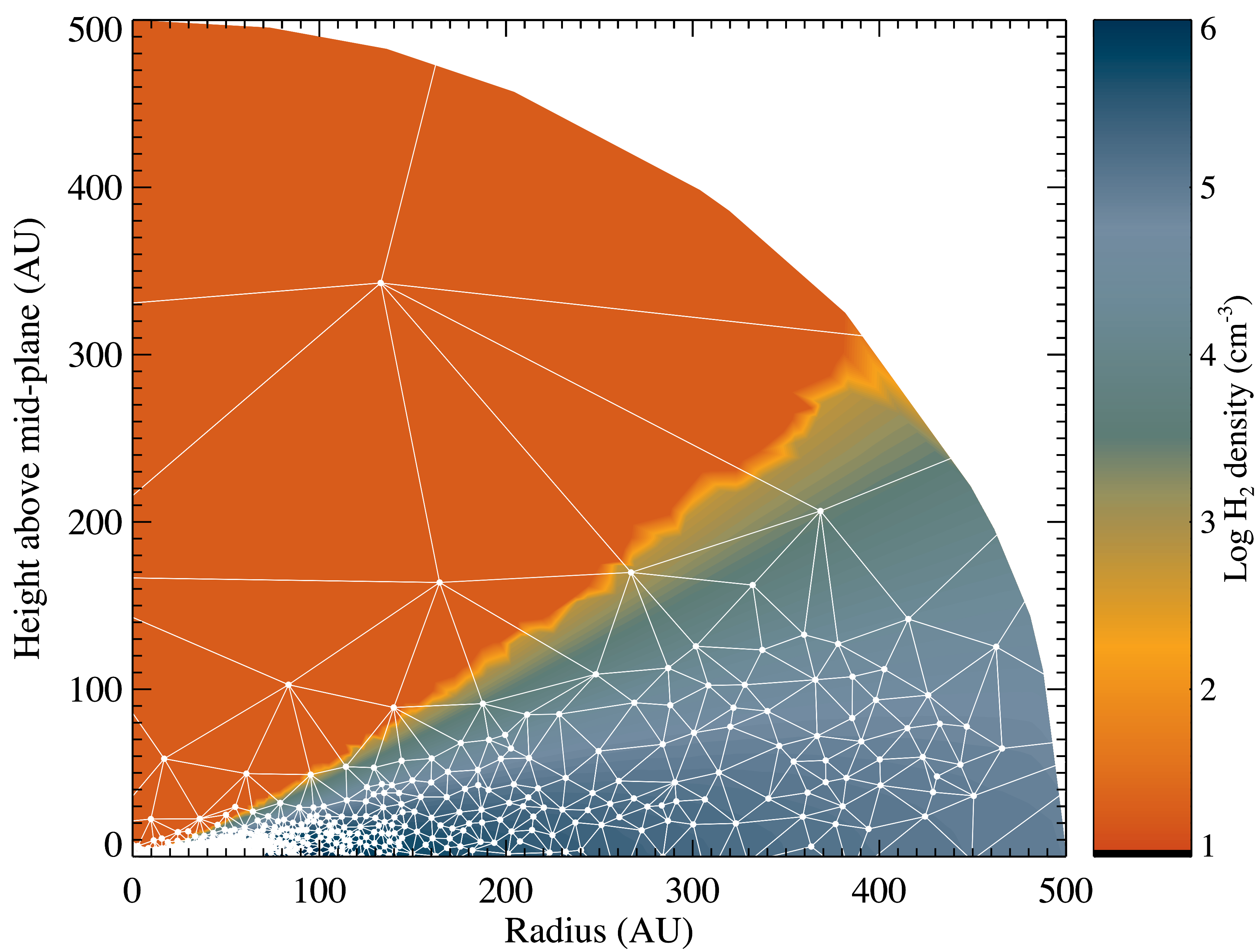
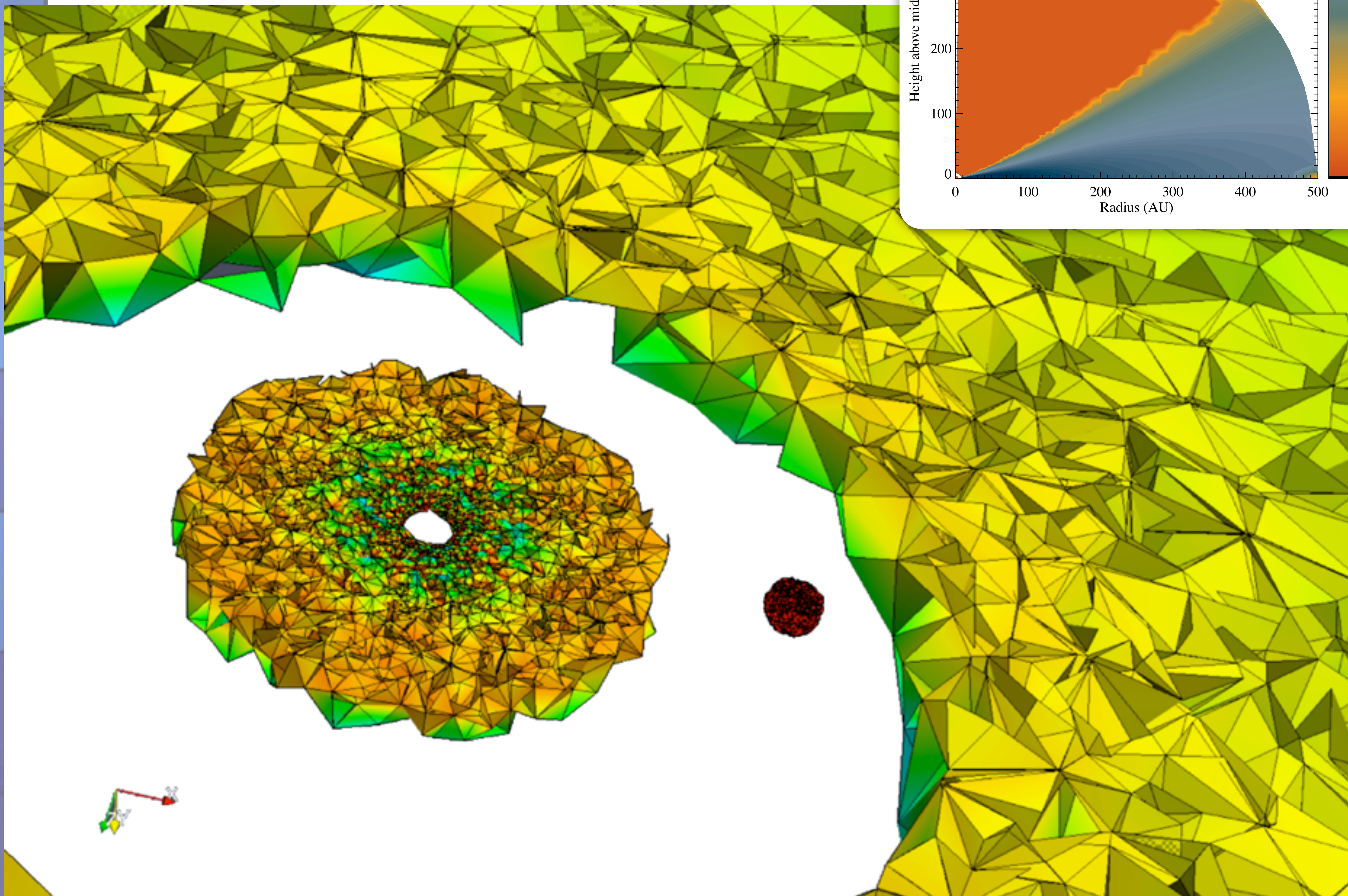
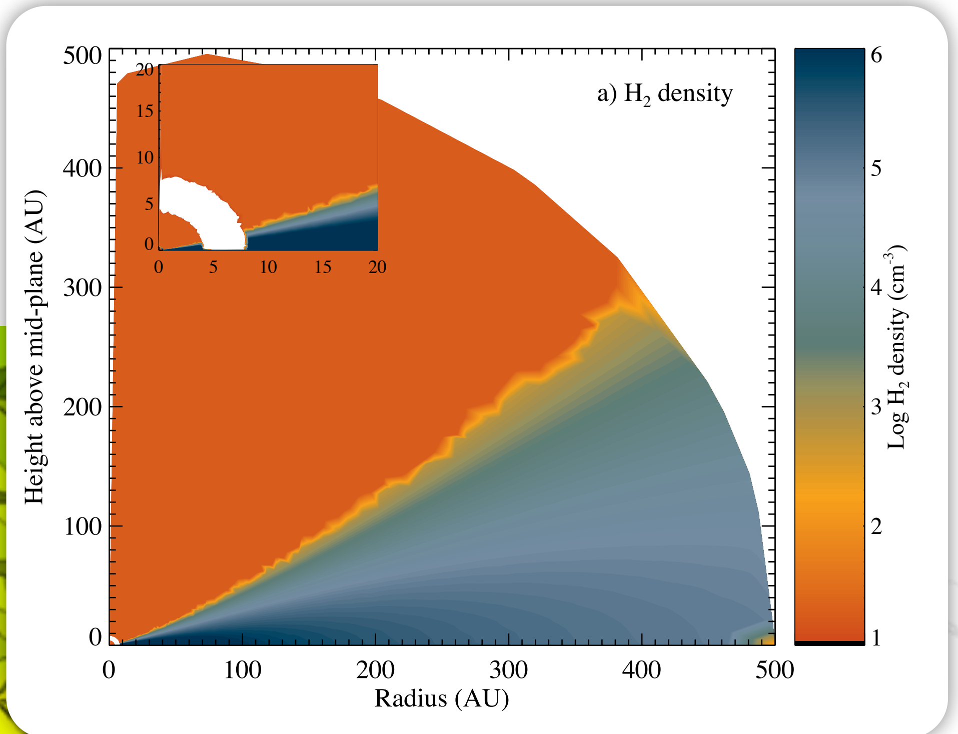


3D PROTOPLANETARY DISK WITH A PROTOPLANET





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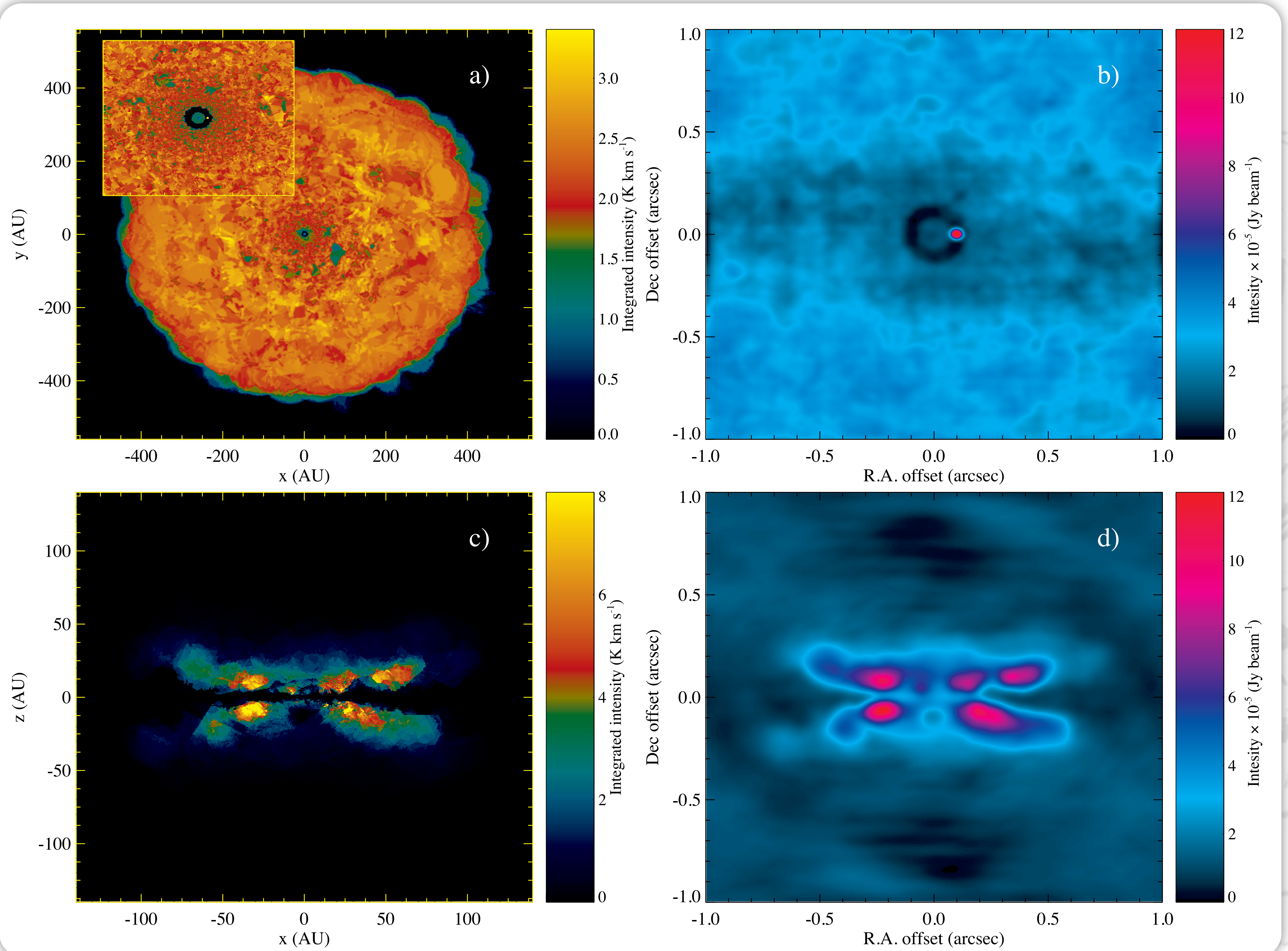

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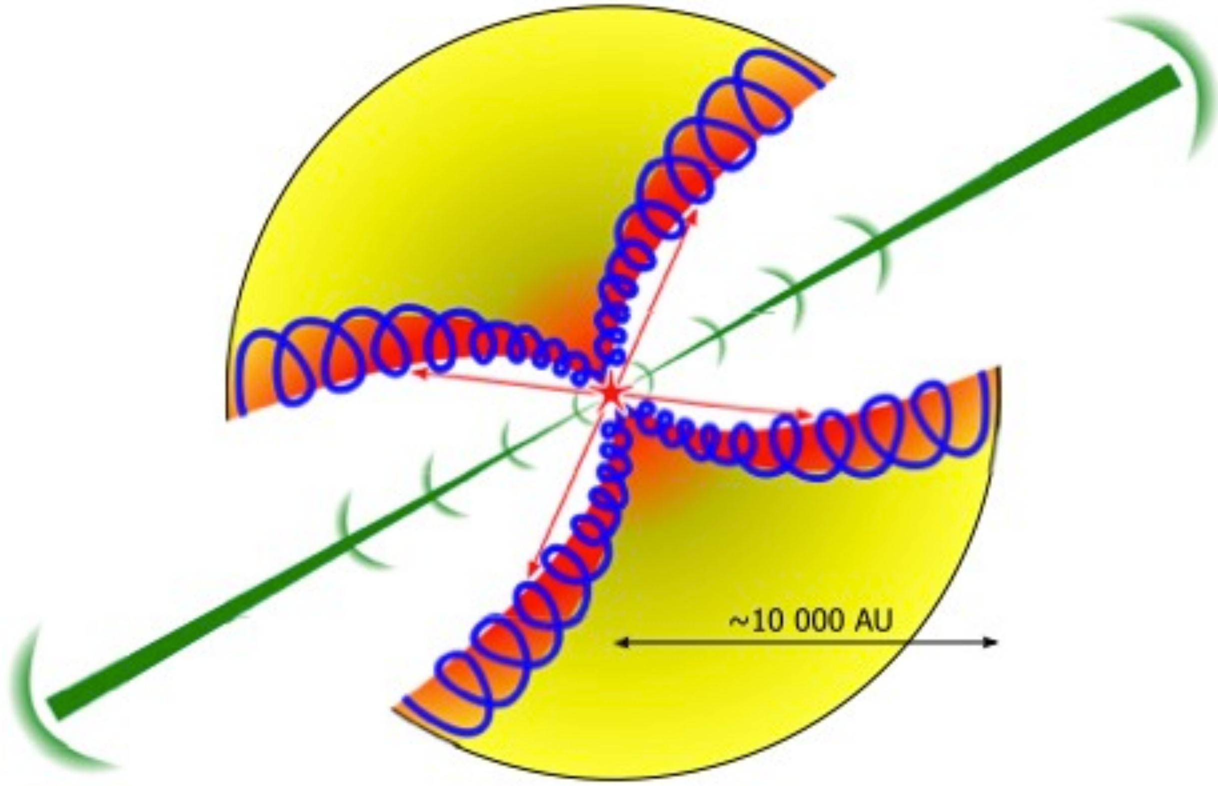
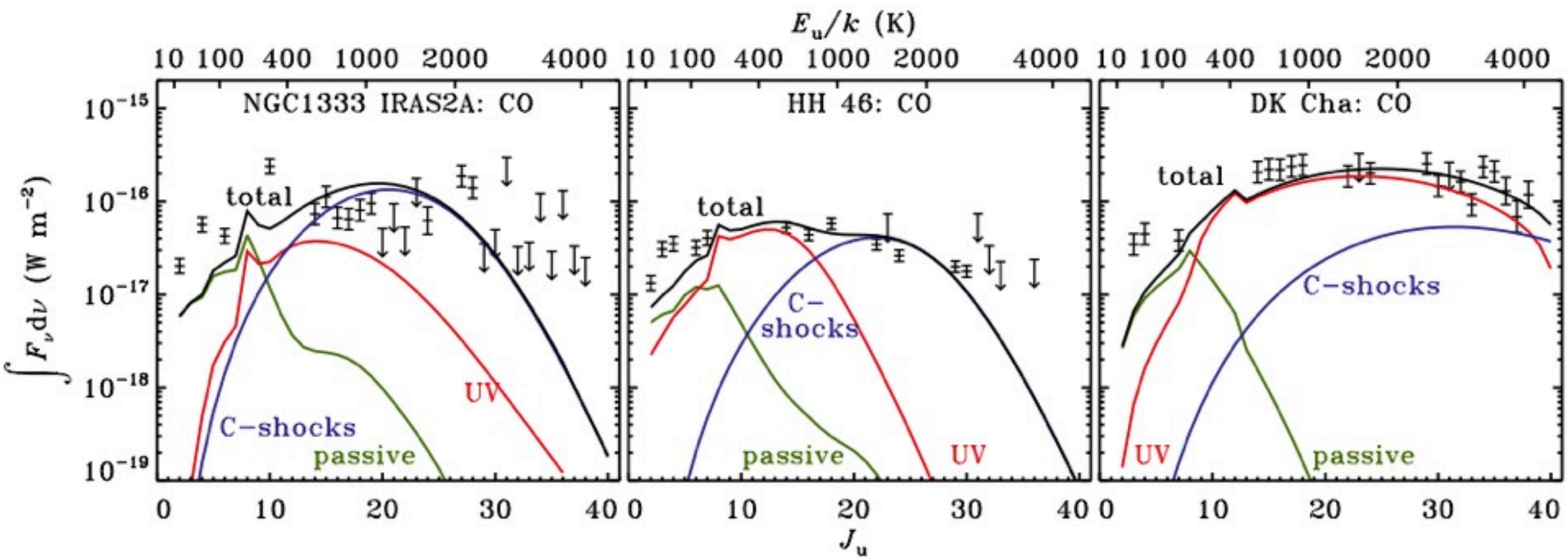
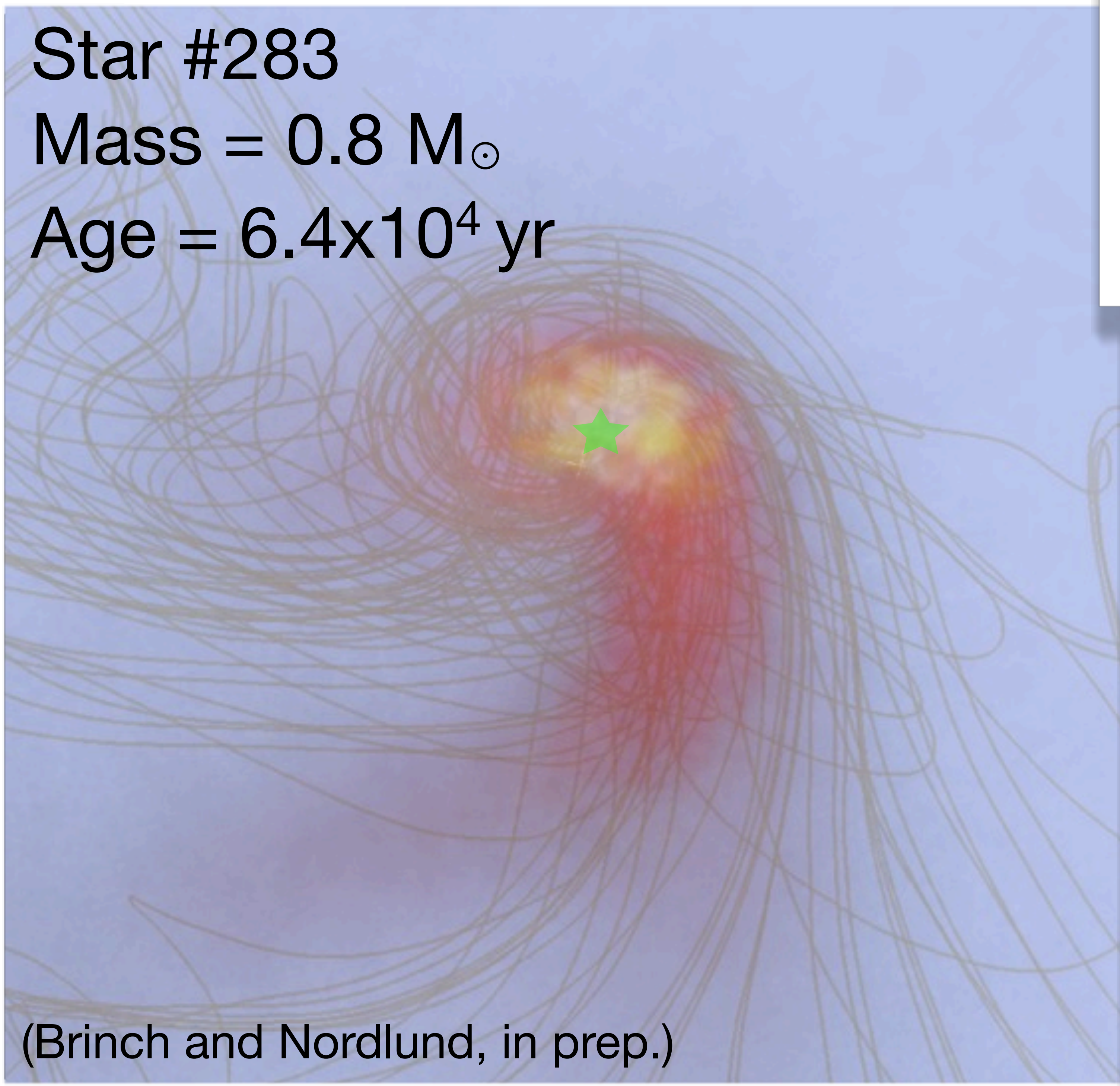
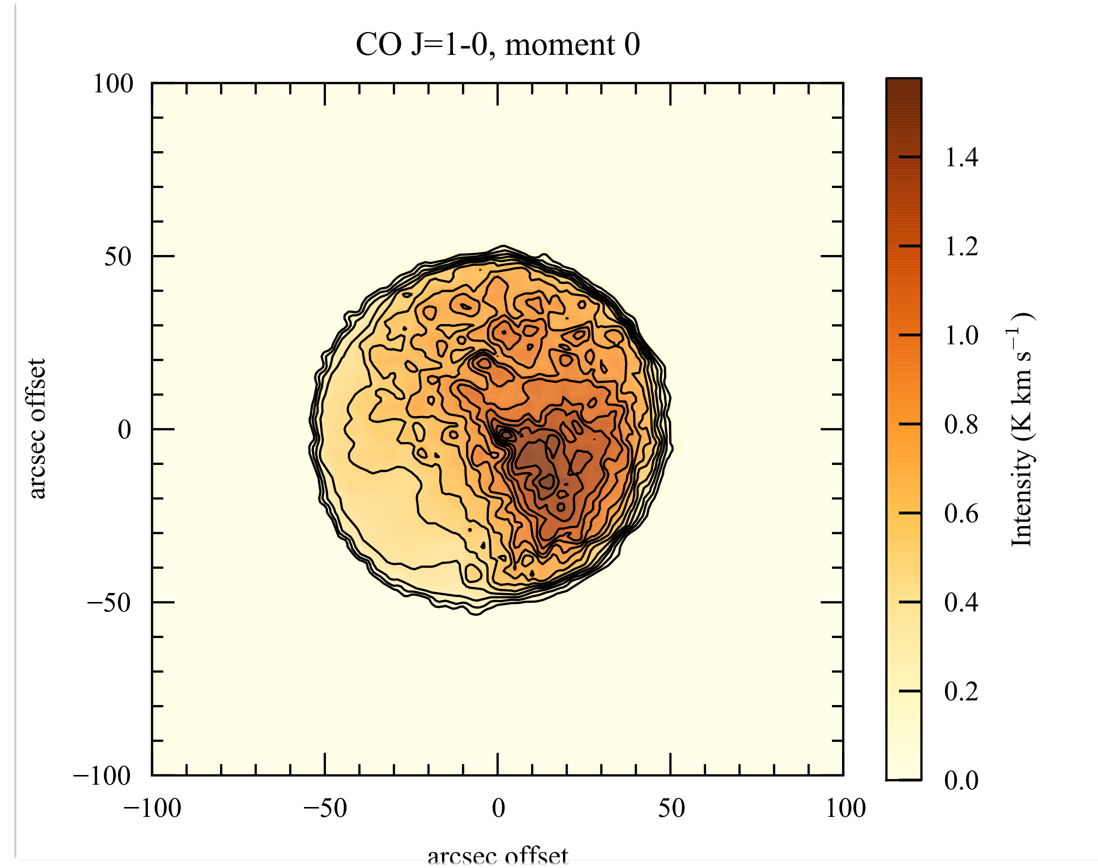


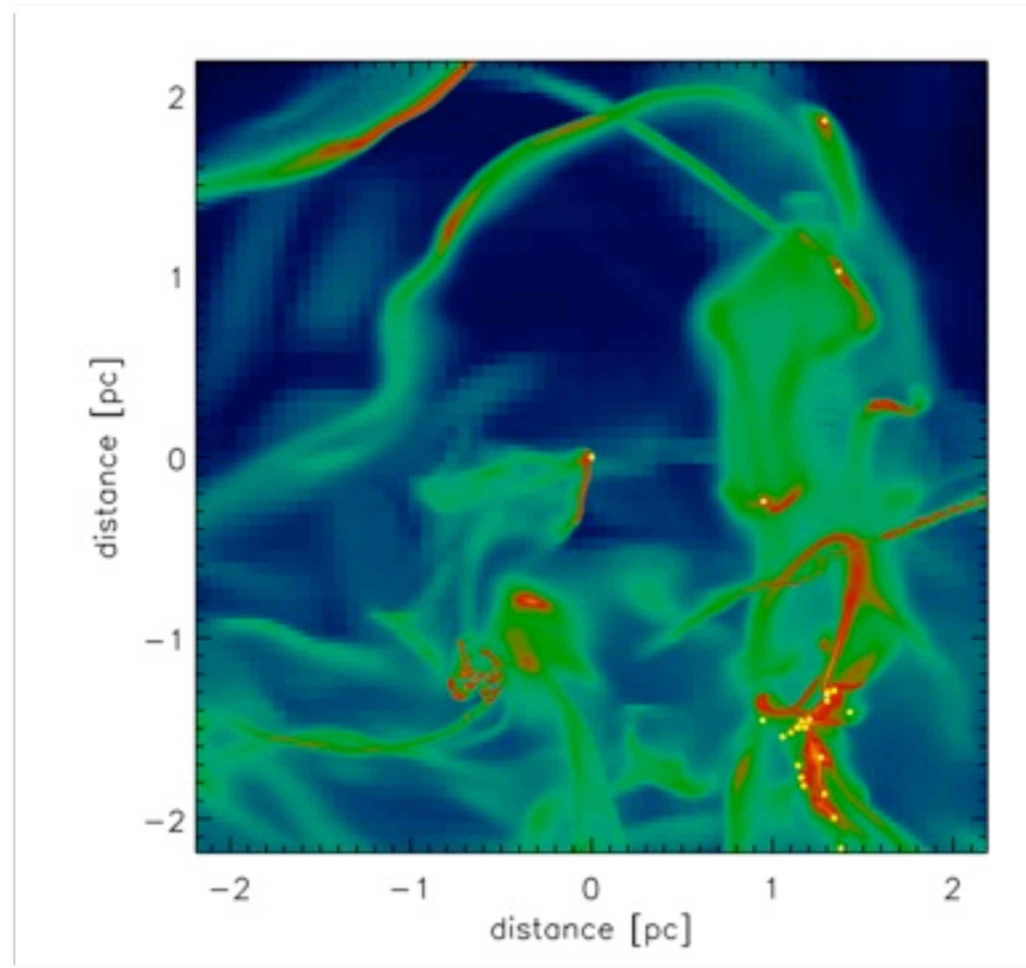


(Visser et al., 2012)

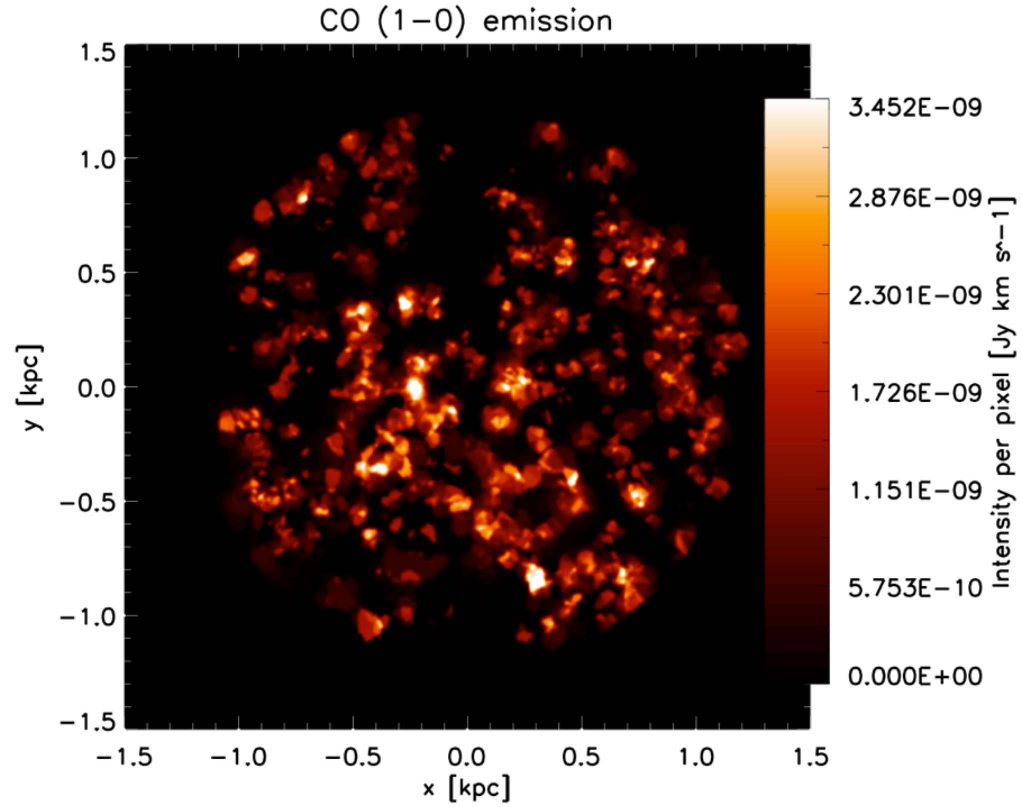
NUMERICAL SIMULATIONS AND RADIATIVE TRANSFER

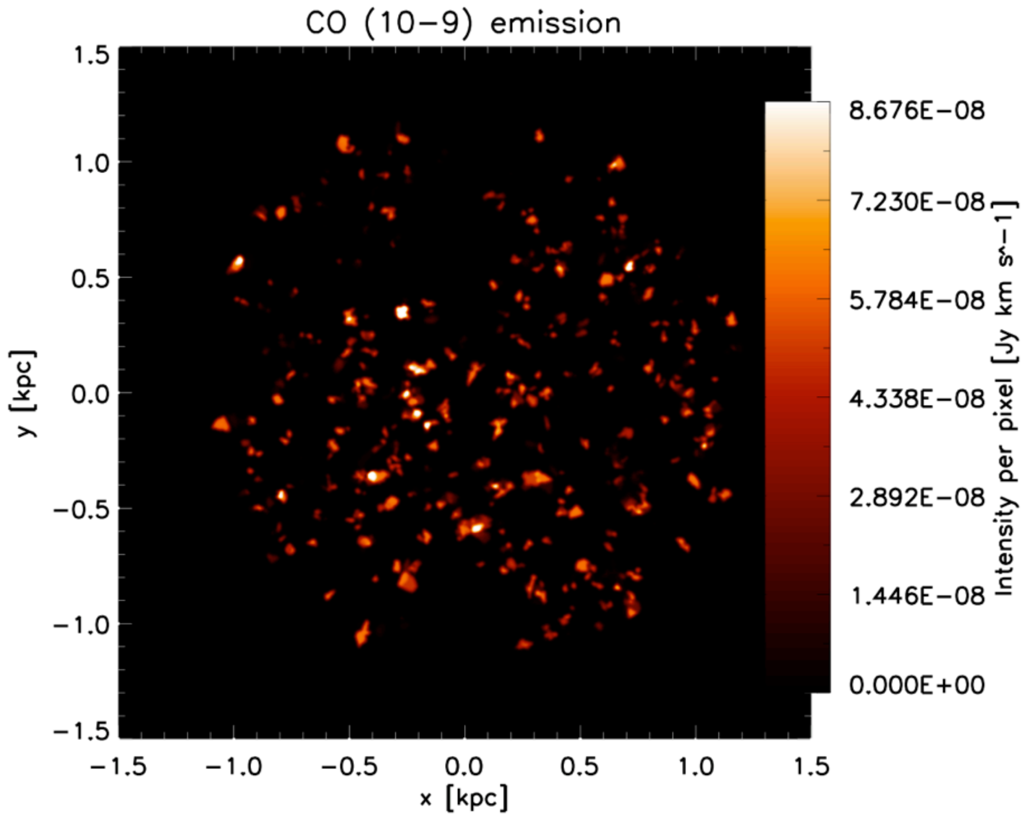






RADIATIVE TRANSFER CALCULATIONS ON MODELS OF GALAXIES

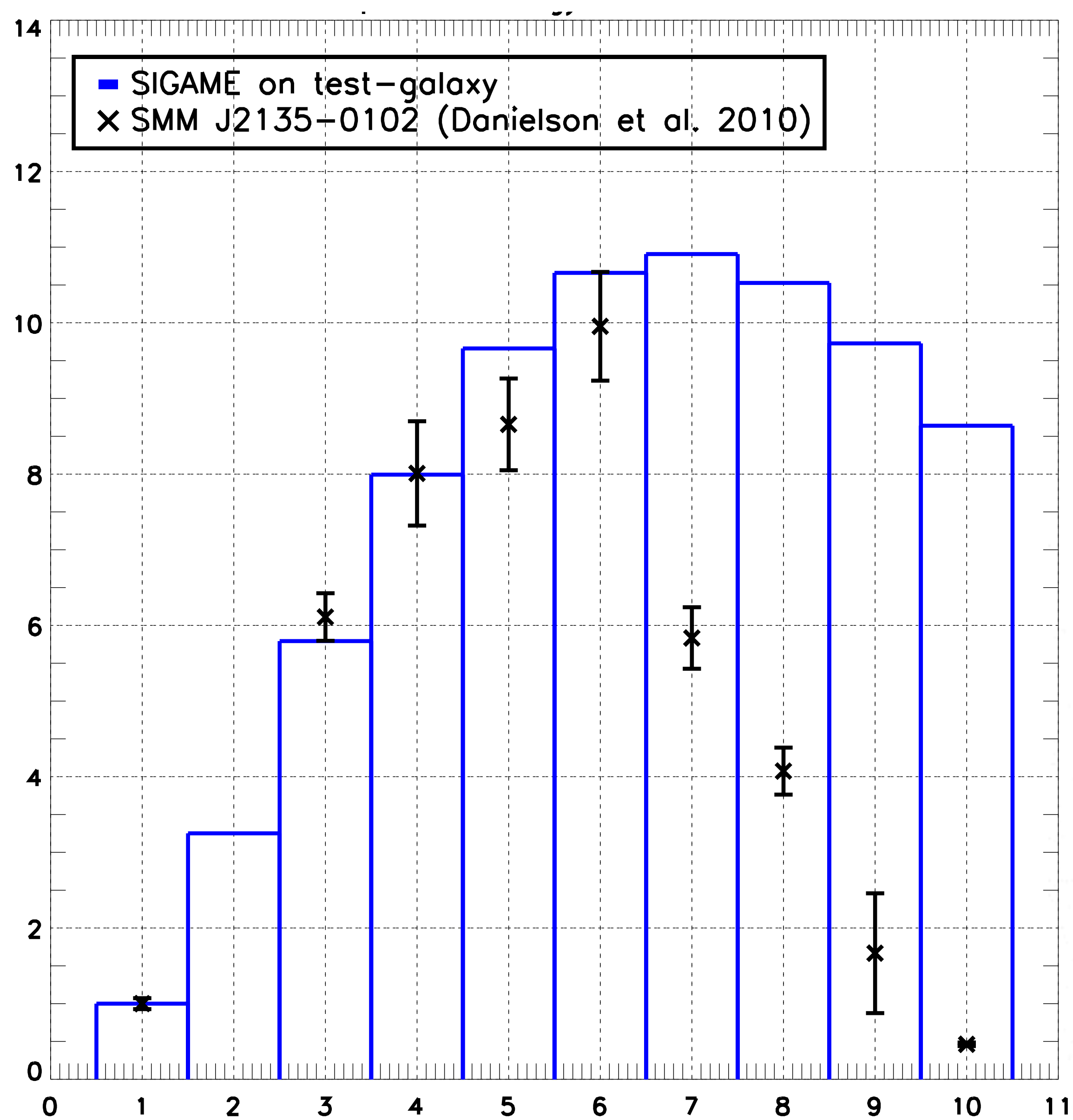




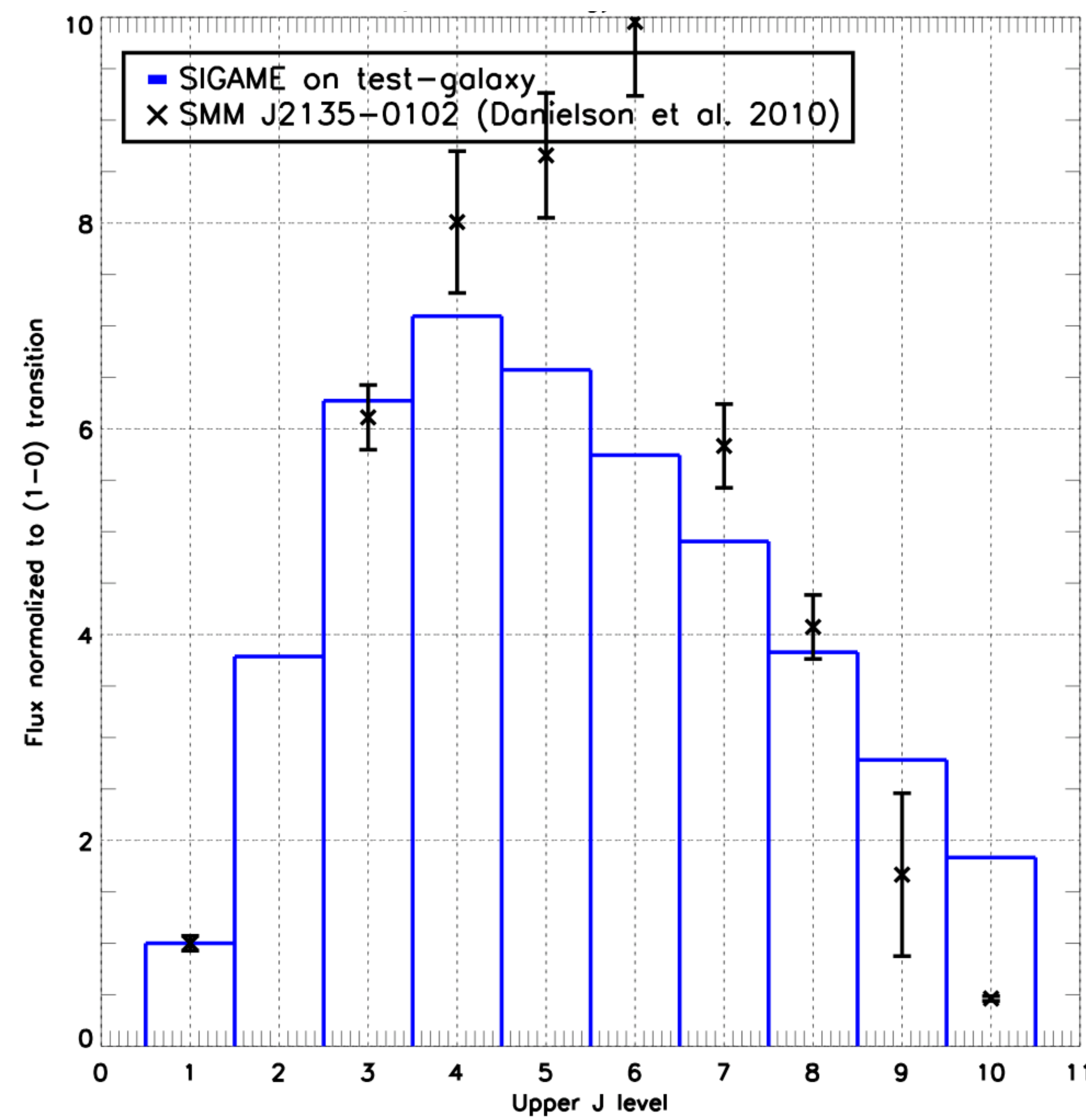
See poster by Karen Pardos Olsen

RADIATIVE TRANSFER CALCULATIONS ON MODELS OF GALAXIES

T=30K



T=20K



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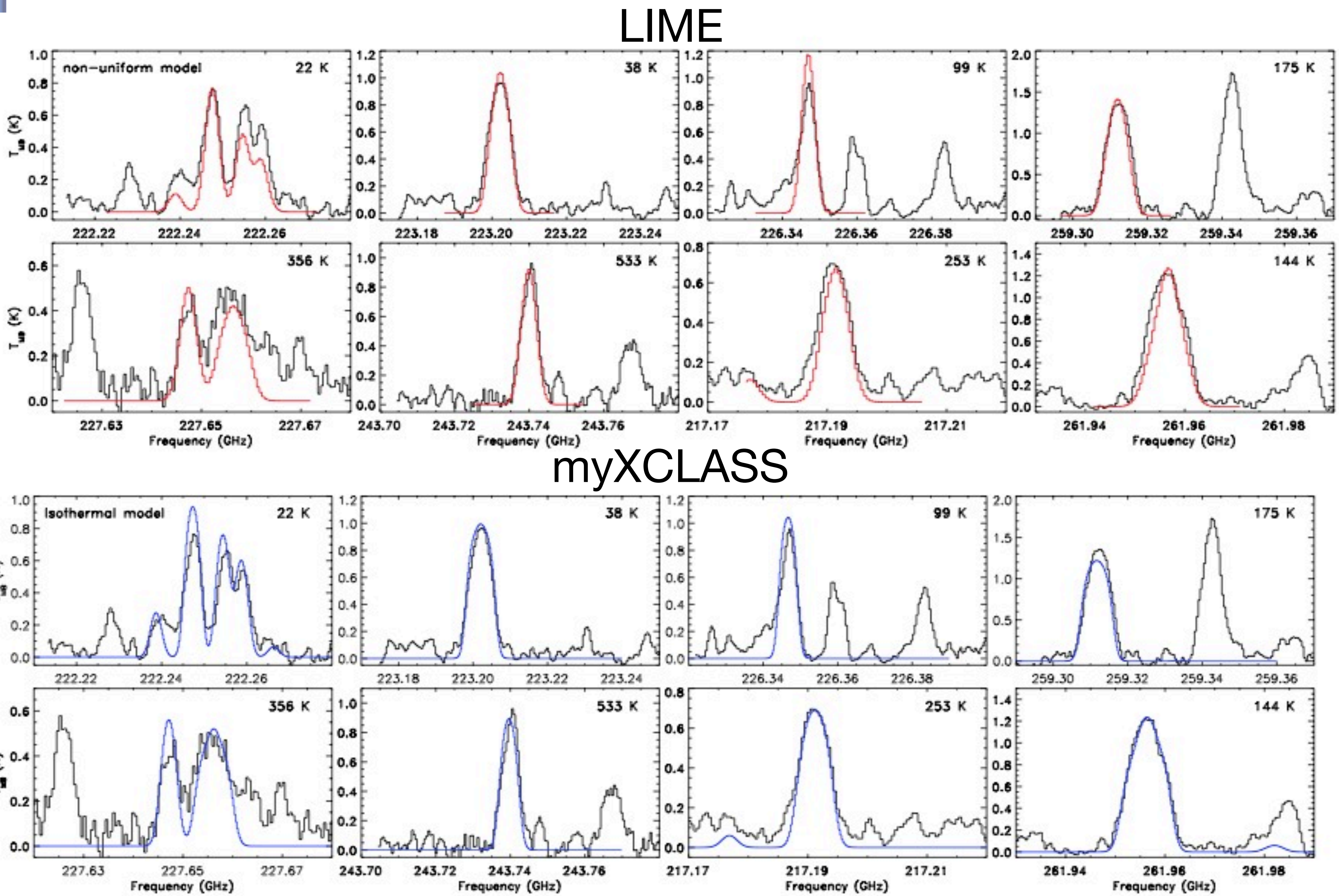
HIGH-RESOLUTION COMPLEX ORGANICS



(Bisschop et al., submitted)

CONCLUDING REMARKS

- Pick a code that is best suited to solve your particular problem.
- Radiative transfer modeling is (can be) very difficult, but the solutions are usually robust.
- High dimensional radiative transfer require high dimensional input models (where are the theorists?)