Cosmology, structure formation, and the first stars

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First Frontiers Summer School

www.alexji.com/Ji_FFSS2019.pdf

Buzzword List

A

- Dark matter
- Dark energy
- Baryon
- Scale factor
- Redshift
- Hubble Constant
- CMB, Planck
- BBN
- Lithium problem

B

- Structure formation
- Dark matter halo
- Galaxy formation
- Halo mass function
- Stellar mass function
- Feedback
- N-body simulation
- Hydro simulation
- [Reionization]

C

- Pop I, II, III stars
- Stellar archaeology
- CEMP stars
- [C]EMP-no, -r, -i, -s
- Stellar halo
- Dwarf galaxies
- Spinstars
- Mixing and fallback SN
- Type II, Type Ia supernova

Outline

Large scales

- Spherical cosmology
  - Expansion history
  - Big Bang Nucleosynthesis
- Structure formation and galaxy formation
- The First Stars and metal-poor star abundances

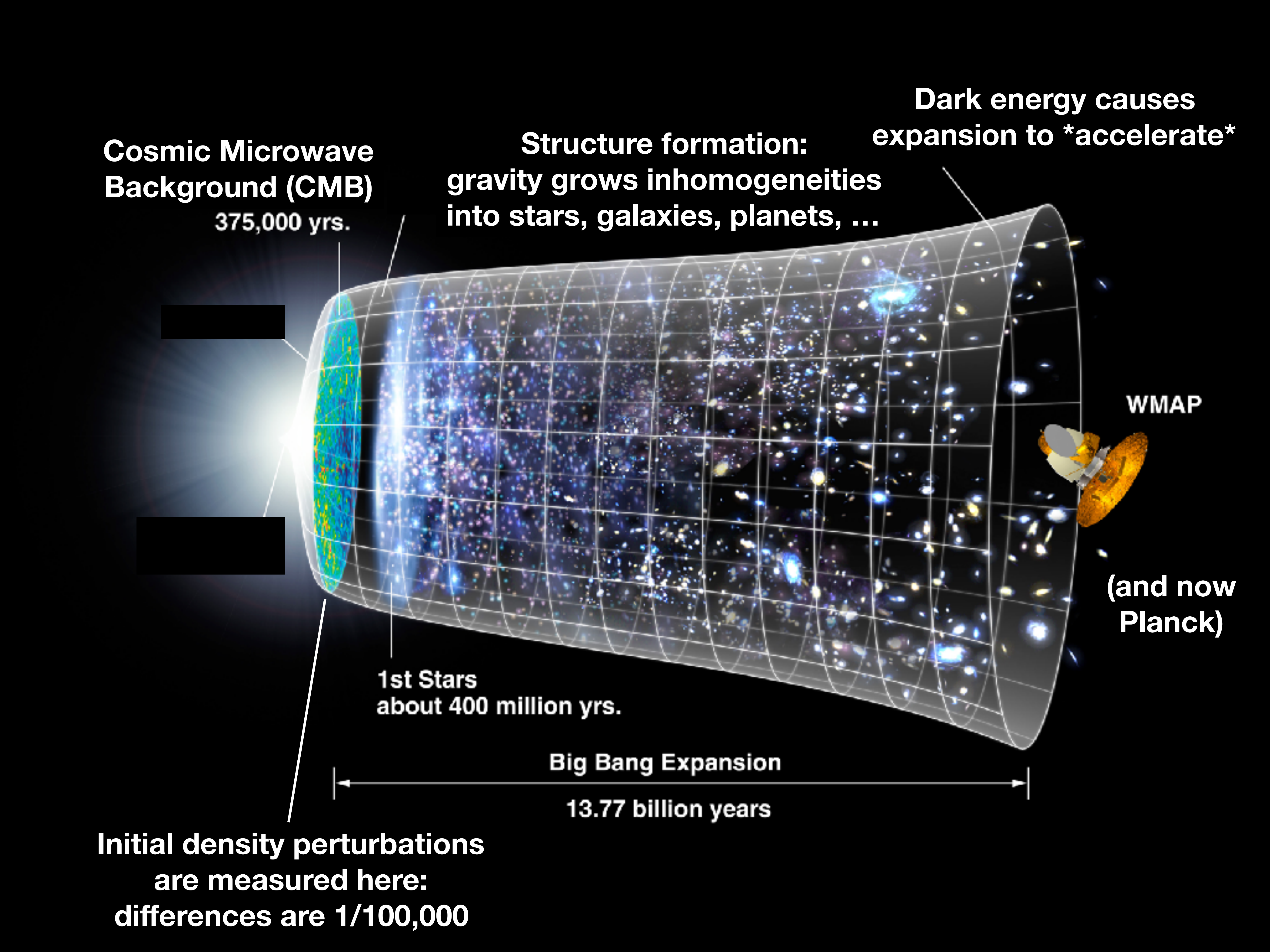
Small scales

Astronomical Distances

Large scales

- Gigaparsec (Gpc): size of universe — **3.1e25 m**
- Megaparsec (Mpc): size between large galaxies — **3.1e22 m**
- kiloparsec (kpc): size of galaxies — **3.1e19 m**
- parsec (pc): size between stars — **3.1e16 m** — **3.3 lightyear**
- astronomical unit (AU): size between planets — **1.5e11 m** — **8.3 lightmin**
- Solar radius ($R_{\odot}$): size of stars — **7.0e8 m**
- Jupiter radius (R_J): size of gas planets — **7.0e7 m**
- Earth radius ($R_{\oplus}$): size of rocky planets — **6.4e6 m**
- Neutron stars — **~1.0e4 m**

Small scales



Cosmic Microwave Background (CMB)
375,000 yrs.
Structure formation: gravity grows inhomogeneities into stars, galaxies, planets, …
Dark energy causes expansion to *accelerate*
[redacted]
[redacted]
WMAP
(and now Planck)
1st Stars about 400 million yrs.
Big Bang Expansion
13.77 billion years
Initial density perturbations are measured here: differences are 1/100,000

Universe timeline

Event	Redshift	Time
Big bang	z = infinity	t=0
Big bang nucleosynthesis	z ~ 3e9	~3 min
Matter-radiation equality	~3380	~50 kyr
Cosmic microwave background	z~1100	~370 kyr
First stars	z~25	~130 Myr
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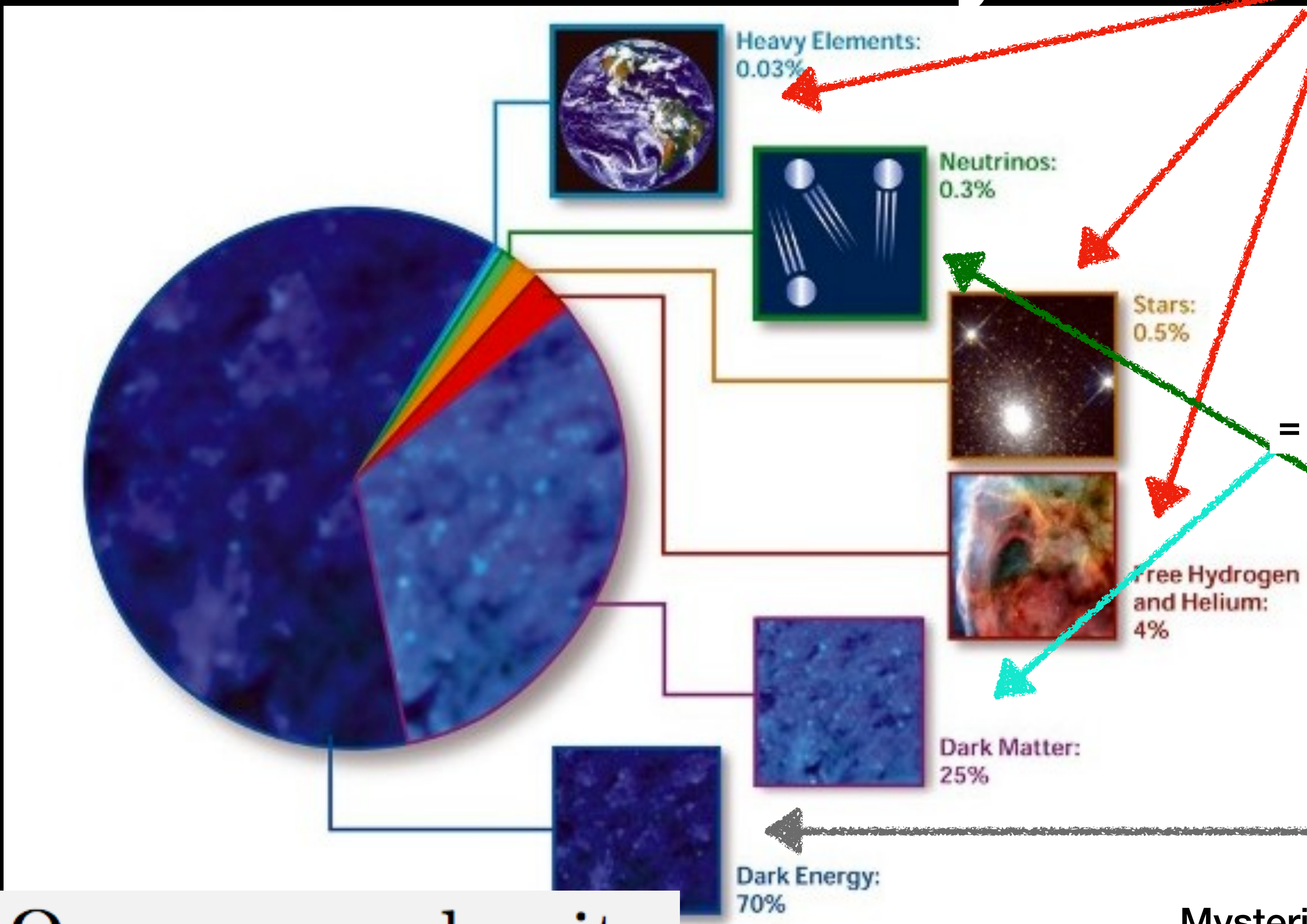
Today	z=0	13.8 Gyr

Higher redshift -> earlier in universe history; [k,M,G]yr = [kilo,mega,giga]yr

http://www.astro.ucla.edu/~wright/CosmoCalc.html, Planck 2015 parameters

Universe’s Composition Today



“Baryons” = normal matter

$$\Omega_{b,0}$$

$$\Omega_{M,0}$$

All matter = baryons + dark matter

$$\Omega_{r,0}$$

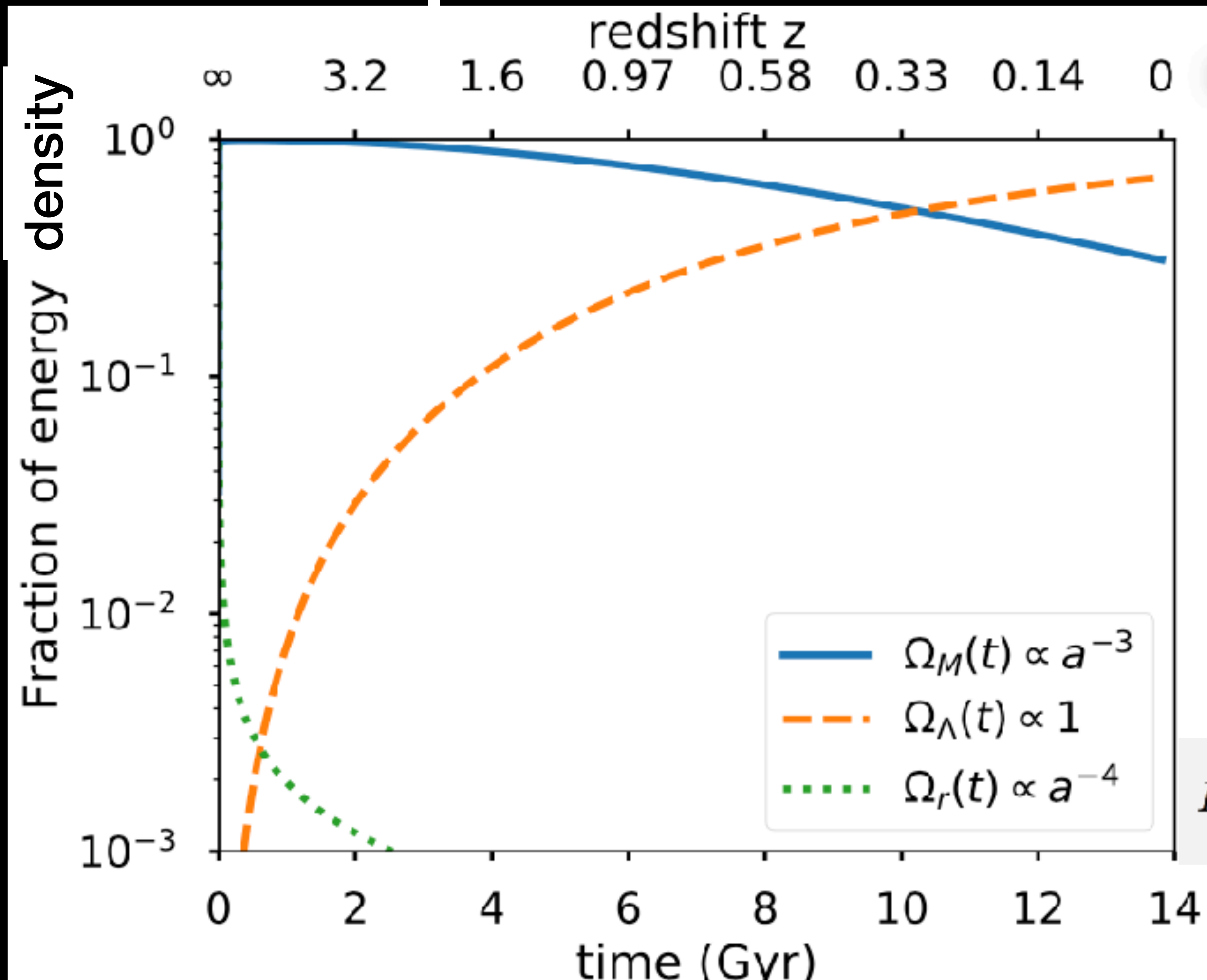
Relativistic/ Radiation (also includes photons)

$$\Omega_{\Lambda,0}$$

Mysterious stuff “Cosmological Constant”

$$\Omega \propto \text{energy density}$$

The relative dominance of each component varies over time



a = scale factor ~size of universe

Expanding universe dilutes matter and radiation energy density

Universe transitions from radiation dominated to matter dominated to Lambda dominated

$$E = \frac{hc}{\lambda}$$

Expansion History Basics

Key takeaways: cosmology predicts a(t)
a <-> redshift <-> time

- Input/Assumptions:
  - General Relativity; homogeneous/isotropic universe
  - Composition of the universe

- Output: expansion history->“radius” as a function of time.

- **a(t) = “scale factor”** $a(t=0) = 0.0$ $a(\text{today}) = 1.0$

- **z = redshift**: **a = 1/(1+z)** [redshift is observable!]

$$z = \frac{\Delta\lambda}{\lambda} = \frac{\Delta v}{c}$$

- H(z) = Hubble parameter
  $H_0 = H(z=0)$ = Hubble “constant”

$$H(z) = H(a) = \frac{\dot{a}}{a}$$

Solving for a(t) (optional this afternoon)

"Friedmann Equation"

$$H^2(a) = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2}\rho(a)$$

energy density

$$\frac{\rho(a)}{\rho_c} = \Omega_{M,0}a^{-3} + \Omega_{r,0}a^{-4} + \Omega_{\Lambda,0}a^{0} + \Omega_{k,0}a^{-2}$$

$$\Omega_{M,0} = 0.31 \qquad \Omega_{\Lambda,0} = 0.69$$

$$\Omega_{r,0} = 10^{-4.04} \qquad \Omega_{k,0} \equiv 0$$

Given these measured values, you can calculate a(t) by solving a differential equation
Then a(t) gives you everything else you want

Planck 2015 cosmological parameters

Solving for a(t) (optional this afternoon)

$$\frac{1}{a}\frac{da}{dt} = \sqrt{\frac{8\pi G}{3c^2}}\sqrt{0.31a^{-3} + 10^{-4.04}a^{-4} + 0.69}$$

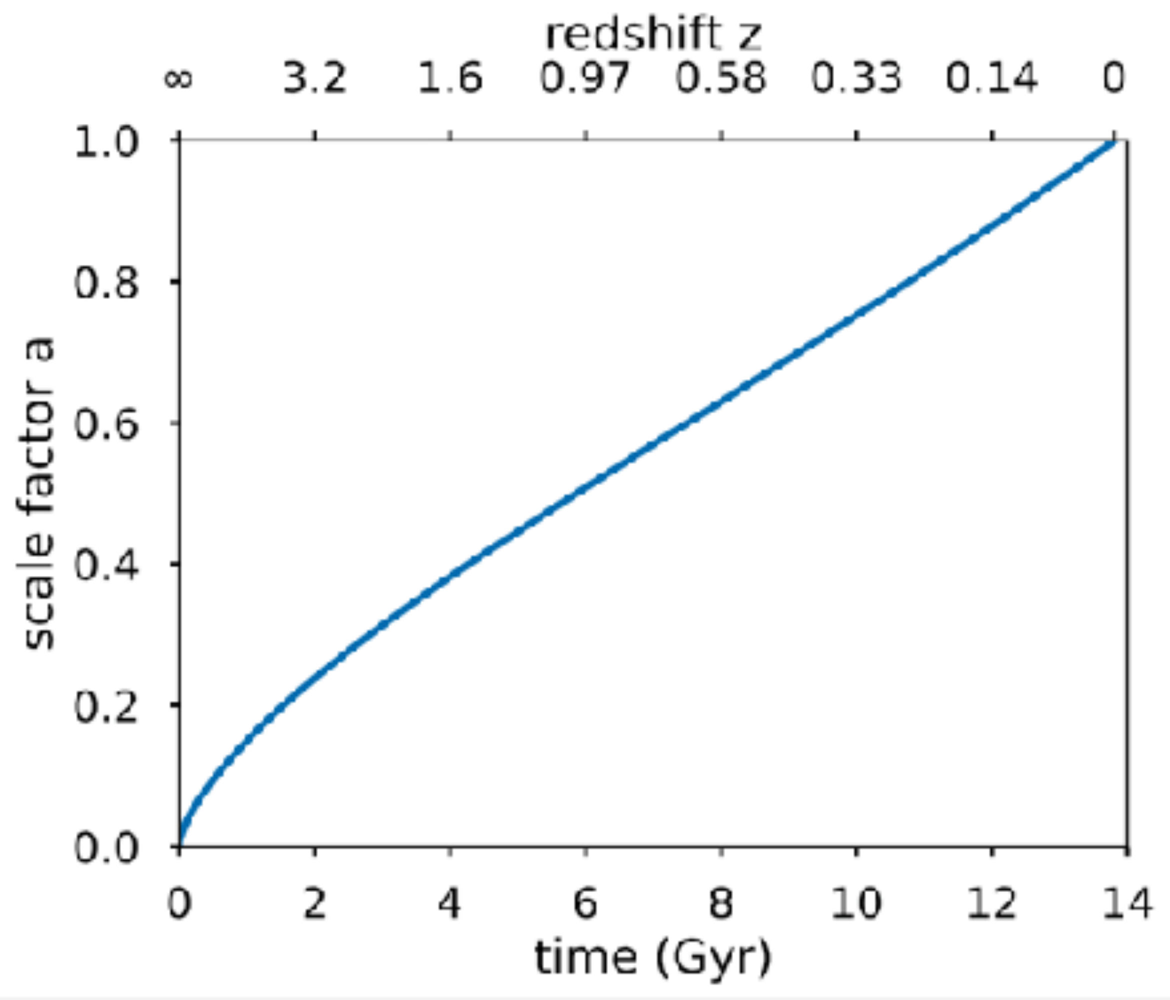
$$\frac{da}{a\sqrt{0.31a^{-3} + 10^{-4.04}a^{-4} + 0.69}} = \sqrt{\frac{8\pi G}{3c^2}}dt$$

$$\int_{a=0}^{a=1} \frac{da}{a\sqrt{0.31a^{-3} + 10^{-4.04}a^{-4} + 0.69}} = \sqrt{\frac{8\pi G}{3c^2}}\int_{t=0}^{t=\mathrm{today}} dt$$

Remember that a = 1/(1+z) so you can also find the age of the universe at any redshift

Expansion History Summary

- The universe is made of (dark/baryonic) matter, radiation, and dark energy
- This tells us how fast the universe expands with time
- z <-> a <-> time
- Also the *temperature* of the universe evolves with time



$$T = T_0(1 + z) = T_0/a$$

$$T_0 = 2.725 \text{ K}$$

$$E = \frac{hc}{\lambda}$$

Big Bang Nucleosynthesis

In the first minutes after the big bang, the entire universe is very hot.
Freeze out of n-p equilibrium, then some nucleosynthesis with p and n

Freeze out approximation:
balance between
n-p reaction rate and
universe expansion

Freeze out also applies
to other types of particles
(e.g. dark matter)

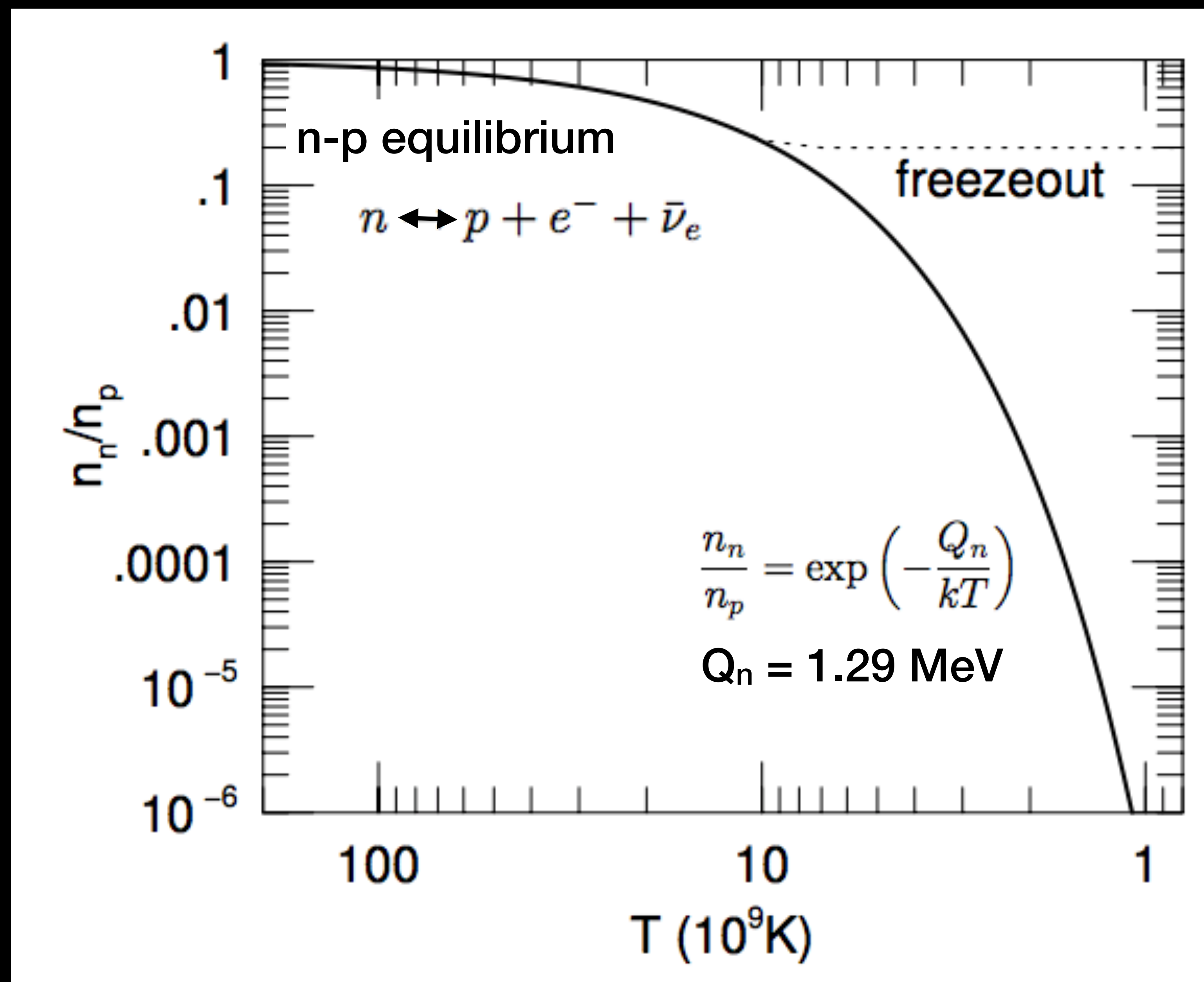
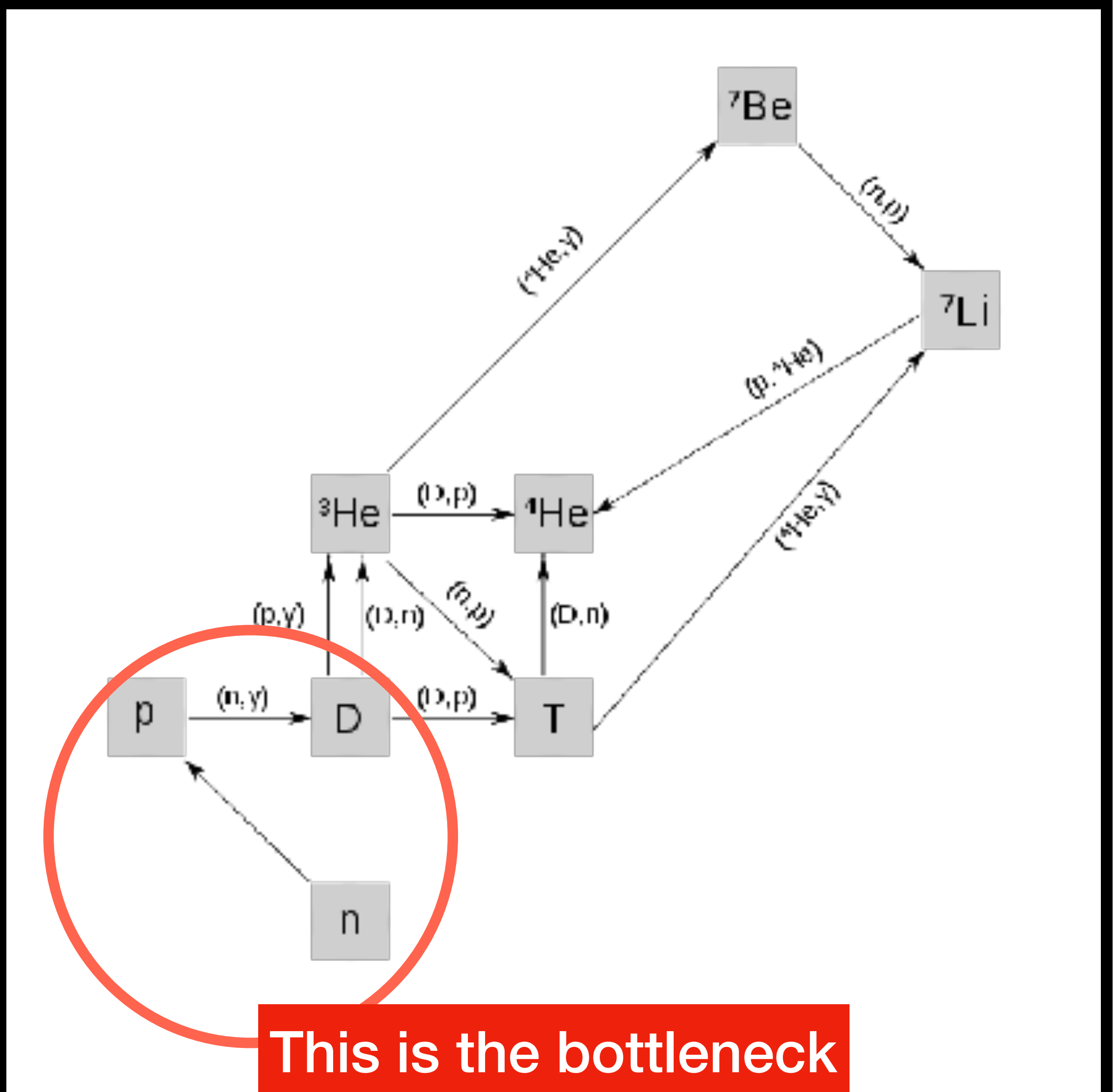
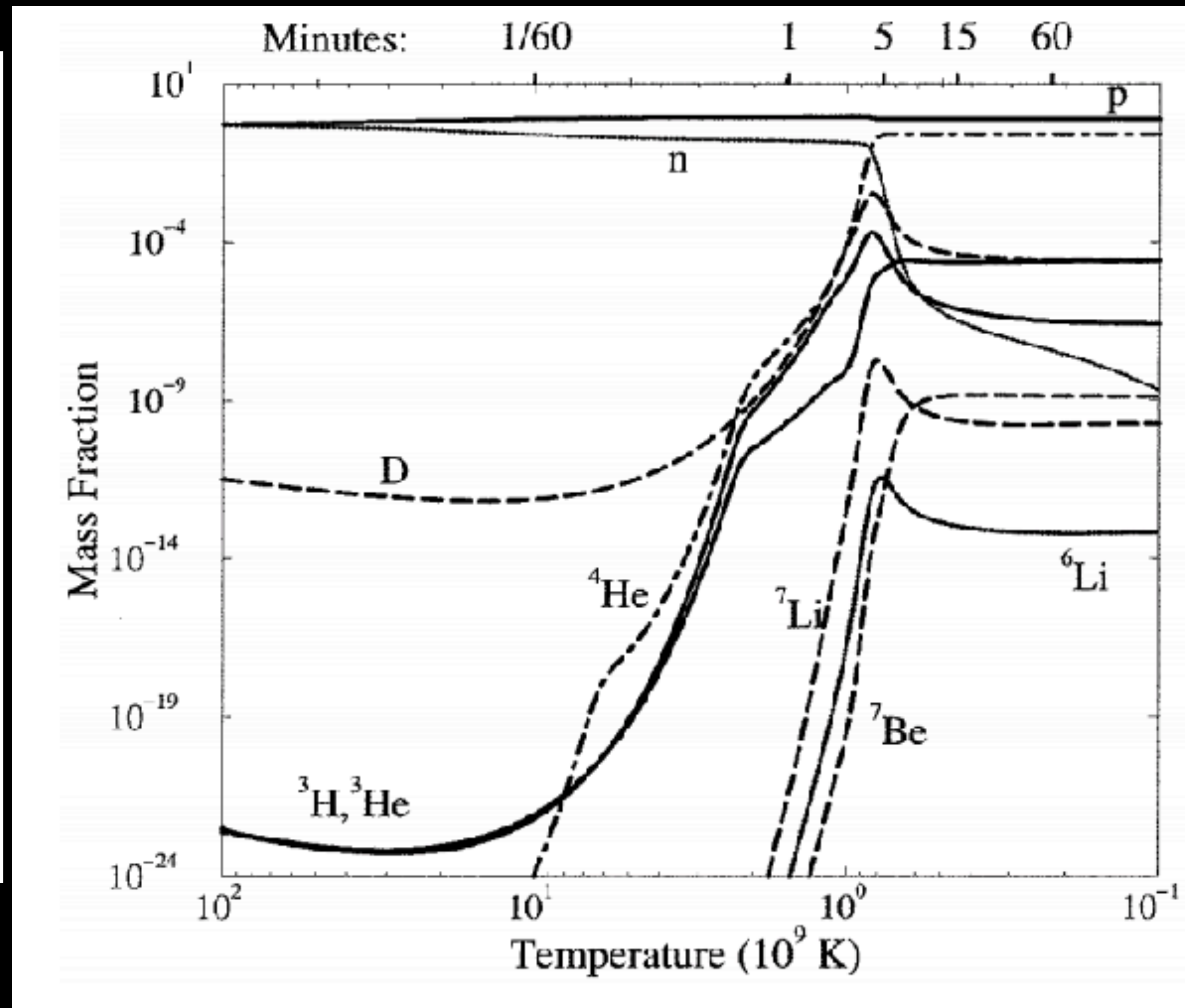


Figure: Ryden, Introduction to Cosmology Ch 10

Big Bang Nucleosynthesis



0th order Approximation:
Fuse all n with p into D
Fuse all D into 4He



Negligible amounts of heavier elements

Figure: Wikimedia Commons

Figure: Ryden, Introduction to Cosmology Ch 10

BBN Matches Cosmology

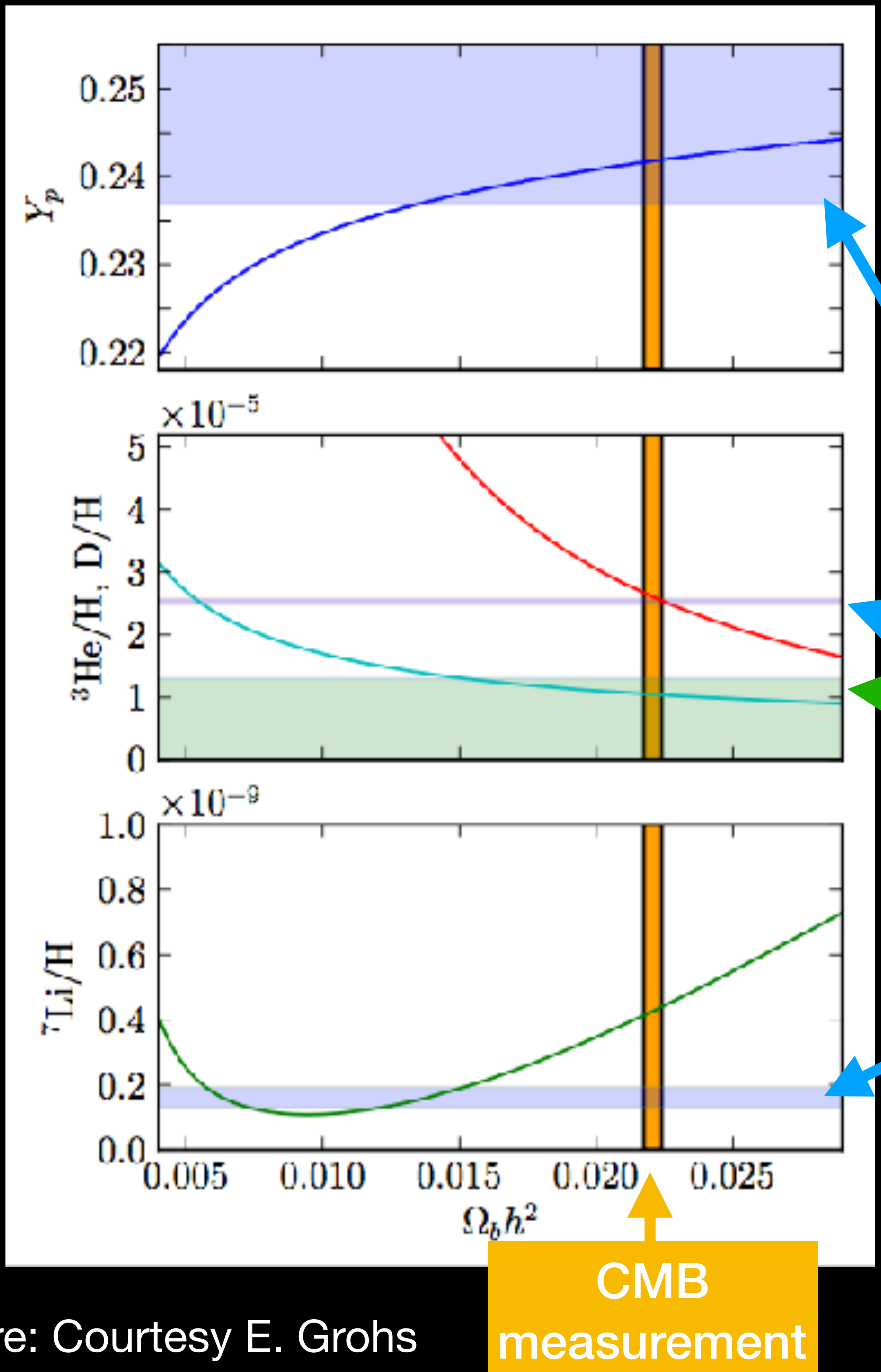


Figure: Courtesy E. Grohs

Changing the net amount of baryons (Ω_b) affects when D forms.
More baryons
-> earlier D synthesis
-> more free neutrons put in nuclei
-> more helium

Astronomy measurements

- 4He: in metal-poor gas (emission)
- Deuterium, 3He limits: metal-poor gas (absorption)
- 7Li: in metal-poor stars
  Note there is a discrepancy:
  The lithium problem.

Universe timeline

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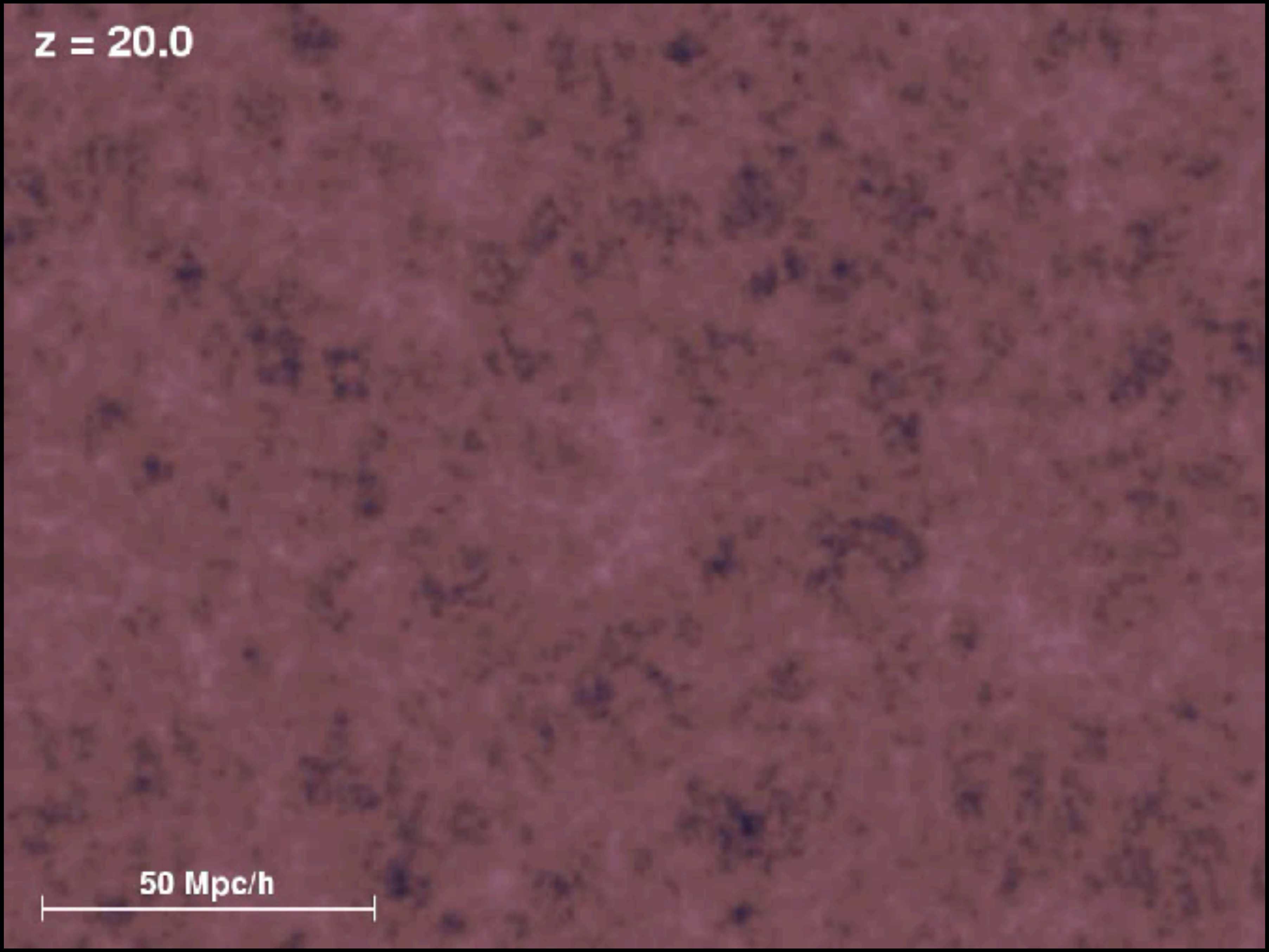
Structure Formation

Growth of matter inhomogeneities

- 0th order: the universe is homogeneous + isotropic
- 1st order: linear growth of initial density perturbations
  -> power spectrum
- 2nd+ order: nonlinear growth of linear perturbations
  -> dark matter halos [needs simulations]
- NOTE: dark matter is >80% of total mass,
  it dominates the gravity.

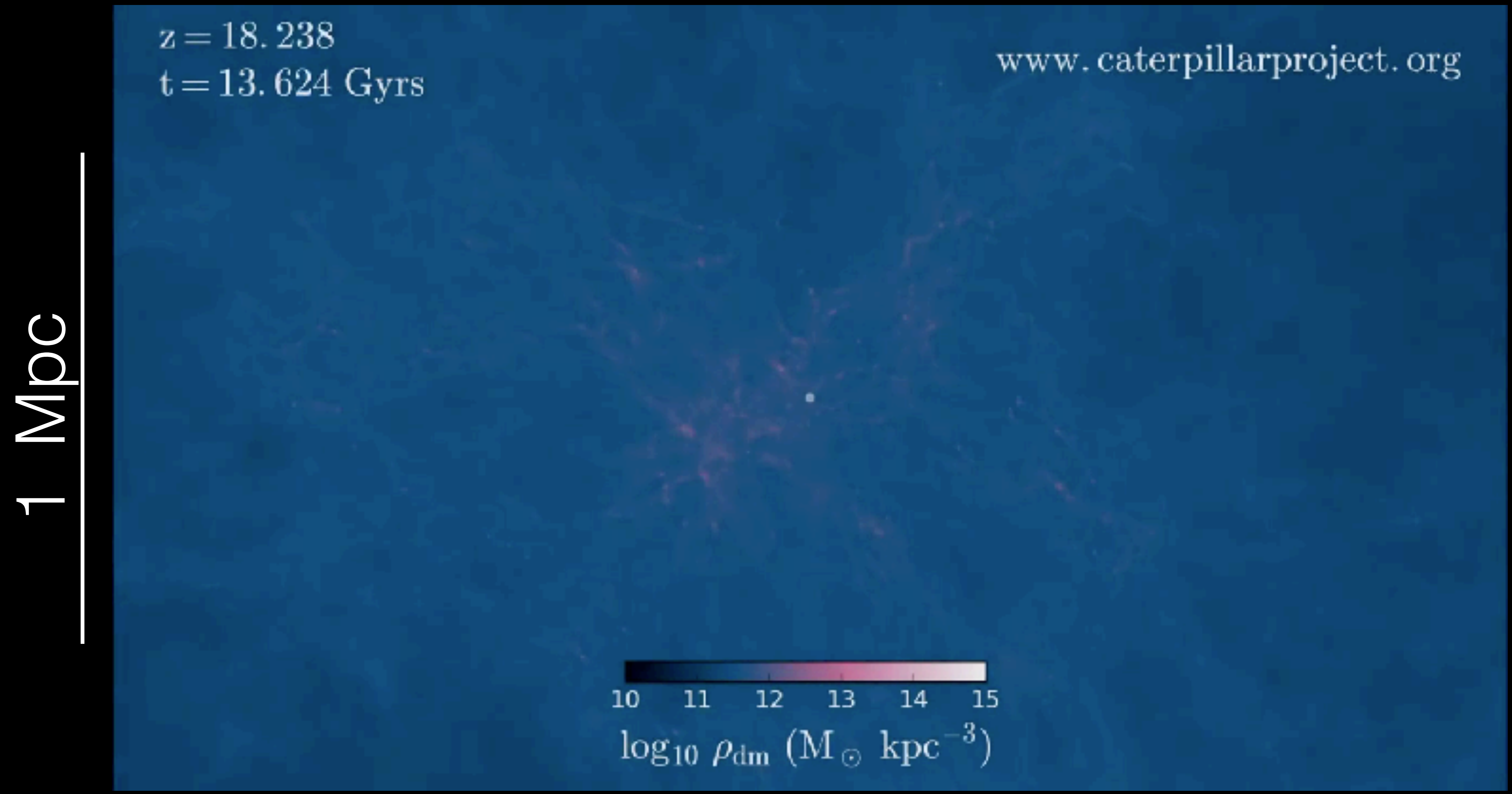
Growth of structure



~10^{10} dark matter particles, each particle mass ~10^9 M_{sun}
(Our Milky Way is ~10^{12} M_{sun})

V. Springel et al. (2005)

Assembling a Milky Way in Dark Matter

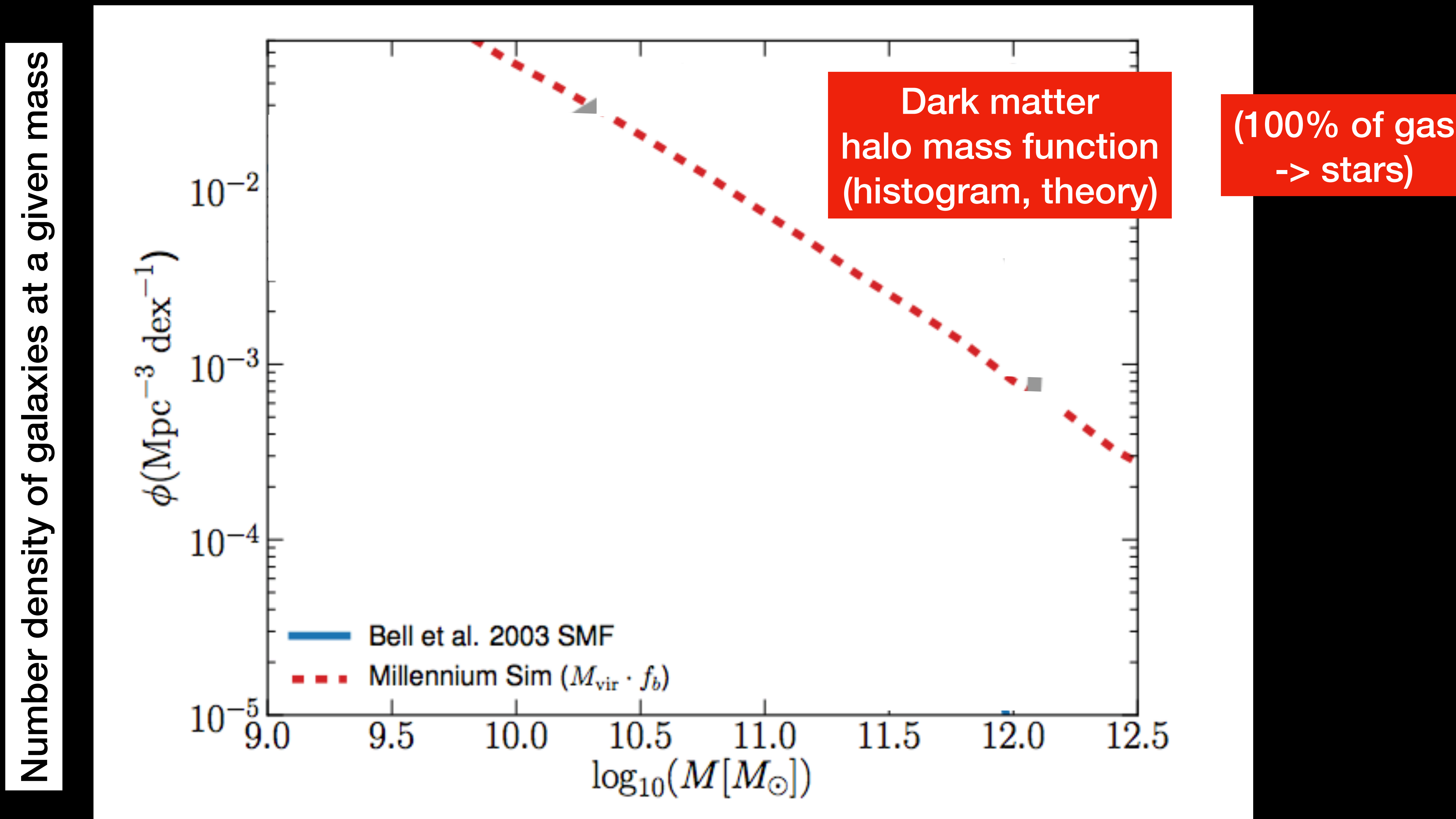


Zoom-in simulation of one galaxy: each particle is ~10^4 M_{sun}
Gravitationally bound structures = "dark matter halos"
One galaxy lives at the center of each halo

"Hierarchical structure formation": big things build up from small things
Early galaxy (z>3) is a bunch of small systems that later merge

Griffen, Ji et al. 2016

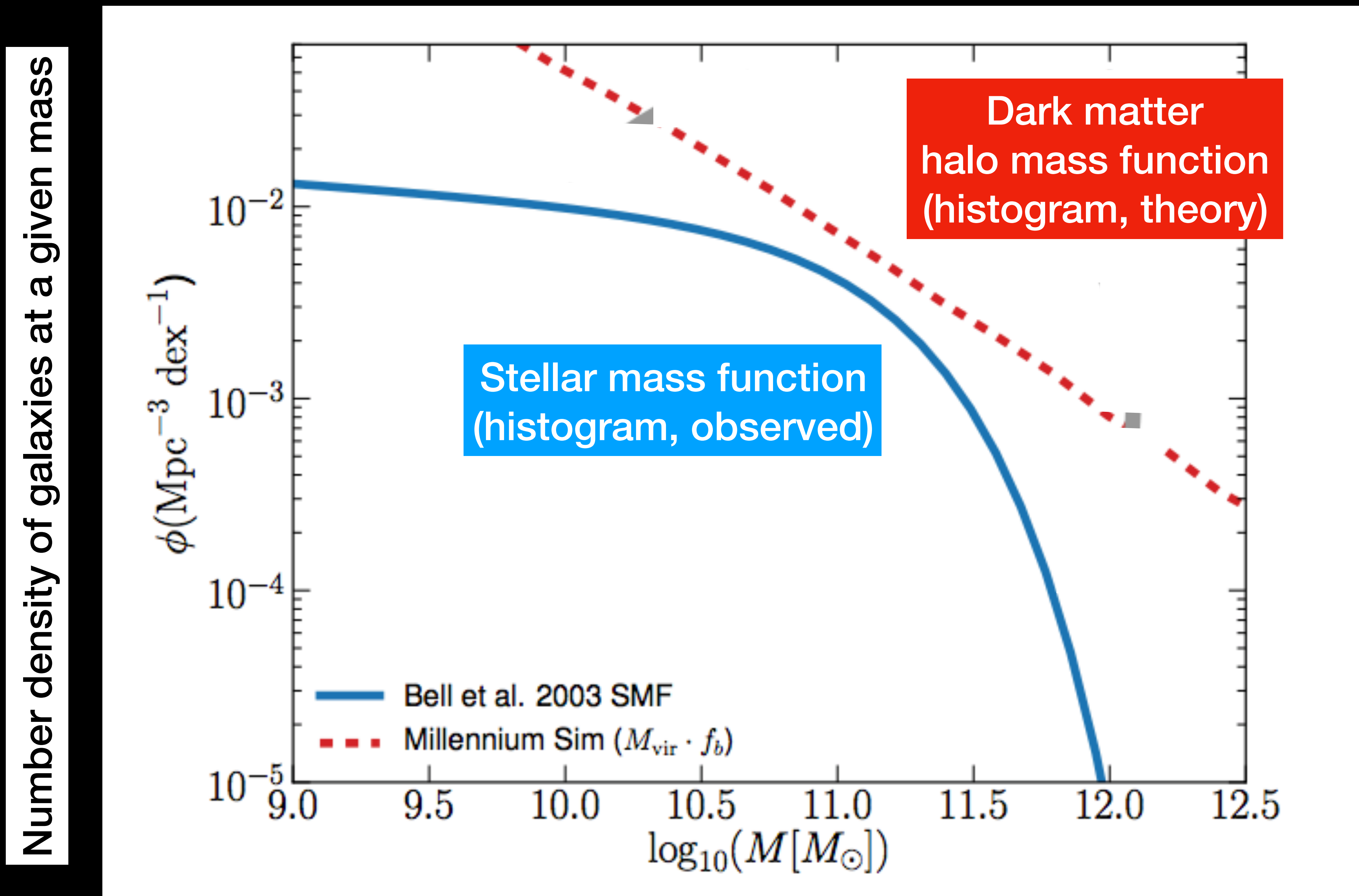
Galaxy Formation



A galaxy's job is to turn gas into stars

Figure: Mutch et al. 2013

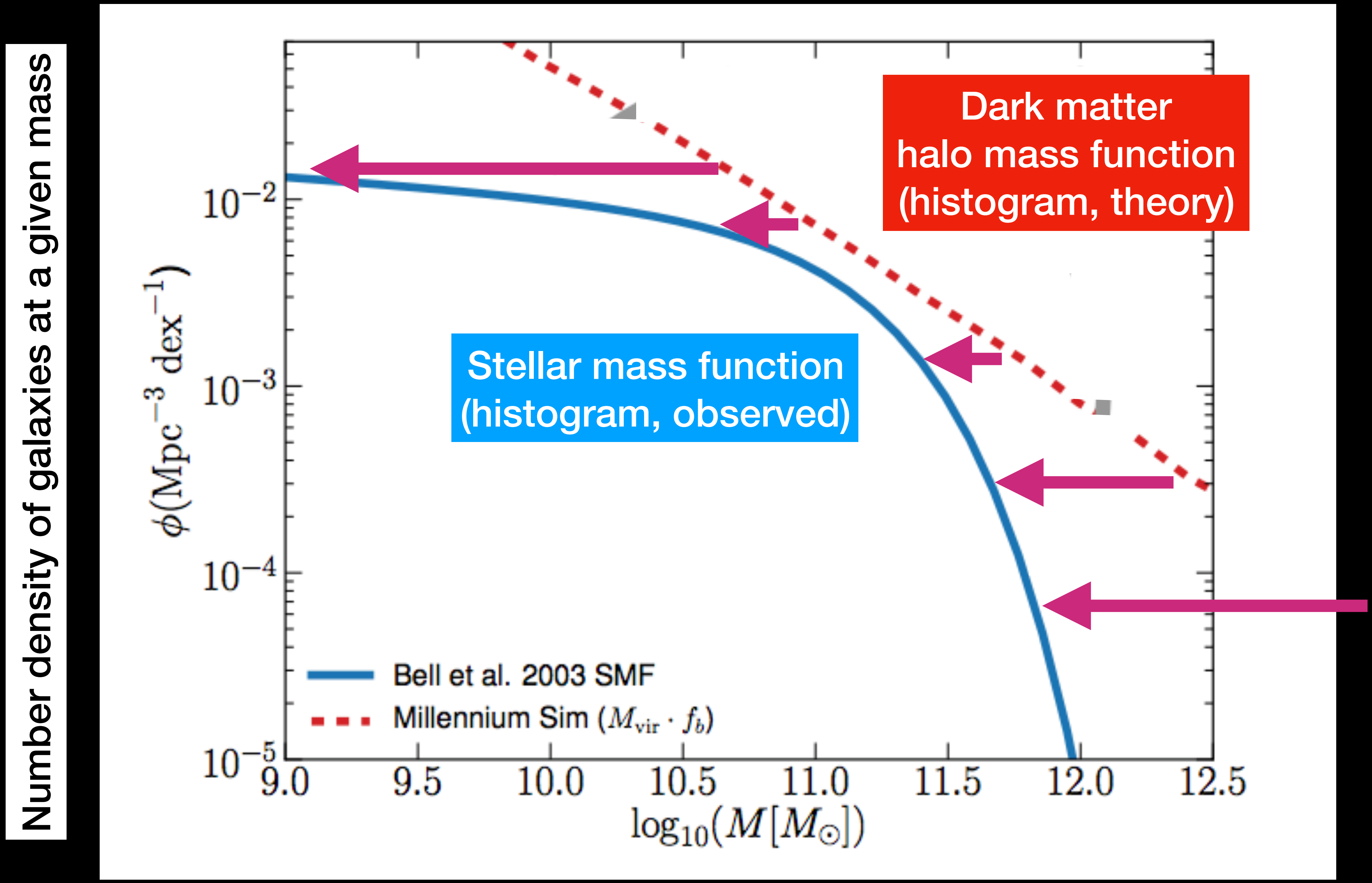
Galaxy Formation



A galaxy's job is to turn gas into stars
Most galaxies are bad at this job

Figure: Mutch et al. 2013

Galaxy Formation



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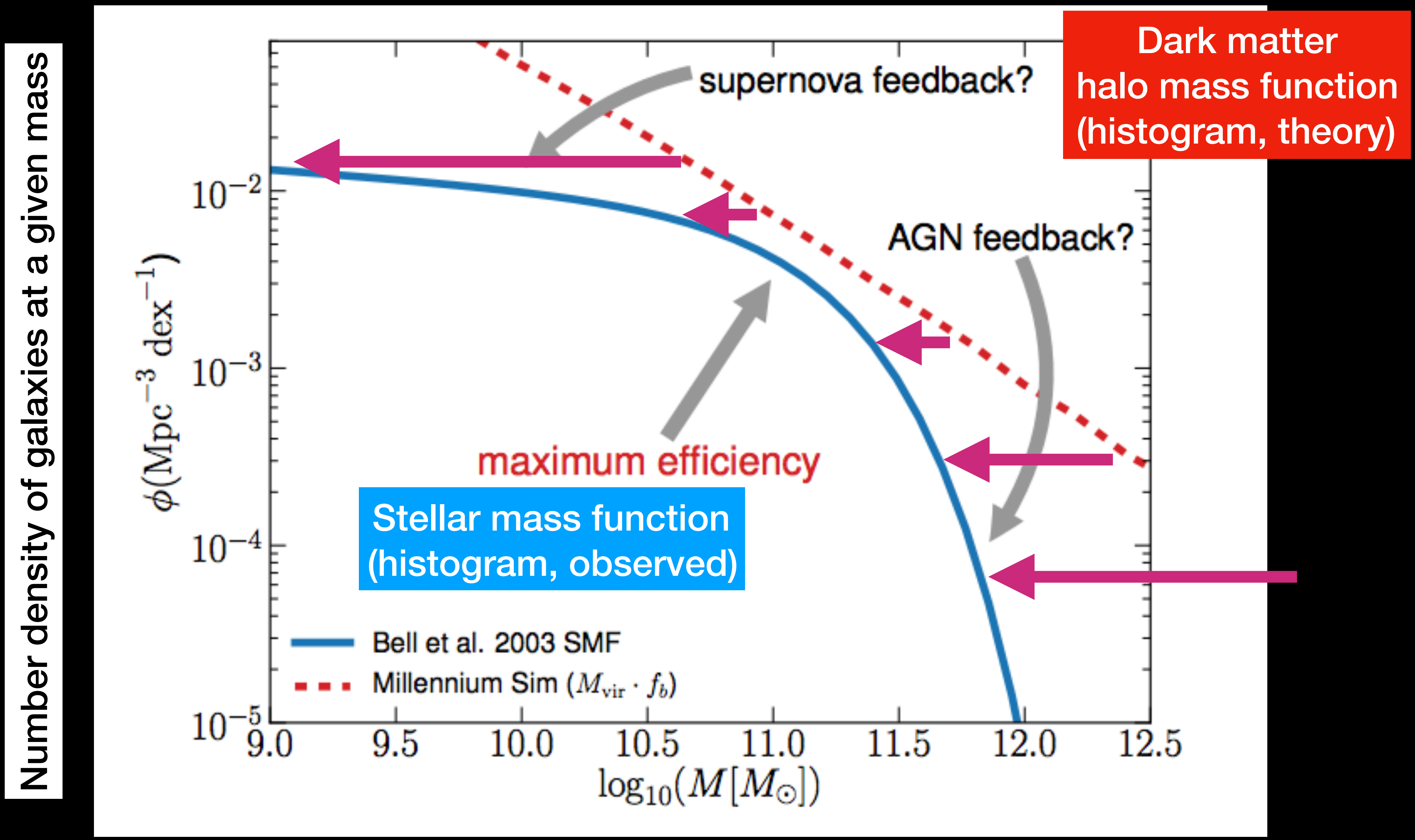
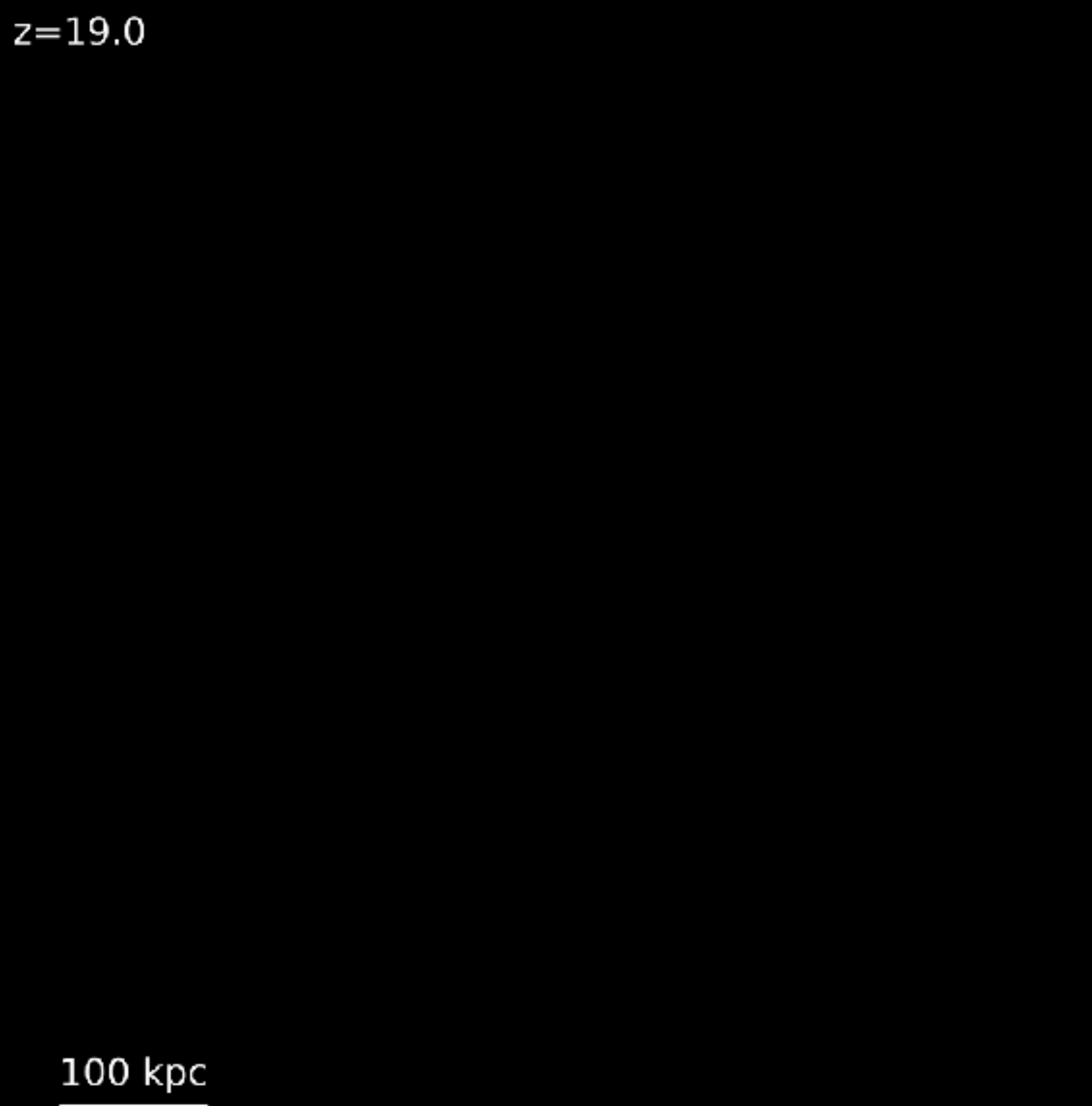


A galaxy's job is to turn gas into stars

Most galaxies are bad at this job due to feedback

Figure: Mutch et al. 2013

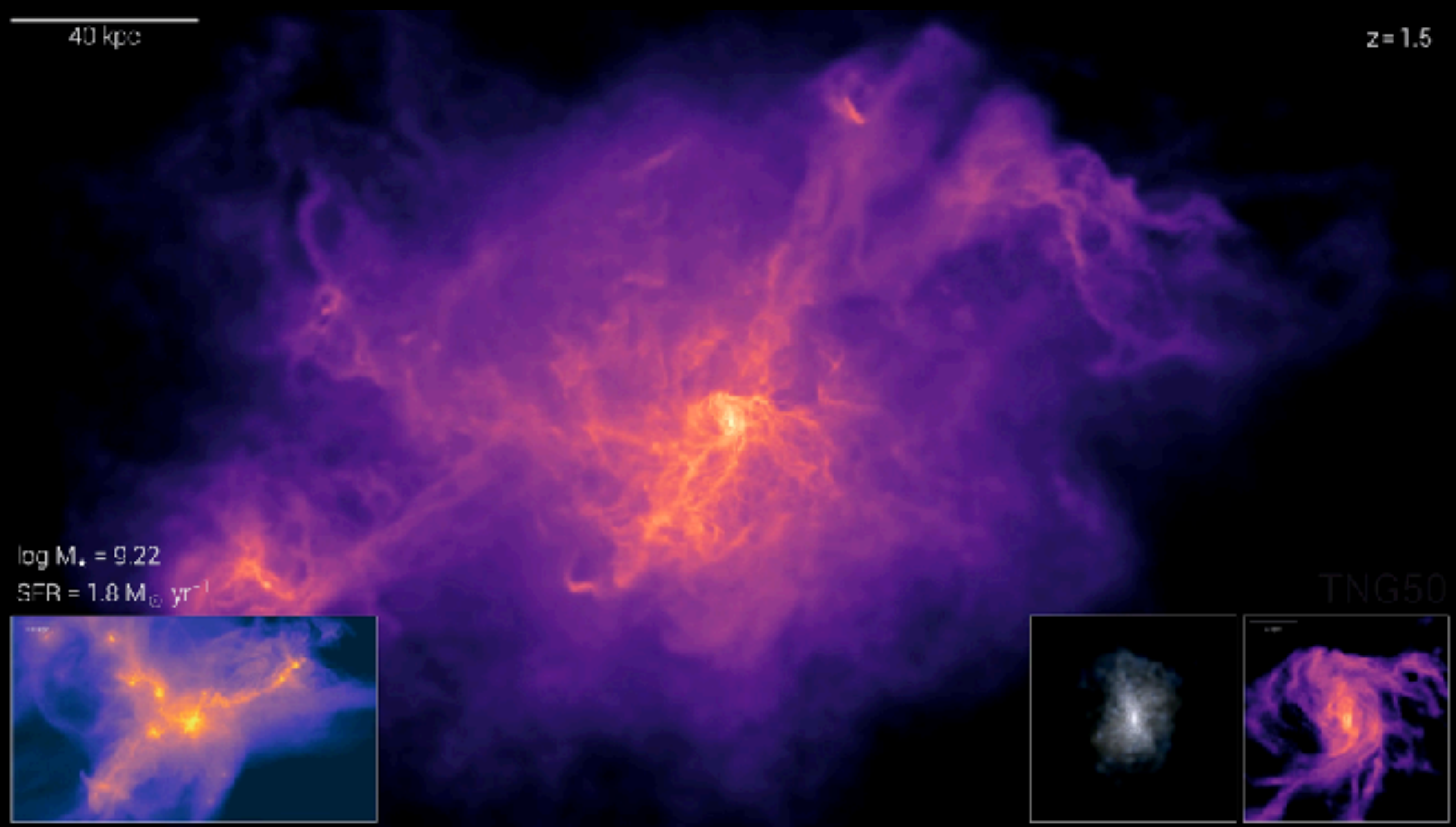
“Hydro” simulations



- Include gas, stars, metals/cooling, stellar feedback,
- Many now include AGN (supermassive black hole) feedback, radiation pressure, reionization, magnetic fields, cosmic rays, …
- Feedback details are an open question

Latte simulations, Andrew Wetzel; $m_{DM} \sim 10^5\ M_{sun}$, $m_{star} \sim 10^4\ M_{sun}$

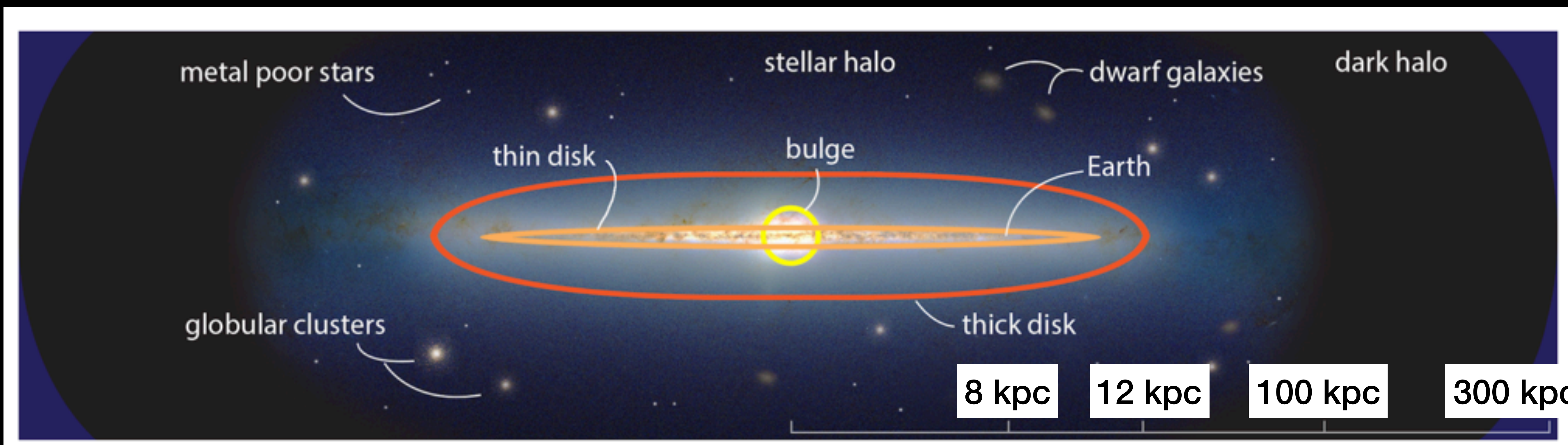
“Hydro” simulations



Synthesized metals go into other stars, the interstellar medium (ISM), the circumgalactic medium (CGM), the intergalactic medium (IGM).
We can only see the *most abundant elements* in the IGM, CGM, and most of the ISM: e.g., H, He, CNO, Fe.
This is one reason we tend to focus on stars.

Illustris TNG simulations http://www.tng-project.org/media/

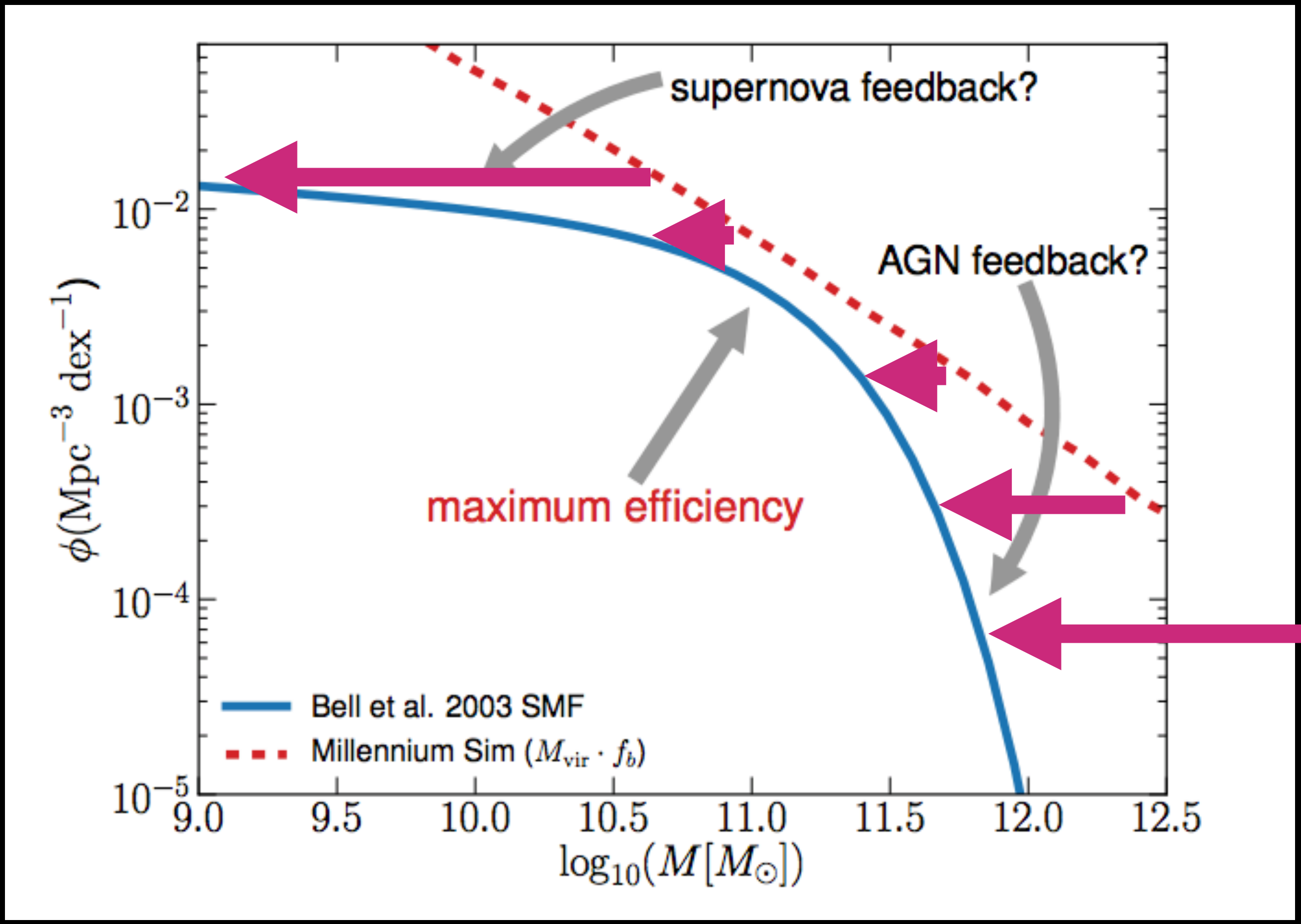
The final result: something like our Milky Way



Frebel 2018 ARNP

Structure/Galaxy Formation Summary

- The universe is not homogeneous
- Density fluctuations described by the Power Spectrum
- Nonlinear density fluctuations -> dark matter halos
- “One galaxy per halo”
- **Open question is how much feedback**
- Only most abundant elements observed outside of stars



Universe timeline

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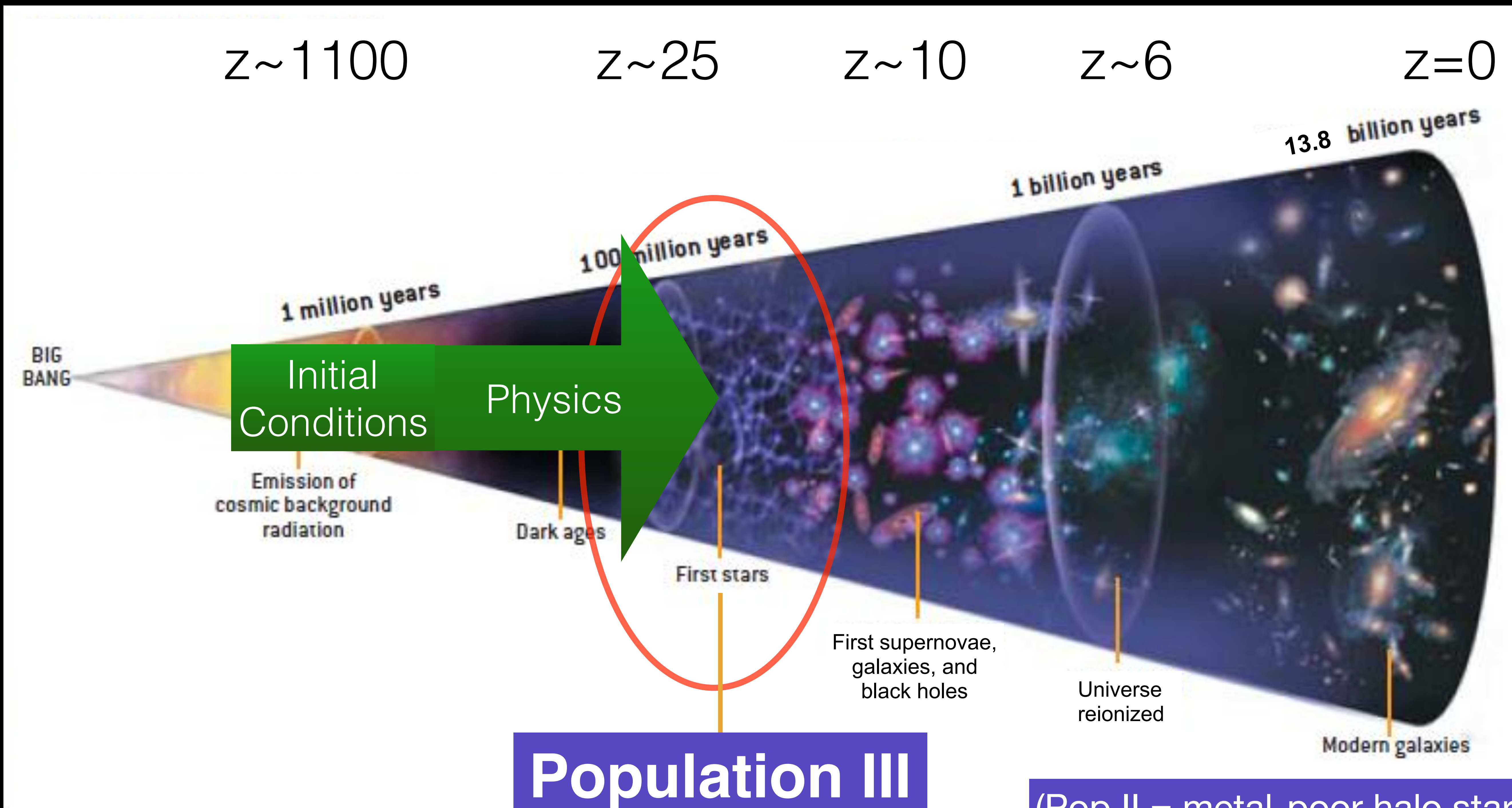
http://www.astro.ucla.edu/~wright/CosmoCalc.html, Planck 2015 parameters

The First Stars are theoretically “easy”



Population III
Metal-free star formation

(Pop II = metal-poor halo stars)
(Pop I = metal-rich disk stars)

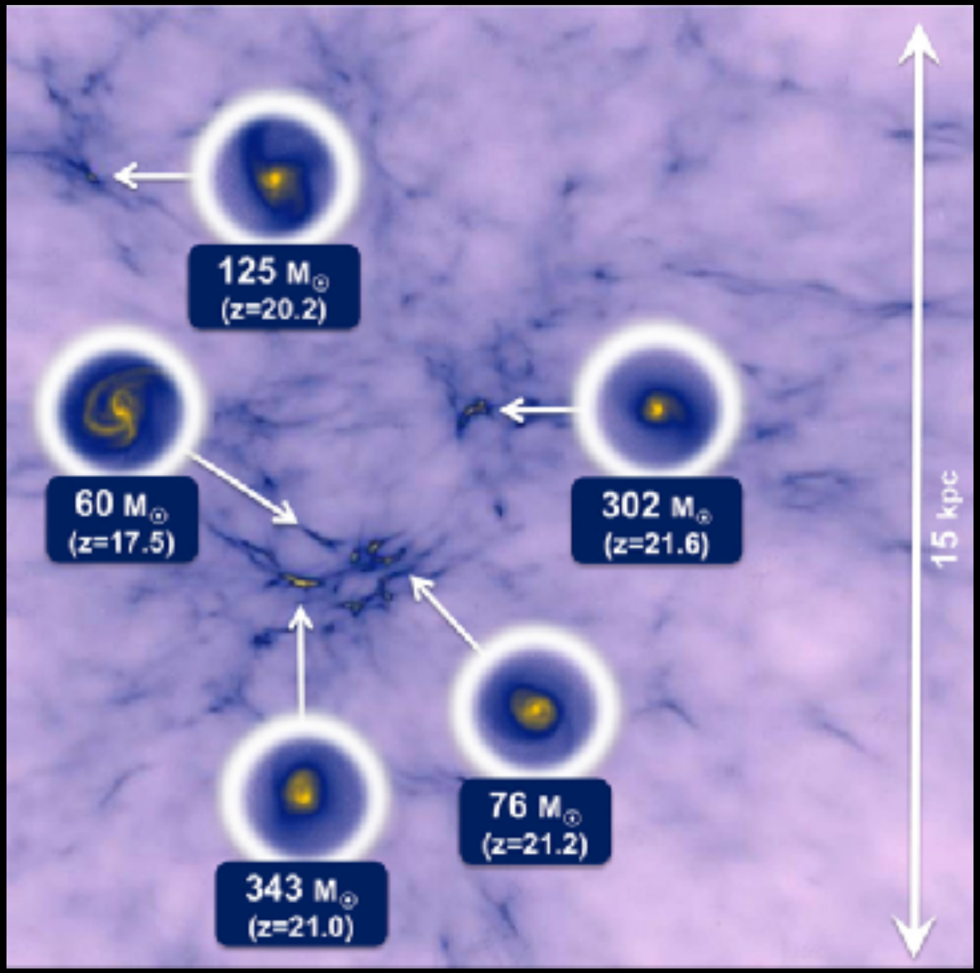
Only H, He ⟶ **First Metals**

“Metals” = element heavier than He

Scientific American

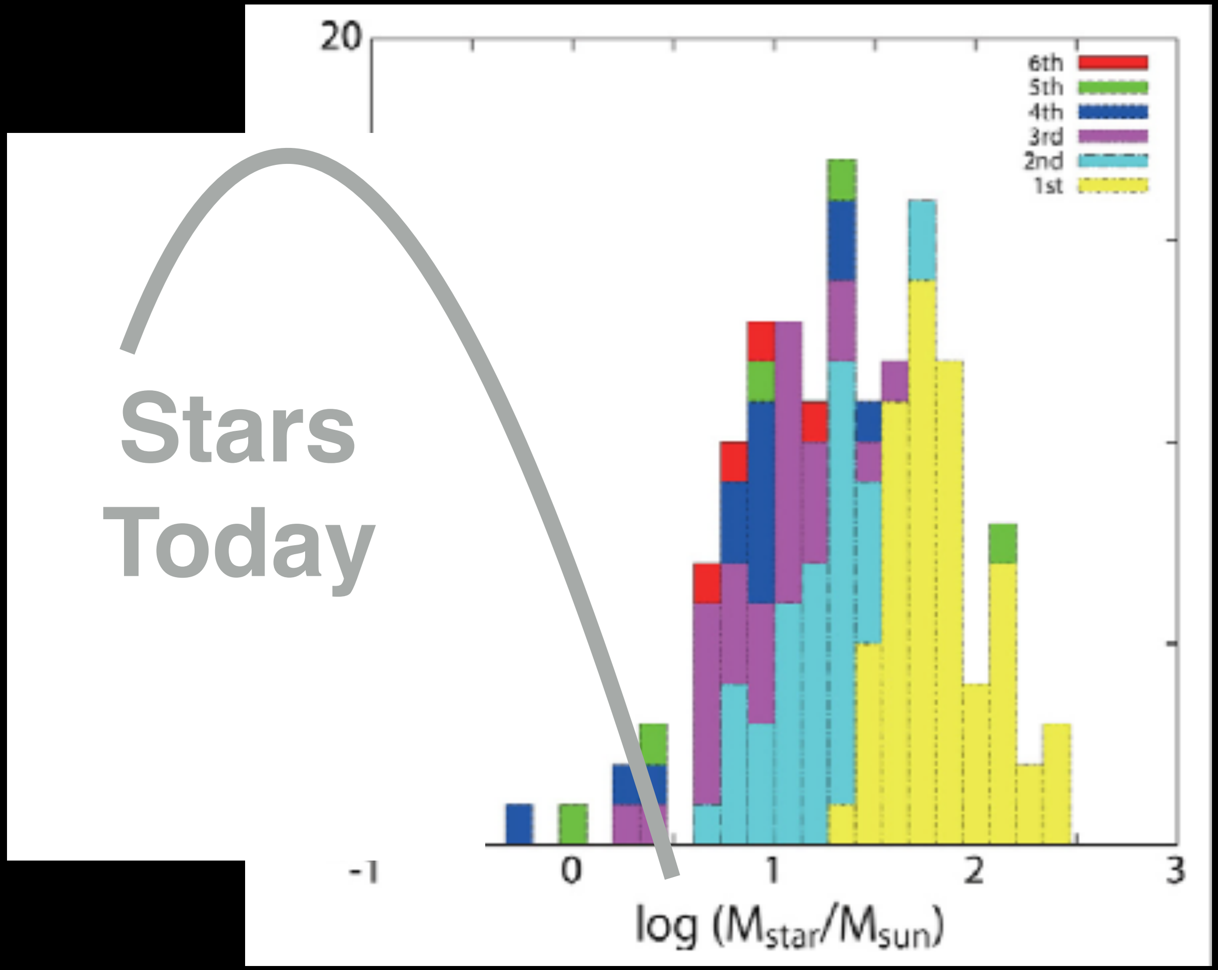
Theoretical Predictions for the First Stars

Form in **minihalos** due to H_2 cooling



Hirano et al. 2014

High mass stars
10-100 M_{sun} per star!



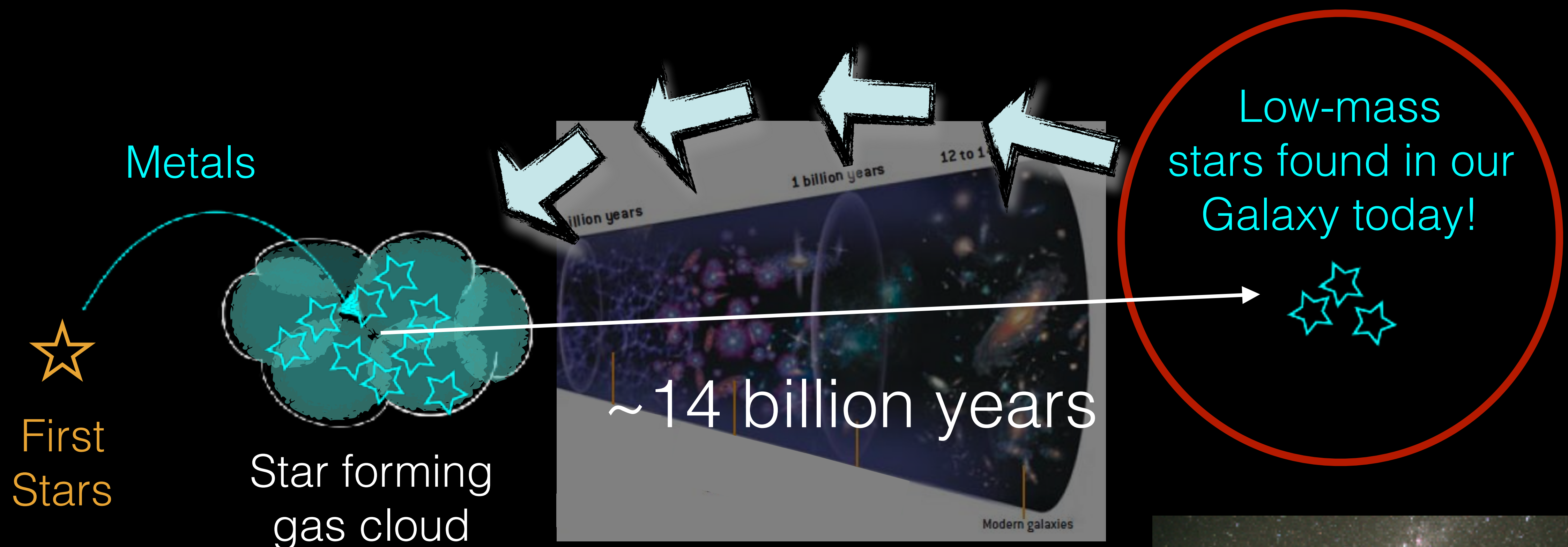
Susa et al. 2014

Pop III stars all gone today, but make first metals

Alex Ji

Stellar Archaeology

A way to probe chemical signatures from the early universe



Observe chemical abundances of these -> chemical content of ancient gas clouds!

Look for *2nd-generation* stars that preserve chemical signatures of the first stars (almost the only observational probe)

Assembling a Milky Way

Yellow: First Stars
Minihalos
z~25

Red: First Galaxies
Atomic Cooling Halos
z~10-20

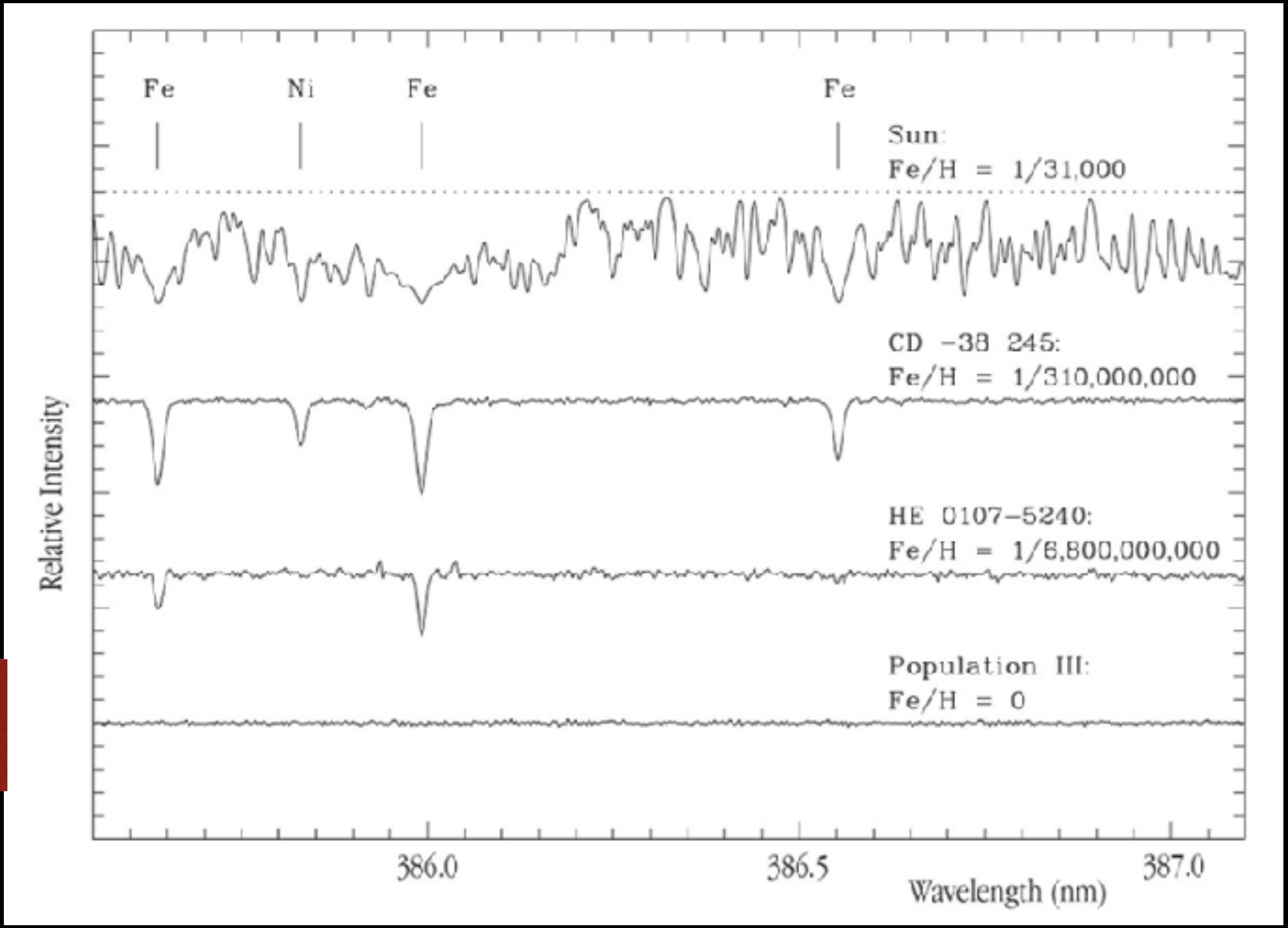
Griffen, Ji et al. 2016, Griffen, Dooley, Ji et al. 2017

Use **Spectroscopy** To Measure Chemical Abundances

Metal-rich

Metal-poor

Metal-free
(not real data)



[Fe/H]=0.0

[Fe/H]=-4.0

[Fe/H]=-5.4

[Fe/H]=-∞

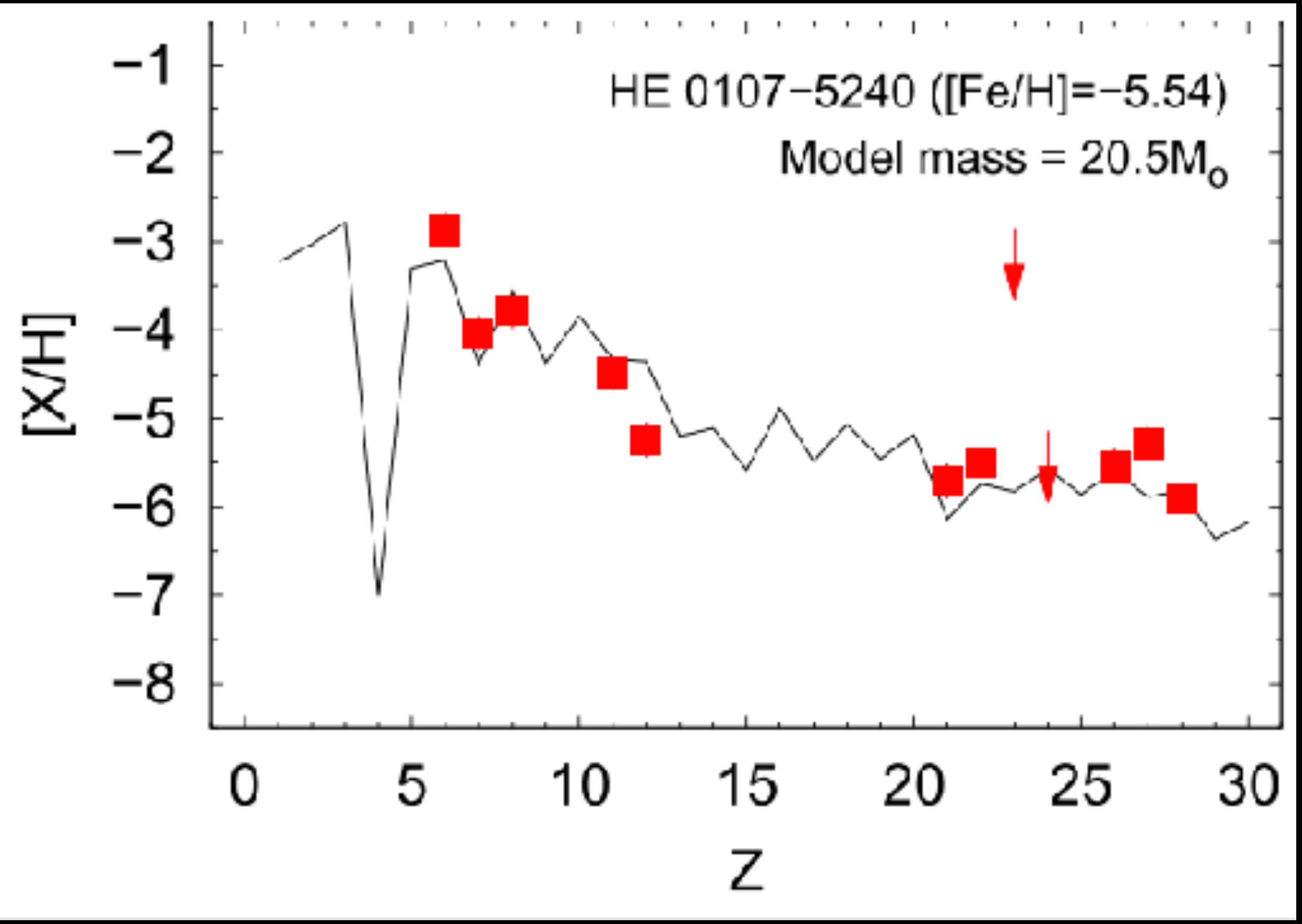
$$[A/B] \equiv \log_{10}(N_A/N_B) - \log_{10}(N_{A,\odot}/N_{B,\odot})$$

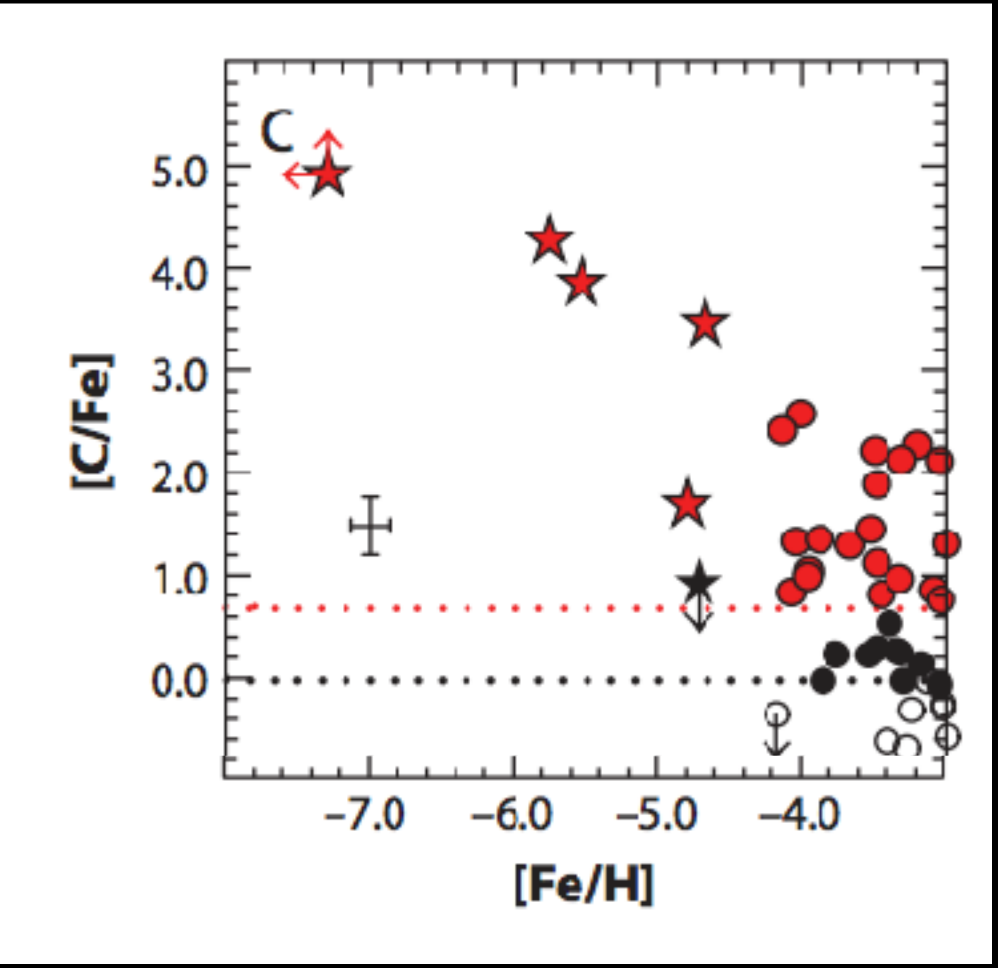
Typical (bad) assumption: $[Fe/H] \lesssim -3$ ➞ second generation star

(The more metal-poor, the better)

Alex Ji

Two main types of figures



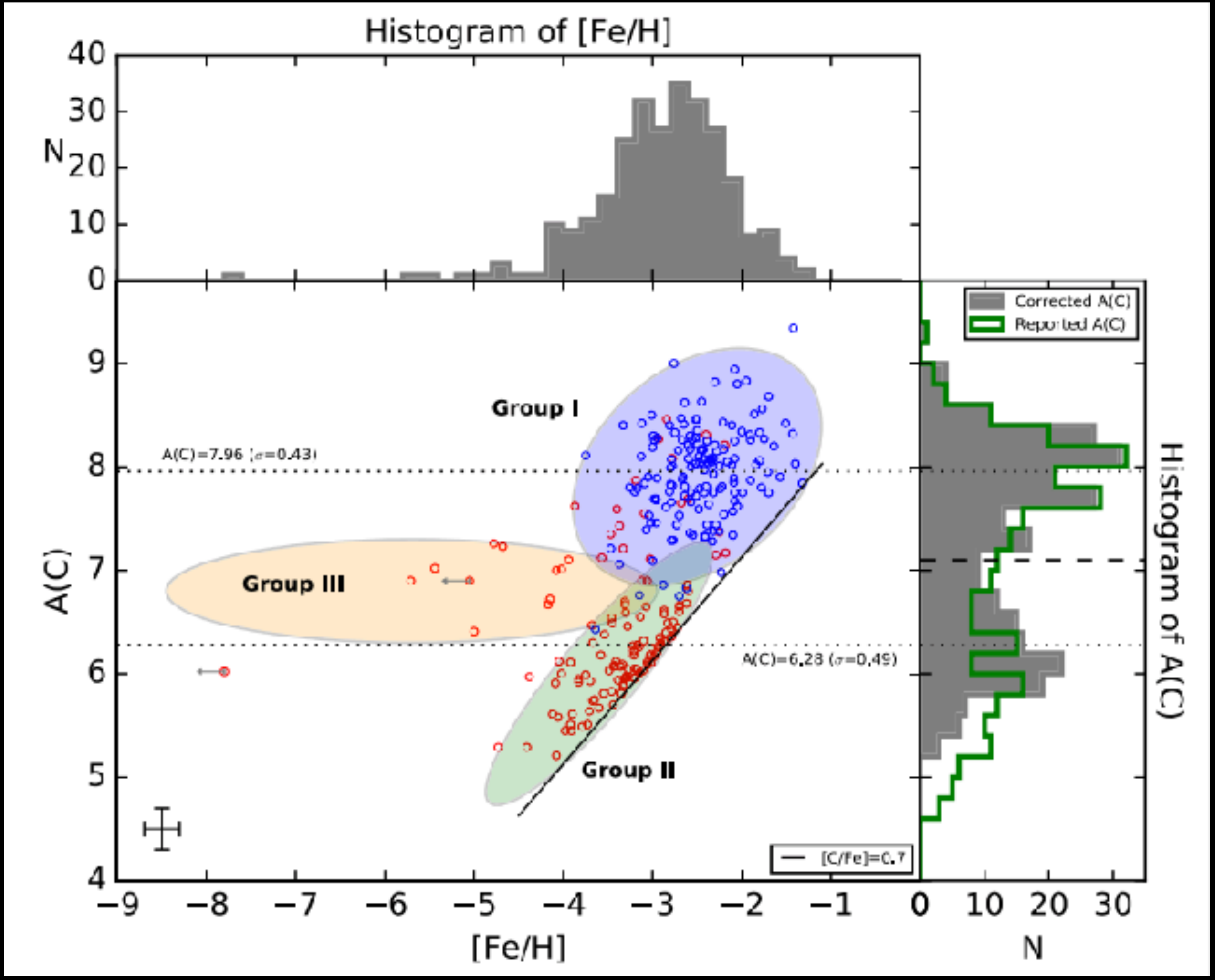


- **Single star, multiple elements (Z)** y-axis can be [X/H],[X/Fe],logε(X),A(X)
- **Used for comparing to nucleosynthesis models**
- **Usually assume: elements come from one source**

- **Multiple stars, two elements** Usually [X/Fe] and [Fe/H]
- **Used for overall element trends**
- **Also used for *chemical evolution*:** mixing multiple element sources
- **Usually assume stars from the same galaxy/gas reservoir**

Placco+15, Frebel & Norris 15

Carbon-Enhanced Metal-Poor (CEMP) Stars the key robust Pop III abundance signature



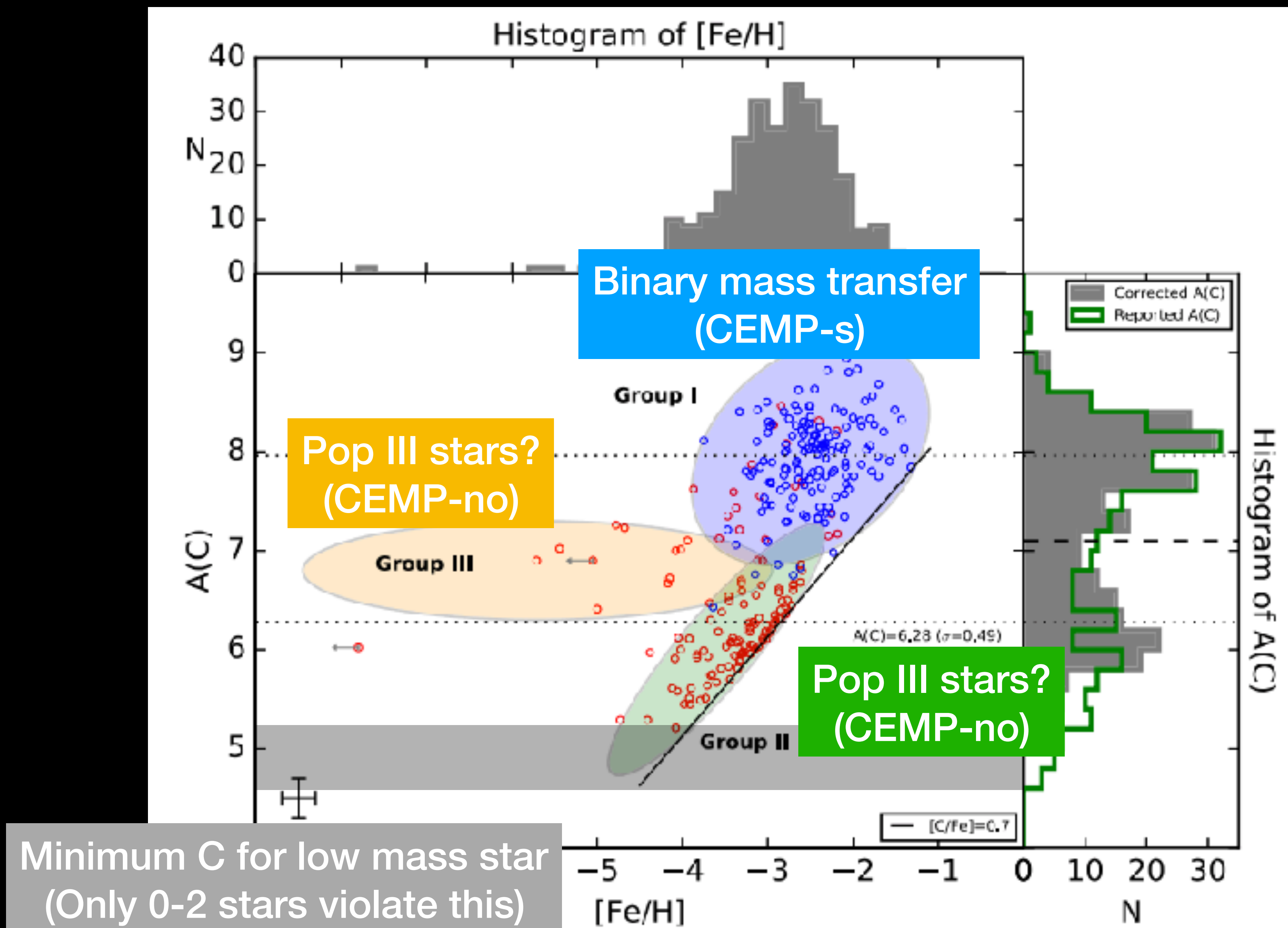
J. Yoon+16

Reasons for Carbon Enhancement

- Unique Pop III abundance signatures
  - Supernovae (faint SN, mixing+fallback SN, jet/asymmetric SN)
  - Stellar winds from rapidly rotating massive stars (spinstars)
- External pollution
  - Carbon transferred from a binary AGB companion (now a WD) [will be accompanied by s-process elements]
- Surviving star bias
  - Easier to form low mass stars in gas with higher carbon (Other stars form but are dead)

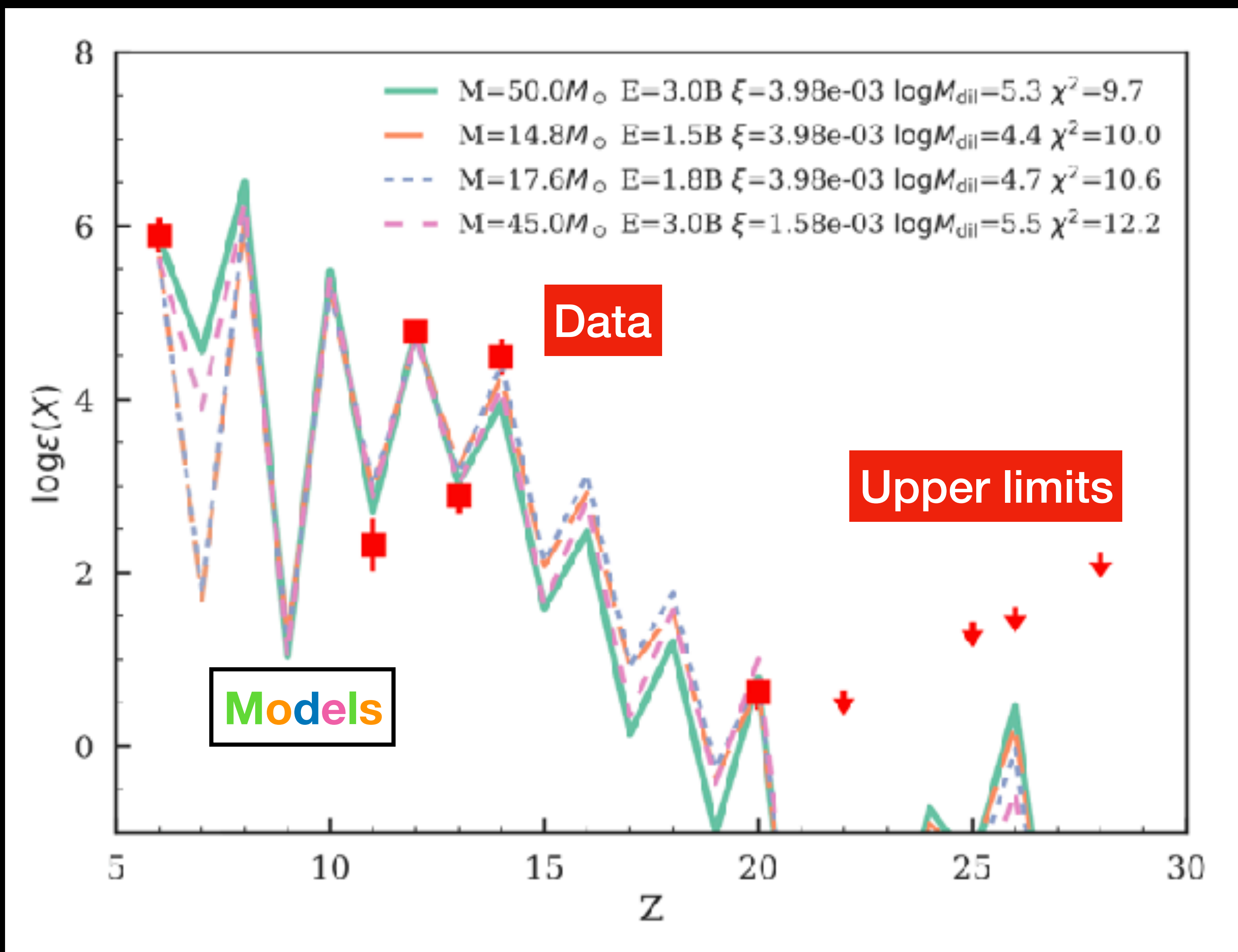
Norris+13, Frebel & Norris 15

At least some CEMP stars have Pop III signatures



J. Yoon+16

Detailed fits to abundances



Fitting Heger+Woosley 2010 Pop III CCSN models to a star with [Fe/H] < -6

- **Search through a grid of nucleosynthesis models,**
- **Find the *ratios* that fit best (in a chi^2 sense).**

- **Free parameter: overall normalization (gas dilution)**

- **Be careful:** errors are rarely actually Gaussian, so chi^2 is not strictly applicable

- **Be careful:** it is almost never true that a star's abundances can be described by a *single* nucleosynthetic source (e.g. one CCSN)

Frebel, Ji et al. 2019

Metal-poor stars are good for studying other individual nucleosynthetic events

- Present-day stellar abundances are the product of several Gyr of chemical evolution
- Metal-poor stars should have less chemical evolution
- Metal-poor stars empirically have more abundance scatter -> has not averaged out
- The few ages we have suggest ages >12 Gyr

Nucleosynthesis

Nuclear physics
Stellar evolution
Supernovae
Stellar populations

$[X / H]$

Abundances
Atomic physics
Stellar atmospheres

Hierarchical galaxy formation
Gas accretion and expulsion
Metal mixing
Star formation

Galaxy Formation

Table 1 Classes and Signatures of Metal-Poor Stars

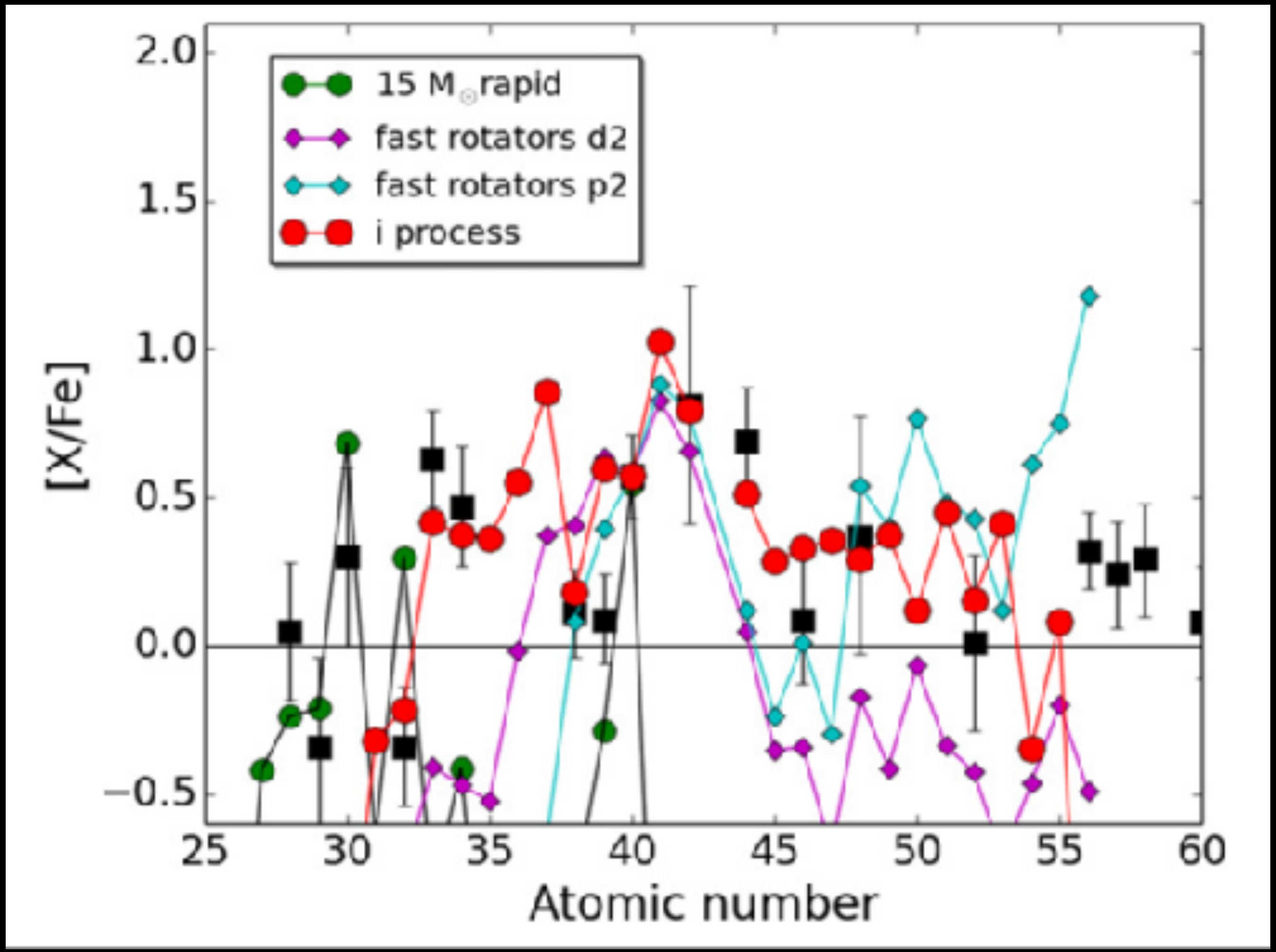
Description	Definition	Abbreviation
Population III stars	Postulated first stars, formed from metal-free gas	Pop III
Population II stars	Old (halo) stars formed from low-metallicity gas	Pop II
Population I stars	Young (disk) metal-rich stars	Pop I
Super metal-rich	[Fe/H] > 0.0	MR
Solar	[Fe/H] $= 0.0$	
Metal-poor	[Fe/H] < -1.0	MP
Very metal-poor	[Fe/H] < -2.0	VMP
Extremely metal-poor	[Fe/H] < -3.0	EMP
Ultra metal-poor	[Fe/H] < -4.0	UMP
Hyper metal-poor	[Fe/H] < -5.0	HMP
Mega metal-poor	[Fe/H] < -6.0	MMP
~~Septa metal-poor~~	~~[Fe/H] < −7.0~~	~~SMP~~
~~Octa metal-poor~~	~~[Fe/H] < −8.0~~	~~OMP~~
~~Giga metal-poor~~	~~[Fe/H] < −9.0~~	~~GMP~~
~~Ridiculously metal-poor~~	~~[Fe/H] < −10.0~~	~~RMP~~
Signature	**Metal-poor stars with neutron-capture element patterns**	**Abbreviation**
Main r-process	$0.3 \leq$ [Eu/Fe] $\leq +1.0$ and [Ba/Eu] < 0.0	r-I
	[Eu/Fe] $> +1.0$ and [Ba/Eu] < 0.0	r-II
Limited r-process[a]	[Eu/Fe] < 0.3, [Sr/Ba] > 0.5, and [Sr/Eu] > 0.0	r_{lim}
s-process:	[Ba/Fe] $> +1.0$, [Ba/Eu] $> +0.5$; also [Ba/Pb] > -1.5	s
r- and s-process	$0.0 <$ [Ba/Eu] $< +0.5$ and $-1.0 <$ [Ba/Pb] < -0.5[b]	$r+s$
i-process	$0.0 <$ [La/Eu] $< +0.6$ and [Hf/Ir] ~ 1.0[c]	i
Signature	**Metal-poor stars with other element characteristics**	**Abbreviation**
Neutron-capture-*normal*	[Ba/Fe] < 0	no
Carbon-enhancement	[C/Fe] $> +0.7$, for $\log(L/L_\odot) \leq 2.3$	CEMP[d]
	[C/Fe] $\geq (+3.0 - \log(L/L_\odot))$, for $\log(L/L_\odot) > 2.3$[e]	
α-element enhancement	[Mg, Si, Ca, Ti/Fe] $\sim +0.4$	α-enhanced

Frebel 2018, ARNP, https://arxiv.org/abs/1806.08955

	[Ba/Fe] < 0.0 **-no**	**[Ba/Fe] > 0.0** **[Ba/Eu] < 0** **-r**	**[Ba/Fe] > 0.0** **[Ba/Eu] > 0** **-s**
[C/Fe] > 0.7 **CEMP** “Enhanced”	CEMP-no Pop III signatures?	CEMP-r r-process (and Pop III?)	CEMP-s s-process and C from mass transfer
[C/Fe] < 0.7 **VMP/EMP** “Extremely”	EMP-no Pop III signatures?	EMP-r r-process	EMP-s s-process from chemical evolution
	-no = “normal”	**r-I: [Eu/Fe] > 0.3** **r-II: [Eu/Fe] > 1.0** **(uncorrelated with C)**	**CEMP-s at higher [Fe/H]** **(correlated with C)**

CEMP-r/s: looks like s-process but has Eu. Now thought to be i-process

[C]EMP-r/s (= i?)

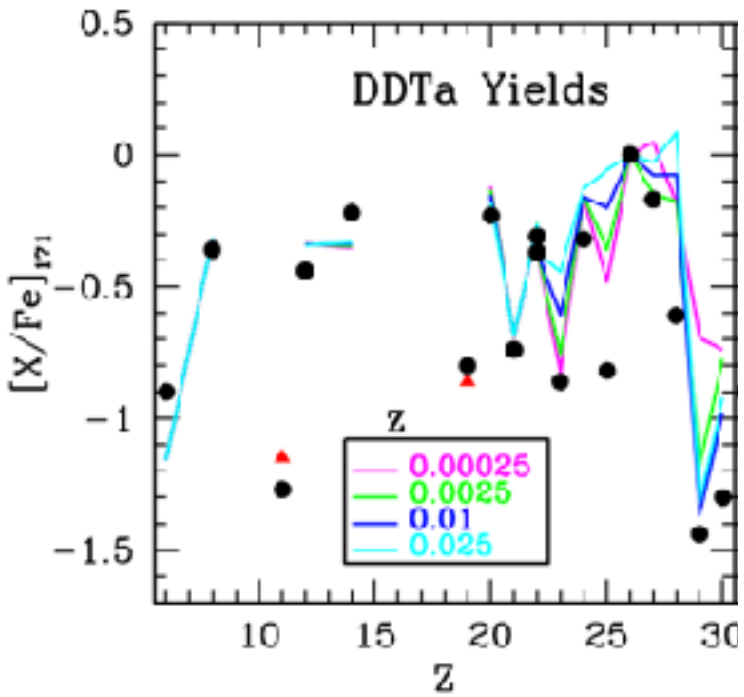


Stars previously thought to be r/s may be due to the i-process (intermediate neutron-to-seed ratios)

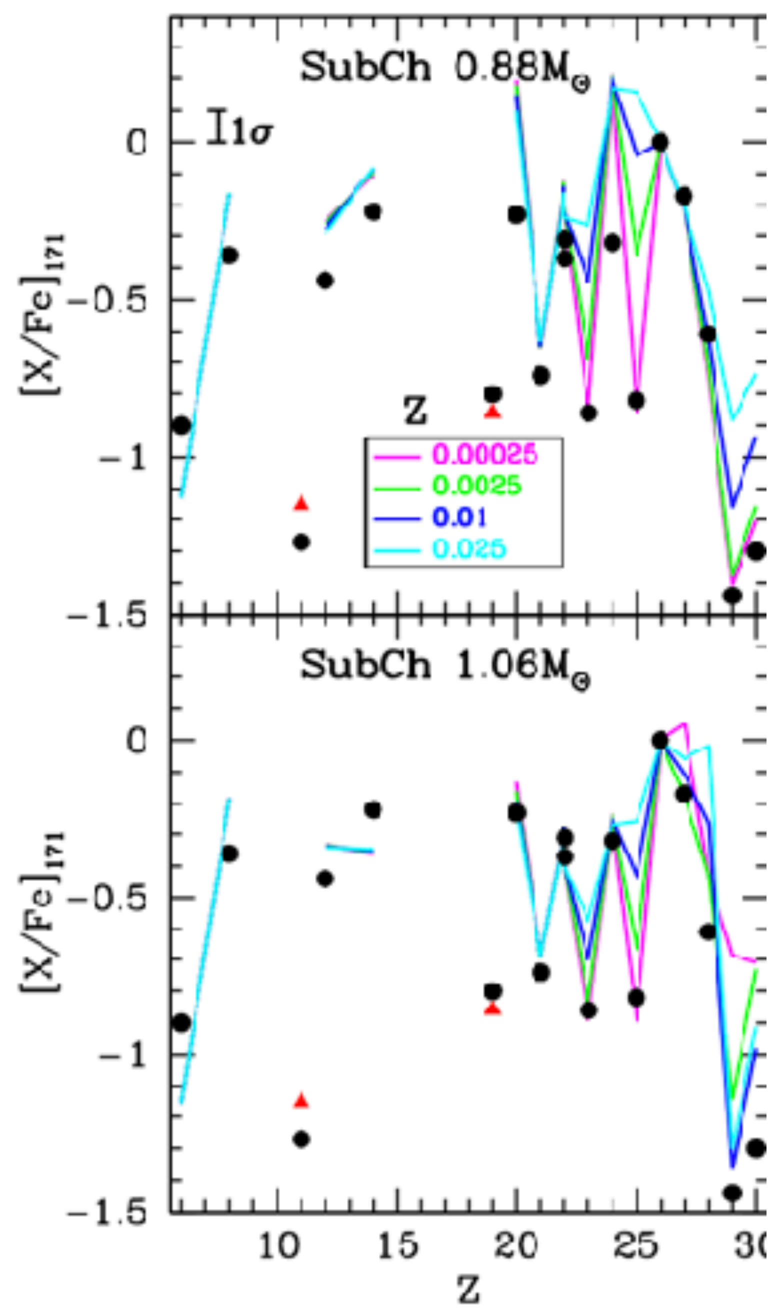
Roederer et al. 2016

Type Ia Yields

Chandrasekhar mass WD



sub-Ch WD



Different Type Ia SN models make different Fe-peak yields

Especially for [Mn,Co,Ni/Fe] (Z=25, 27, 28)

This star is a Fe-rich outlier in a dwarf galaxy.

By comparing to other stars in that galaxy, this star's Fe was mostly made in a sub-Ch WD explosion

Dwarf galaxies -> delayed nucleosynthesis

McWilliam et al. 2018

Buzzword List

- Dark matter
- Dark energy
- Baryon
- Scale factor
- Redshift
- Hubble Constant
- CMB
- BBN
- Lithium problem

- Structure formation
- Dark matter halo
- Halo mass function
- Stellar mass function
- Feedback
- N-body simulation
- Hydro simulation
- [Reionization]

- Pop I, II, III stars
- Stellar archaeology
- CEMP stars
- [C]EMP-no, -r, -i, -s
- Stellar halo
- Dwarf galaxies
- Spinstars
- Mixing and fallback SN
- Type II, Type Ia supernova

Extra Slides

Useful links

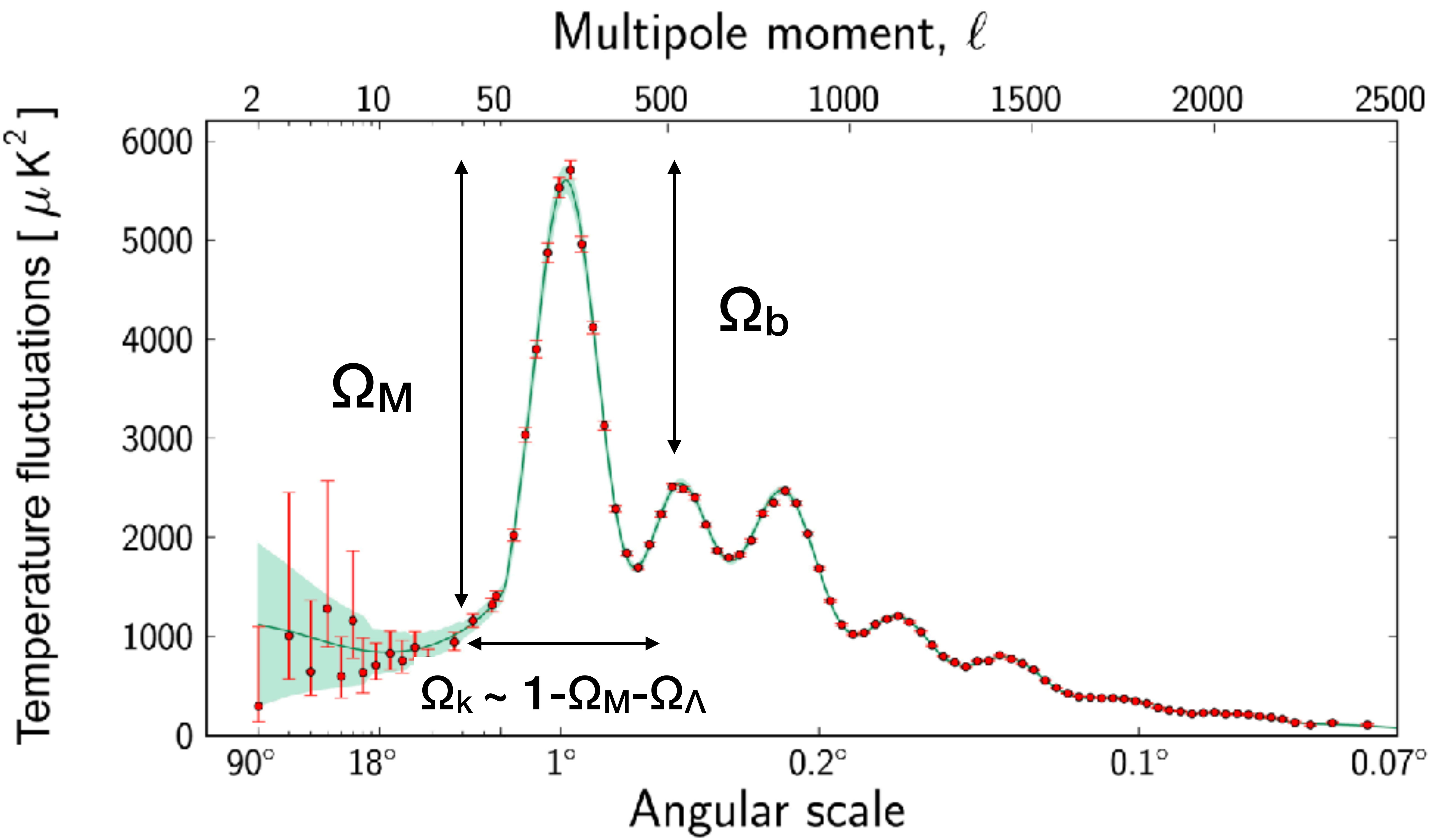
- Hogg 2000: cosmological distance measures
  https://arxiv.org/abs/astro-ph/9905116

- Planck 2015 cosmological parameters (most precise):
  https://arxiv.org/abs/1502.01589

- Croton 2013: converting between simulation and physical coordinates with little h
  https://arxiv.org/abs/1308.4150

- Ned Wright's Cosmology calculator:
  http://www.astro.ucla.edu/~wright/CosmoCalc.html

- Max Tegmark's CMB movies:
  https://space.mit.edu/home/tegmark/movies.html


Multipole moment, ℓ
2
10
50
500
1000
1500
2000
2500
Temperature fluctuations [μK^2]
6000
5000
4000
3000
2000
1000
0
Ω_M
Ω_b
$\Omega_k \sim 1-\Omega_M-\Omega_\Lambda$
90°
18°
1°
0.2°
0.1°
0.07°
Angular scale

Planck 2015

Matter power spectrum

- Power spectrum: correlations of matter density fluctuations at every characteristic distance.
- Primordial power spectrum is cut off in early universe
- Power spectrum constrains dark matter properties
- (Power spectrum = fourier transformation of correlation function)

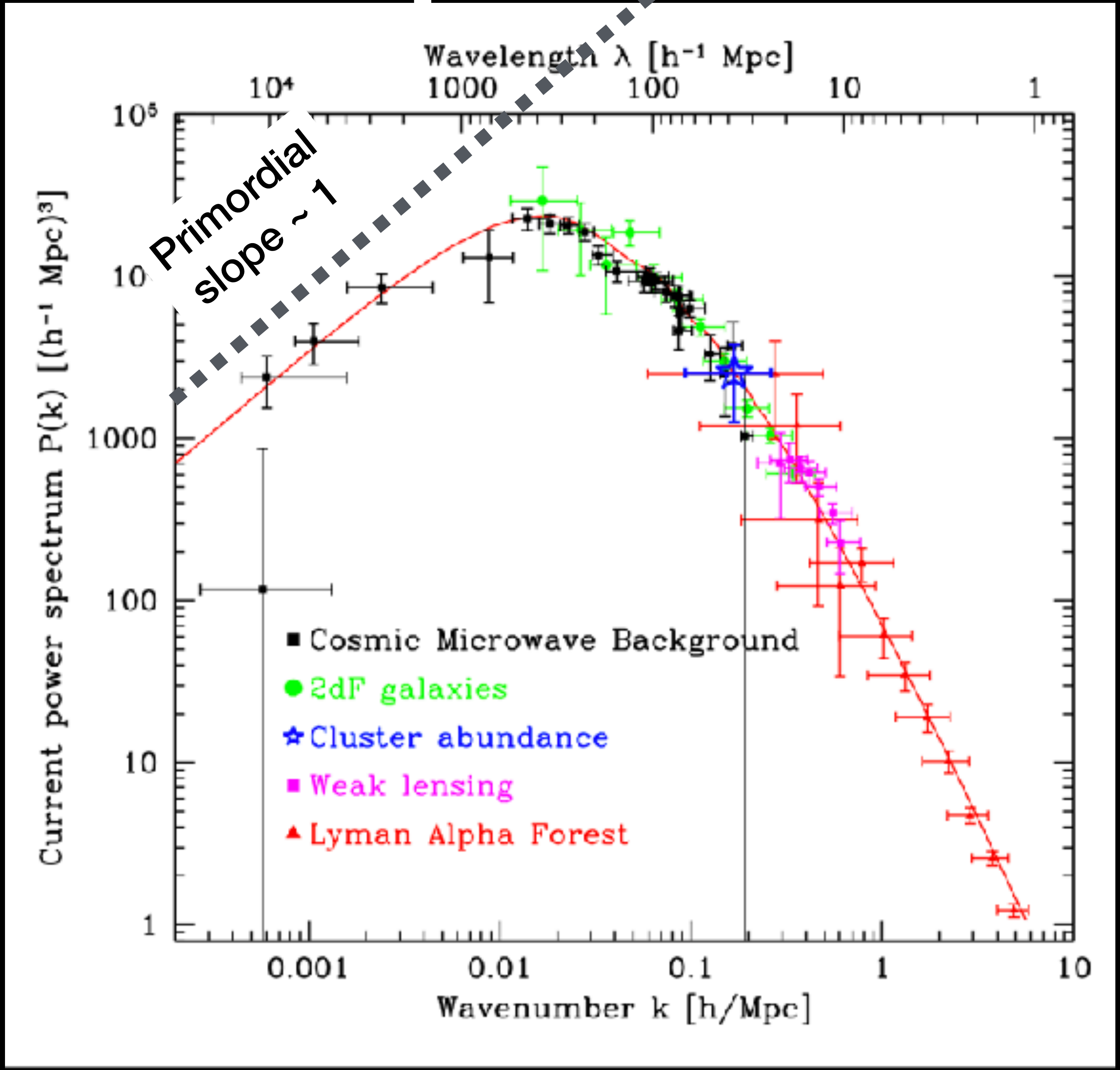
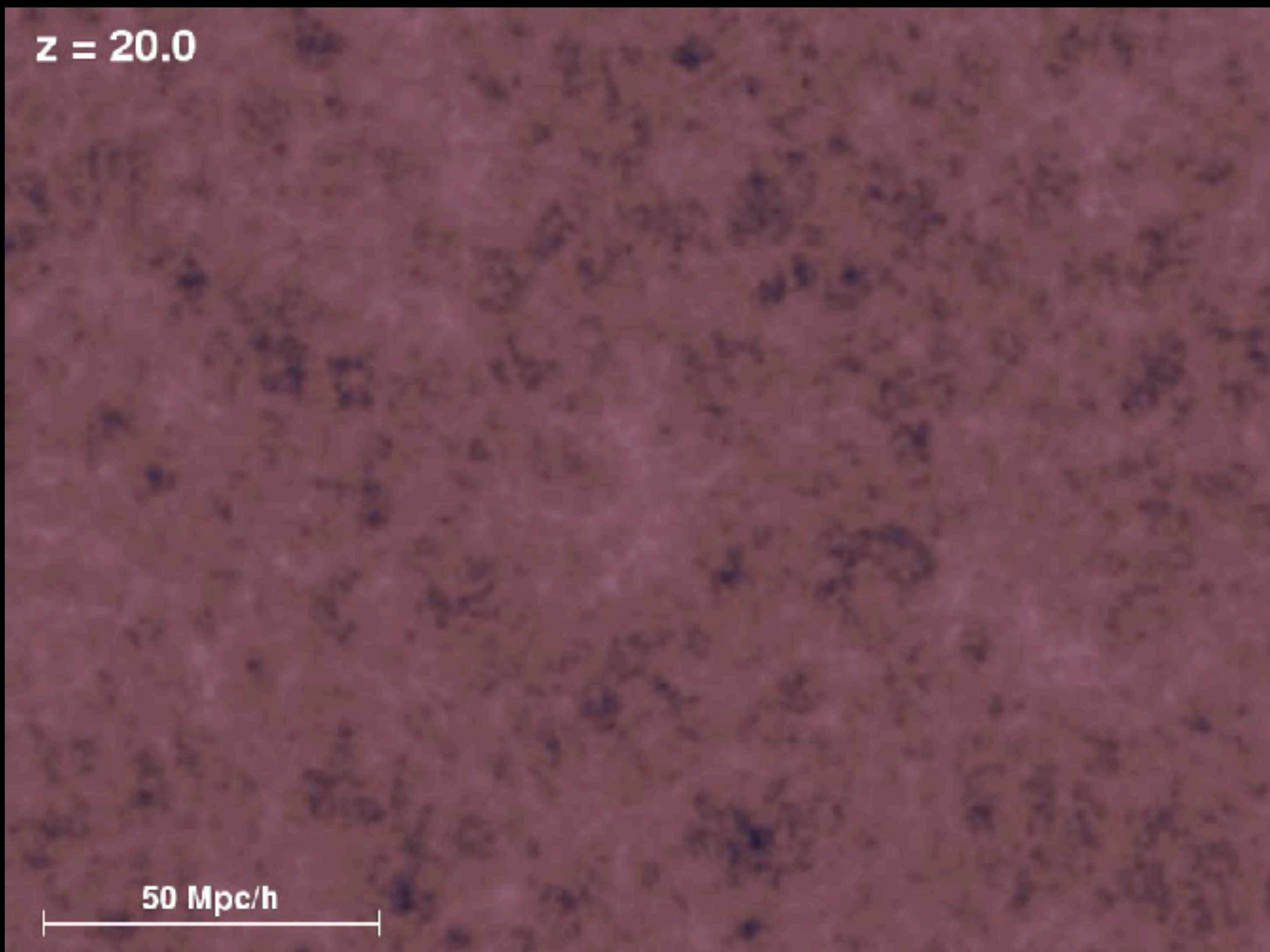
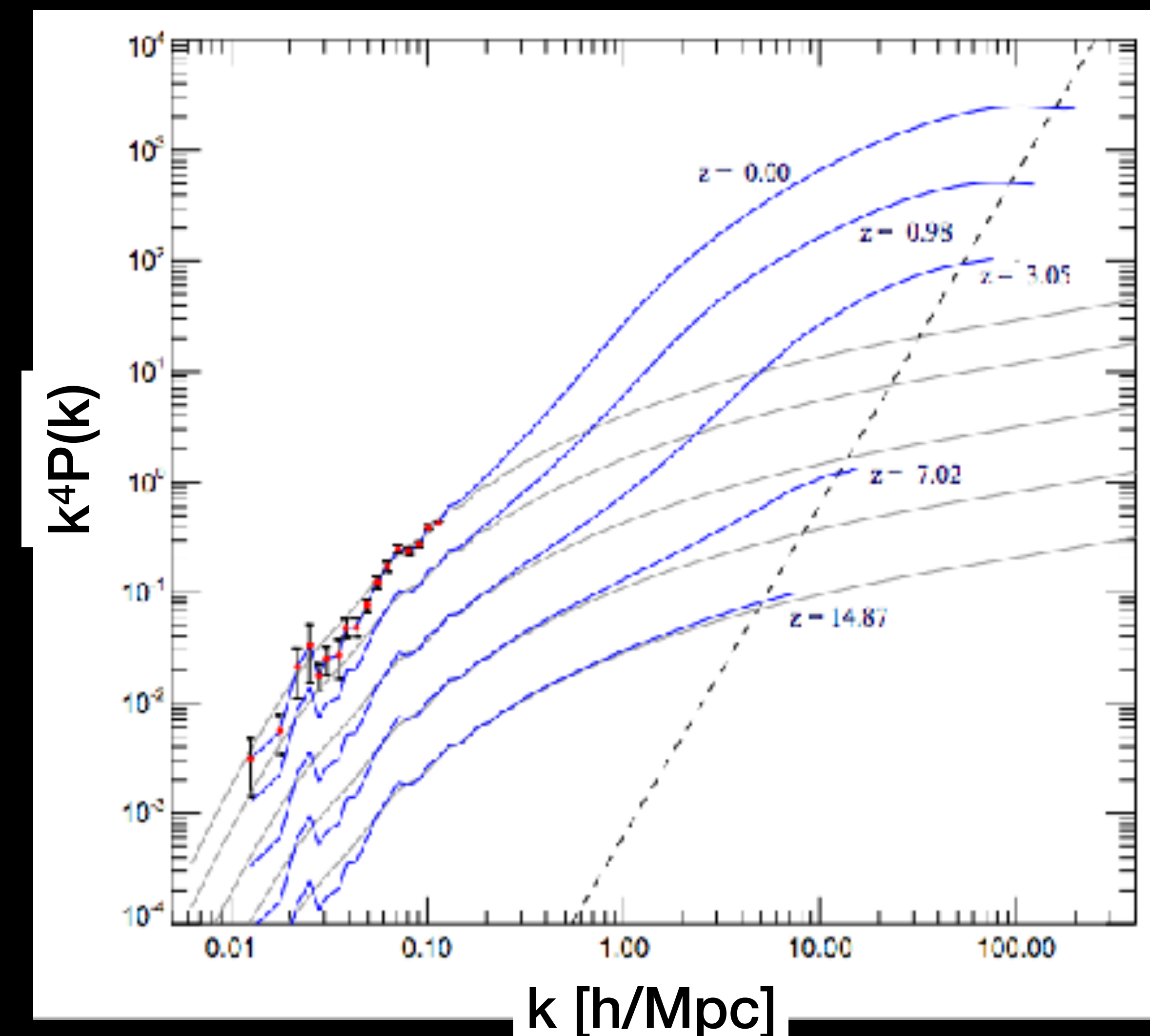


Figure: Courtesy M. Tegmark (data as of 2002)

Nonlinear matter power spectrum: Requires simulations



~10^{10} dark matter particles, each mass ~10^{9} M_{sun}
(Our Milky Way is ~10^{12} M_{sun})

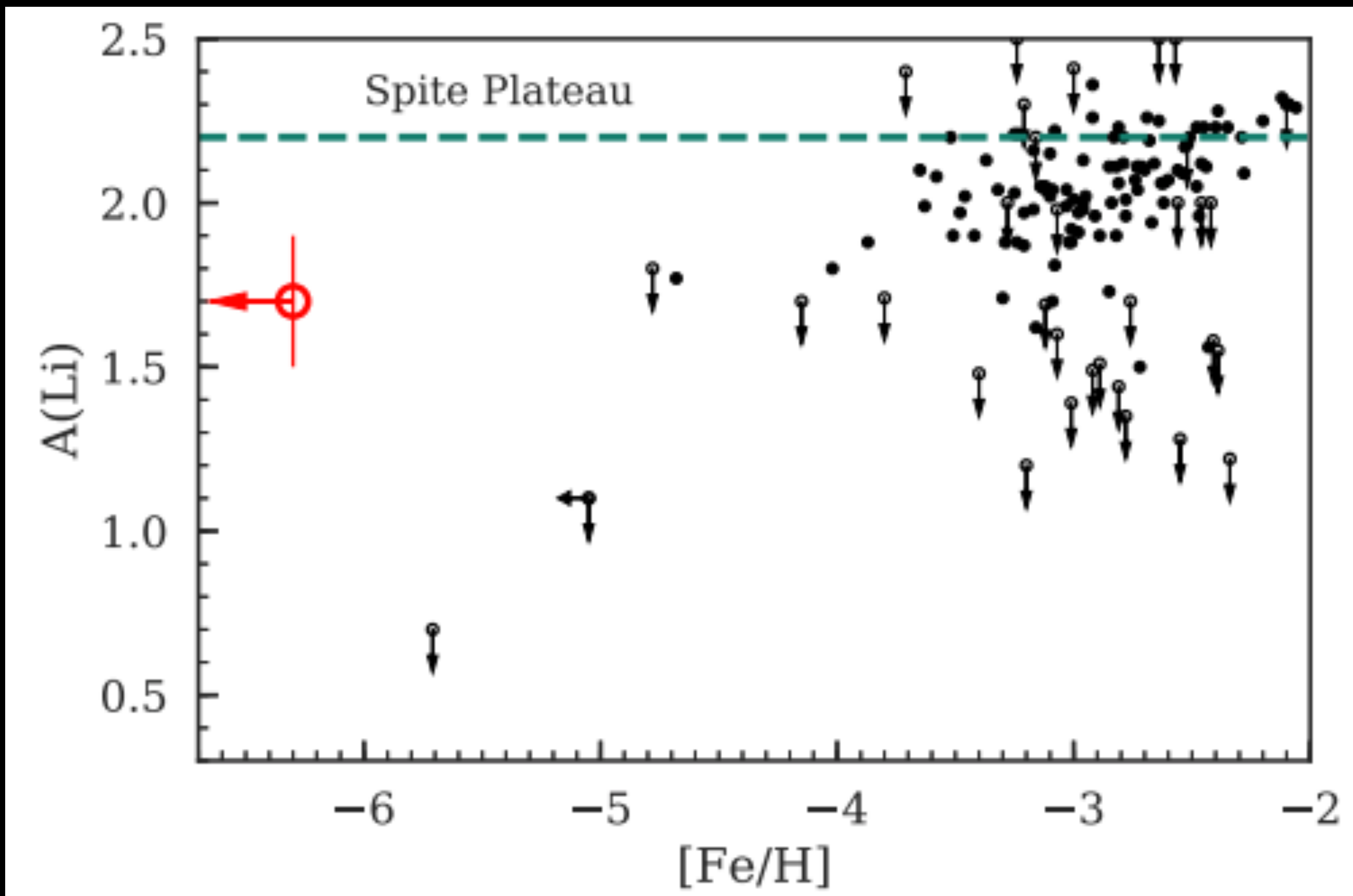


Grey = linear growth
Blue = nonlinear simulation

At "late" times, goes nonlinear at small scales/high k

V. Springel et al. (2005)

Lithium in metal-poor stars



The Spite plateau breaks down at low [Fe/H]…

no one knows why

Frebel, Ji et al. 2019

Energy timeline