First Stars/Cosmological Reionization

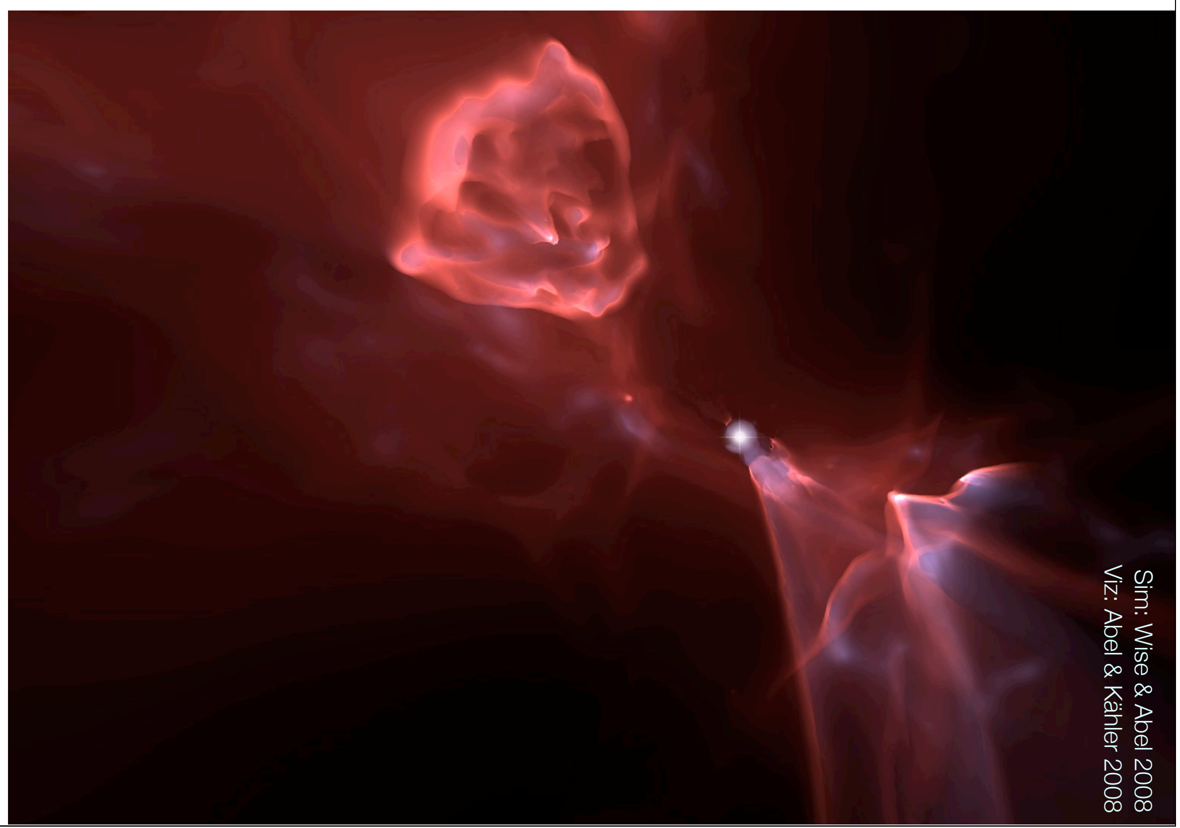
Tom Abel
KIPAC/Stanford

- Predicting Sources: A way forward
- Fossil Records?
- Summary

Sim & Viz: Alvarez, Kähler & Abel 2008

Sources:

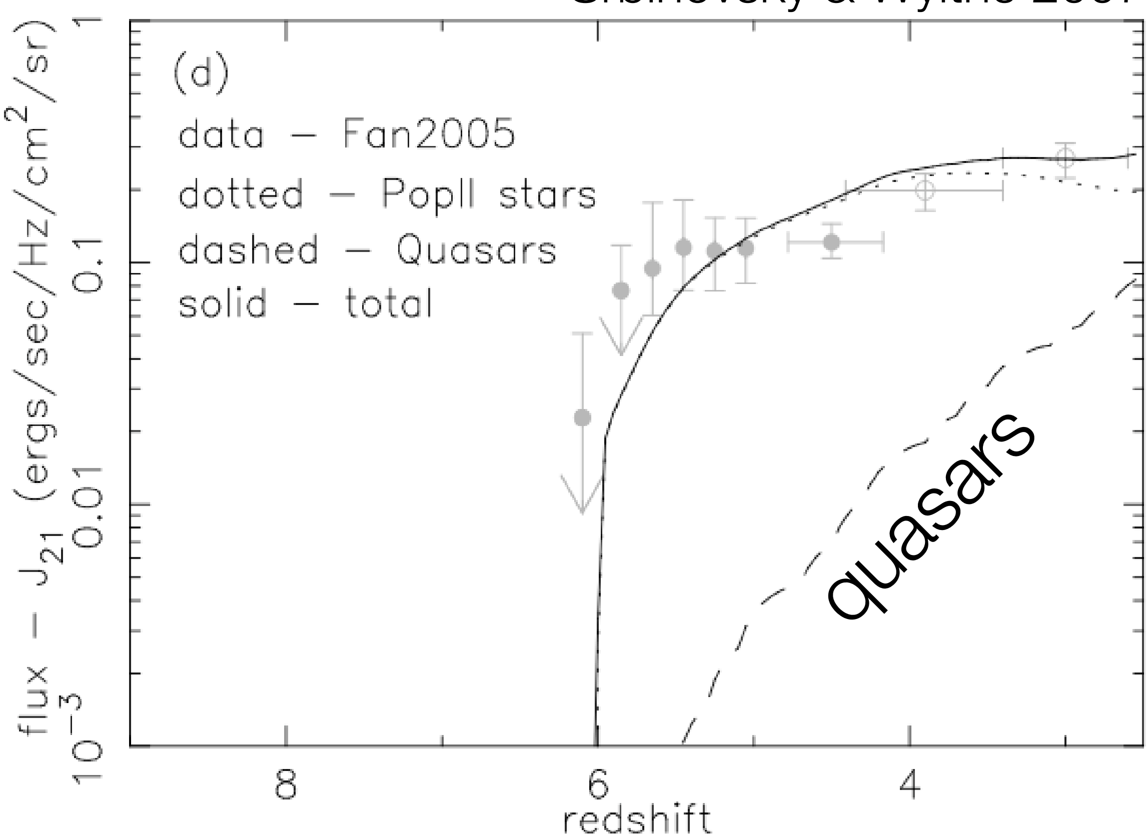
- First stars
- Why not mini-quasars?
- First Galaxies



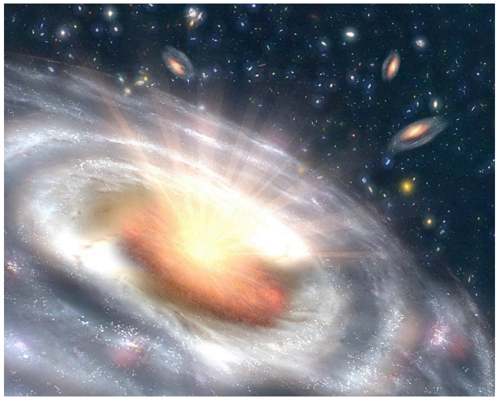
Galaxies rather than Quasars are the most likely responsible sources

- Less than 15% at z=6 from quasars
- Are there mini-quasars and relic decaying particle contributions?

Srbinovsky & Wyithe 2007



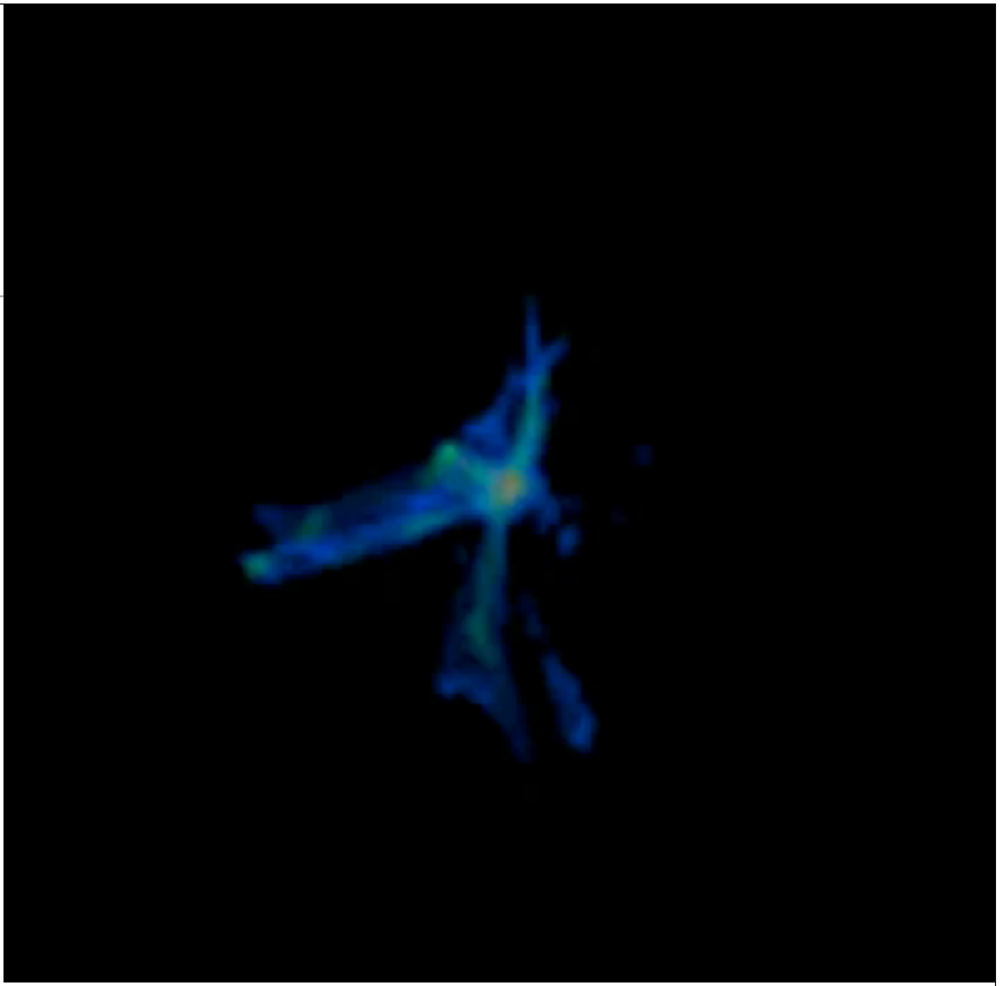
Shapiro 1986
Madau 1999
Fan et al 2001
Yan & Windhorst 2004
Stiavelli et al 2004



Sources
Understanding First Stars is an 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

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

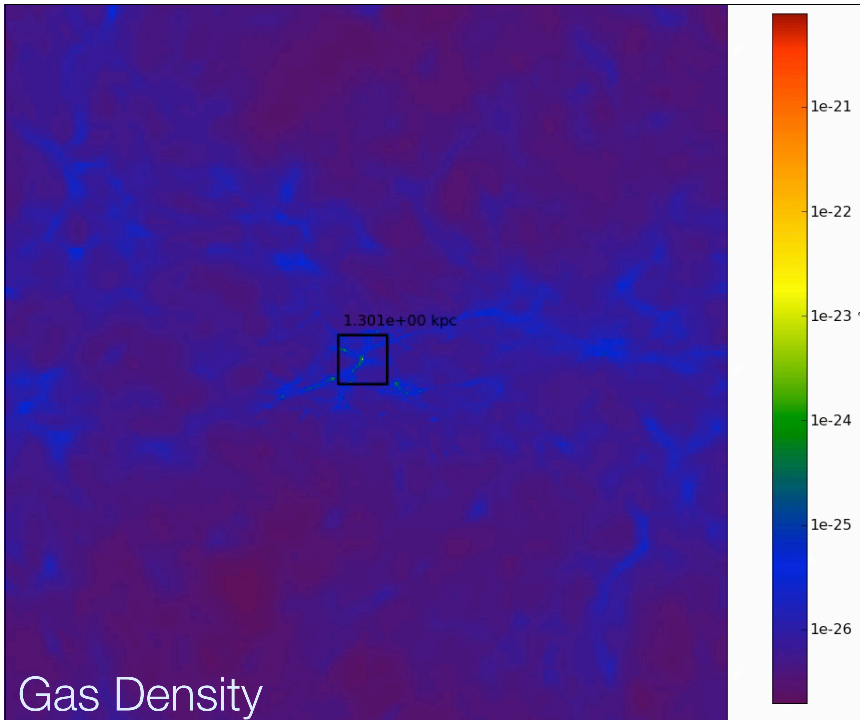


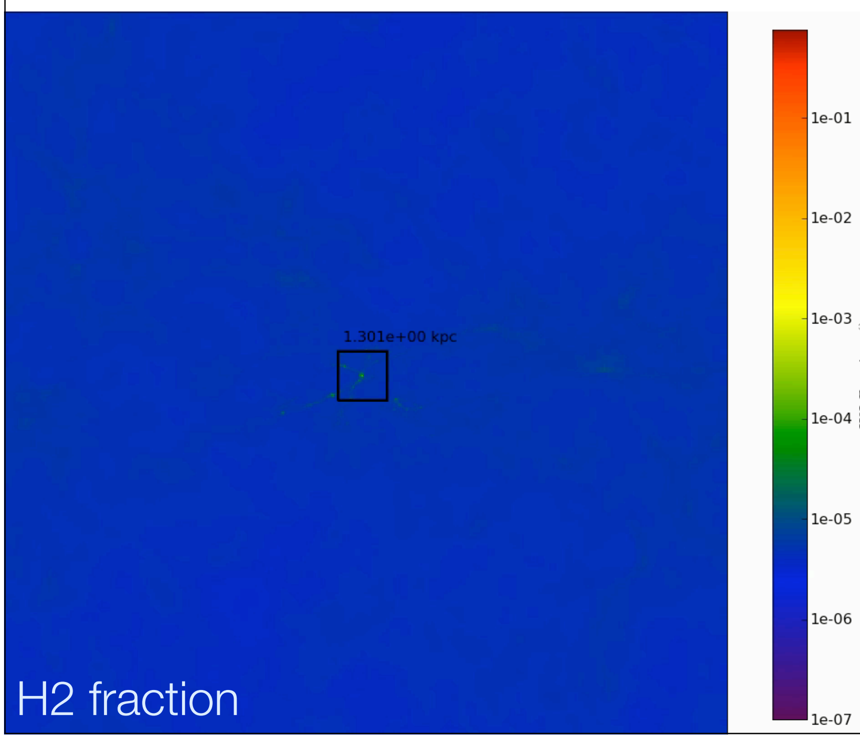
Ralf Kähler & Tom Abel for PBS Origins. Aired Dec 04

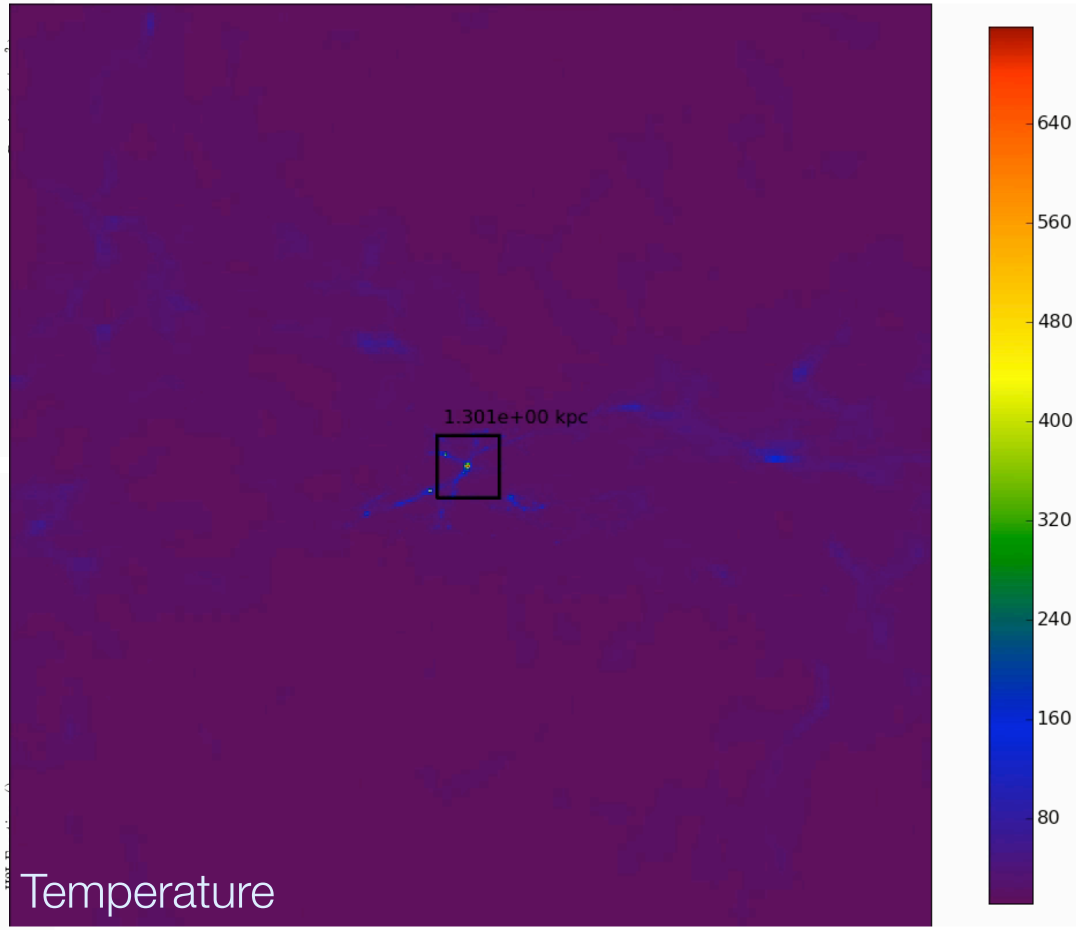
$$\frac{R_\odot}{R_{\rm Milky Way}} \approx 10^{-12}$$

$$\frac{P_{\odot,\rm Kepler}}{t_{\rm Hubble}(z=30)} \approx 10^{-12}$$

Ab inito cosmological simulation of the Formation of the First Protostars





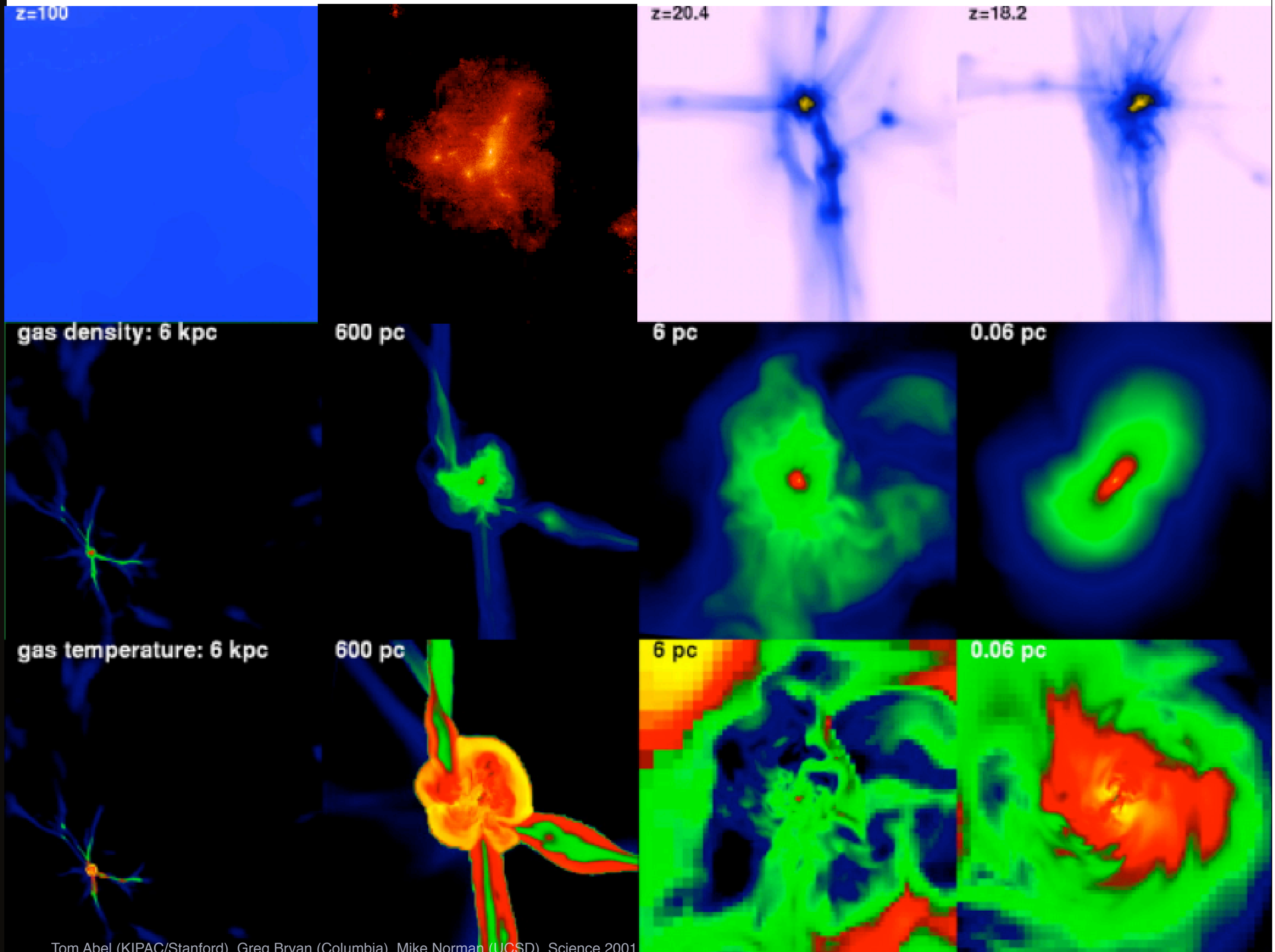


12 orders of magnitude in length
23 in density
10 Jupiter mass at formation as in spherical symmetry

Matt Turk, Brian O'Shea & Tom Abel in prep.

First cooling objects

The First Stars

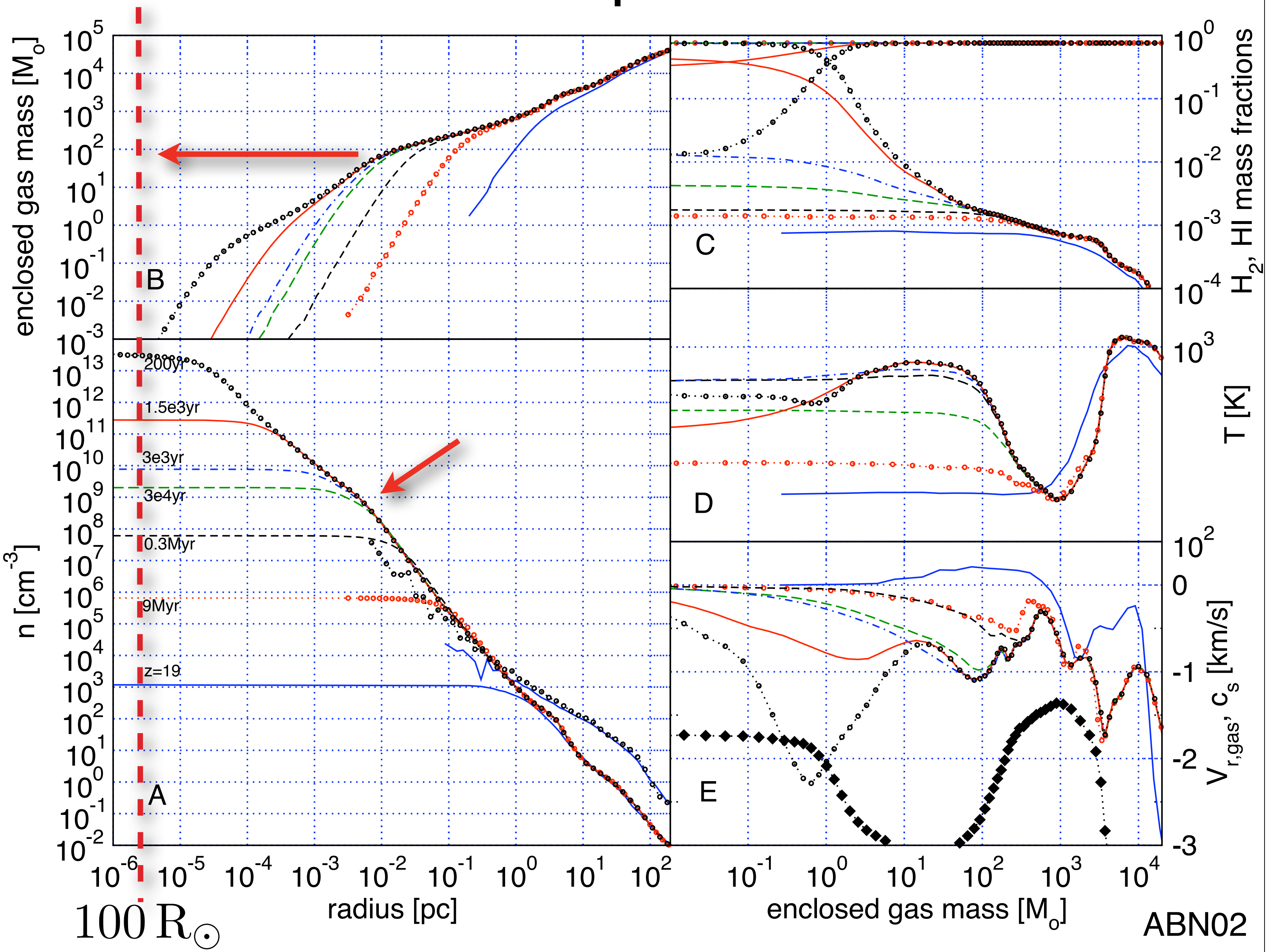


Tom Abel (KIPAC/Stanford), Greg Bryan (Columbia), Mike Norman (UCSD), Science 2001

Tom Abel
KIPAC/Stanford

Evolution of the Collapse

The First Stars



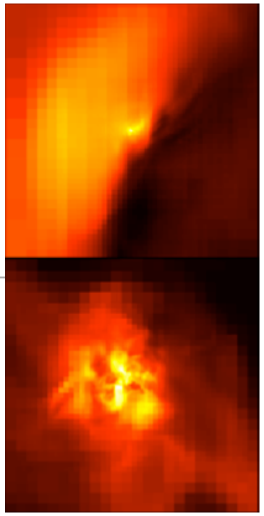
ABN02

Tom Abel
KIPAC/Stanford

We find

First Stars are isolated and very massive

- Theoretical uncertainty: 30 - 300 solar mass



Matt Turk, Tom Abel, Brian O'Shea in prep. (KIPAC)

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.

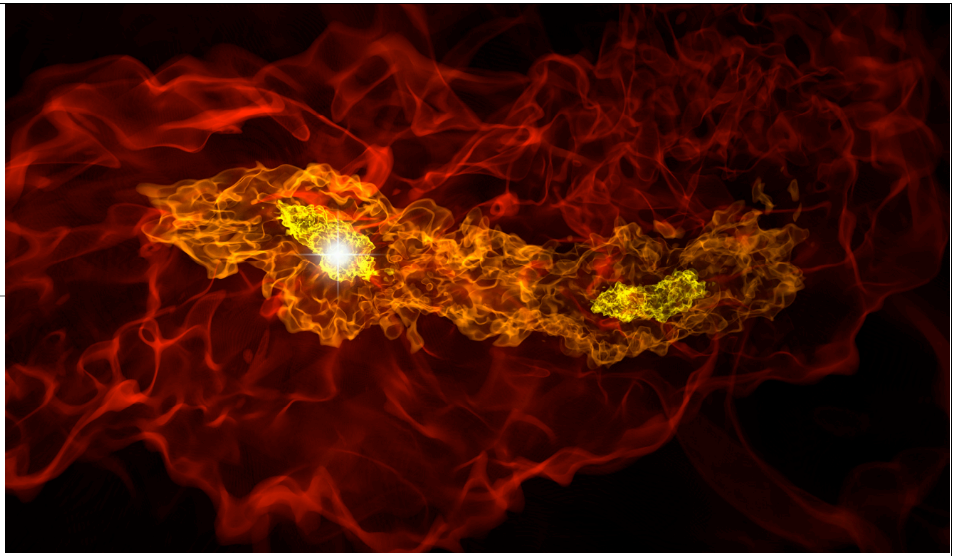
Perfectly consistent with observations!
Could have been a real problem for LCDM!

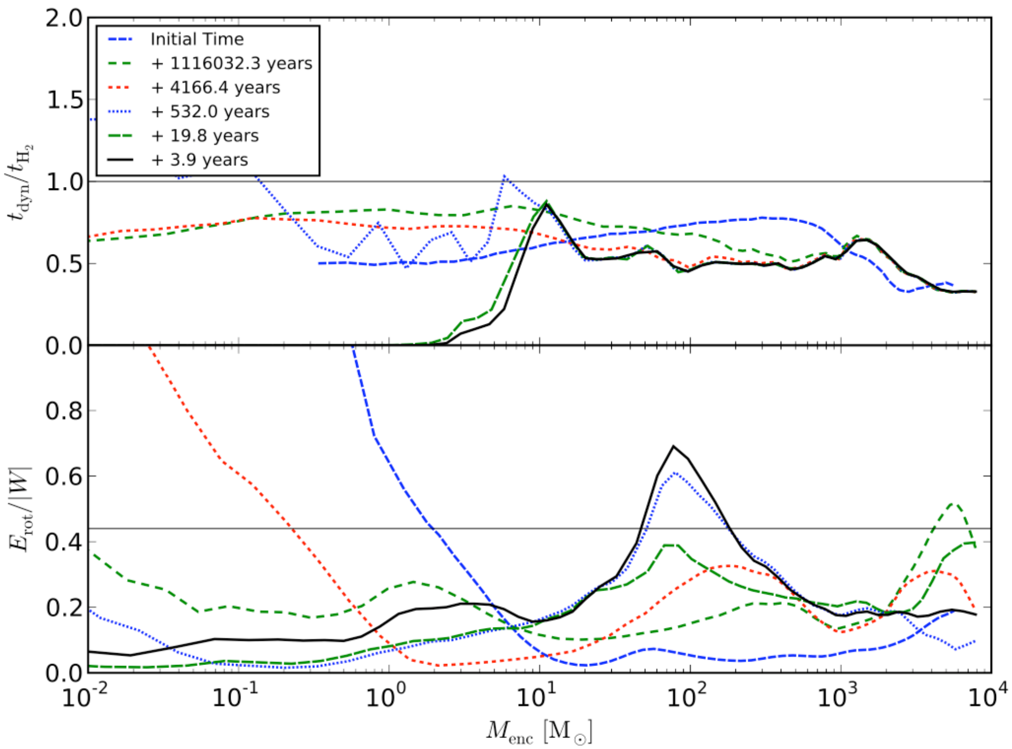
- New:
  - Can go all the way to proto-stars now!
  - Pop III.2 stars are a factor of few less massive

cosmological: Abel 1995; Abel et al 1998; Abel, Bryan & Norman 2000, 2002; O'Shea, Abel, Whalen & Norman 1995; O'Shea et al 2006; Yoshida et al 2006; Gao et al 2006, Yoshida et al 2008a,b; Turk, Abel & O'Shea 2009 in prep
idealized spheres: Bodenheimer 1986; Haiman et al 1997; Omukai & Nishi 1998; Bromm et al 1999,2000,2002; Ripamonti & Abel 2004

Binaries! Multiples?

- In one of five very high resolution studies we see the gas to fragment into two cores at densities ~10^{12} cm^{-3}
- Separation 800 AU, collapse much faster than orbital time.
- Rare (?) because usually one forms a bar that transports the angular momentum too quickly, decreasing the rotational energy below the critical value.

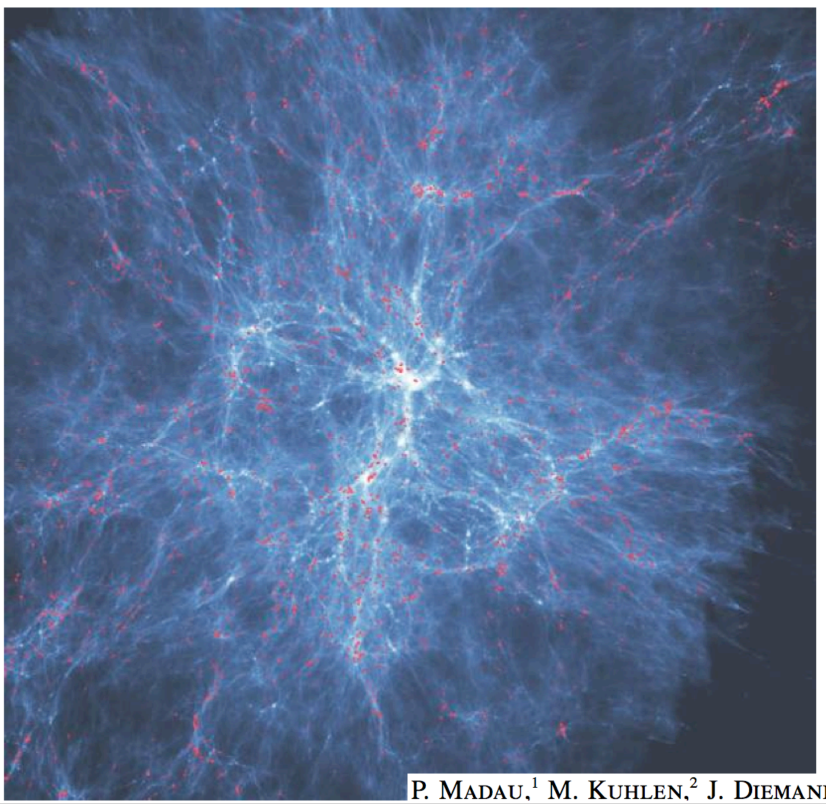


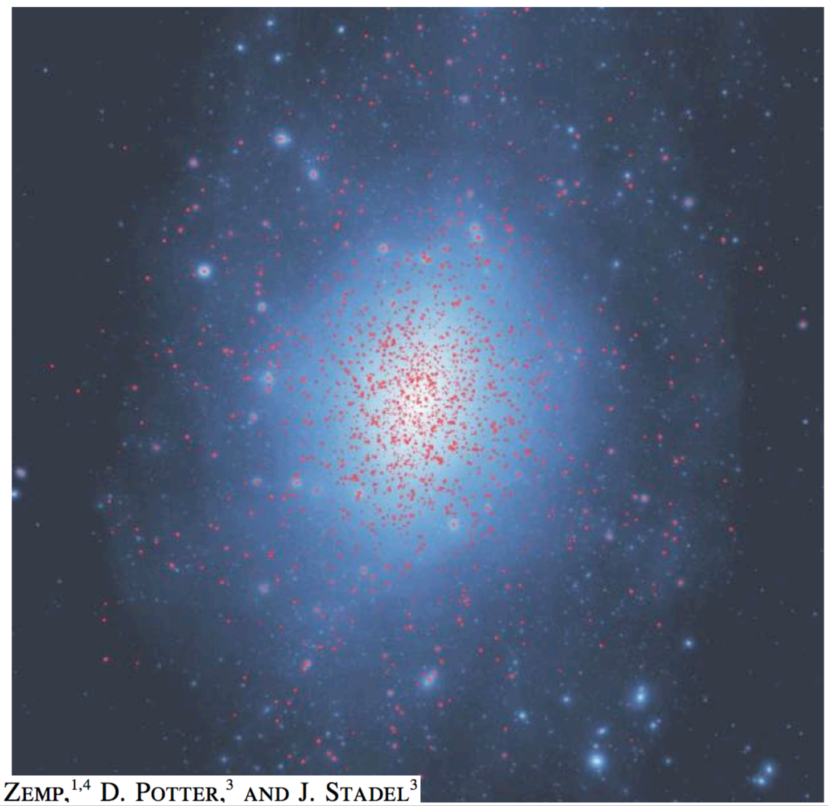


Matt Turk, Tom Abel, Brian O'Shea, Science, 2009 (KIPAC)
Viz: Ralf Kähler, Matt Turk, Tom Abel. (KIPAC)

The simulations finding high mass -short lived- stars for population III is consistent with observed number of Milky Way satelites

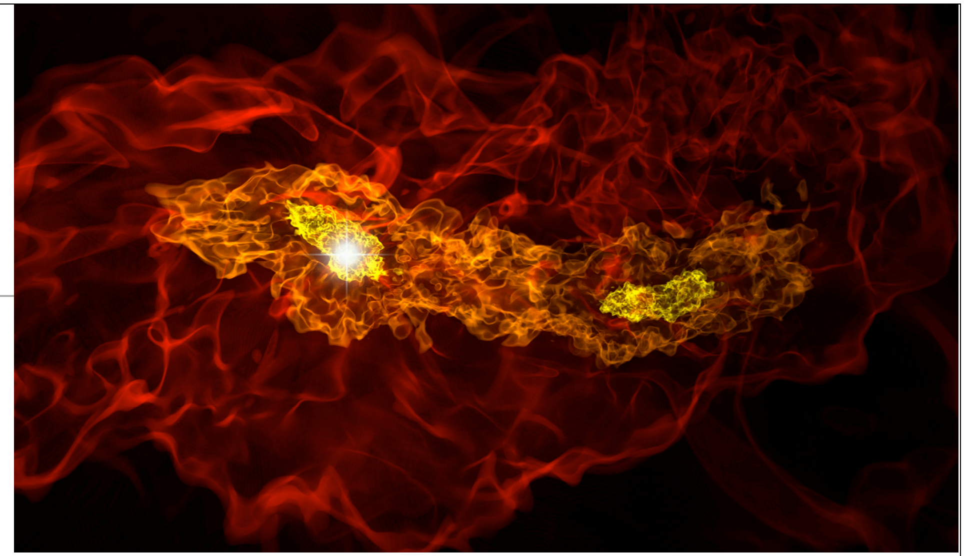
- Madau et al 2008:
  Analyzed very high resolution N-body only simulation of Milky Way sized dark matter halo: Via Lactea II
- Allowing for low mass stars (< 90% of sun) would over predict number of satellites by a factor of ~50





P. MADAU,[1] M. KUHLEN,[2] J. DIEMAND,[1] B. MOORE,[3] M. ZEMP,[1,4] D. POTTER,[3] AND J. STADEL[3]

Binaries! Multiples?



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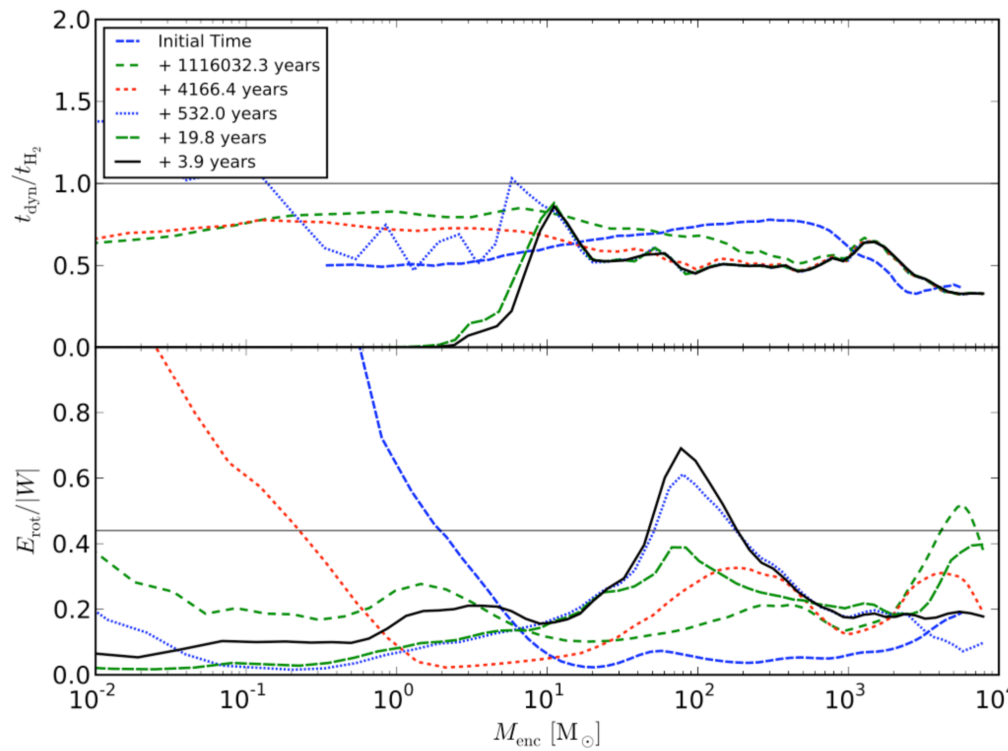
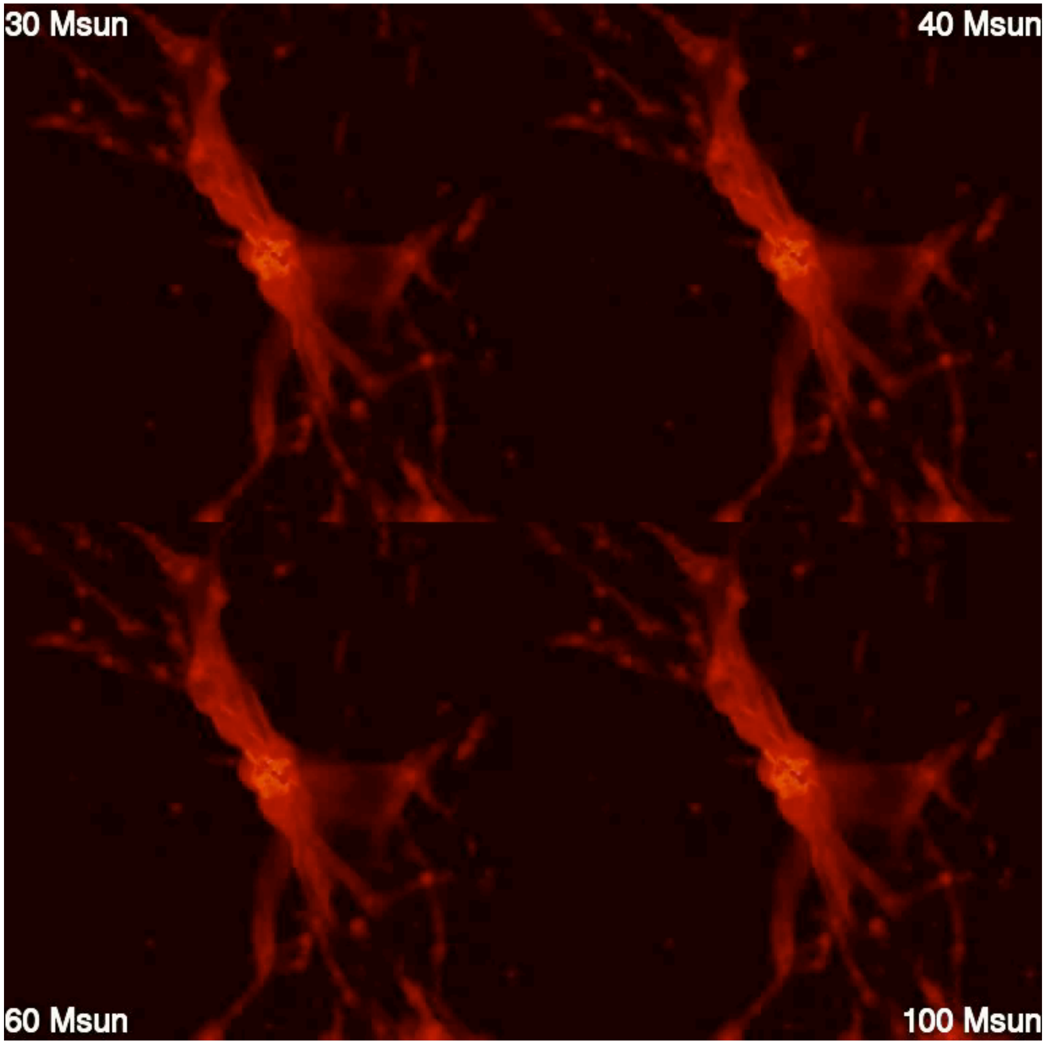


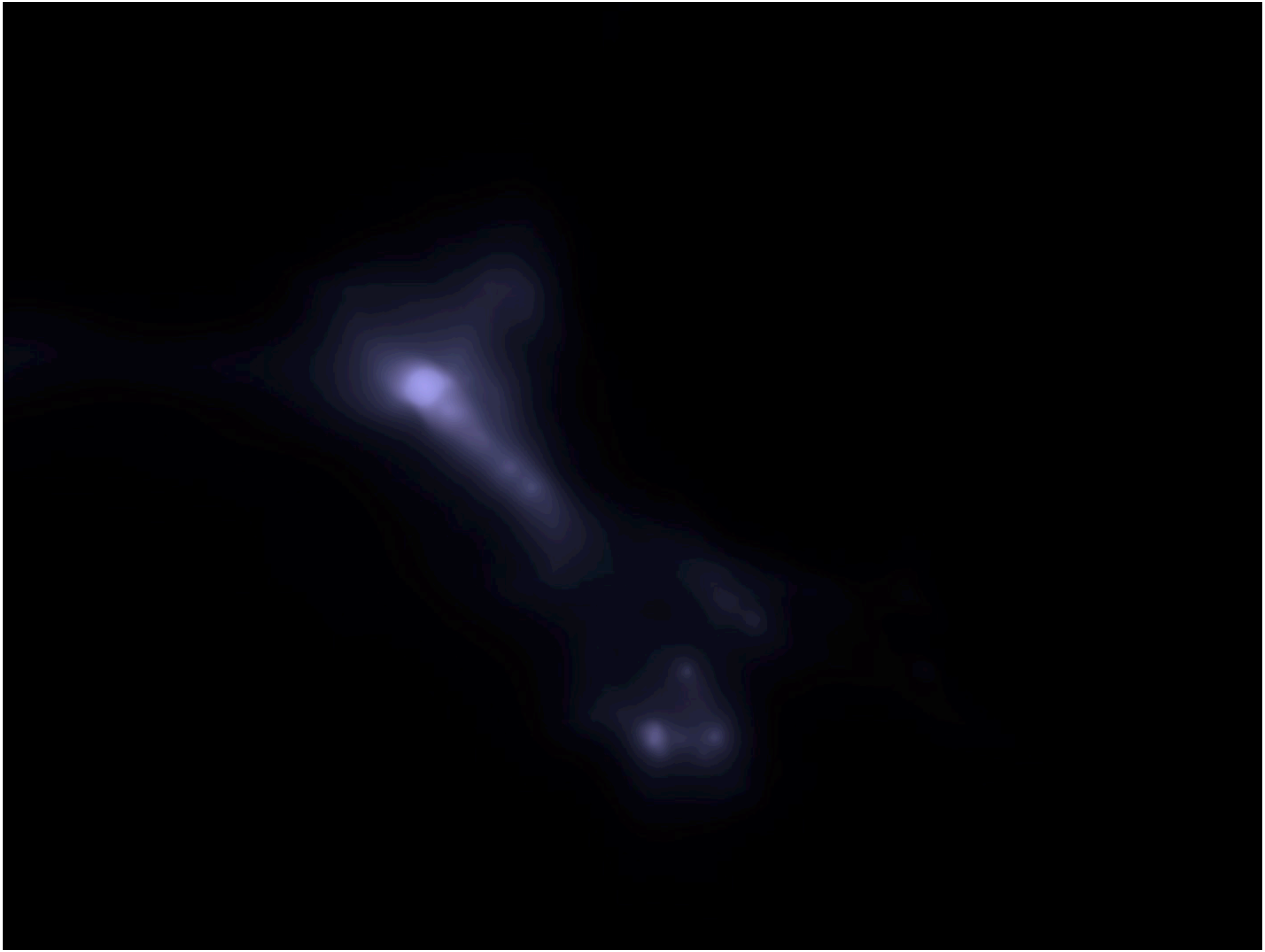
Matt Turk, Tom Abel, Brian O'Shea Science 2009. (KIPAC)
Viz: Ralf Kähler, Matt Turk, Tom Abel. (KIPAC)

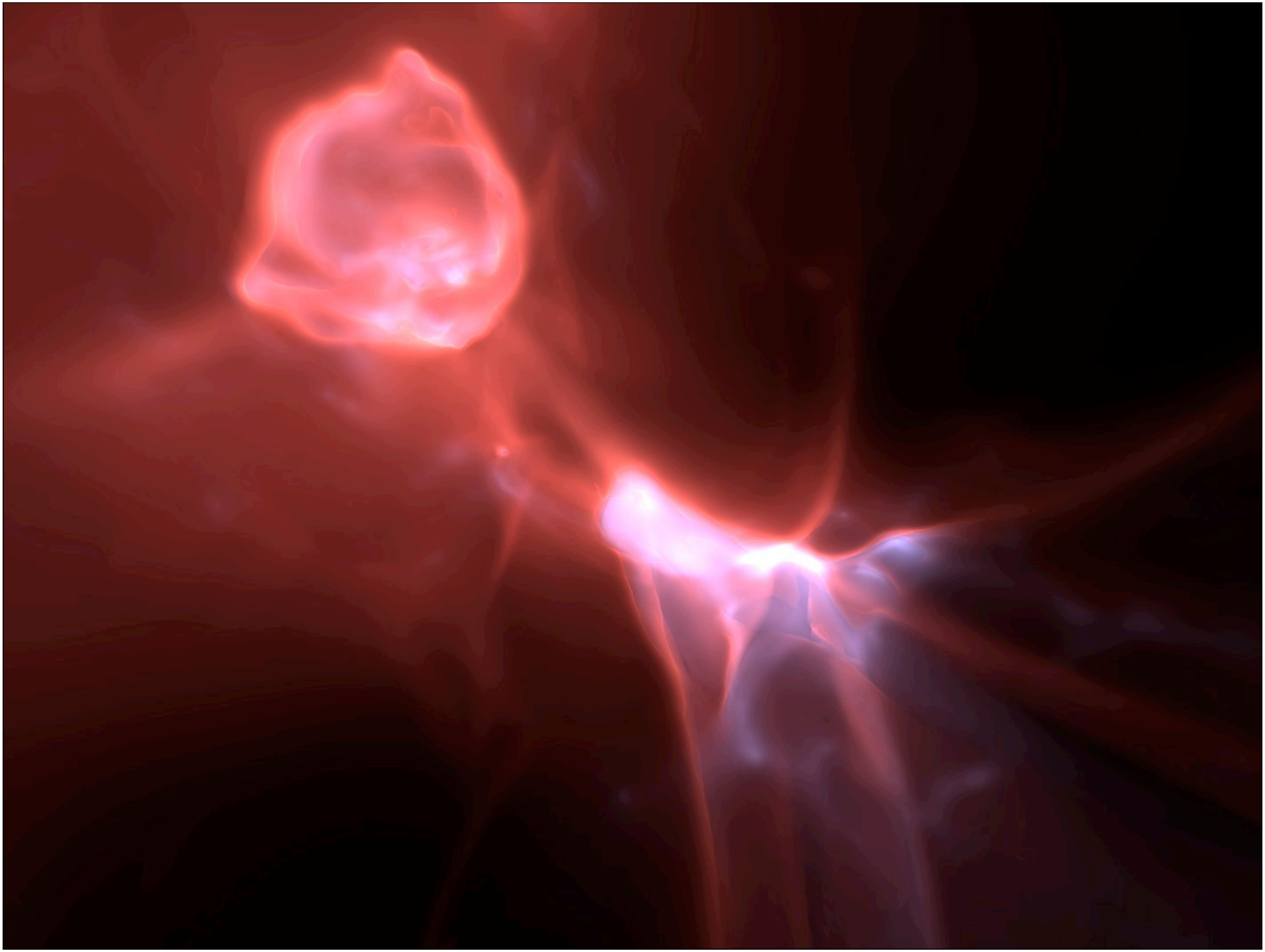
Clear consequences of very massive first stars:

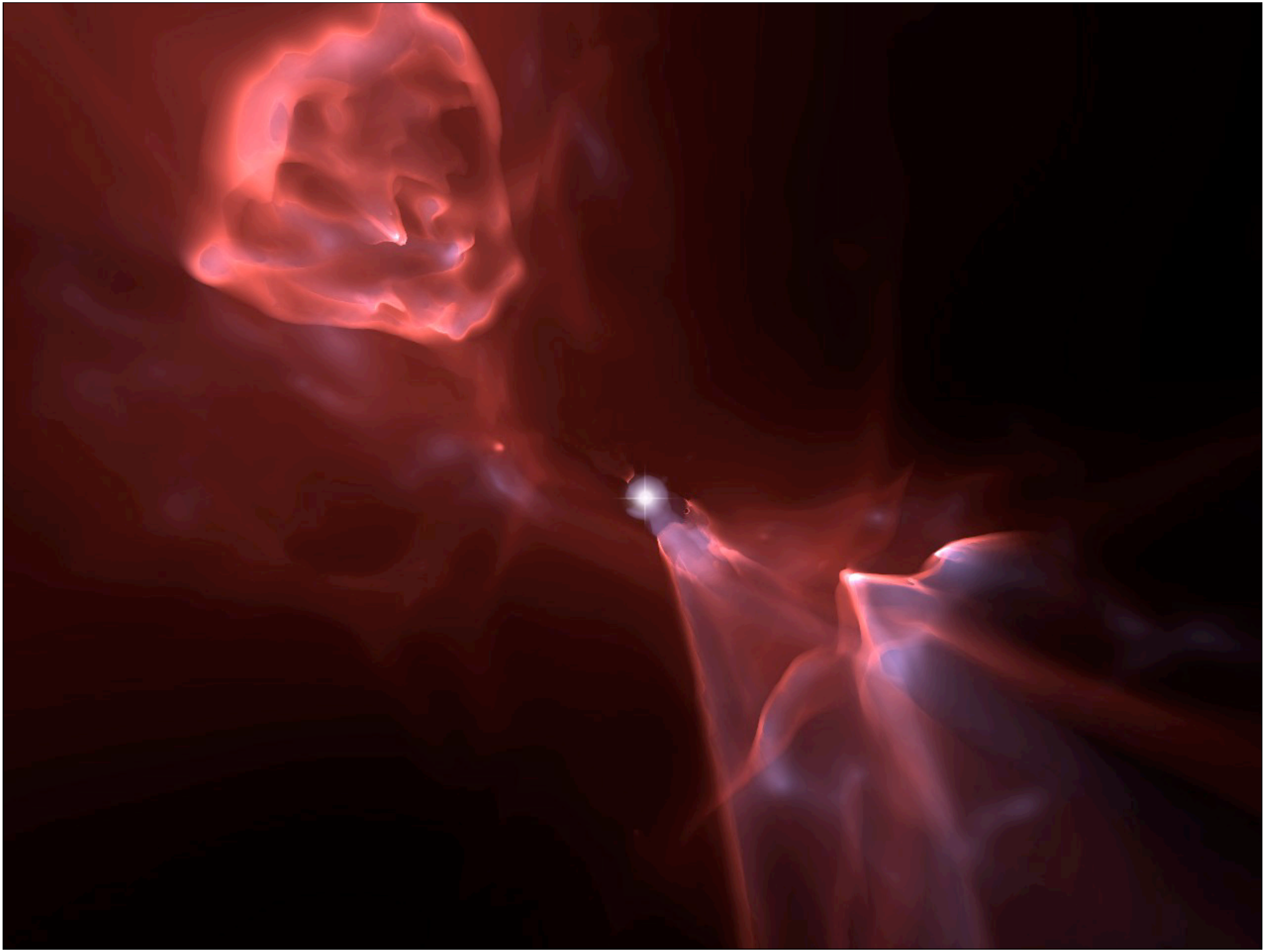
- Entire mass range are strong UV emitters
- Live fast, die young. (2.7 Myr)
- Fragile Environment
  - Globular Cluster mass halo but ~100 times as large, i.e.
    small v_{esc} ~ 2 km/s
  - Birth clouds are evaporated
- First exact radiation hydrodynamic calculations



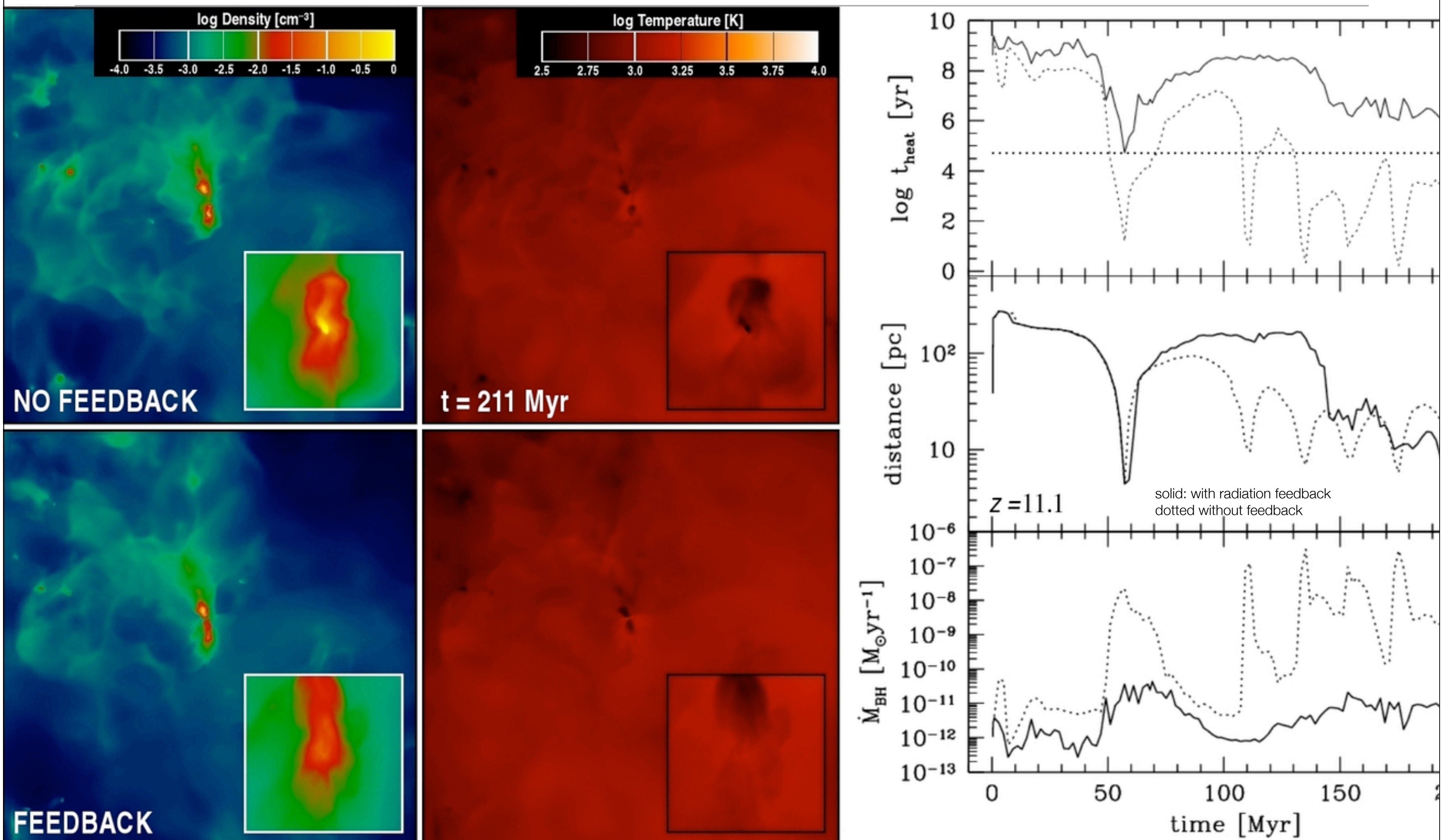
Wise & Abel 2007





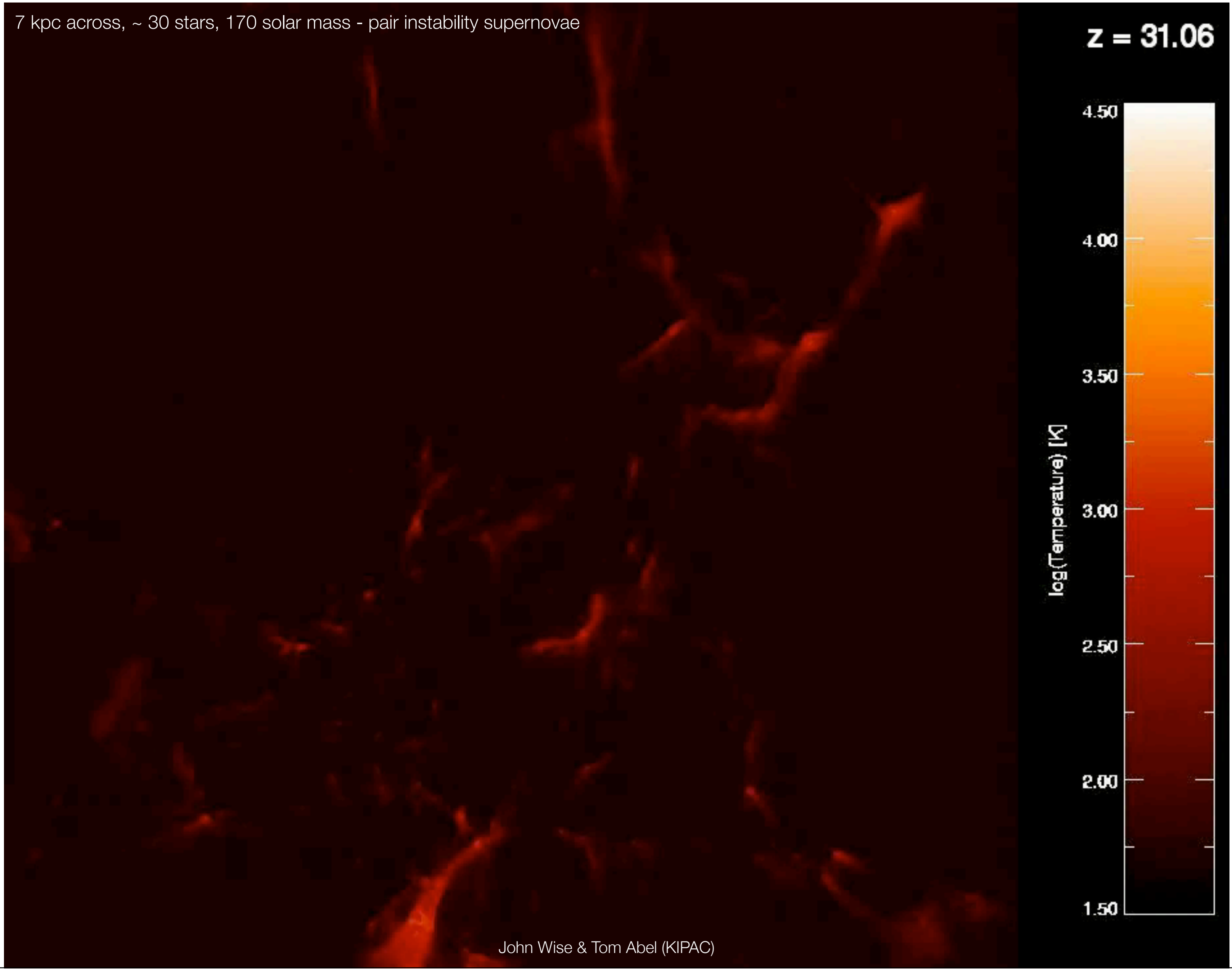


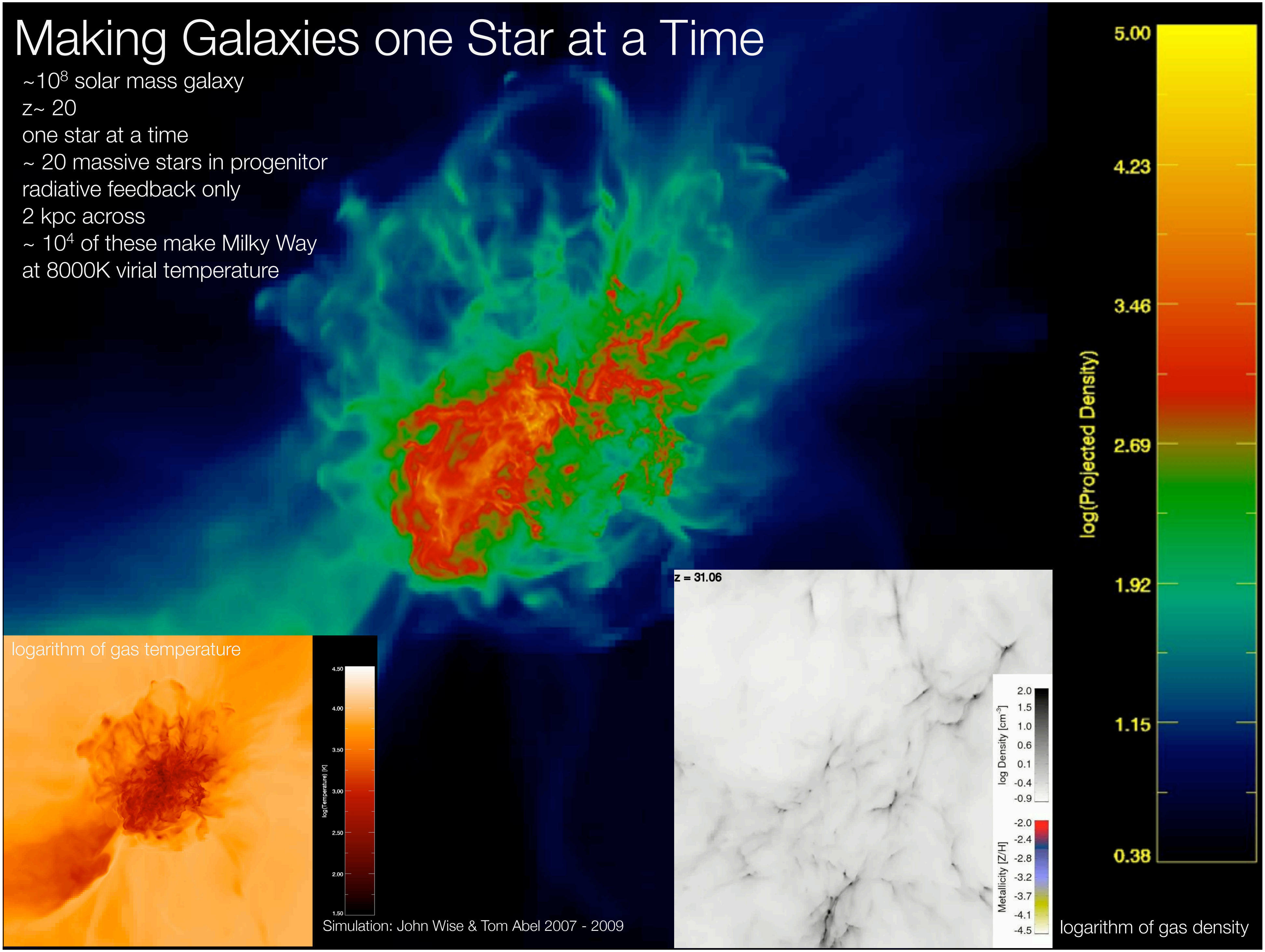
Insignificant BH accretion - no mini quasars through this process, nor pre-cursors of Quasars, large local feedback.



Alvarez, Wise & Abel astro-ph, couple of weeks ago

First galaxies, one star at a time

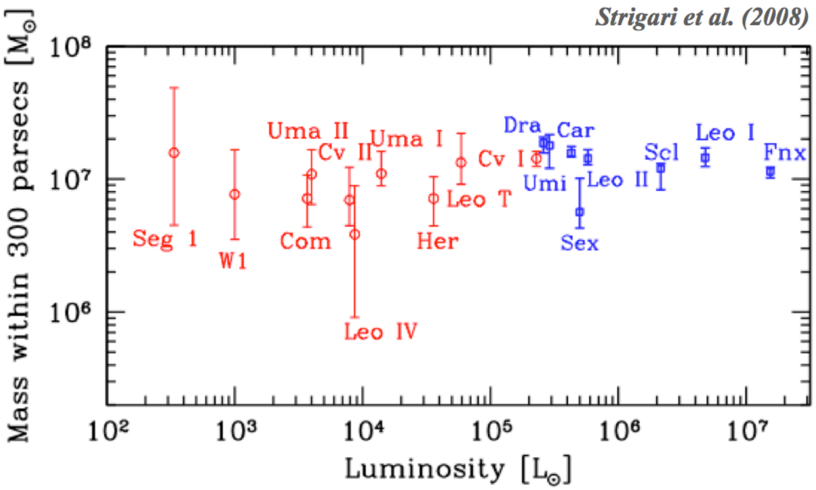


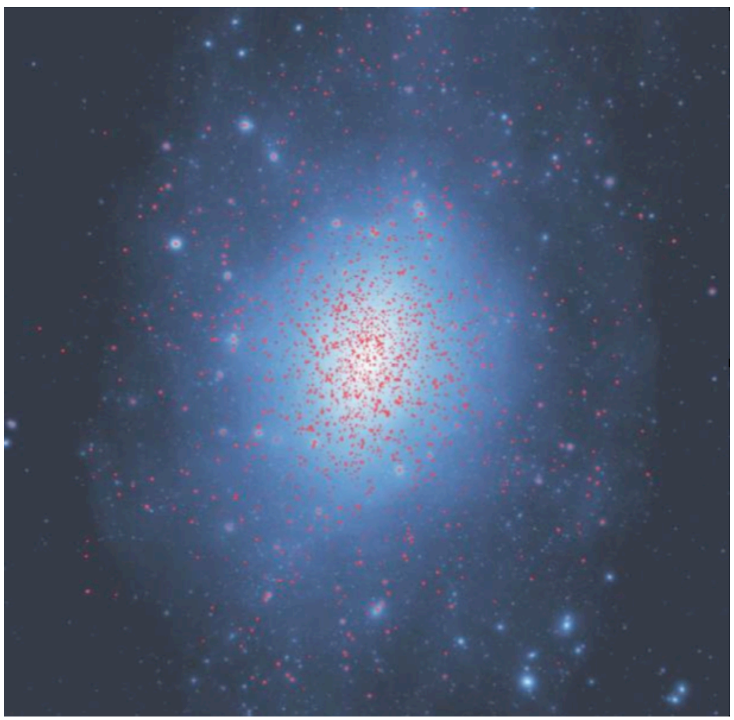


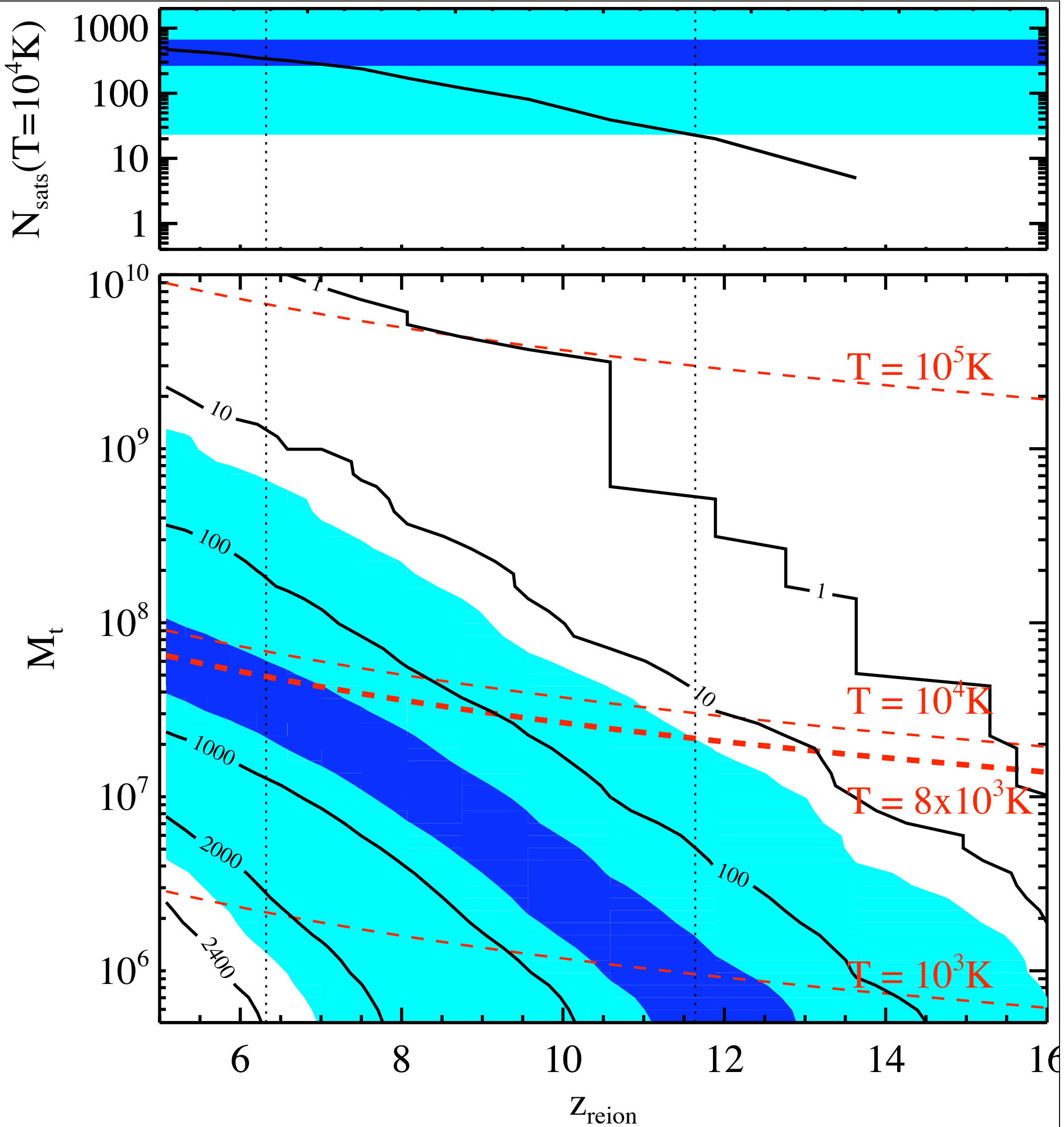
Making Galaxies one Star at a Time
~10^8 solar mass galaxy
z~ 20
one star at a time
~ 20 massive stars in progenitor
radiative feedback only
2 kpc across
~ 10^4 of these make Milky Way
at 8000K virial temperature
5.00
4.23
3.46
2.69
1.92
1.15
0.38
log(Projected Density)
logarithm of gas density
logarithm of gas temperature
4.50
4.00
3.50
3.00
2.50
2.00
1.50
log(Temperature) [K]
Simulation: John Wise & Tom Abel 2007 - 2009
z = 31.06
2.0
1.5
1.0
0.6
0.1
-0.4
-0.9
log Density [cm^-3]
-2.0
-2.4
-2.8
-3.2
-3.7
-4.1
-4.5
Metallicity [Z/H]

Fossil Record

using Via Lactea II



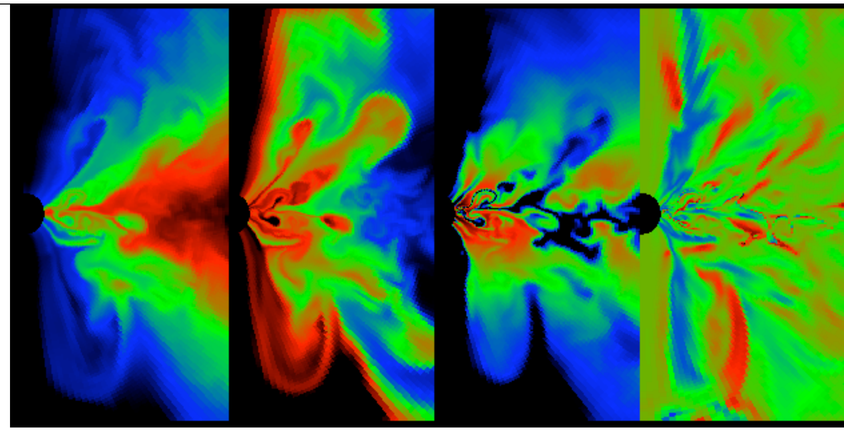


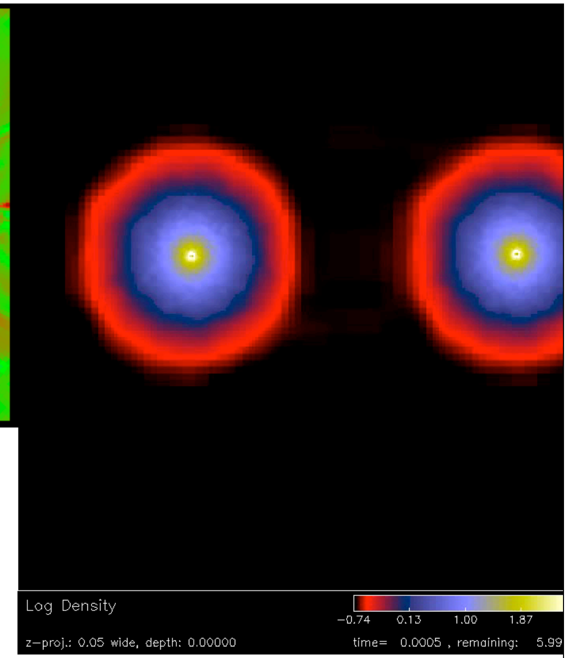


Michael T. Busha, Marcelo A. Alvarez, Risa H. Wechsler, Tom Abel, Louis E. Strigari ApJ

SMBH from direct gaseous collapse?

- Assume no molecules can be formed (very bad assumption ...)
- Only H, He cooling leads to the first cooling objects to be ~ 1e8 solar masses which have a central 1e5 solar mass cloud contract fast.
- See it as a numerical experiment to study the collapse of a turbulent cloud
- Interesting also as a model to start studying the role of turbulence in galaxy formation

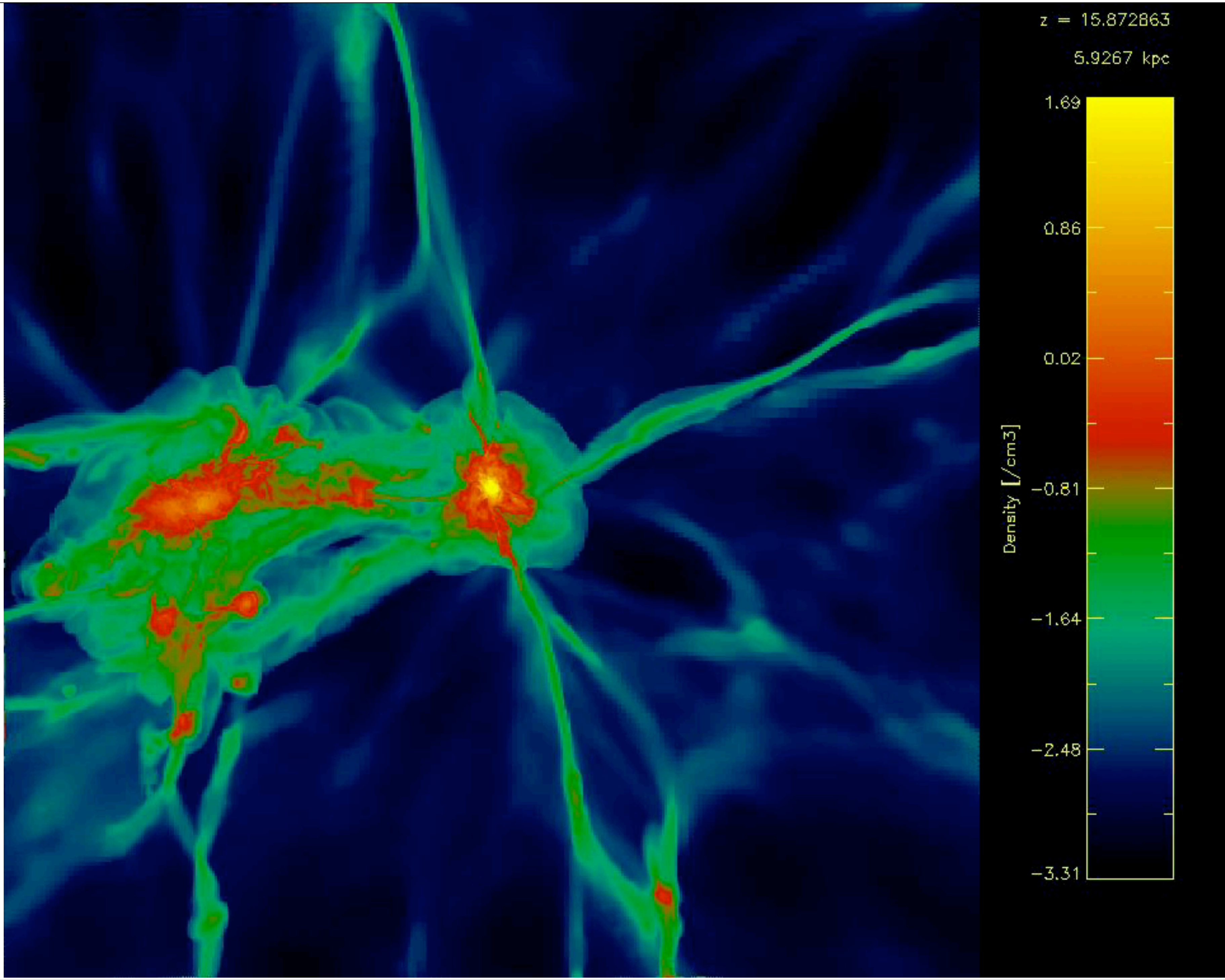




More puzzles: Ang. Momentum

- A 3.3 billion solar mass black hole as a Schwarzschild radius of
  10 billion km = 1e13 m
  gas must come from ~ 1 kpc scale
  ~ 3e19 m
  so needs to collapse by factor 1e6

- Angular momentum of one particle:
  j = radius * tangential velocity
- conservation: j = const. -> v = j/r
  velocity increases by factor 1e6
- Worse even for smaller black holes


z = 15.872863
5.9267 kpc
1.69
0.86
0.02
−0.81
−1.64
−2.48
−3.31
Density [/cm3]

Vorticity generation

- Gravitational Merging drives turbulence
- Relevant for
    - B-field amplification
    - Chemical Mixing
    - Fragmentation

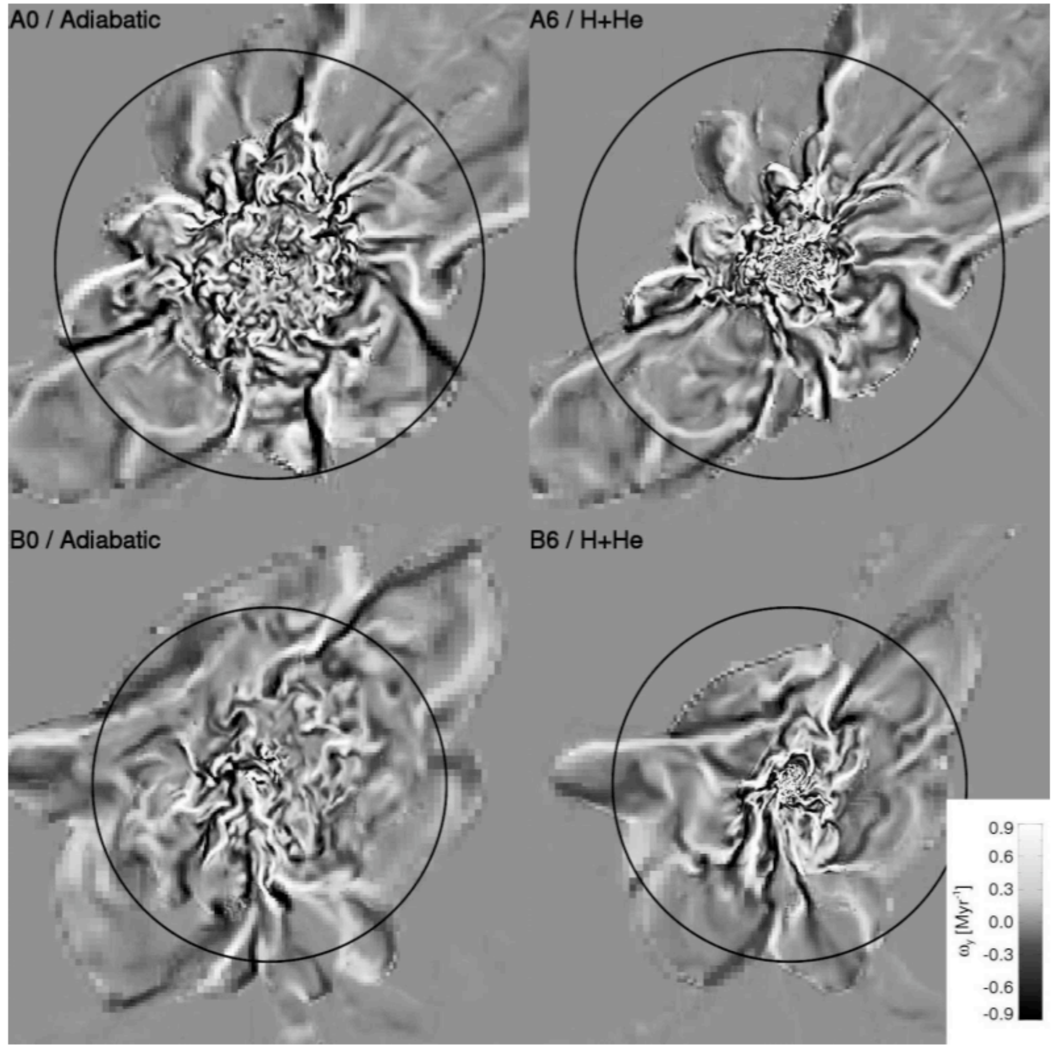
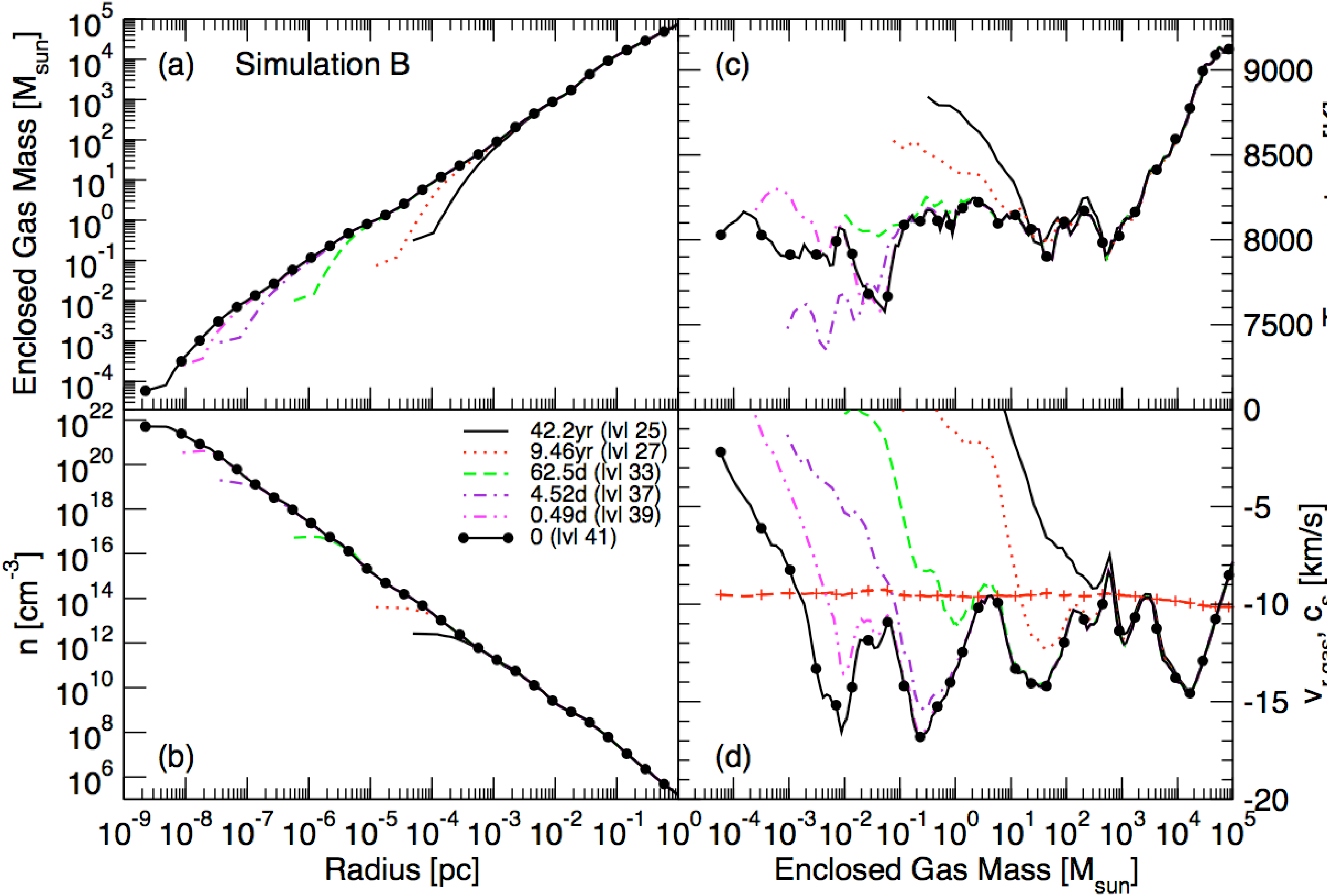


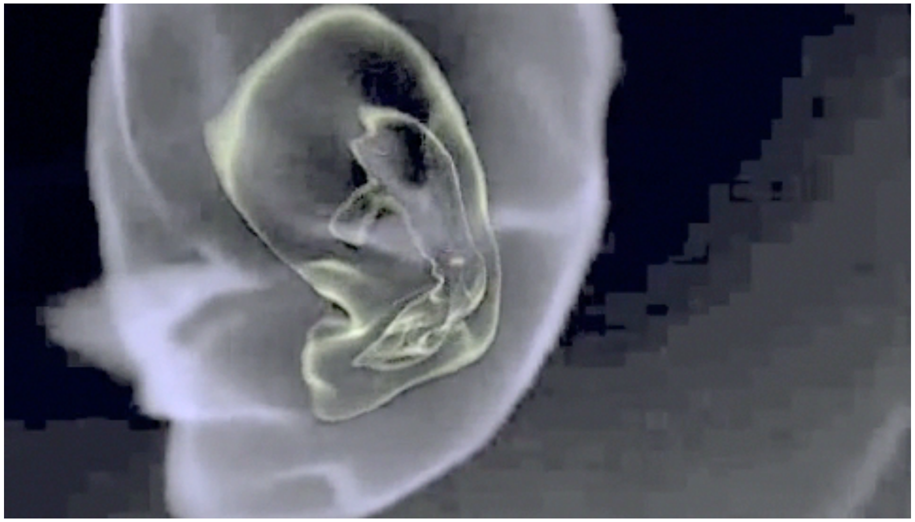
Fig. 3.6.— Two-dimensional slices of the component perpendicular to the slice of vorticity $(\nabla \times \mathbf{v})$ at $z = z_{c,\mathrm{Ly}\alpha}$ for Simulations A0, A6, B0, and B6. The fields of view are the same as in Figure 3.5. This quantity emphasizes the large- and small-scale turbulent eddies in the halo.

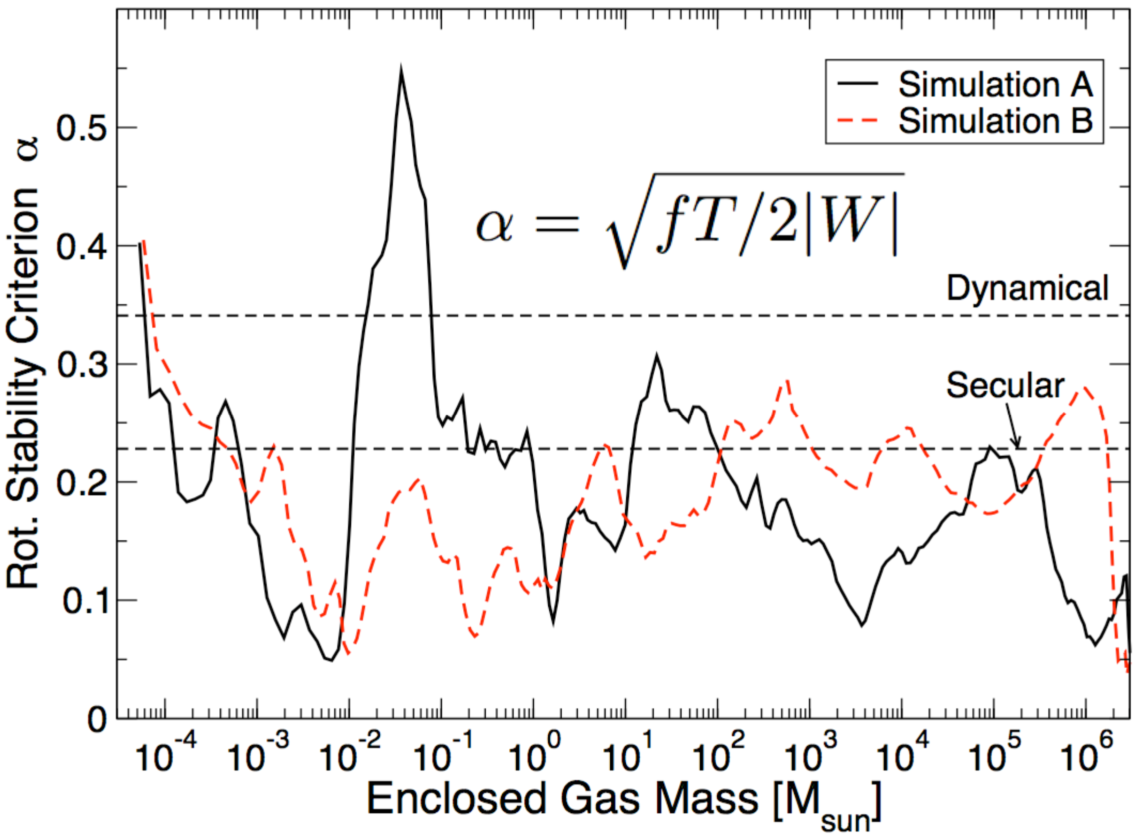


(a) Simulation B
(b)
(c)
(d)
Enclosed Gas Mass [M_sun]
n [cm^-3]
Radius [pc]
Temperature [K]
v_r,gas, c_s [km/s]
42.2yr (lvl 25)
9.46yr (lvl 27)
62.5d (lvl 33)
4.52d (lvl 37)
0.49d (lvl 39)
0 (lvl 41)

Instabilities

- Bars within bars, disks within disks, bars within disks ...
- Angular momentum transfer efficient when all we have is gravity, hydrodynamics and cooling while we continue to drive turbulence
- Collapse small fraction of total material can be very fast because of large reservoir to give angular momentum to.

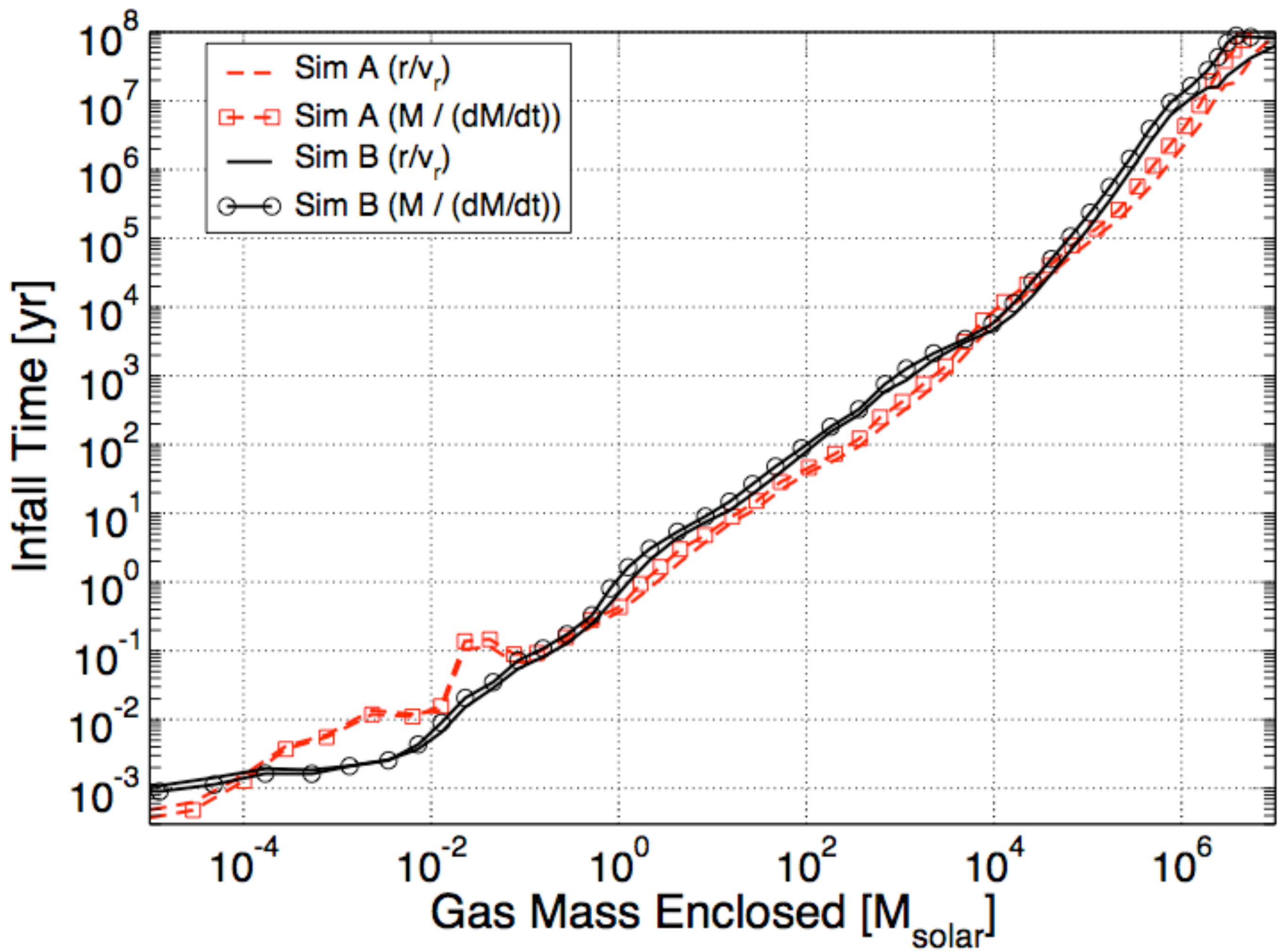




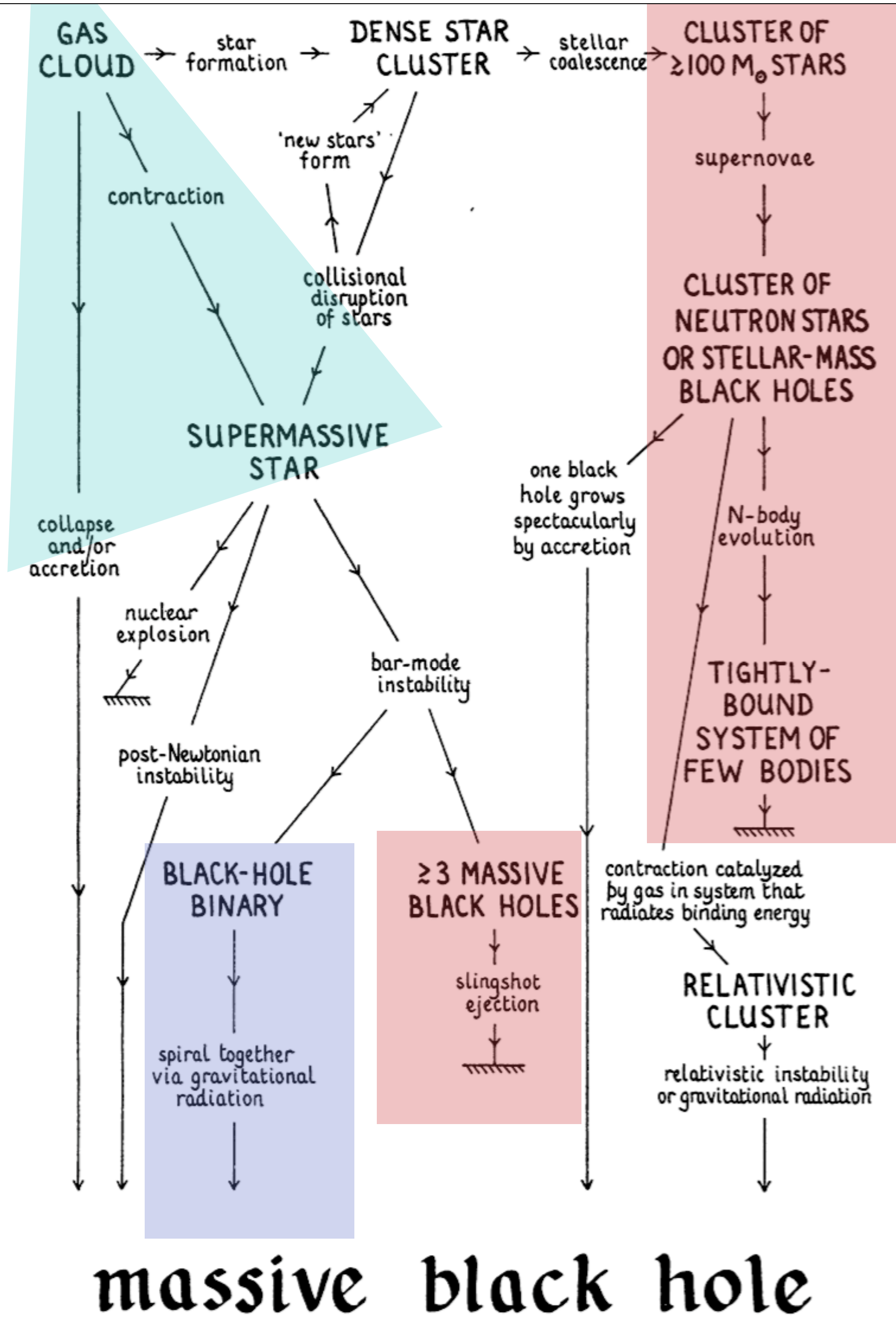
Wise, Turk & Abel ApJ 2007

e.g. Chandrasekhar 1964 Ellipsoidal Figures of Equilibrium

High Dynamic Range in Time



Accessible to direct simulations in hydrodynamic and MHD limits
Dynamic range > 1e10

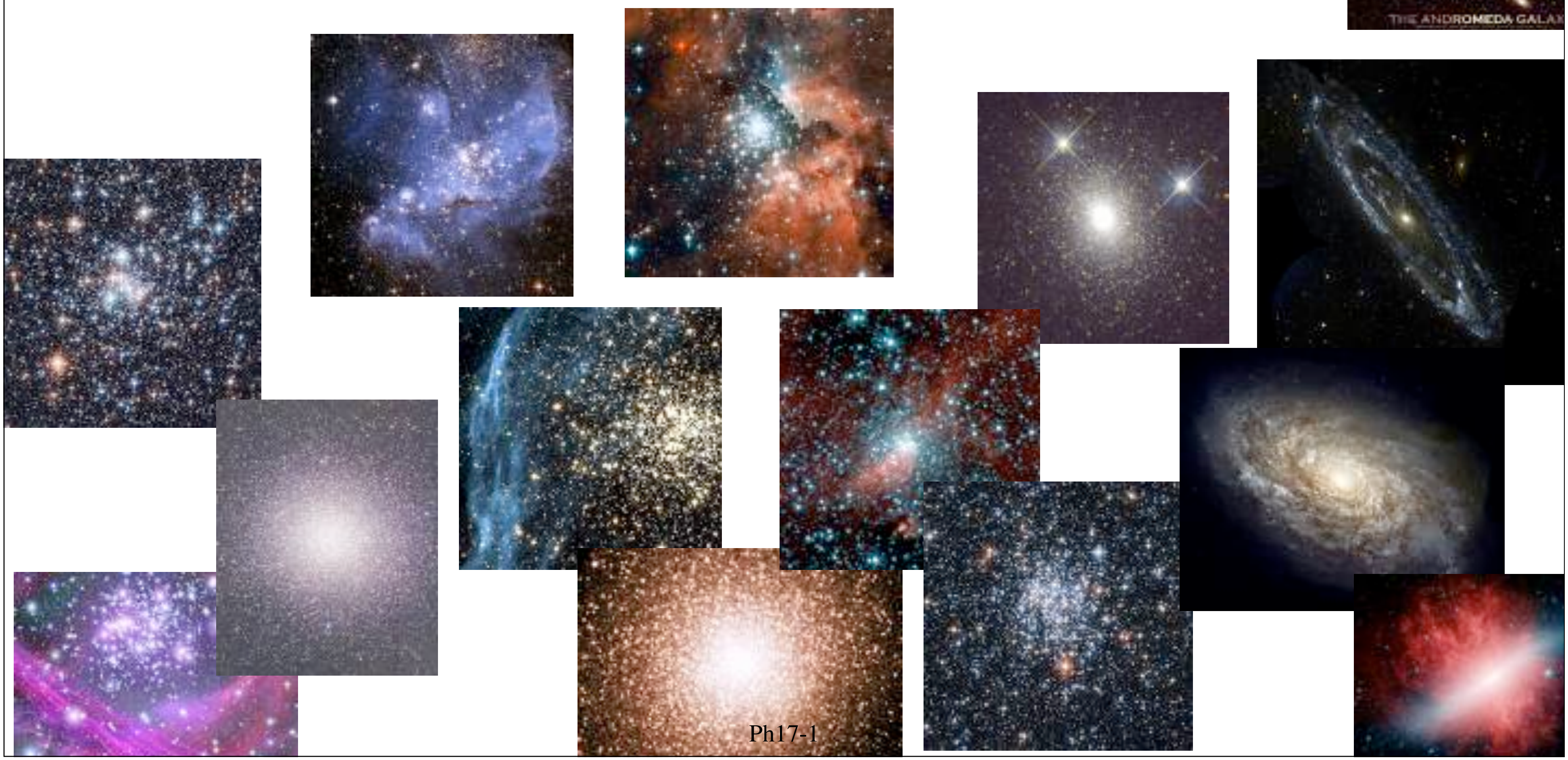


Accessible to direct simulations in N-body limit
> 1e6 particles

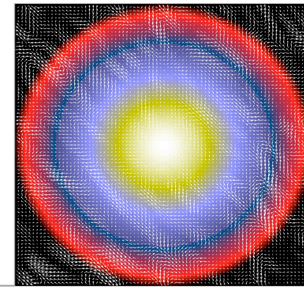
Numerical Relativity

Martin Rees 1980

- Why does the gas not make stars but instead is available to grow black holes



A Model, clump fed outflow regulated



- Dense clump molecular cloud: cored isothermal sphere

$$\rho(r) = \frac{\rho_c}{1 + (r/r_c)^2},$$

$$\rho_c = 1.0\times10^{-19}$$

- L = 2 pc; r_c = L/6;
- Cloud mass within a radius of 1 pc: M = 1215 M_o
- Isothermal sound speed: 0.265 km/s
- We model proto-stellar growth by Bondi-Hoyle accretion.
- Top grid resolution 128^3. Four level of AMR level using Jeans refinement criterion (Jeans number 4), corresponding to 200 AU best resolution.

Final Sink Particle Mass Function (FSPMF - IMF?)

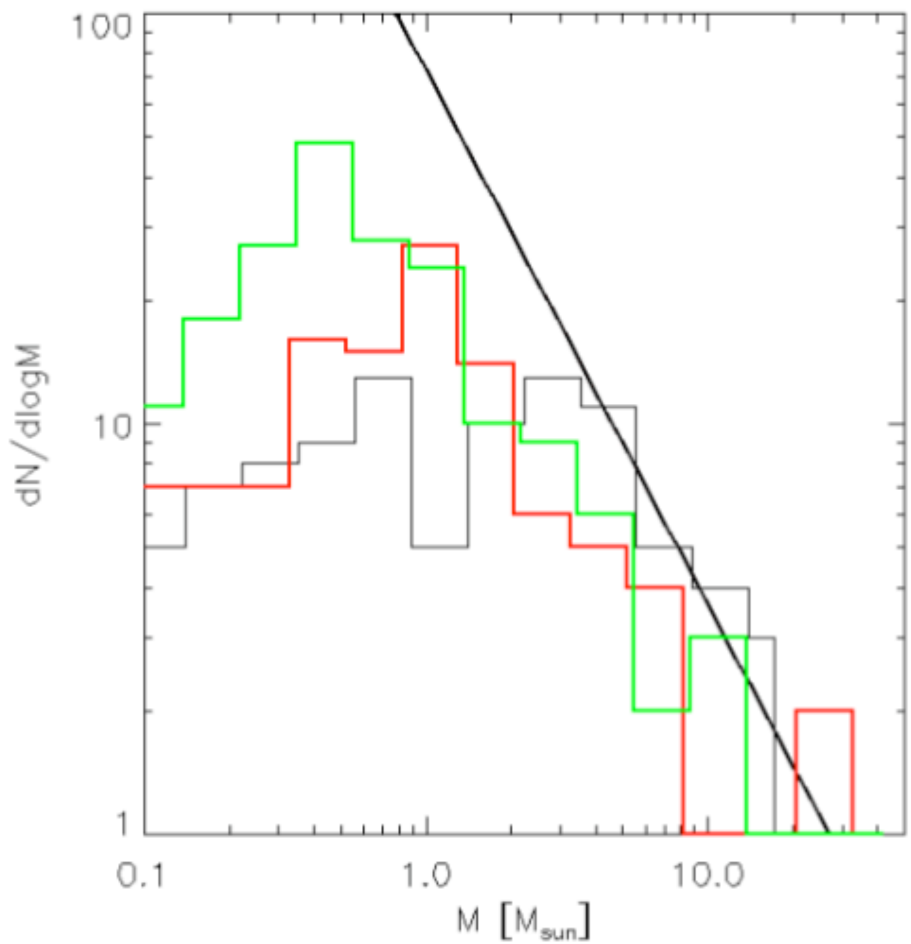
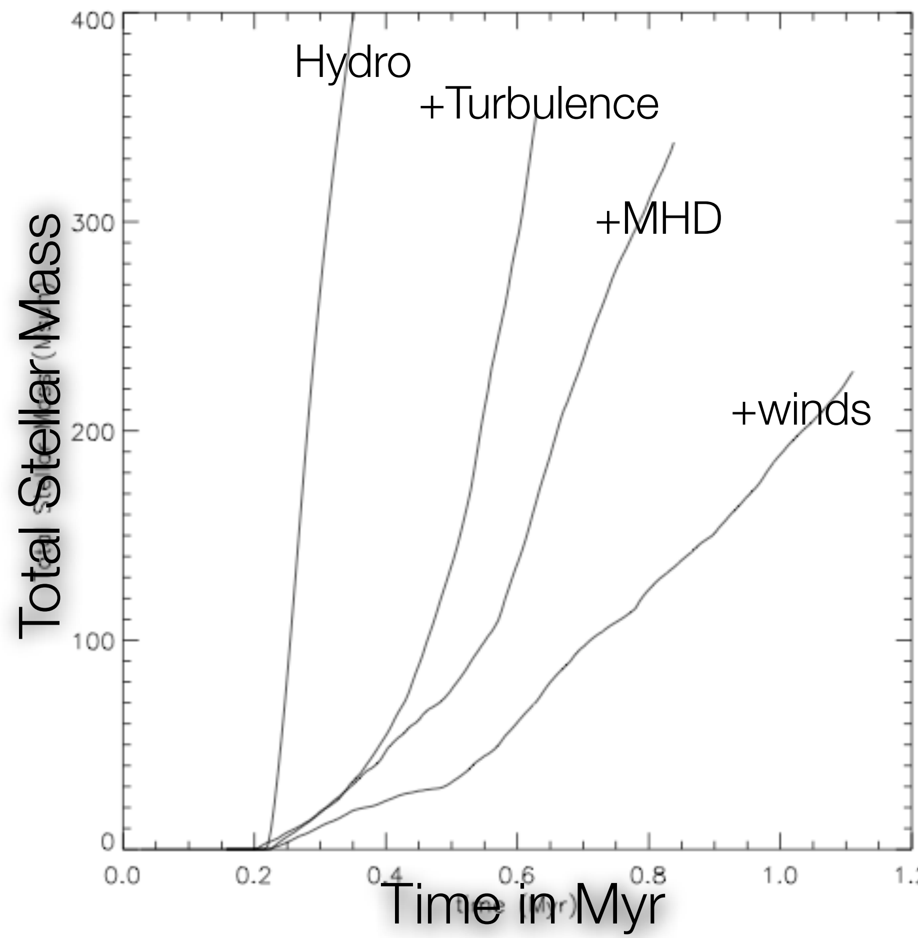


Fig. 2.12.— The sink particle IMF for HD (black), MHD (red) and WIND (green) when they have the same SFE $\sim 16\%$. The thick black line gives the Salpeter IMF slope of -2.35.

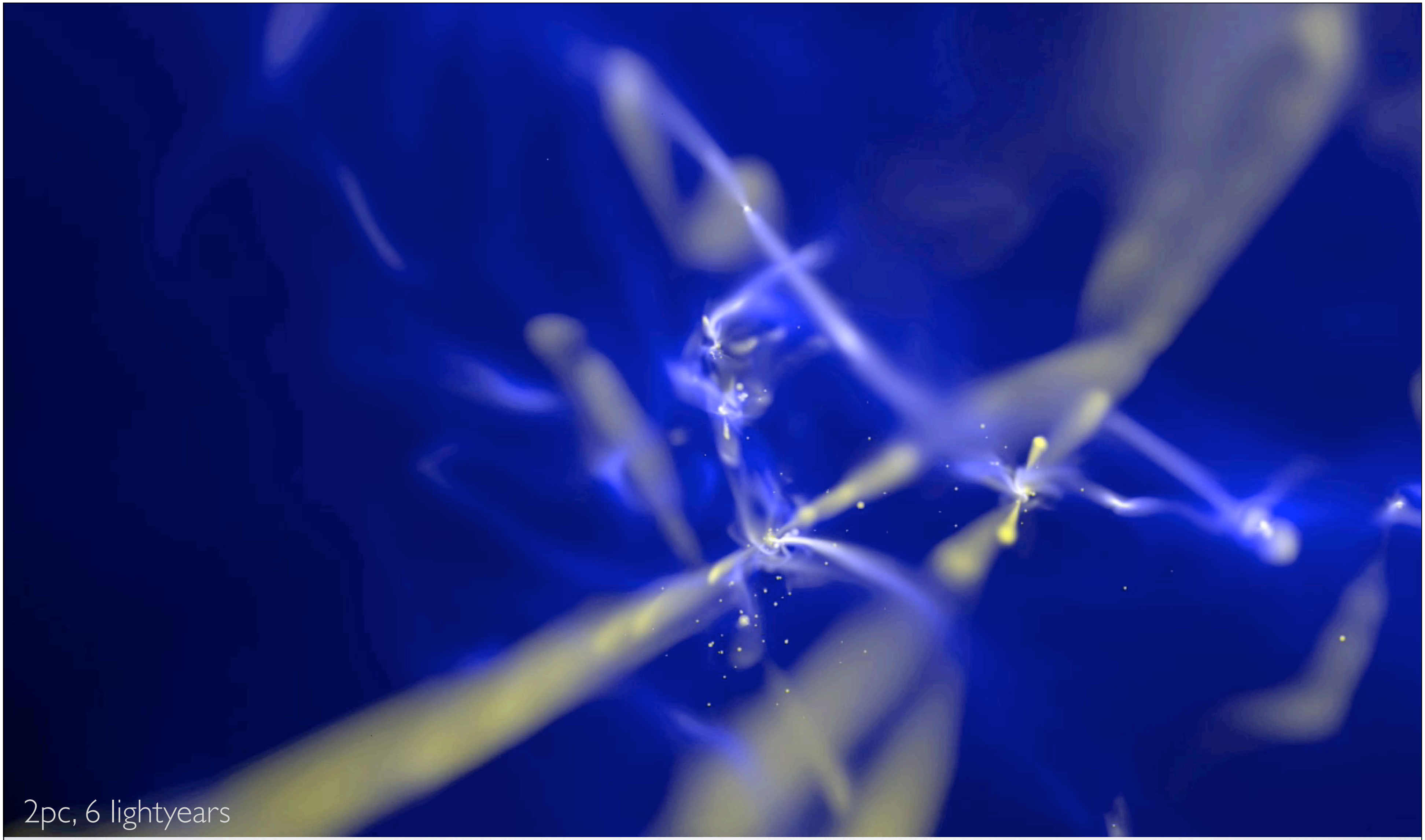
Relevant physics in star formation

- Stellar Winds clearly relevant
- Hydro/MHD models form stars much to quickly
- Winds keep turbulence allow cloud to form stars for many dynamical times
- First Model with sustained star formation over many dynamical times without large scale driving

- Our models still are missing
  - ambipolar diffusion
  - IR radiation



Wang, Li, Abel, Nakamura 2009 in prep.



Formation of a Star Cluster in the Milky Way

Sim: Wang, Li, Abel, Nakamura 2009 repeated.

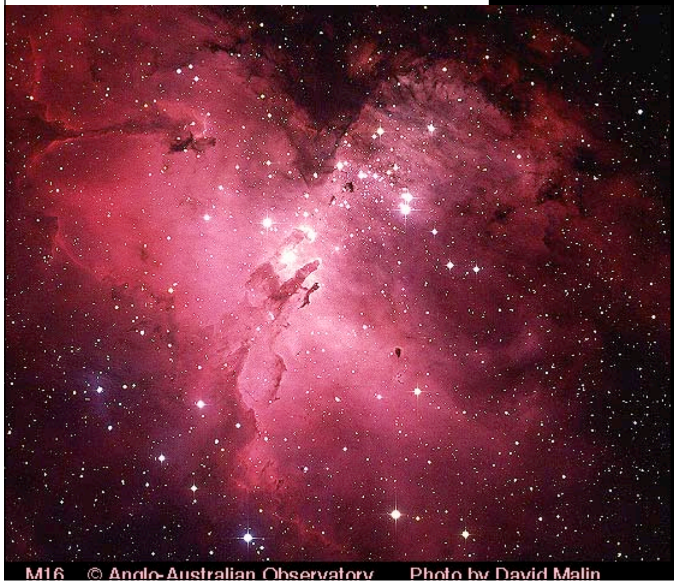
Viz: Kähler, Wang & Abel 2009

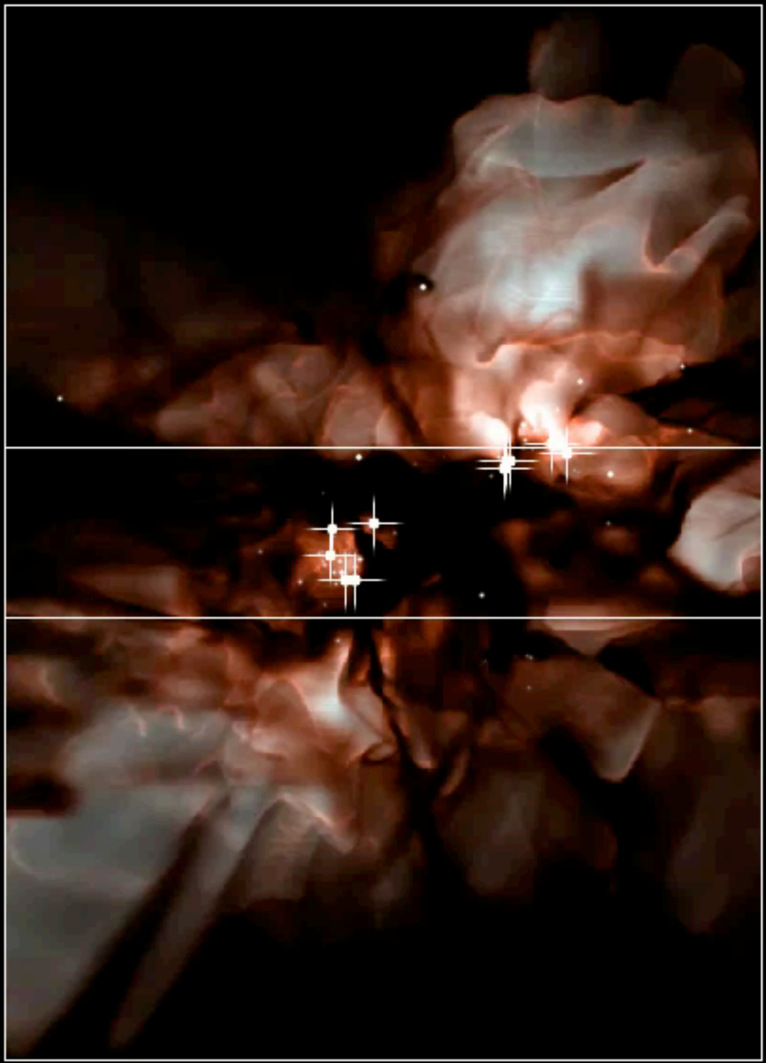
Log of column density: blue-white

yellow: kinetic energy - jets from young stars

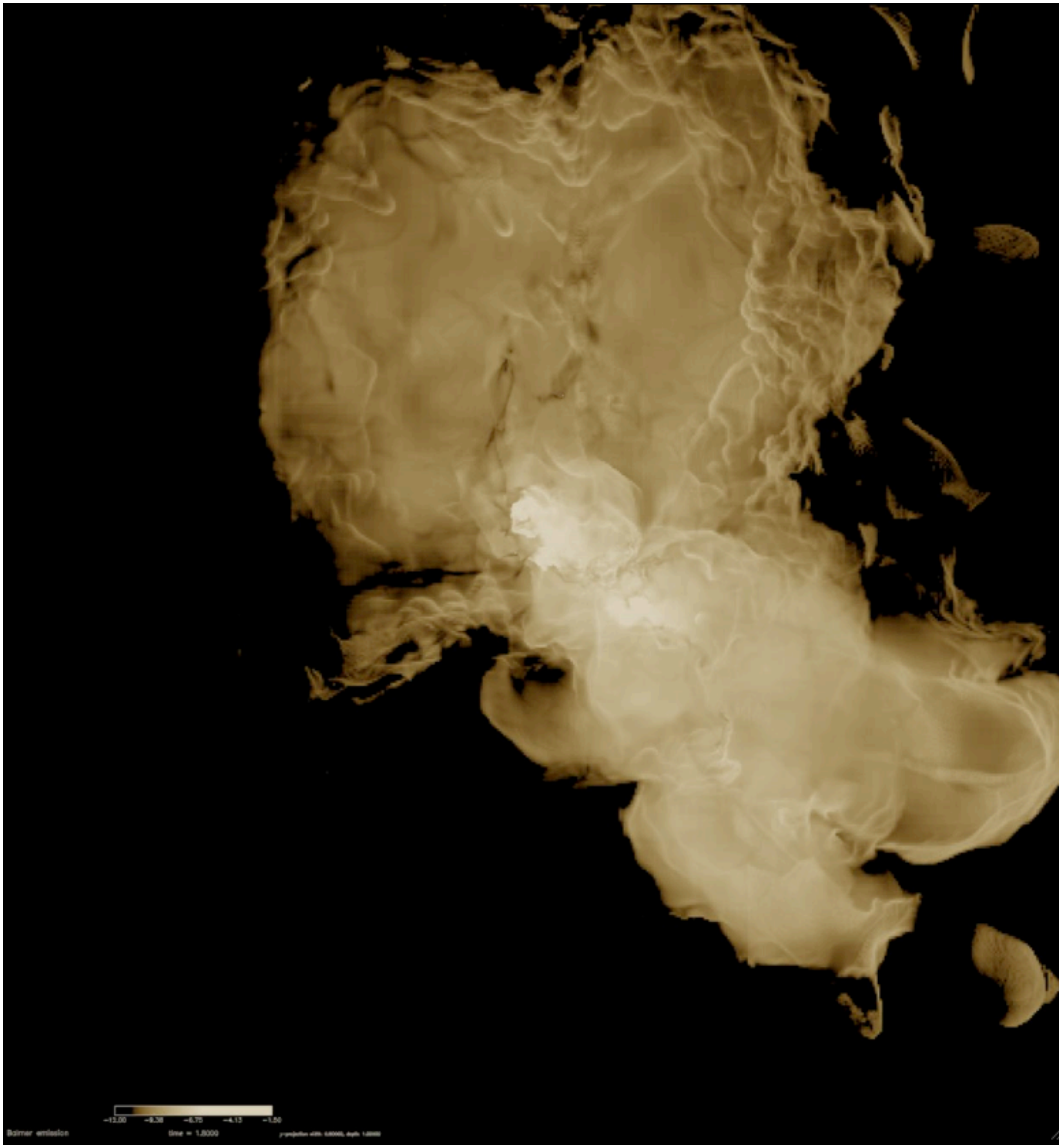
Using local HII regions as Laboratory for Star Formation?

- Massive Stars light up initial conditions
- Radio, IFU spectroscopy etc. give 3D data cube
- Model Radio - Xrays
- Turb., Gravity, MHD, Winds, HII regions, IMF including brown dwarfs

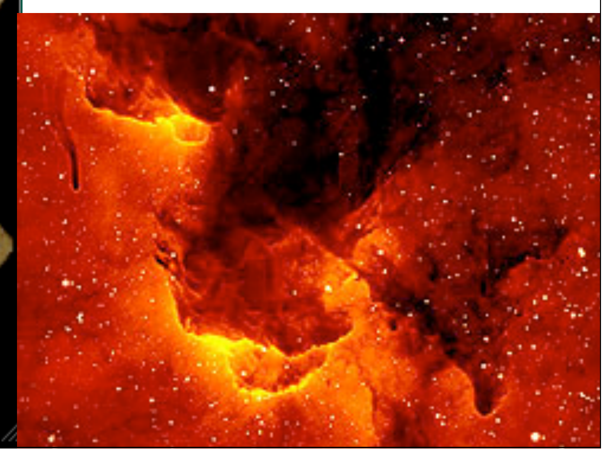




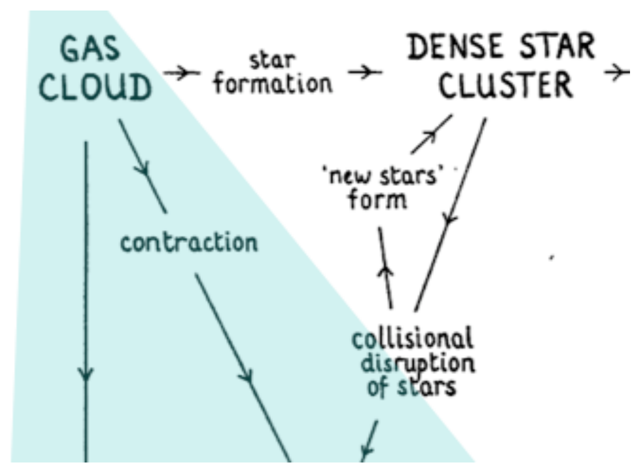
Vis: Iannucci, Wang & Abel in progress
Sim: Wang & Abel



Balmer emission.



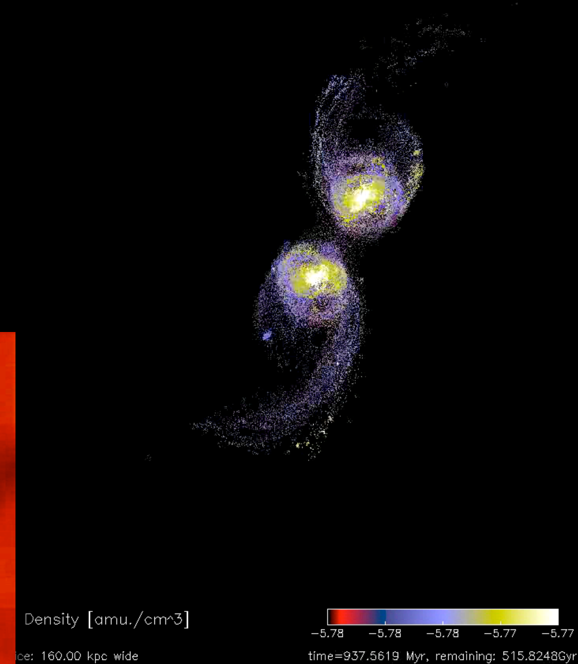
Yes, but what are the Initial Conditions?

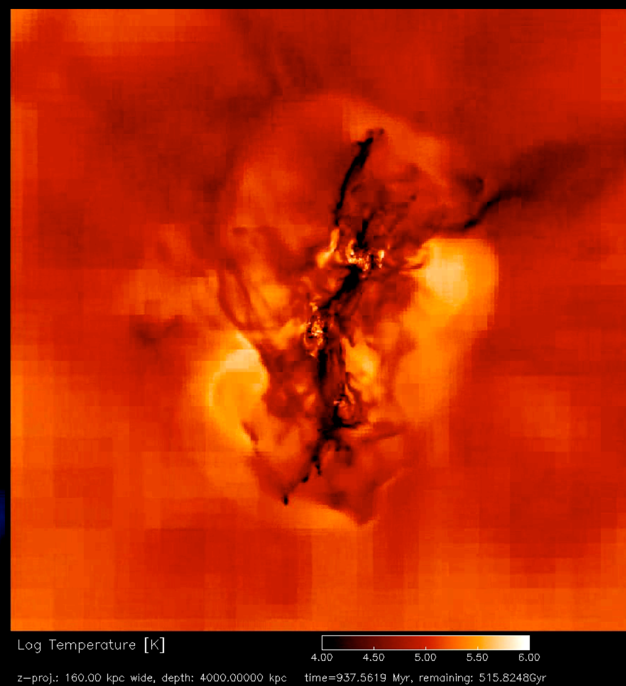


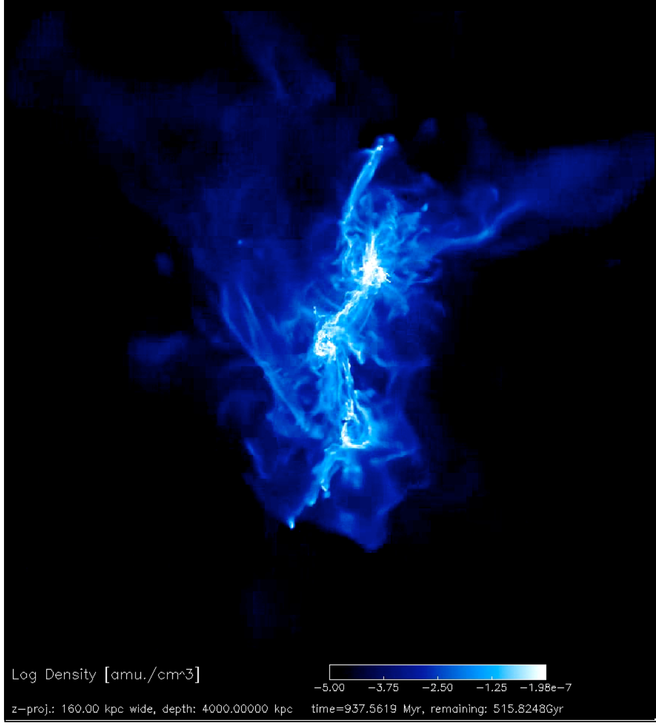
Galaxy Mergers with Adaptive Mesh Refinement

Sim: Ji-hoon Kim, John Wise, Tom Abel 2009, ApJL

Viz: Kim & Abel 2009



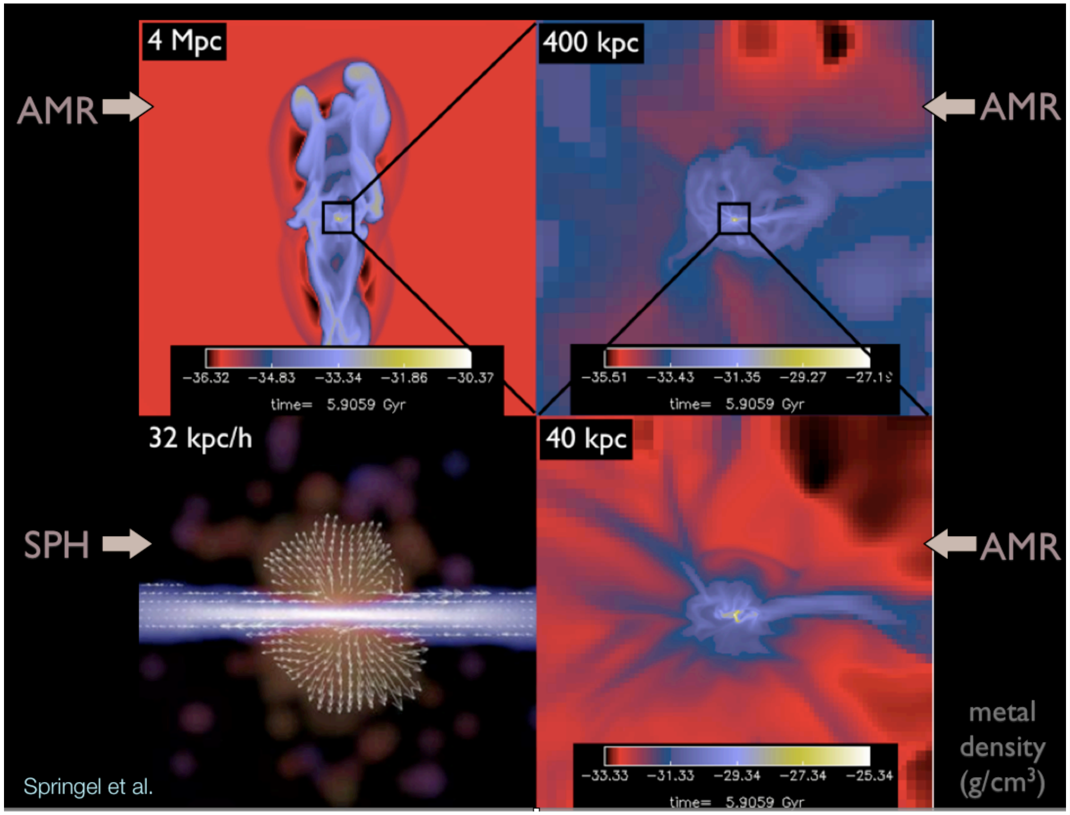




2 galaxies: 2e11 solar mass each
Evolving over 2 Gyrs
Follow star formation, supernova feedback @ 2pc resolution
100 times # of resolution elements than previous studies

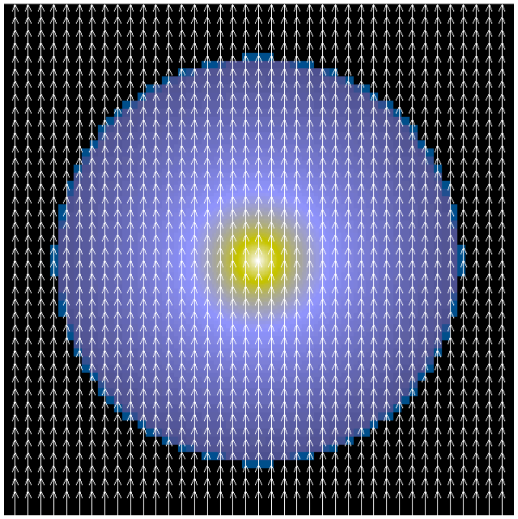
Galaxy Merger simulations

- mass resolution of 1000 solar mass, ~ pc spatial resolution in 4 Mpc box
- Future directions
  - Study Molecular Cloud Formation and detailed modeling of star formation on the 100 AU scale rather than the pc scale
  - Better dust modeling
  - further improvements to star formation and feedback prescription
  - MHD
  - Radiative AGN feedback

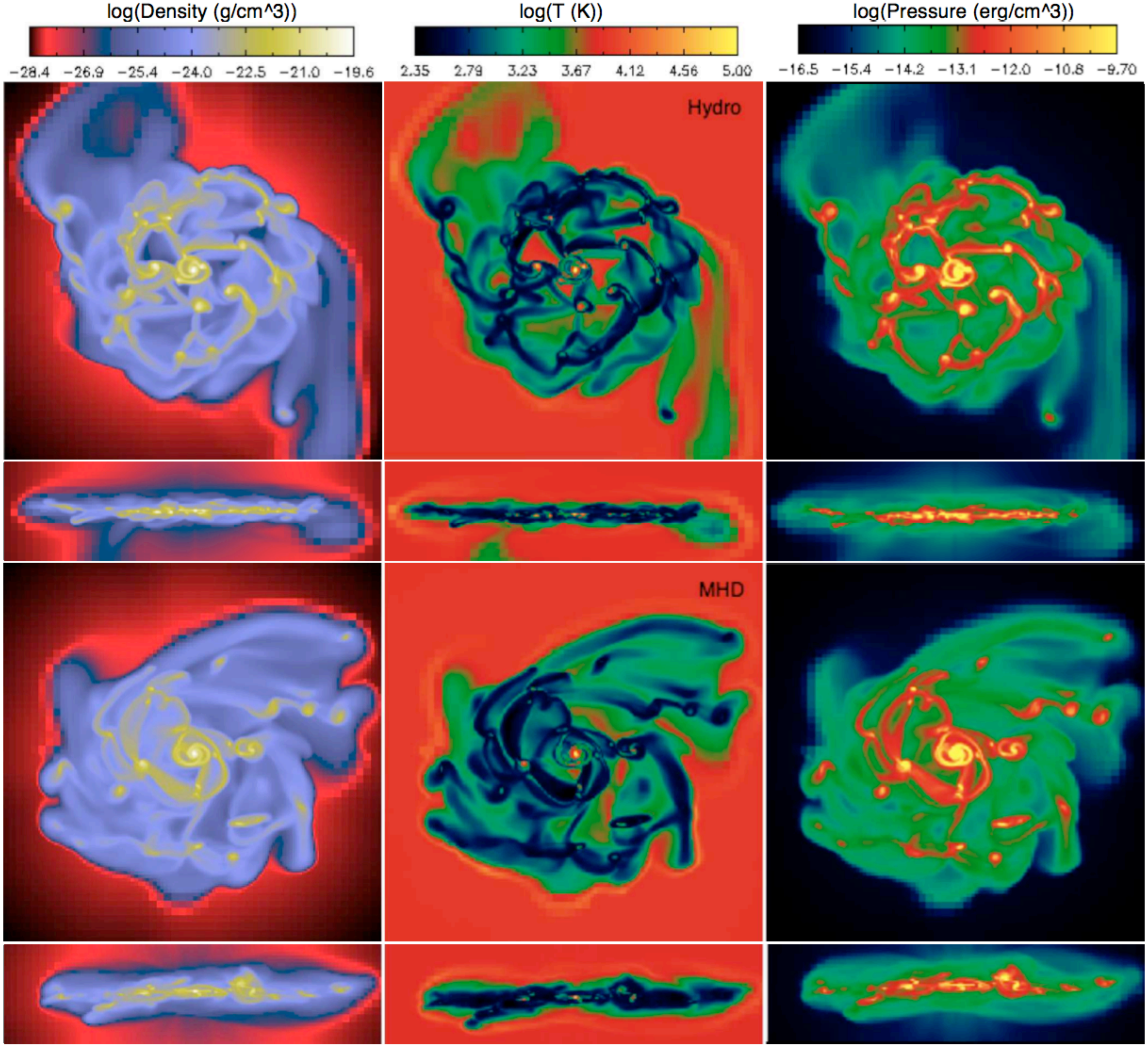


Galactic magnetic field amplification

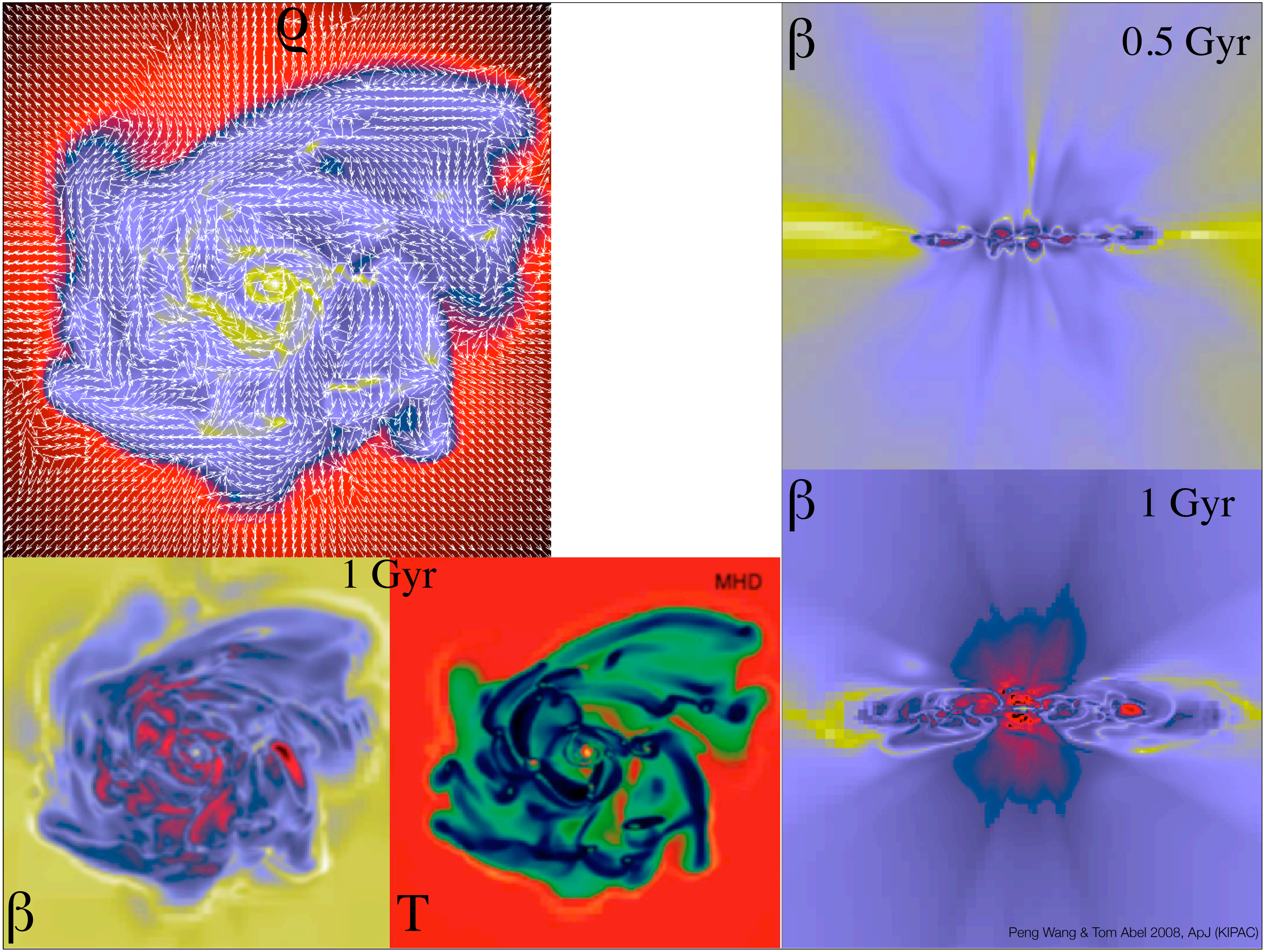
I) The simplest conceivable numerical experiments.



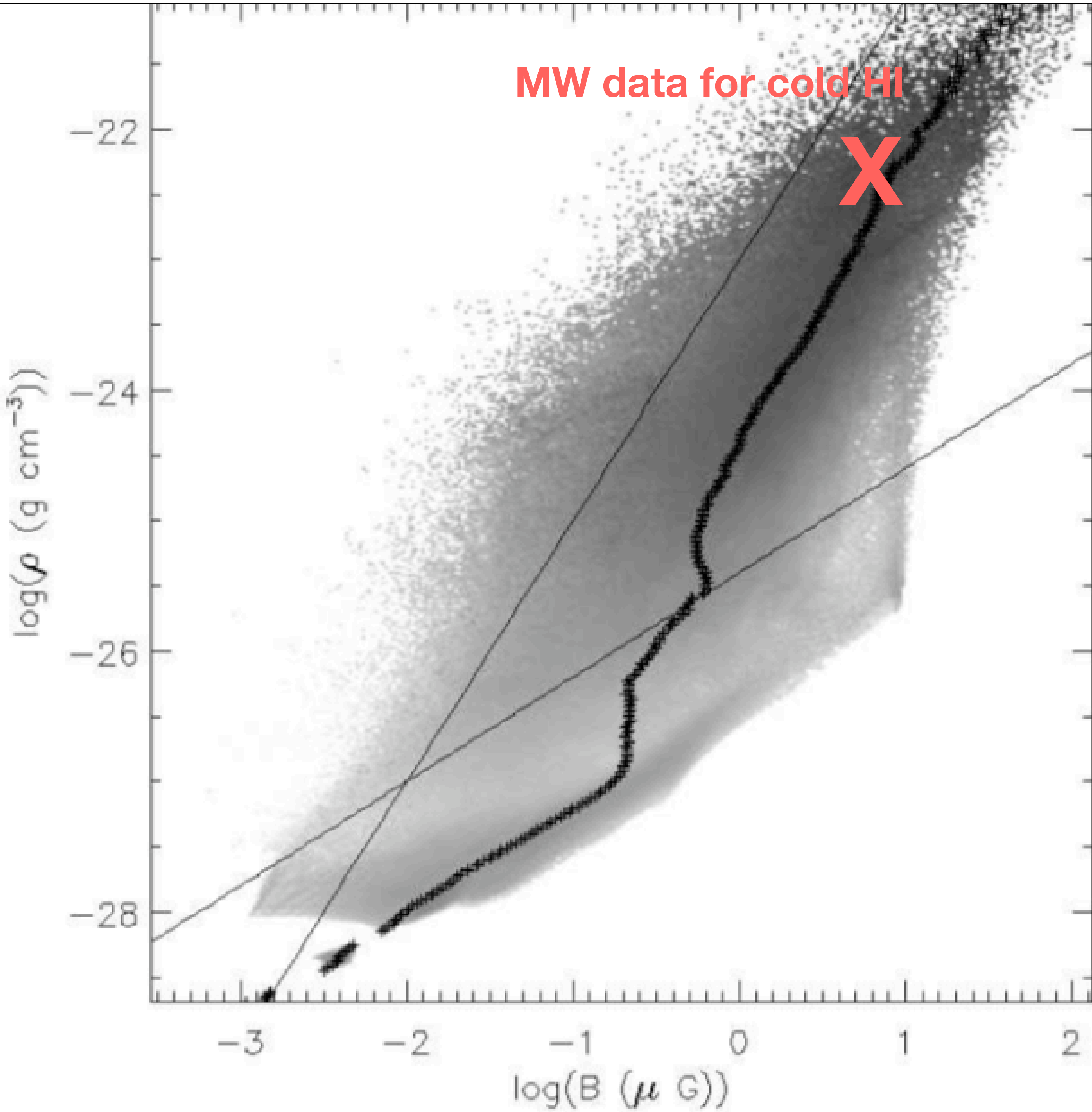
- First MHD global model of a disk
- Isolated NFW halo 1e10 Msun at z=2 with concentration=10, modeled as external potential
- Spherical gas distribution with NFW profile and baryon fraction 0.1
- Rotation speed corresponds to spin parameter 0.05.
- Gaussian random velocity field with amplitude the halo virial velocity
- Uniform 1e-9G B field in z direction motivated by:
  * 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 particles



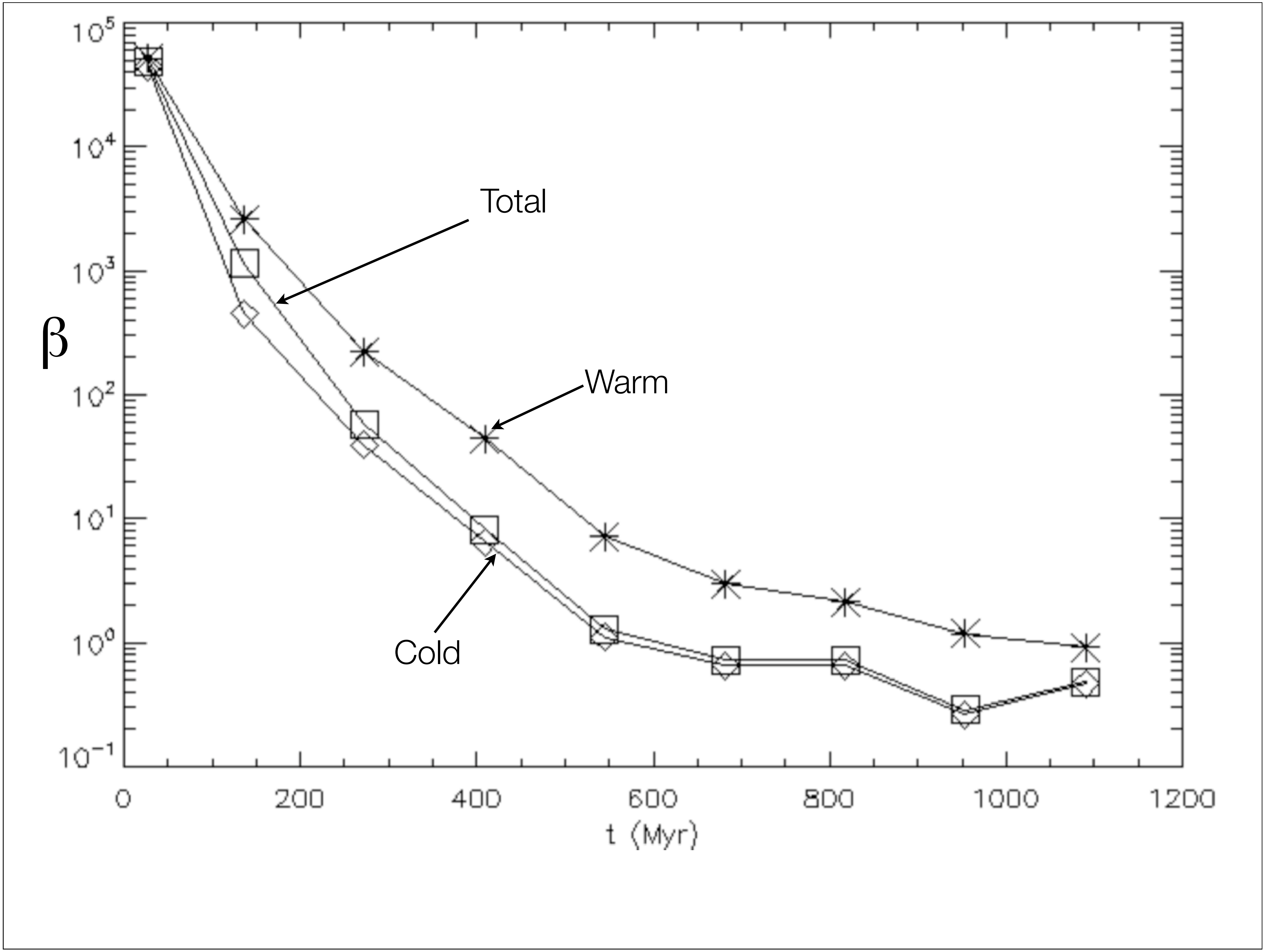
log(Density (g/cm^3))
−28.4 −26.9 −25.4 −24.0 −22.5 −21.0 −19.6
log(T (K))
2.35 2.79 3.23 3.67 4.12 4.56 5.00
log(Pressure (erg/cm^3))
−16.5 −15.4 −14.2 −13.1 −12.0 −10.8 −9.70
Hydro
MHD



ϱ
β
0.5 Gyr
β
1 Gyr
1 Gyr
MHD
β
T
Peng Wang & Tom Abel 2008, ApJ (KIPAC)

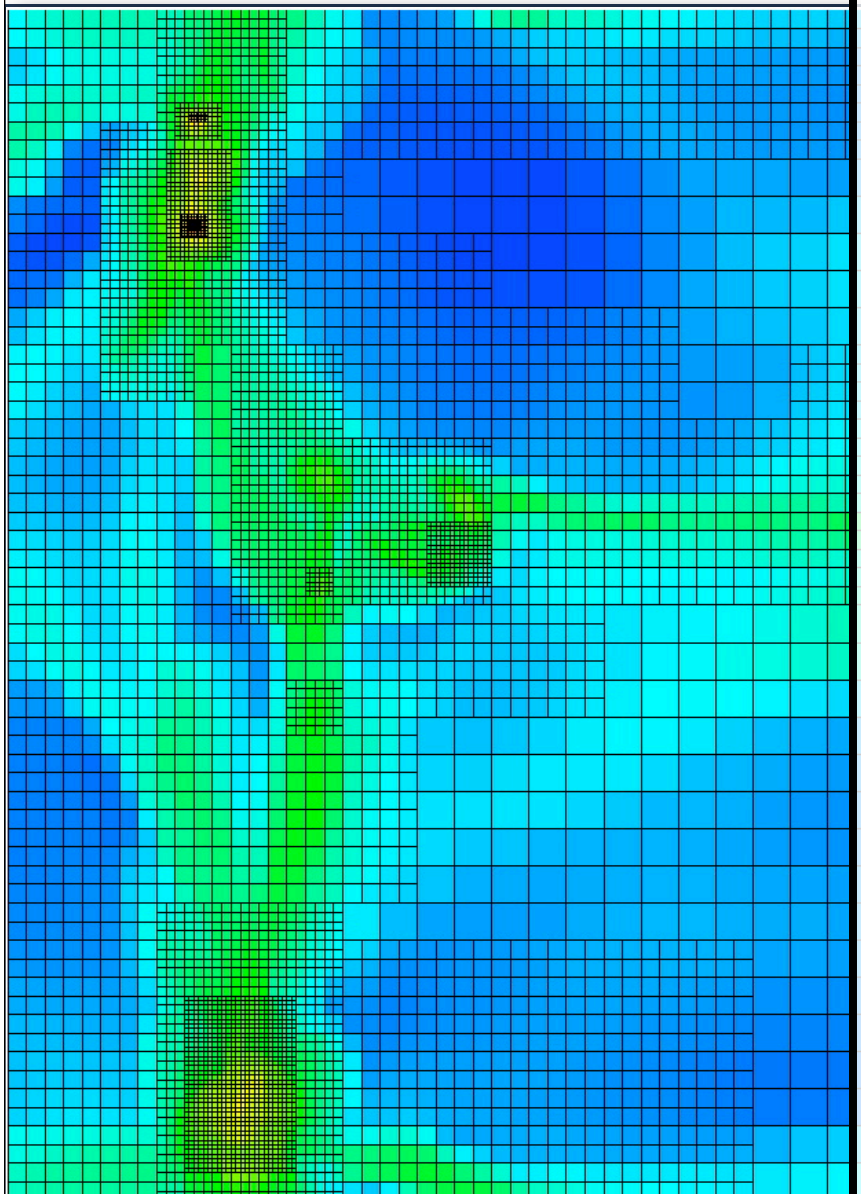


Peng Wang & Tom Abel 2008, ApJ (KIPAC)



β
Total
Warm
Cold
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
0
200
400
600
800
1000
1200
t (Myr)

Enzo



Versatile AMR Code — Bryan & Norman (1997, 1999)

Physics:

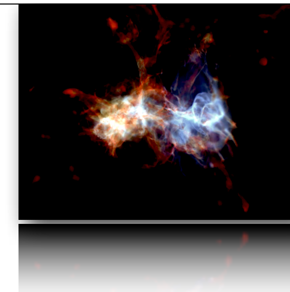
- Gravity (Gas, Dark Matter, Cosmology)
- Hydrodynamics (ZEUS/PPM)
- Non-equilibrium chemistry — Abel et al. (1997)
- Radiation transport — Abel & Wandelt (2002), Wise & Abel 2007-
- MHD — Wang & Abel (2008)
- Relativistic Hydro — Wang, Abel & Zhang (2008)
- Shearing Box boundaries — Zhao & Abel (2009)
- MUSCL hydro solvers — Wang & Abel (2008)
- MPI/CUDA/OpenCL MHD — Wang & Abel (2009)

Refinement:

- Baryon overdensity
- Dark matter overdensity — Truelove et al. (1997)
- Jeans length by >4 cells
- Current Refinement |B|/rot(B)

Up to 41 levels=2^{50} dynamic range (10^{14}) — Wise, Turk, & Abel (2008)

Summary



- Reionziation HI data on the horizon!
- Wide range of birth, life & death of the first massive stars are being explored on super computers.
- HII regions of the first stars evaporate their host-halos leave a medium with ~ 1 cm^{-3} density. Limits black hole accretion -> No mini-quasars but large local feedback.
- Clear need to further develop star formation simulations to capture scale << pc
- Approach this by calibrating model of star formation on the observations in the Milky Way test them in Galaxy Mergers to arrive at plausible predictions for the high redshift Universe.
- Build Galaxies one Star at a Time
  - Enormous impact from early feedback: f_B, spins, etc.
  - Still more physics we need to implement ...
    - Cosmic Rays being the most challenging