Dark Matter Structures

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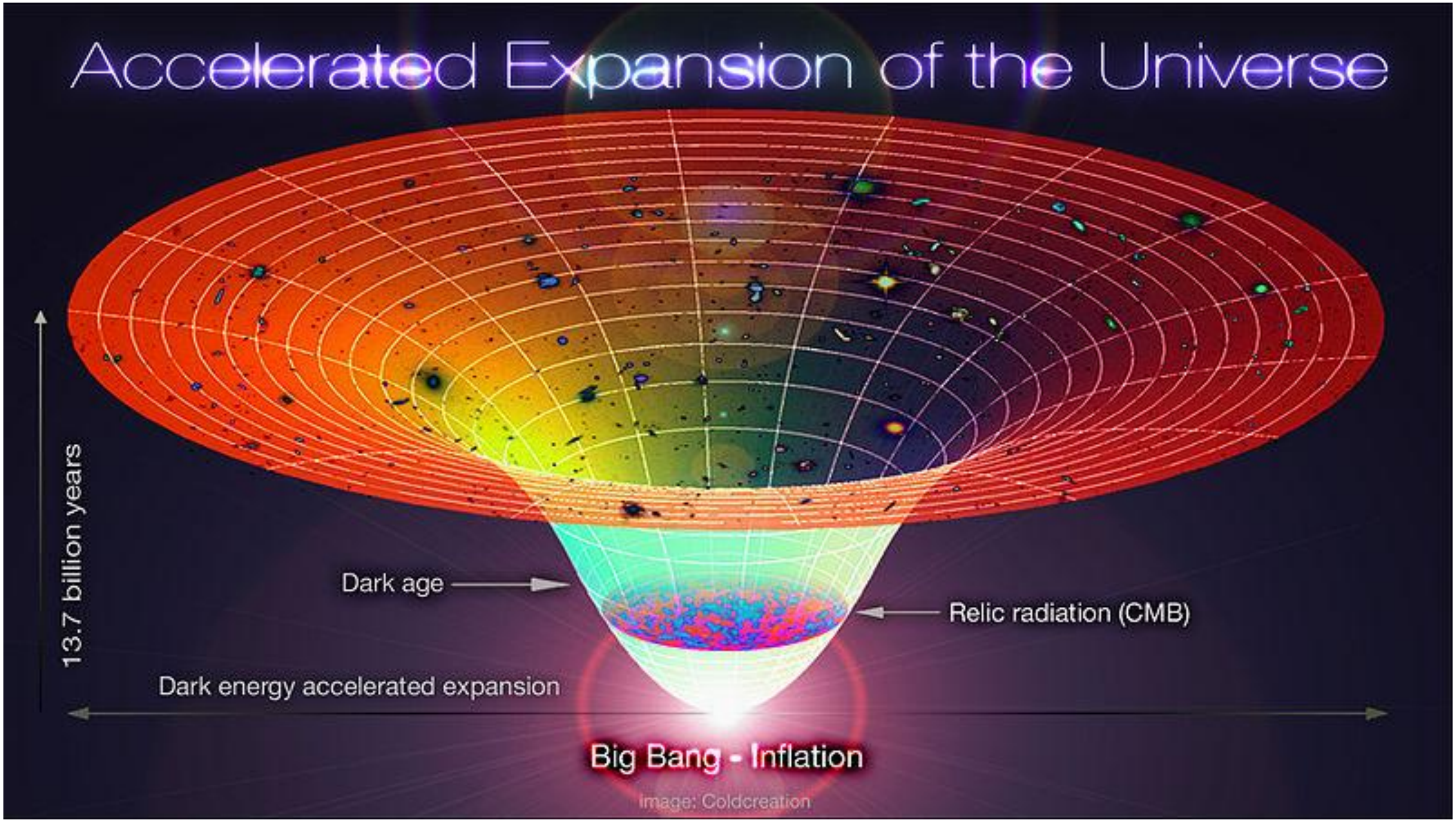
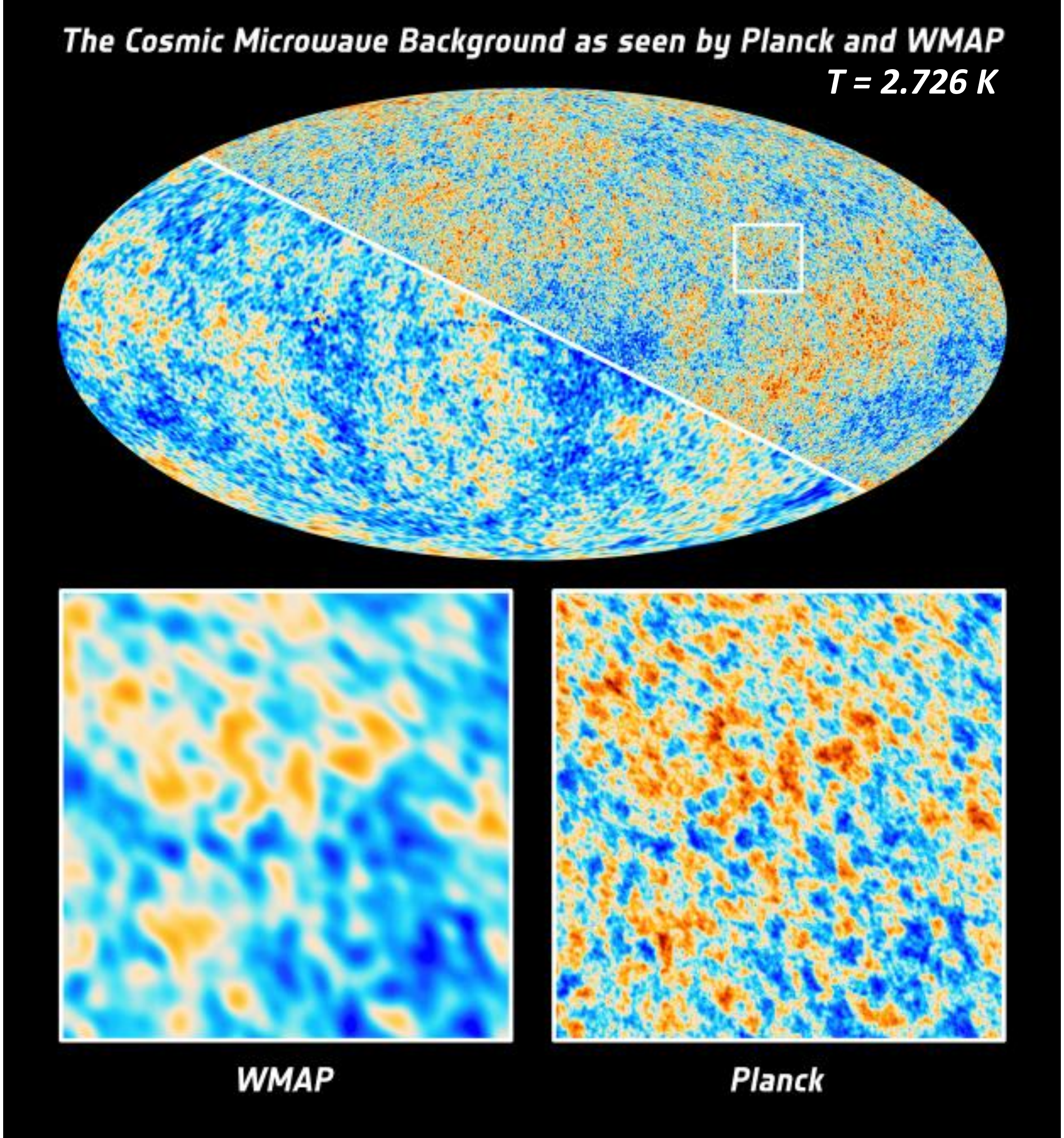


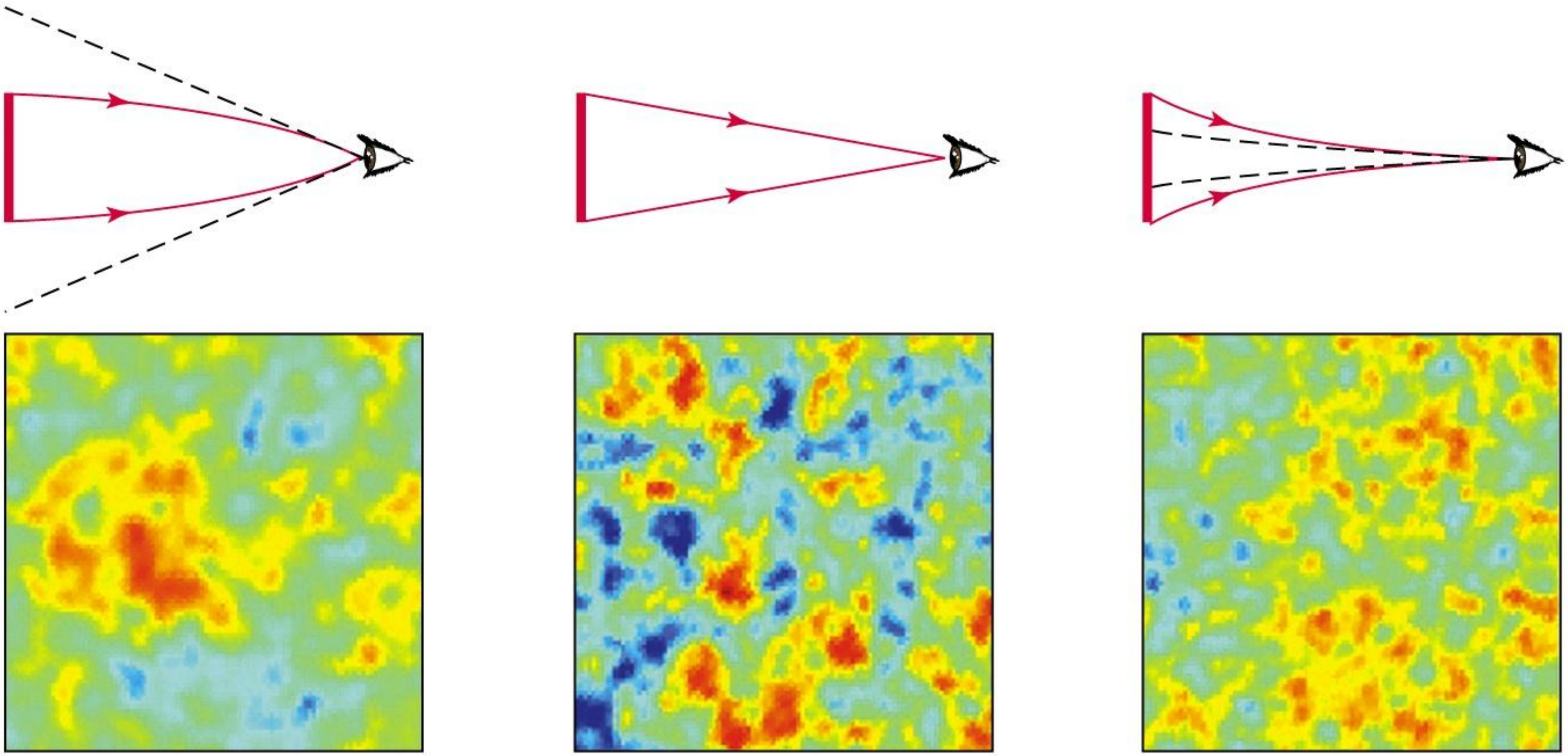
Accelerated Expansion of the Universe
13.7 billion years
Dark age
Relic radiation (CMB)
Dark energy accelerated expansion
Big Bang - Inflation
image: Coldcreation

- Big Bang Nucleo-synthesis
- Cosmic Background Radiation
- Galaxy clusters and clustering
- Galaxy rotation curves
- Our galaxy


The Cosmic Microwave Background as seen by Planck and WMAP
T = 2.726 K
WMAP
Planck

Geometrical Test of curvature:

Standard Rod = Hubble volume at Last Scattering

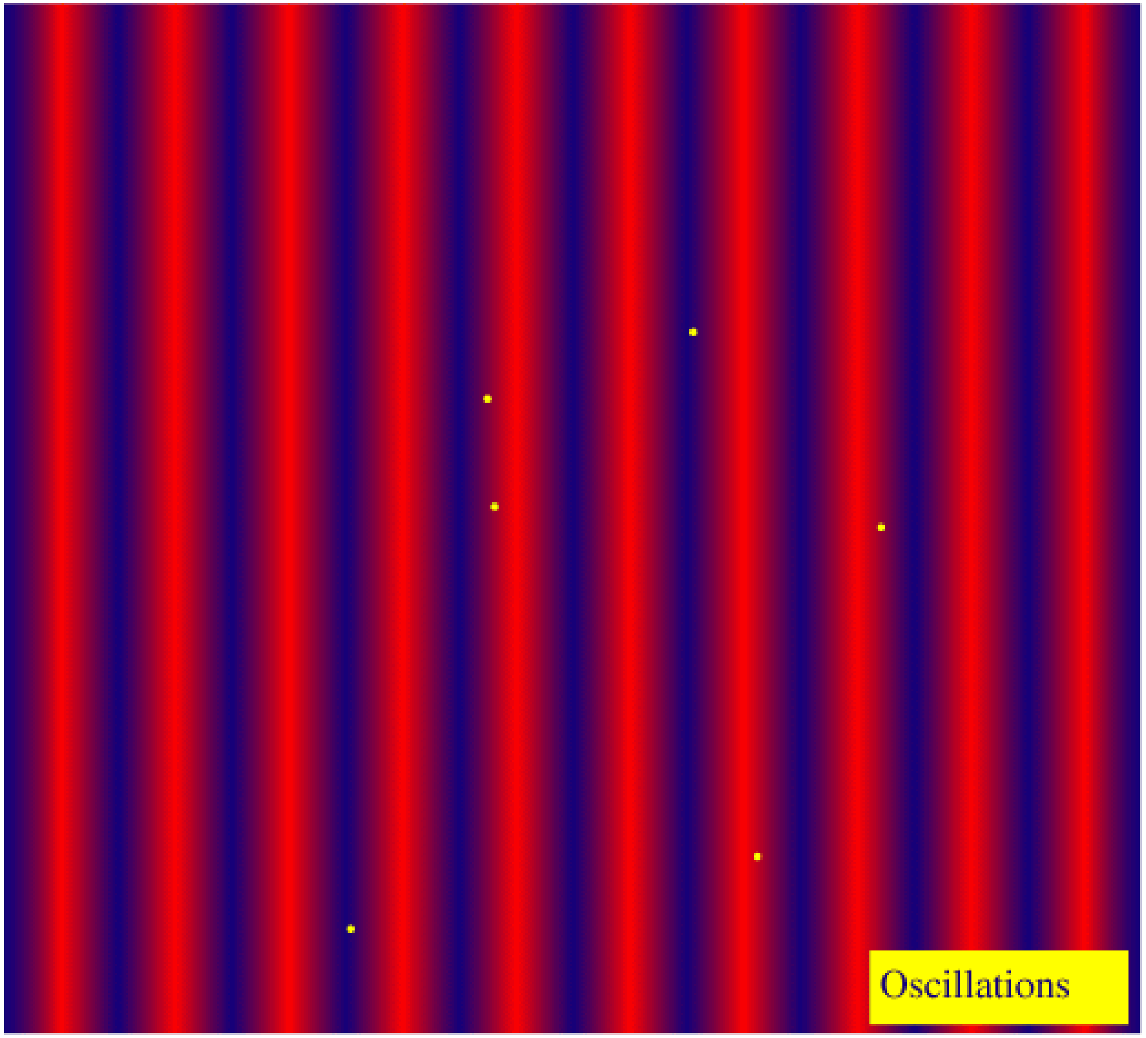


a If universe is closed, “hot spots” appear larger than actual size

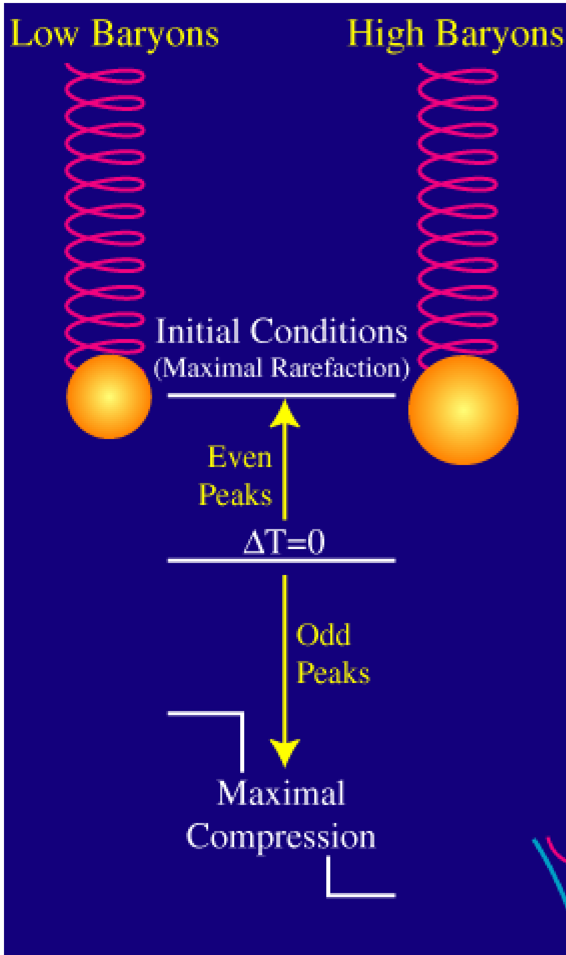
b If universe is flat, “hot spots” appear actual size

c If universe is open, “hot spots” appear smaller than actual size

Spatial temperature variations → angular anisotropies on ever smaller scales as time progresses.



W. Hu: background.uchicago.edu



Baryons enhance difference between even and odd peaks

Can determine ratio of baryonic to non-baryonic matter

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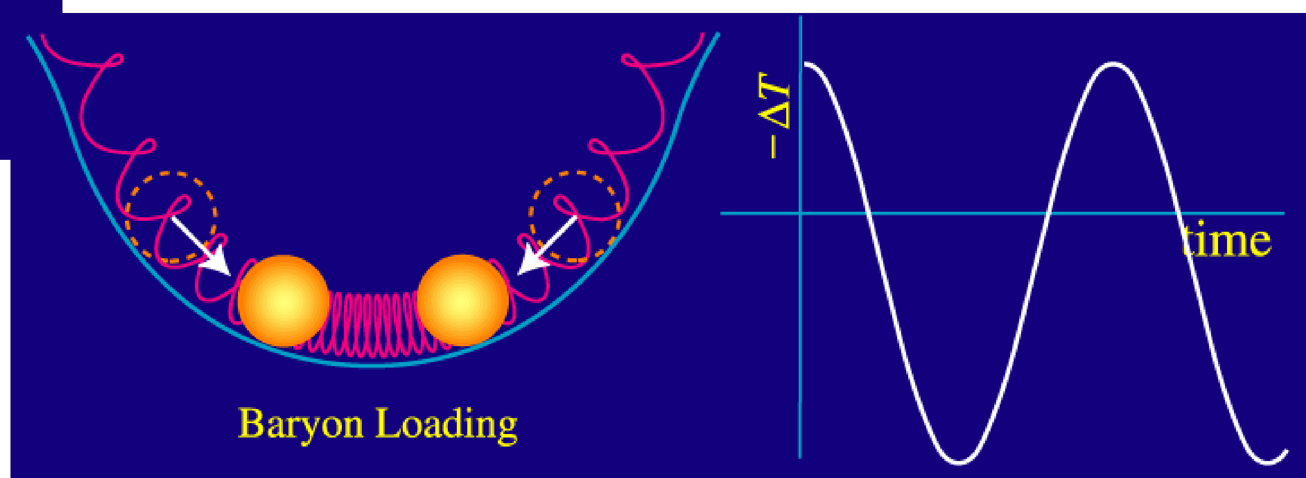

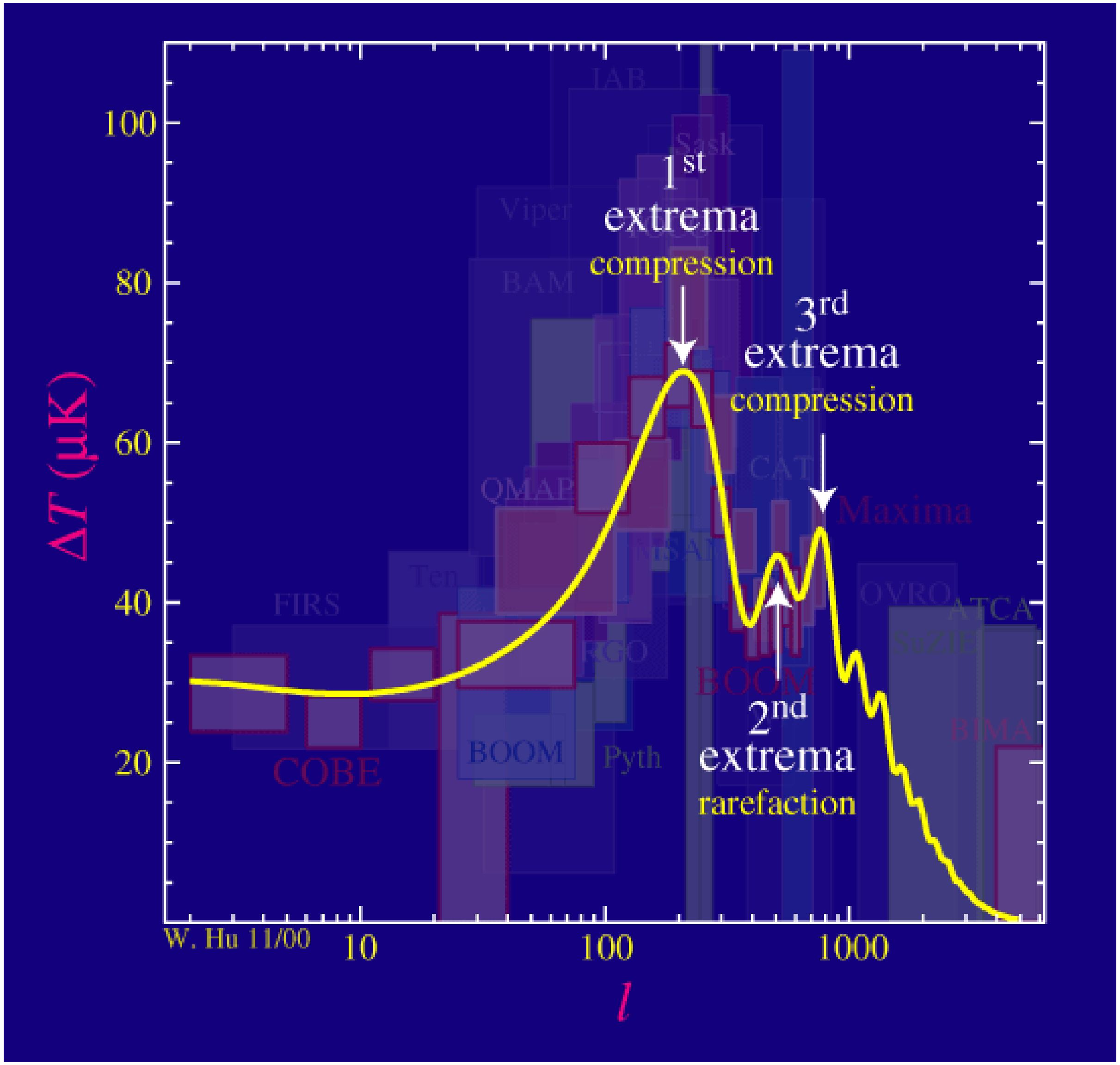

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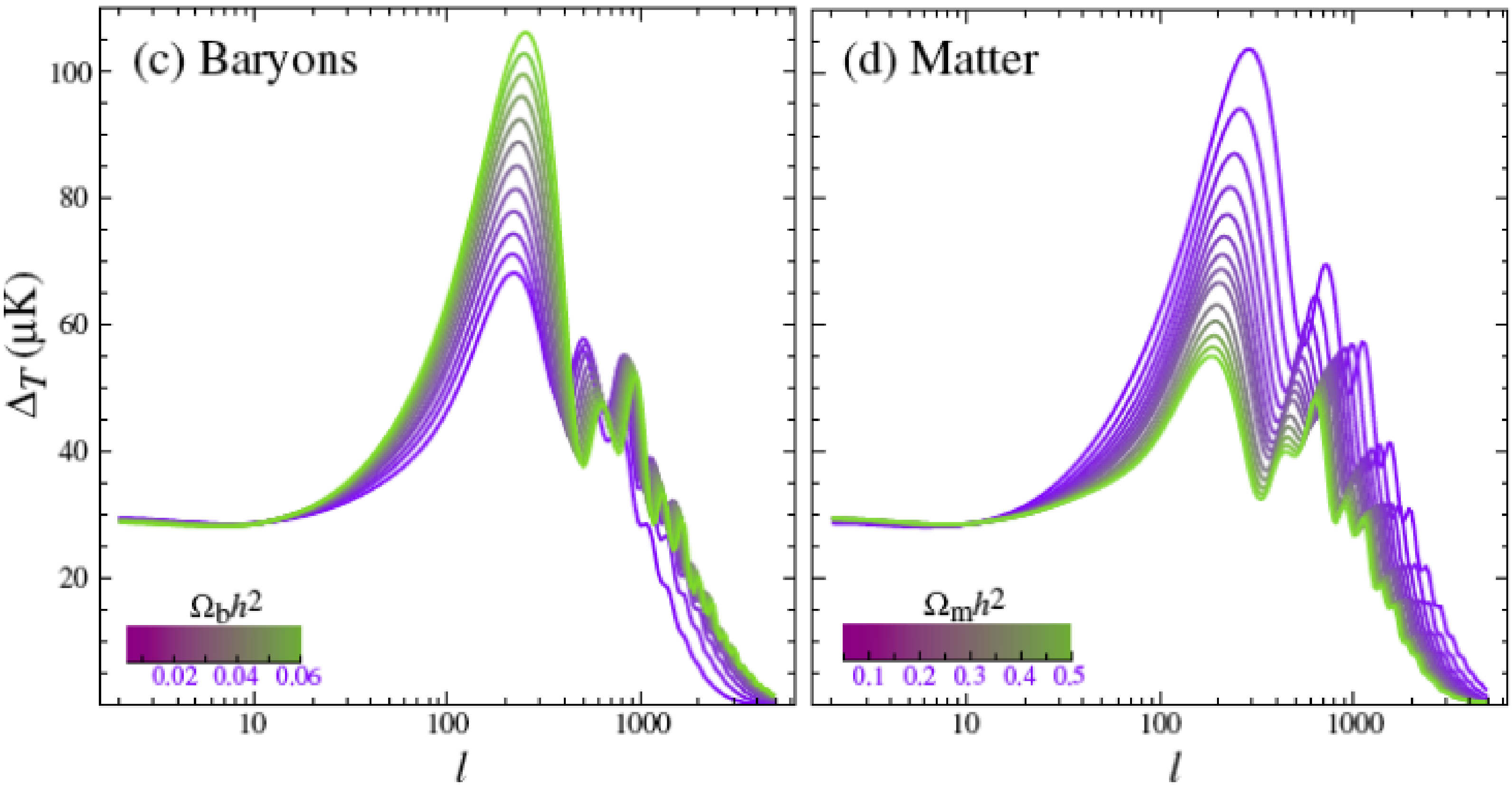
Anisotropies – quantified by power spectrum – depend on geometry and constituents of universe



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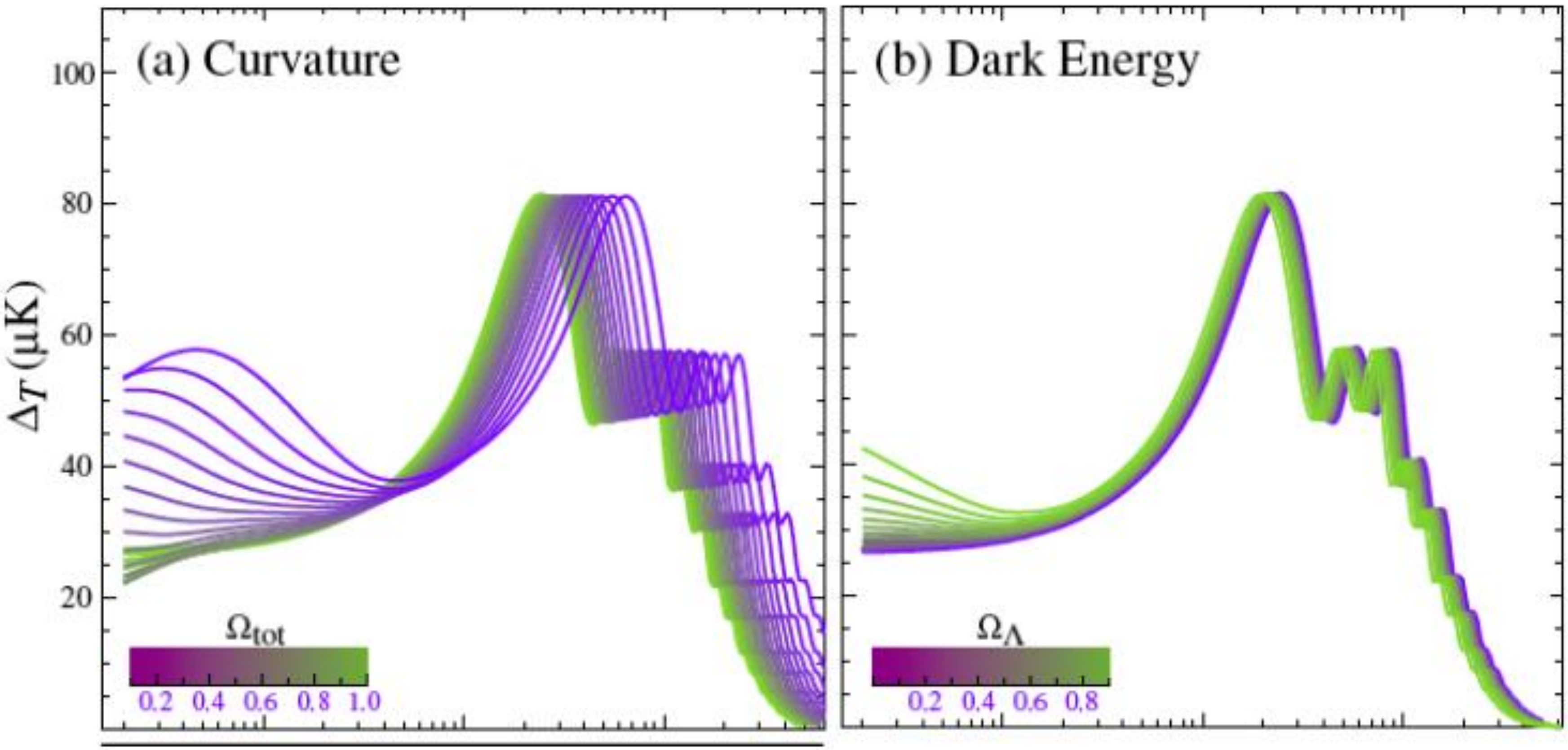

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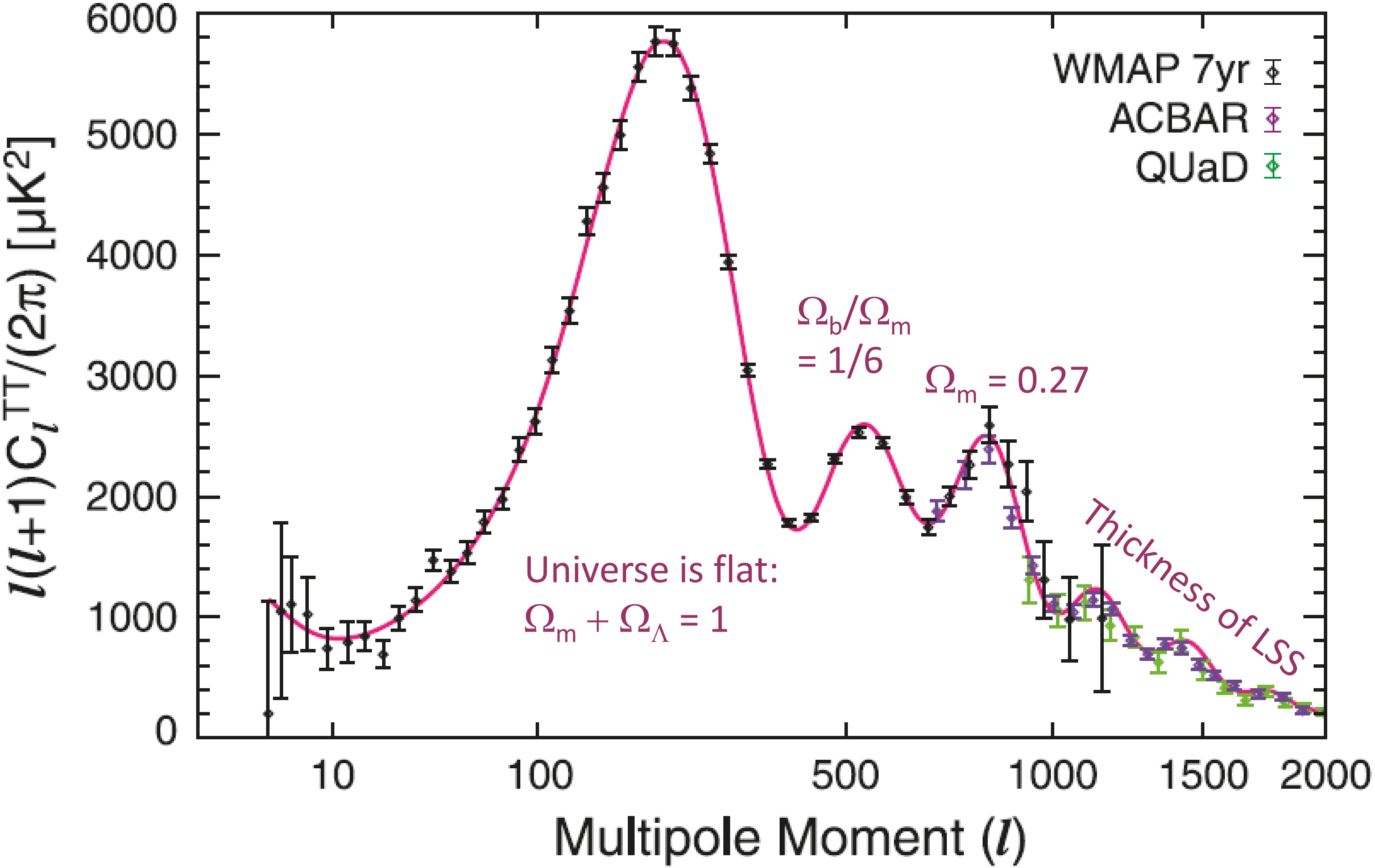
Consistency checks from damping

•Raising the baryon density shifts the damping tail to higher multipoles

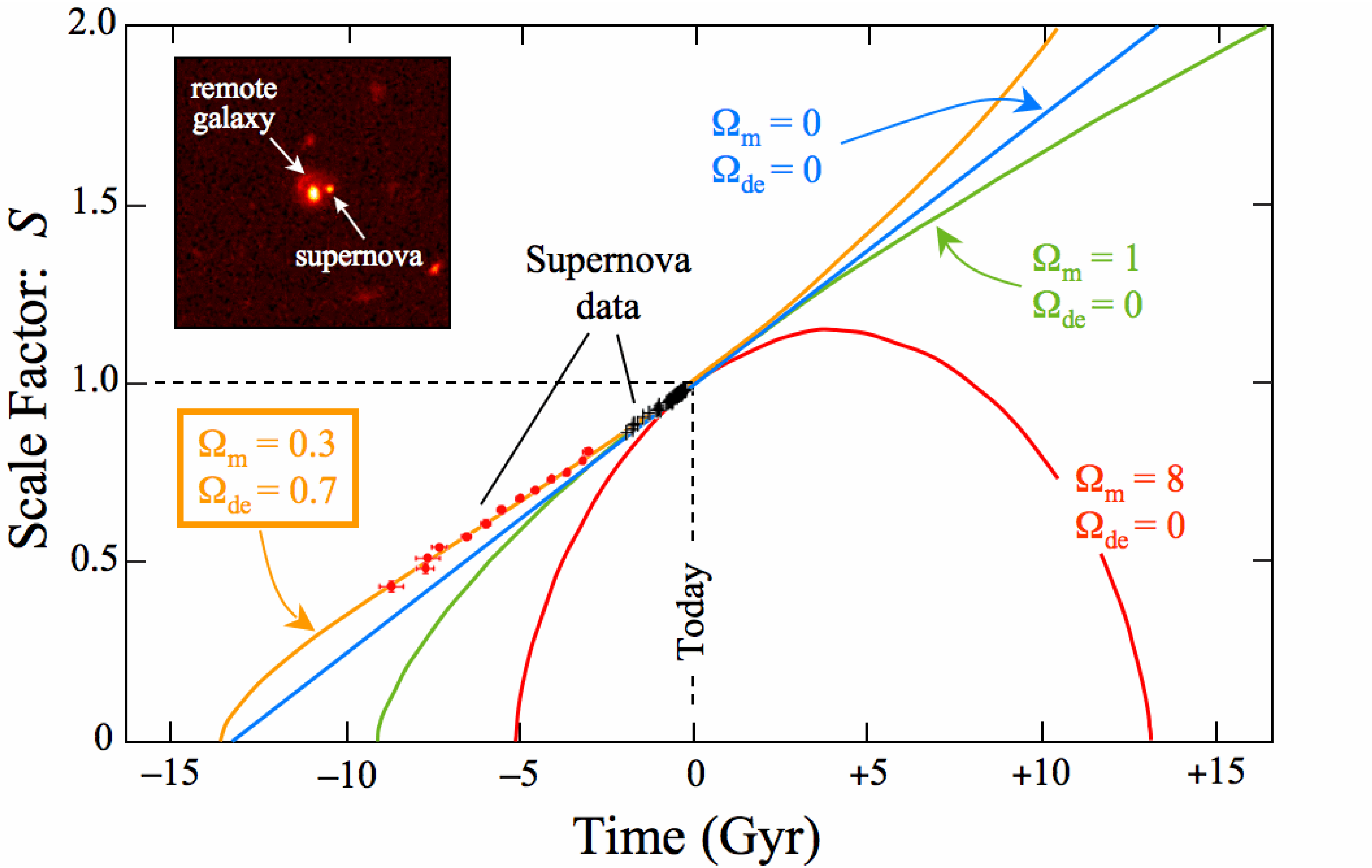
•Raising the matter density shifts the damping tail to lower multipoles

•Consistency checks from the damping tail verify or falsify our assumptions about recombination and initial conditions.



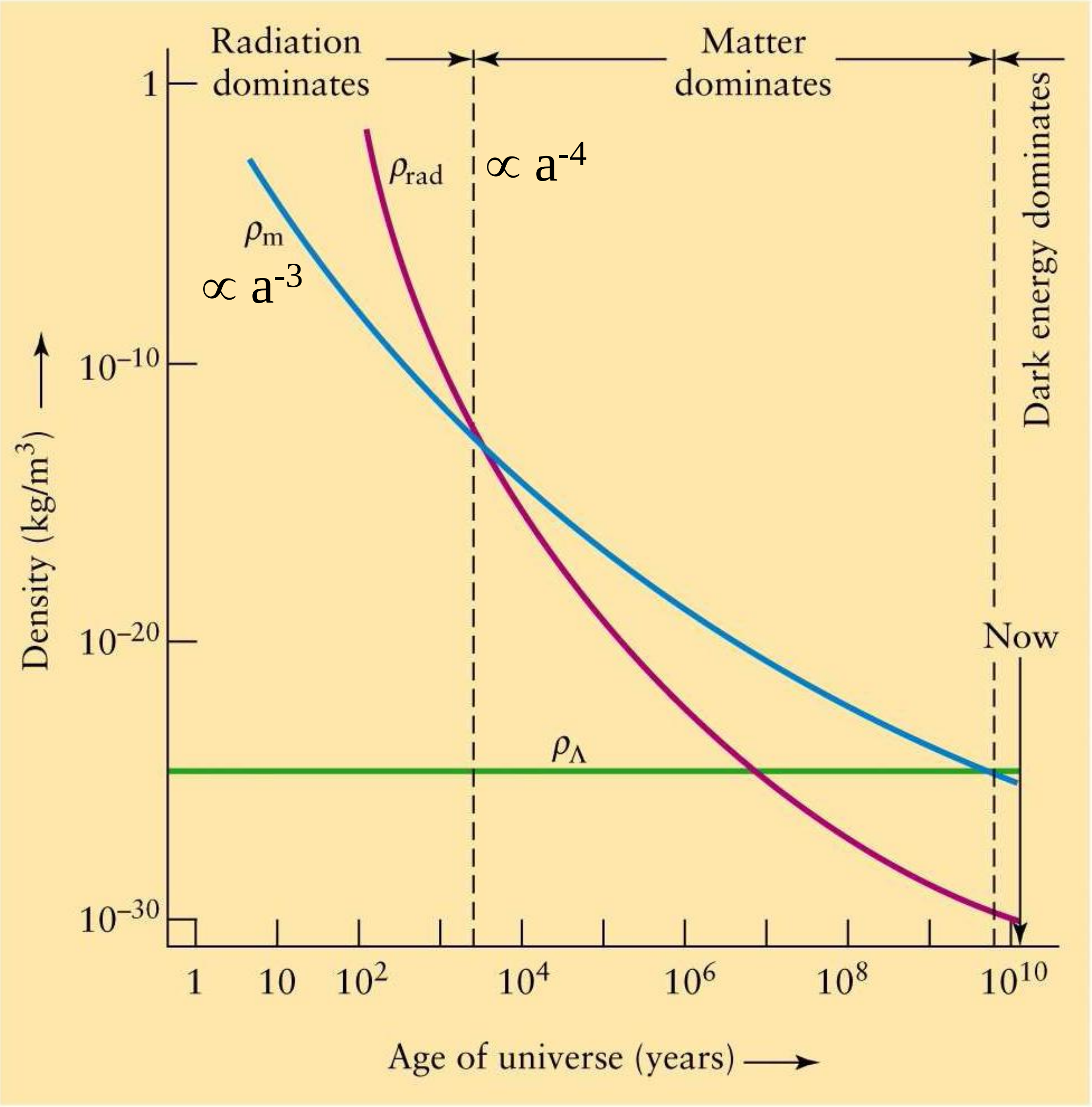
Adiabatic (same fluctuations in all components)

~~vs Iso-curvature (net fluctuation is zero)~~



2.0
1.5
1.0
0.5
0
Scale Factor: S
remote galaxy
supernova
Supernova data
Today
Ωm = 0
Ωde = 0
Ωm = 1
Ωde = 0
Ωm = 0.3
Ωde = 0.7
Ωm = 8
Ωde = 0
−15
−10
−5
0
+5
+10
+15
Time (Gyr)

In the beginning there was … Light (energy density dominated by radiation)



Primordial nucleosynthesis

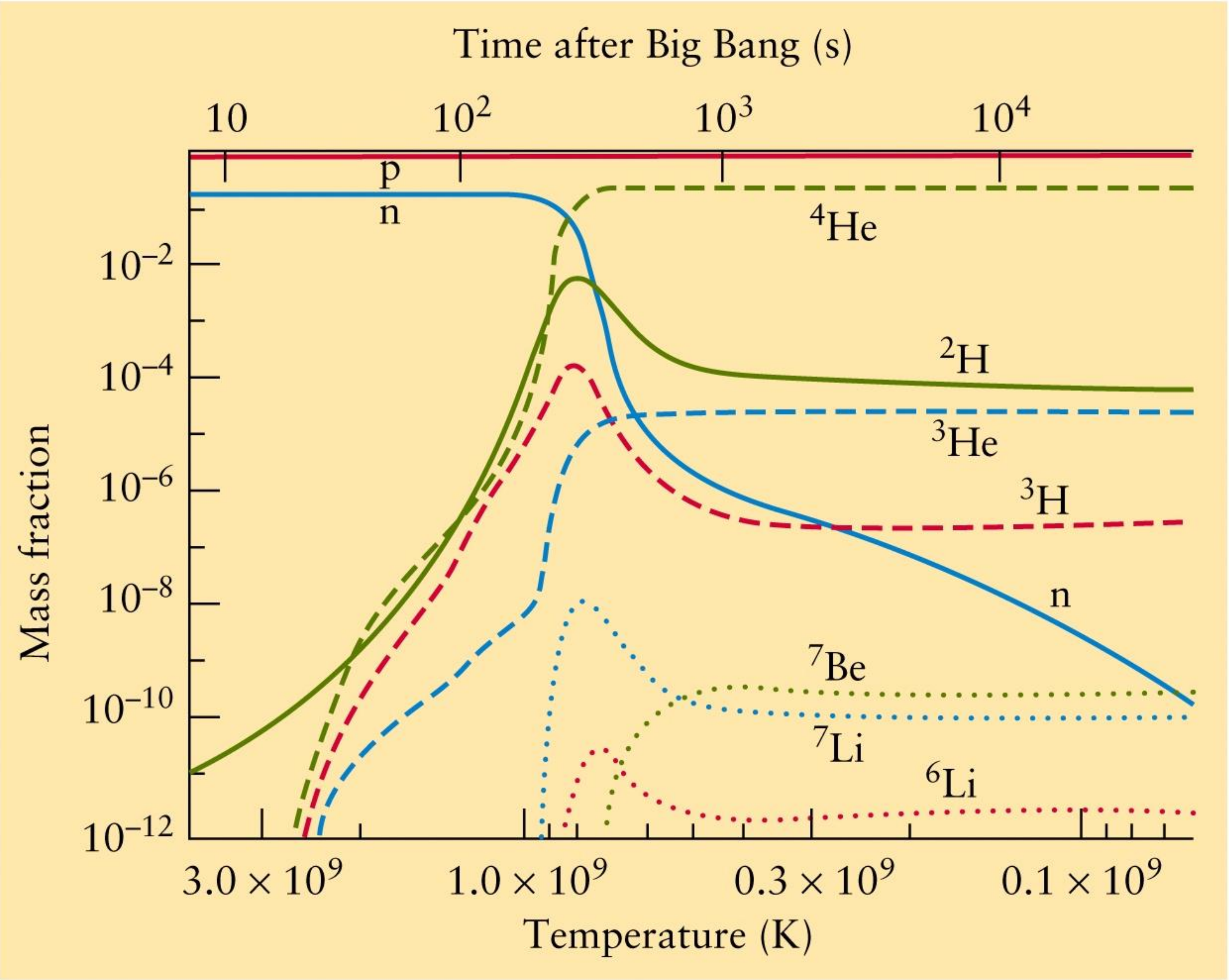
The universe today is 75% hydrogen and 23% helium, and about 2% everything else. How did this happen?

We know helium is made inside stars. If the universe started as entirely hydrogen, could it have made so much helium? No.

The very early universe was so hot that if the universe had originally been made of hydrogen alone, nuclear reactions should have occurred and created helium. Expected amount of helium agrees precisely with observed 25%.

Primordial Nucleosynthesis

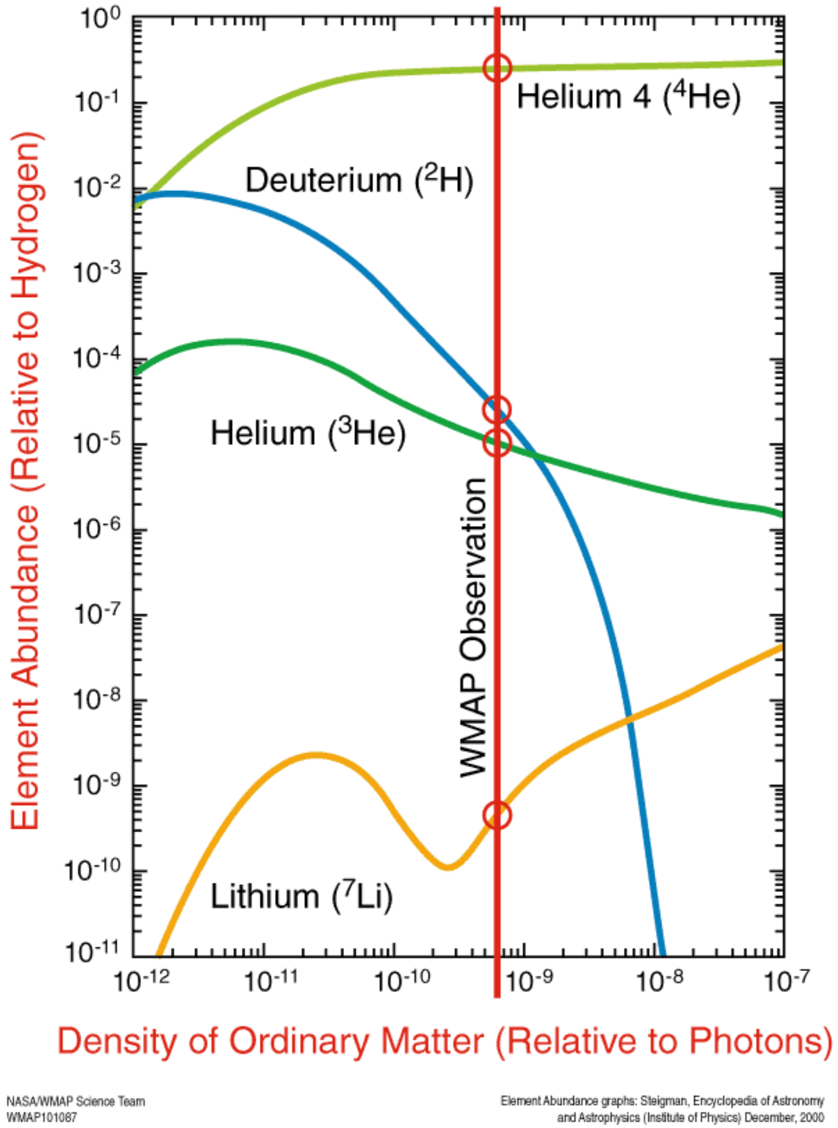
- $n \rightarrow p + e^- + \underline{\nu}$ (easy: half-life *10.5* mins)
- $p + e^- \rightarrow n + \nu$ (easy only if e^- common)
- After $t=1$ sec, e^- no longer common, so p cannot become n, so number of n declines
- $p + n \rightarrow {}^2H + \gamma$ (but Deuterium unstable)
- When $t=3$ mins photons no longer able to destroy ${}^2H$: Helium can form
- After $t=15$ mins, $T=4\times10^8$ *K,* universe too cool to provide energetic collisions (recall nuclei have + charge): epoch of primordial nucleosynthesis ends

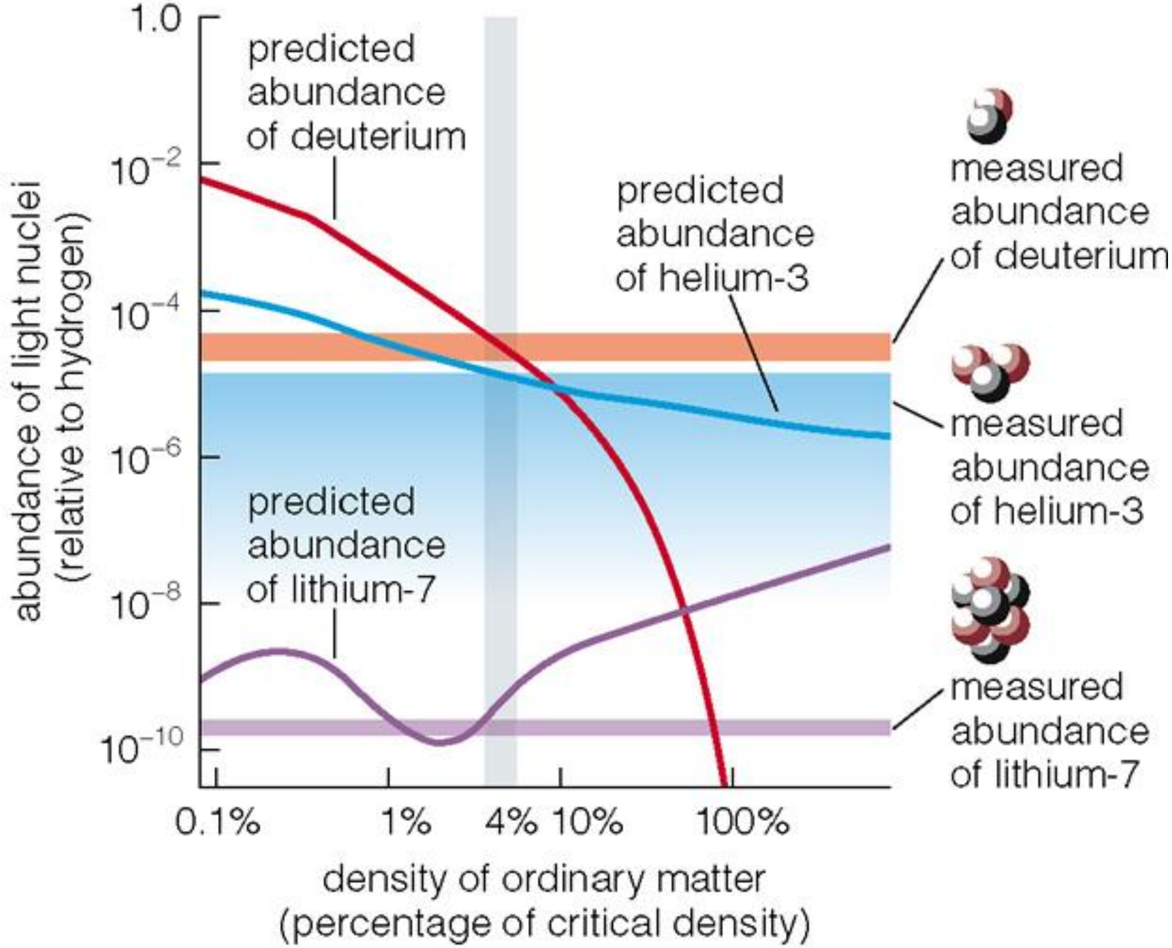


Time after Big Bang (s)
10
10^2
10^3
10^4
p
n
^4He
^2H
^3He
^3H
n
^7Be
^7Li
^6Li
Mass fraction
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
3.0×10^9
1.0×10^9
0.3×10^9
0.1×10^9
Temperature (K)

Exact 'yields' depend on baryon-photon ratio η

- More baryons → earlier start to BBNS → more ^{4}He produced (and less D and ^{3}He left over)
- If $\eta < 10^{-12}$ not enough He produced
- If $\eta > 10^{-7}$ all neutrons → He before decaying, so He/H mass ratio → 1/3
- D better than ^{3}He to check (stronger function of η)



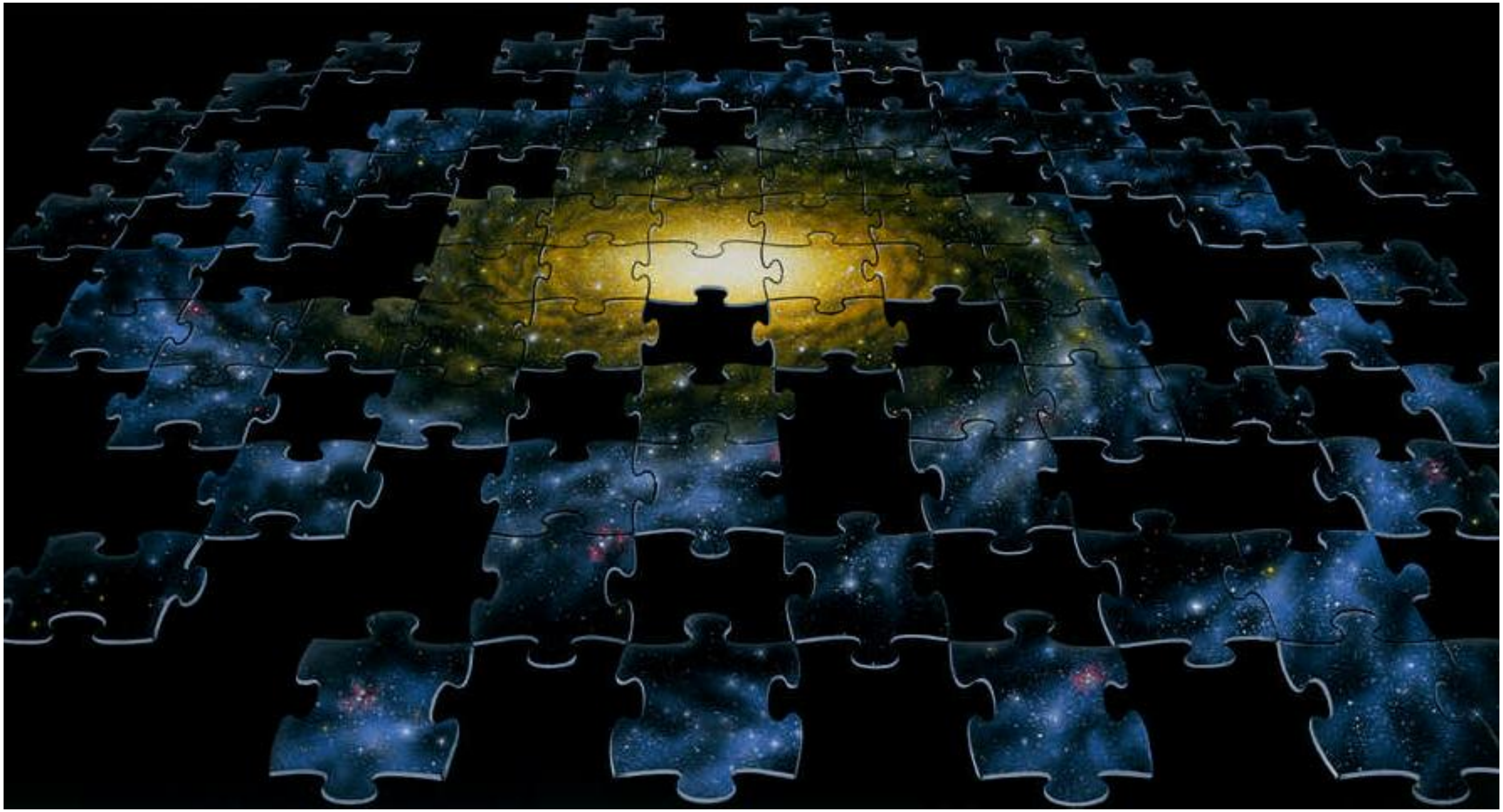


Abundances of other light elements agree with Big Bang model having 4.4% normal matter – evidence for Weakly Interacting Massive Particles

BBNS says that baryons cannot account for all the matter we infer from CMB observations:
Most mass must be non-baryonic

In addition, at least some (most) of the baryons in the Universe must not have made optical star light:
Most baryons must be dark.

Dark Matter?



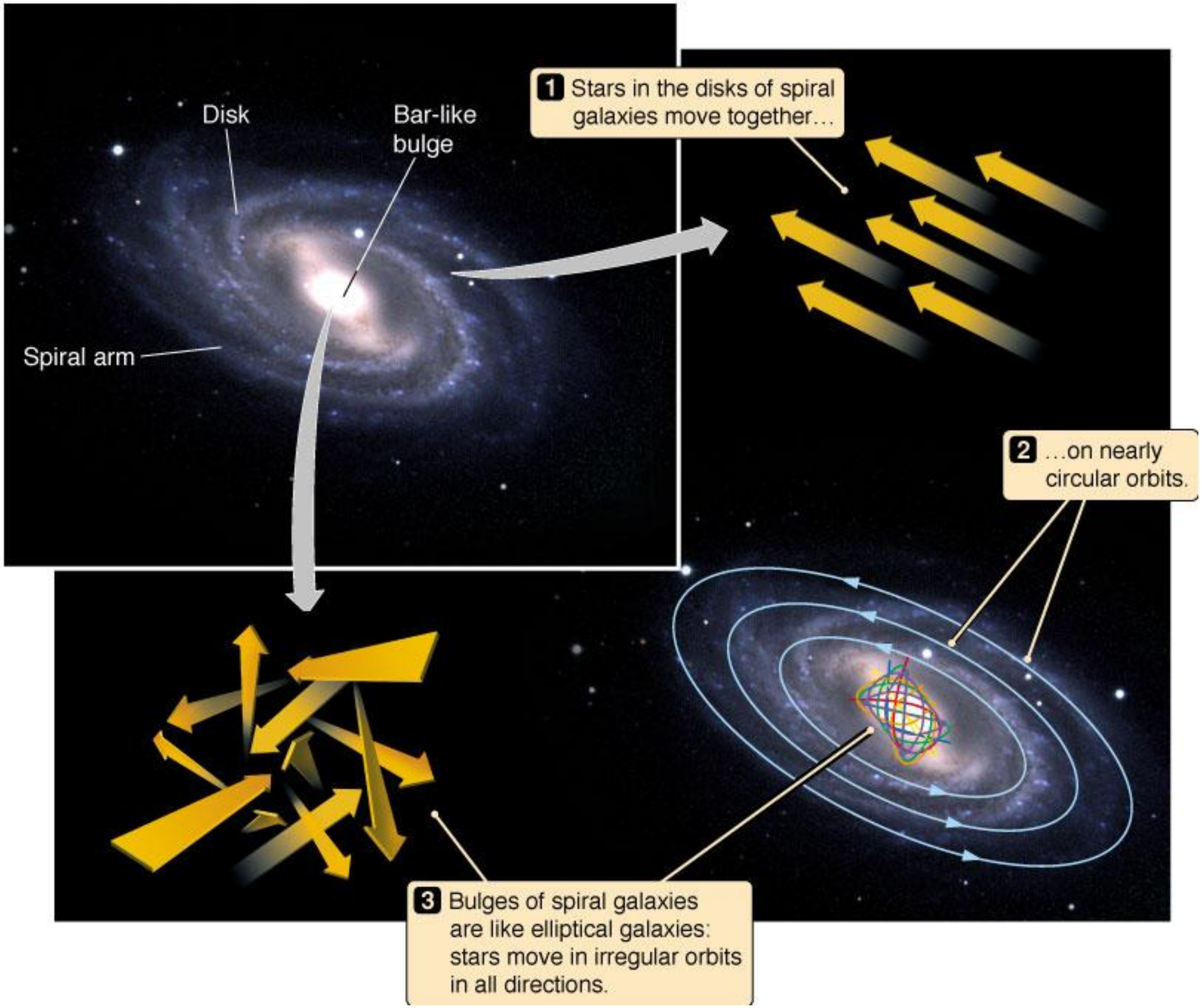
Missing pieces

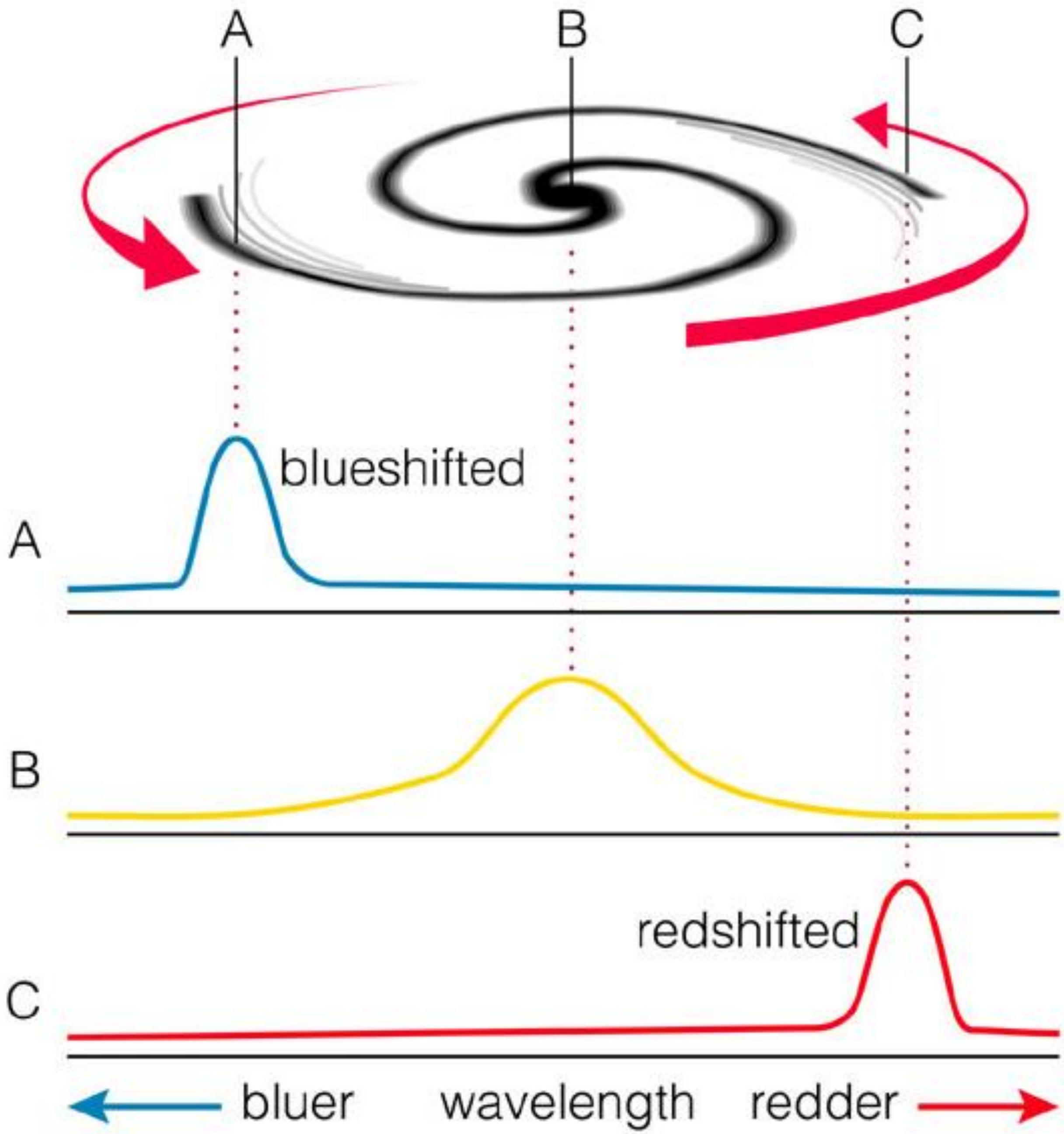
Rotation curves

$$v^2 = GM(<r)/r$$

- Keplerian: $v^2 = GM(<r)/r$
  - Point mass has v decreasing as $1/\mathrm{sqrt}(r)$
- Isothermal: v^2 = constant, so $M(<r)$ increases linearly with r
  - Think of v^2 as temperature

Stellar orbits in a spiral galaxy





We can measure rotation curves of other spiral galaxies using the Doppler shift of the 21-cm line of atomic H

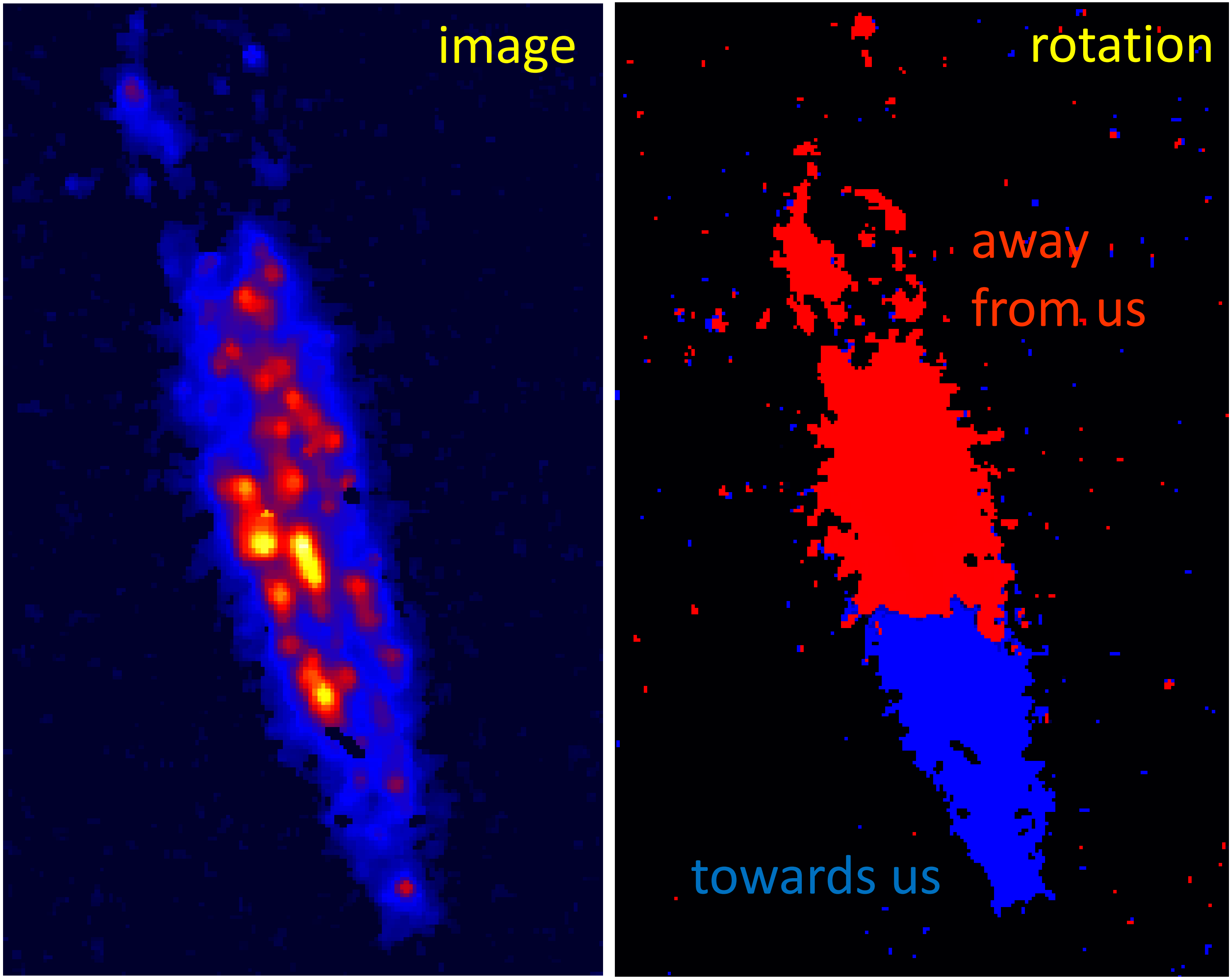
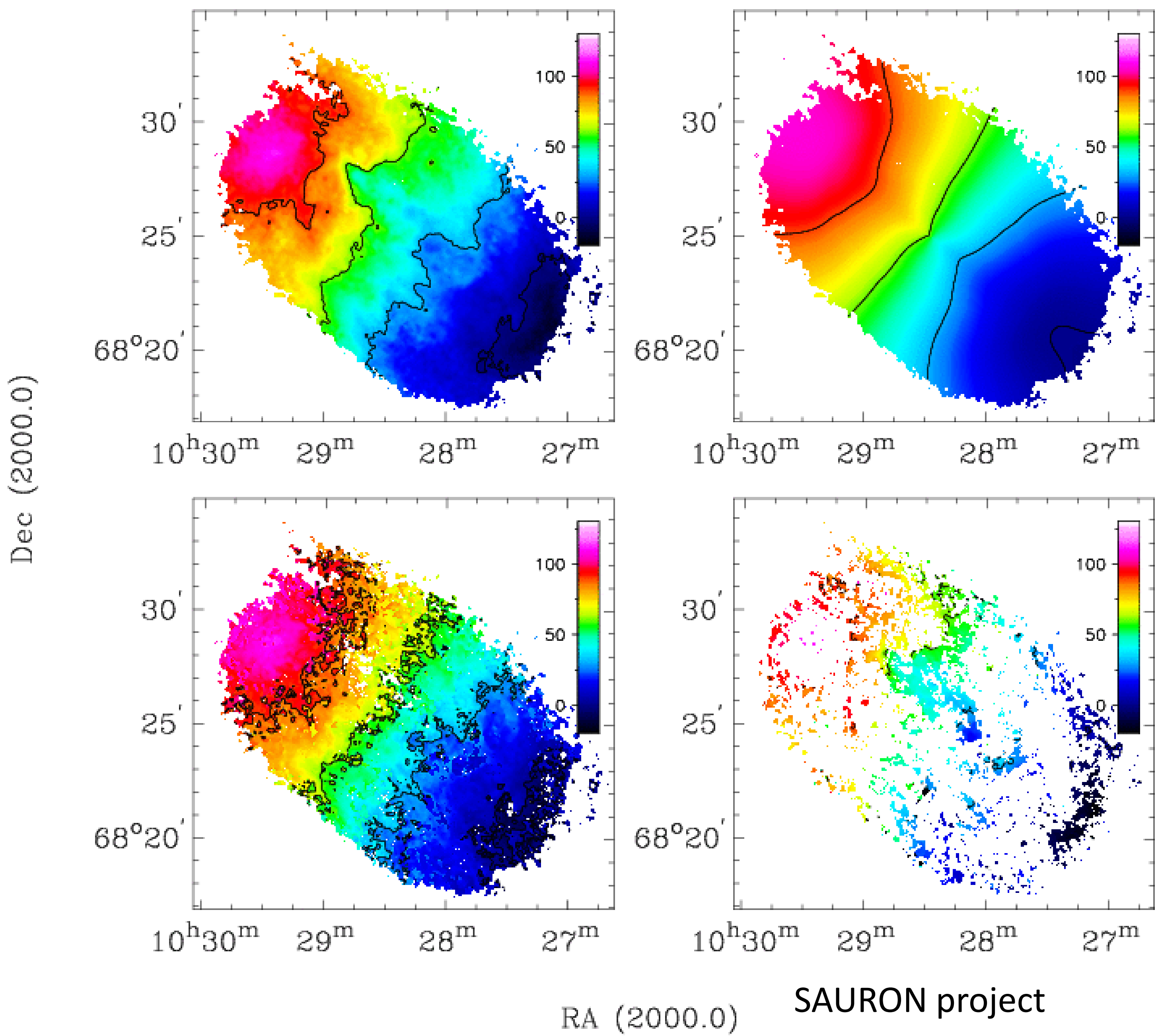
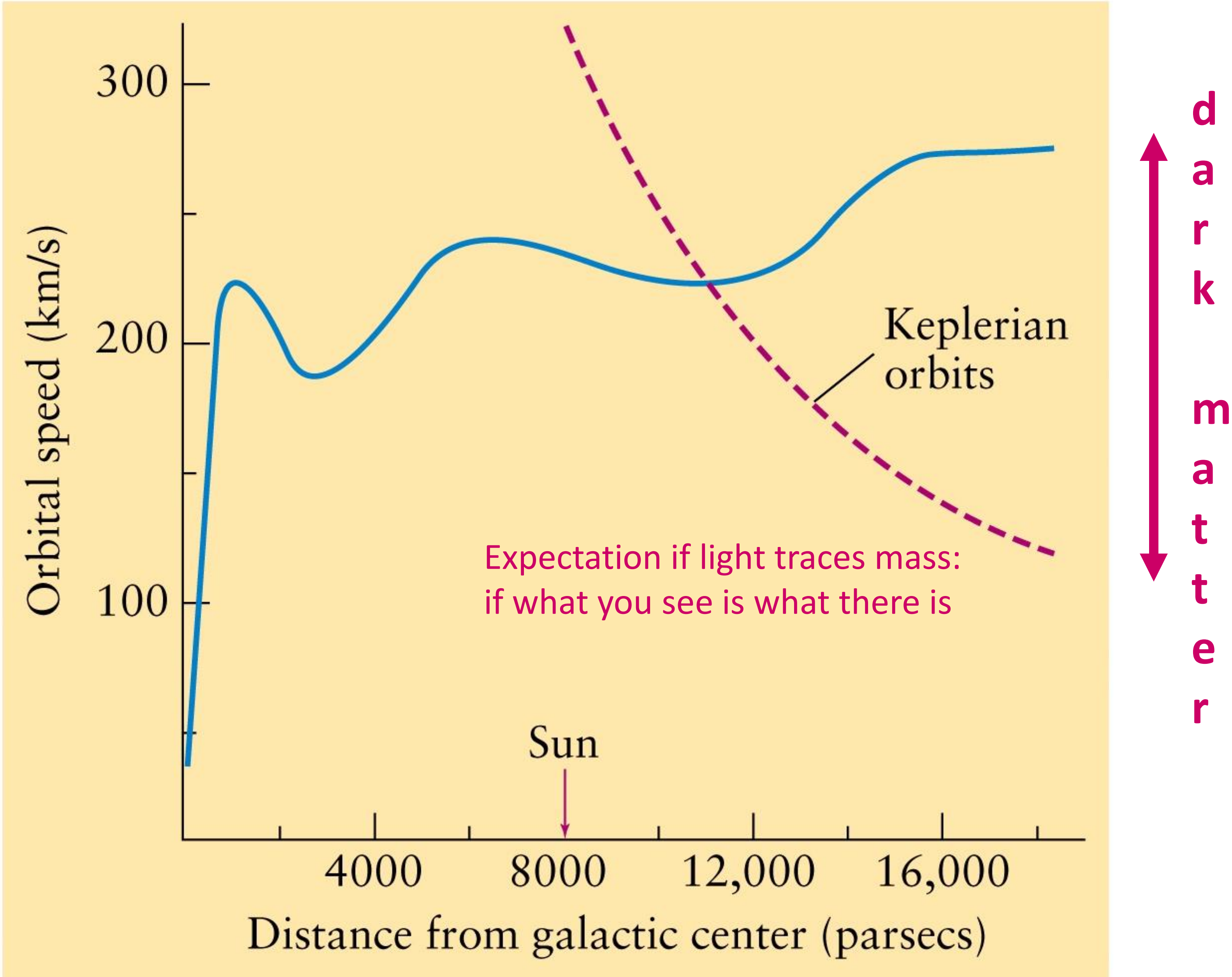
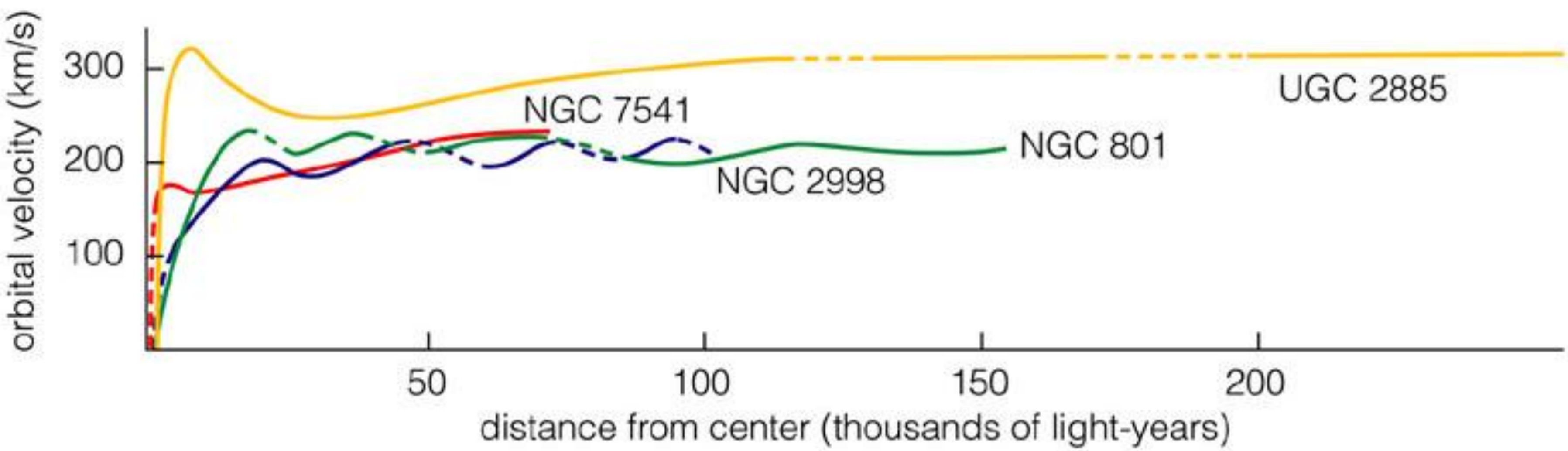


image
rotation
away
from us
towards us



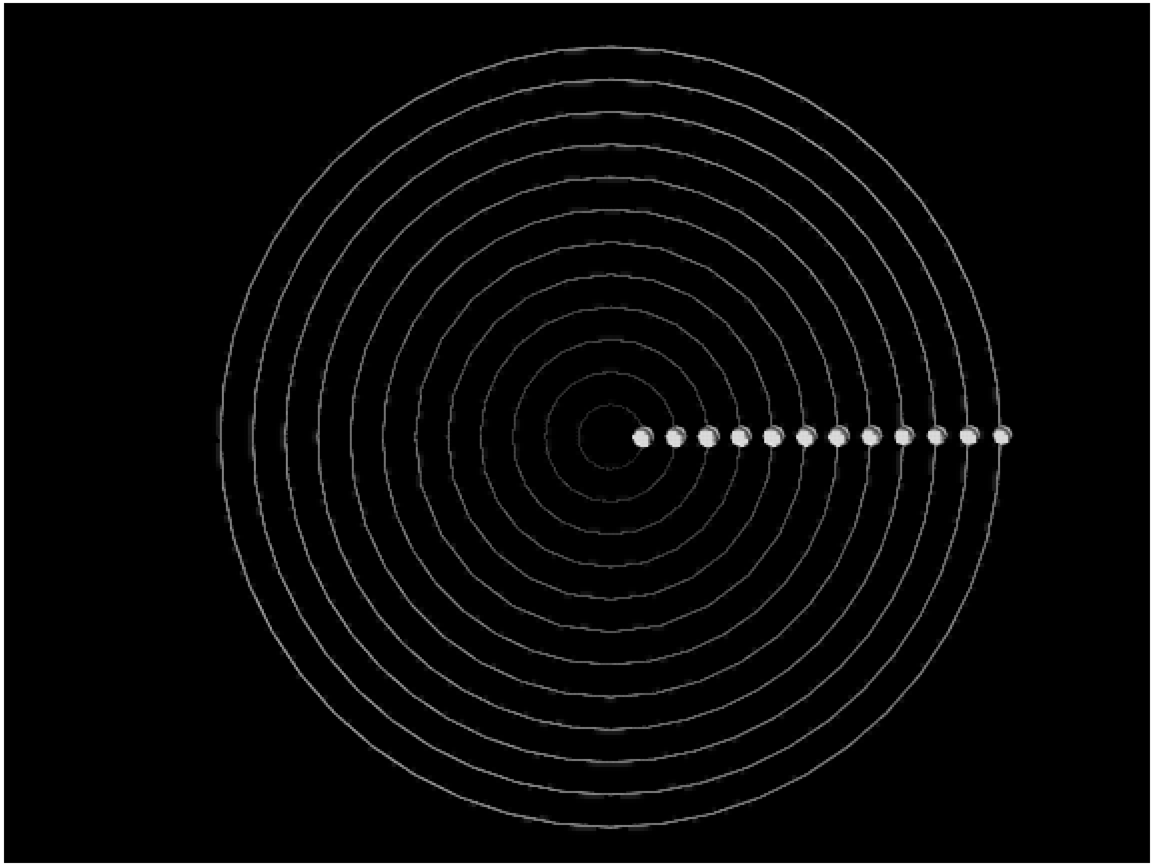
SAURON project


Orbital speed (km/s)
300
200
100
Distance from galactic center (parsecs)
4000
8000
12,000
16,000
Sun
Keplerian orbits
Expectation if light traces mass:
if what you see is what there is
dark matter

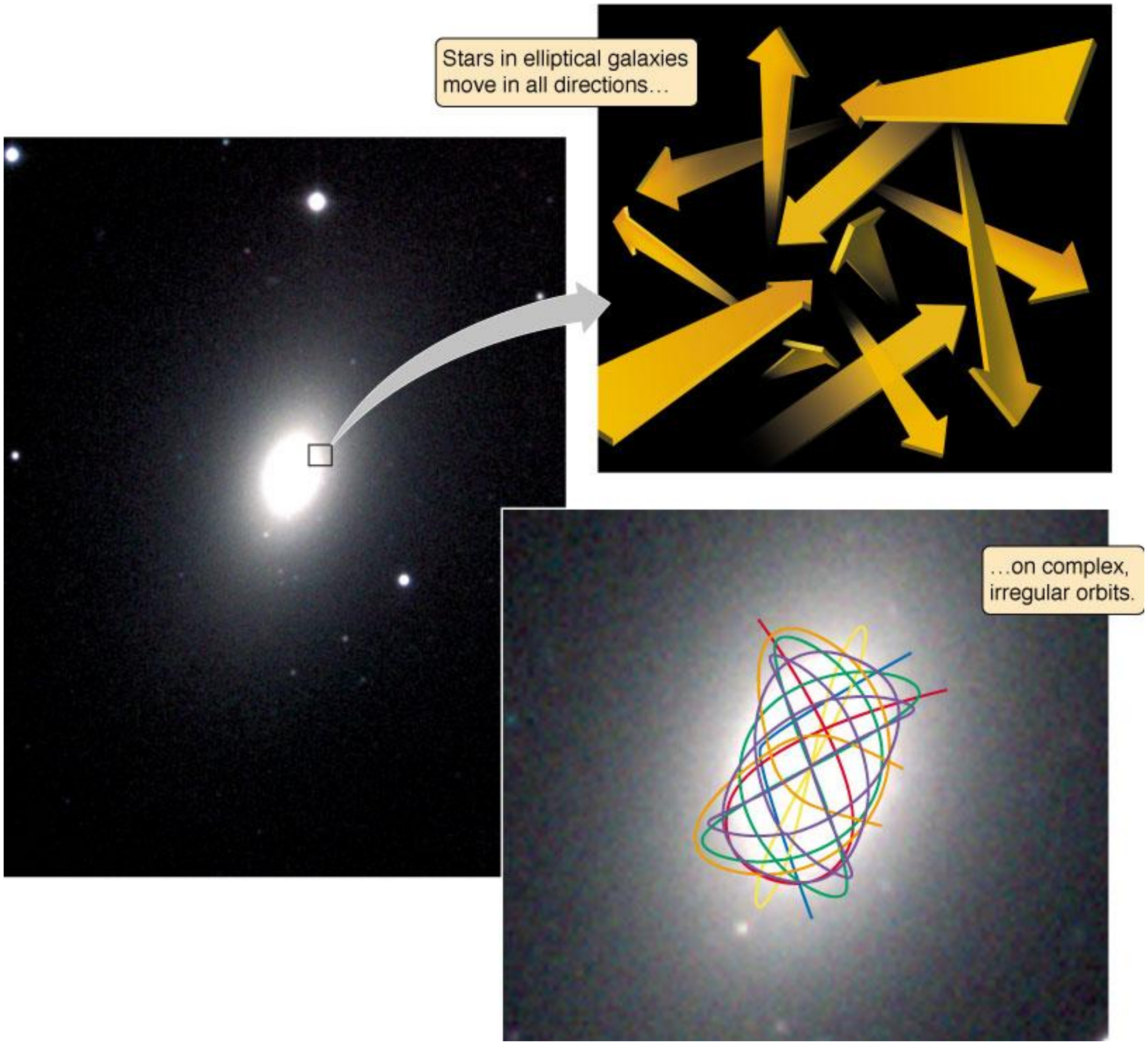


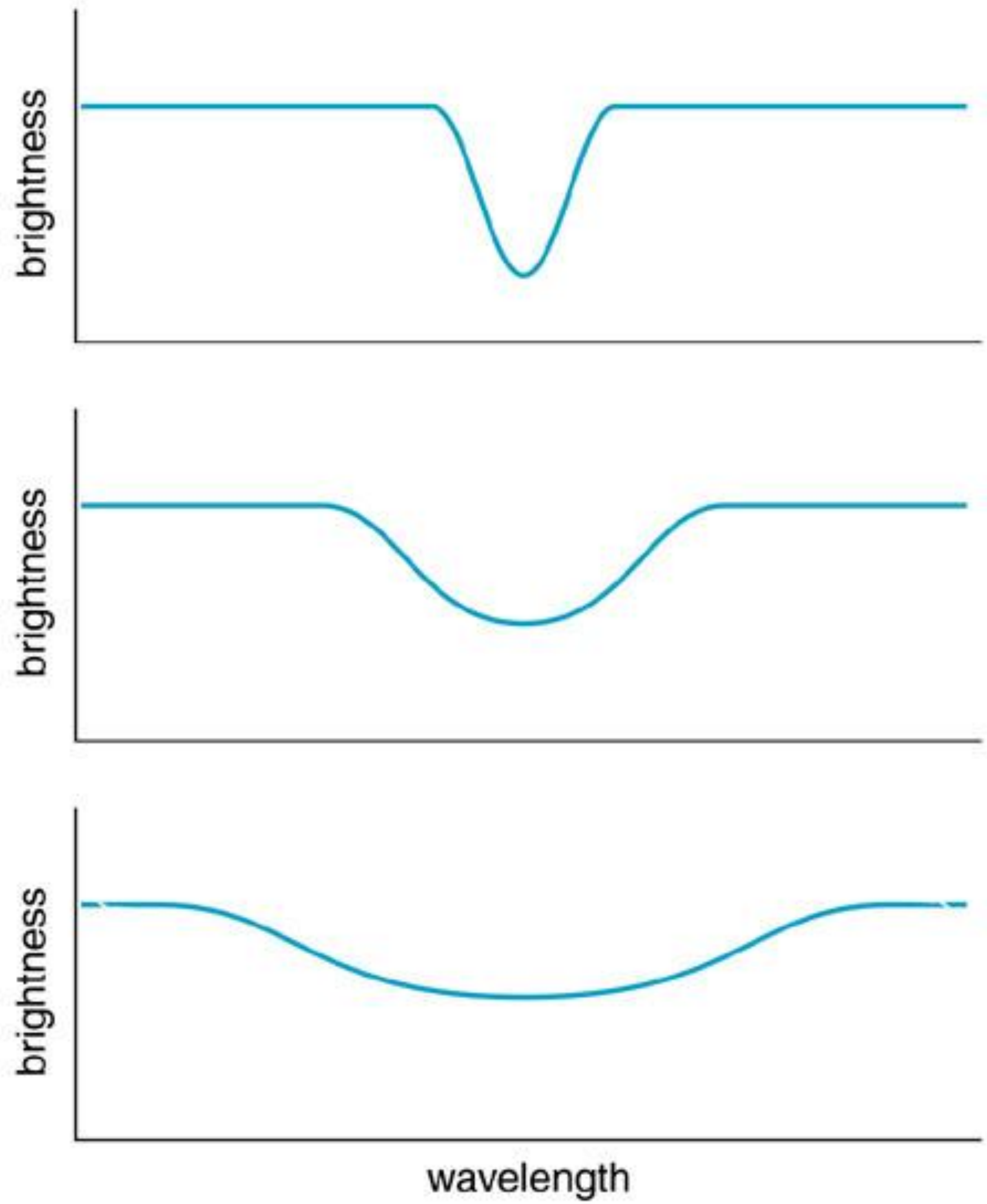
Spiral galaxies all tend to have *flat rotation curves* indicating large amounts of dark matter even at distances where there is little light.

Science: The destruction of a beautiful idea by an ugly fact



Stellar orbits in an elliptical galaxy

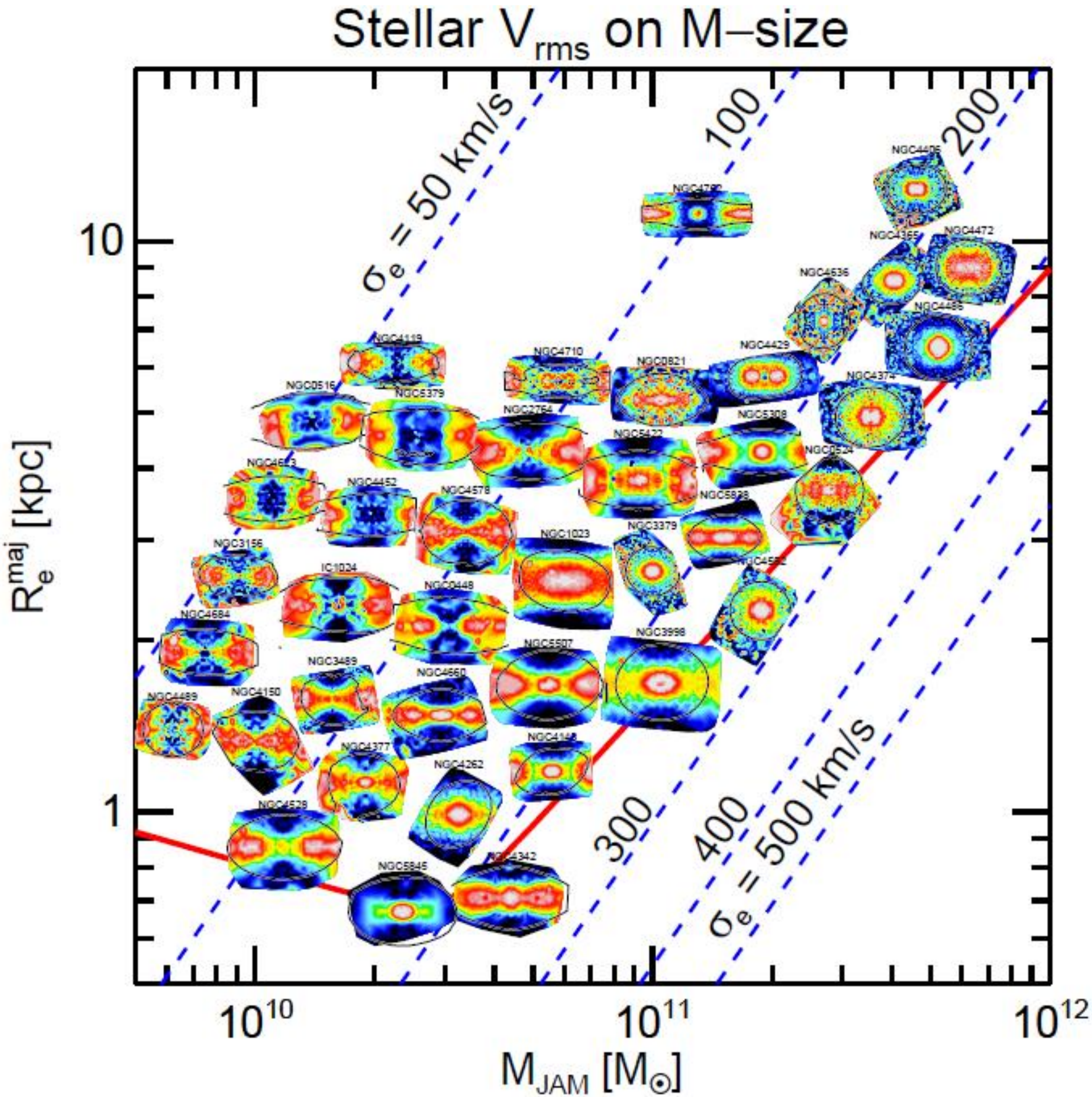




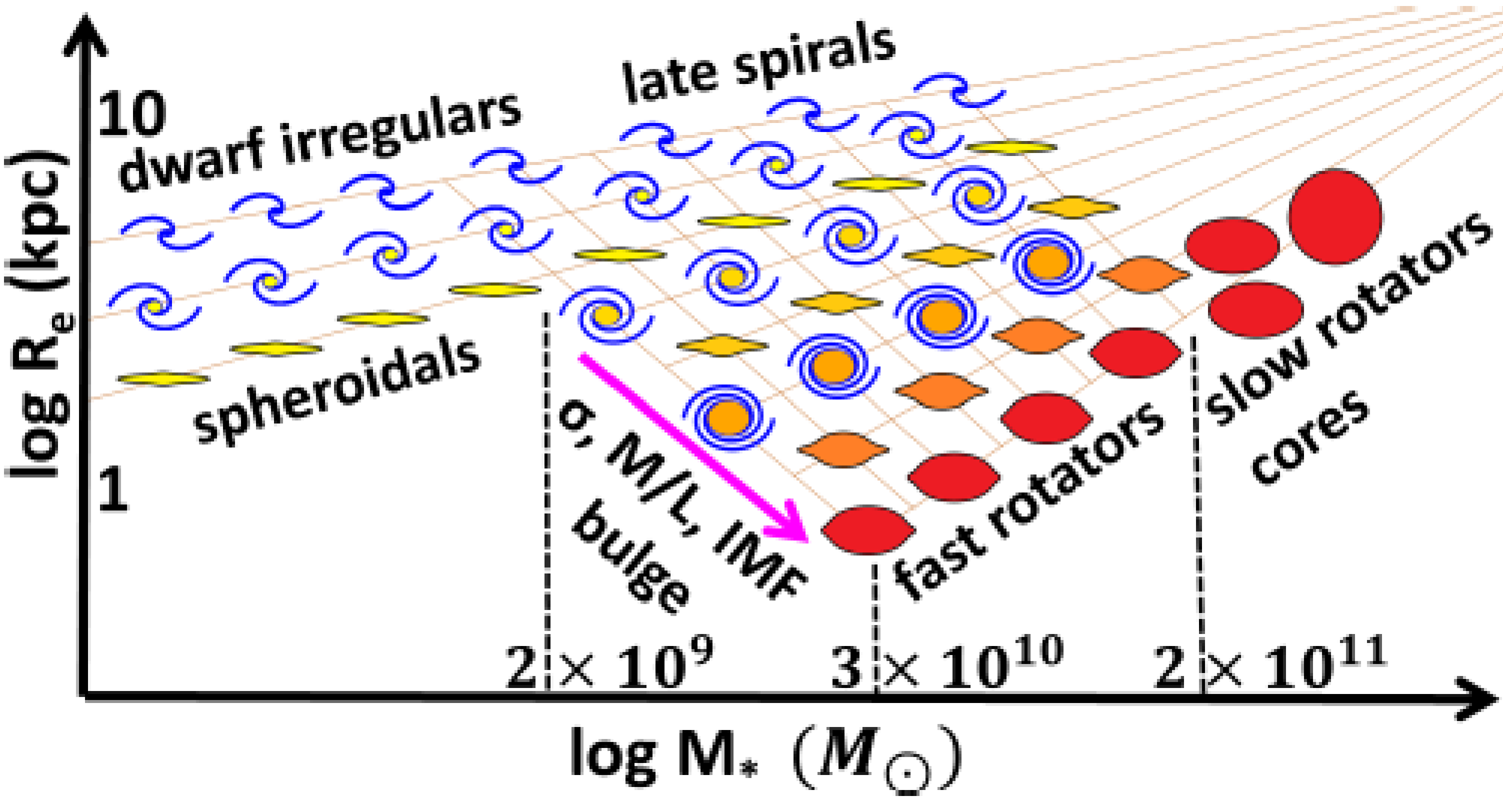
Broadening of spectral lines in elliptical galaxies tells us how fast the stars are orbiting

These galaxies also have dark matter:

$M(<r)/M_{sun} > L(<r)/L_{sun}$

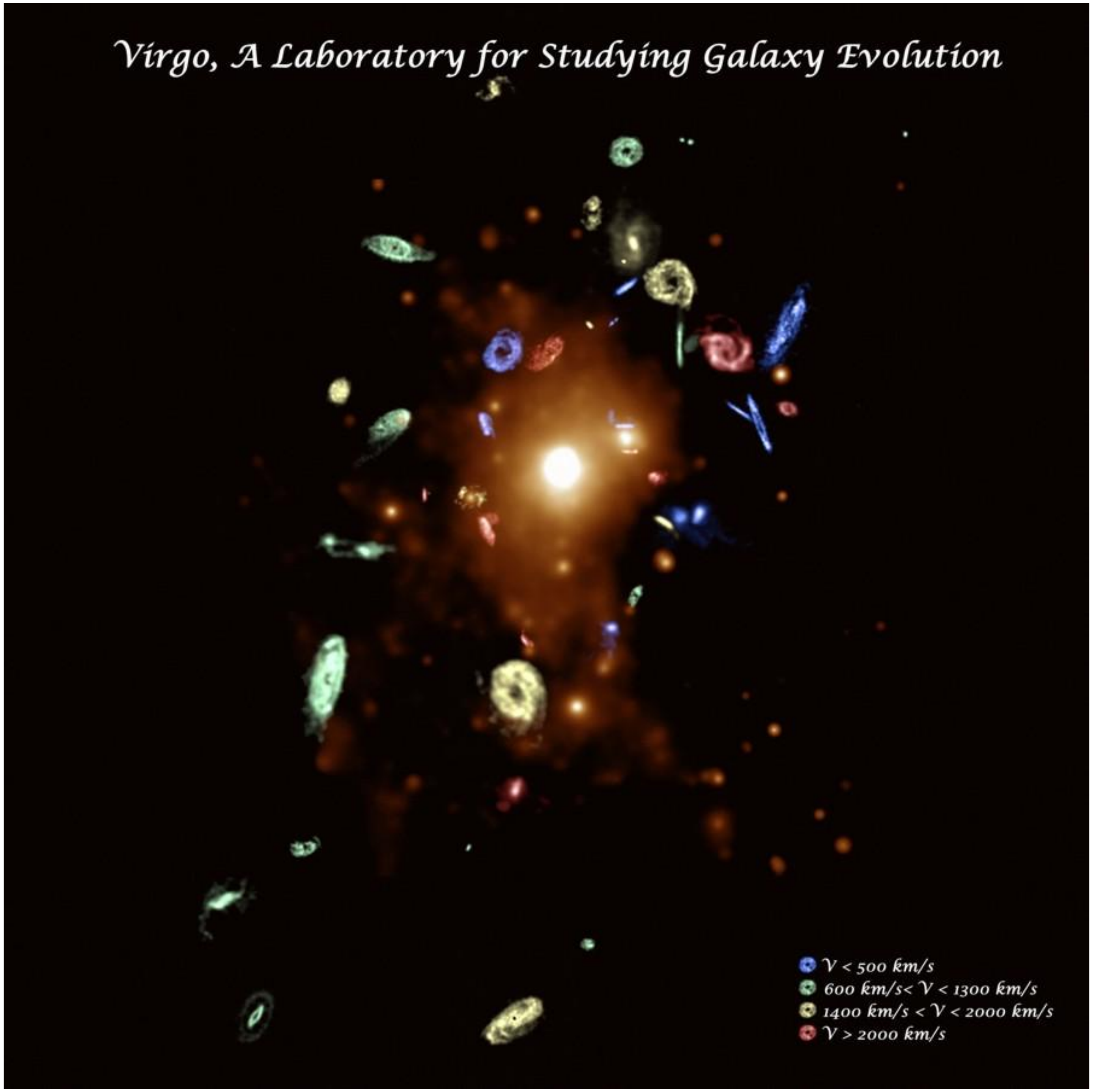


Stellar V_{rms} on M–size
σ_e = 50 km/s
100
200
300
400
σ_e = 500 km/s
R_e^{maj} [kpc]
10
1
10^{10}
10^{11}
10^{12}
M_{JAM} [$M_\odot$]



late spirals
10
dwarf irregulars
log R_e (kpc)
spheroidals
σ, M/L, IMF
bulge
fast rotators
slow rotators
cores
1
2 × 10^9
3 × 10^10
2 × 10^11
log M_* (M_⊙)

Clusters of galaxies

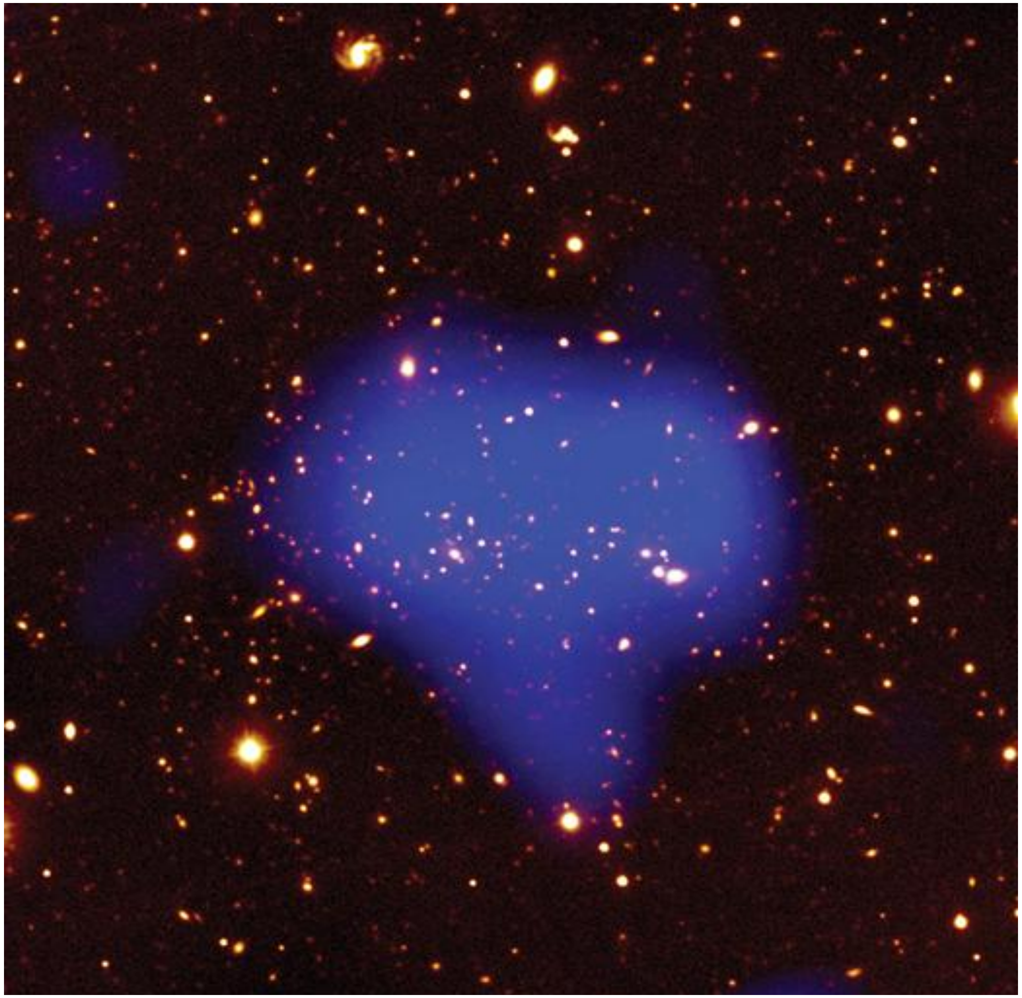


We can measure the velocities of galaxies in a cluster from their Doppler shifts

Speeds must be smaller than sqrt of 2GM(<R)/R

Observed rms speed v + observed cluster centric distance R → $M(<R) = Rv^2/2G$

This mass is about ***50 times*** larger than the mass in stars



Clusters contain large amounts of hot X-ray emitting gas

Temperature of gas (particle motions) → cluster mass:

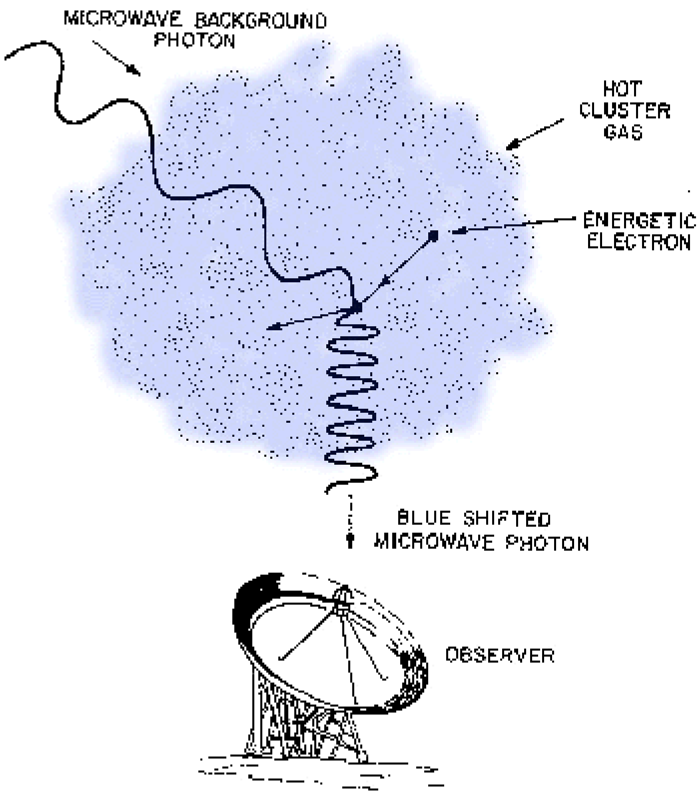
85% dark matter

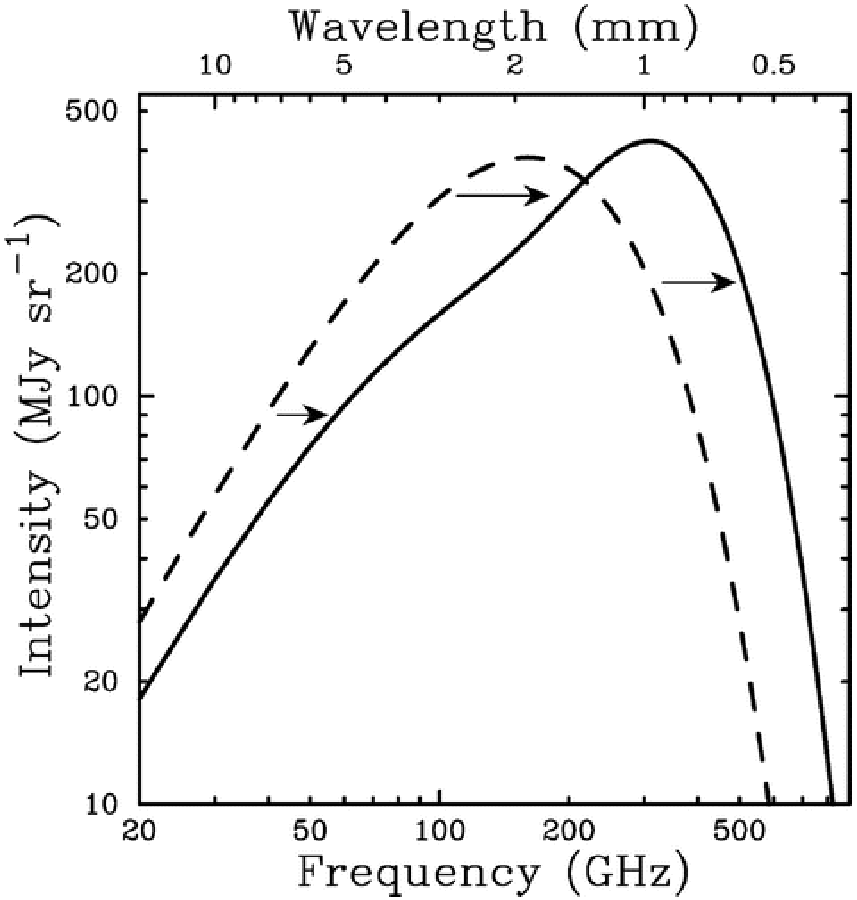
13% hot gas

2% stars

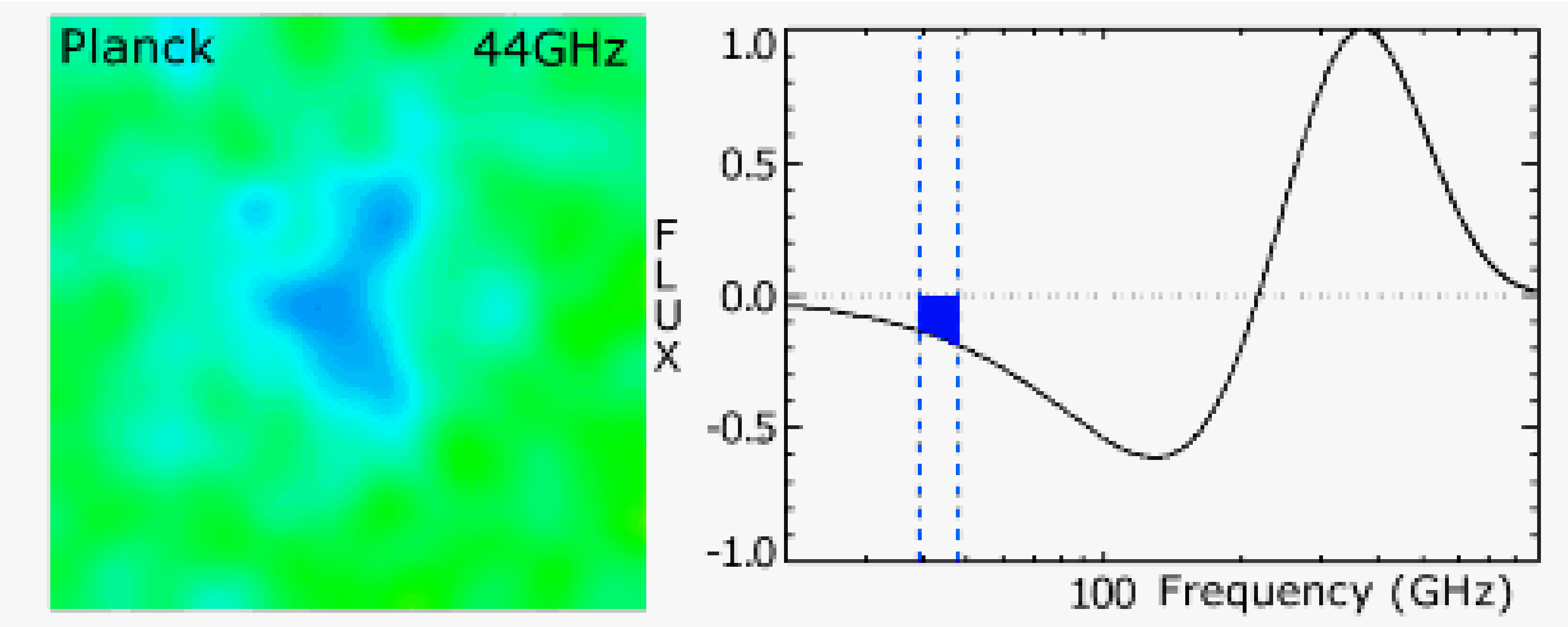
T_{Xray} and galaxy motions v give consistent mass estimates

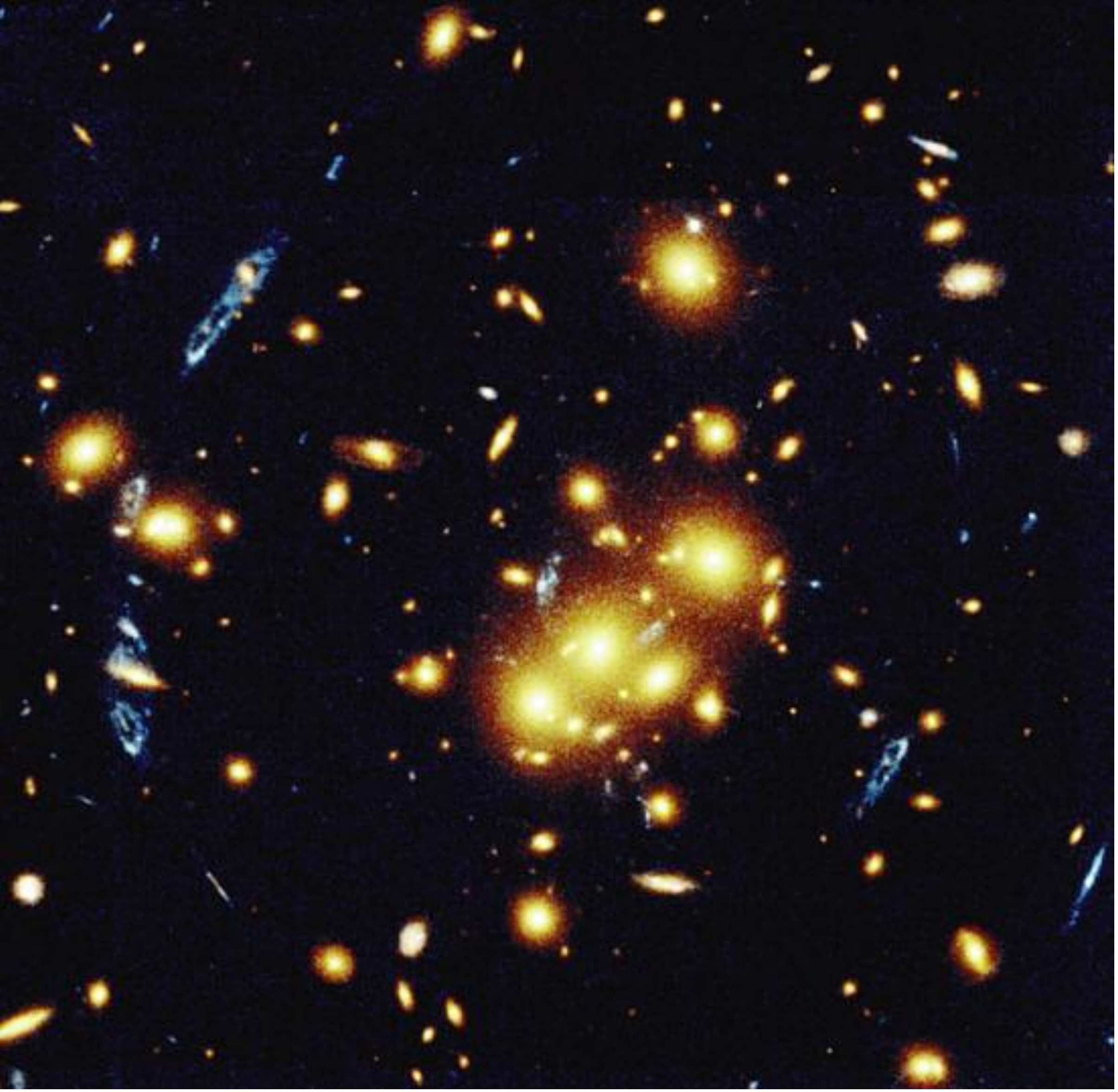
Can also look for clusters using the Sunyaev-Zeldovich effect(s)

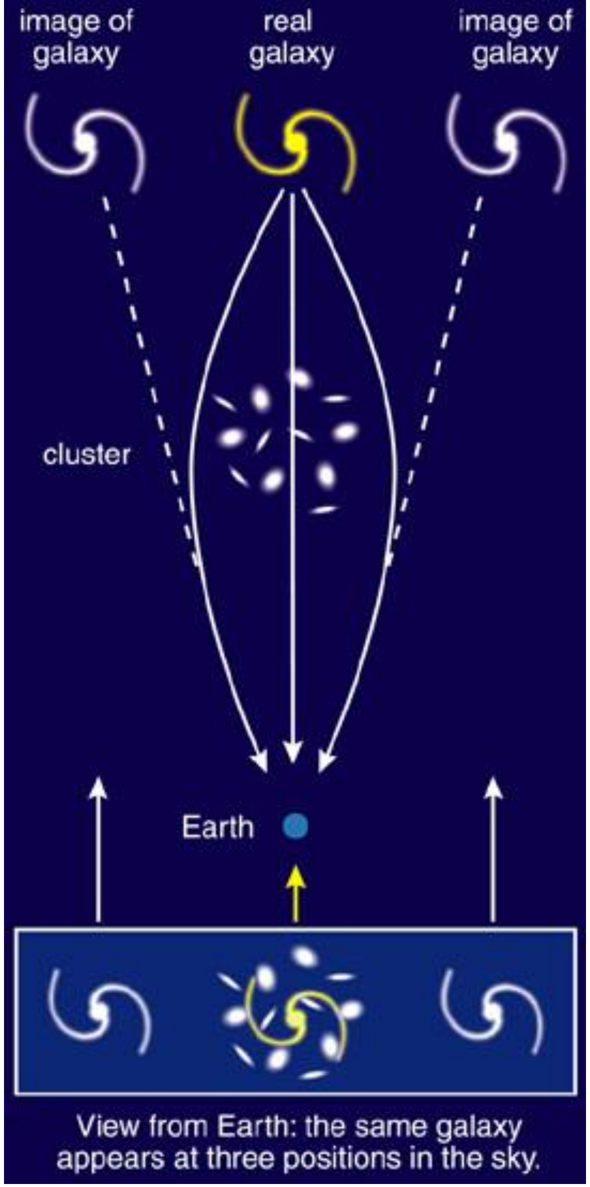




- Unique spectral signature: decrease in the CMB intensity at frequencies below ~218 GHz, increase at higher frequencies.

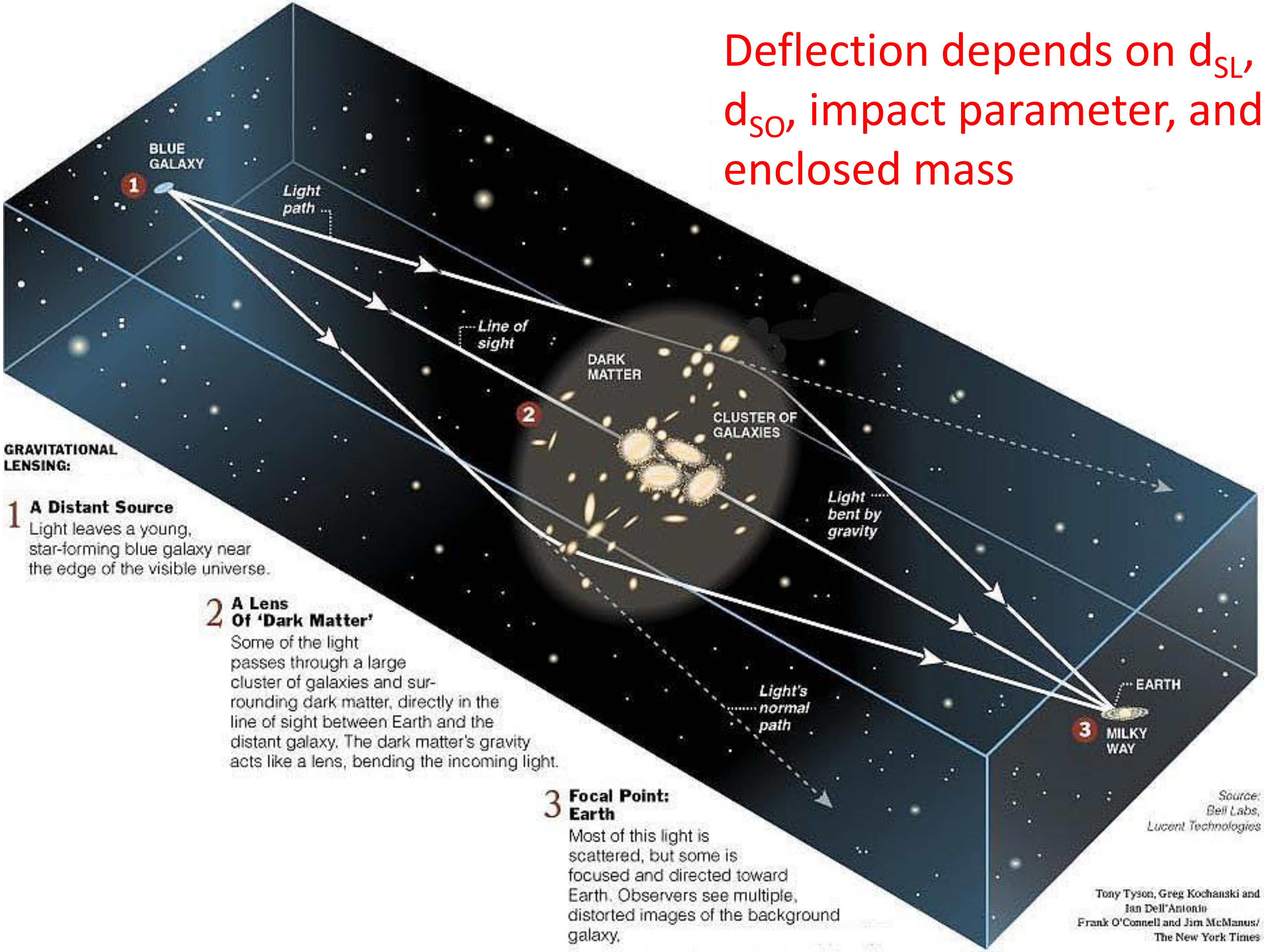




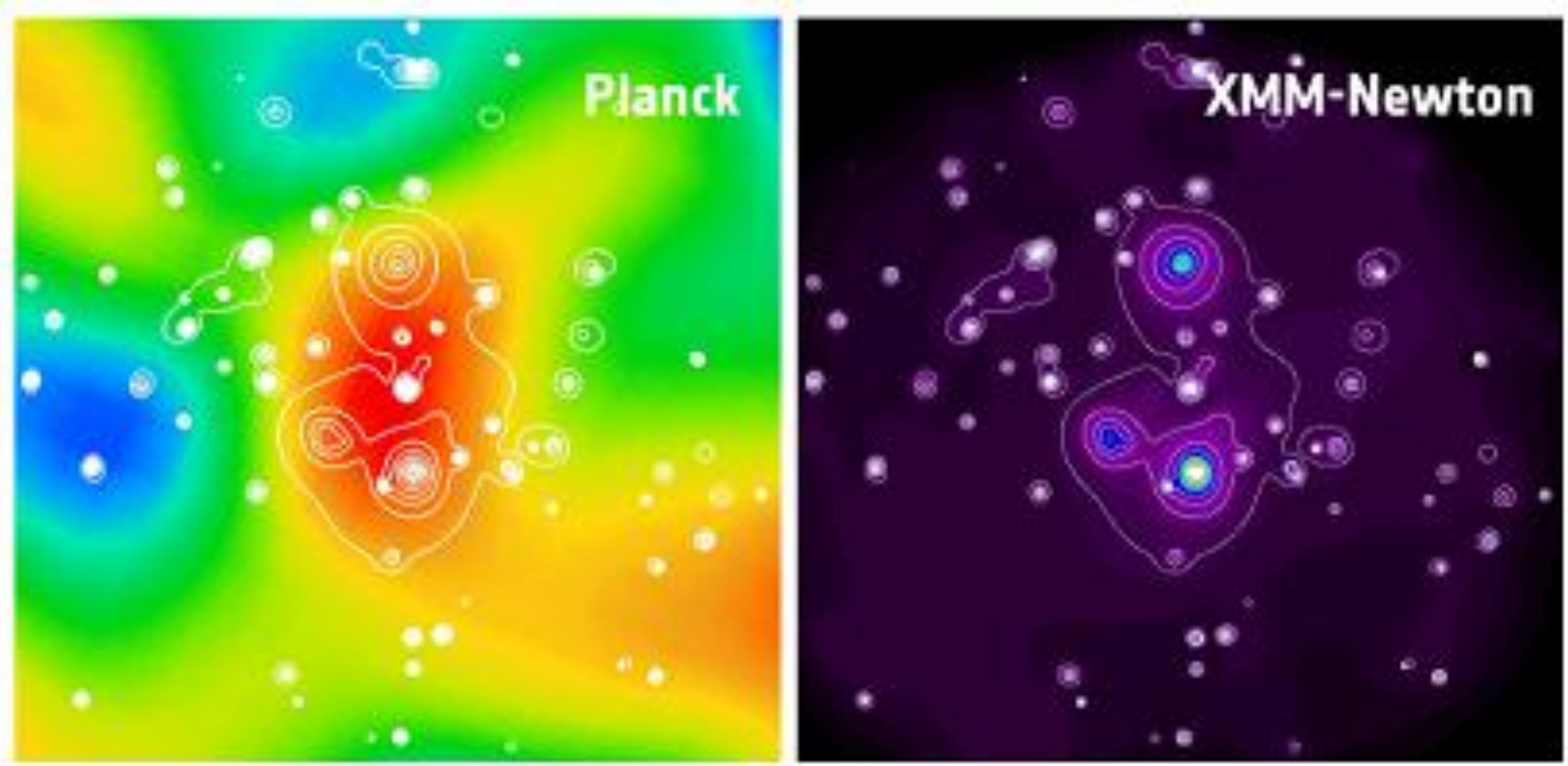


Gravitational lensing, the bending of light rays by gravity, also provides estimate of a cluster's mass

Deflection depends on d_{SL}, d_{SO}, impact parameter, and enclosed mass

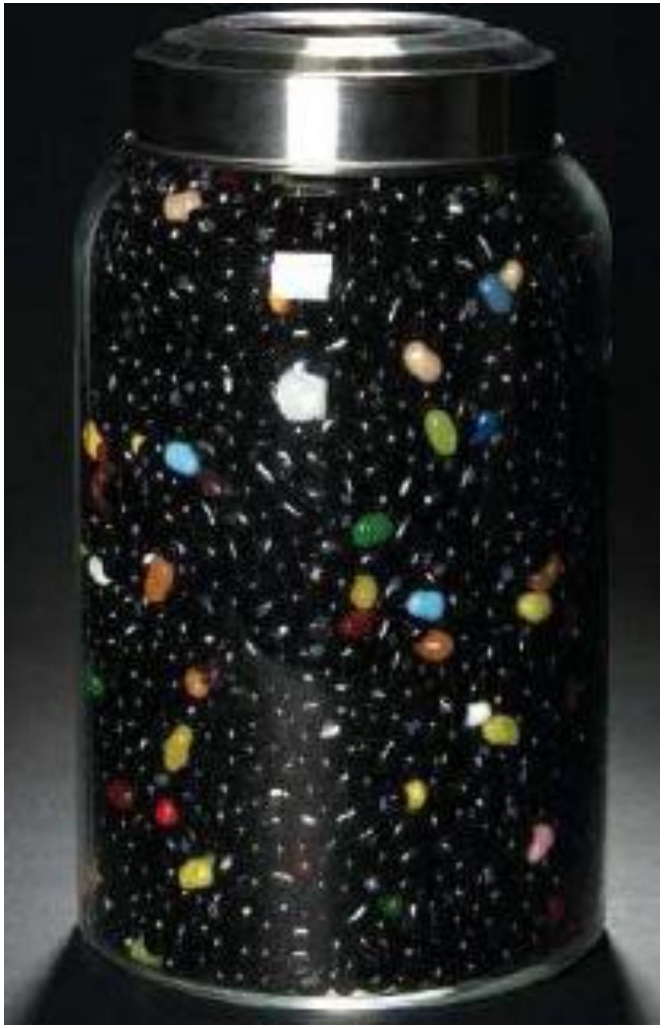


Crudely speaking: Lensing→Mass, SZ→pressure, Xray→Temperature

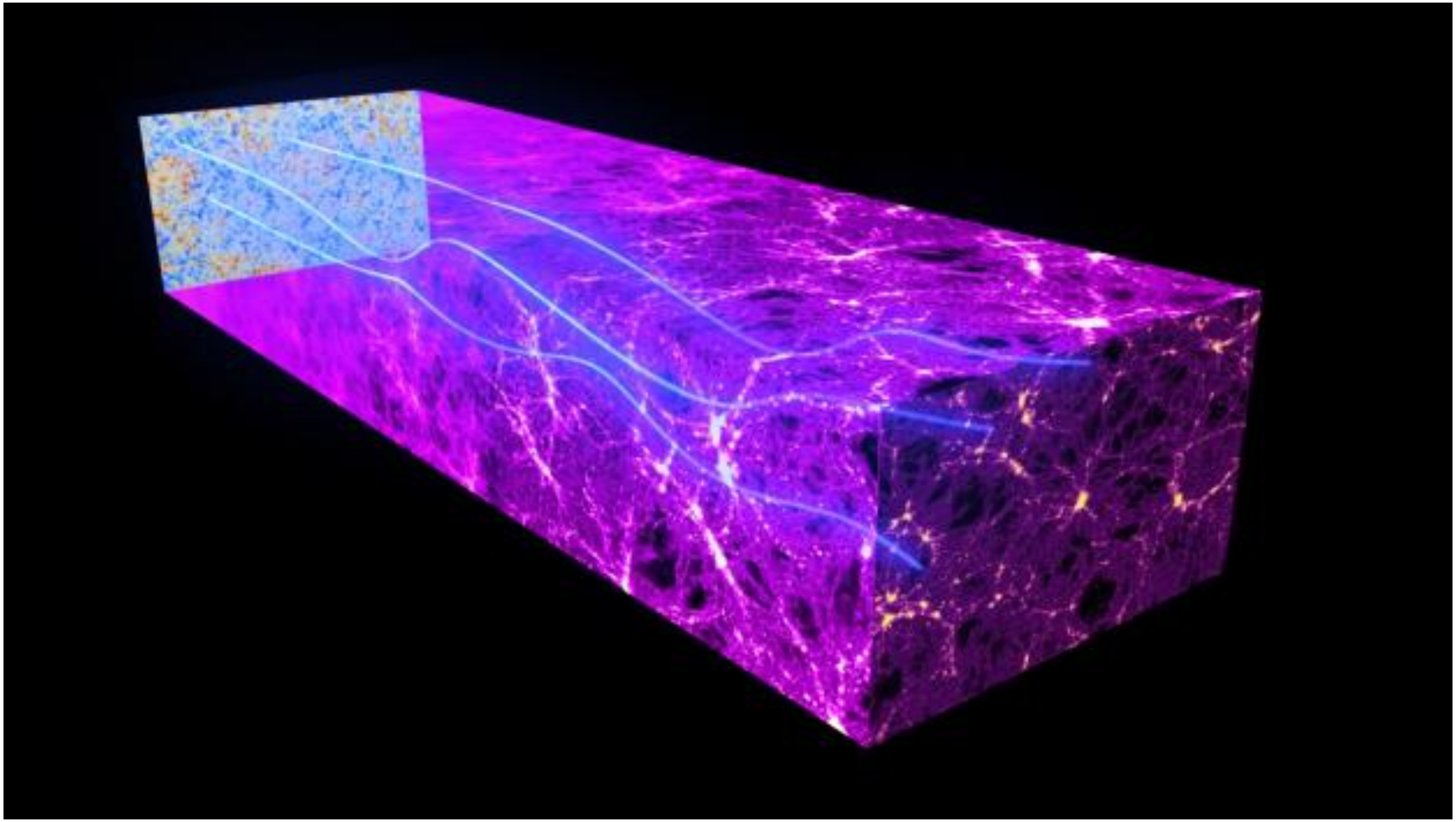


When combined with hydrostatic equilibrium all yield consistent mass estimates

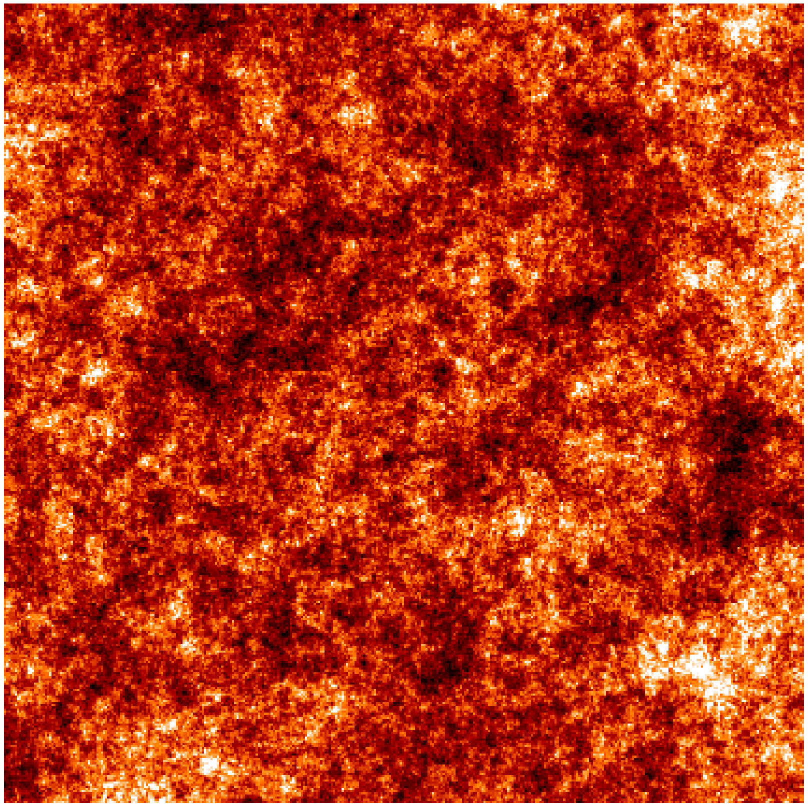
95% of the Universe is dark



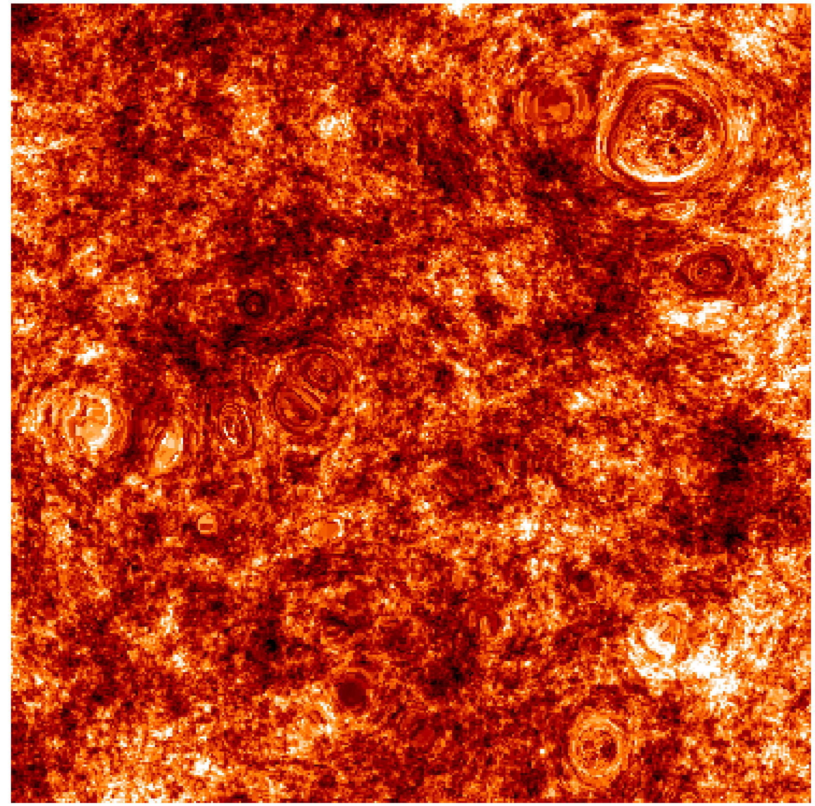
Gravitational lensing



Lensing of the CMB

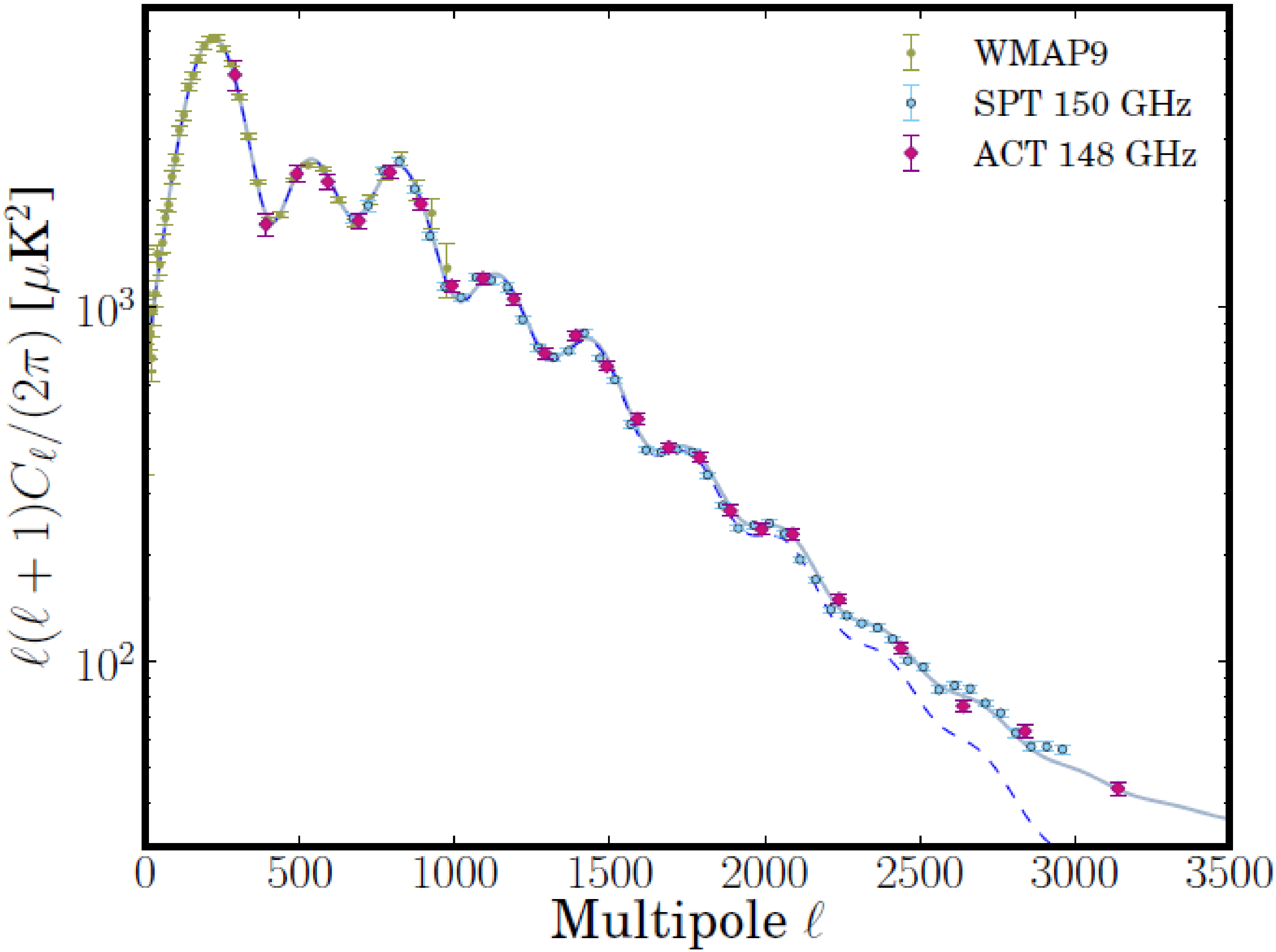


Primordial



Lensed

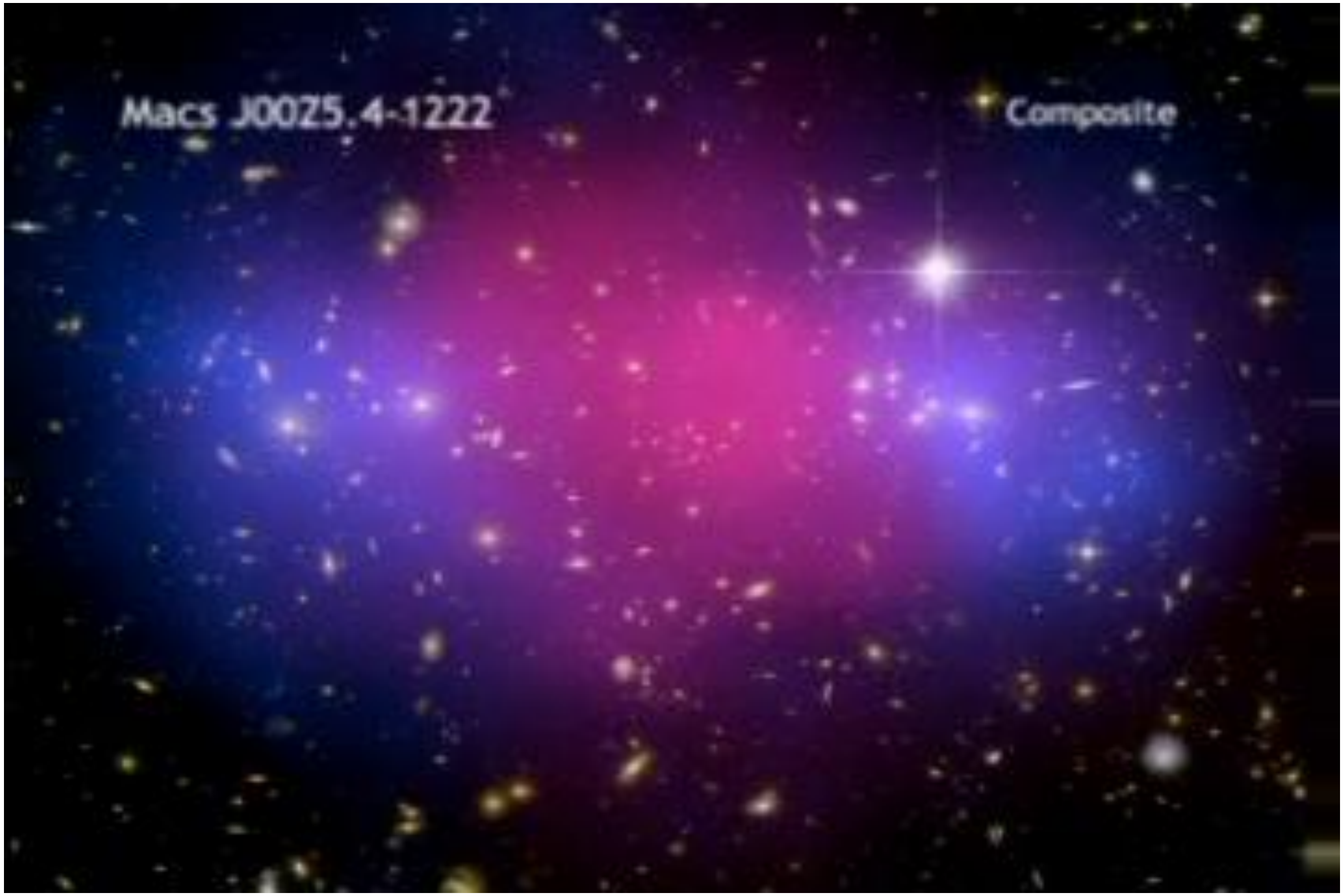
Experiments have just started measuring this effect



WMAP9
SPT 150 GHz
ACT 148 GHz
10^3
10^2
$\ell(\ell+1)C_\ell/(2\pi)$ [μK^2]
0
500
1000
1500
2000
2500
3000
3500
Multipole ℓ

‘Bullet’-like clusters:

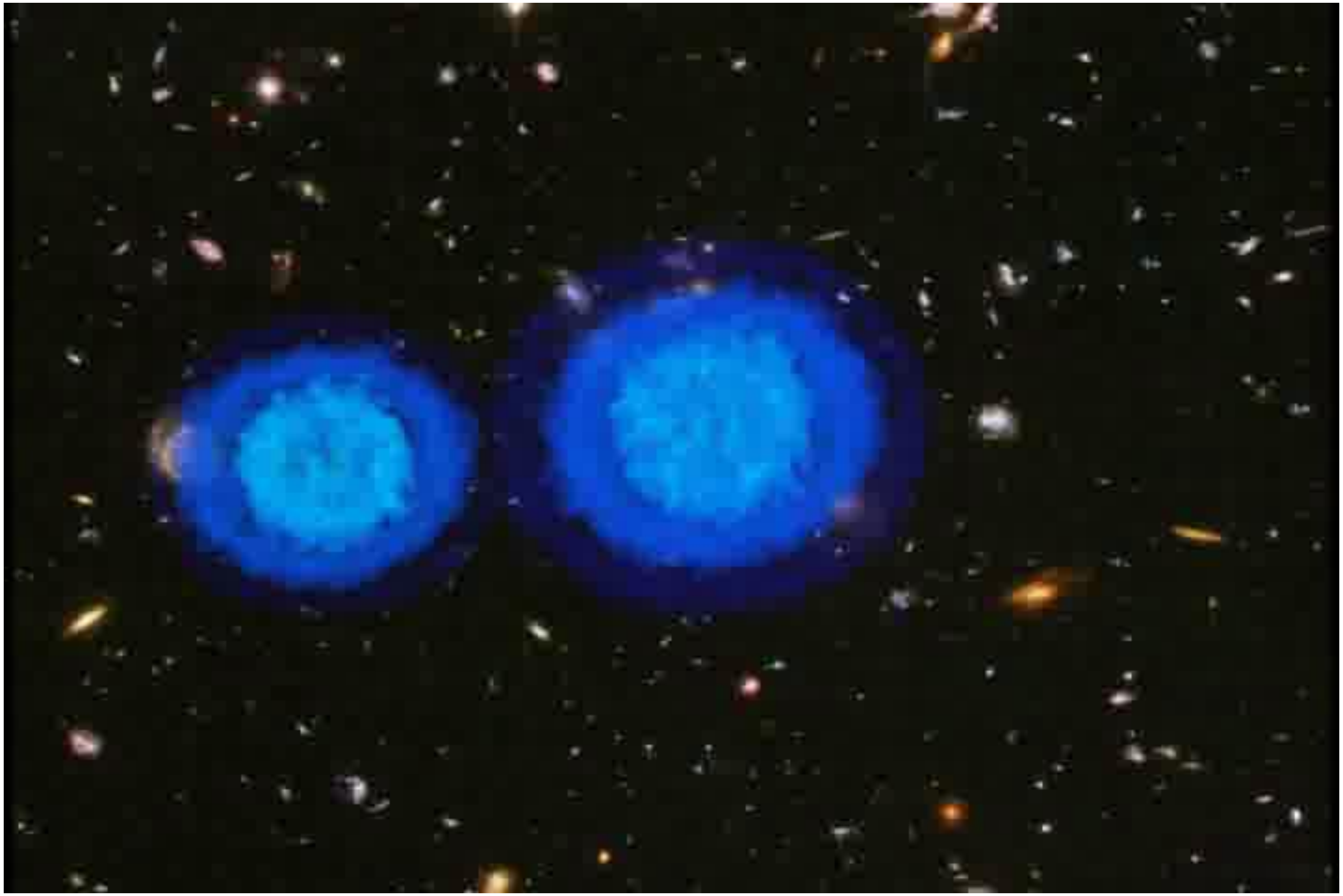
Dark matter ~ collisionless, $\sigma/m < 1\ cm^2/g$



Lensing mass

Xray photons

Simulation of collision

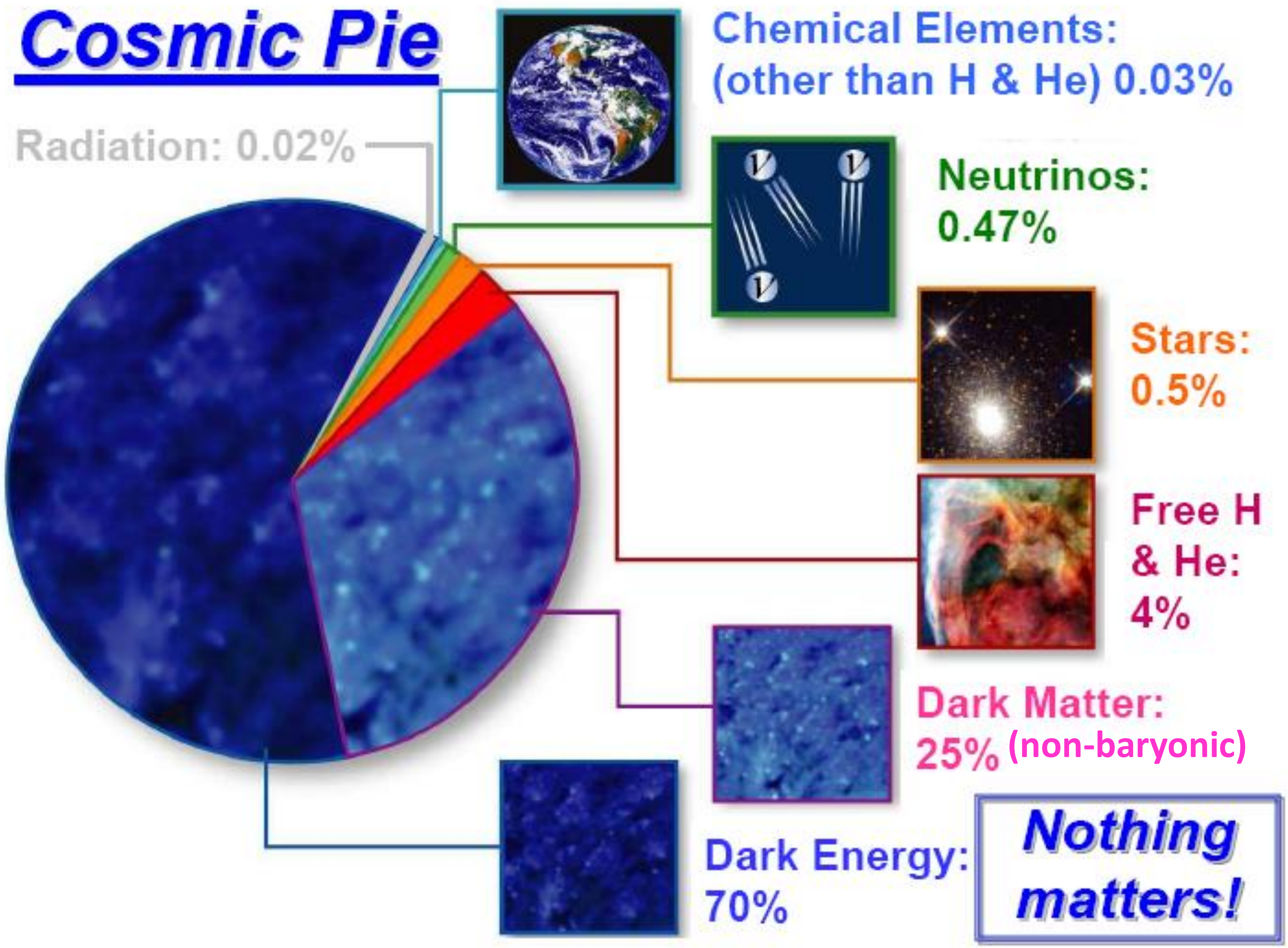


Baryonic gas (~20% of total mass) collisional;
Dark matter (most of the mass) <u>collisionless</u>

What's the matter?

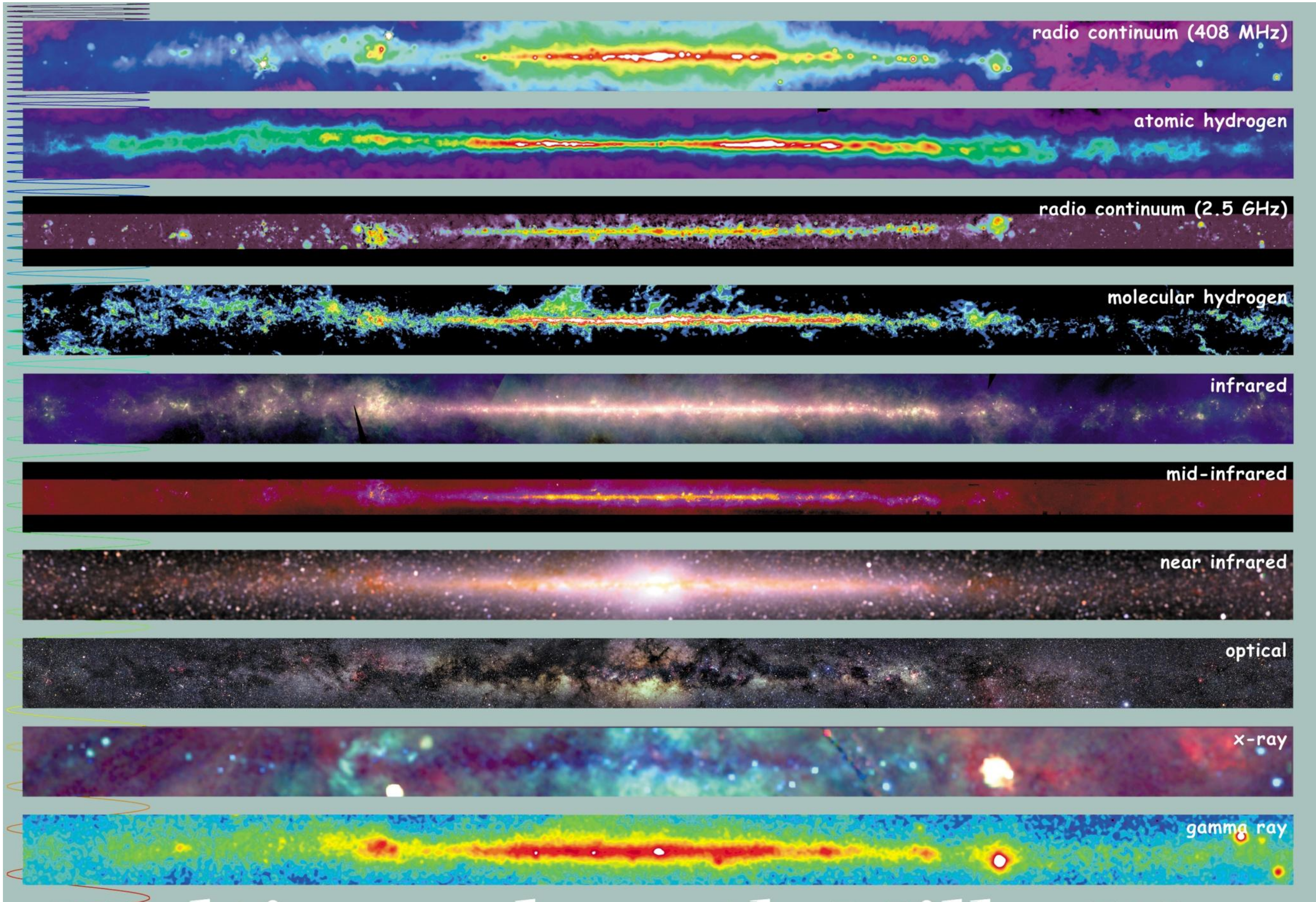
- WIMPs: Weakly Interacting Massive Particles
- MACHOs: Massive Compact Halo Objects
- RAMBOs: Robust Agglomerations of Massive Baryonic Objects

- Your Name Here: If you pay attention to the other speakers!

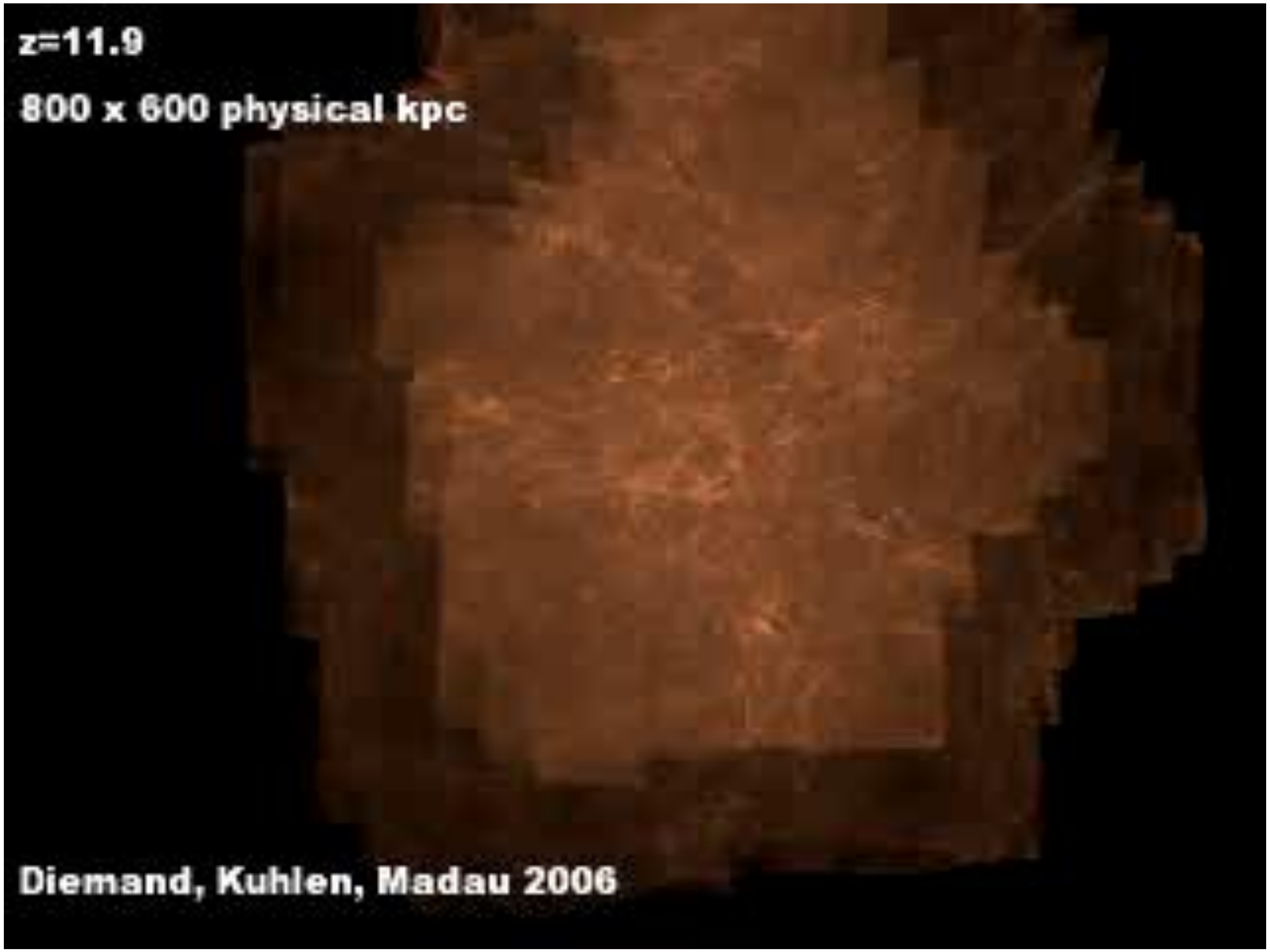


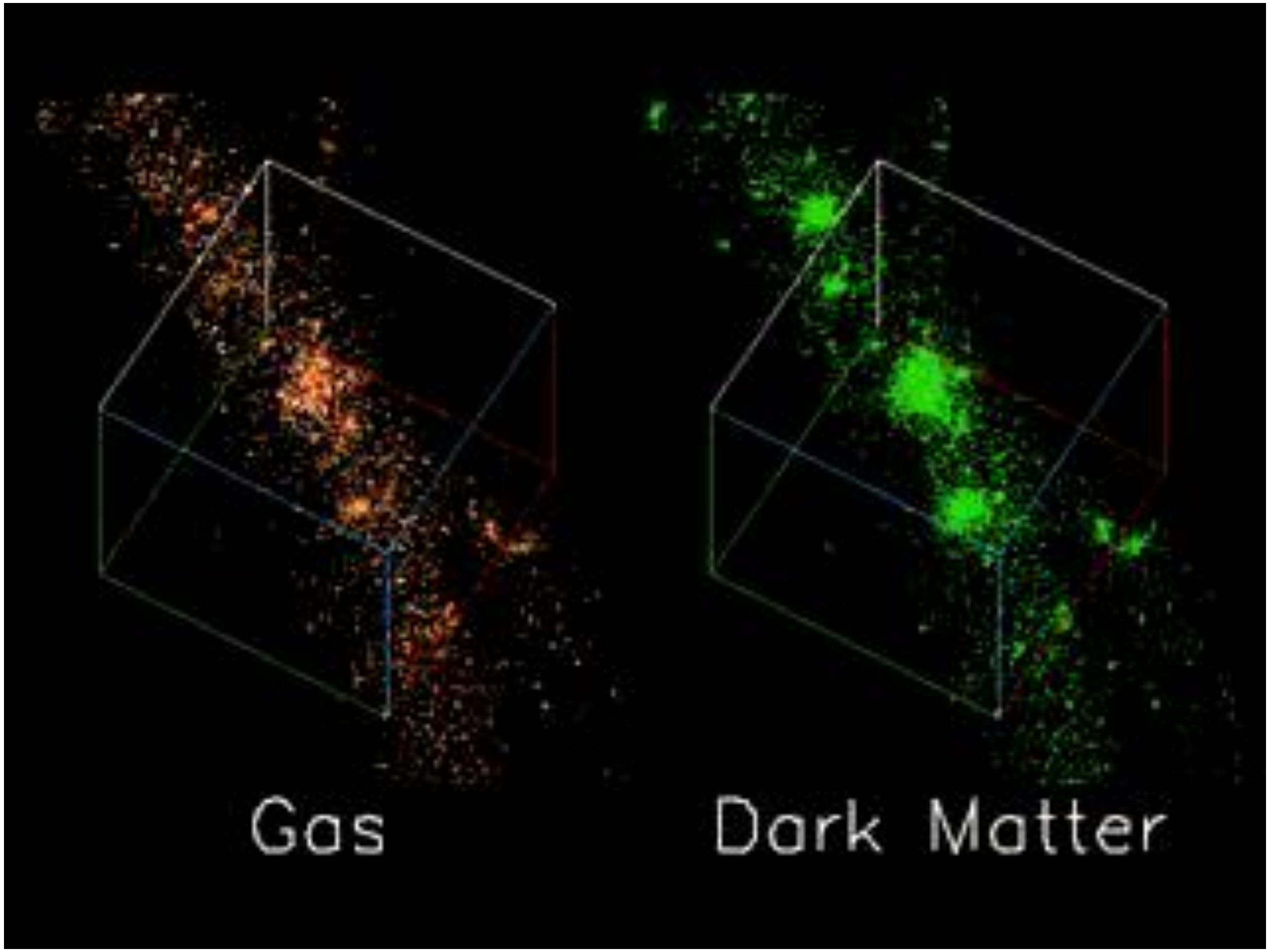
Cosmic Pie
Radiation: 0.02%
Chemical Elements:
(other than H & He) 0.03%
Neutrinos:
0.47%
Stars:
0.5%
Free H
& He:
4%
Dark Matter:
25% (non-baryonic)
Dark Energy:
70%
Nothing
matters!

Our galaxy in multiple wavelengths

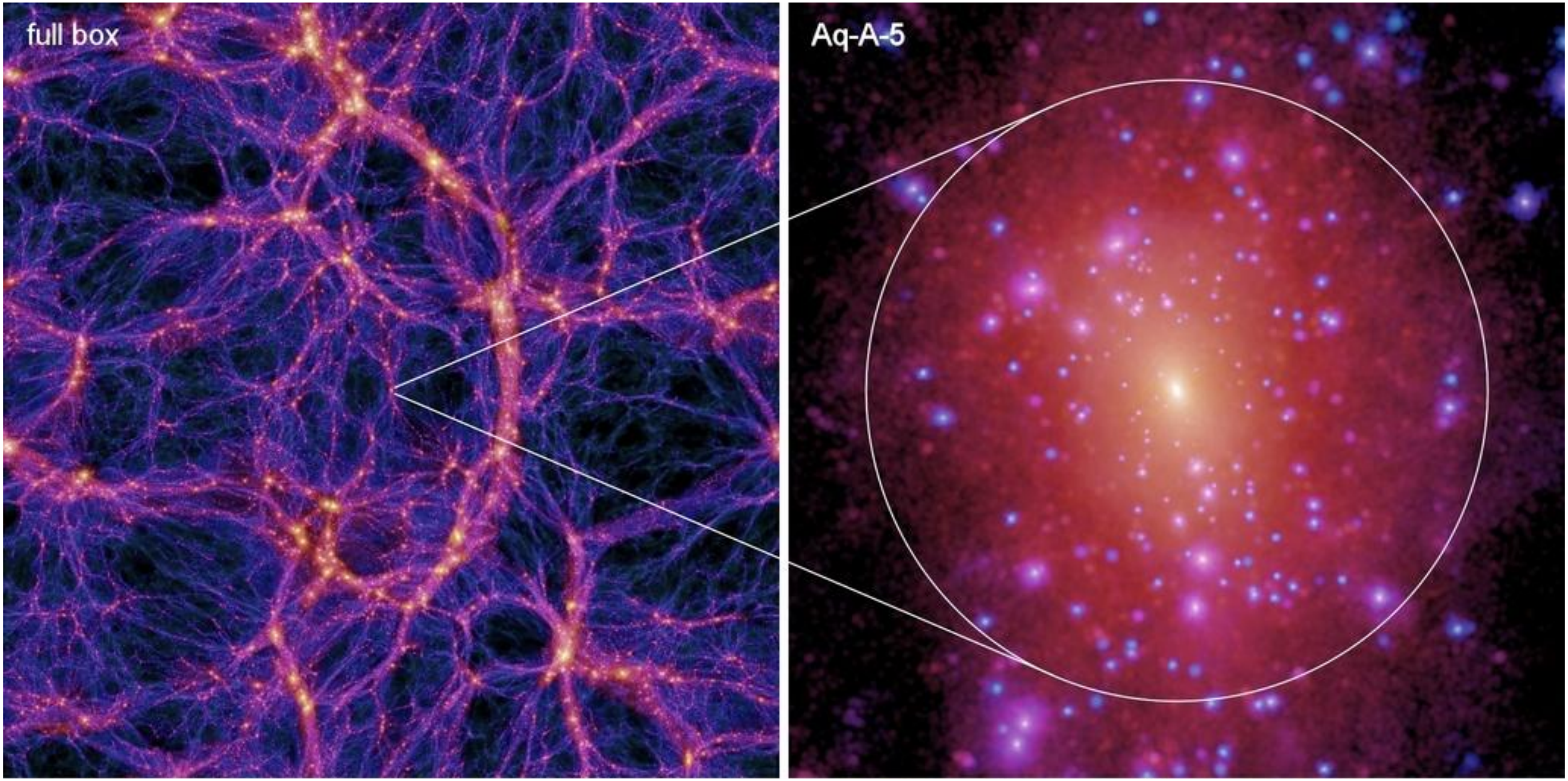


Formation of our galaxy

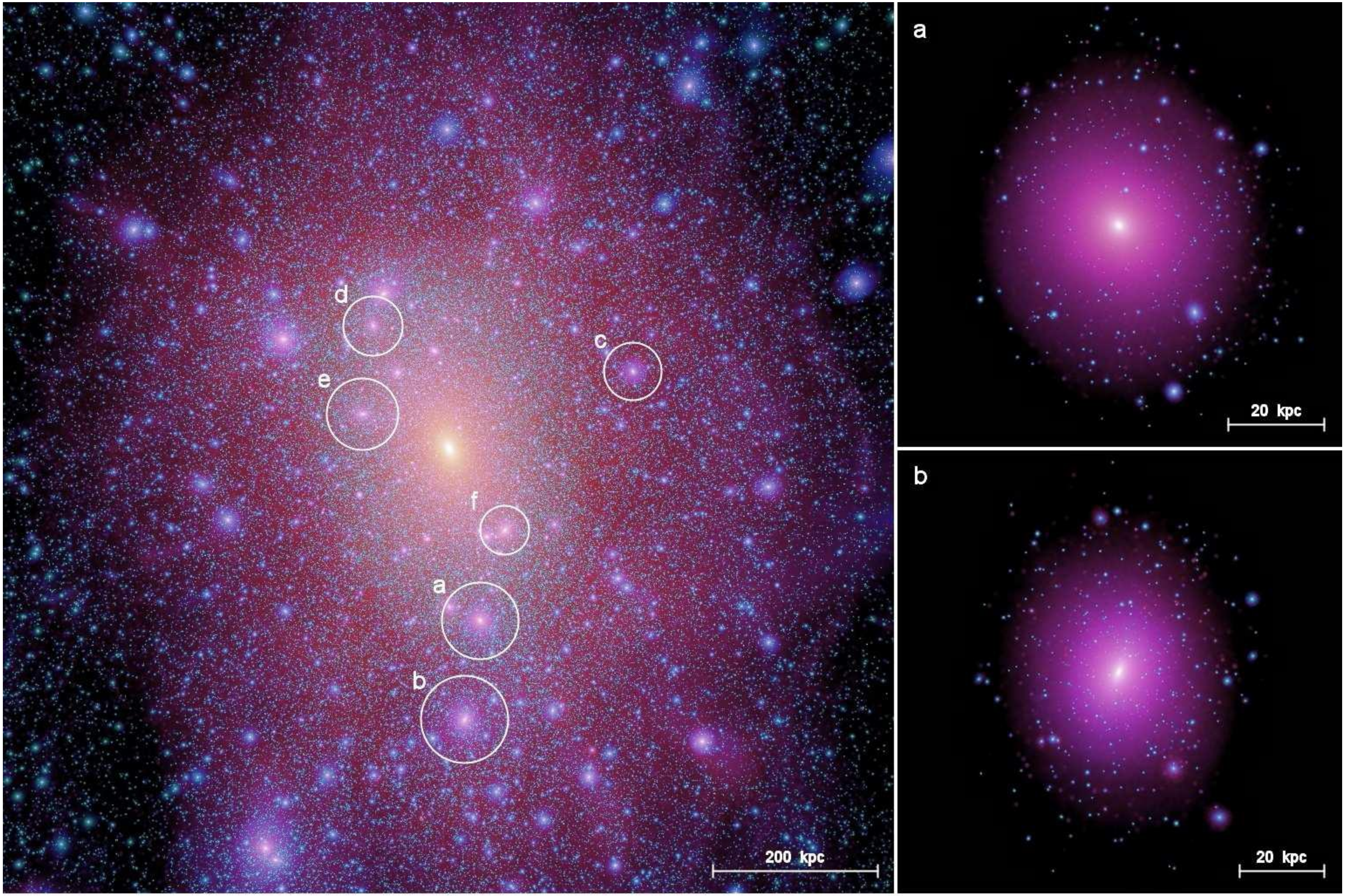



Gas
Dark Matter

Aquarius simulations



$m_{particle} \sim 10^4\ M_{sun}$ (Springel et al. 2008)

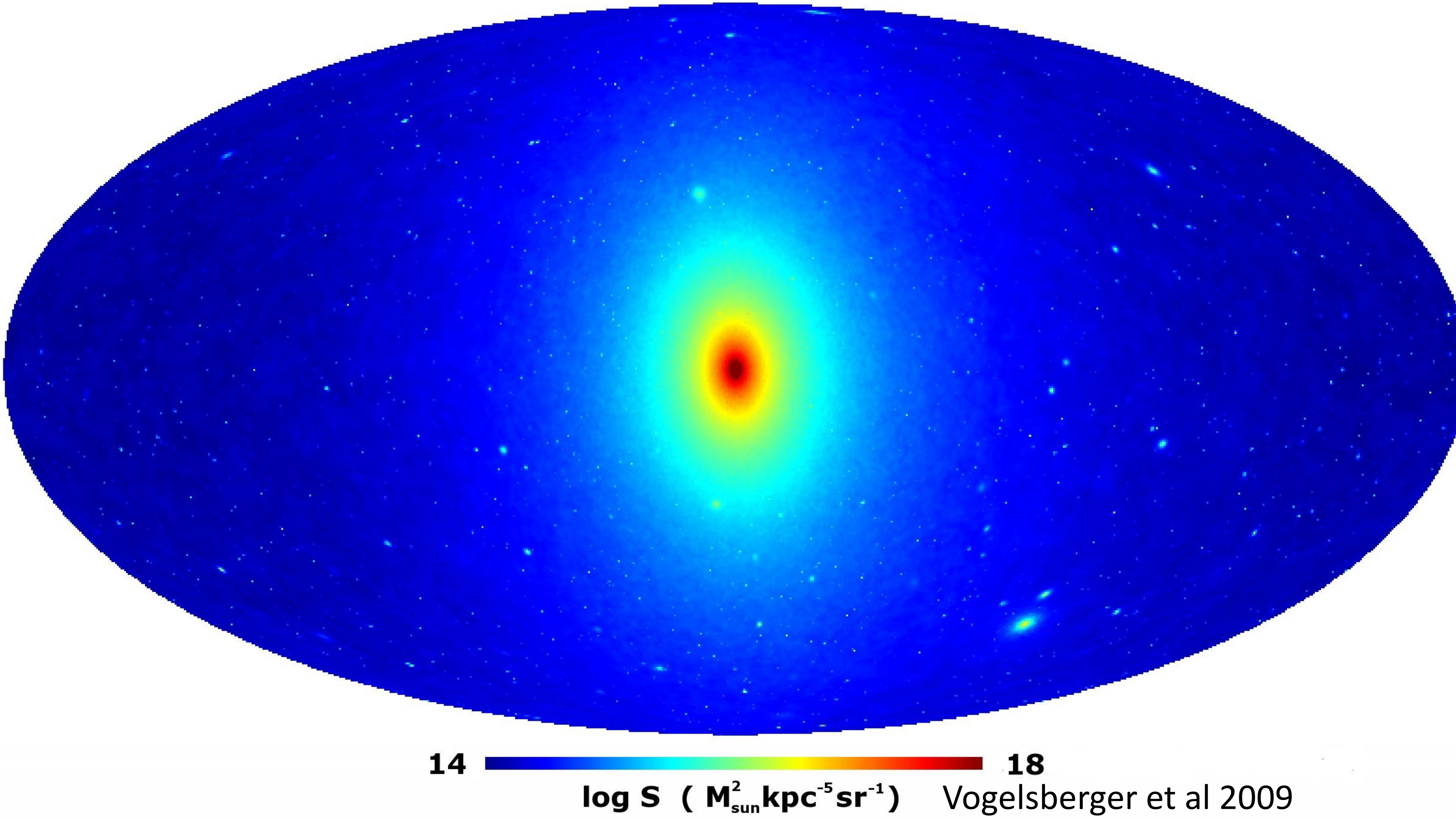


Aquarius simulations (Springel et al 2008)

Substructure

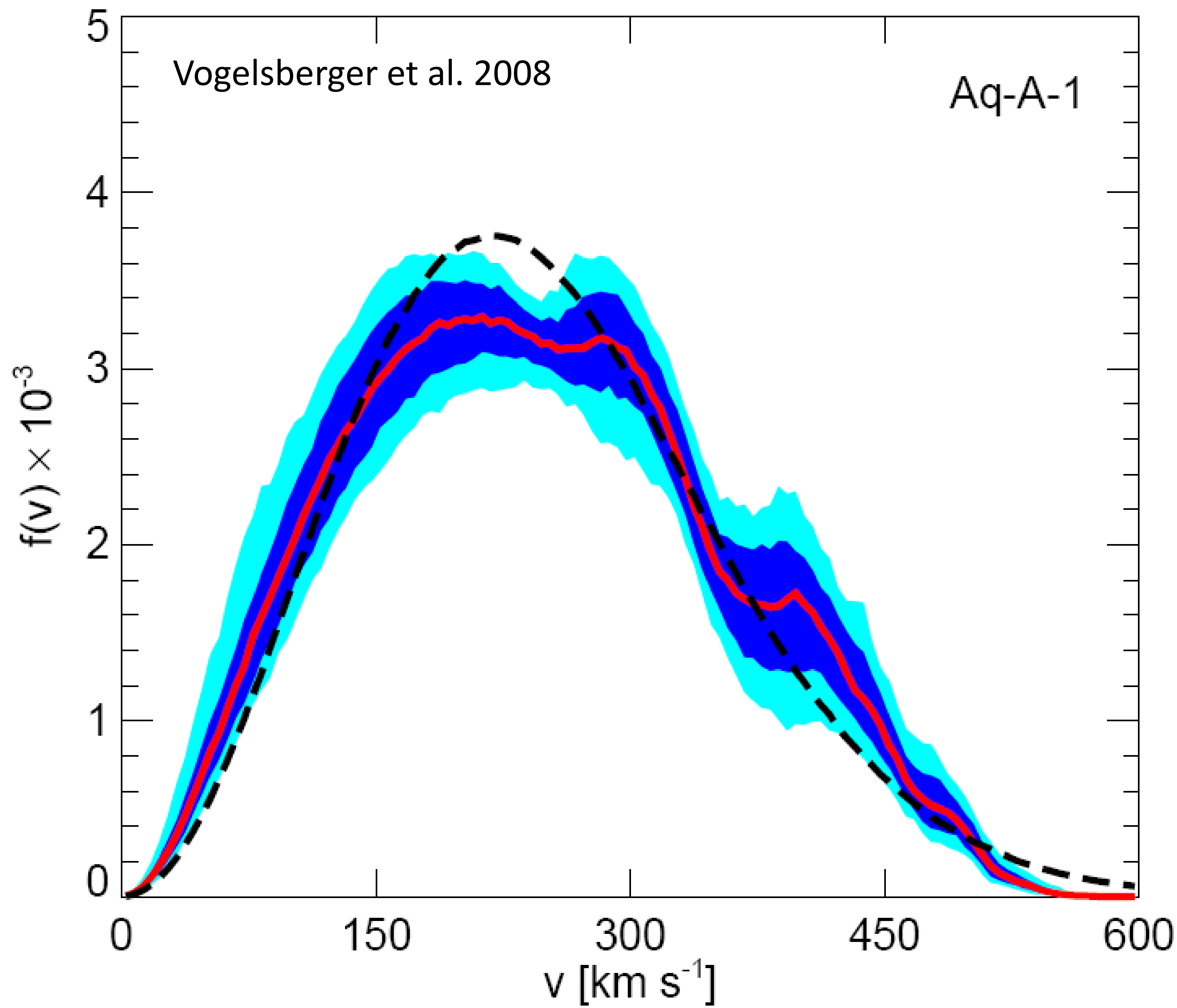
- accounts for less than 20% of the total mass
- fraction of mass in substructure smaller towards center

Expected flux distribution …



Vogelsberger et al 2009

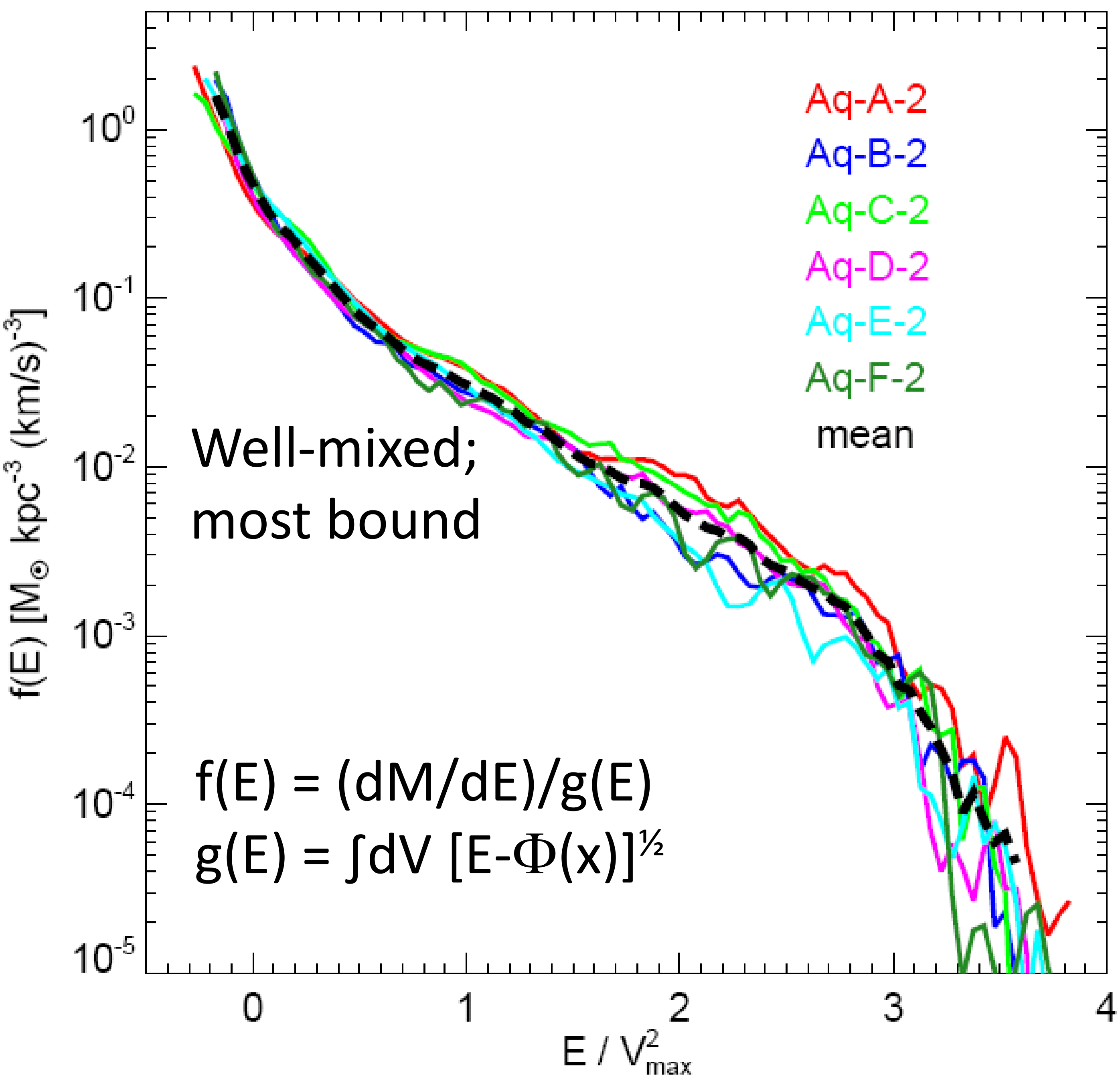
… dominated by smooth component



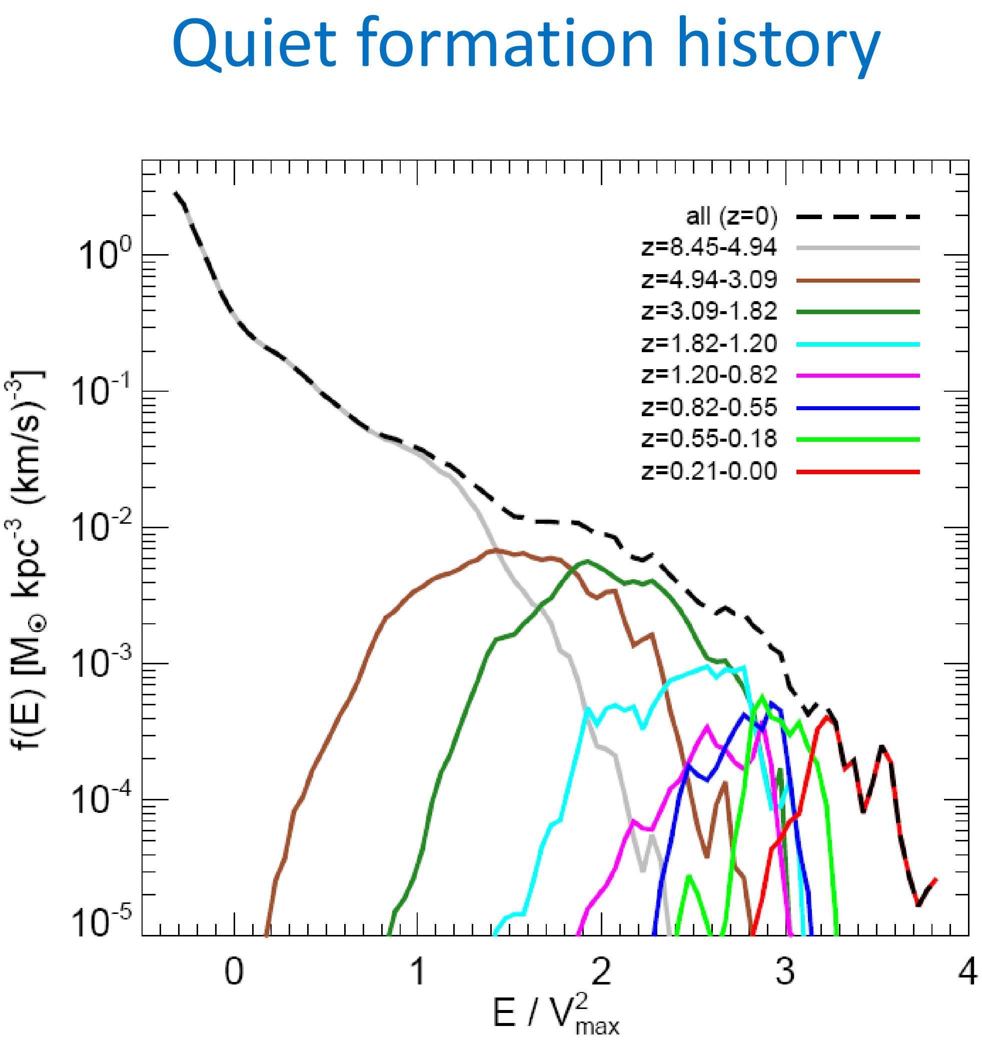
Same bumps in f(v) from different spatial positions

(bumps not due to individual subclumps)

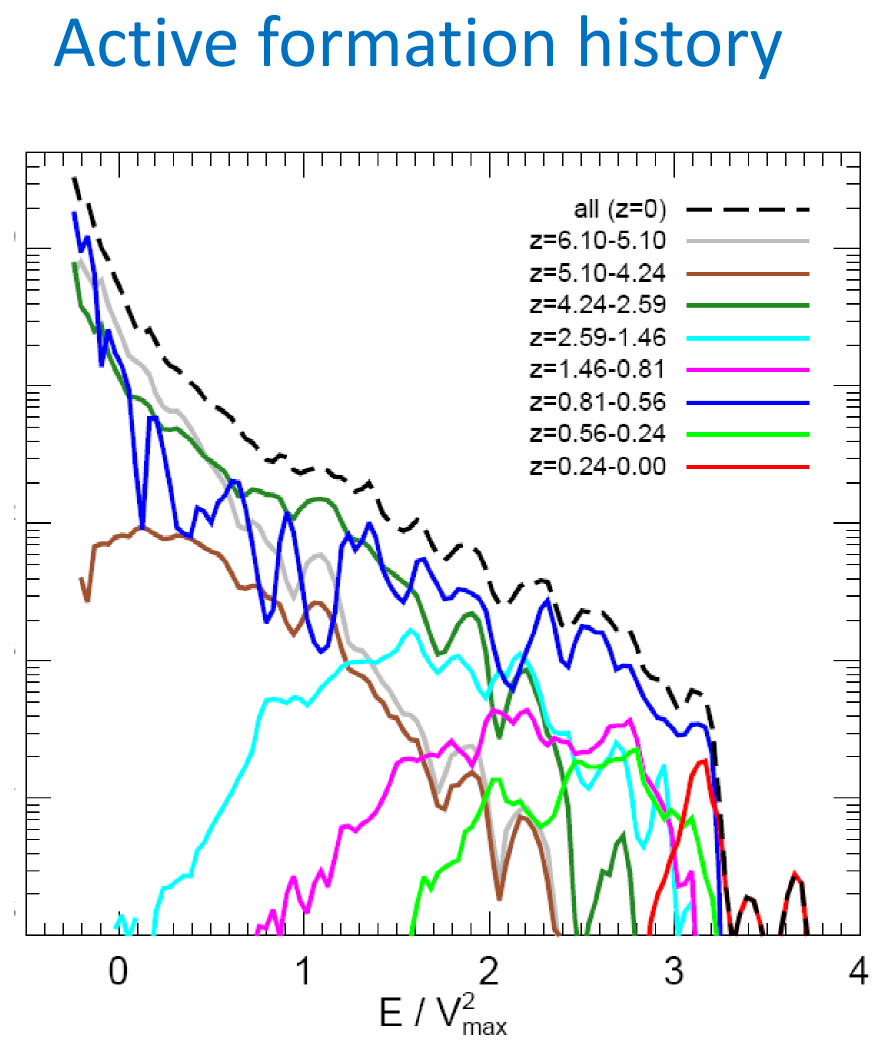
(average over many 2 kpc regions within 8 kpc of halo center)



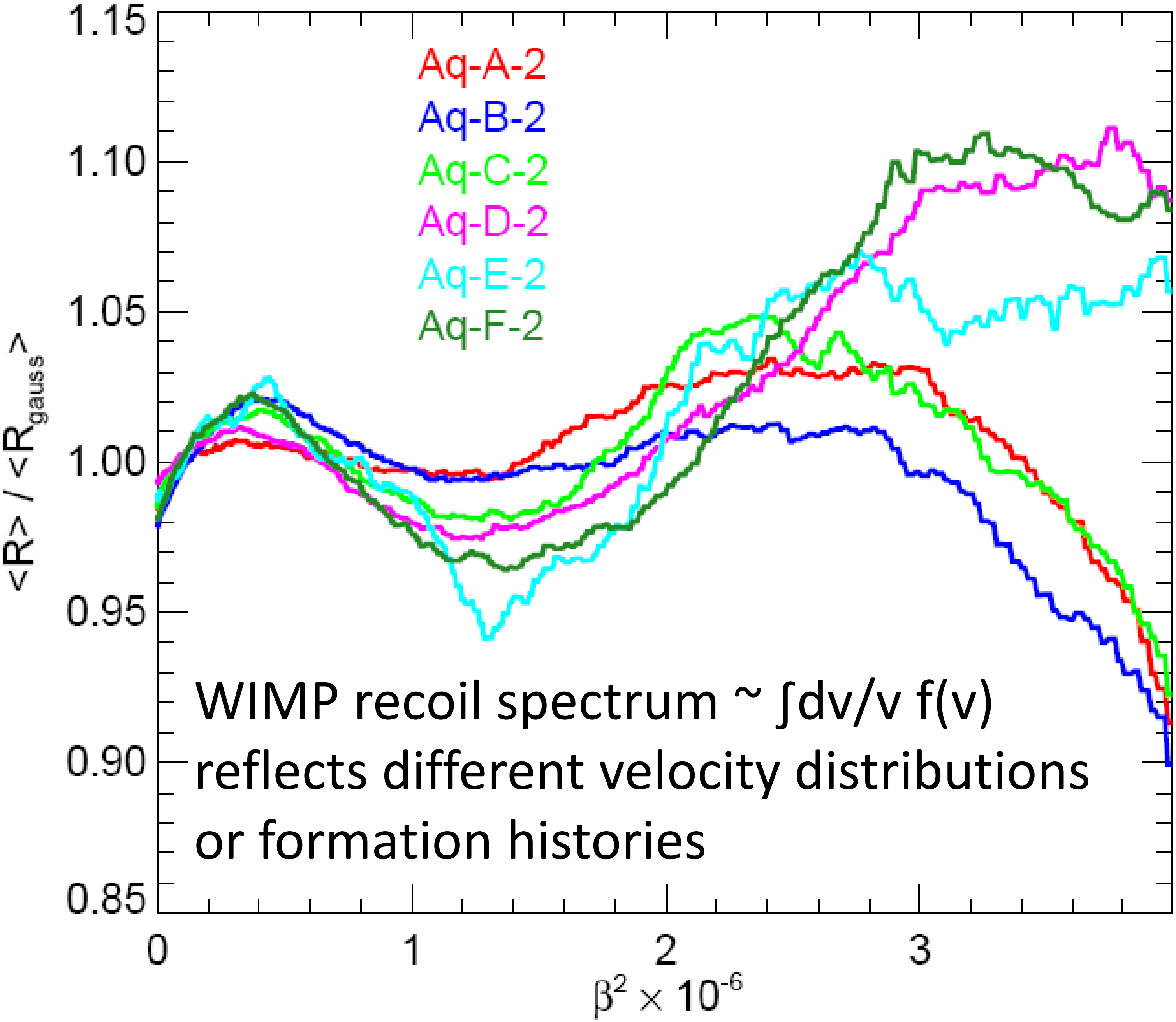
Aq-A-2
Aq-B-2
Aq-C-2
Aq-D-2
Aq-E-2
Aq-F-2
mean
Well-mixed;
most bound
f(E) = (dM/dE)/g(E)
g(E) = ∫dV [E-Φ(x)]½
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
1
2
3
4
$f(E)\ [M_\odot\ kpc^{-3}\ (km/s)^{-3}]$
$E\ /\ V_{max}^2$

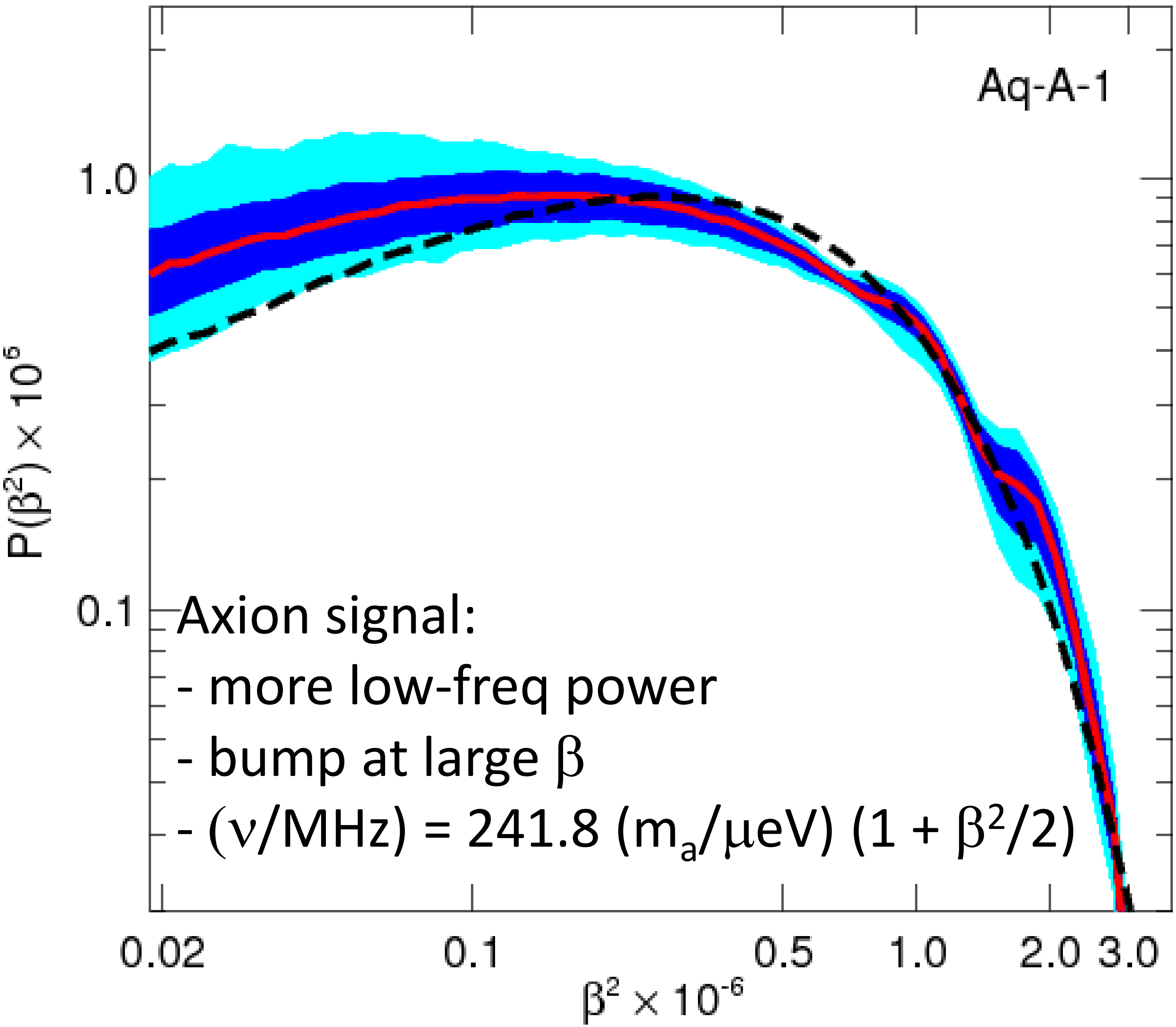


Quiet formation history
all (z=0)
z=8.45-4.94
z=4.94-3.09
z=3.09-1.82
z=1.82-1.20
z=1.20-0.82
z=0.82-0.55
z=0.55-0.18
z=0.21-0.00
f(E) [M⊙ kpc⁻³ (km/s)⁻³]
E / V²max



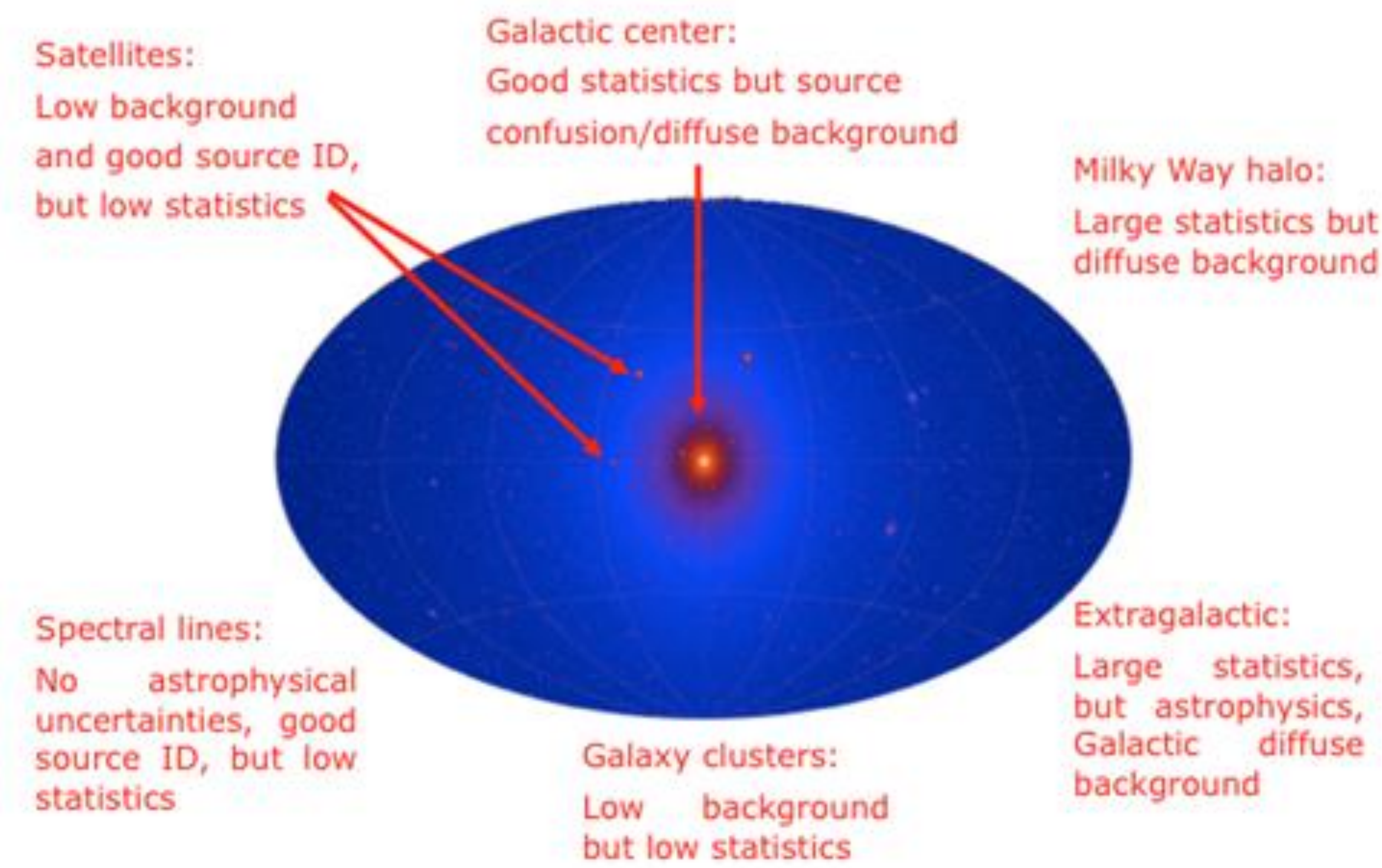
Active formation history
all (z=0)
z=6.10-5.10
z=5.10-4.24
z=4.24-2.59
z=2.59-1.46
z=1.46-0.81
z=0.81-0.56
z=0.56-0.24
z=0.24-0.00
E / V²max


Aq-A-2
Aq-B-2
Aq-C-2
Aq-D-2
Aq-E-2
Aq-F-2
WIMP recoil spectrum ~ ∫dv/v f(v)
reflects different velocity distributions
or formation histories
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0
1
2
3
$\langle R \rangle / \langle R_{gauss} \rangle$
$\beta^2 \times 10^{-6}$


Aq-A-1
1.0
0.1
$P(\beta^2) \times 10^6$
0.02
0.1
0.5
1.0
2.0
3.0
$\beta^2 \times 10^{-6}$
Axion signal:
- more low-freq power
- bump at large β
- $(\nu/\mathrm{MHz}) = 241.8\ (m_a/\mu\mathrm{eV})\ (1 + \beta^2/2)$

Conclusions

- Dark matter mass, velocity distributions rather smooth (no obvious streams)
- Significant deviations from Maxwellian (multivariate Gaussian) velocity distribution
- Formation history leaves imprint in phase-space energy distribution


Satellites:
Low background and good source ID, but low statistics
Galactic center:
Good statistics but source confusion/diffuse background
Milky Way halo:
Large statistics but diffuse background
Spectral lines:
No astrophysical uncertainties, good source ID, but low statistics
Galaxy clusters:
Low background but low statistics
Extragalactic:
Large statistics, but astrophysics, Galactic diffuse background

Dark Matter in Large Scale Structure