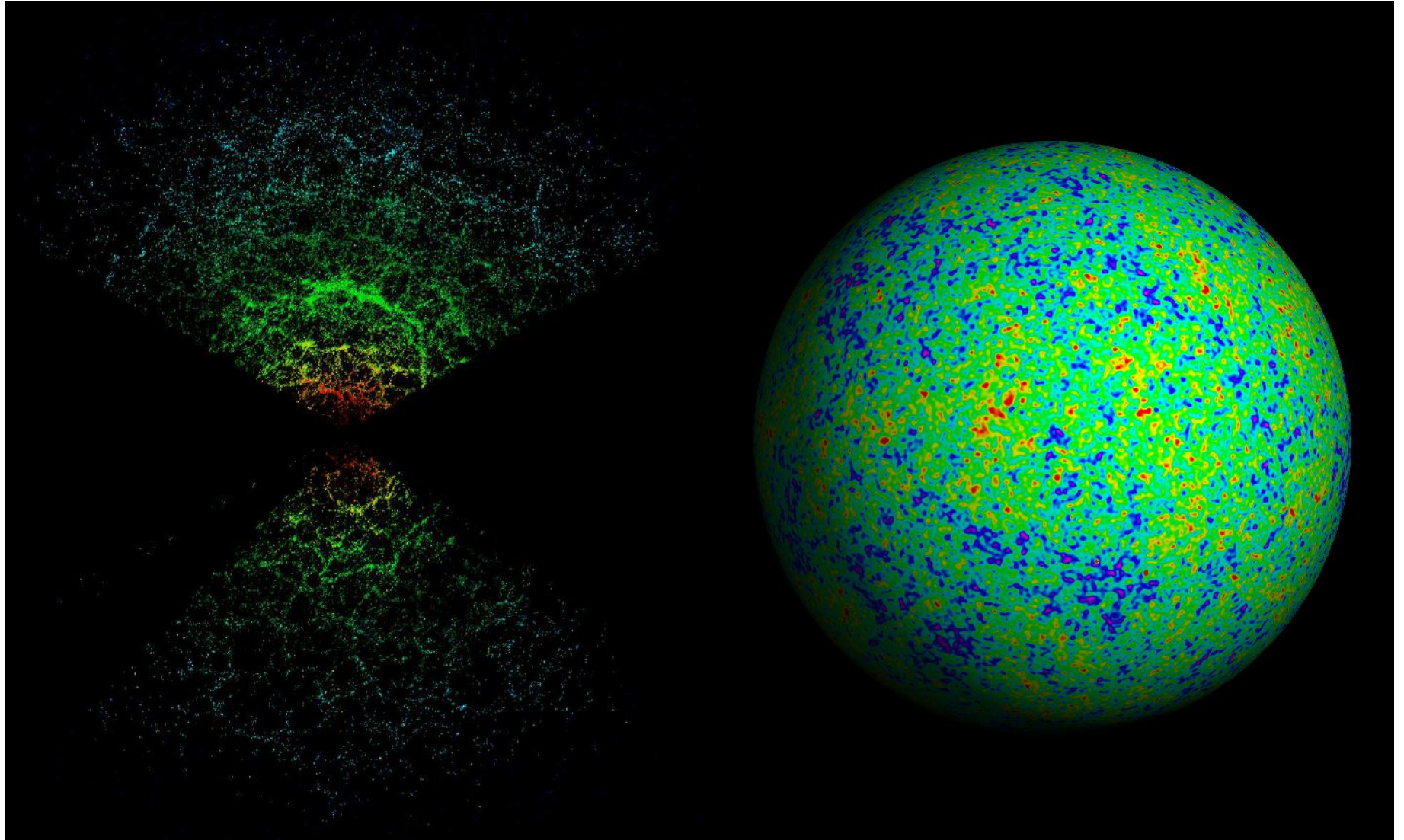
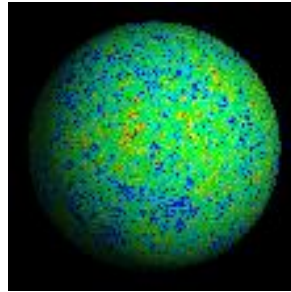


The dark side of our universe

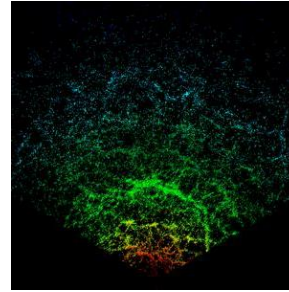


Max Tegmark, MIT

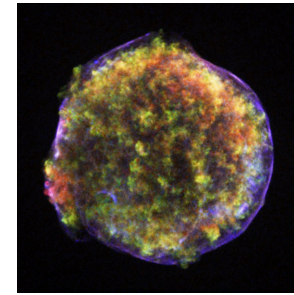
ga



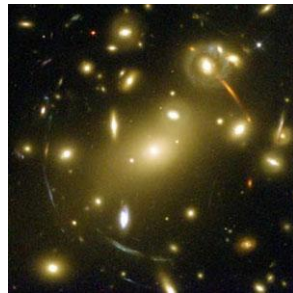
Microwave background



Galaxy surveys

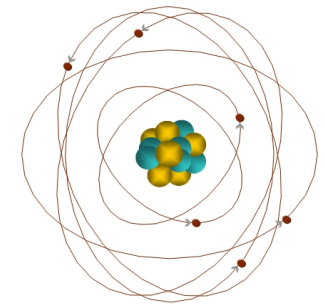


Supernovae Ia

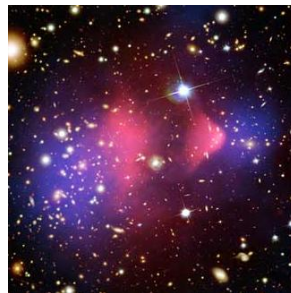


Gravitational lensing

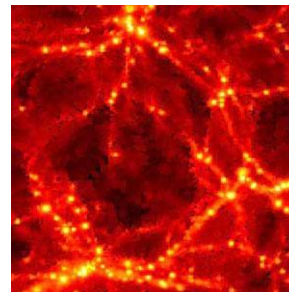
THE COSMIC SMÖRGÅSBORD



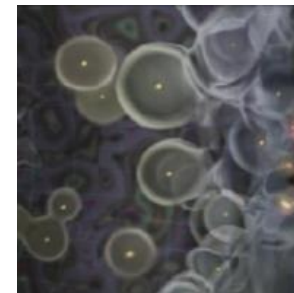
Big Bang nucleosynthesis



Galaxy clusters



Lyman α forest

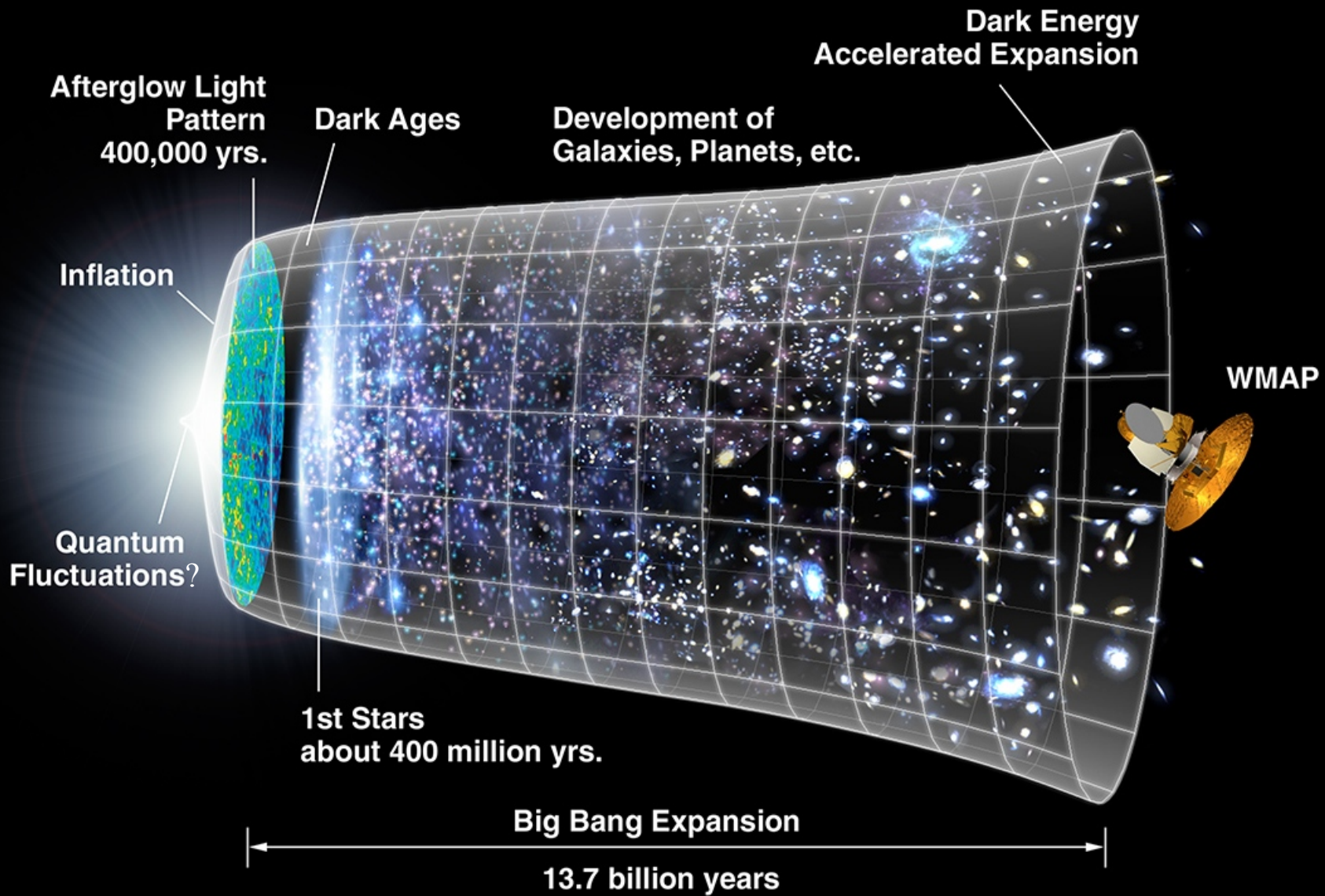


Neutral hydrogen tomography



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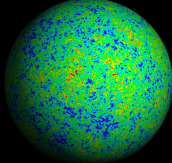
What have
we learned?



 **WMAP movie**

EVIDENCE?

Evidence for Big Bang:

- Darkness of night sky! (Olber)
- Distant objects look you 
- Observed galaxy recession (Hubble's law)
- Existence of CMB
- Correct predictions of big bang nucleosynthesis

*Plenty enough bang
for most people to
call "big" ...*

Evidence for *what*, exactly?

Our entire observable universe was once as hot as the core of the Sun, doubling its size in a under a second.

- *Not* evidence for a singularity

EVIDENCE:

Big Bang

Nucleosynthesis

happened

(correctly predicts the
abundance of light elements)

George Gamow
1904-1968
(Ukrainian)

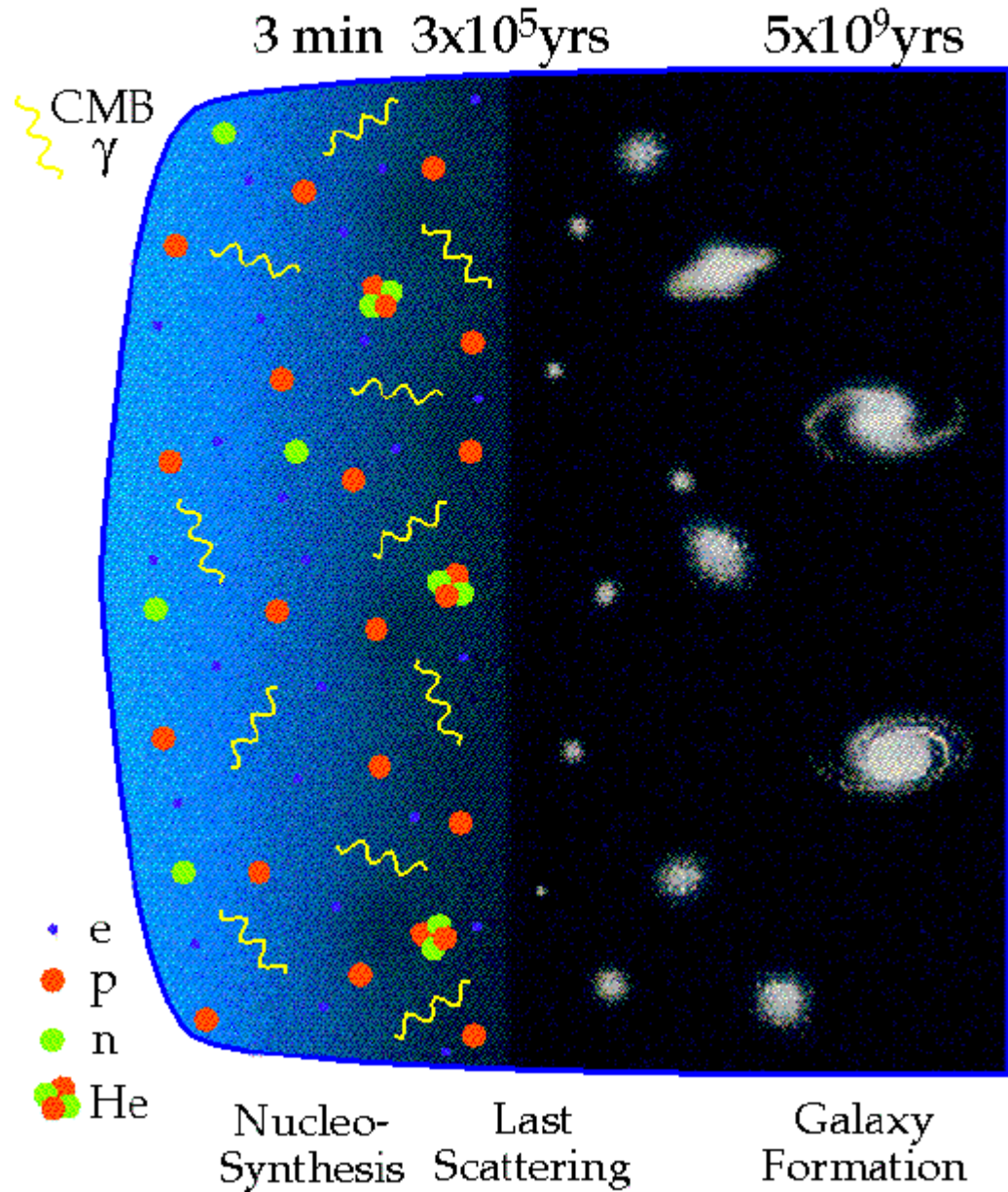


Evidence:

The Universe
was once hot
enough to be a
fusion reactor!

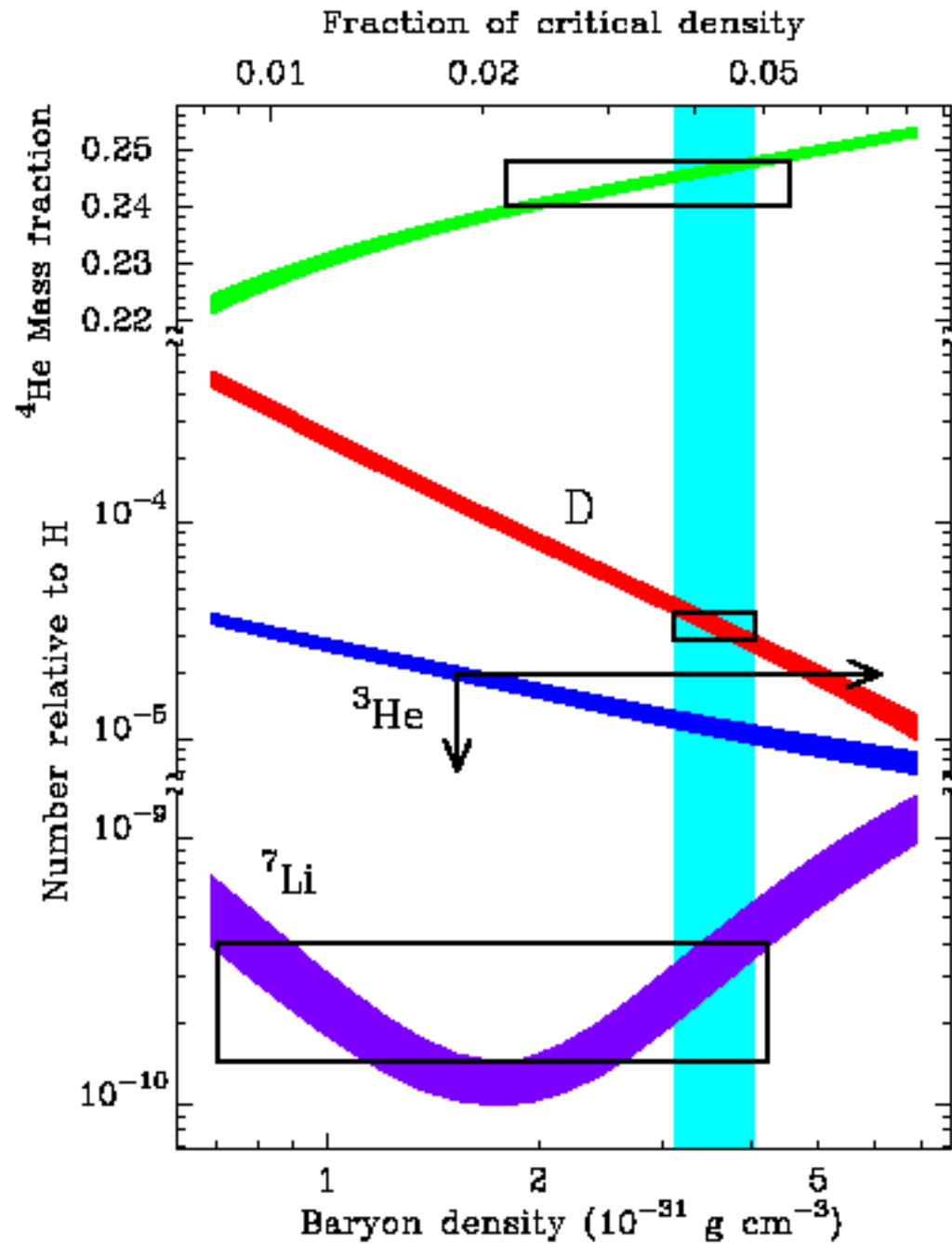
CMB

(Very) Brief History



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Tytler et al 2000, astro-ph/0001318



EVIDENCE:

The fine details of
cosmic clumpiness

$z = 1000$

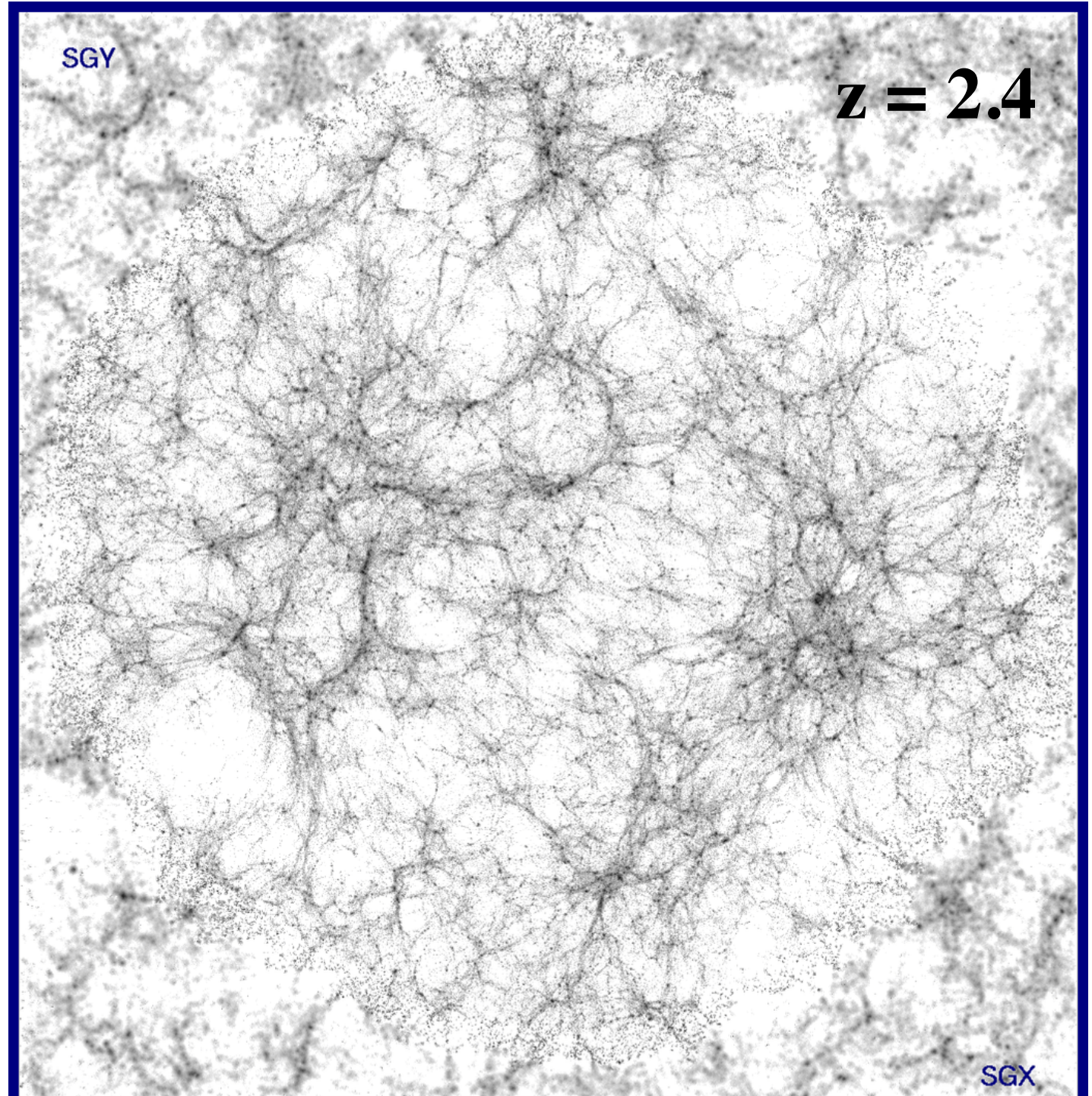


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Mathis, Lemson, Springel, Kauffmann, White & Dekel 2001

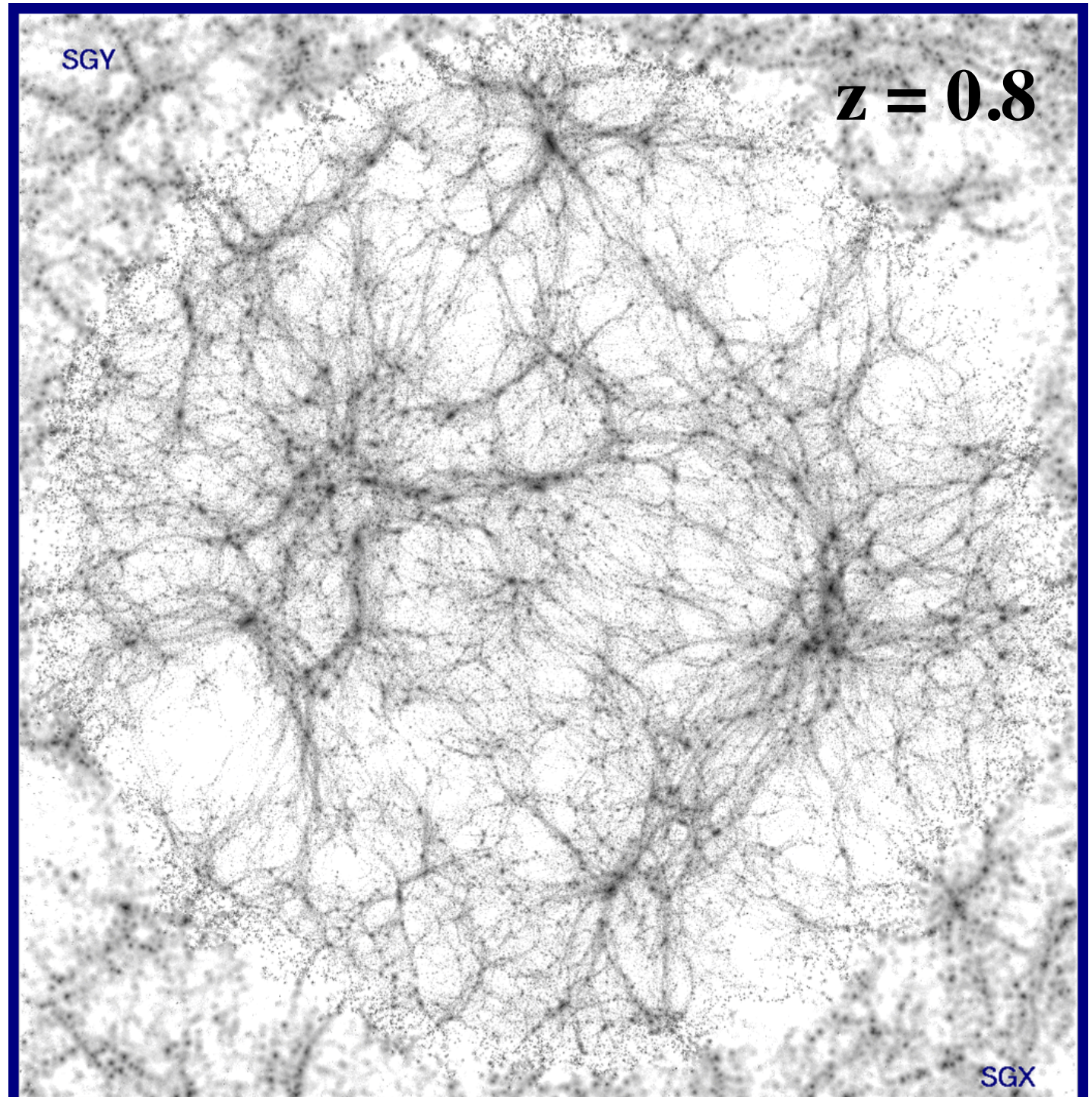


Λ CDM local universe at $z=2.4$ ($\Lambda=0.7$, $\Omega=0.3$, $h=0.7$)
Constrained within 8000 km/s by the IRAS 1.2 Jy survey

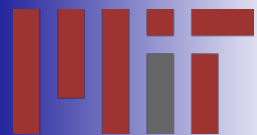


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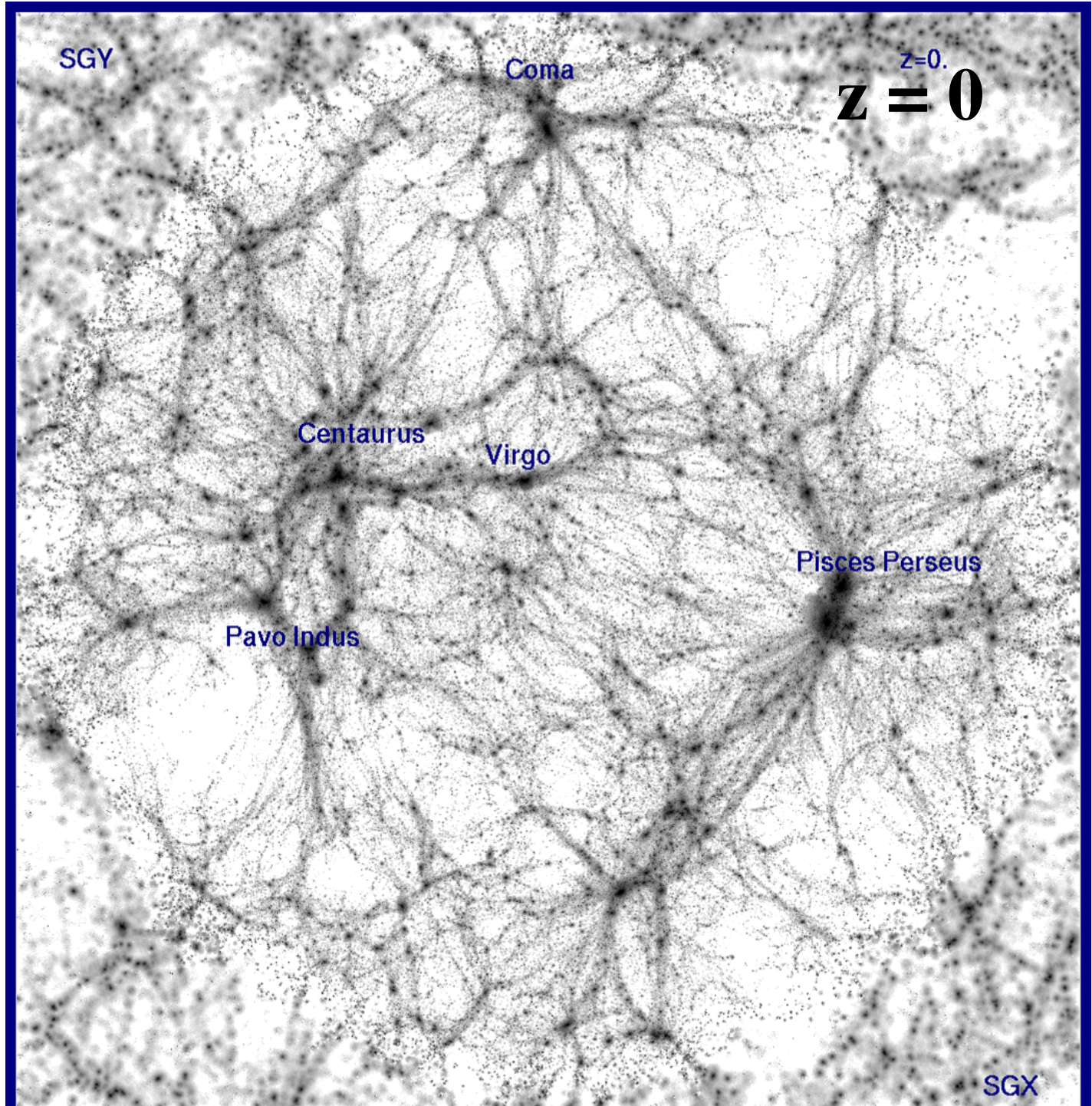
Mathis, Lemson, Springel, Kauffmann, White & Dekel 2001



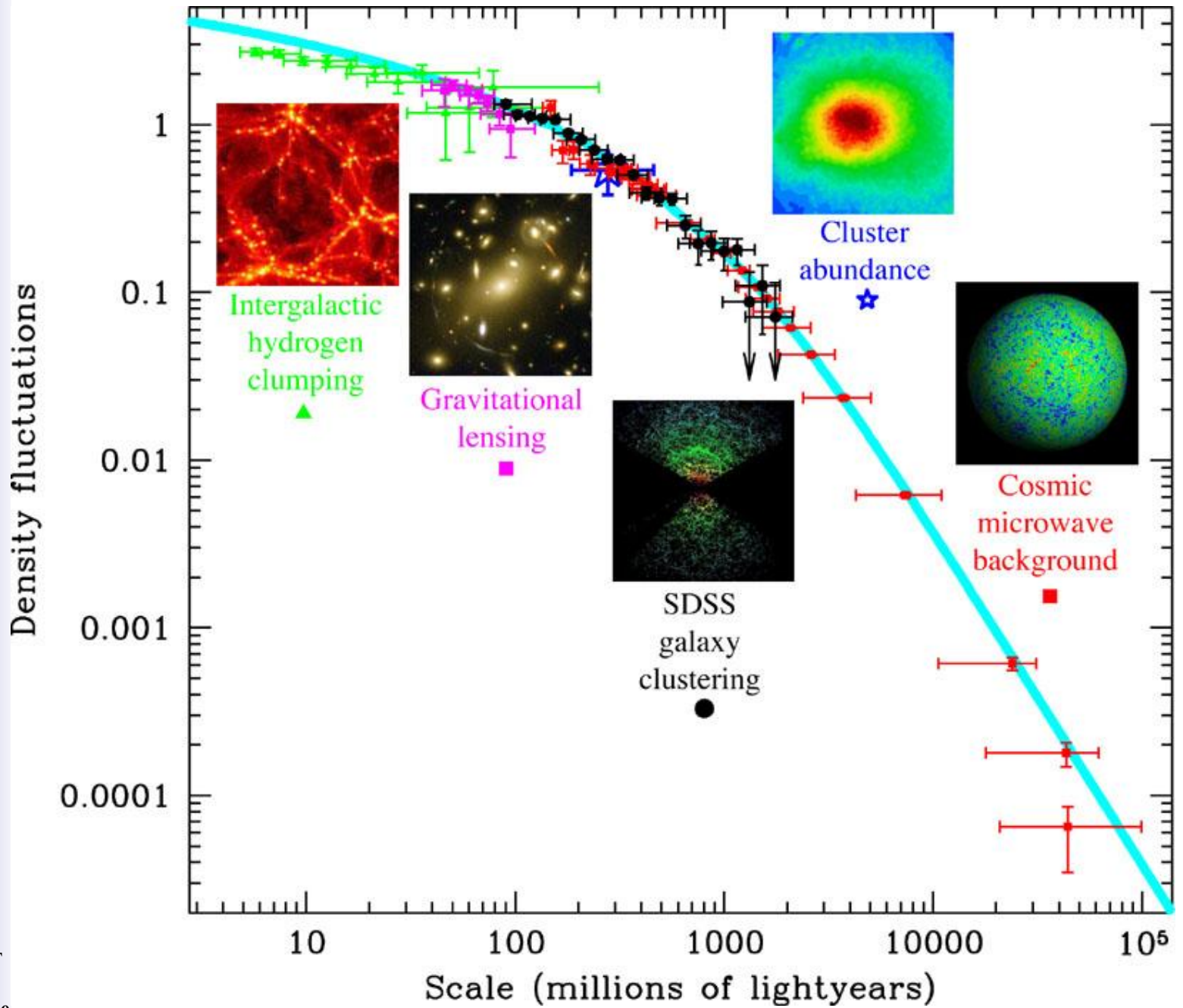
Λ CDM local universe at $z=0.8$ ($\Lambda=0.7$, $\Omega=0.3$, $h=0.7$)
Constrained within 8000 km/s by the IRAS 1.2 Jy survey



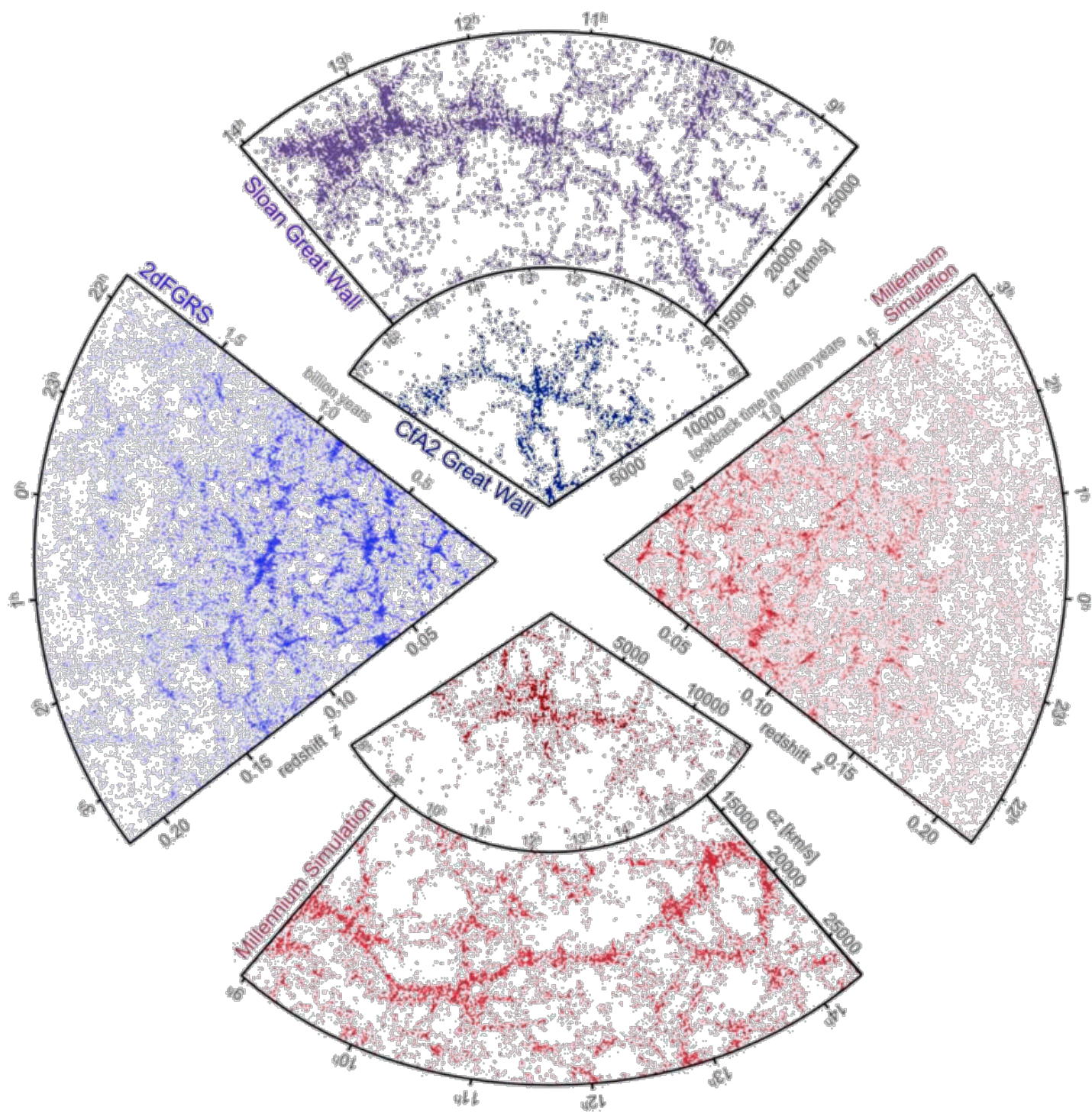
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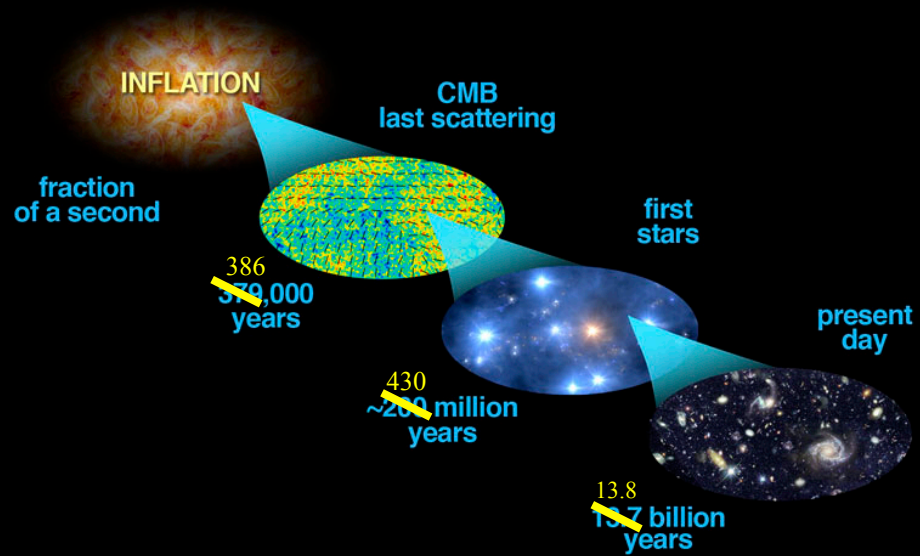


Λ CDM local universe ($\Lambda=0.7$, $\Omega=0.3$, $h=0.7$)
Constrained within 8000 km/s by the IRAS 1.2 Jy survey



Springel, Frenk & White 2006, Nature, 440, 11

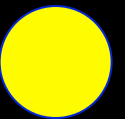
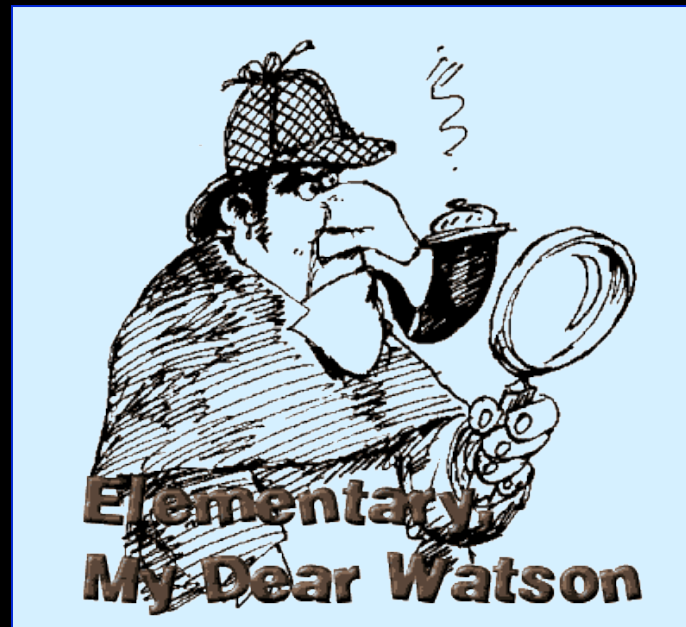


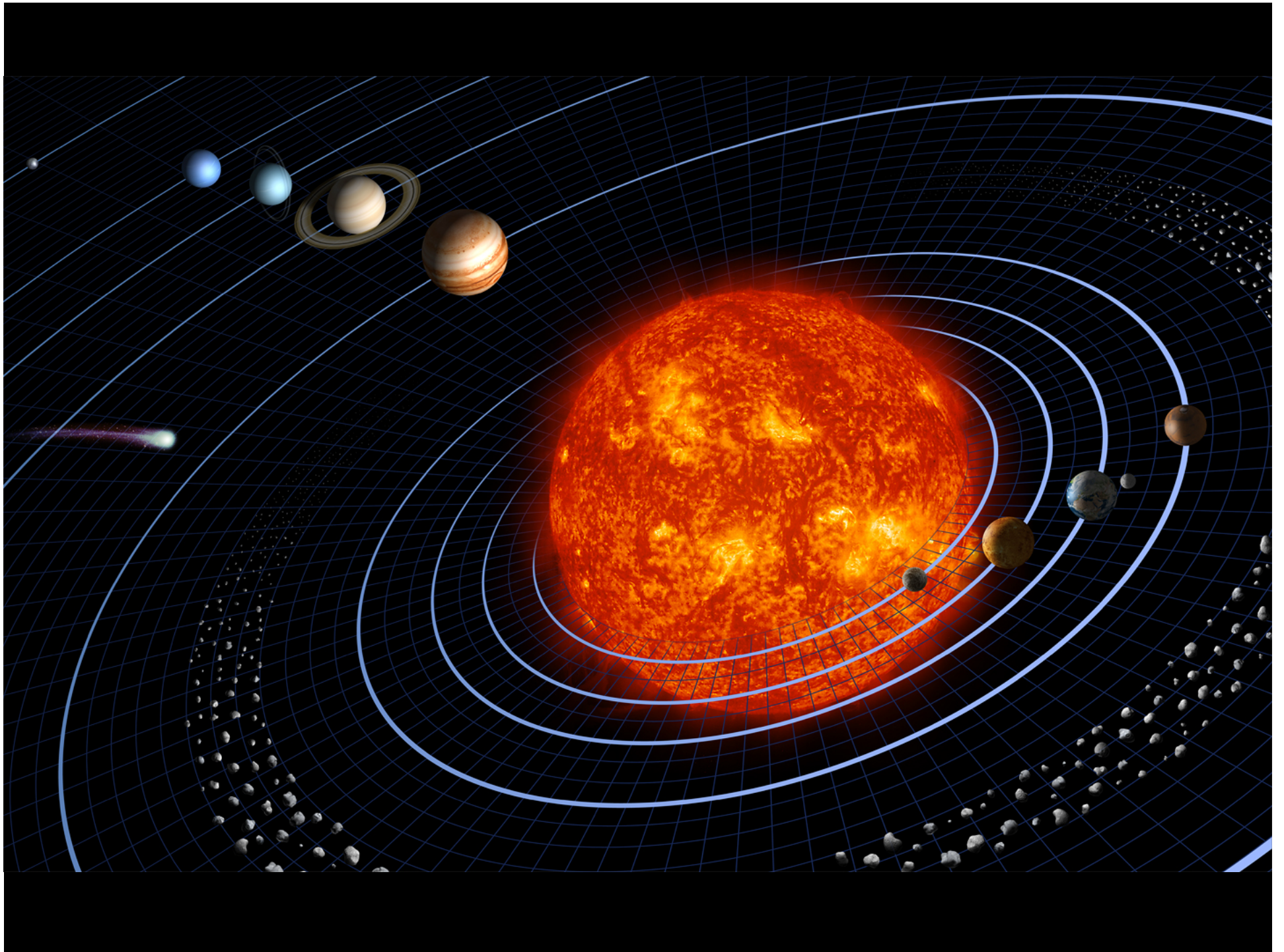


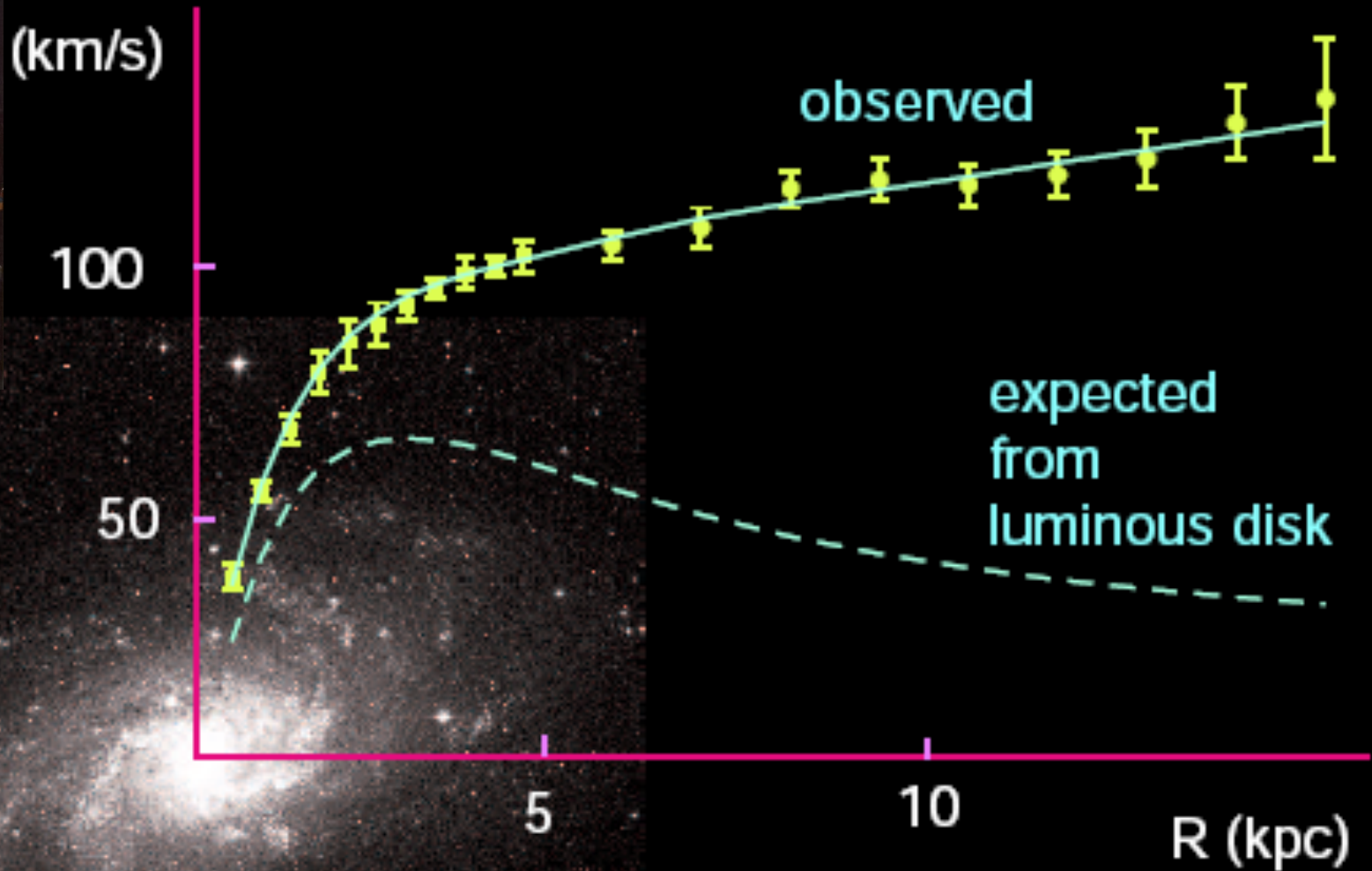
Cosmic history parameters:

z_{eq}	3057^{+105}_{-102}	Matter-radiation Equality redshift
z_{rec}	$1090.25^{+0.93}_{-0.91}$	Recombination redshift
z_{ion}	$11.1^{+2.2}_{-2.7}$	Reionization redshift (abrupt)
z_{acc}	$0.855^{+0.059}_{-0.059}$	Acceleration redshift
t_{eq}	$0.0634^{+0.0045}_{-0.0041}$ Myr	Matter-radiation Equality time
t_{rec}	$0.3856^{+0.0040}_{-0.0040}$ Myr	Recombination time
t_{ion}	$0.43^{+0.20}_{-0.10}$ Gyr	Reionization time
t_{acc}	$6.74^{+0.25}_{-0.24}$ Gyr	Acceleration time
t_{now}	$13.76^{+0.15}_{-0.15}$ Gyr	Age of Universe now

Dark matter



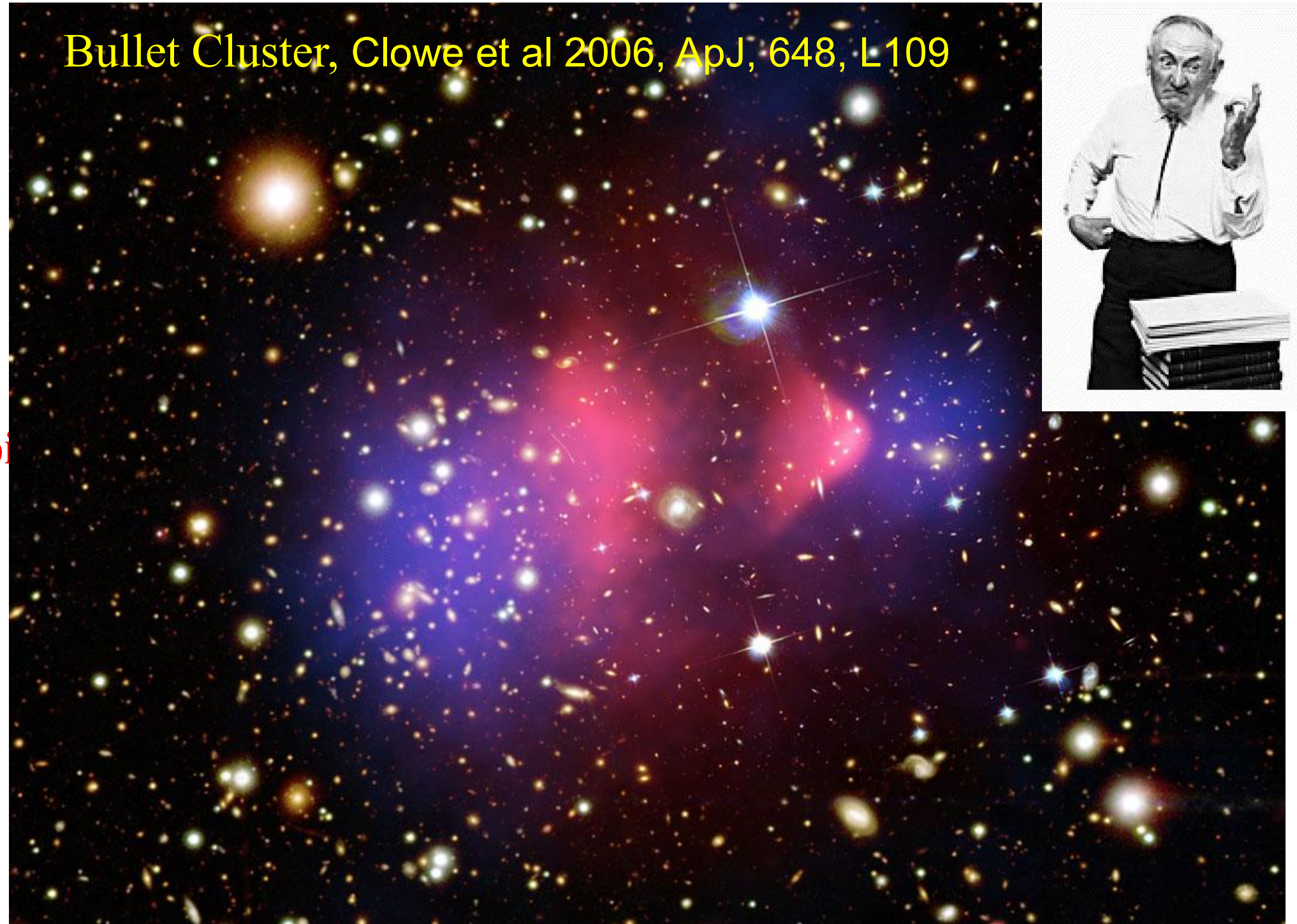
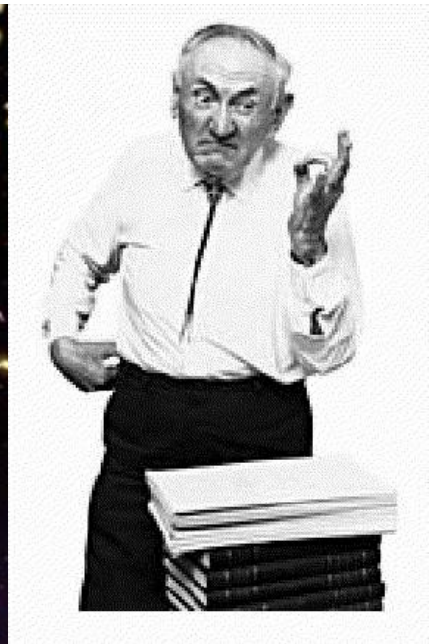




M33 rotation curve

(fig. 1)

Bullet Cluster, Clowe et al 2006, ApJ, 648, L109



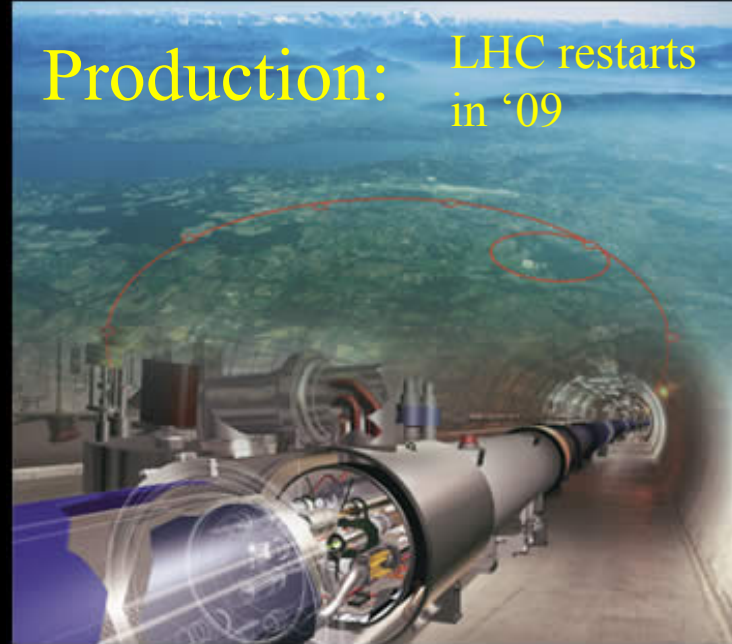
Four roads to dark matter: *catch it, infer it, make it, weigh it*

Direct:



Production:

LHC restarts
in '09



Indirect:

Fermi (né
GLAST)
launched
6/11-08,
Pamela



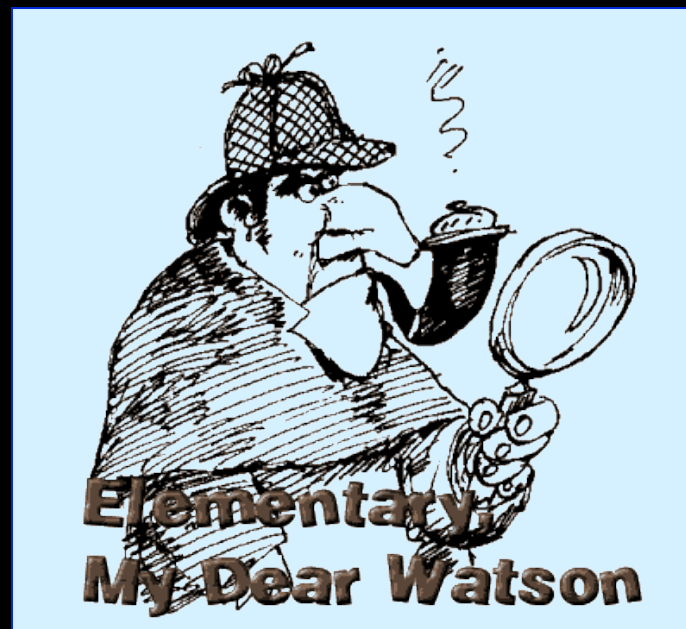
Gravitational:

Planck launch
scheduled for
February 2009

21 cm
tomography
coming



Dark energy

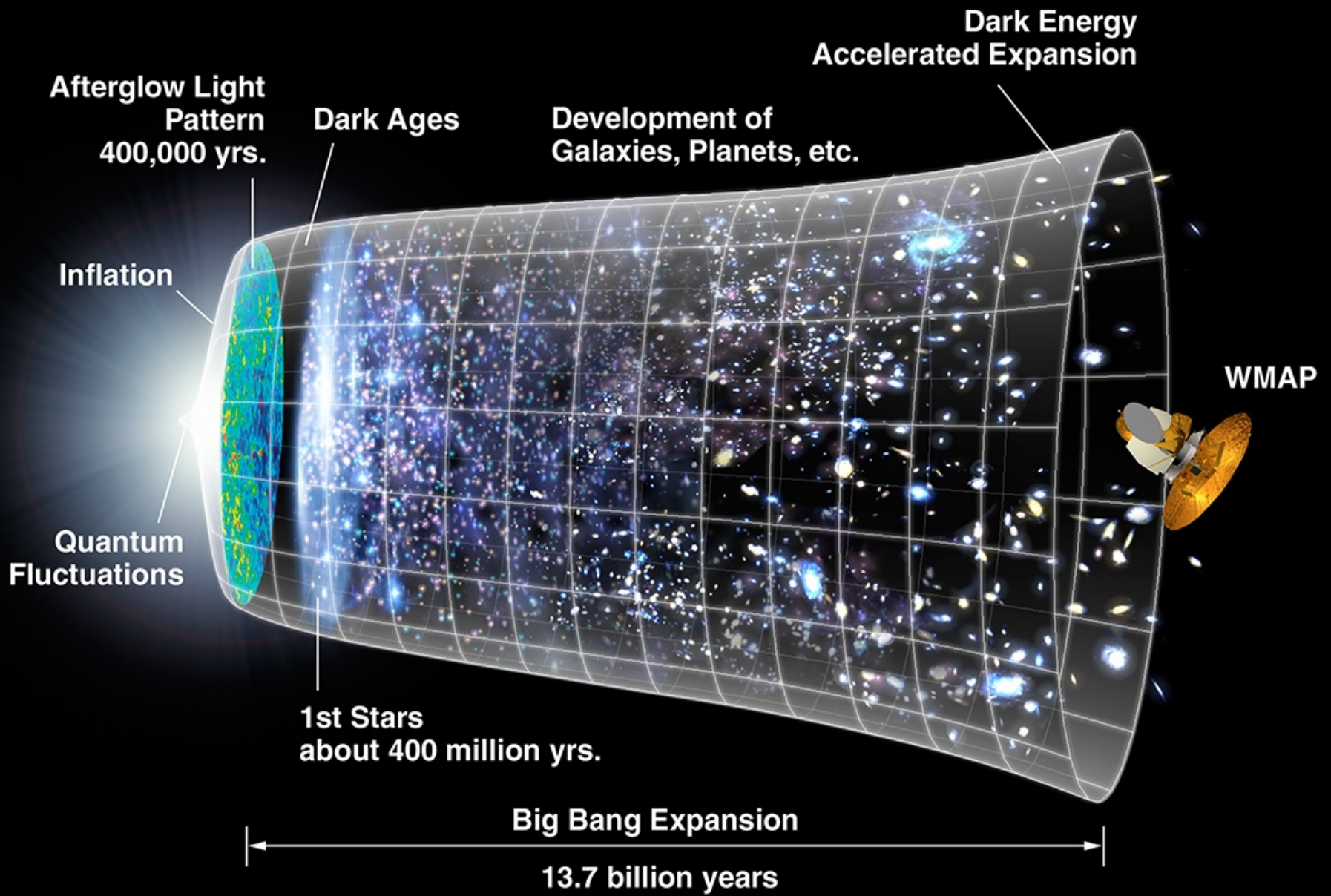


**Elementary,
My Dear Watson**

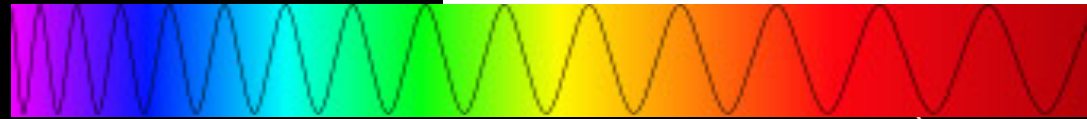
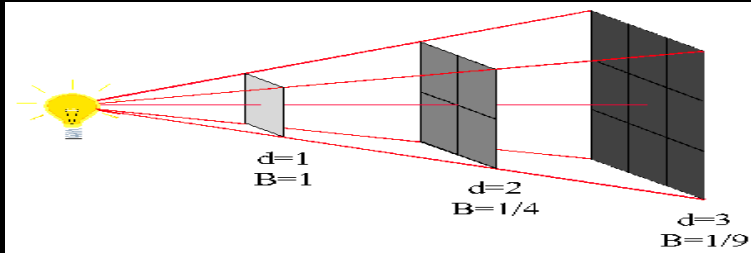
0th order:

Measuring
Expansion:
 $a(t) \Leftrightarrow H(z)$

Figure from WMAP team



Distant light is {
-dimmed →
-redshifted ↓



Afterglow Light Pattern
400,000 yrs.

Dark Ages

Development of
Galaxies, Planets, etc.

Inflation

Quantum
Fluctuations

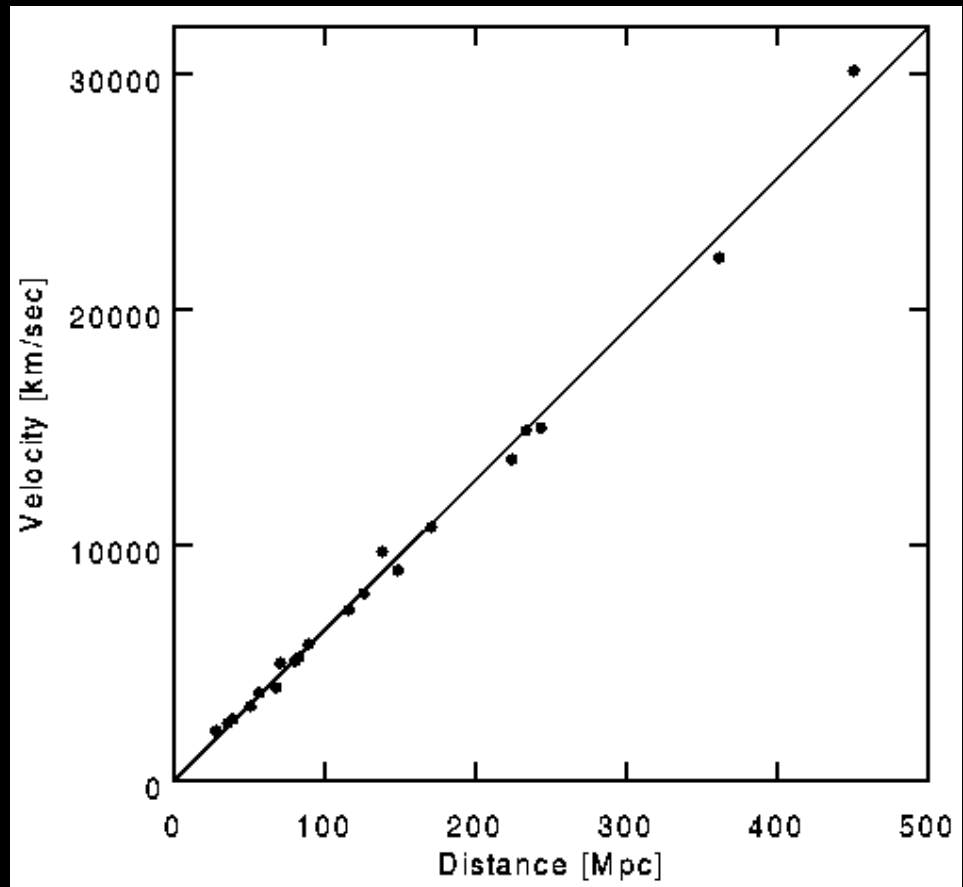
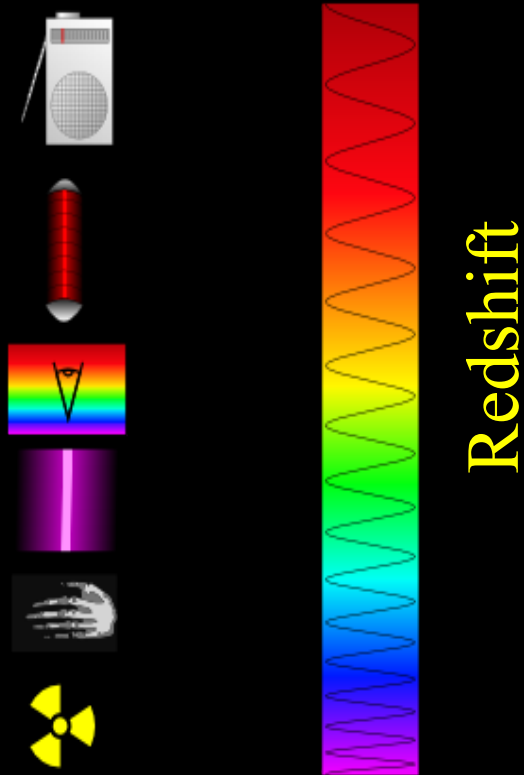
1st Stars
about 400 million yrs.

WMAP

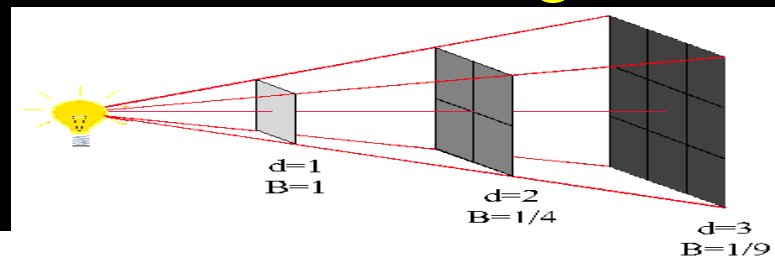
Big Bang Expansion

13.7 billion years

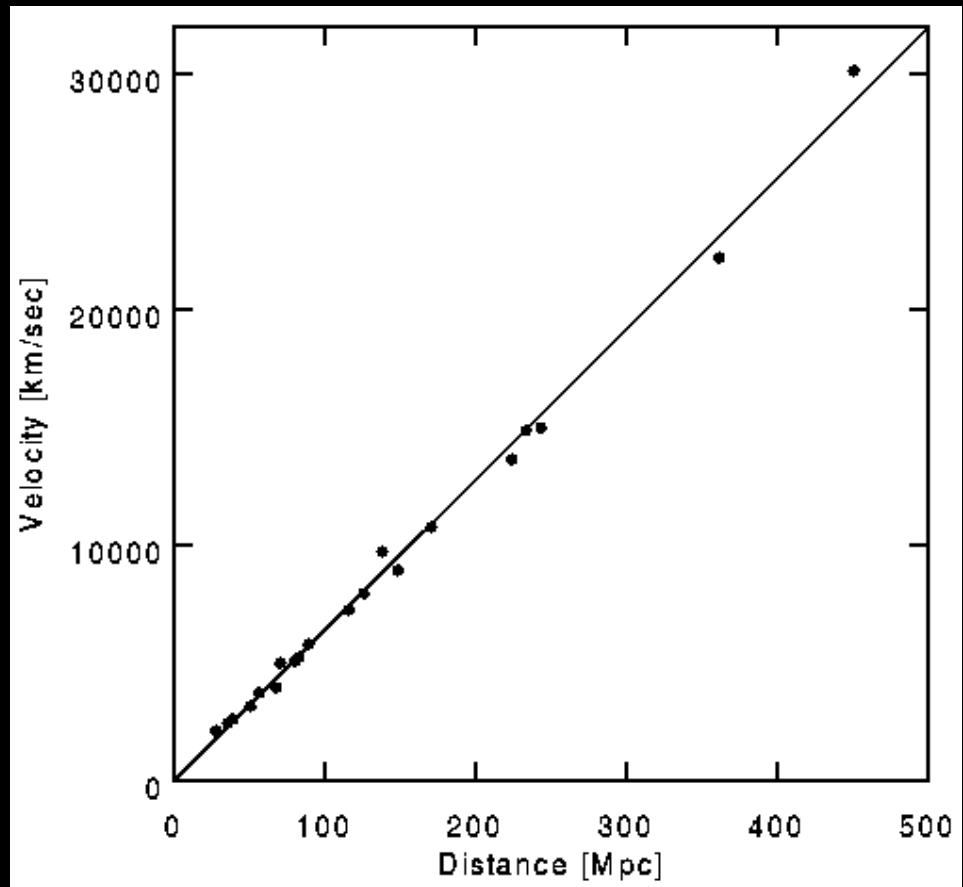
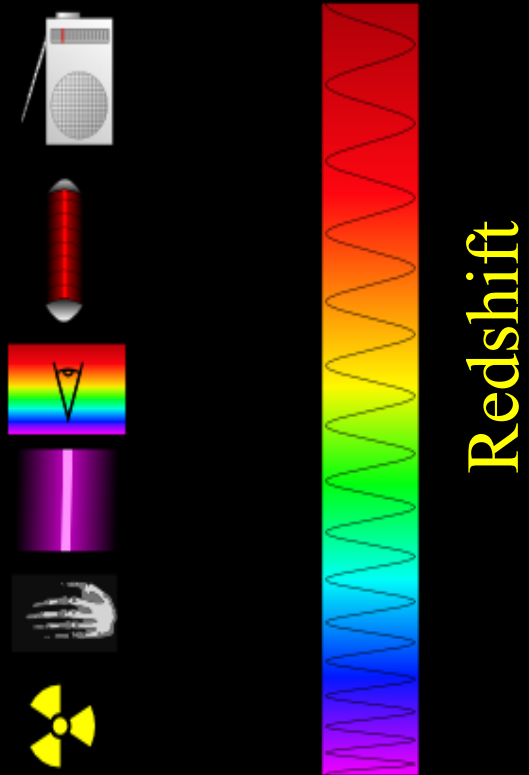
Distant light is {
-dimmed
-redshifted



Dimming

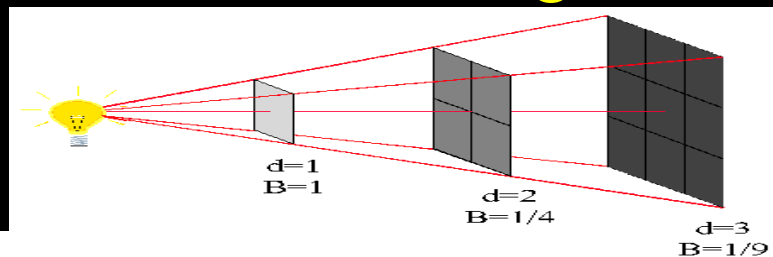


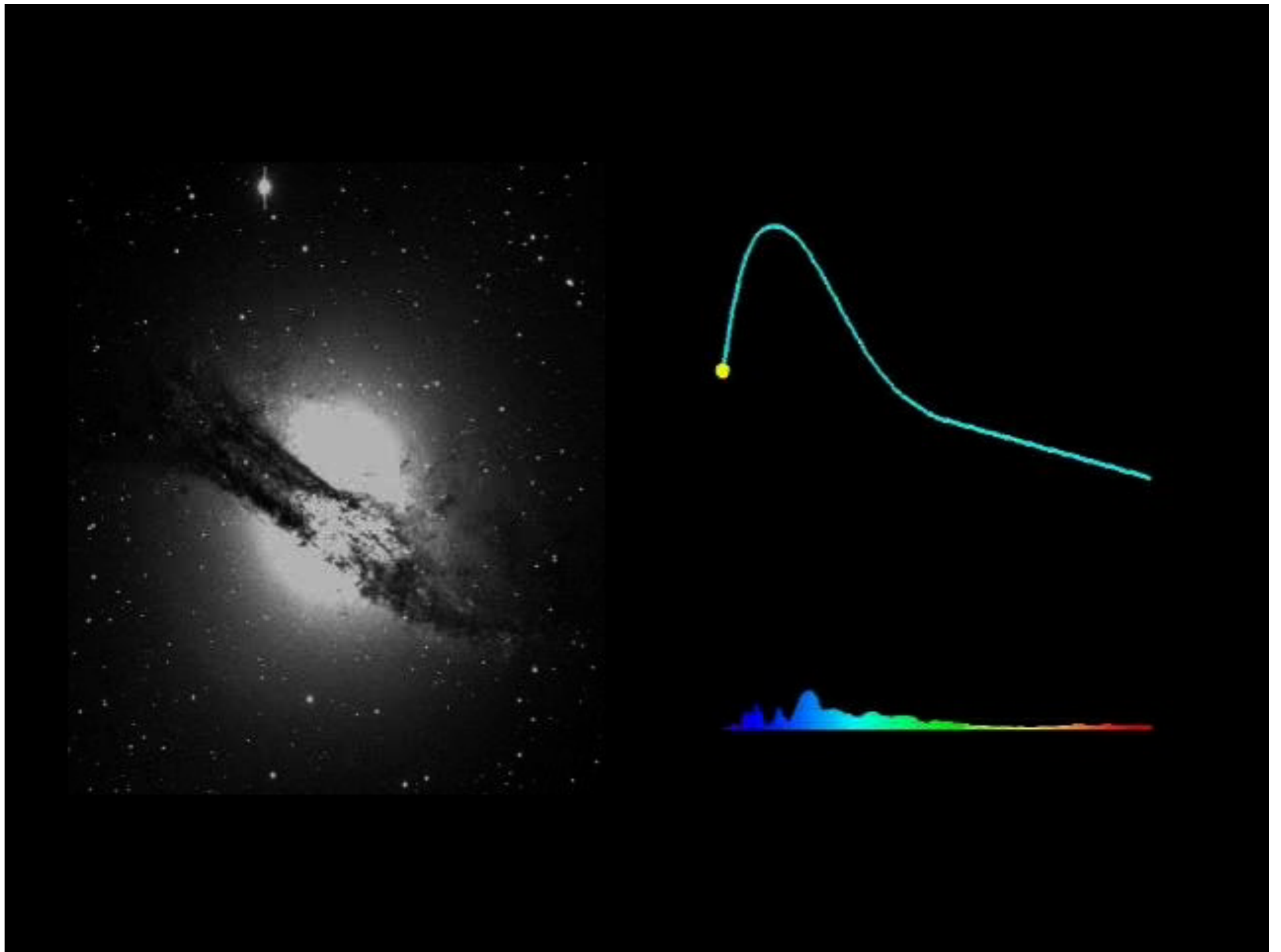
Distant light is {
-dimmed
-redshifted



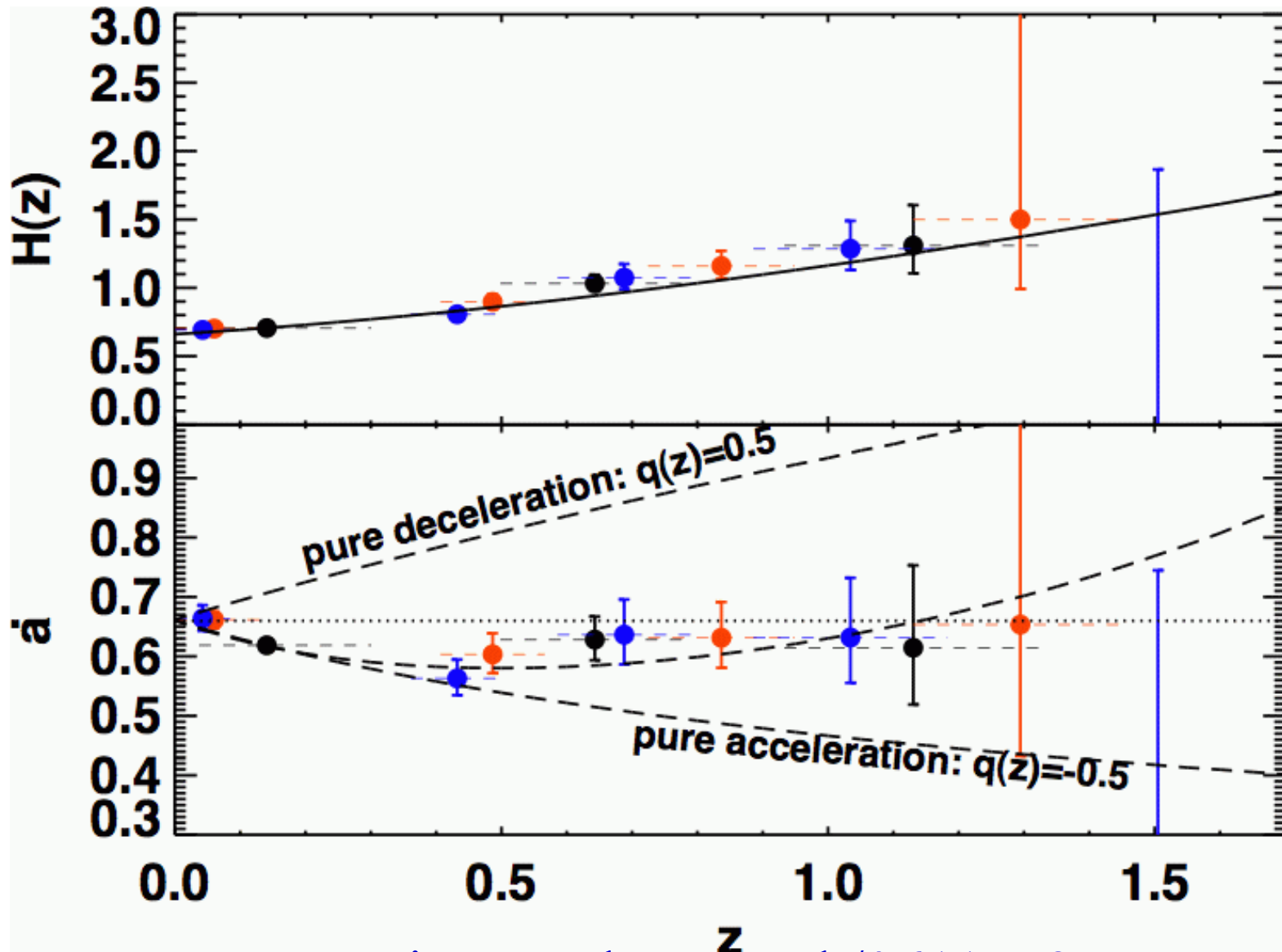
Dimming

Standard candles,
rulers or clocks



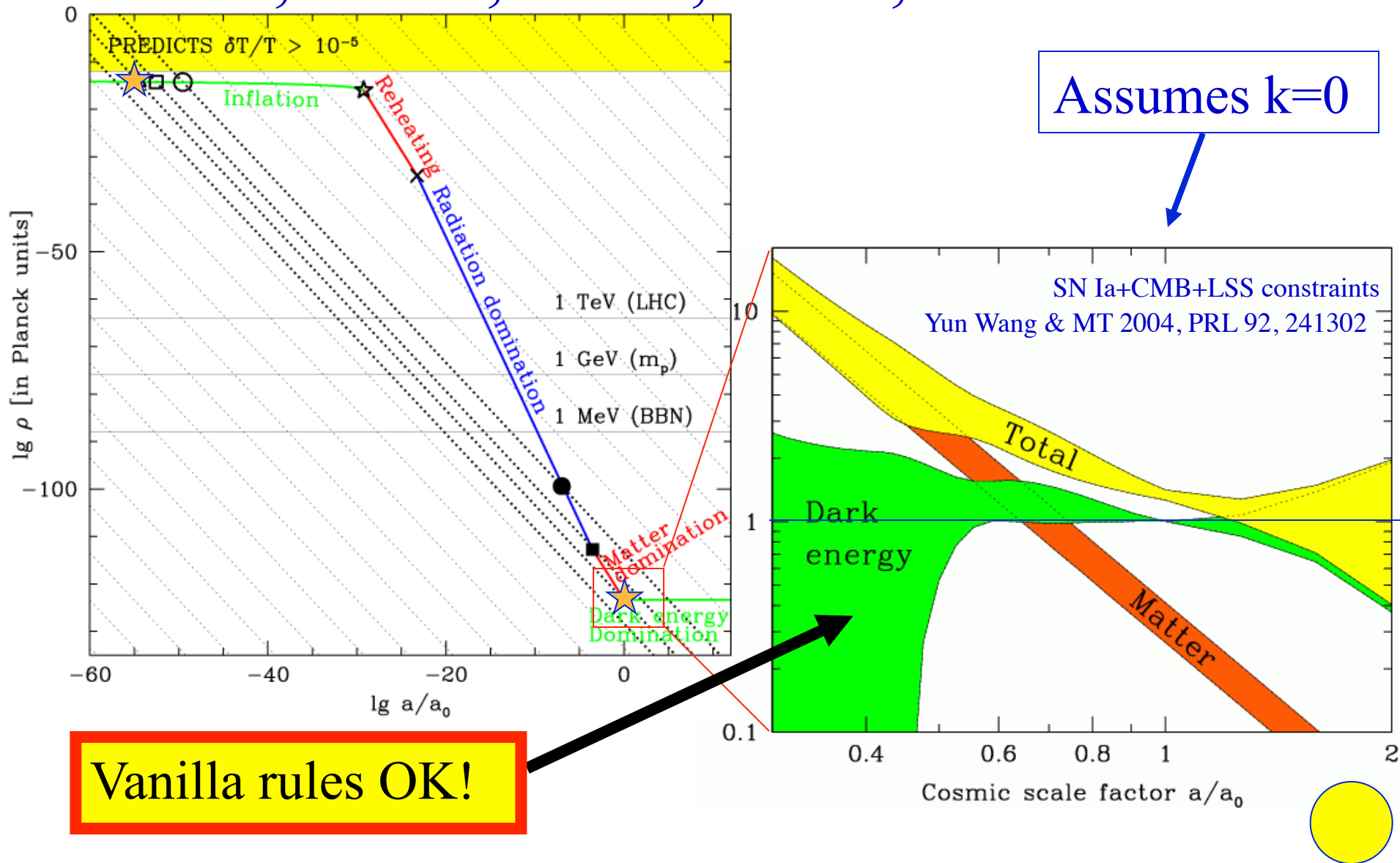


What we've learned about $H(z)$ from SN Ia

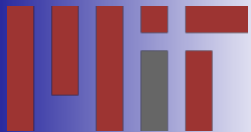
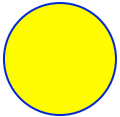


Riess et al, astro-ph/0611572

What we've learned about $H(z)$ from SN Ia, CMB, BAO, BBN, etc:



Vanilla rules OK!



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DO ANY OF THESE QUESTIONS CONFUSE YOU?

1. What is the Universe expanding into?
2. How can stuff be more than 14 billion light years away when the Universe is only 14 billion light years old?
3. Where in space did the Big Bang explosion happen?
4. Did the Big Bang happen at a single point?
5. How could a the Big Bang create an infinite space in a finite time?
6. How could space not be infinite?
7. If the Universe is only 10 billion years old, how can we see objects that are now 30 billion light years away?
8. Don't galaxies receding faster than c violate relativity theory?
9. Are galaxies really moving away from us, or is space just expanding?
10. Is the Milky Way expanding?
11. Do we have evidence for a Big Bang singularity?
12. What came before the Big Bang?
13. Should I feel insignificant?