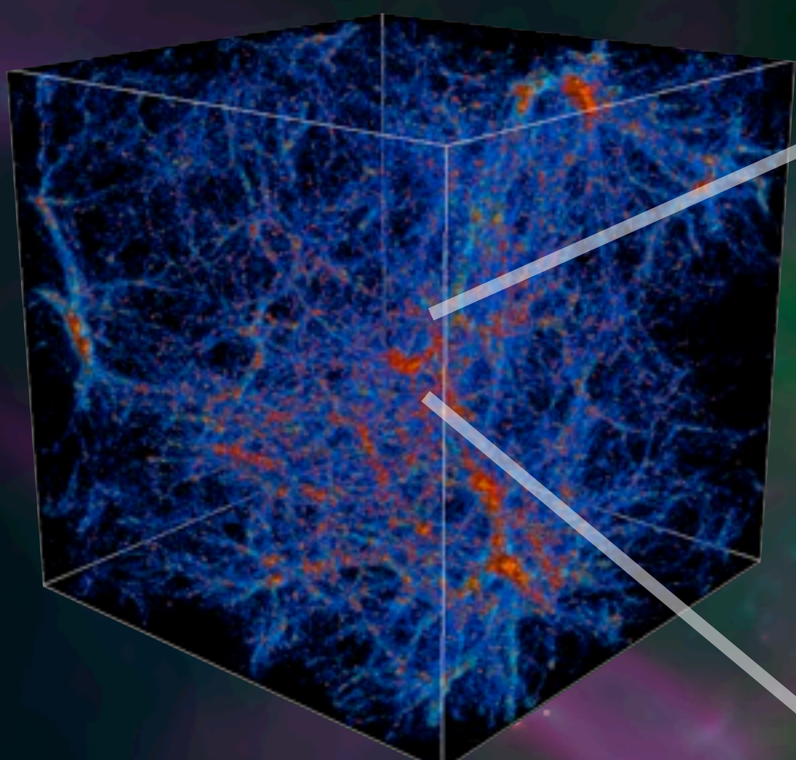
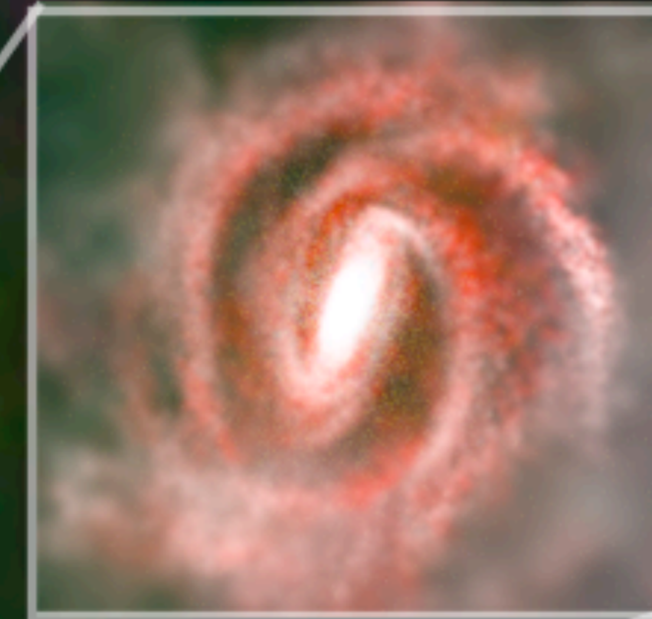
Cosmology and Structure Formation





長峯健太郎

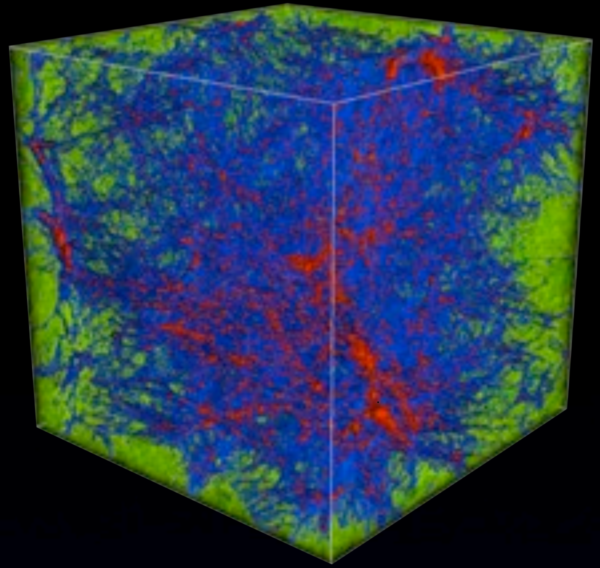
Ken Nagamine
Osaka / UNLV

Recent Collaborators:

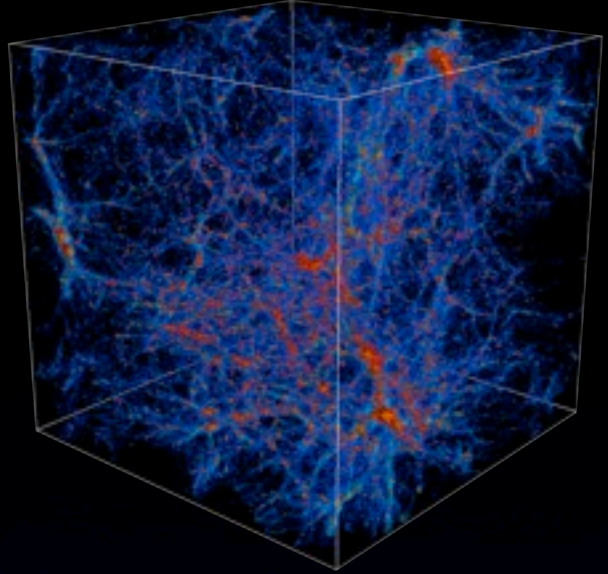
- Robert Thompson (Arizona)
- Jun-Hwan Choi (UT Austin)
- Jason Jaacks (UT Austin)
- Yuu Niino (NAOJ)
- Keita Todoroki (UNLV)
- Hide Yajima (Edinburgh)

Past Collaborators:

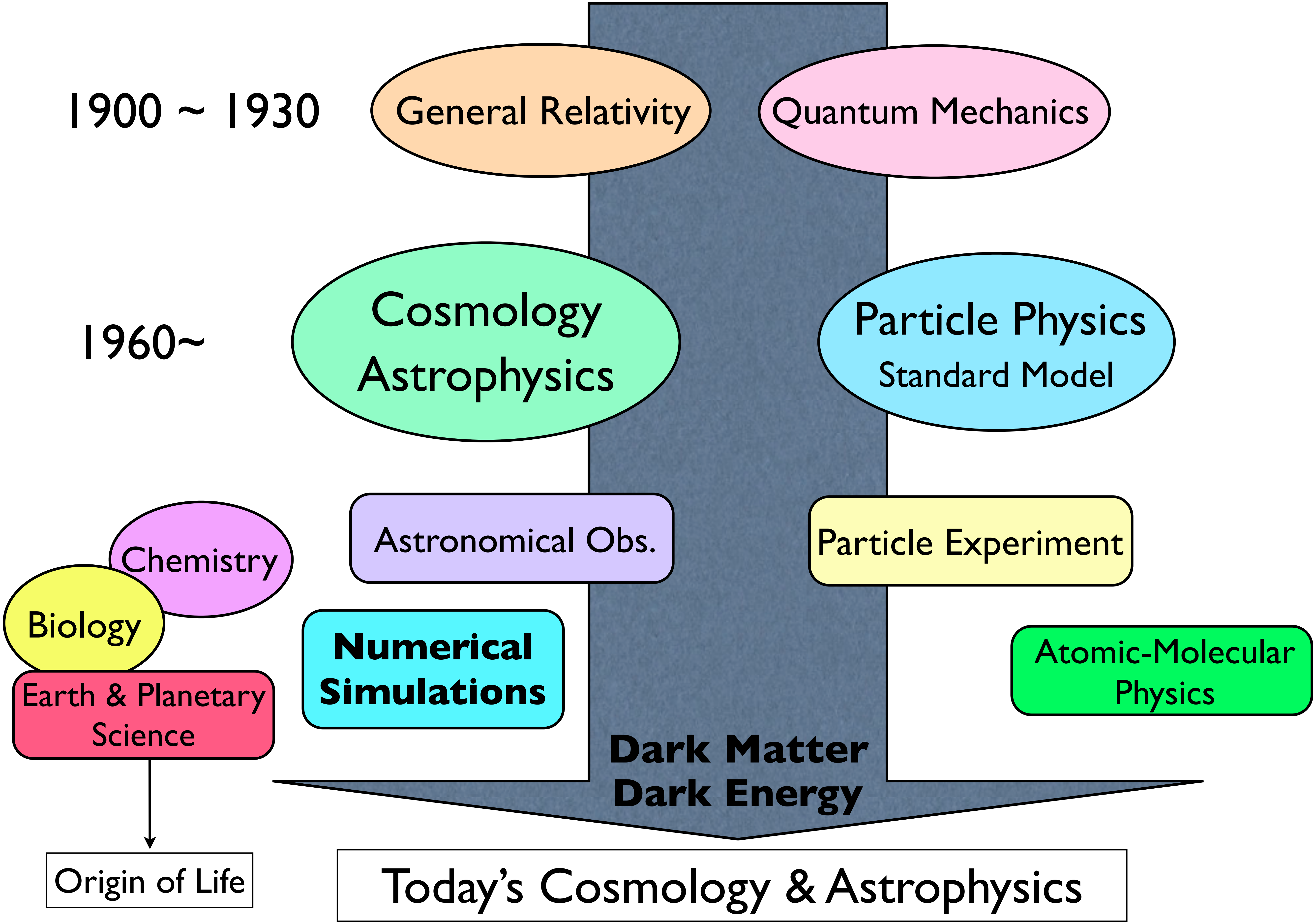
R. Cen, M. Fukugita, L. Hernquist, M. Norman, B.W. O’Shea, J. Ostriker, V. Springel, A. Wolfe



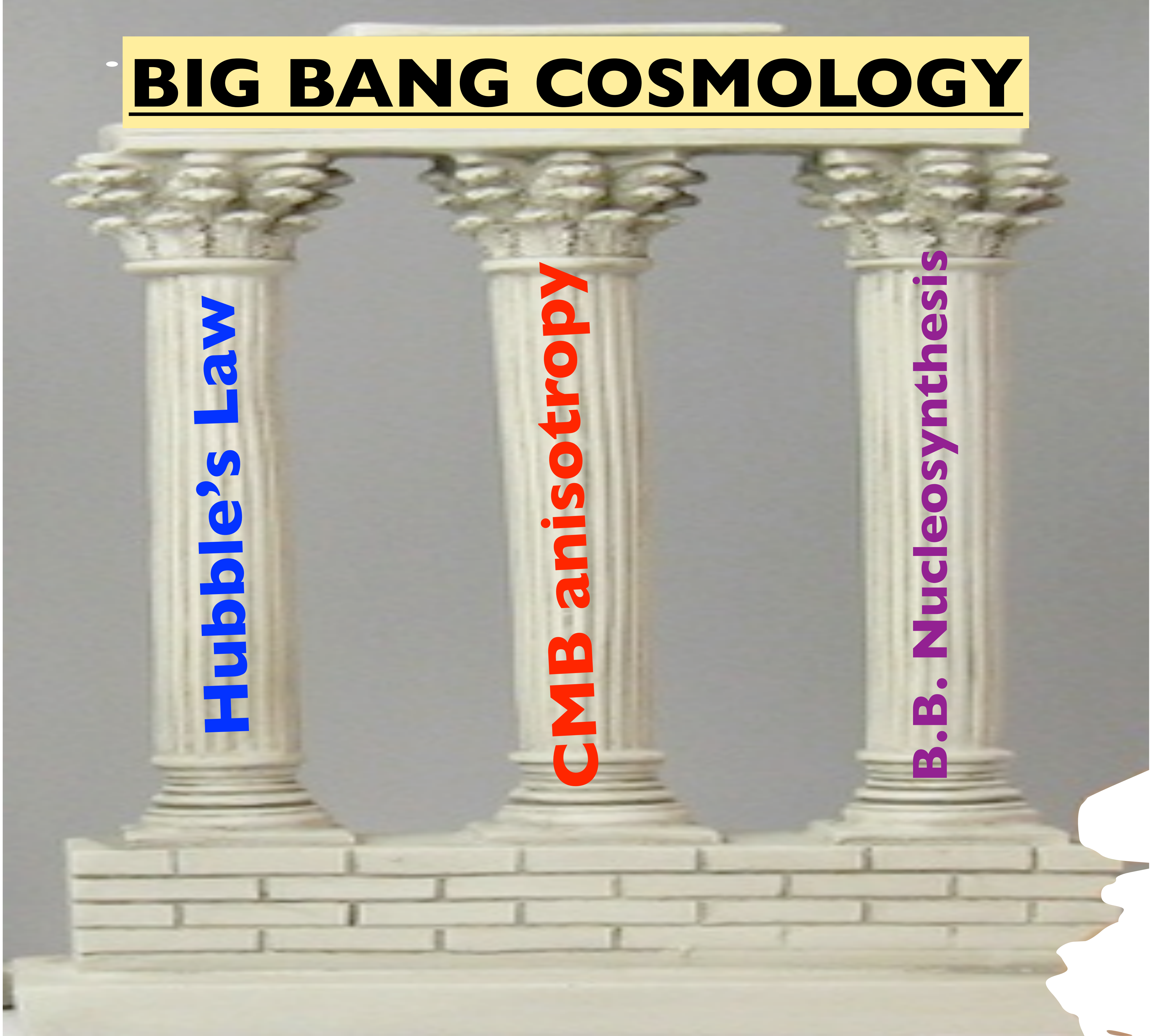
Outline

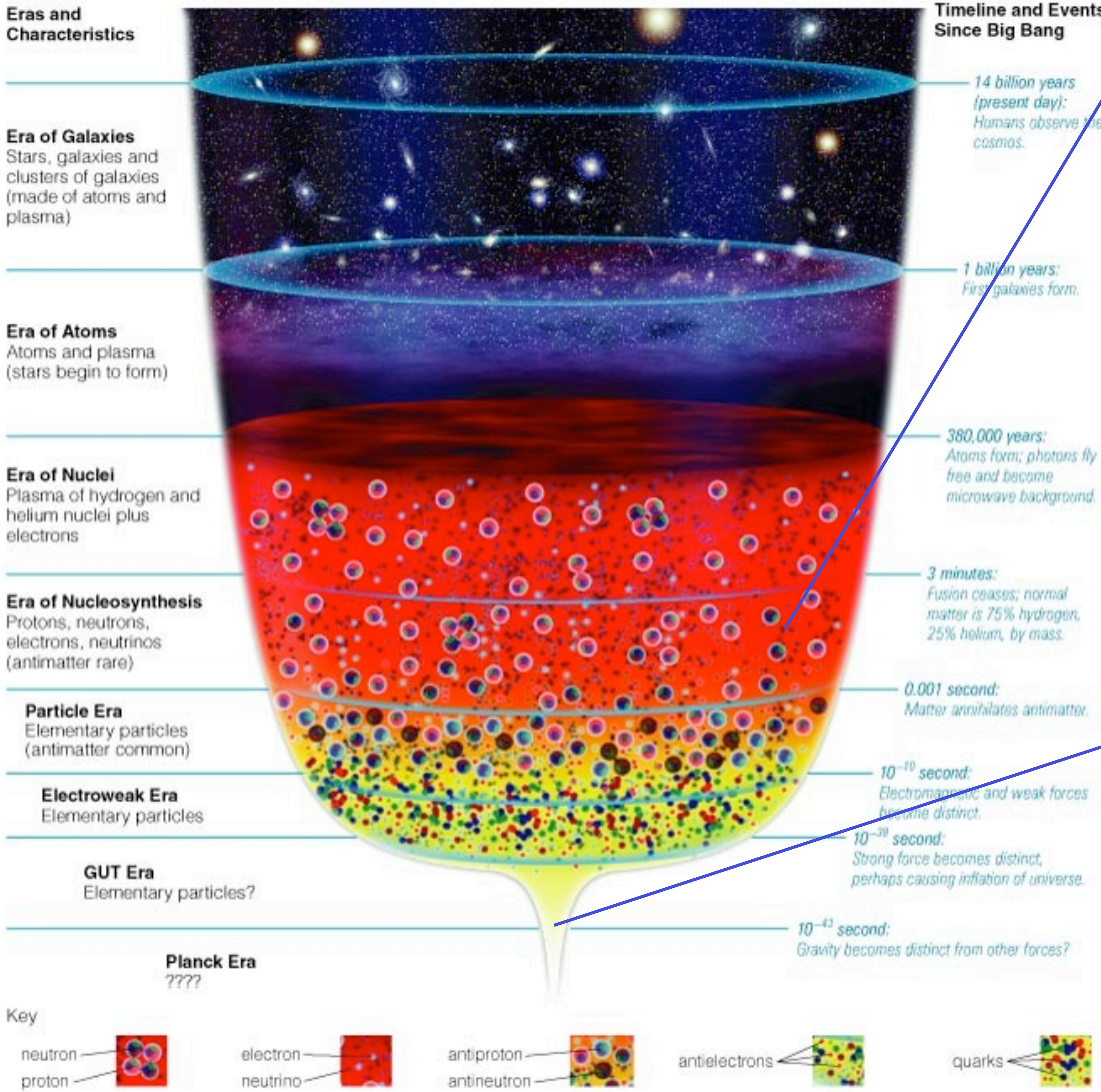


- **Overview of the Field**
- Observational Cosmology & Computational Cosmology
- **The 3rd Revolution:** Cosmo. Zoom-in Hydro Simulation
- Importance of Feedback in fully non-linear regime
- **Conclusions** -- Towards 2020s


1900 ~ 1930
General Relativity
Quantum Mechanics
1960~
Cosmology
Astrophysics
Particle Physics
Standard Model
Chemistry
Biology
Astronomical Obs.
Particle Experiment
Numerical Simulations
Earth & Planetary Science
Atomic-Molecular Physics
Dark Matter
Dark Energy
Origin of Life
Today's Cosmology & Astrophysics

BIG BANG COSMOLOGY





Era of Nucleosynthesis

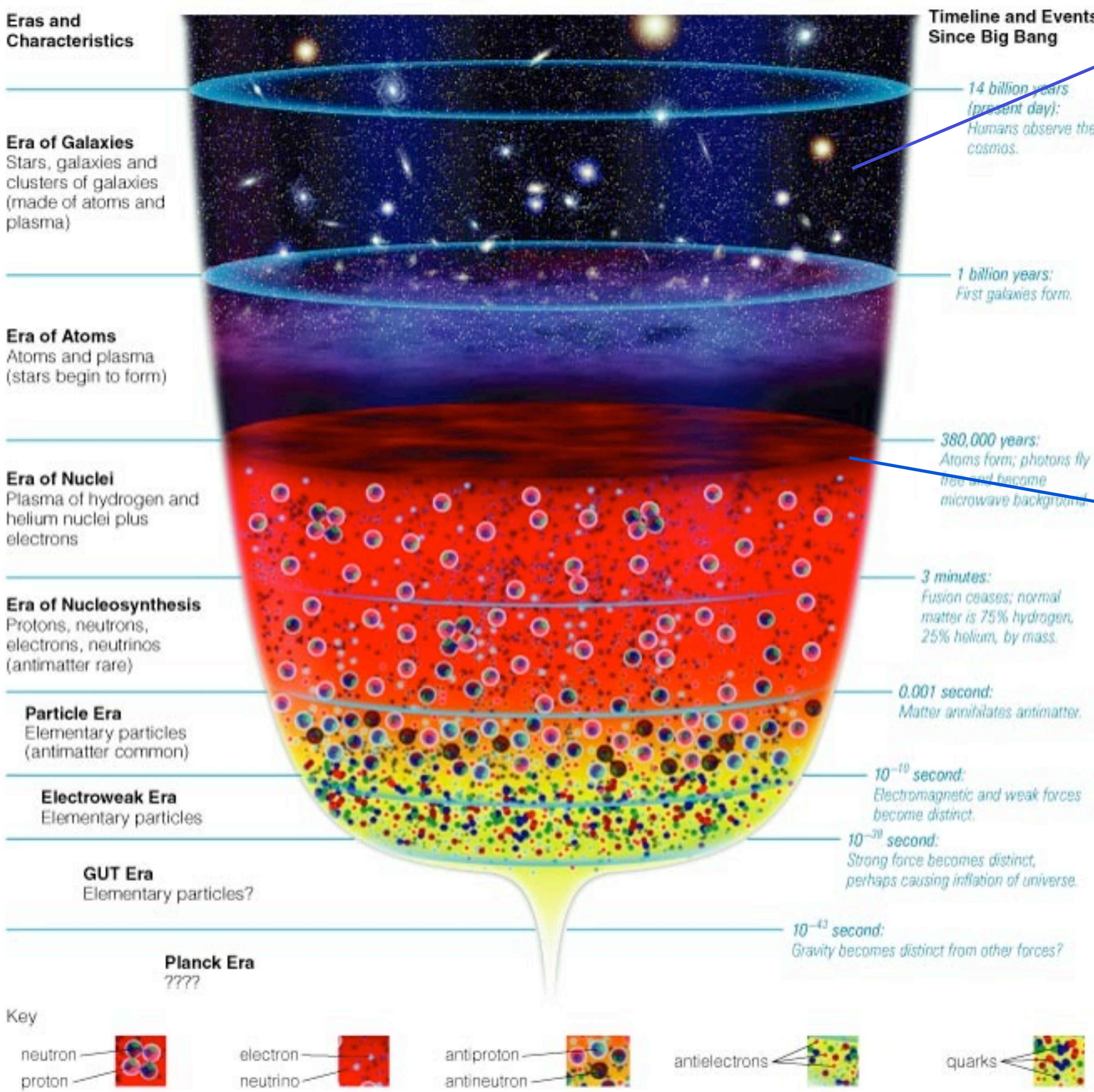
~3 min after Big Bang

Protons, neutrons, electrons formed, BUT electrons not attached.

Planck Era

Before ~10^{-43} sec

No working theory of physics!



Era of Galaxies

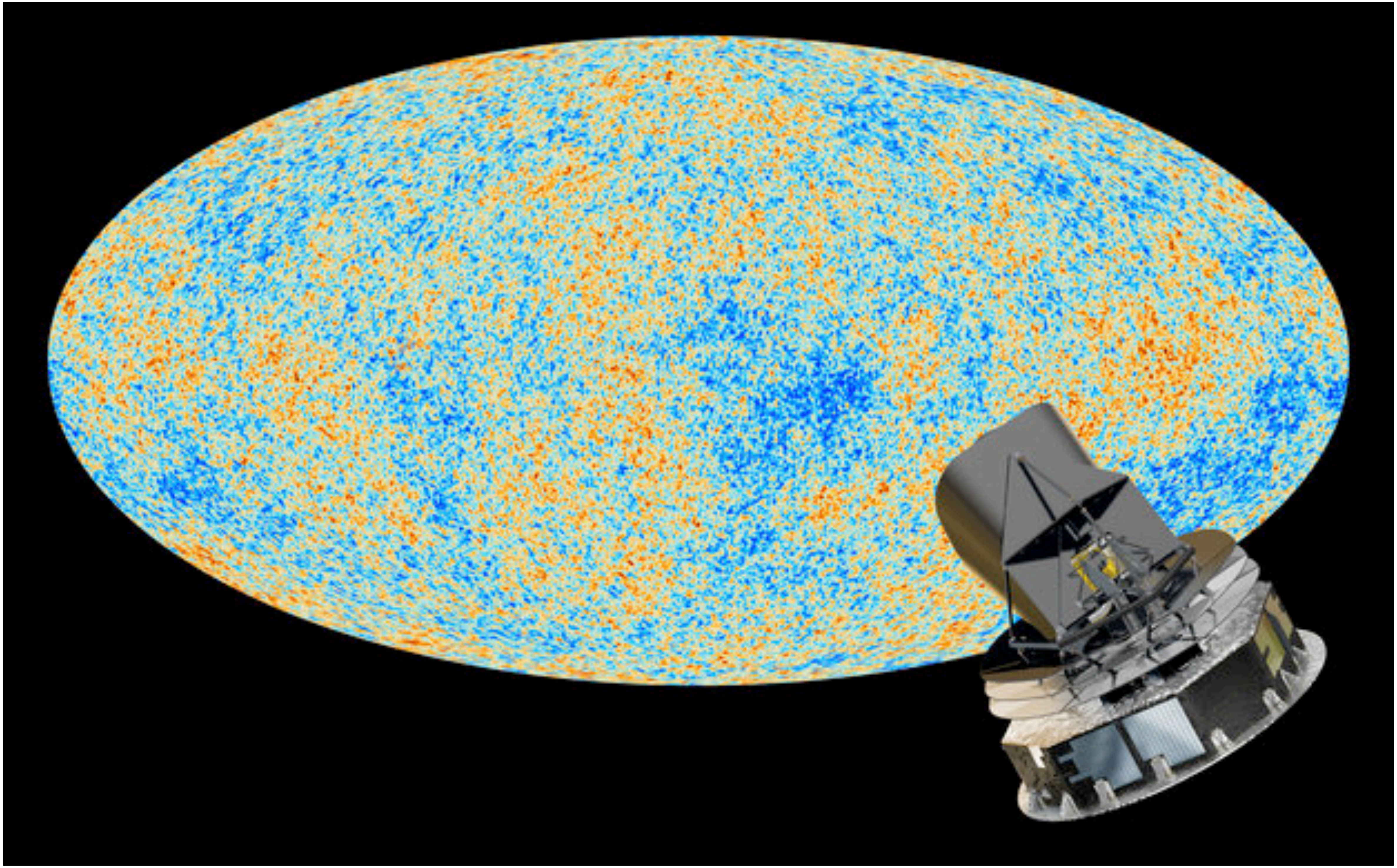
Galaxies form at age **~ 1 billion years**

Era of Nuclei

Neutral hydrogen forms at age **~380,000 years; "last-scattering surface"**

CMB is released

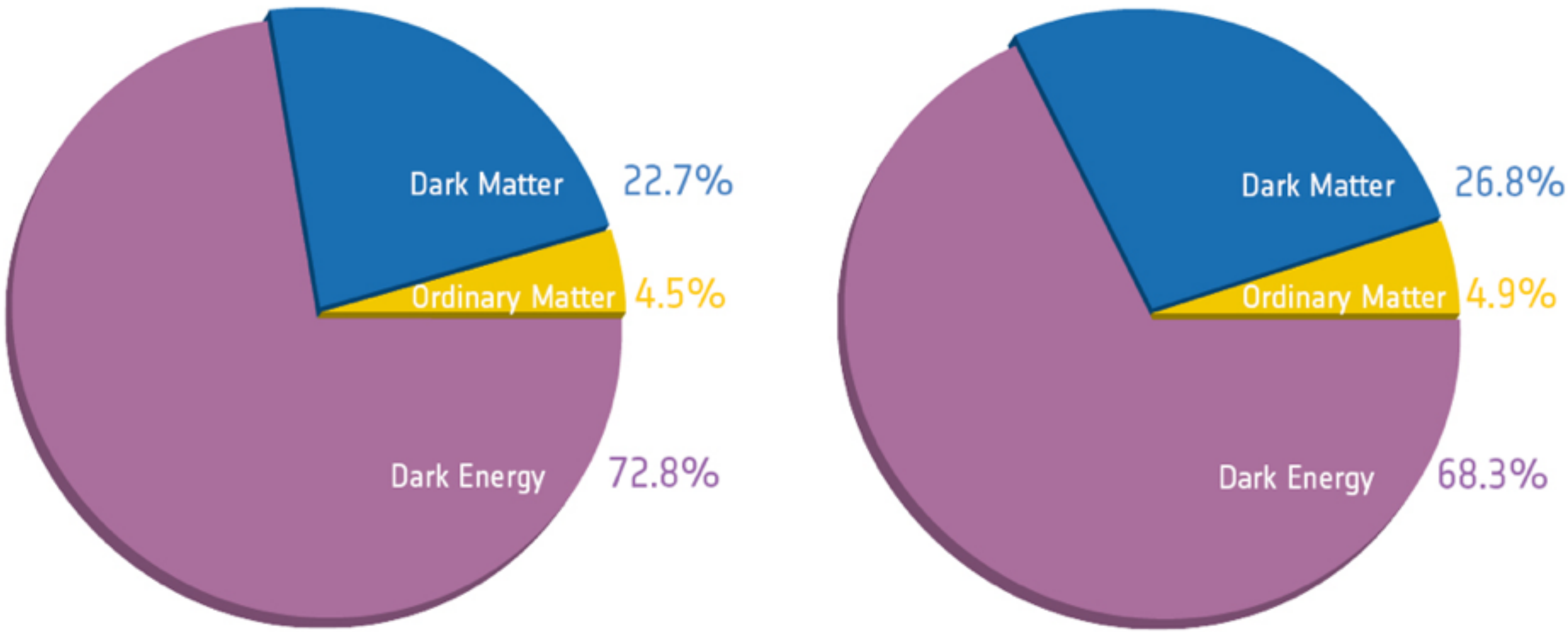
Planck satellite result



T ~ 2.7K with ~10^{-5} fluctuations

ESA March 2013

Cosmic Energy Budget



Before Planck

After Planck

ESA March 2013

Einstein Equation

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Cosmological Constant

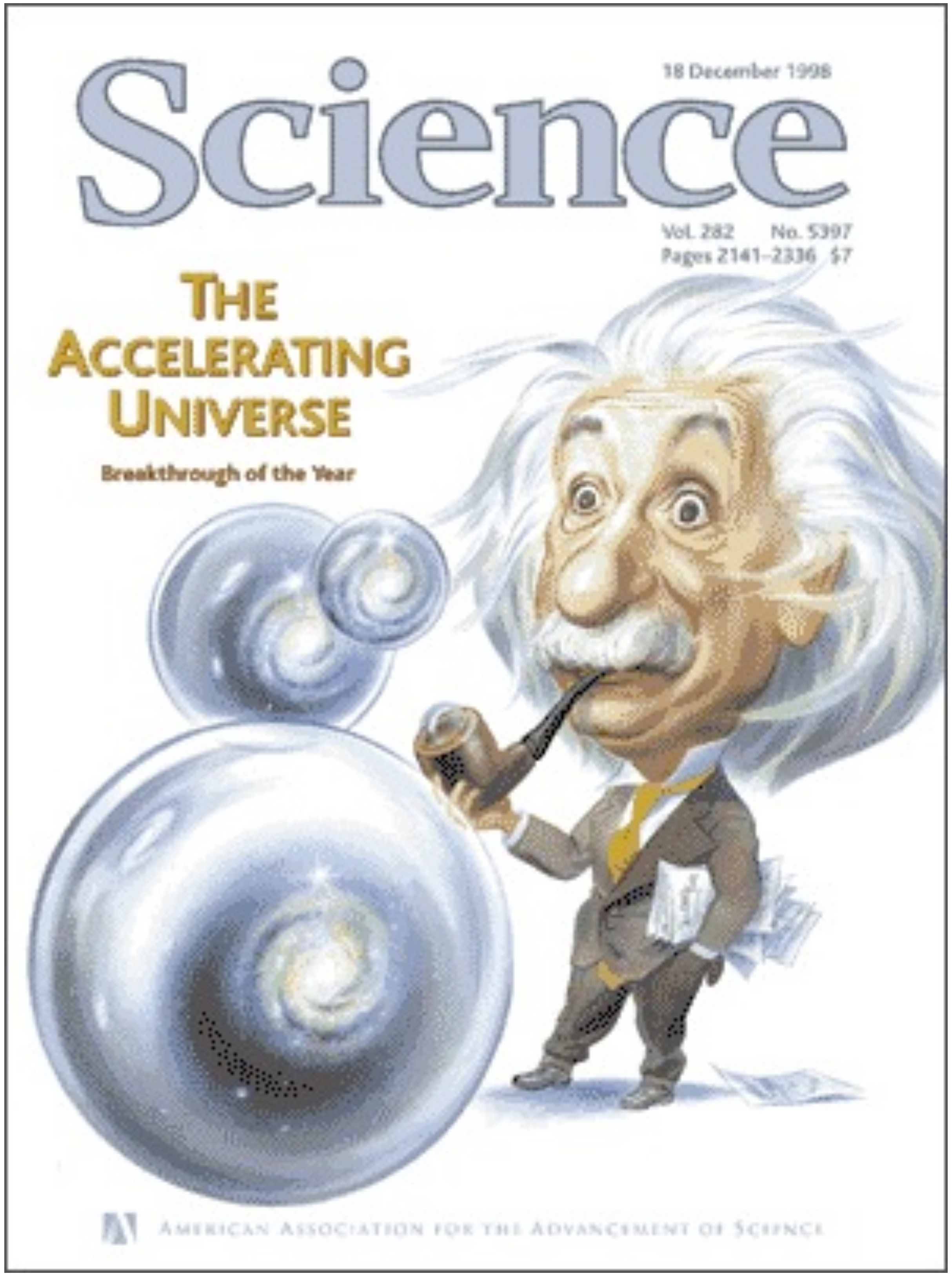
or

Dark Energy

(vacuum energy?)

Non-zero Cosmological Constant !

- In 1998, two groups independently reported the non-zero cosmological constant
- Observed distant Type Ia supernovae to make a better Hubble diagram.
- "Λ" acts as a repulsive force
- Non-zero Λ suggests accelerating universe!



Dec 1998 issue

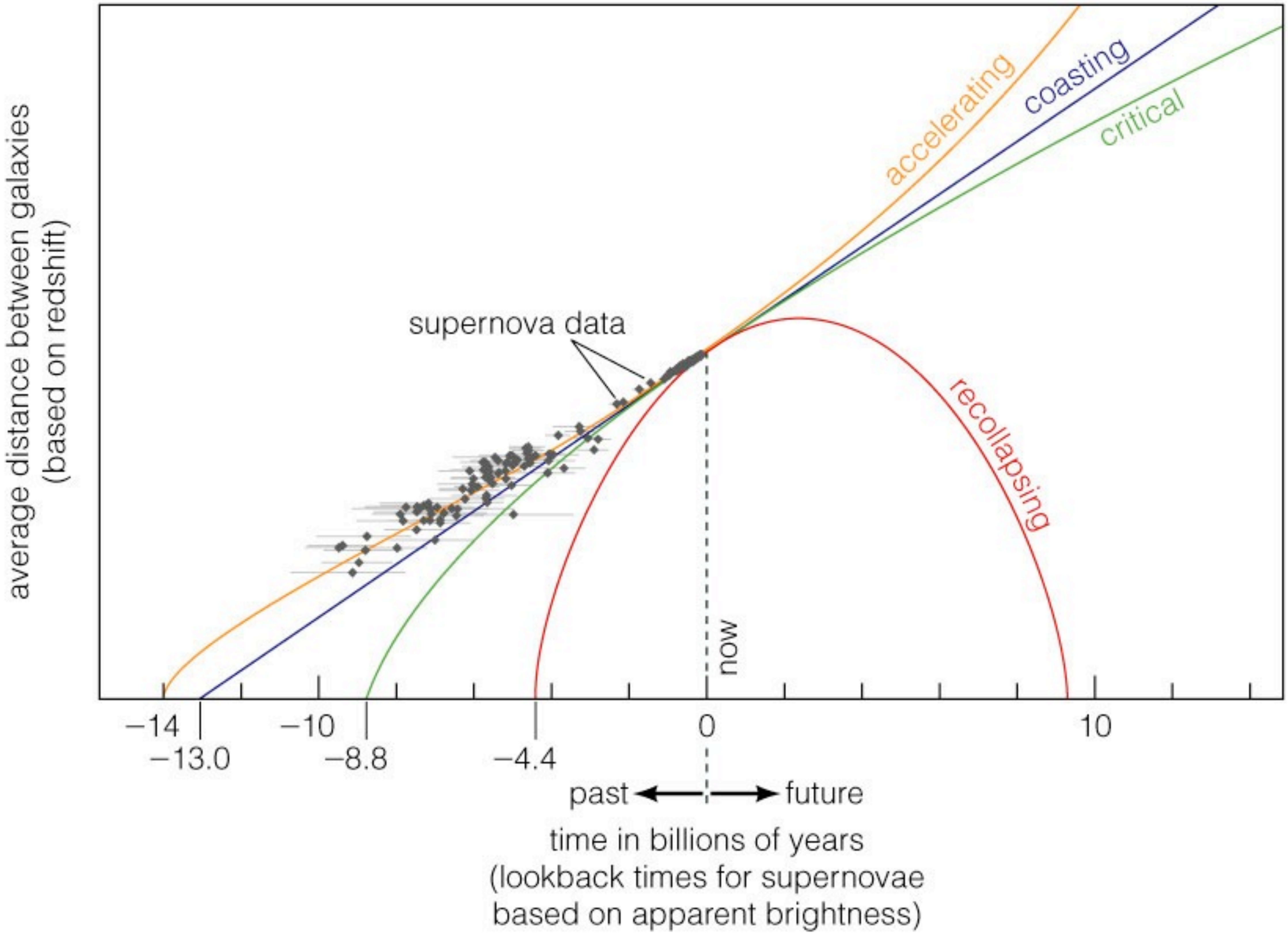
2011 Nobel Prize in Physics

Saul Perlmutter

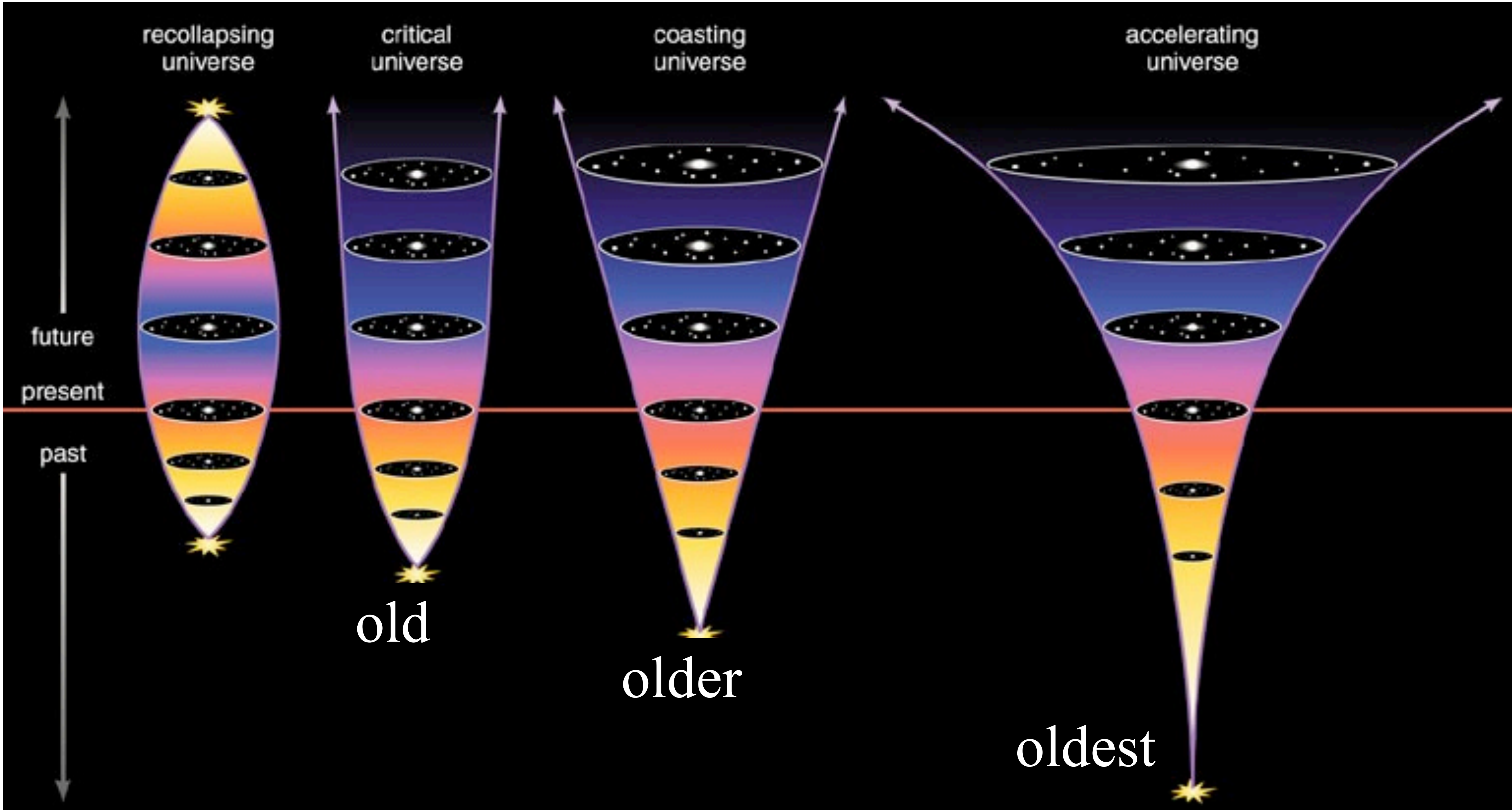
Brian Schmidt

Adam Riess

for the discovery of the accelerating expansion of the Universe through observations of distant supernovae.



Accelerating universe is the best-fit model to the supernova data.



Estimated age depends on both ***dark matter*** and ***dark energy***

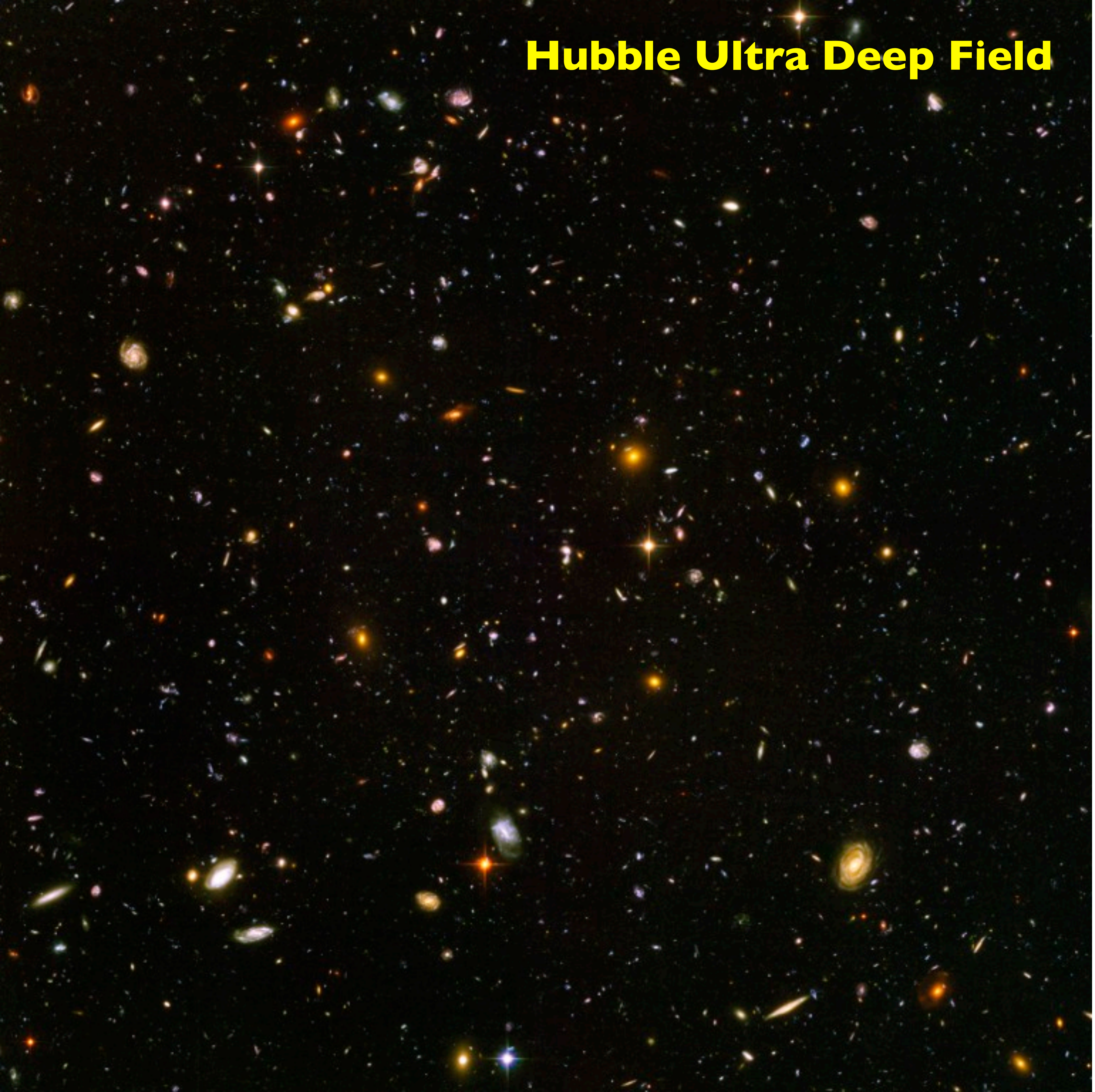
(the current size of our universe is given.)

II:
Structure Formation

Cosmologists use galaxies to learn about the Universe.

Therefore, we need to understand **galaxy formation** much better to do `precision cosmology'.

selection bias, sample variance, cosmic variance, redshift evolution, color dependence, ...



HUDF

Deepest universe that the humankind have ever seen.

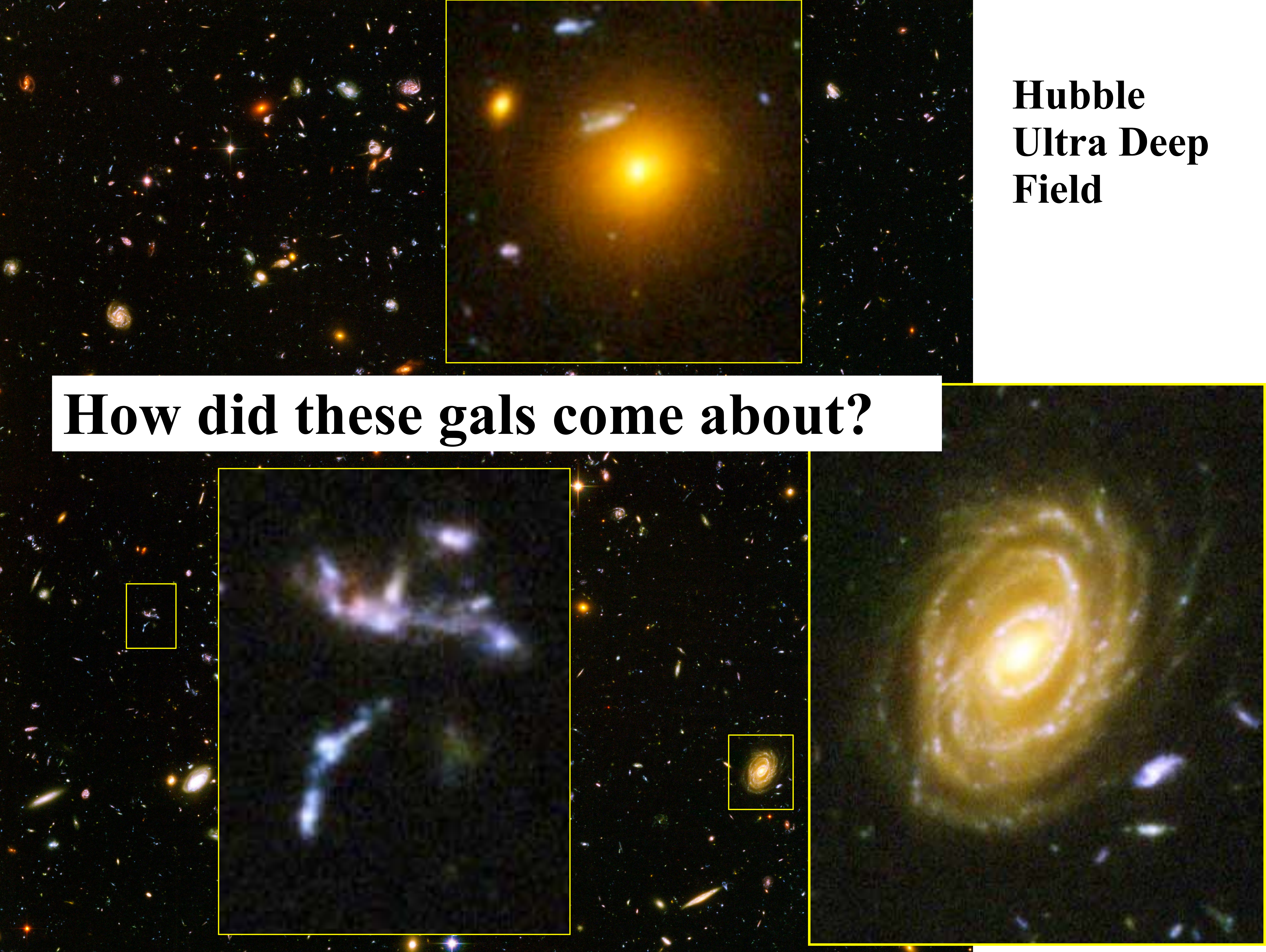
2003~2004

↓

Hubble Extreme Deep Field (XDF)

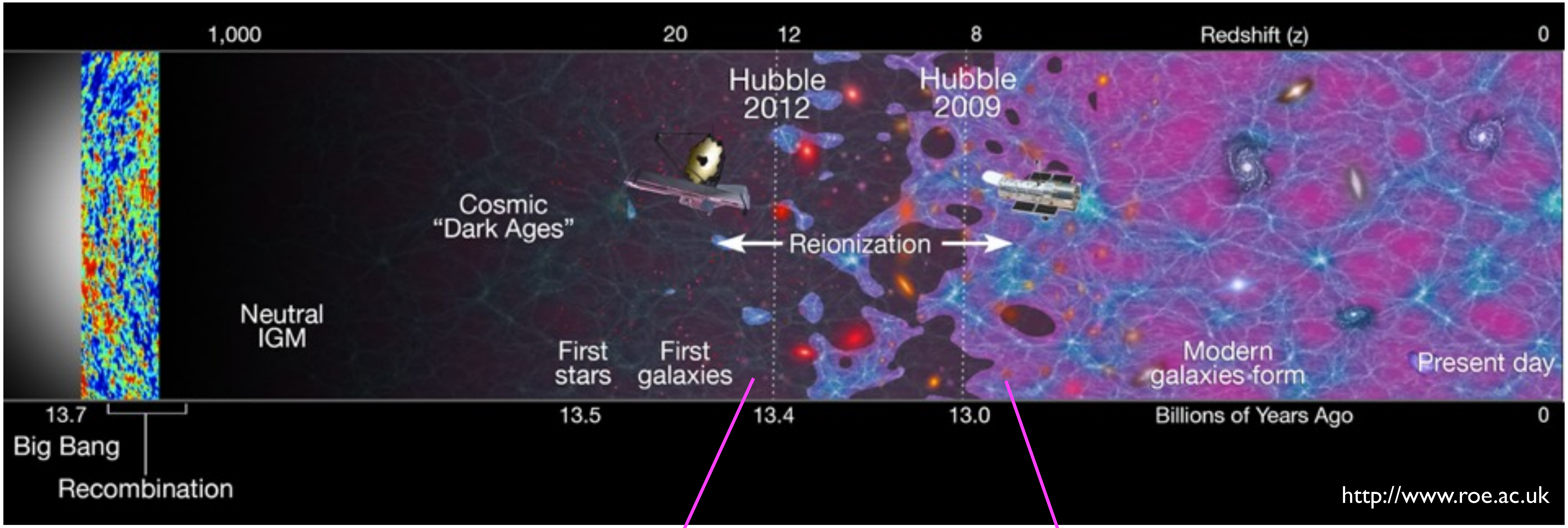
2012

Hubble Ultra Deep Field



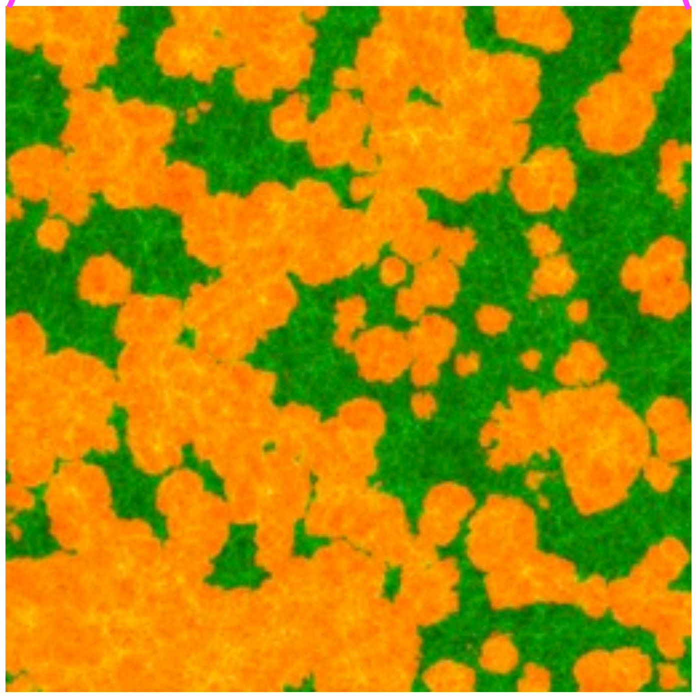
How did these gals come about?

Cosmic Timeline

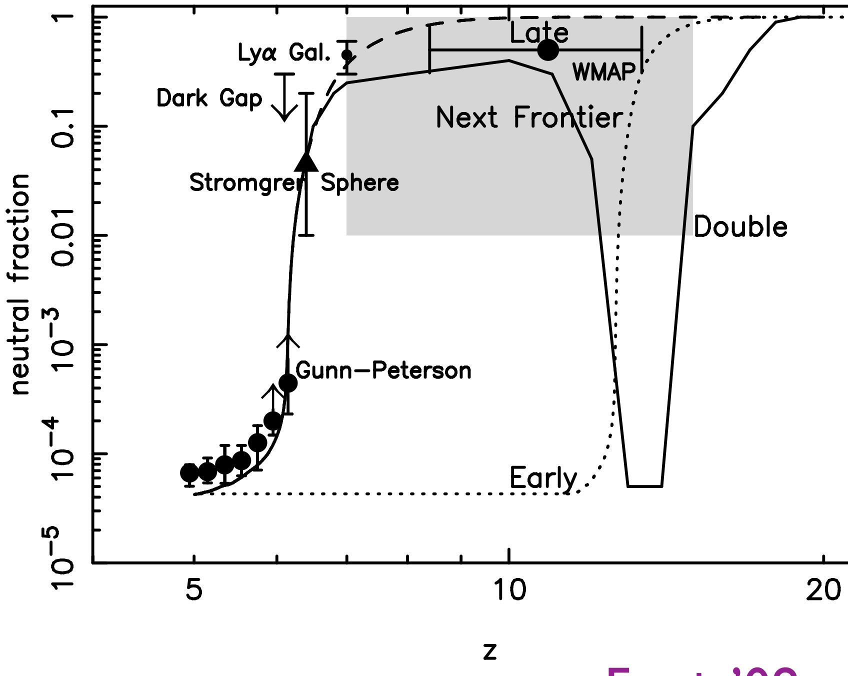


Observations are rapidly approaching the first galaxies

What are the sources responsible for reionization & early chemical enrichment?



Illiev+ '06

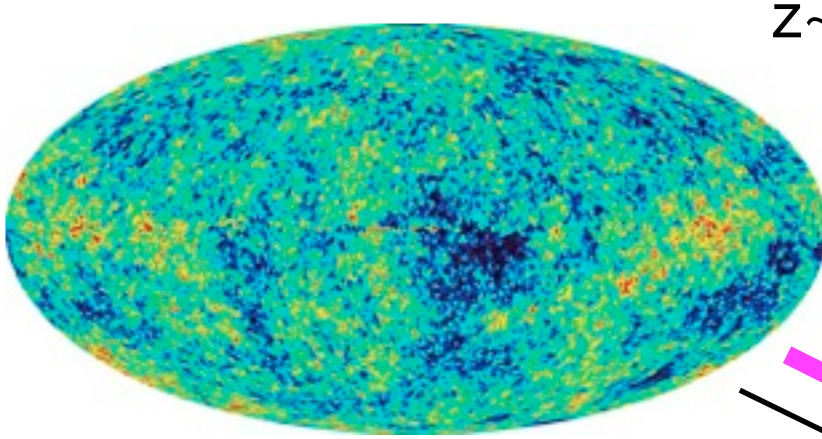


Fan+ '08

Computational Cosmology

Self-consistent galaxy formation scenario from first principles (as much as possible)

z~1000



Initial conditions

z=100

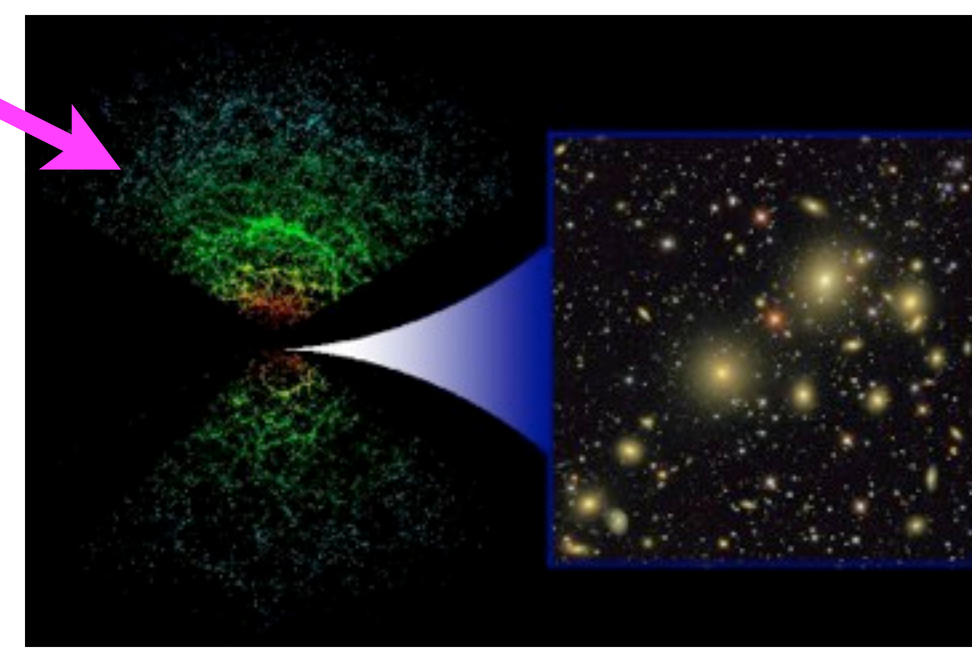
z=10

z=3

radiative cooling/heating, star formation, feedback

cosmological params, dark energy, dark matter, **baryons**
gravity + hydrodynamics

z=0

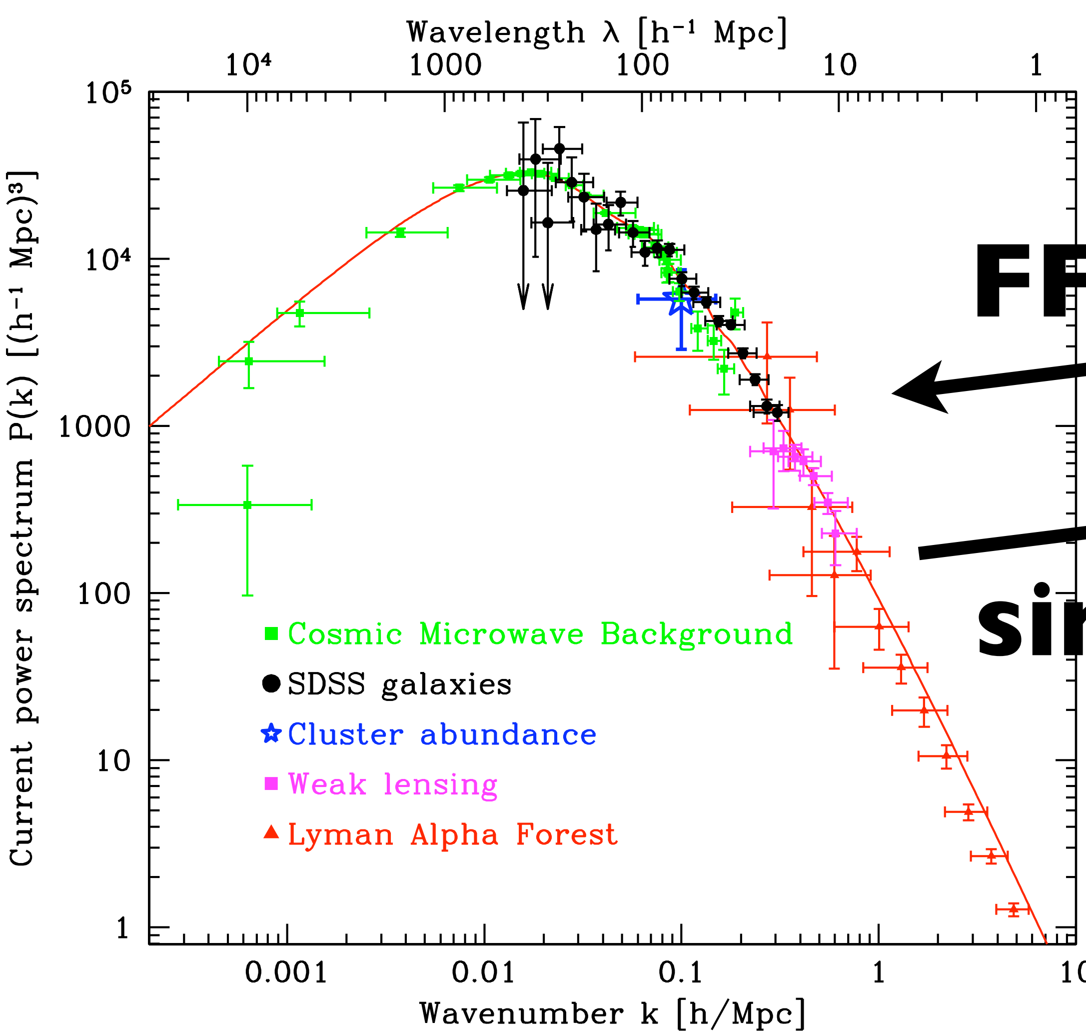


Concordance ΛCDM model

WMAP, Planck:
SN Ia

$$(\Omega_M, \Omega_\Lambda, \Omega_b, h, \sigma_8, n_s) \approx (0.3, 0.7, 0.04, 0.7, 0.8, 0.96)$$

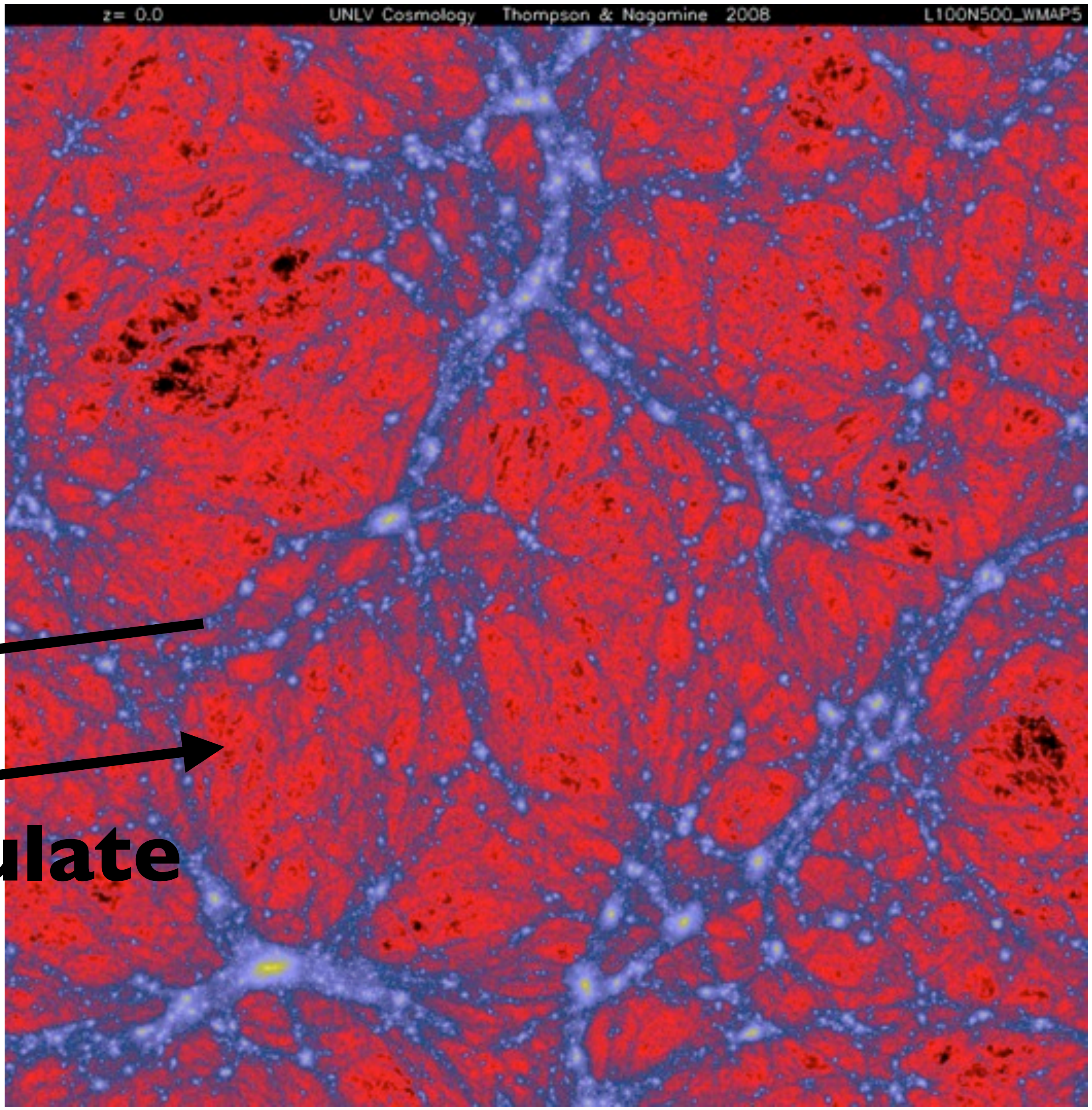
- Successful on large-scales
- Can we understand galaxy formation in the context of ΛCDM model?



Tegmark+ (2004)

FFT

simulate

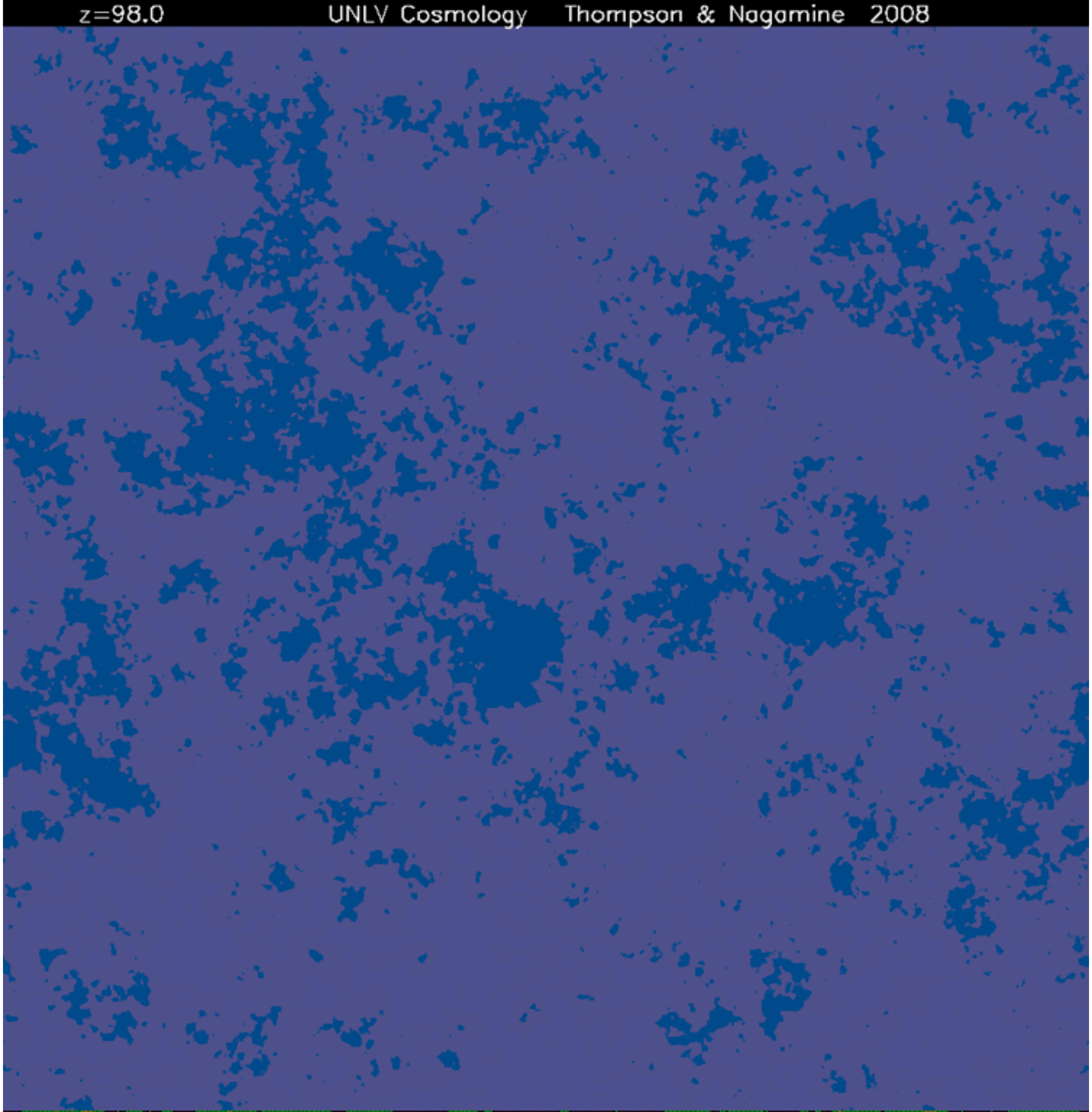


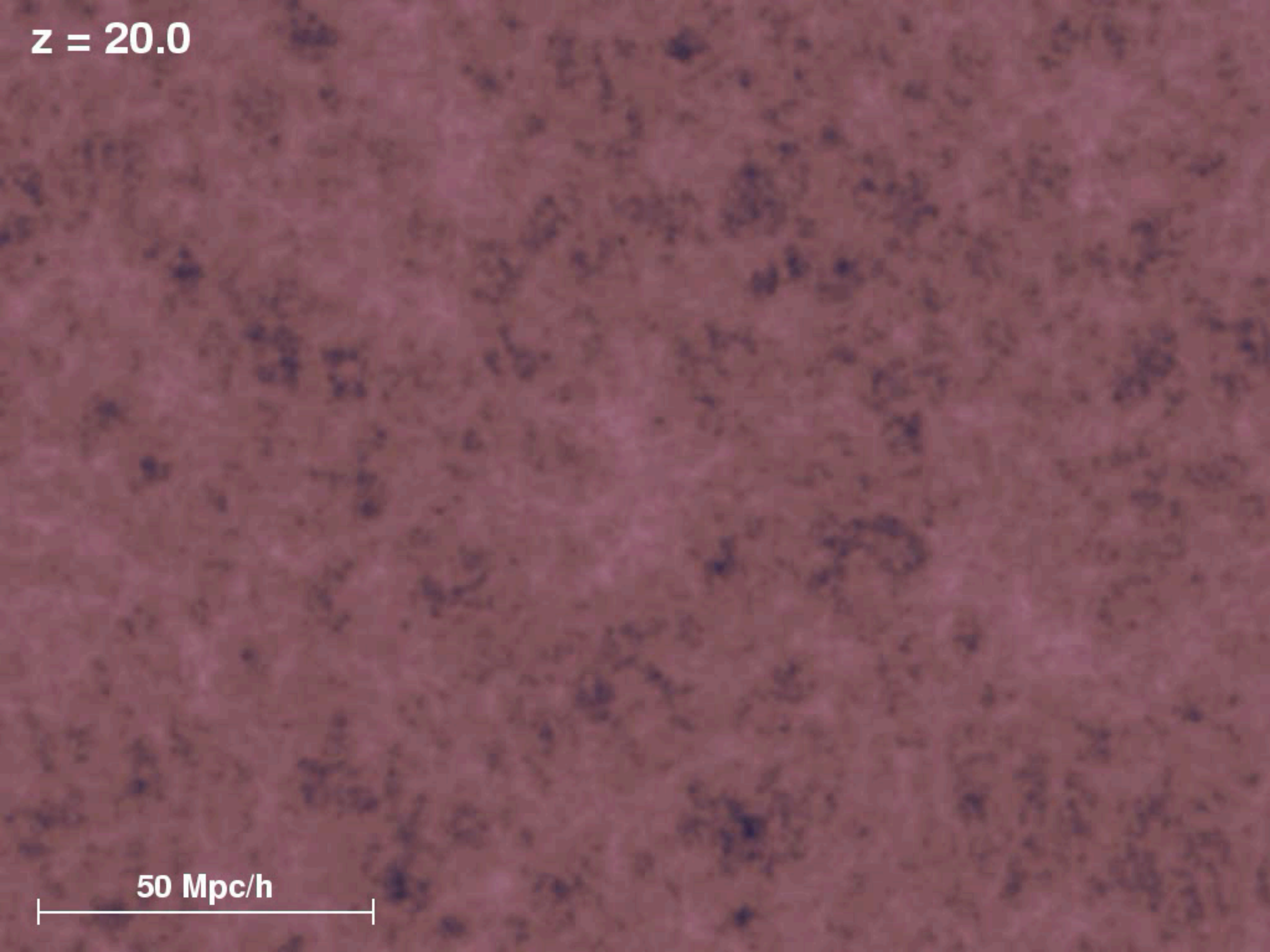
"Back-bone of structure"

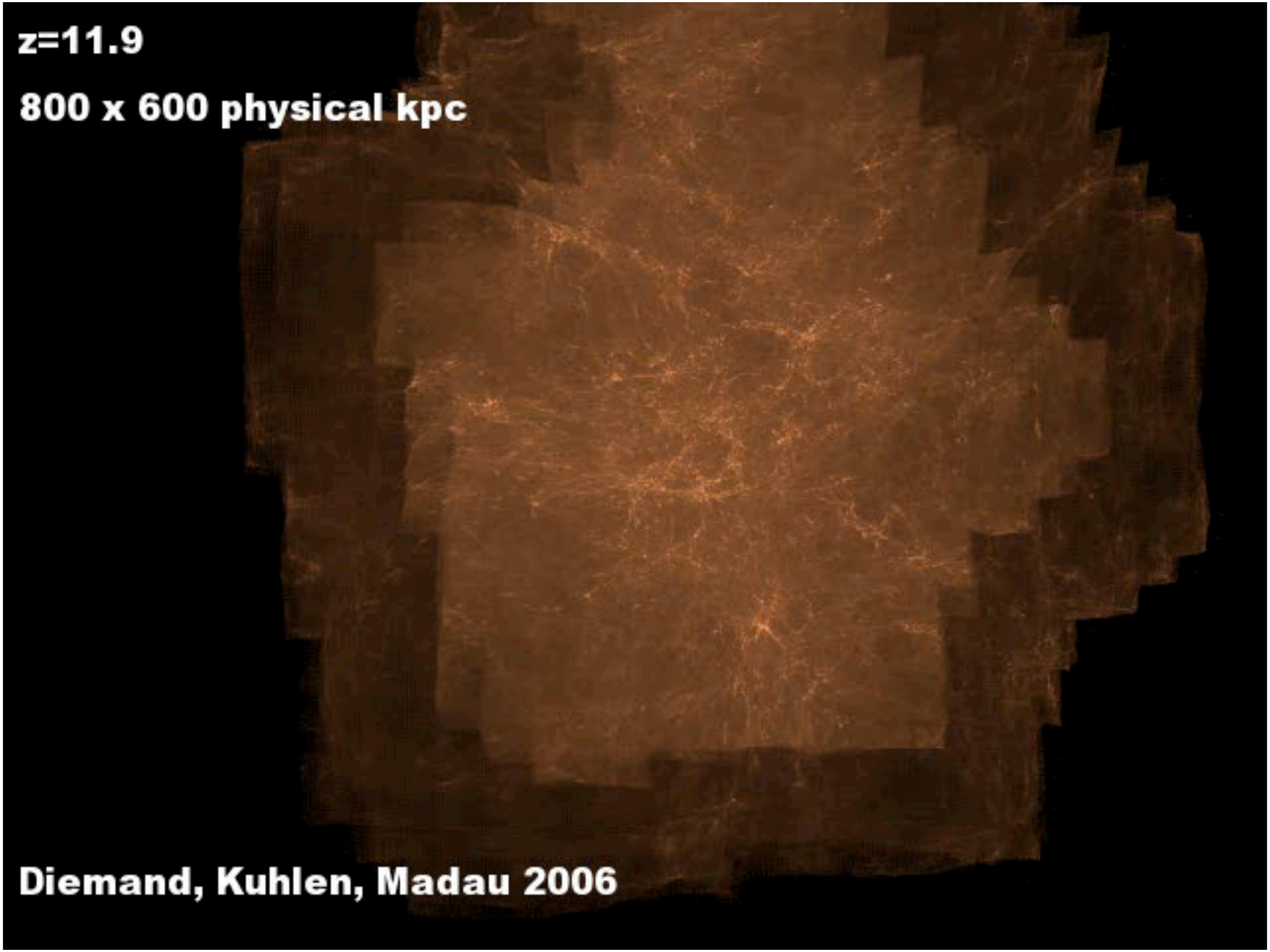
サイズ
３億光年

100 Mpc/h
across

500^3
DM ptcl




z = 20.0
50 Mpc/h


z=11.9
800 x 600 physical kpc
Diemand, Kuhlen, Madau 2006

Ironic Fact

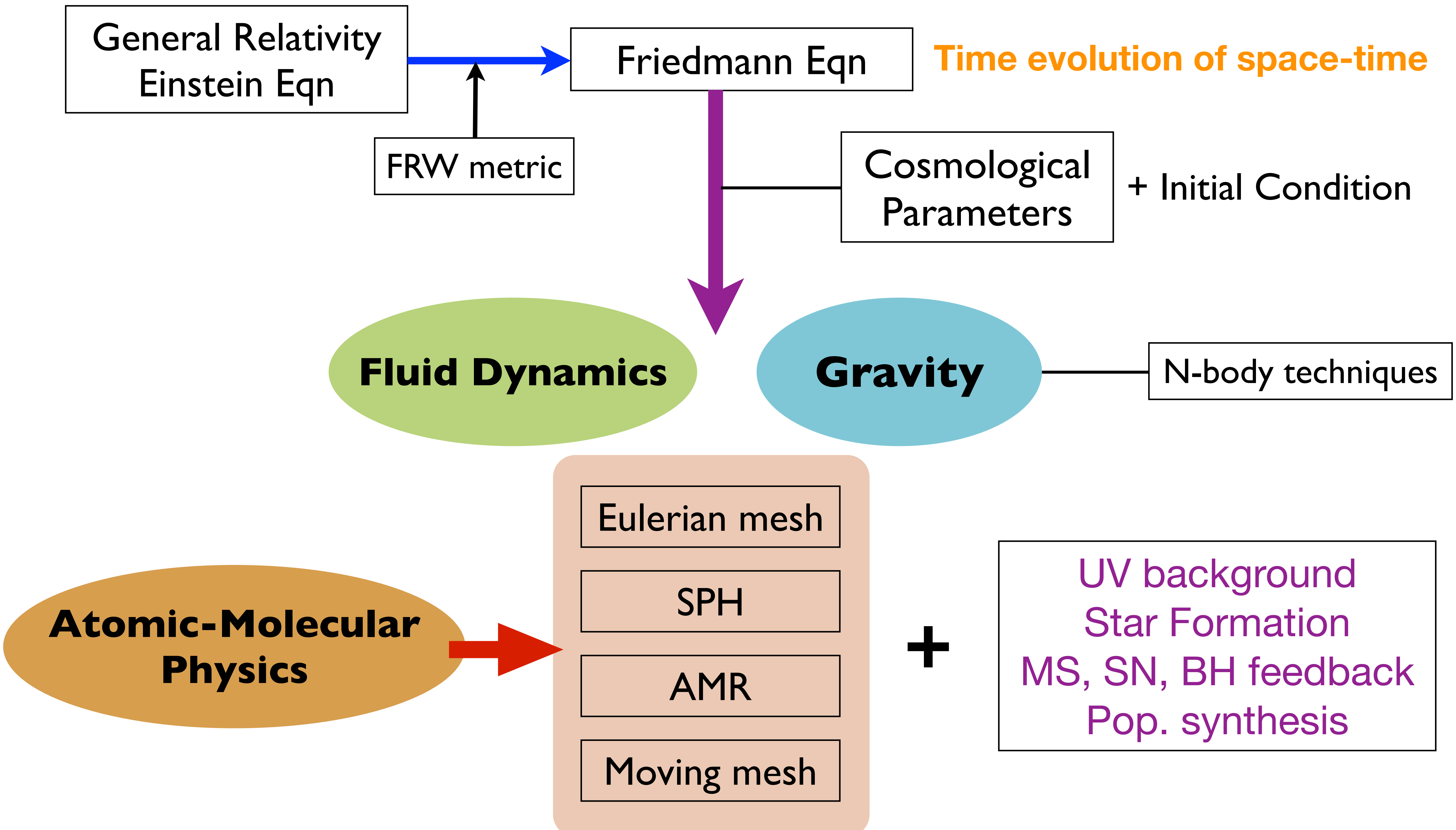
- `Dark Matter' itself is not understood.
- But structure formation from DM can be predicted well.

(given the ptcl cross section.)

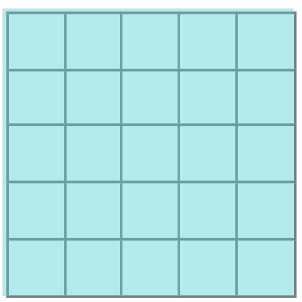
$$(\Omega_M, \Omega_\Lambda, \Omega_b, h, \sigma_8, n_s) \approx (0.3, 0.7, 0.04, 0.7, 0.8, 0.96)$$

$$\Omega_{DM} \approx 0.26$$

Theoretical Framework of Comp. Cosmology

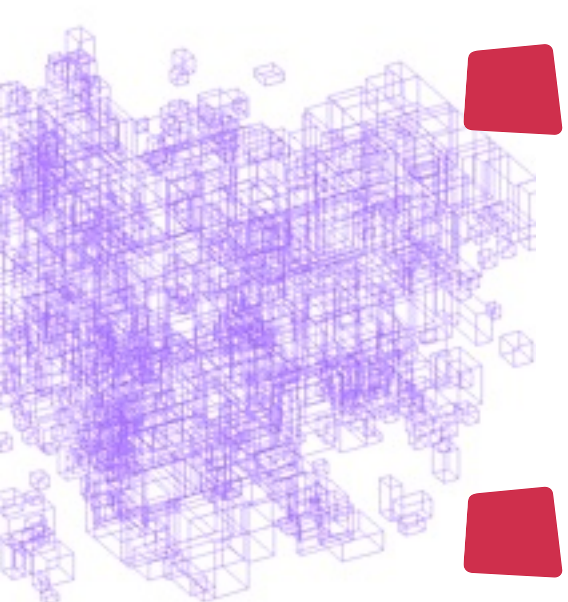


Cosmological Hydro Codes



Eulerian mesh (e.g. Cen & Ostriker '92; KN+'01)

- Eulerian mesh, PM gravity solver, shock capturing hydro
- fast; good baryonic mass res. at early times
- low final spatial resolution in high-ρ regions, but good at low-ρ regions

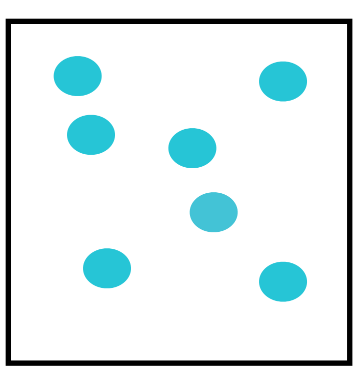


AMR (adaptive mesh refinement: e.g. Enzo, RAMSES, etc.)

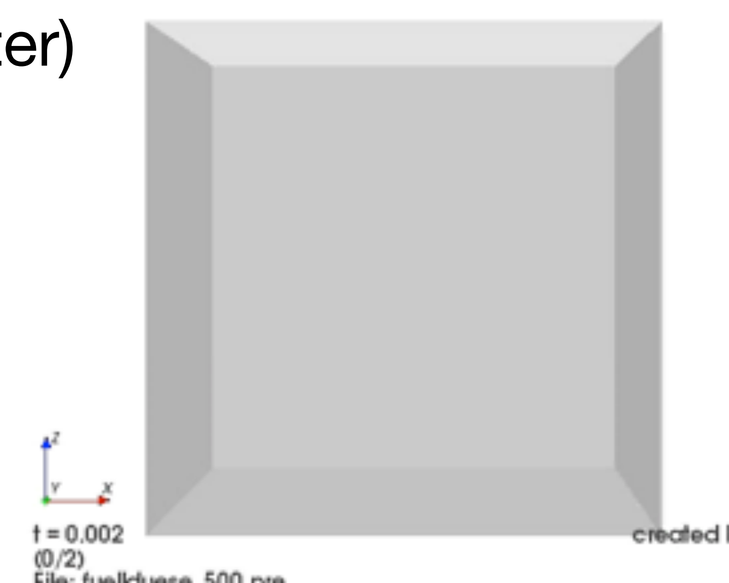
- Eulerian root grid, refine as necessary
- multi-grid PM gravity solver, ZEUS hydro, PPM hydro
- high dynamic range, but slower

AMR-SPH comparison:
O'Shea, KN+ '05

SPH (Smoothed Particle Hydrodynamics: e.g. GADGET, GASOLINE, etc.)



- Lagrangian, particle-based (both gas & dark matter)
- Tree-PM for gravity
- SPH for hydro
- fast; good spatial resolution in high-ρ region, but
  not so good in low-ρ region



Cosmological SPH Simulations

- **modified GADGET-3 SPH code** (Springel '05+α)
  radiative cooling/heating (w/ metals), SF model, SN & galactic wind feedback with multicomponent variable velocity (MVV) model (Choi & KN '11), self-shielding correction (KN+10)
- **Advantage over zoom-in runs: larger statistical samples of galaxies**

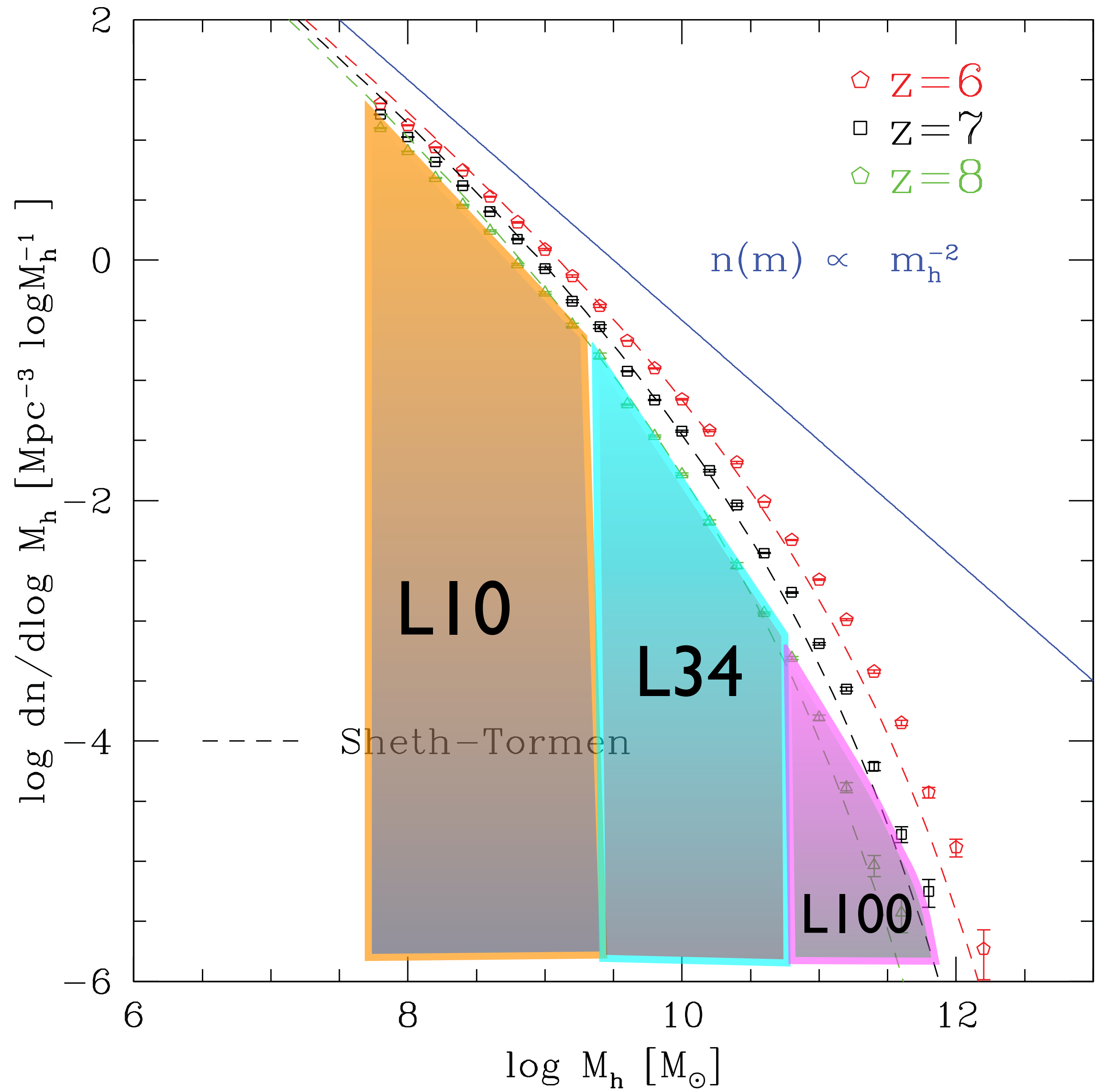
Run Name	Box Size [h^{-1} Mpc]	Particle Count DM & Gas	$m_{\rm dm}$ [h^{-1} $M_\odot$]	$m_{\rm gas}$ [h^{-1} $M_\odot$]	ϵ com [h^{-1} kpc]
N144L10	10.00	2×144^3	2.01×10^7	4.09×10^6	2.77
N500L34	33.75	2×500^3	1.84×10^7	3.76×10^6	2.70
N600L10	10.00	2×600^3	2.78×10^5	5.65×10^4	0.67
N400L10	10.00	2×400^3	9.37×10^5	1.91×10^5	1.00
N400L34	33.75	2×400^3	3.60×10^7	7.34×10^6	3.38
N600L100	100.00	2×600^3	2.78×10^8	5.65×10^7	4.30

Fiducial: Pressure-based SF model — Schaye & Dalla Vecchia '08; Choi & KN '09, '10, '11

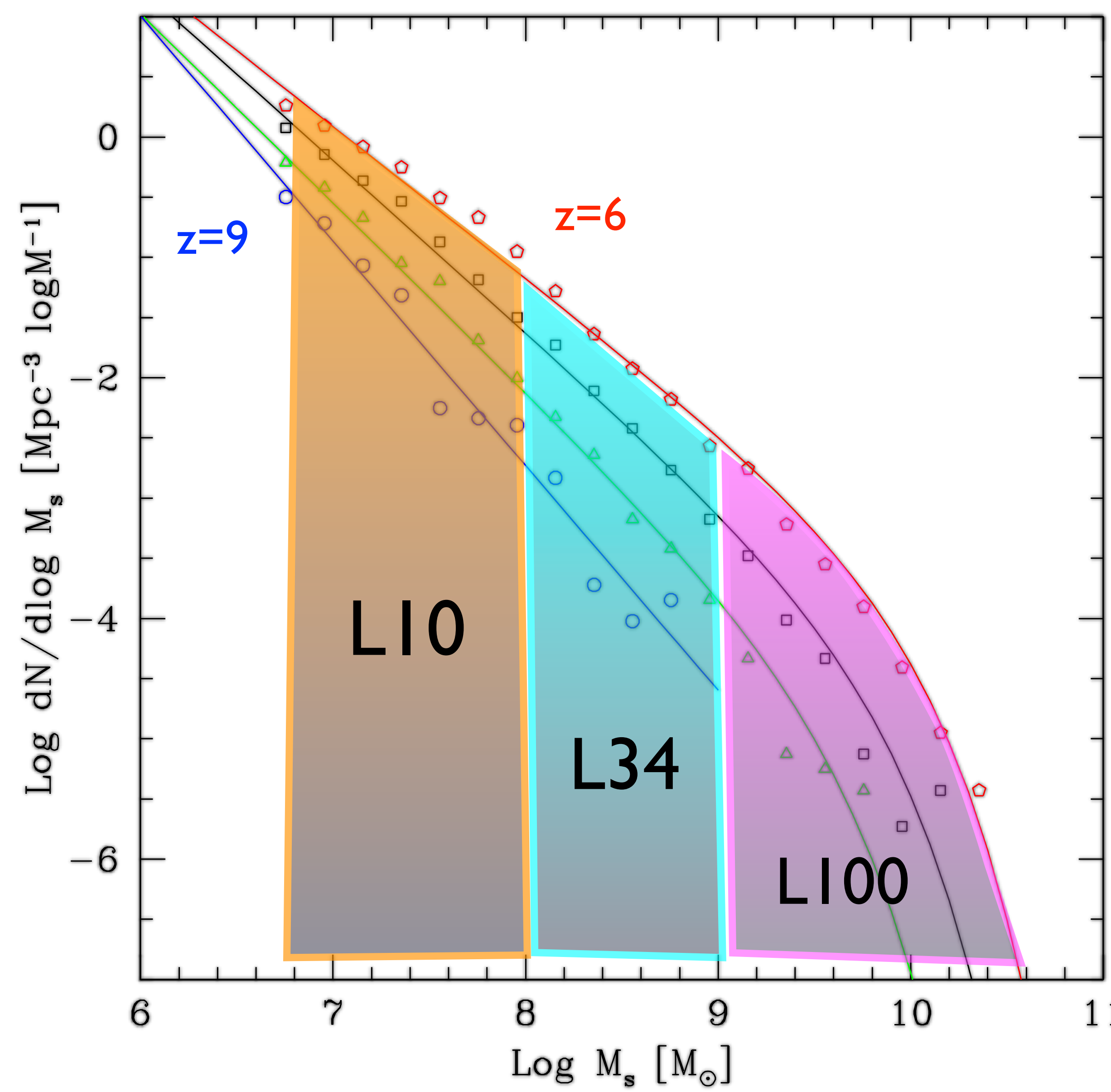
H_2-SF model — Thompson, KN+ '13

Composite Mass Functions

Halo mass fcn



Galaxy Stellar Mass Fcn (GSMF)



Jaacks, Choi & KN '12a

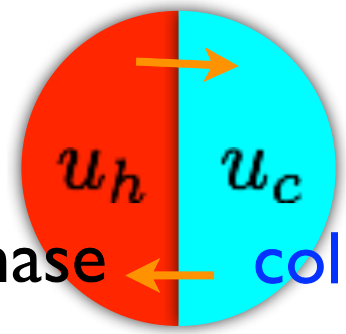
Sub-grid Multiphase ISM model

Each SPH ptcl is pictured as a multiphase hybrid gas.

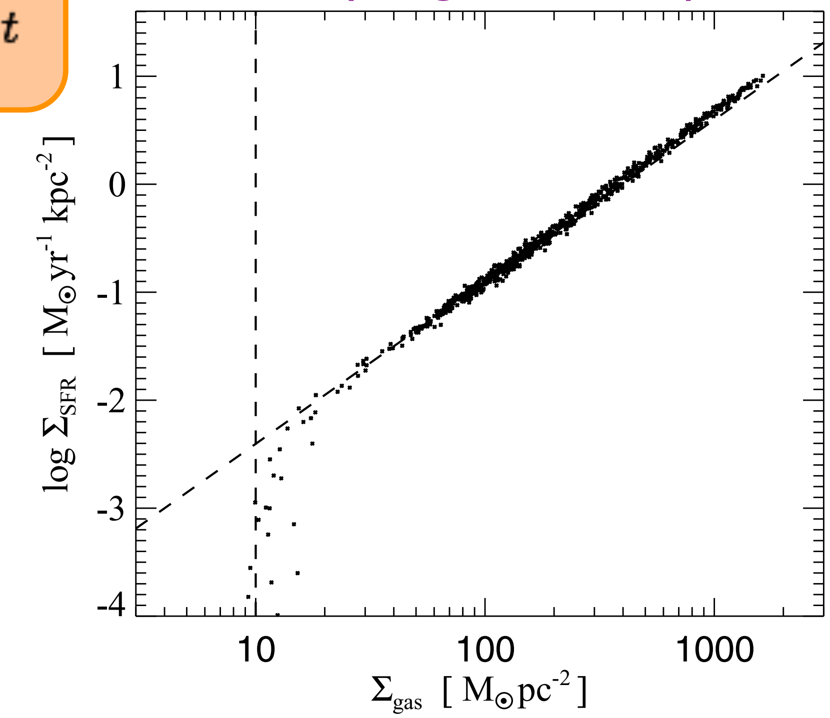
(cf. Yepes+ '97)

$$\rho_h \frac{du_h}{dt} = \beta \frac{\rho_c}{t_\star}(u_{sn} + u_c - u_h) - A\beta\frac{\rho_c}{t_\star}(u_h - u_c) - f\Lambda_{net}$$

$$u_c = \text{const.}$$



Springel & Hernquist '03



SFR: $$\dot{\rho}_\star = (1-\beta)\,\frac{\rho_c}{t_\star}$$

cold gas

gas recycling fraction

$$t_\star = t_\star^0 \left(\frac{\rho_g}{\rho_{\rm th}}\right)^{-0.5}$$

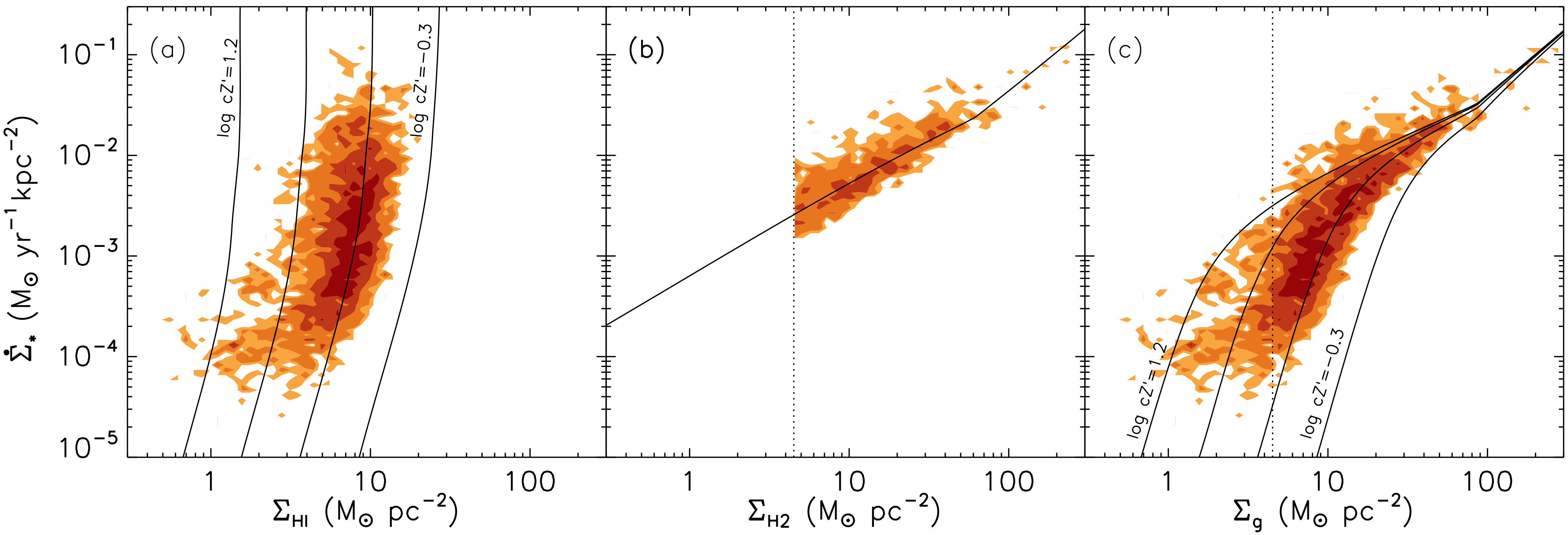
$$t_\star^0 = 2.1\,\rm Gyr$$

(controls the normalization; or equivalently, the SF efficiency.)

($n_{th} \sim 0.1$ - 1 cm^{-3})

But, no manifest dependency on metallicity

H_2 dependence of SF

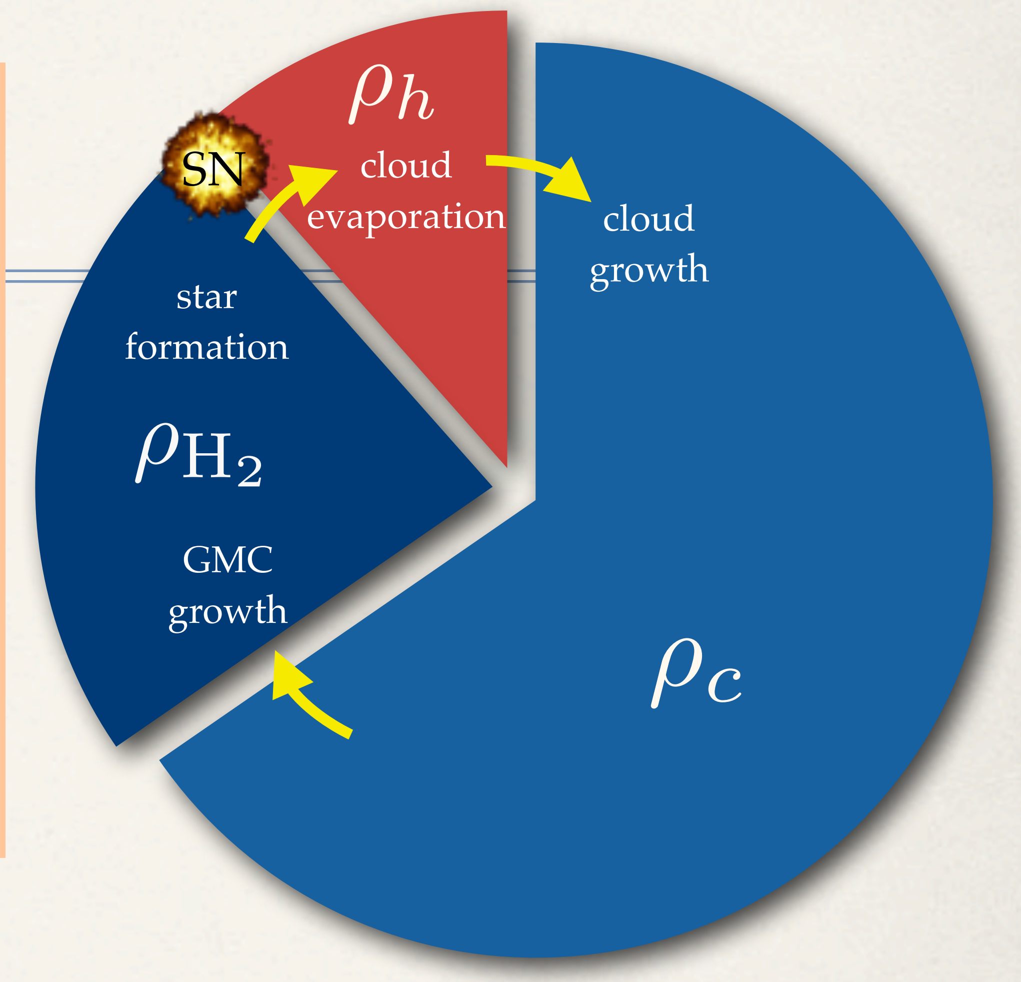


- **SF tightly correlates with molecular gas** **(e.g., Bigiel+ ’08)**
- **Spread can be understood as metallicity dependence**

(Krumholz+ ’09)

SPH implementation

- We modify the multiphase model to include the H_2 mass fraction.
- Change t_* --> *free-fall time* of the region.
- SF efficiency: $\varepsilon_{ff} = 0.01$
  (Krumholz & Tan 2007, Lada et al. 2010).



$$\dot{\rho}_* = (1-\beta)\epsilon_{ff}\frac{\rho_{H_2}}{t_*}$$

where

$$t_\star = t_{ff} = \sqrt{\frac{3\pi}{32G\rho_{gas}}}$$

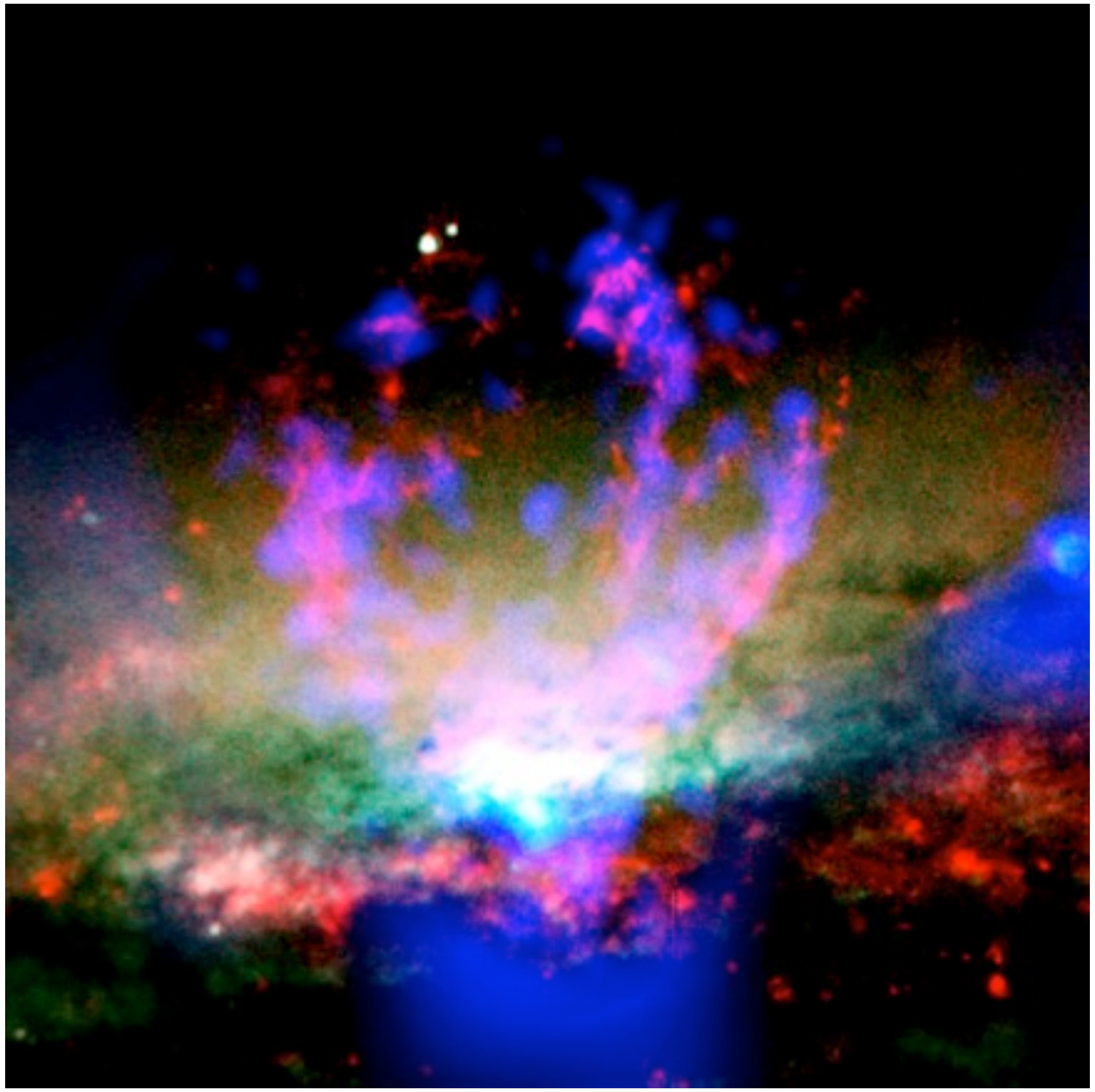
Thompson, KN+ '13

(cf. Christensen+; Gnedin+, Robertson+…..)

Prevalence of Galactic Wind Feedback

-- Pollution of Intergalactic Medium by metals

M82 Purple: $H\alpha+N_{II}$ Blue: HST, optical

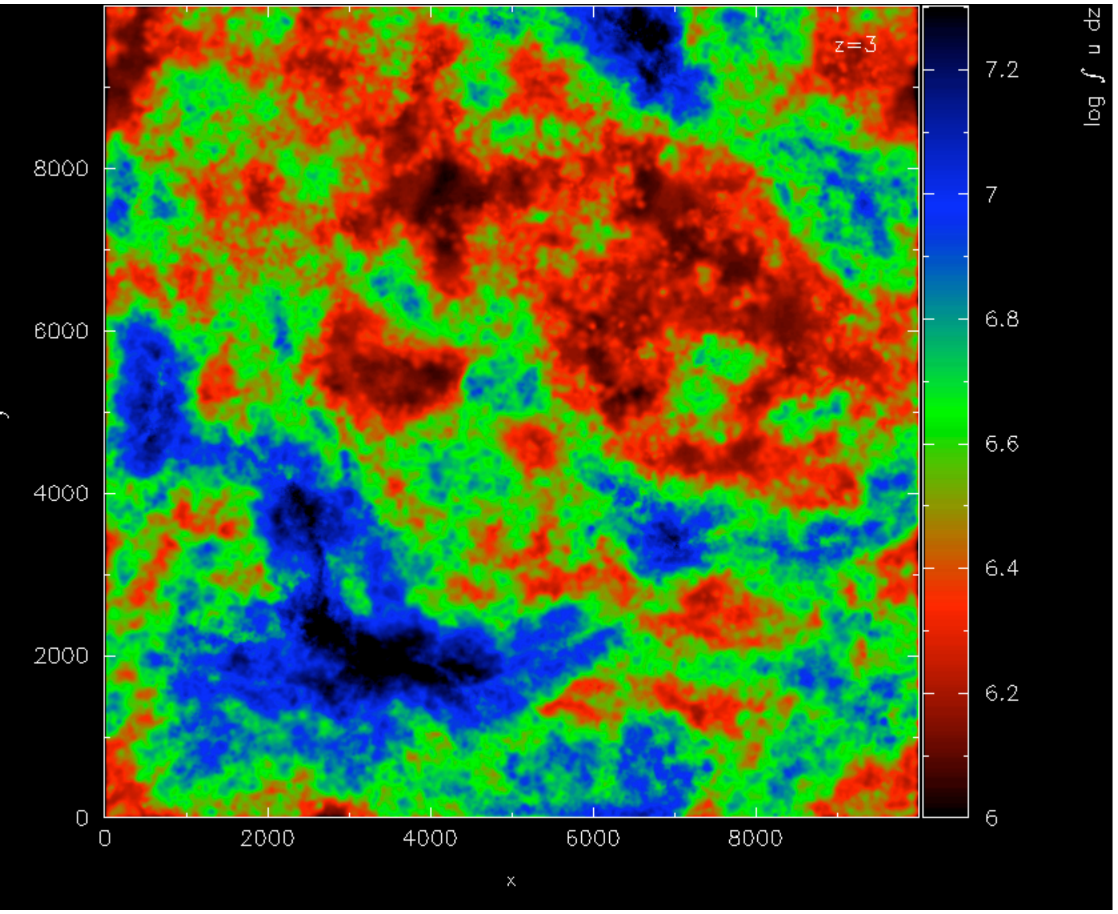


NGC3079

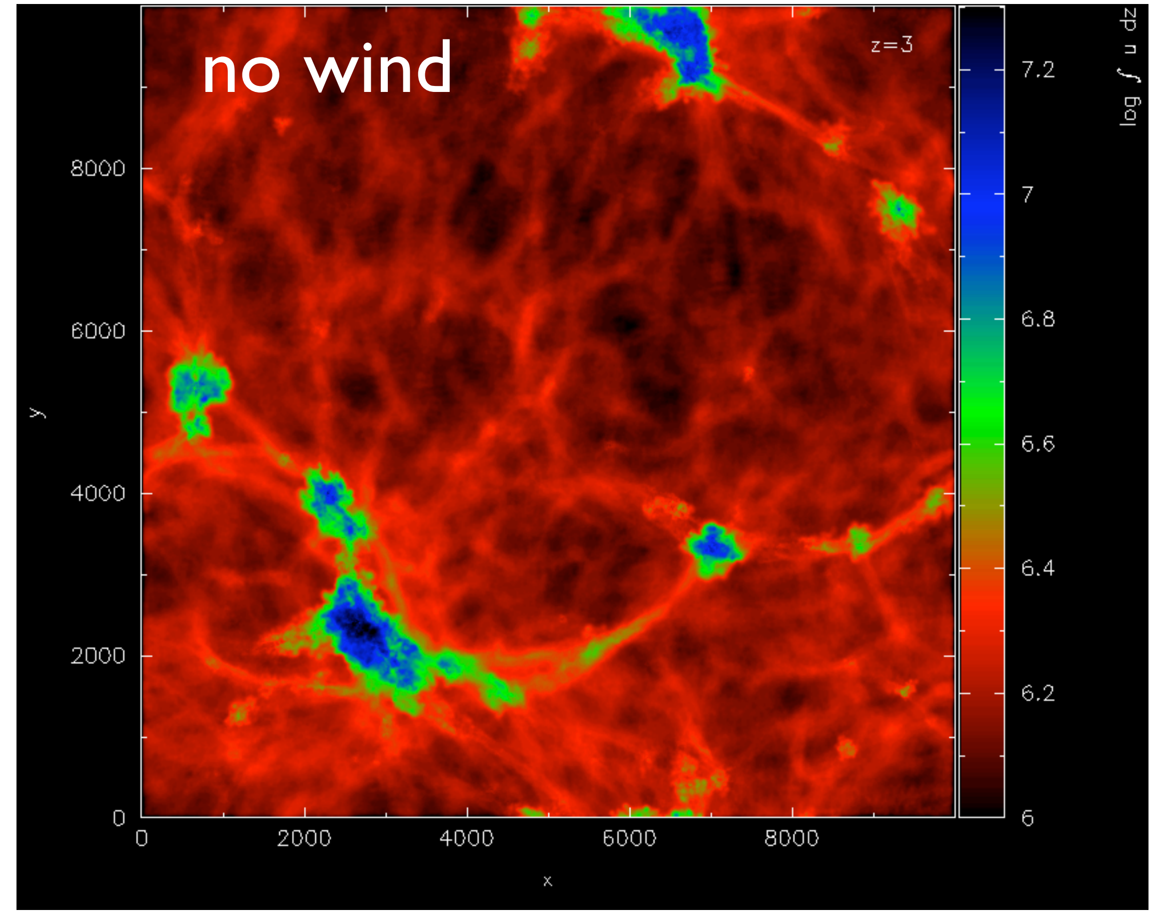
Blue: Chandra (X-ray)
Red Green: HST (optical)

SN feedback & Wind model

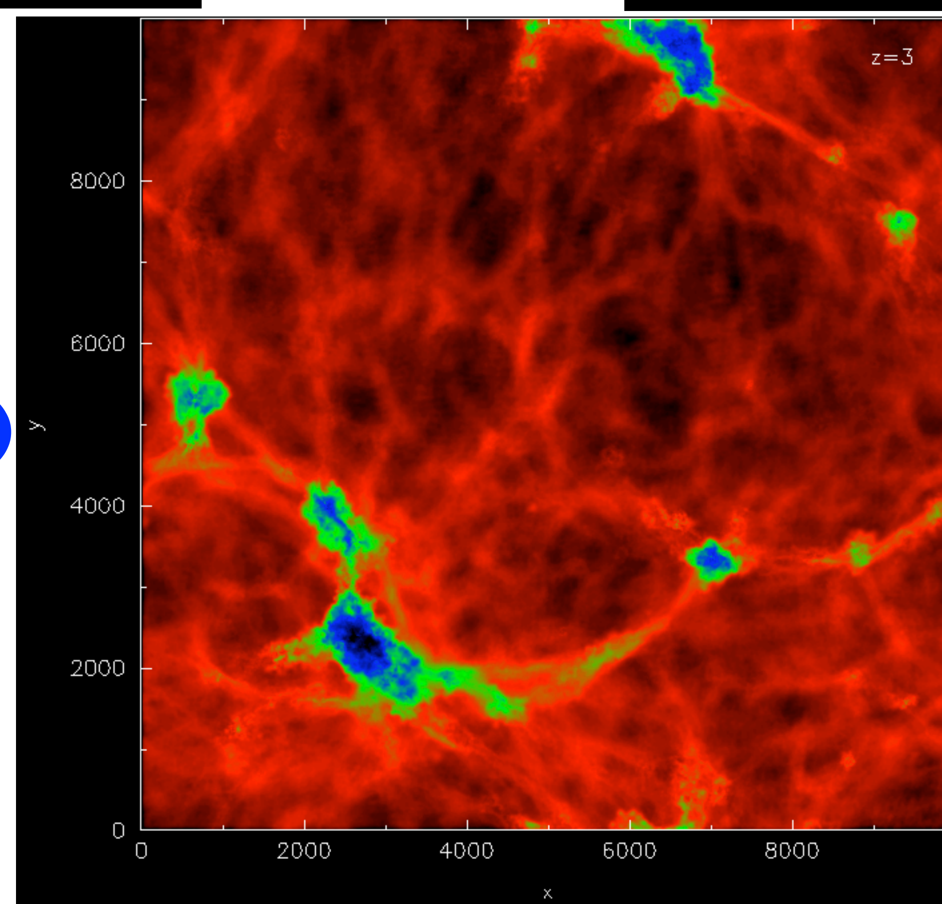
constant speed (SH03)



10 Mpc/h across



Multicomponent variable velocity (MVV) wind model (based on momentum-driven wind)

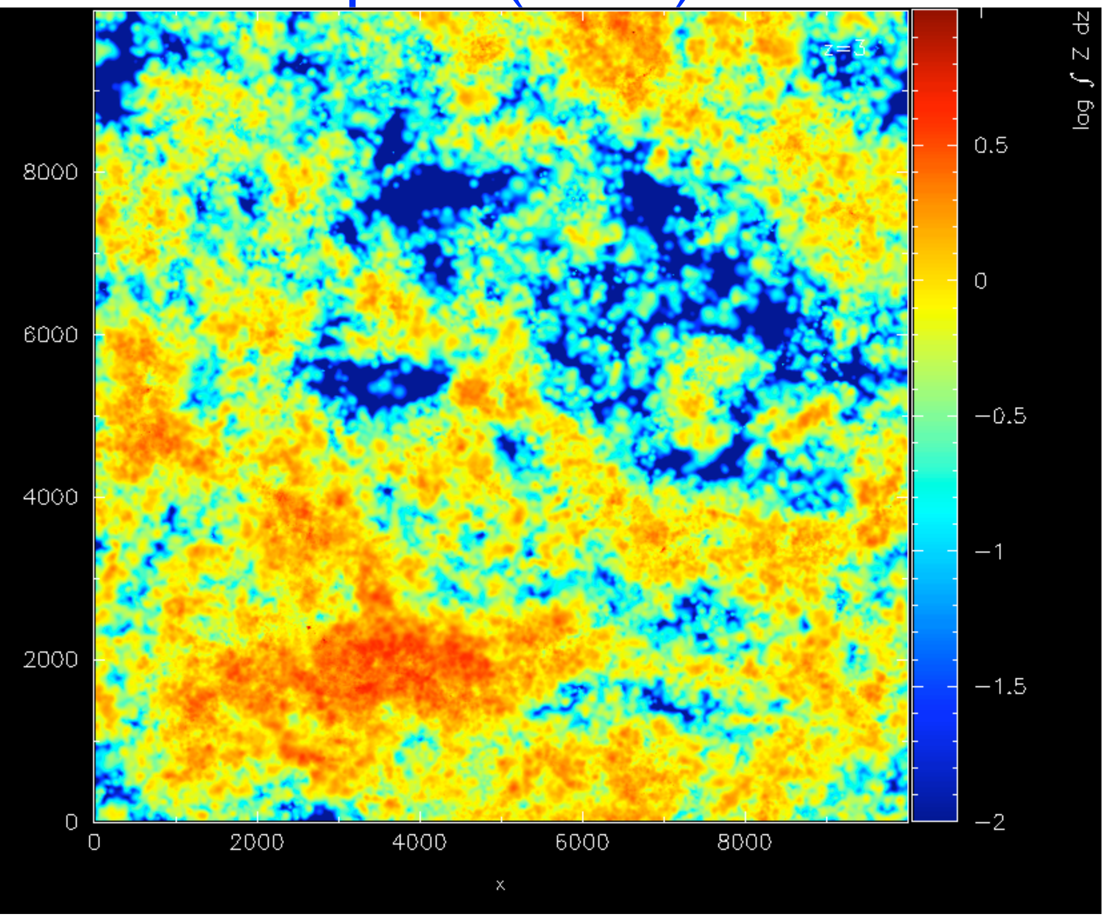


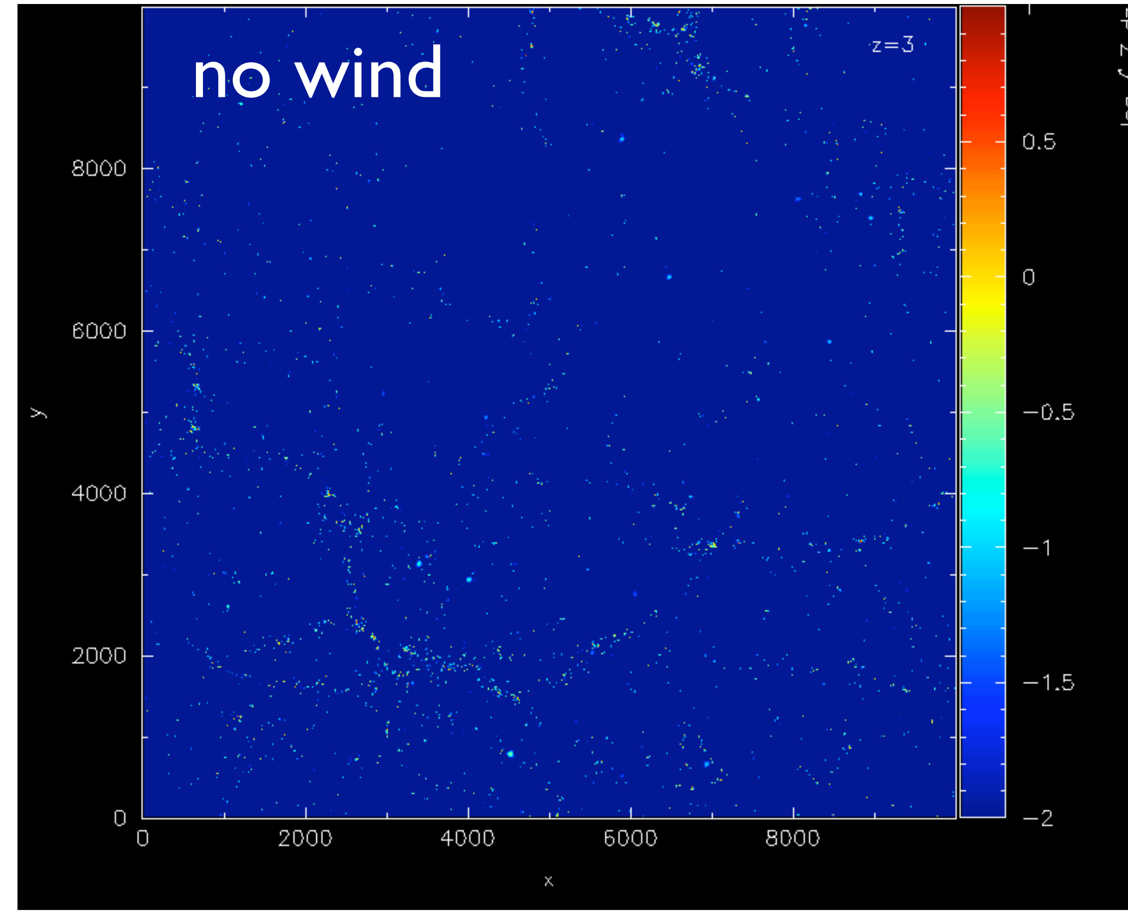
Projected internal energy (~temperature) distribution

Choi & KN '10

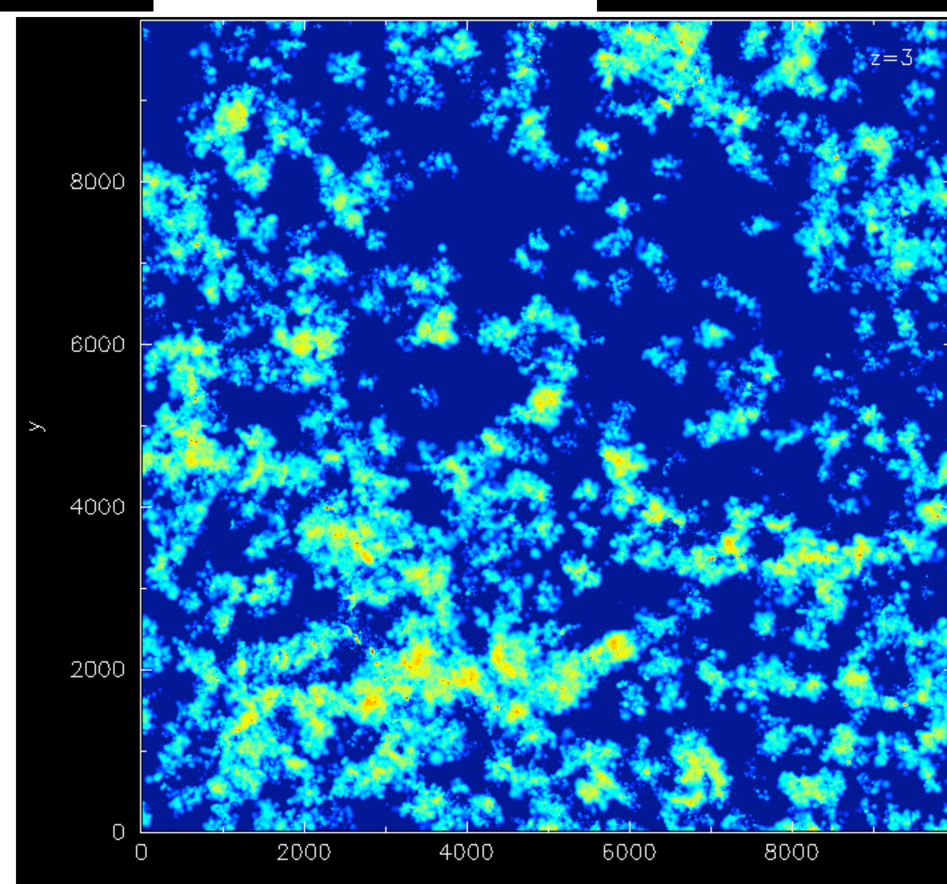
SN feedback & IGM Enrichment

constant speed (SH03)





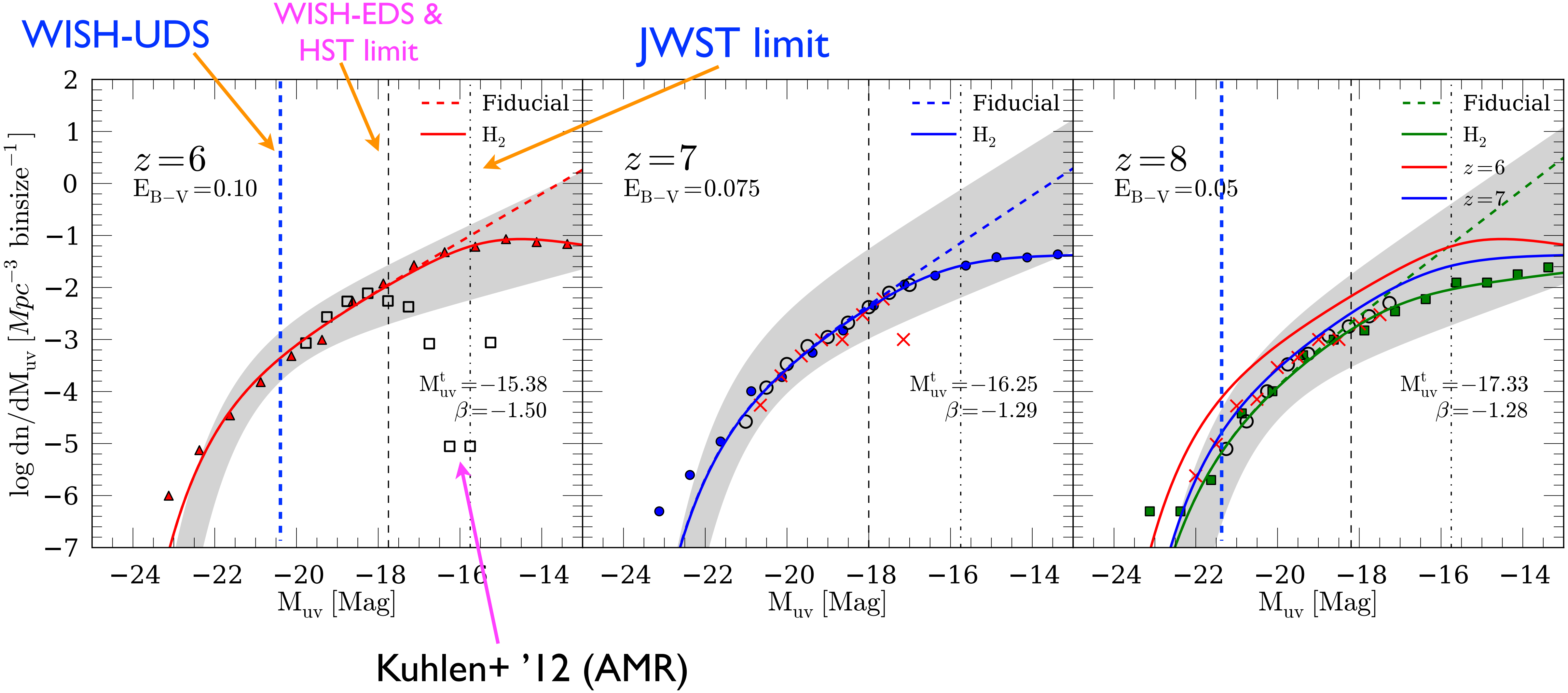
Multicomponent variable velocity (MVV) wind model (based on momentum-driven wind)



Projected metallicity distribution

Choi & KN '10

LFs with H_2-SF model



(cf. O'Shea, KN+'05: Enzo-Gadget comparison)

Modified Schechter Func.

$$\Phi(L) = \phi^* \left(\frac{L}{L^*}\right)^{\alpha} \exp\left(-\frac{L}{L^*}\right)\left[1+\left(\frac{L}{L^t}\right)^{\beta}\right]^{-1},$$

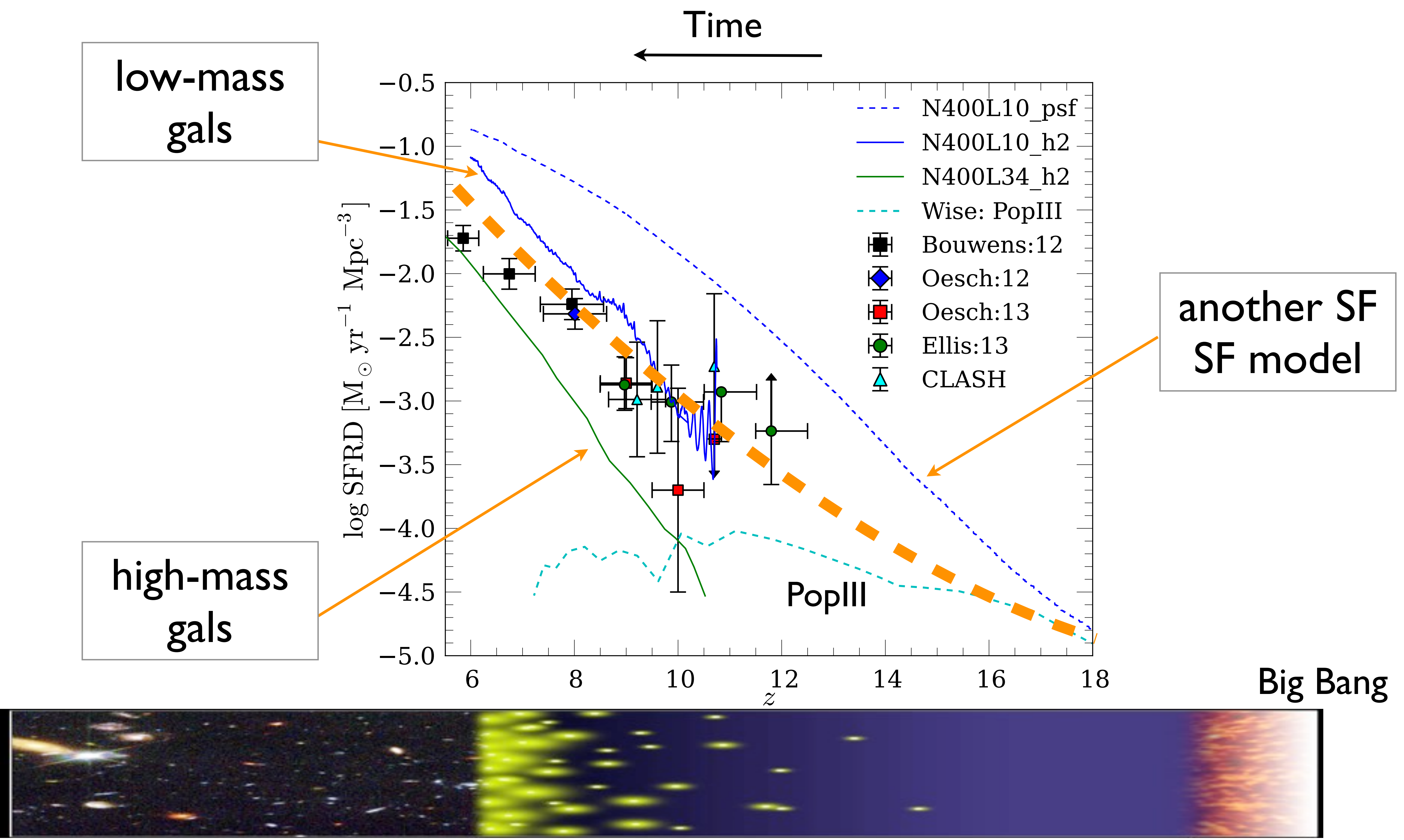
Loveday+ '97

# of low-mass gals is significantly reduced at M_{uv}>-16

Future test with JWST.

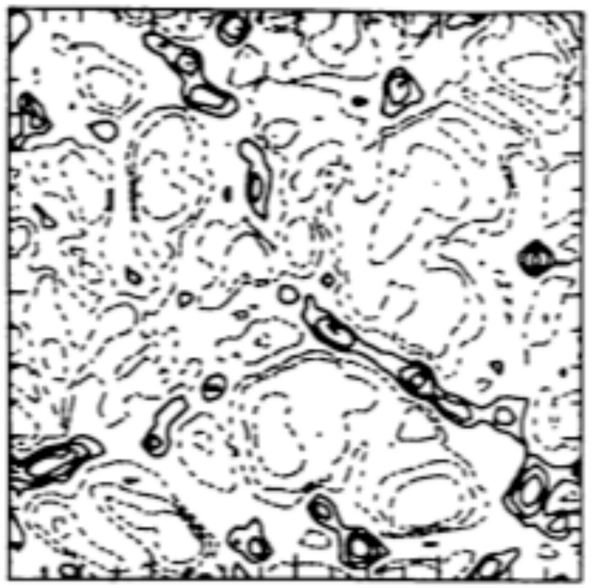
Jaacks, Thompson, KN '13

SF in the Reionization Epoch



Three Revolutions in Cosmological Hydro Simulations

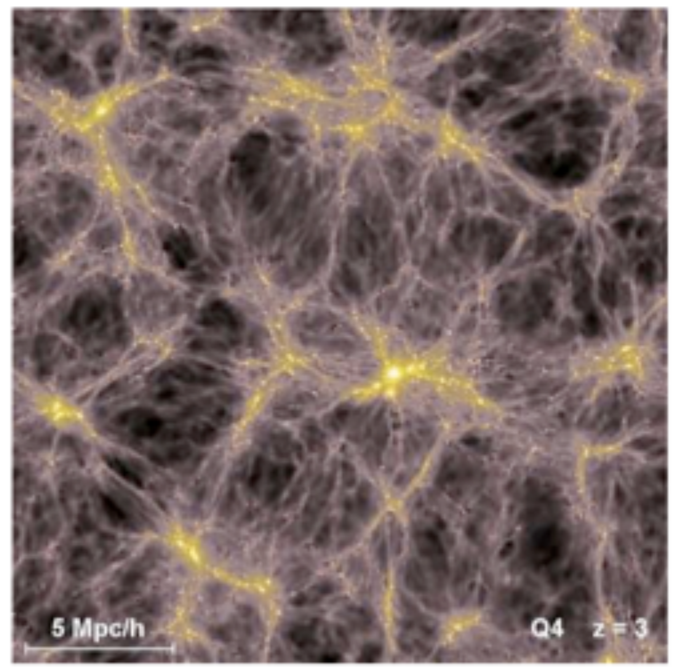
1990': 1st Revolution	2001-2011 2nd Rev.	2012~ 3rd Rev.



First cosmological, but coarse calculation

Resolution~100 kpc

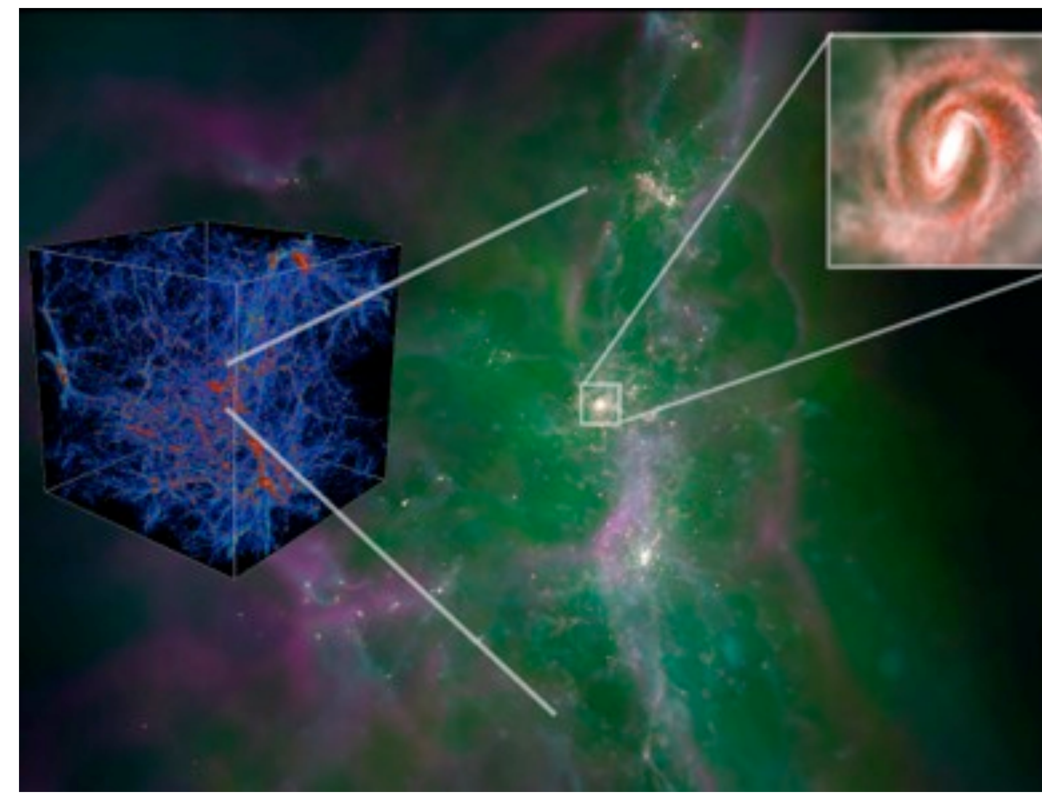
E.g., Cen '92
Katz+ '96



Larger scale, medium resolution **w. subgrid models**

Resolution~ few kpc

E.g., KN+ '01
Springel & Hernquist '03



Zoom-in method allows much higher res.

Resolution~ 20pc

What can we address w. Hydro Sims?

Cosmological (10-100 Mpc/h box)

- Large-scale structure in DM & gas (Voids, Genus)
- DM halo & galaxy distribution (2pt corr. fcn, bias)
- Intergalactic Medium (IGM) ionization (Lyα forest)
- Galaxy Mass/Luminosity/SFR/colors
- Cosmic SFR, Stellar mass density
- ……

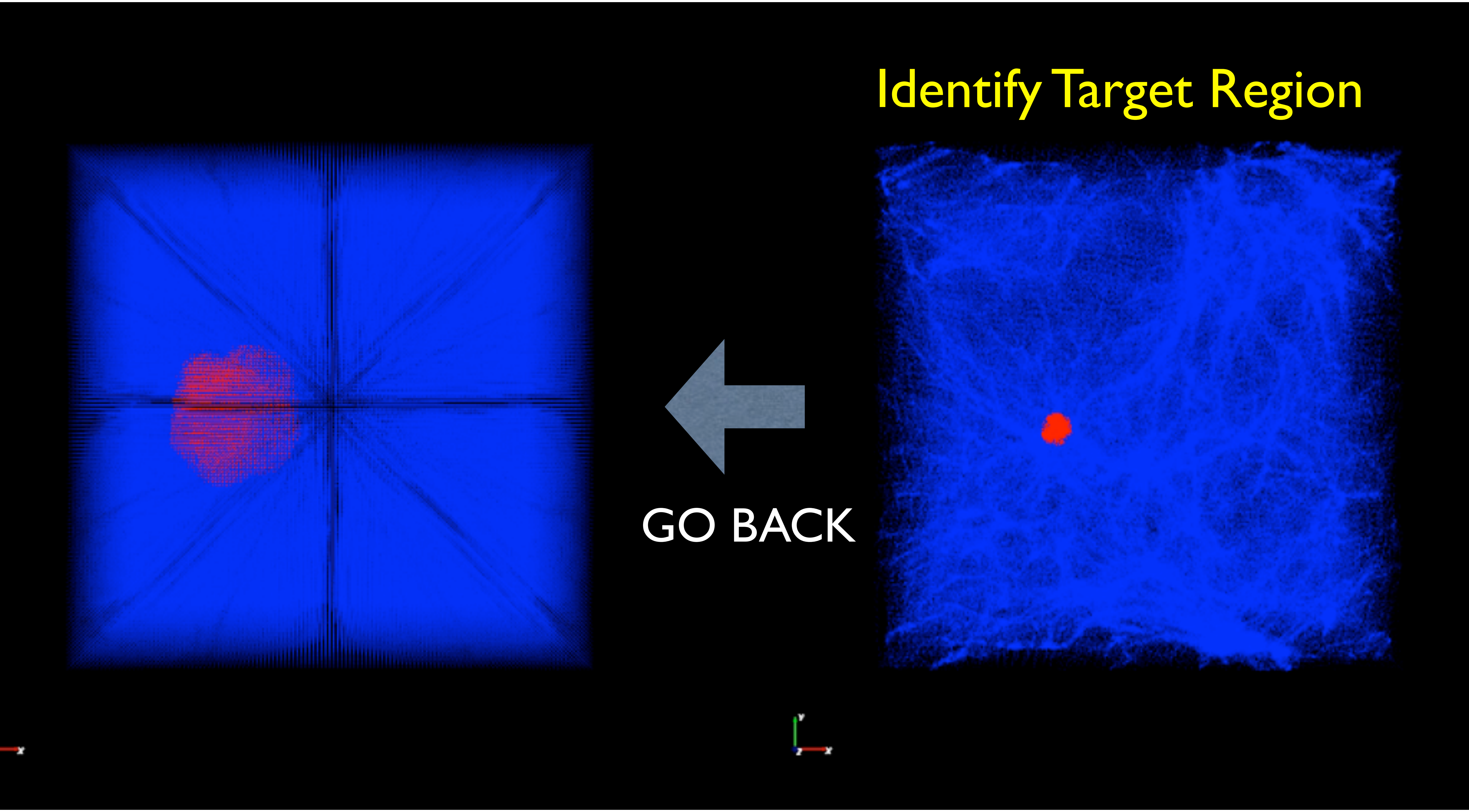
Zoom-in Sims

- Galaxy internal structure: halo, bulge, disk, circum-galactic medium (CGM)
- multiphase ISM structure
- Feedback processes: stellar wind, radiation, AGN, dust, …

3rd Revolution:

Cosmological zoom-in hydro simulations

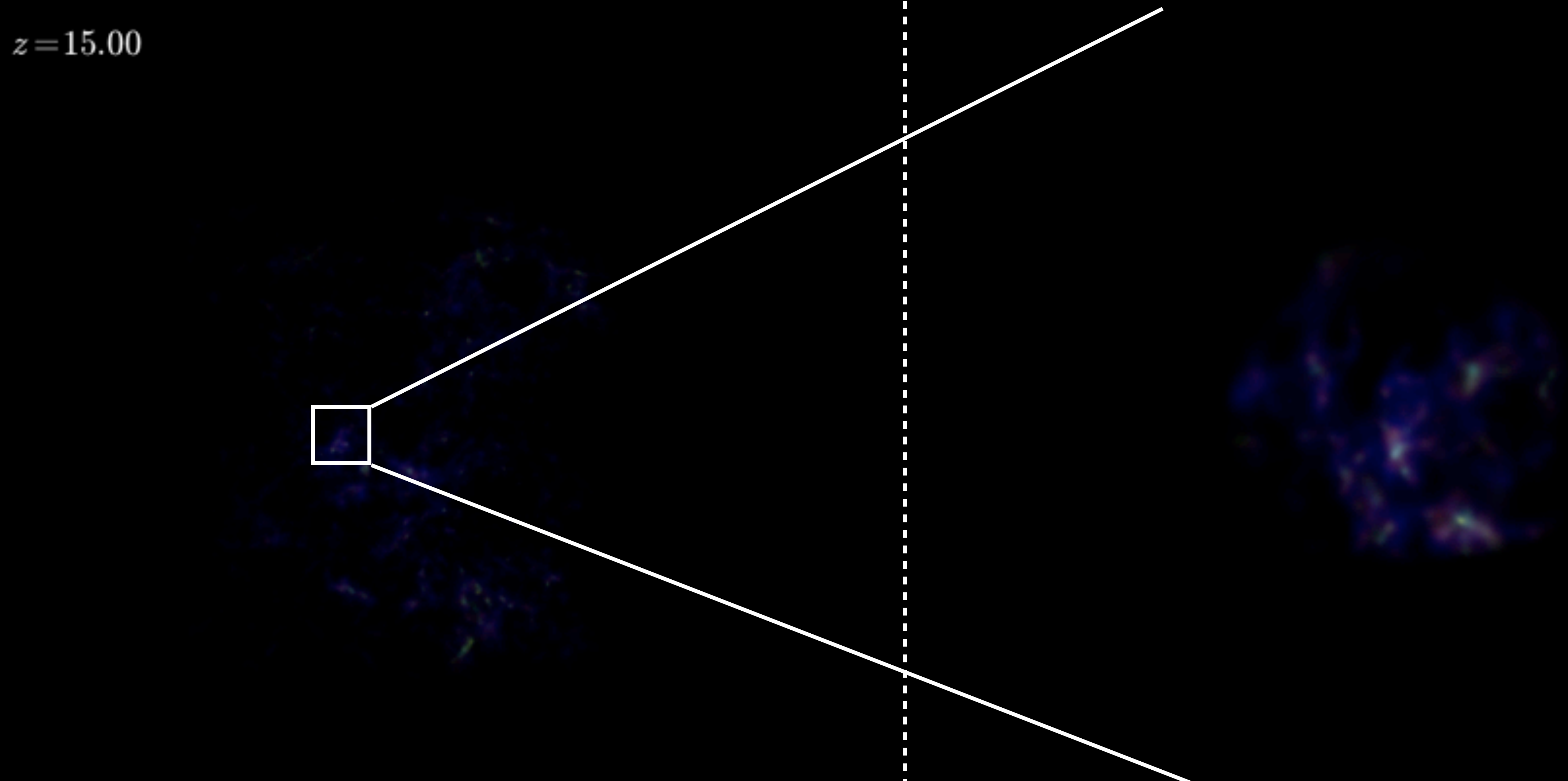
Setting Up a Zoom-in Simulation



MUSIC (Hahn & Abel '11) +
Thompson's python analyses codes

Cosmological box

Zoom-in region

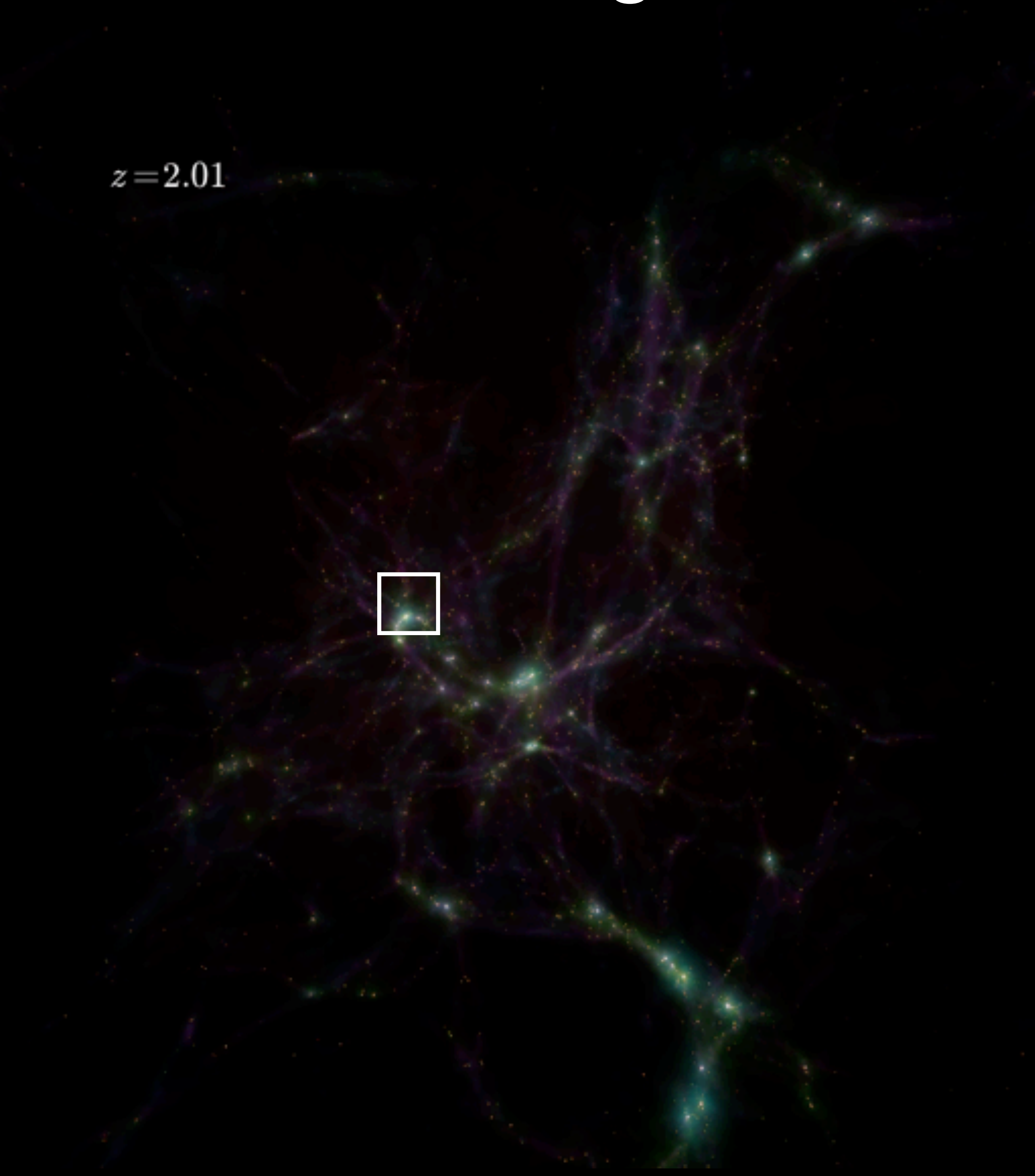


color=temperature, intensity=gas density

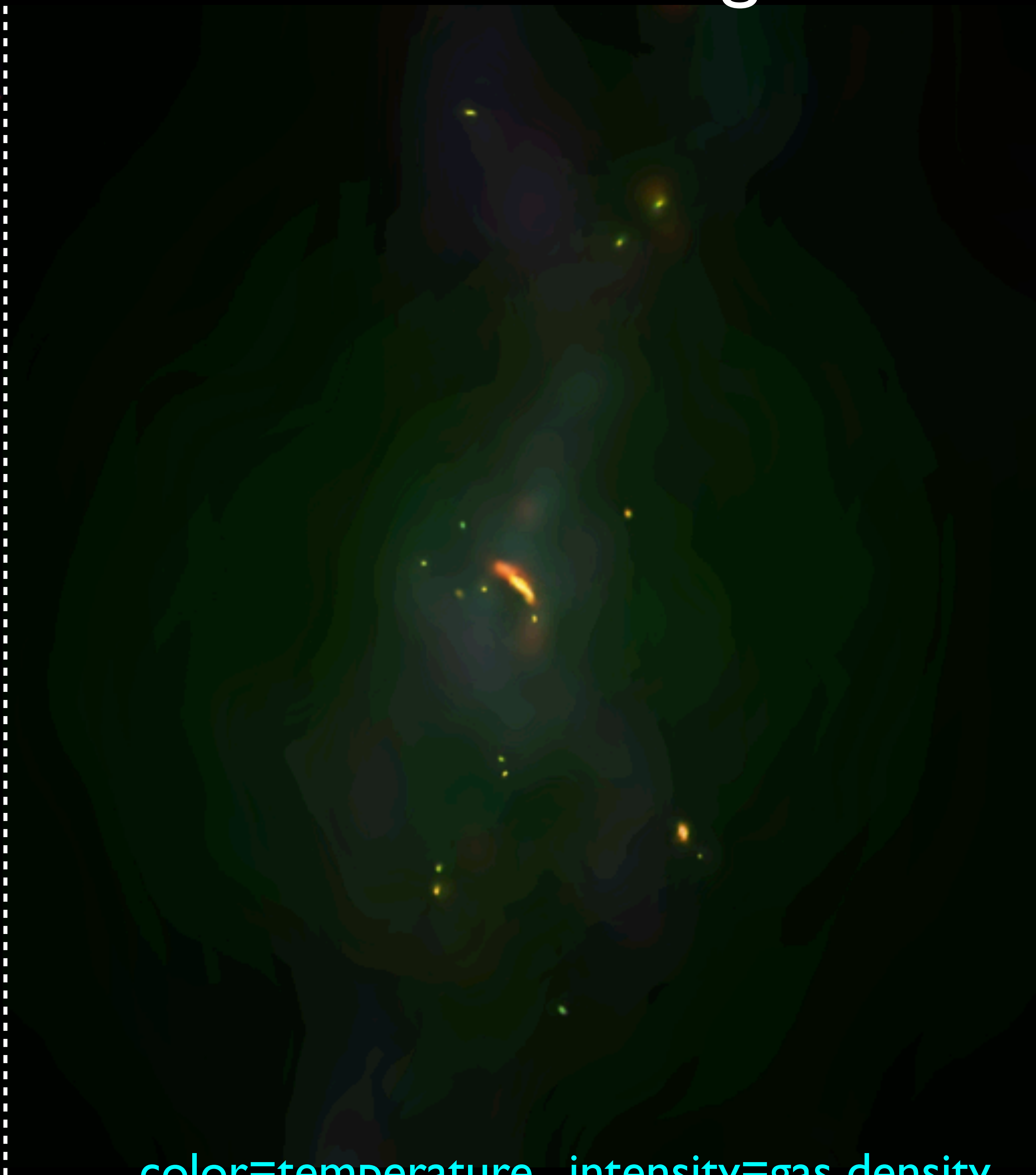
yellow dots = stars

Thompson & Nagamine '13

Cosmological box



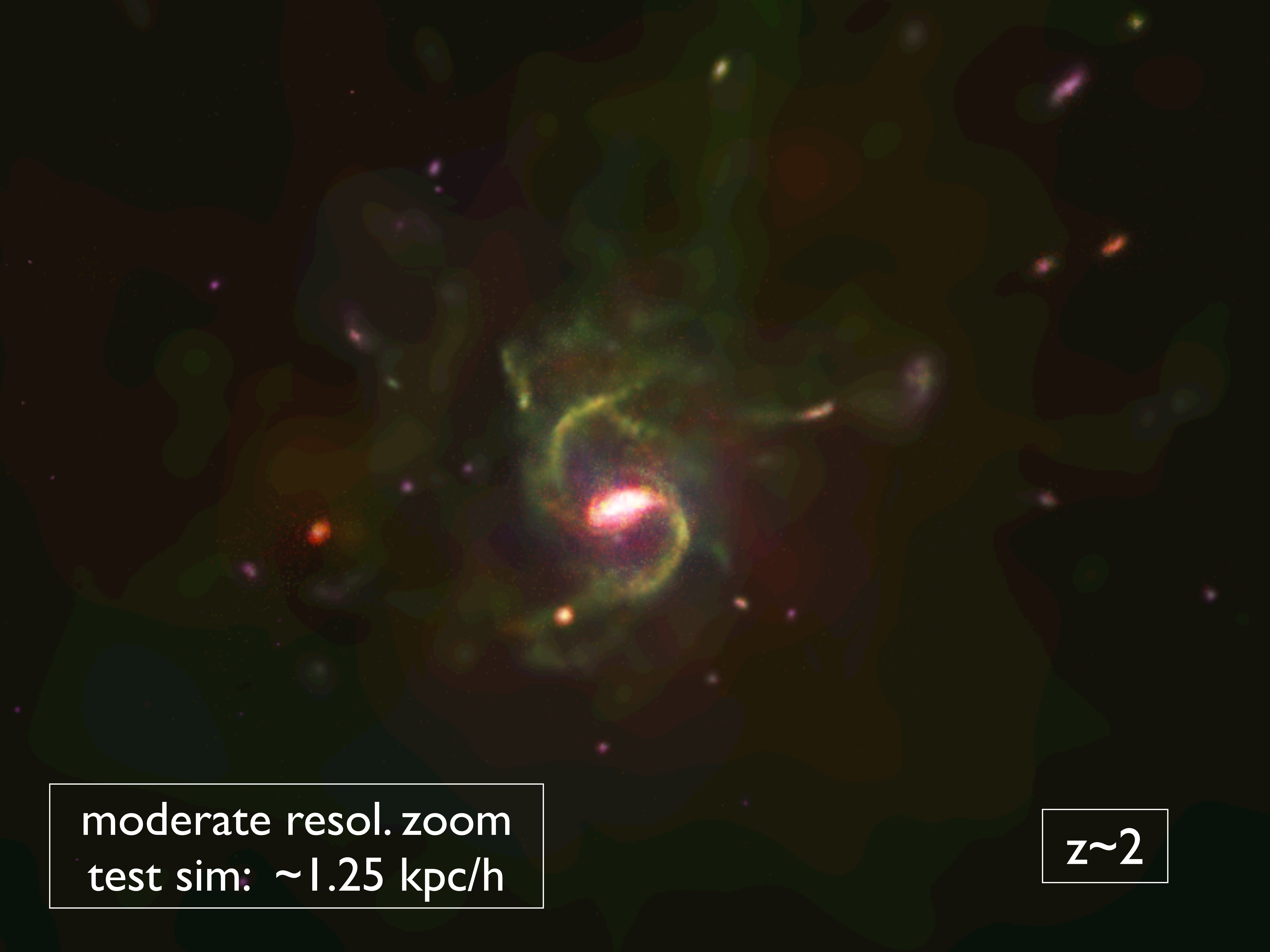
Zoom-in region

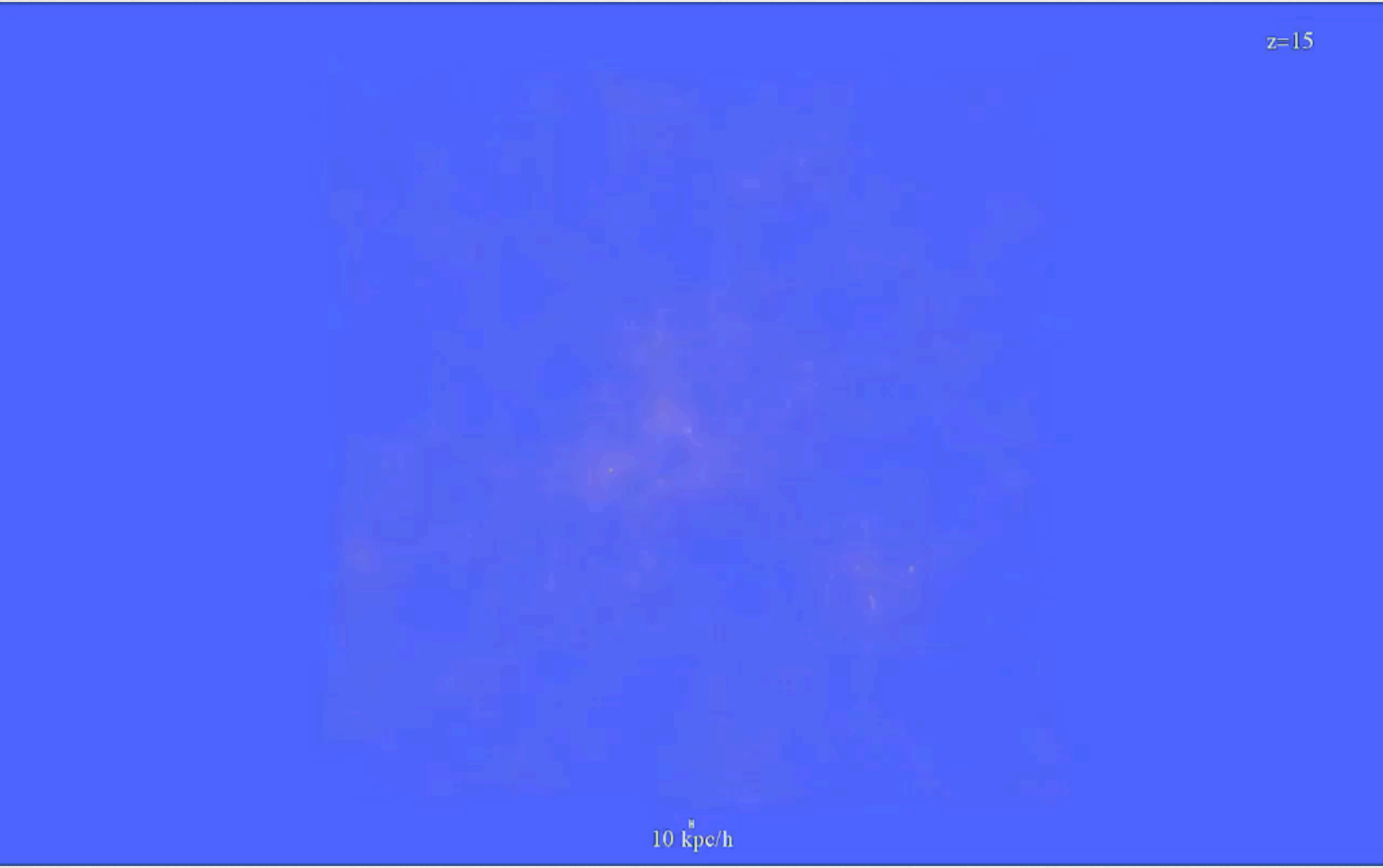


color=temperature, intensity=gas density

yellow dots = stars

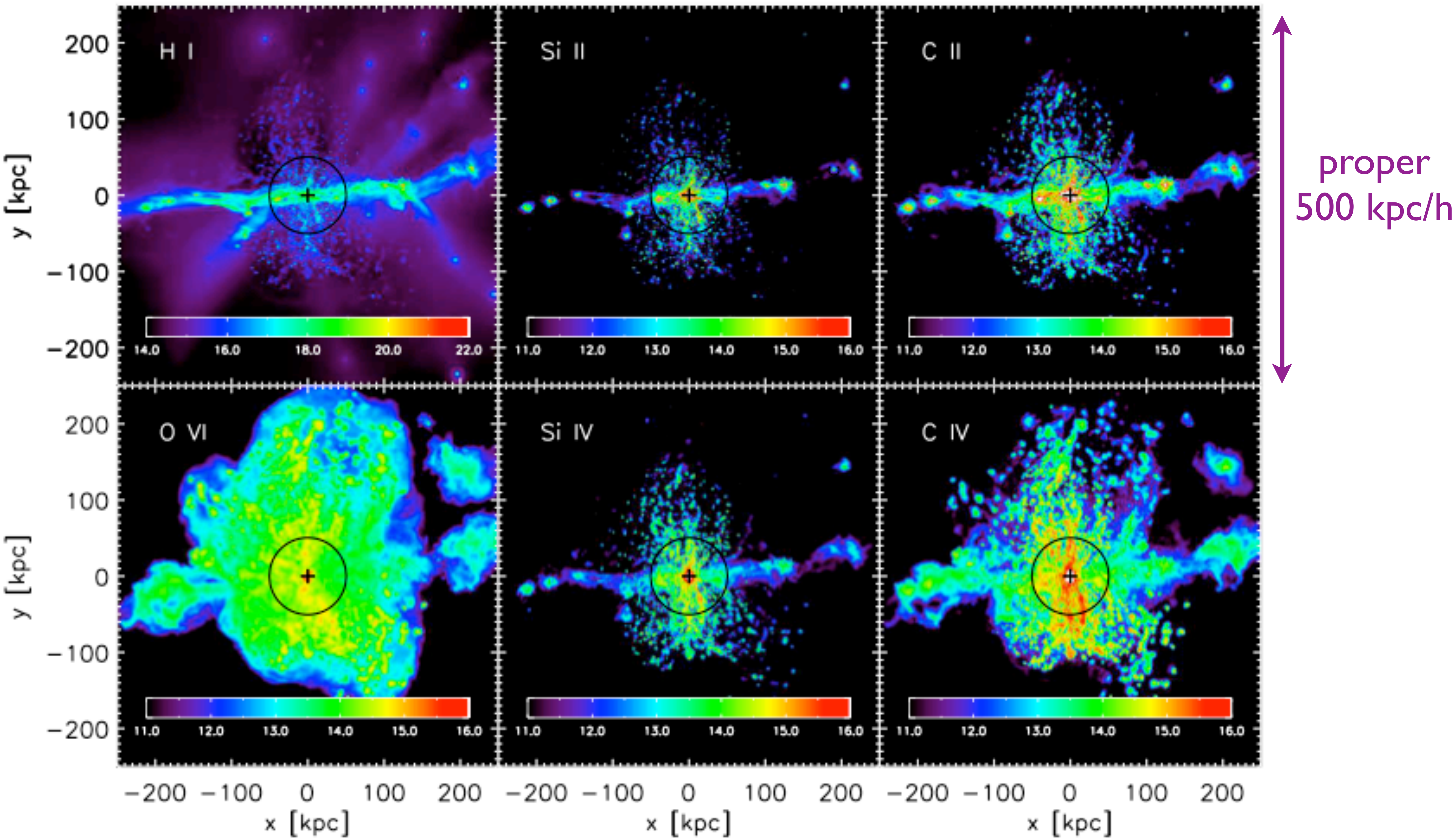
Thompson & Nagamine '13


moderate resol. zoom
test sim: ~1.25 kpc/h
z~2


z=15
10 kpc/h

Circum-galactic medium (CGM)

(can be probed by quasar absorption lines)

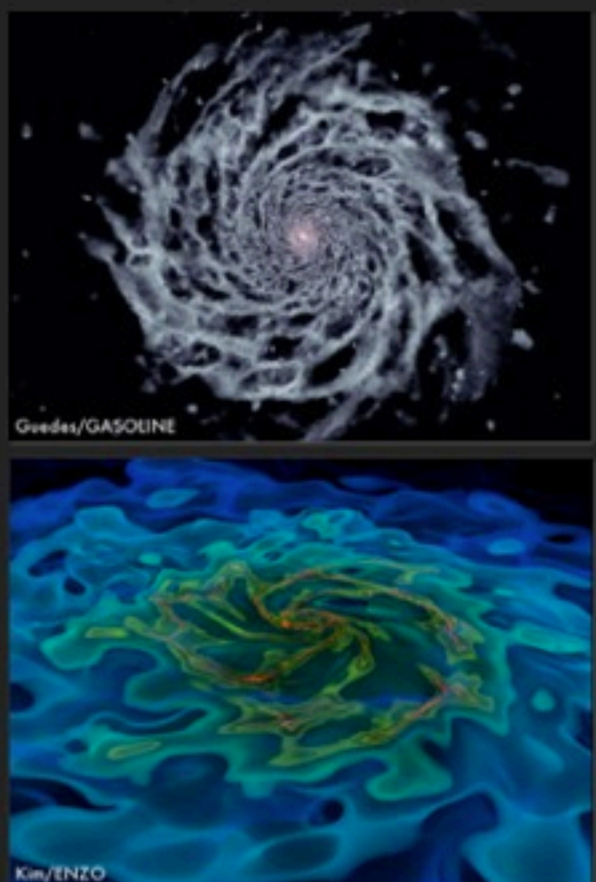


z=2.8 Eris2 zoom-in simulation (Shen+ '13)

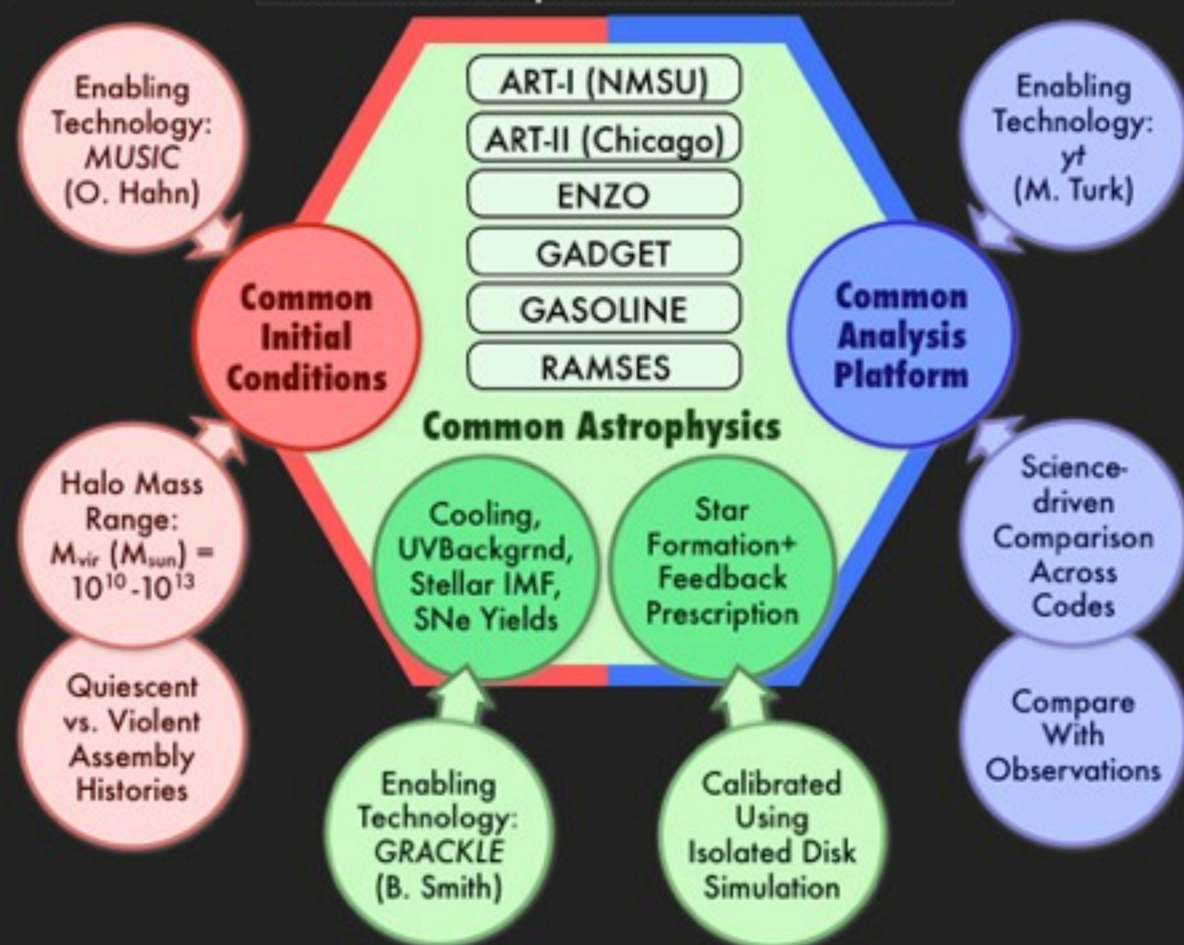
AGORA

A High-resolution Galaxy Simulations Comparison Initiative: www.AGORAsimulations.org

High-res Galaxy Simulations



AGORA Comparison Infrastructure



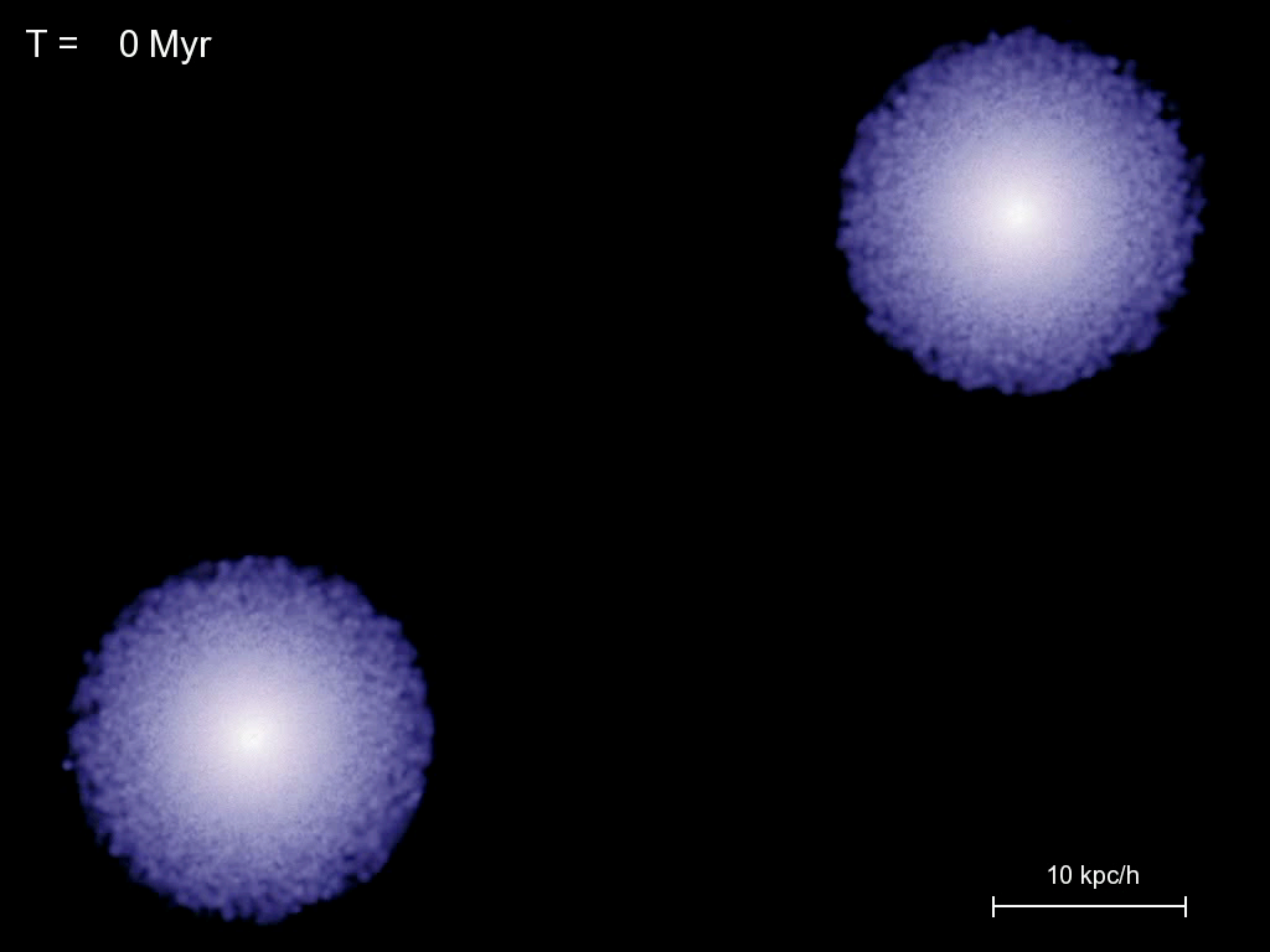
AGORA Goal & Team

- GOAL: A collaborative, multi-platform study to raise the realism and predictive power of galaxy formation simulations
- TEAM: 94 participants from 47 institutions worldwide, Aug. 2013
- DATA SHARING: Simulations outputs and analysis softewares will be shared with the community

- Contact: santacruzgalaxy@gmail.com
- AGORA First light: First paper by Ji-hoon Kim et al. (arXiv:1308.2669)
- Project funded in part by:

www.AGORAsimulations.org

Kim+ ’13 (arXiv:1308.2669)


T =   0 Myr
10 kpc/h

Galaxy Merger Simulations

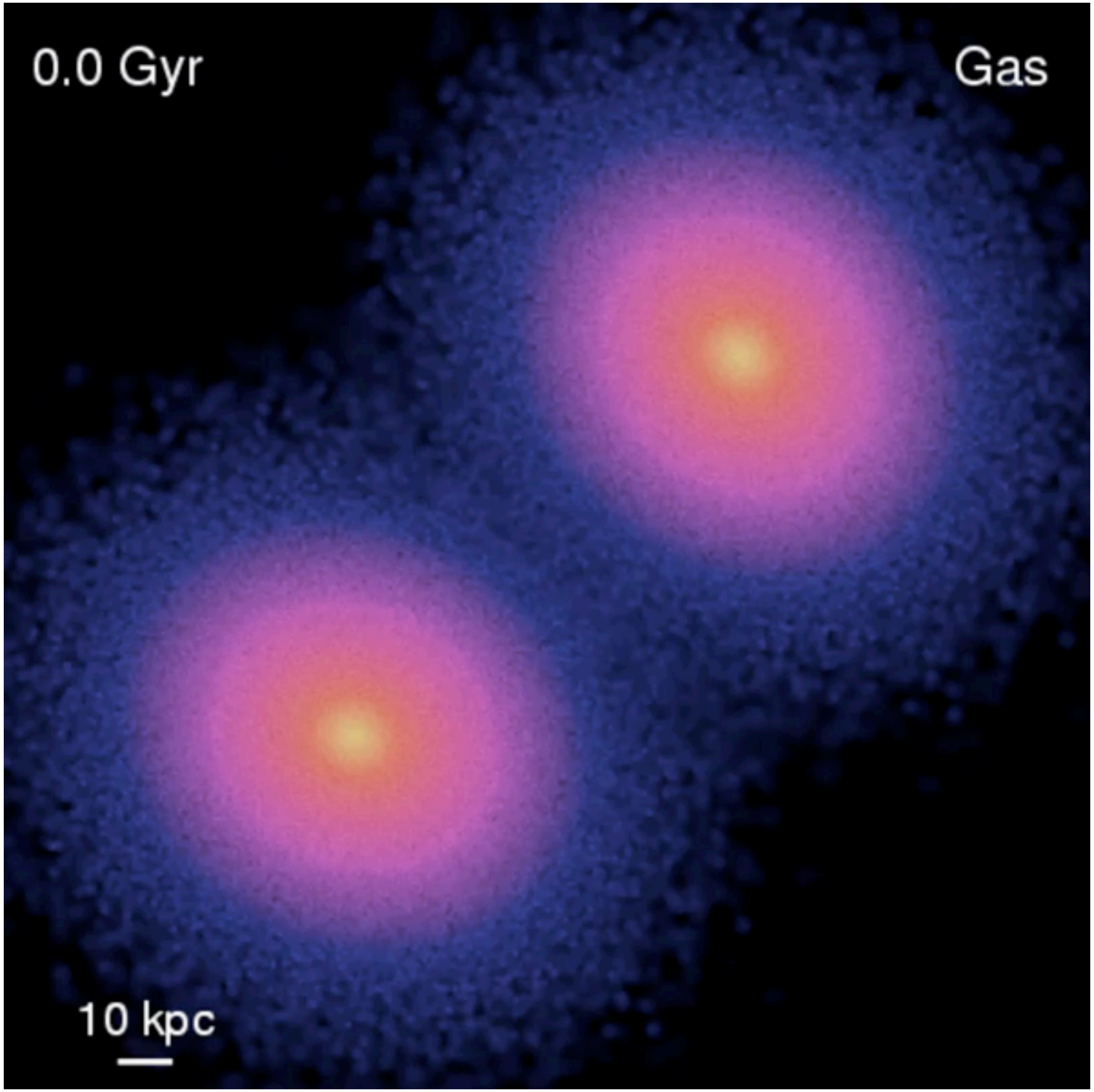
Springel+ '05; Di Matteo+….

Stellar Feedback:
radiation pressure, direct momentum (stellar wind), shock heating, photoionization heating

But, this is not in cosmological context.

Resolution:

$m_p \lesssim 1000 M_\odot$, $\varepsilon \sim 3$pc



Hopkins+ '13
(GADGET SPH)

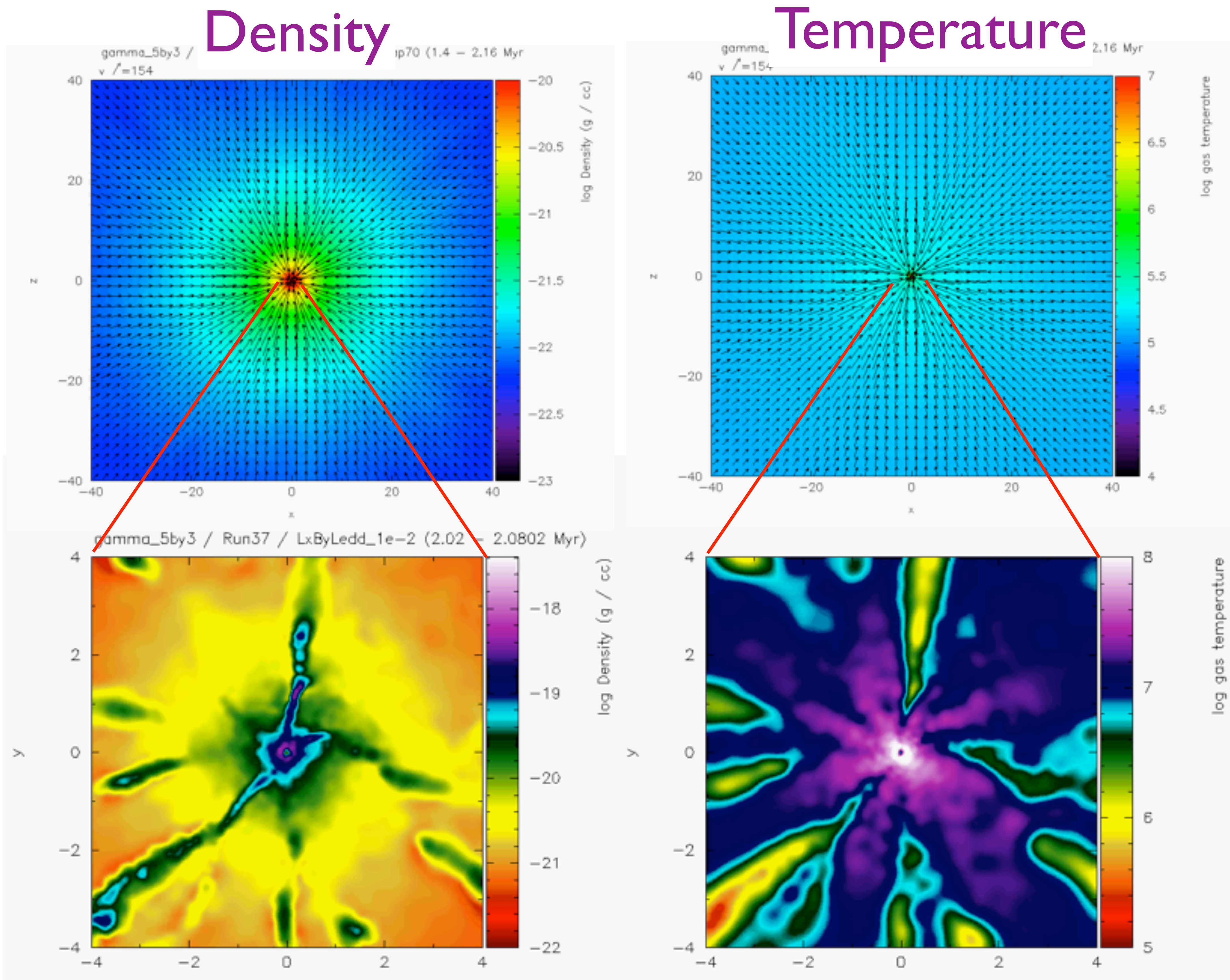
Accretion onto Supermassive Black Hole

w. radiation feedback

Barai, Proga, KN '11

inner ±40pc

inner ±4pc



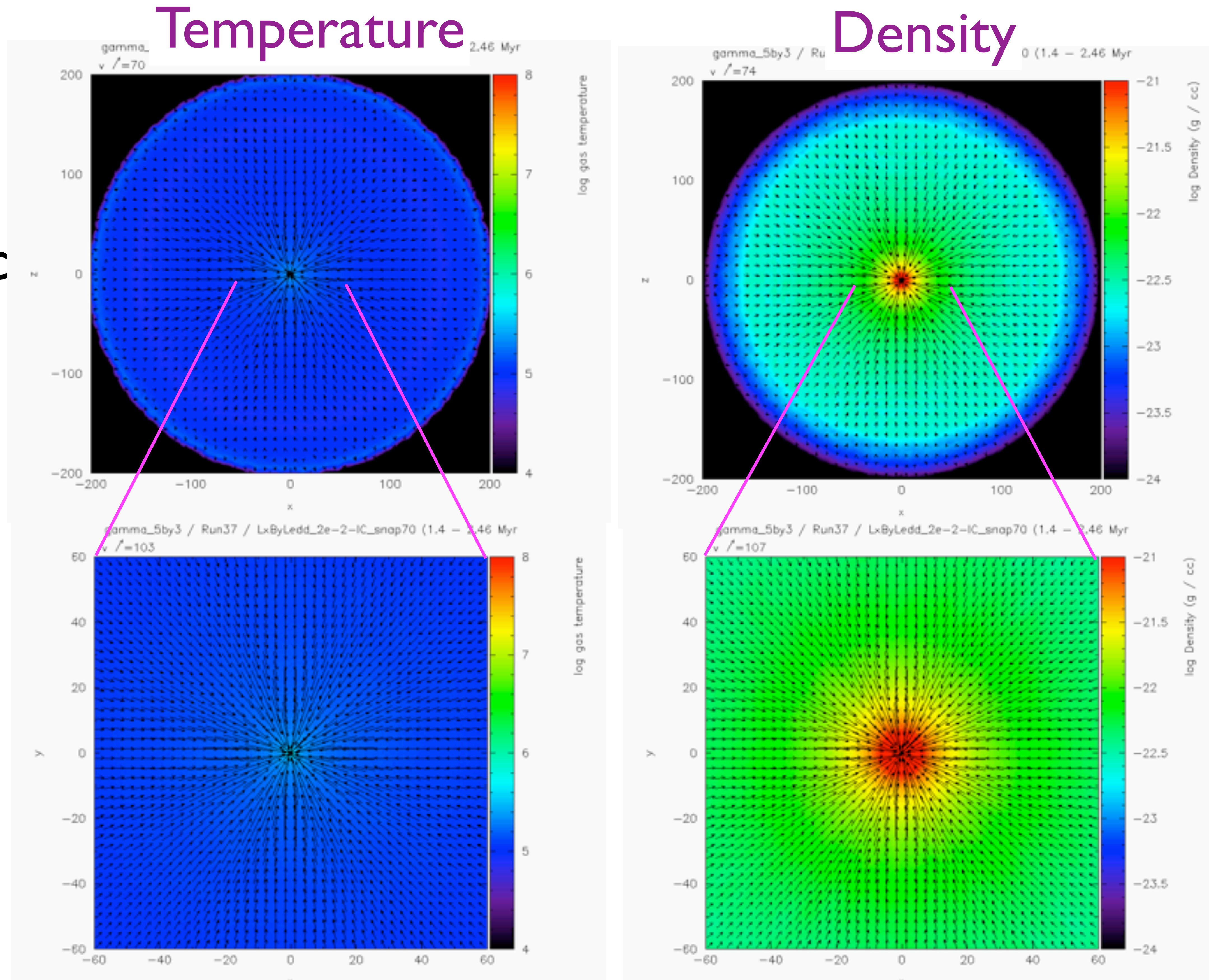
Accretion onto Supermassive Black Hole

w. radiation feedback

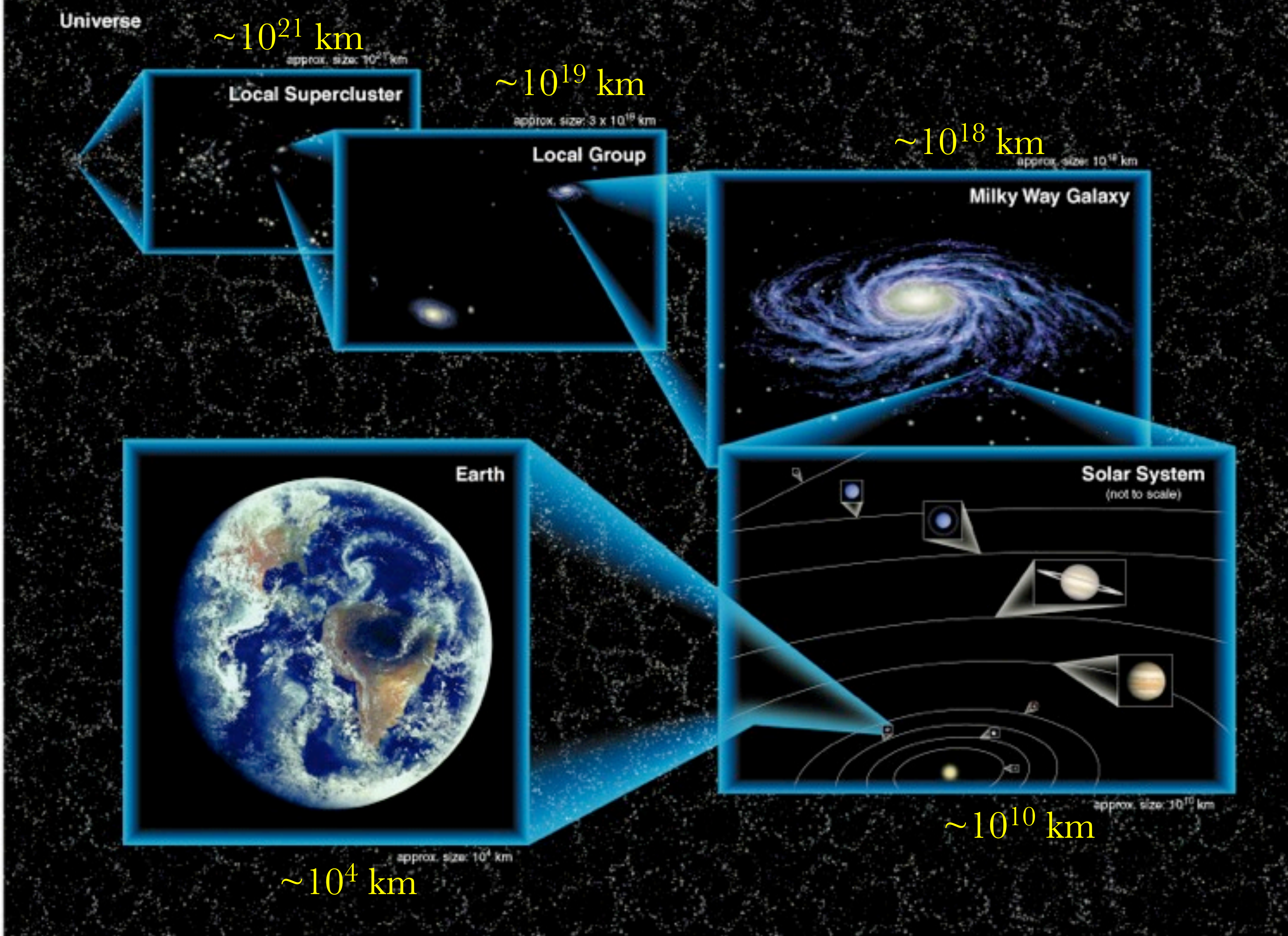
Barai, Proga, KN '11

± 200pc

inner ±60pc



Hierarchical Structure in the Universe



Dept. of Earth & Space Science

(宇宙地球科学専攻)

Universe

Theoretical Astrophysics (Nagamine)

IR Astronomy (Shibai)

Xray Astro (Tsunemi)

Earth & Planet

Kondo

Sasaki

Terada

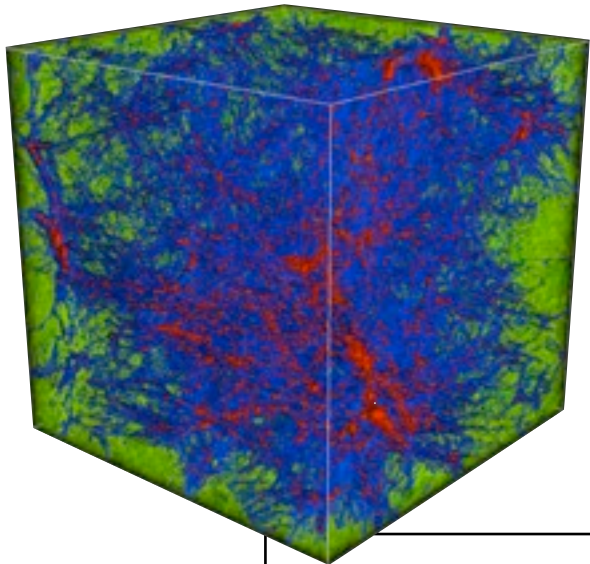
Nakashima

Material

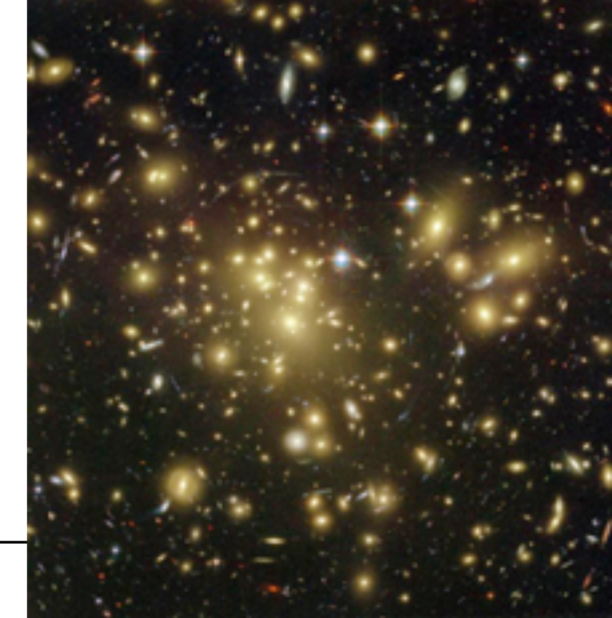
Theoretical Condensed Matter (Kawamura)

Life

Physical Geochemistry (Nakashima)



Theoretical Astrophysics Group



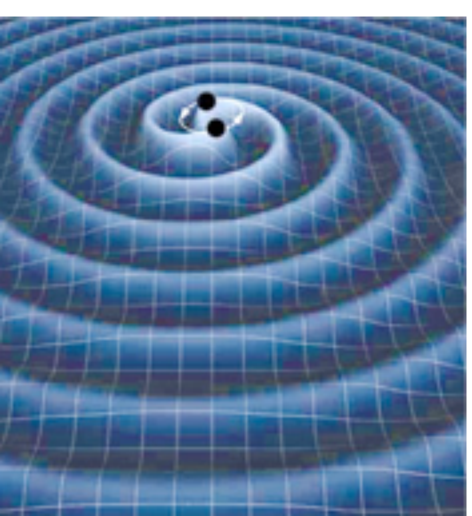
Nagamine
Cosmology &
Structure Formation

Fujita
High-energy Astrophysics
Galaxy Clusters, Cosmic Ray
Acceleration

KAGRA

Tagoshi
Gravitational Wave
Astronomy
KAGRA data analysis

Tsuribe
Star Formation,
Protoplanetary Disks



Conclusions & Future

- **Cosmology** is a mature field with ample data.
- \`**Computational Cosmology**' provides a vision of **nonlinear structure formation**
- *Both* full-box & zoom-in cosmo runs are useful.
- More work on Star Formation & Feedback (from MS, SN & BHs) towards 2020.
- Challenges: color bimodality, downsizing (gal & AGN), gal--SMBH coevolution, etc.

UNLV

大阪大学
OSAKA UNIVERSITY