Blackboard Lunch
Formation of the First Stars in the Universe

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Outline

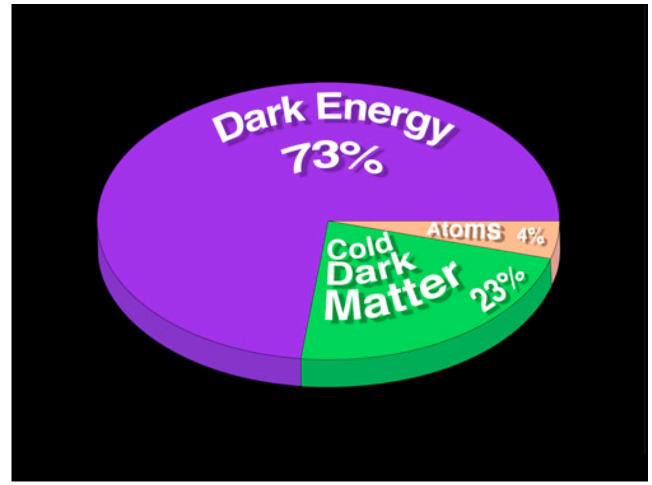
- **Relevant Cosmology**
  - Composition
  - Thermal Evolution
  - Density fluctuations
    - *Gas / CDM & Jeans filtering*
    - *= velocity fluctuations*
- **Relevant Molecular Physics**
  - H2 formation
    - *gas phase*
    - *three body*
  - H2 radiative processes
- **Gravo-chemo-thermal Instability**
  - Fragmentation criteria
  - Summarize mass scales - Predictions?

Outline (cont.)

- **Numerical Techniques & Results**
  - Chemistry
  - 0D, 1D & 3D,
  - AMR & SPH
    - *Russian doll fragmentation*
    - *High mass accretion rates*
- **Some Open Questions**
  - Final mass scale: need technique that is predictive to better than factor of 10
  - Star formation in regions affected by the first stars
  - ...
- **Conclude**

Relevant Cosmology

- **Composition**
  - 73 percent dark energy
  - 23 percent cold dark matter
  - 4 percent baryons
- **CDM**
  - Collisionless
  - Many candidates
- **Gas**
  - 76 % hydrogen
  - 24 % helium
  - D/H ~ 3 x 10^{-5}
- **Photons**
  - ~ 2 billion per baryon
- **Age**
  - 13.7 +- 0.1 billion years
- **etc.**
  - Neutrinos, etc. irrelevant



Thermal Evolution of the Intergalactic Medium

- **Residual e- fraction**
  - freezes out at 10^{-4} in number fraction
    - *competition of recombination with expansion time scale*
- **Compton Heating**
  - couples electron temperature to photon temperature until redshift ~ 130

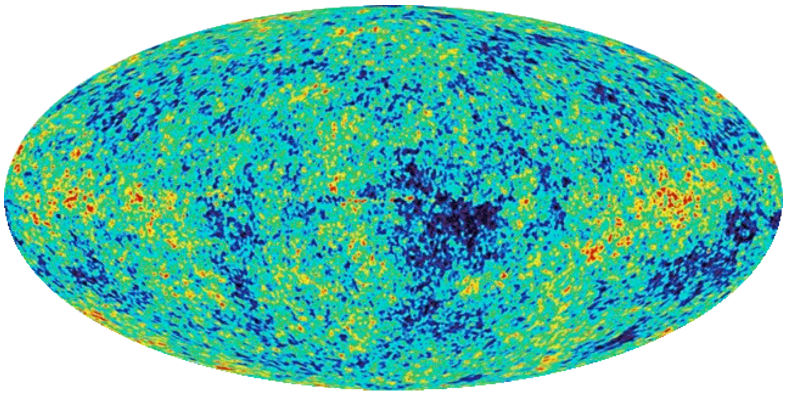
$$T_{IGM} \propto (1+z)$$

- **Adiabatic Expansion**

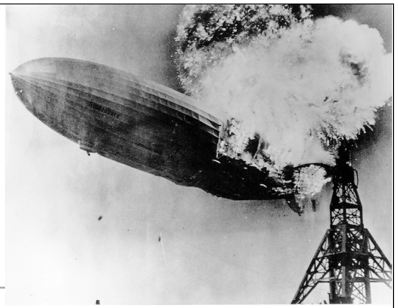
$$T_{IGM} \propto (1+z)^2$$

- **Once sources UV radiation form**

$$T_{IGM} \sim 10^4\,\mathrm{K}$$



Relevant Molecular Physics



- **H2 formation**
  - Gas phase

$$
\begin{aligned}
\mathrm{H} &+ \mathrm{e}^- \rightarrow \mathrm{H}^- + h\nu, \\
\mathrm{H}^- &+ \mathrm{H} \rightarrow \mathrm{H}_2 + \mathrm{e}^-,
\end{aligned}
$$

    e^- out of equilibrium --> solve kinetic reaction network
  - 3 body reaction

$$3\ \mathrm{H} \rightarrow \mathrm{H}_2 + \mathrm{H}$$

- **Ro-vibrational cooling**
  - 512 K, 809K excitation temperature of lowest levels --> ~ 200 K minimum temperature in collapse
  - Critical density ~ 10^4 cm^{-3}
  - Optically thick > 10^{12} cm^{-3}
- **Collision Induced Emission**
  - Continuum radiation starting at n ~ 10^{14} cm^{-3} and optically thick already at n ~ 10^{17} cm^{-3}

Density Fluctuations

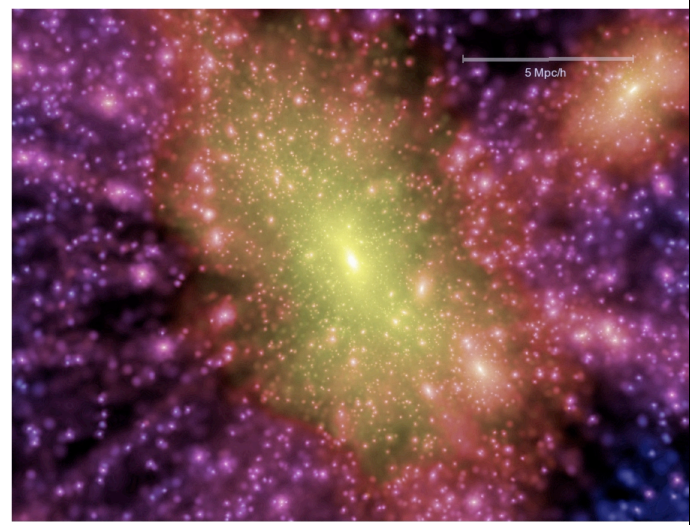
- **One function ...**
  - Gaussian at any scale
  - dM/M
  - free streaming scale
  - Turn over: Radiation vs matter dominated phase
- **Gas**
  - Silk damping
  - Catch up after recombination

Gravo-chemo-thermal instability

- **Gravitational instability**
  - Density perturbation only grow linearly in expanding universe
  - Smallest Scale Dark Matter perturbations already non-linear at z ~ 100
  - Dark matter grows hierarchically: non-linear merging
  - Average density of halo ~ 200 of mean density at formation

  - Jeans Mass
    - *Gas pressure vs DM potential*
      ~ 10^4 M_o $[(1+z)/10]^{3/2}$
  - Purely adiabatic gas physics until enough H_2 is formed
  - 1000 Kelvin relevant temperature
  - ~ 10^5 - 10^6 solar masses

$$\frac{\delta\rho}{\rho} \propto \frac{1}{1+z}$$



Thermal Instability

THERMAL INSTABILITY

GEORGE B. FIELD
Princeton University Observatory

Received June 4, 1964; revised March 30, 1965

ABSTRACT

The stability of a dilute gas in mechanical and thermal equilibrium is studied with a view to applications to non-gravitational condensation phenomena in astronomy. It is shown that, under a wide range of conditions, thermal equilibrium is unstable and can result in the formation of condensations of higher density and lower temperature than are found in the surrounding medium The instability criterion is shown to differ considerably from certain criteria proposed by previous authors. The modifications due to finite speed of sound, to thermal conduction, to a magnetic field, to rotation, to an external gravitational field, and to expansion of the medium are studied. Applications are made to the solar chromosphere and corona, to the interstellar medium in the galactic disk and halo, to planetary nebulae, and to intergalactic matter. It is shown that the principle of thermal instability is closely related to the formation of solar prominences, to condensations in planetary nebulae, and to condensation of galaxies from the intergalactic medium.

$$T_0 \mathfrak{L}_T - \rho_0 \mathfrak{L}_\rho < 0$$

Chemical Instability

- **Three body H_2 formation**
  - Very fast because $$t_{3H} \propto \frac{1}{\rho^2}$$
  - Increases H_2 fraction by ~ 1000, enhances cooling at $n \sim 10^9$ cm^{-3}

Hierarchical Fragmentation

- **Continuous breakup**
  - Until opacity limit
  - Necessary condition:
    - $t_{cool} < t_{dyn}$

ON THE FRAGMENTATION OF GAS CLOUDS INTO GALAXIES AND STARS

F. HOYLE*
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Received June 1, 1953

ABSTRACT

The present paper seeks to trace the steps whereby an extensive cloud of density 10^{-27} gm/cm^3 evolves, first into galaxies and then into stars. The indication is that galaxies are likely to form, not as single objects, but in clusters. Stars apparently form at an early stage in the history of a galaxy. There would seem to be reason why the average mass of such stars should lie somewhat below the solar mass.

I. INTRODUCTION

The arguments of the present paper, it should be stated at the outset, are of a mainly tentative character: the theory is still too qualitative and its comparison with observation not sufficiently strict to justify a stronger statement. Yet, in spite of these shortcomings, there seem to be rather many points where the idea of fragmentation—of gravitational turbulence, as it might be called—holds out hope of explaining important observational data that it seems worth while to describe the process at some length.

As examples of the problems that come within the scope of the present paper the following may be mentioned. Why do galaxies tend to occur in clusters?[1] Why are the masses of the galaxies mainly confined in the range $3 \times 10^9 \odot$ to $3 \times 10^{11} \odot$, with possibly a tendency to fall into two groups at the ends of this range?[2] Why is the typical mass of a type II star of order $\odot$? Why do type II stars apparently form almost simultaneously with the origin of a galaxy?

Relevant Mass scales

- **~ 3 · 10^5 M_o**
  - $n \sim 1$; $T \sim 10^3$ K
  - Chemical time scales ~ dynamical times
- **~ 100 M_o**
  - $n \sim 10^5$; $T \sim 200$ K
  - Critical density of H_2 and minimum temperature reachable by H_2 cooling
- **~ 1 M_o**
  - $n \sim 10^9$; $T \sim 200$ K
  - three body H_2 formation still at T_{min}
- **~ 10^{-2} M_o**
  - $n \sim 10^{15}$; $T \sim 1000$K; continuum transport wins over H_2

$$M_J \propto \frac{T^{3/2}}{\sqrt{\rho}}$$

Predictions?

Kinetic Rate Equations

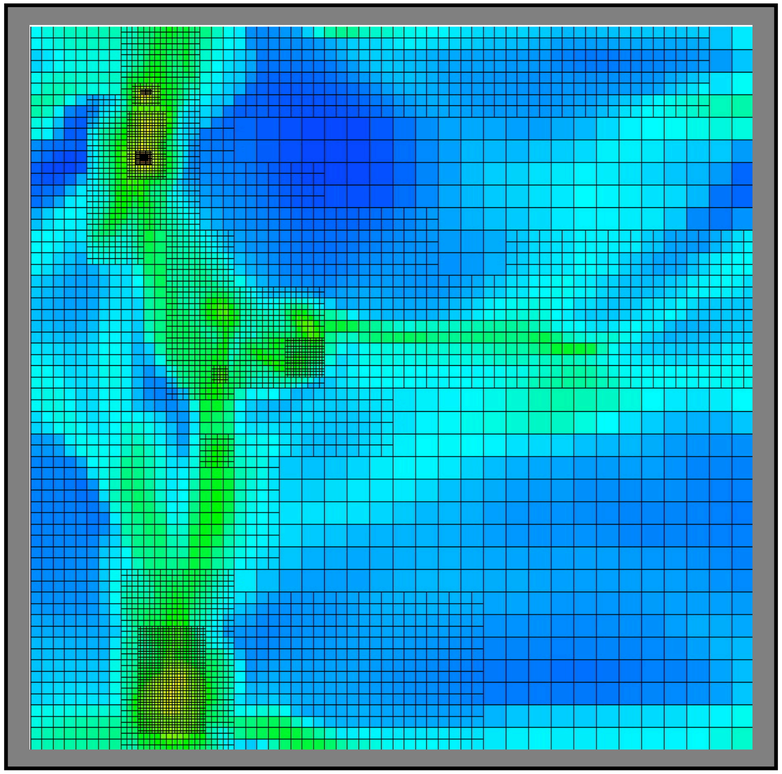
- **Reactive flow problem**
- **Chemistry out of equilibrium**
  - stiff set of coupled ODEs
  - expensive to solve
  - 0D or 1D models until 1995
- **Fast solvers allowed 3D calculations starting mid 90ies**

Numerical Techniques

- **Adaptive Mesh Refinement**

$$\begin{aligned} \frac{D\rho}{Dt} + \rho\nabla\cdot\vec{v} &= 0, \\ \rho\frac{D\vec{v}}{Dt} &= -\nabla P - \rho\nabla\Phi, \\ \frac{D(\rho\epsilon)}{Dt} - \frac{P}{\rho^2}\frac{D\rho}{Dt} &= (\Gamma - \Lambda) \\ \nabla^2\Phi &= 4\pi G. \end{aligned}$$

  - Recursively refine regions of interest
  - rectangular patches
  - refinement factor typically 2
  - has been used up to 42 to levels by my group resulting in a dynamic range of ~10^{15}
- **Cons**
  - difficult to program, use, analyze



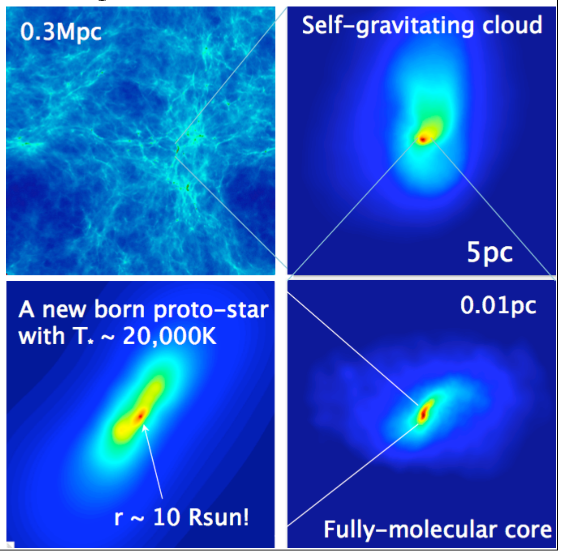
Smoothed Particle Hydrodynamics

- **Kernel smoothing to**
  - estimate local quantities
  - define differentials
- **Pros**
  - Very robust technique
    - *no code crashes*
    - *easy to use and analyze*
  - Takes advantage of tree gravity codes
  - Lagrangian
- **Cons**
  - Difficulty with multiphase gas
  - smears shocks and contact discontinuities
  - artificial surface tension
- **Yields identical results despite radically different approach to solving hydrodynamic equations**

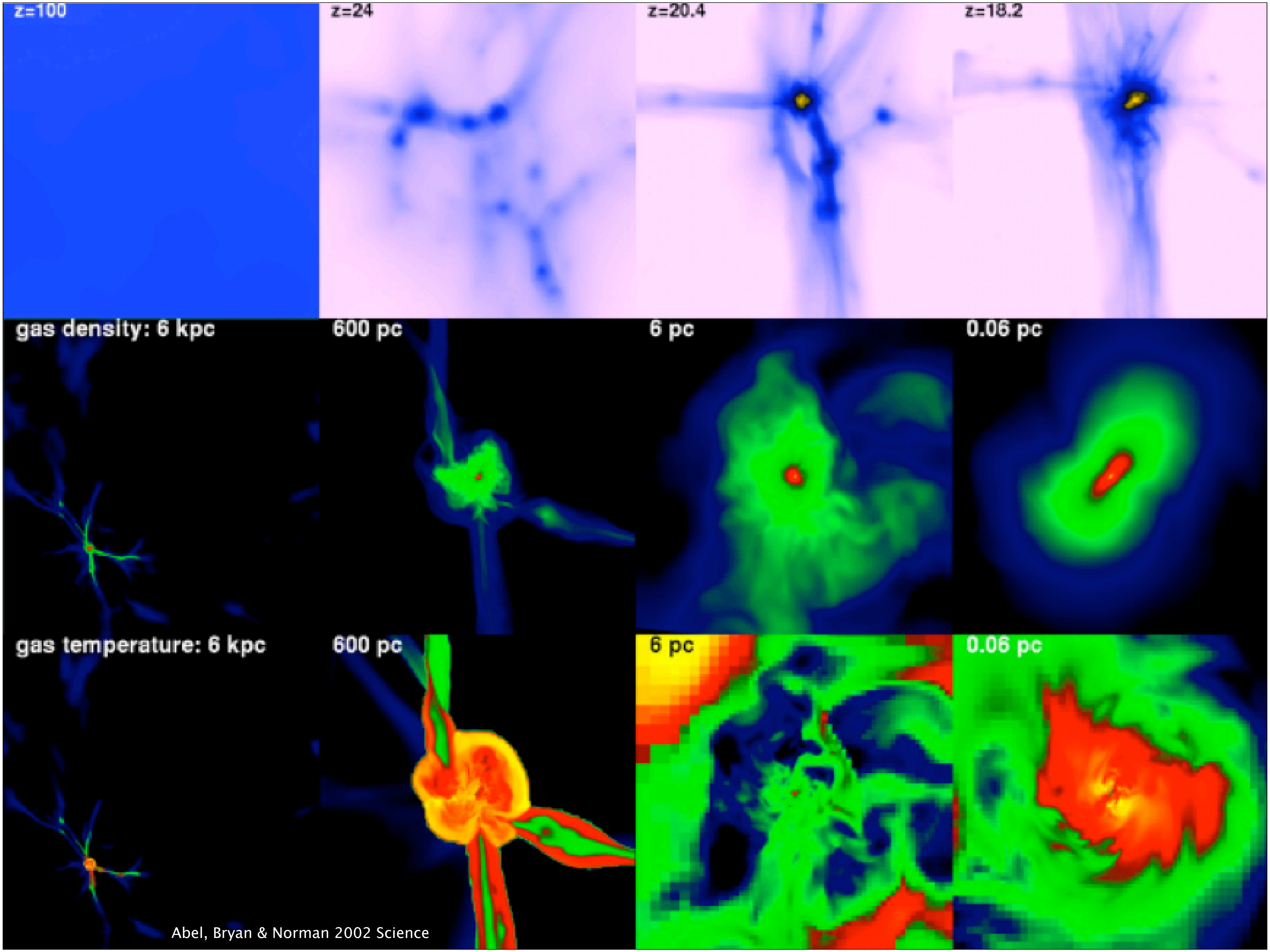
$$A_i(r) = \sum_j m_j \frac{A_j}{\rho_j} W(r_i - r_j, h),$$

$$\nabla A_i(r) = \sum_j m_j \frac{A_j}{\rho_j} \nabla W(r_i - r_j, h).$$

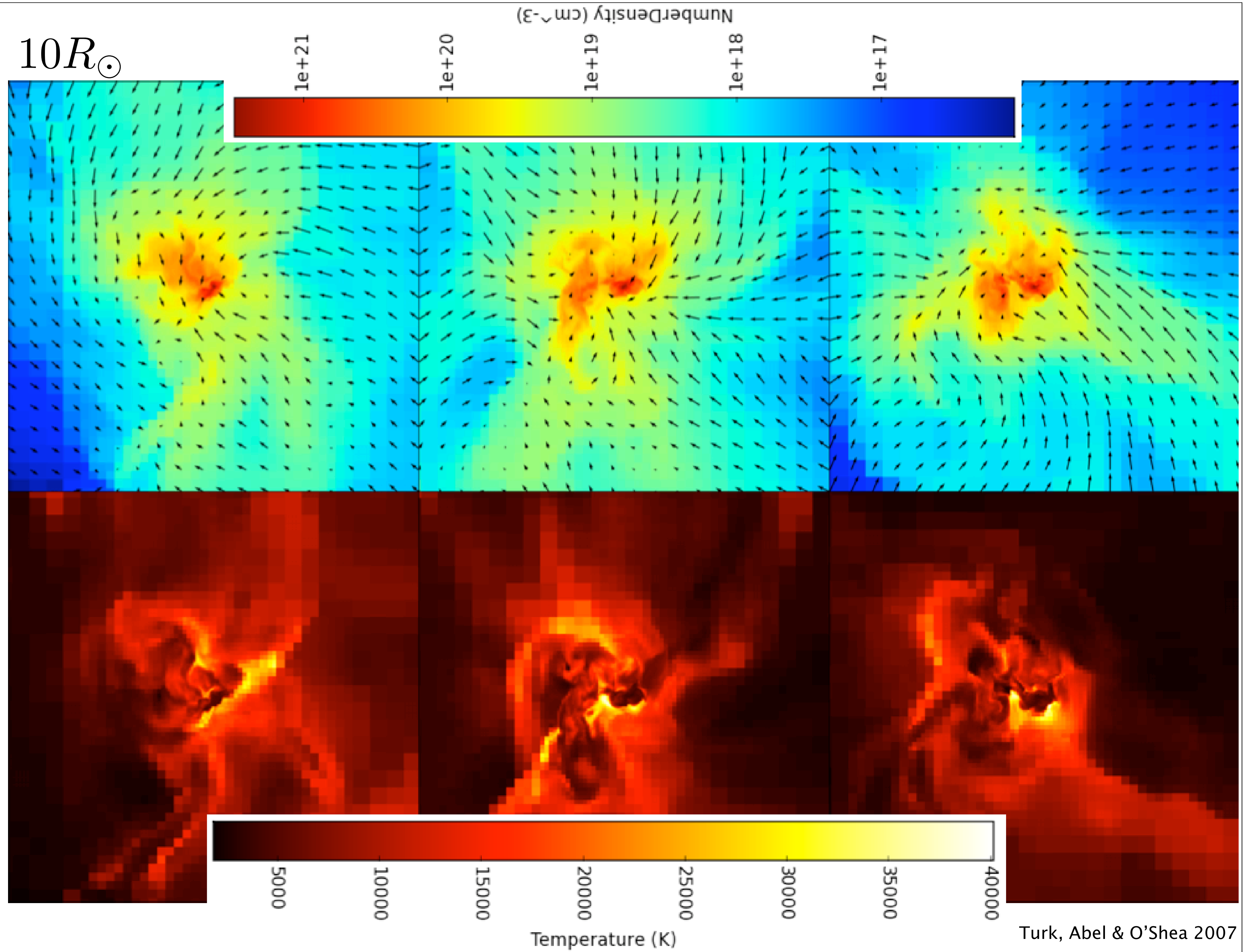
$$\rho_i(r) = \sum_j m_j \frac{\rho_j}{\rho_j} W(r_i - r_j, h) = \sum_j m_j W(r_i - r_j, h),$$



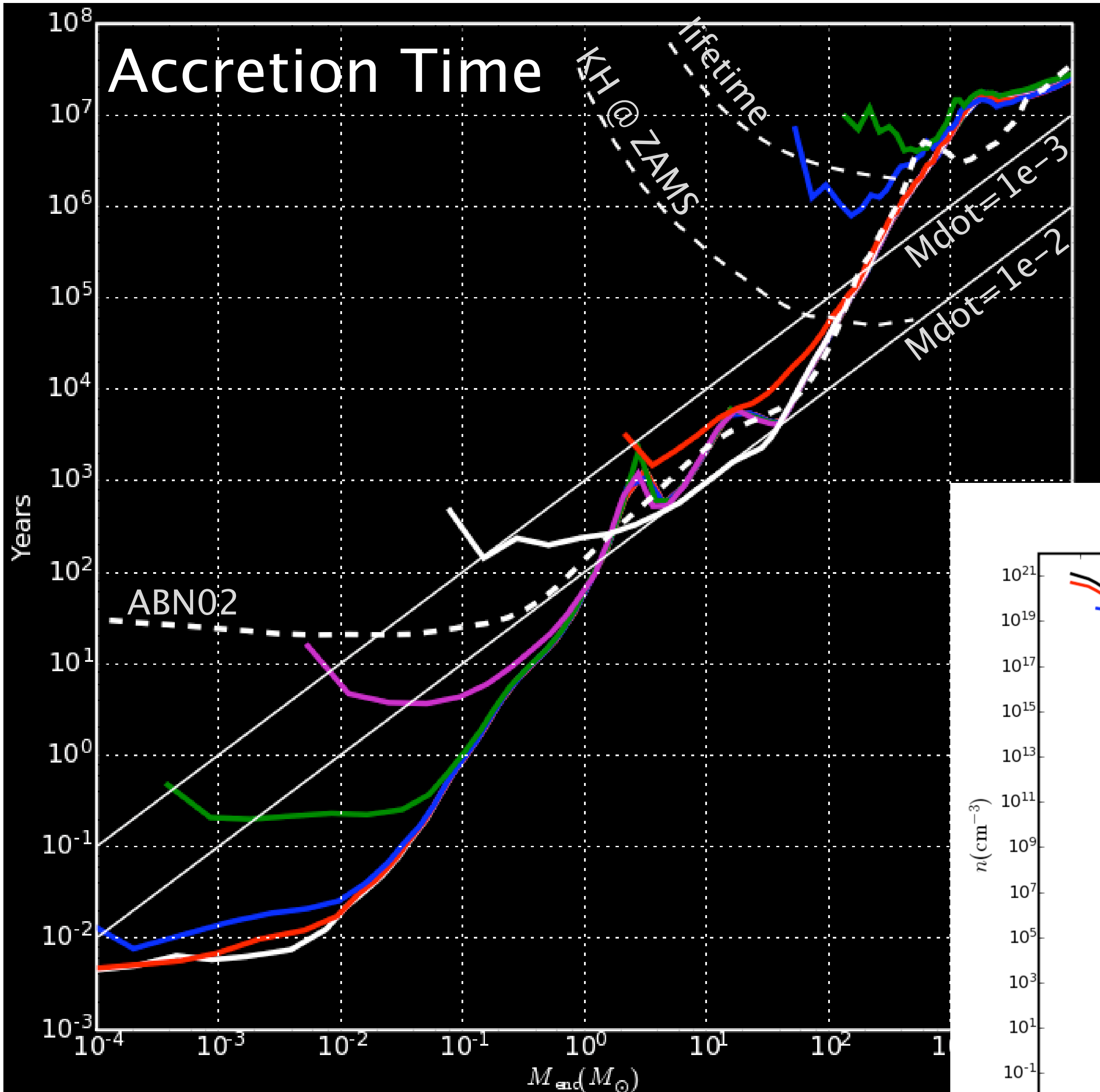
Yoshida, Abel, Hernquist et al 2002-



z=100
z=24
z=20.4
z=18.2
gas density: 6 kpc
600 pc
6 pc
0.06 pc
gas temperature: 6 kpc
600 pc
6 pc
0.06 pc
Abel, Bryan & Norman 2002 Science



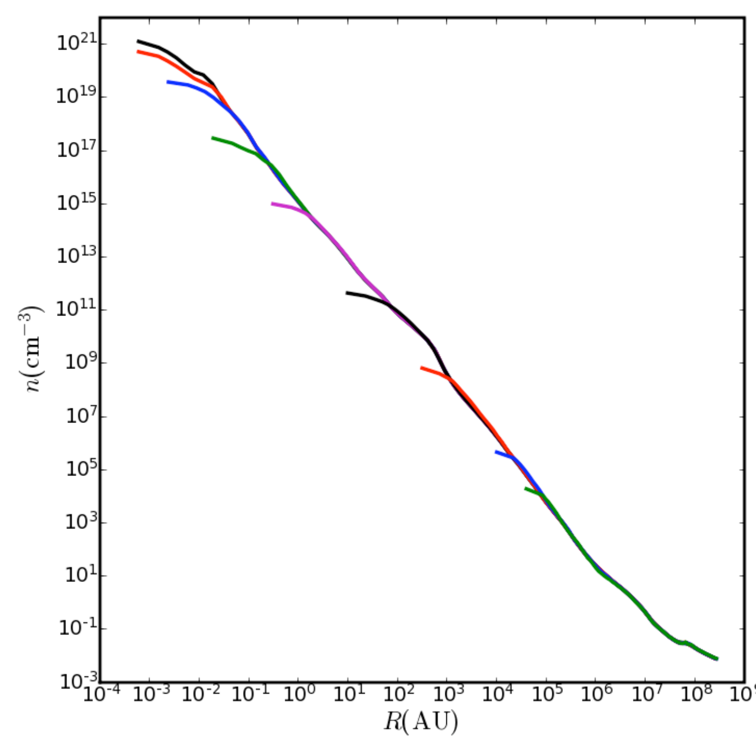
$10R_\odot$
NumberDensity (cm^-3)
1e+21
1e+20
1e+19
1e+18
1e+17
5000
10000
15000
20000
25000
30000
35000
40000
Temperature (K)
Turk, Abel & O'Shea 2007



Turk, Abel & O'Shea 2007 in prep

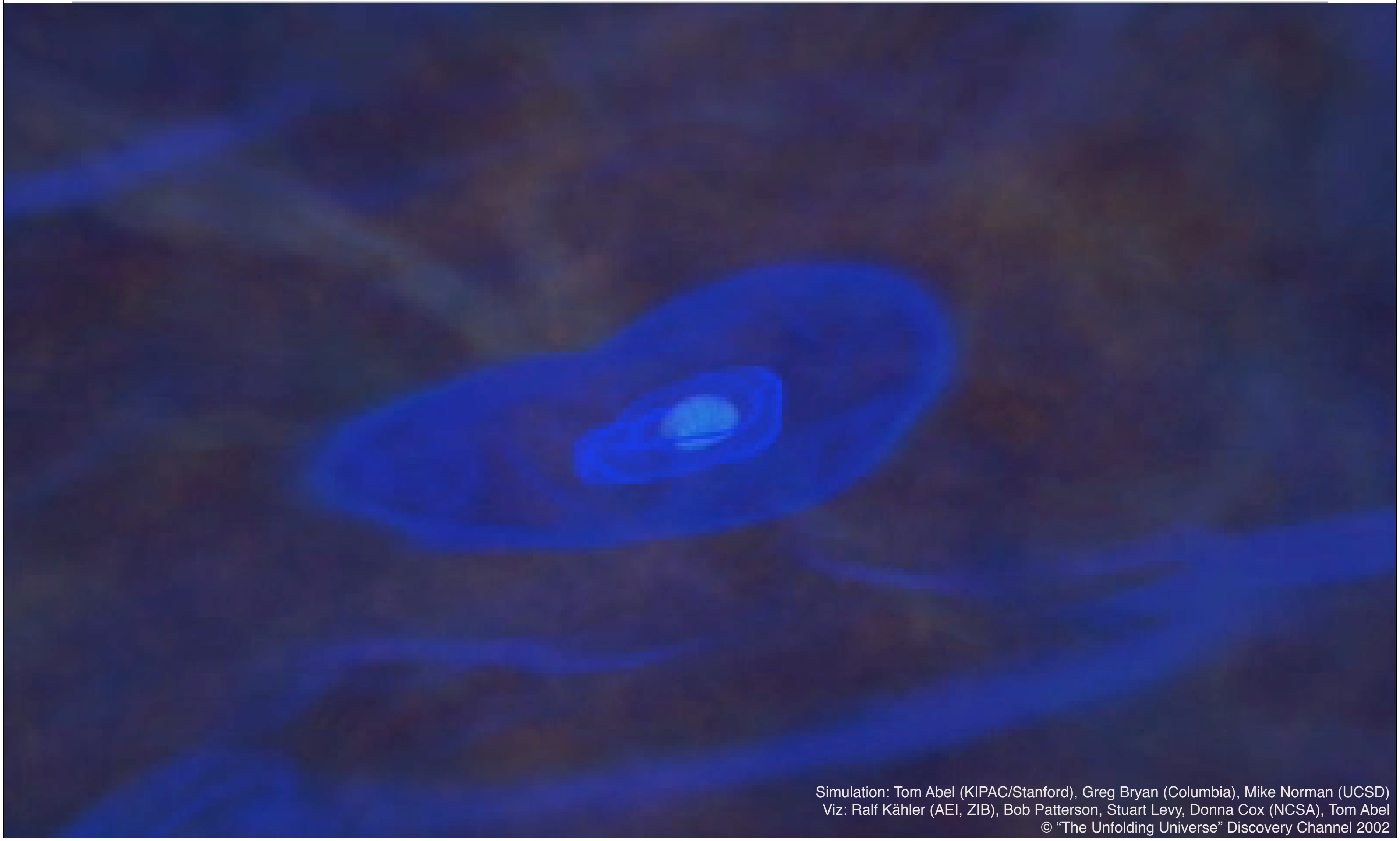
dynamic range: 2e13
min dx = 0.1 R_{sun}
16 cells per jeans length

High density, temperature, equation of state, radiation transport corrections, collision induced emission.



The first 100 million years in one sentence

Small dark matter halos form first, gas follows, hydrogen molecules form and make the gas shine, it collapses 10 million times further, ignites hydrogen fusion, makes a massive star, radiation disperses birth-cloud, explodes in a supernovae which releases carbon, oxygen, etc., collapses again, makes more stars, more explosions, more than 10 million massive stars later: us



Recap

First Stars are isolated and very massive

- Theoretical uncertainty: 30 - 300 solar mass

Many simulations with **four very different numerical techniques** and a large range of numerical resolutions have **converged** to this result. Some of these calculations capture over 20 orders of magnitude in density and reach the proto-stellar accretion phase!

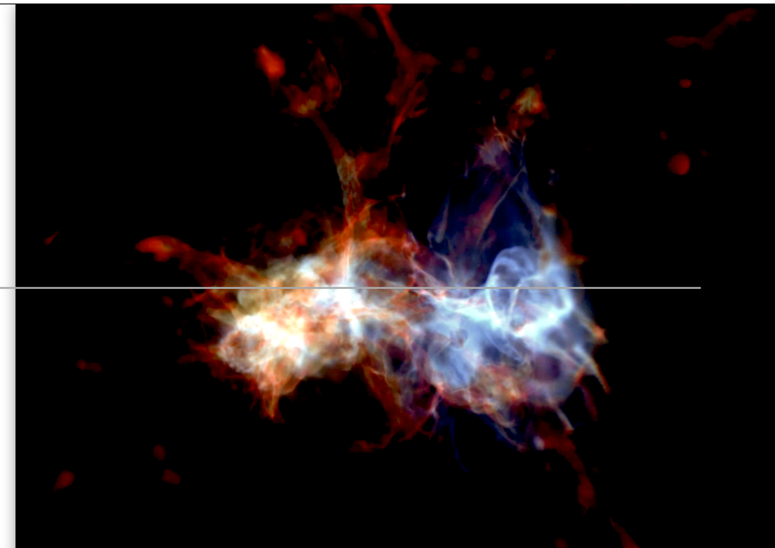
Non-equilibrium chemistry & cooling, three body H2 formation, chemical heating, H2 line transfer, collision induced emission and its transport, and sufficient resolution to capture chemo-thermal and gravitational instabilities. Stable results against variations on all so far test dark matter variations, as well as strong soft UV backgrounds.

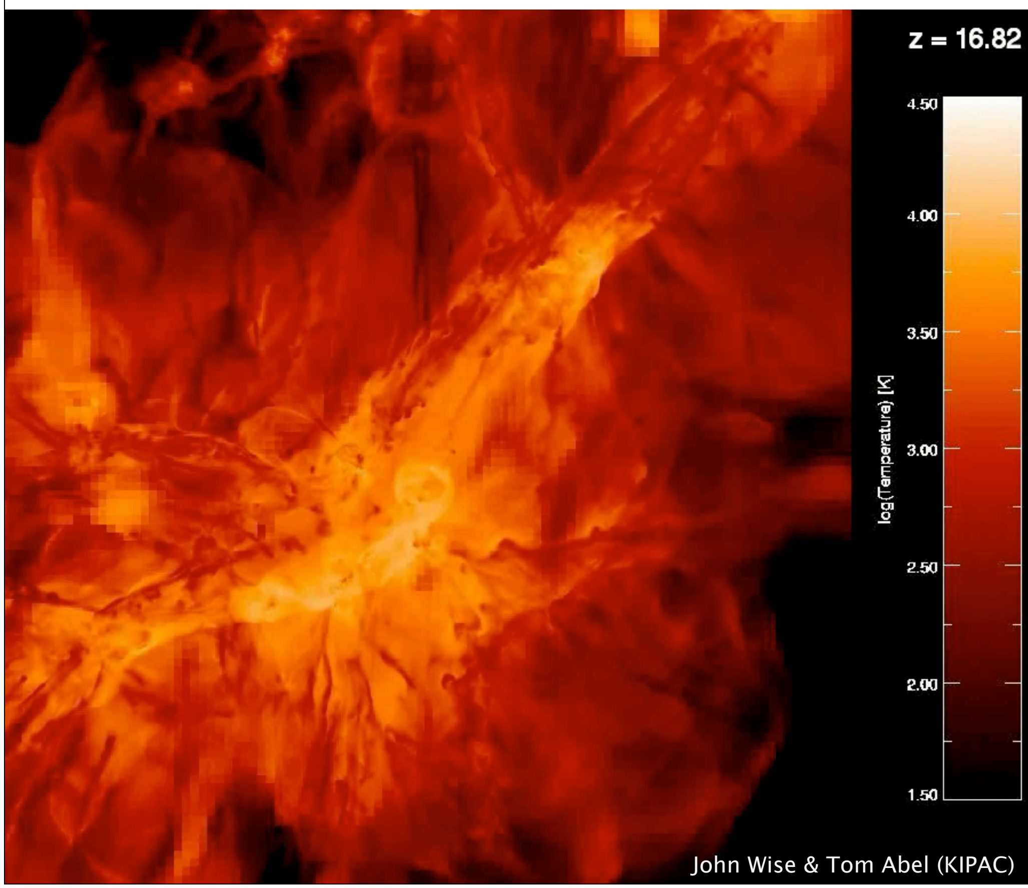
Perfectly consistent with observations!
Could have been a real problem!

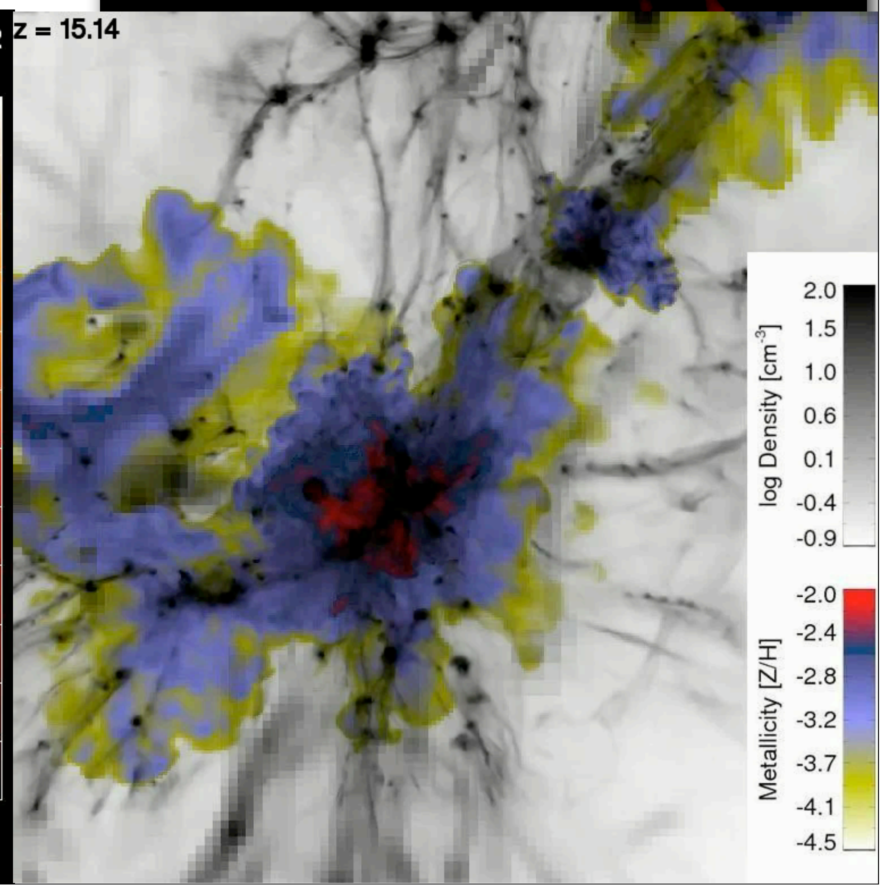
cosmological: Abel 1995; Abel et al 1998; Abel, Bryan & Norman 2000, 2002; O'Shea et al 2006; Yoshida et al 2006; Gao et al 2006, Yoshida et al 2007 in prep; Turk, Abel & O'Shea 2007 in prep
idealized spheres: Bodenheimer 1986; Haiman et al 1997; Omukai & Nishi 1998; Bromm et al 1999,2000,2002; Ripamonti & Abel 2004

Galaxies, one star at a time

10,000 such
patches make
Milky Way
~ 1e5 first star remnants
early element enrichment

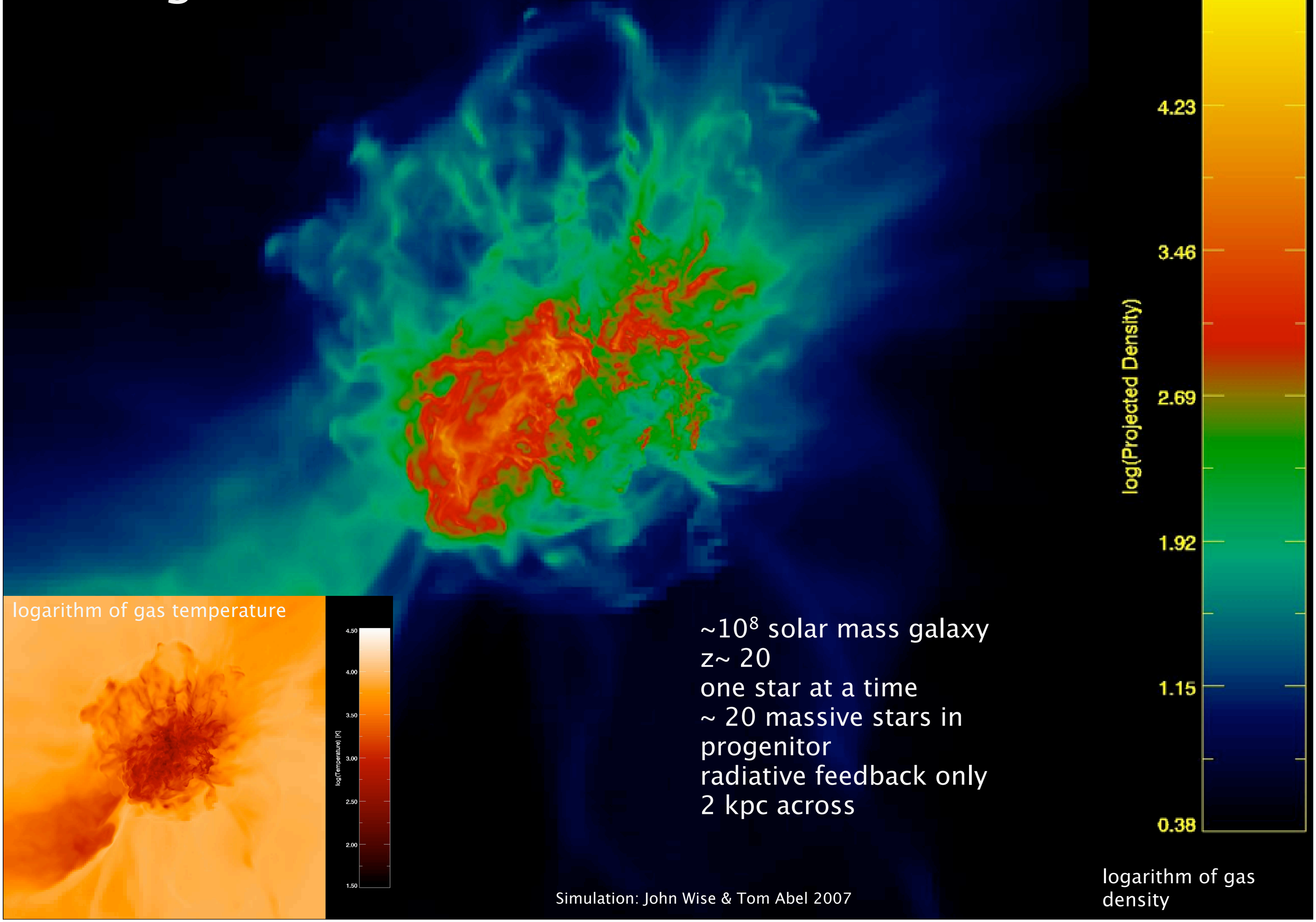


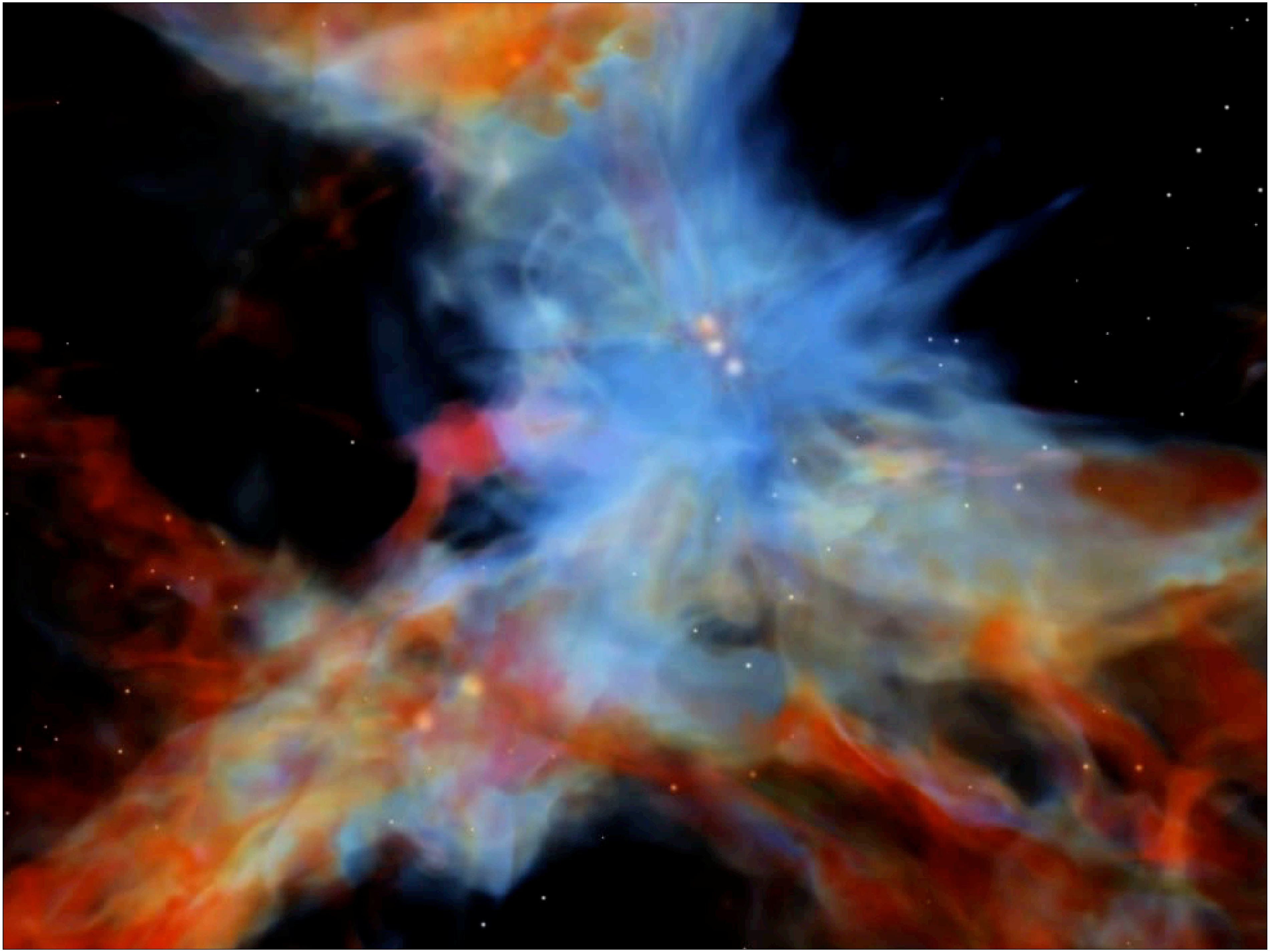




John Wise & Tom Abel (KIPAC)

Making Galaxies one Star at a Time





Many new open questions

- **Feedback of proto-star on its own accretion**
  - what physics sets the final mass of the first star?
  - Further fragmentation in disk around first stars?
- **Star formation in regions affected by the first stars**
  - Relic HII regions
  - Chemically affected regions have been previously ionized and shocked by supernovae remnants
  - Radiation backgrounds
- **Impact on galaxy formation?**
  - Its all hierarchical so first galaxies will undoubtedly influence next scale in hierarchy. Just how?
- **Generation of magnetic fields**

Conclusions

- **First luminous objects in the Universe are very massive stars**
  - not super massive black holes nor clusters of jupiter sized objects
  - All relevant mass scales derived from molecular physics
- **Immediate consequences**
  - Heavy element enrichment
  - Beginning of cosmological reionization
  - Early stellar remnant black holes
  - Early magnetic field production
  - etc.
  - all being studied with numerical simulations
- **Analytic understanding being developed**
  - mostly with hindsight and guided by numerical simulations
  - lots to do