The First Stars

Crete 2008

LECTURE 1

Viz: Stuart Levy, Bob Patterson, Donna Cox (NCSA), Data: Hipparcos, Brent Tully, and other sources

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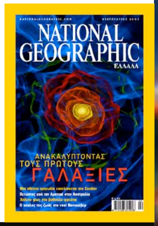
First Stars: Overview

The First Stars

Ab Initio Structure Formation
- Motivation
- Physics & Chemistry
- Methods
- Results
  - Very massive first stars
  - First HII regions
  - UV dissociation of H_2?
- & Observations
  - High-z SNe rate

Summary

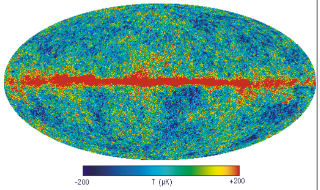


Initial Conditions of Structure Formation

First Stars

- CMB, SNIa, Galaxy Surveys, weak lensing, etc. enable precision cosmology.
- CMB hot and cold spots indicative of large scale density perturbations
- Within ΛCDM density fluctuations expected down to free streaming scale
- Density fluctuations Gaussian at a given scale
- Statistically understood and predictable at all scales and redshifts above ~ 100, analytically because: $\delta\rho/\rho \ll 1$

^{7}Li/H $\sim 10^{-10}$, D/H$\sim 10^{-5}$, ^{3}He/H $\sim 10^{-5}$
$0.236 \le {}^4\mathrm{He/H} \le 0.254$



Ω_b	0.0474 ± 0.0014
Ω_c	0.243 ± 0.013
Ω_Λ	0.709 ± 0.014
$\Omega_m h^2$	$0.1412^{+0.0031}_{-0.0030}$
σ_8	$0.851^{+0.020}_{-0.019}$
t_0	13.64 ± 0.11 Gyr
θ_*	0.010421 ± 0.000026
t_*	372389^{+2555}_{-2633} yr
z_d	$1022.0^{+1.3}_{-1.2}$
z_{reion}	11.7 ± 1.4

Density perturbations in CDM

Weakly Interacting Massive Particle
  favored mass range: 0.1-100GeV ->
  classical free streaming scale $6\times10^{-13}M_o\ (m/1\mathrm{GeV})^{-4}$.
  free streaming SUSY: $\sim1\times10^{-6}M_o$ (Schwartz et al 2001)
Scale-free power spectrum of Gaussian initial density perturbations
DM objects build up from the free streaming scale to galaxy size

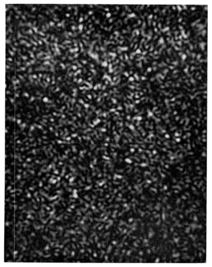
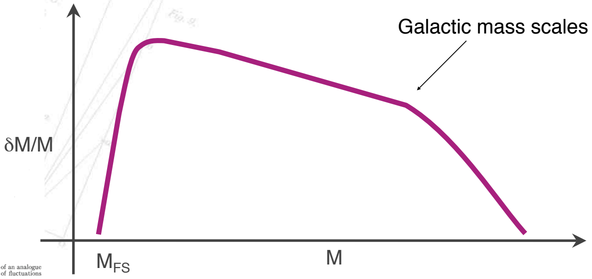


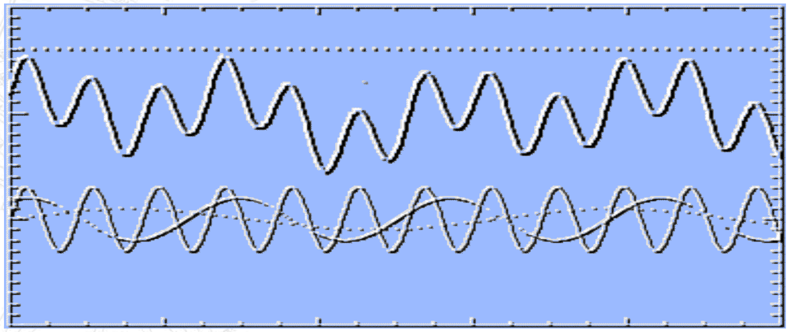
FIG. 2.—An early phase in the formation of globular clusters reconstructed by means of an analogue device. Pictured is a laser scintillation pattern, a two-dimensional random distribution of fluctuations characterizing a flat power spectrum with a short-wave cutoff.

Peebles & Dicke 1968



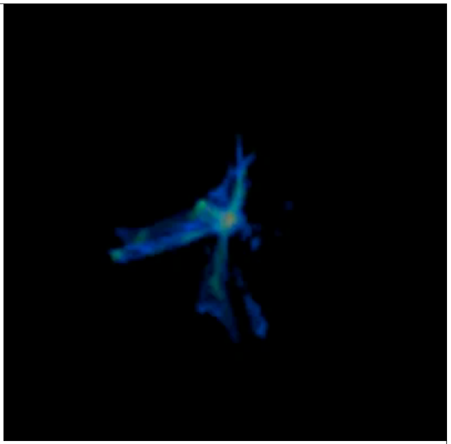
Natural Biasing in CDM

- Small things form first. Period.
- Very first things form on top of larger ones



Physics & Scales

- Physics problem:
  - Initial Conditions: Constituents, Density Fluctuations, Thermal History
  - Physics: Gravity, MHD, Chemistry, Radiative Cooling, Radiation Transport, Cosmic Rays, Dust drift & cooling, Supernovae, Stellar evolution, etc.
  - Transition from Linear to Non-Linear:
  - Use a computer!



Ralf Kähler & Tom Abel for PBS Origins. Aired Dec 04

$$\frac{\mathbf{R}_\odot}{\mathbf{R}_{\mathbf{MilkyWay}}} \approx \mathbf{10^{-12}} \qquad \frac{\mathbf{P}_{\odot,\mathbf{Kepler}}}{\mathbf{t}_{\mathbf{Hubble}}(\mathbf{z}=\mathbf{30})} \approx \mathbf{10^{-12}}$$

Jeans Mass, when can Gravity win?

$$t_{ff} = \sqrt{\frac{3\pi}{32G\rho}} \qquad M = \frac{4\pi}{3}r^3\rho$$

$$t_{sc} = \frac{r}{c_s} \qquad c_{\mathrm{ideal}} = \sqrt{\gamma\cdot\frac{p}{\rho}} = \sqrt{\frac{\gamma\cdot R\cdot T}{M}} = \sqrt{\frac{\gamma\cdot k\cdot T}{m}}$$

$$r = c_s\, t_{ff} \qquad M_{Jeans} \propto T^{3/2}\rho^{-1/2}$$

so we need to know the temperature ...

$$P \propto \rho^\gamma$$

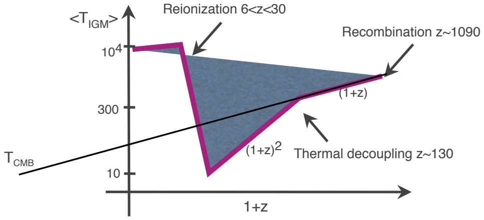
$$\gamma = \frac{5}{3} \quad P \propto \rho^{5/3} \quad T \propto \rho^{2/3} \quad M_{Jeans} \propto \rho^{1/2}$$

$$\gamma = 1 \quad P \propto \rho \quad T = const. \quad M_{Jeans} \propto \rho^{-1/2}$$

Peebles & Dicke 1968, Hutchins 1976, Couchman & Rees 1986,

Thermal History of the IGM

Thermal and chemical history of the intergalactic medium
- low IGM temperature in the dark ages
- some free electrons left over from recombination
  - -> allow coupling through Compton scattering
  - -> catalysts for the chemistry



$$T \propto \rho^{2/3}$$

$$\rho \propto (1+z)^3$$

$$T \propto (1+z)^2$$

Residual Ionization Fraction

$$t_{rec} = \frac{n_e}{k_{rec}\, n_e\, n_p} \qquad \sim \frac{2000}{x} \text{ years } @ \ z = 1100$$

- After recombination, the recombination reaction time scale gets long -> Freeze Out
- x ~ 10^{-4}

$$k_{rec} \sim 2 \times 10^{-13} \left(\frac{T}{10^4\mathrm{K}}\right)^{-0.9} \ \mathrm{cm^3 s^{-1}}$$

$$\bar{n_B} \sim 2 \times 10^{-7} (1+z)^3 \mathrm{cm}^{-3}$$

Peebles 1968

Coronal Limit

- Atoms and molecules have very complex intrinsic properties, and their chemical behavior varies sometimes drastically with the specific quantum-mechanical state they occupy. For atoms and ions at moderate or low densities like in the solar corona (electron number density ne ~ 10^8 - 10^9 cm), the following features of thermo-dynamic equilibrium do **not** hold (Sobelman et al. 1979):
  • Boltzmann distribution of atoms over excited states.
  • Saha distribution of atoms over degrees of ionization.
  • Principle of detailed balance.
- The velocity distribution of the free electrons is, however, as a rule nearly always Maxwellian. In this low-density limit we know that the level distributions are given by,

  $$\frac{N_i^k}{N_i^j} = n_e \frac{\langle v\sigma_{jk}\rangle}{A_k}$$

  where N^k_i denotes the number density of the species i in its level k, $\langle v\sigma_{jk}\rangle$ the rate coefficient for excitation from level j up to level k, A_k the total probability for spontaneous transition from all higher levels down to k. This approximation is applicable, if, **ne** **<<** A_k/ $\langle v\sigma_{jk}\rangle$ ~ at least **1e17 /cm³** electron densities.

- One important assumption here is that collisional excitations outweigh radiative excitations which is always true as long as there are only moderate external radiation fluxes.
- For us the most important point is that we find nearly **every atom in its ground state.**

Primordial Gas Chemistry

$$\frac{dn_i}{dt} = C - D\, n_i$$

(1) $\mathrm{H} + e^- \rightarrow \mathrm{H}^+ + 2e^-$
(2) $\mathrm{H}^+ + e^- \rightarrow \mathrm{H} + h\nu$
(3) $\mathrm{He} + e^- \rightarrow \mathrm{He}^+ + 2e^-$
(4) $\mathrm{He}^+ + e^- \rightarrow \mathrm{He} + h\nu$
(5) $\mathrm{He}^+ + e^- \rightarrow \mathrm{He}^{++} + 2e^-$
(6) $\mathrm{He}^{++} + e^- \rightarrow \mathrm{He}^+ + h\nu$

(7) $\mathrm{H} + e^- \rightarrow \mathrm{H}^- + h\nu$
(8) $\mathrm{H} + \mathrm{H}^- \rightarrow \mathrm{H}_2 + e^-$
(9) $\mathrm{H} + \mathrm{H}^+ \rightarrow \mathrm{H}_2^+ + h\nu$
(10) $\mathrm{H}_2^+ + \mathrm{H} \rightarrow \mathrm{H}_2 + \mathrm{H}^+$

(10) $\mathrm{H}_2^+ + \mathrm{H} \rightarrow \mathrm{H}_2 + \mathrm{H}^+$
(11) $\mathrm{H}_2 + \mathrm{H}^+ \rightarrow \mathrm{H}_2^+ + \mathrm{H}$
(12) $\mathrm{H}_2 + e^- \rightarrow 2\,\mathrm{H} + e^-$
(13) $\mathrm{H}_2 + \mathrm{H} \rightarrow 3\,\mathrm{H}$
(14) $\mathrm{H}^- + e^- \rightarrow \mathrm{H} + 2e^-$
(15) $\mathrm{H}^- + \mathrm{H} \rightarrow 2\,\mathrm{H} + e^-$
(16) $\mathrm{H}^- + \mathrm{H}^+ \rightarrow 2\,\mathrm{H}$
(17) $\mathrm{H}^- + \mathrm{H}^+ \rightarrow \mathrm{H}_2^+ + e^-$
(18) $\mathrm{H}_2^+ + e^- \rightarrow 2\,\mathrm{H}$
(19) $\mathrm{H}_2^+ + \mathrm{H}^- \rightarrow \mathrm{H}_2 + \mathrm{H}$

$\mathrm{H}^+ + \mathrm{D} \rightarrow \mathrm{H} + \mathrm{D}^+$
$\mathrm{H} + \mathrm{D}^+ \rightarrow \mathrm{H}^+ + \mathrm{D}$
$\mathrm{H}_2 + \mathrm{D}^+ \rightarrow \mathrm{HD} + \mathrm{H}^+$
$\mathrm{HD} + \mathrm{H}^+ \rightarrow \mathrm{H}_2 + \mathrm{D}^+$
$\mathrm{H}_2 + \mathrm{D} \rightarrow \mathrm{HD} + \mathrm{H}$
$\mathrm{HD} + \mathrm{H} \rightarrow \mathrm{H}_2 + \mathrm{D}$

High density:
3H -> H2 + H
#13 changes

Cooling by H2 molecules

First Stars

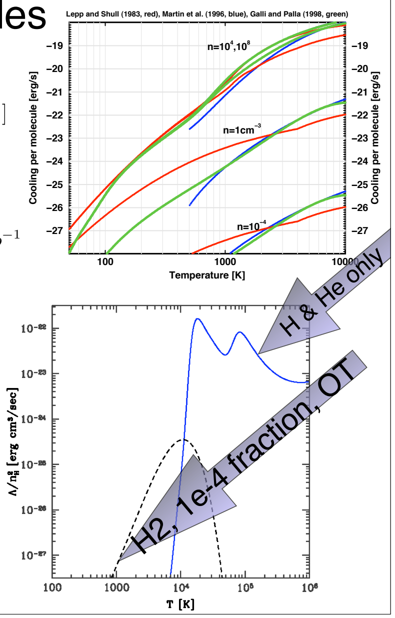
$$e = \frac{n\,k_B\,T}{\gamma - 1} \qquad \dot{e} = -n_{\mathrm{H}_2}\,n_{\mathrm{H}}\Lambda(T) \quad [\frac{\mathrm{erg}}{\mathrm{cm}^3\,\mathrm{s}}]$$

$$t_{cool} \equiv \frac{e}{\dot{e}}$$

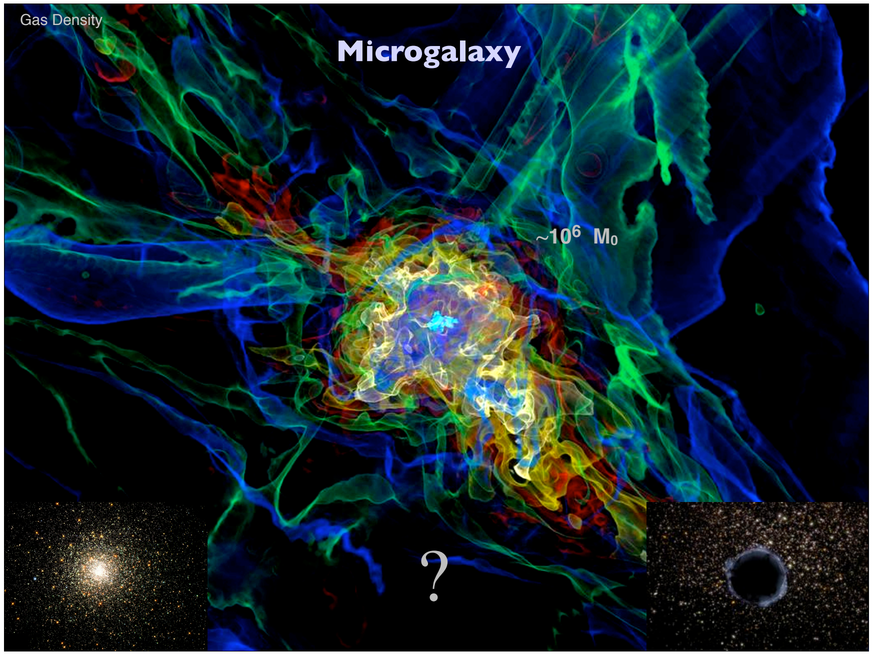
qualitative change at $n \gtrsim 10^4\,\mathrm{cm}^{-3}$:

$$n \lesssim 10^4\,\mathrm{cm}^{-3}: \quad \Lambda_{H2} \propto (n_H\,n_{H_2}) \rightarrow t_{cool} \propto \rho^{-1}$$
$$n \gtrsim 10^4\,\mathrm{cm}^{-3}: \quad \Lambda_{H2} \propto n_{H_2} \rightarrow t_{cool} \propto \rho^{0}$$

- Density scale is introduced by cooling physics
- Temperature scale introduced by lowest rotational states of dominant coolant
- Introduces mass scale ~ 100 solar mass



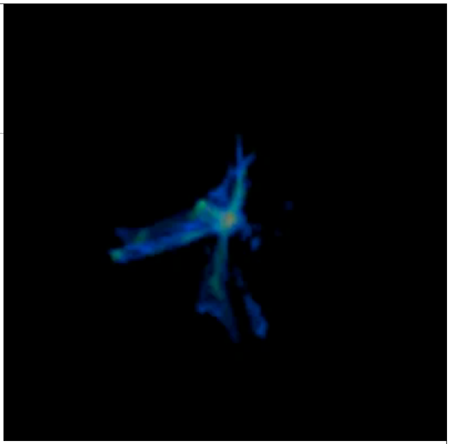
Tom Abel
KIPAC/Stanford



Initial Value Problem

- Initial Conditions: COBE/ACBAR/Boomerang/WMAP/CfA/SDDS/2DF/CDMS/DAMA/Edelweiss/... + Theory: Constituents, Density Fluctuations, Thermal History
- Physics: Gravity, MHD, Chemistry, Radiative Cooling, Radiation Transport, Cosmic Rays, Dust drift & cooling, Supernovae, Stellar evolution, etc.
- Transition from Linear to Non-Linear:
- Using patched based structured adaptive (space & time) mesh refinement

- Differs from current day star formation:
- Complete ICs are known
- Chemistry, cooling, B, known



Ralf Kähler & Tom Abel for PBS Origins. Aired Dec 04

$$\frac{\mathbf{R}_\odot}{\mathbf{R}_{\mathbf{Milky Way}}} \approx 10^{-12}$$

$$\frac{\mathbf{P}_{\odot,\mathbf{Kepler}}}{\mathbf{t}_{\mathbf{Hubble}}(\mathbf{z}=\mathbf{30})} \approx 10^{-12}$$

Solving Reaction Networks

First Stars

- Very fast non-equilibrium solver for 12 species chemistry [Abel et al 97, Anninos et al 97, Turk & Abel 08 in prep]
- Use charge and nuclei conservation to speed up conservation

$$\frac{dn_i}{dt} = C - D\,n_i \qquad n_i^{t+\delta t} = \frac{C^{t+\delta t}\delta t + n_i^t}{D^{t+\delta t}\delta t + 1}$$

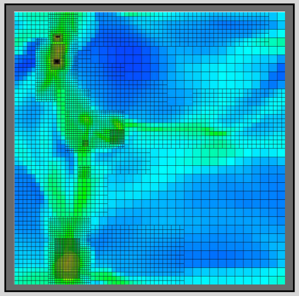
$$n_i^{t+\delta t} D^{t+\delta t}\delta t + n_i^{t+\delta t} = C^{t+\delta t}\delta t + n_i^t$$

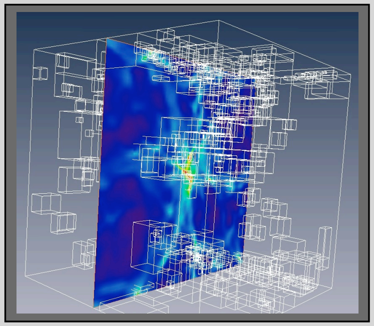
$$n_i^{t+\delta t} - n_i^t = \left(C^{t+\delta t} - n_i^{t+\delta t} D^{t+\delta t}\right)\delta t$$

Tom Abel
KIPAC/Stanford

Cosmological Adaptive Mesh Refinement

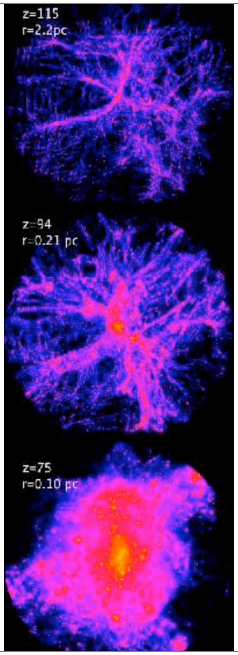
- **Enzo:** Bryan and Norman 1997-; Abel et al 97; Anninos et al 97; Bryan, Abel & Norman 2002; O'Shea et al; Abel, Wise & Bryan 2006; Wang, Abel & Zhang 2008; Wang & Abel 2008
  - ~90,000 lines of code in C++ and F77
  - Cosmological Radiation Hydrodynamics adapting in space and time
  - Dynamic range up to 1e15 using quadruple precision coordinates in space and time
  - Dynamically load balanced parallel with MPI
  - Gravity, DM, Gas, Chemistry, Radiation, star formation & feedback
  - Current **new** Developments **@ KIPAC**: new dimensionally unsplit hydro algorithms, higher order time updates, exact **3D radiation transport**, very high density chemistry, HD & fine structure line cooling, relativistic hydro, **MHD**, new visualization toolkits





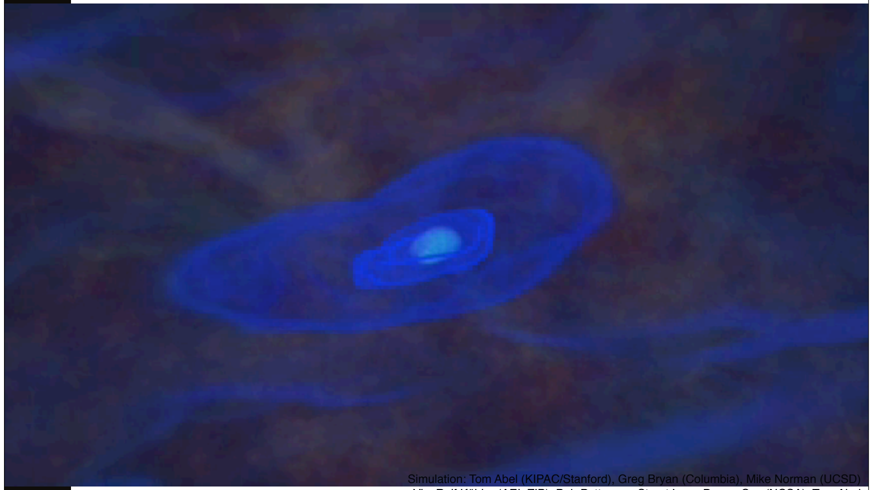
The First Stars

First Structures in the Universe



Diemand, Kuhlen & Madau 2006

The First Stars



Simulation: Tom Abel (KIPAC/Stanford), Greg Bryan (Columbia), Mike Norman (UCSD)
Viz: Ralf Kähler (AEI, ZIB), Bob Patterson, Stuart Levy, Donna Cox (NCSA), Tom Abel
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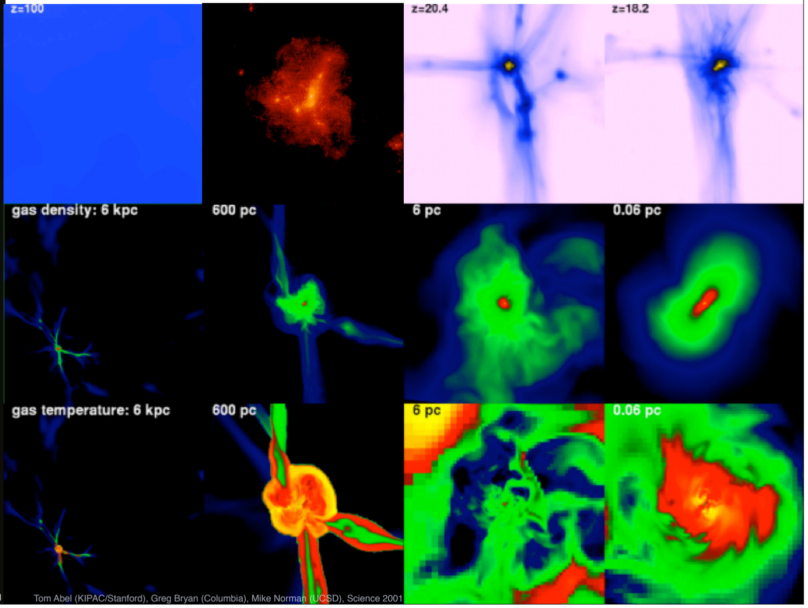
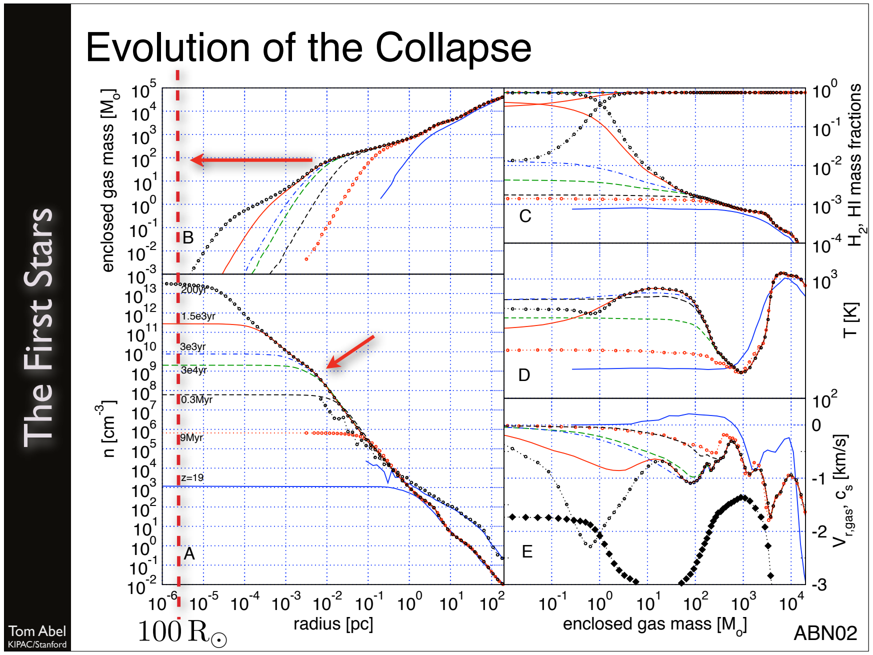
The First Stars

First cooling objects



Tom Abel (KIPAC/Stanford), Greg Bryan (Columbia), Mike Norman (UCSD), Science 2001

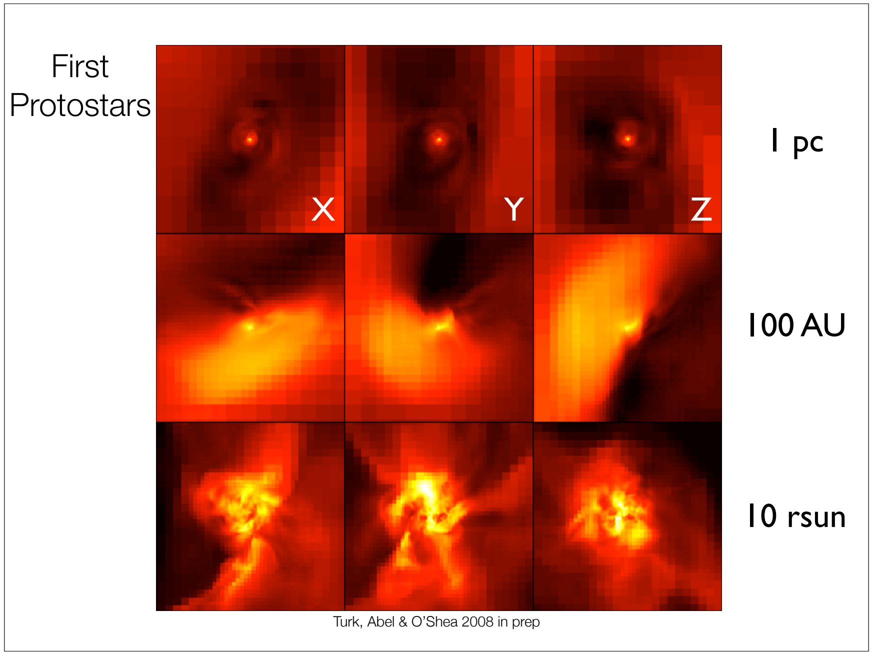


The First Stars

Evolution of the Collapse

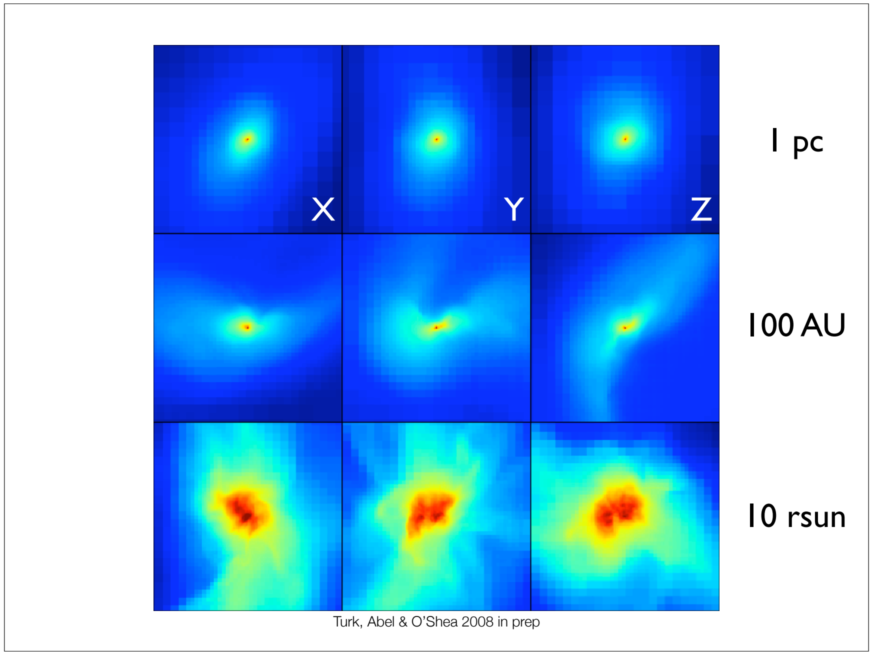
ABN02

Tom Abel
KIPAC/Stanford



First Protostars

Turk, Abel & O'Shea 2008 in prep



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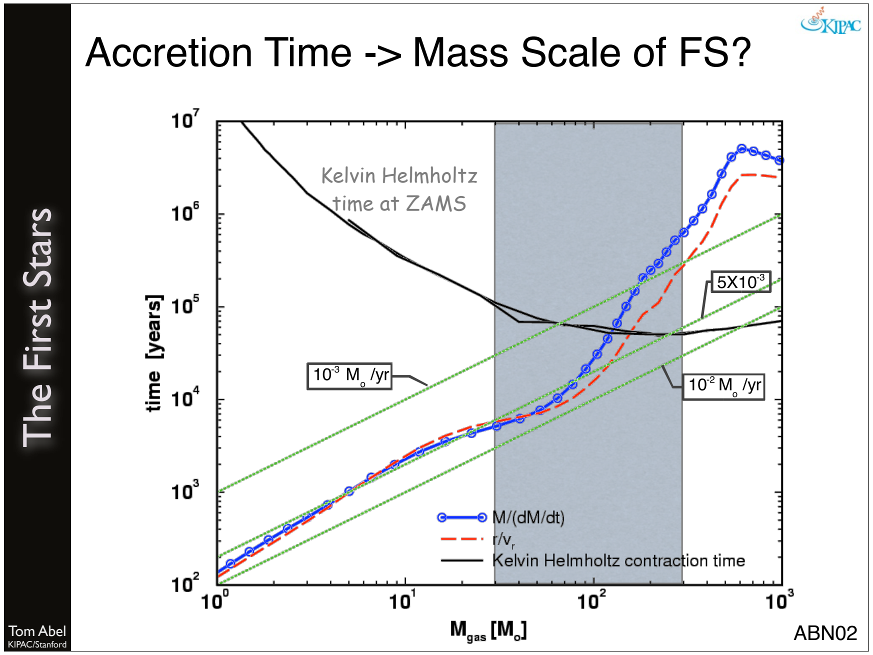

The First Stars

Accretion Time -> Mass Scale of FS?

ABN02

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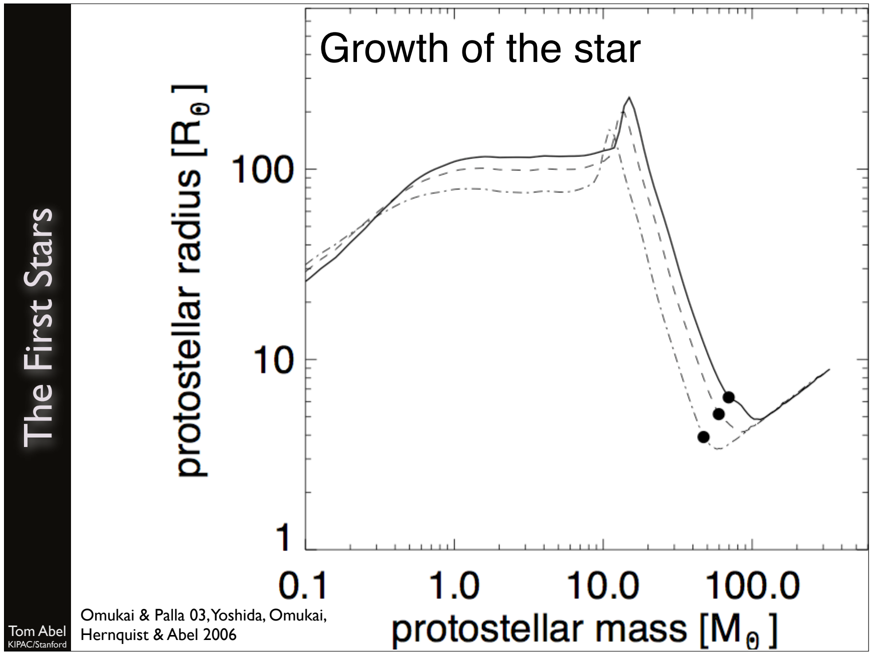
KIPAC/Stanford



Growth of the star

Omukai & Palla 03, Yoshida, Omukai, Hernquist & Abel 2006

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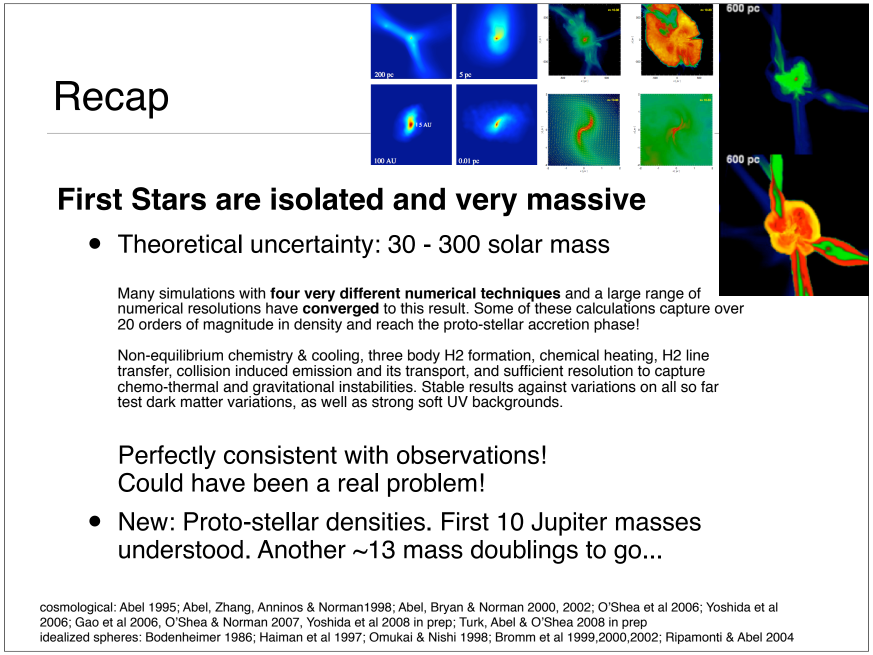
KIPAC/Stanford



Recap

First Stars are isolated and very massive

- Theoretical uncertainty: 30 - 300 solar mass

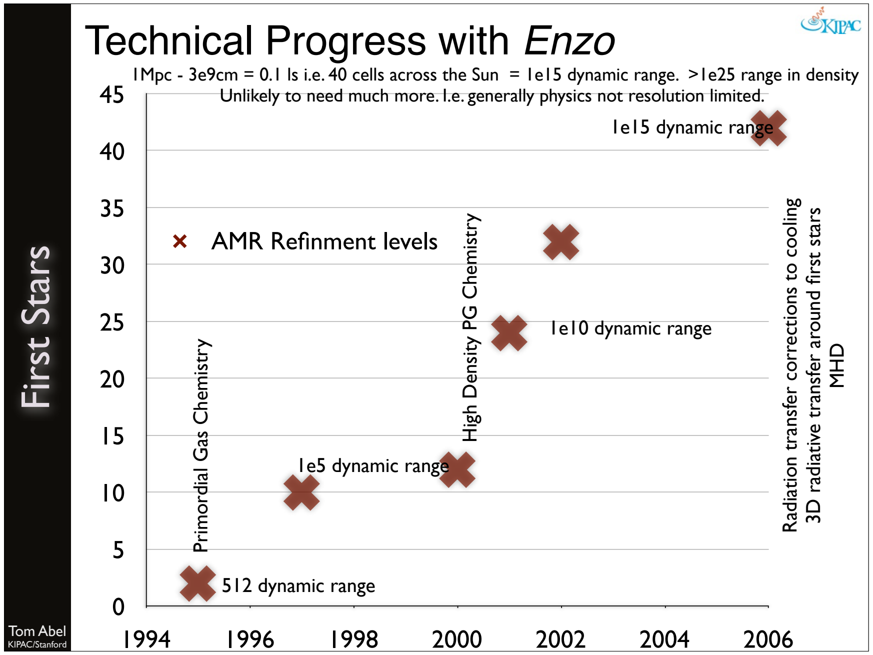
Many simulations with **four very different numerical techniques** and a large range of numerical resolutions have **converged** to this result. Some of these calculations capture over 20 orders of magnitude in density and reach the proto-stellar accretion phase!

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!

- New: Proto-stellar densities. First 10 Jupiter masses understood. Another ~13 mass doublings to go...

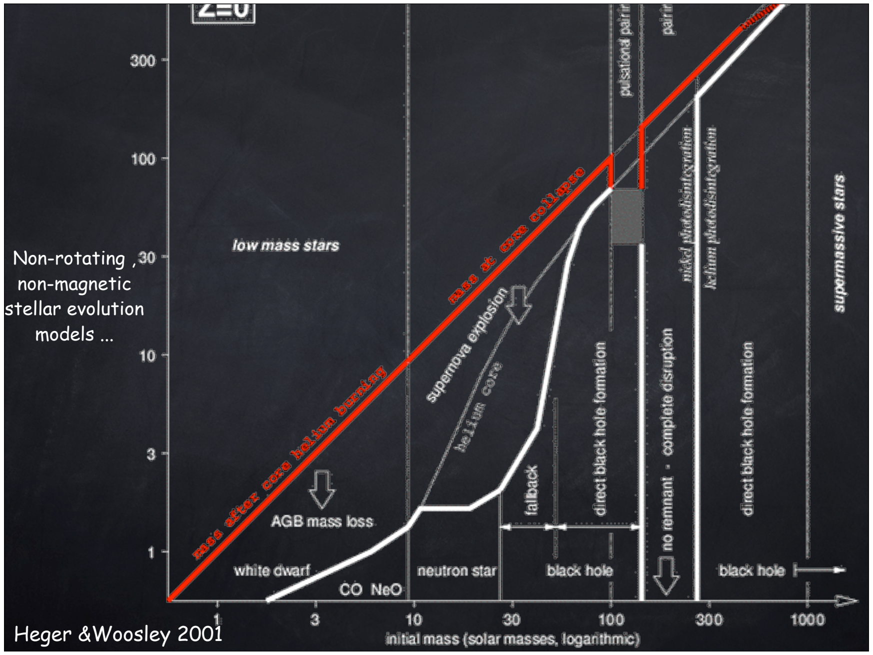
cosmological: Abel 1995; Abel, Zhang, Anninos & Norman1998; Abel, Bryan & Norman 2000, 2002; O'Shea et al 2006; Yoshida et al 2006; Gao et al 2006, O'Shea & Norman 2007, Yoshida et al 2008 in prep; Turk, Abel & O'Shea 2008 in prep
idealized spheres: Bodenheimer 1986; Haiman et al 1997; Omukai & Nishi 1998; Bromm et al 1999,2000,2002; Ripamonti & Abel 2004



Technical Progress with *Enzo*

1Mpc - 3e9cm = 0.1 ls i.e. 40 cells across the Sun = 1e15 dynamic range. >1e25 range in density
Unlikely to need much more. I.e. generally physics not resolution limited.

Tom Abel
KIPAC/Stanford



Non-rotating , non-magnetic stellar evolution models ...

Heger &Woosley 2001

Clear consequences of very massive first stars:

- Entire mass range are strong UV emitters
- Live fast, die young. (~2.7 Myr)
- Fragile Environment
  - Globular Cluster mass halo but ~100 times as large -> small v_{esc} ~ 2 km/s
  - Birth clouds are evaporated

3D Cosmological Radiation Hydrodynamics

$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \frac{\partial I_\nu}{\partial r} = -\kappa I_\nu$$

Transfer done along adaptive rays
Case B recombination

Focus on point sources

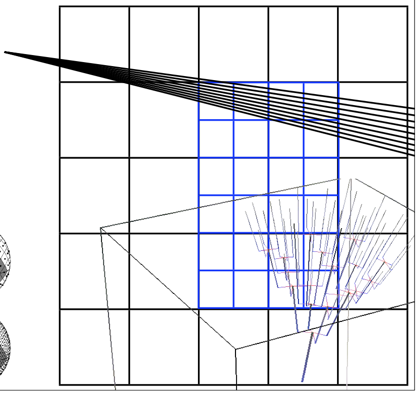
Early methods: Abel, Norman & Madau 1999 ApJ; Abel & Wandelt 2002, MNRAS; Variable Eddington tensors: Gnedin & Abel 2001, NewA

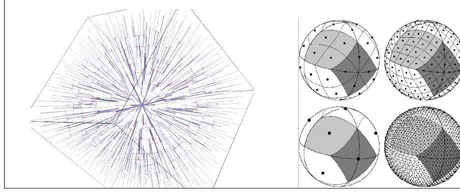
Latest: Abel, Wise & Bryan 06 ApJL, Wise & Abel 2007 and Wise, Abel, Wang 2008 in prep.
Keeps time dependence of transfer equation

Exact Adaptive ray-tracing of PhotonPackages using HEALPIX pixelization of the sphere. Photon conserving at any resolution.

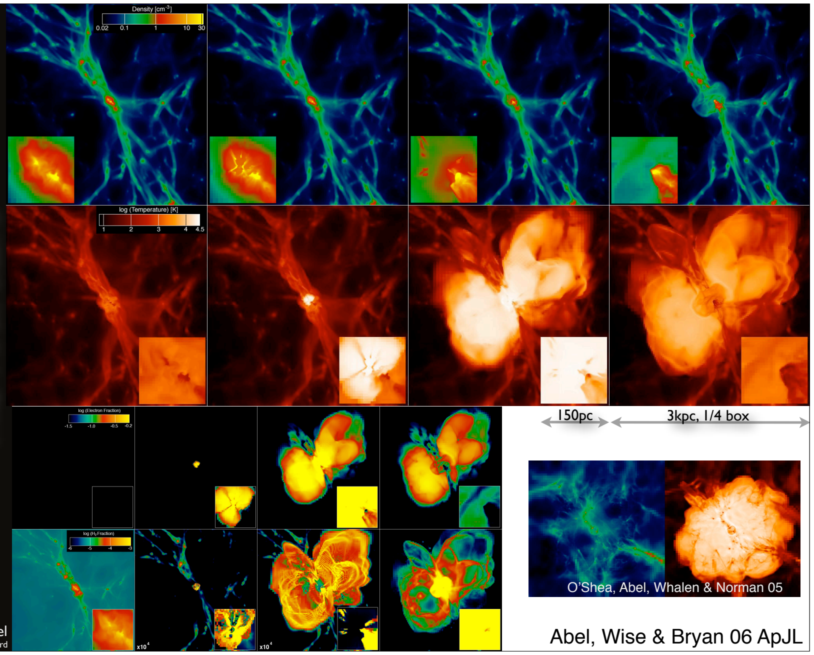
Parallel using MPI and dynamic load balancing.

Fully coupled with non-equilibrium chemistry and hydrodynamics.





The First Stars



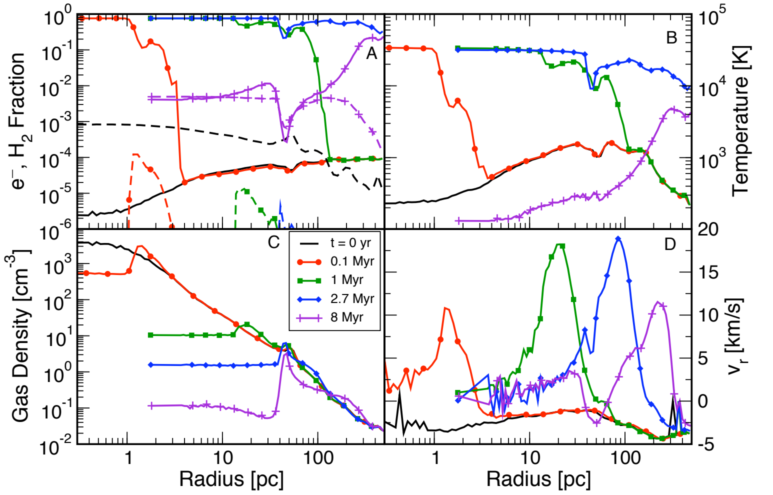
Abel, Wise & Bryan 06 ApJL

Tom Abel
KIPAC/Stanford

The First Stars

Early HII regions in 3D

agree generally with 1D of Whalen, Abel and Norman 05 and Kiteyama & Yoshida 05



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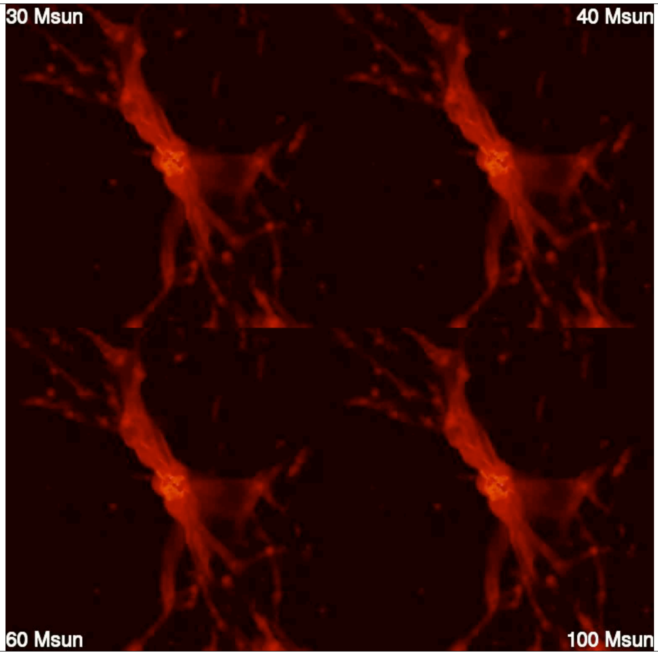
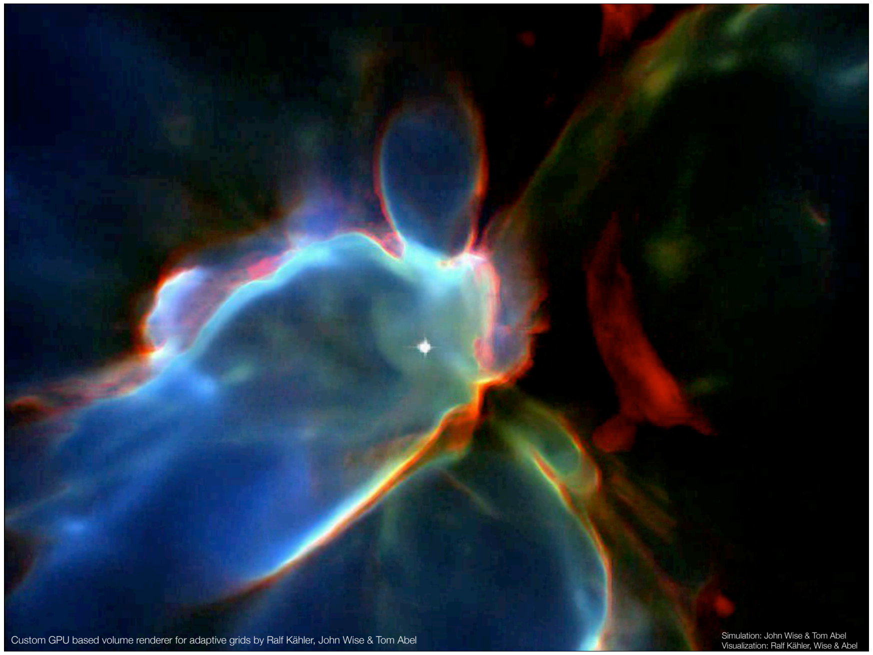


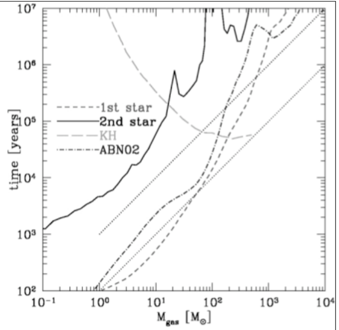


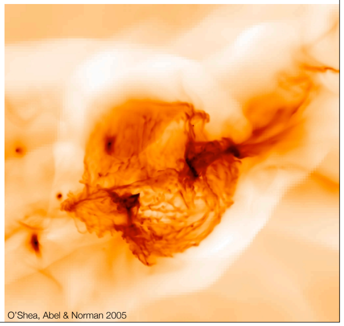
Custom GPU based volume renderer for adaptive grids by Ralf Kähler, John Wise & Tom Abel

Simulation: John Wise & Tom Abel
Visualization: Ralf Kähler, Wise & Abel

Pop III.2

- Exciting development over past three years.
- Stars forming from previously ionized yet not metal enriched material typically will give a factor of a few lower masses.
- Profound consequences for metal enrichment and studying the fossil record.
- Can no longer neglect e- and proton collisions for H_2 cooling (Glover & Abel 2008)

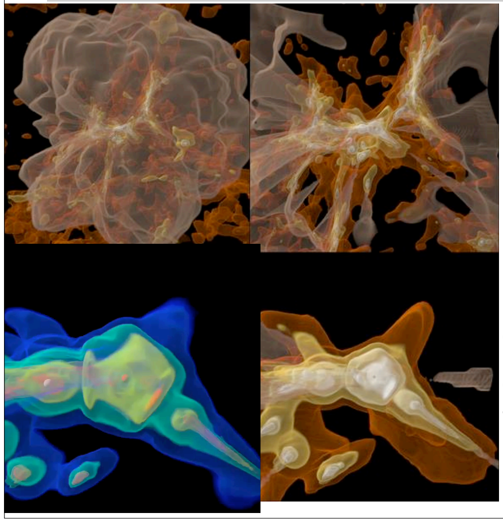


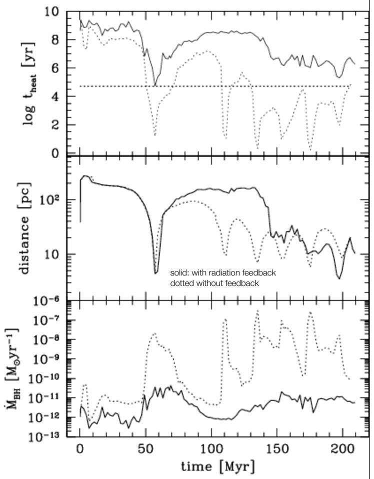


O'Shea, Abel & Norman 2005

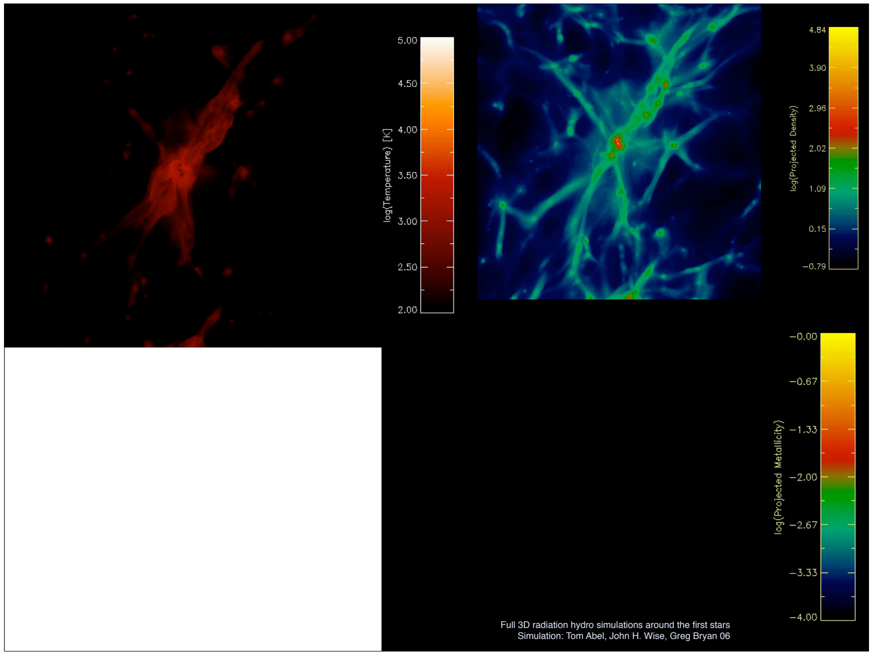
3D simulations: O'Shea et al 2005, Yoshida et al 2007, Johnson et al 2007

Insignificant BH accretion - no mini quasars through this process, nor ubiquitous pre-cursors of Quasars.

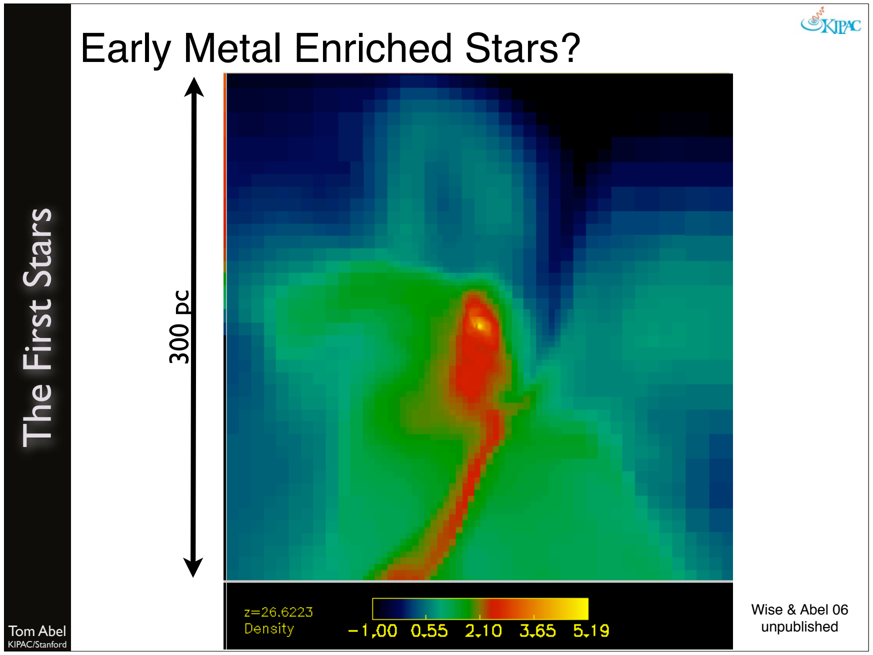




Alvarez, Wise & Abel in prep.



Full 3D radiation hydro simulations around the first stars
Simulation: Tom Abel, John H. Wise, Greg Bryan 06

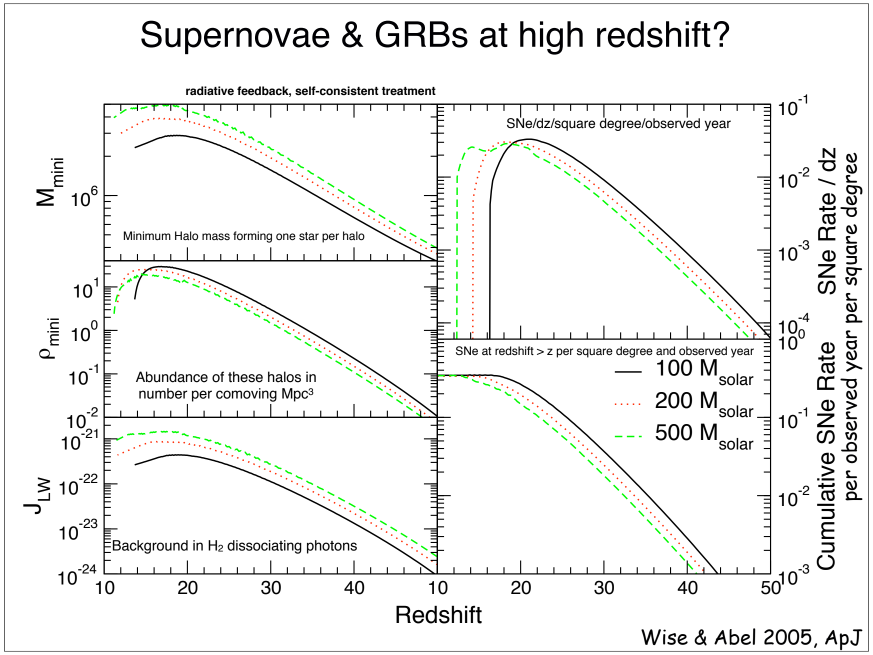


Early Metal Enriched Stars?

Wise & Abel 06
unpublished

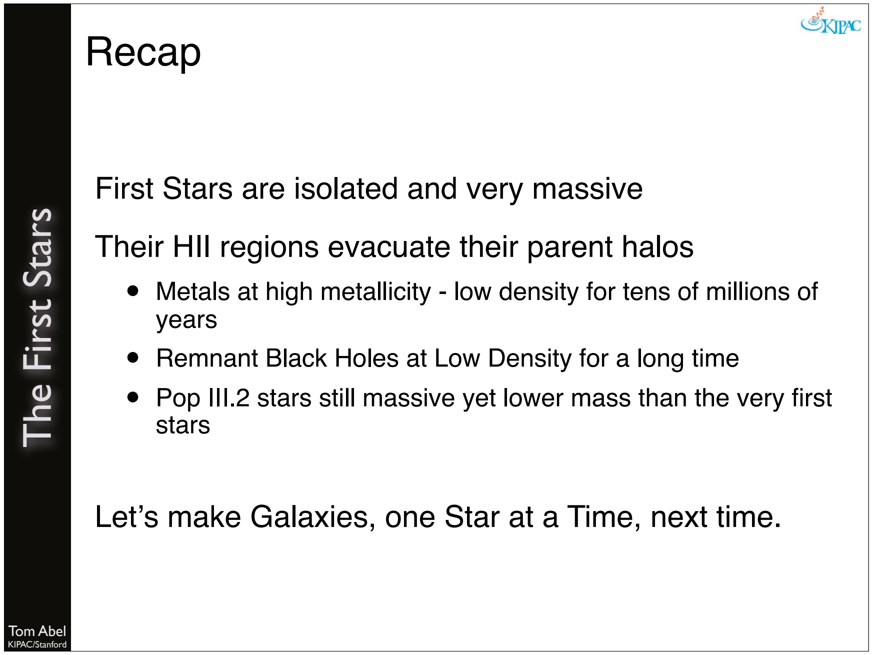
The First Stars

Tom Abel
KIPAC/Stanford



Supernovae & GRBs at high redshift?

Wise & Abel 2005, ApJ



Recap

First Stars are isolated and very massive

Their HII regions evacuate their parent halos

- Metals at high metallicity - low density for tens of millions of years
- Remnant Black Holes at Low Density for a long time
- Pop III.2 stars still massive yet lower mass than the very first stars

Let's make Galaxies, one Star at a Time, next time.

The First Stars

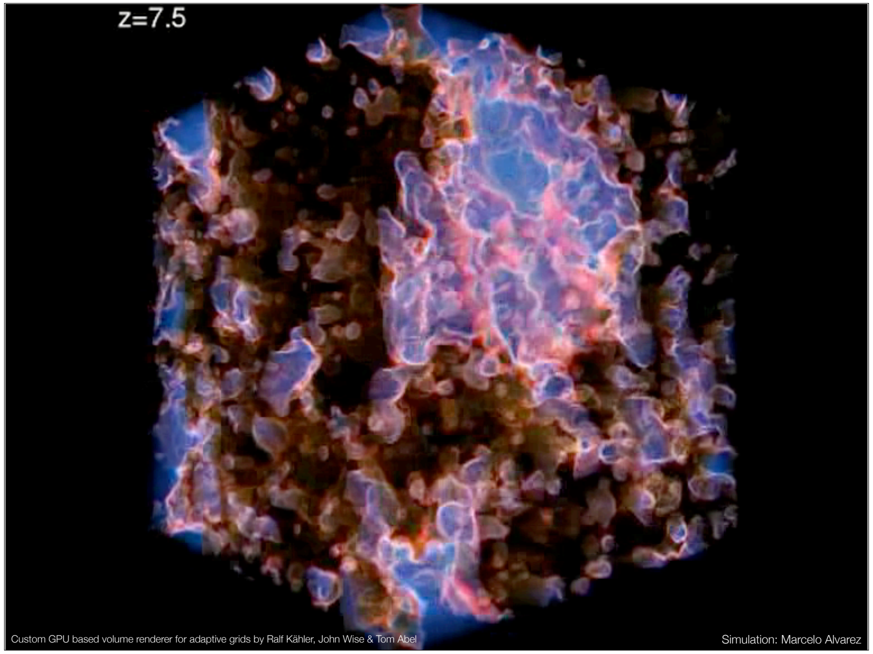
Tom Abel
KIPAC/Stanford

The First Stars

Crete 2008

LECTURE 2

Tom Abel
KIPAC/Stanford



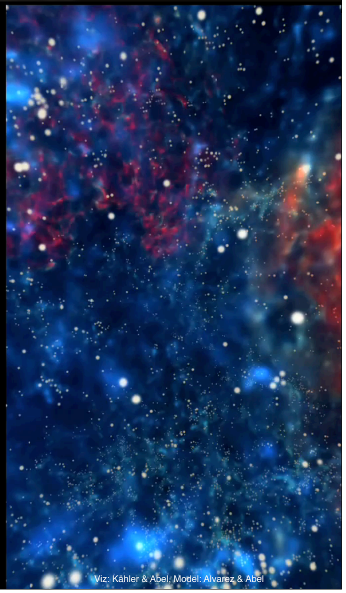
Custom GPU based volume renderer for adaptive grids by Ralf Kähler, John Wise & Tom Abel

Simulation: Marcelo Alvarez

The First Stars

Making Galaxies

Molecules dissociated?
One Star at a Time
Star Formation at all epochs
Turbulent Heating
Magnetic Fields

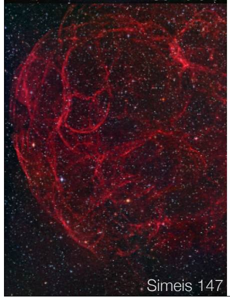


Viz: Kähler & Abel, Model: Alvarez & Abel

Tom Abel
KIPAC/Stanford

Orion

Sombrero



Simeis 147

Galaxy Formation models

missing:	included:
• B field	• DM dynamics
• Cosmic Rays	• “Hydrodynamics”
• Radiation Transport & Physics	• Some cooling
• Molecules	• “Star formation”
• Dust	• “Supernova feedback”
• Radiation Pressure on Dust	• “AGN feedback”
• HII regions	

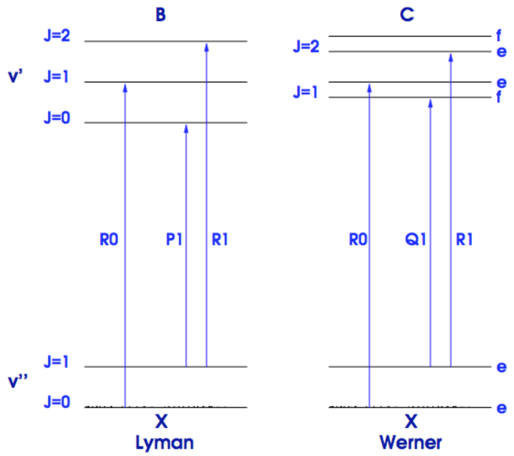
Not ab initio

H2 can be dissociated by photons!

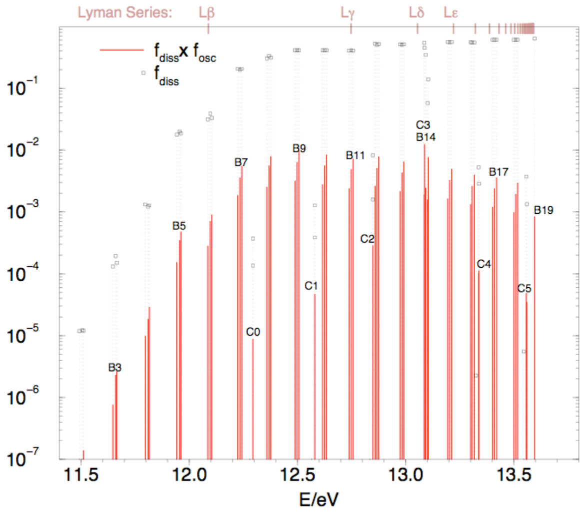
- so perhaps after the very first stars formed there is no reason to worry about molecules anymore?

Lyman Werner Band Dissociation

electronic excited states above the binding energy!



Lyman Werner Bands



Olbers Integral & Background vs Direct

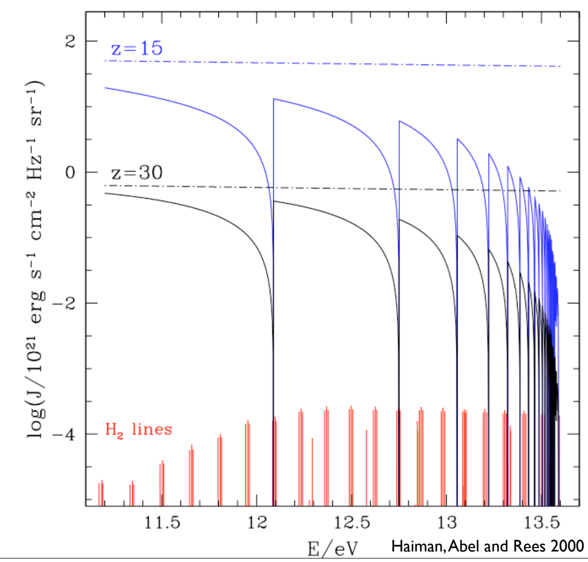
Assume infinite number of infinitely old sources in an infinite Universe.

$$F \propto \frac{1}{r^2}$$ Flux from one source

$$N \propto r^3$$ Number of Sources

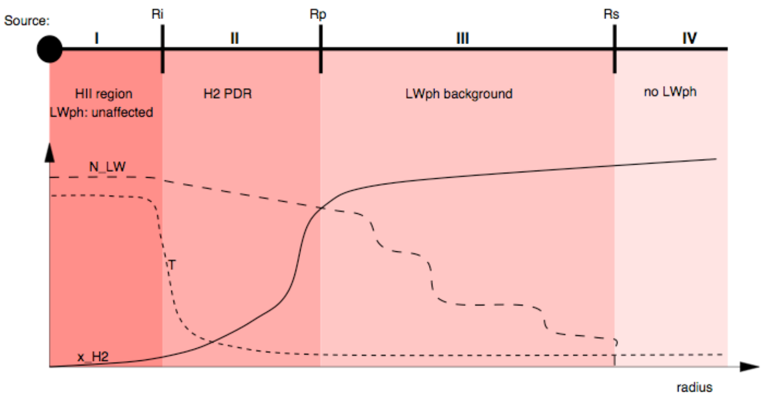
Total Flux diverges
Why is the night sky dark?

Lyman Werner Bands



Haiman, Abel and Rees 2000

Cosmological PDRs

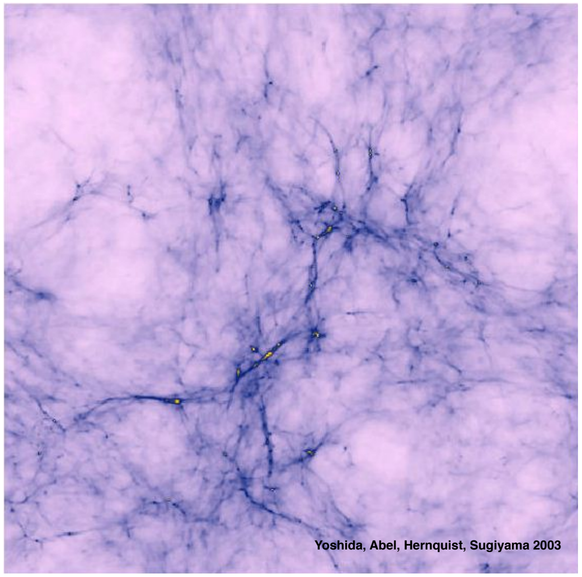


Haiman, Abel and Rees 2000

Redshift 20,
600 comoving kpc,
2x288^3 particles
> 40 million particles

$$\dot{n}_{H_2} + = -k_{LW}\, n_{H_2}$$

k_{LW} computed for different assumed LW fluxes

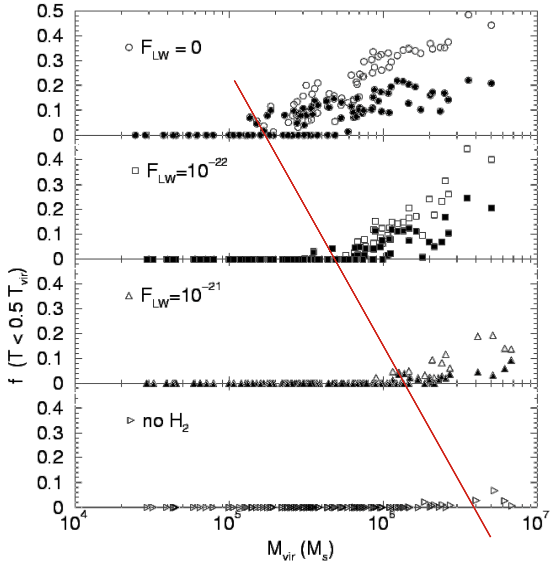


Yoshida, Abel, Hernquist, Sugiyama 2003

H2 Negative Radiative Feedback

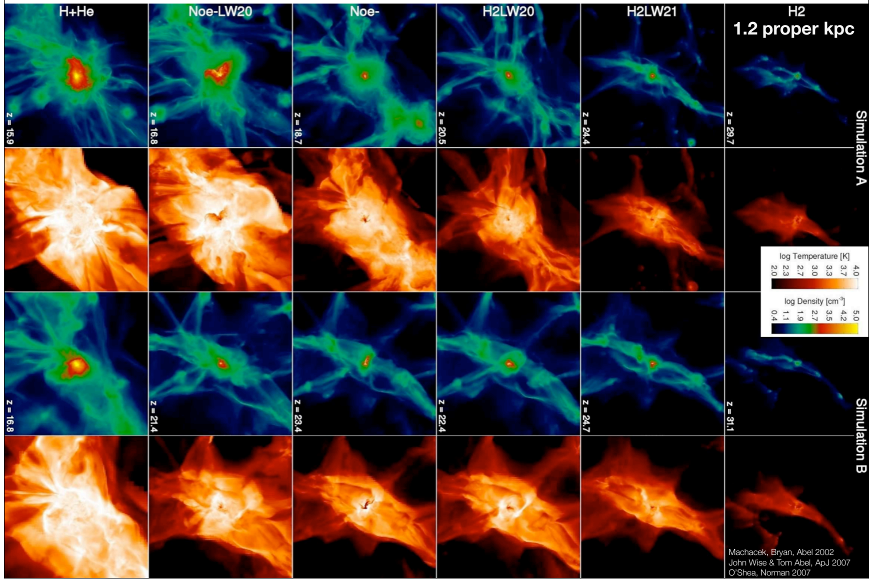
Haiman, Loeb & Rees 1997
Ciardi, Ferrara and Abel 2000
Haiman, Abel and Rees 2000,
Machacek, Bryan and Abel 2001
Glover & Brandt 2001

Yoshida, Abel, Hernquist,
Sugiyama 2003
Wise & Abel 2007
O'Shea & Norman 2007



Machacek, Bryan and Abel 2001

Strong H_2 suppression from dissociating UV background? No!



Machacek, Bryan, Abel 2002
John Wise & Tom Abel, ApJ 2007
O'Shea, Norman 2007

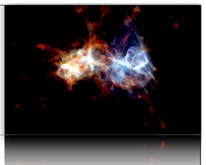
Key Fact

First Stars

- **Any region** in the Universe forming structure will **first** have **halos** in the mass range form 1e5 to 3e6 solar masses that **cool via molecular hydrogen**
- All simulated cases so far make individual stars in the centers of them.
- Neglecting Molecular Cooling is not justified, ever.

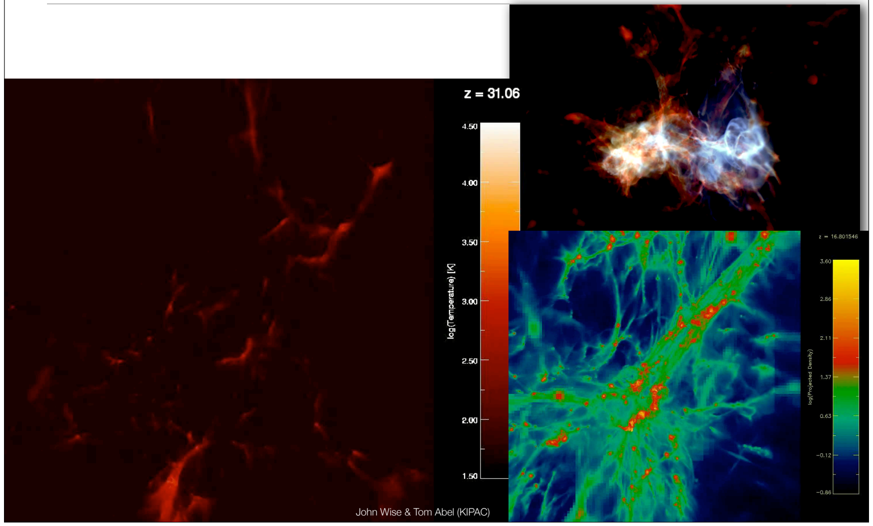
Tom Abel
KIPAC/Stanford

Galaxies one Star at a Time



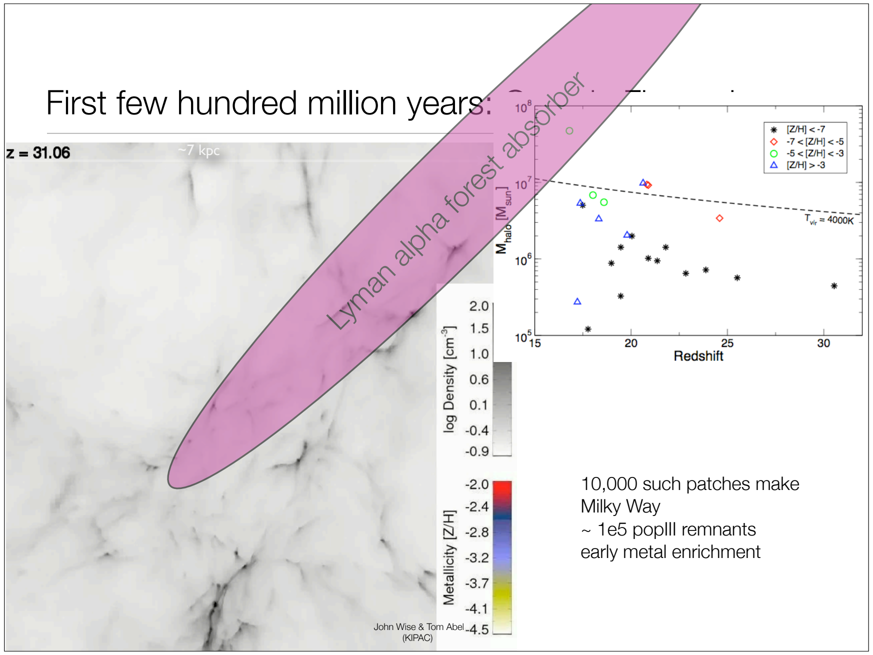
- Cosmological Initial Conditions starting at z~200. Adaptive mesh refinement with 12 levels of a factor of 2, dynamic range of 5e5, mass resolution down to 0.01 solar mass in high density regions.
- H2 fraction > 5e-4 & Core less than 0.1 pc & Converging flow -> Form PopIII star
- Assume 170 solar mass stars or 100 solar mass stars either gives strong pair instability supernovae or no supernovae with black hole remnant.
- Gather assumed stellar mass into a particle, follow radiation from its main sequence and if a supernova is assumed start at 0.01 pc as a thermal bomb.
- Study the galaxy properties under these different assumptions.

Galaxies, one star at a time

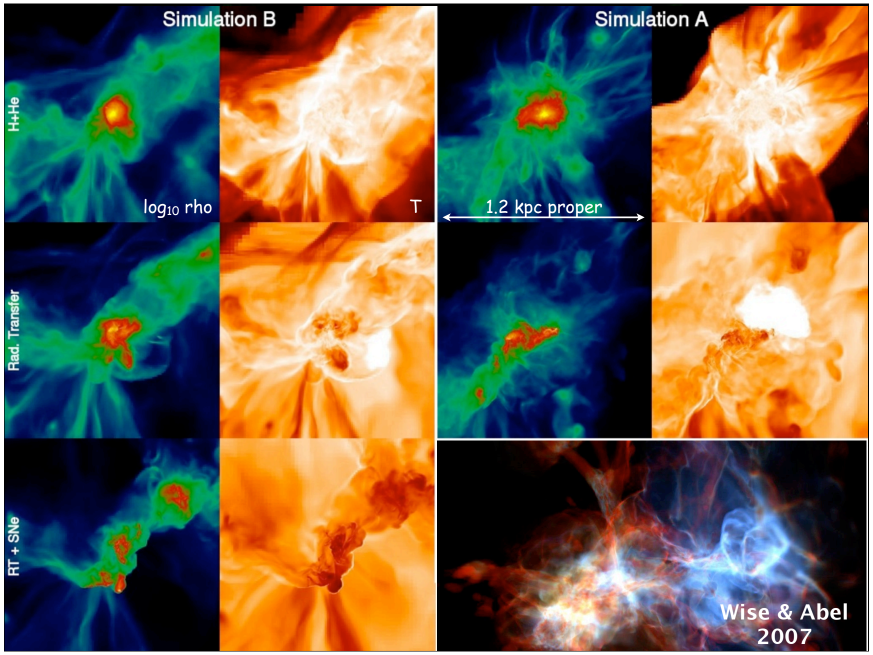


John Wise & Tom Abel (KIPAC)

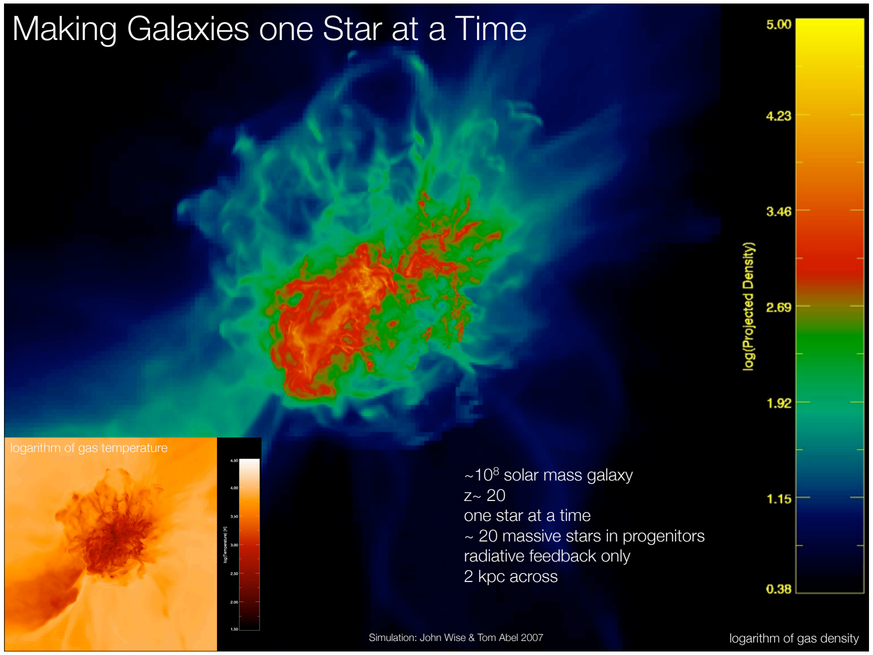
First few hundred million years:



10,000 such patches make
Milky Way
~ 1e5 popIII remnants
early metal enrichment



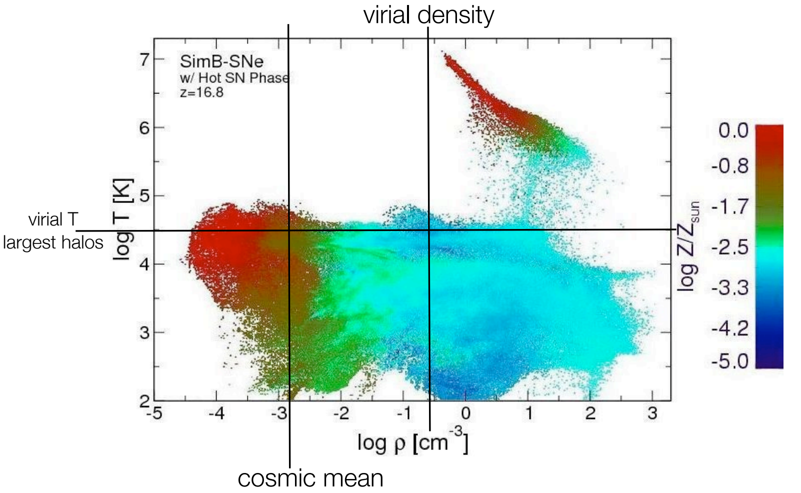
Making Galaxies one Star at a Time



~10^8 solar mass galaxy
z~ 20
one star at a time
~ 20 massive stars in progenitors
radiative feedback only
2 kpc across

Simulation: John Wise & Tom Abel 2007

Phase diagram



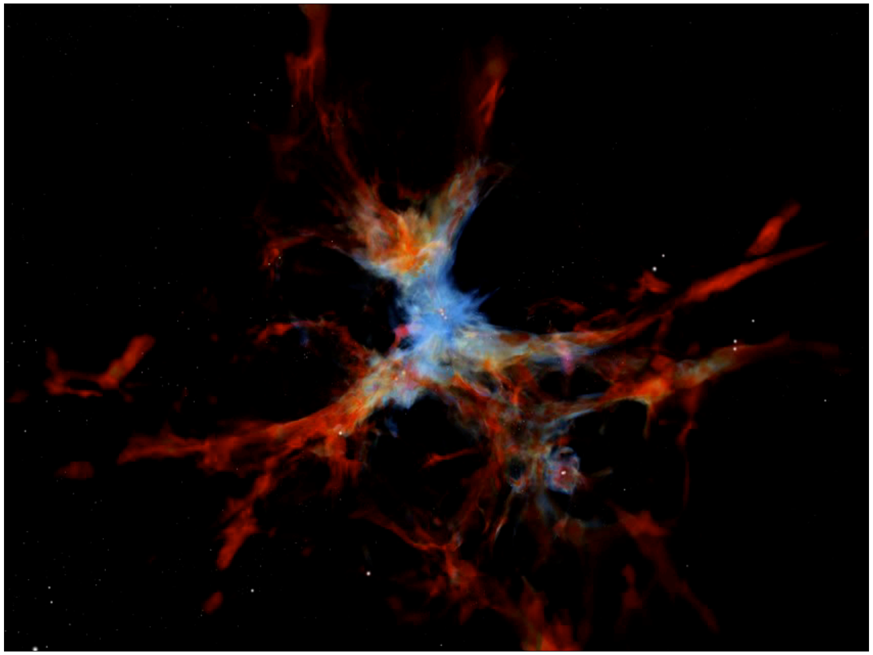
How big of a difference do Pop III stars make for the first galaxies?

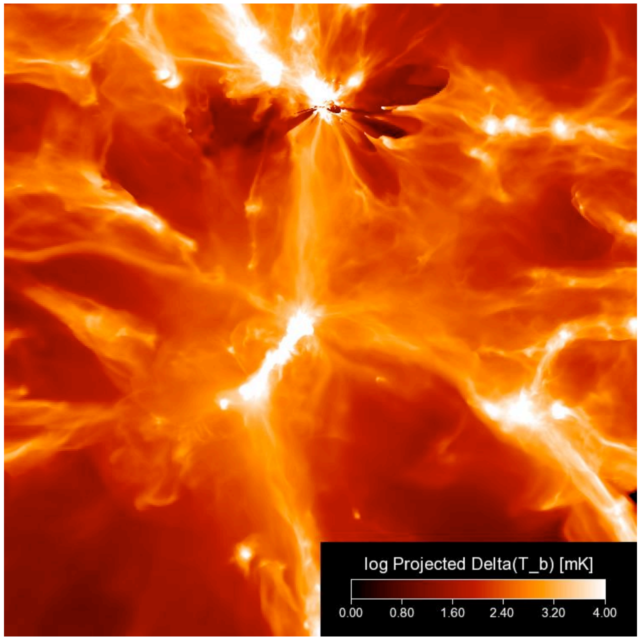
- ☐ Feedback is different from an effective equation of state

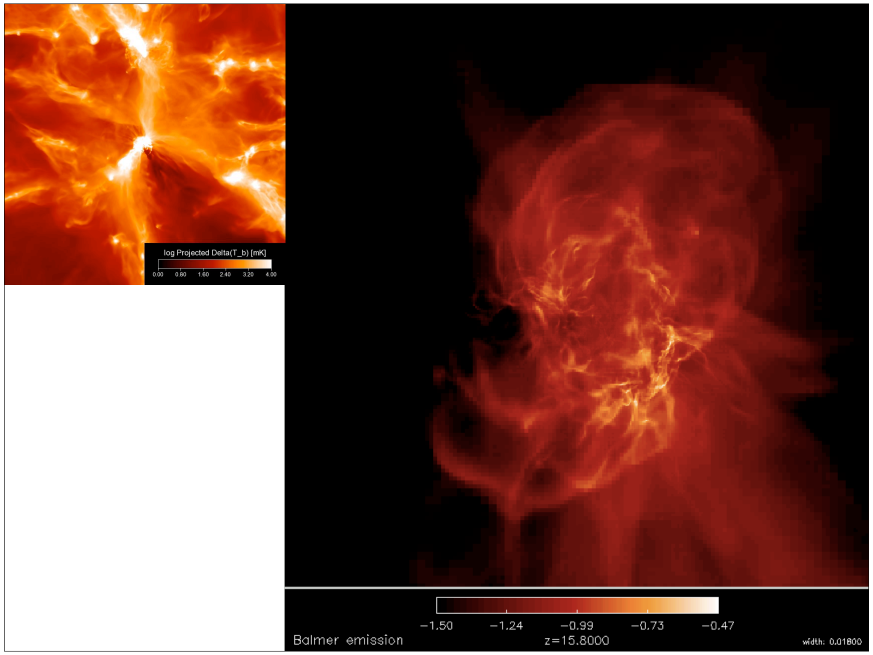
	Halo Mass [$M_\odot$]	Spin Parameter
Simulation A	3.47×10^7	0.030
Simulation B	3.50×10^7	0.022

	N★ (< rvir)	N★ (< 3rvir)	Mgas / Mtot	λgas	
SimA-Std H+He cooling	…	…	0.14	0.010	
SimA-SF transfer only	14	16	1/2 0.081	0.053	5
SimB-Std H+He cooling	…	…	0.14	0.010	
SimB-SF transfer only	13	19	4/5 0.11	0.022	2
SimB-SNe full	7	13	1/3 0.049	0.097	10

Wise & Abel 2007

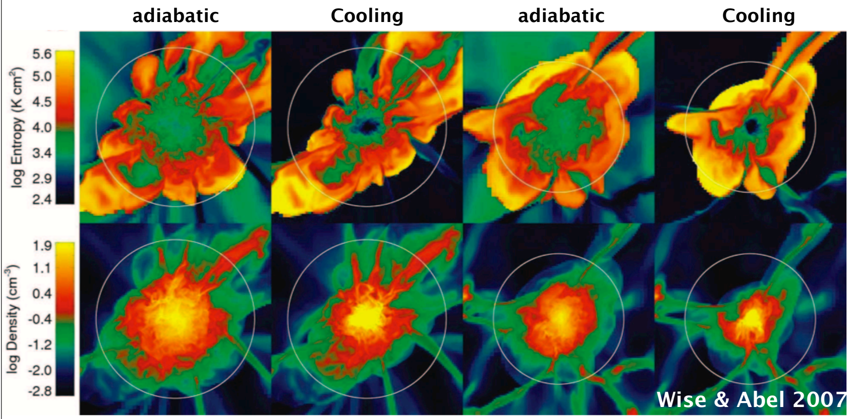






Virialization of Baryons

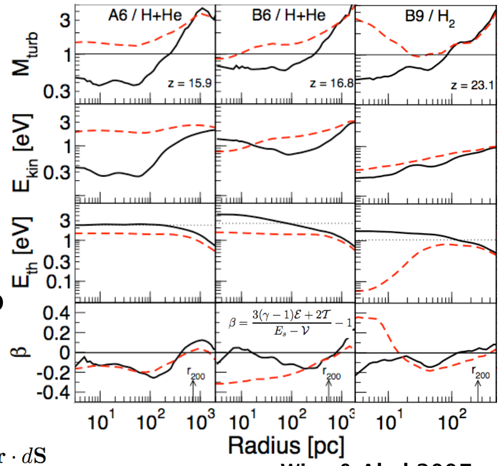
	Halo Mass [$M_\odot$]	Central Jeans Mass [$M_\odot$]	Central Jeans Length [pc]	Spin Parameter
Simulation A	3.47×10^7	4.7×10^5	7.9	0.030
Simulation B	3.50×10^7	1.0×10^5	1.5	0.022



Wise & Abel 2007

Virialized kinetically

- solid: adiabatic
  dashed: cooling
- Turbulent Mach numbers > 1
- If gas can cool to tens of Kelvin $M_{turb} > 10$

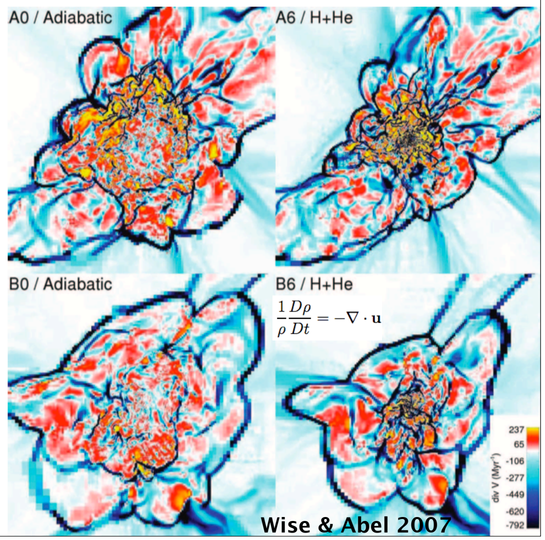


$$\frac{1}{2}\frac{D^2 I}{Dt^2} = 2\mathcal{T} + \mathcal{V} + 3(\gamma-1)\mathcal{E} - \int p\,\mathbf{r}\cdot d\mathbf{S}$$

Wise & Abel 2007

Turbulence in proto-galaxies

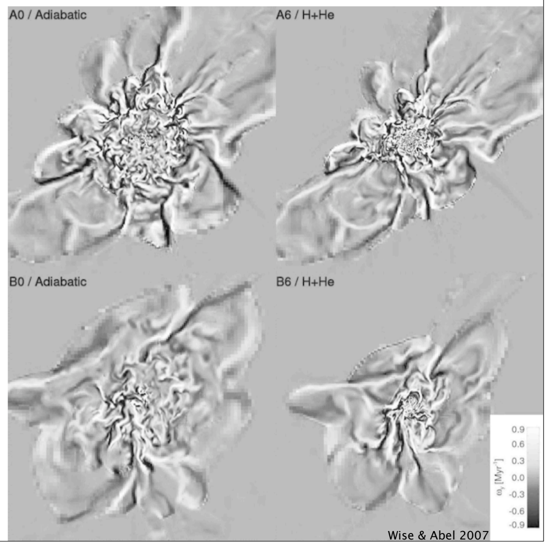
- Shocks down to smallest scales
- Do not diminish dramatically inside virial radius



Wise & Abel 2007

Turbulence in proto-galaxies

- y component of vorticity (rot(v)) in x-z plane
- Shocks down to smallest scales
- Local angular momentum more relevant than global amount!



Wise & Abel 2007

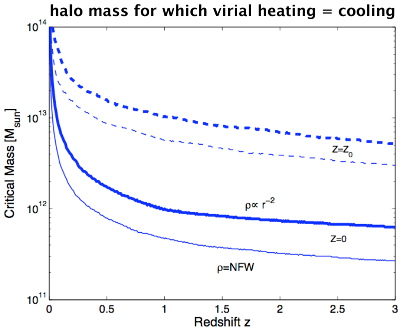
$$\frac{1}{2}\frac{D^2 I}{Dt^2} = 2\mathcal{T} + \mathcal{V} + 3(\gamma - 1)\mathcal{E} - \int p\,\mathbf{r}\cdot d\mathbf{S}$$

Virialization Heating

$$T_{vir} = \frac{\mu m_p G^{2/3} \Delta_c^{1/3} \Omega_m^{1/3} H_0^{2/3}}{16^{1/3} k_B} M^{2/3}(1+z)$$
$$= 4.8\times10^{-3}\left(\frac{M}{M_\odot}\right)^{2/3}(1+z)$$
$$\times\left(\frac{\Omega_m}{0.3}\right)^{1/3}\left(\frac{\Delta_c}{178}\right)^{1/3}\left(\frac{\mu}{0.59}\right)K\ , \qquad (1)$$

Using $dz/dt = -H_0[\Omega_m(1+z)^5 + \Omega_\Lambda(1+z)^2]^{1/2}$ in a ΛCDM cosmology and differentiating Eq. (1), one finds

$$\Gamma = -\frac{3}{2}\frac{\mu m_p G^{2/3} \Delta_c^{1/3} \Omega_m^{1/3} H_0^{5/3}}{54^{1/3}} M^{-1/3}\frac{dM}{dz}$$
$$\times[\Omega_m(1+z)^7 + \Omega_\Lambda(1+z)^4]^{1/2}$$
$$= -2.95\times10^{-8}\left(\frac{M}{M_\odot}\right)^{-\frac{1}{3}}\frac{d(M/M_\odot)}{dz}$$
$$\times[\Omega_m(1+z)^7 + \Omega_\Lambda(1+z)^4]^{1/2}$$
$$\times\left(\frac{\Omega_m}{0.3}\right)^{\frac{1}{3}}\left(\frac{\Delta_c}{178}\right)^{\frac{1}{3}}\left(\frac{\mu}{0.59}\right)\mathrm{eVGyr}^{-1}\ , \qquad (2)$$



Gas in halos with less than 1e12 solar masses
cannot virialize with hydrostatic pressure!
It must virialize with kinetic (turbulent) energy
or collapse very rapidly
cold / hot flow transition

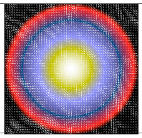
Wang & Abel 2007

Effects of Pop III Stars on Galaxy Formation are being modeled. What's needed next?

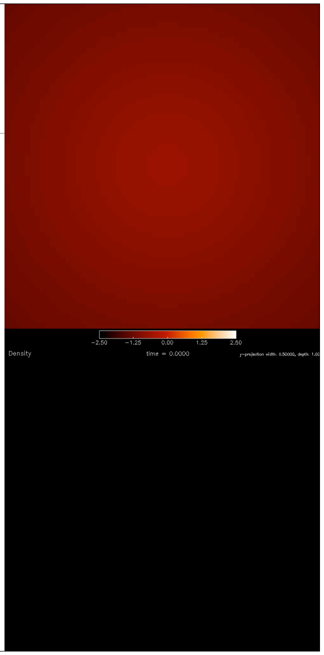
- Carbon and Oxygen fine structure line cooling
  - Well understood microphysics: quite straightforward to do
- **Dust:** formation, destruction, cooling, radiation pressure on, drift, coupling to B, ...
  - Not straightforward at all. Best local example, Carbon stars, irrelevant early on.
- How do most Stars form?
  - Still a puzzle. Long lived molecular clouds, multiplicity, Universality of IMF, ...
- Magnetization of ISM, IGM from early supernovae
  - Completely new issues that have not been addressed before
- Cosmic Ray production in early Supernovae and perhaps structure formation shocks?
  - Only the very simplest of ideas explored so far

CALIFORNIA NEBULA, NGC1499
500 pc = 1,500 light years away
30 pc long
Xi Persei, منكب mankib, Shoulder of Pleiades:
O7.5III
330,000 solar luminosities
~40 solar masses, Teff=3.7e4K

Local Star Formation



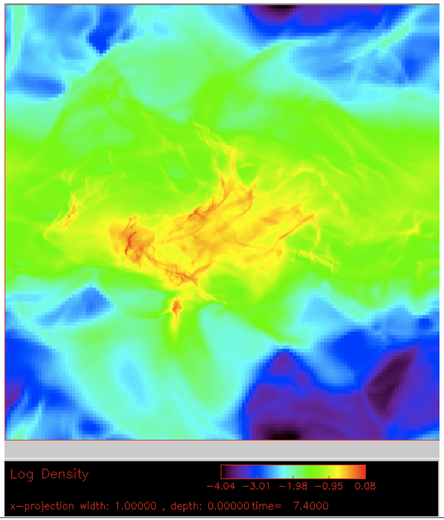
- A 1e4 Msun cloud, radius 3.6 pc with central flat core (~1000 Msun) and r^{-2} envelope, central density ~ 10^4 /cm^3.
- Initial Kolmogorov turbulent velocity spectrum with Mach 10.
- We model proto-stellar growth by Bondi-Hoyle accretion.
- Cooling down to 10 K using a fitted cooling function, which essentially keeps gas isothermal.
- Top grid resolution 128^3. Four level of AMR level using Jeans refinement criterion (Jeans number 4), corresponding to 1000 AU best resolution.
- Adaptive ray tracing for UV ionizing radiation coupled with HLL-PLM Hydro/MHD solver.
- Main sequence luminosity for radiating stars (>10 Msun).



Wang & Abel 2008, in progress.

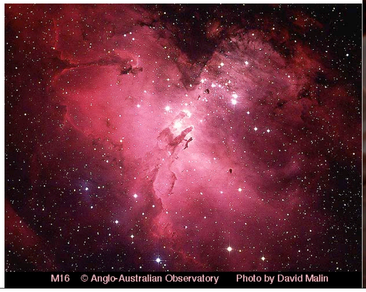
Initial Conditions for Star Formation

- Force driving with fixed pattern
- Shaped force to mimic central concentrated conditions
- 5 levels of refinement
- Jeans length at least resolved by 8 cells

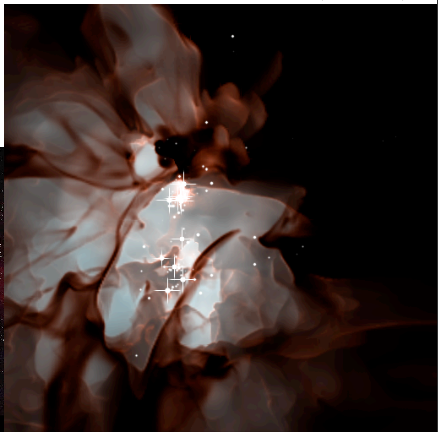


Using local HII regions as Laboratory for Star Formation

- Massive Stars light up initial conditions
- IFU spectroscopy possible in many lines
- Radio - Xrays

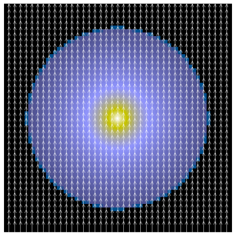

M16 © Anglo-Australian Observatory Photo by David Malin

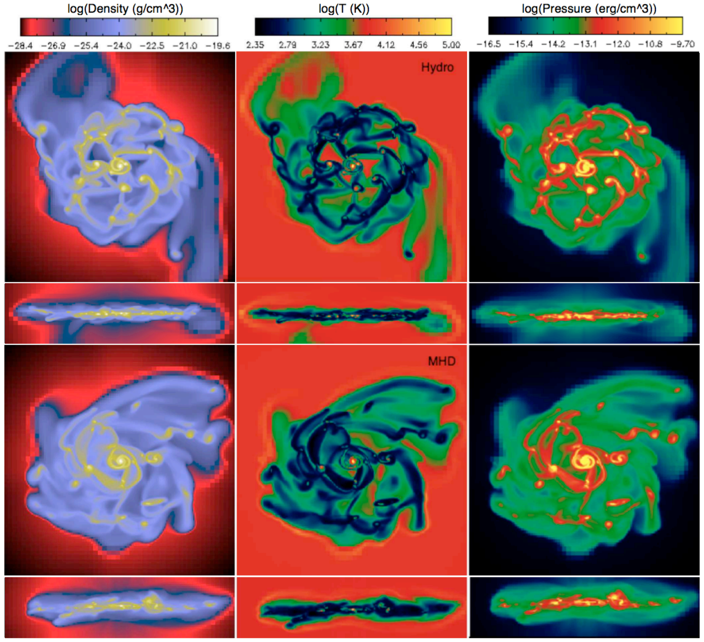
Ianucci, Wang & Abel in progress

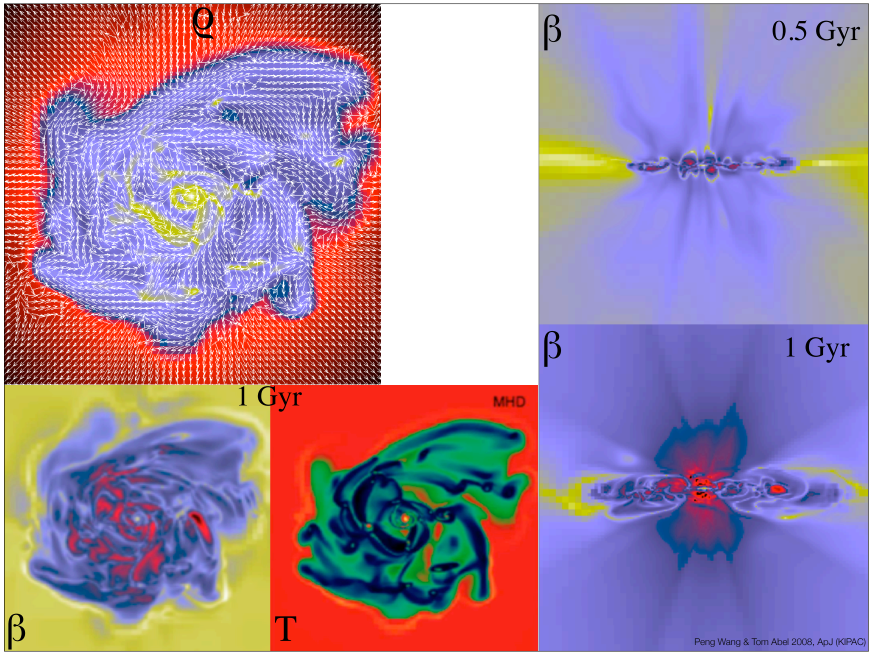


Galactic magnetic field amplification
I) The simplest conceivable numerical experiments.

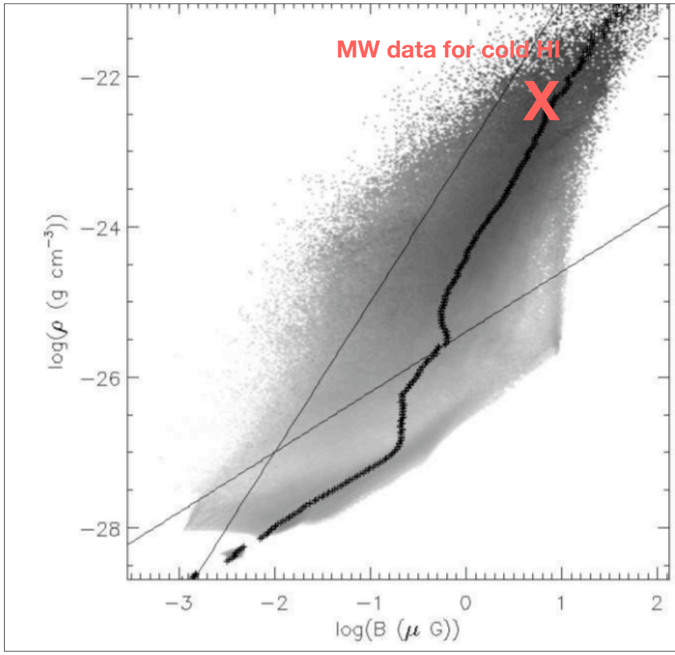
- First MHD global model of a disk
- Isolated NFW halo 1e10 Msun at z=2 with concentration=10, modeled as external potential
- Spherical gas distribution with NFW profile and baryon fraction 0.1
- Rotation speed corresponds to spin parameter 0.05.
- Gaussian random velocity field with amplitude the halo virial velocity
- Uniform 1e-9G B field in z direction
  * Faraday rotation measured in high-z damped Lya system
  * Beryllium and boron abundance in galactic halo stars
  * Protogalactic turbulence due to merger, etc.
  * Supernova ejecta and extended radio lobes
- Cooling function down to 300 K using the Sarazin & White fit.
- Local temperature floor to avoid artificial fragmentation instead of star particle



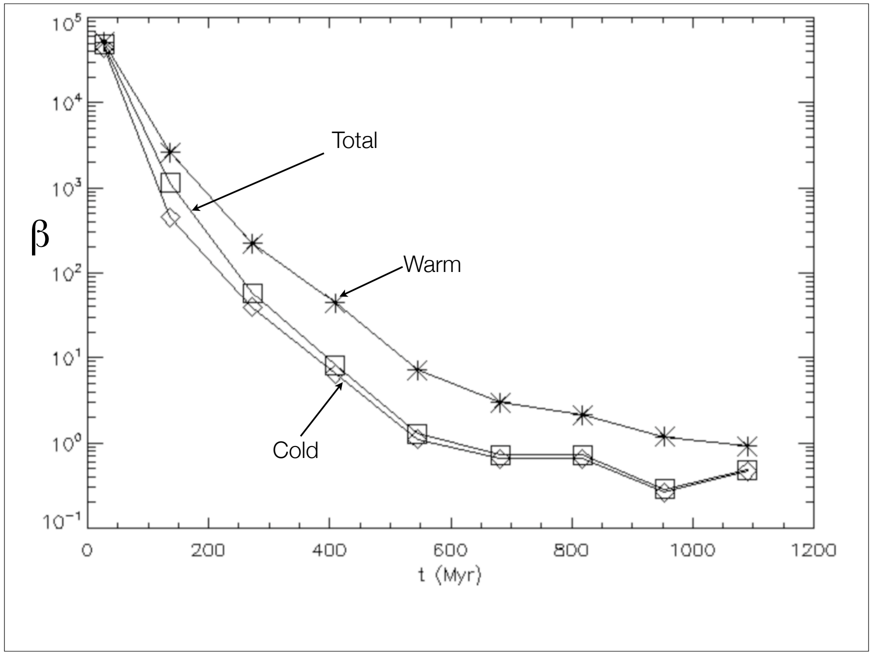




Peng Wang & Tom Abel 2008, ApJ (KIPAC)



Peng Wang & Tom Abel 2008, ApJ (KIPAC)



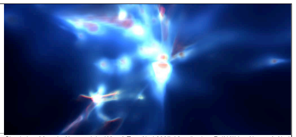
Computational Physics is fun

- continuously building better tools
- Is typically more general and minimizes need for assumptions
- solve problems that are intractable analytically
- Great starting point to develop analytical theory

The First Stars

Tom Abel
KIPAC/Stanford

Summary


Simulation: Marcelo Alvarez, John Wise & Tom Abel 2007 Visualization: Ralf Kähler, Alvarez & Abel

- Wide range of birth, life & death of the first massive stars are being explored on super computers.
- H_2 always relevant in early structure formation. Period.
- Ab initio calculations of galaxy formation: one Star at a Time
    - Enormous impact from early feedback: f_B, spins, etc.
    - kpc scales predicted with great confidence. Larger scales require more a priori phenomenological inputs.
    - Now is the Time !
    - Still more physics we need to implement ...
- Magnetic fields are quickly amplified to equi-partition values and lead to magnetic flux in halo material. We expect also galaxies at very high redshifts to contain fields of significant strengths. Look for synchrotron emission from these.
- HII regions, supernova remnants as well as planetary nebulae should be excellent places to test our methodology required to make progress in galaxy formation


Simulation: John Wise & Tom Abel 2007 Visualization: Ralf Kähler, Wise & Abel

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References

T. Abel, P. Anninos, Y. Zhang, and M. L. Norman. Modeling primordial gas in numerical cosmology. *New Astronomy*, 2:181–207, Aug. 1997.
T. Abel, P. Anninos, M. L. Norman, and Y. Zhang. First Structure Formation. I. Primordial Star-forming Regions in Hierarchical Models. , 508:518–529, Dec. 1998.
T. Abel, G. L. Bryan, and M. L. Norman. The Formation of the First Star in the Universe. *Science*, 295:93–98, Jan. 2002.
V. Bromm, P. S. Coppi, and R. B. Larson. The Formation of the First Stars. I. The Primordial Star-forming Cloud. , 564:23–51, Jan. 2002.
H. M. P. Couchman and M. J. Rees. Pregalactic evolution in cosmologies with cold dark matter. , 221:53–62, July 1986.
N. Y. Gnedin and J. P. Ostriker. Reionization of the Universe and the Early Production of Metals. , 486:581–+, Sept. 1997.
N. Y. Gnedin. Cosmological Reionization by Stellar Sources. , 535:530–554, June 2000.
Z. Haiman, T. Abel, and M. J. Rees. The Radiative Feedback of the First Cosmological Objects. , 534:11–24, May 2000.
A. Kashlinsky and M. J. Rees. Formation of population III stars and pregalactic evolution. , 205:955–971, Dec. 1983.
R. B. Larson. Numerical calculations of the dynamics of collapsing proto-star. , 145:271–+, 1969.
A. Loeb and R. Barkana. The Reionization of the Universe by the First Stars and Quasars. , 39:19–66, 2001.
J. Peebles and R. Dicke, Origin of the Globular Star Clusters, ApJ, 154, 891, 1968.
E. Ripamonti and T. Abel. Fragmentation and the formation of primordial protostars: the possible role of collision-induced emission. , 348:1019–1034, Mar. 2004.
E. Ripamonti, F. Haardt, A. Ferrara, and M. Colpi. Radiation from the first forming stars. , 334:401–418, Aug. 2002.
K. Tassis, T. Abel, G. L. Bryan, and M. L. Norman. Numerical Simulations of High-Redshift Star Formation in Dwarf Galaxies. , 587:13–24, Apr. 2003.
M. Tegmark, J. Silk, M. J. Rees, A. Blanchard, T. Abel, and F. Palla. How Small Were the First Cosmological Objects? , 474:1–+, Jan. 1997.
Peng Wang & Tom Abel 2008, Magnetohydrodynamic Simulations of Disk Galaxy Formation: The Magnetization of the Cold and Warm Medium, accepted to ApJ.
John Wise & Tom Abel 2008, How the First Stars start Cosmological Reionization, accepted to ApJ.
John Wise & Tom Abel 2008, Resolving the Formation of Proto-Galaxies III) The Nature of Early Dwarf Galaxies, accepted to ApJ.