What have we learned from observational cosmology ? (observer's point of view)

Jean-Christophe Hamilton
CNRS - IN2P3 - APC - Paris

Outline

- ΛCDM: the concordance model
- Observational evidences for ΛCDM
  - ★ The Cosmic Microwave Background and the early Universe
  - ★ Dark Matter
  - ★ Dark Energy
  - ★ Tests of the cosmological principle
  - ★ Tests of the Big-Bang paradigm
- Summary

ΛCDM foundations

Assumptions

General Relativity + Cosmological Principle

→ Calculations →

FLRW Cosmological Model + ~12 Free parameters

→ Many independent Observations + Fitting →

ΛCDM

- There is not much room out of this scheme
  - ★ Recusing the cosmological principle (obs. constraints)
  - ★ Extensions/modifications to G.R. (obs. constraints)
  - ★ Modelling of the energy content of the Universe (obs. constraints + particle physics)

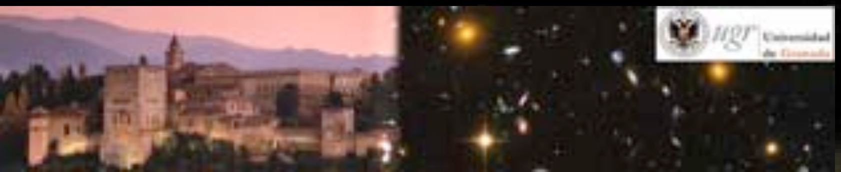
The ΛCDM model

- ★ FLRW expanding Universe (Hot Big-Bang)
  - General Relativity + Cosmological Principle
  - Hubble constant ~ 70 km.s^{-1}.Mpc^{-1}
  - CMB blackbody, BigBang Nucleosynthesis

- ★ The Universe is ~ flat : $\Omega_{tot} \approx 1$
  - CMB anisotropies + Hubble constant

- ★ It contains ~ 22 % of Dark Matter (unknown)
  - Galaxies rotation curves, Clusters X, weak-lensing, Structure formation, CMB

- ★ It contains ~ 74% of Dark Energy (unknown)
  - SNIa fainter than expected ⇒ further ⇒ acceleration
  - CMB+H, direct measurements of Ω_m, ISW effect



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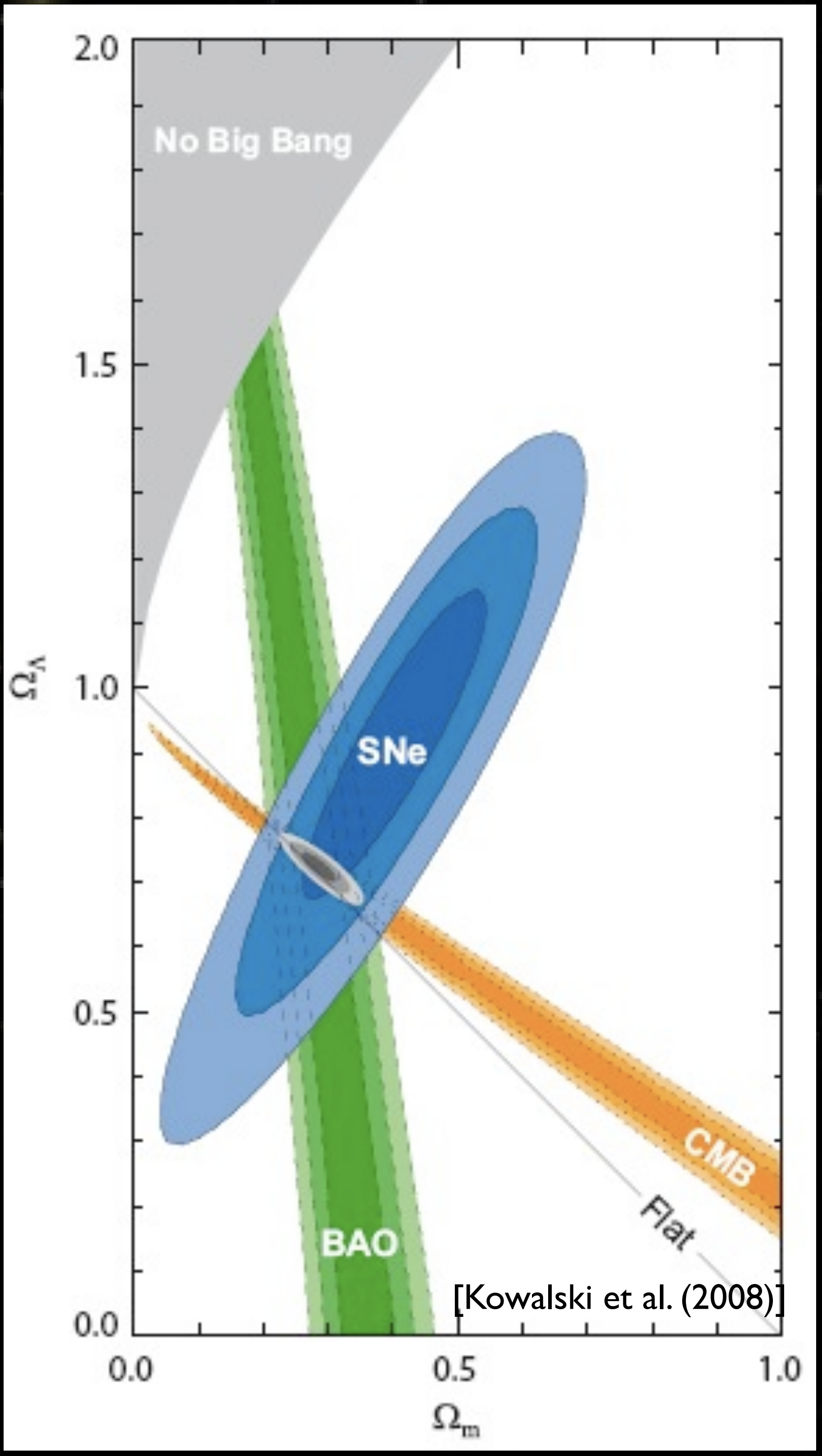

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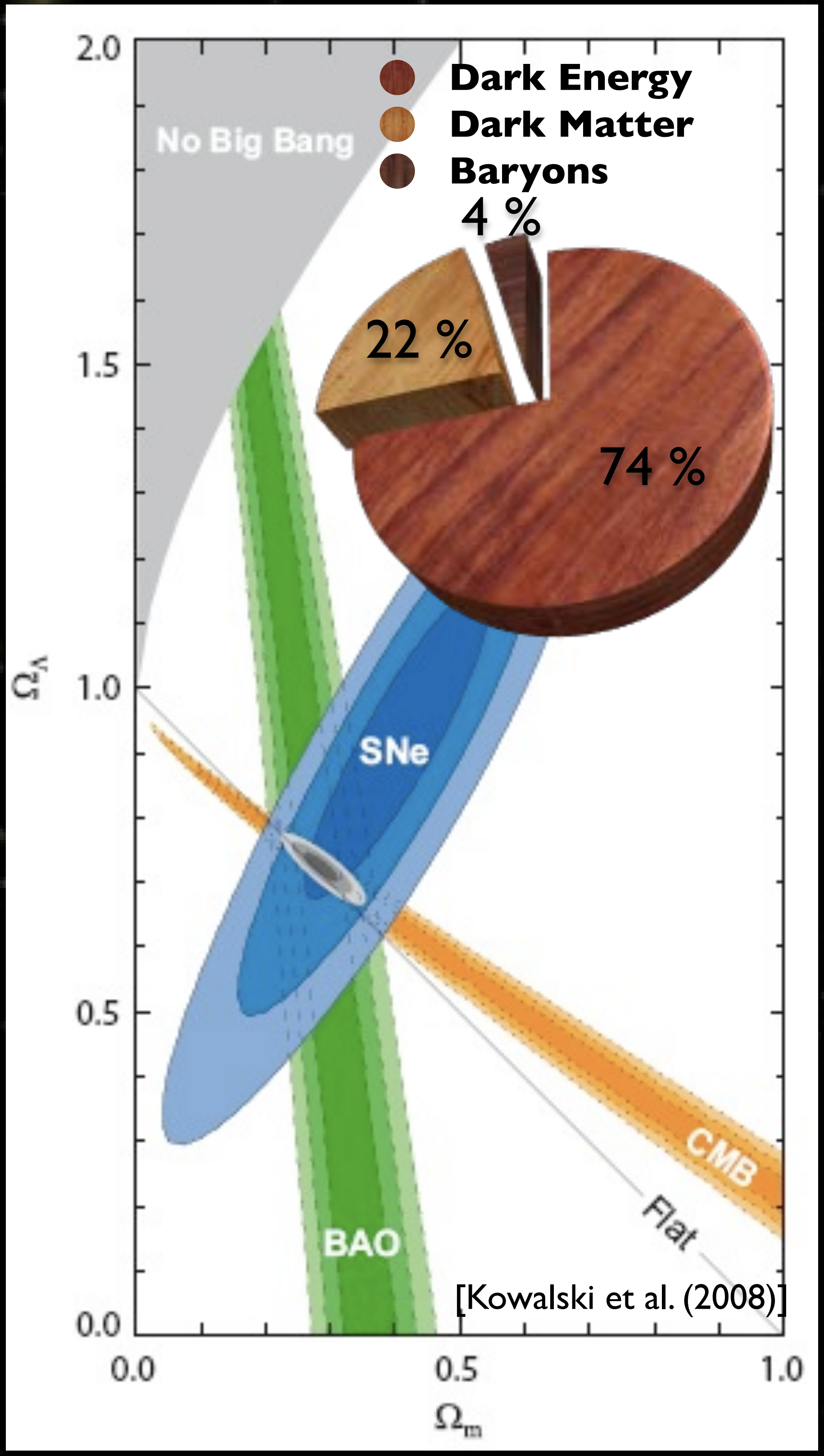

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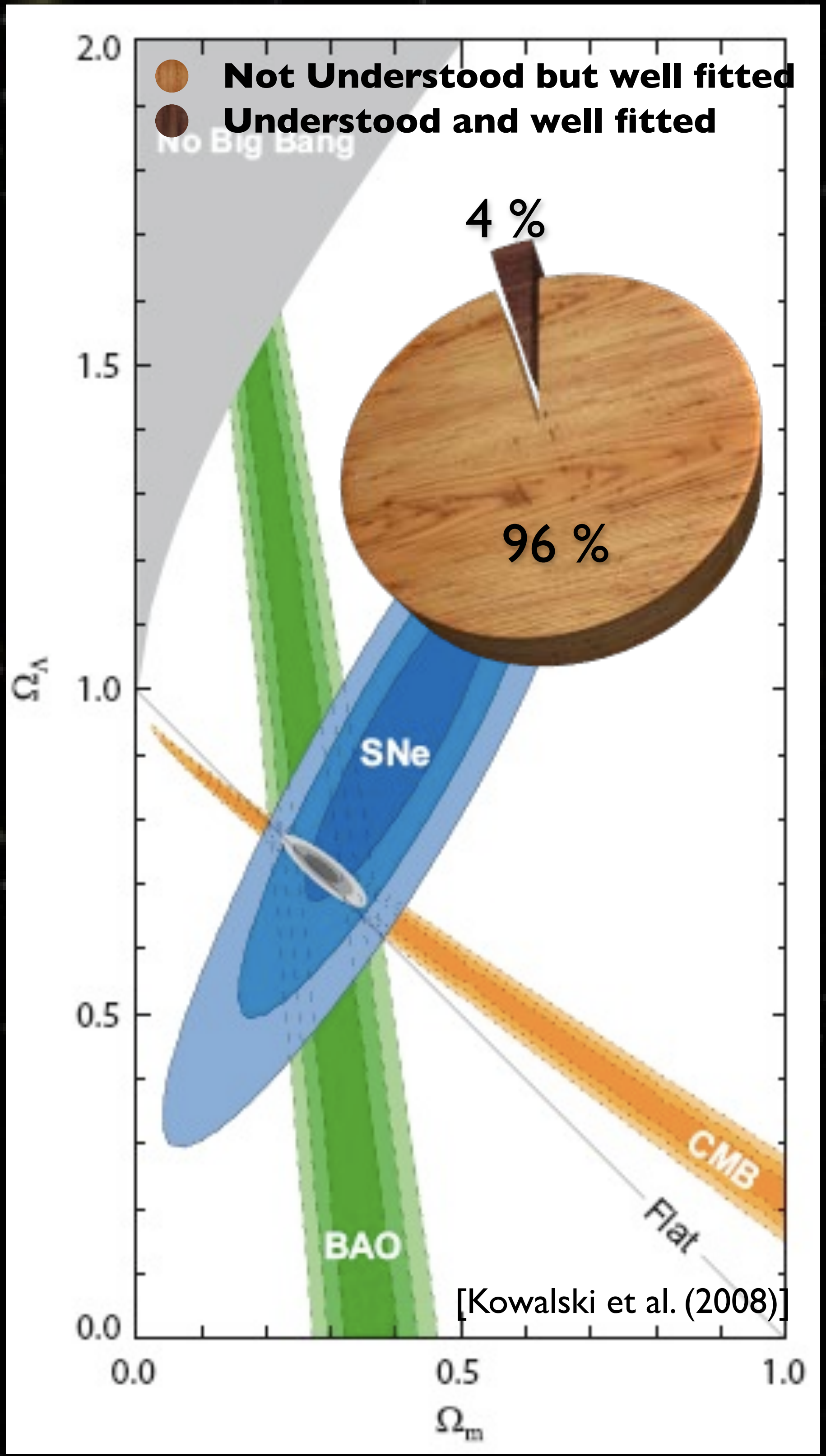

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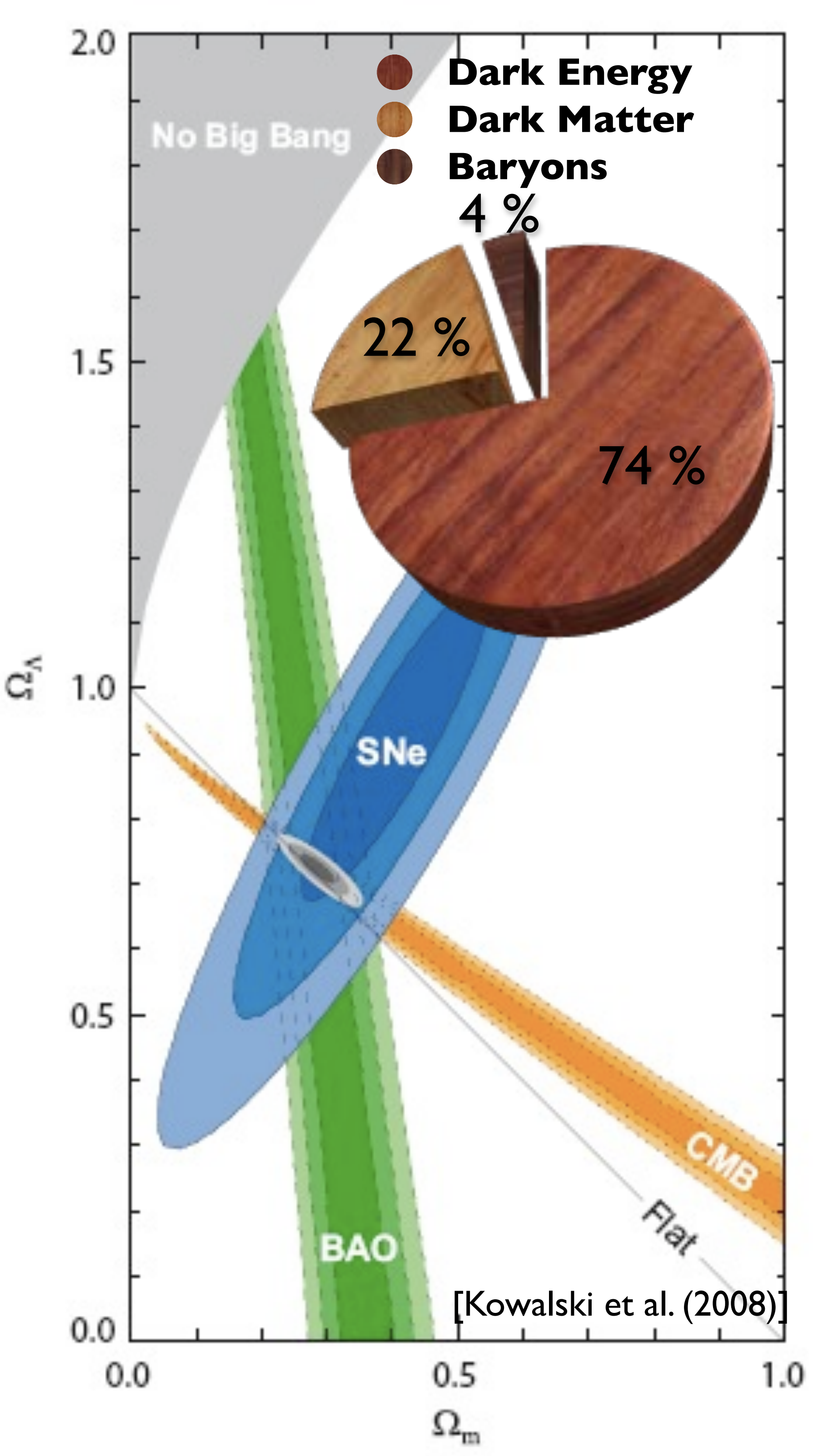
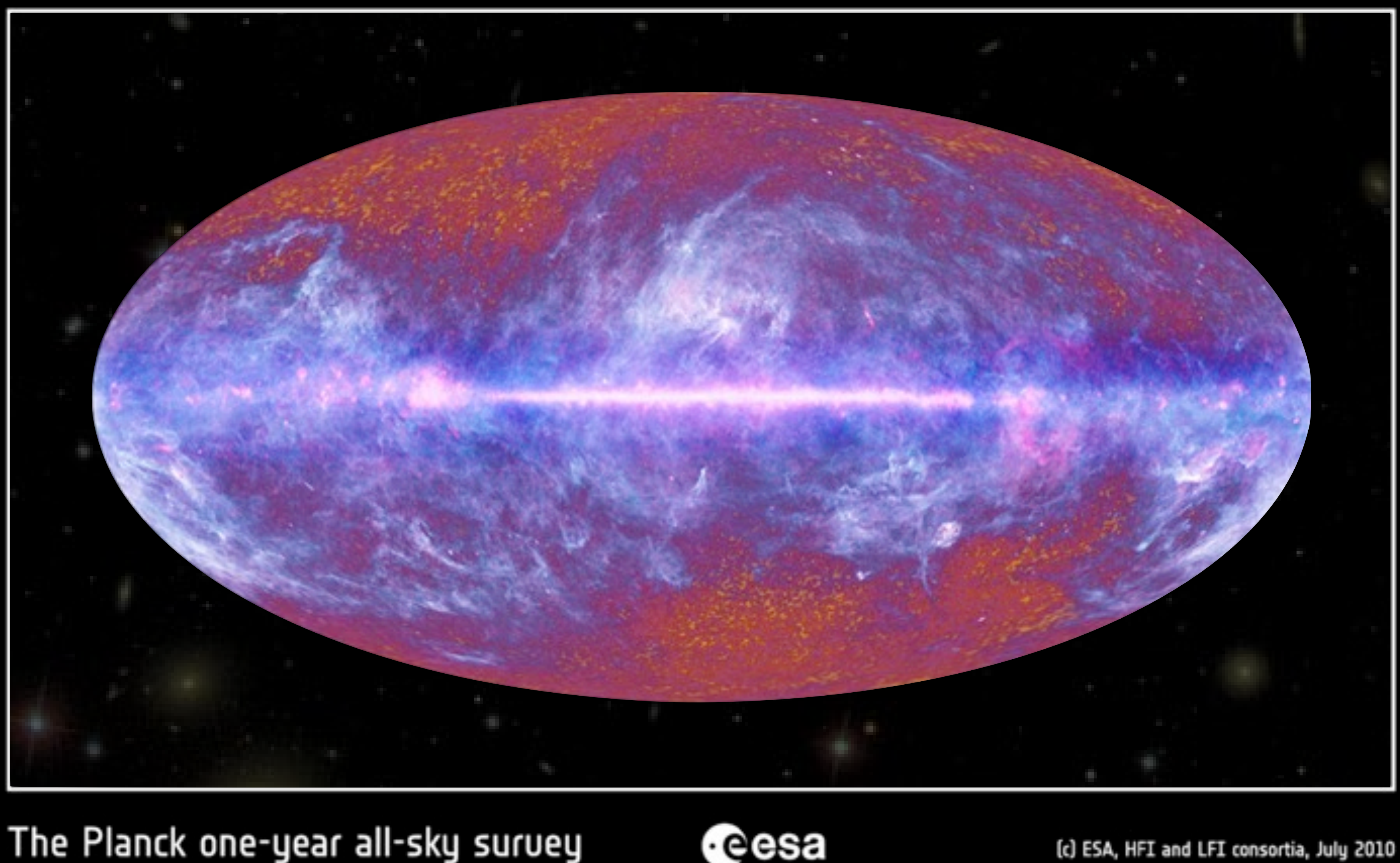


[Kowalski et al. (2008)]

Cosmic Microwave background



CMB Physics

- Origin
  - ★ Early Universe
    - Ionized ⇒ opaque to photons
    - thermal equilibrium
  - ★ T << 13.6 eV
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    - CMB emitted. Blackbody at 3000K (z=1000)
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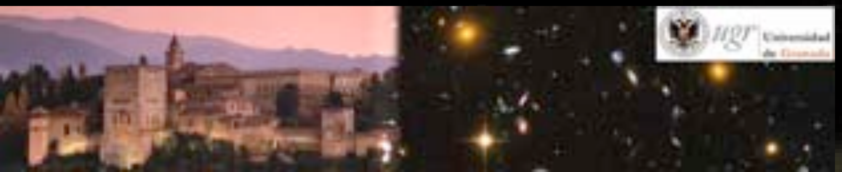

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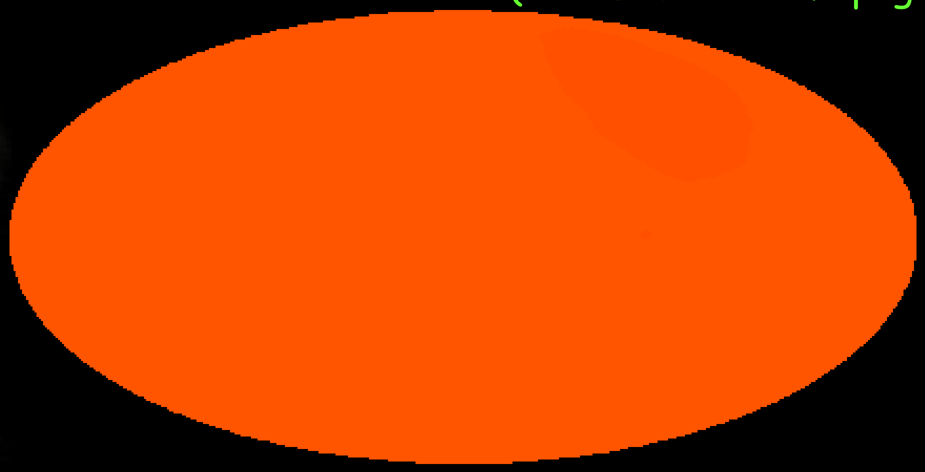

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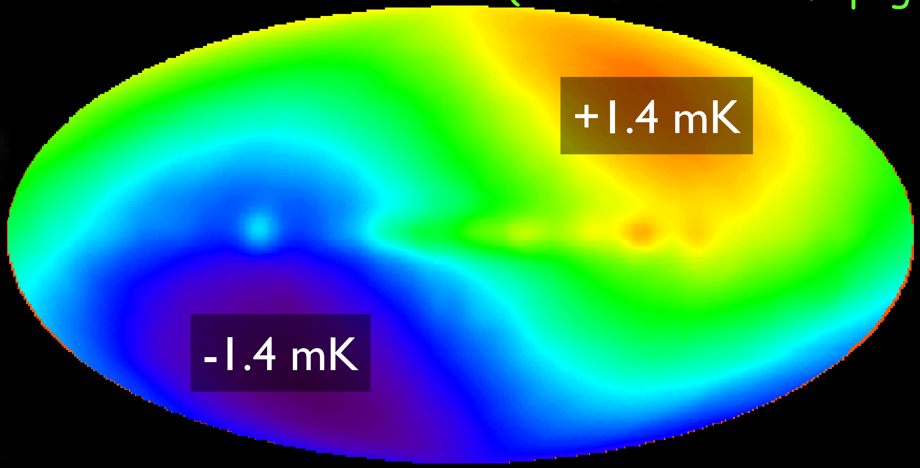

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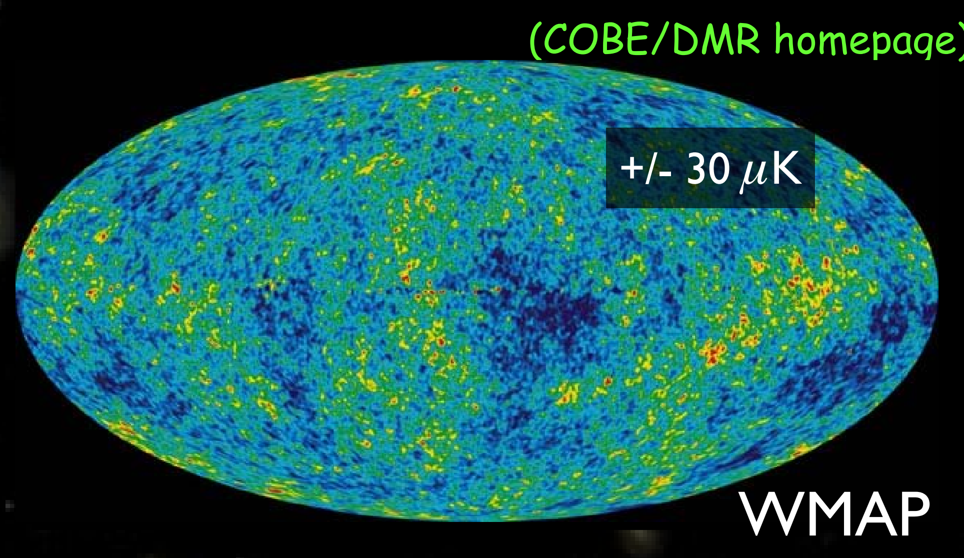

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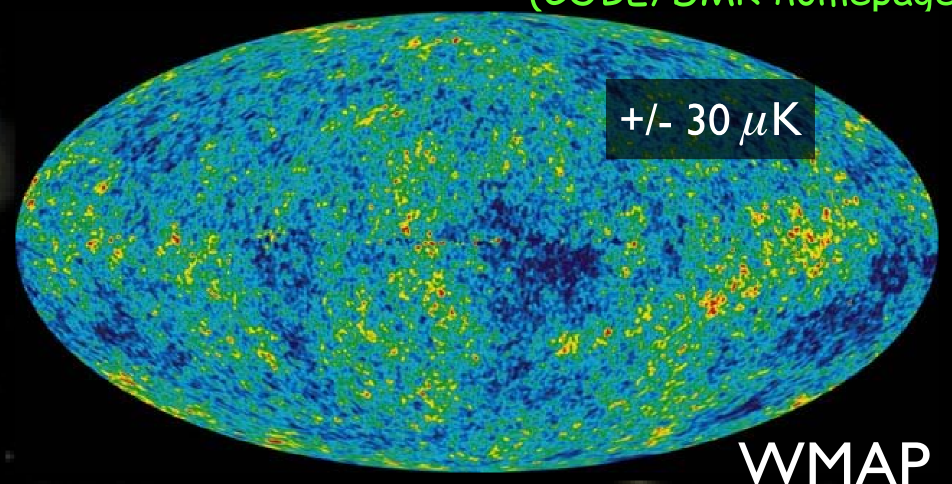

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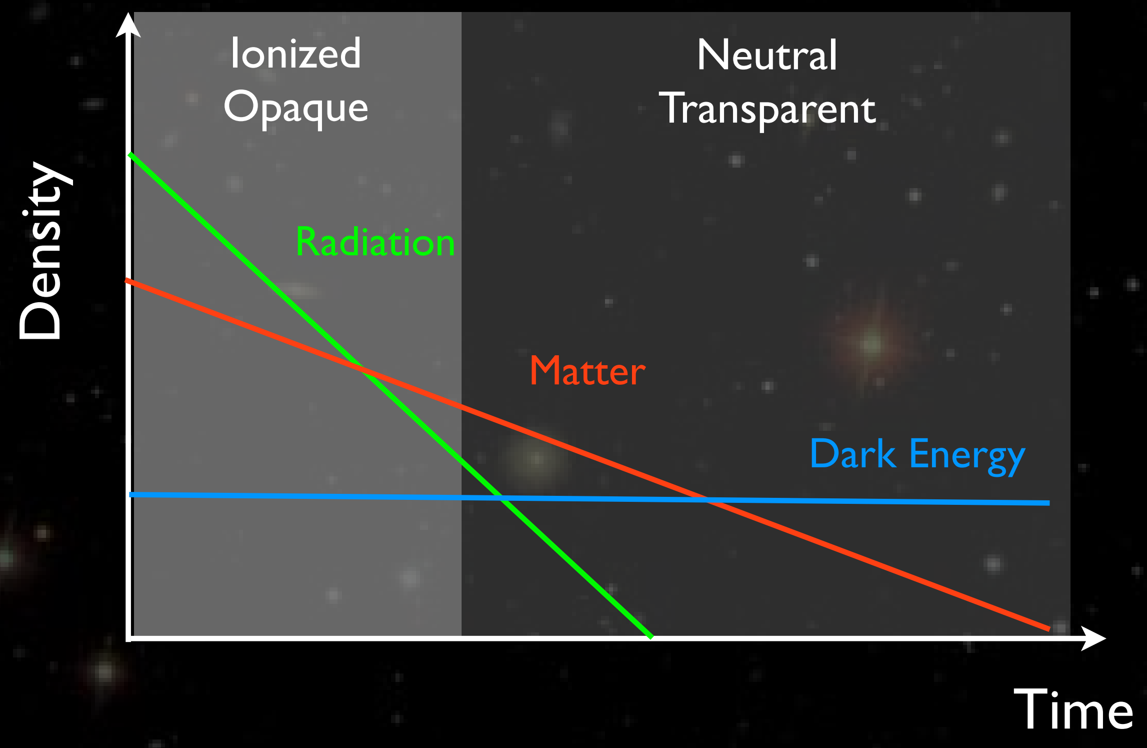

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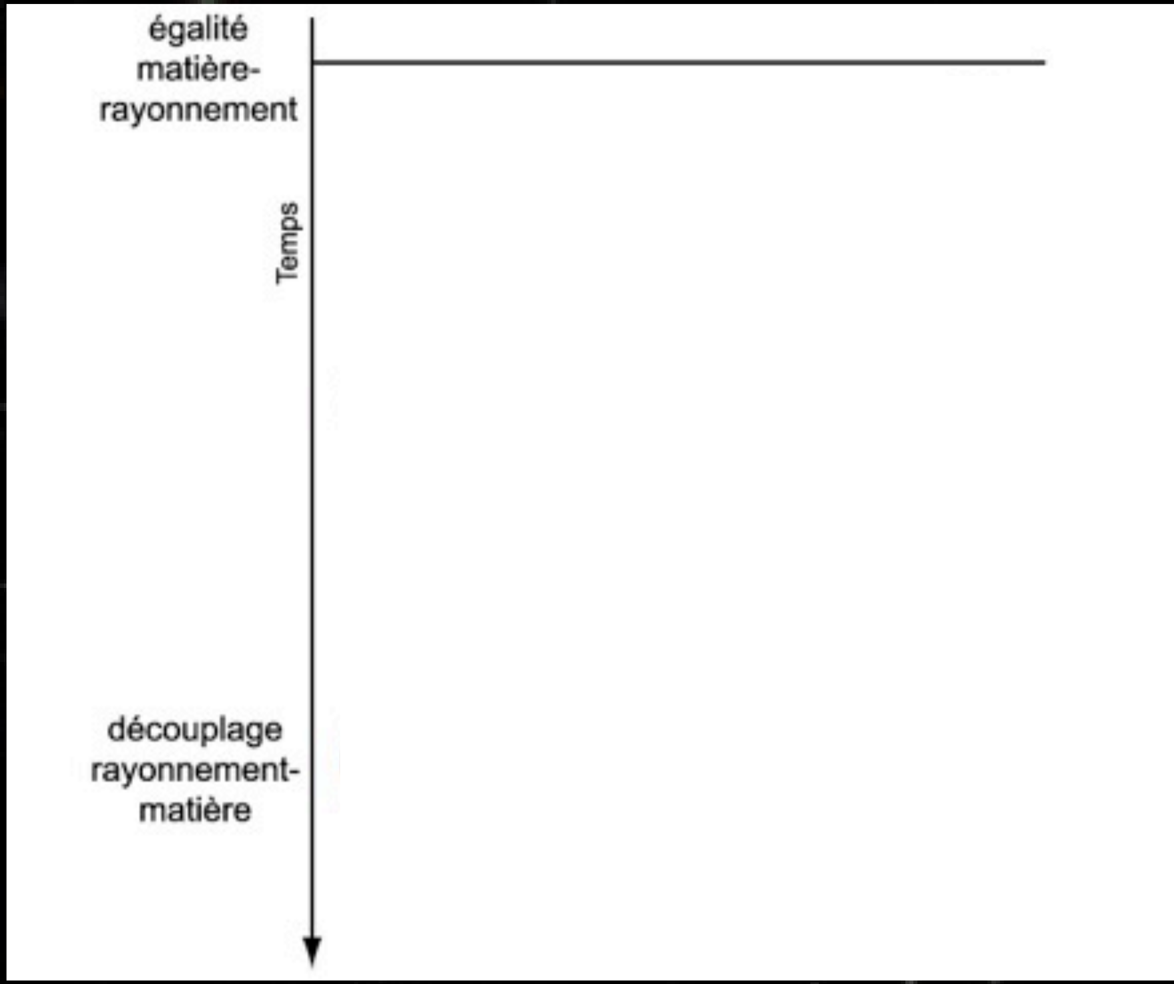

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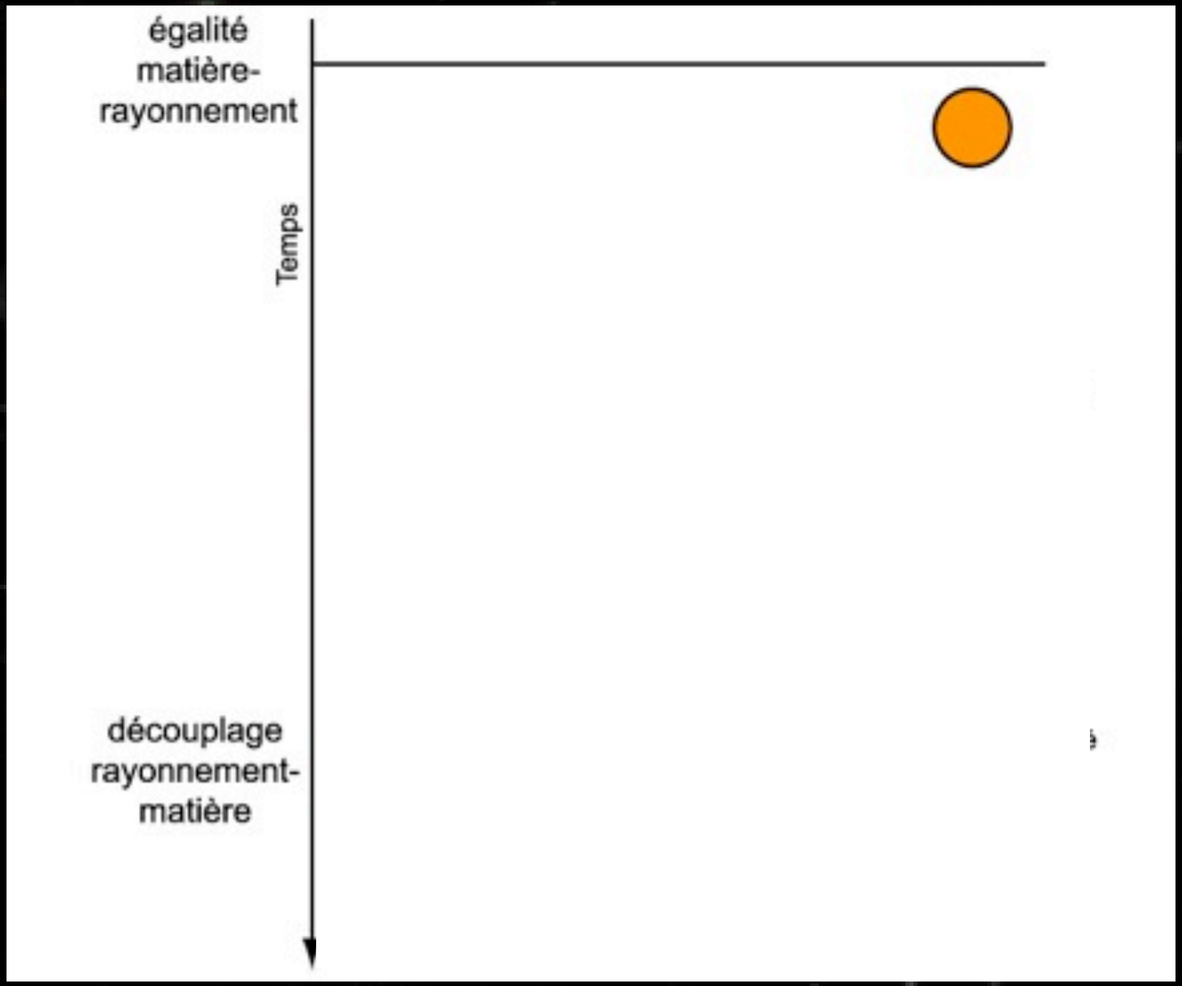

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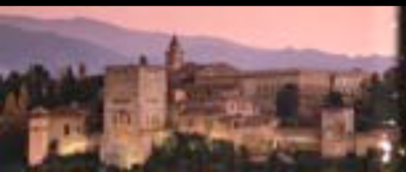

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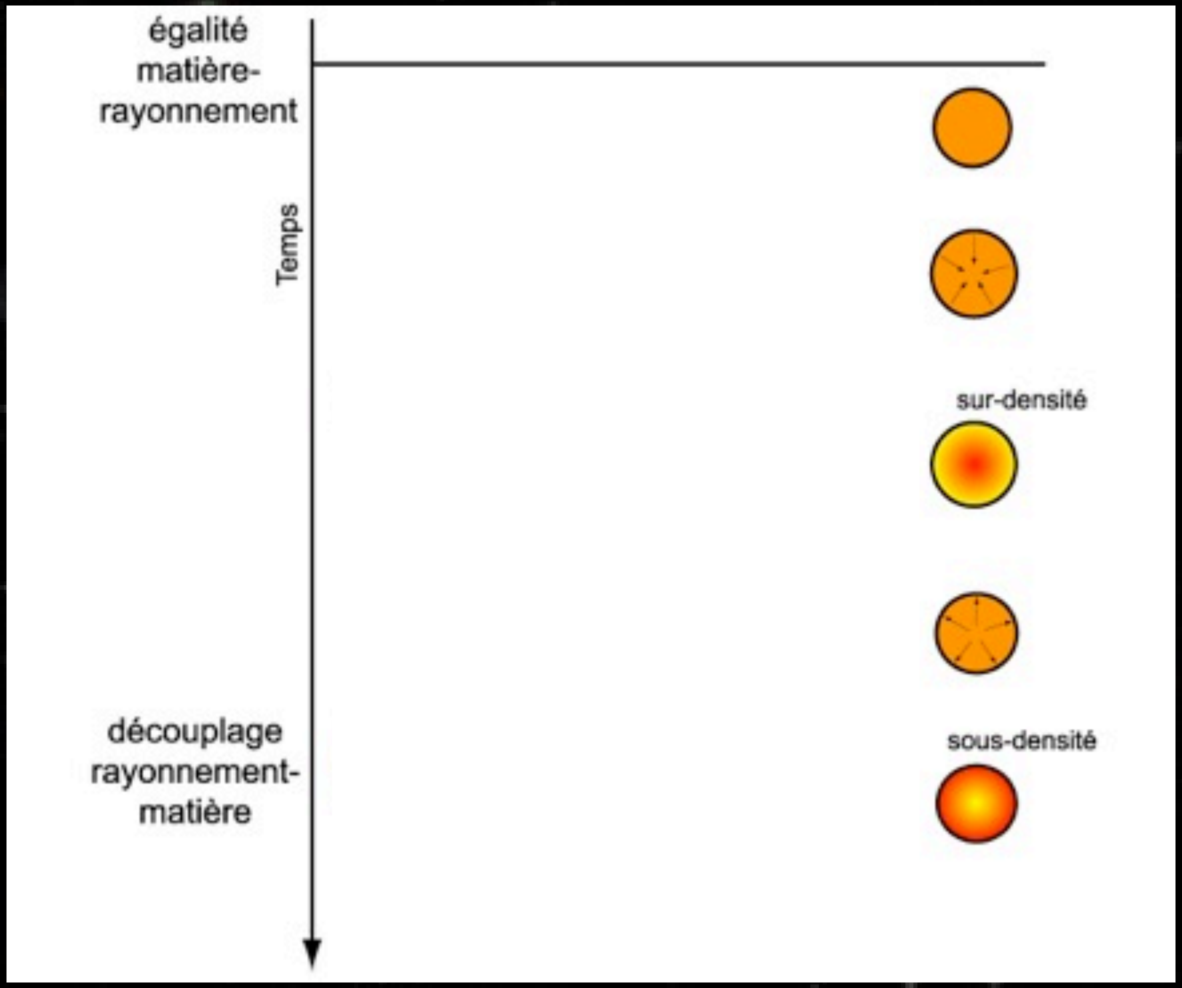

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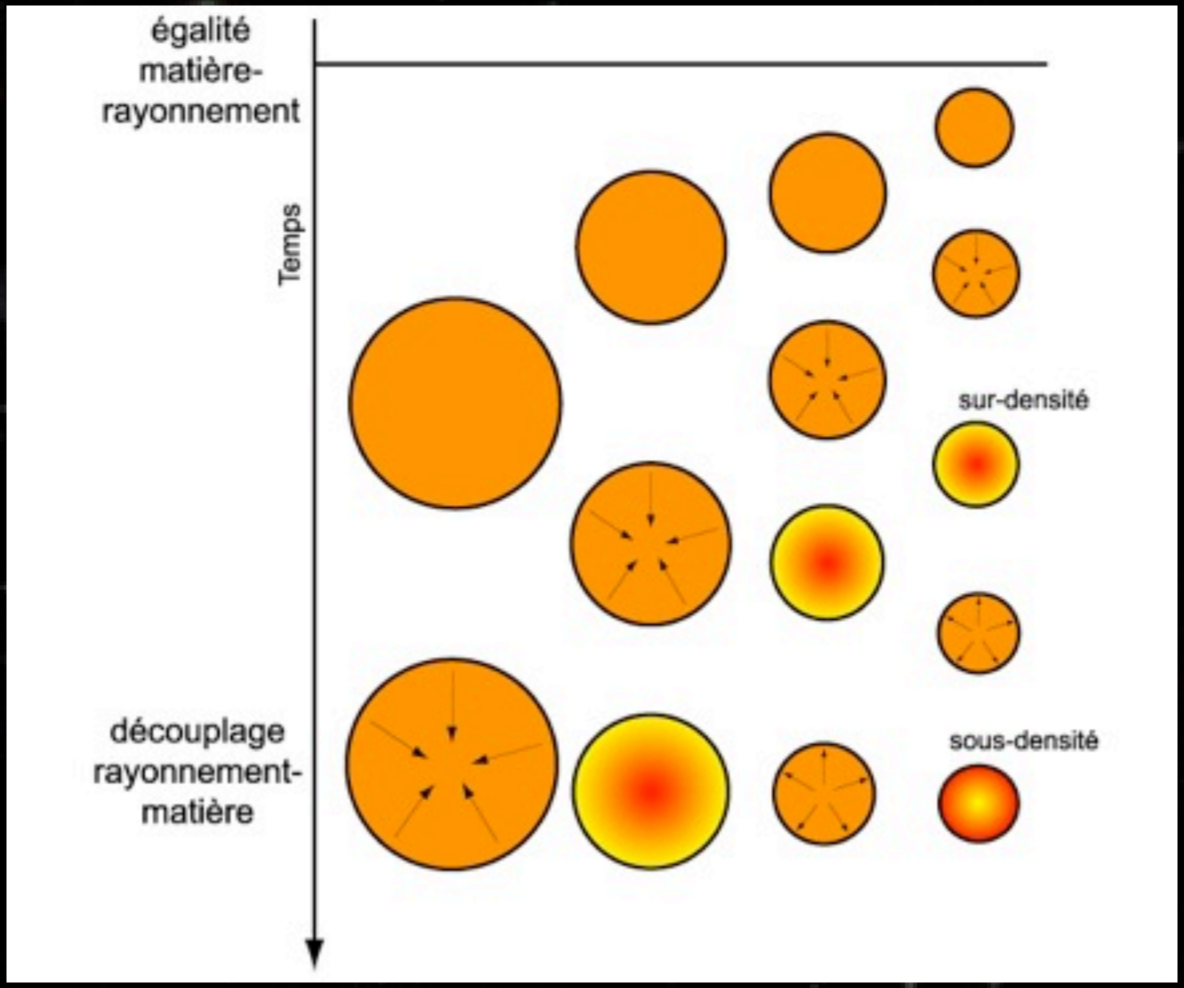

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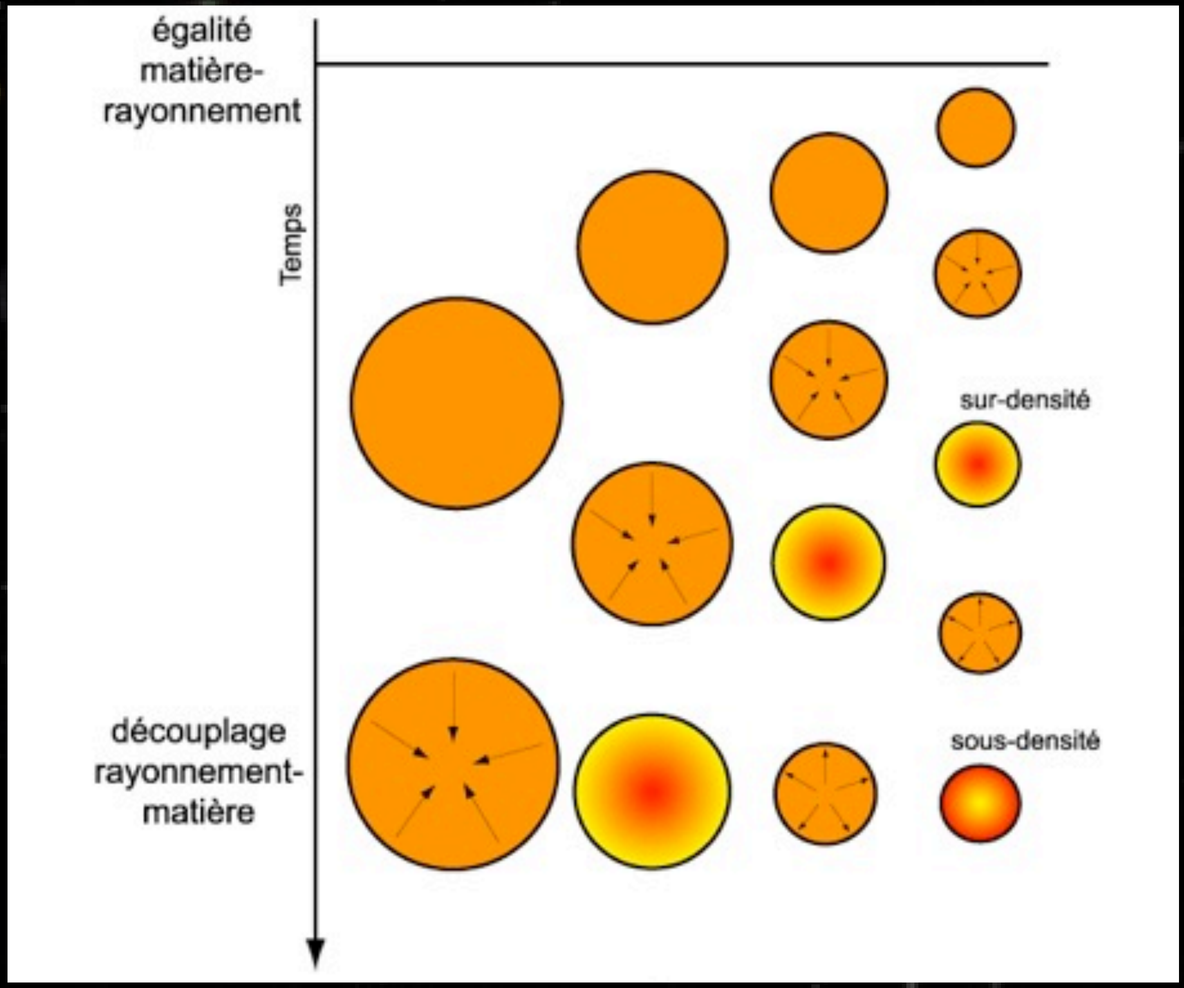
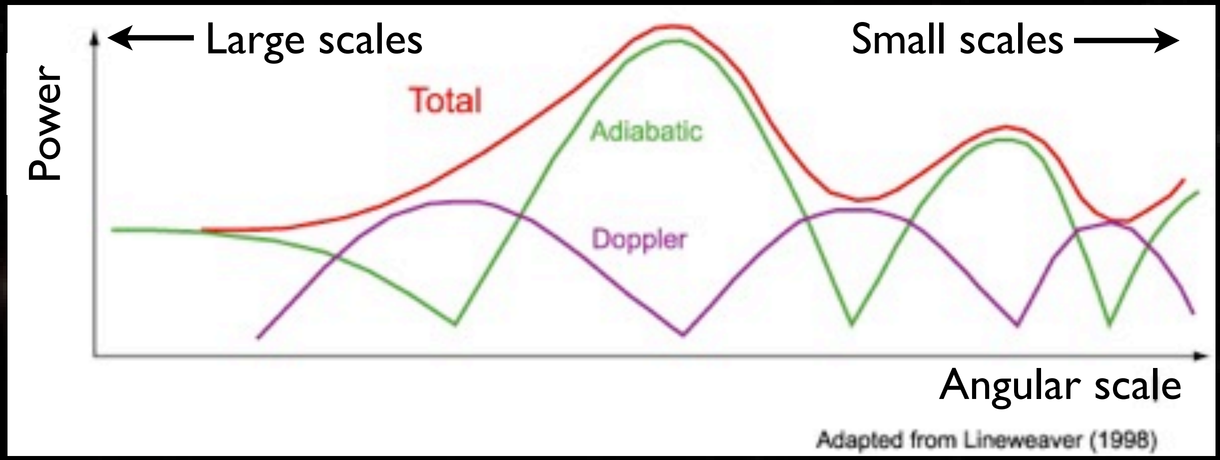
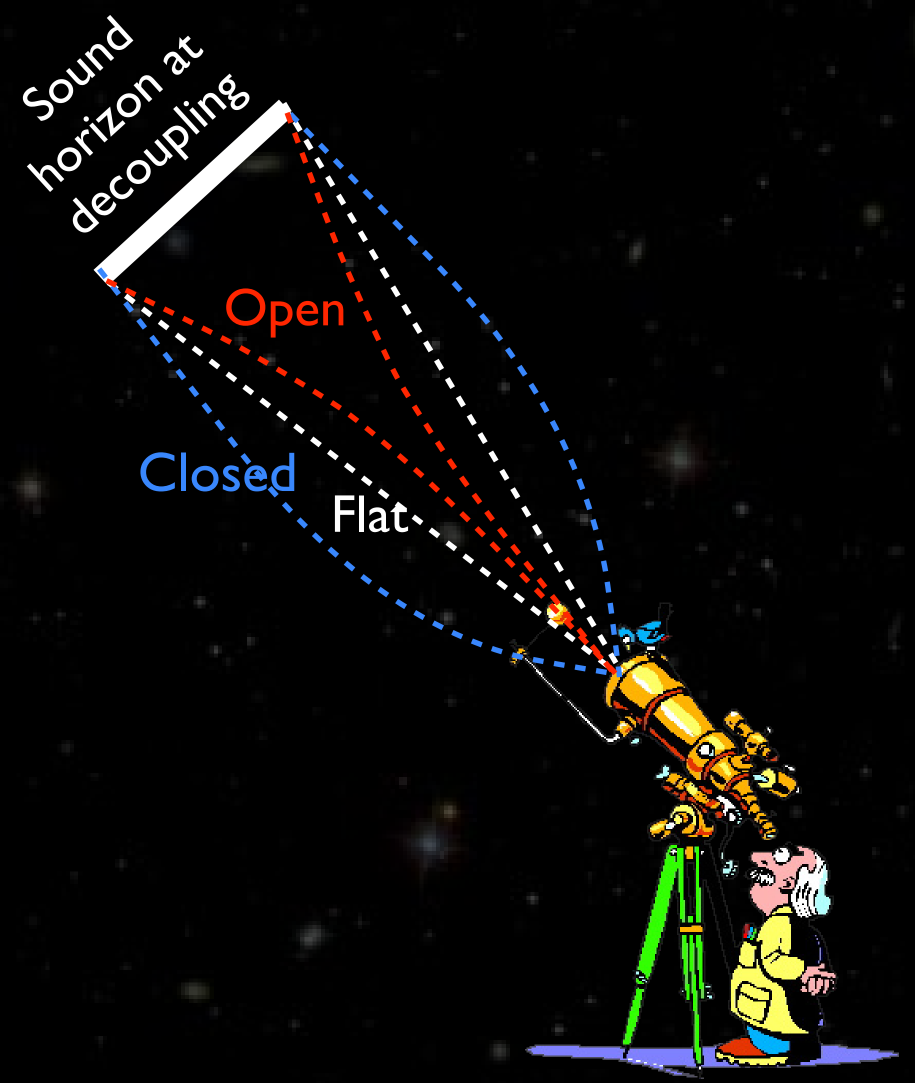
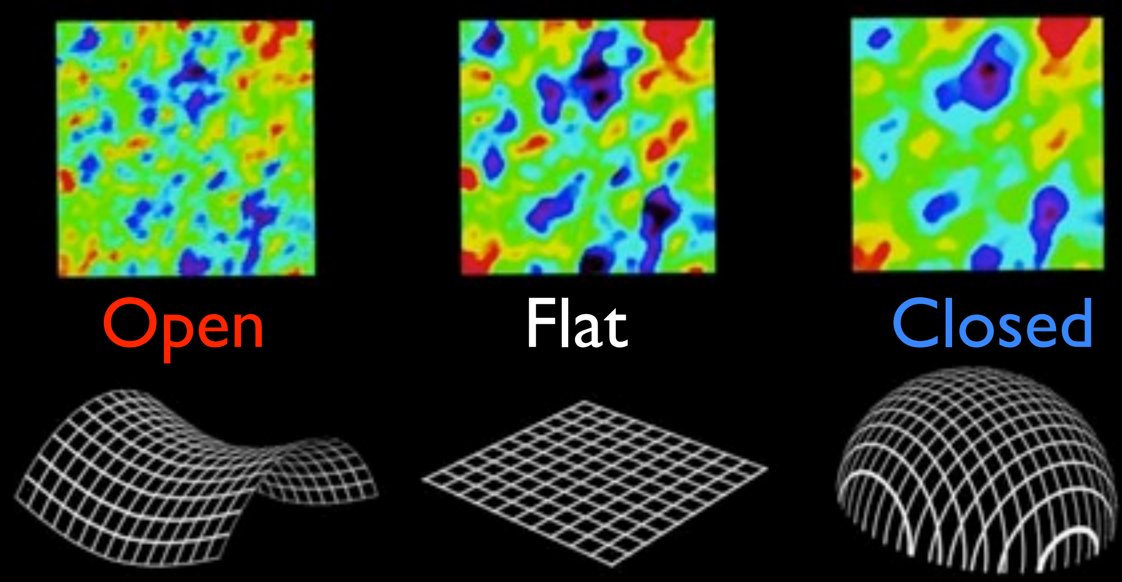




Influence of the cosmological parameters





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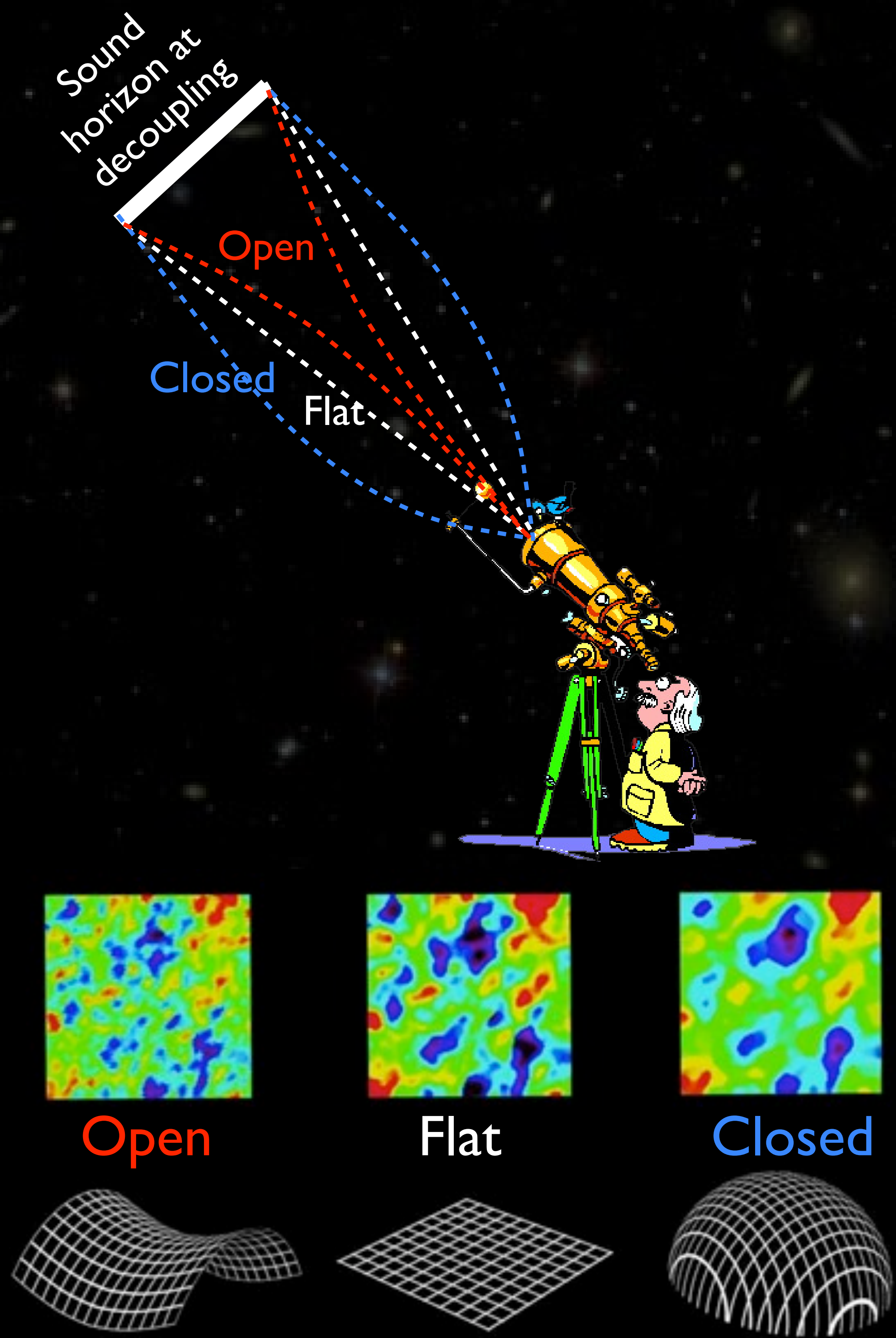
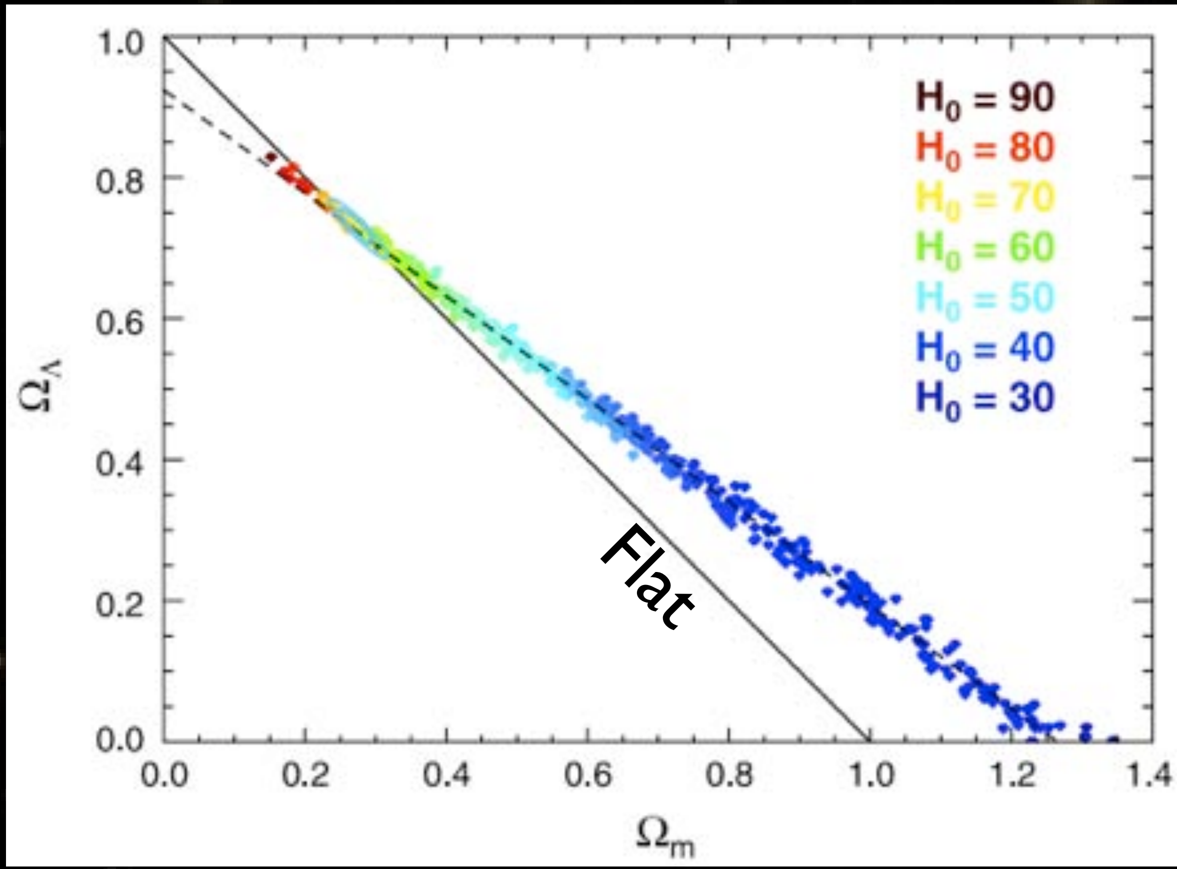


Actually slightly more complex due to the degeneracy with H et Λ



WMAP 7y

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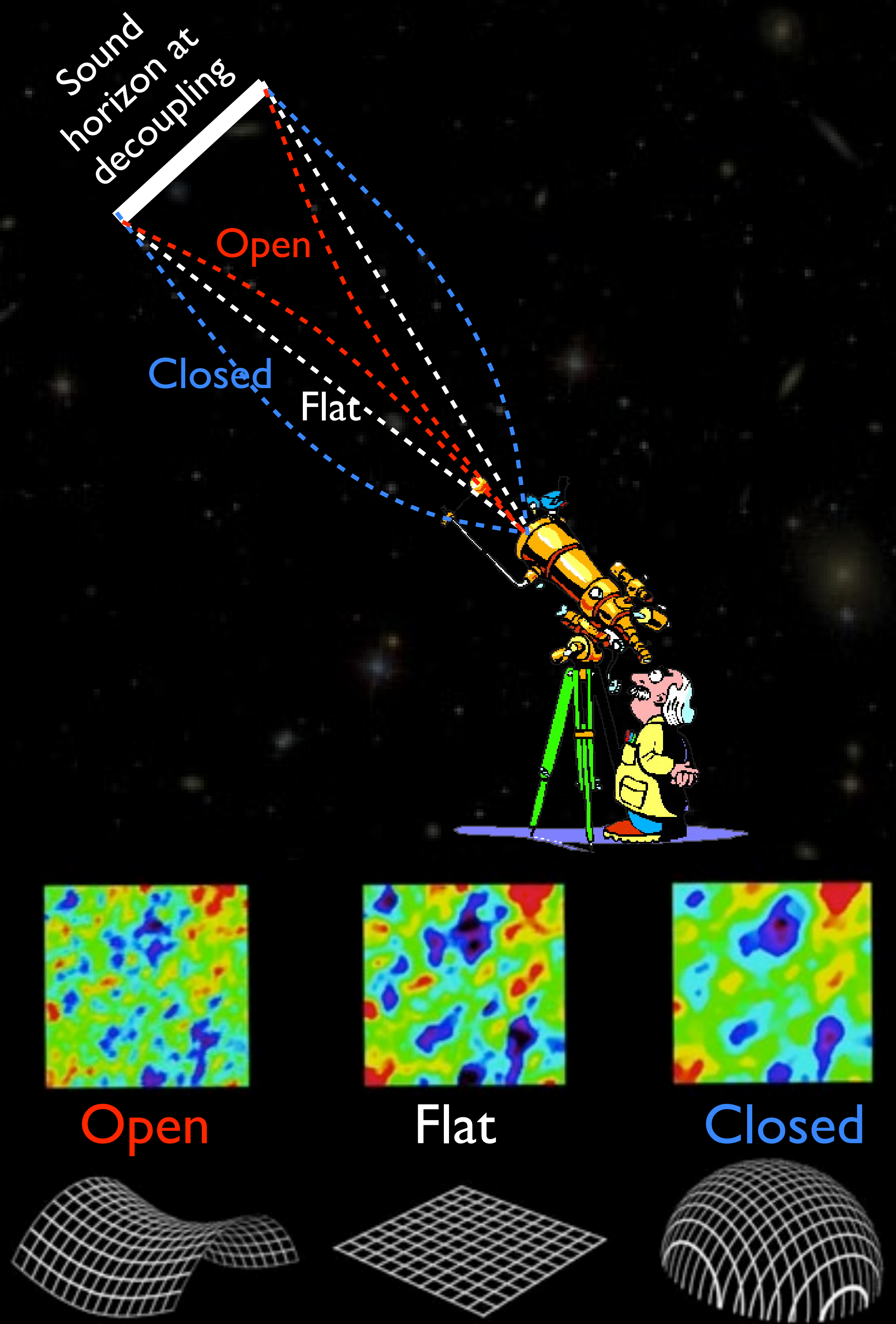

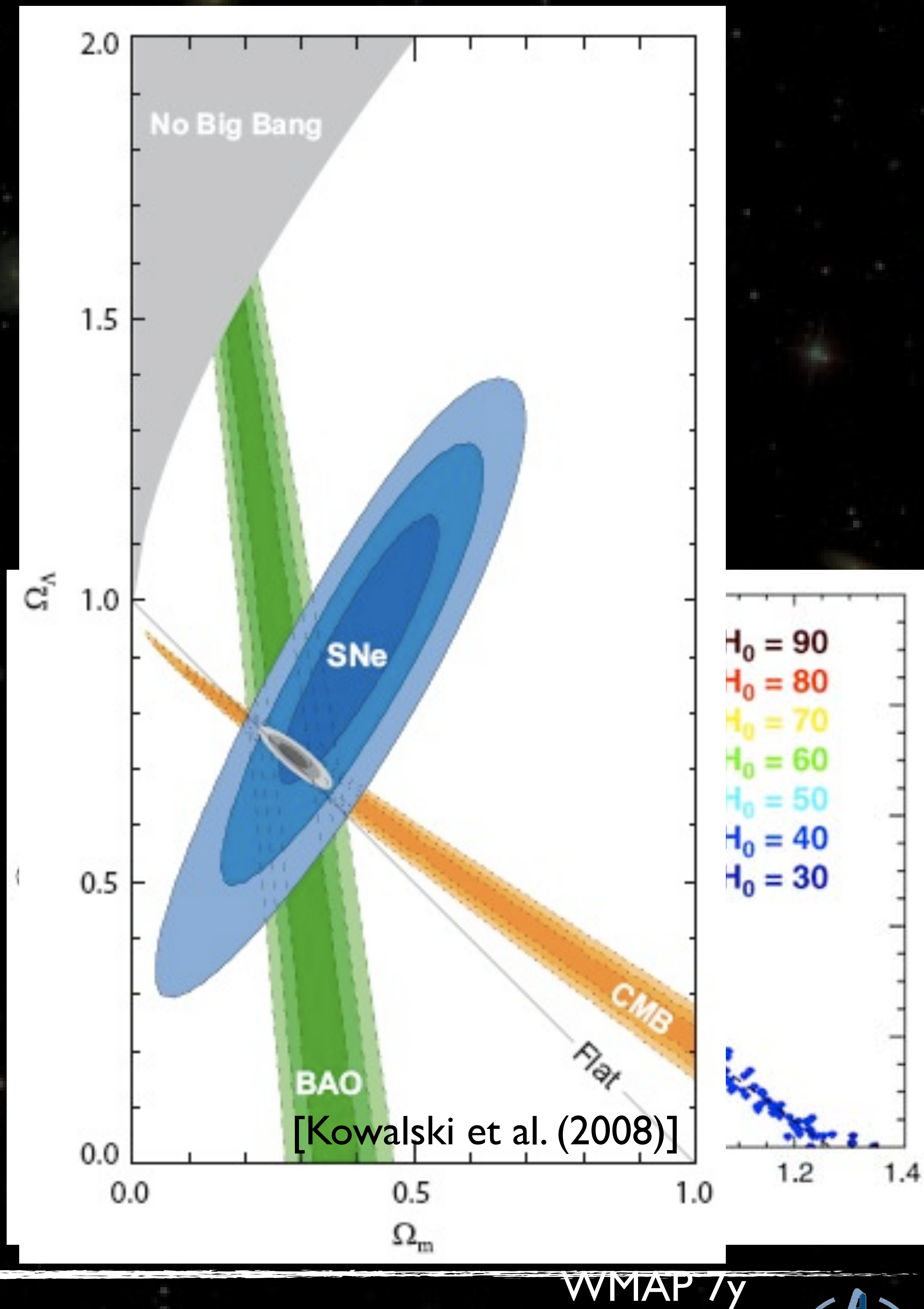

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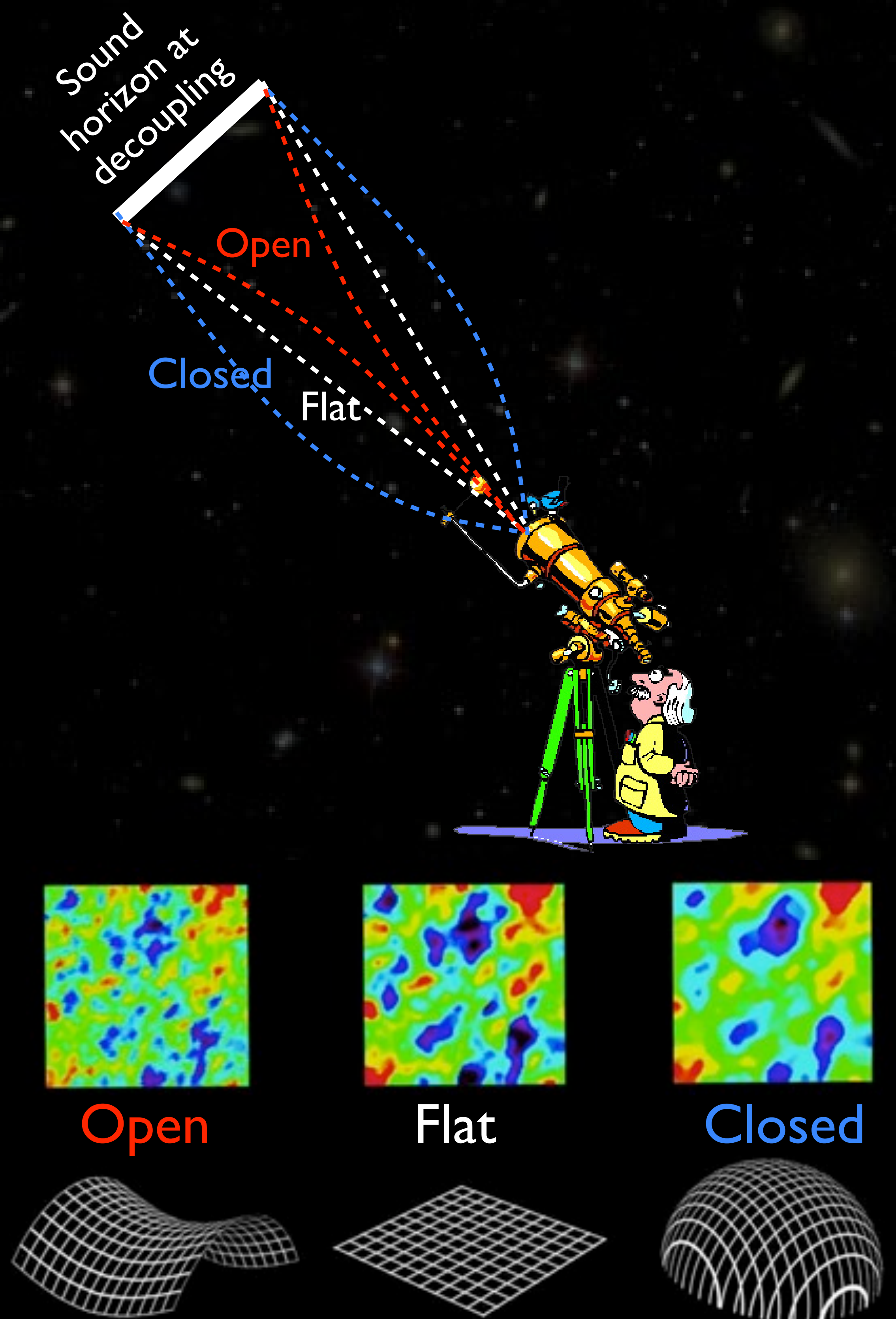
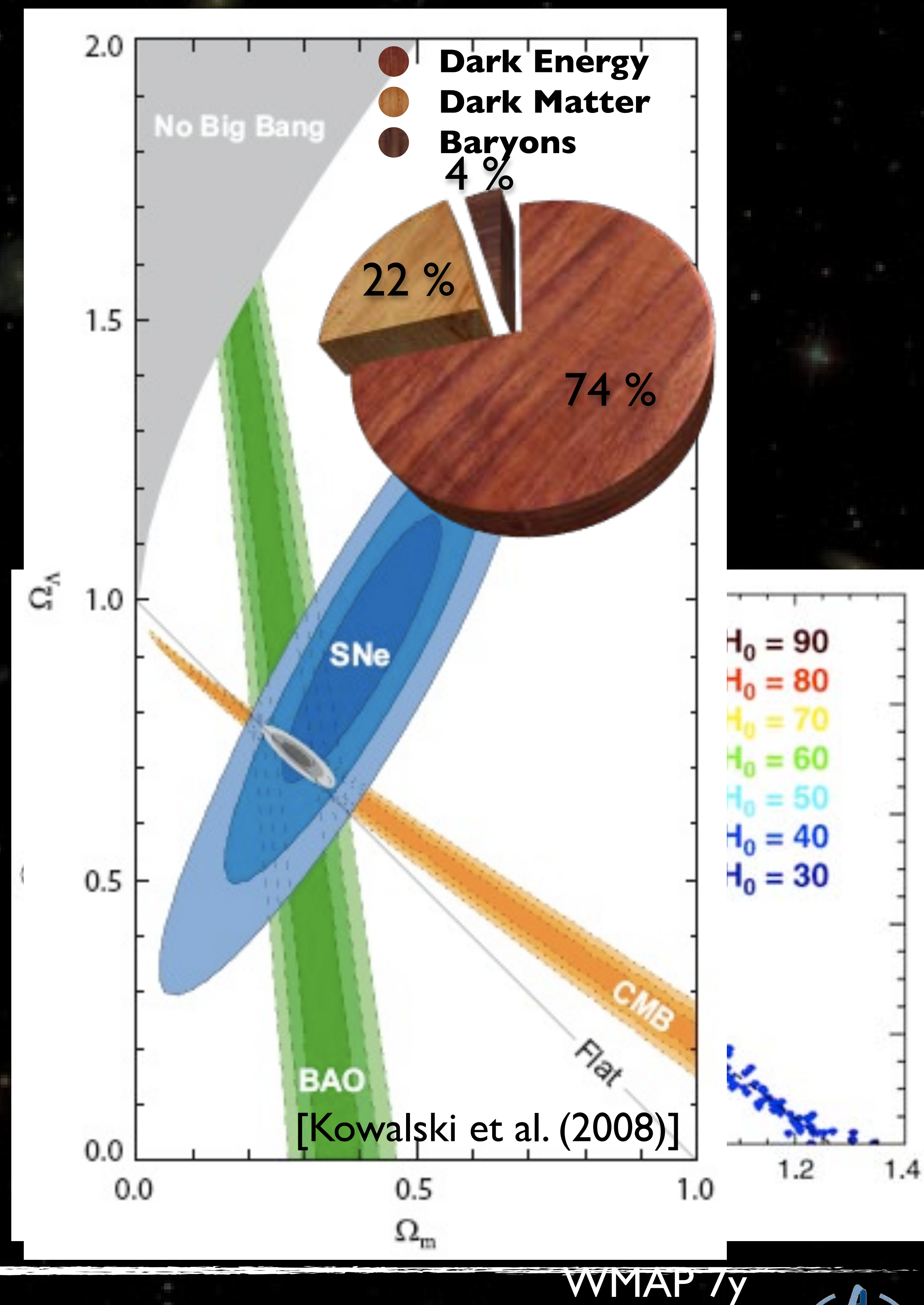
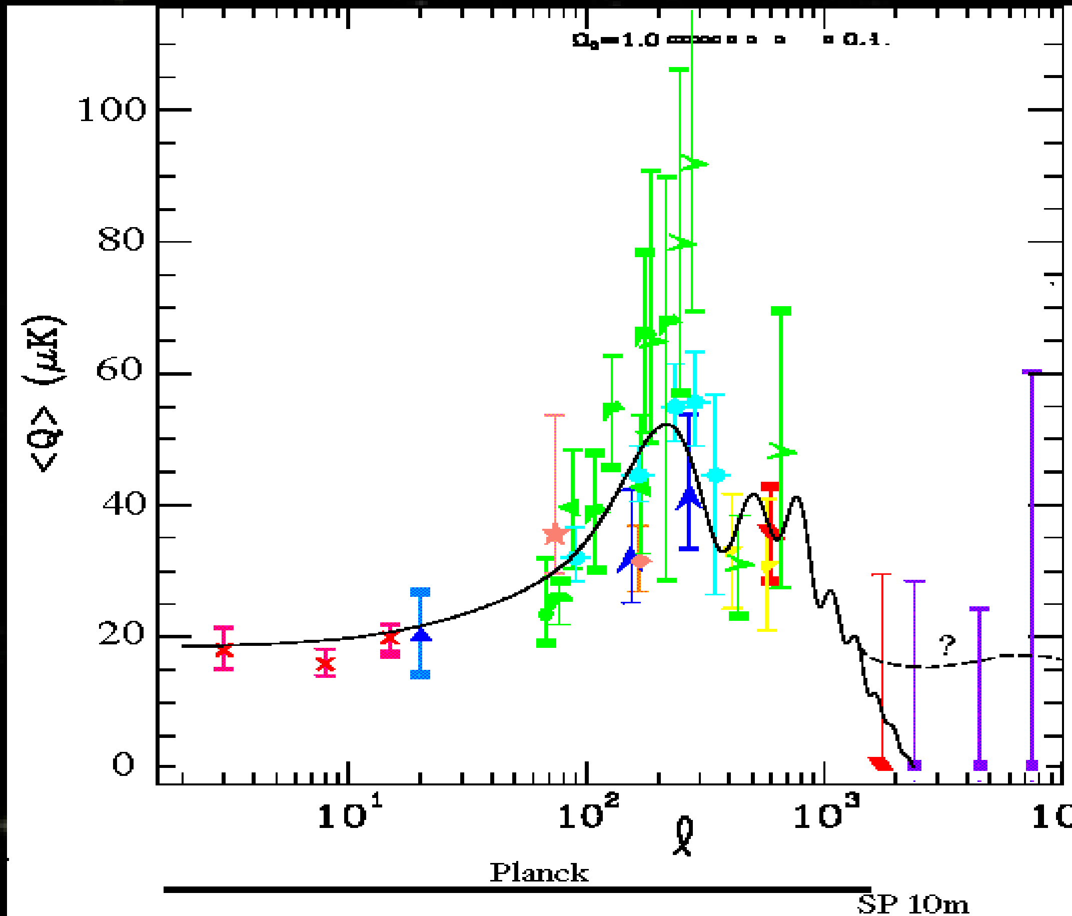
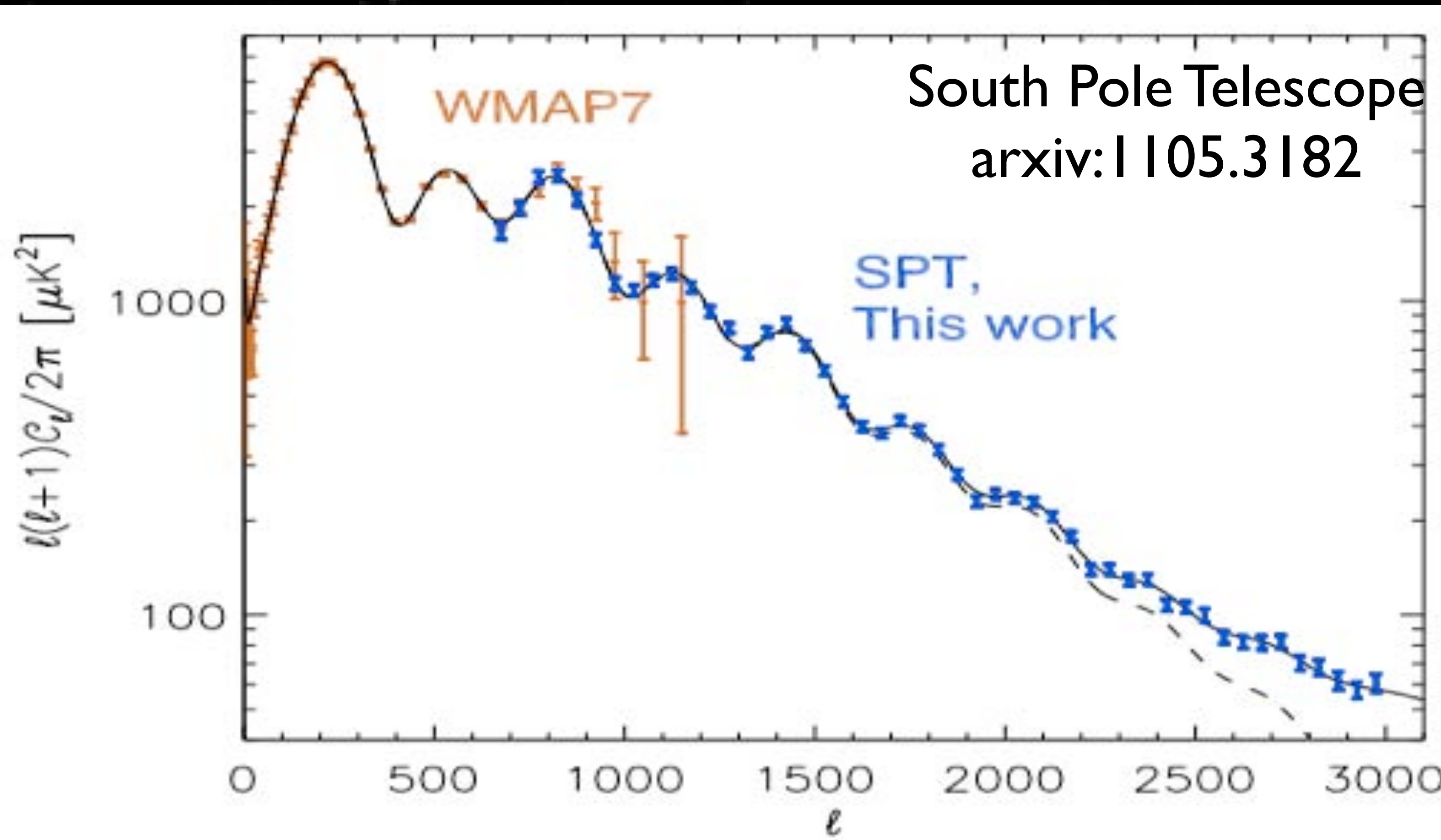




Tremendous progress over the last decade





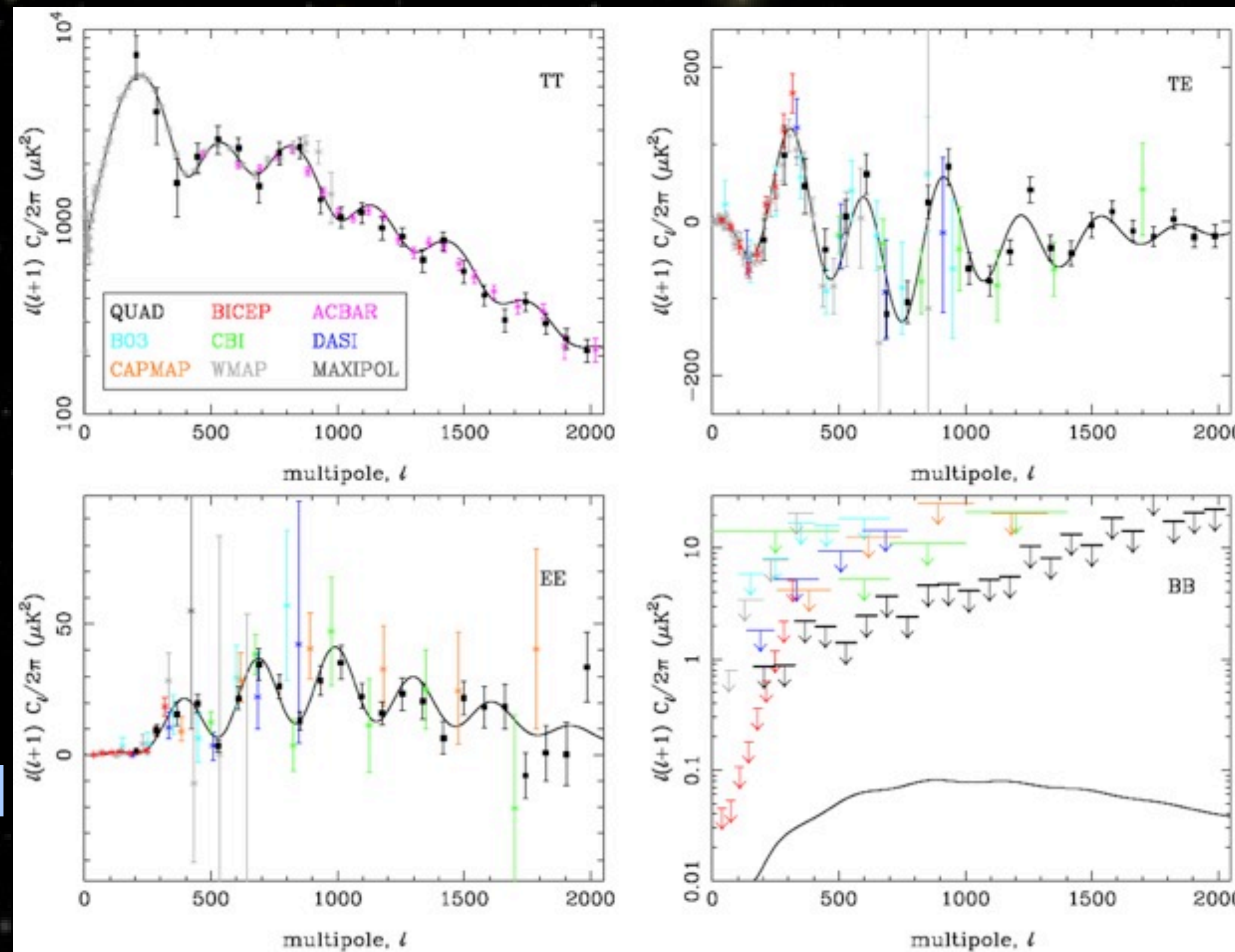
1999 2011

Huge success : thousands of independant points fitted with less than 10 parameters and a χ^2/ndf about 1

Theoretical curve predicted in 1987 [Bond & Efstathiou] without any data ...

CMB Polarization

- Predicted long ago
  - ★ electrons/photons scattering before decoupling
- Detection 2001
  - ★ DASI et CBI (interferometers)
- Later measurements:
  - ★ WMAP, QUAD, BICEP ...
  - ★ Perfect agreement with temperature measurements
- Correspondance between TT peaks and EE troughs
  - ★ Typical of adiabatic primordial fluctuations (generated by inflation for instance ...)



[QUAD Collaboration: Arxiv:0906.1003]

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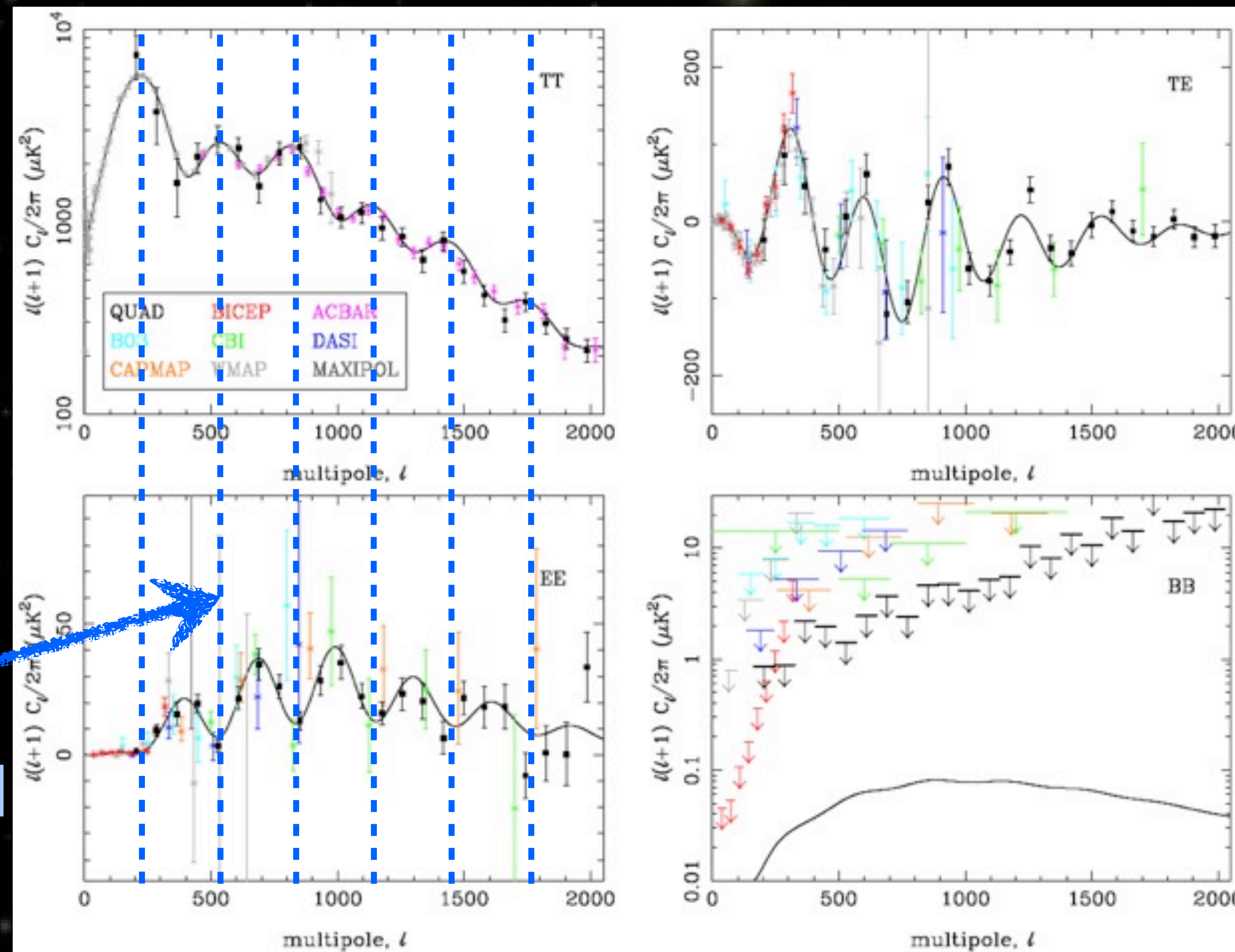

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Major steps for CMB

- 1965: Dicovery by Penzias & Wilson
  - ★ Isotropic black-body radiation at T~3K
- 1992: COBE
  - ★ Anisotropies discovered $DT/T=10^{-5}$
  - ★ Black-body confirmed
- 1999: Boomerang and Maxima
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→ • Confirmation of adiabatic primordial perturbations
• Precision cosmology

Major steps for CMB

- 1965: Dicovery by Penzias & Wilson
  - ★ Isotropic black-body radiation at T~3K
- 1992: COBE
  - ★ Anisotropies discovered $DT/T=10^{-5}$
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- 2001: DASI & CBI
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- 2003: WMAP
  - ★ Exquisite full-sky measurement of T and E
- 2013: Planck
  - ★ Ultimate measurements of T and E
- 20XX: B-modes experiments
  - ★ primordial gravitational waves

→ • Big-Bang confirmed...
• Where are the anisotropies ?

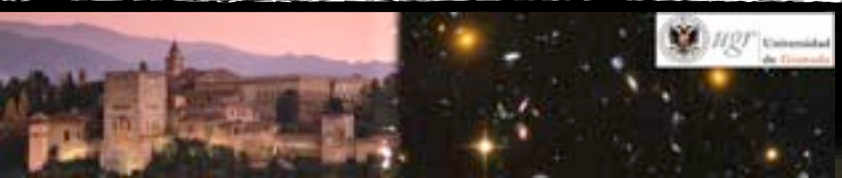
→ • Cold Dark Matter strongly favoured

→ • Topological defects excluded
• Inflation favoured
• Evidence for flatness

→ • Major prediction confirmed

→ • Confirmation of adiabatic primordial perturbations
• Precision cosmology

→ • Ultimate T and E spectra
• factor 3 gain on cosmological parameters



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→ • Exploration of inflationary physics

Primordial fluctuations: where are we standing ?

Inflation predictions

• **Flatness, Homogeneity**	✔
• **Nature of perturbations:** ★ TT peaks at the same location as EE troughs [predicted] ➡ Adiabatic perturbations	✔
• **Spectral index** $P(k) \propto k^{n_s - 1}$ ★ SPT+WMAP [arxiv:1105.3182] $n_s = 0.9663 \pm 0.0112$ ➡ Almost scale invariant spectrum [predicted]	✔
• **Gaussianity** ★ No convincing evidence for non-gaussianity (despite impressive efforts)	✔
• **Tensor perturbations of the metric** ★ No B-mode detection (yet ...)	?

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Dark Matter

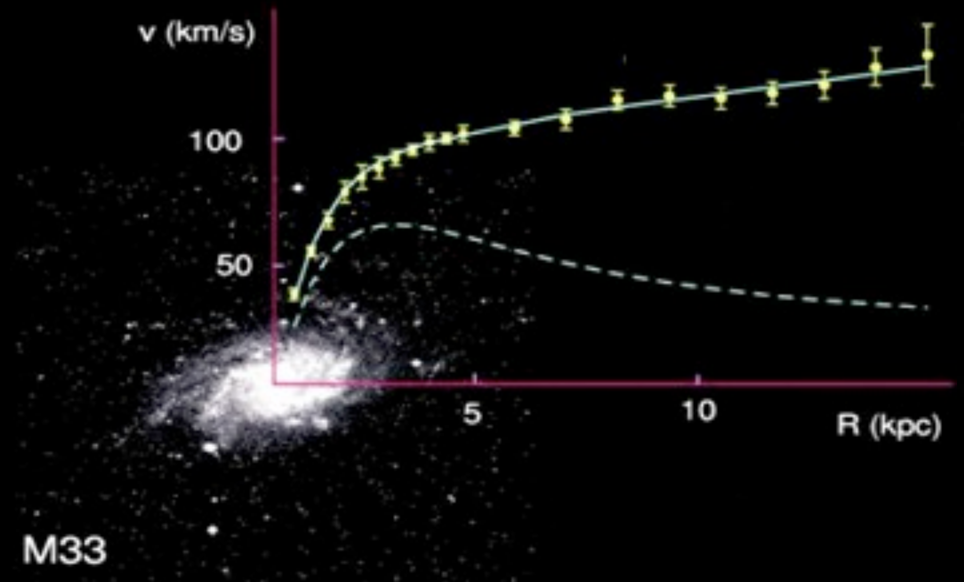
Bullet Cluster

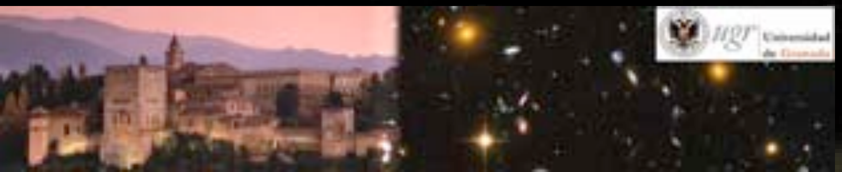
Dark Matter

- **Clusters dynamics:**
  - ★ Zwicky 1933
    - velocity dispersion gives kinetic energy
    - Distances between galaxies gives potential energy
    - Virial theorem allows to infer mass
    - 100-500 times larger than stellar mass
  - ★ X emission from hot gaz in clusters
    - gaz far more extended than galaxies in clusters
    - BUT:
      - gaz can account for a factor 2 in mass
      - gaz needs to be heated to 10^7-10^8K
    - ➡ ~85% dark matter needed

Coma cluster (image X: ROSAT)

- **Galaxies rotation curves**
  - ★ Stars velocities too high in outer parts
  - ★ well explained by a dark matter halo with ~ 200 times the stellar mass





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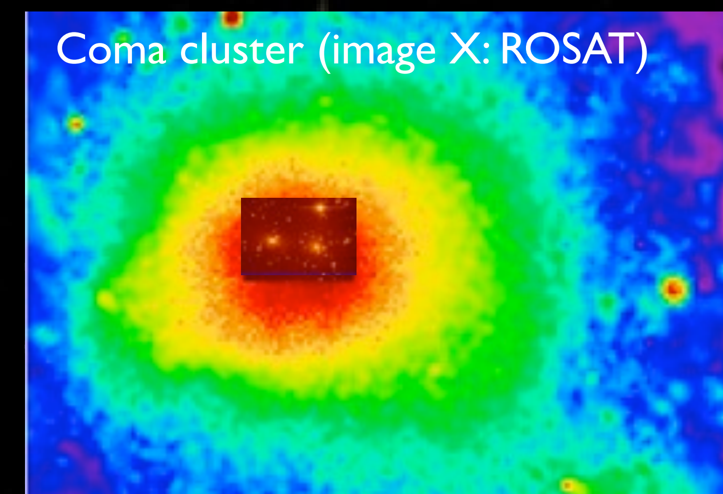

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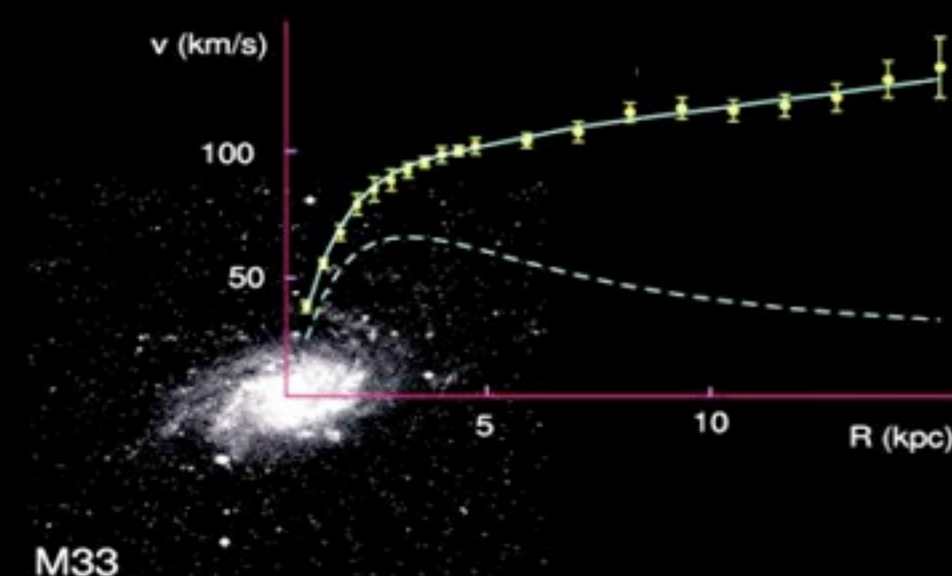
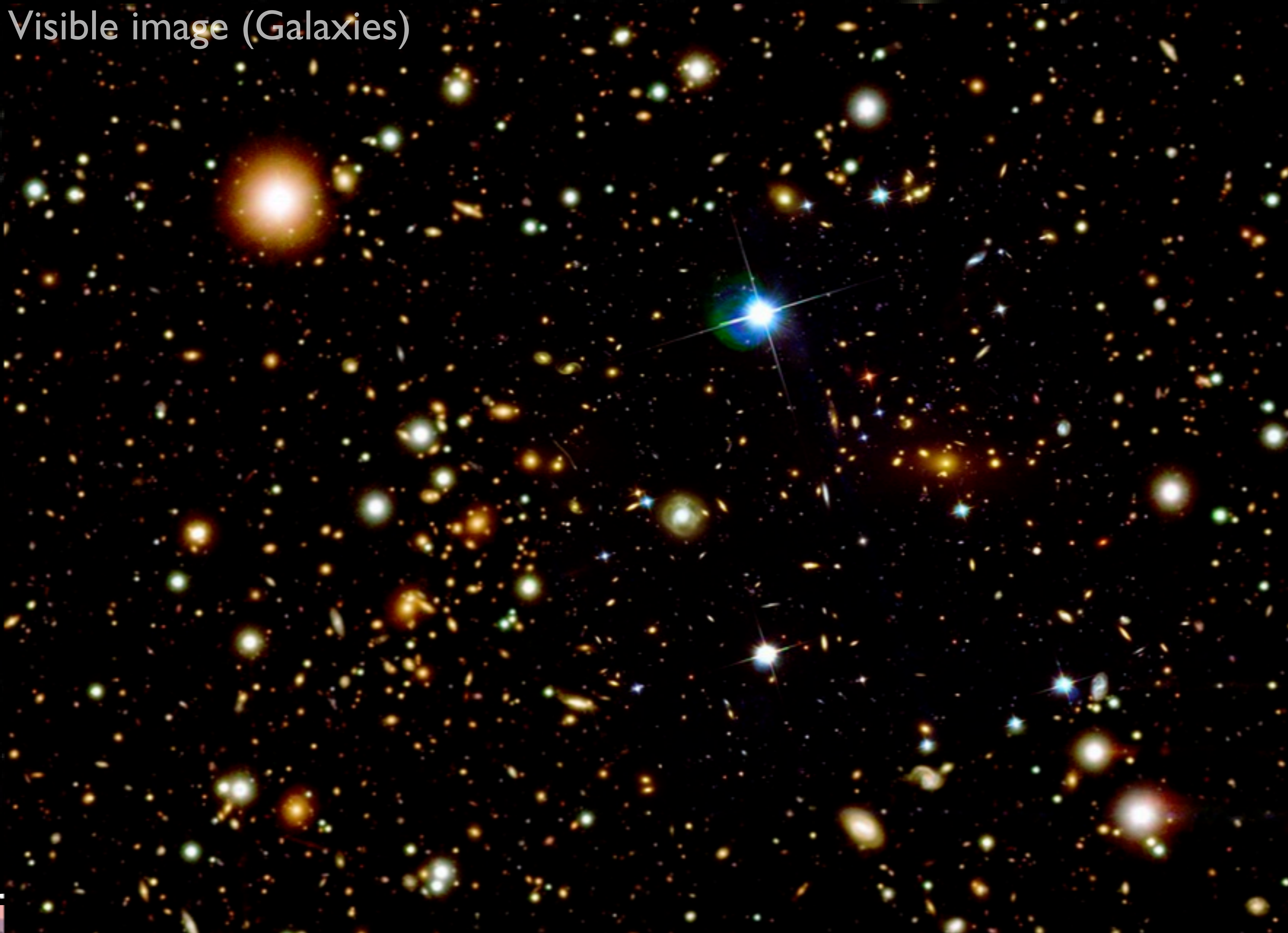


The Bullet Cluster

Visible image (Galaxies)



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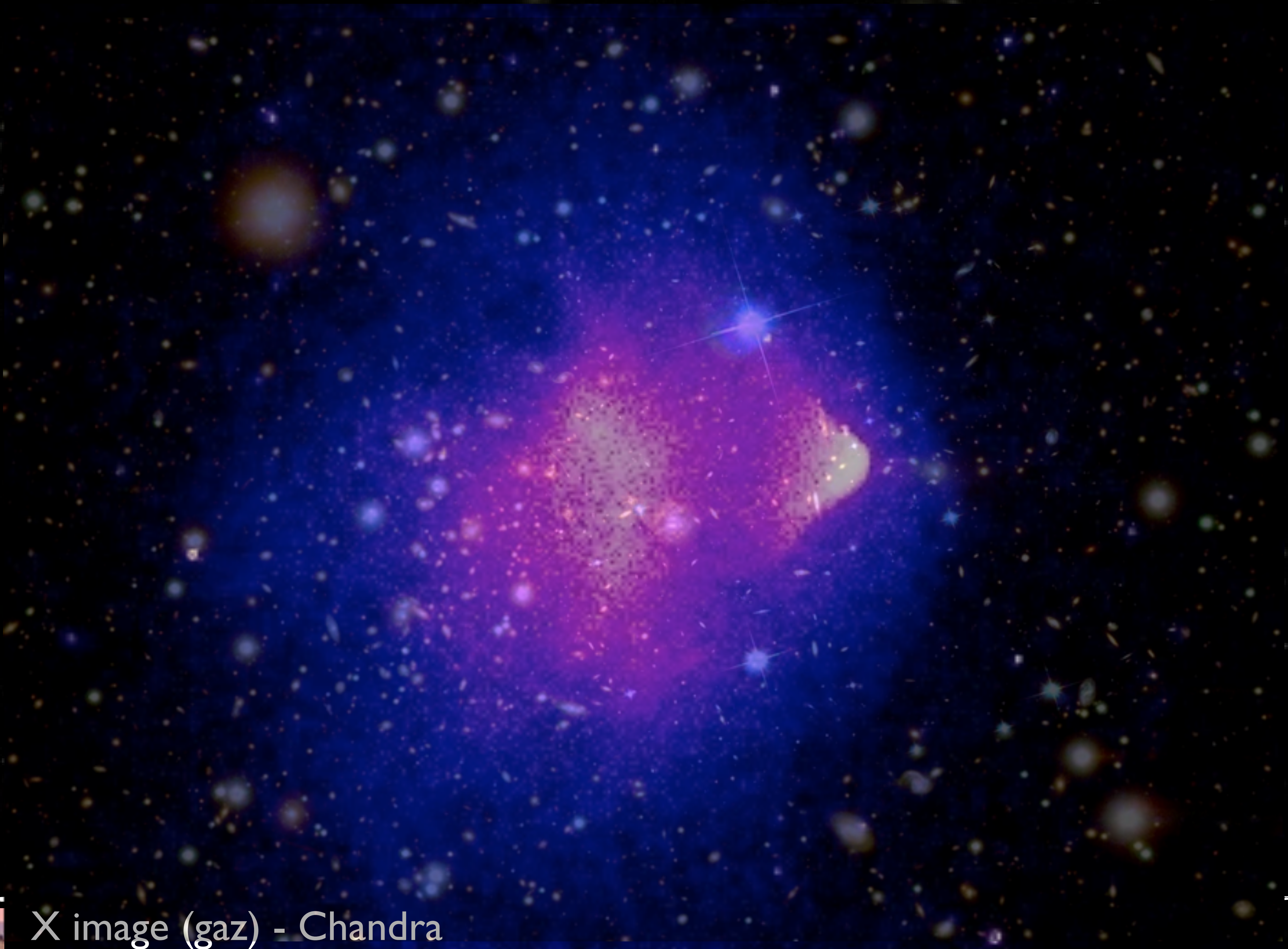

X image (gaz) - Chandra

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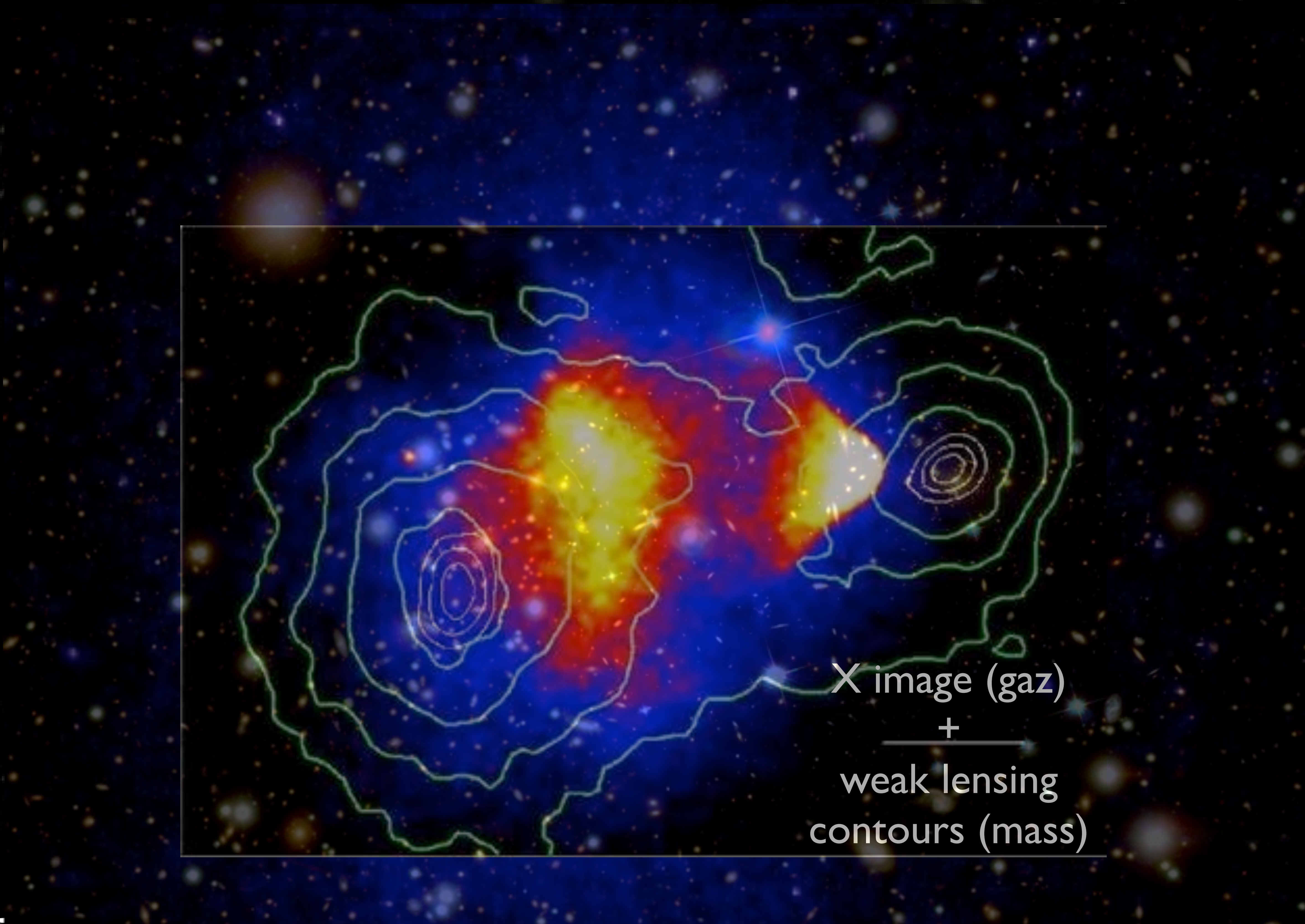

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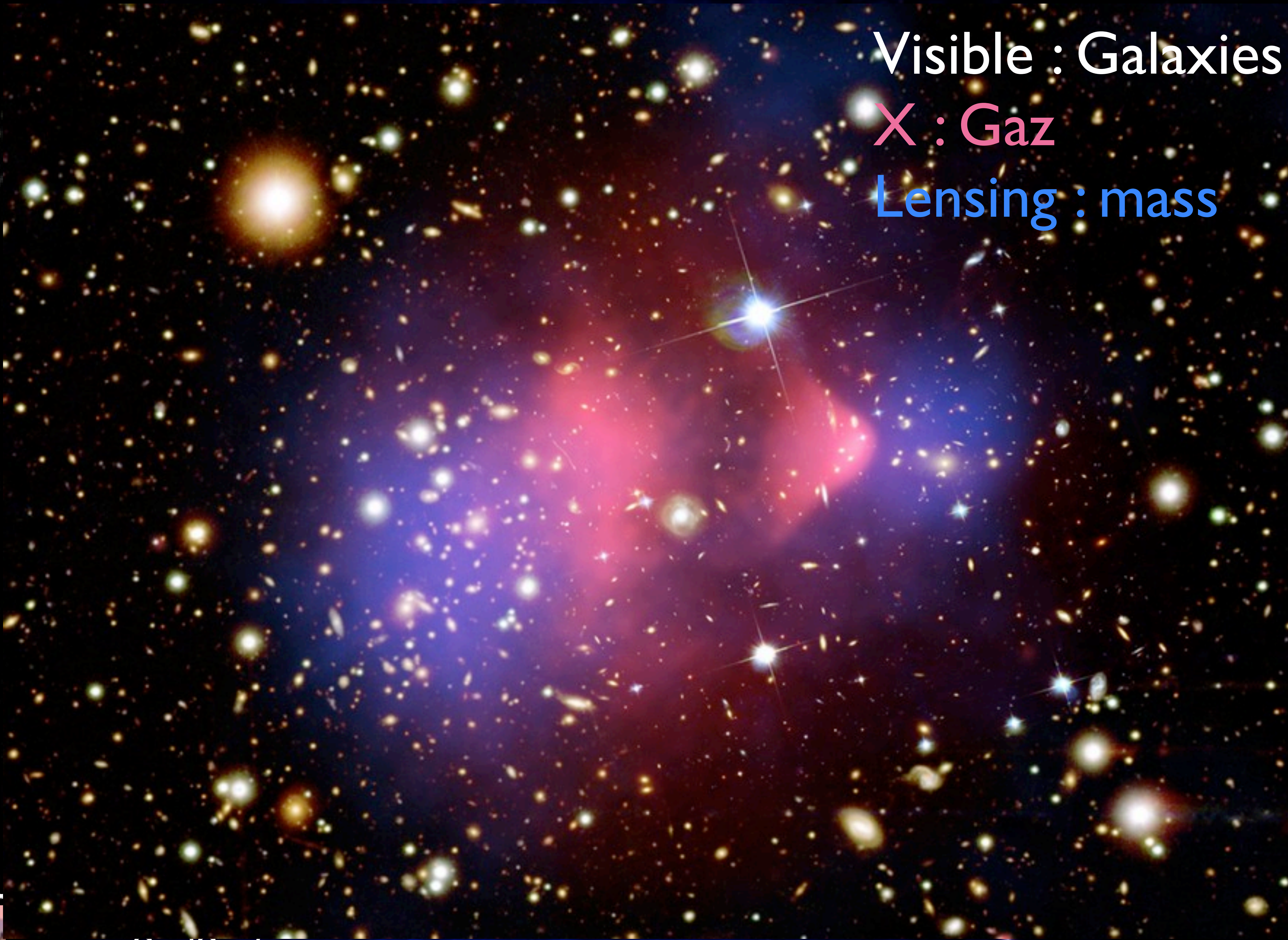


Bullet Cluster

- Collision of two clusters
- Galaxies and dark matter are non collisional
  - ★ They pass without seeing each other
- Gaz is collisional
  - ★ it stays at the center and is heated
  - ★ Shock waves appear
- Strongest argument for Dark Matter ?

but ... there exists a counter example...

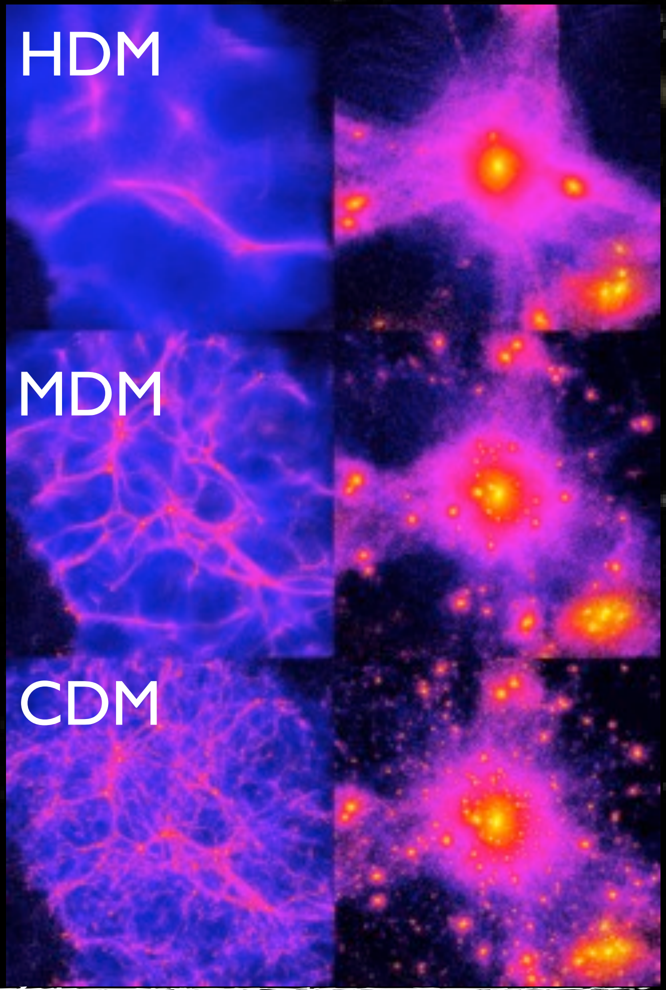
[From F. Combes]

Abell 520
z=0.02
[Mahdavi et al. 2007]

Dark Matter core coincides with gaz, not with galaxies...

Structure formation requires Dark Matter

- Primordial anisotropies
  - ★ very weak from CMB: 1/100 000
- Gravitational collapse
  - ★ starts at matter-radiation equality for ordinary matter
  - ★ Then expansion slows down the contraction
  - ★ This is not enough to explain observations
  - ★ More matter is needed
  - ★ Some matter needs to start collapsing earlier
    - Needs to be decoupled earlier than baryons...
  - ★ Needs to be slow enough (heavy) so that small structures form
- Cold Dark Matter required (CDM)



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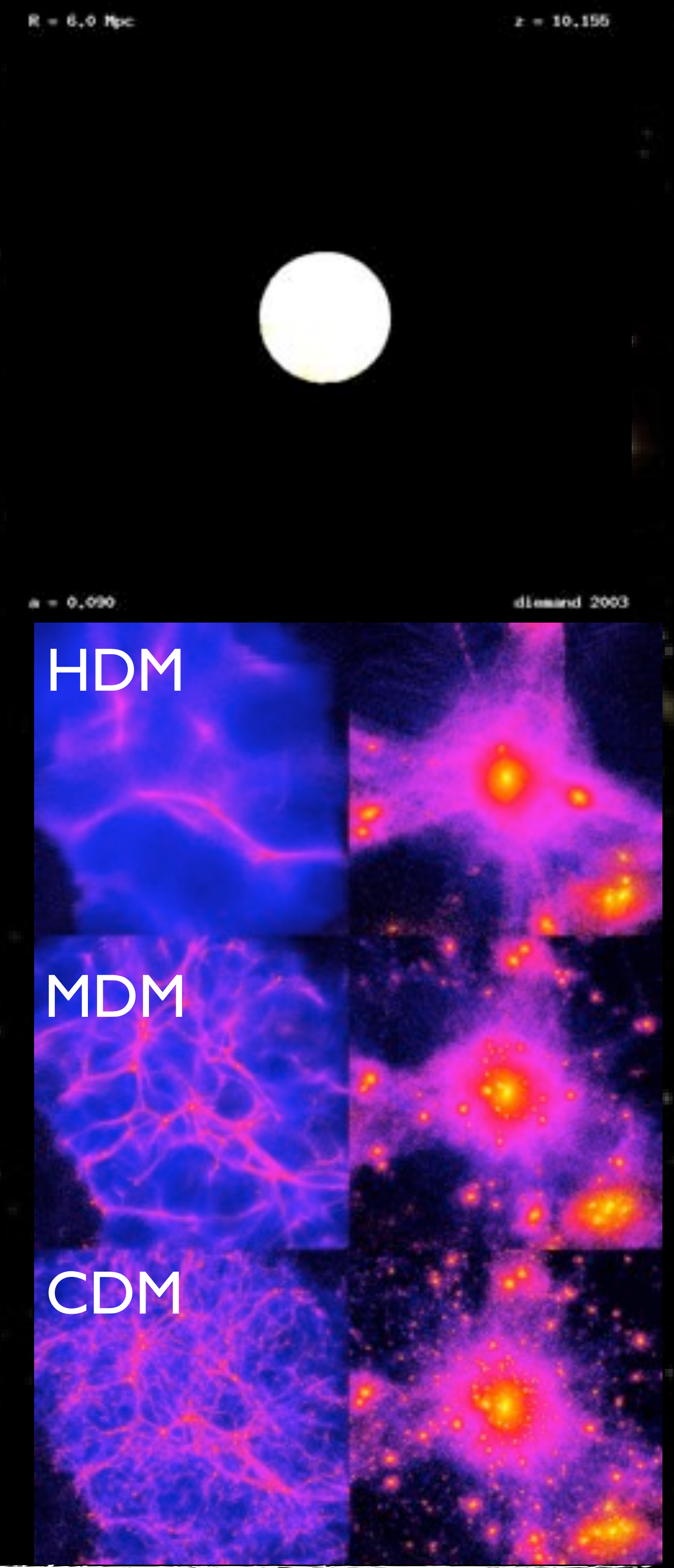
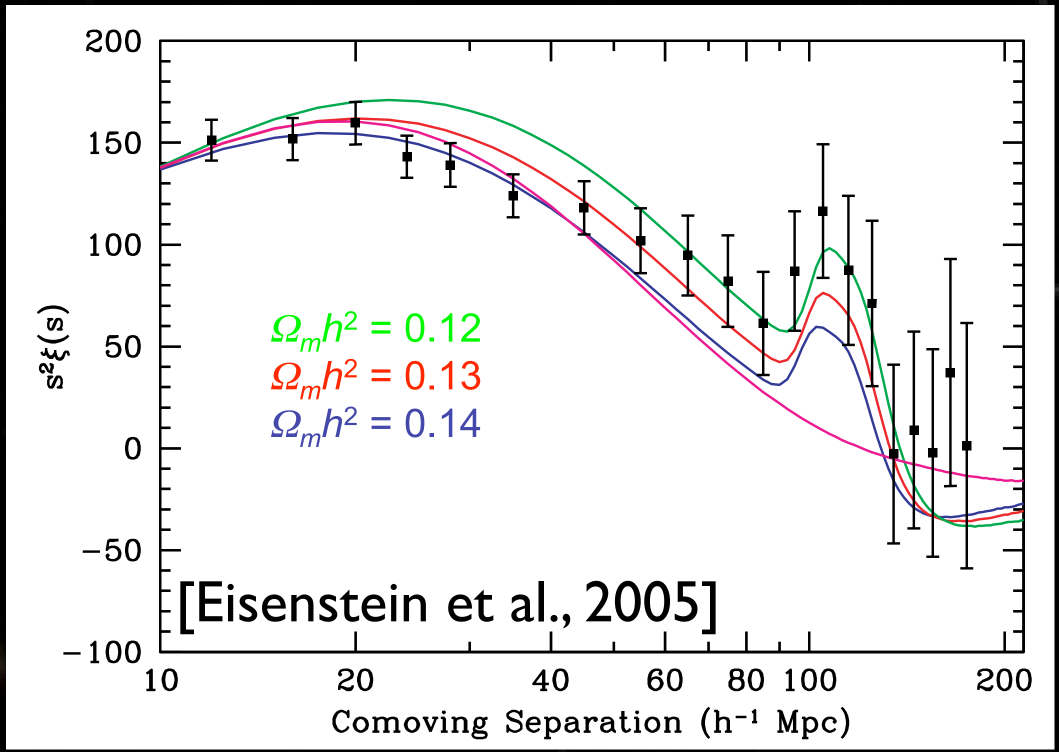


Baryonic Acoustic Oscillations

- BAO:
  - ★ Acoustic Oscillations:
    - between matter/radiation equality and decoupling
    - Sound wave propagation
    - Stops at decoupling
    - ➡ Observed in the CMB
  - ★ Now:
    - Each D.M. peak surrounded by a spherical excess
    - ➡ Galaxies prefereably form there
    - peak in the 2-pts correlation function of matter
    - Standard ruler for angular distance test
  - ★ Meaning:
    - Prediction confirmed ! at the right place !
    - This is among the strongest evidences for Ω_m=0.3 and the presence of Dark Matter



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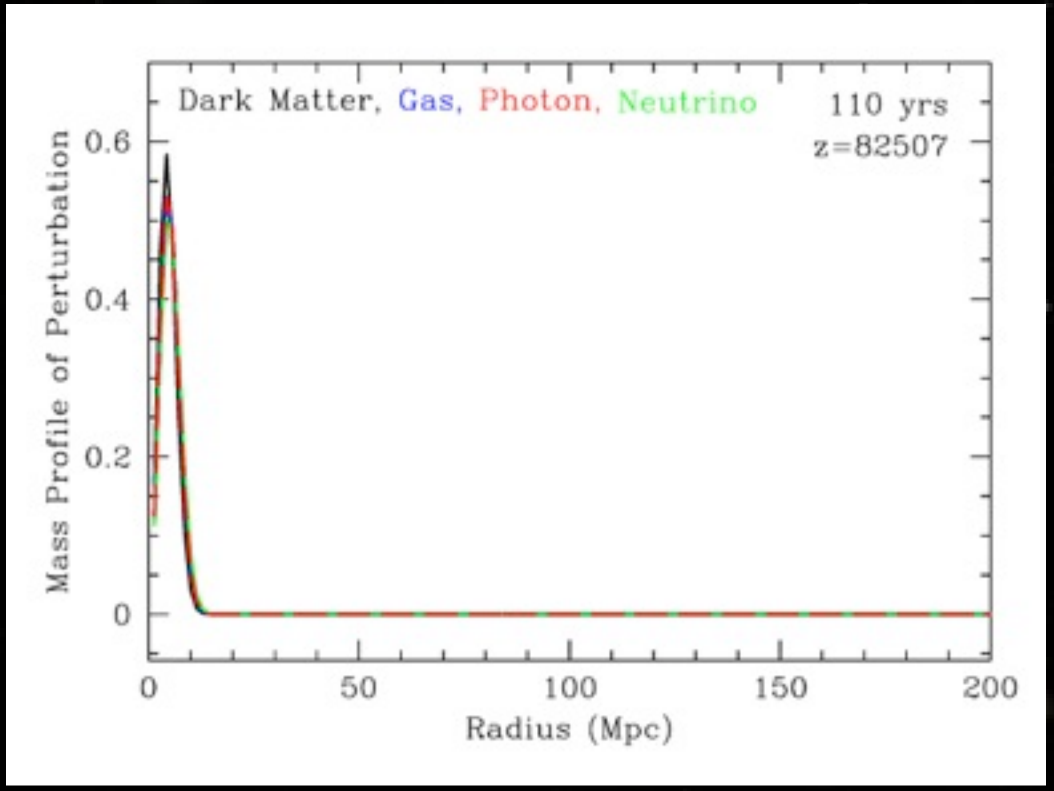
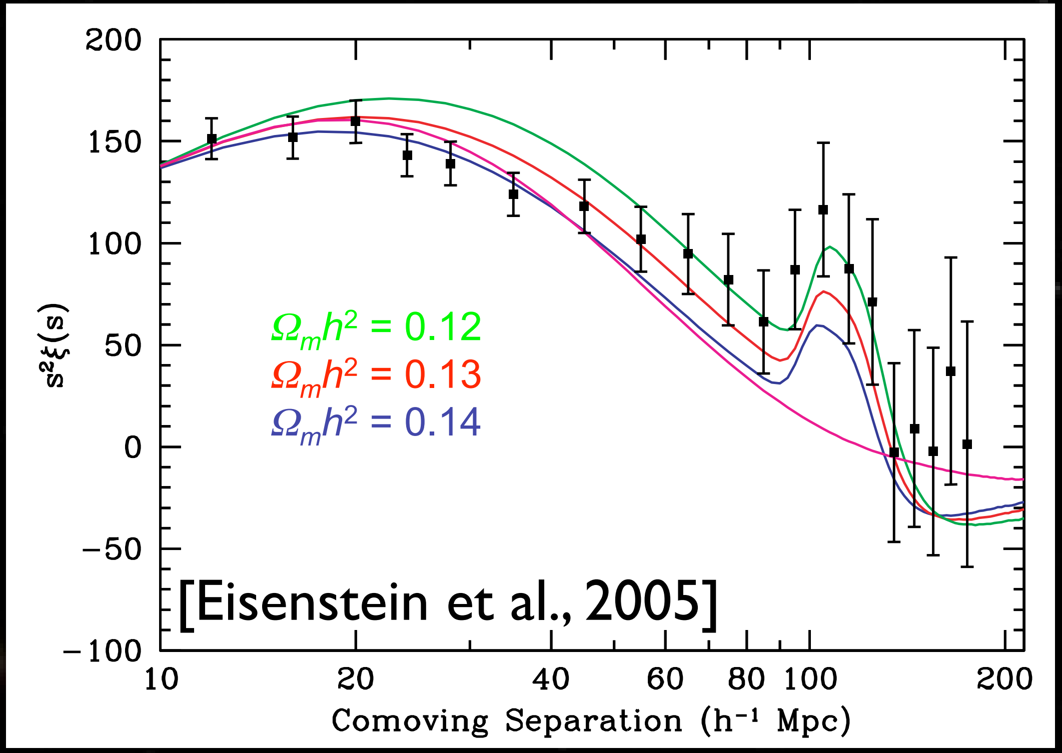
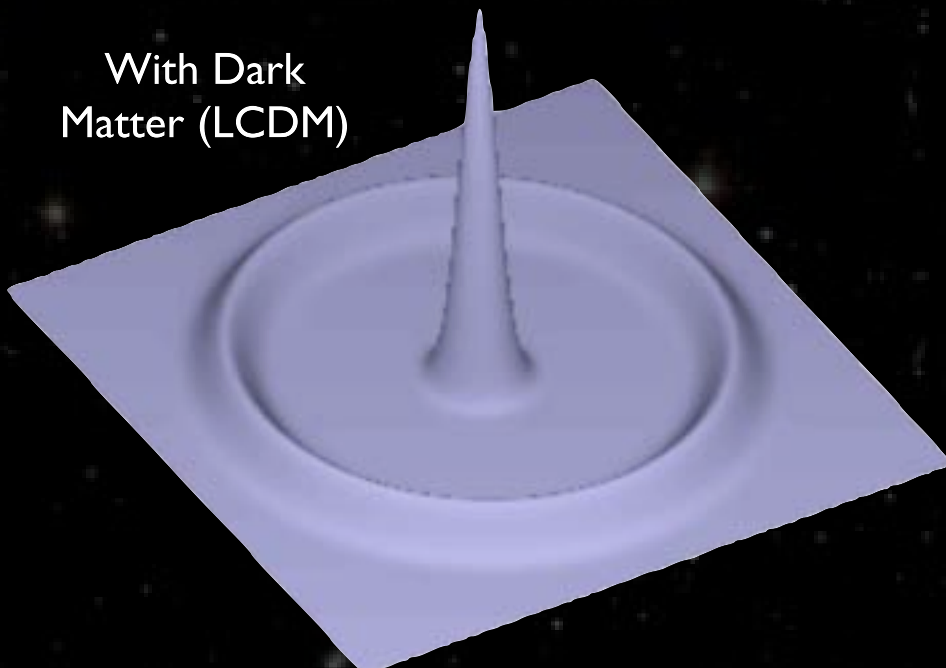


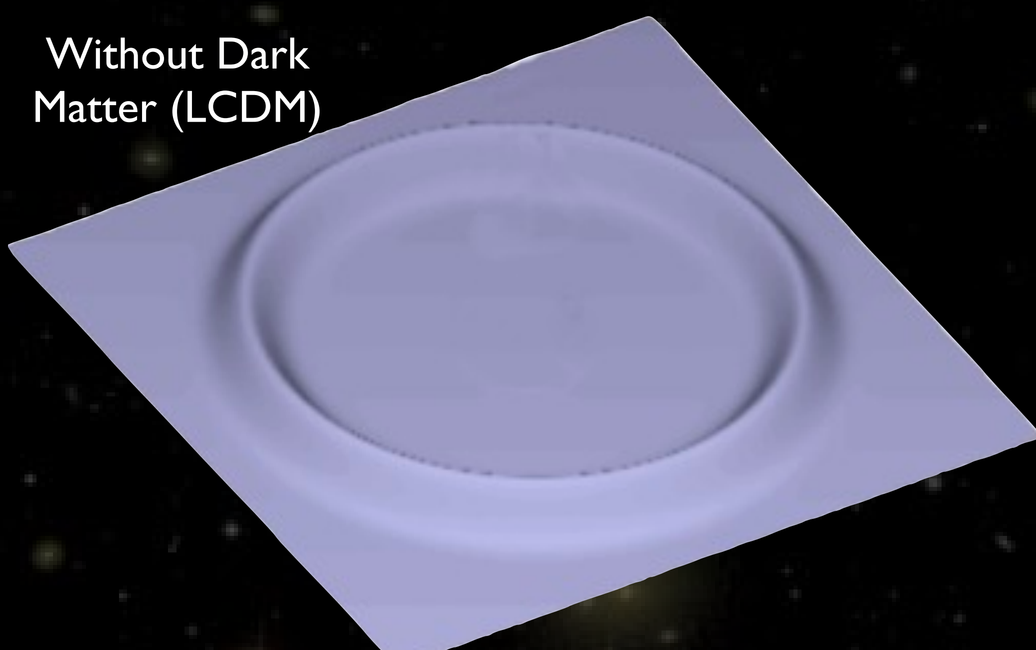


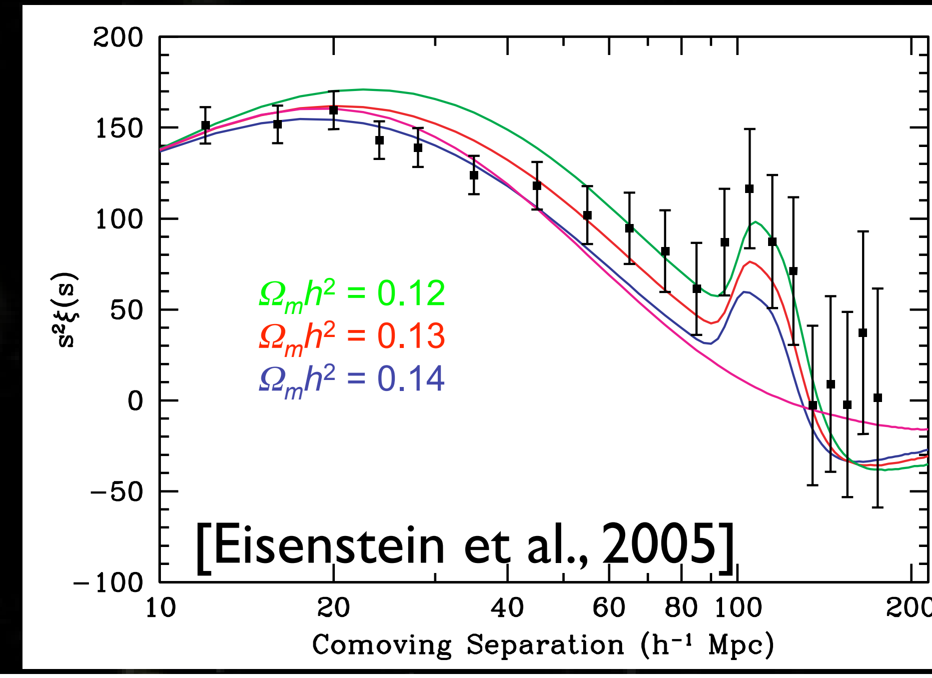
BAO support Dark Matter

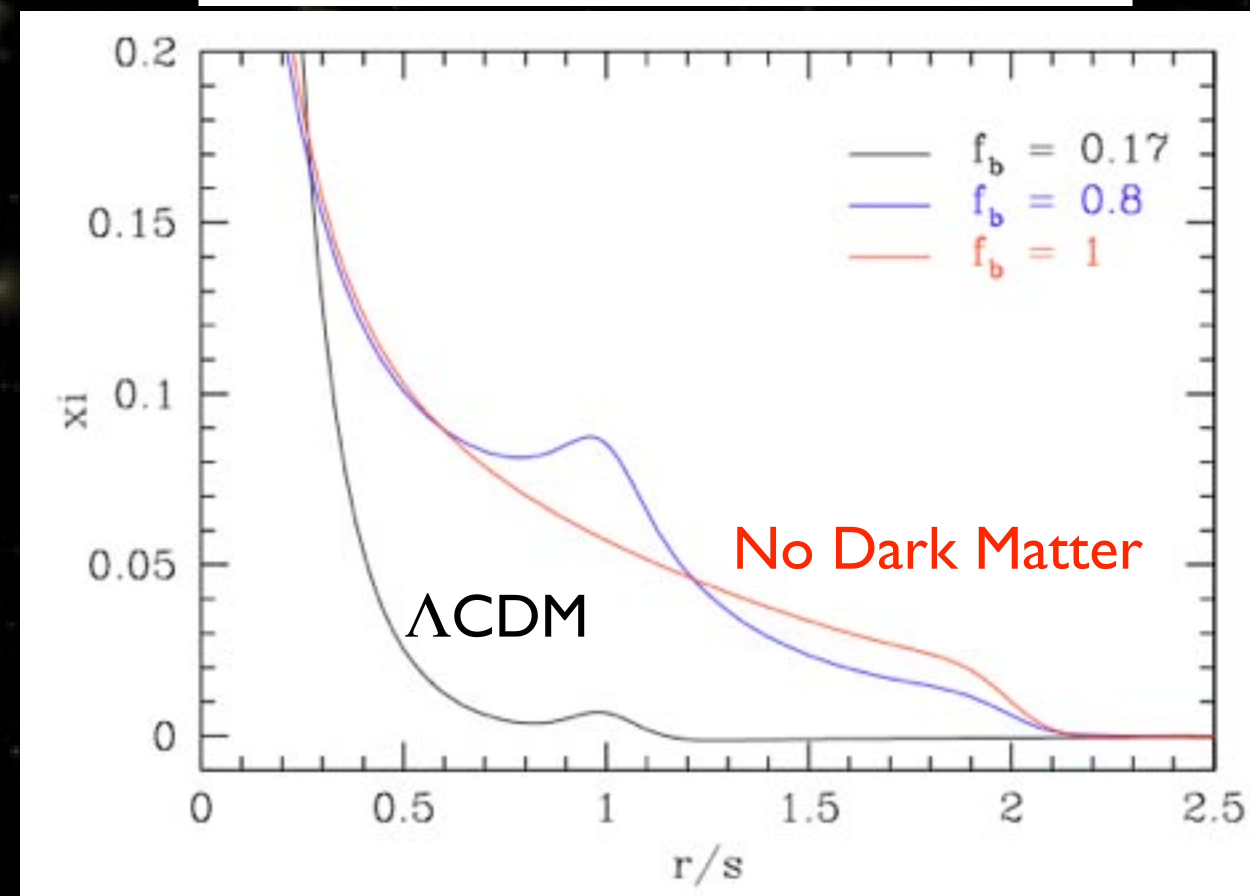
With Dark Matter (LCDM)



Without Dark Matter (LCDM)

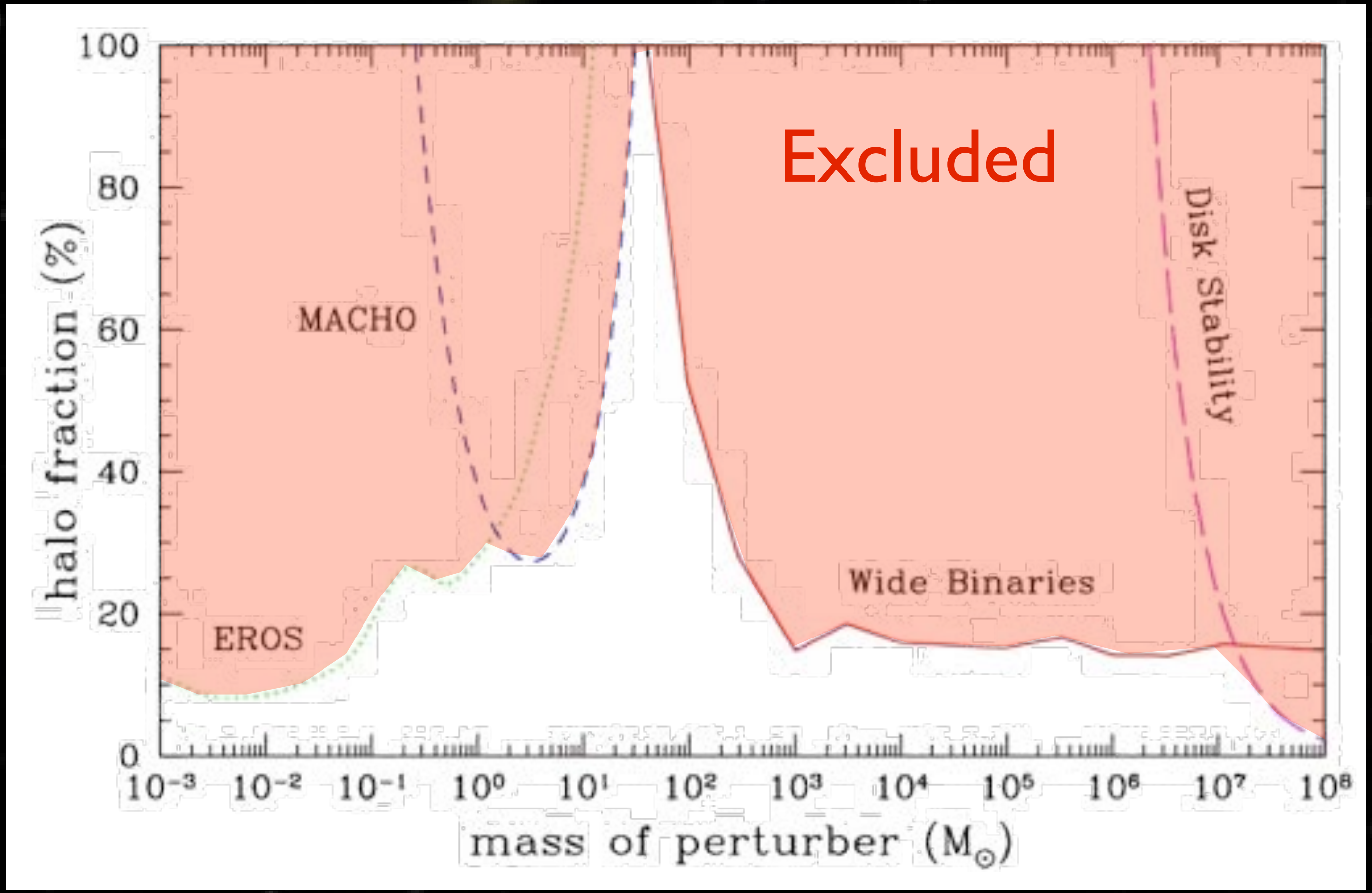






Candidates for Dark Matter

- Compact objects
  - Black holes, brown dwarfs
  - Essentially excluded in the late 90s
- Particle Physics



- Modifications of Gravity

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- Particle Physics
  - ★ Supersymetry
    - minimal models seem disfavored by LHC
    - Resists direct search (Edelweiss, CDMS, Xenon)
      - BUT: DAMA, COGENT, CRESST claim for detection
  - ★ Extra dimensions, Axions
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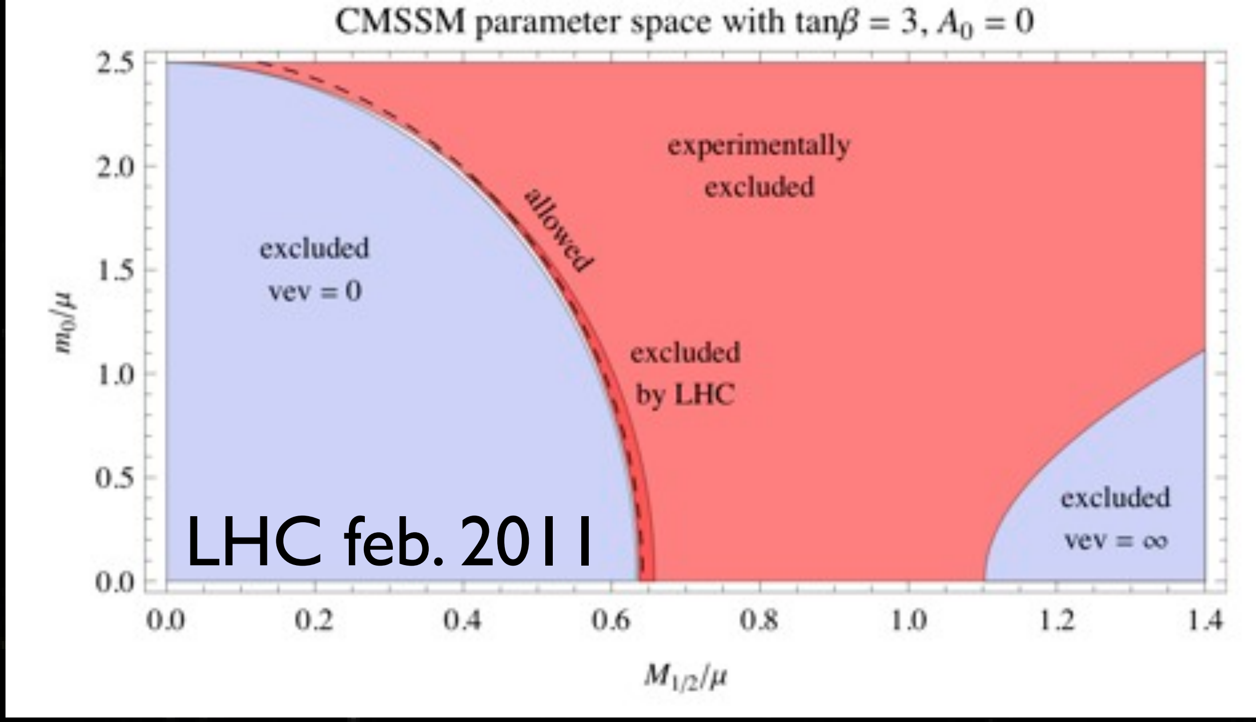

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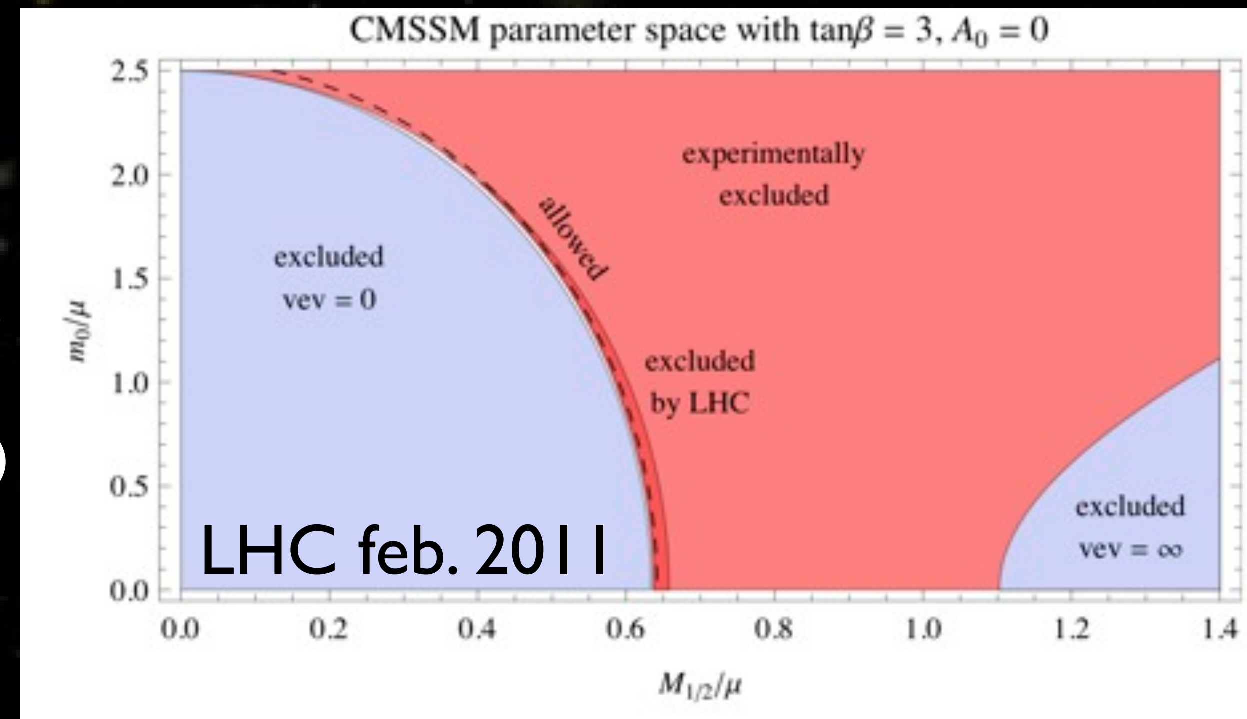

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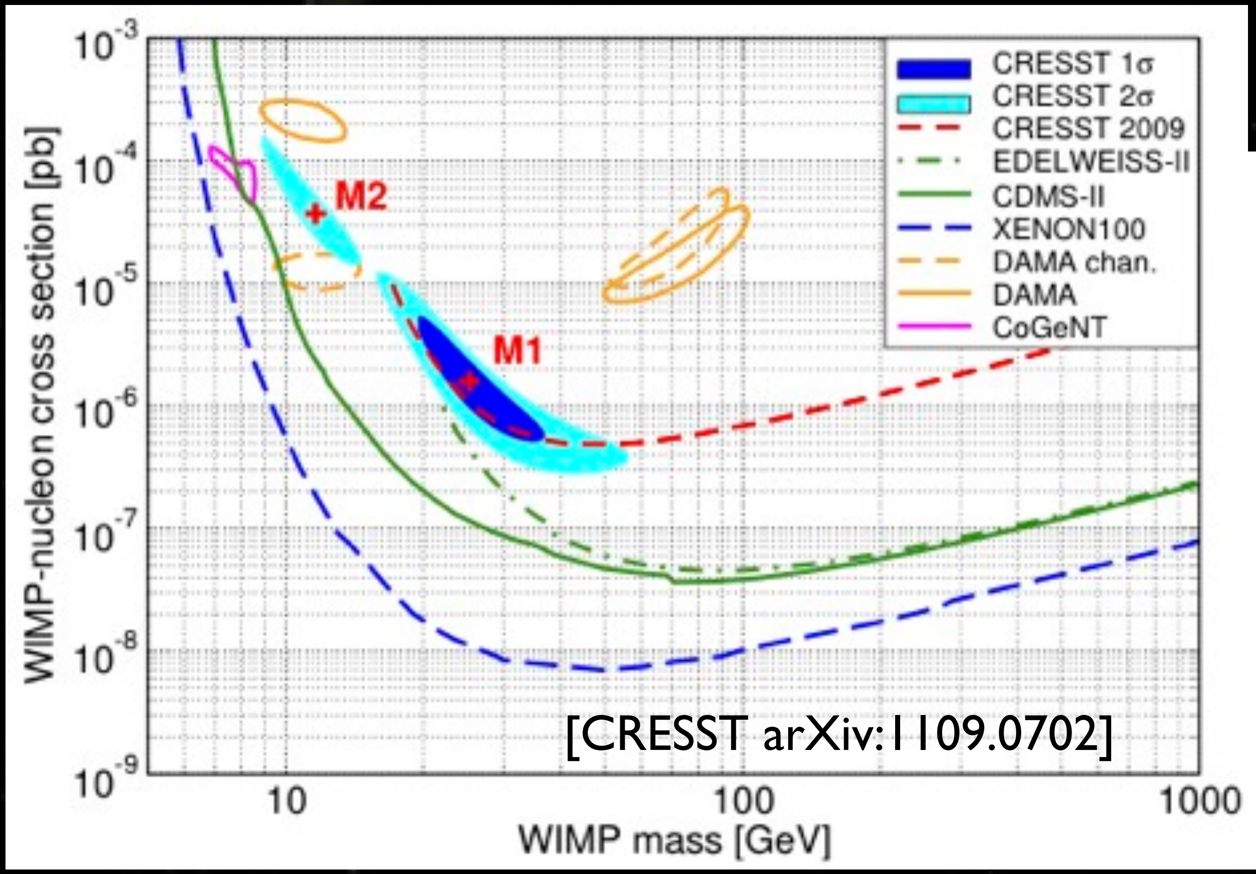

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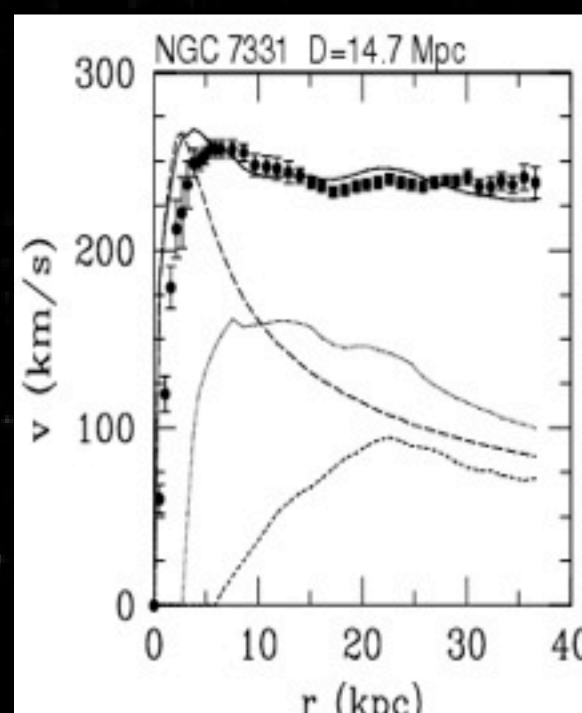
- Modifications of Gravity
  - ★ D.M. is only seen through gravitationnal effects
  - ★ MOND/TeVeS

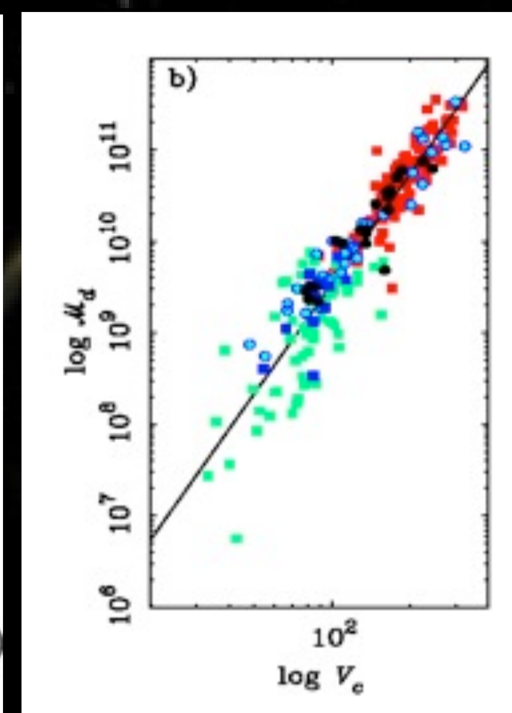
MOND

- new fundamental principle of dynamics: $F = \begin{cases} m\frac{a^2}{a_0} & \text{si } a < a_0 \\ ma & \text{si } a > a_0 \end{cases}$
- Newton force: $F = \frac{GMm}{r^2}$
- Circular orbit: $a = \frac{v^2}{r}$

MOND

$$\Rightarrow \frac{GM}{r^2} = \frac{a^2}{a_0}$$
$$\Rightarrow a = \sqrt{GMa_0 r}$$
$$\Rightarrow \frac{v^2}{r} = \sqrt{GMa_0 r}$$
$$\Rightarrow v = (GMa_0)^{1/4}$$
$$\Rightarrow L \propto M \propto v^4$$





→ Flat rotation curves ←✗

→ Tully-Fisher relation ←✗

Newton Dynamics:

$$\Rightarrow \frac{GM}{r^2} = a$$
$$\Rightarrow \frac{v^2}{r} = \sqrt{GMr^2}$$
$$\Rightarrow v = \sqrt{\frac{GM}{r}}$$
$$\Rightarrow L \propto M \propto rv^2$$

Impressive but MOND fails on everything else...

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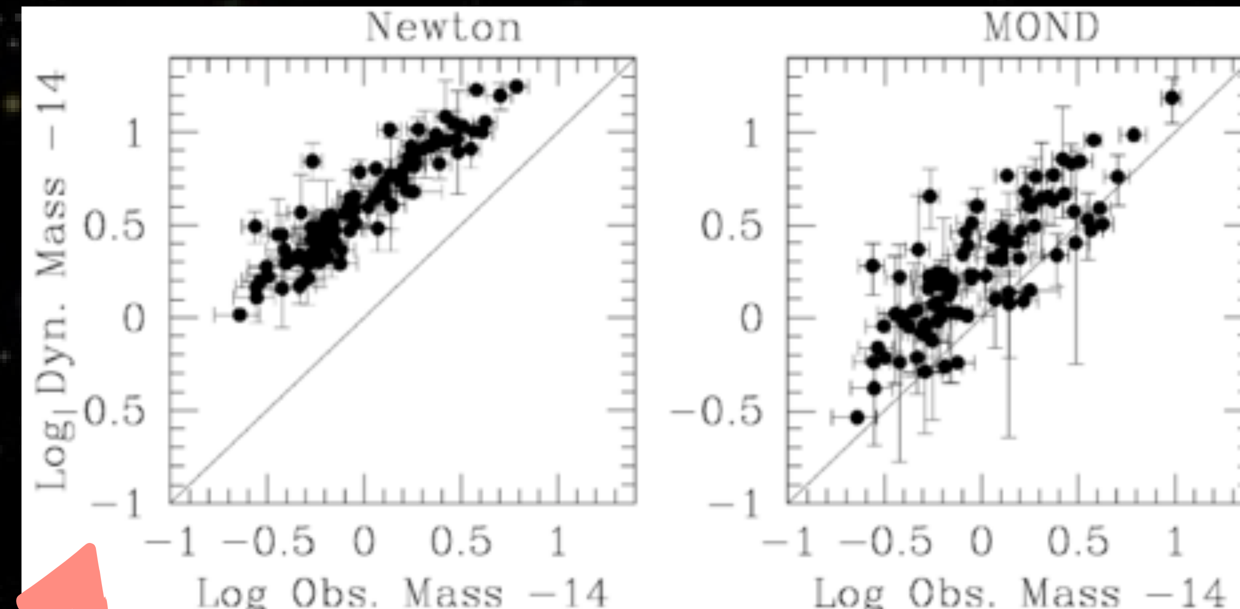
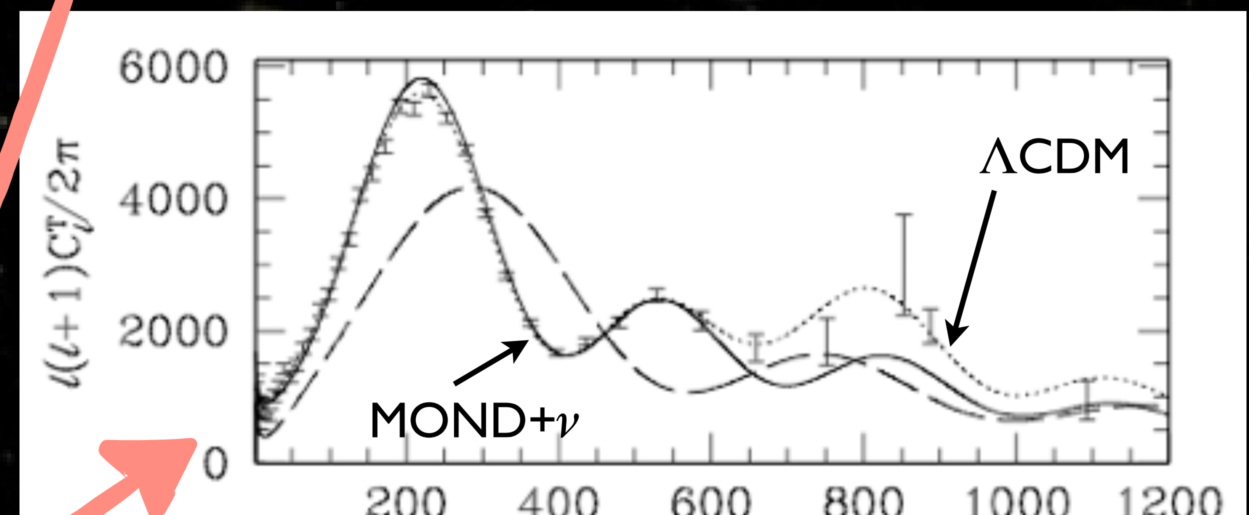
- **Modifications of Gravity**
  - ★ D.M. is only seen through gravitationnal effects
  - ★ MOND/TeVeS: appealing but ...
    - still requires a lot of neutrinos to explain galaxy rotation curves and clusters and CMB
    - CMB hard to fit now, obvious disagreement with BAO observed in distribution of galaxies
    - Does it really seem more sensible than D.M. ?





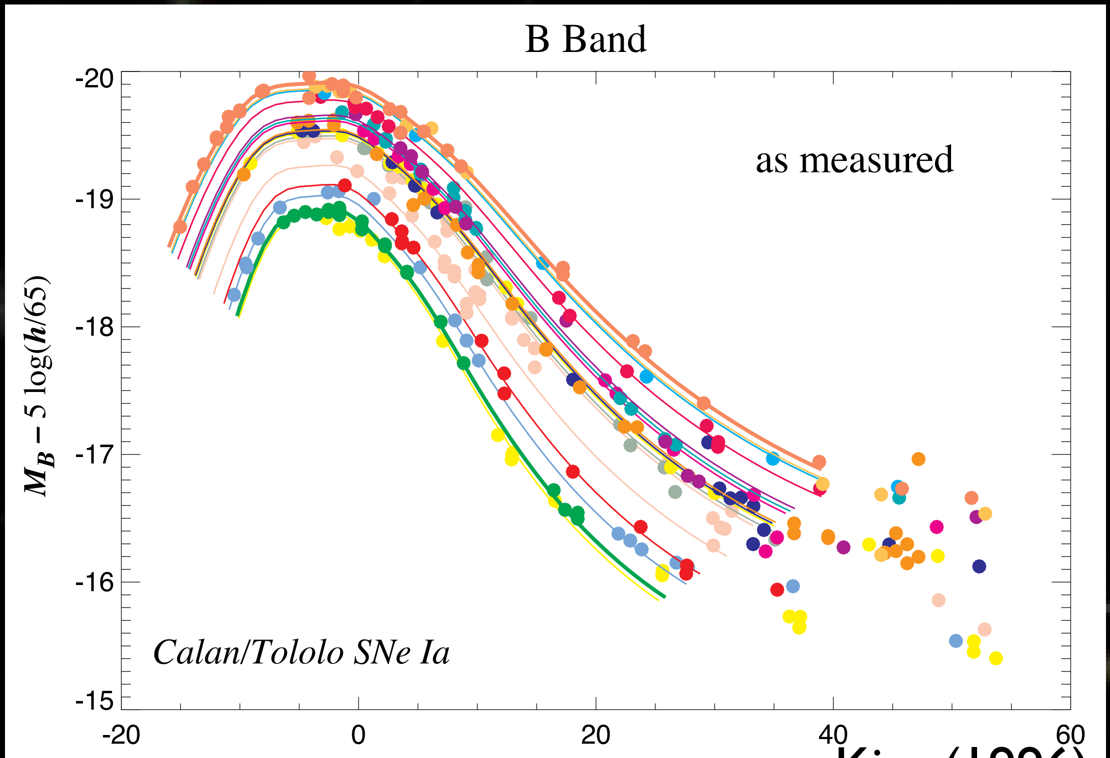
[Skordis et al. 2006]

$$F = \begin{cases} m\frac{a^2}{a_0} & \text{si } a < a_0 \\ ma & \text{si } a > a_0 \end{cases}$$

Dark Energy

SNIa: accelerated expansion (1998)

- Standard candles
  - ★ bright (more that host galaxy)
  - ★ standardizable (within ~ 0.15 mag)
- Luminosity distance Vs. z
  - ★ SNIa fainter than expected
  - ★ Possible systematics well controlled



Kim (1996)

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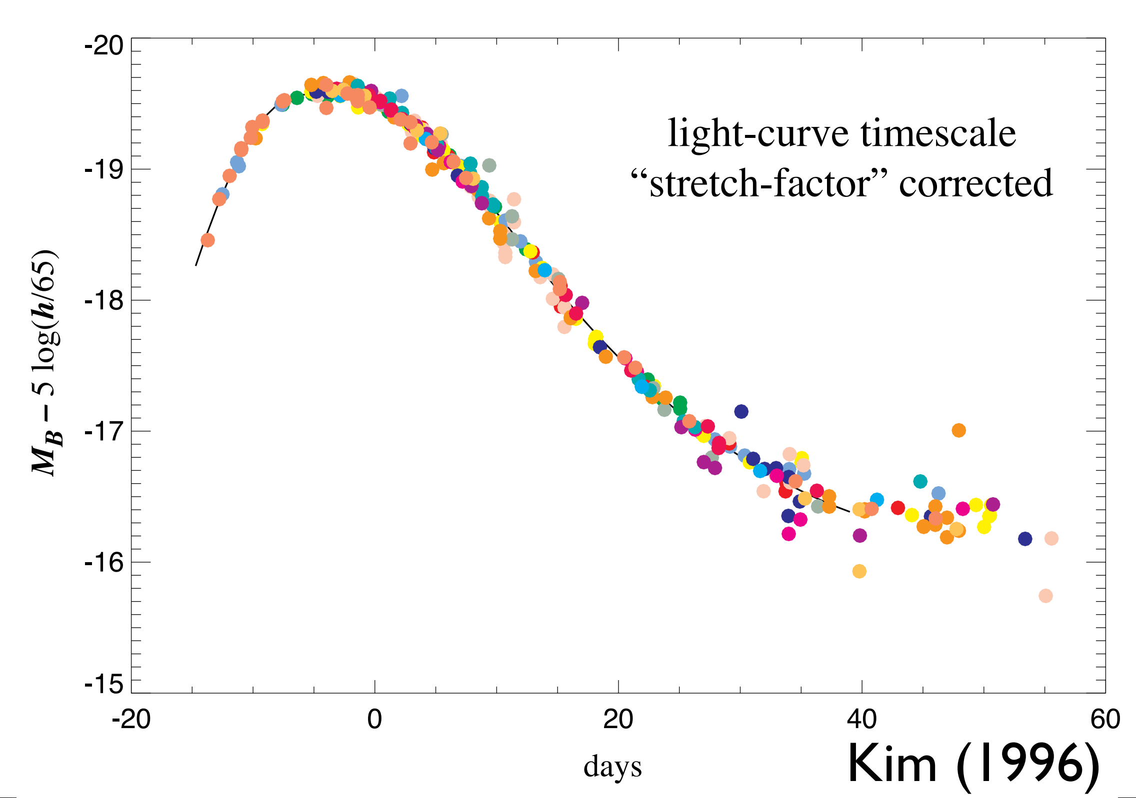

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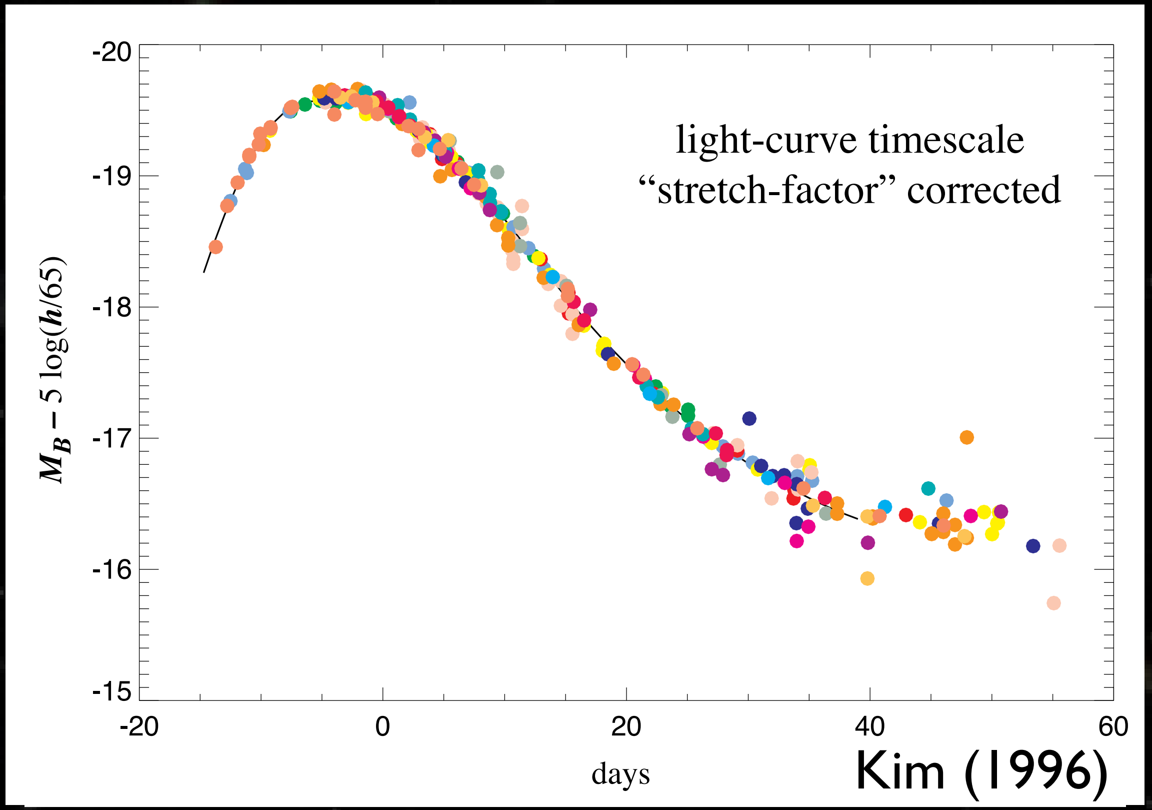

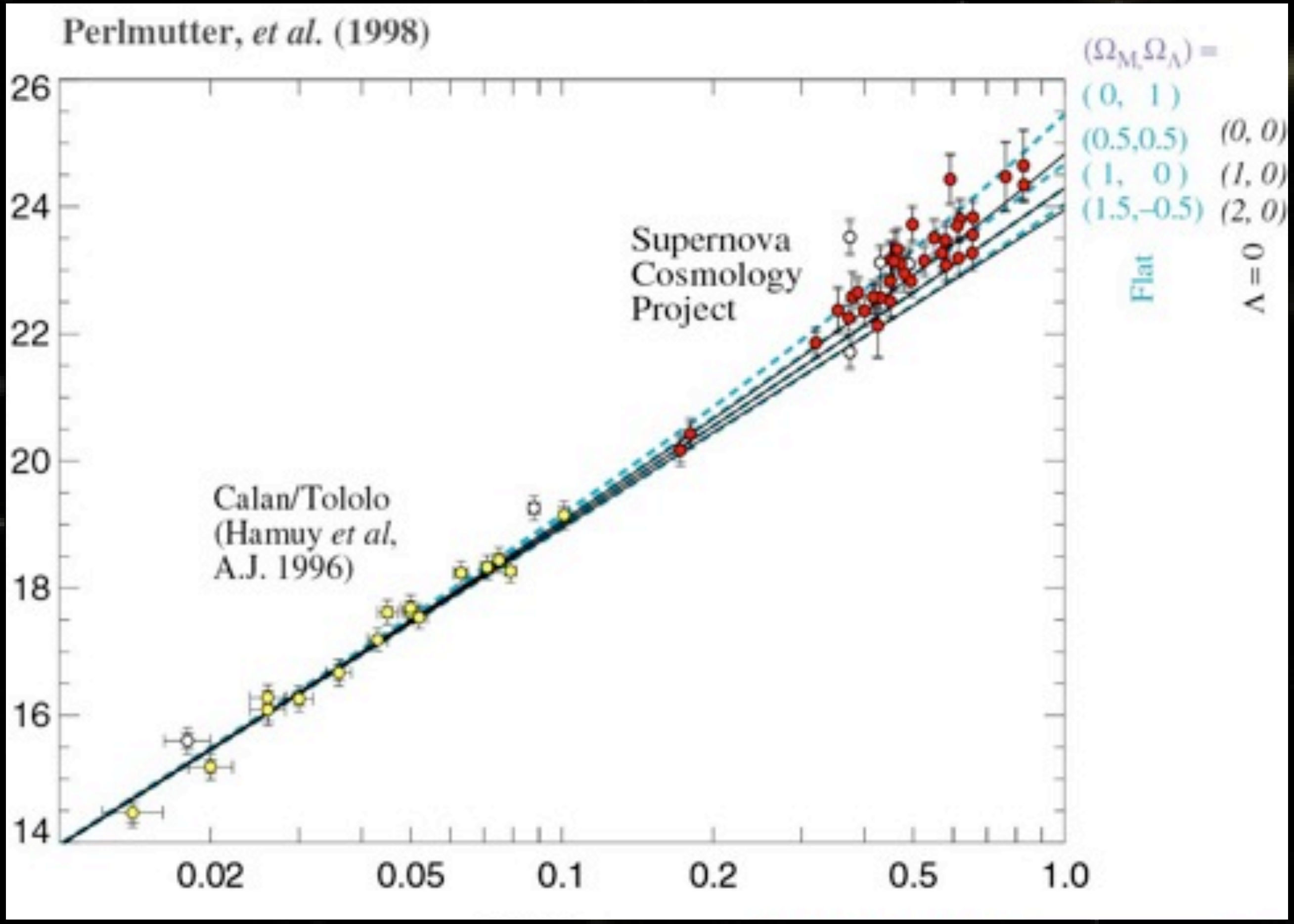

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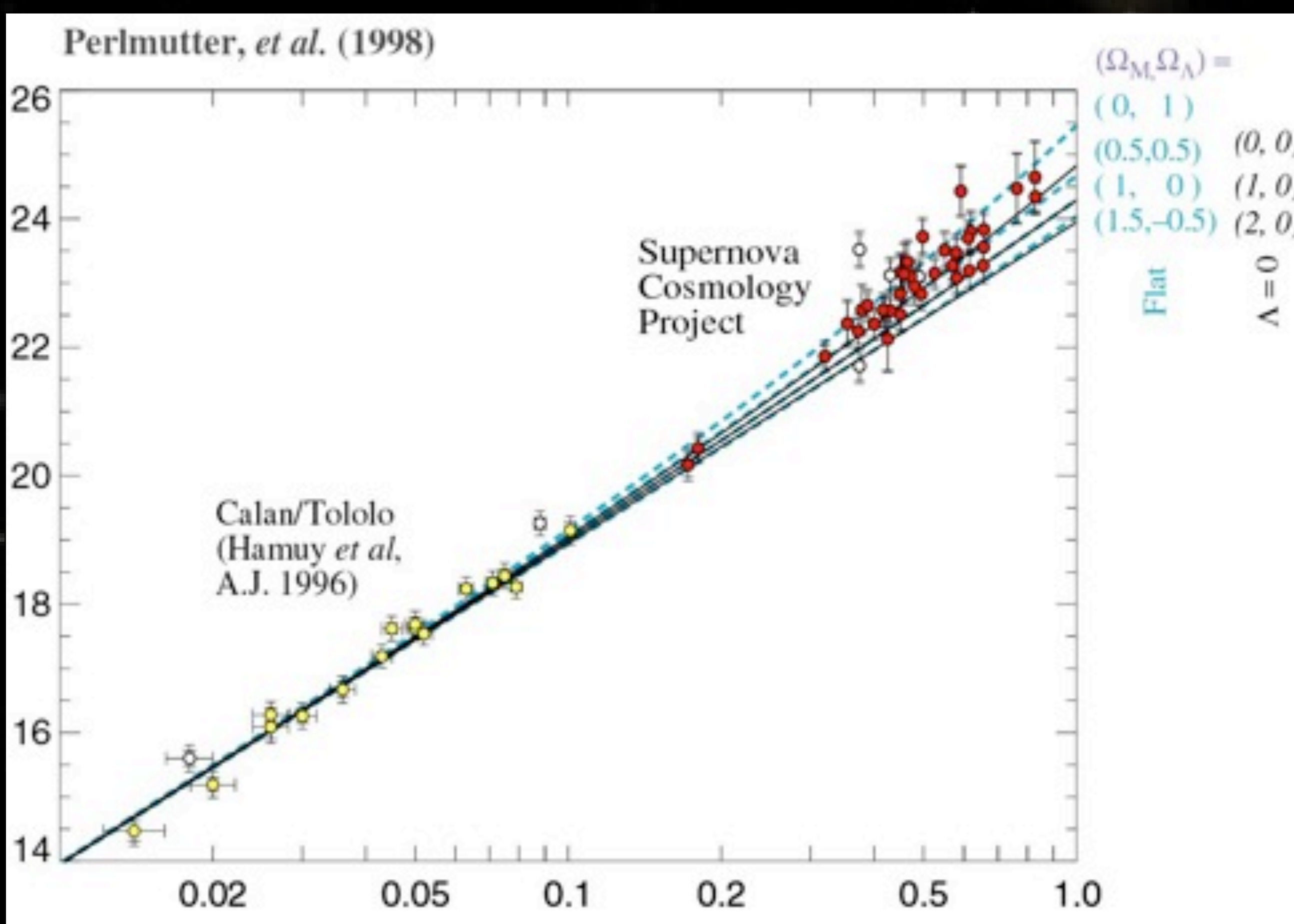

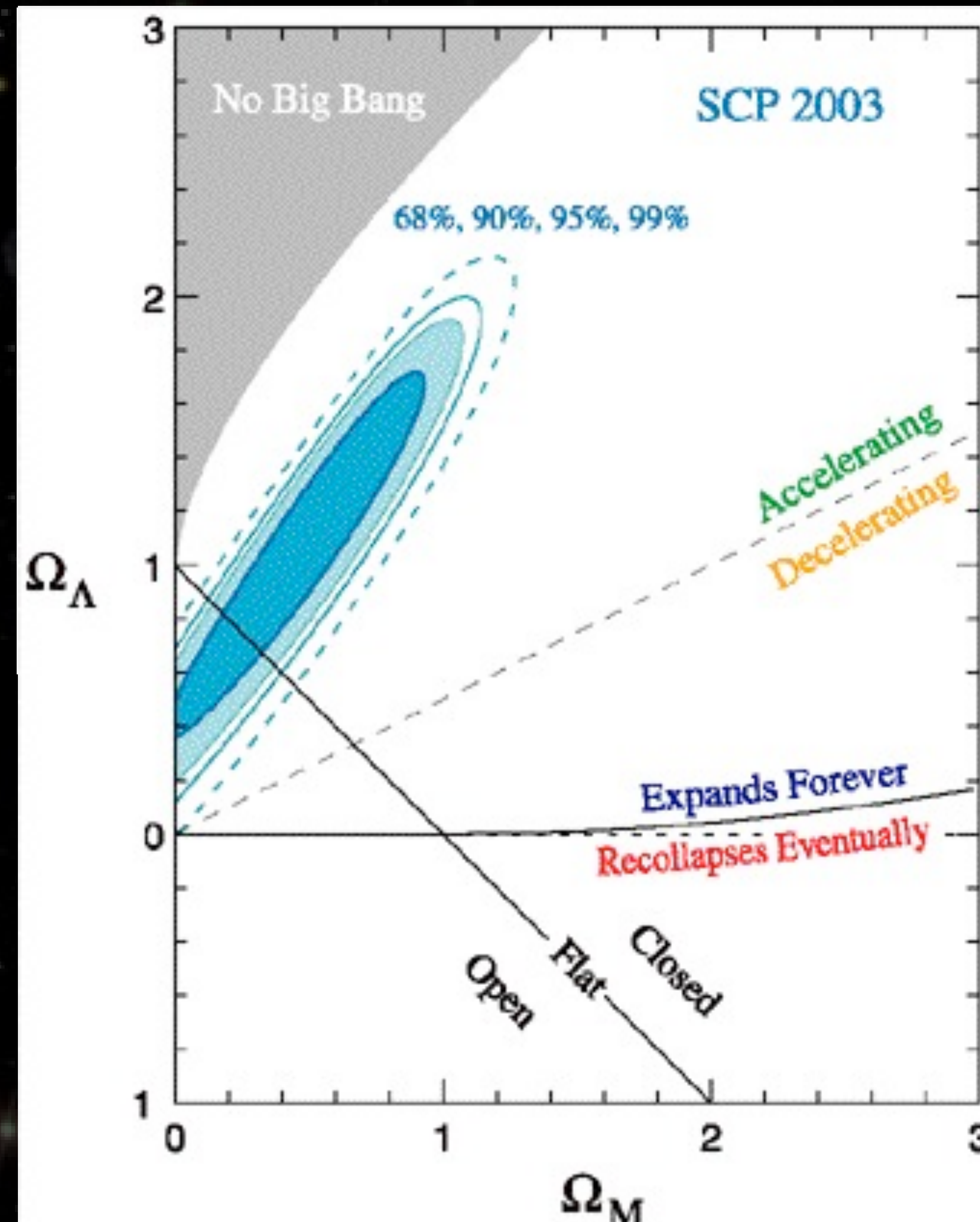

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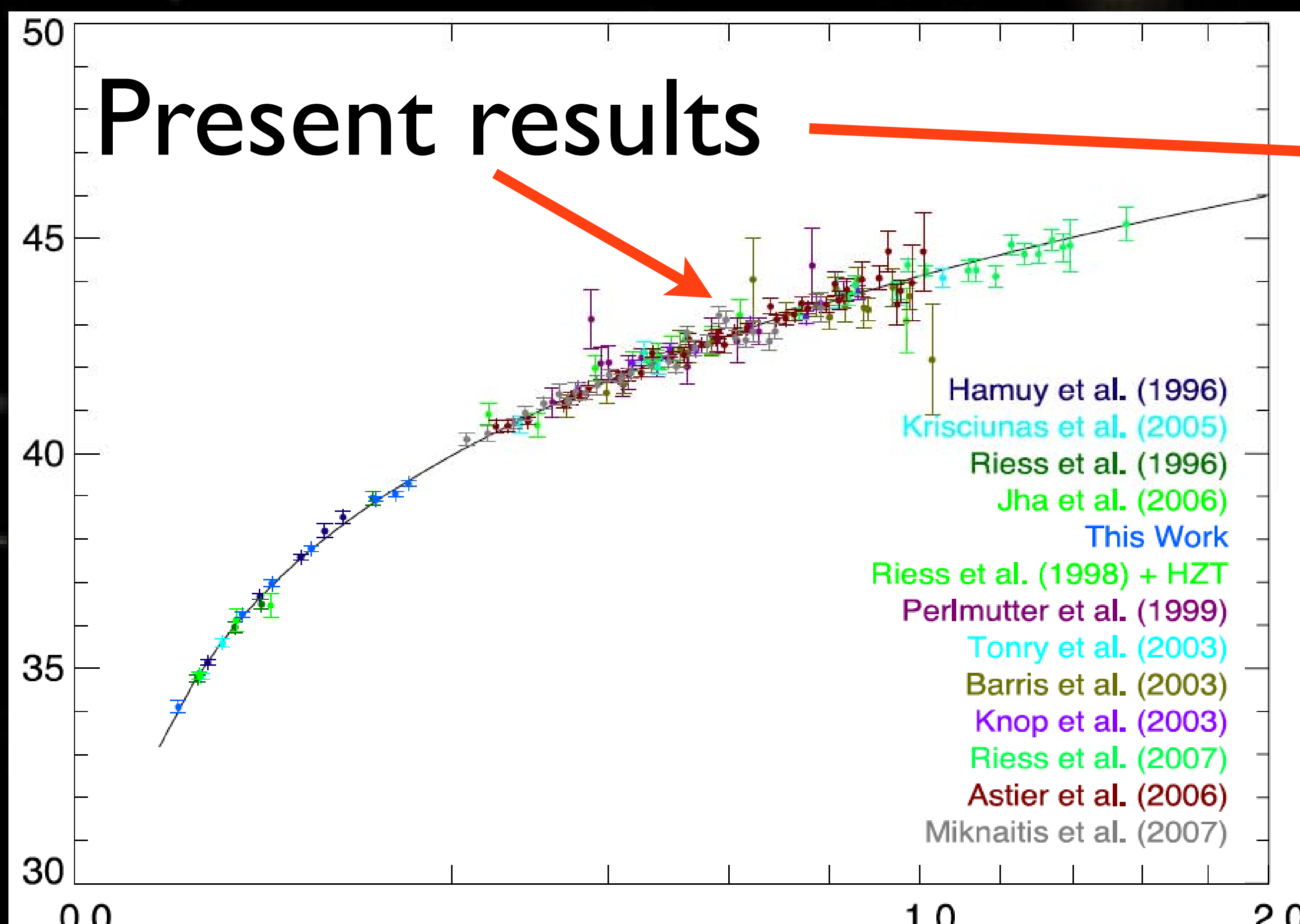

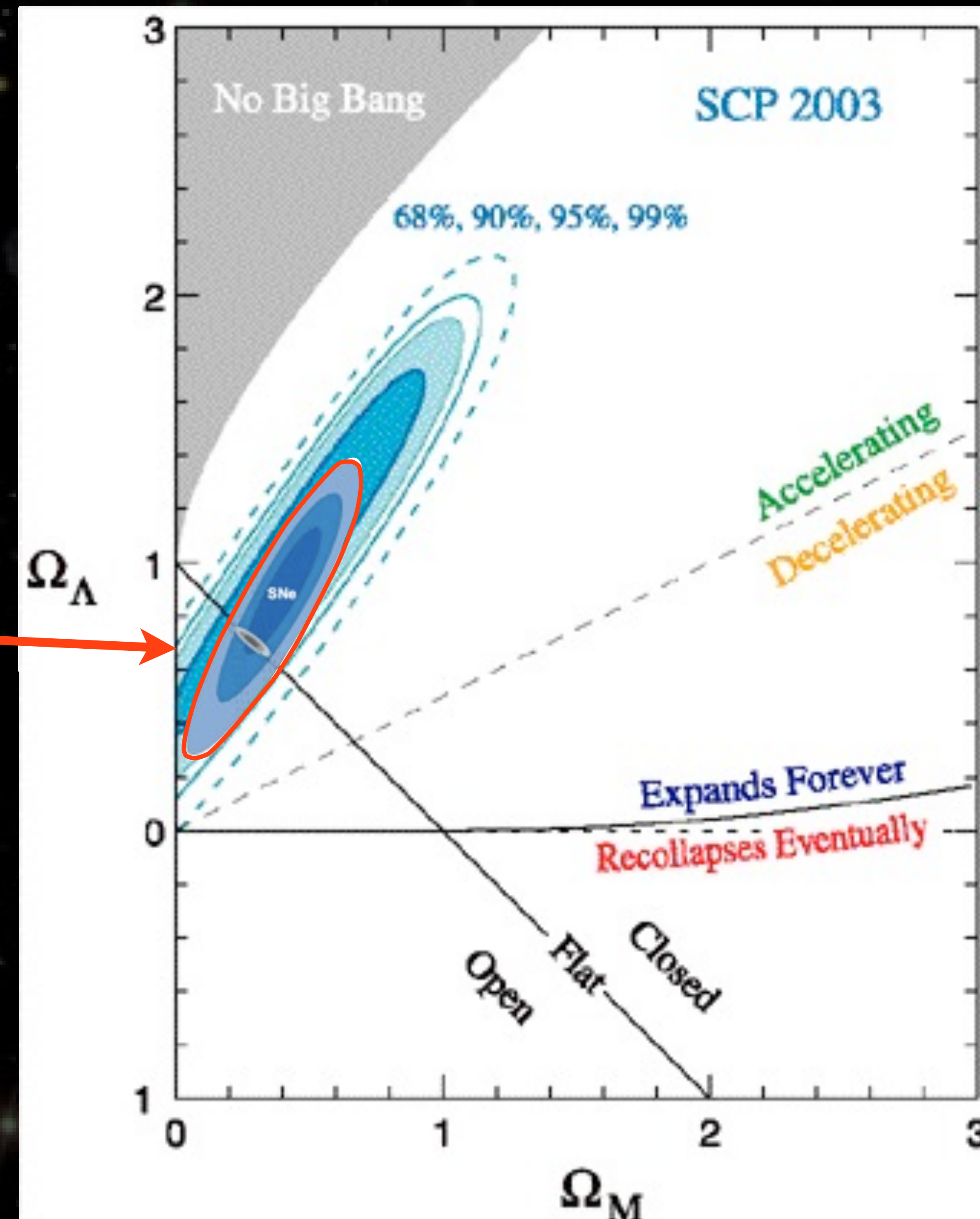

Actually, the idea was around...

Letters to Nature

Nature **348**, 705-707 (27 December 1990) | doi:10.1038/348705a0; Accepted 31 October 1990

The cosmological constant and cold dark matter

G. Efstathiou, W. J. Sutherland & S. J. Maddox

1. Department of Physics, University of Oxford, Oxford 0X1 3RH, UK

THE cold dark matter (CDM) model[1–4] for the formation and distribution of galaxies in a universe with exactly the critical density is theoretically appealing and has proved to be durable, but recent work[5–8] suggests that there is more cosmological structure on very large scales (l > 10 h^{-1} Mpc, where h is the Hubble constant H_0 in units of 100 km s^{-1} Mpc^{-1}) than simple versions of the CDM theory predict. We argue here that the successes of the CDM theory can be retained and the new observations accommodated in a spatially flat cosmology in which as much as 80% of the critical density is provided by a positive cosmological constant, which is dynamically equivalent to endowing the vacuum with a non-zero energy density. In such a universe, expansion was dominated by CDM until a recent epoch, but is now governed by the cosmological constant. As well as explaining large-scale structure, a cosmological constant can account for the lack of fluctuations in the microwave background and the large number of certain kinds of object found at high redshift.

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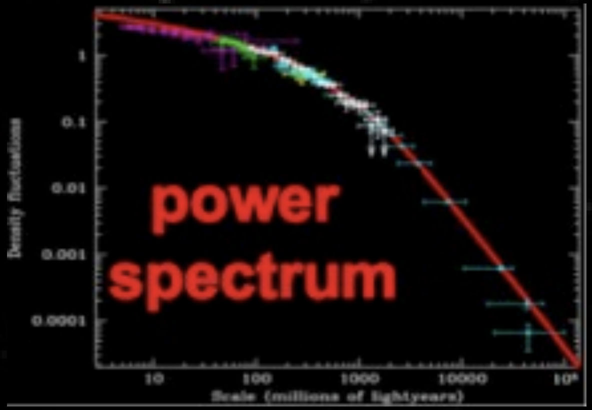
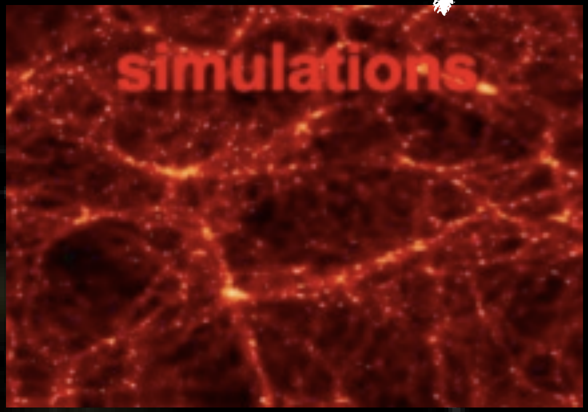
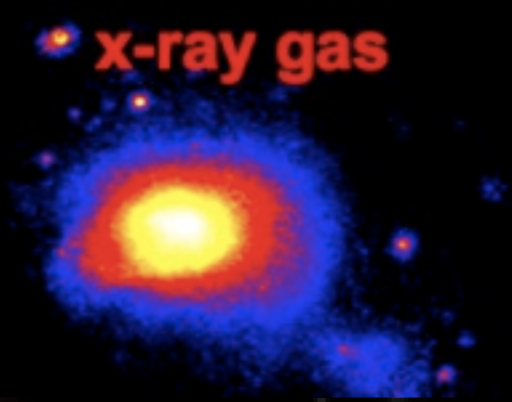
Cosmic substraction: *1-0.3=0.7*



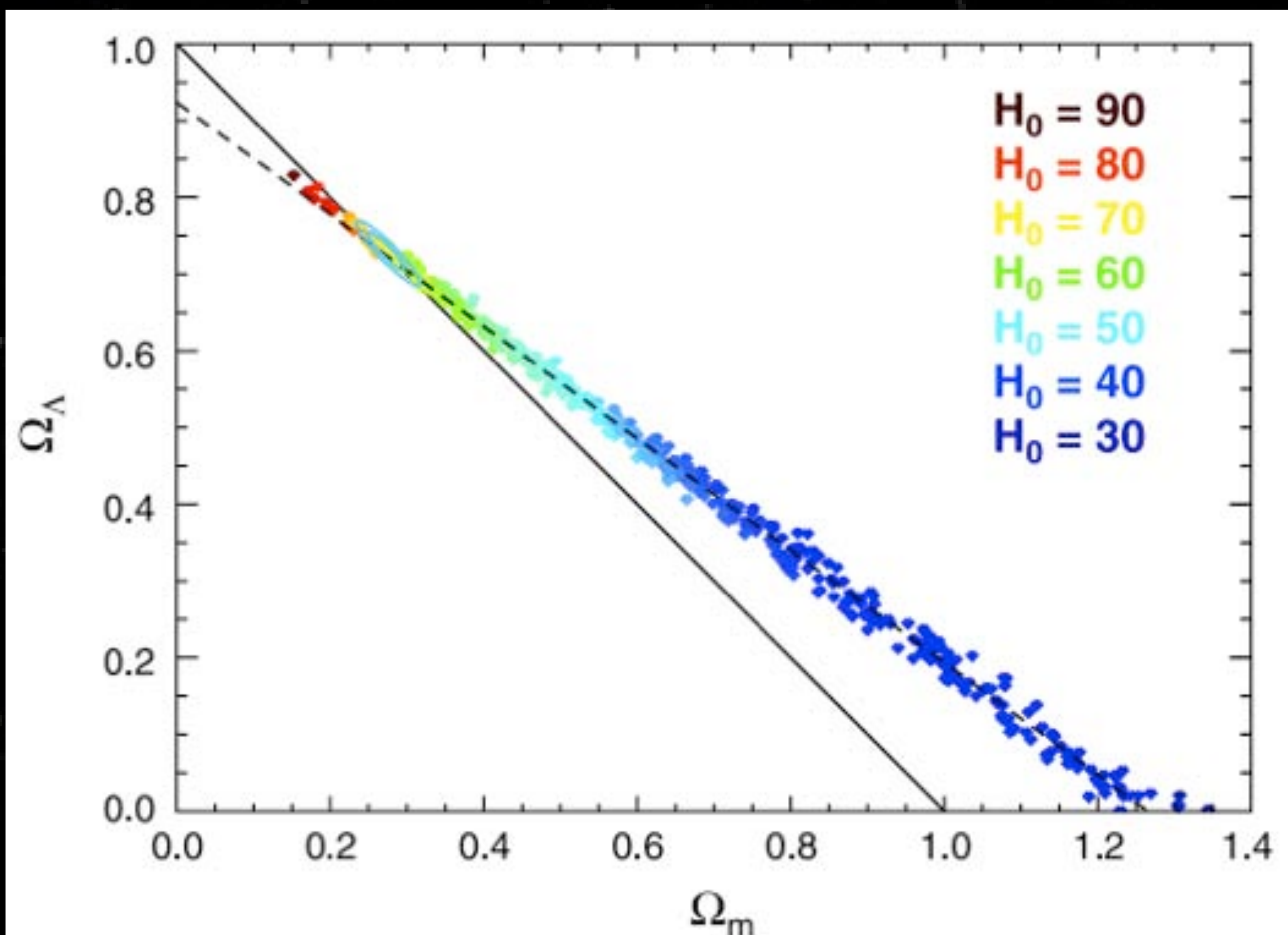
$\Omega_m \sim 0.3$



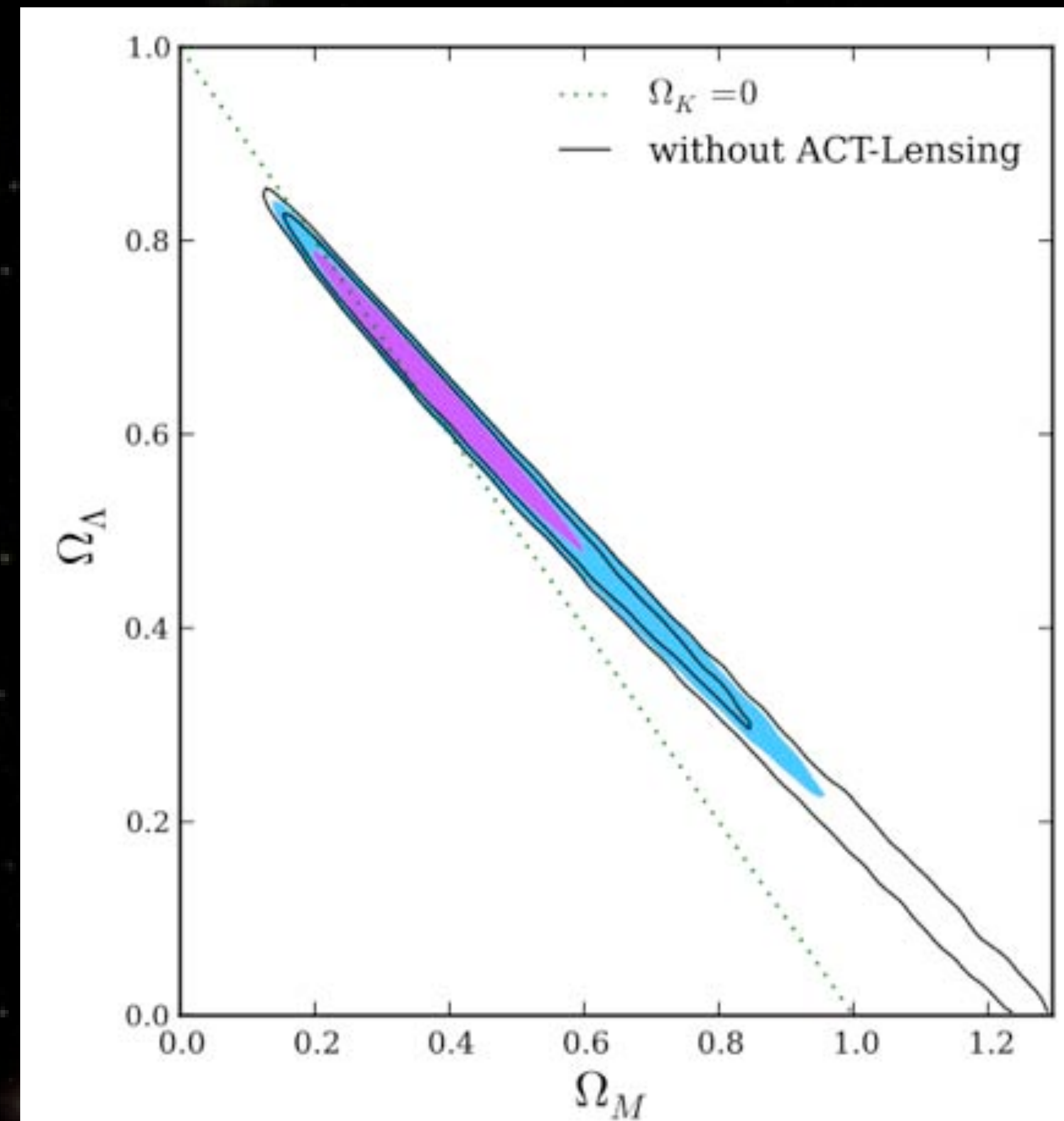


From R. Kolb

evidence for D.E. from CMB alone



WMAP 7y

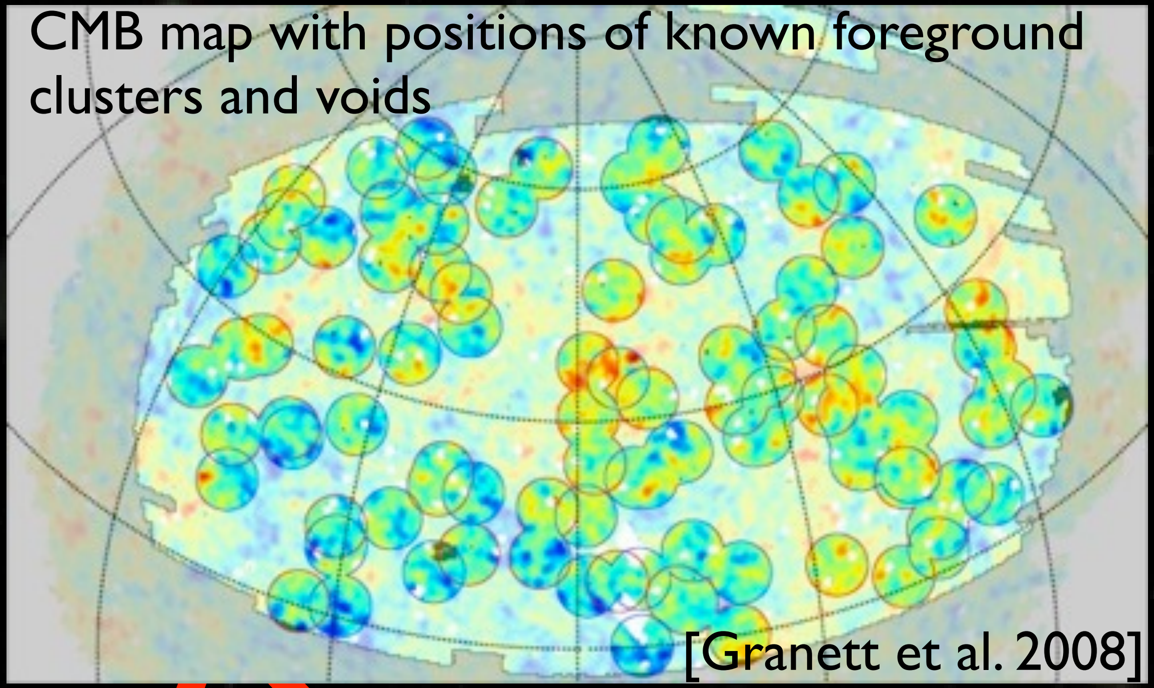


WMAP 7y + ACT (no H_0)

[Sherwin et al. 2011]

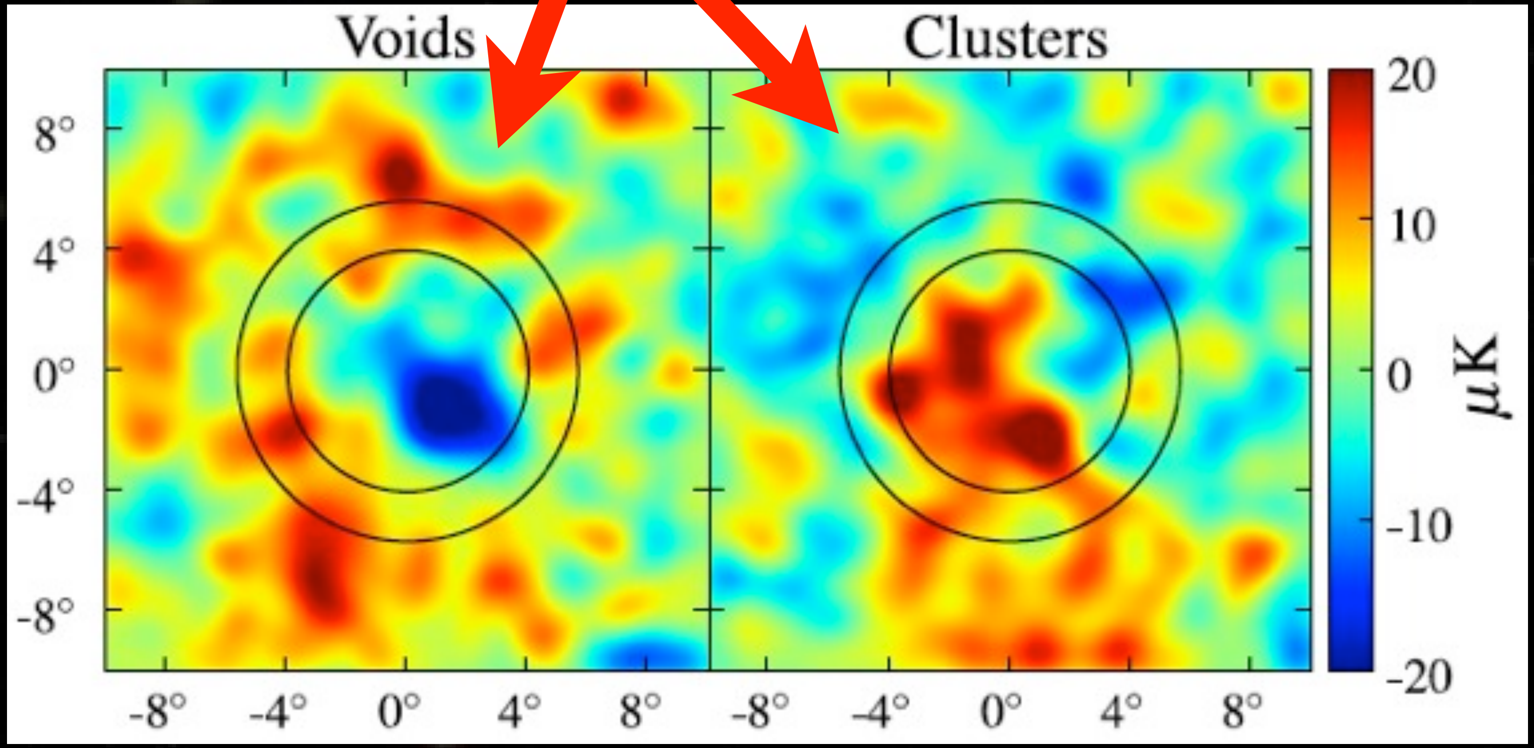
ISW effect: independent probe

- Integrated Sachs-Wolfe effect
  - ★ Photons gain energy falling into clusters potential wells
  - ★ They loose energy escaping
  - ★ In the presence of Dark Energy the net result is not zero
  - ➡ Correlation between CMB hot/cold spot expected with foreground clusters/voids



➡ 4σ level detection by various teams

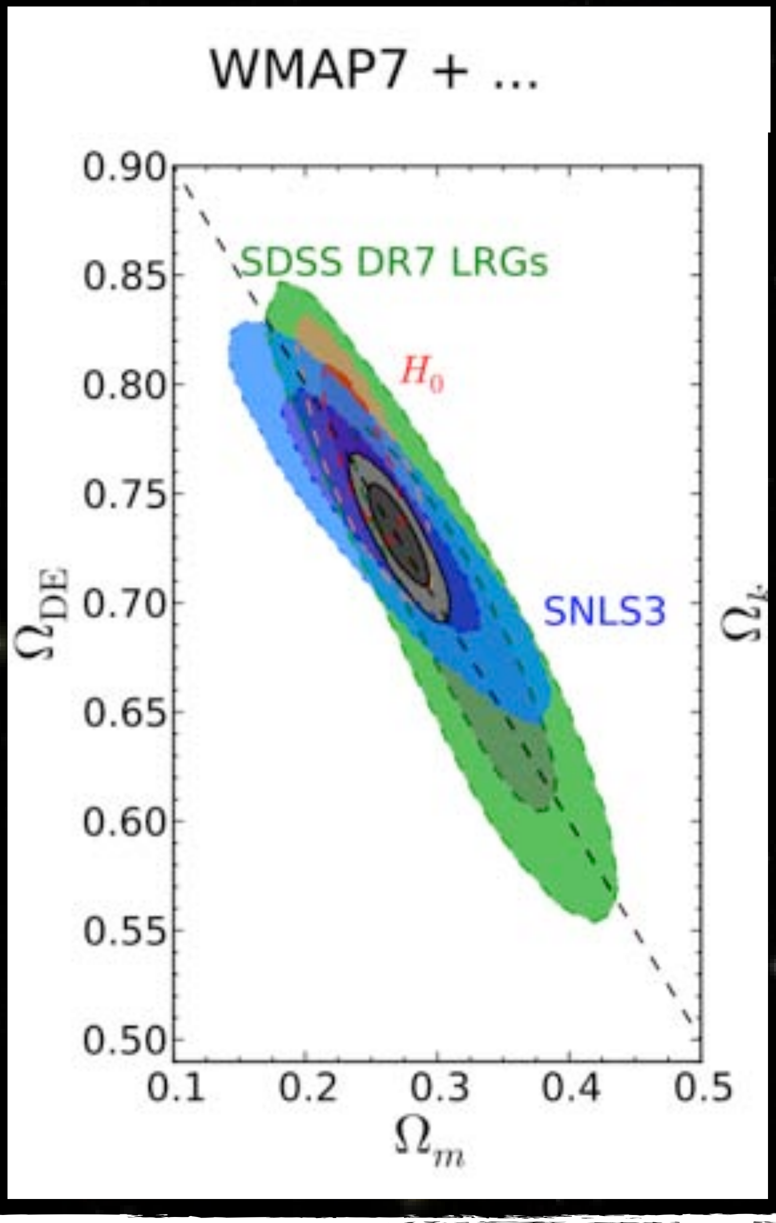
➡ N.B. expected effect is zero if no D.E. (or more generally if no acceleration)

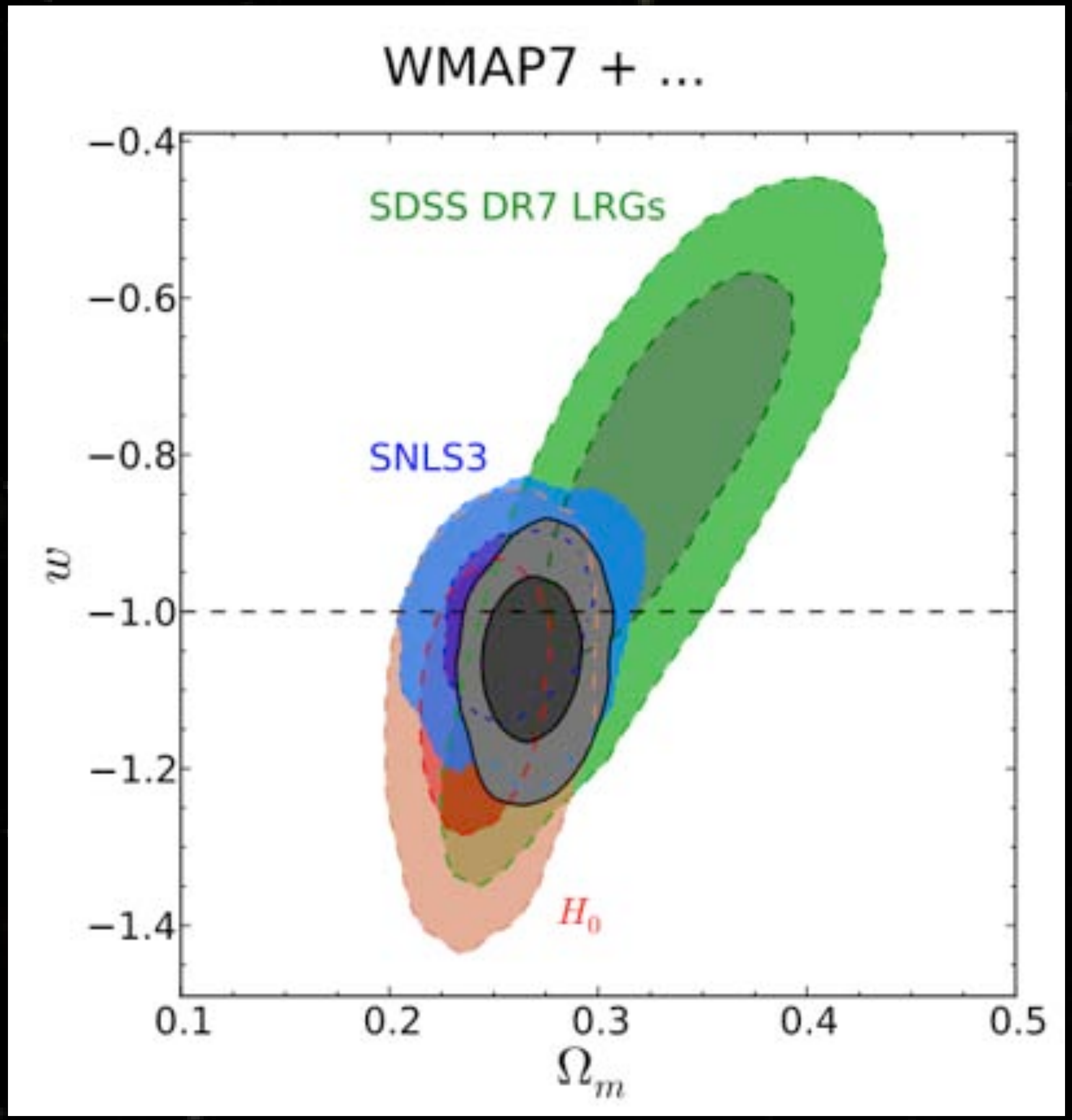


[Granett et al. 2008]

Finally, with latest data

- Dark Energy Equation of state: $p = w\rho$
  - ★ w=-1 ⇔ pure cosmological constant (or scalar field)





Bug or reality ?

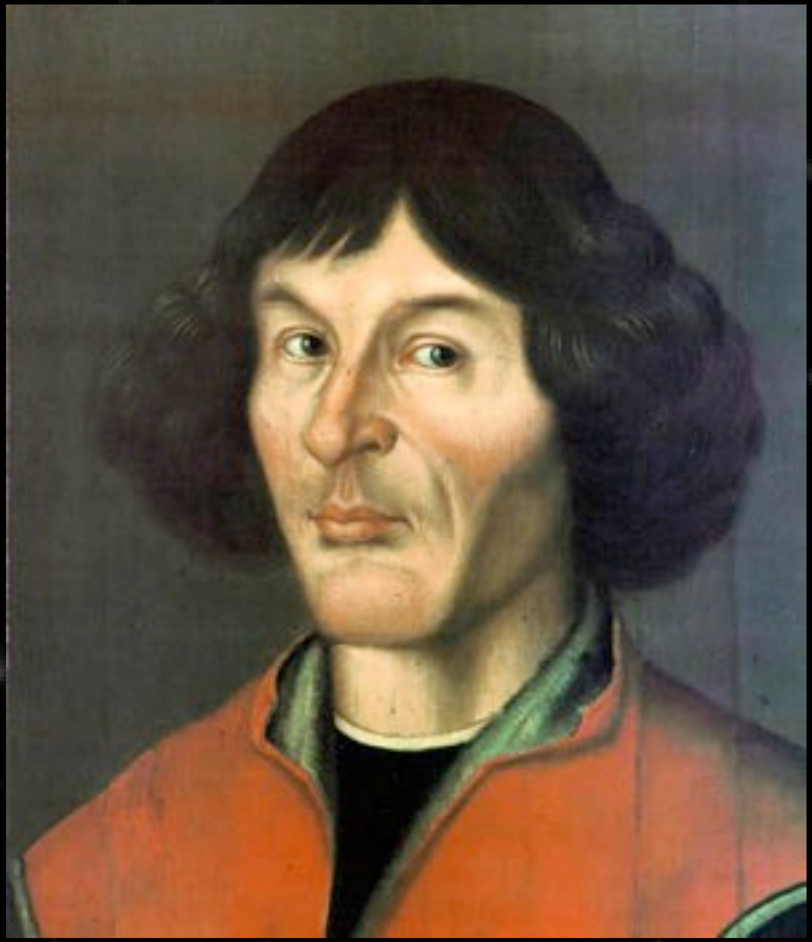
- **So the Universe really seems to be accelerating...**
  - ★ «we are in a void» explanation excluded by lack of kSZ effect [Zhang and Stebbins 2011]

- **$\Omega_{D.E.}$~0.7 with and equation of state w~-1**
  - ★ It really looks like a cosmological constant
  - ★ or maybe a scalar field depending on which side in Einstein's Equation

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

- **Now ... is it really serious ?**
  - ★ No scalar field has ever been observed
  - ★ Strong disagreement with particle physics vacuum
    - From H_0 and Ω_Λ: $\Lambda \sim 10^{-52}$ m^{-2}
    - From Planck scale physics: $\Lambda \sim 10^{70}$ m-2
  - ★ Something deep is obviously not understood...

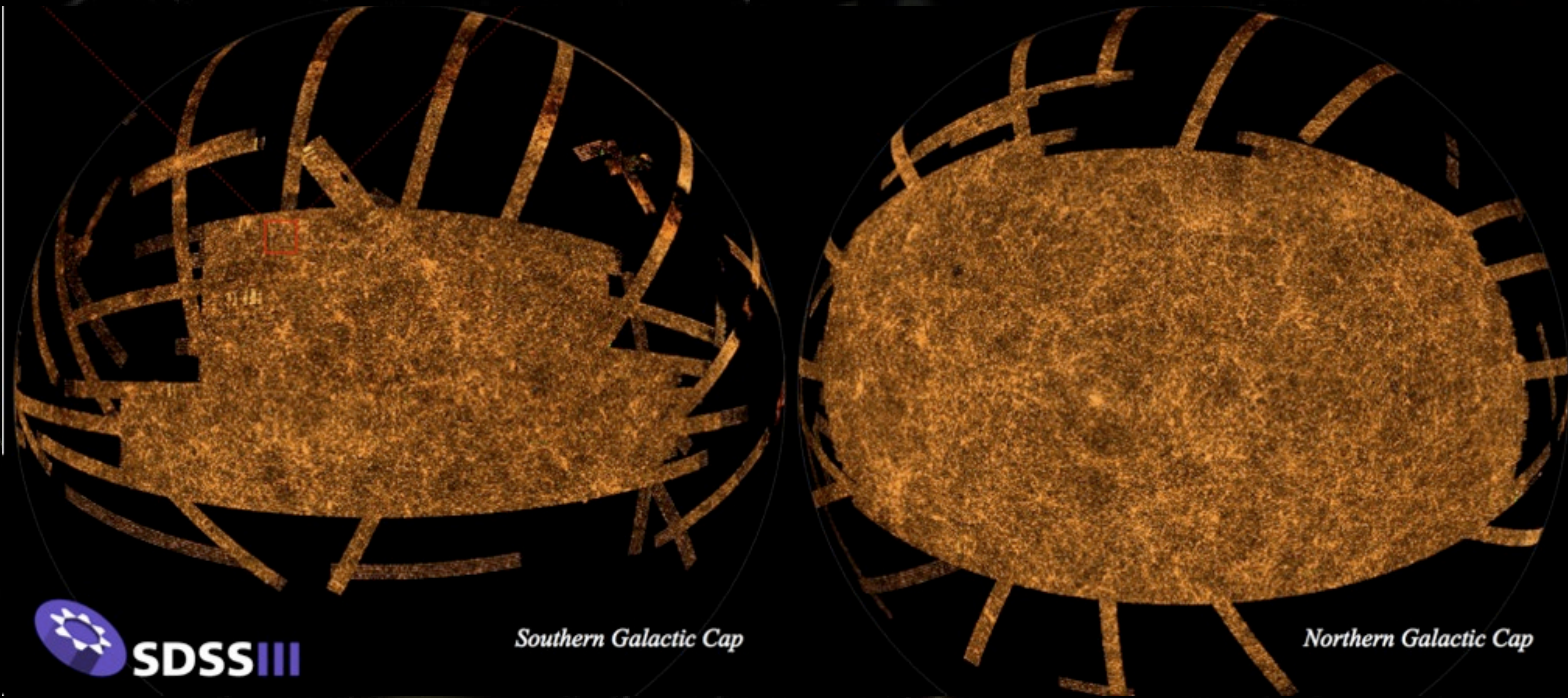
Tests of the Cosmological principle



Mikołaj Kopernik

Cosmological Principle tests

- At first a simplifying hypothesis
- Isotropy tested with increasing success (here z~1)

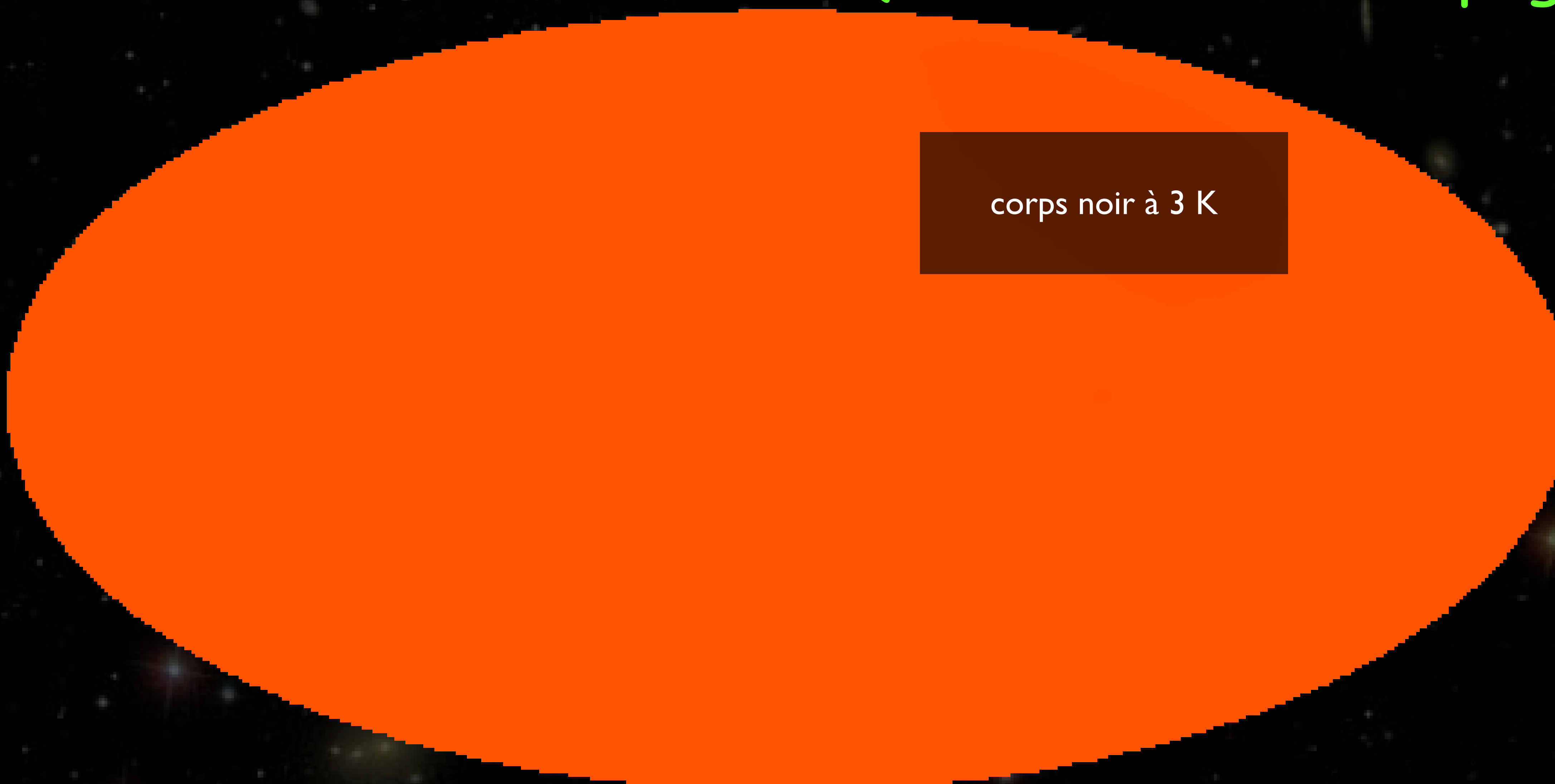


470 Millions objects, 1.5 million on the way of being spectred

Cosmological Principle tests

- At first a simplifying hypothesis
- Isotropy tested with increasing success (here z~1000)

(COBE/DMR homepage)



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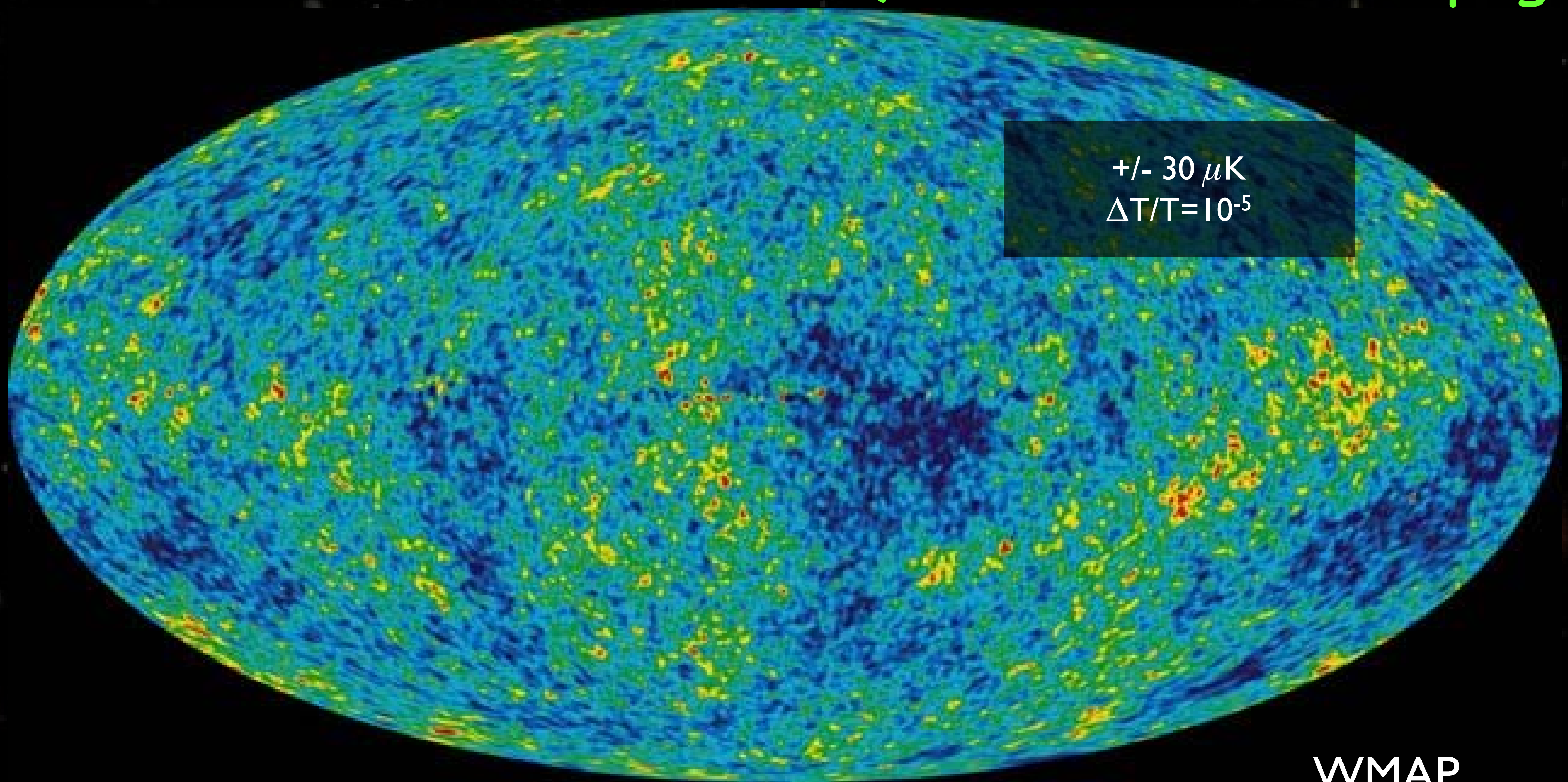


WMAP

Cosmological Principle tests

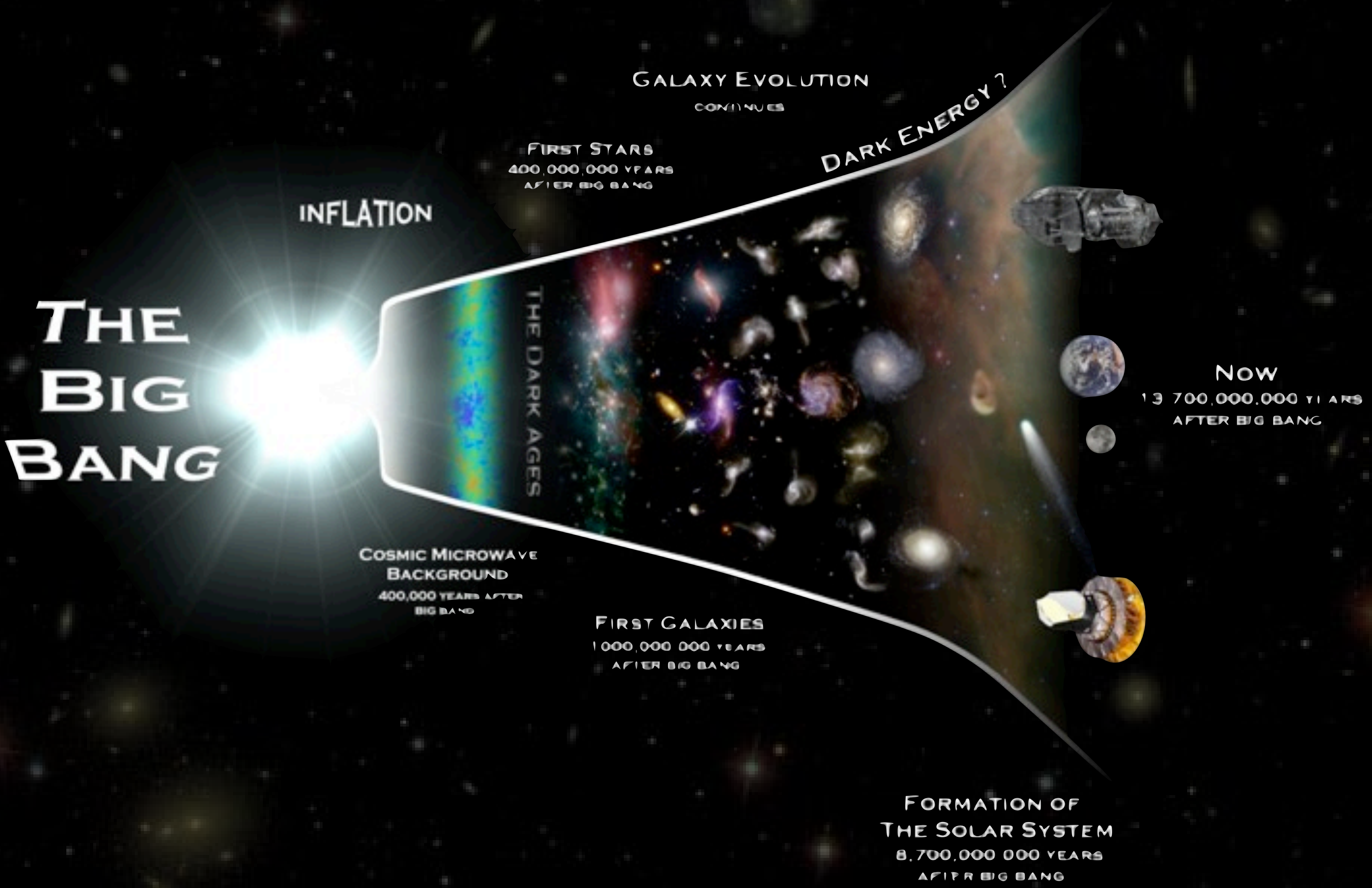
- At first a simplifying hypothesis
- Isotropy tested with increasing success

- If Copernican principle is assumed
  - ★ Every observer would see similar matter/CMB distribution
  - ➡ homogeneity follows [Maartens, 2011]
  - ★ But no strong observational basis for Copernican principle...

- Testing the Copernican Principle
  - ★ Spectral distorsions on the CMB
    - Black-Body nature [Caldwell and Stebbins, 2008]
    - lack of kinetic-SZ effect on small scales [Zhang and Stebbins, 2010]
  - ★ future: time drifts of cosmological redshifts [Uzan et al, 2008]

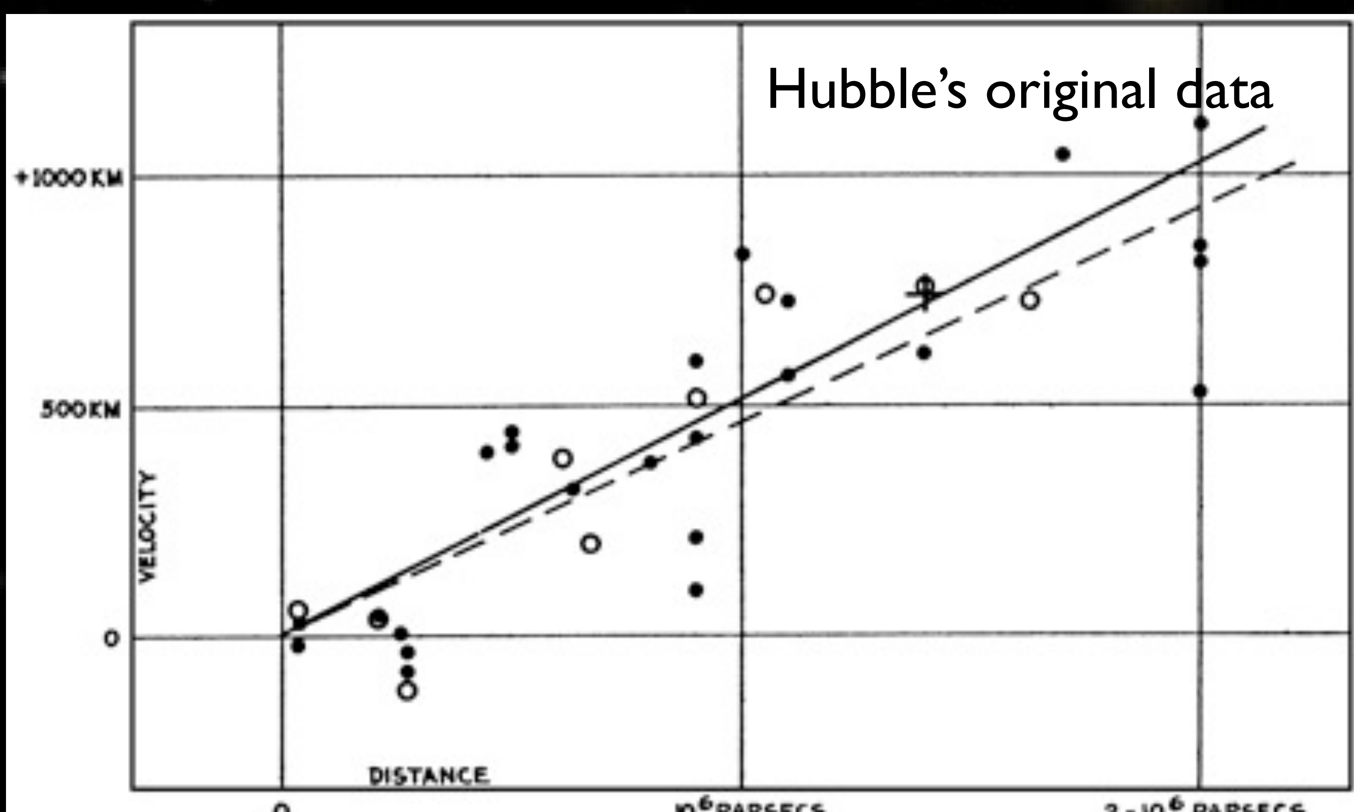
- Basically it seems fine...

Tests of the Hot Big-Bang paradigm

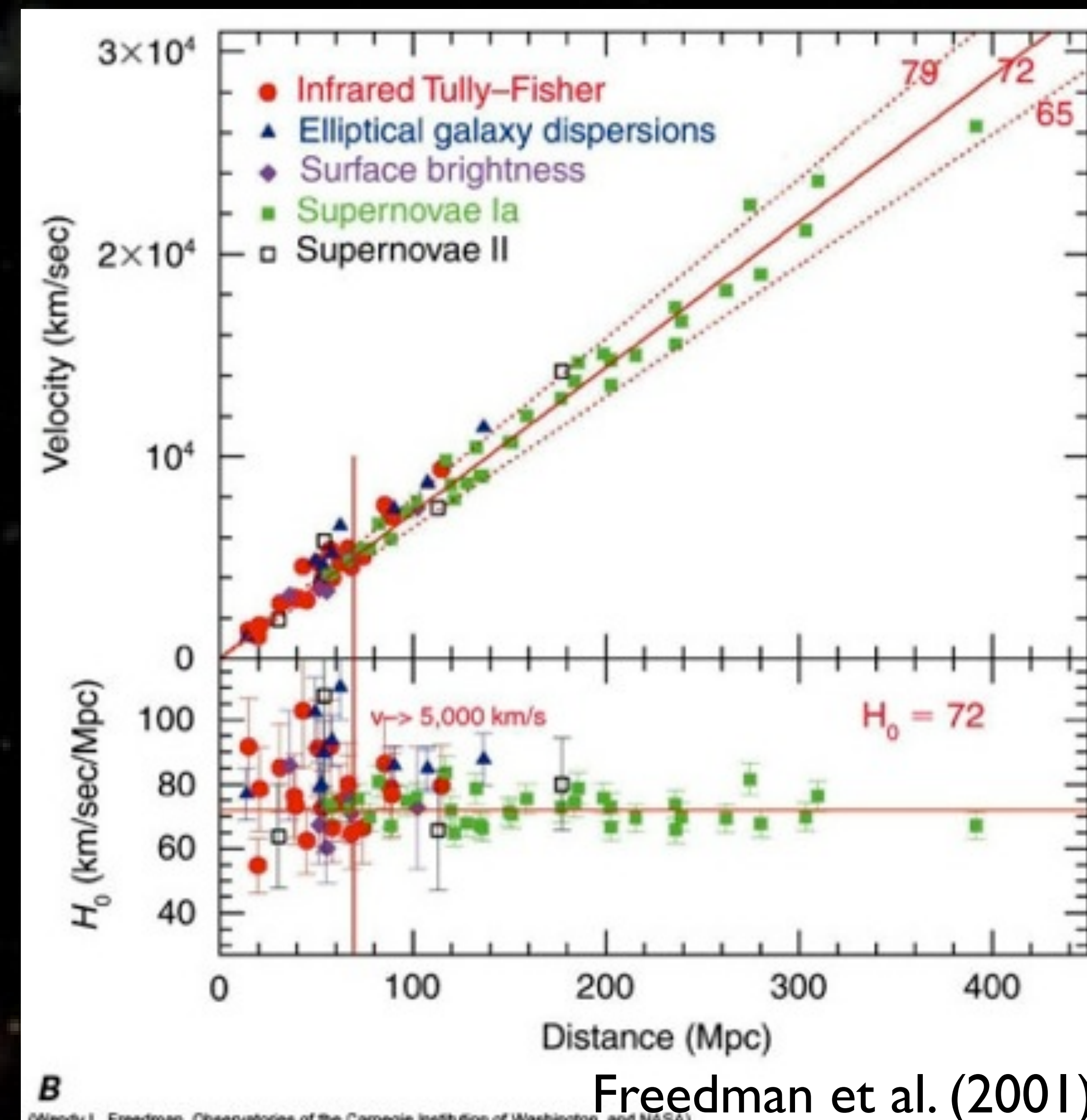


Hubble's law

- Long debate on H_0 value
- Now stabilized:
- $H0 = 72 \pm 3(stat) \pm 7(syst)$
  - ★ main systematics:
    - Cepheids metallicity
    - Distance to LMC



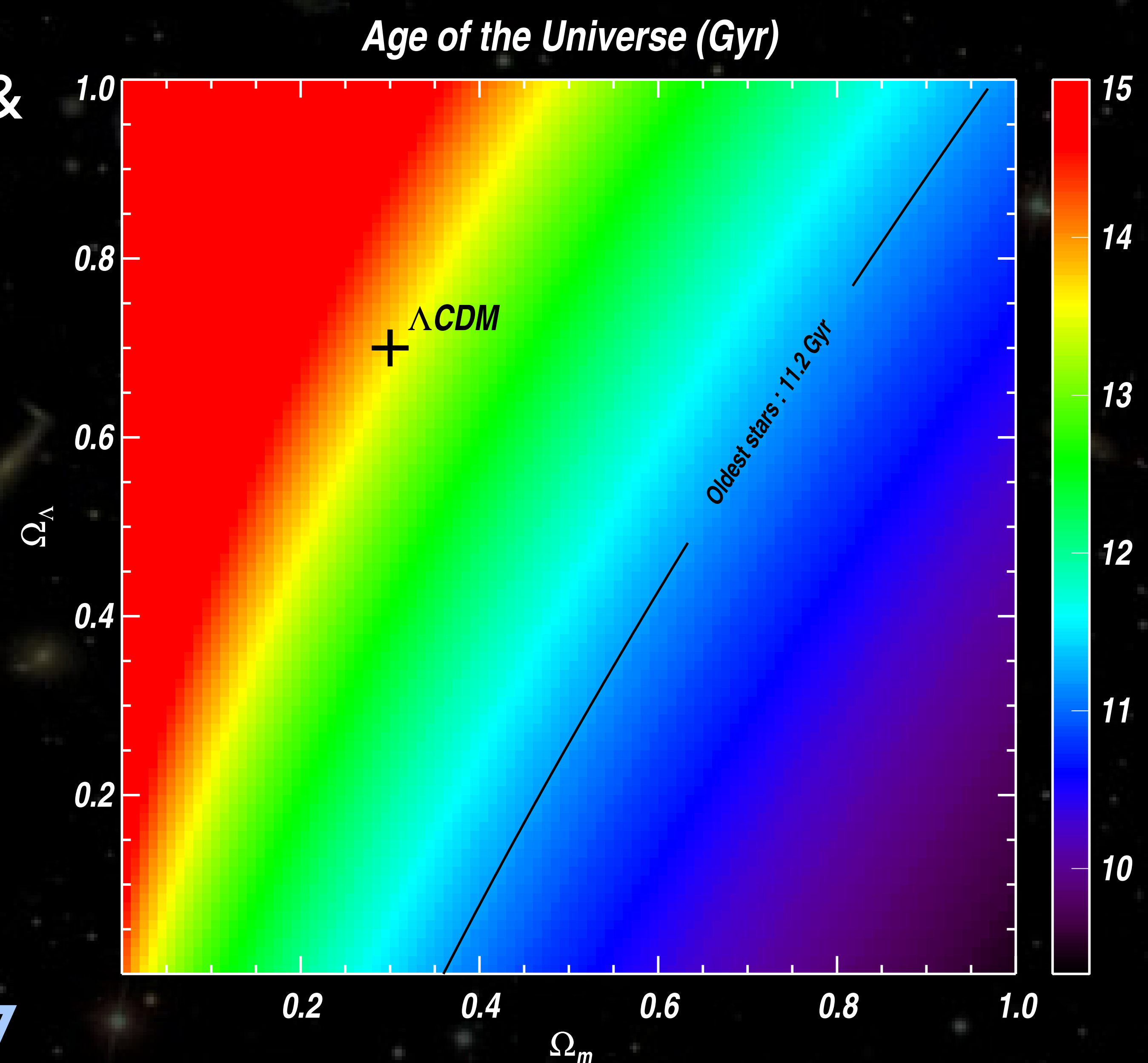
1927 : H_0 ~ 500 km/s/Mpc



2001: H_0 = 72 km/s/Mpc

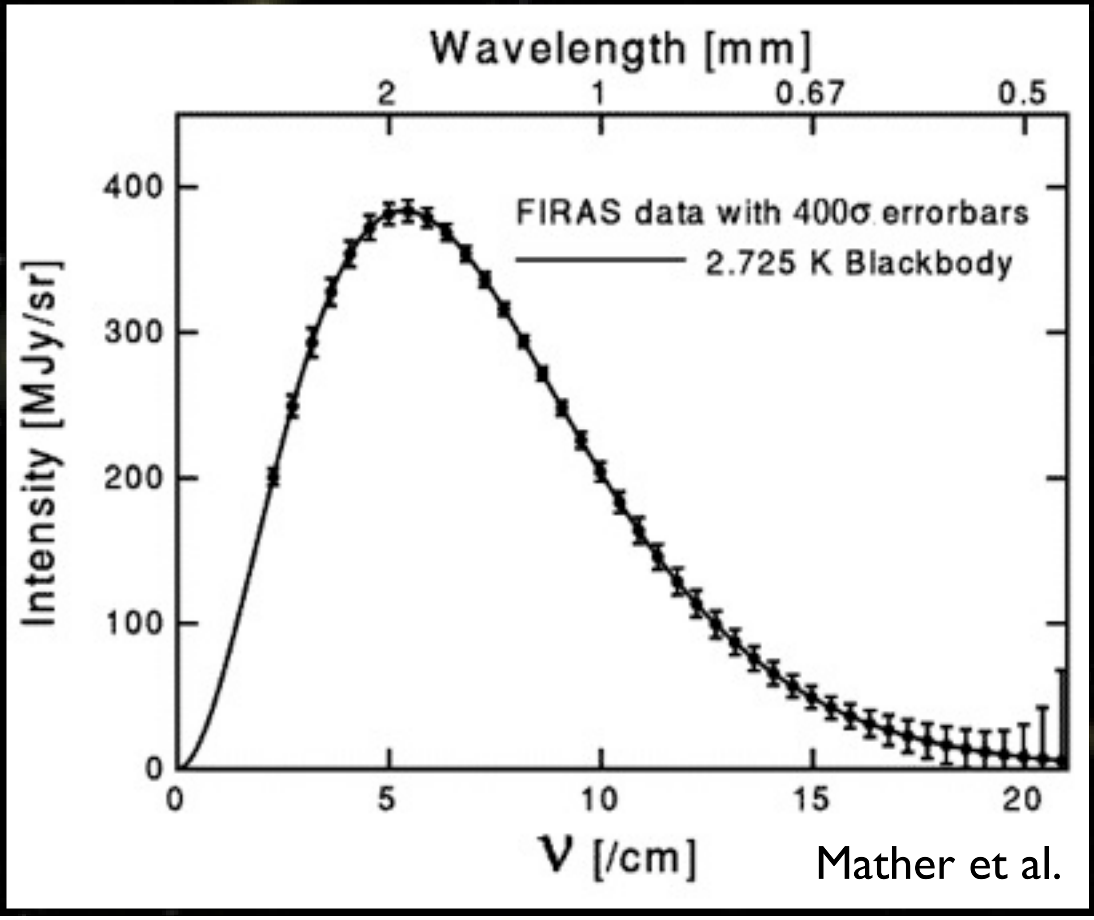
Age of stars supports ΛCDM

- Oldest stars in Milky Way globular clusters:
  - ★ age > 11.2 Gyr (95% C.L.) [Krauss & Chaboyer, 2003]
- Time since Big-Bang depends on content in FLRW
  - ★ in open Ω_m=0.3 : 11.3 Gyr
  - ★ in flat Ω_m=1 : 9.2 Gyr
  - ★ in ΛCDM : 13.7 Gyr
- But: SDSS J102915+172927
  - ★ Ridiculously low metals, no Li, age~13 Gyr?



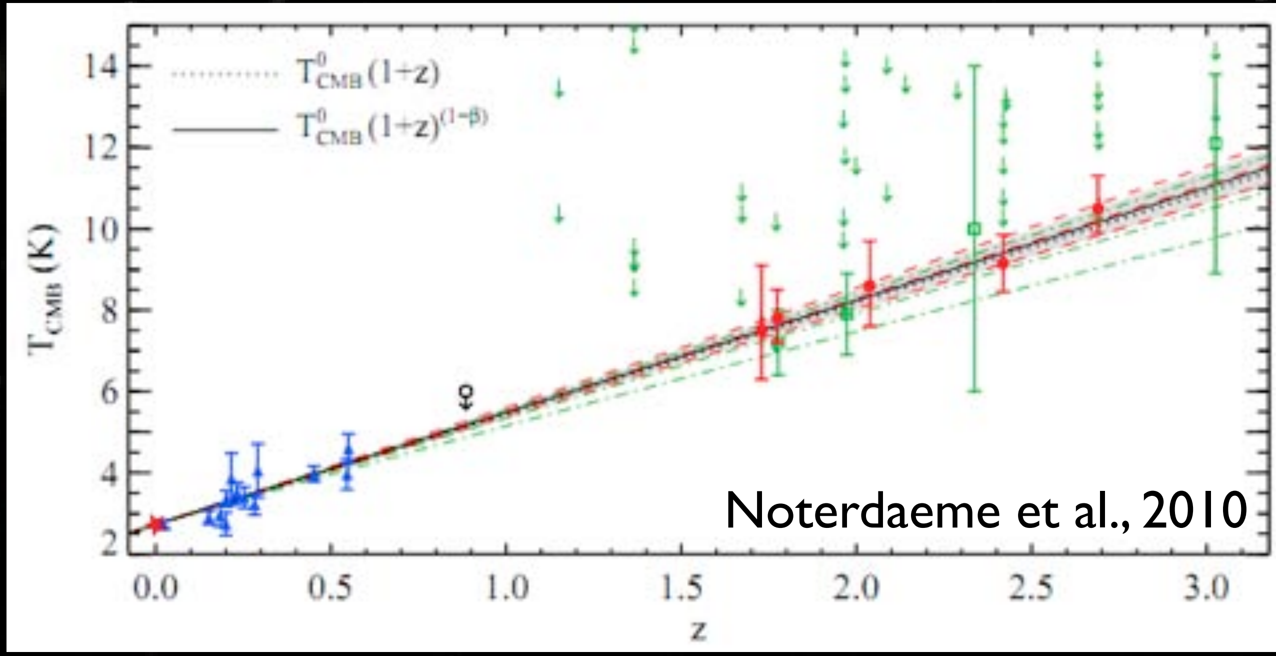
Black Body spectrum of the CMB

- Thermal equilibrium in the past
  - ★ photons: small mean free path in the hot plasma
  - ★ decoupled when Universe becomes neutral
  - ★ Black Body observed today



- Tests of T_{CMB} as a function of z
  - ★ Low-z: S-Z effect in clusters (scattering of CMB photons on the hot gas)
  - ★ High-z: rotational excitation of the CO molecules in QSOs absorption systemas

- In perfect agreement with ΛCDM



Primordial nucleosynthesis

- Gamow 1948:
  - ★ Earlier (high T) nuclei were broken
    - in early times: γ,p,n
    - form nuclei when T is low enough
    - Nuclear reactions stop when T too low
  - ★ Abundances calculated from theory
  - ★ free parameter: fraction of baryons Ω_b

The Origin of Elements and the Separation of Galaxies

G. Gamow

George Washington University, Washington, D. C.

June 21, 1948

- Difficult measurements:
  - ★ Fusion in stars modify the picture
    - Metal poor stars, Ly-α forest of QSOs
- Excellent agreement
  - ★ **Matches CMB Ω_b**
  - ★ possible problem: ^{7}Li
    - Maybe... but measurement is extremely difficult (could be burnt in stars)
  - ★ N.B.: $\Omega_b h^2 \sim 0.02$ is small...

    ➡ open Universe or dark stuff ?

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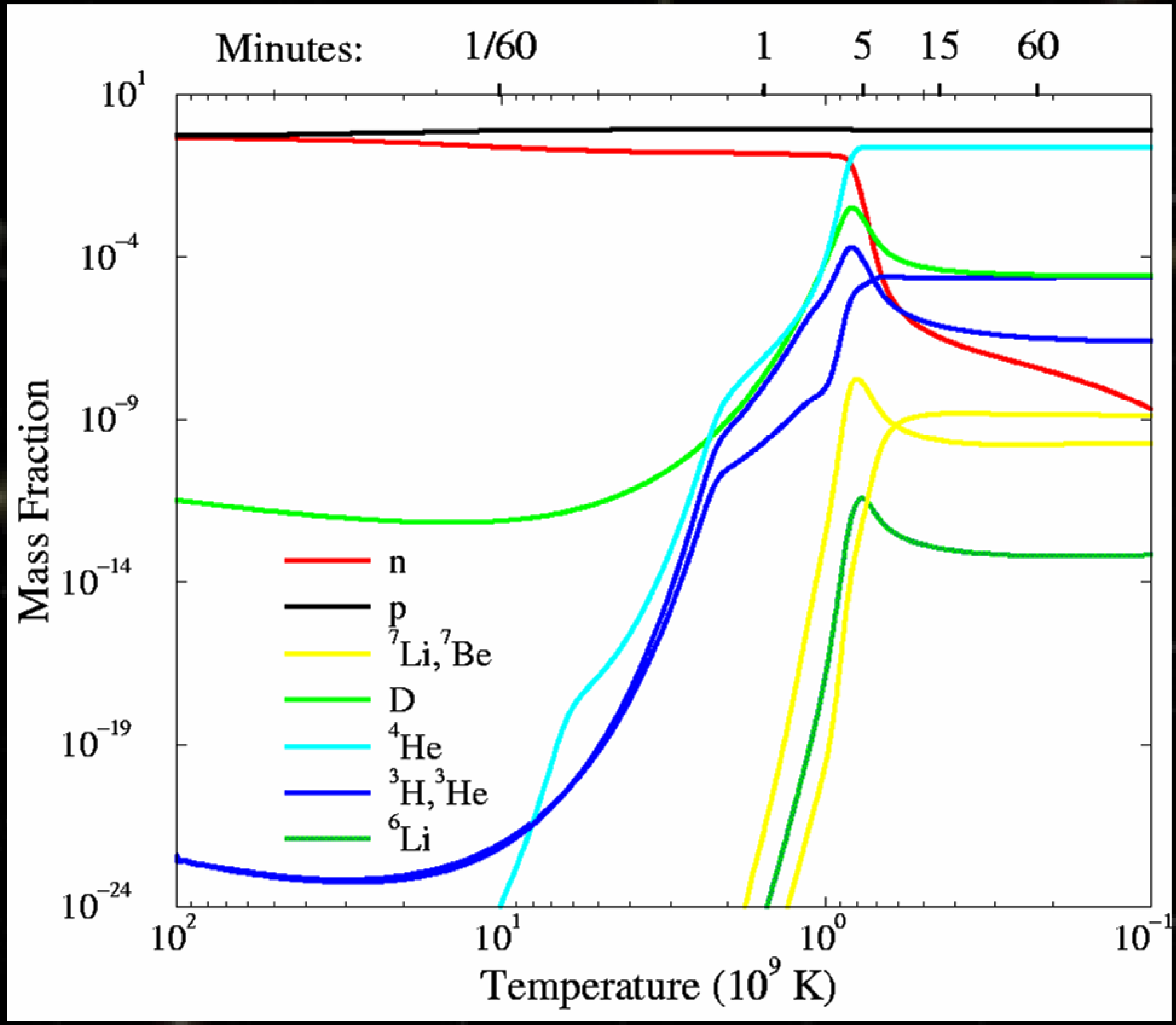

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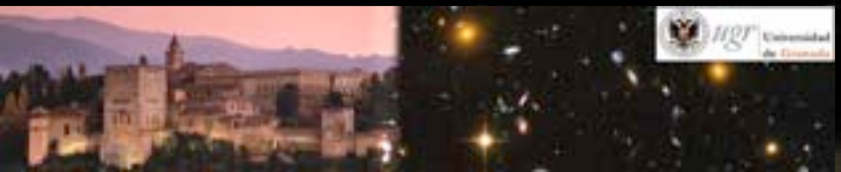

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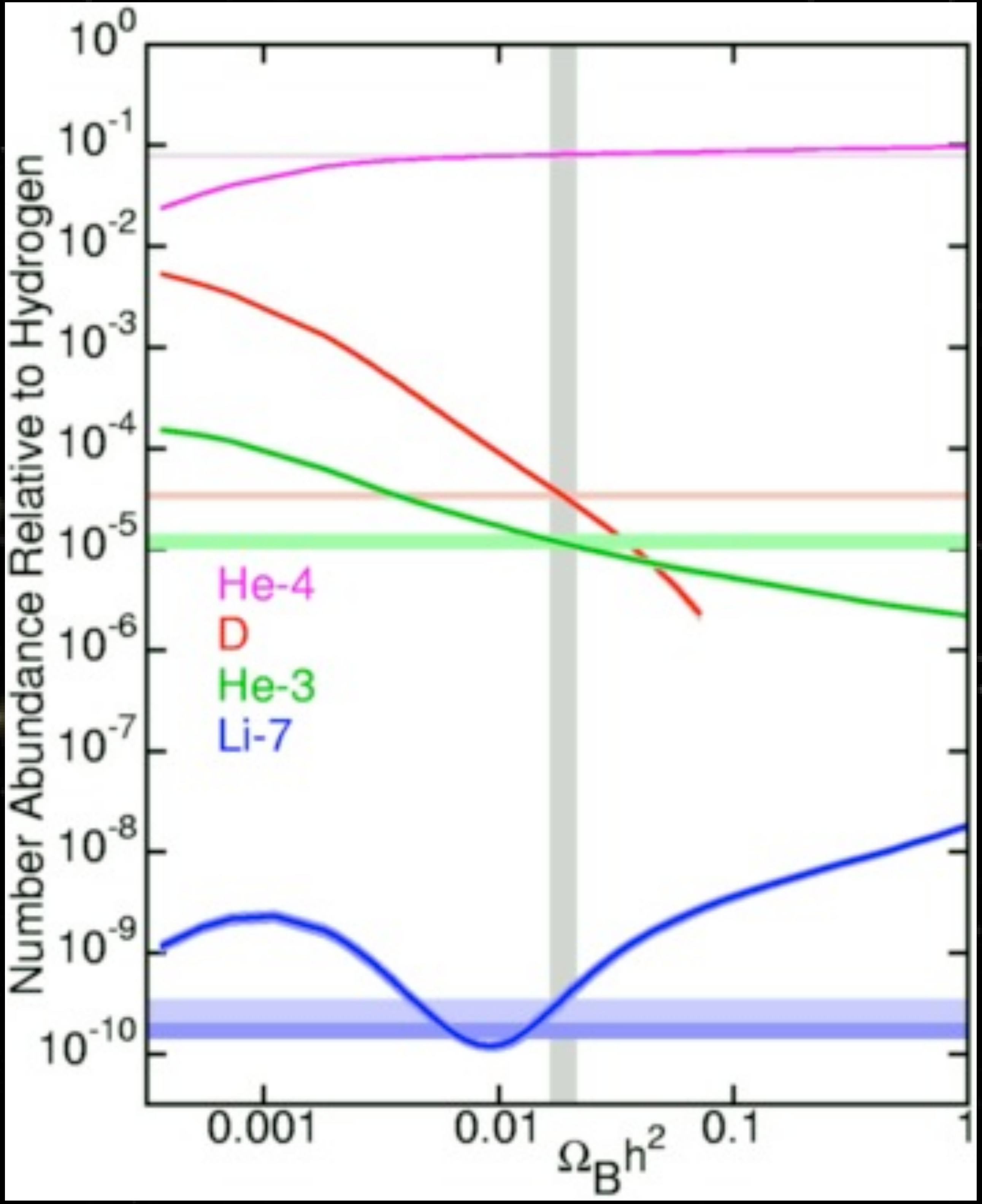

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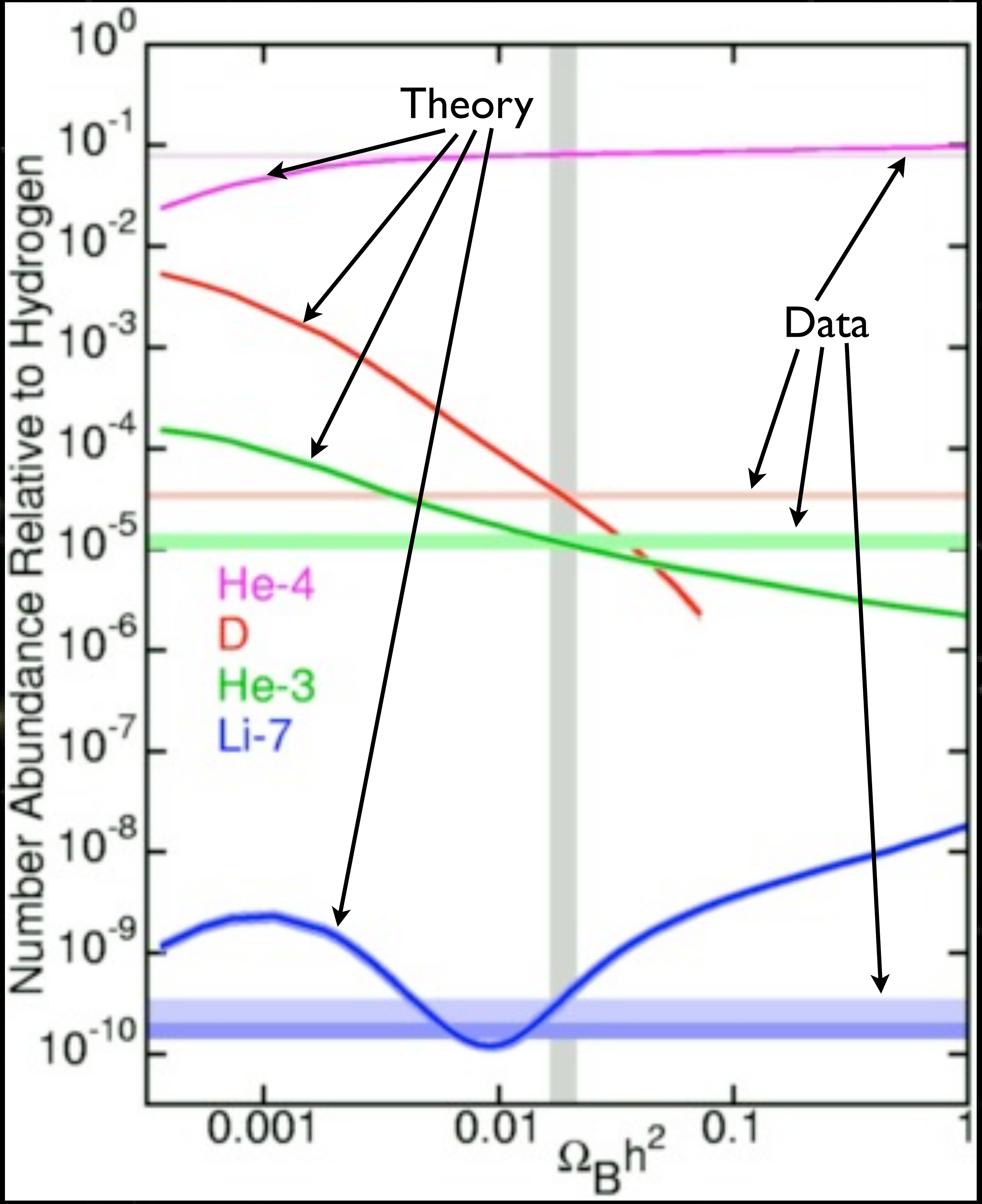

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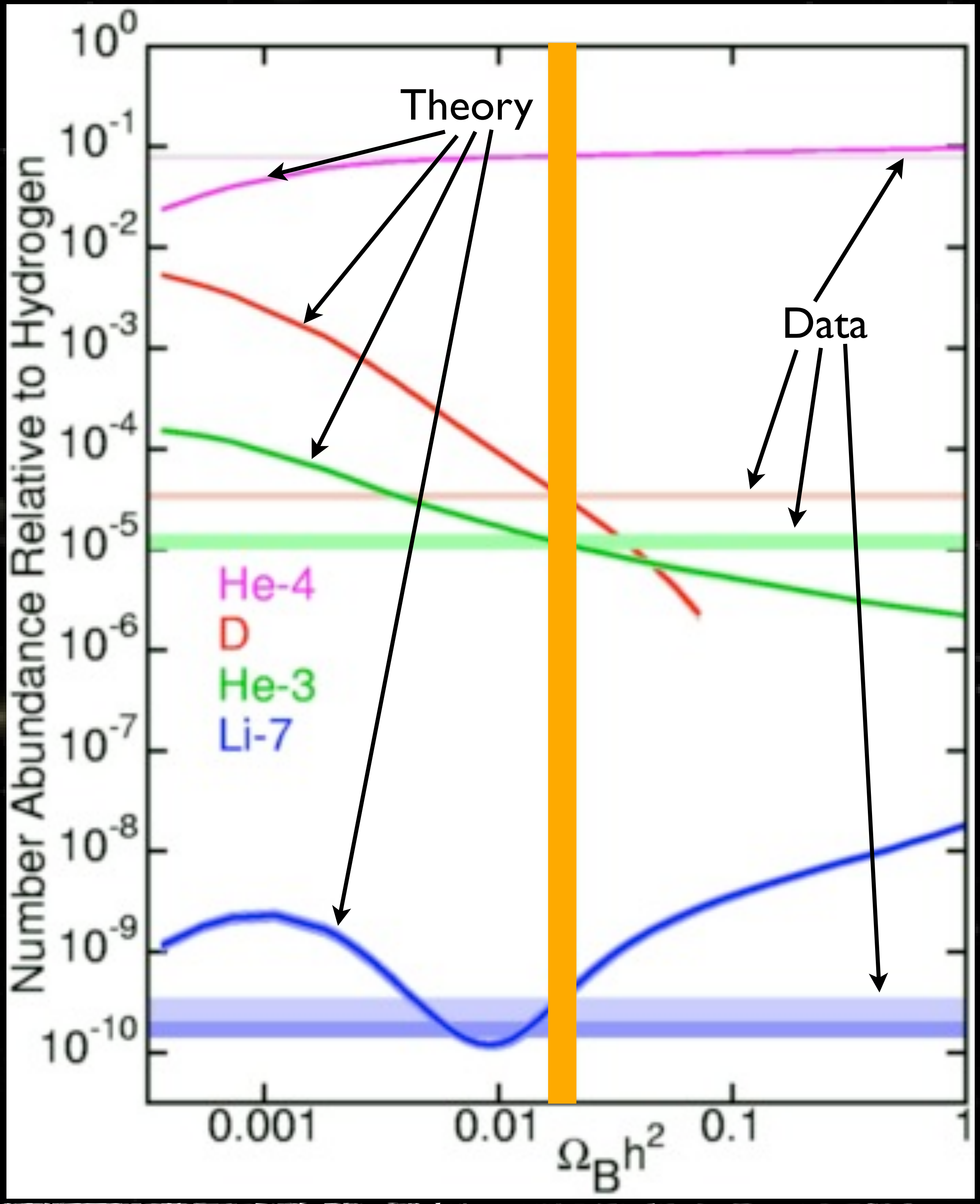
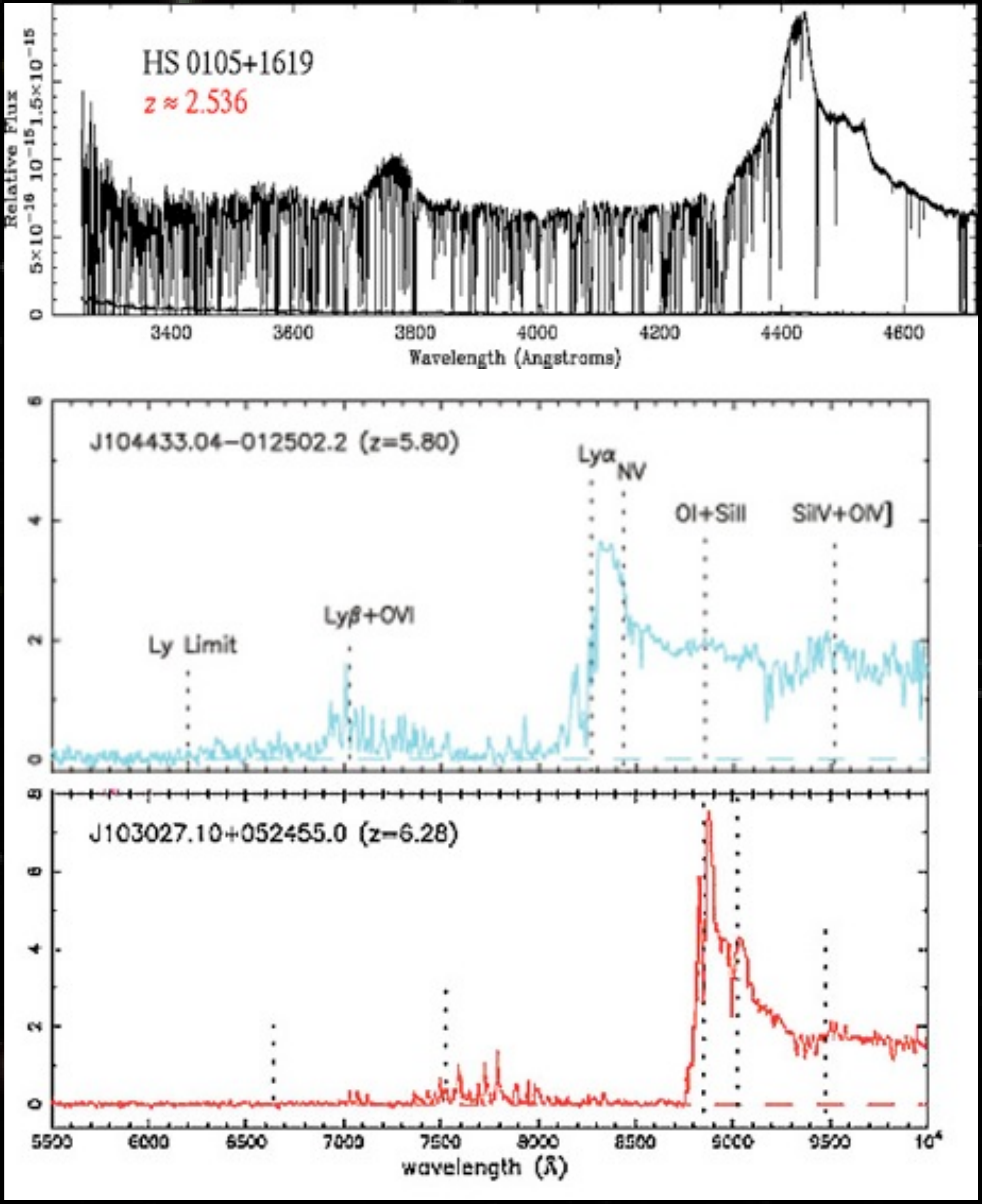


Reionization

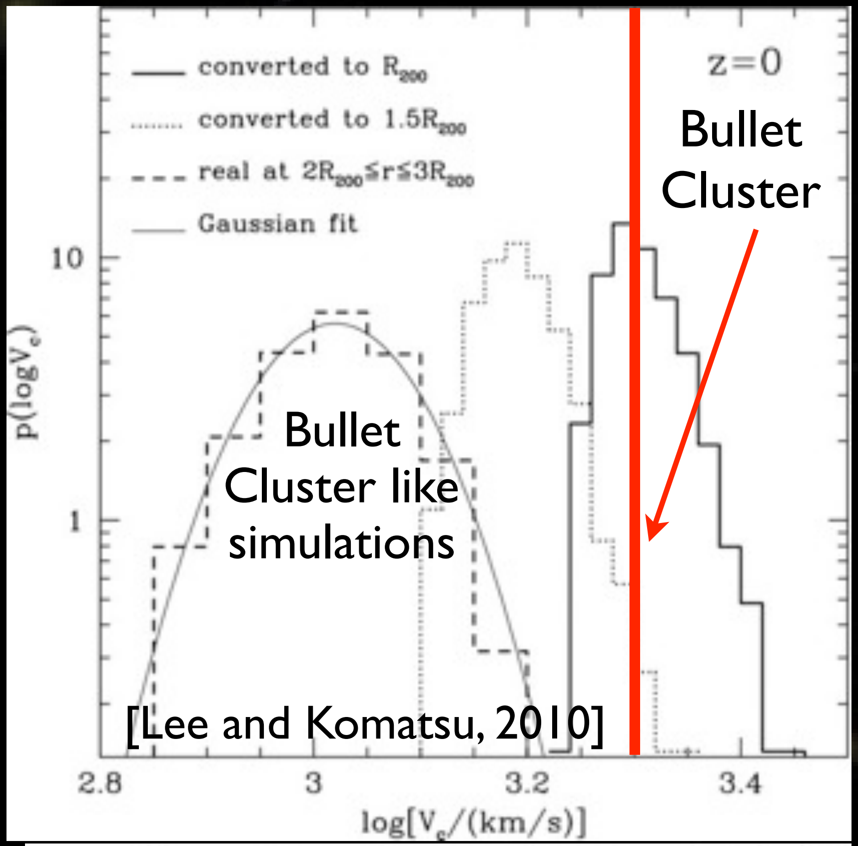
- Dark ages & reionization
  - ★ Neutral medium after CMB realease
    - UV light is absorbed by neutral H
    - Universe opaque to starlight
  - ★ First stars & QSOs produce UV
    - Universe starts to reionize
    - UV absorption less efficient
    - Reionization complete at z~6
    - Universe transparent to UV
- Test: Gunn-Peterson effect
  - ★ Light from 1st quasars should be completely absorbed up to H-alpha line
  - ★ In more recent quasars one should see partial absorption only (Ly-α forest)
  - ★ Predicted long before observation
- Reionization epoch dating matches CMB inferred one

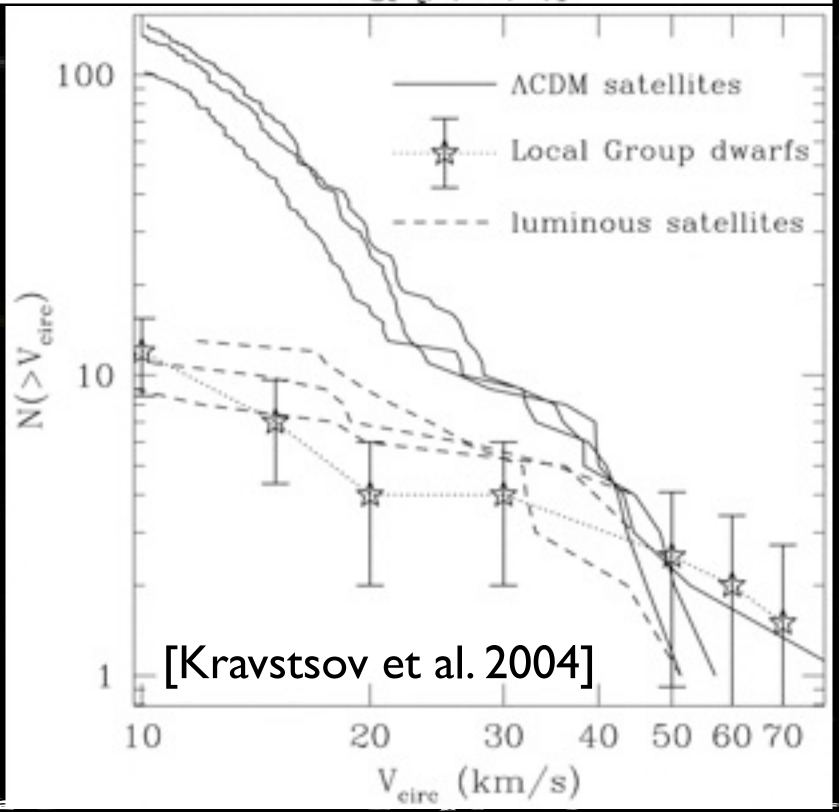


ΛCDM Problems

ΛCDM Issues

- Dark Matter
- Dark Energy
- BBN Lithium problem
  - ★ + star SDSS J102915+172927 ?
- Galactic-scale dynamics:
  - Even with D.M., the «bullet cluster» is weird:
    - Gaz shock seems to involve huge velocities that are not expected in ΛCDM
  - not enough satellites w.r.t. simulations
  - Tully Fisher relation is empirical in ΛCDM but explained in MOND
  - cusps at center of galaxies unobserved
  - ➡ Most of this could be explained by lack of realism or resolution of simulations...
- CMB low multipoles/axis of evil
  - ➡ not serious (just my two cents)





Conclusions (as an observer)

- ΛCDM has firm theoretical and observational basis
  - ★ Confirmed by independent probes
  - ★ Successfully predictive
    - CMB fluctuations/polarization, odd/even peaks, scalar index slightly below 1
    - BAO
    - Gunn-Peterson effect
- Requires large amounts of unobserved/unexplained stuff
  - ★ Dark Matter
  - ★ Dark Energy
  - ➡ Both very convincing from the observational point of view
- Also requires complex analysis of complex data
  - ★ In most cases analyses are well tested for robustness w.r.t. assumptions
  - ★ Complexity doesn't make it wrong
- Cosmology is obviously not finished, maybe just starting...
  - ★ «C'est à la fin du bal qu'on paie les musiciens ...»


COSMOLOGY MARCHES ON
Where did it all come from?
C3
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C3
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S. Harris