3D Radiative Transfer

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Outline Part I

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   - Star Formation
   - Radiative Transfer and MHD
   - Radiative Processes
2. Equations
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   - The Step to Line Transfer
   - Optimization Tools
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   - Waves in a kinetic World

Outline Part II

6. Images from Simulation Data

Low & High Mass Cloud Core Collapse
Observational versus Simulation Resolution

7. Inverse 3D Radiative Transfer

3D Density Structures from Images:
- ρ Ophiuchi D
- Barnard 68

The Best-Hidden Secret in Star Formation:
- Evidence for Disks around Massive Stars

8. AstroGrid-D

Connecting heterogeneous ressources
Middleware to schedule
- compute jobs
- queries
- telescopes
- work flows

Introduction

$$\frac{1}{\pi} \int_0^\infty d\lambda \; \kappa_{abs}(\lambda, \vec{x}) \int_{\bigcirc} d\vec{n}' \; I(\lambda, \vec{x}$$

Time [yrs] 10^3 10^4 10^5 10^6 10^7 solar-type

Magnetic fields?

Molecular Cloud Cores

1D/2D/3D? Fragmentation

External Initialization?

Turbulence?

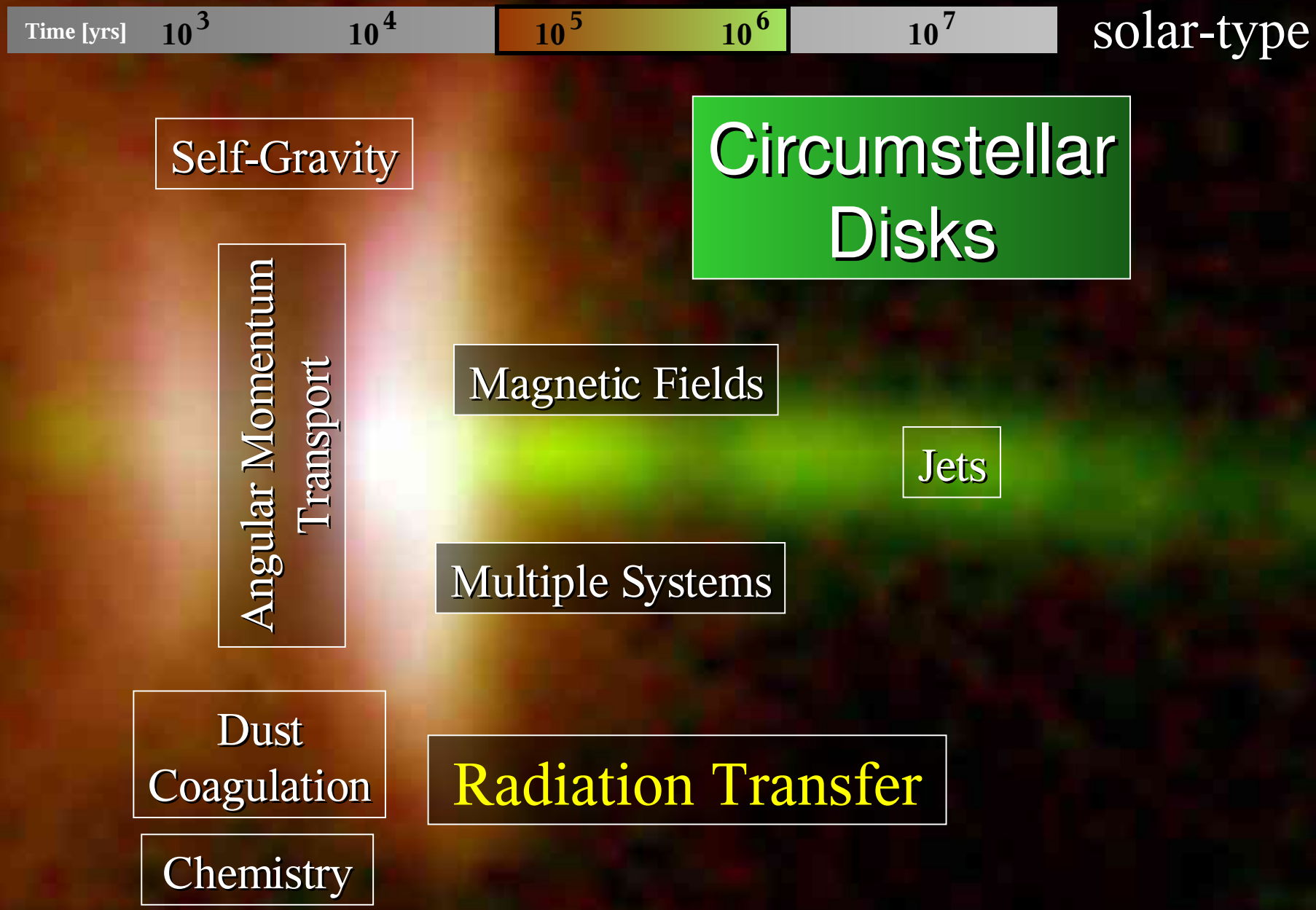
Dust

Cooling

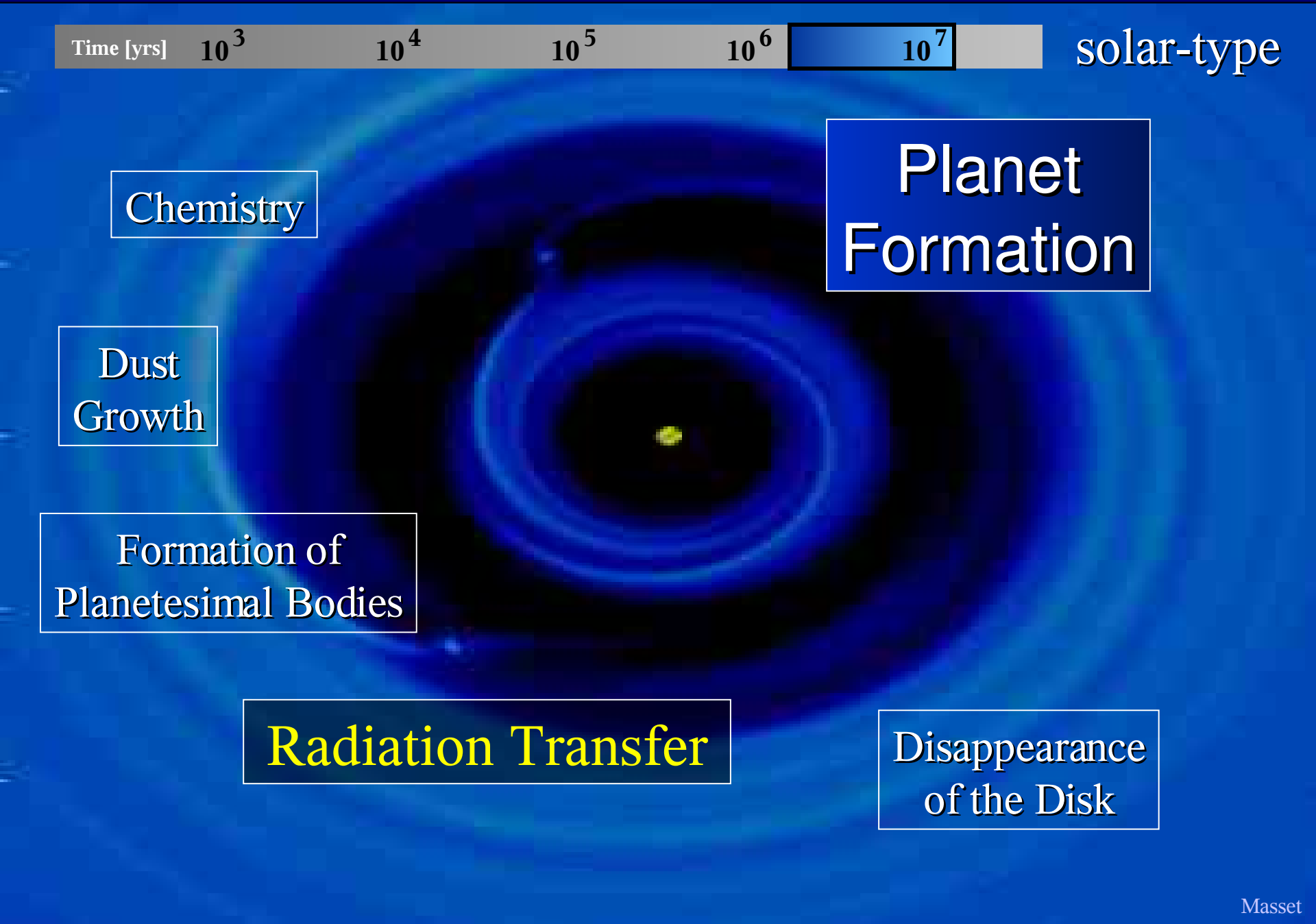
Chemistry

Radiation Transfer

Globules IC2944, HST



HH30, HST WFPC2


Time [yrs]
10^3
10^4
10^5
10^6
10^7
solar-type
Chemistry
Planet Formation
Dust Growth
Formation of Planetesimal Bodies
Radiation Transfer
Disappearance of the Disk

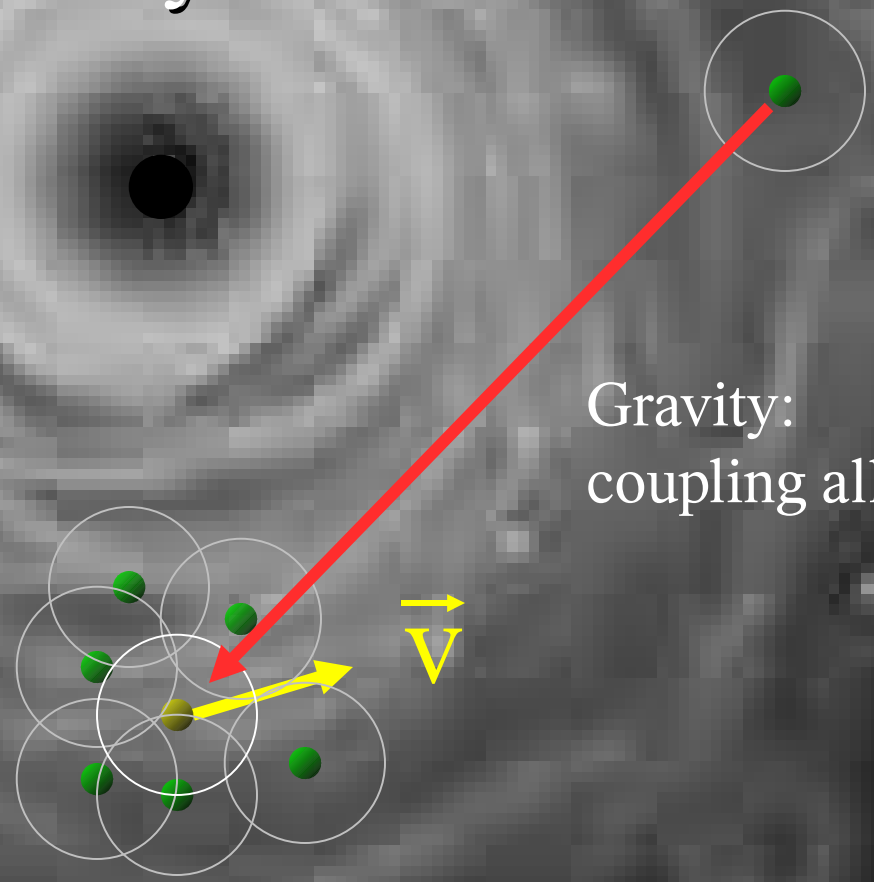
Masset

(Magneto-) Hydro Dynamics

4D

velocity field

$\vec{v}$ (x,y,z,t)

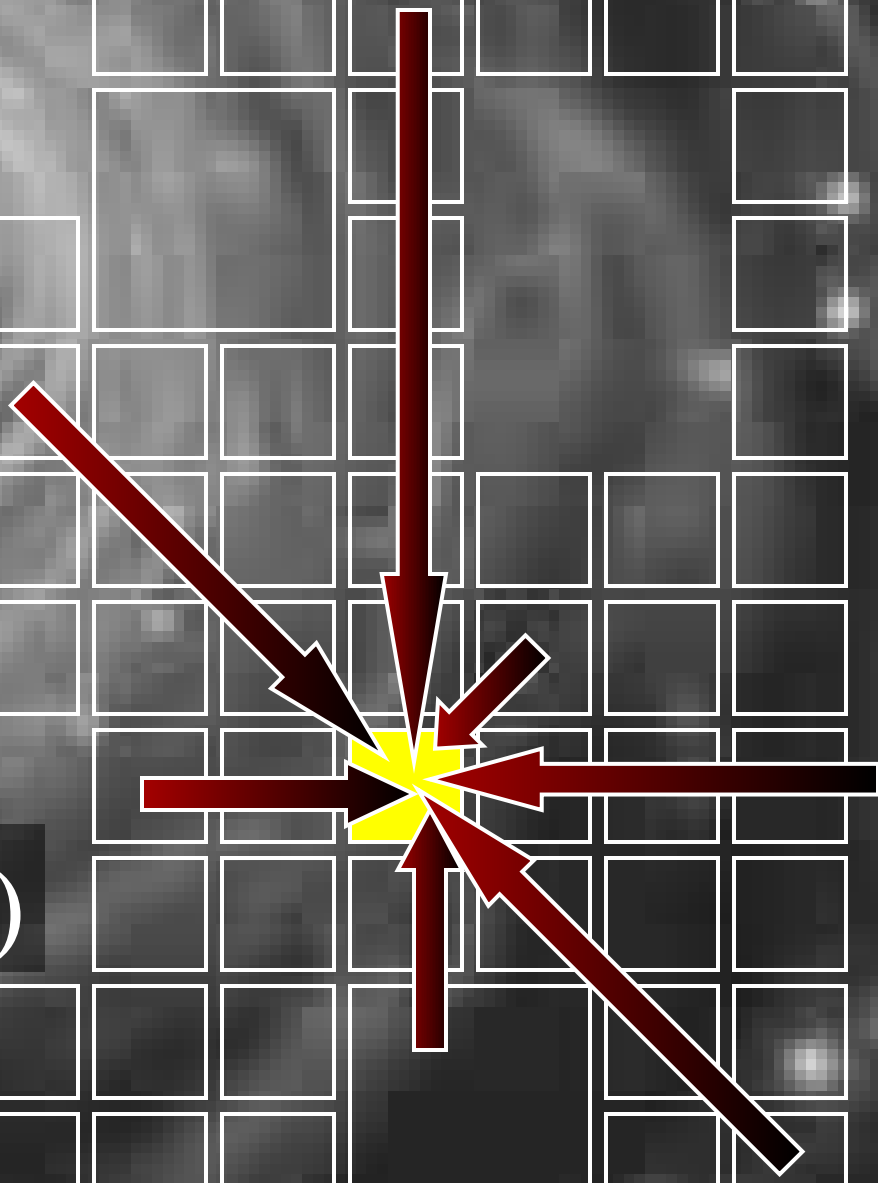


Gravity:
coupling all particles

Radiative Transfer

7D

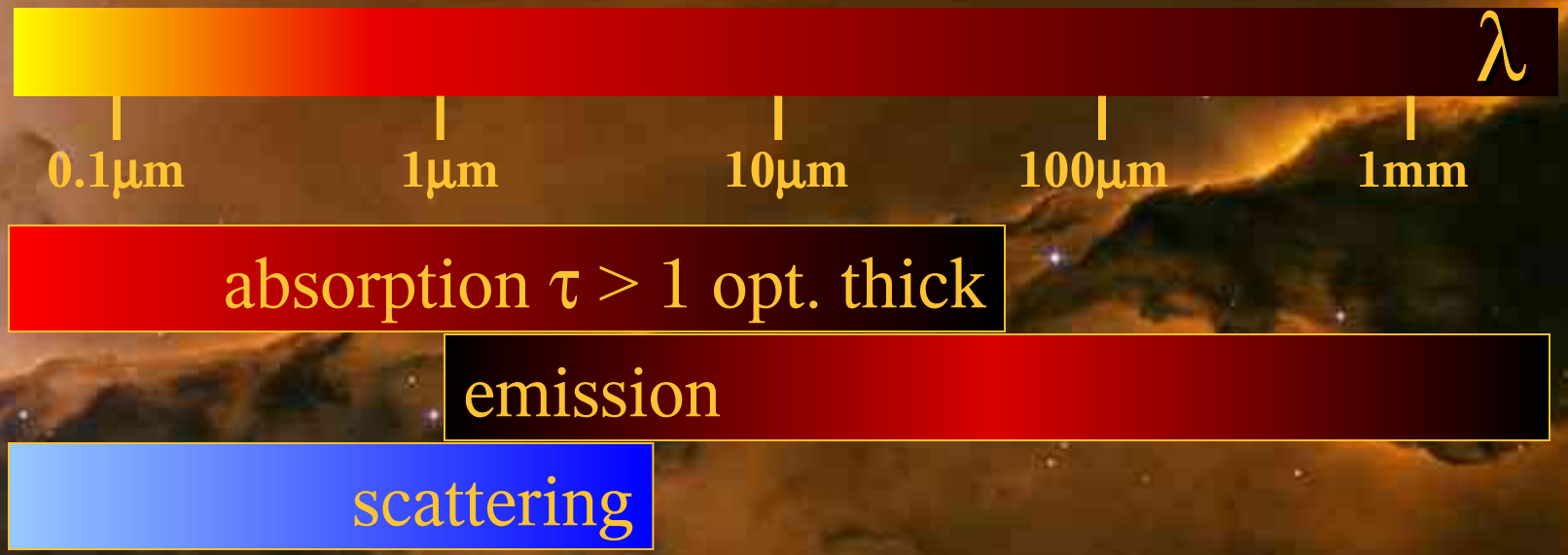
Interaction of all cells

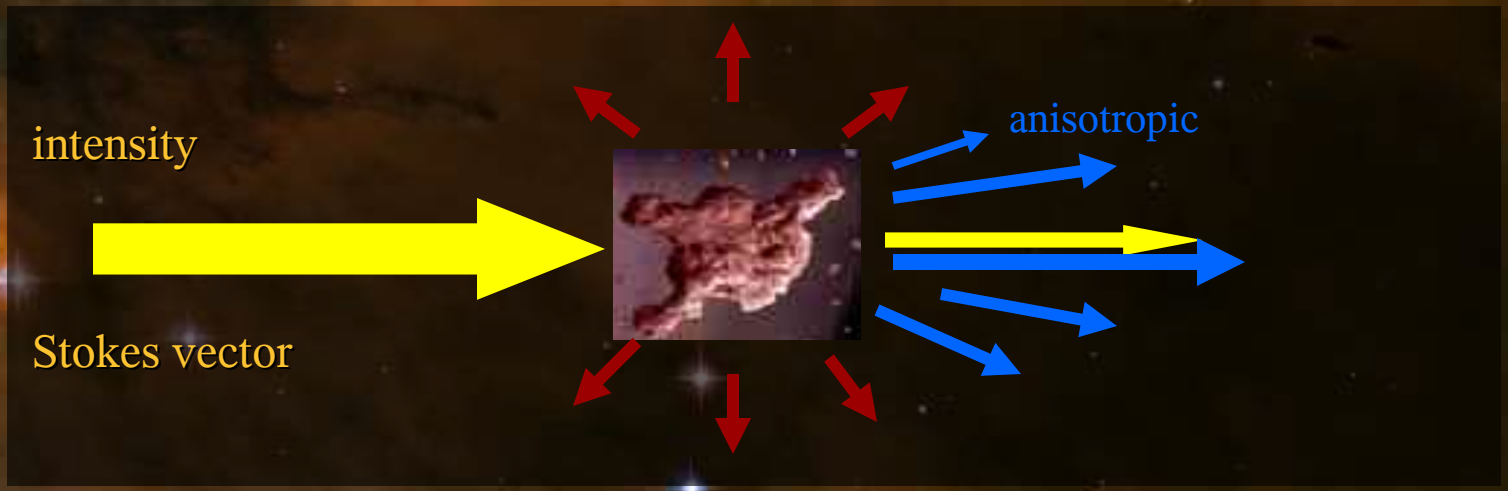


intensity

$I(\lambda, x, y, z, \theta, \phi, t)$

Radiative processes





3D Transport Equation for Continuum Radiation

$$\vec{n}\nabla_x I(\lambda, \vec{x}, \vec{n}) = -\kappa_{ext}(\lambda, \vec{x})\, I(\lambda, \vec{x}, \vec{n})$$

change of intensity *I* along a direction ***n***

extinction by dust particles

1.-order partial differential equation, solution vector ~ 10 GB

3D Transport Equation for Continuum Radiation

$$\vec{n}\nabla_x I(\lambda, \vec{x}, \vec{n}) = -\kappa_{ext}(\lambda, \vec{x})\ I(\lambda, \vec{x}, \vec{n})$$

$$+\kappa_{abs}(\lambda, \vec{x})\ B[\lambda, T(\vec{x})]$$

re-emission
by dust particles

3D Transport Equation for Continuum Radiation

$$\vec{n}\nabla_x I(\lambda,\vec{x},\vec{n}) = -\kappa_{ext}(\lambda,\vec{x})\ I(\lambda,\vec{x},\vec{n})$$
$$+\kappa_{abs}(\lambda,\vec{x})\ B[\lambda,T(\vec{x})]$$

local energy density equilibrium

$$\int_0^\infty d\lambda\ \kappa_{abs}(\lambda,\vec{x})\ B[\lambda,T(\vec{x})] =$$

all absorbed energy density

$$\frac{1}{4\pi}\int_0^\infty d\lambda\ \kappa_{abs}(\lambda,\vec{x})\int_{\bigcirc} d\vec{n}'\ I(\lambda,\vec{x},\vec{n}')$$

3D Transport Equation for Continuum Radiation

$$\vec{n}\nabla_x I(\lambda,\vec{x},\vec{n}) = -\kappa_{ext}(\lambda,\vec{x})\ I(\lambda,\vec{x},\vec{n})$$
$$+\kappa_{abs}(\lambda,\vec{x})\ B[\lambda,T(\vec{x})]$$

local energy density equilibrium

all re-emitted energy density

$$\int_0^\infty d\lambda\ \kappa_{abs}(\lambda,\vec{x})\ B[\lambda,T(\vec{x})] =$$

$$\frac{1}{4\pi}\int_0^\infty d\lambda\ \kappa_{abs}(\lambda,\vec{x}) \int_{\bigcirc} d\vec{n}'\ I(\lambda,\vec{x},\vec{n}')$$

3D Transport Equation for Continuum Radiation

$$\vec{n}\nabla_x I(\lambda,\vec{x},\vec{n}) = -\kappa_{ext}(\lambda,\vec{x})\; I(\lambda,\vec{x},\vec{n})$$

$$+\kappa_{abs}(\lambda,\vec{x})\; B[\lambda,T(\vec{x})]$$

scattering in the considered direction ***n***

$$+\frac{\kappa_{sca}(\lambda,\vec{x})}{4\pi}\int_{\bigcirc} d\vec{n}'\; p(\lambda,\vec{n},\vec{n}')\; I(\lambda,\vec{x},\vec{n}')$$

phase function

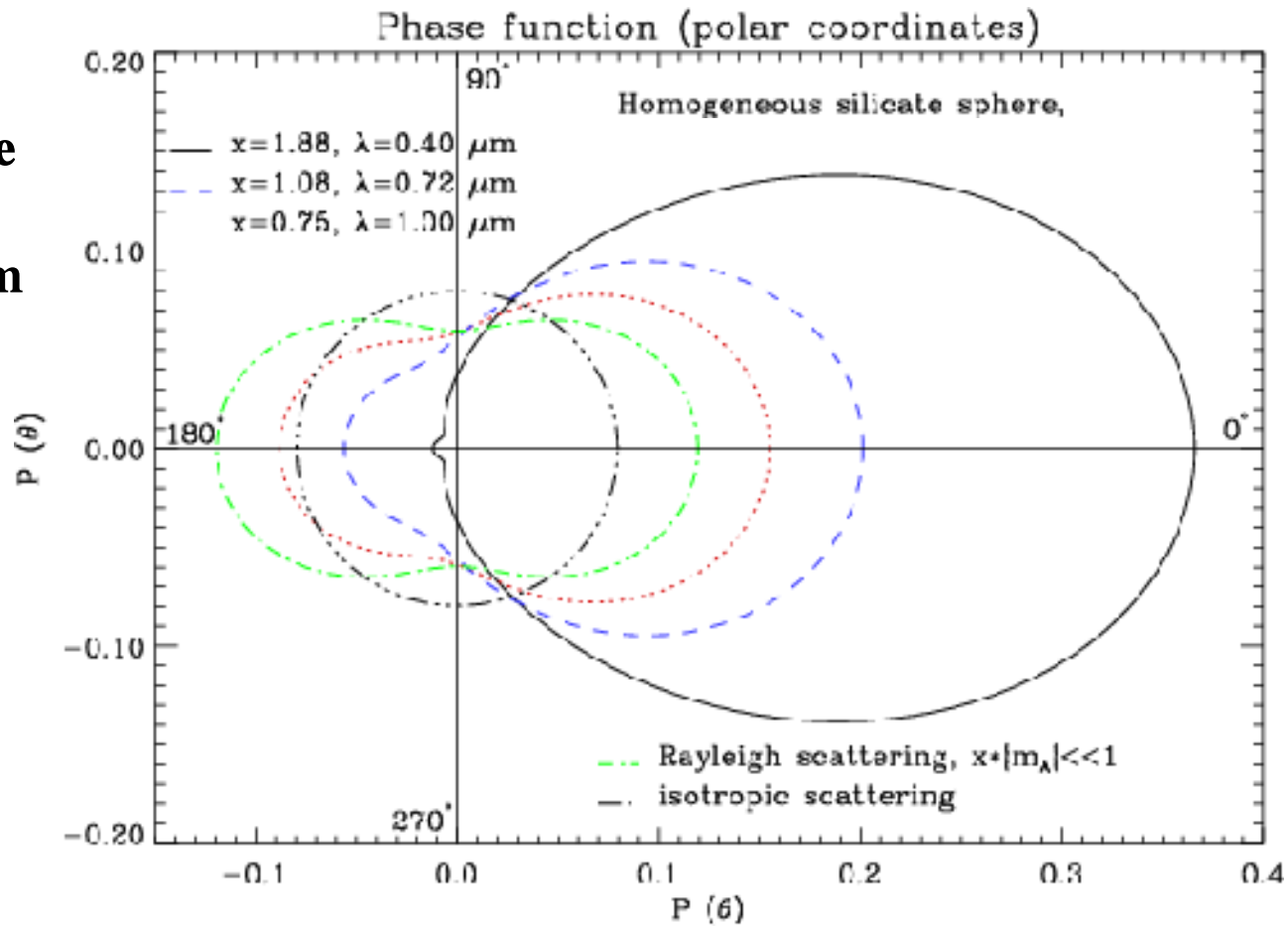
$$\int_0^\infty d\lambda\; \kappa_{abs}(\lambda,\vec{x})\; B[\lambda,T(\vec{x})] =$$

$$\frac{1}{4\pi}\int_0^\infty d\lambda\; \kappa_{abs}(\lambda,\vec{x})\int_{\bigcirc} d\vec{n}'\; I(\lambda,\vec{x},\vec{n}')$$

~~Isotropic~~ or anisotropic scattering?

$$+\frac{\kappa_{sca}(\lambda,\vec{x})}{4\pi}\int_{\bigcirc} d\vec{n}'\, p(\lambda,\vec{n},\vec{n}')\, I(\lambda,\vec{x},\vec{n}')$$

dust particle size: 0.12 µm

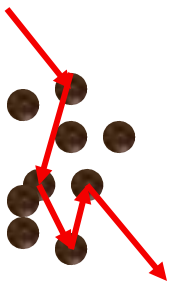


The most-used radiative transfer approximation in MHD:

Flux-limited Diffusion

Radiative transfer equation **into** moment equations

$$J_\nu = \frac{1}{4\pi}\int_\Omega I_\nu \, d\Omega \qquad H_\nu = \frac{1}{4\pi}\int_\Omega I_\nu \hat{\mathbf{s}} \, d\Omega. \qquad \text{etc.}$$



Diffusion (optically thick):

$$H \sim D \operatorname{grad} J$$

"Vacuum" (optically thin):

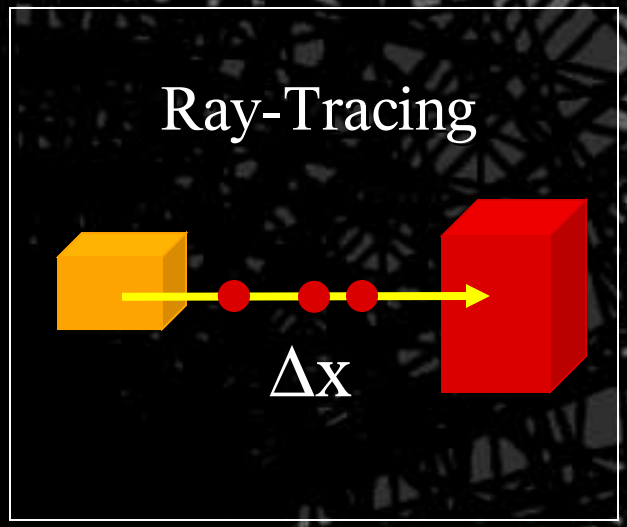
$$H \sim J$$

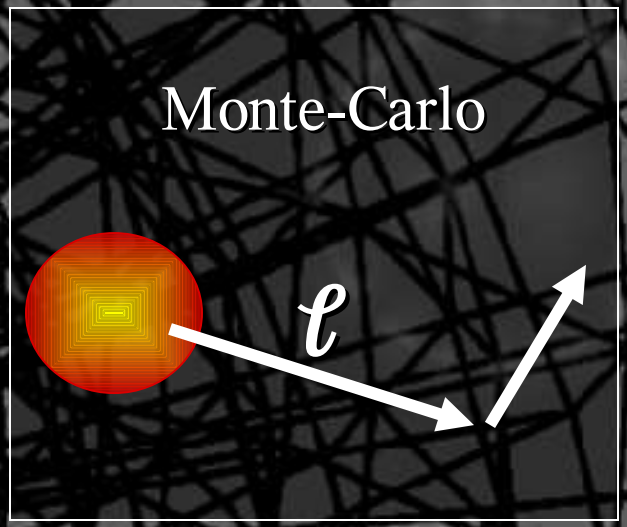
closure equation:

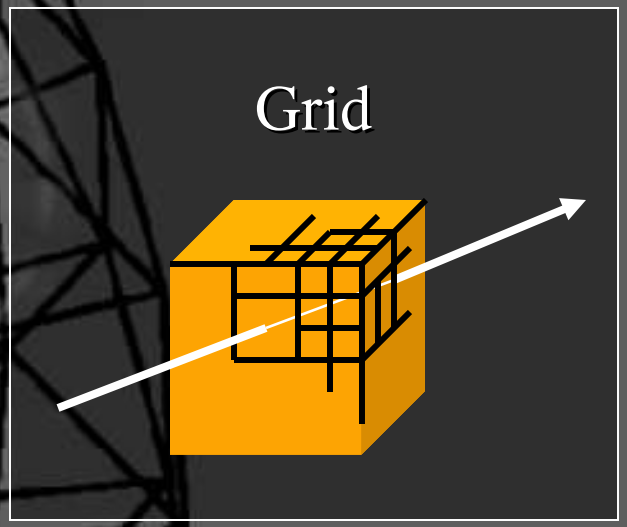
Levermore & Pomraning 1981:

Create a closure relation fitting both limiting cases

How to solve the radiative transfer equation?





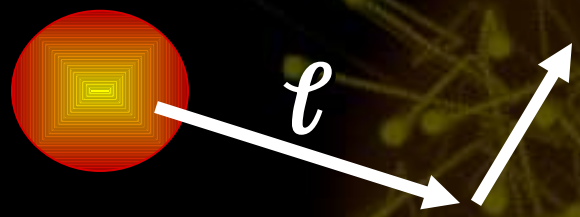


Others:
- Moment
- Spectral
- Multi-Grid
- Finite Volume
- …

Various approaches to improve the solution methods:
- Unstructured Grids
- Beam splitting
- Photon splitting
- …

How to solve the radiative transfer equation?

Monte-Carlo



Not a solution but a ***simulation*** technique:
Follow a photon interaction at ℓ

- Calculates interaction precisely (polarization)
- Flexible technique for complicated structures
- Code development within one PhD lifetime

- No explicit error control
- Problem with low and high optical depth

Task: Resolution in Monte Carlo Simulations

scattering

3a: How many photons have to be send to this location to cover all possible directions (isotropic scattering) with a mean resolution of about 10 degrees?

18*36=648 (500)

Task: Resolution in Monte Carlo Simulations

scattering

3b: How many photons are needed to cover the direction space after 6 scattering events with a mean resolution of about 10 degrees?

Task: Resolution in Monte Carlo Simulations

scattering

3b: How many photons are needed to cover the direction space after 6 scattering events with a mean resolution of about 10 degrees?

1.7×10^{15}

Task: Resolution in Monte Carlo Simulations

scattering

3c: During each interaction, ½ of the radiation is absorbed and distributed over the unit sphere. What is left of the intensity after 6 interactions?

Task: Resolution in Monte Carlo Simulations

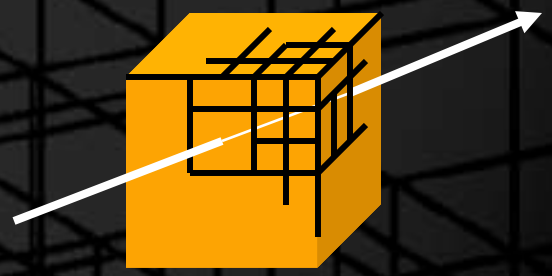
scattering

3c: During each interaction, ½ of the radiation is absorbed and distributed over the unit sphere. What is left of the intensity after 6 interactions?

4×10^{-9}

How to solve the radiative transfer equation?

Grid



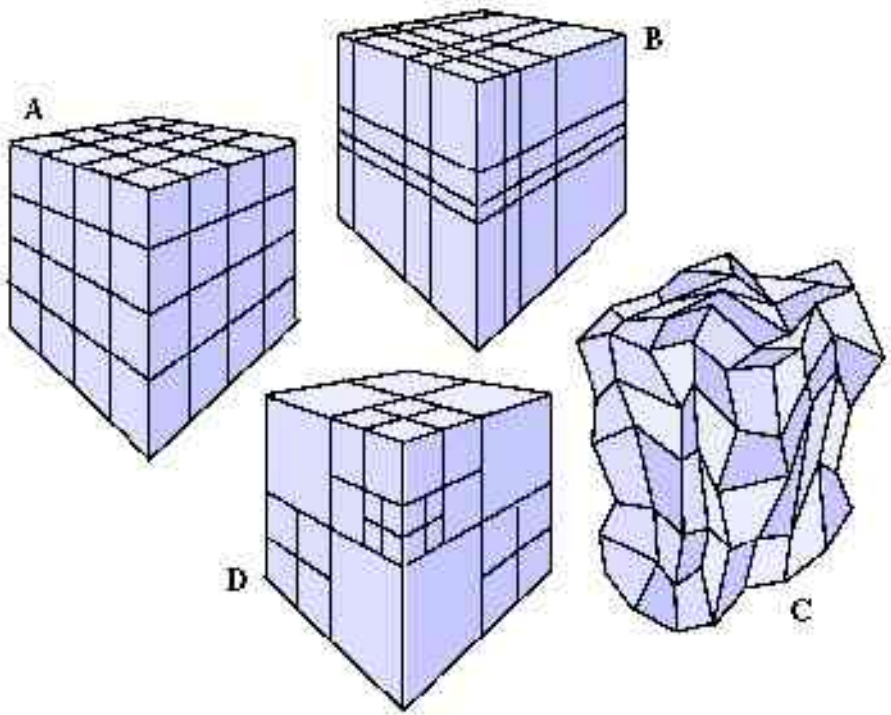
Technique:
Solve equation
on grid recursively

- Good portion can be precalculated (including errors)
- Flexible technique for complicated structures

- Numerical diffusion
- Interpolation errors
- Coarse direction resolution

Steinacker, Hackert, Steinacker, Bacmann 2002
Steinacker, Bacmann, Henning 2002

Adaptive grids for radiative transfer



Adapt to what?

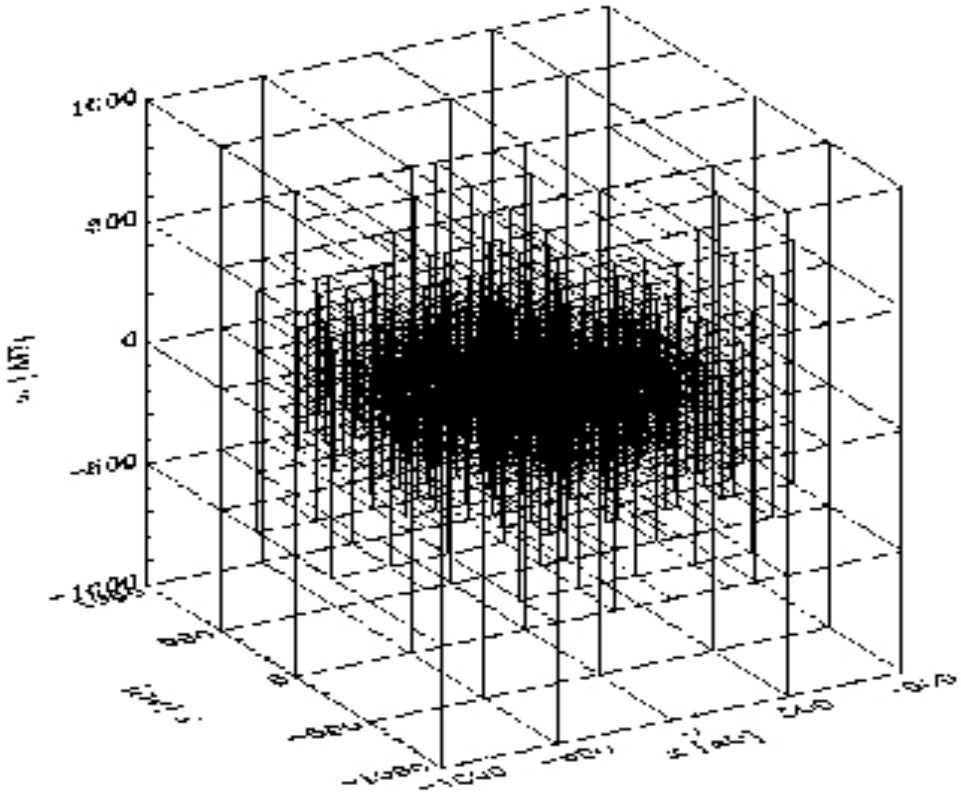
$$\tau = \kappa \, \Delta x << 1$$

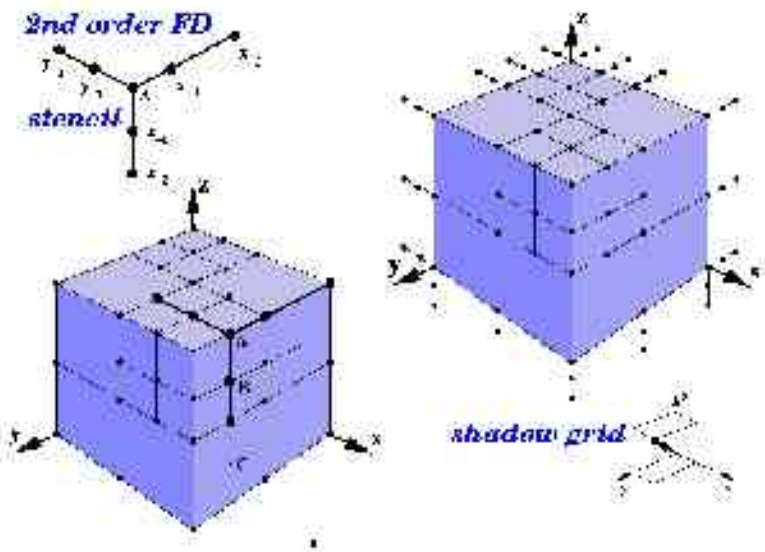
$$\tau(\lambda)!$$

Multi-wavelengths grids

Adaptive grids for radiative transfer

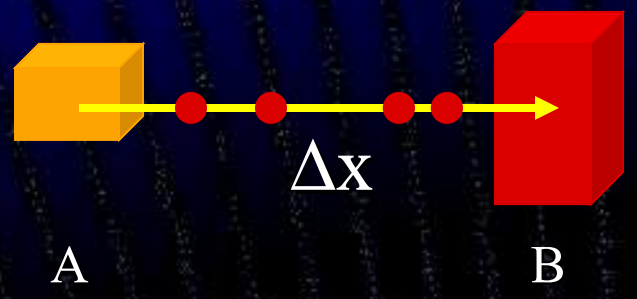
Steinacker, Bacmann, Henning 2002
Steinacker, Hackert, Steinacker, Bacmann 2002





How to solve the radiative transfer equation?

Ray-Tracing

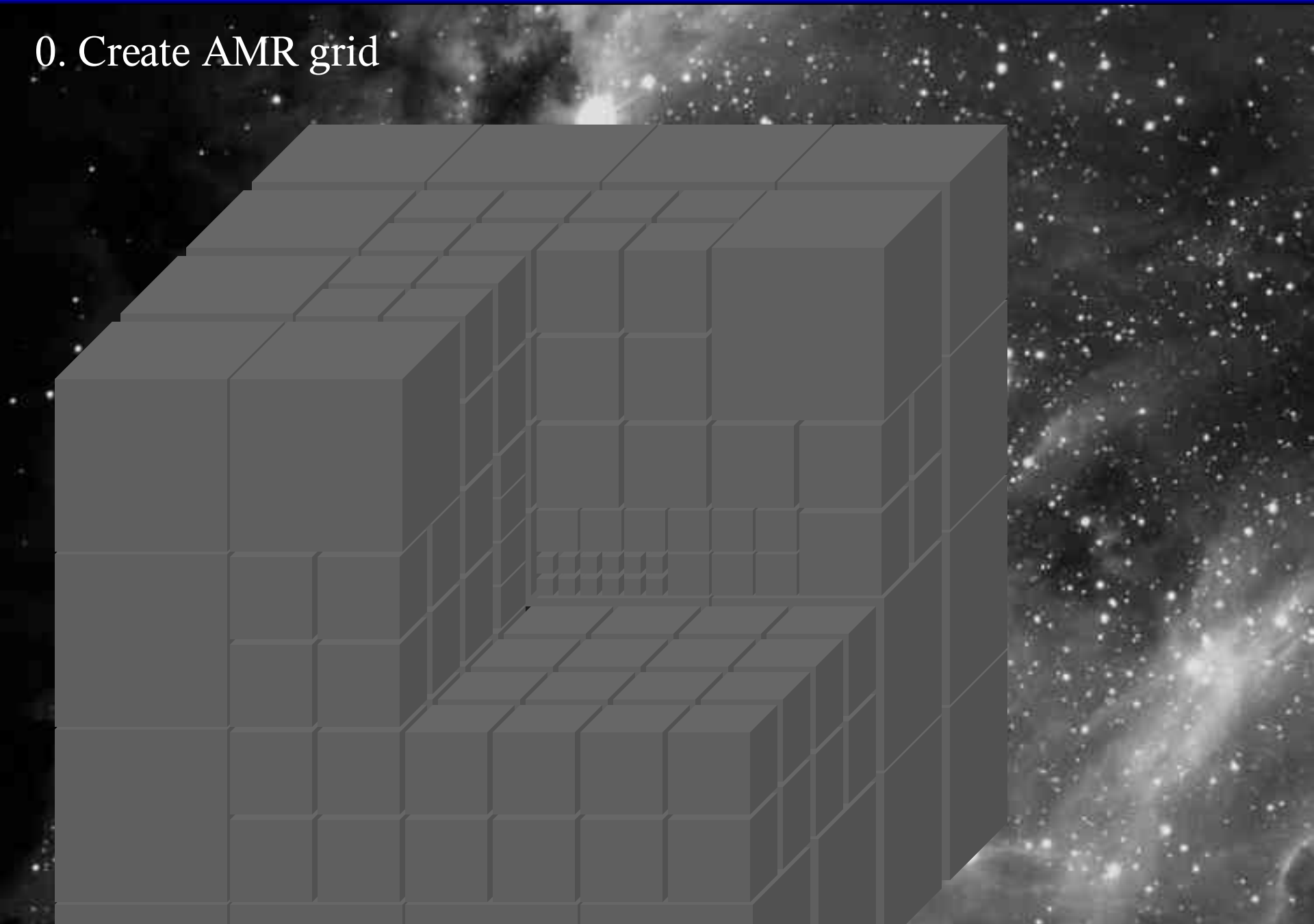


Technique:
Follow a ray
through the domain
calculating the change in I
from A to B

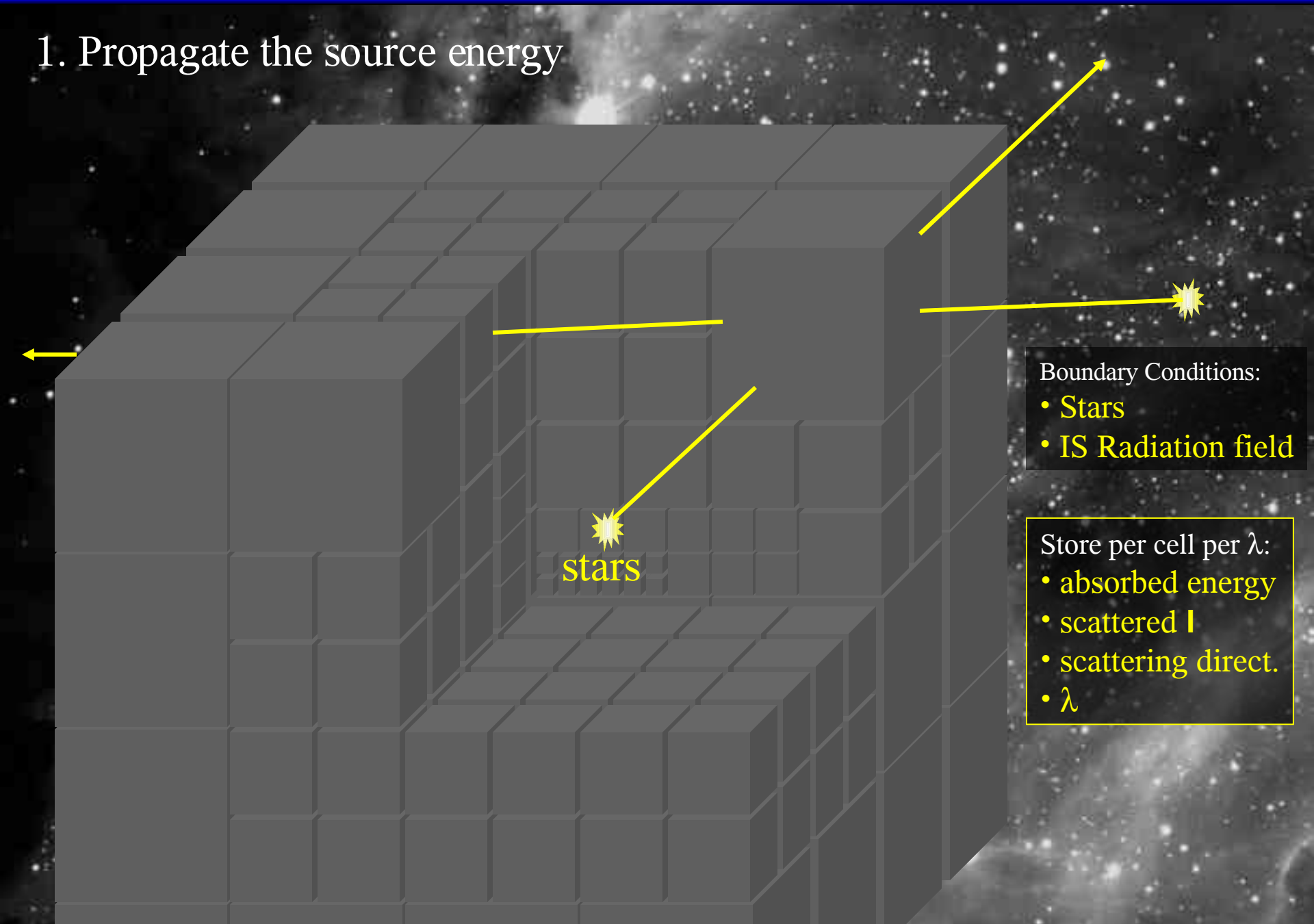
- Very accurate (e.g. high-order Runge Kutta)
- Allows for adaptive step size control (error control)

- Often calls the density function
- Problems with high optical depth

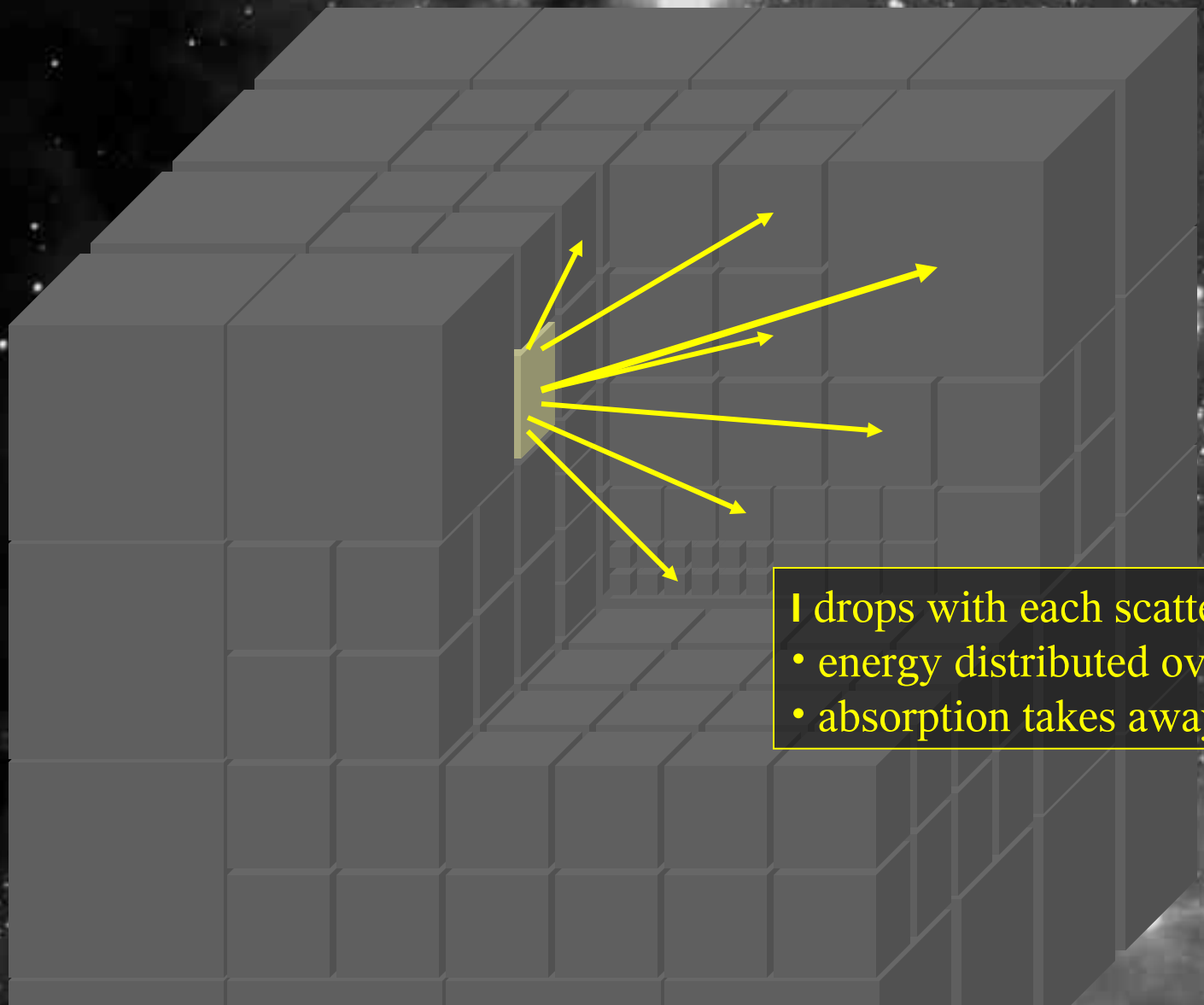
0. Create AMR grid



1. Propagate the source energy



2. Propagate the scattered radiation

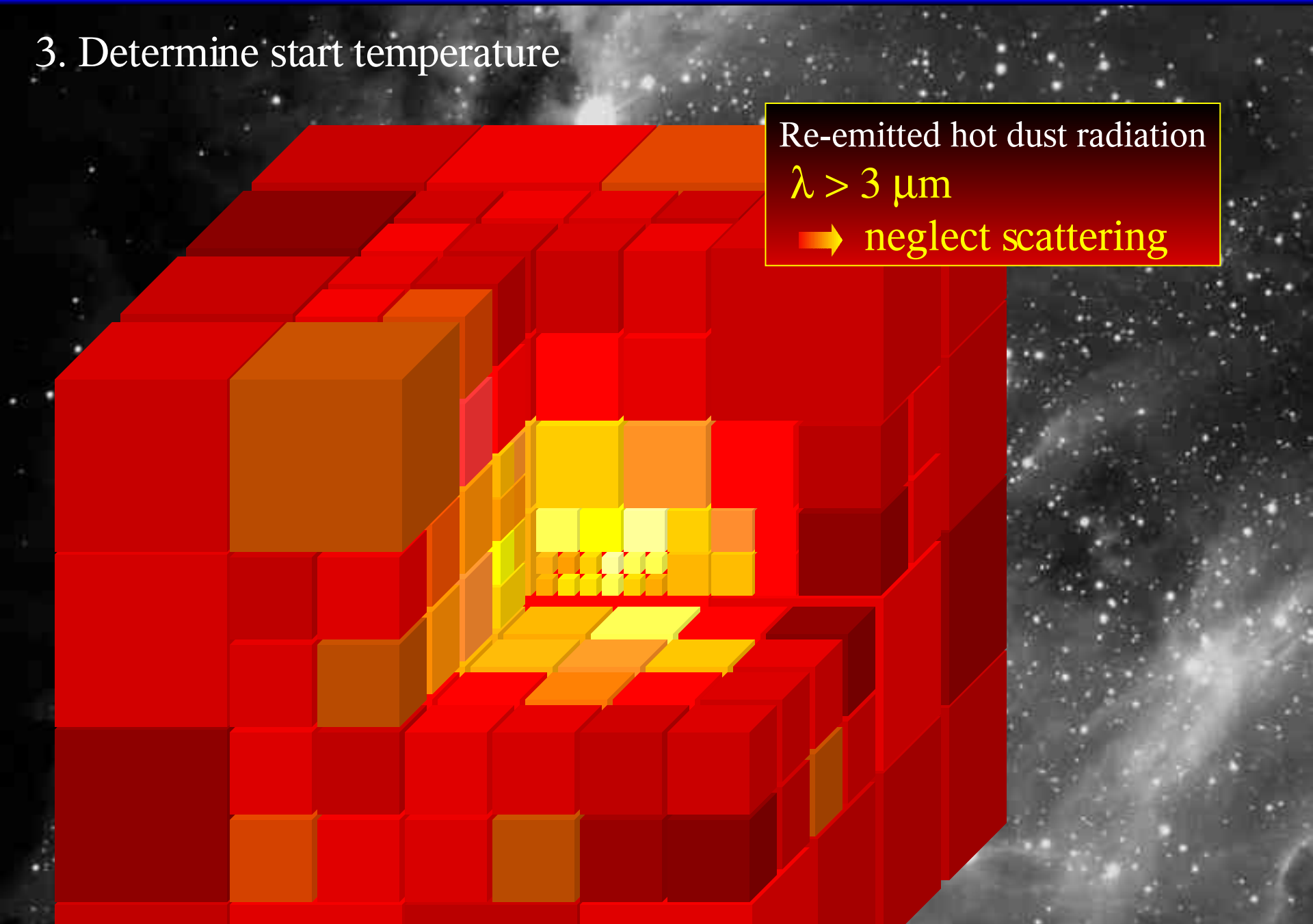


Per cell per λ:
- follow rays

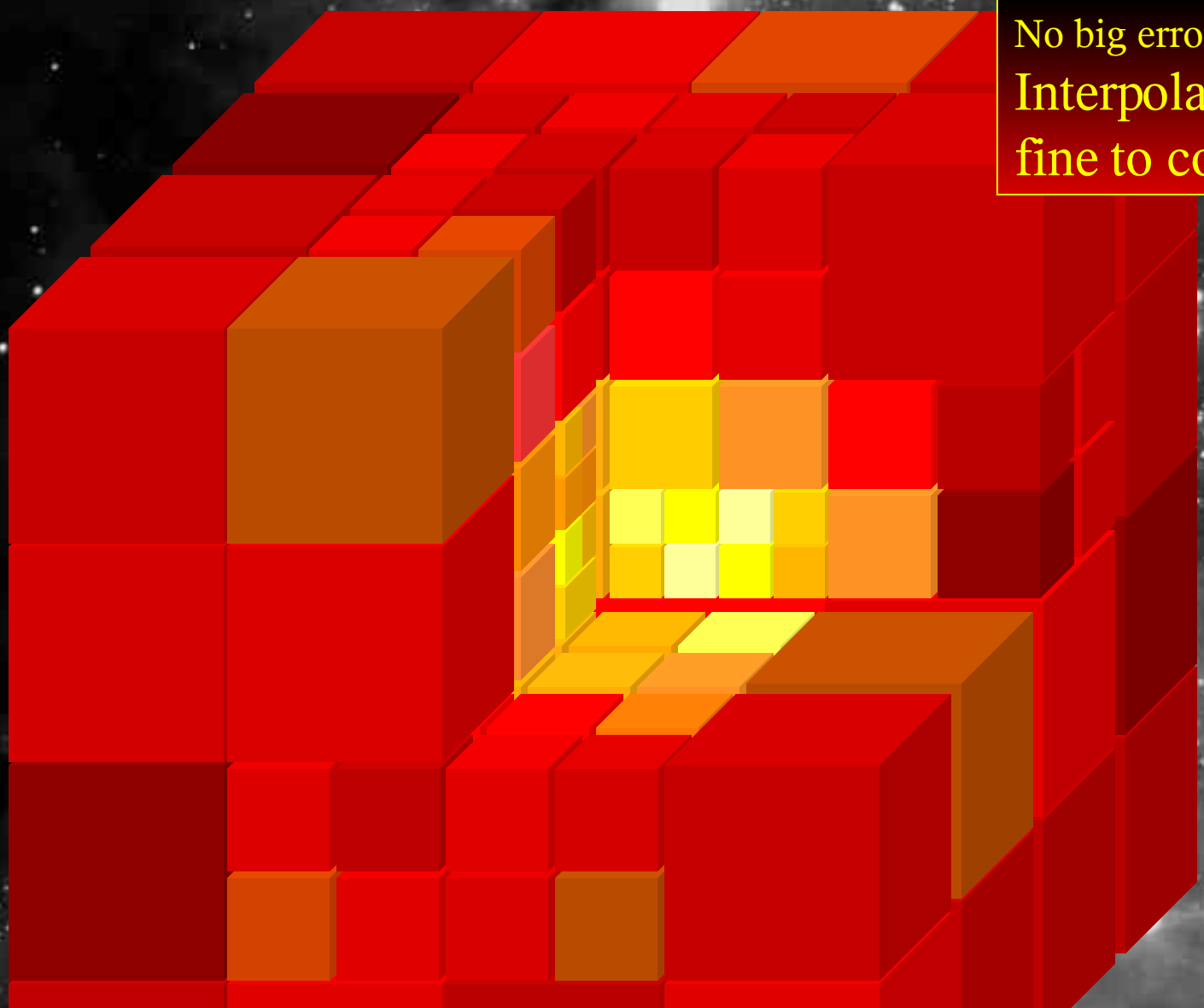
Store per cell per λ:
- absorbed energy
- scattered **I**
- scattering direct.
- λ

I drops with each scattering iteration:
- energy distributed over directions
- absorption takes away energy

3. Determine start temperature

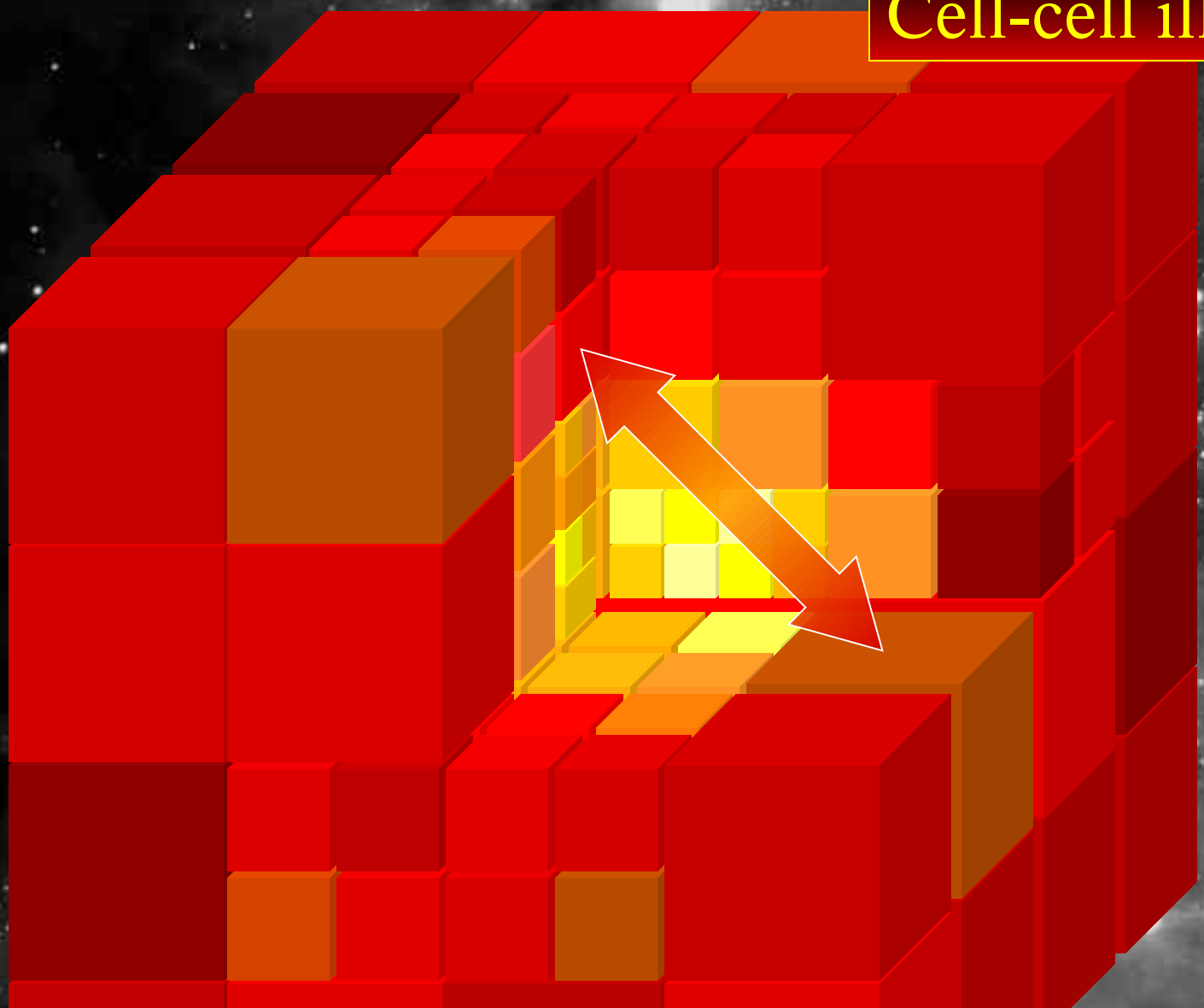


4. Switch to MIR grid



No big error:
Interpolation from fine to coarse grid

5. Determine temperature



Cell-cell illumination

for N cells:
N*N/2 steps

Steinacker, Bacmann, Henning 2006

Ray-tracing at high optical depth

optically thin

$\tau \sim 10^6$

optically thick

Ray-tracer is using diffusion limit

speed-up by factor 800

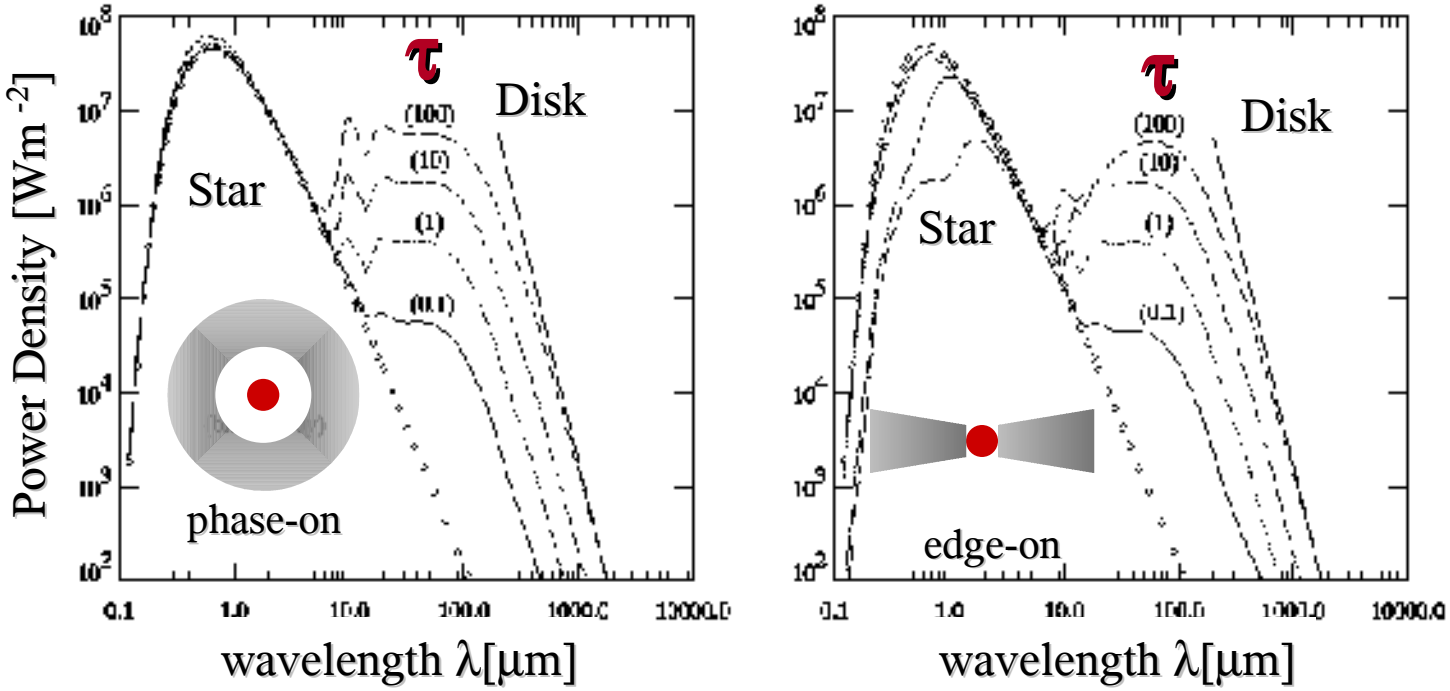
Hubble M17

Pascucci et al. 2004

2D SED Benchmark

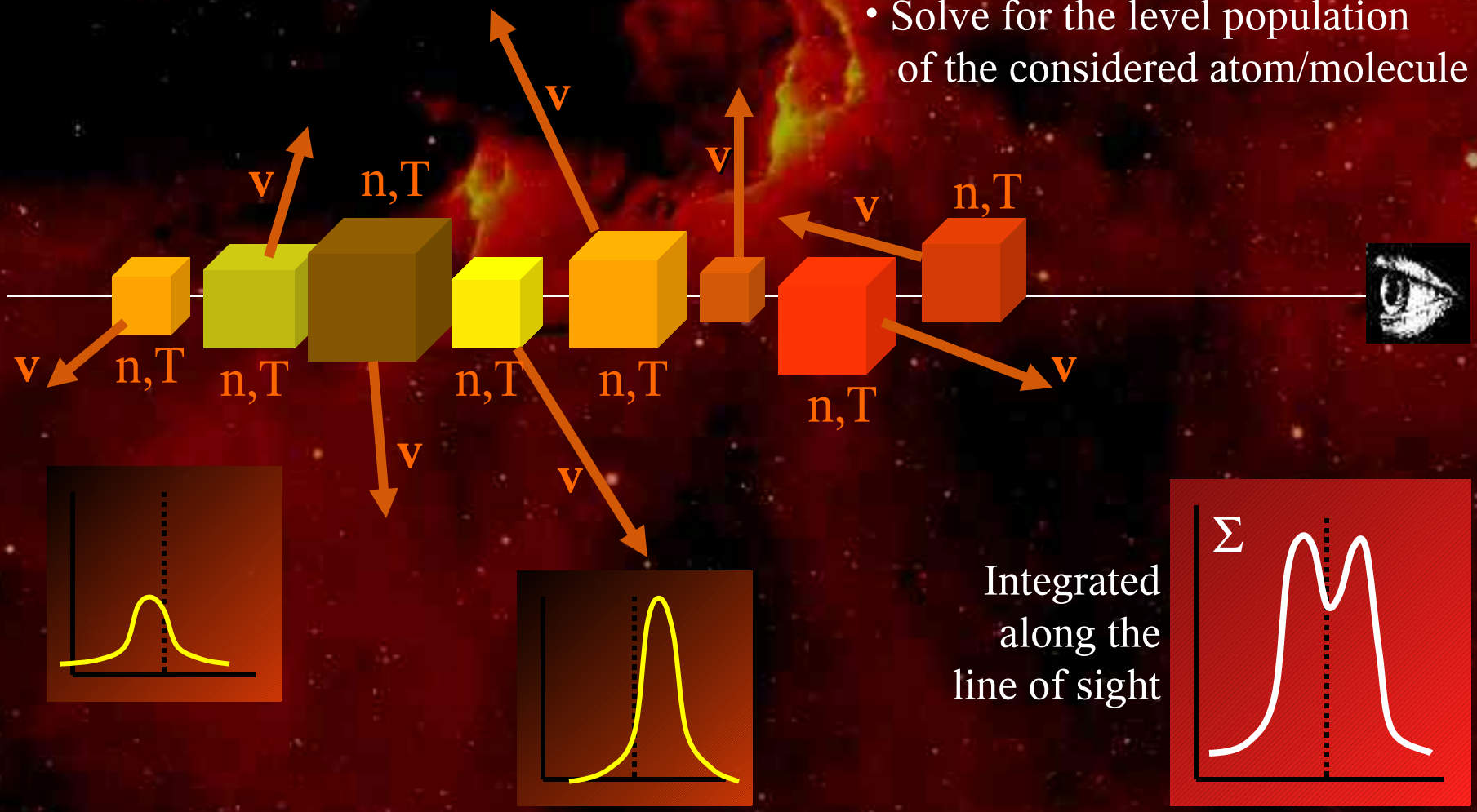
calculated with five state-of-the-art european continuum radiative transfer codes (Monte-Carlo & grid codes)

Spectral Energy Density: Star and Circumstellar Disk



Line transfer compared to continuum transfer

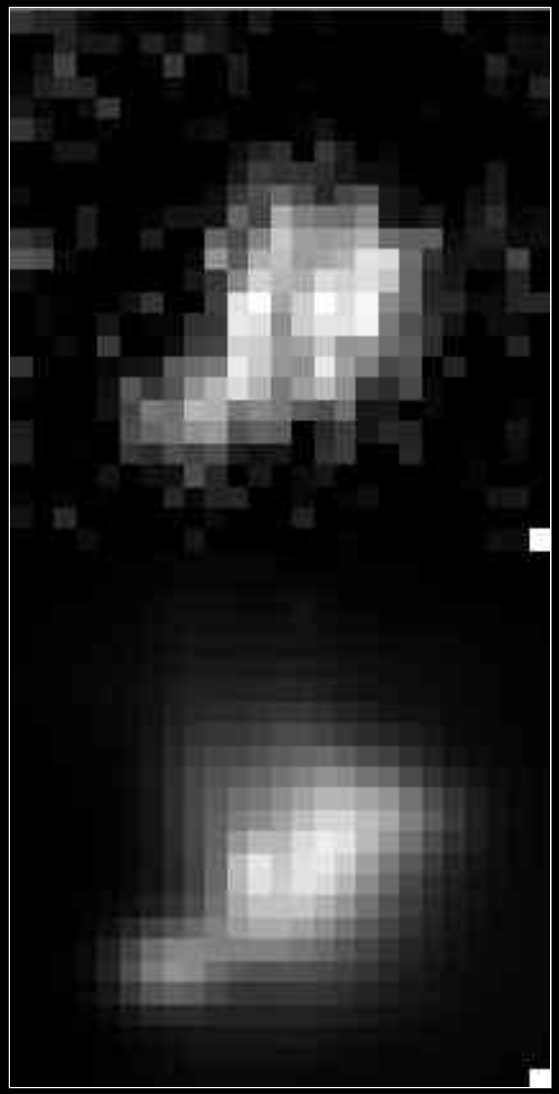
- Derivative with respect to λ
- Solve for the level population of the considered atom/molecule



Integrated along the line of sight

Fits incorporating many parameter

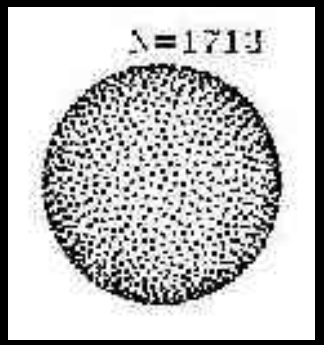
Thamm et al. 1994
Steinacker et al. 1996
Steinacker, Henning 2003
Steinacker et al. 2004



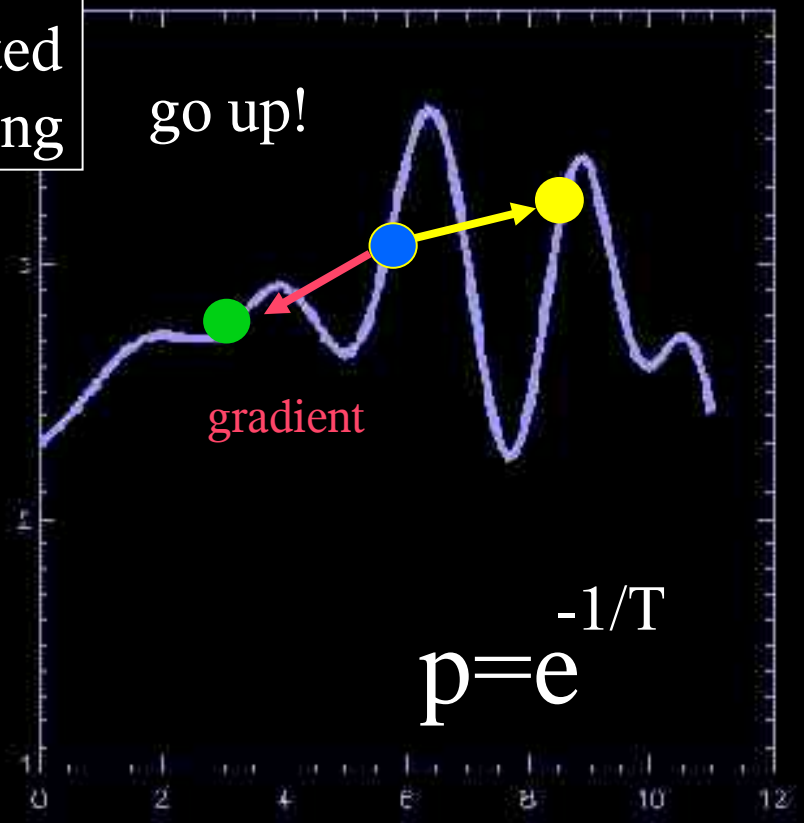
How to find the minimum of the χ^2?

How to cover the *entire* parameter space?

Simulated Annealing



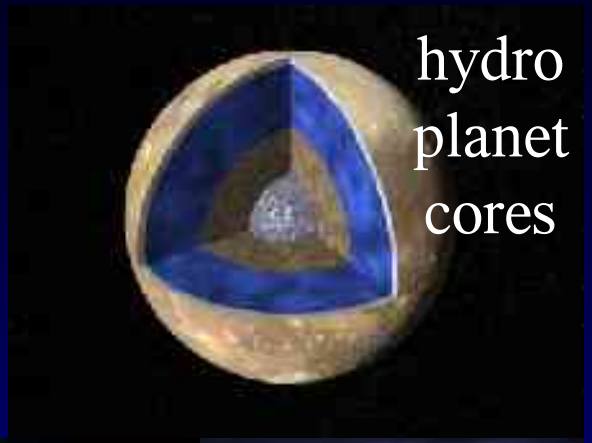
Cubature of the sphere

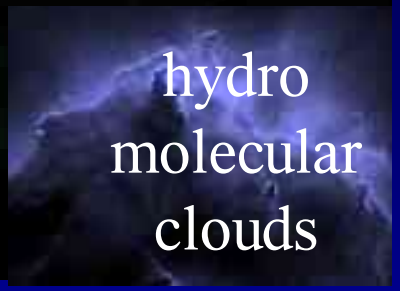


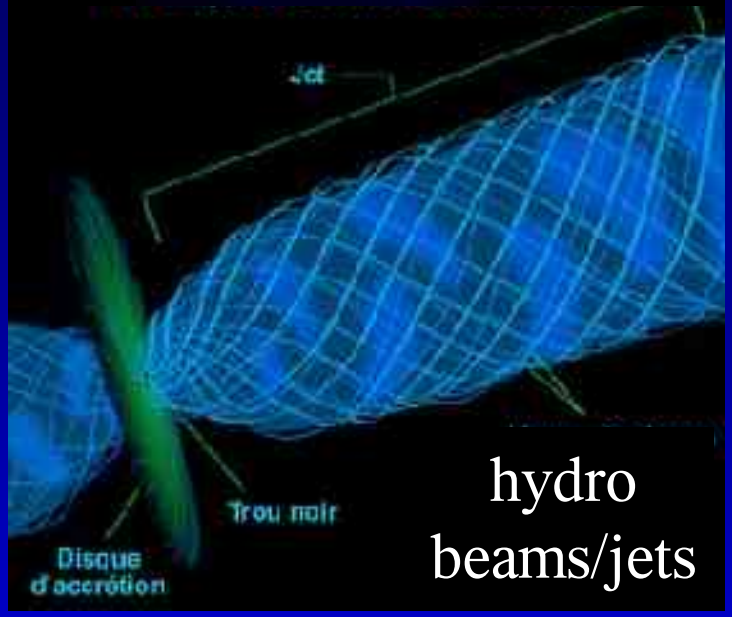
$$p=e^{-1/T}$$

Large group of fanatics:

The sect of fluid believers

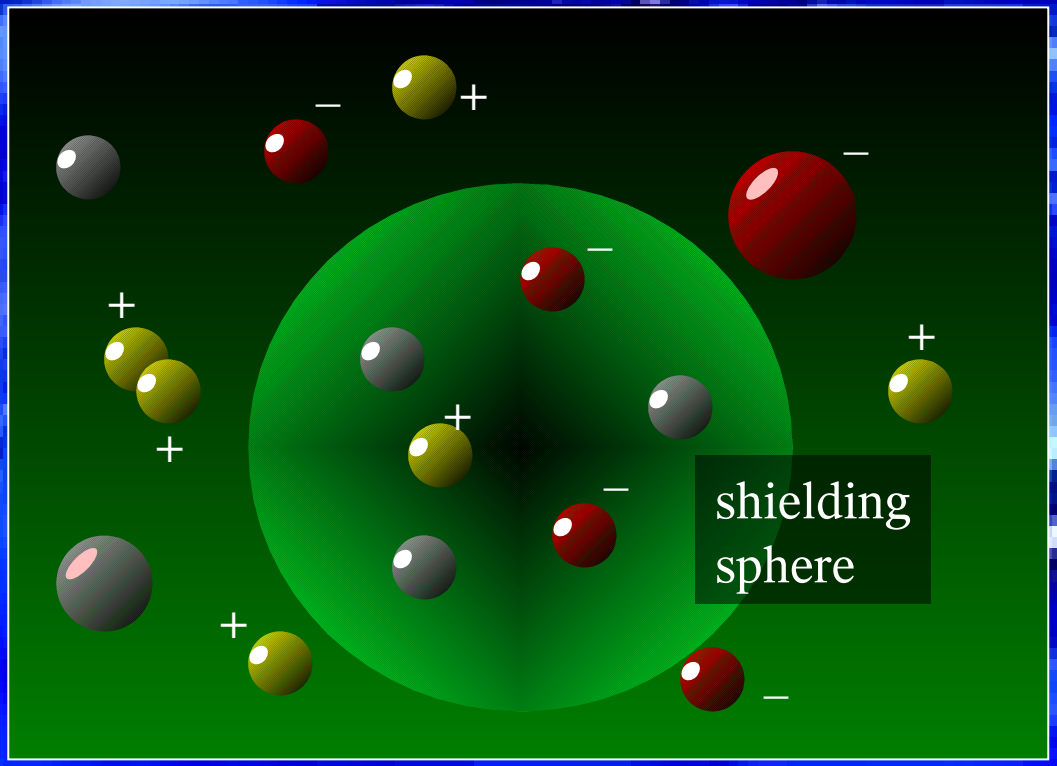






Beyond the fluid world ...

Beyond the fluid world ...



Kinetic theory

Where is each particles in phase space?
particle distribution

$$f(\vec{x}_1, \vec{v}_1, \vec{x}_2, \vec{v}_2, \ldots, \vec{x}_N, \vec{v}_N, t)$$

large number of particles N

How many particles
are in a certain phase space element?

$$f(\vec{x}, \vec{v}, t)$$

We need an equation.

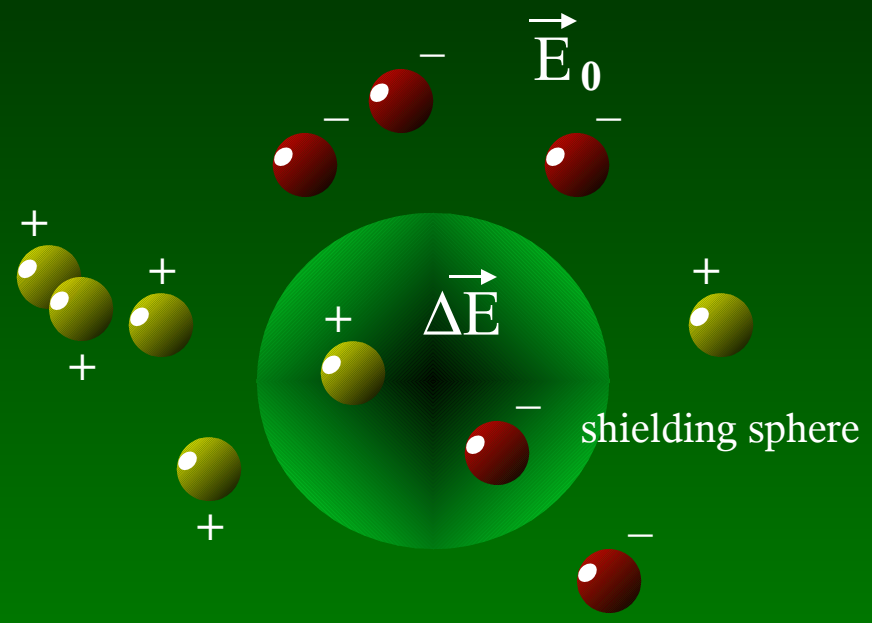
like: particle number constant over time

$$\frac{df}{dt} = 0$$

$$\boxed{df = \frac{\delta f}{\delta t} dt + \frac{\delta f}{\delta x_1} dx_1 + \ldots + \frac{\delta f}{\delta v_3} dv_3}$$

Particle distribution function:

$$f(\vec{x}, \vec{v}, t)$$



$$d\vec{v} = \frac{q}{m}\left(\vec{E} + \frac{1}{c}\vec{v} \times \vec{B}\right) dt$$

Lorentz force

$$\vec{E} = \vec{E}_0 + \Delta\vec{E}$$

"Boltzmann equation"

A special case...

Moments of the Boltzmann equation

integrate over d^3v: continuity equation

$*mv$, integrate over d^3v: momentum equation

$*mv^2$, integrate over d^3v: energy equation

sum over all particles

because collisions are keeping them together

charge density = 0

equation of state: incompressible/isothermal/adiabatic

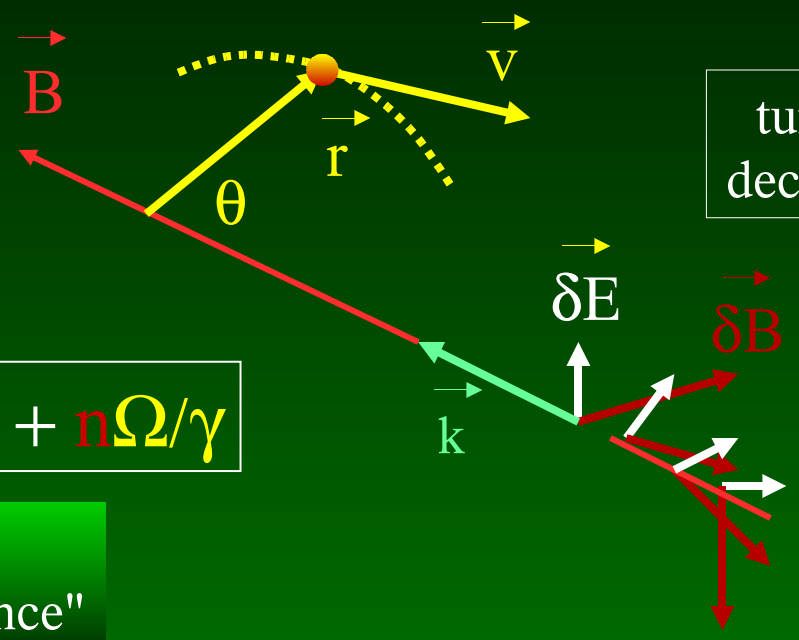
MHD

Acceleration of high-energy solar particles

Steinacker, Schlickeiser, Dröge 1989
Schlickeiser, Steinacker 1989
Steinacker, Schlickeiser 1989
Bech, Steinacker, Schlickeiser 1990
Achatz, Steinacker, Schlickeiser 1991
Steinacker, Miller 1992
Miller, Steinacker 1992
Steinacker, Jaekel, Schlickeiser 1993

Electrons
Protons
Ions
thermal to
highly relativistic

When f (θ)
gets anisotropic?



turbulence spectrum
decay of plasma waves

$$\omega = kv \cos\theta + n\Omega/\gamma$$

Alfvén-, Whistler-,
ion cyclotron waves

"Co-moving
gyro-resonance"

wave polarization

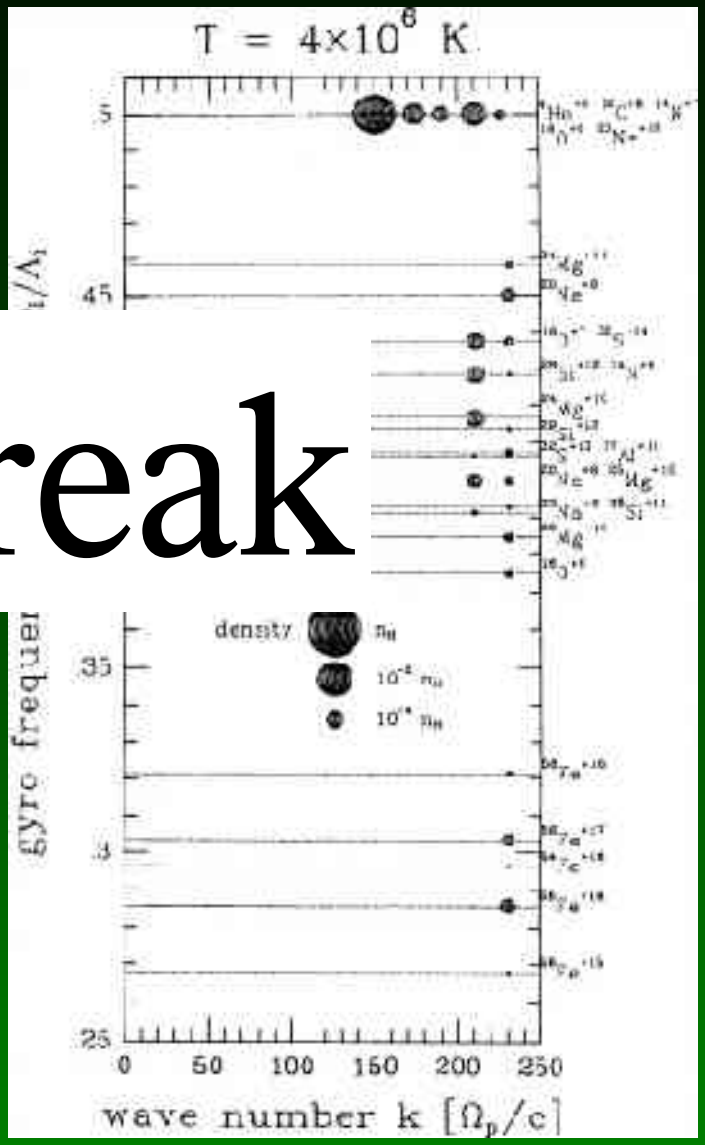
Dispersion relation

Steinacker, Meyer, Steinacker, Reames 1997

Warm p-e-He-plasma:

$$\{[k^2c^2\cos^2\theta - \omega_c^2 K_1][k^2c^2 - \omega_c^2(K_0+K_1)] + \omega_c^4 K_2^2\}\omega_c^2 K_3$$
$$+ k^2c^2\sin^2\theta\{[k^2c^2 - \omega_c^2(K_0+K_1)]\omega_c^2 K_1 - \omega_c^4 K_2^2\}$$
$$+ \omega_c^2 K_4[k^2c^2 -$$
$$-\omega_c^2 K_5\{[k^2c^2 \text{ c}$$
$$+ \omega_c^2 K_2[k^2c^2 \text{ si}$$

5 min break



Numerics:
Muller method with extreme accuracy:
Each number has to be stored with
1000 digits

Image construction

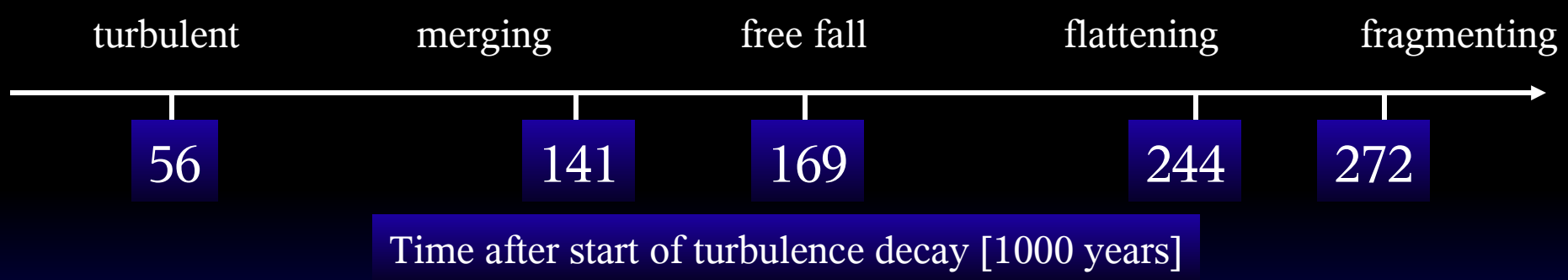
Forward 3D Radiative Transfer

density → image

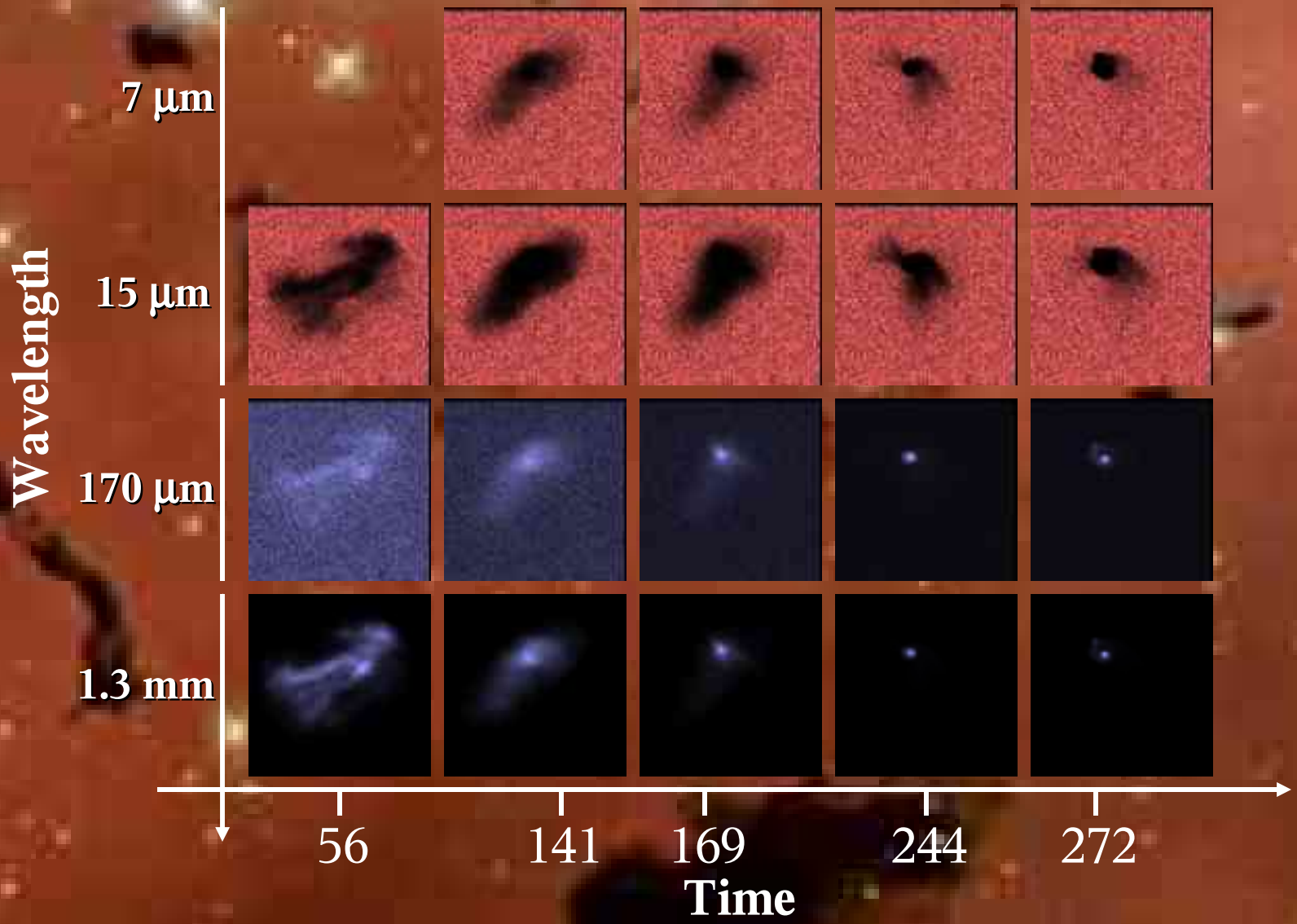
Evolution of a collapsing low-mass cloud core

Steinacker, Lang, Burkert, Bacmann, Henning 2004

Smoothed Particle Hydrodynamics



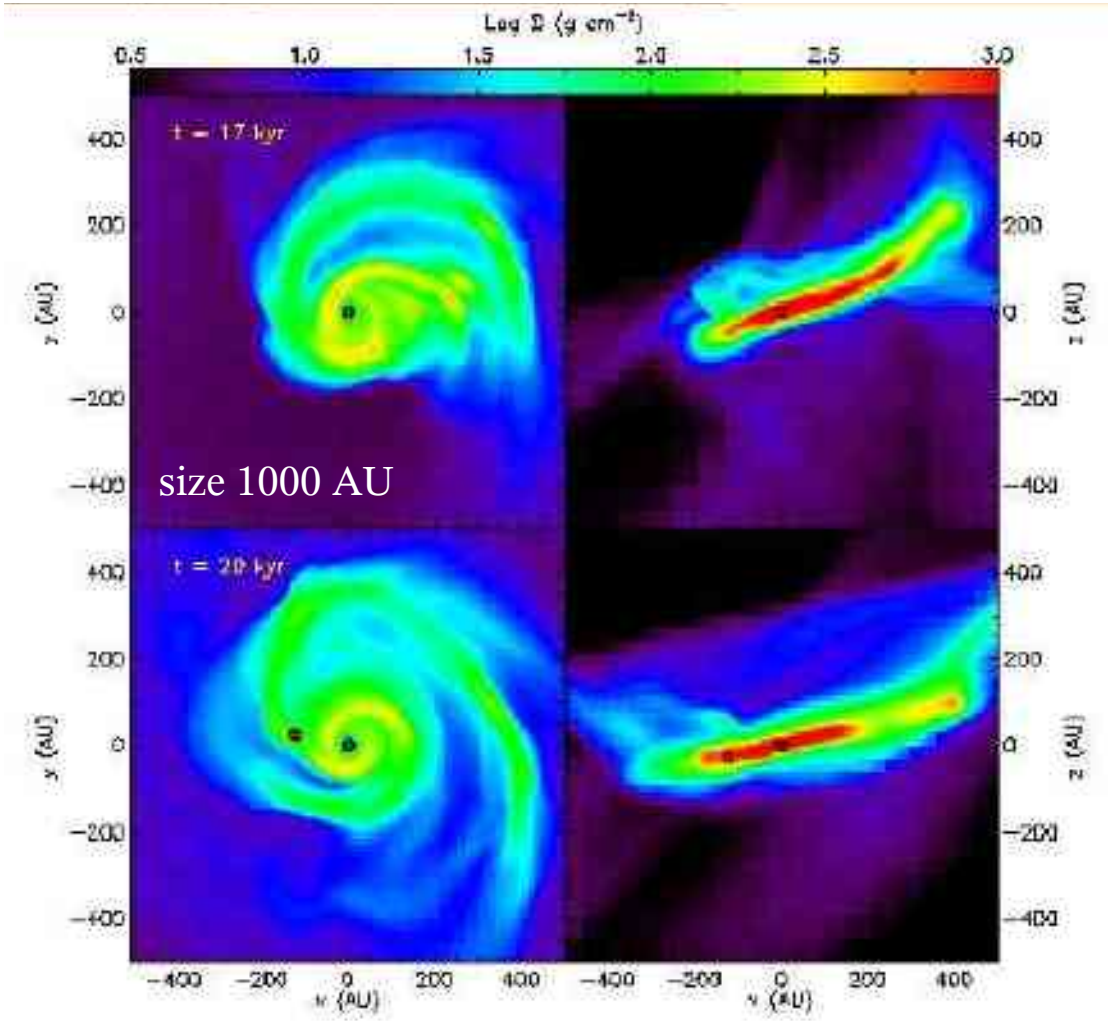
Produce images of the core evolution



3D HD collapse of a massive molecular cloud core

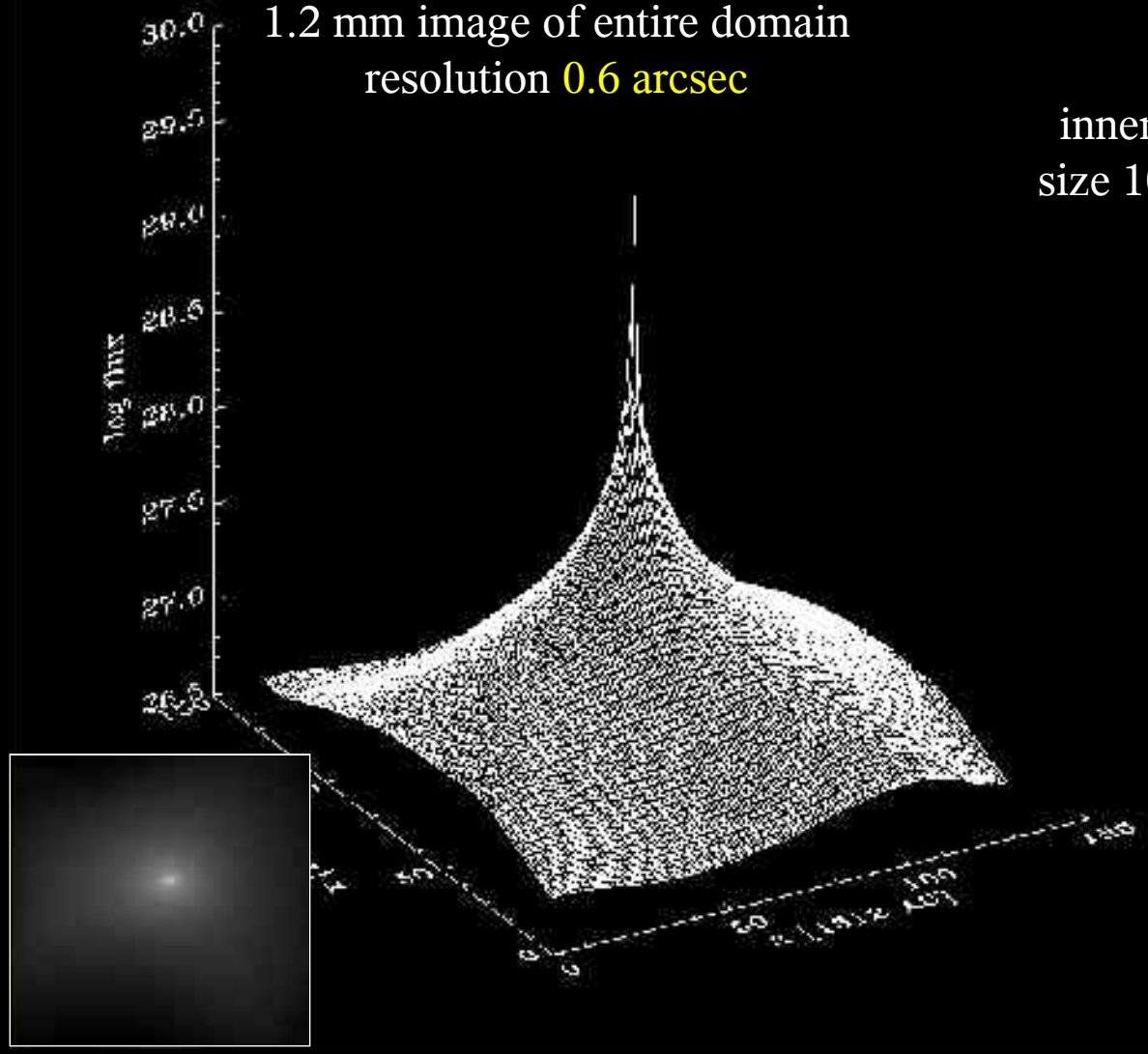
Krumholz, Klein & McKee 2006

ORION MHD AMR code with flux-limited diffusion

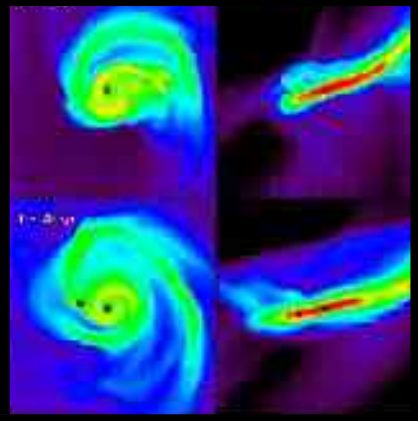


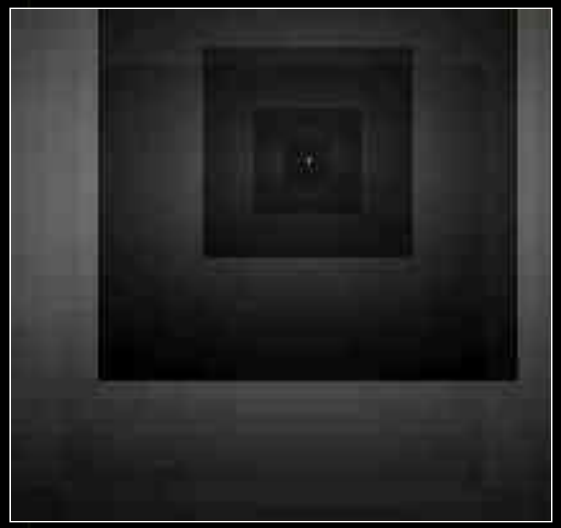
Resolving the inner part of a massive core at a distance of 2 kpc

1.2 mm image of entire domain
resolution 0.6 arcsec



inner pixel:
size 1000 AU





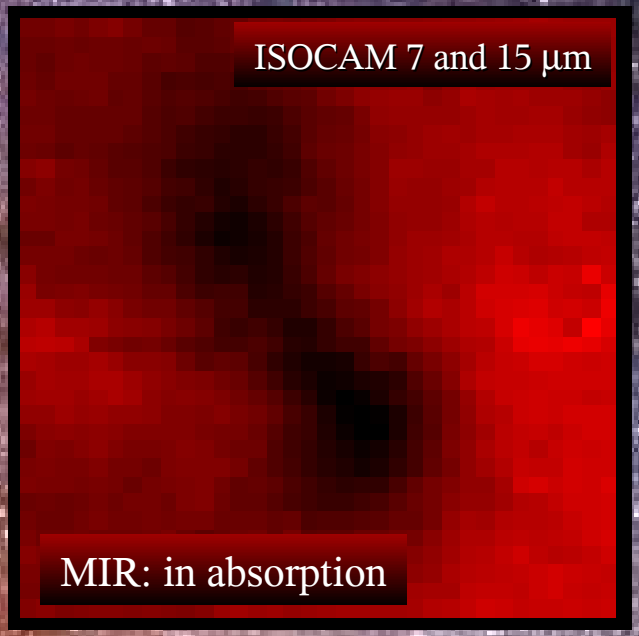
Density re-construction

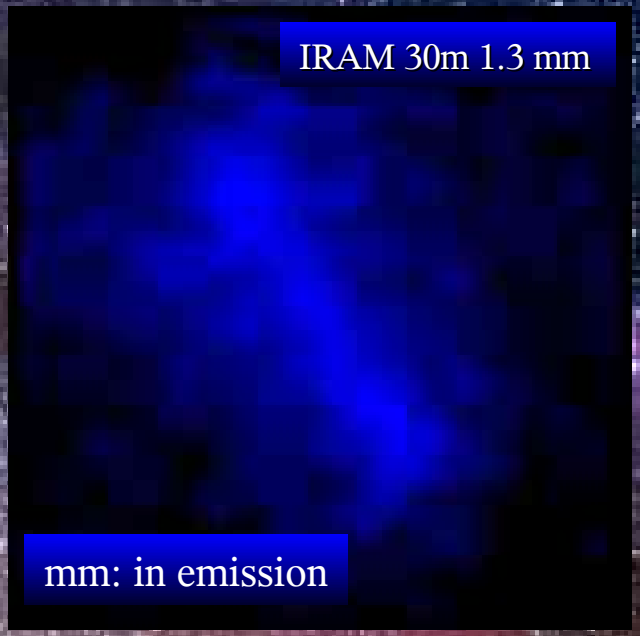
Inverse 3D Radiative Transfer

density ← images

ρ Ophiuchi

Molecular cloud core D

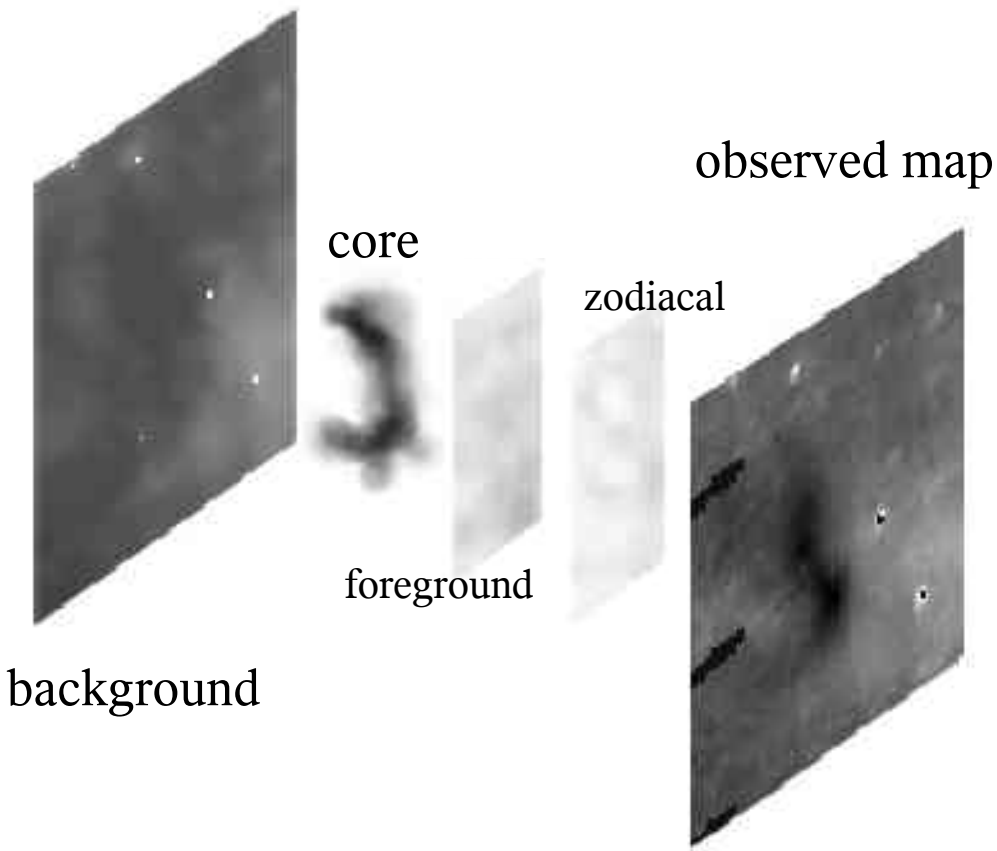




Step 1: Determine the column density

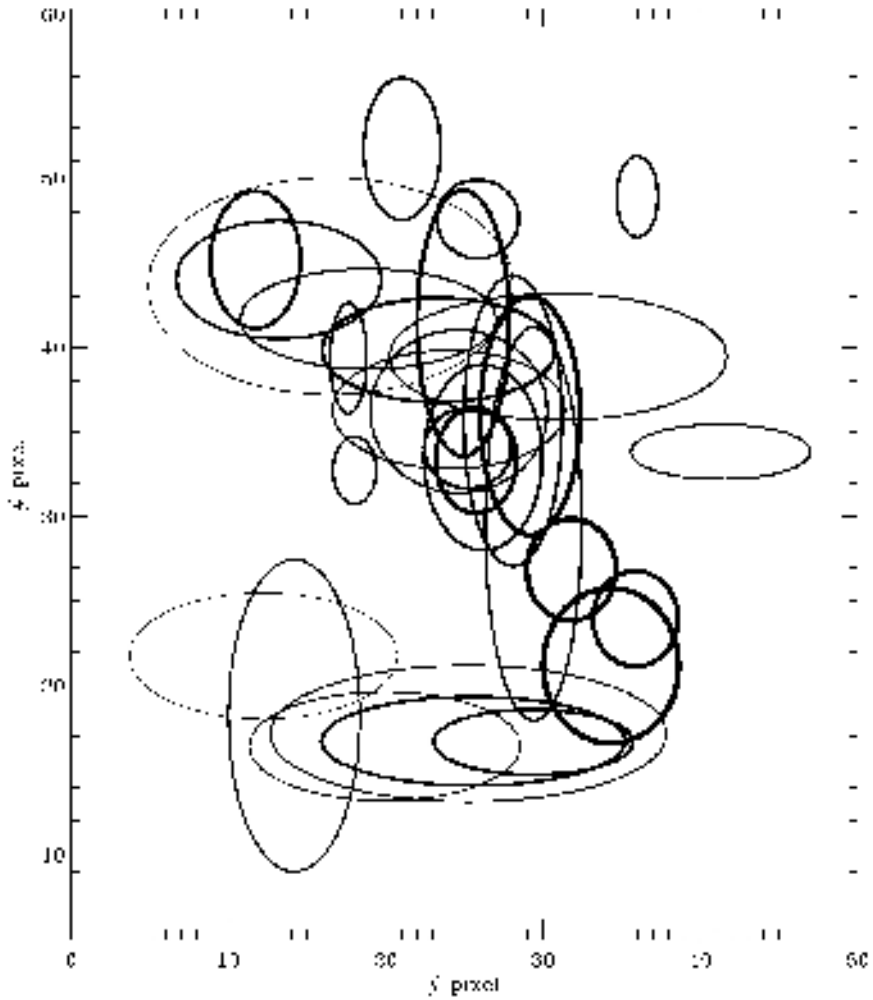
Steinacker, Bacmann, Henning, Klessen, Stickel 2005

Interpolate background intensity I_b



Step 1: Determine the column density

Use 30 Gaussian distributions to model the density

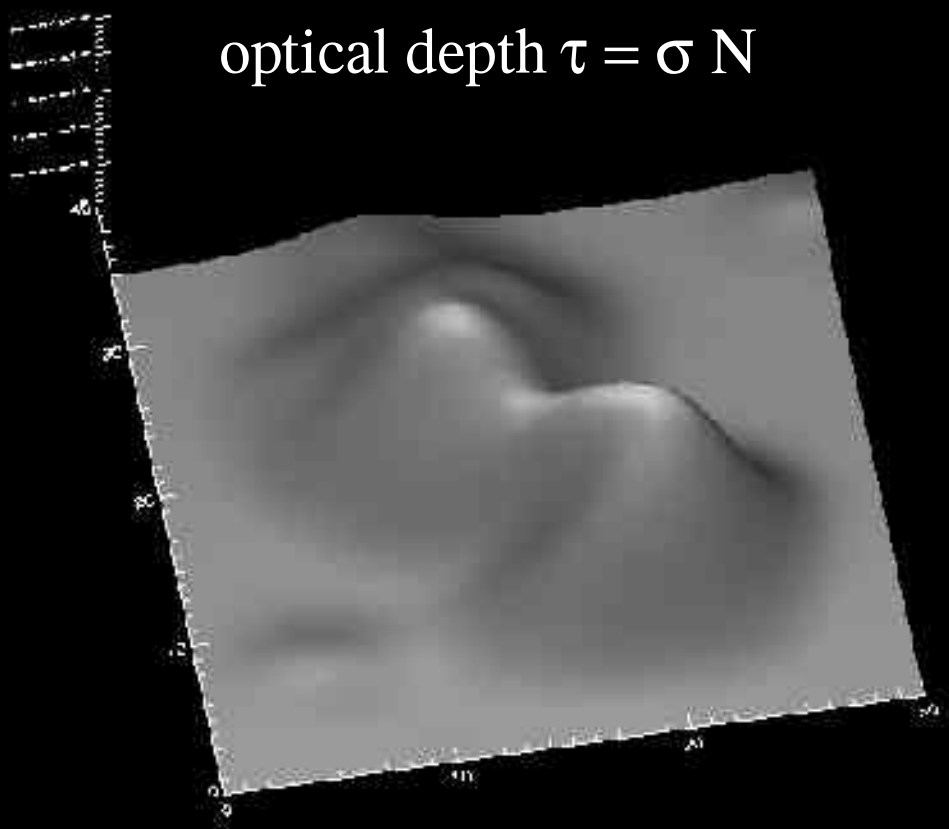


$$I(x,y) = I_b(x,y)\, e^{-\sigma(x,y)\, N(x,y)}$$

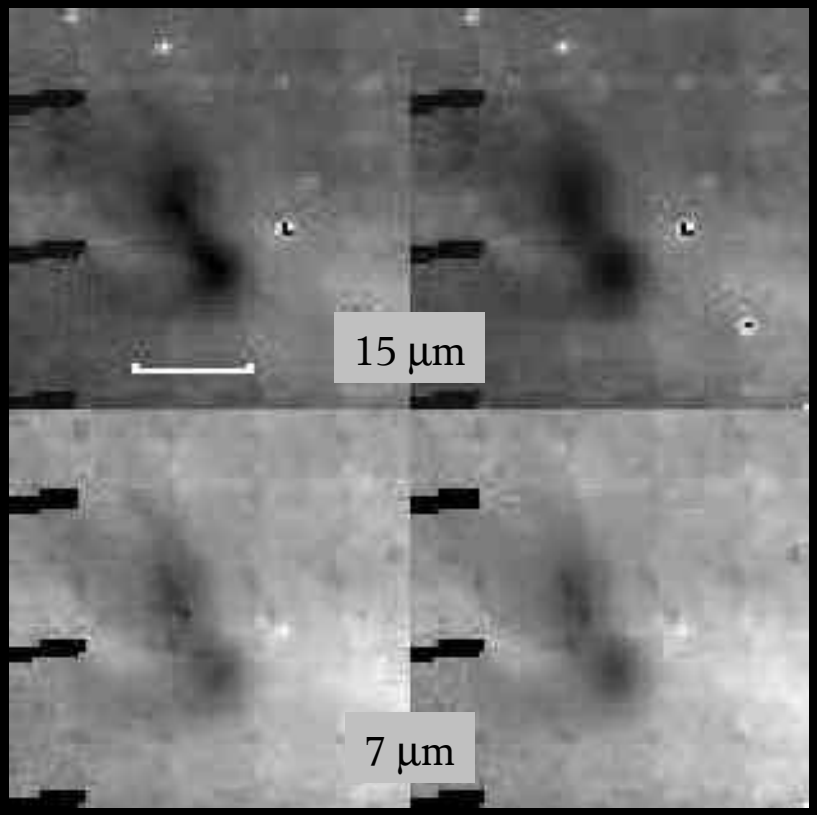
150 parameter
1430 pixels to fit
(simulated annealing)

Step 1: Determine the column density

optical depth $\tau = \sigma N$



Observed maps Model maps



Step 2: Fitting the mm map

$$I \sim \int_{-\infty}^{+\infty} dx' \; n(x') \; B[T(x')]$$

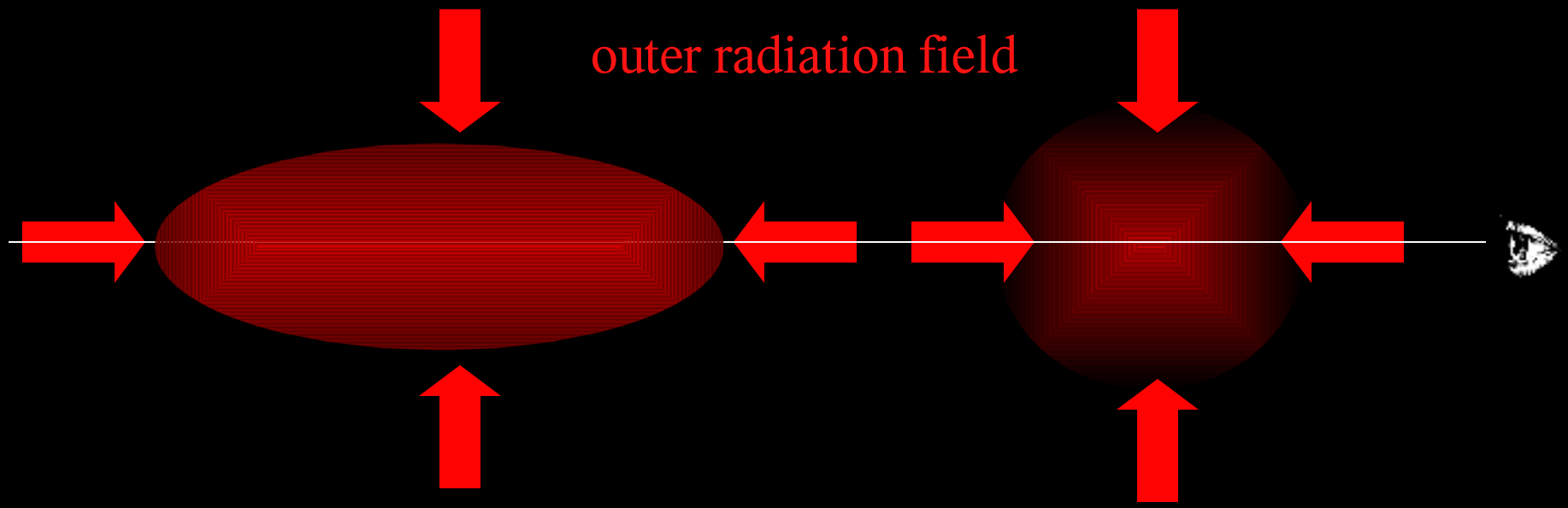
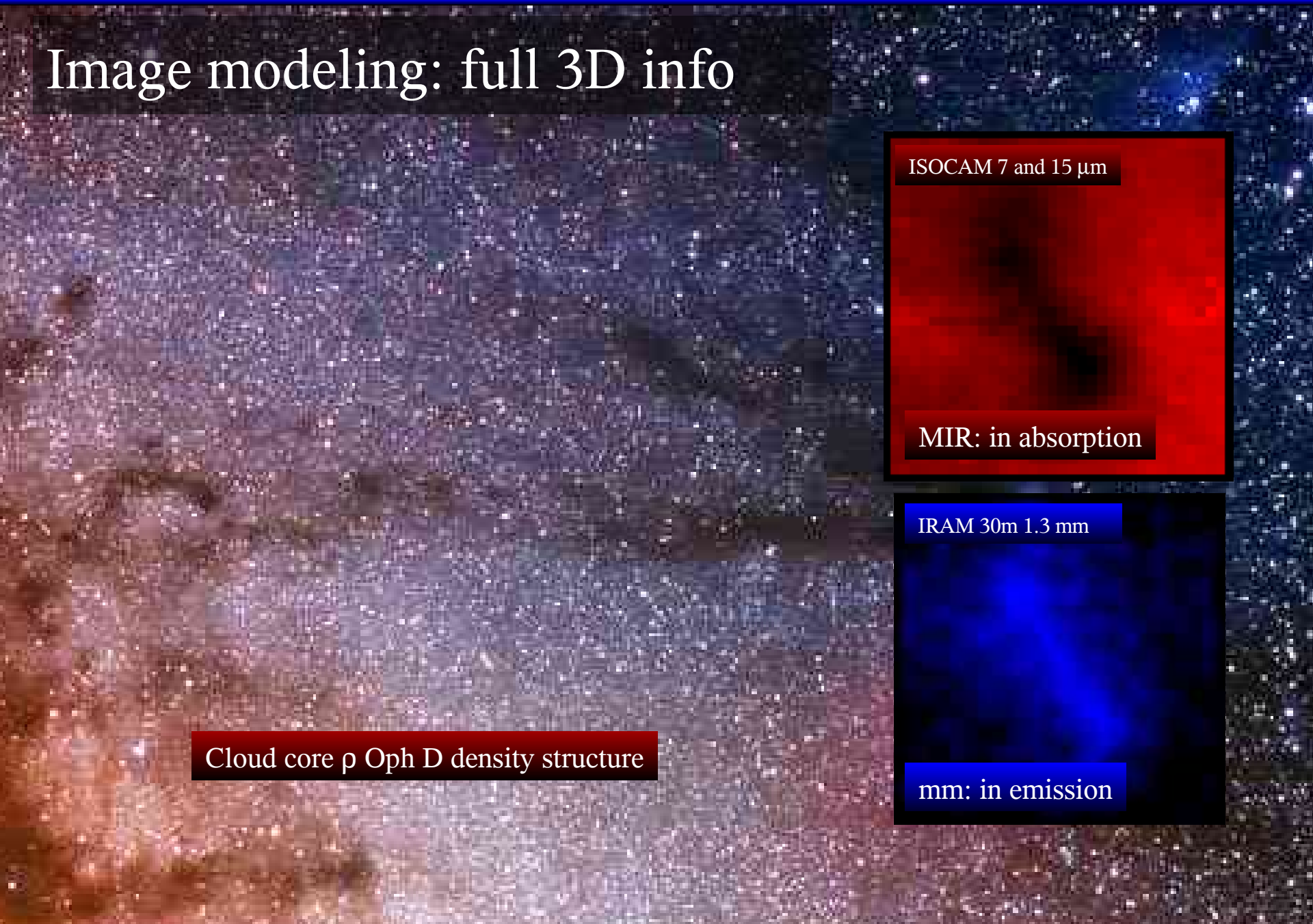


Image modeling: full 3D info



2001

letters to nature

Internal structure of a cold dark molecular cloud inferred from the extinction of background starlight

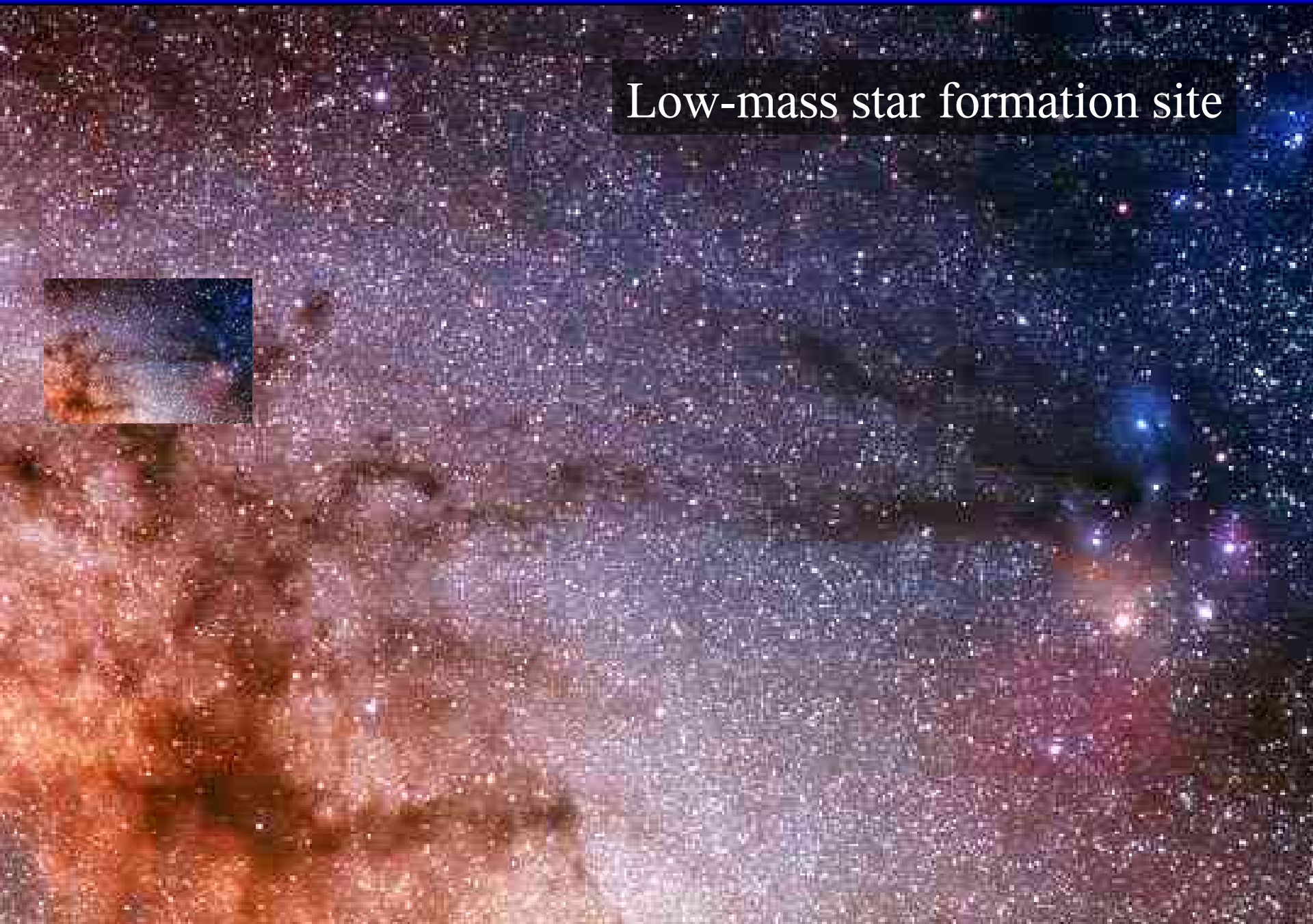
Alves, Lada, & Lada

* European Southern Observatory, Karl-Schwarzschild Straße 2, D-85748 Garching b. München, Germany
† Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, Massachusetts 02138, USA
‡ Astronomy Department, University of Florida, Gainsville, Florida 32608, USA

Stars and planets form within dark molecular clouds, but little is understood about the internal structure of these clouds, and consequently about the initial conditions that give rise to star and planet formation. The clouds are primarily composed of molecular hydrogen, which is virtually inaccessible to direct observation. But the clouds also contain dust, which is well mixed with the gas and which has well understood effects on the transmission of light. Here we use sensitive near-infrared measurements of the light from background stars as it is absorbed and scattered by trace amounts of dust to probe the internal structure of the dark cloud Barnard 68 with unprecedented detail. We find the cloud's density structure to be very well described by the equations for a pressure-confined, self-gravitating isothermal sphere that is critically stable according to the Bonnor–Ebert criteria[1,2]. As a result we can precisely specify the physical conditions inside a dark cloud on the verge of collapse to form a star.

Molecular clouds are primarily composed of molecular hydrogen mixed with trace impurities including interstellar dust grains and

ref. 11). Barnard 68 appears to be part of a string of dense clouds (Barnard 68, 69 and 70) located within a well known superbubble of hot gas, Loop I, created by the combined action of stellar winds and supernova explosions[12,13] from extinct massive stars which were once part of the Scorpio–Centaurus OB association. This cloud lies in the direction of the centre of the Galaxy but above the Galactic


Low-mass star formation site

ρ Ophiuchi

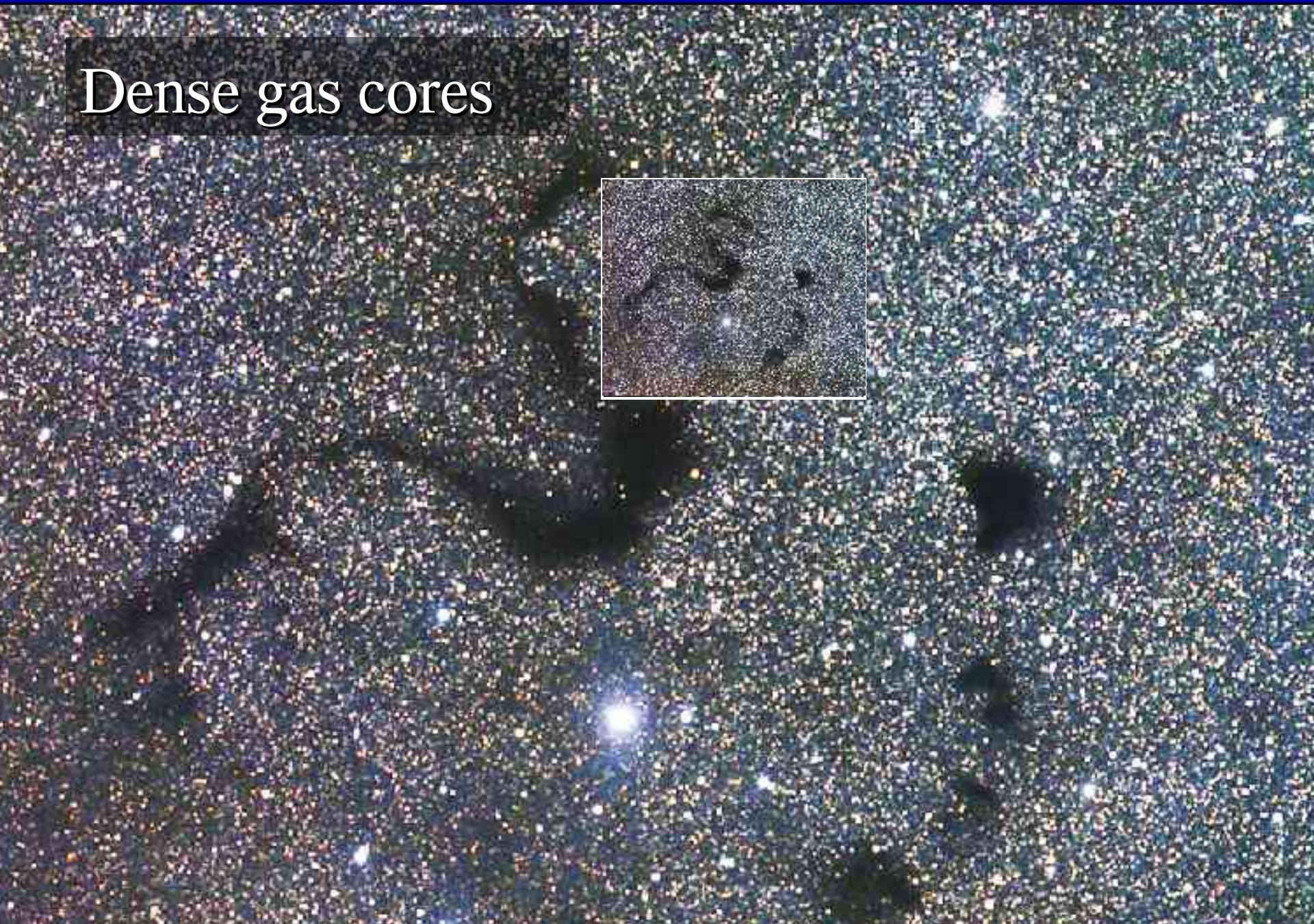
Low-mass star formation site

ρ Ophiuchi

Low-mass star formation site

ρ Ophiuchi

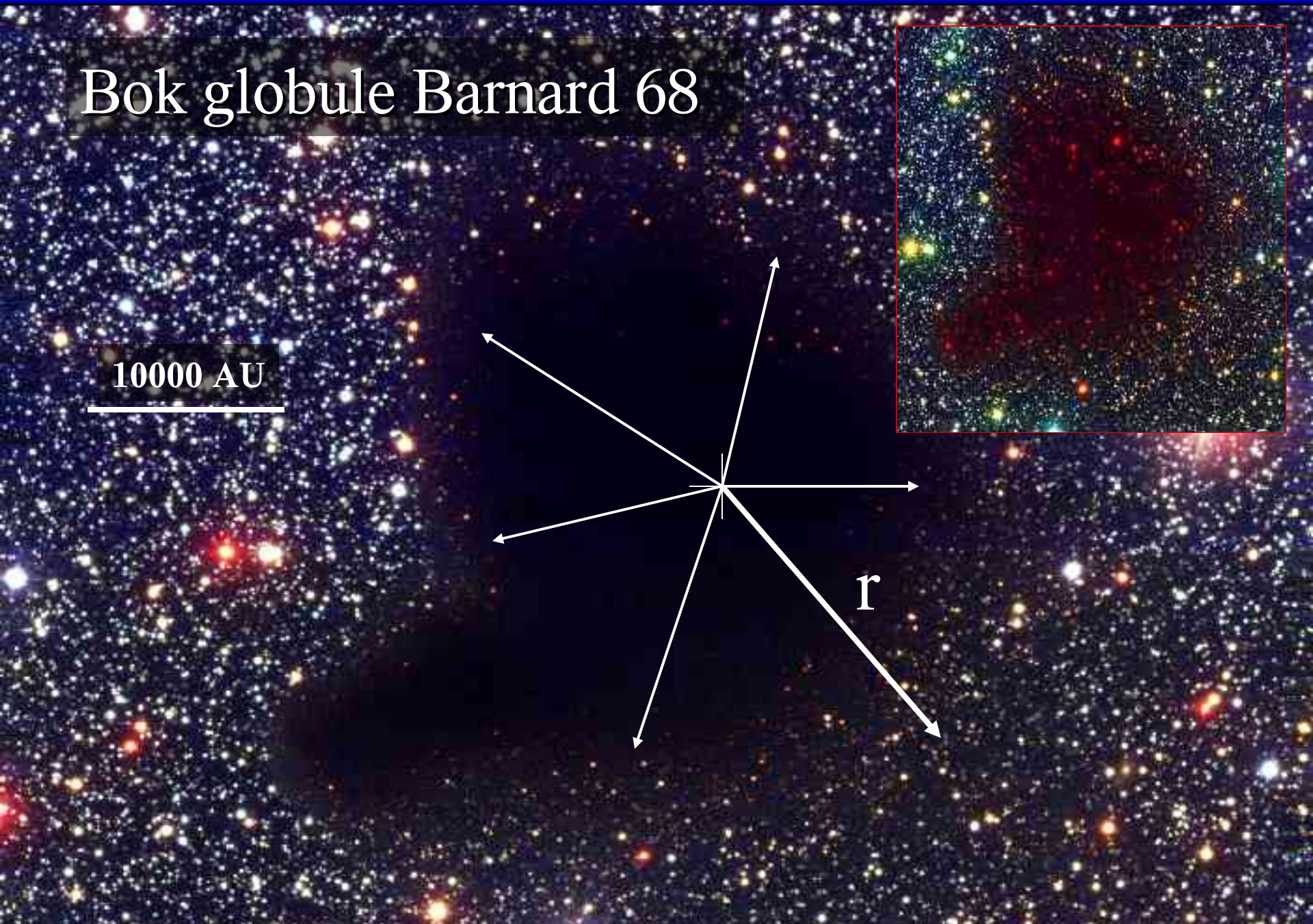
Dense gas cores

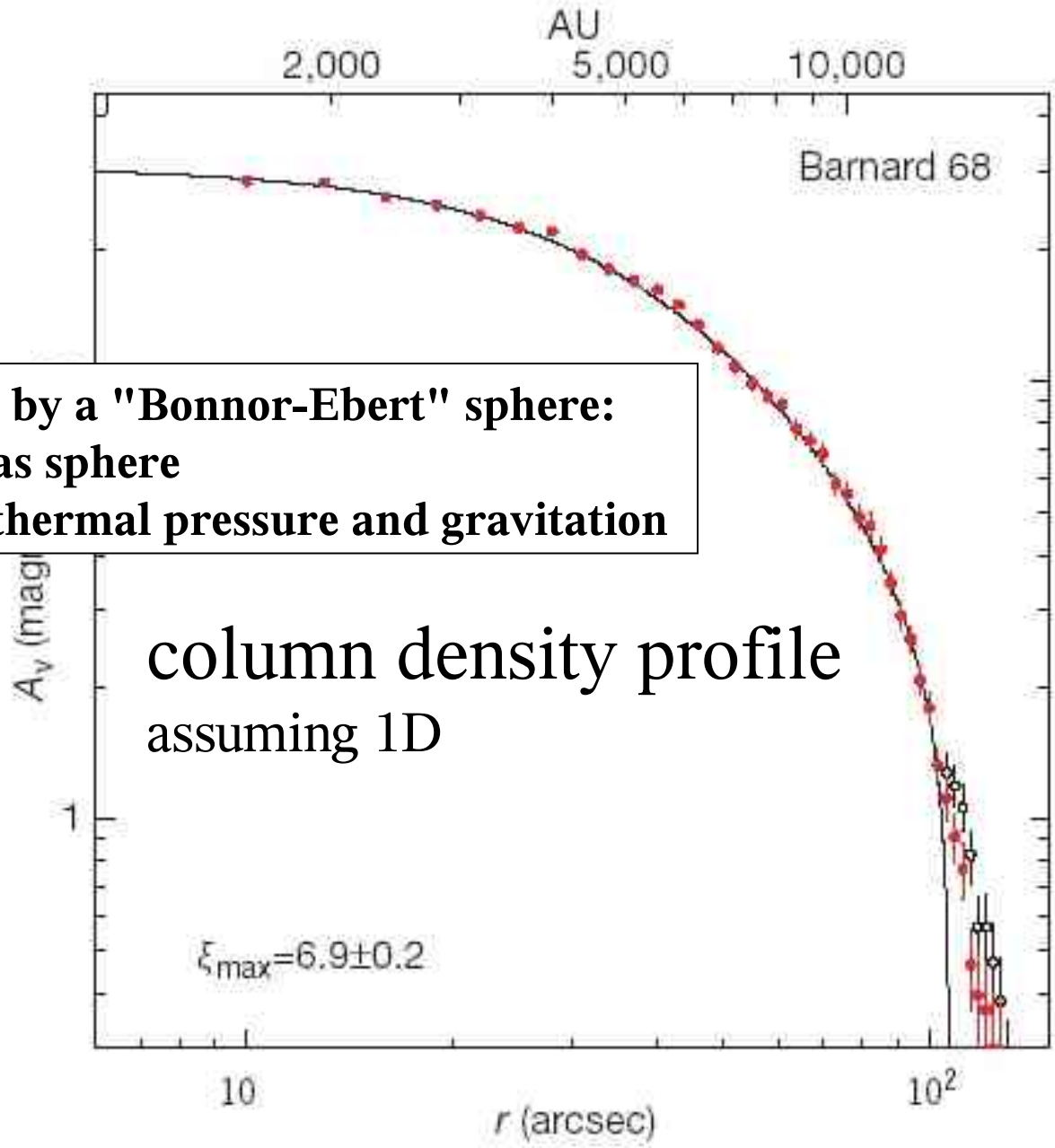


Dense gas cores

Bok globule Barnard 68

Bok globule Barnard 68

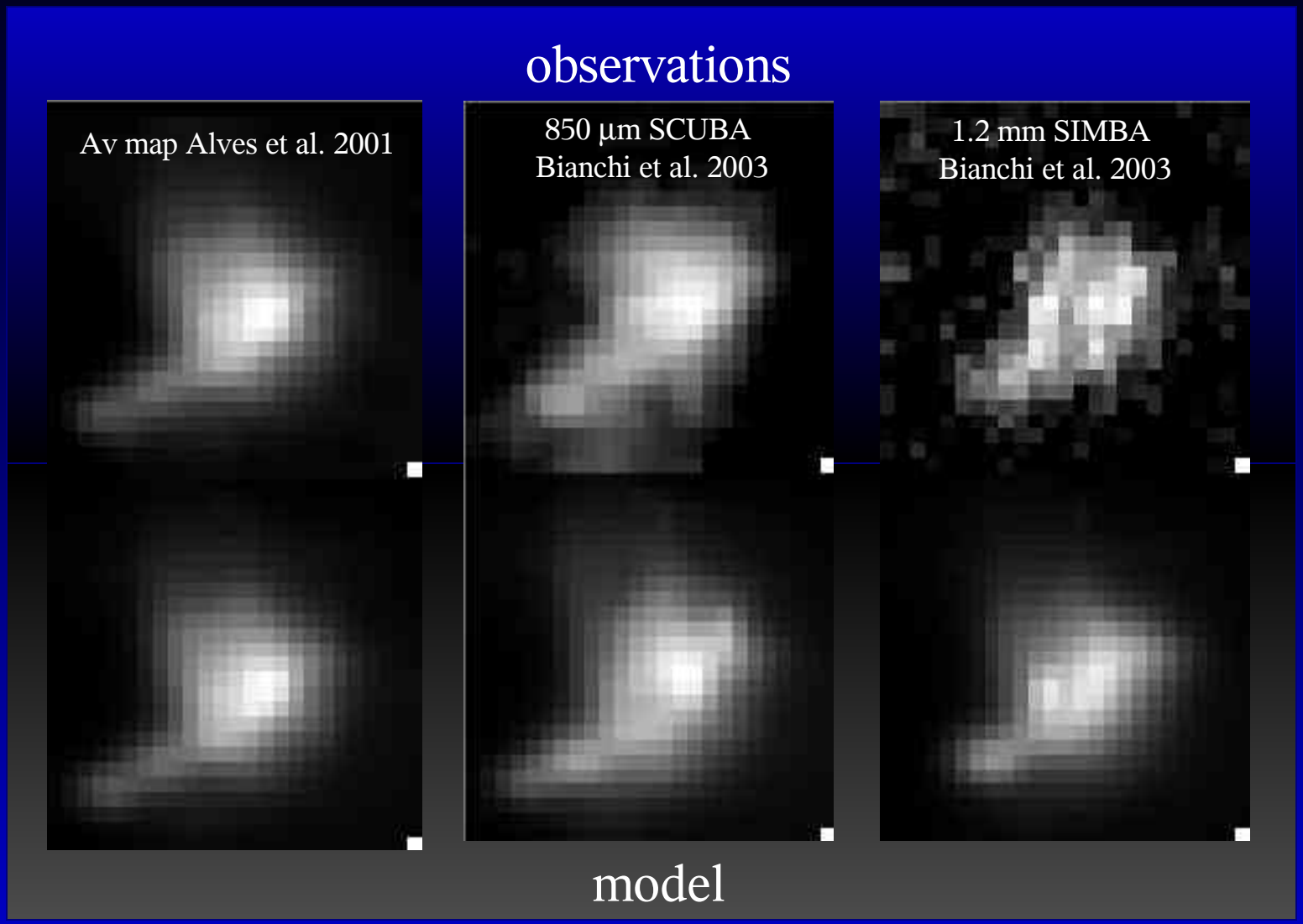




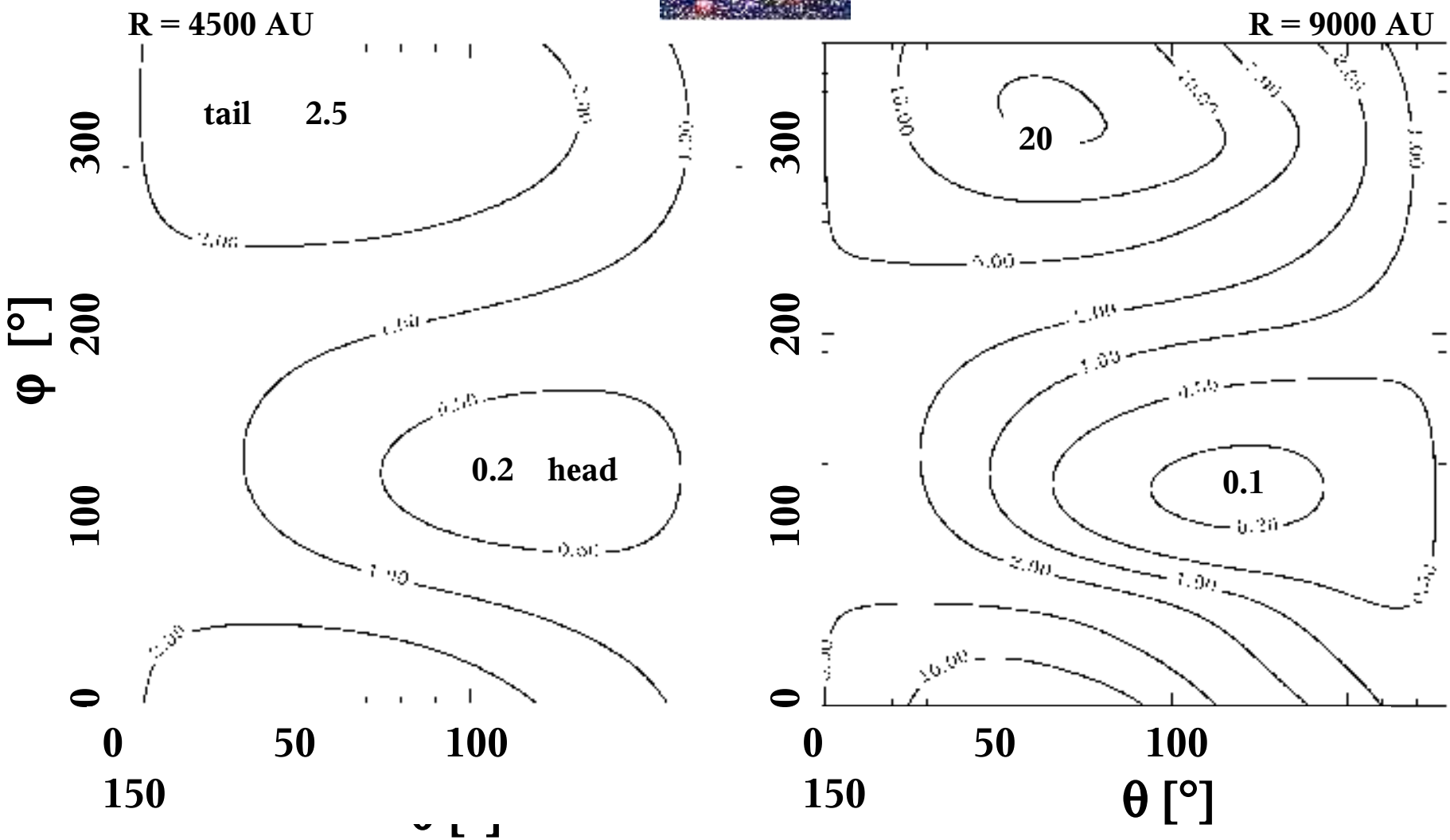
Very good fit by a "Bonnor-Ebert" sphere:
Isothermal gas sphere
balanced by thermal pressure and gravitation

column density profile
assuming 1D

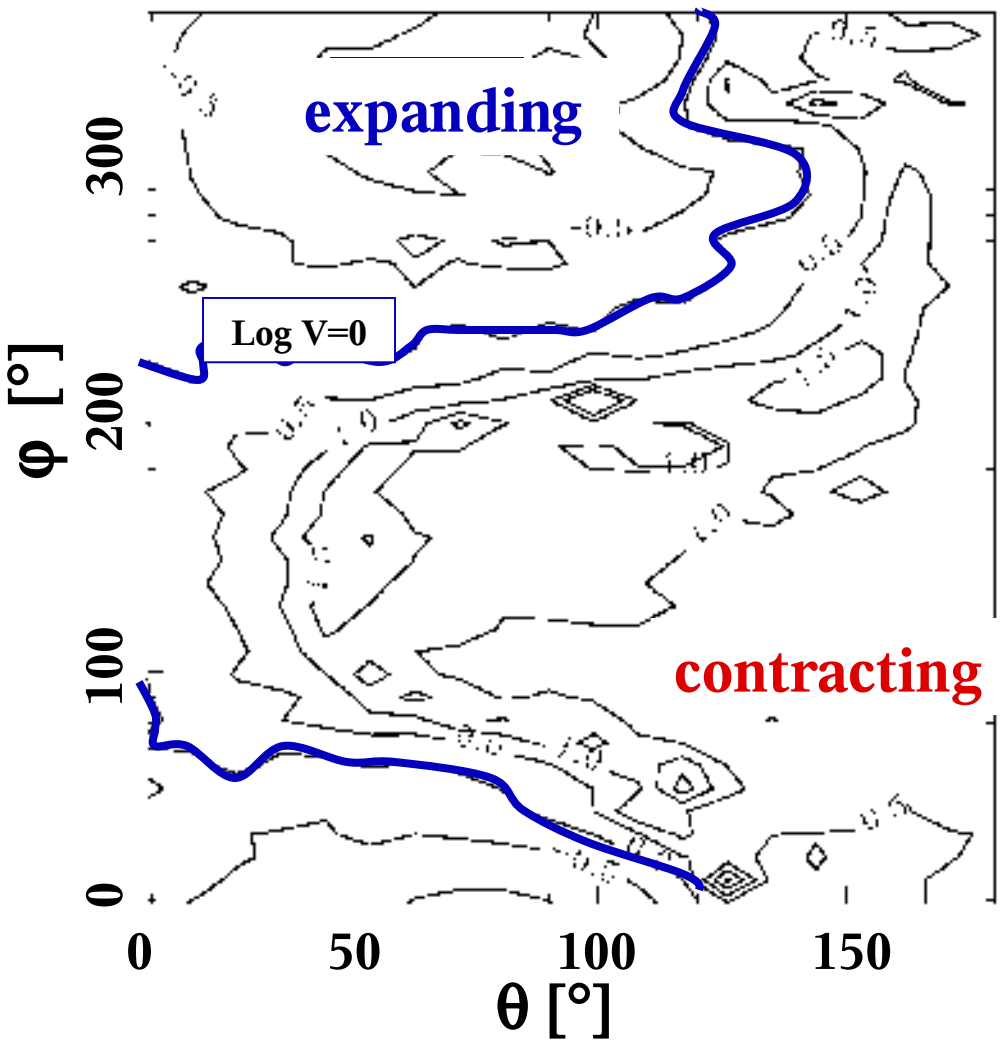
Fits of B68


observations
Av map Alves et al. 2001
850 µm SCUBA
Bianchi et al. 2003
1.2 mm SIMBA
Bianchi et al. 2003
model

B68 is not a sphere



B68 is close to gravo-thermal balance

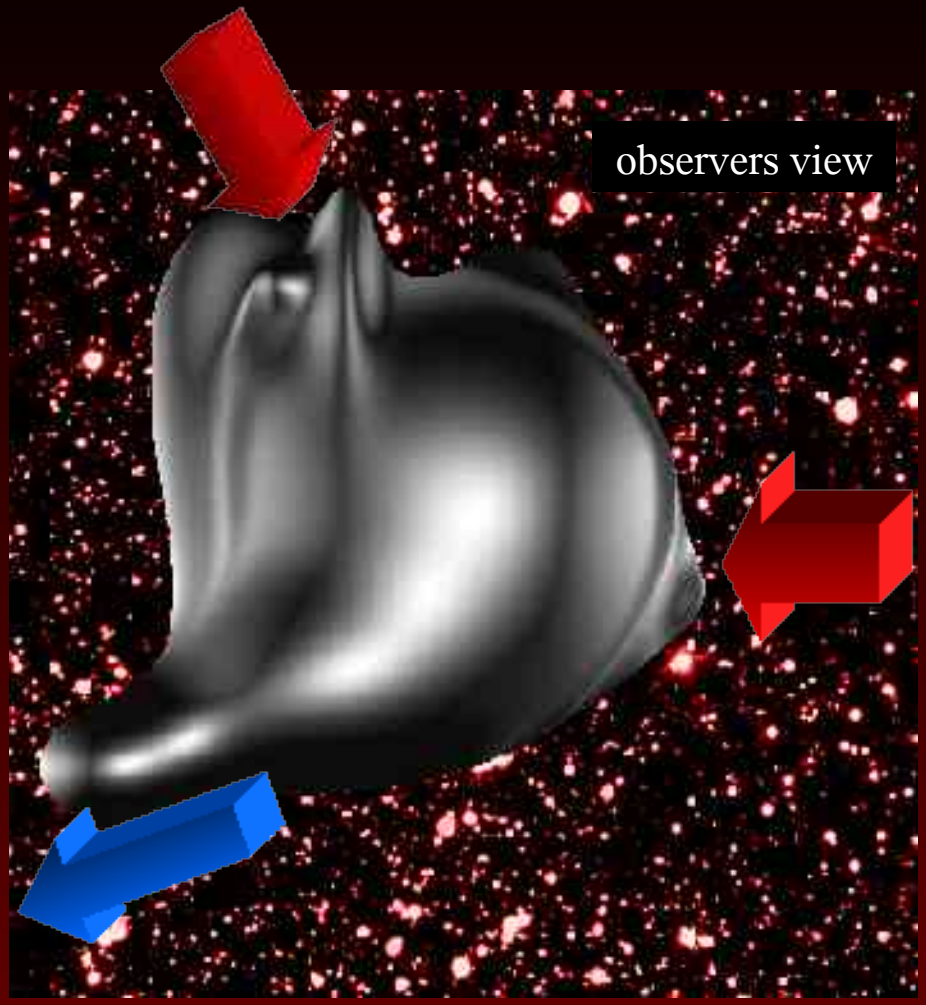


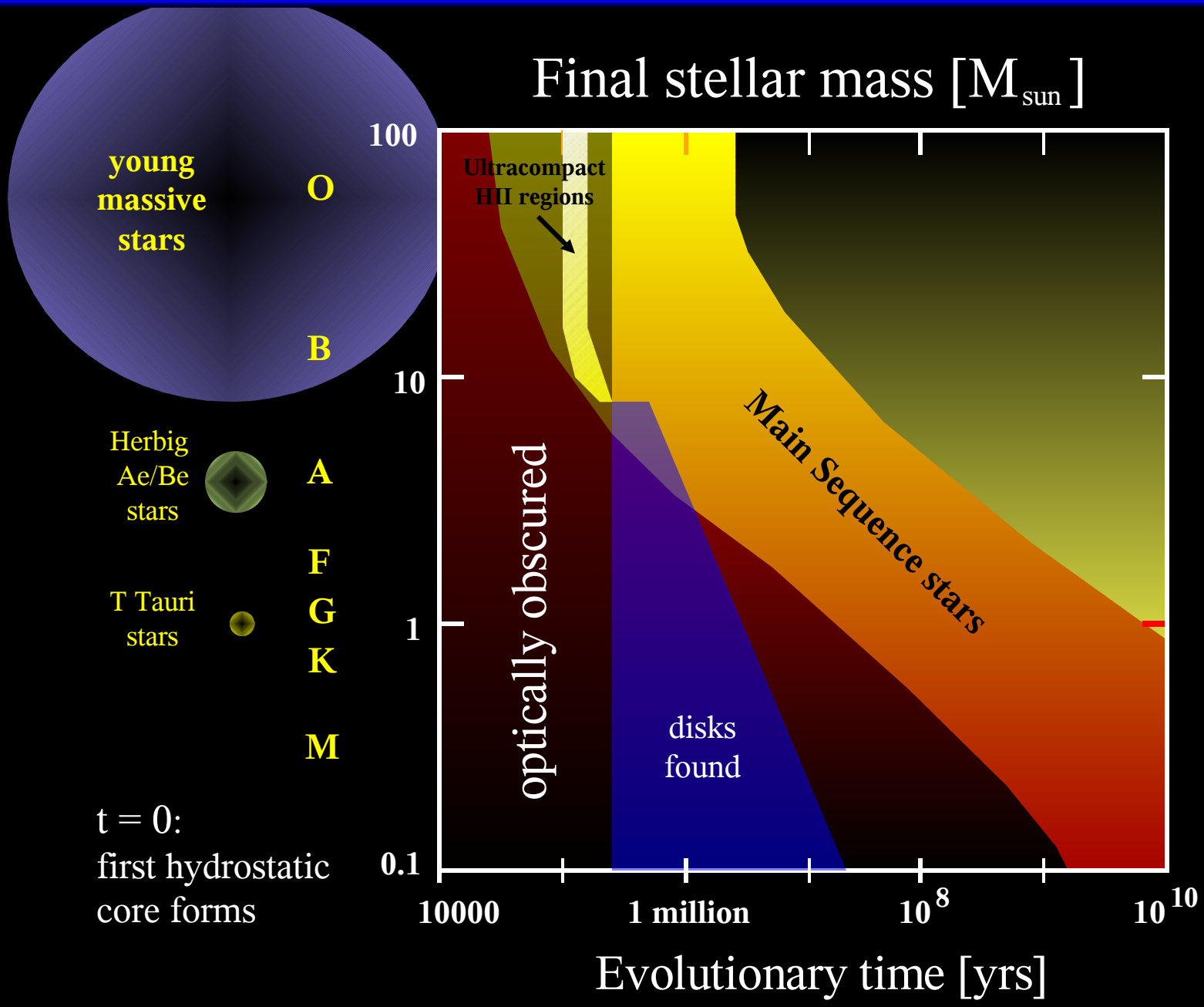
Lane-Emden equation

$$\frac{1}{r^2}\frac{d}{dr}\left(\frac{r^2}{\rho}\frac{d\rho}{dr}\right) = -\frac{4\pi\, Gm\rho}{kT}$$

$$V = \frac{\frac{4\pi\, Gm\rho}{kT}}{\frac{d}{dr}\left(\frac{r^2}{\rho}\frac{d\rho}{dr}\right)}$$

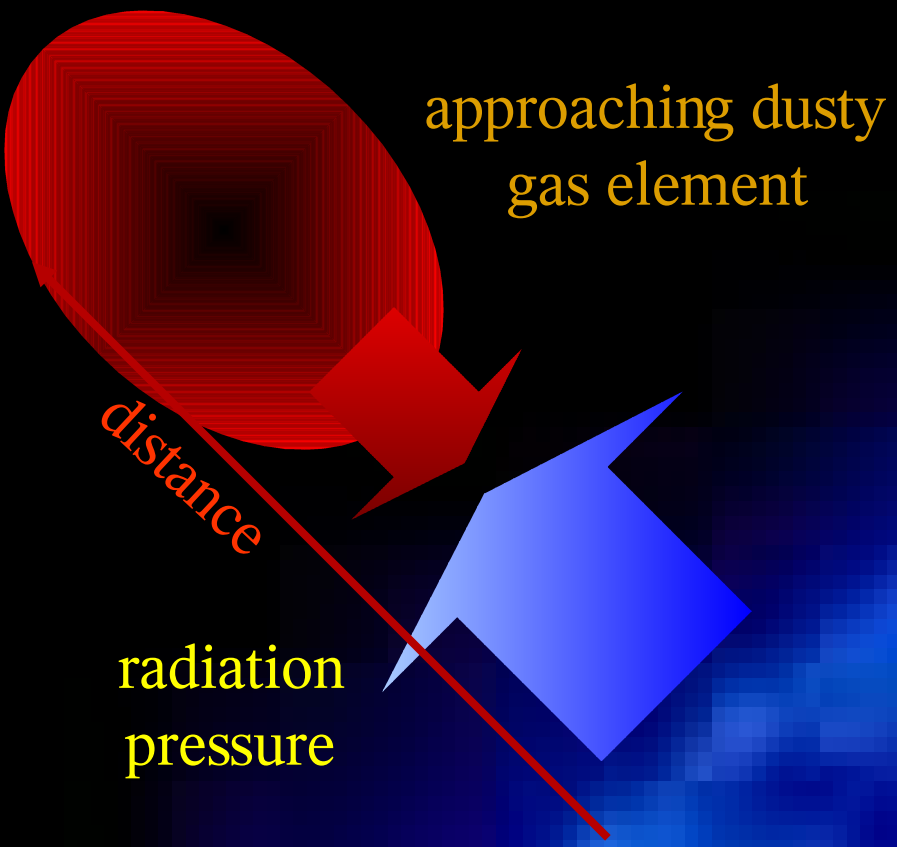
Determination of kinematical properties





t = 0:
first hydrostatic core forms

after H.Yorke



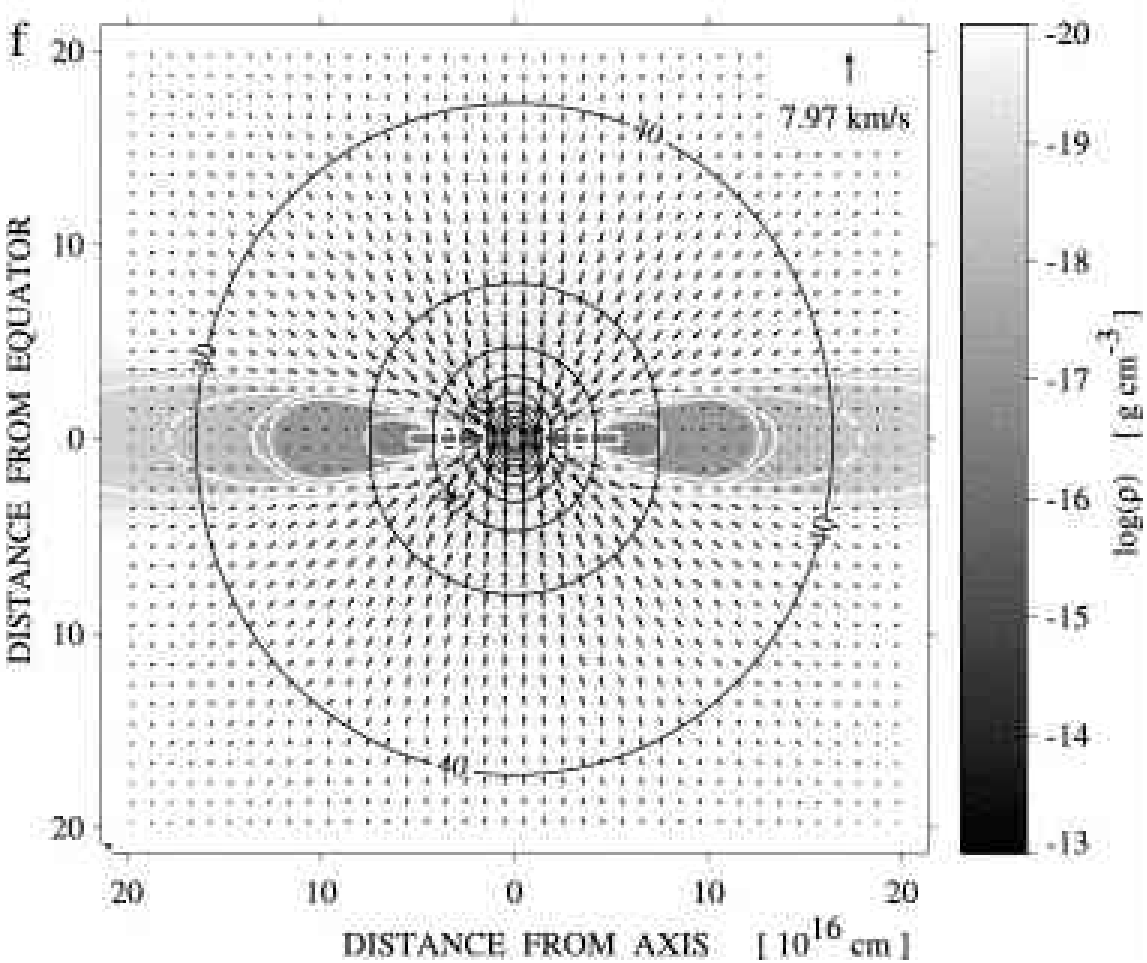
How to form a 50 solar masses star?

Wolfire & Cassinelli 1987 using 1D calculations:

The should be no high-mass star above 10 solar masses!

2D models: 33 M_{sol} stars can form from accretion disks

Yorke & Sonnhalter 2002



Wavelength-dependent Radiative Transfer !

Image modeling: SO-1

Jürgen Steinacker


M17


low mass disk
SO-1
~ 8000 AU
Chini et al. Nature 2004
ISAAC/VLT 2.2 μm

Model: A disk around a young massive object

Jet

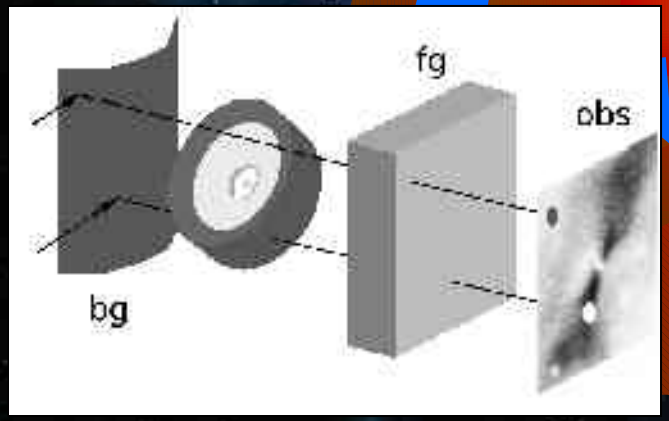
Accretion signatures

(Kepler) rotation

Hour glass-shaped reflection nebula

- Use the high-resolution of the VLT image (60AU/pixel)
- Use the rare configuration of a silhouette structure

Symmetry pattern



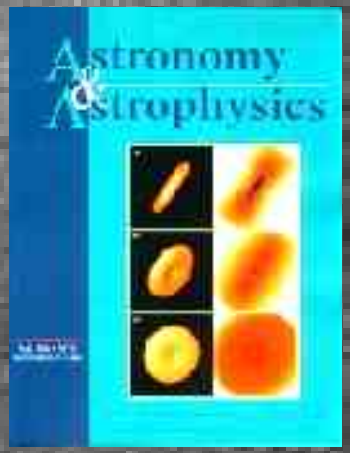
Counter jet
symmetric if edge-on disk

low mass disk

~ 8000 AU

SO-1

Diskmass: 0.2-13 solar masses



Steinacker et al. 2006

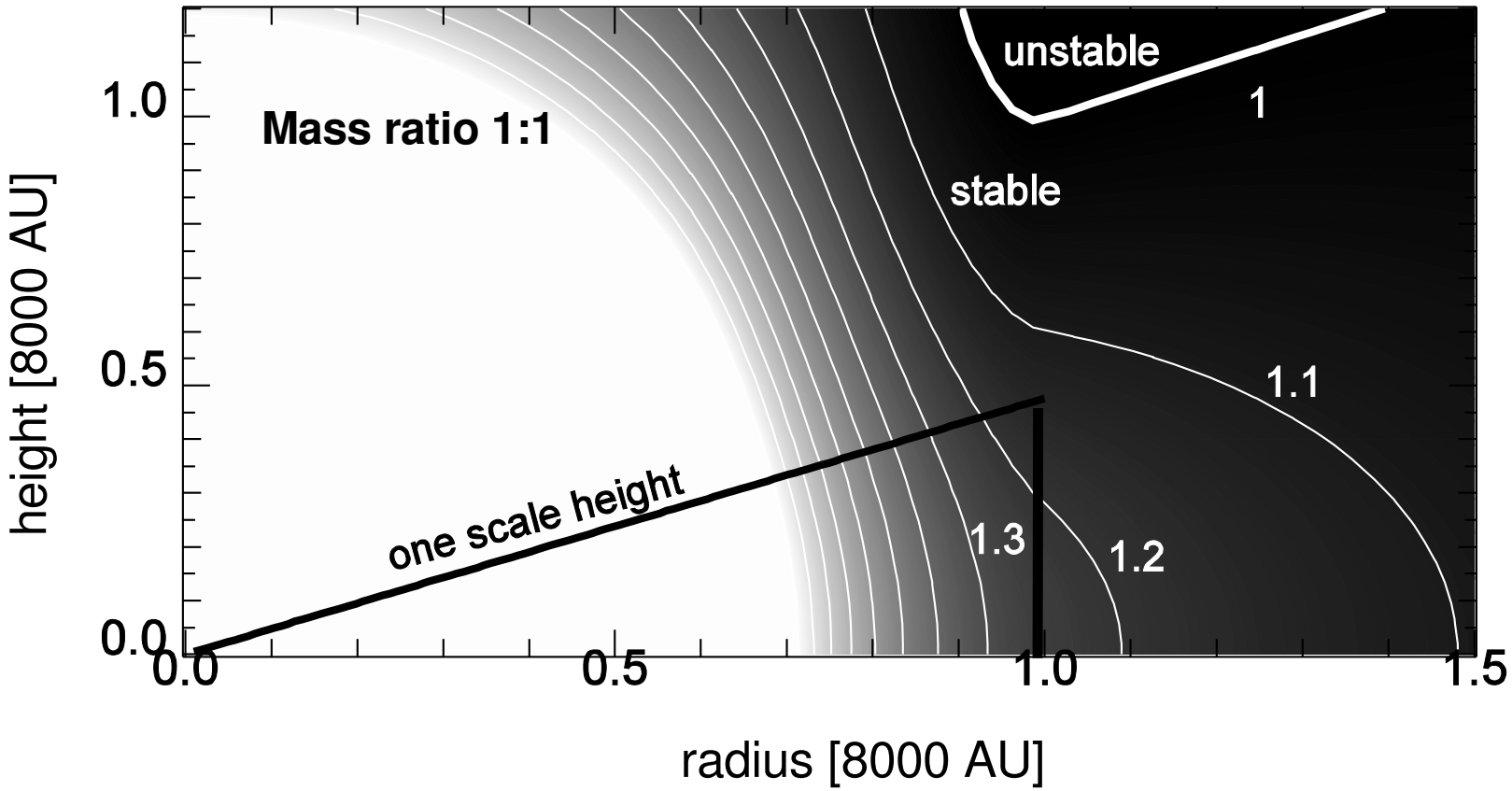
ISAAC/VLT 2.2 μm

Steinacker, Chini, Nielbock, Nürnberger, Hoffmeister, Hure, Semenov 2006

Given both star and disk are massive:

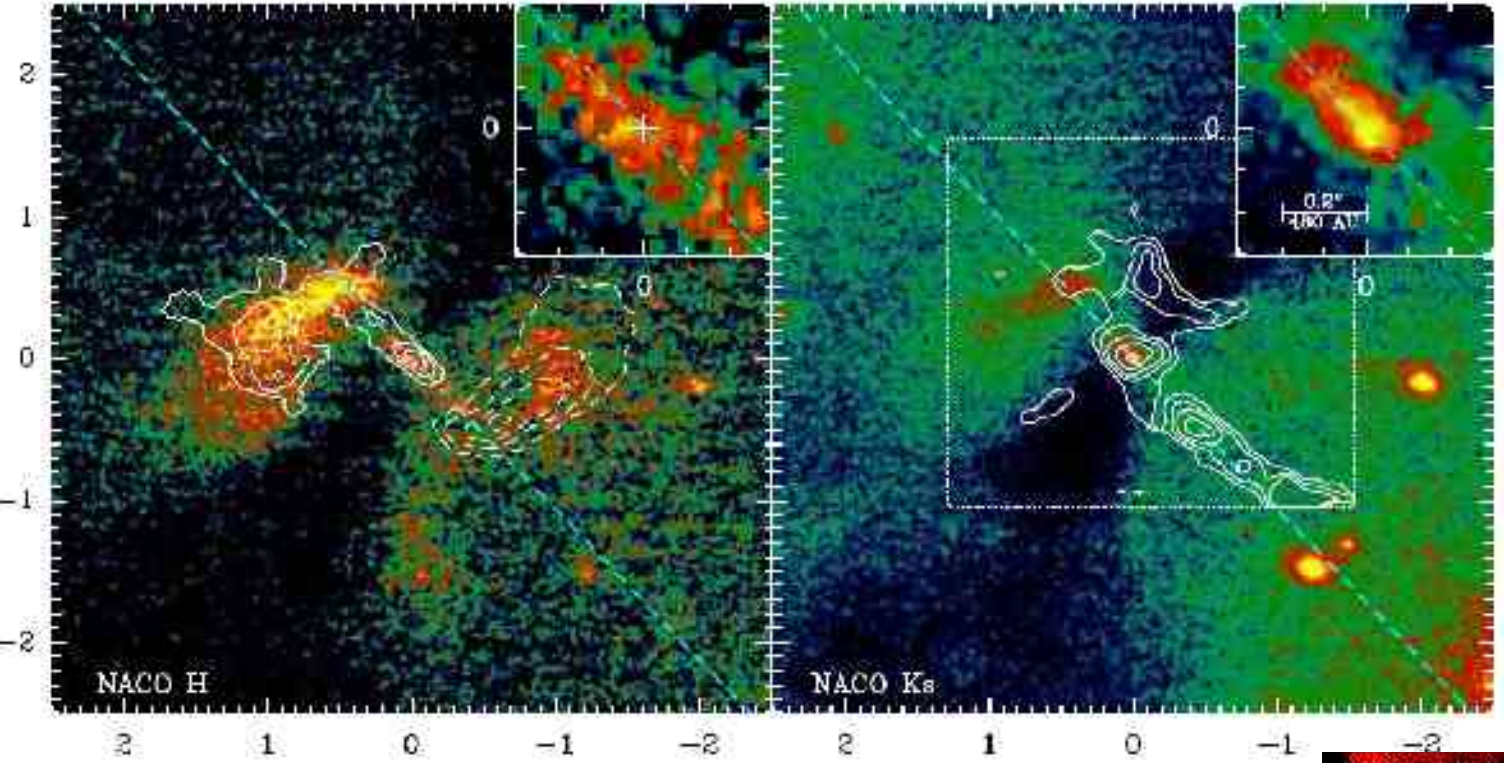
Is such a disk stable?

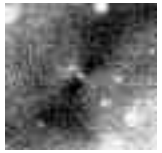
$$\frac{\text{central gravitational acceleration}}{\text{disk gravitational acceleration}}$$



Nielbock, Chini, Hoffmeister, Nürnberger, Scheyda, Steinacker 2007
Nürnberger et al. 2007

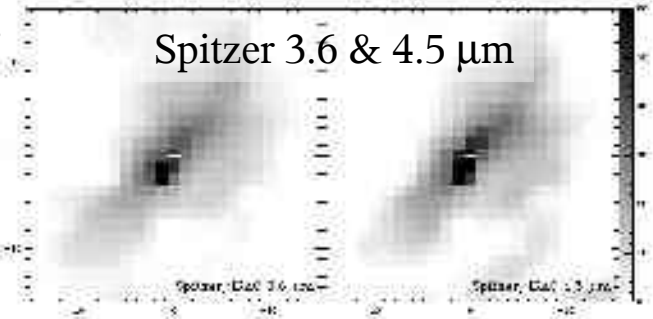
Central region resolved down to 240 AU

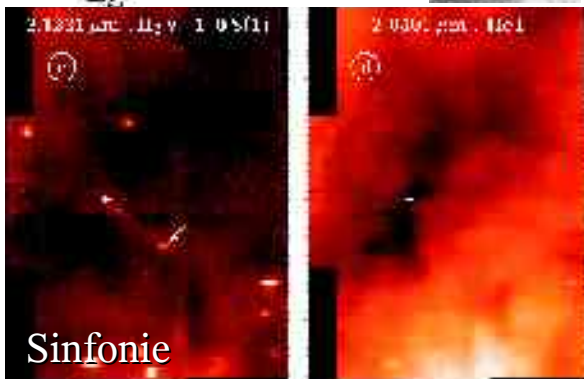




Extinction map from Spitzer as well as H2 emission at the disk surface indicate

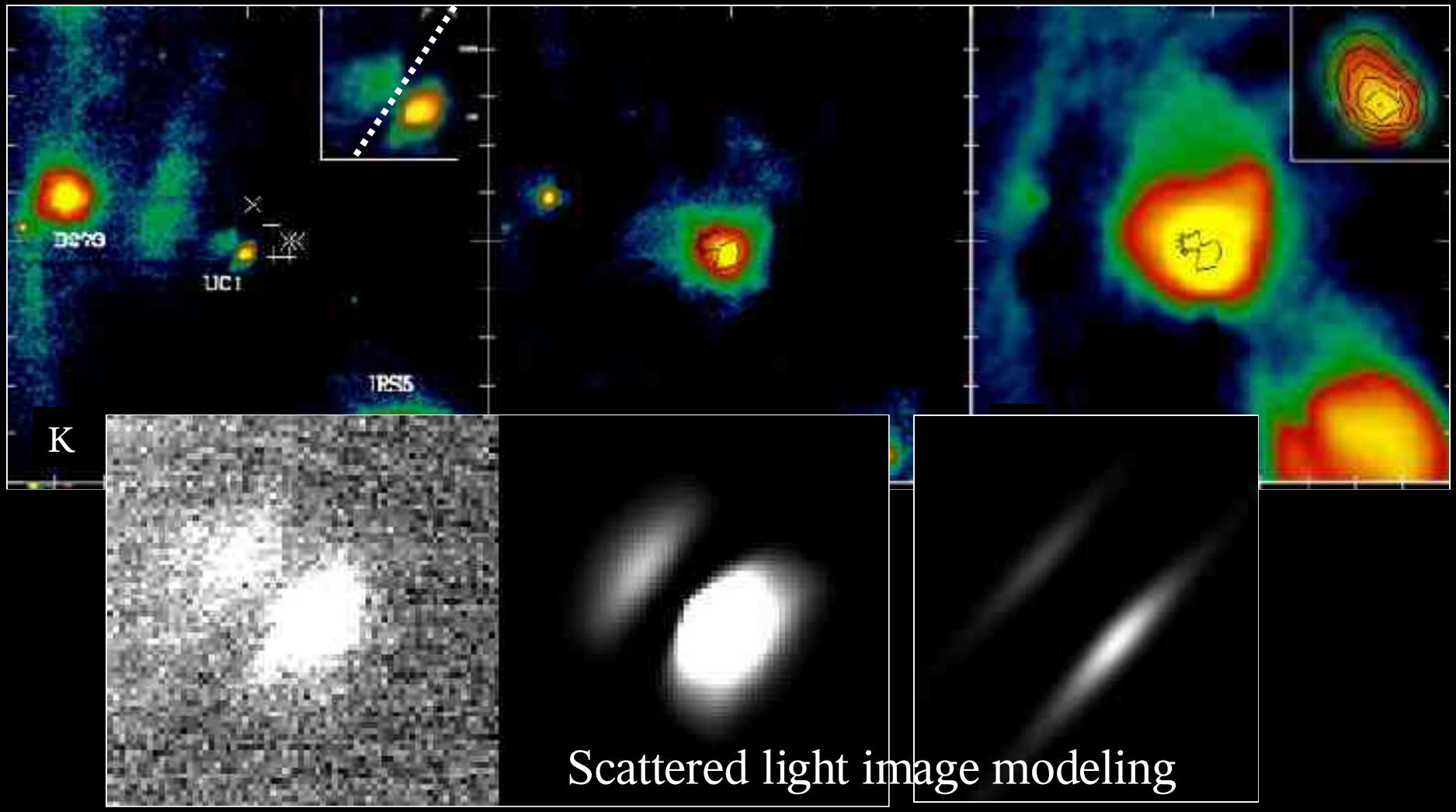
B4 star





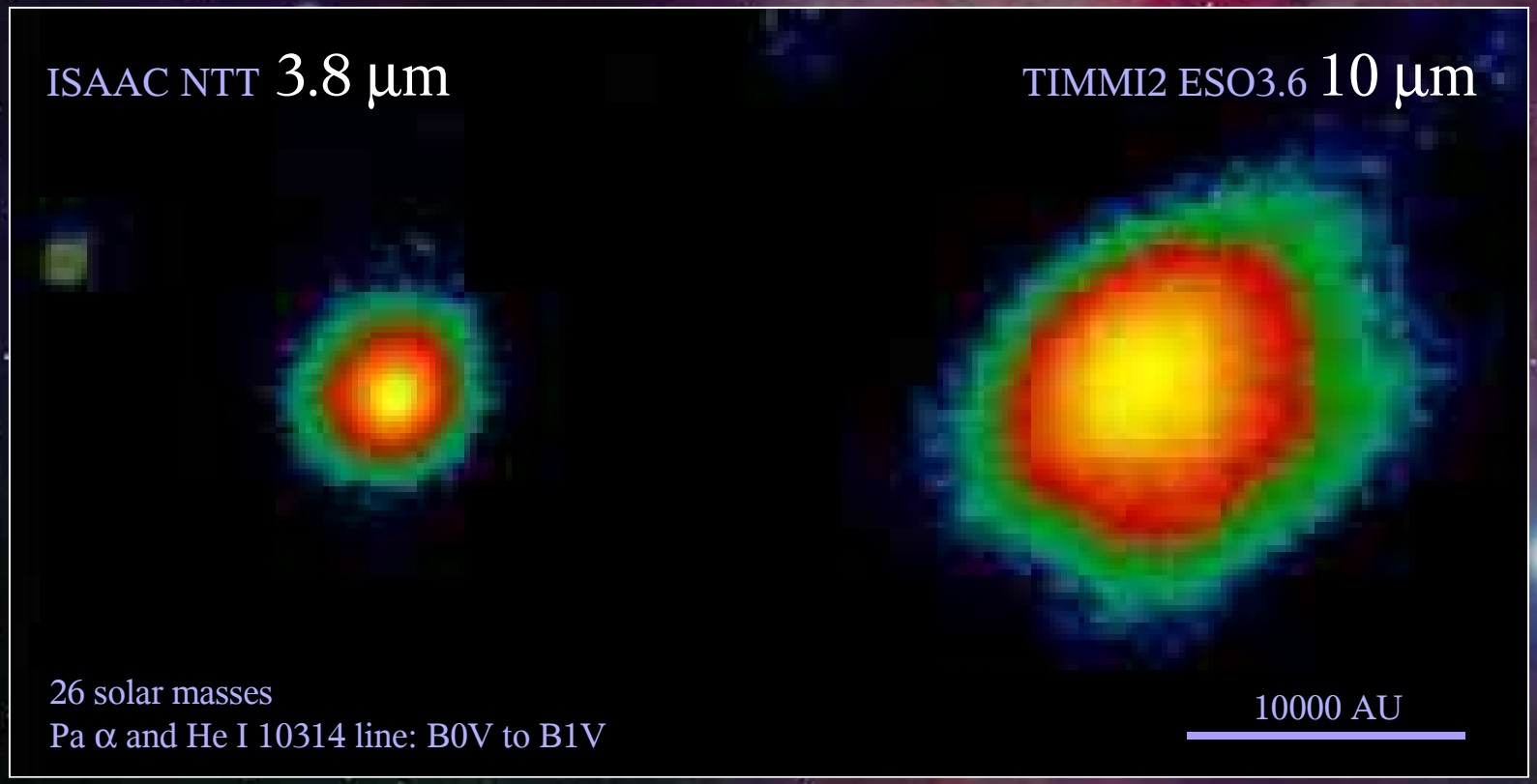
Nielbock, Chini, Hoffmeister, Scheyda, Steinacker, Nürnberger, Siebenmorgen 2006

UC1 – A *hyper*-compact HII region

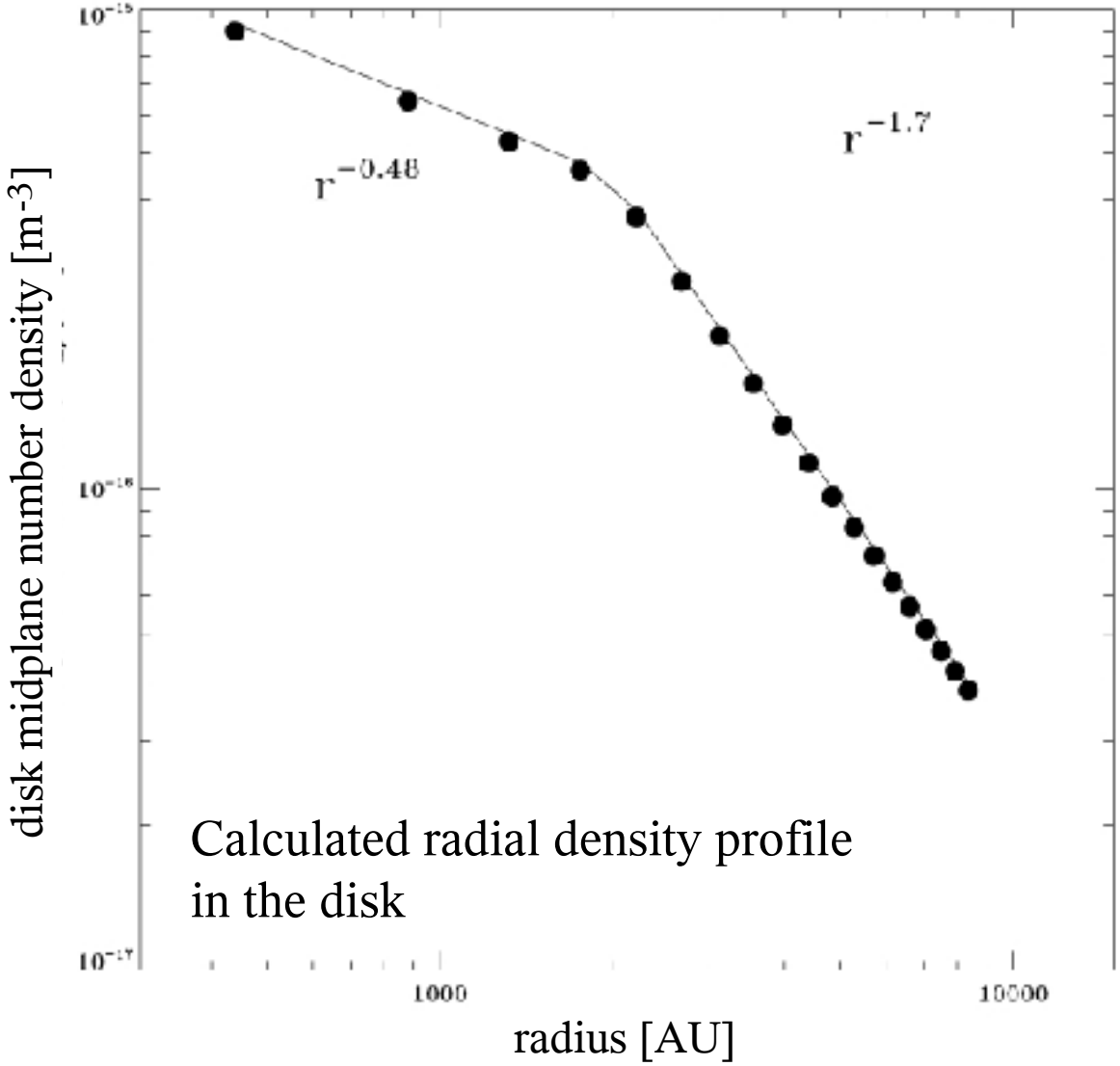


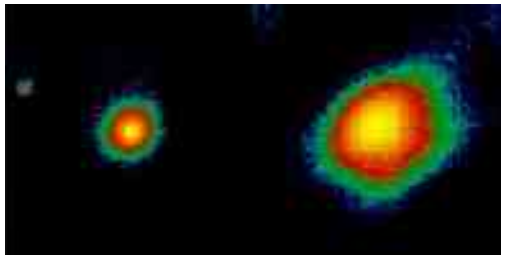
Chini, Hoffmeister, Nielbock, Scheyda, Steinacker, Siebenmorgen, Nürnberger 2006

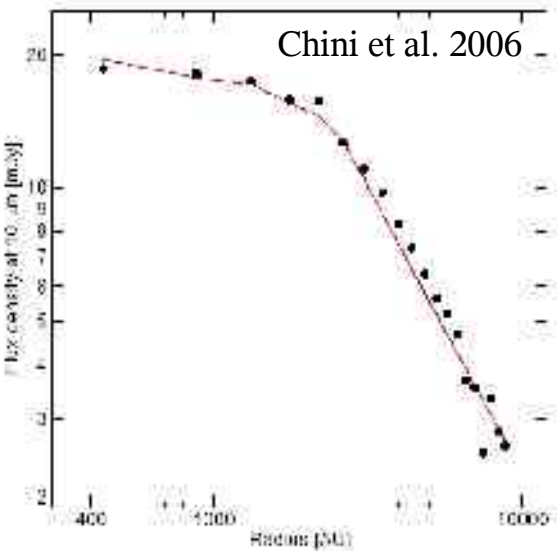
A remnant disk around a massive star (B0)



Indication for an inner cavity



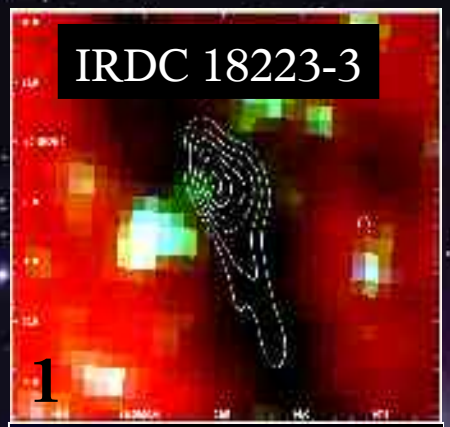


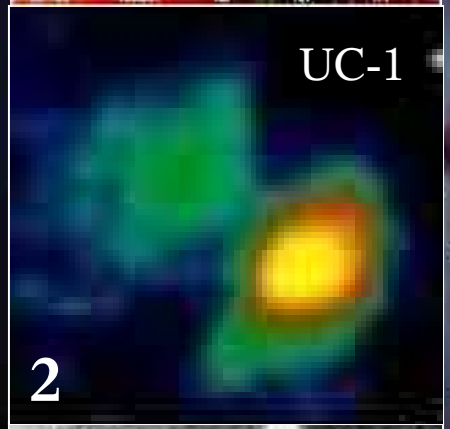


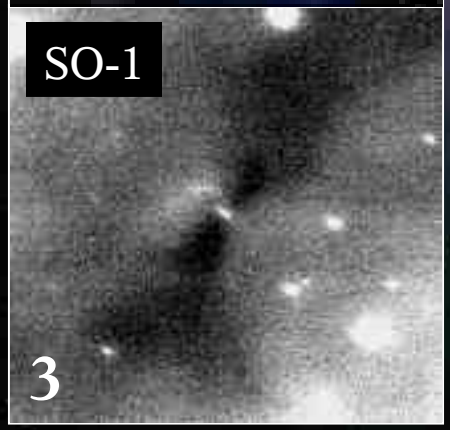
Observed radial flux profile in the disk

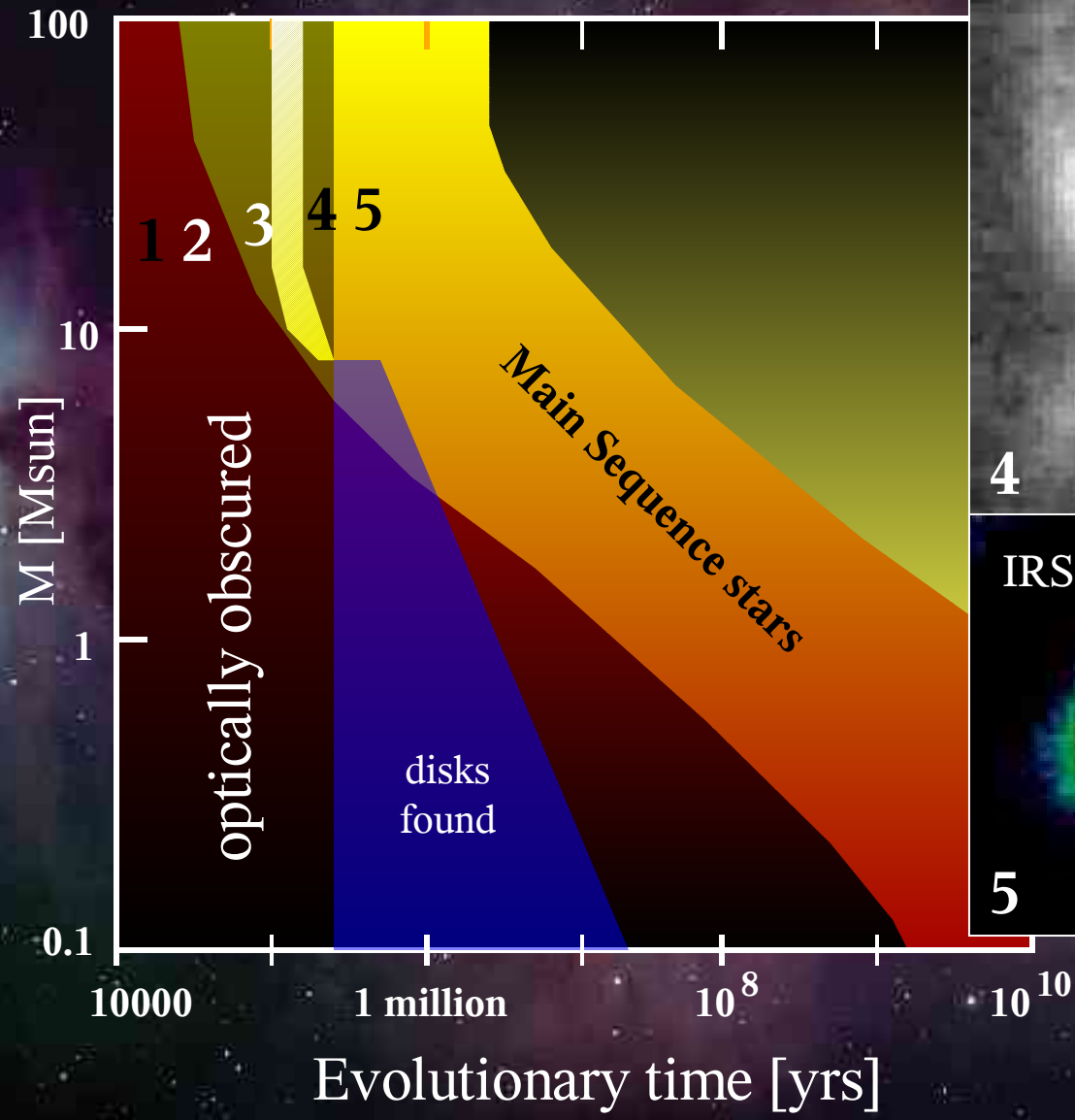
Growing evidence for disk-like structures around Young Massive Stars

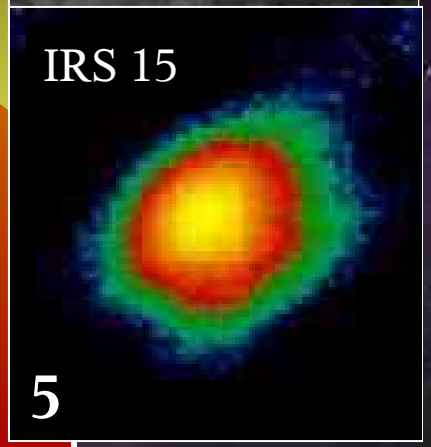
Jürgen Steinacker











3D modeling of the dust distribution of the galaxy M33

collaboration with:
J. Braine (Bordeaux)
E. Athanassoula (Marseille)

Multi-λ image modeling

Input: dust model

Output: 3D dust distribution
stellar population

Spitzer

Optical 1m

German Astronomy Community Grid

www.astrogrid-d.org

German Astronomy Grid of compute and data resources

Submit a data query, a compute job, an observation, or a complete workflow.

The Grid will know what to do where.

Bundesministerium
für Bildung
und Forschung

Partners

Dimension 1: wealth of fields within the astro-topic

MPI für Gravitationsphysik Potsdam
MPI für Astrophysik Garching
MPI für extraterristrische Physik Garching
MPI für Radioastronomie Bonn
MPI für Astronomie Heidelberg

Computer Science

Konrad-Zuse-Zentrum für Informationstechnik Berlin
Informatik, Technische Universität München
Institut für Informatik, Universität Potsdam

Astrophysics

Astrophysikalisches Institut Potsdam
Zentrum für Astronomie der Universität Heidelberg
Universitätssternwarte der LMU München

Computer Center

Max-Planck-Rechenzentrum Garching
Leibniz-Rechenzentrum München
Forschungszentrum Karlsruhe

Dimension 2: wealth of fields within the grid-topic

Funded by the
Bundesministerium
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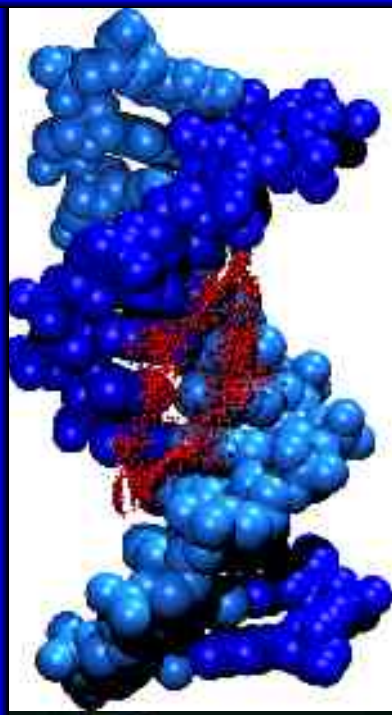
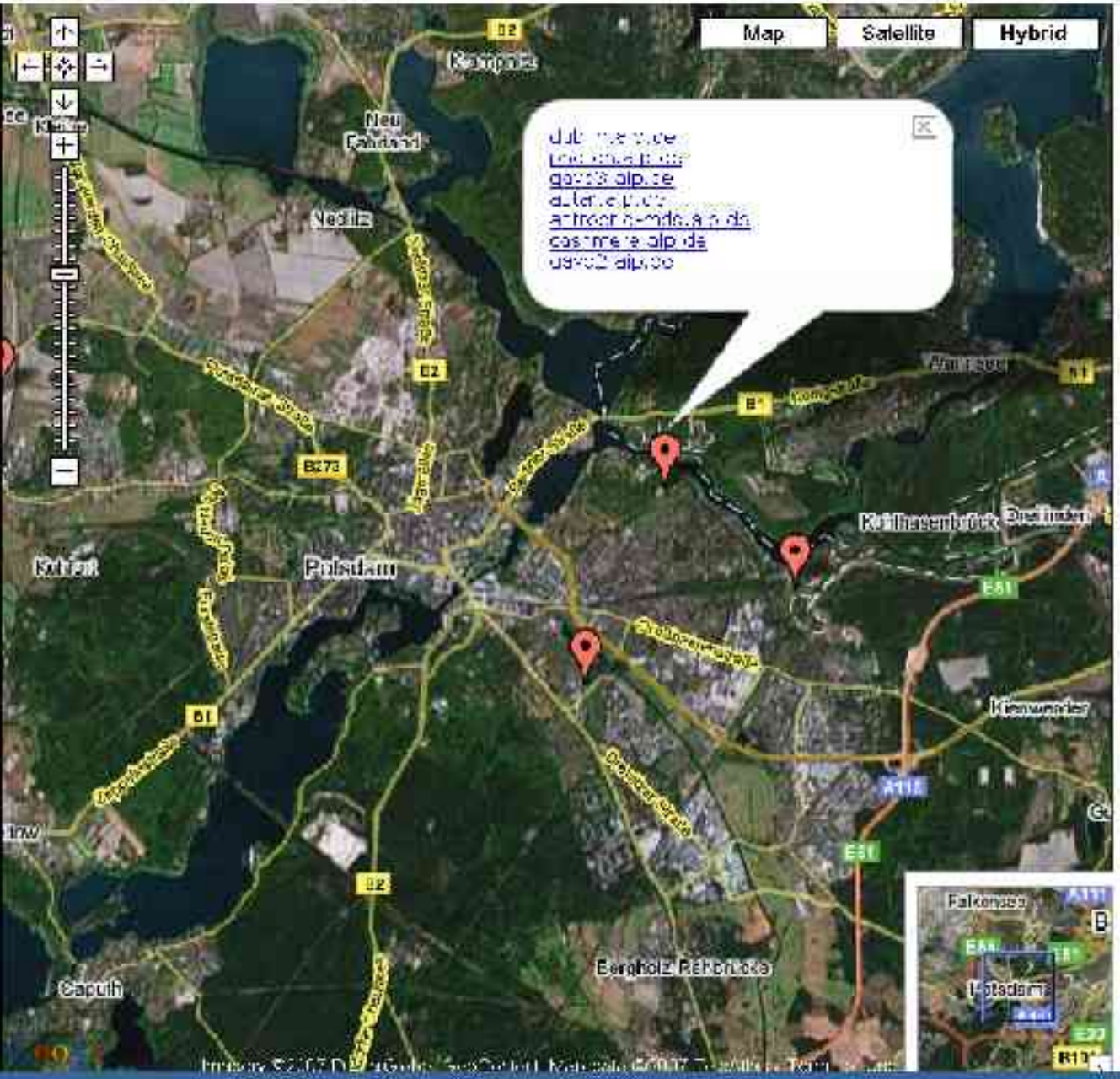
und Forschung

D-GRID incorporates:

- Climate Research (C3)
- High Energy Physics (HEP)
- Engineering (InGrid)
- Medicine (MediGrid)
- Humanities (TextGrid)
- Astronomy (AstroGrid)



GridMap



photon.aip.de

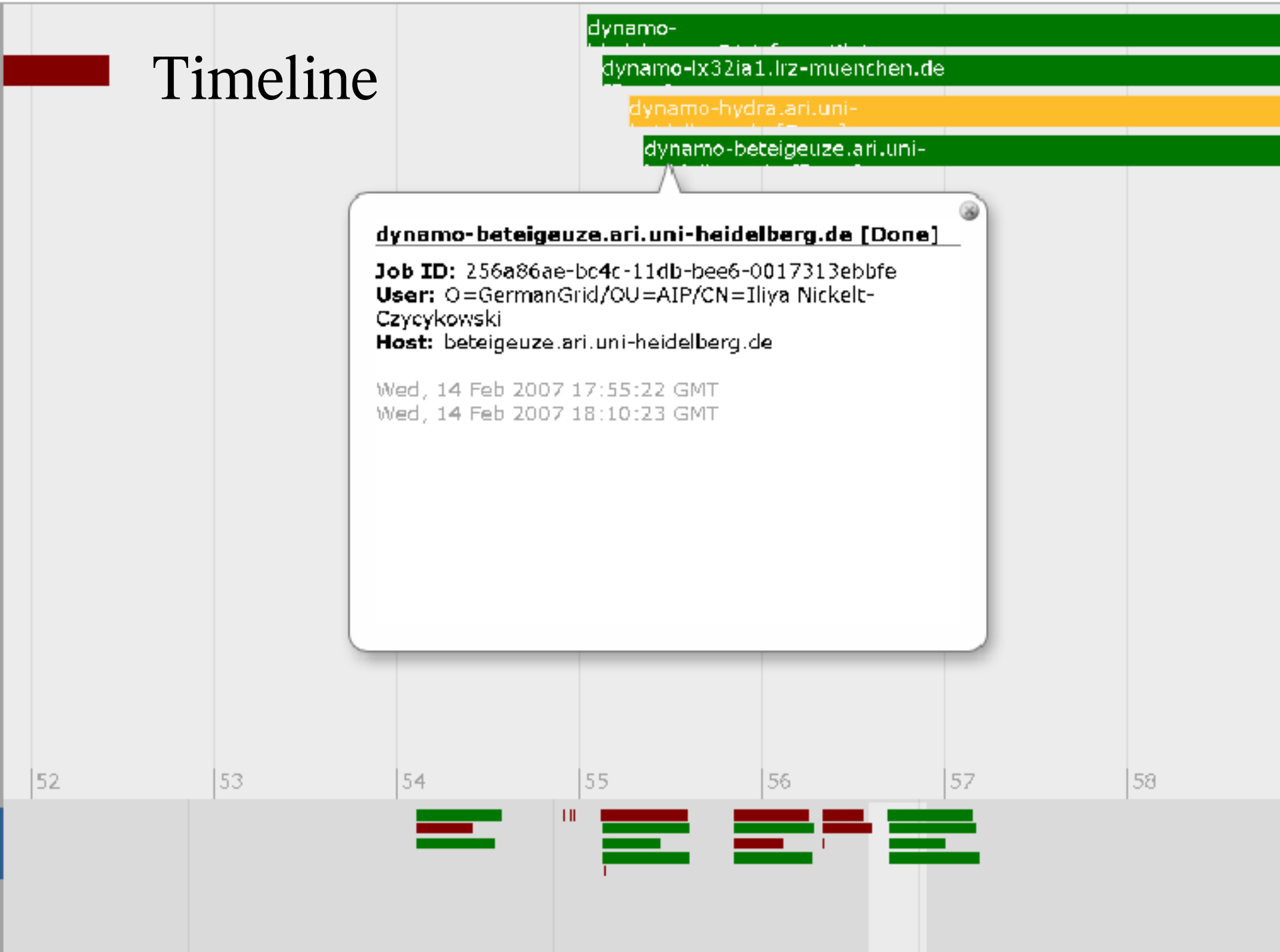
Fork

default 272 CPUs

Active jobs

name	state	jobid
nbody6_3.07	Done	[illegible]
dynamo-photon.aip.de	[illegible]	[illegible]
dynamo-photon.aip.de	Active	[illegible]
dynamo-photon.aip.de	ERROR	[illegible]
nbody6	Done	[illegible]
sleep	Done	[illegible]
[illegible]	[illegible]	[illegible]
dynamo	Done	[illegible]
sleep	Done	[illegible]
nbody6	Done	[illegible]
[illegible]	[illegible]	[illegible]
dynamo-photon.aip.de	ERROR	[illegible]
nbody6	Done	[illegible]

Timeline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dynamo-lx32ia1.lrz-muenchen.de
dynamo-hydra.ari.uni-
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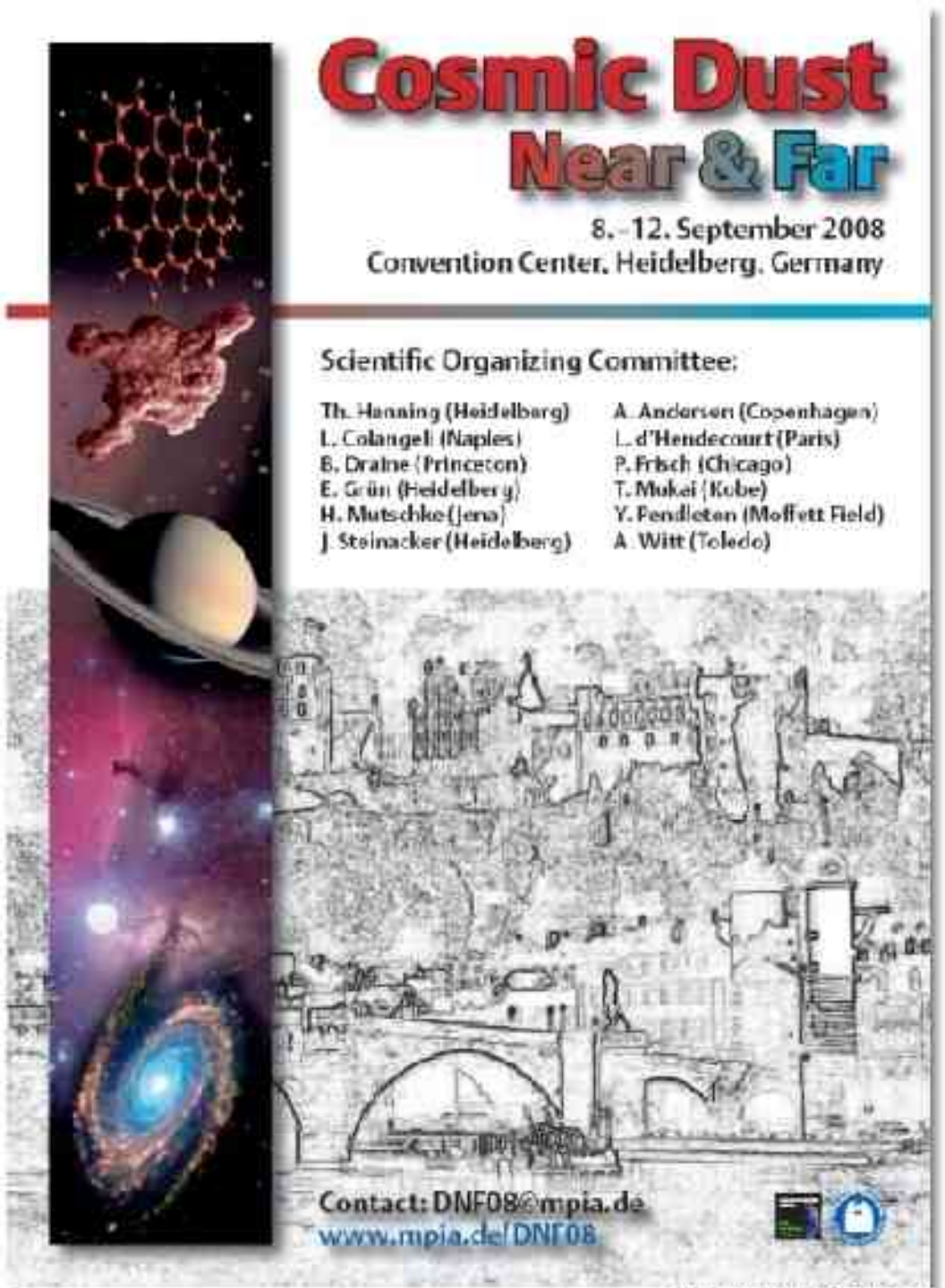

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3D Radiative Transfer

Jürgen Steinacker
(MPIA/ZAH Heidelberg)

Thank you.