Filling the Cosmos with (Virtual) Stars

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Outline

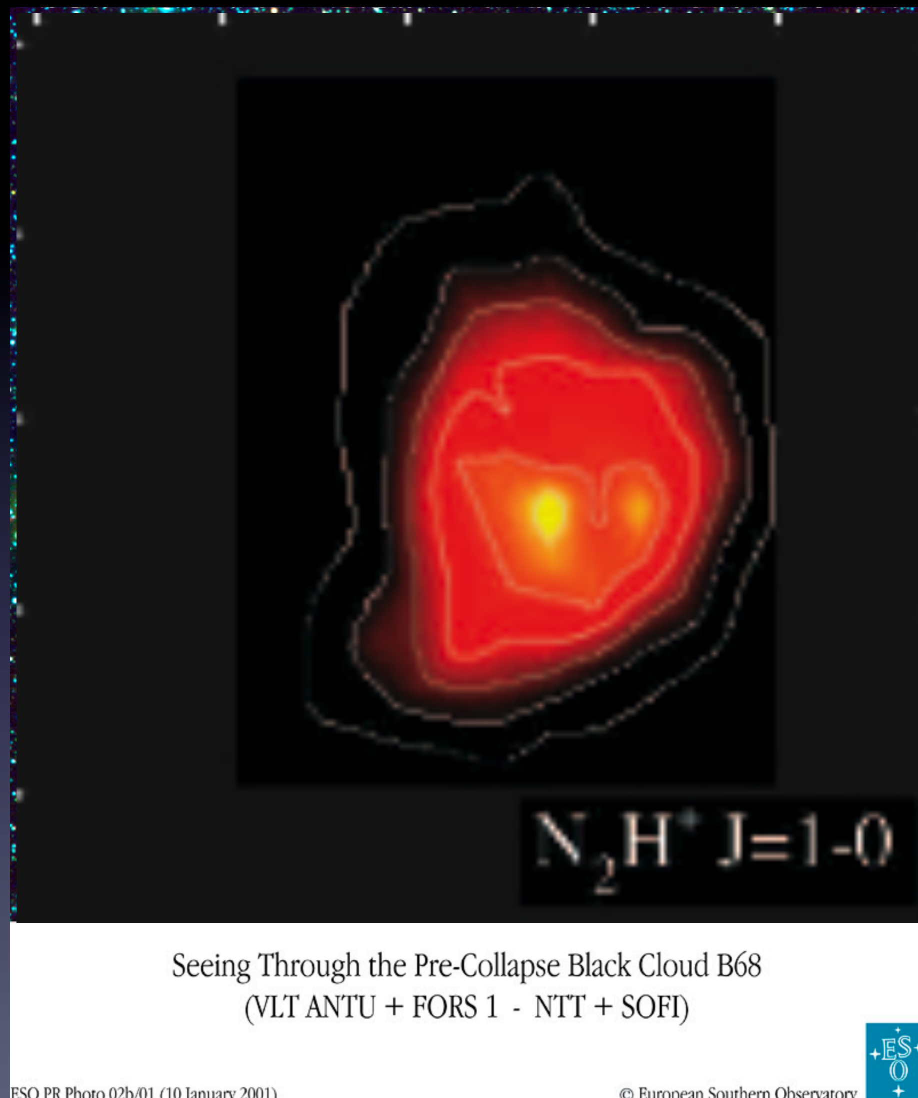
- What is the interstellar medium, and how is it related to star formation?
- Why is this a problem for supercomputers?
- What are the big questions, and how do simulations help answer them?

What you get if you google image search "interstellar medium"…

"The black light of the interstellar medium of deep space illumines all that is not, to be seen and not to 'Be'. To 'Be' and not seen – this is the path of the Panther woman.

From the hydrogen oceans of Deep Space she condenses rain. Water precipitates from Her Vast Womb, falling onto planets open to Her Life–giving moisture."

Hier ist wahrhaftig ein loch im Himmel!*



* "Here truly is a hole in Heaven!"
-- William Herschel, as remembered by his sister Caroline, 1784

INVESTIGATIONS ON THE SPECTRUM AND ORBIT OF δ *ORIONIS*.[1]

By J. Hartmann.

TABLE III.

λ	No. of Plates	Mean Error	Remarks
3933.68	7	(±0.34)	*Ca*; always exceedingly weak and narrow.
4069.49	3	±0.16	
4097.49	5	0.14	*Si*
4116.28	11	0.07	*Si*
4144.94	2	0.28	
4200.42	2	0.20	*H*δ' according to Pickering's nomenclature.
4541.78	2	0.41	*H*γ' according to Pickering's nomenclature.
4649.68	16	0.14	Probably a group; 4 tenth-meters wide.
4686.20	10	0.12	

Among the lines in Table III the calcium line at λ 3934 exhibits a very peculiar behavior. It is distinguished from all the other lines of this spectrum, first by the fact that it always appears extraordinarily weak, but almost perfectly sharp; and it therefore attracted my attention that in computing the wave-lengths collected in Table III for this particular line, the agreement between the results from the different plates was decidedly less than for the other, much less sharp lines. Closer study on this point now led me to the quite surprising result *that the calcium line at λ 3934 does not share in the periodic displacements of the lines caused by the orbital motion of the star.*

We are thus led to the assumption that at some point in space in the line of sight between the Sun and δ *Orionis* there is a cloud which produces that absorption, and which recedes with a velocity of 10km, [illegible] we admit the further assum[illegible] probable from the nature of the observed line, that the cloud consists of calcium vapor. This reasoning finds a distinct support in a quite

Postsdam, 1904

THE

ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY
AND ASTRONOMICAL PHYSICS

VOLUME XLIX JANUARY 1919 NUMBER 1

ON THE DARK MARKINGS OF THE SKY
WITH A CATALOGUE OF 182 SUCH OBJECTS

BY E. E. BARNARD

Observations from Lick Observatory!

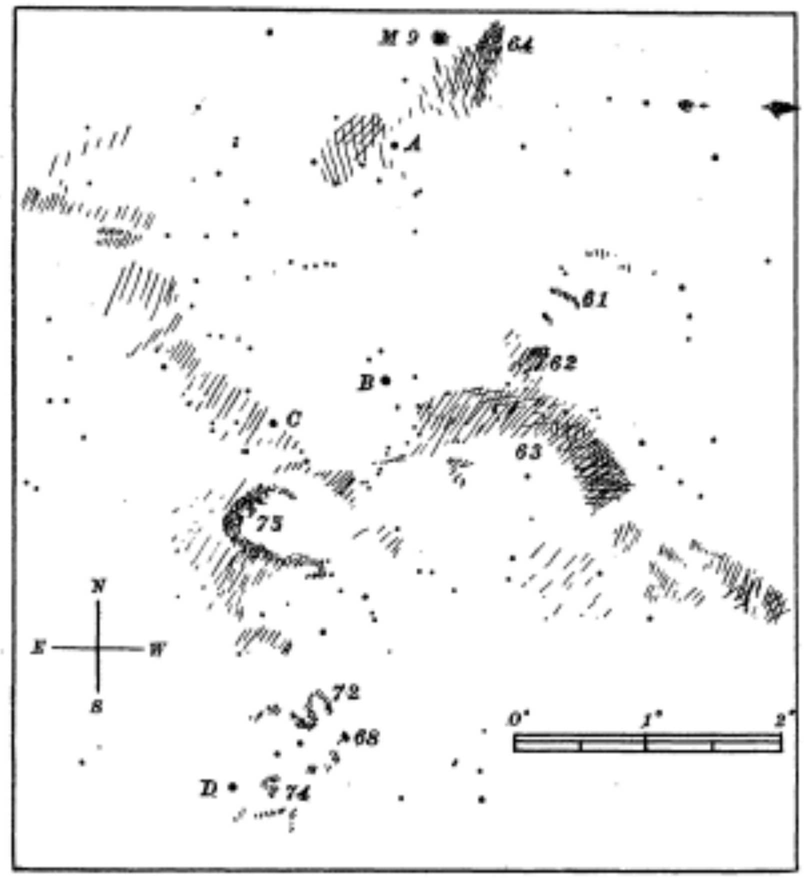


FIG. 2.—Sketch map of Plate I

A Modern View of the ISM

BAKERIAN LECTURE.—*Diffuse Matter in Interstellar Space.*

By A. S. EDDINGTON, F.R.S.

(Received May 21, 1926.)

2. The first part of this investigation is occupied with estimates of the density, temperature and state of ionisation of the matter. As the results have been reached by a kind of successive approximation in which the final conclusions of each section involve reference to the results of other sections, we state these conclusions here :—

(1) The density at an average point in space is about 10^{-24} gm./cm.^{3}.

(2) The temperature (defined by the mean molecular speed) is of the order 10,000°.

(3) The atoms are ionised down to a potential 15–20 volts, so that most valency electrons are set free but the inner groups are intact.

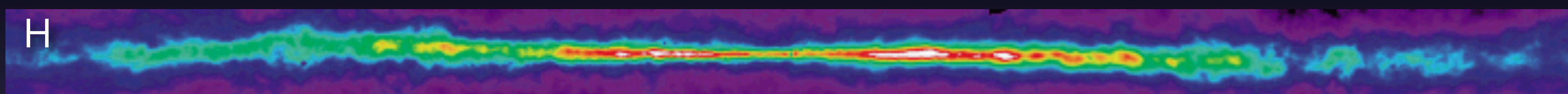
The second part develops the consequences which might affect astronomical observation, and includes discussions of the "fixed" lines in stellar spectra, general absorption of light in space, and accretion of mass by the stars.

ISM made up of many phases

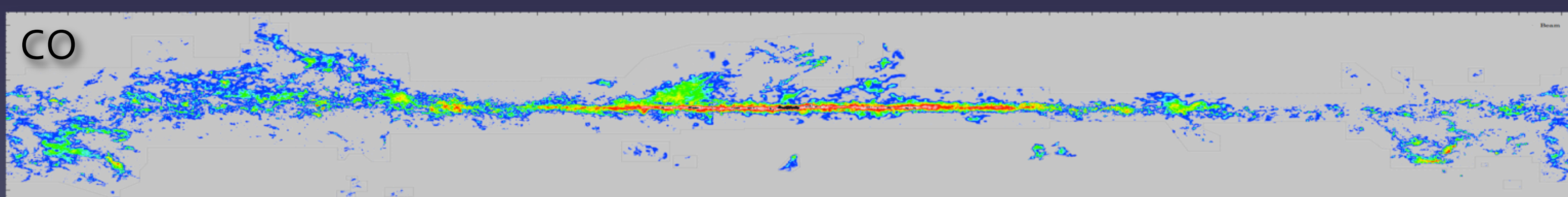
- Most H is atomic, n ~ 1 cm^{-3}, T ~ 1,000 – 10,000 K
- Densest gas is molecular (H_2), n > 100 cm^{-3}, T ~ 10 K

Milky Way Census

Stars: ~10^{11} $M_{\odot}$



Atomic hydrogen: ~10^{10} $M_{\odot}$



Molecular hydrogen: ~3×10^{9} $M_{\odot}$

Evidence for Star Formation

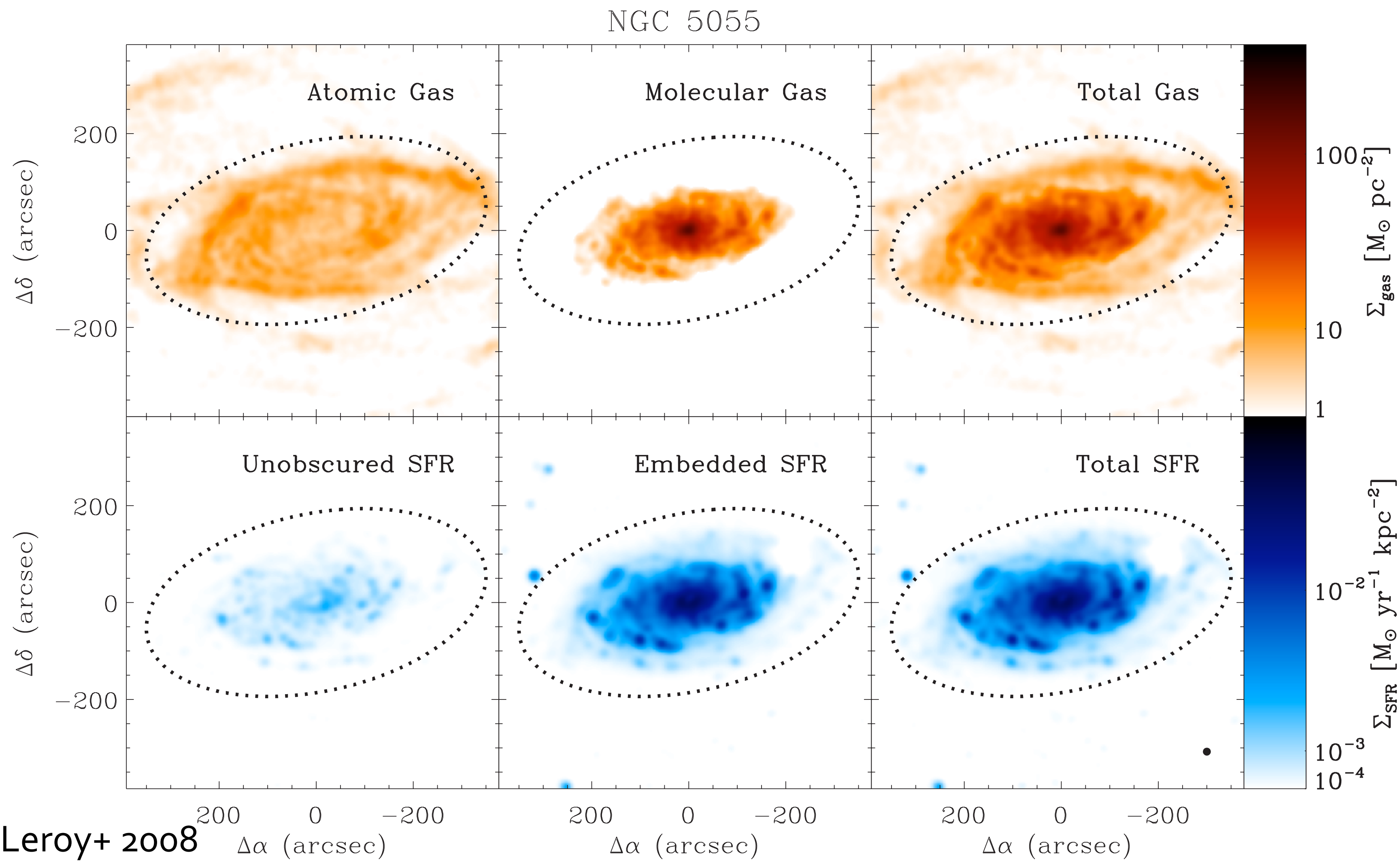
"Mountains of Creation" in W5 Star-Forming Region

Spitzer Space Telescope • IRAC
Visible: DSS

NASA / JPL-Caltech / L. Allen (Harvard-Smithsonian CfA)

ssc2005-23a

Maps of HI, H_2, and SFR



Leroy+ 2008

Why Supercomputers?

- Clouds filled with hypersonic turbulent motions, so analytic treatment impossible
- Many physical processes important
  - Gas flows, gravity, magnetic fields, radiation
- Large range of scales: typical GMC density ~100 cm^{-3}, stellar density ~10^{24} cm^{-3}
- Timescales too long for direct observation

What Does a Simulation Do?

Step 1: start with the underlying equations.

Example: thermal diffusion

$$\frac{\partial T}{\partial t} = -\nabla \cdot \mathbf{F}$$

$$\mathbf{F} = -\kappa \nabla T$$

$$\Longrightarrow$$

$$\frac{\partial T}{\partial t} = \kappa \nabla^2 T$$

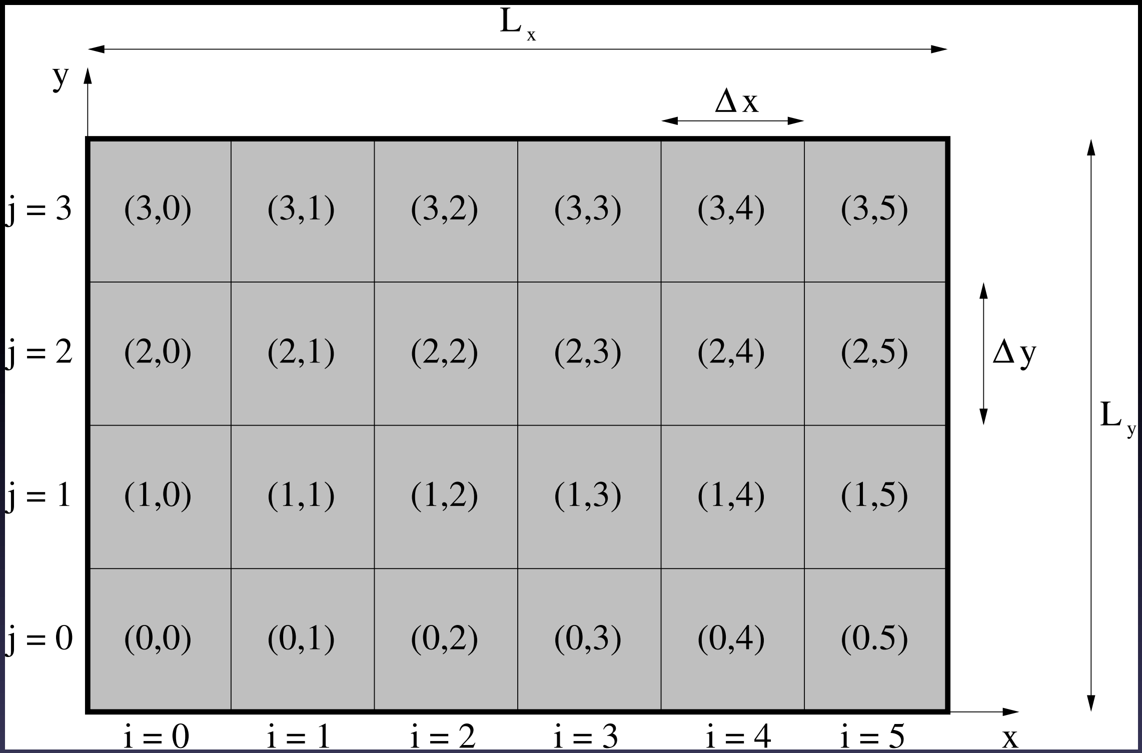
Temperature

Heat flux

Time

Thermal conductivity

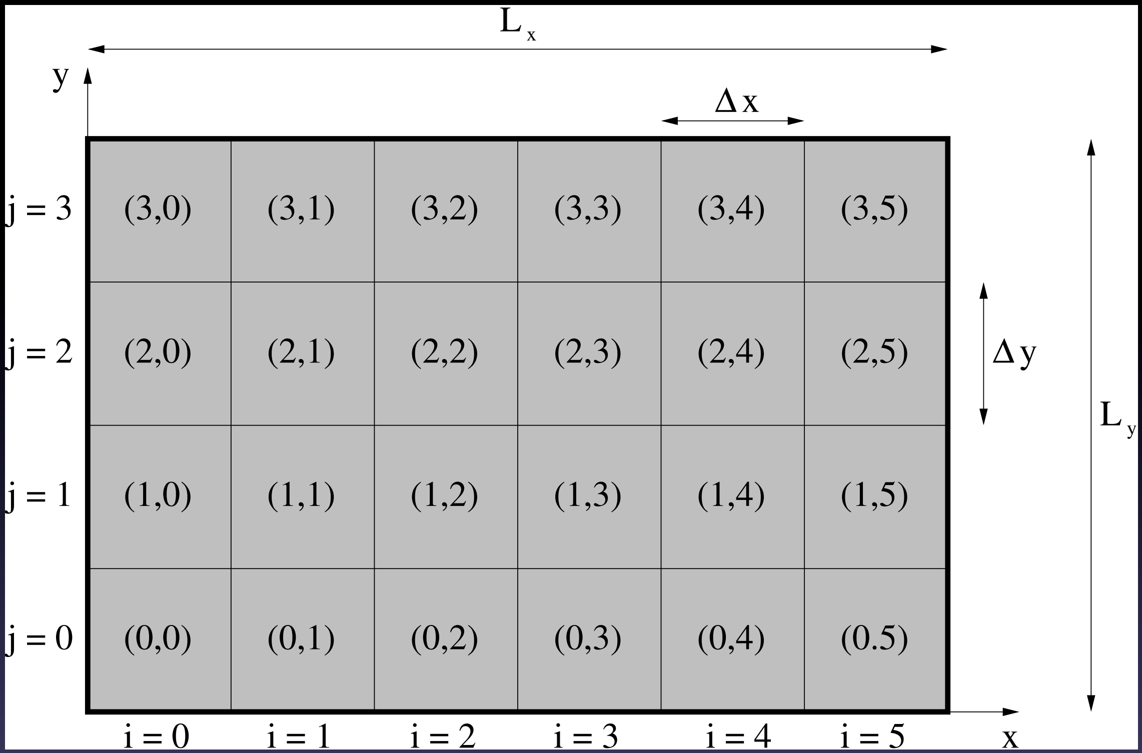
Step 2: Discretize



Discretize in space:

$$\frac{\partial T_{ij}}{\partial t} = \frac{\kappa}{\Delta x^2}\left(T_{i-1,j} + T_{i+1,j} + T_{i,j-1}, +T_{i,j+1} - 4T_{i,j}\right)$$

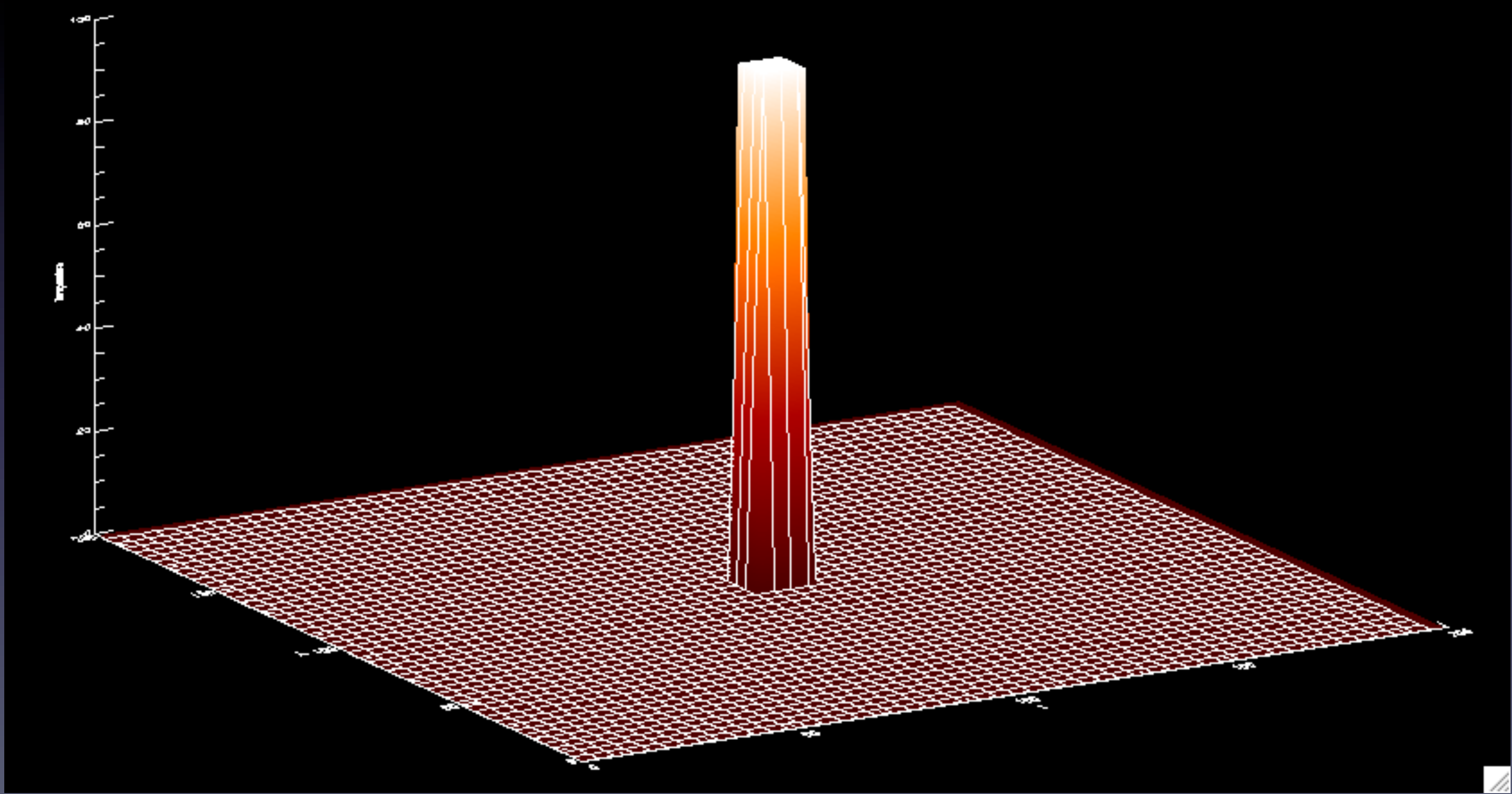
Step 2: Discretize



Discretize in space and time:

$$T_{ij}^{(n+1)} = T_{ij}^{(n)} + \frac{\Delta t}{\Delta x^2}\kappa \left[T_{i-1,j}^{(n)} + T_{i+1,j}^{(n)} + T_{i,j-1}^{(n)}, + T_{i,j+1}^{(n)} - 4T_{i,j}^{(n)} \right]$$

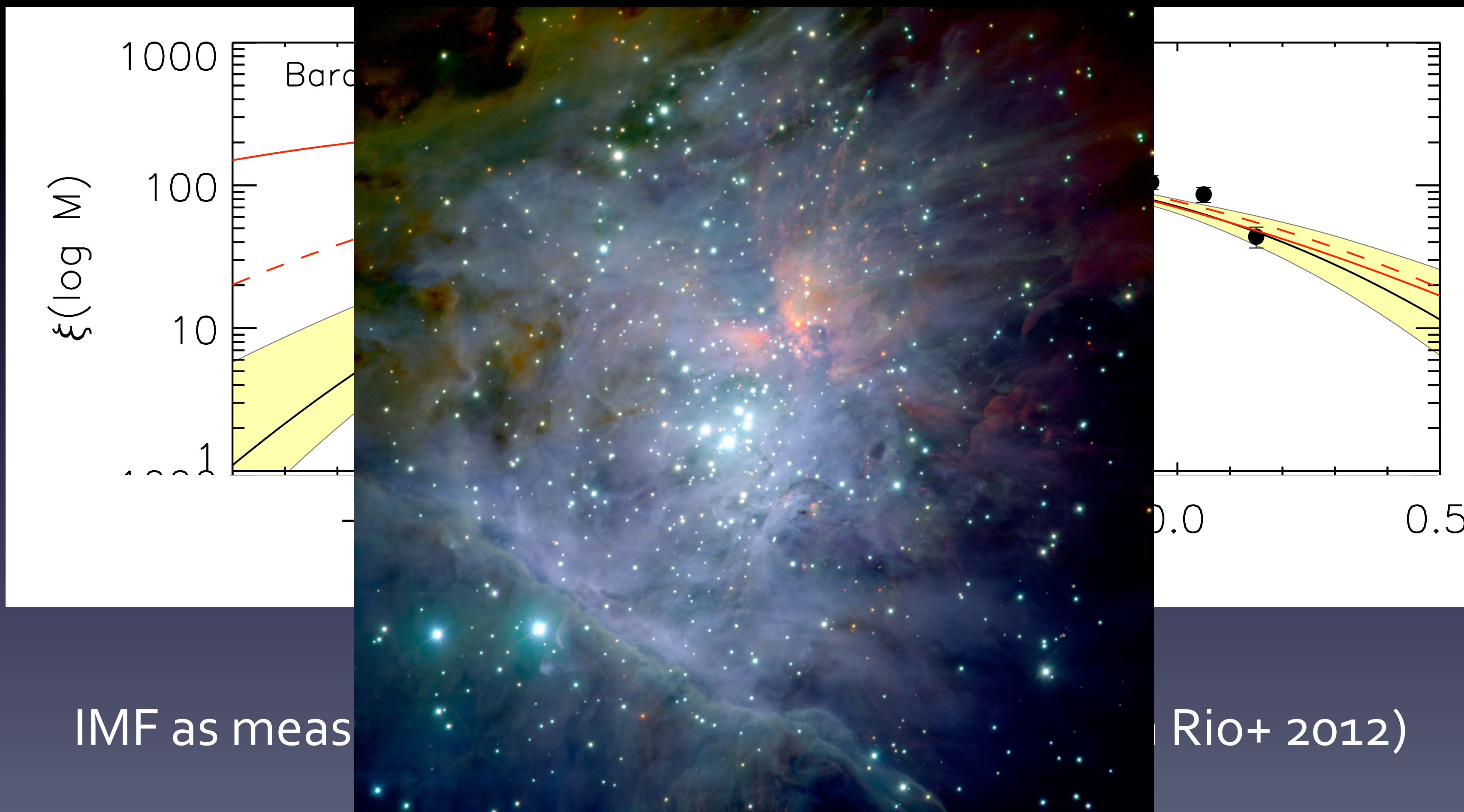
Step 3: Turn the Crank



Star Formation: The Big Questions

- What determines stellar masses?
  - Does stellar mass have an upper limit?
- What determines the rate at which stars form?

The IMF



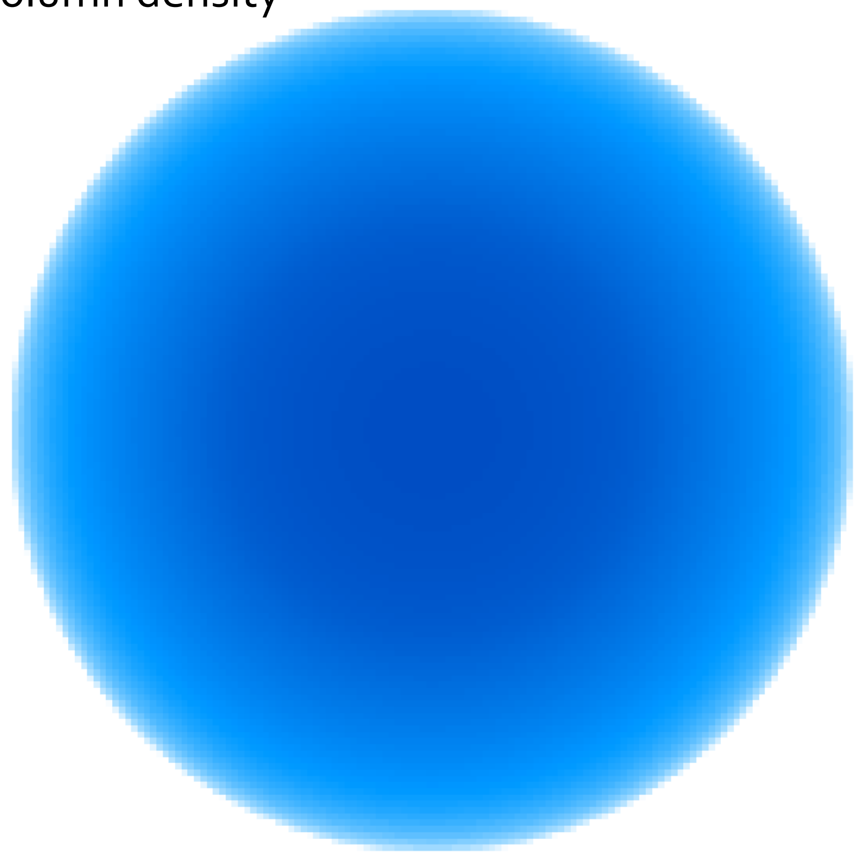
IMF as meas … Rio+ 2012)

Challenges of the IMF

- IMF is universal or nearly so, yet star-forming environments vary greatly. Why?
- Why are stars at the right mass scale to allow nuclear fusion?

Simple Collapsing Cluster Simulation

Column density



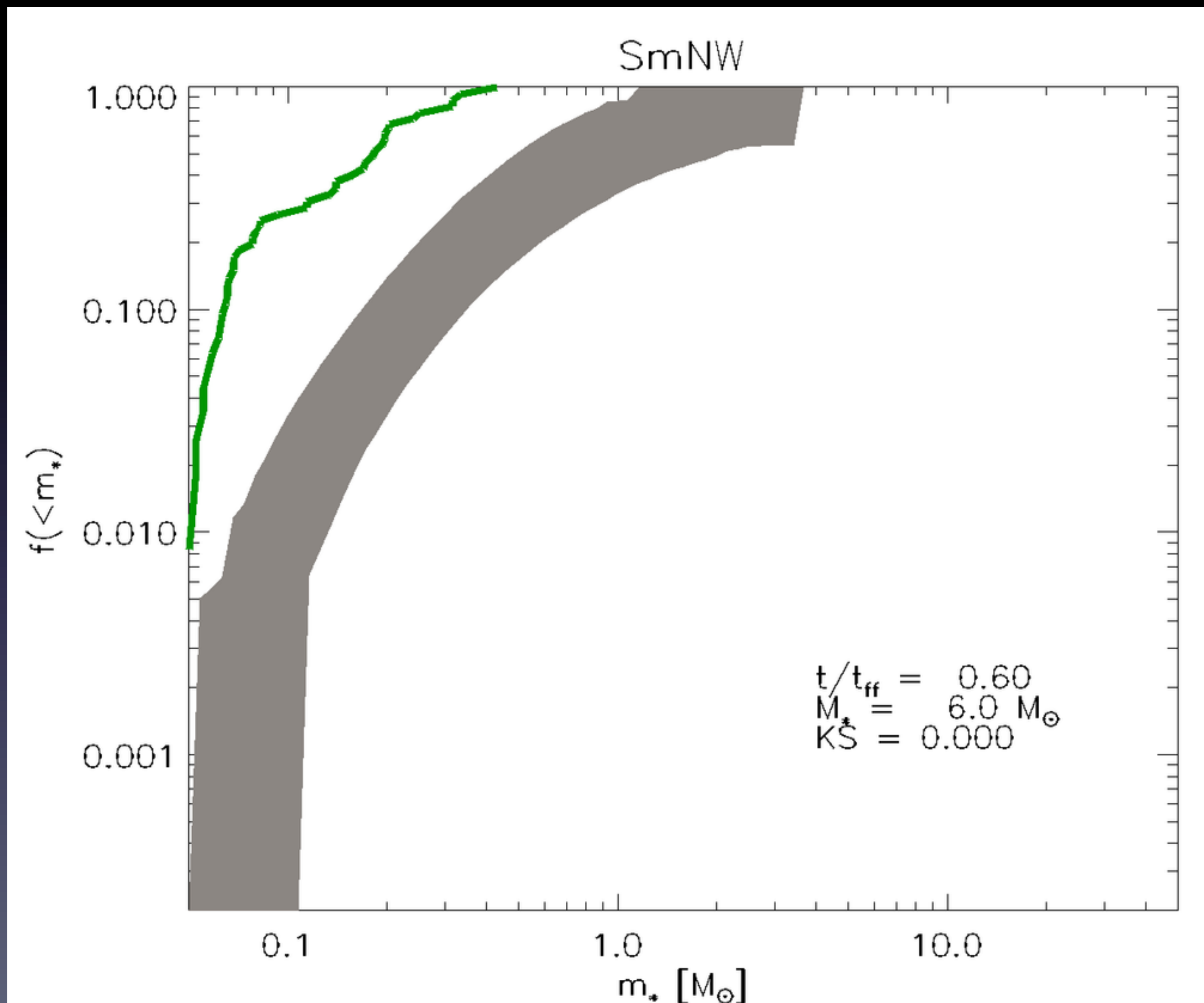
Temperature

Krumholz, Klein, & McKee (2011)

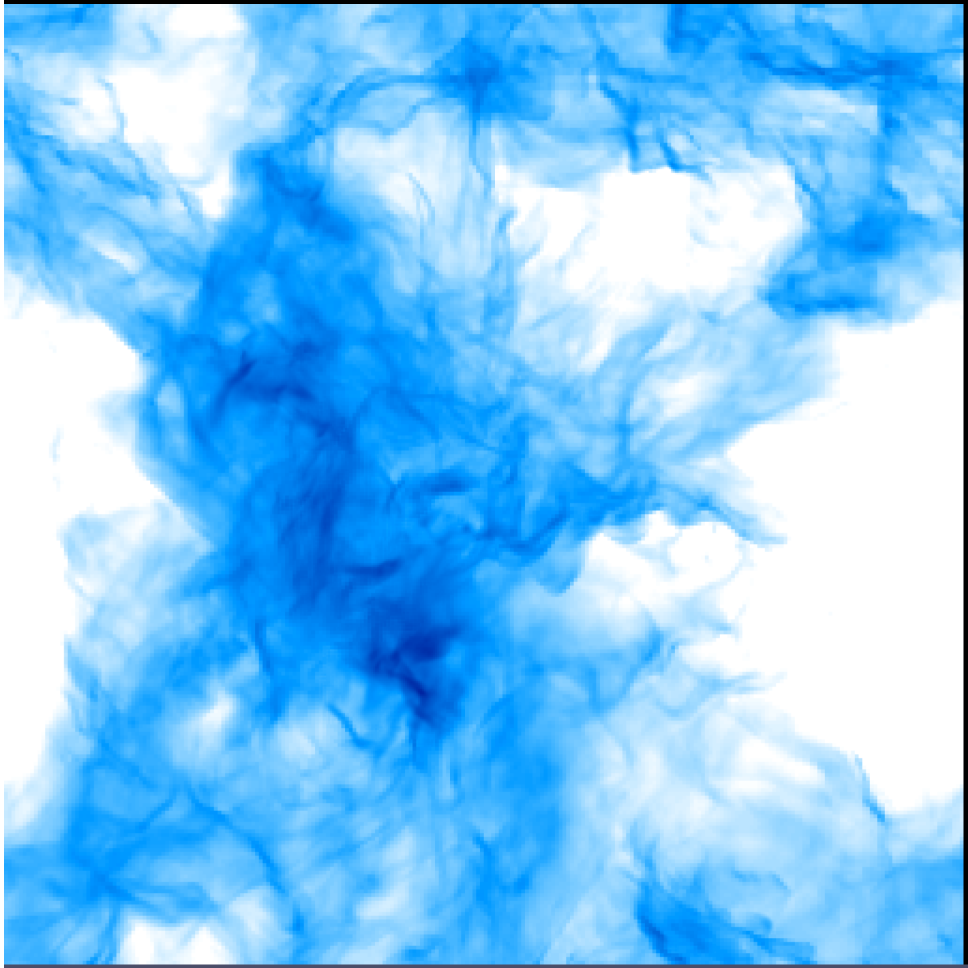
What's included: hydrodynamics, gravity, radiation

Numerical method: AMR

Doesn't Work



Adding More Physics

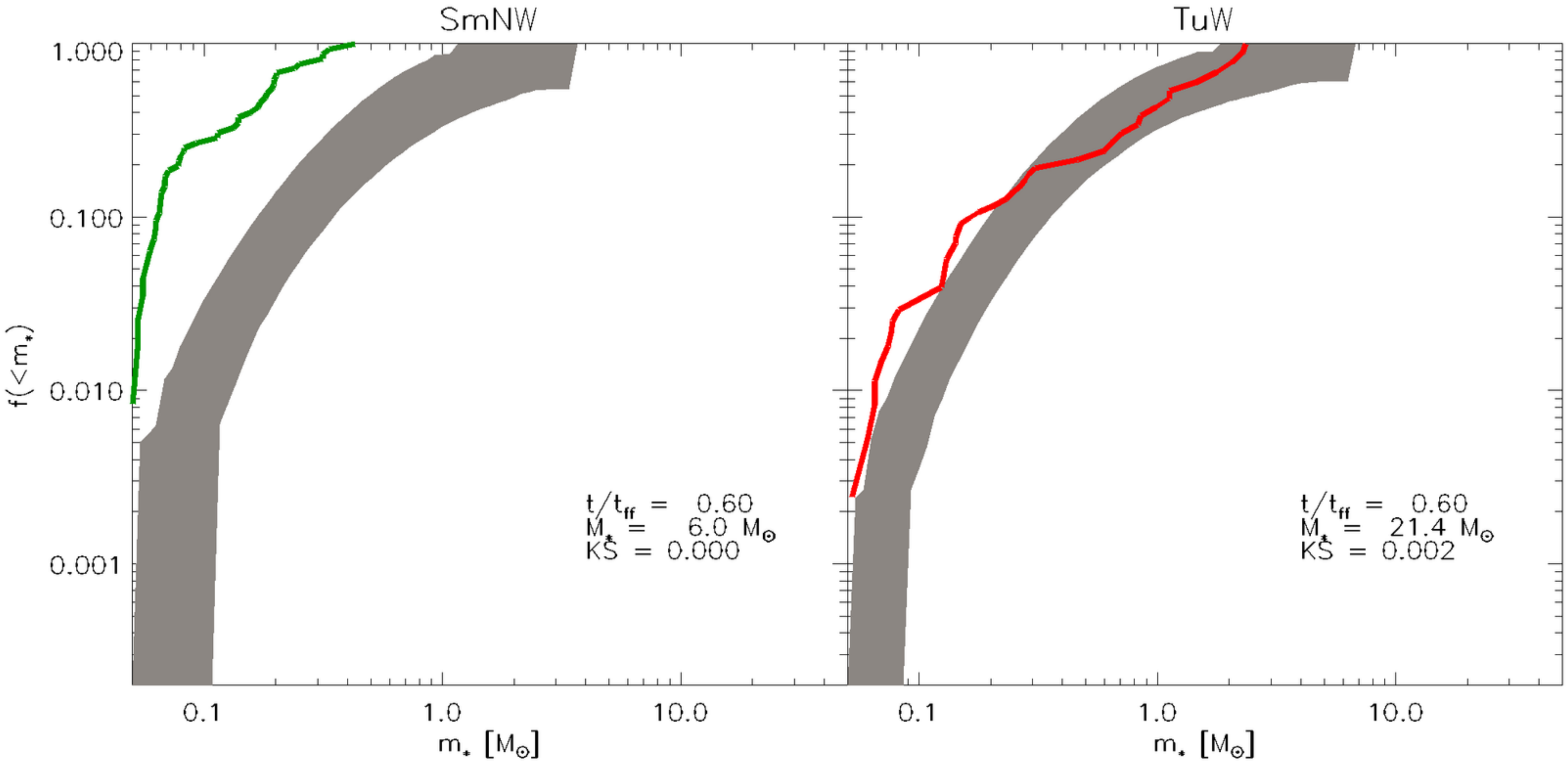


Krumholz, Klein, & McKee (2012)

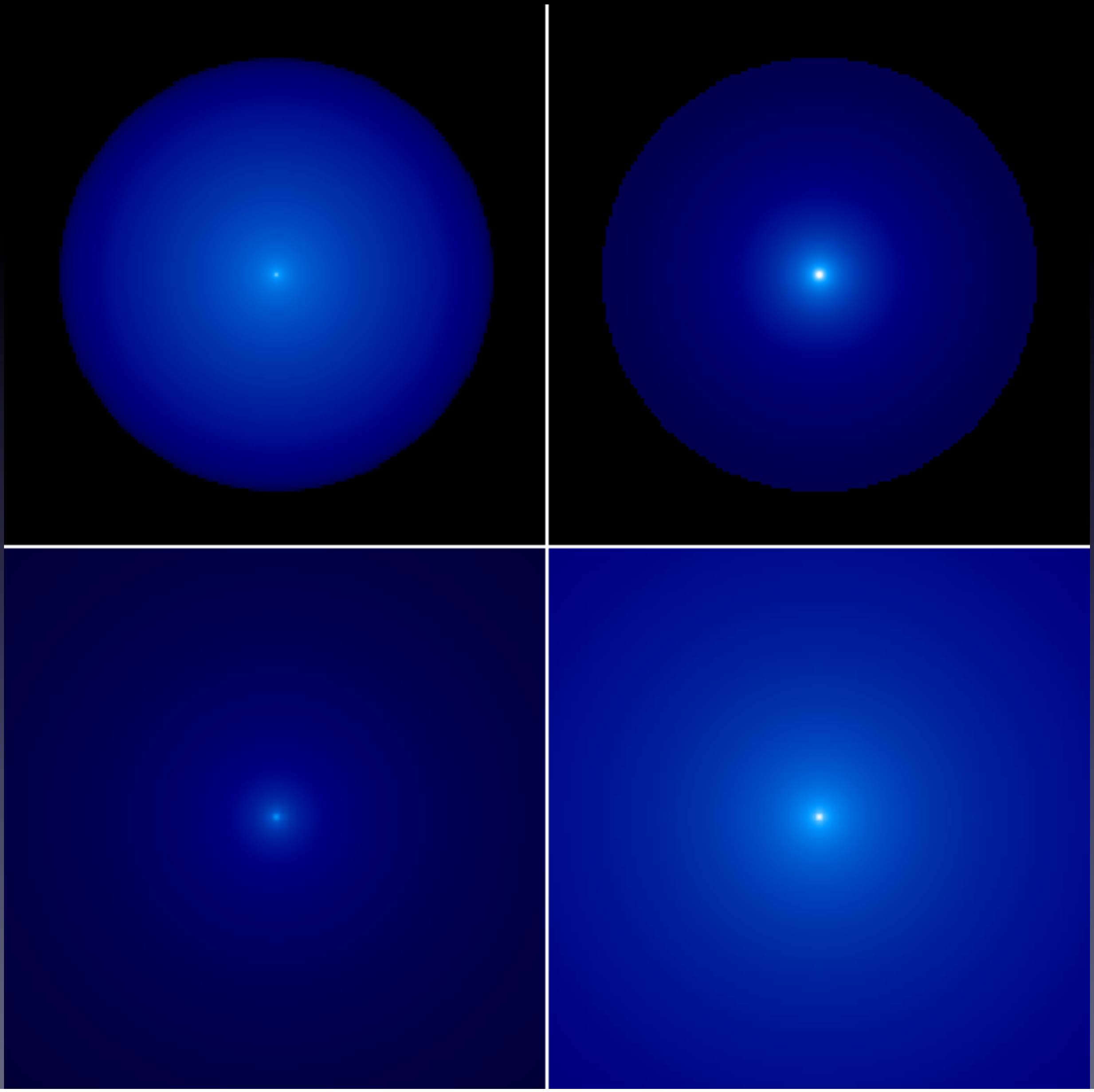
What's included: hydrodynamics, gravity, radiation, protostellar jets

Numerical method: AMR

Works Much Better



Do Stars Have a Mass Limit?

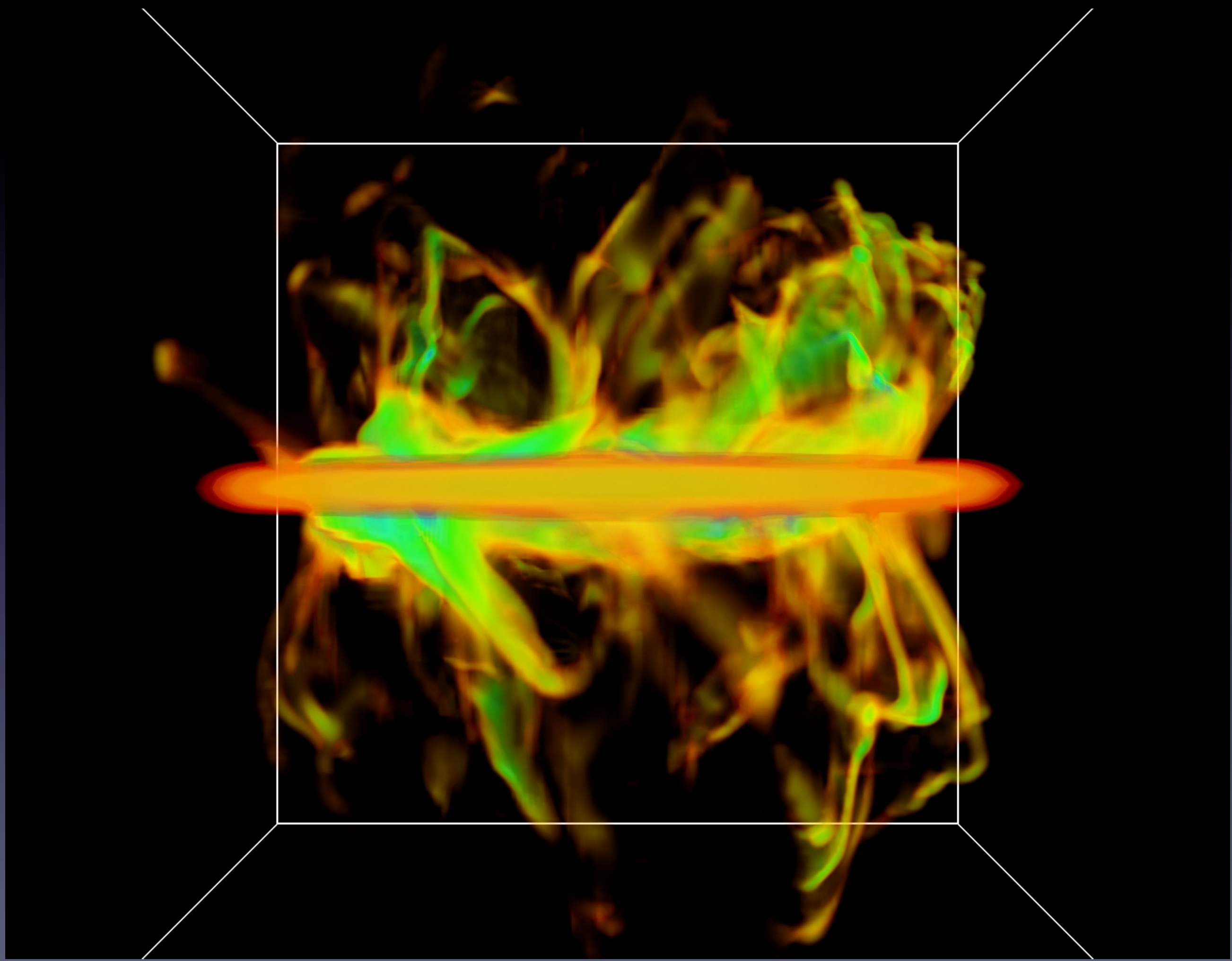


Krumholz+ 2009

What's included: hydrodynamics, gravity, radiation

Numerical method: AMR

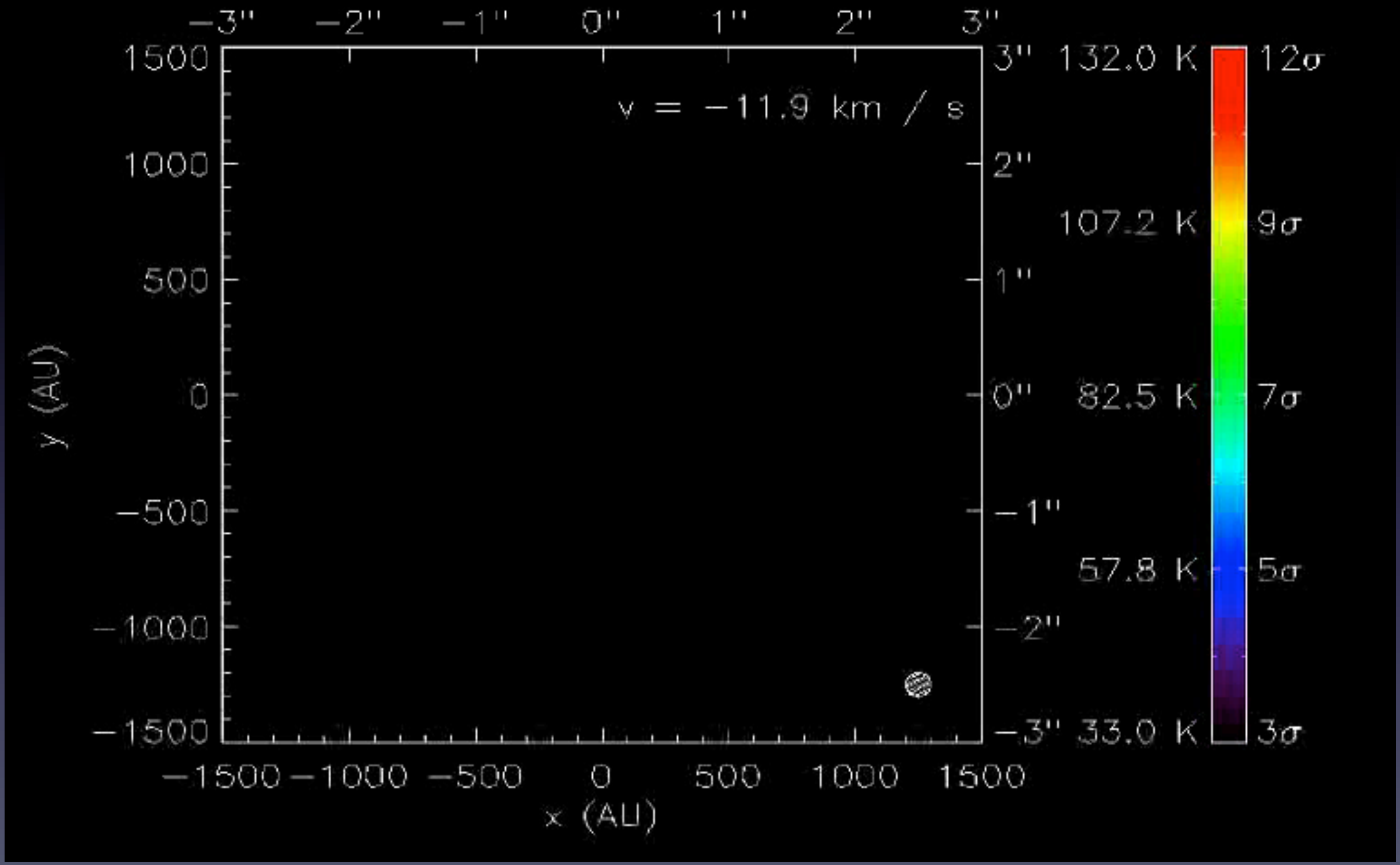
Observational Test: The Disk



The Instrument

Atacama Large Millimeter Array

The Prediction



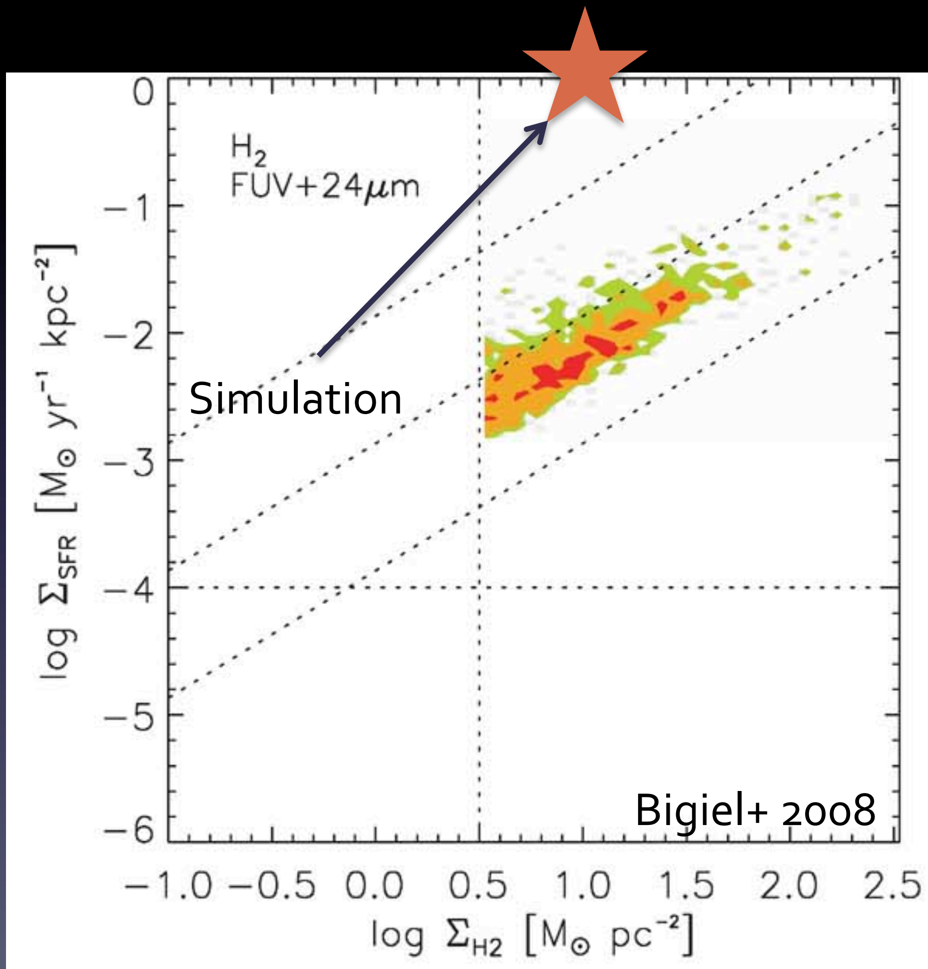
Simulated ALMA observation in CH_3CN 220.7472 GHz (Krumholz+ 2007)
Numerical method: long characteristics

Star Formation Rates: the Simplest Approach

What's included: hydrodynamics, gravity

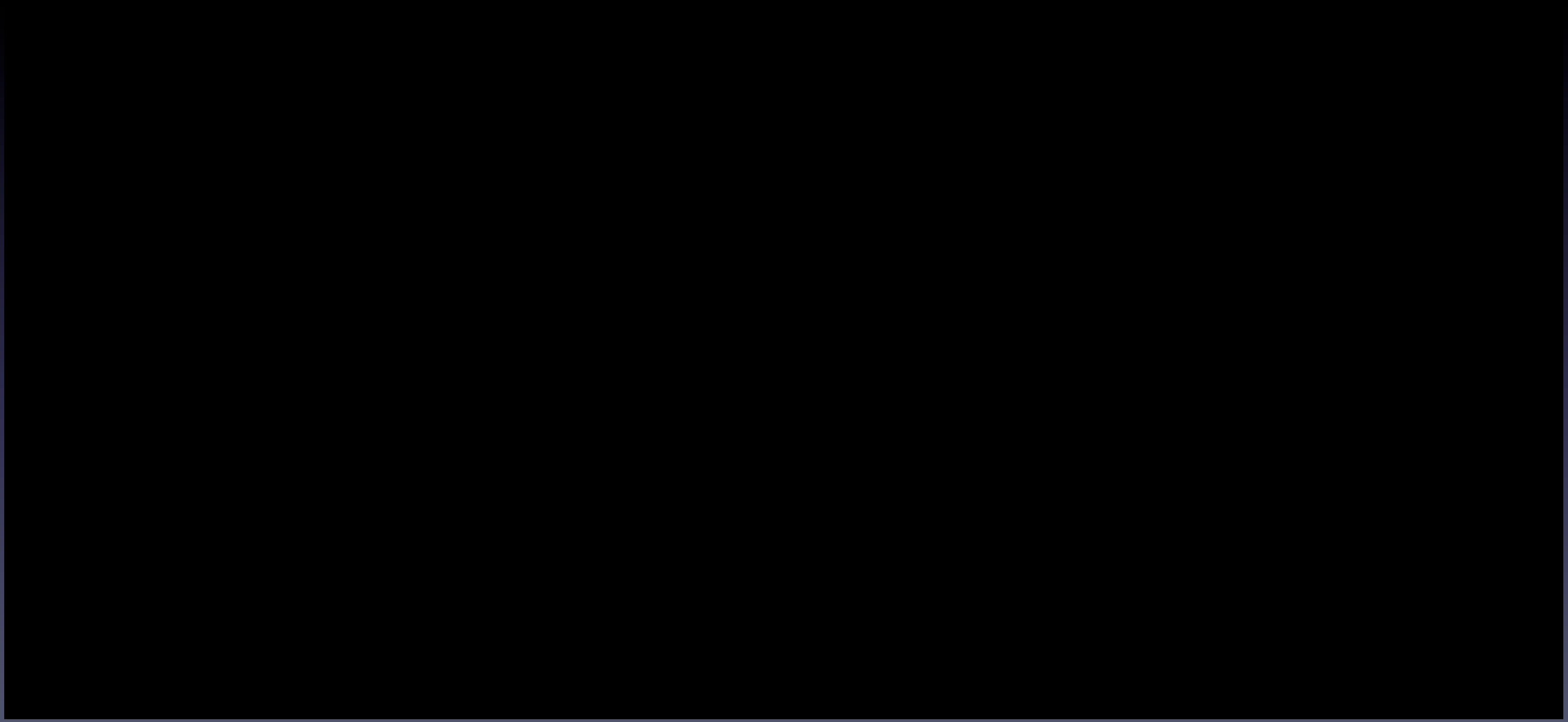
Numerical method: SPH

SFR: The Problem in a Nutshell



- Too fast by a factor of ~100
- Too efficient: simulation forms a gravitationally bound cluster, but most stars not in clusters

Adding More Physics



Simulation: Wang et al. (2009)

What's included: MHD, gravity, protostellar jets
Numerical method: AMR

Concluding Thoughts

- Simulations are the indispensible tool for understanding star formation
- Many big problems not fully solved: origin of stellar masses, star formation rates
- This is probably because we don't have all the necessary physics in the codes yet