

Cosmology, structure formation, and the first stars

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First Frontiers Summer School

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

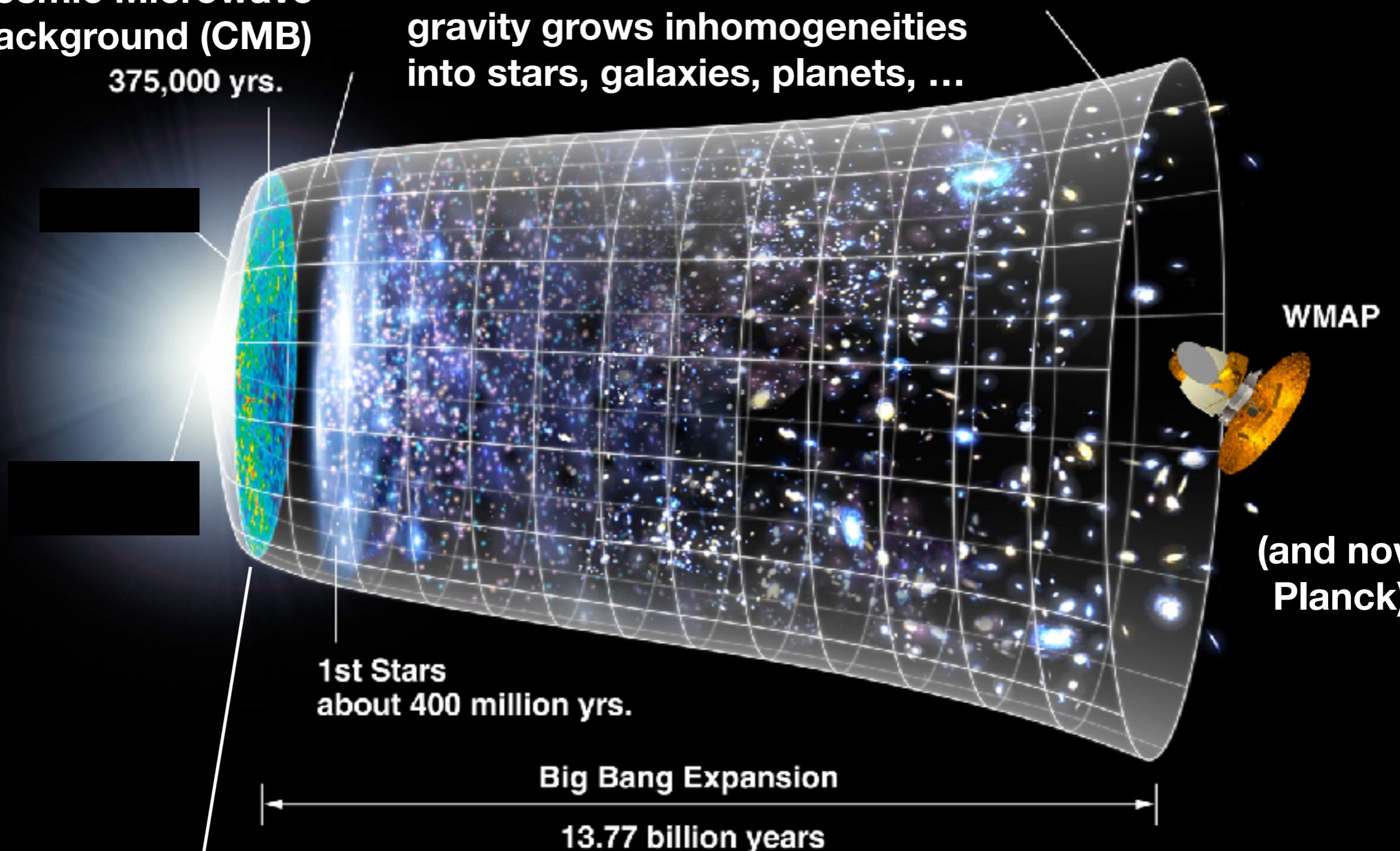
Astronomical Distances

	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 (and white dwarfs)	6.4e6 m	Small scales
• Neutron stars	~1.0e4 m	

**Cosmic Microwave
Background (CMB)**
375,000 yrs.

Structure formation:
gravity grows inhomogeneities
into stars, galaxies, planets, ...

**Dark energy causes
expansion to *accelerate***



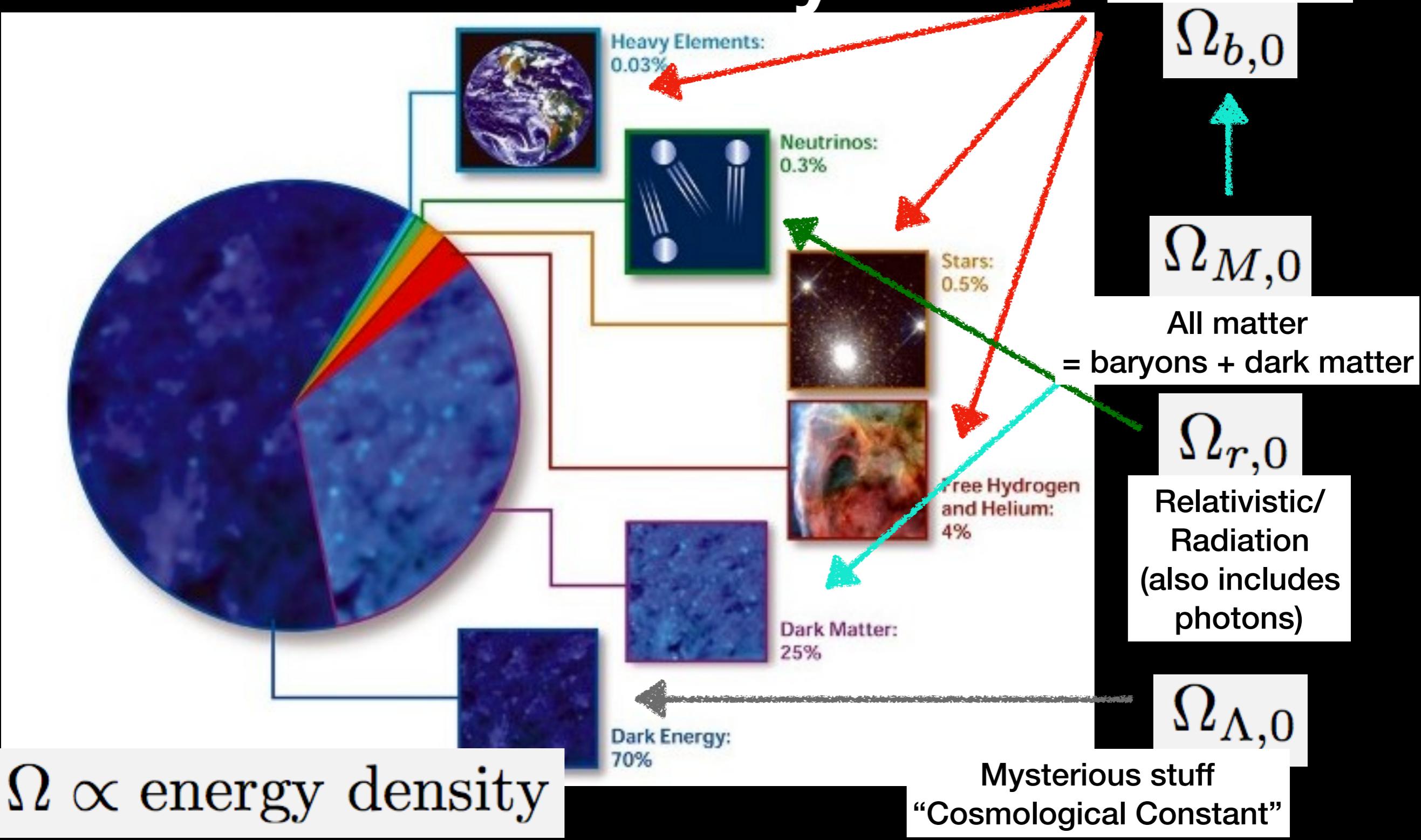
**Initial density perturbations
are measured here:
differences are 1/100,000**

Universe timeline

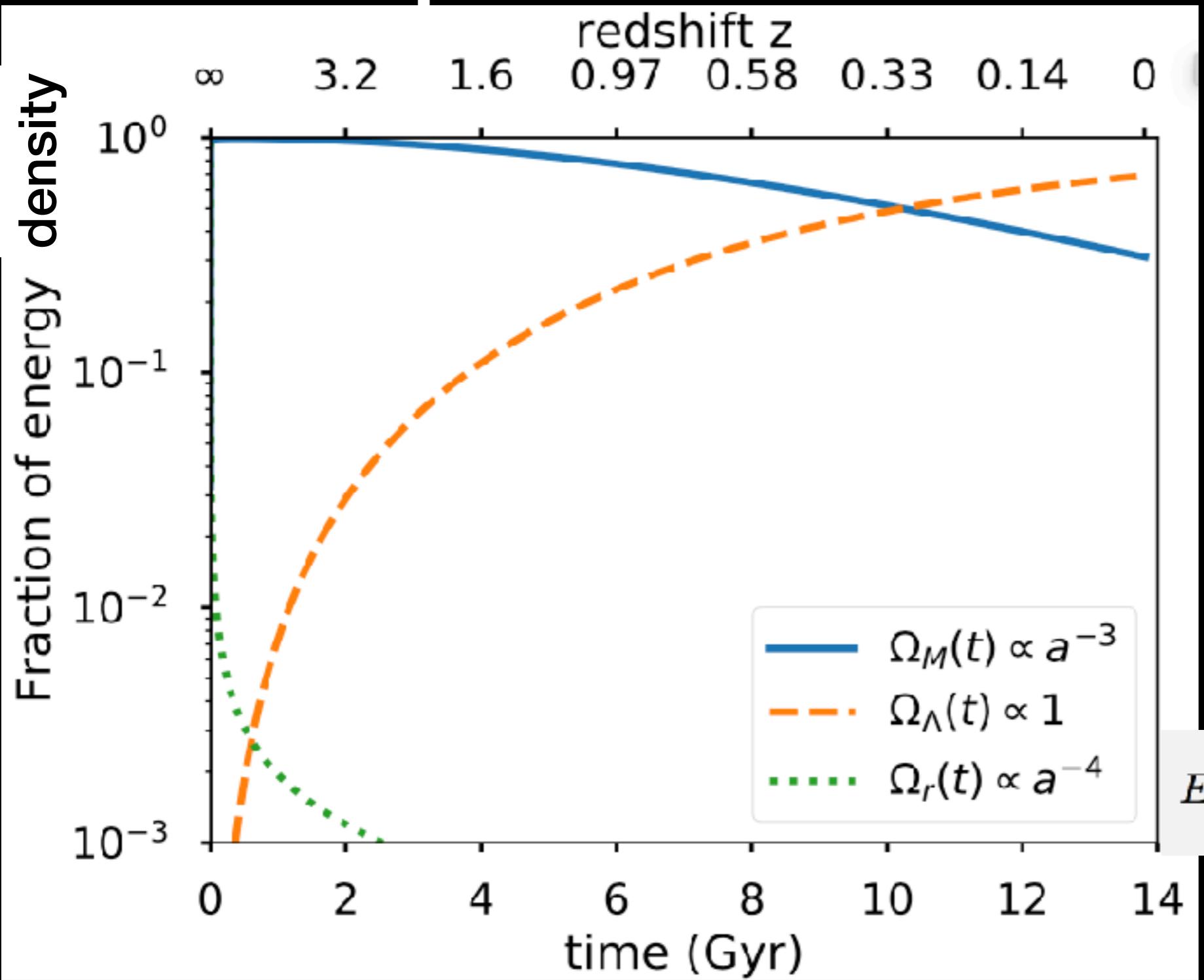
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Big bang	$z = \text{infinity}$	$t=0$
Big bang nucleosynthesis	$z \sim 3\text{e}9$	$\sim 3 \text{ min}$
Matter-radiation equality	~ 3380	$\sim 50 \text{ kyr}$
Cosmic microwave background	$z \sim 1100$	$\sim 370 \text{ kyr}$
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First galaxies	$z \sim 10-20$	$\sim 470 \text{ Myr}$
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Cosmic noon (peak of cosmic star formation)	$z \sim 2-3$	$2-3 \text{ Gyr}$
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Sun/Earth form	$z \sim 0.4$	9.3 Gyr
Matter-lambda equality	$z \sim 0.3$	10.3 Gyr
Today	$z=0$	13.8 Gyr

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

Universe's Composition Today



The relative dominance of each component varies over time



$a = \text{scale factor}$
 $\sim \text{size of universe}$

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 $a(t)$
 $a \leftrightarrow \text{redshift} \leftrightarrow \text{time}$

- Input/Assumptions:
 - General Relativity; homogeneous/isotropic universe
 - Composition of the universe
- Output: expansion history \rightarrow “radius” as a function of time.
- $a(t) = \text{“scale factor”}$ $a(t=0) = 0.0$ $a(\text{today}) = 1.0$
- $z = \text{redshift}$: $a = 1/(1+z)$ [redshift is observable!]
$$z = \frac{\Delta\lambda}{\lambda} = \frac{\Delta v}{c}$$
- $H(z) = \text{Hubble parameter}$
 $H_0 = H(z=0) = \text{Hubble “constant”}$

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

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

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

$$\Omega_{M,0} = 0.31$$

$$\Omega_{\Lambda,0} = 0.69$$

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

$$\Omega_{k,0} \equiv 0$$

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

Solving for $a(t)$ (optional this afternoon)

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

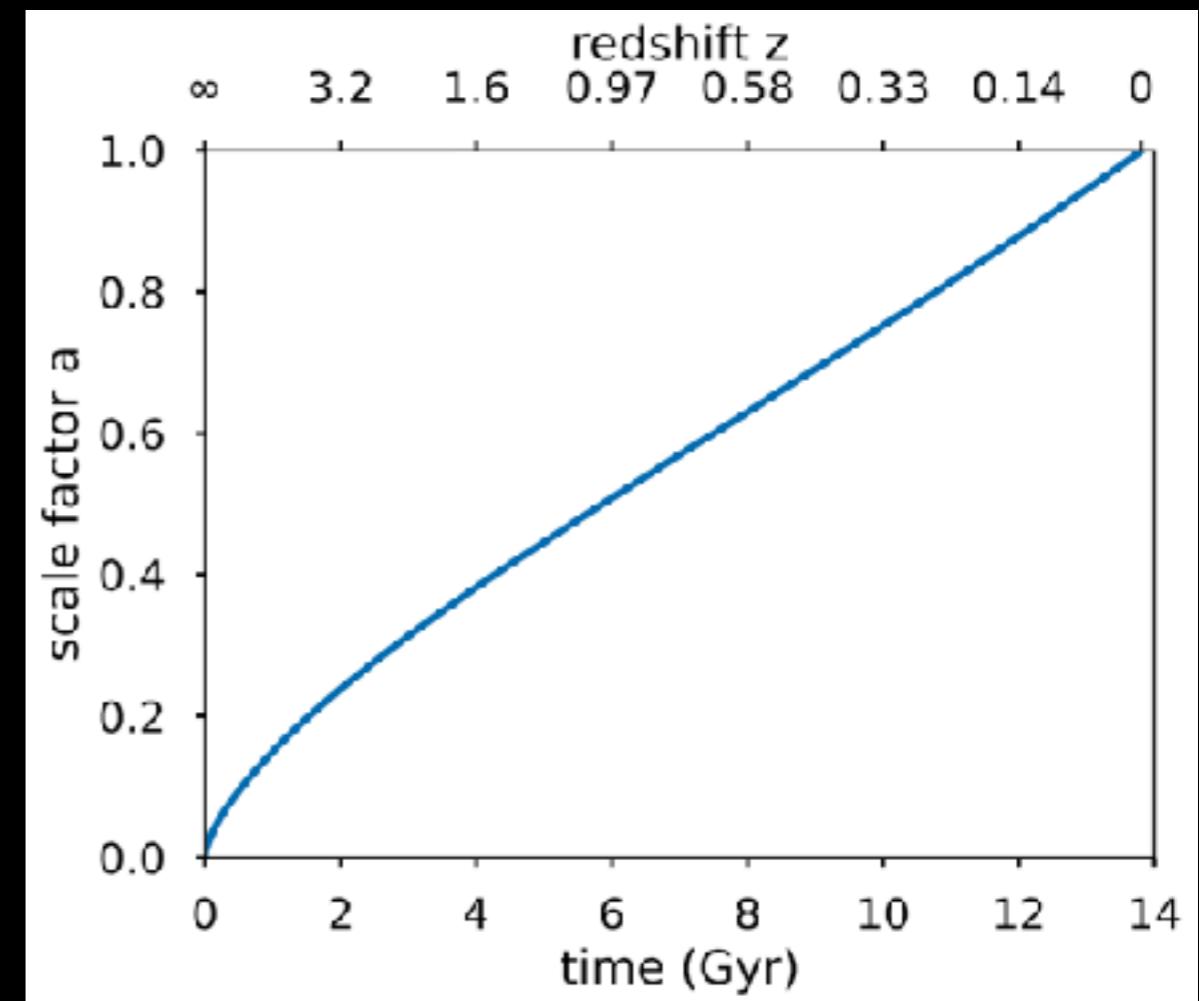
$$\frac{da}{a\sqrt{0.31a^{-3} + 10^{-4.04}a^{-4} + 0.69}} = \sqrt{\frac{8\pi G}{3c^2}} dt$$

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

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
- $z \leftrightarrow a \leftrightarrow \text{time}$
- Also the *temperature* of the universe evolves with time



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

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

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

0.2348 meV

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)

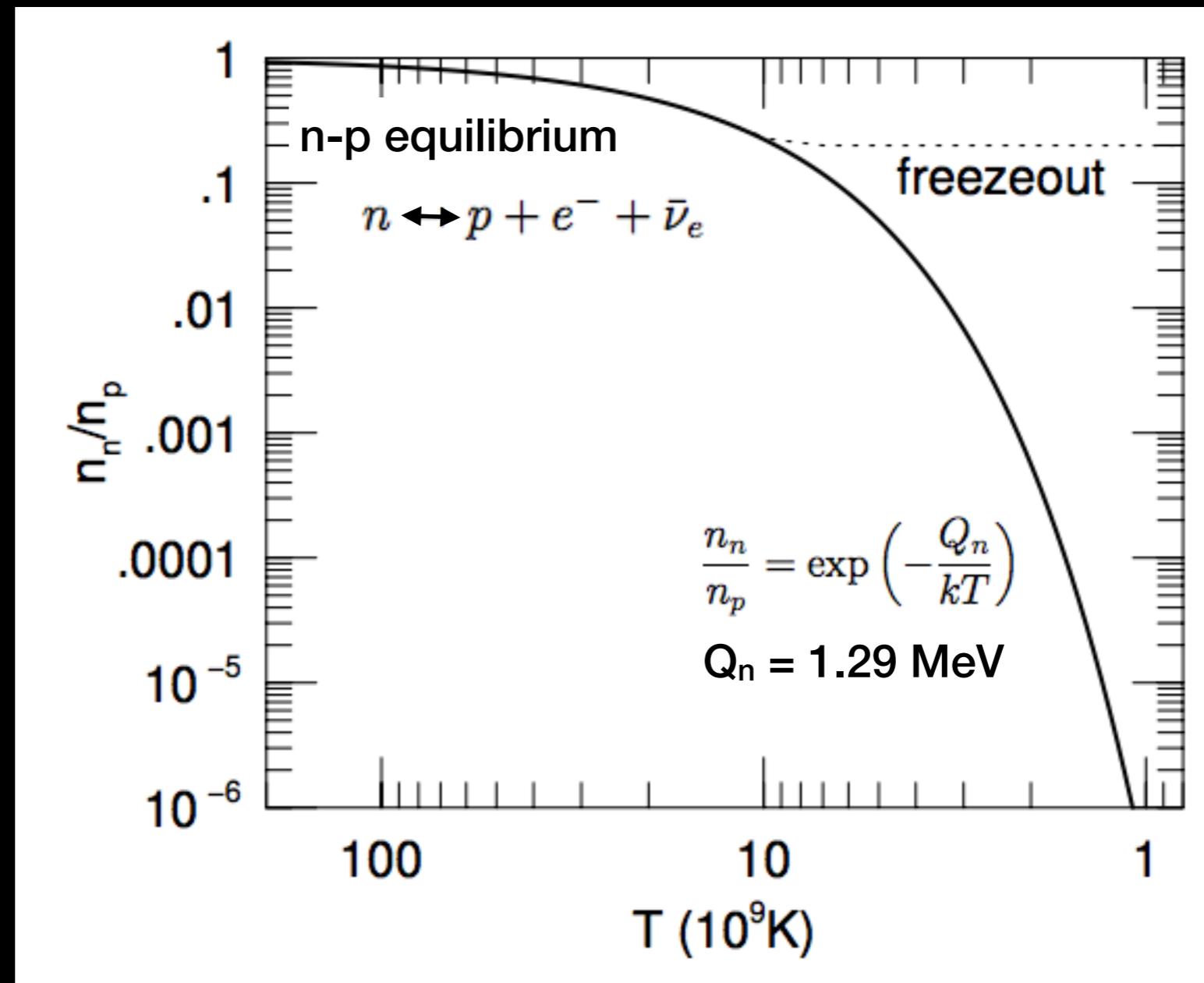
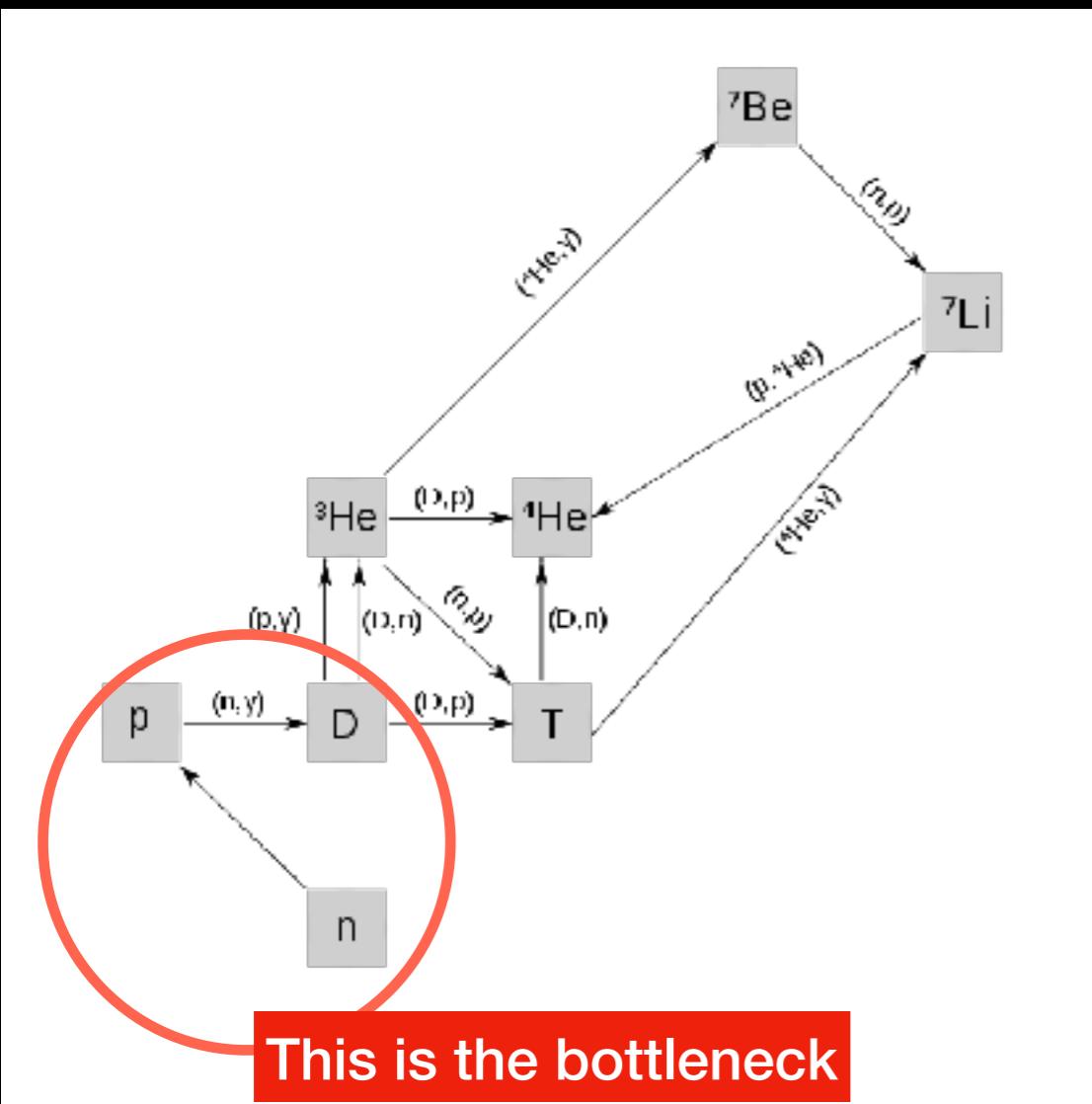
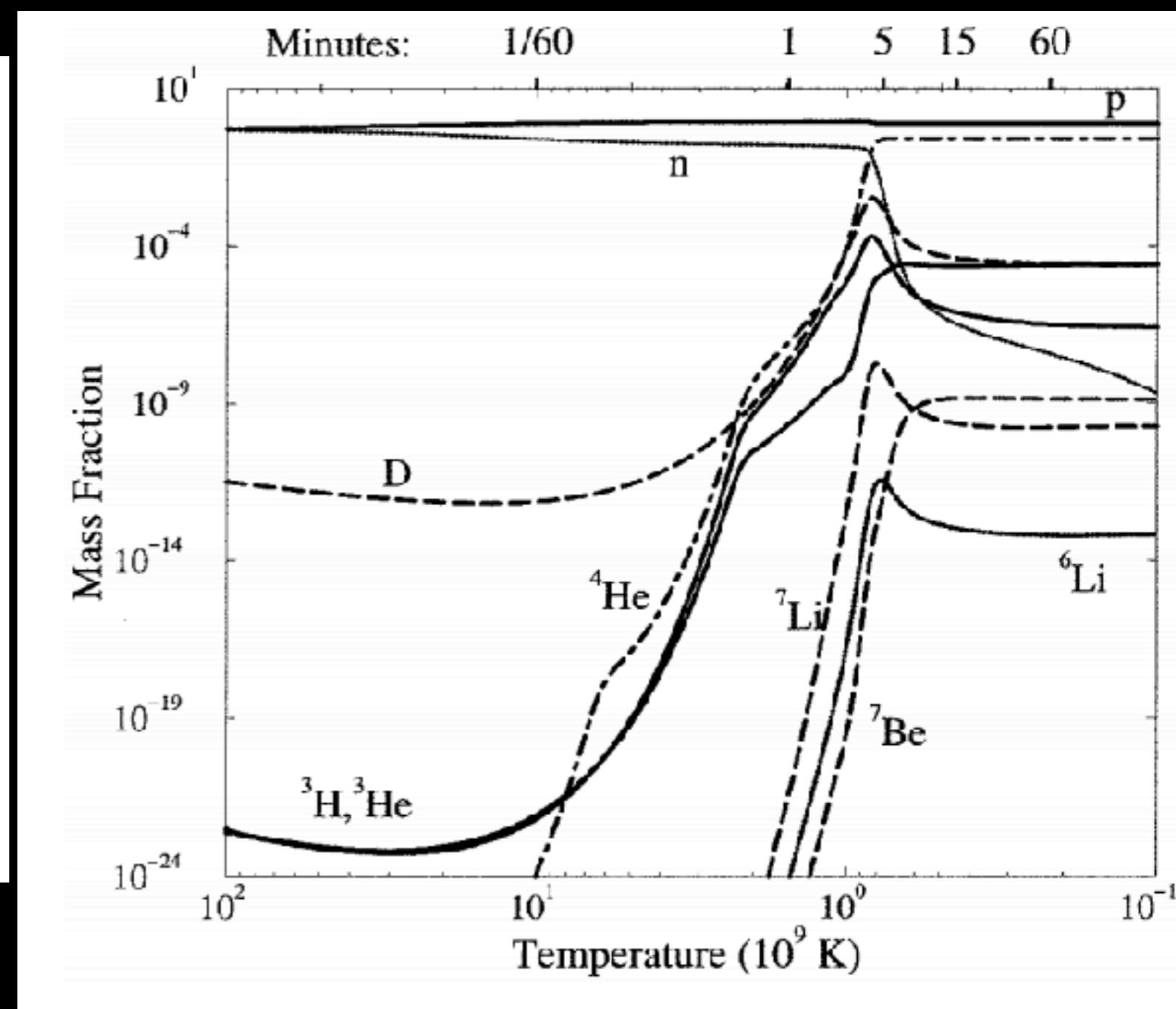


Figure: Ryden, Introduction to Cosmology Ch 10

Big Bang Nucleosynthesis

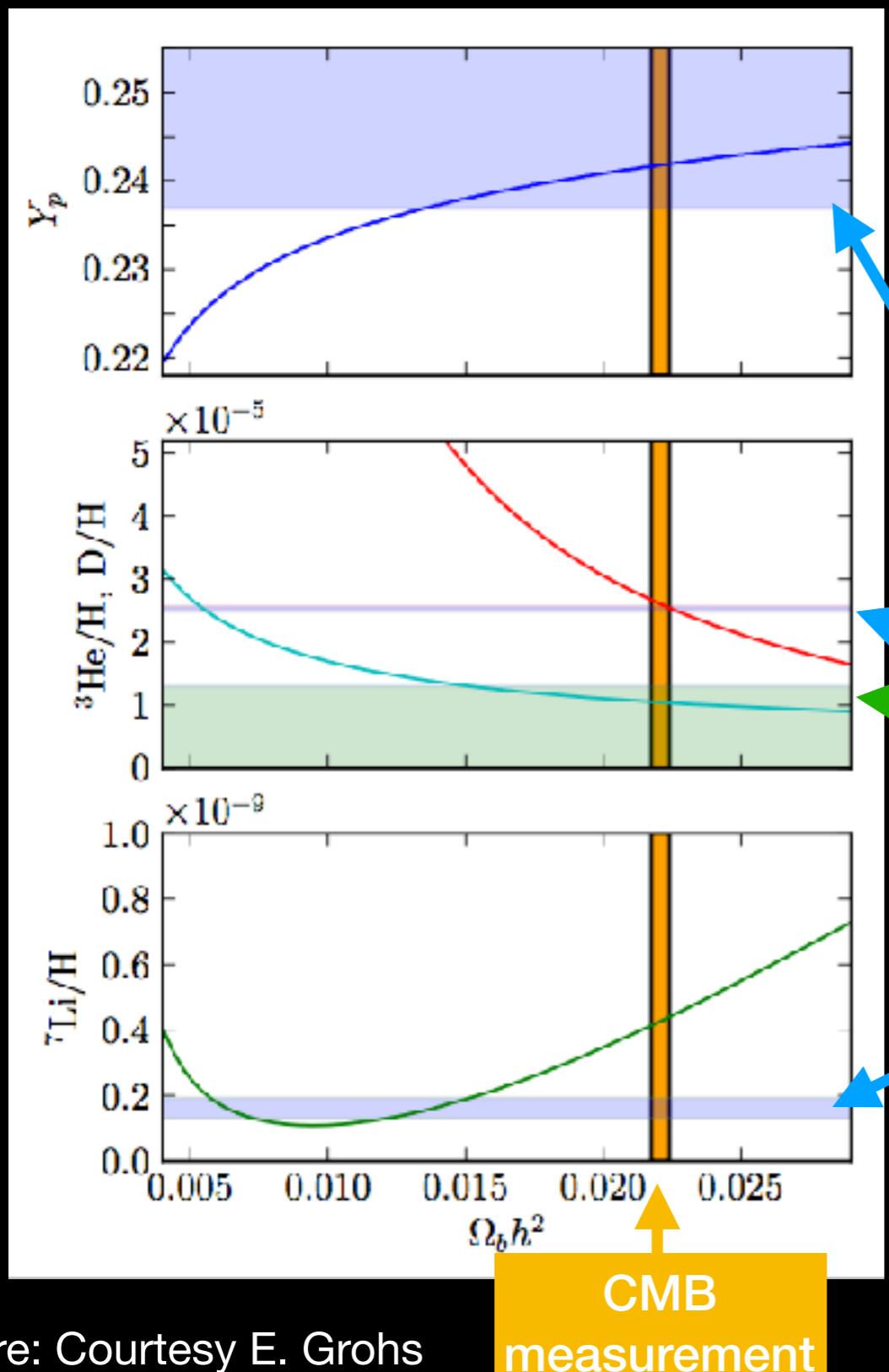


0th order Approximation:
Fuse all n with p into D
Fuse all D into ^4He



Negligible amounts of heavier elements

BBN Matches Cosmology



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

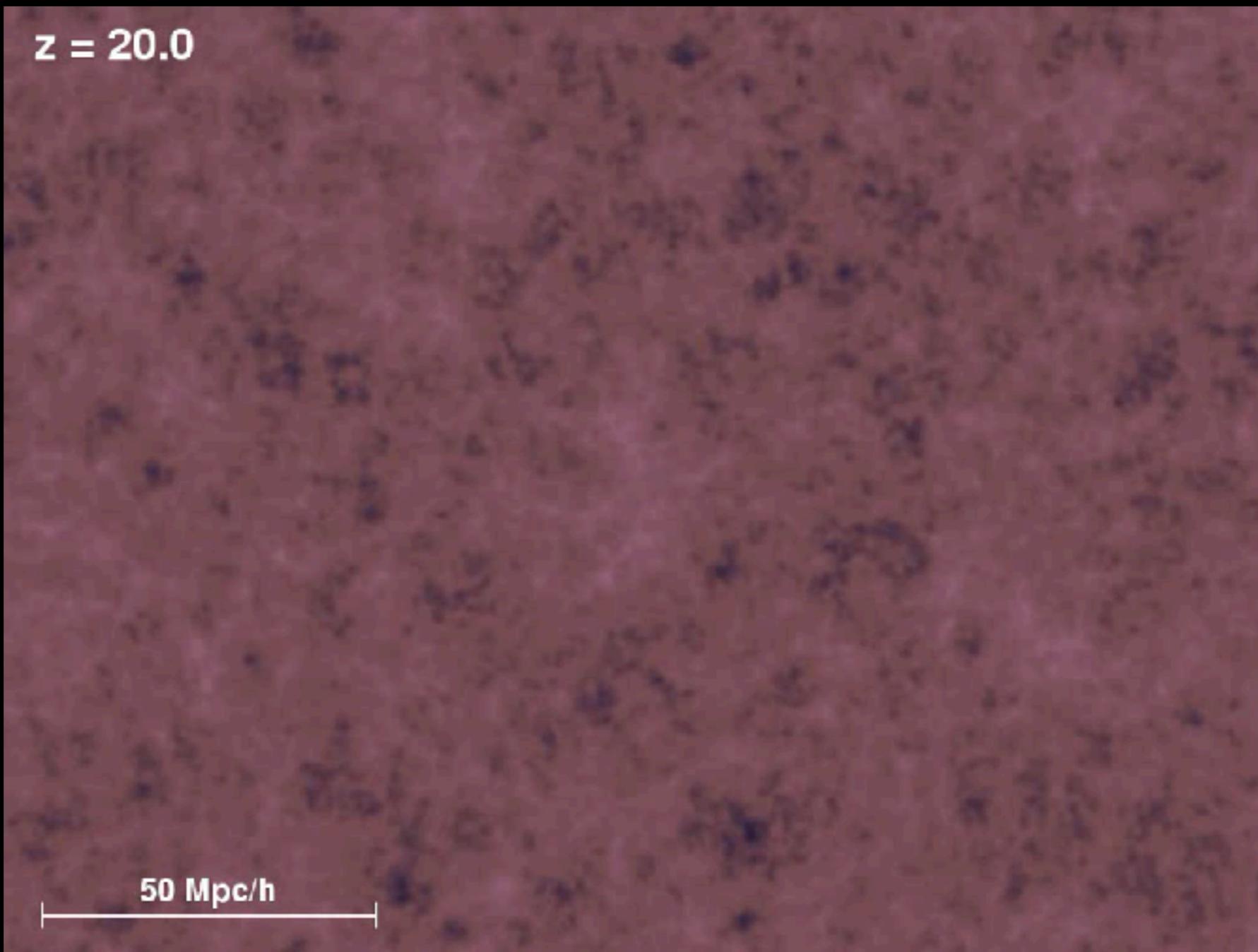
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Structure Formation

Growth of matter inhomogeneities

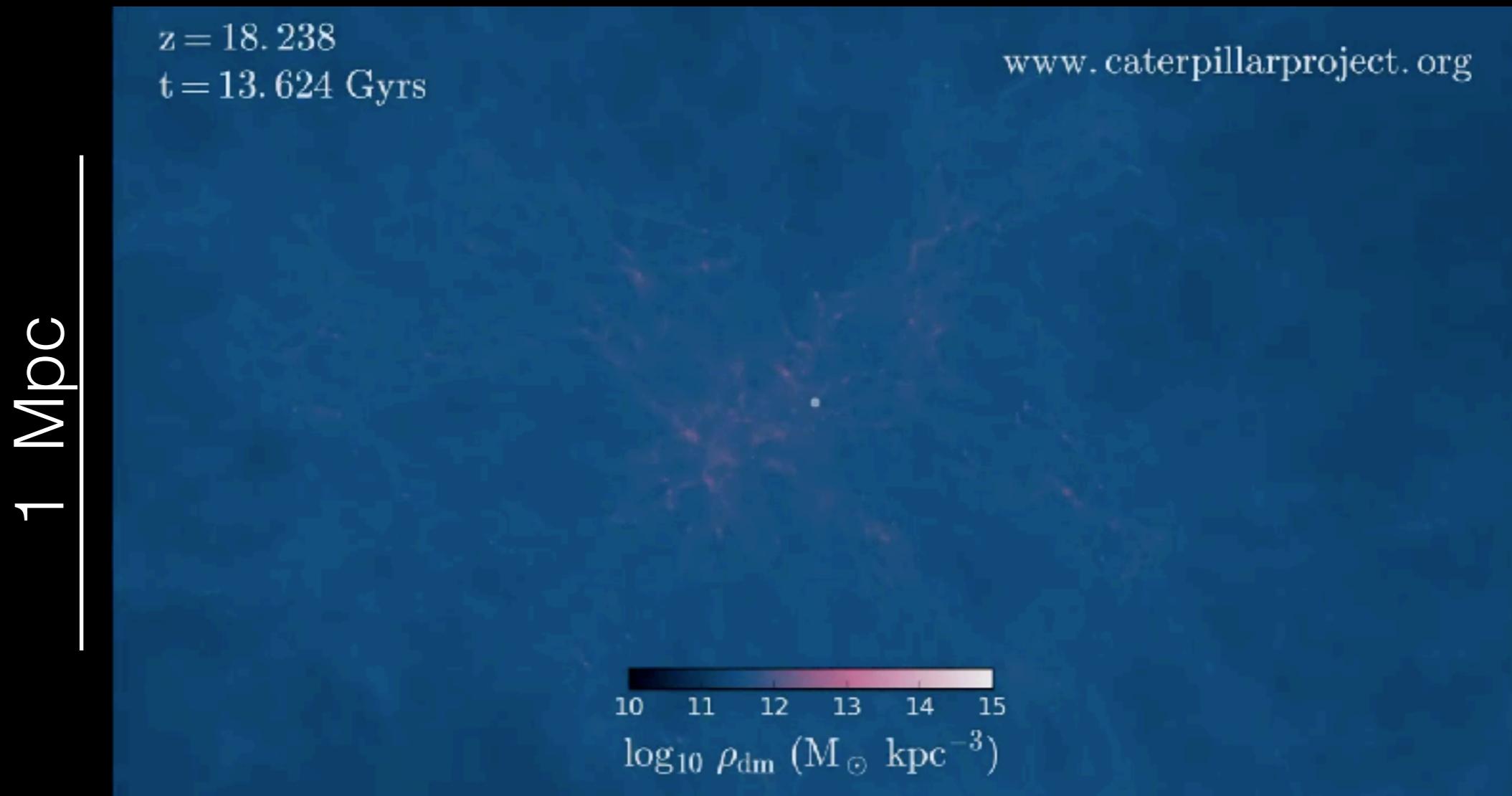
- 0th order: the universe is homogeneous + isotropic
- 1st order: linear growth of initial density perturbations
-> power spectrum
- 2nd+ order: nonlinear growth of linear perturbations
-> dark matter halos [needs simulations]
- NOTE: dark matter is >80% of total mass,
it dominates the gravity.

Growth of structure



**$\sim 10^{10}$ dark matter particles, each particle mass $\sim 10^9 M_{\text{sun}}$
(Our Milky Way is $\sim 10^{12} M_{\text{sun}}$)**

Assembling a Milky Way in Dark Matter



Zoom-in simulation of one galaxy: each particle is $\sim 10^4 M_{\odot}$

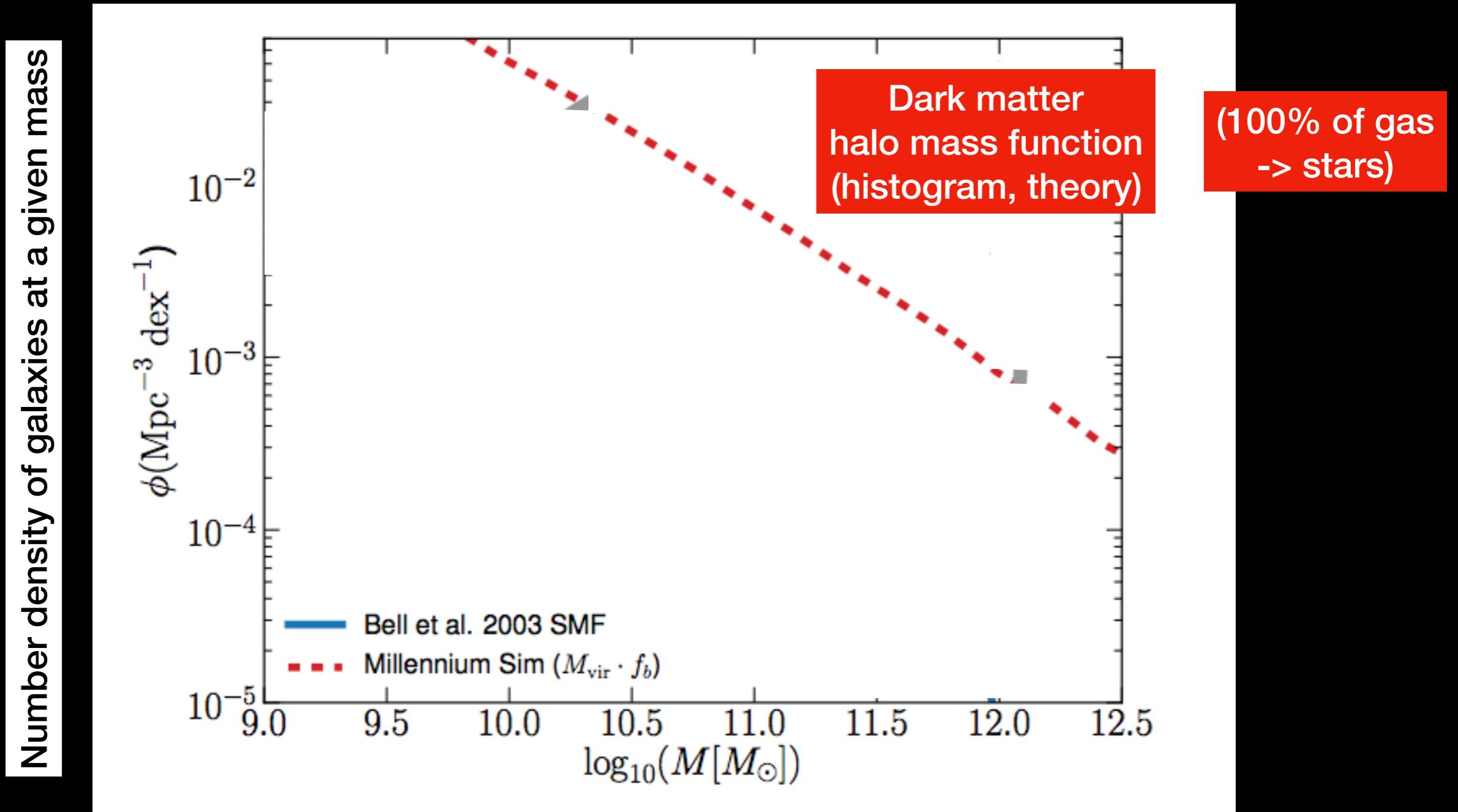
Gravitationally bound structures = “dark matter halos”

One galaxy lives at the center of each halo

“Hierarchical structure formation”: big things build up from small things

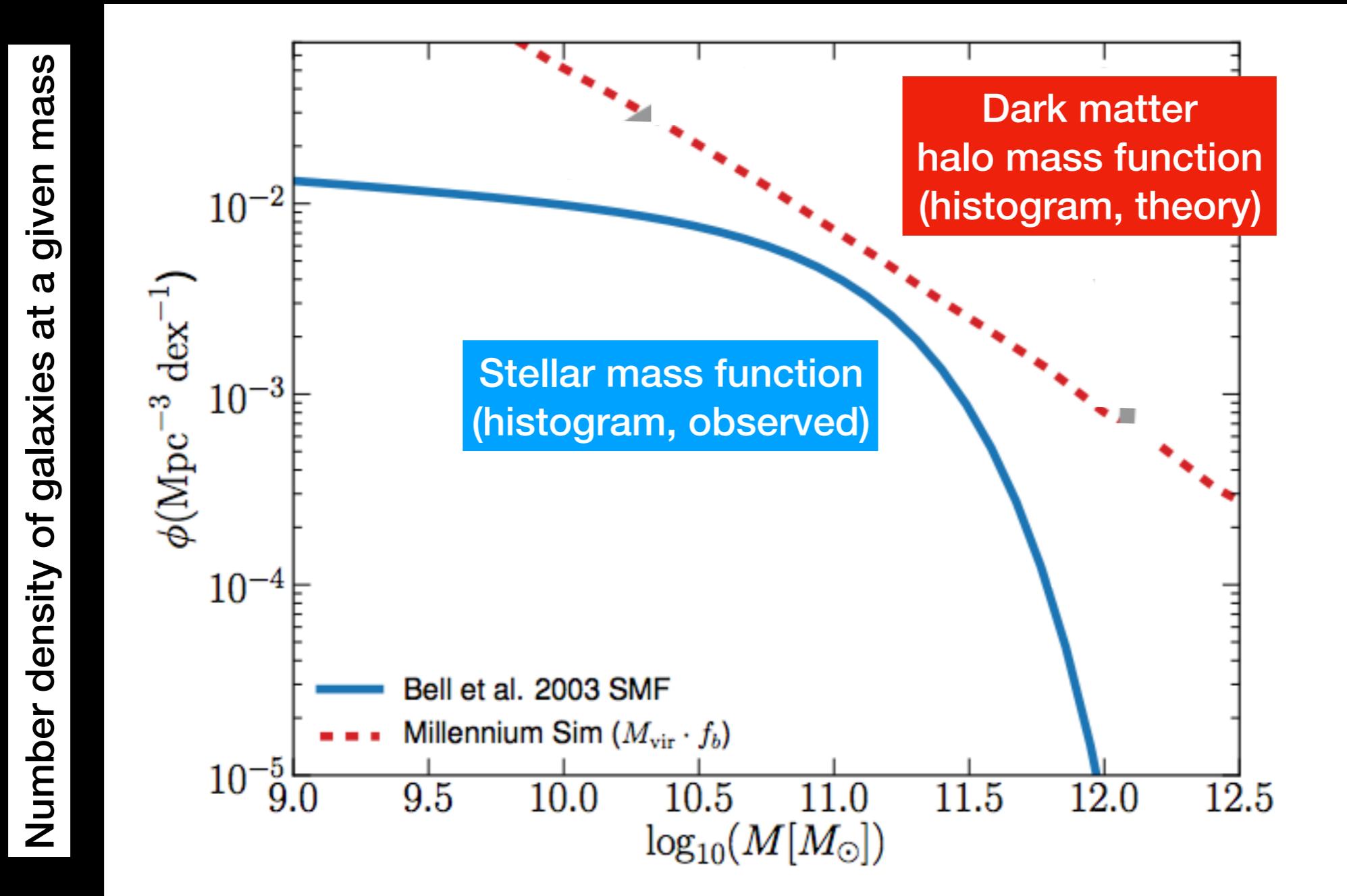
Early galaxy ($z > 3$) is a bunch of small systems that later merge

Galaxy Formation



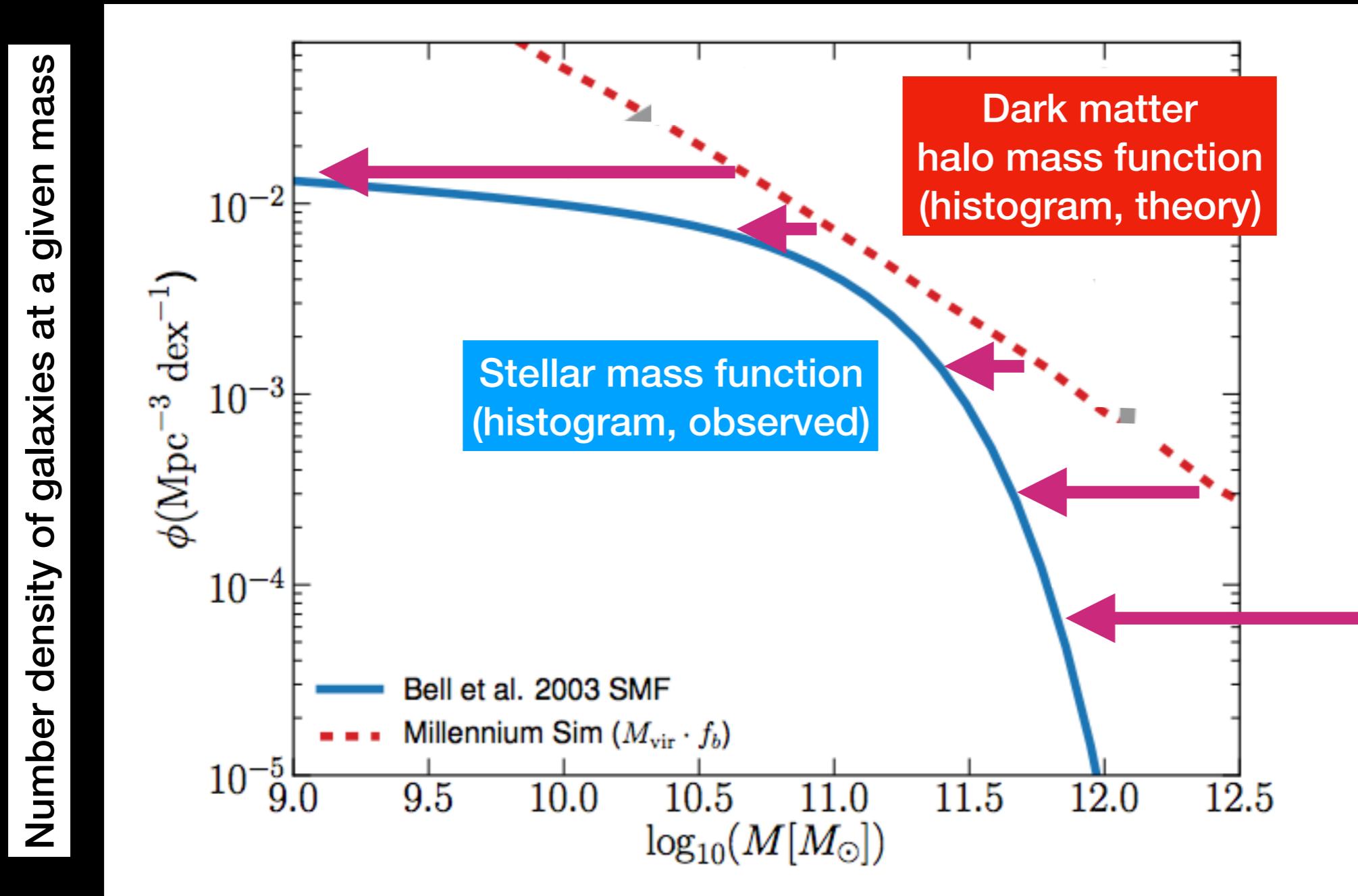
A galaxy's job is to turn gas into stars

Galaxy Formation



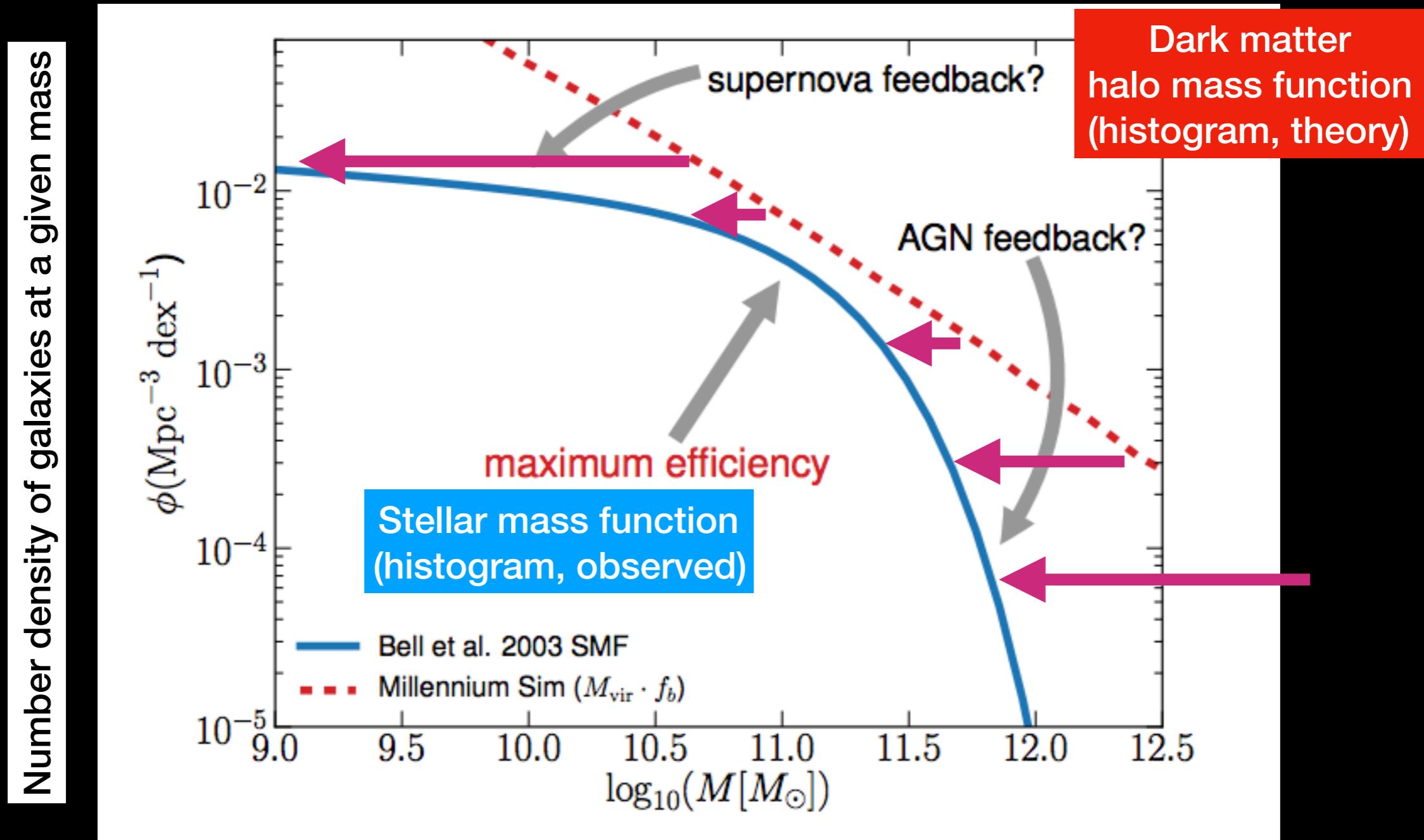
A galaxy's job is to turn gas into stars
Most galaxies are bad at this job

Galaxy Formation



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

Galaxy Formation



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

“Hydro” simulations

$z=19.0$

- 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

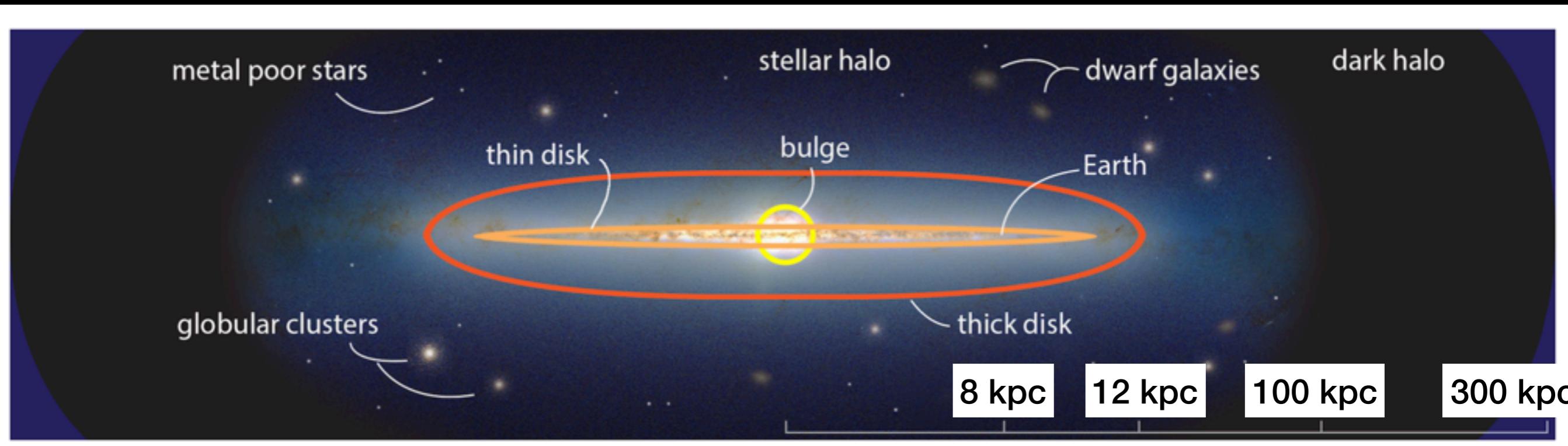
100 kpc

“Hydro” simulations



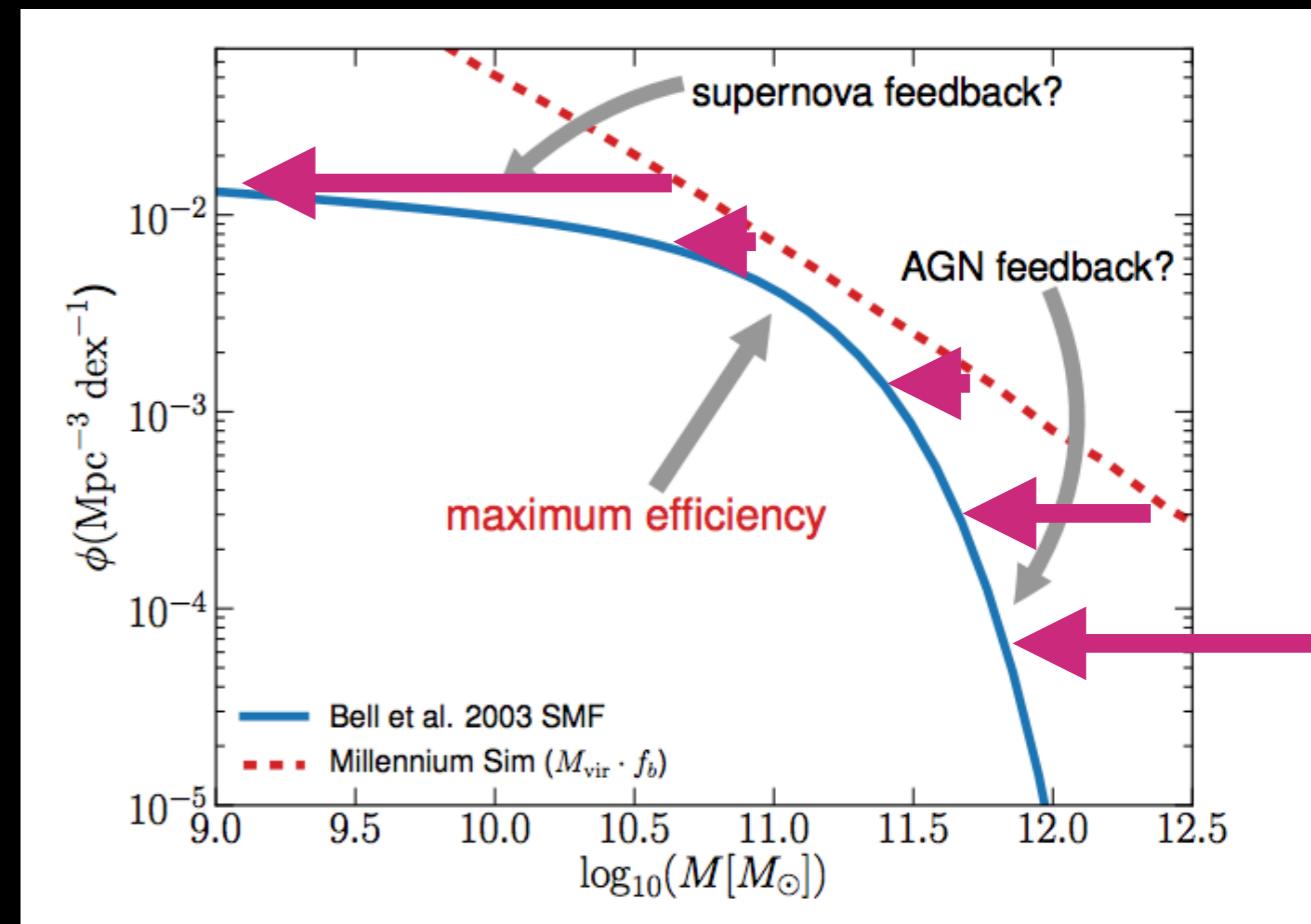
Synthesized metals go into other stars, the interstellar medium (ISM), the circumgalactic medium (CGM), the intergalactic medium (IGM). We can only see the *most abundant elements* in the IGM, CGM, and most of the ISM: e.g., H, He, CNO, Fe. This is one reason we tend to focus on stars.

The final result: something like our Milky Way



Structure/Galaxy Formation Summary

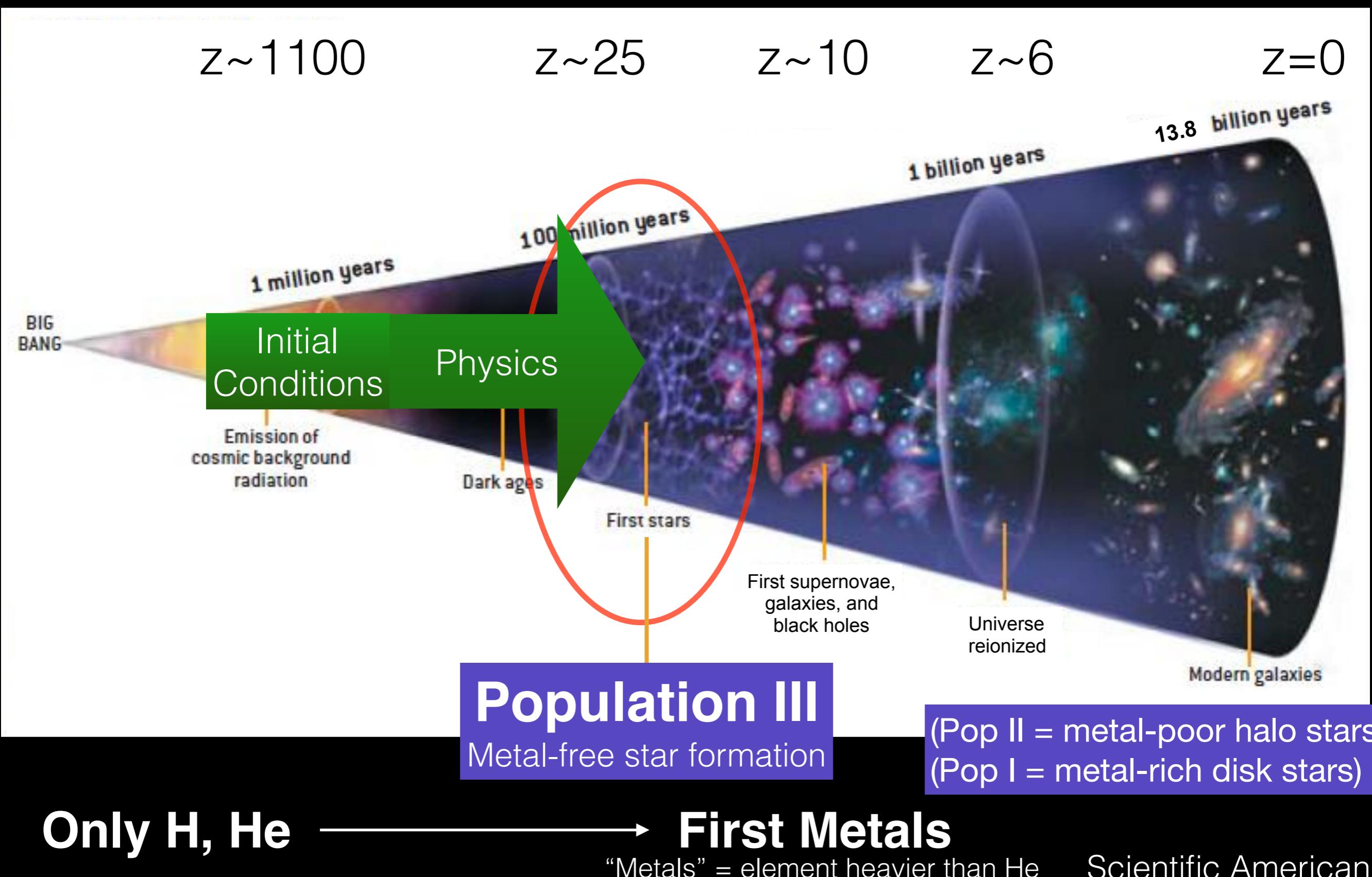
- The universe is not homogeneous
- Density fluctuations described by the Power Spectrum
- Nonlinear density fluctuations -> dark matter halos
- “One galaxy per halo”
- **Open question is how much feedback**
- Only most abundant elements observed outside of stars



Universe timeline

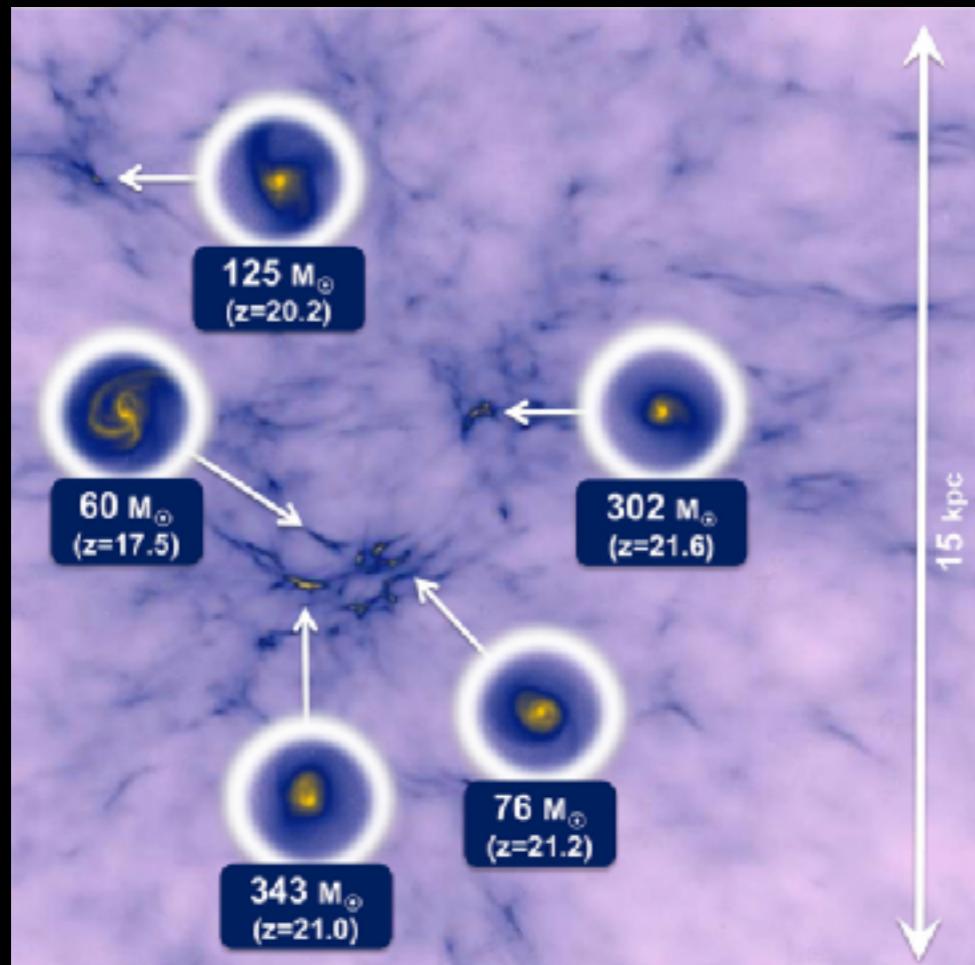
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The First Stars are theoretically “easy”



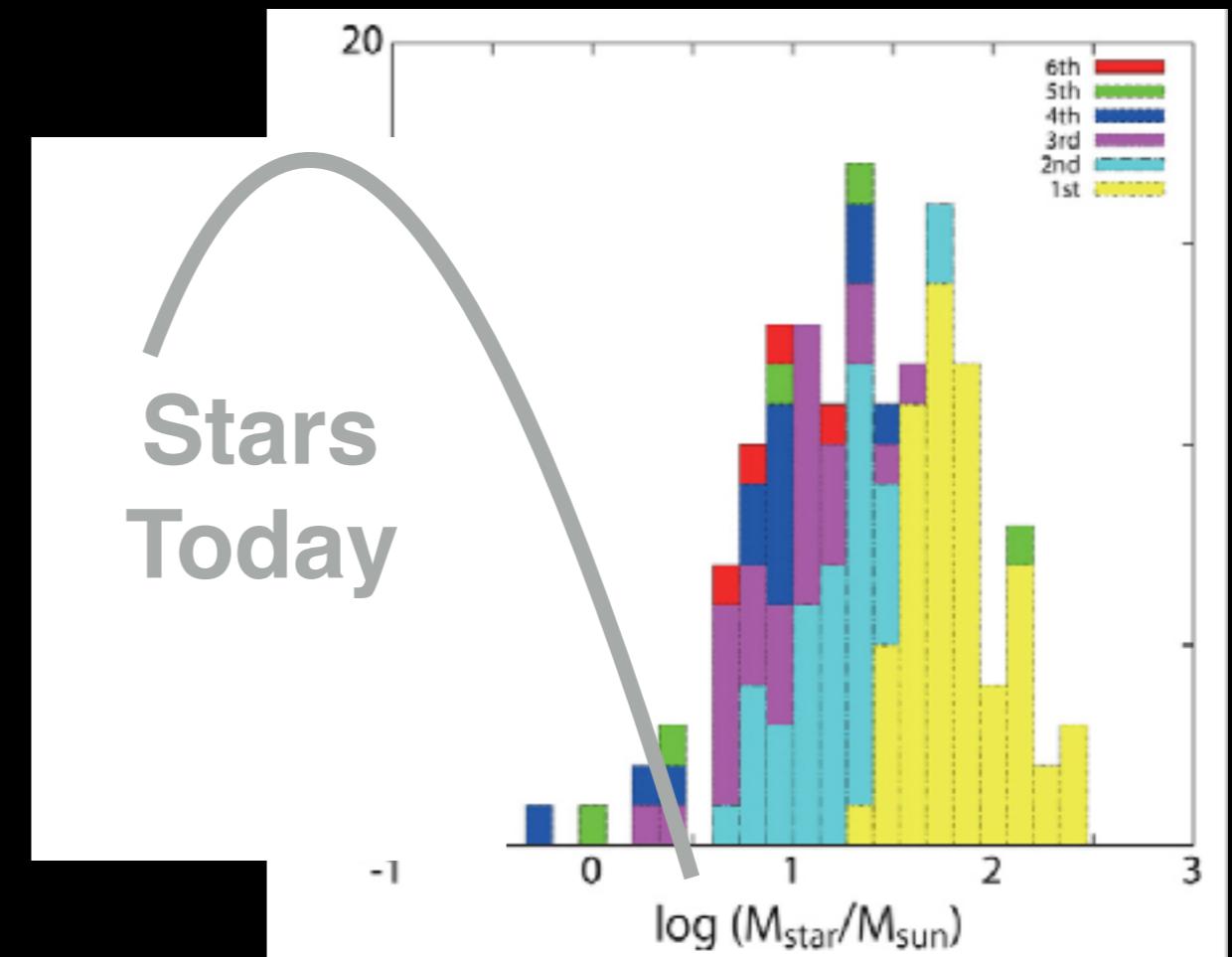
Theoretical Predictions for the First Stars

Form in **minihalos**
due to H₂ cooling



Hirano et al. 2014

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

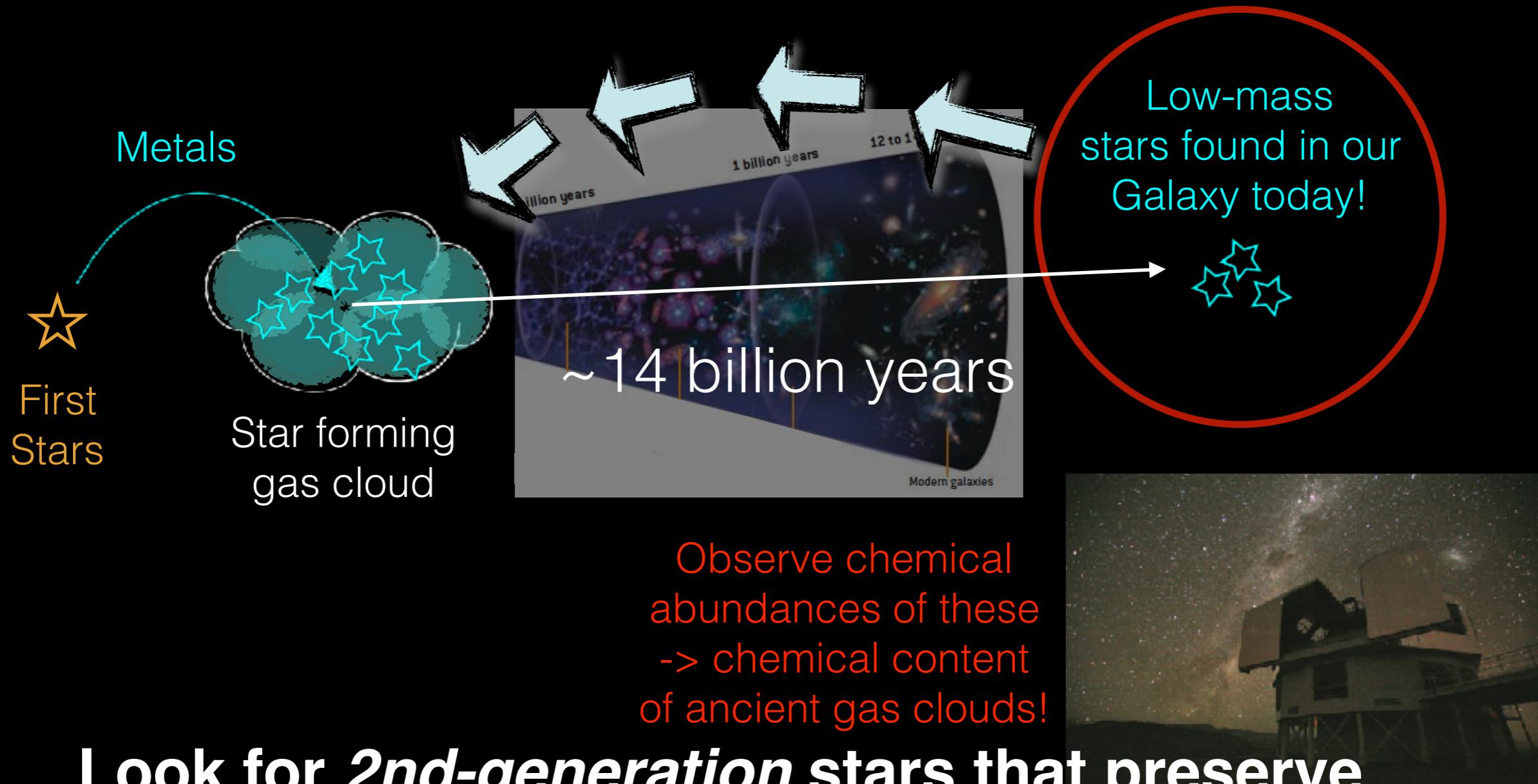


Susa et al. 2014

Pop III stars all gone today, but make first metals

Stellar Archaeology

A way to probe chemical signatures from the early universe



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

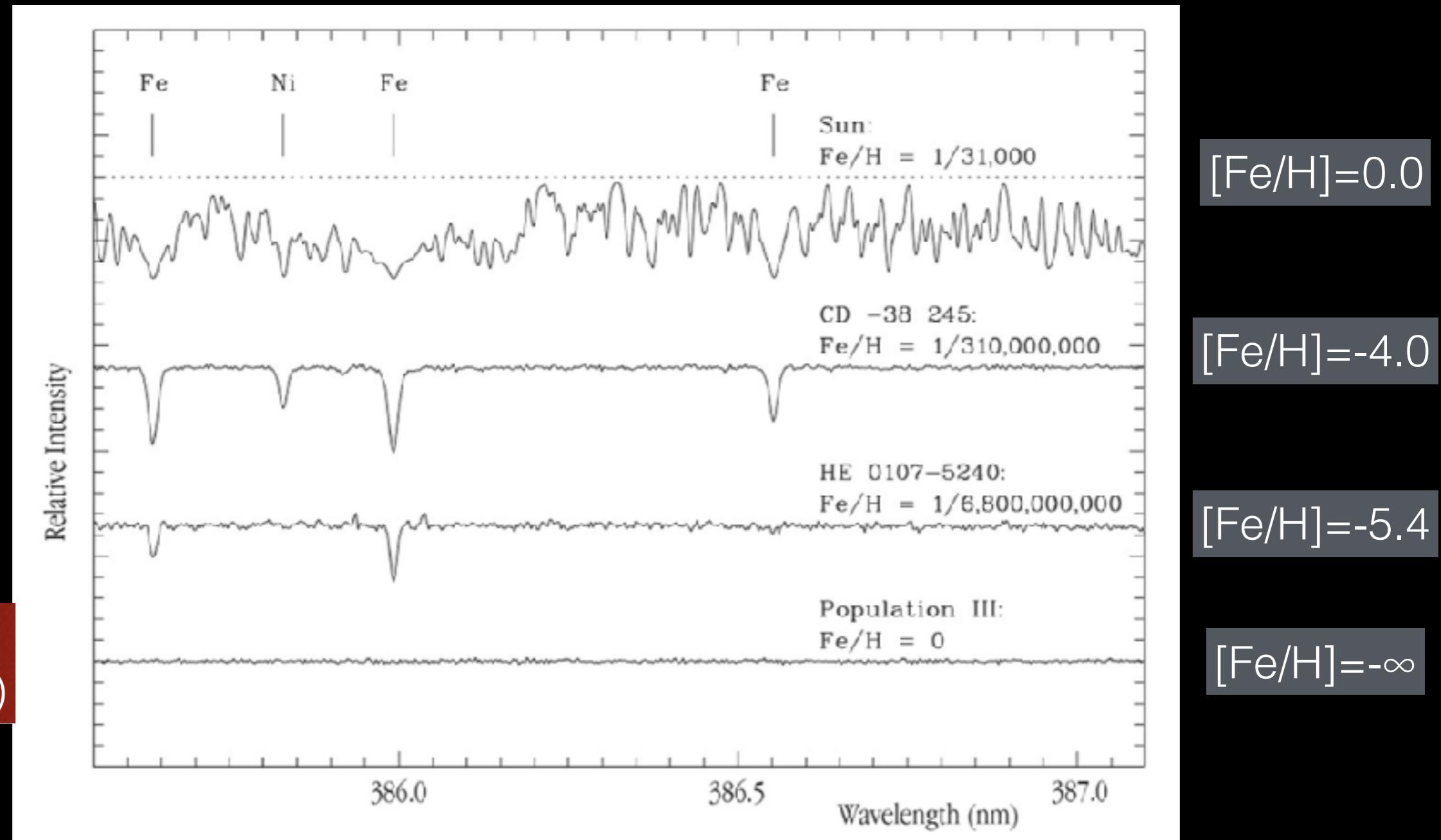
Assembling a Milky Way



Yellow: First Stars
Minihalos
 $z \sim 25$

Red: First Galaxies
Atomic Cooling Halos
 $z \sim 10-20$

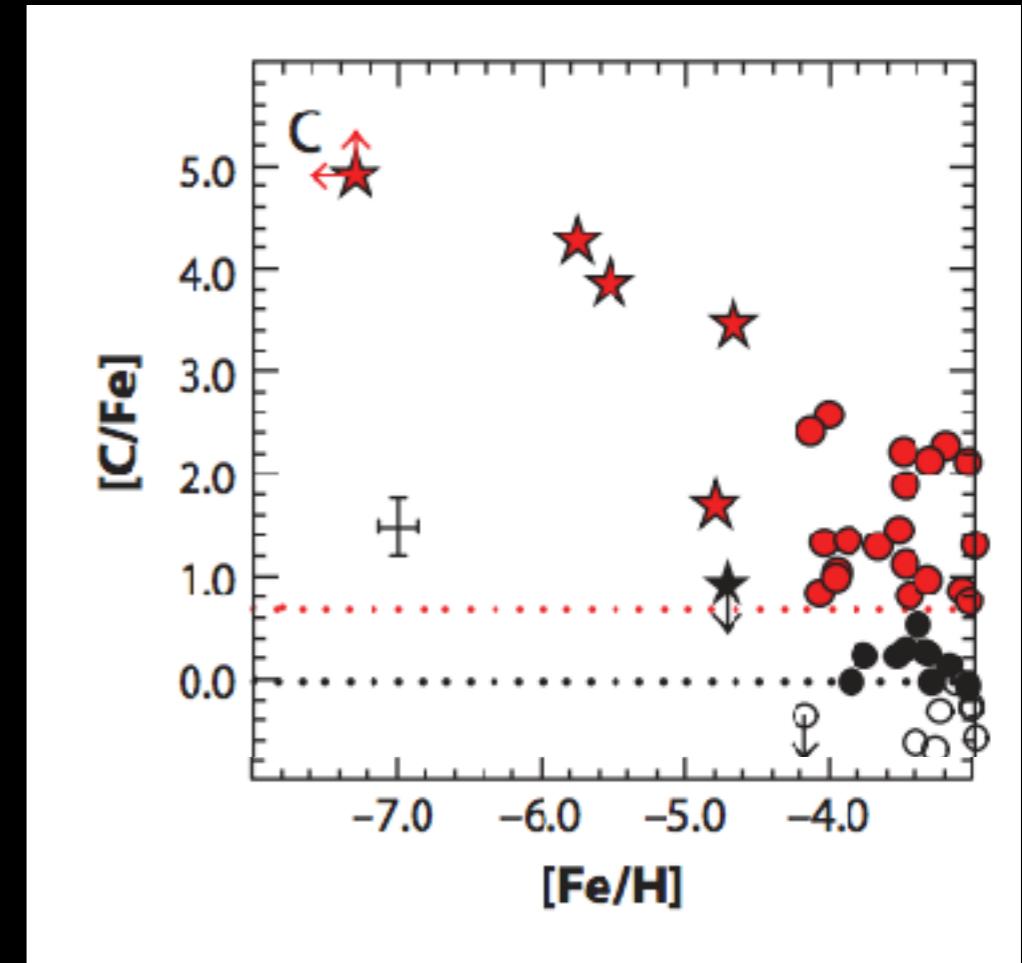
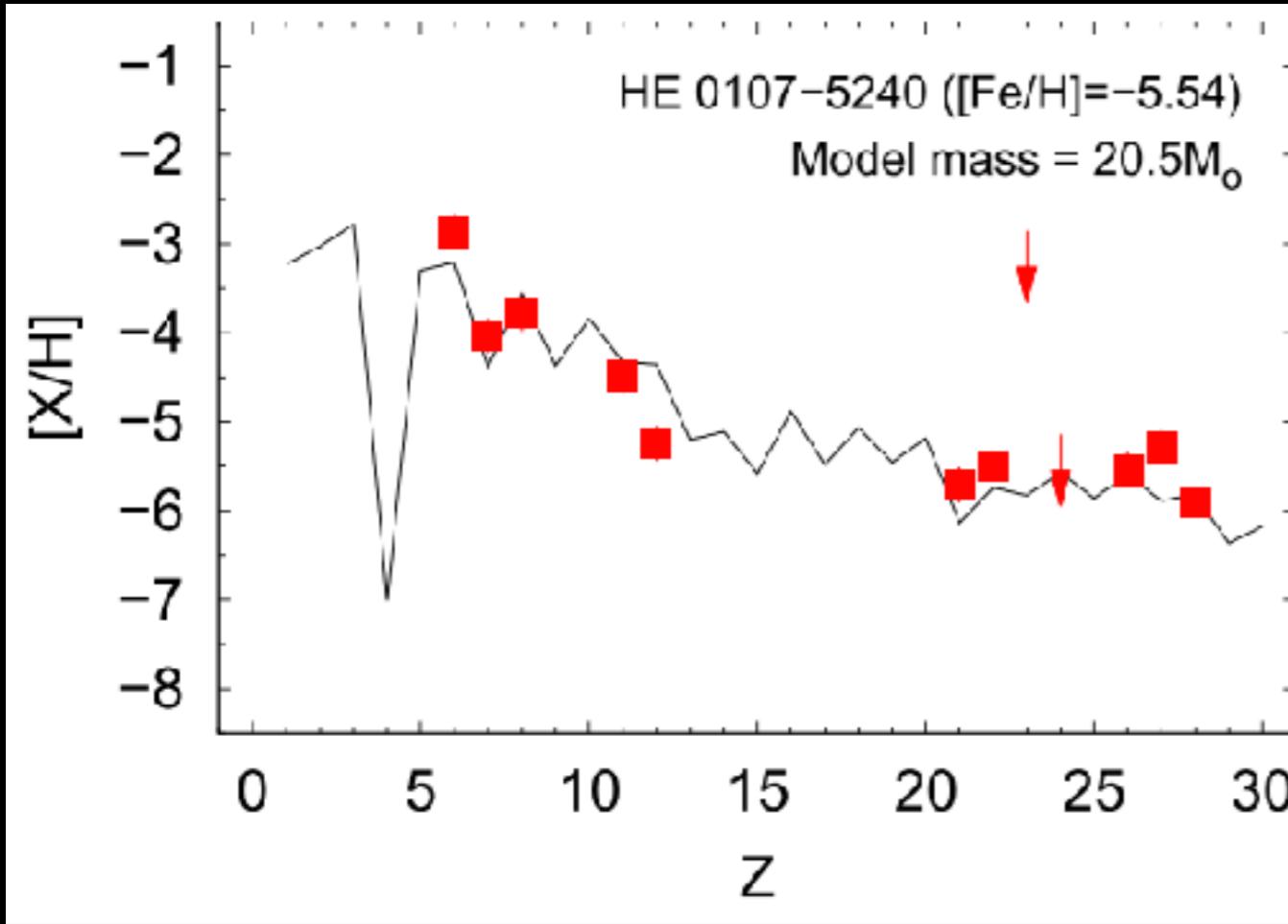
Use Spectroscopy To Measure Chemical Abundances



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

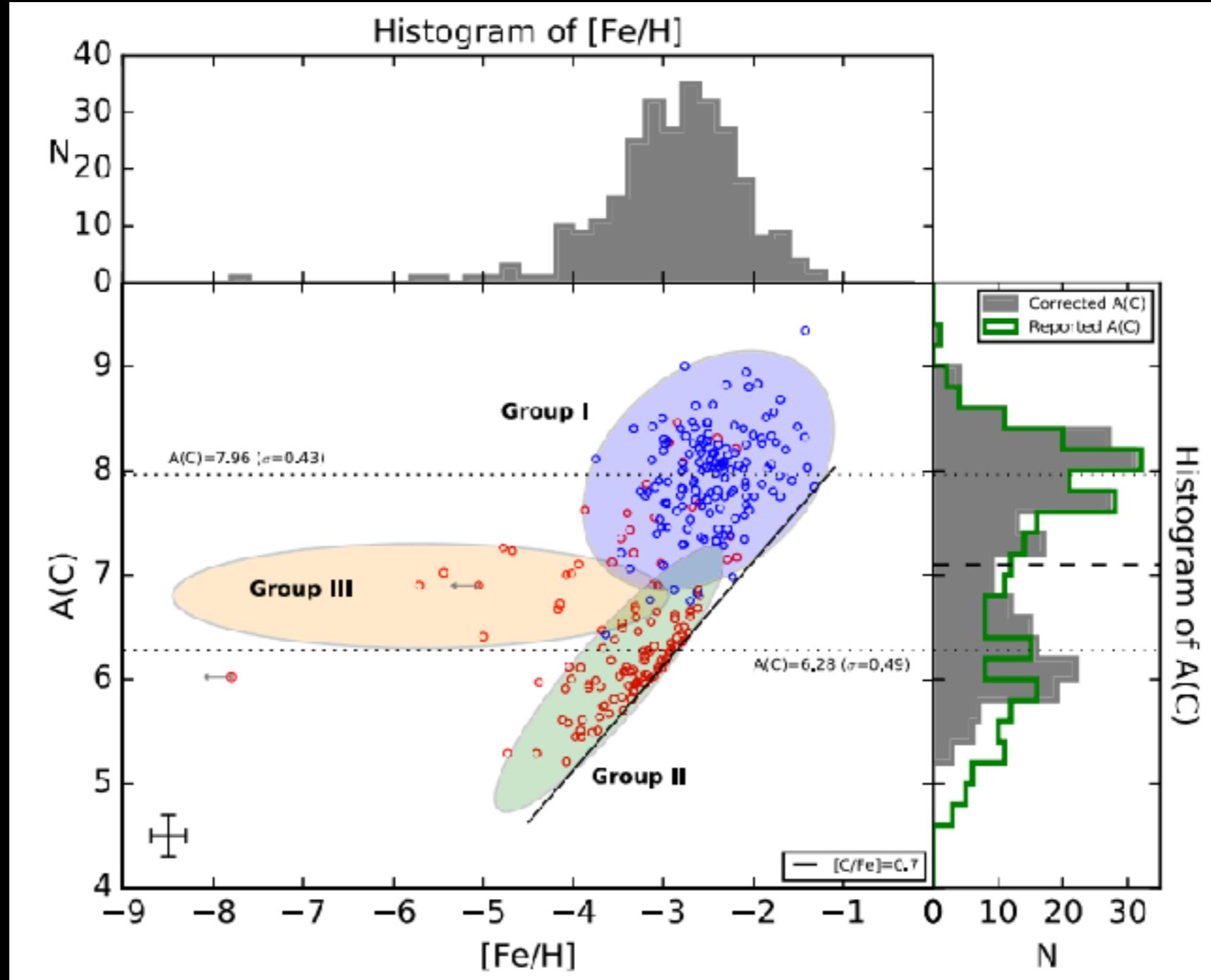
Typical (bad) assumption: $[Fe/H] \lesssim -3 \rightarrow$ second generation star
(The more metal-poor, the better)

Two main types of figures



- **Single star, multiple elements (Z)**
y-axis can be $[X/H], [X/\text{Fe}], \log \epsilon(X), A(X)$
- **Used for comparing to nucleosynthesis models**
- **Usually assume: elements come from one source**
- **Multiple stars, two elements**
Usually $[X/\text{Fe}]$ and $[\text{Fe}/\text{H}]$
- **Used for overall element trends**
- **Also used for *chemical evolution*:**
mixing multiple element sources
- **Usually assume stars from the same galaxy/gas reservoir**

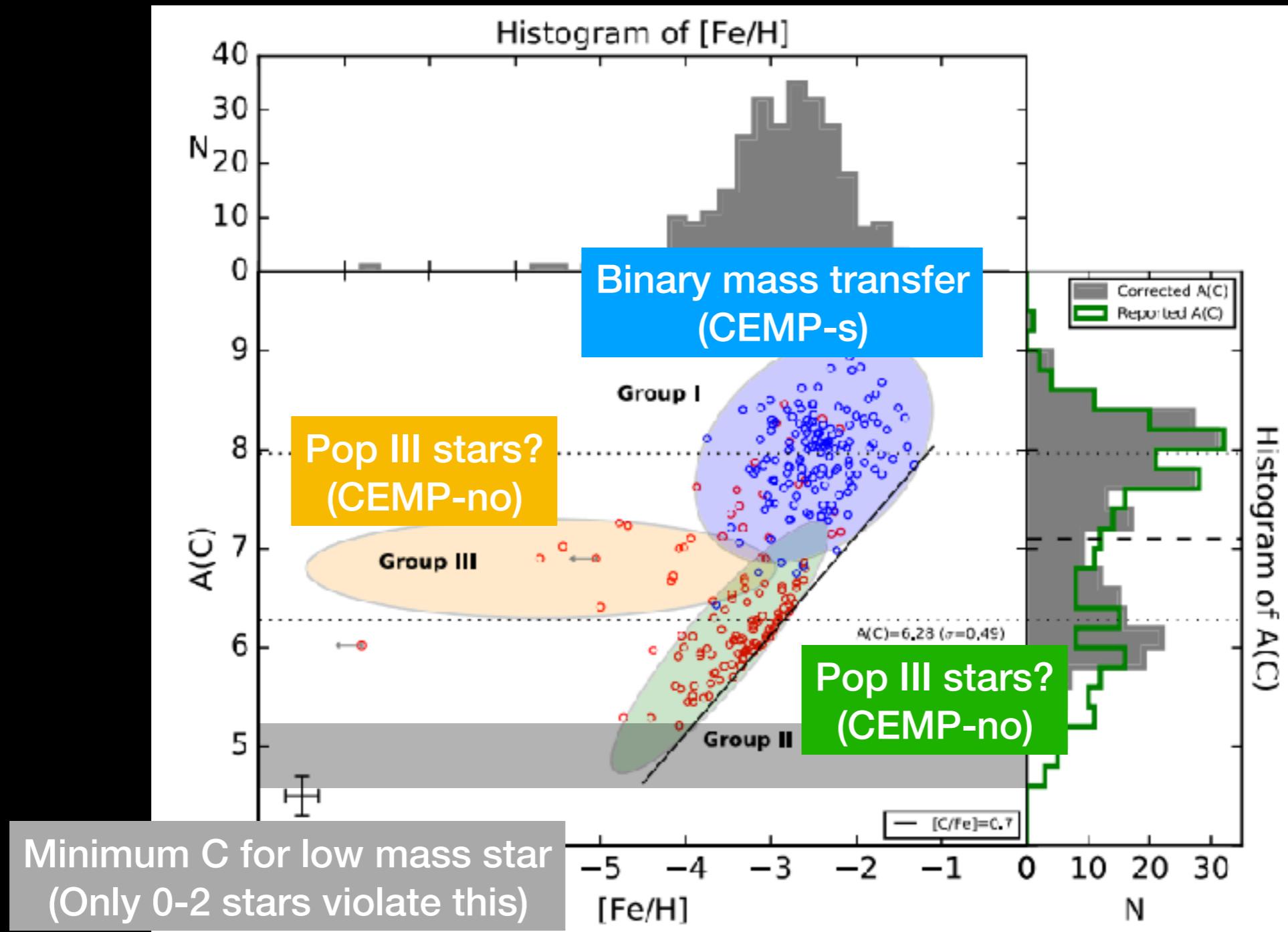
Carbon-Enhanced Metal-Poor (CEMP) Stars the key robust Pop III abundance signature



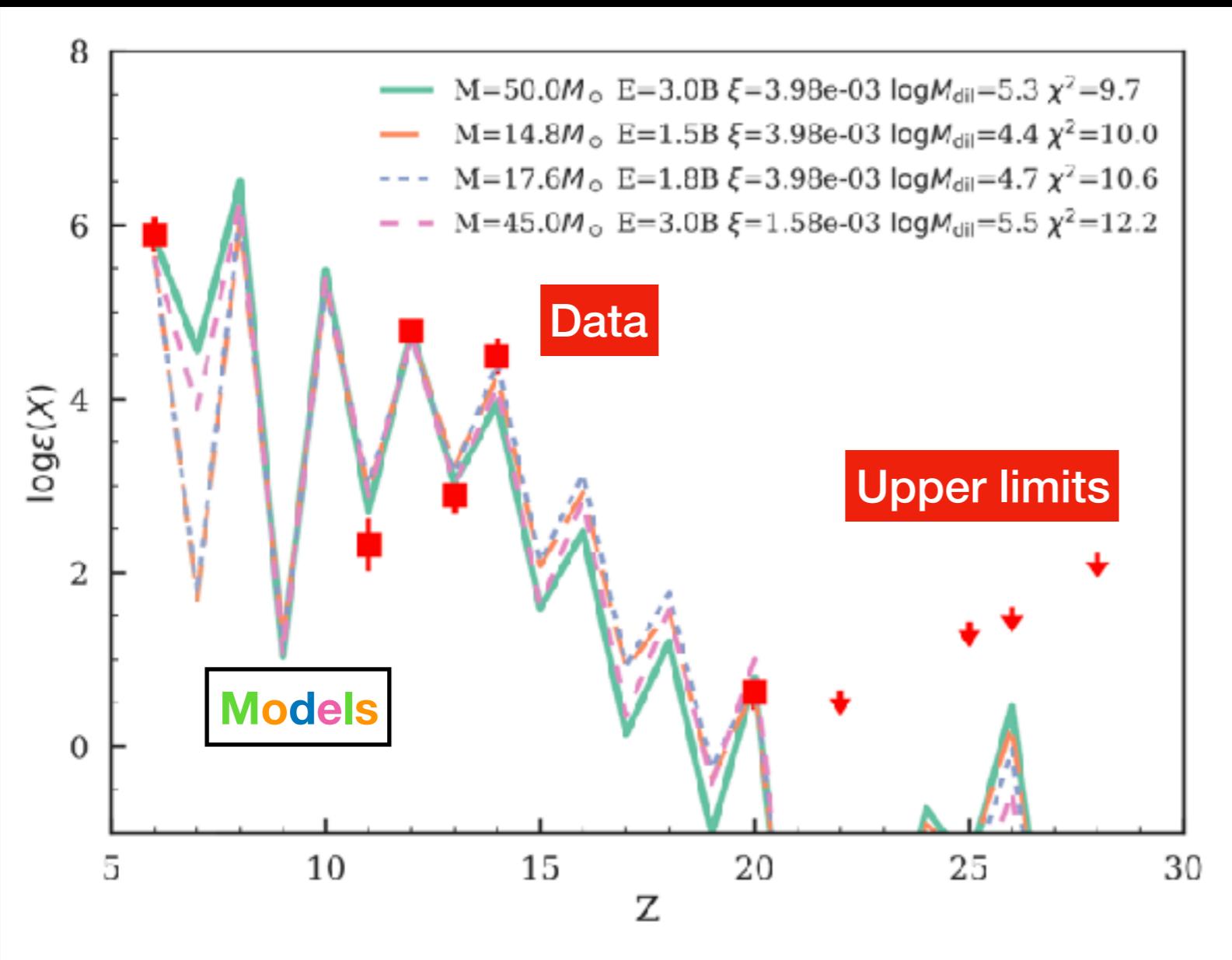
Reasons for Carbon Enhancement

- 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)

At least some CEMP stars have Pop III signatures



Detailed fits to abundances



- Search through a grid of nucleosynthesis models,
- Find the *ratios* that fit best (in a χ^2 sense).
- Free parameter: overall normalization (gas dilution)
- Be careful: errors are rarely actually Gaussian, so χ^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)

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

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



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

[C/Fe] > 0.7
CEMP
 “Enhanced”

[C/Fe] < 0.7
VMP/EMP
 “Extremely”

	$[\text{Ba}/\text{Fe}] < 0.0$ -no	$[\text{Ba}/\text{Fe}] > 0.0$ $[\text{Ba}/\text{Eu}] < 0$ -r	$[\text{Ba}/\text{Fe}] > 0.0$ $[\text{Ba}/\text{Eu}] > 0$ -s
$[\text{C}/\text{Fe}] > 0.7$ CEMP “Enhanced”	CEMP-no Pop III signatures?	CEMP-r r-process (and Pop III?)	CEMP-s s-process and C from mass transfer
$[\text{C}/\text{Fe}] < 0.7$ VMP/EMP “Extremely”	EMP-no Pop III signatures?	EMP-r r-process	EMP-s s-process from chemical evolution

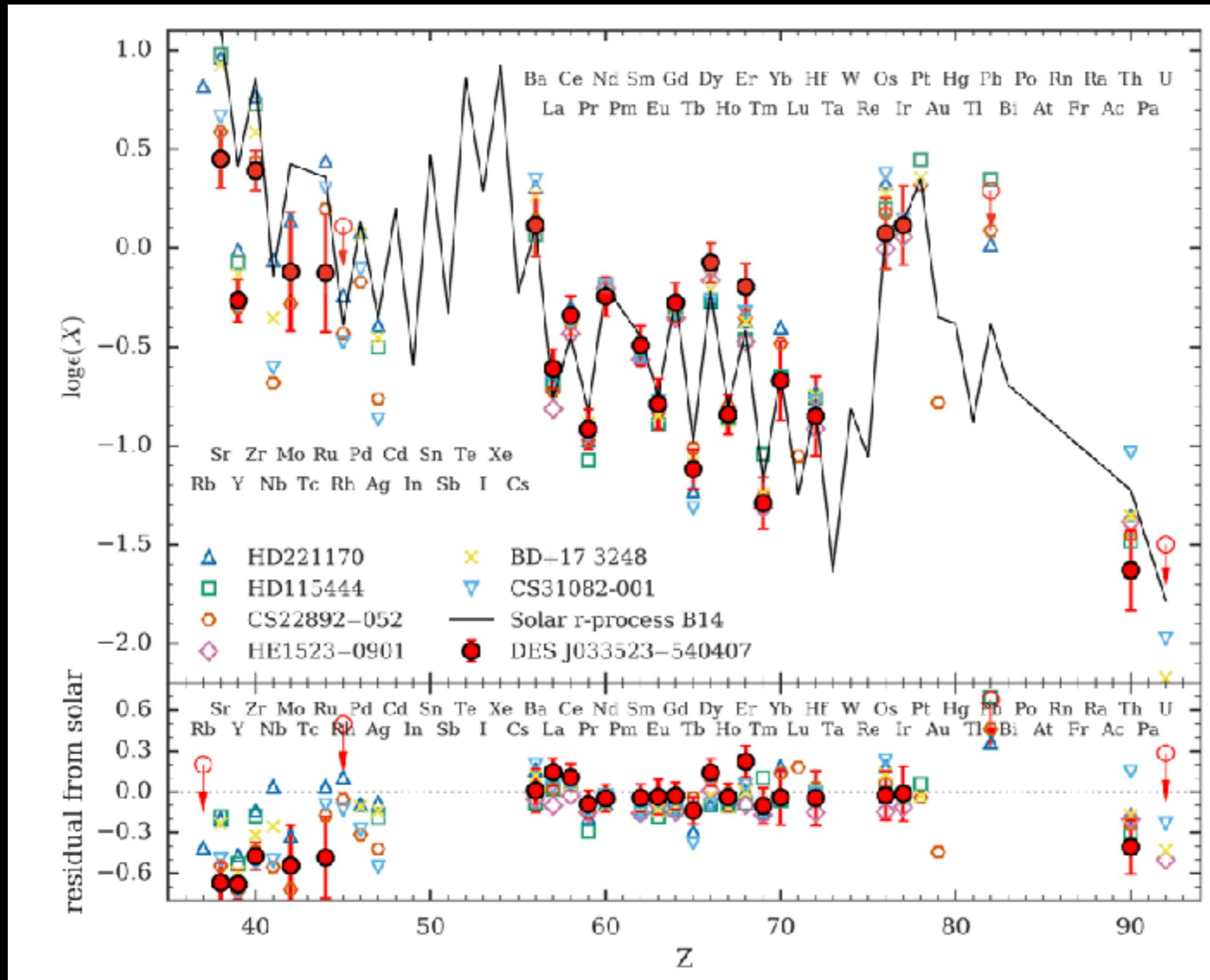
-no = “normal”

r-I: $[\text{Eu}/\text{Fe}] > 0.3$
 r-II: $[\text{Eu}/\text{Fe}] > 1.0$
 (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

The “universal” r-process pattern

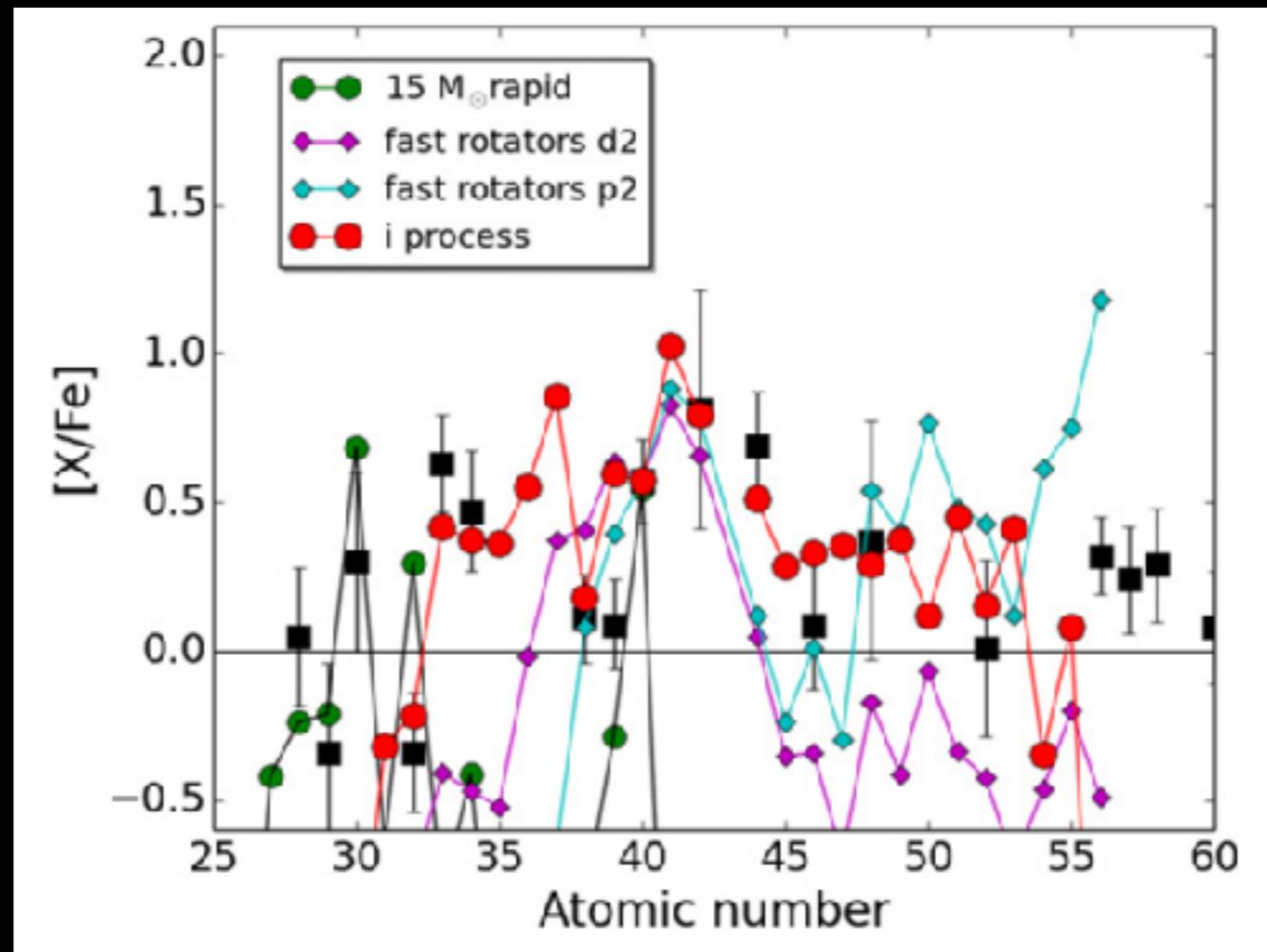


Pattern is identical
(to within ~20%)
from Ba-Ir
 $Z=56-77$

But not $Z < 50$,
or $Z > 89$

Sneden+2008
Ji+Frebel 2018

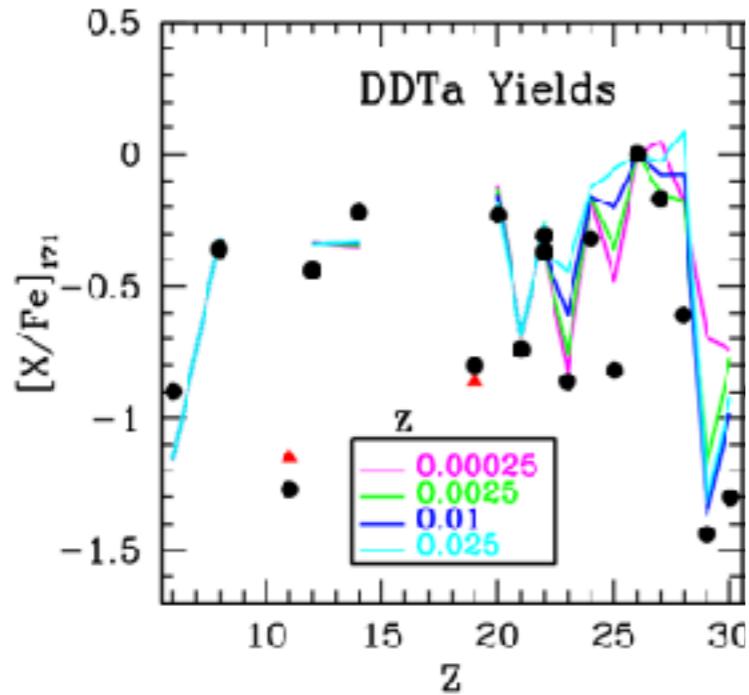
[C]EMP-r/s (= i?)



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

Type Ia Yields

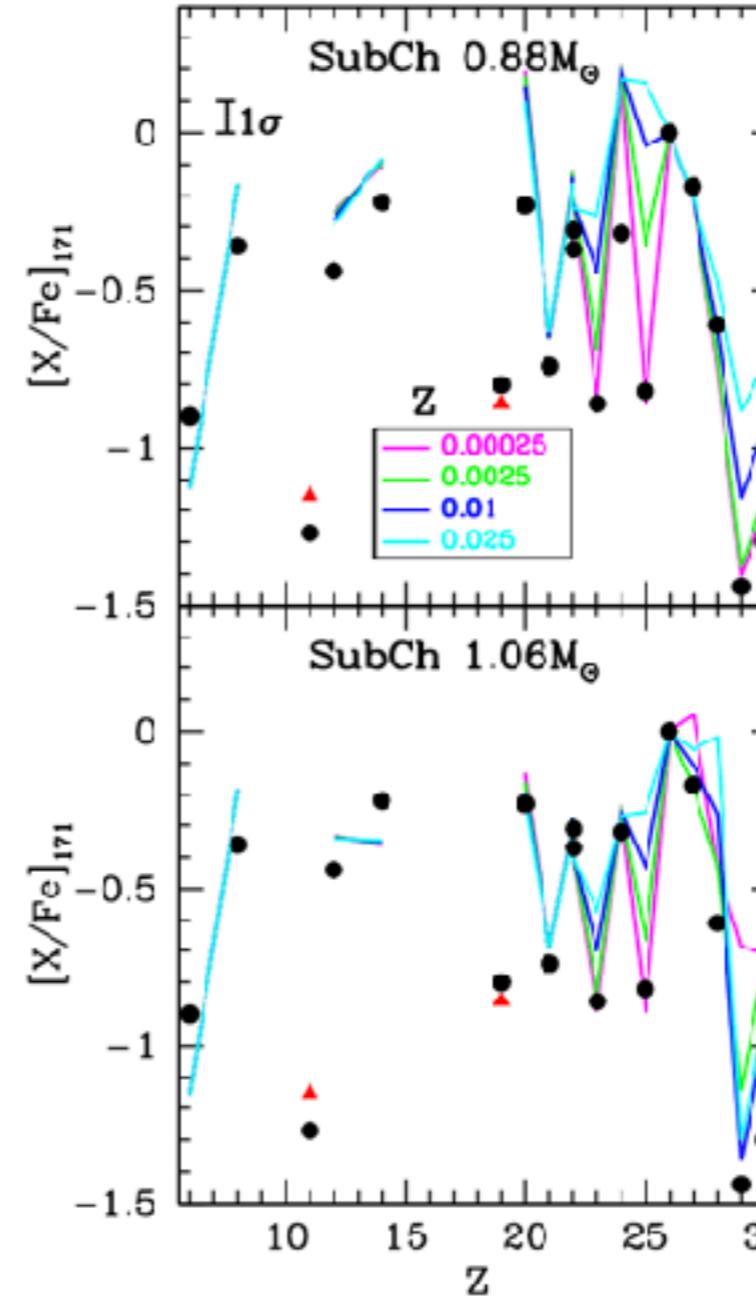
Chandrasekhar mass WD



Different Type Ia SN models make different Fe-peak yields

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

sub-Ch WD



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

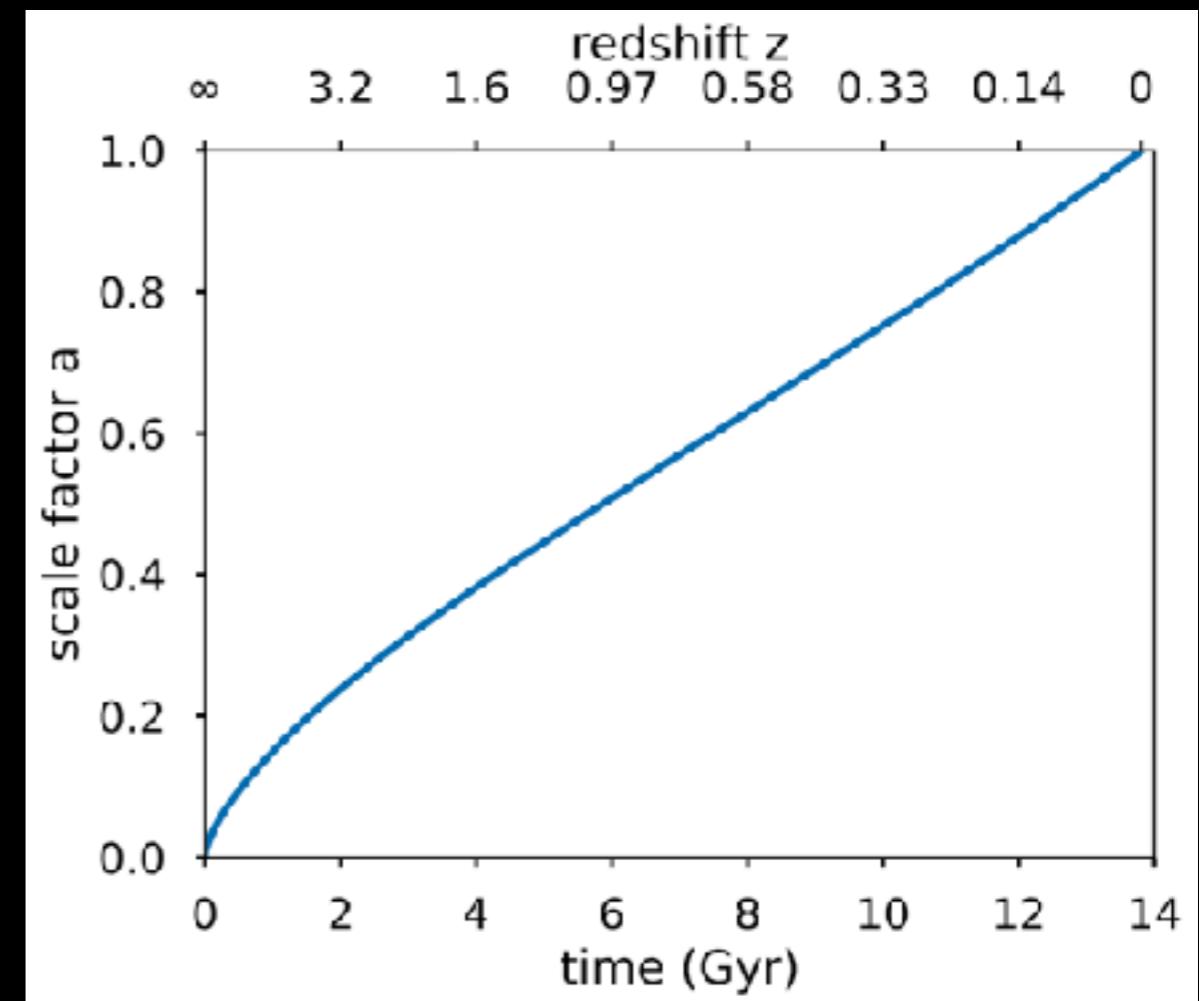
Buzzword List

- Dark matter
 - Structure formation
 - Dark matter halo
 - Halo mass function
 - Stellar mass function
 - Feedback
 - N-body simulation
 - Hydro simulation
 - [Reionization]
- Pop I, II, III stars
- Dark energy
- Stellar archaeology
- Baryon
- CEMP stars
- Redshift
- [C]EMP-no, -r, -i, -s
- Hubble Constant
- Stellar halo
- CMB
- Dwarf galaxies
- BBN
- Spinstars
- Lithium problem
- Mixing and fallback SN
- Type II, Type Ia supernova

Main Figure/Slide Summary

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
- $z \leftrightarrow a \leftrightarrow \text{time}$
- Also the *temperature* of the universe evolves with time



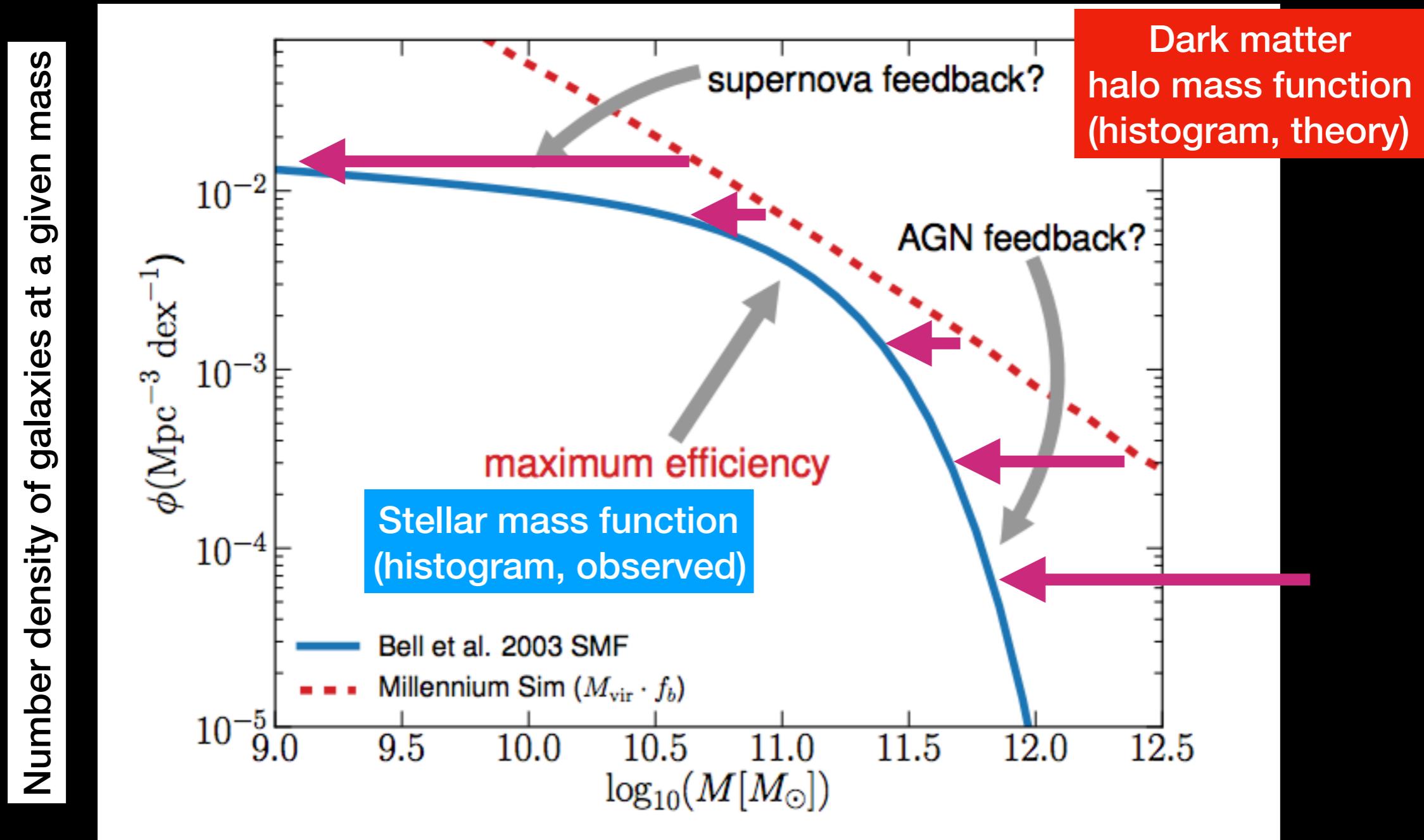
$$T = T_0(1 + z) = T_0/a$$

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

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

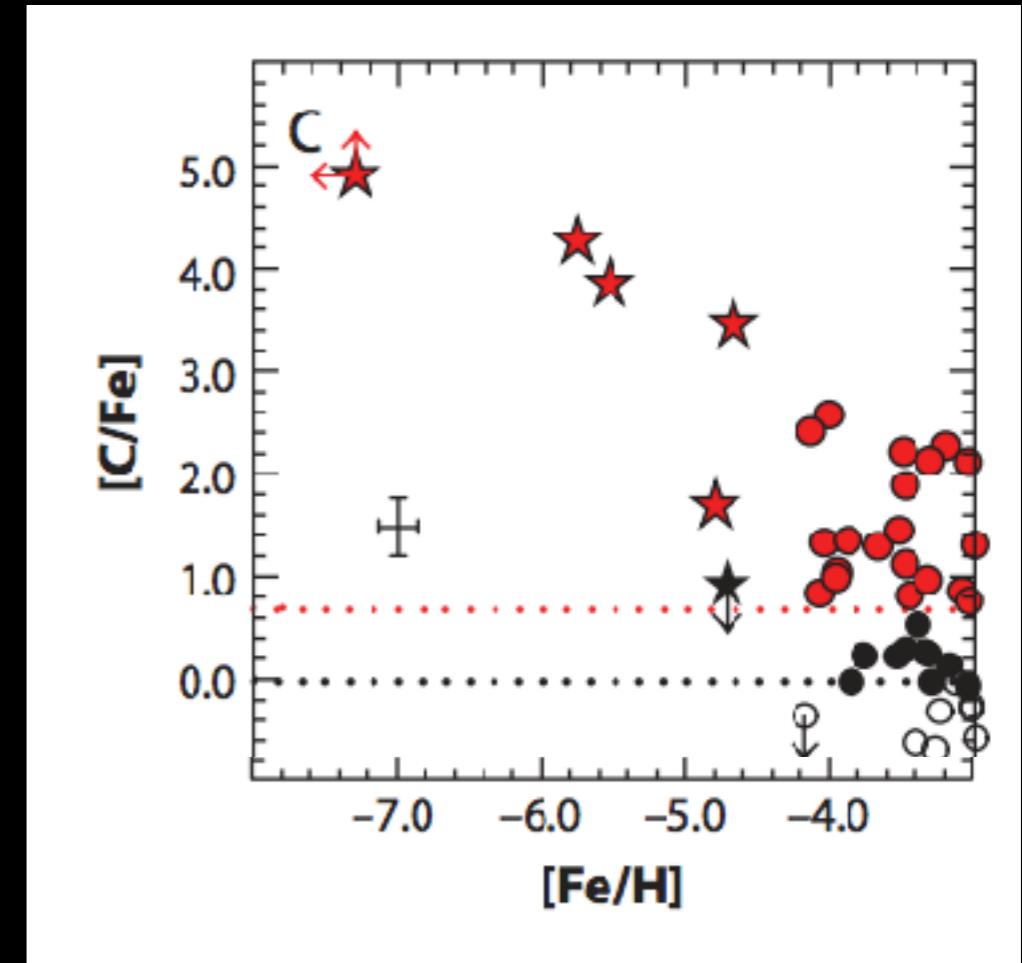
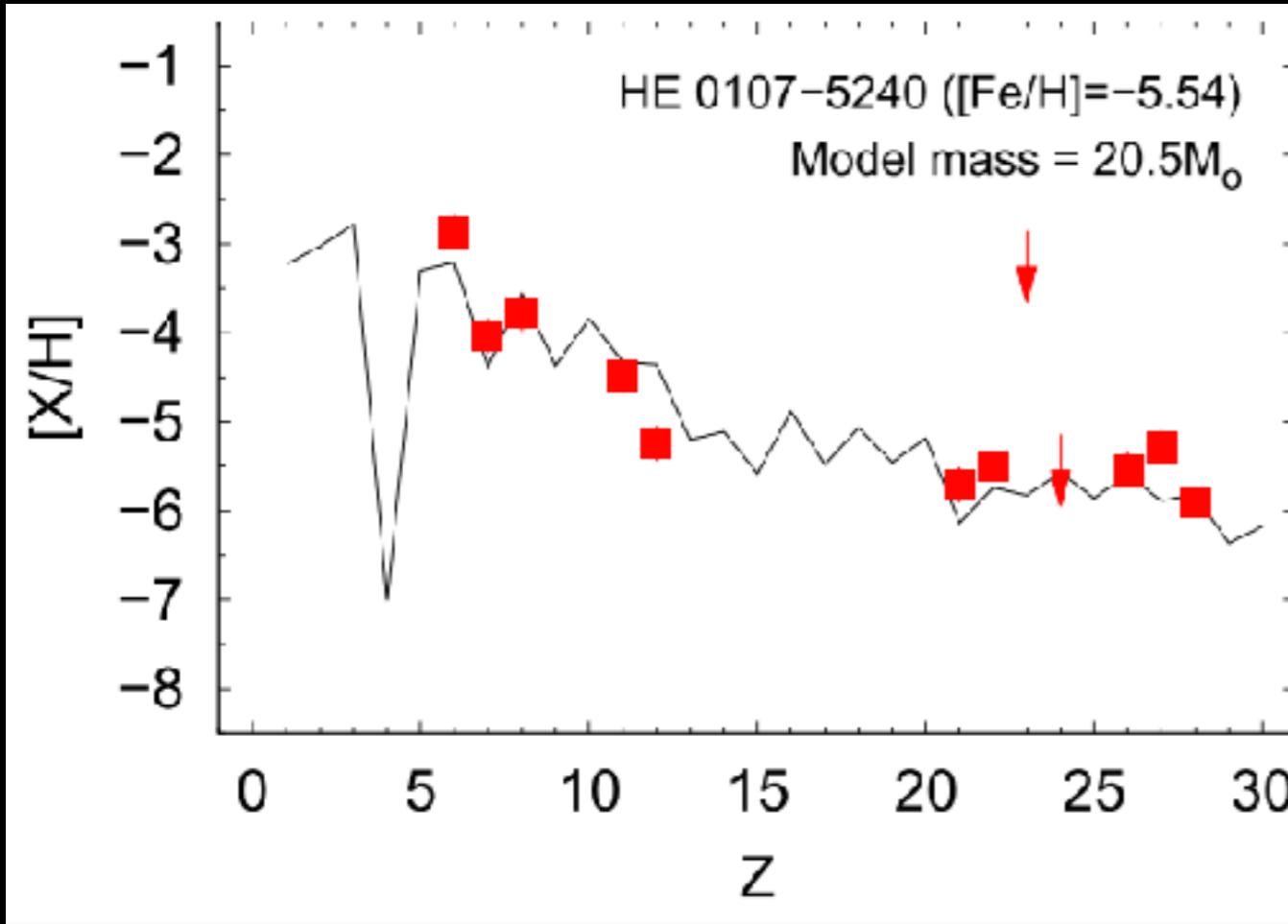
0.2348 meV

Galaxy Formation



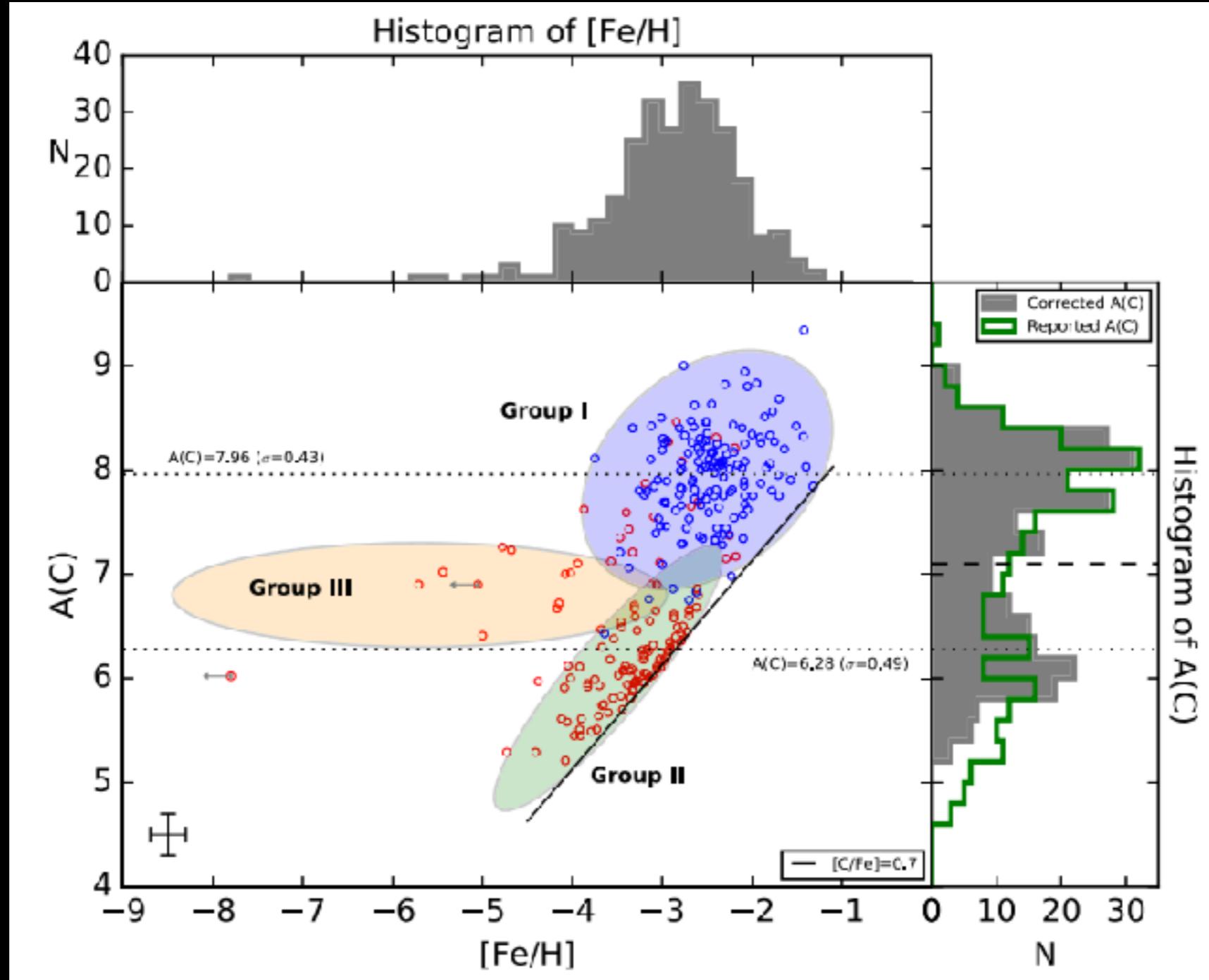
A galaxy's job is to turn gas into stars
Most galaxies are bad at this job due to feedback

Two main types of figures



- **Single star, multiple elements (Z)**
y-axis can be $[X/H], [X/\text{Fe}], \log \epsilon(X), A(X)$
- **Used for comparing to nucleosynthesis models**
- **Usually assume: elements come from one source**
- **Multiple stars, two elements**
Usually $[X/\text{Fe}]$ and $[\text{Fe}/\text{H}]$
- **Used for overall element trends**
- **Also used for *chemical evolution*:**
mixing multiple element sources
- **Usually assume stars from the same galaxy/gas reservoir**

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

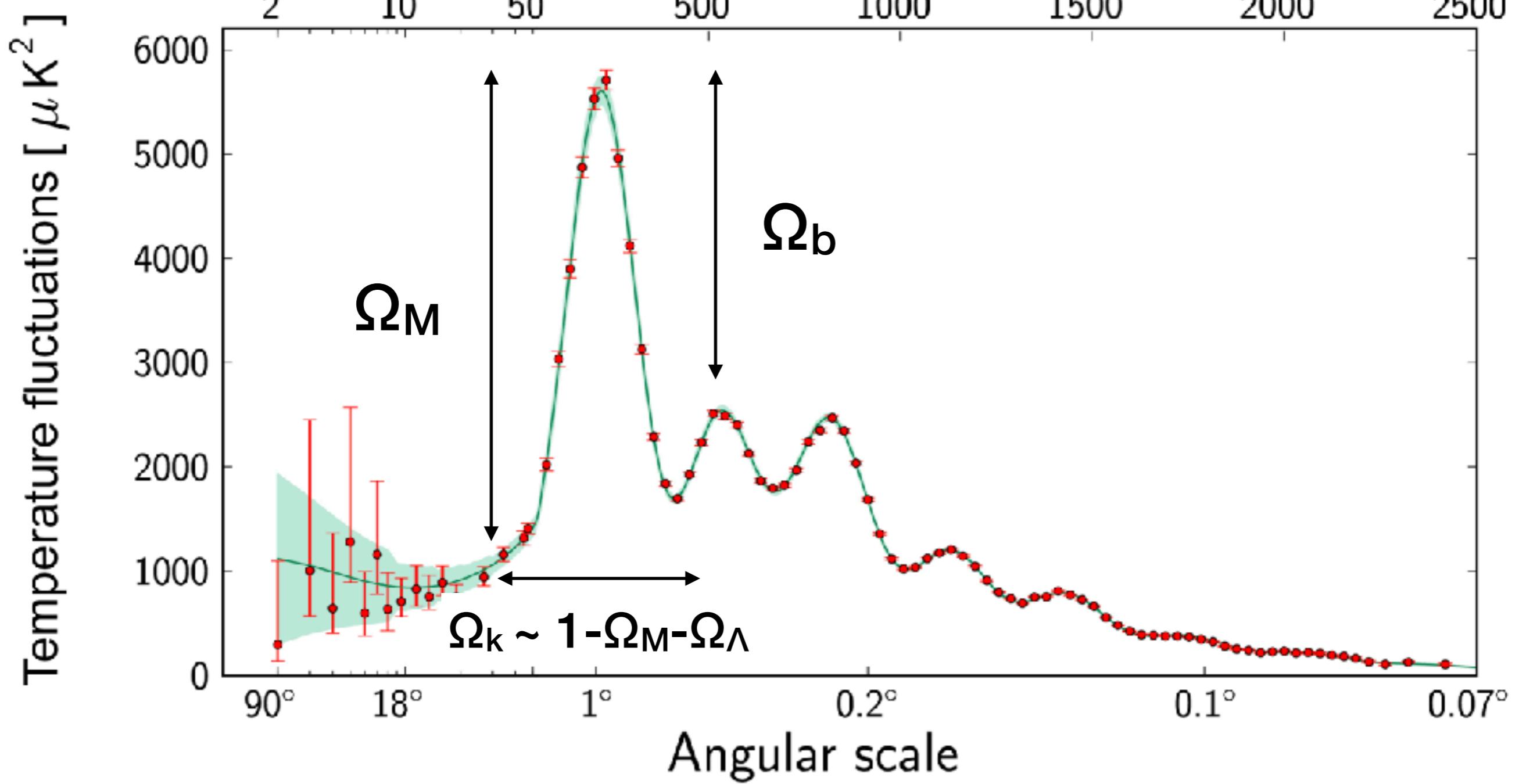


Extra Slides

Useful cosmology 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



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)

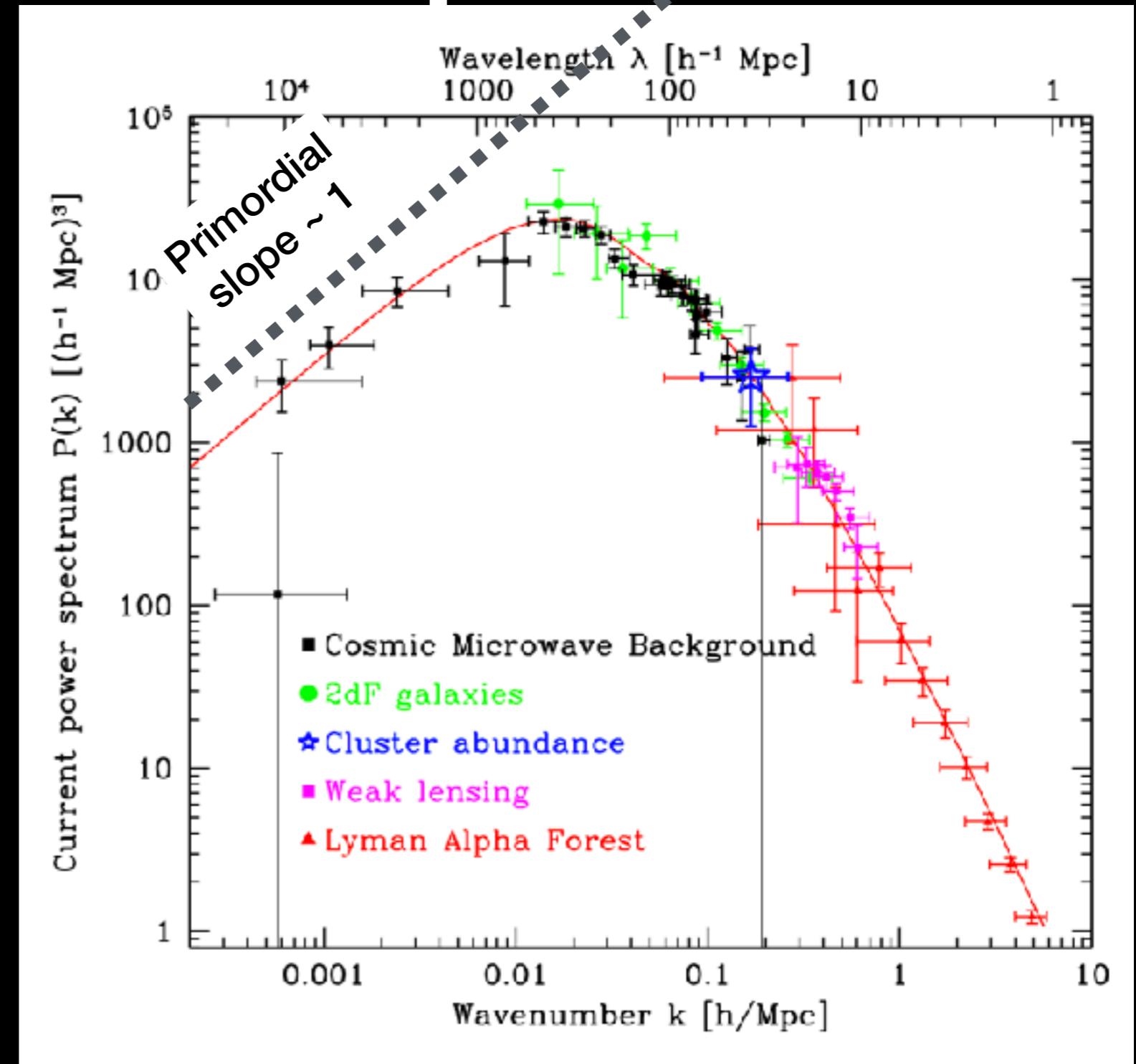
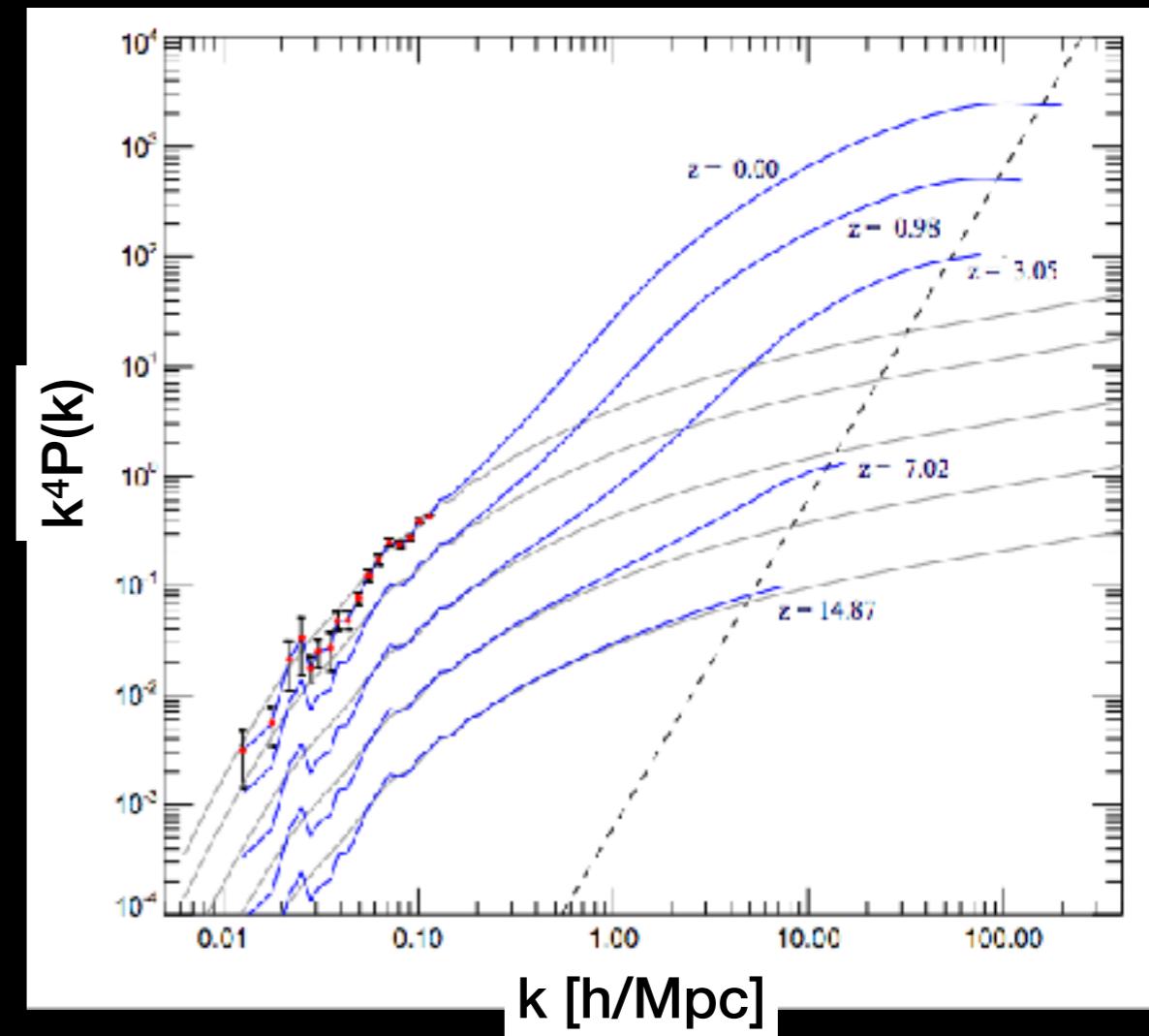
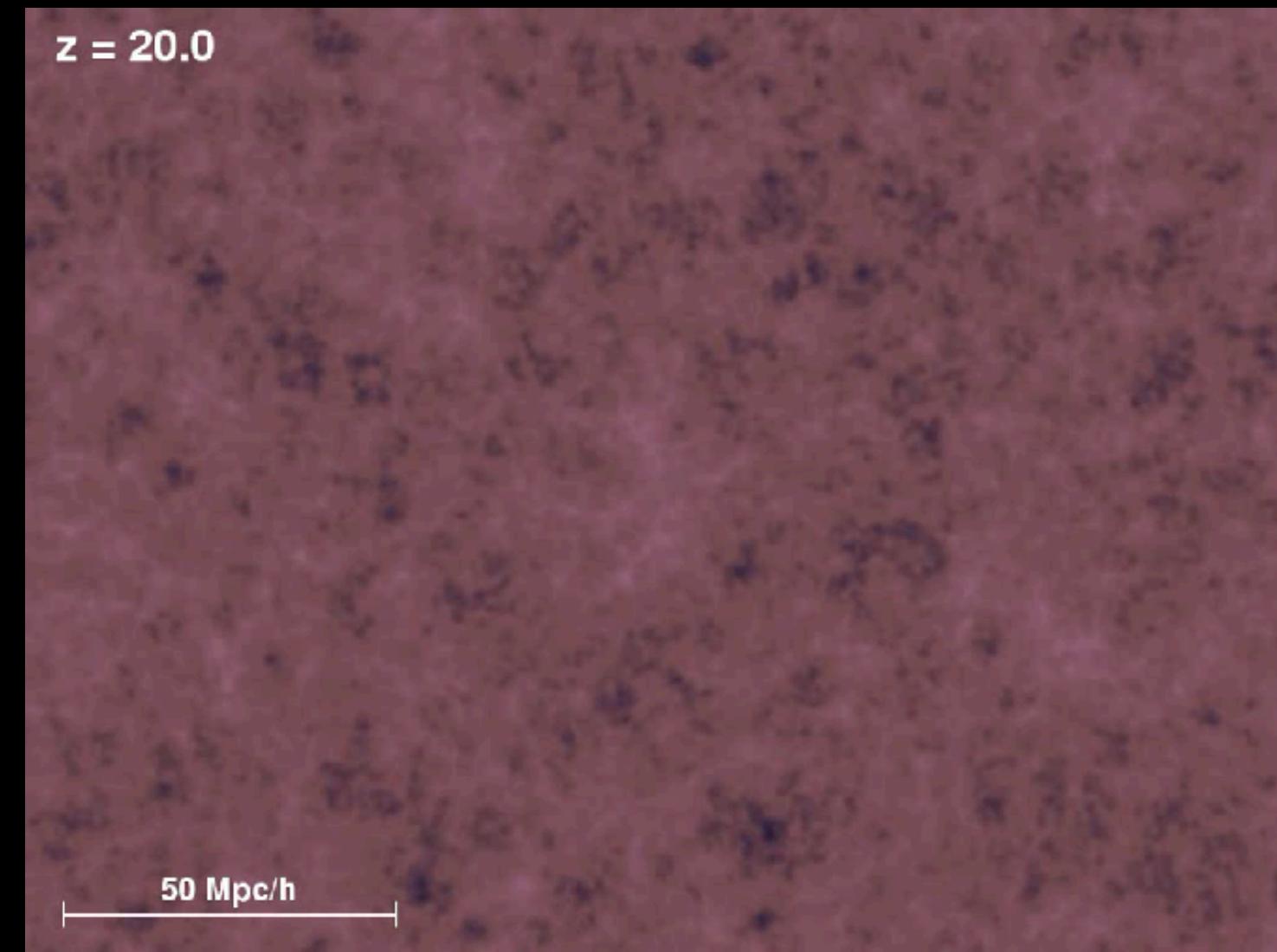


Figure: Courtesy M. Tegmark (data as of 2002)

Nonlinear matter power spectrum: Requires simulations

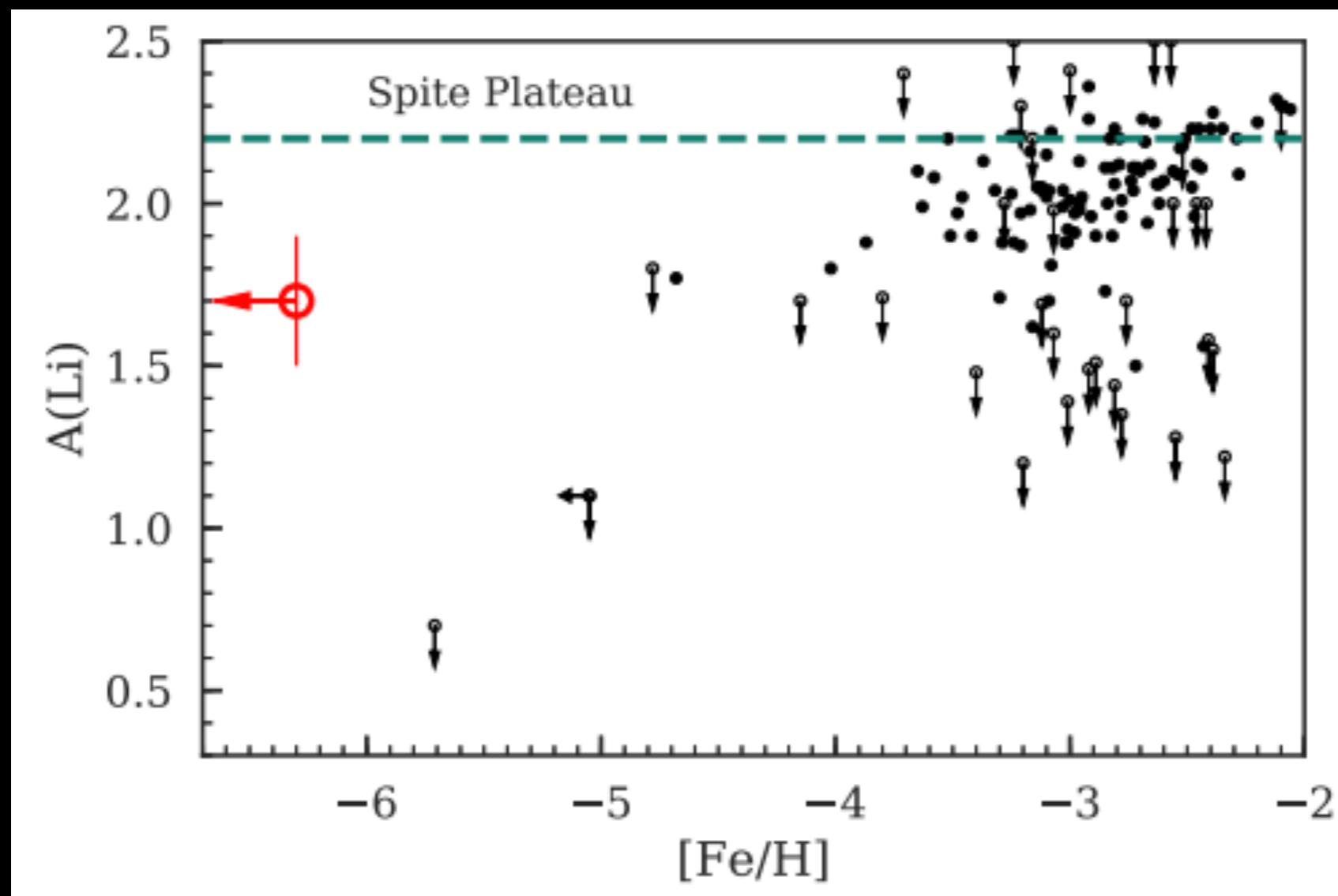


$\sim 10^{10}$ dark matter particles, each mass $\sim 10^9$ M_{sun}
(Our Milky Way is $\sim 10^{12}$ M_{sun})

Grey = linear growth
Blue = nonlinear simulation

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

Lithium in metal-poor stars



**The Spite plateau
breaks down at
low $[\text{Fe}/\text{H}]$...**
no one knows why

Energy timeline

