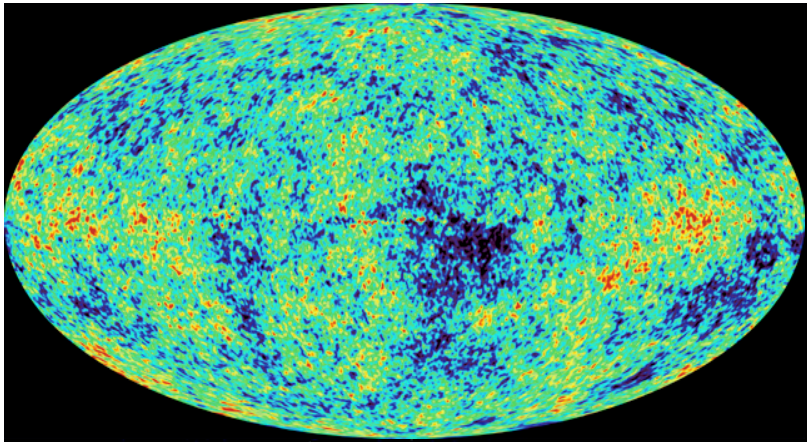
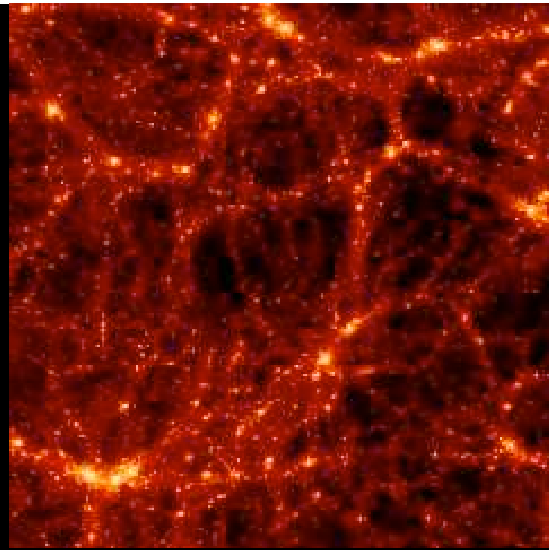
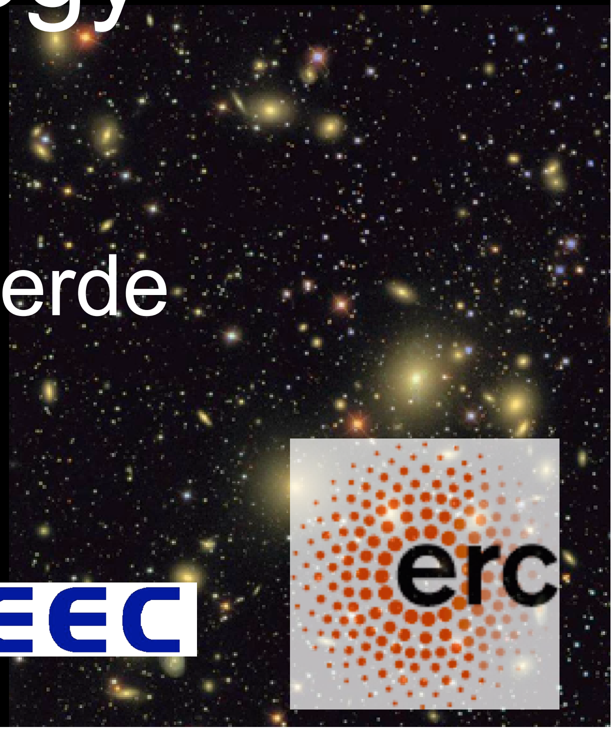






A taste of cosmology

Licia Verde
http://icc.ub.edu/~liciaverde

icrea Institució Catalana de Recerca i Estudis Avançats
ICCUB Institut de Ciències del Cosmos
IEEC
erc

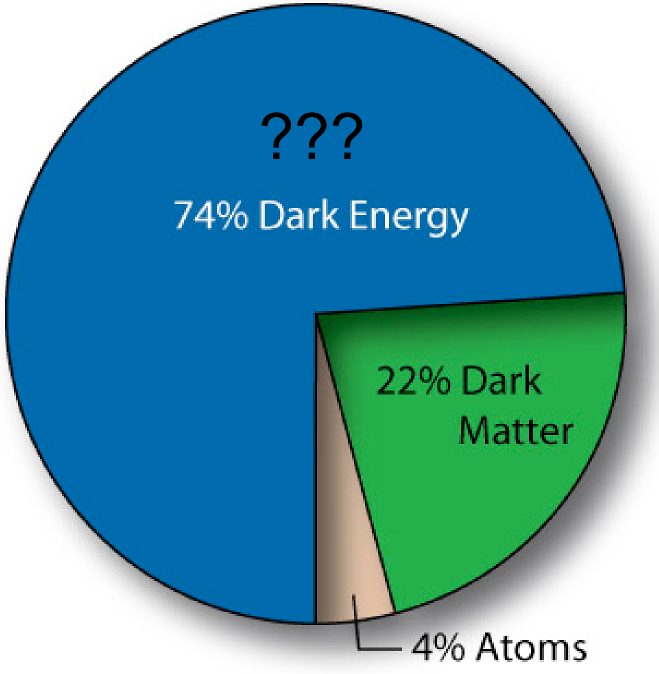
OUTLINE

- The standard cosmological model
- The successes of cosmology over the past 10 years
- Cosmic Microwave Background
- Large-scale structure
- Inflation and outlook for the future

Lectures and additional material will appear at
http://icc.ub.edu/~liciaverde/CLASHEP.html

The standard cosmological model

96% of the Universe is missing!!!



The standard cosmological model

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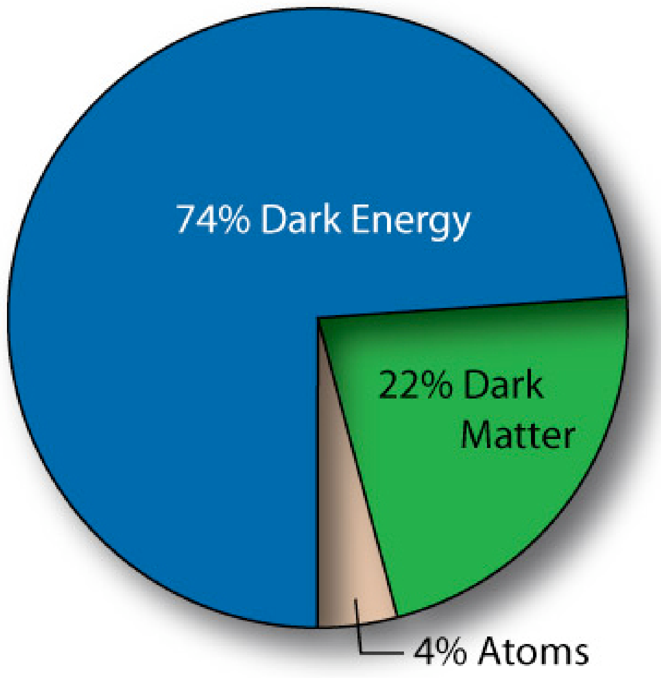
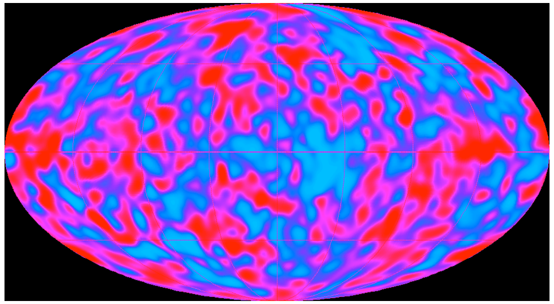


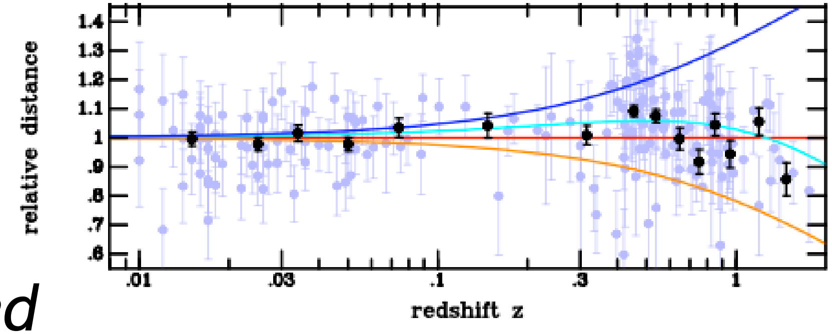
Major questions :

Questions that can be addressed exclusively by looking up at the sky



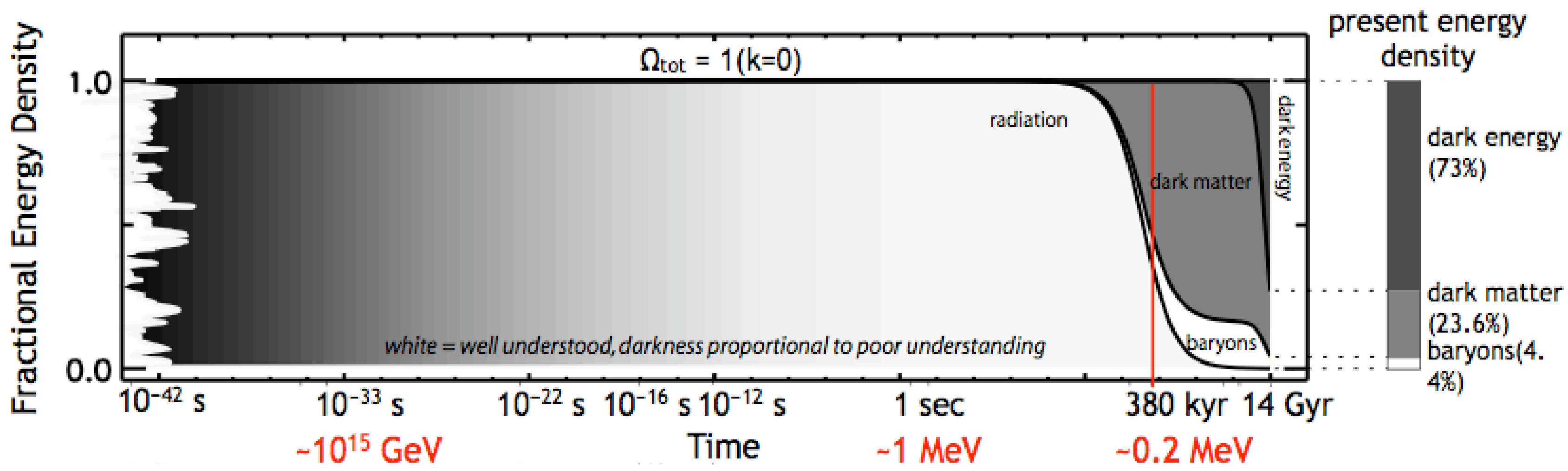
1)What created the primordial perturbations?

2) What makes the Universe accelerate?



These questions may not be unrelated

Cosmic History / Cosmic Mystery



Planck Energy

GUT symmetry

T=100 TeV (ILC X 100)

nucleosynthesis

Generation of primordial perturbations

Cosmic Microwave Background Emitted carries signature of acoustic oscillations and potentially primordial gravitational waves

non-linear growth of perturbations: signature on CMB through weak gravitational lensing

McMahon adapted by Peiris

Aside

Cosmic Variance: Homogeneity and uniformity.

Statistical properties

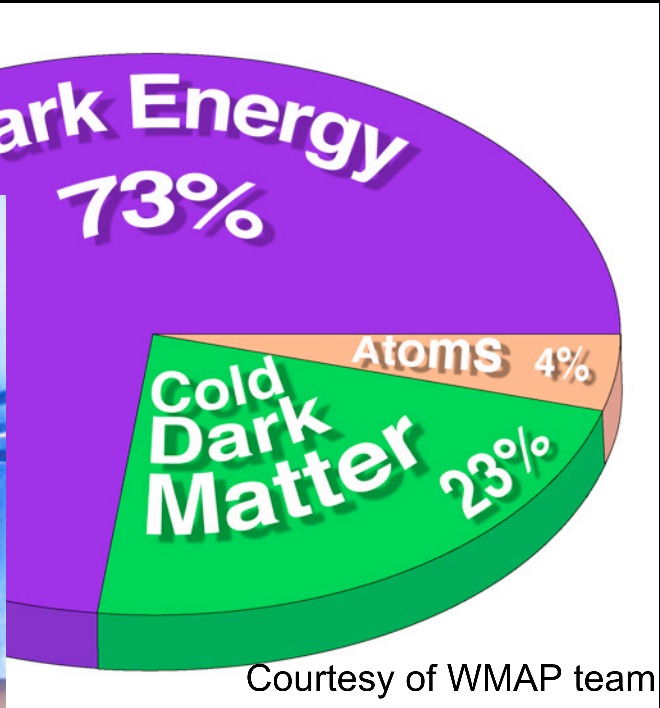
Visible Universe (think of inflation)

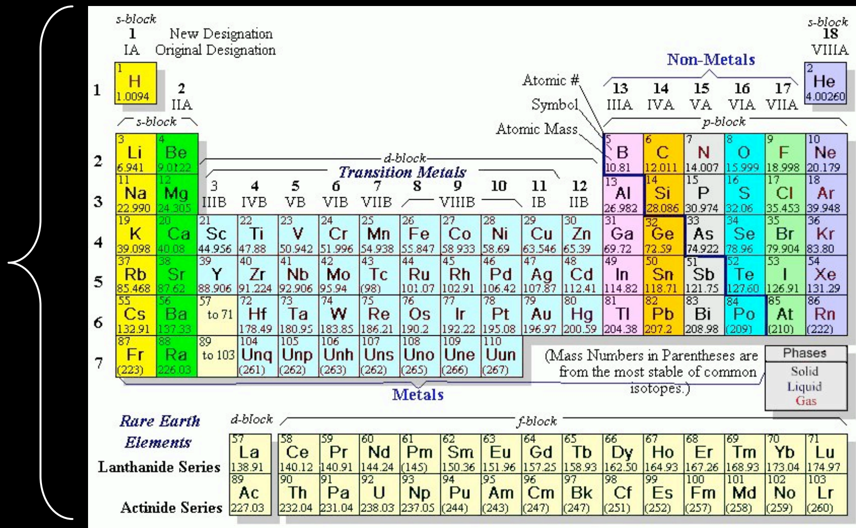
It is only possible to observe part of the Universe at one particular time, so it is difficult to make statistical statements about cosmology on the scale of the entire universe, as the number of independent observations (sample_size) is finite.

Fundamental limit: "Cosmic variance-dominated" measurement

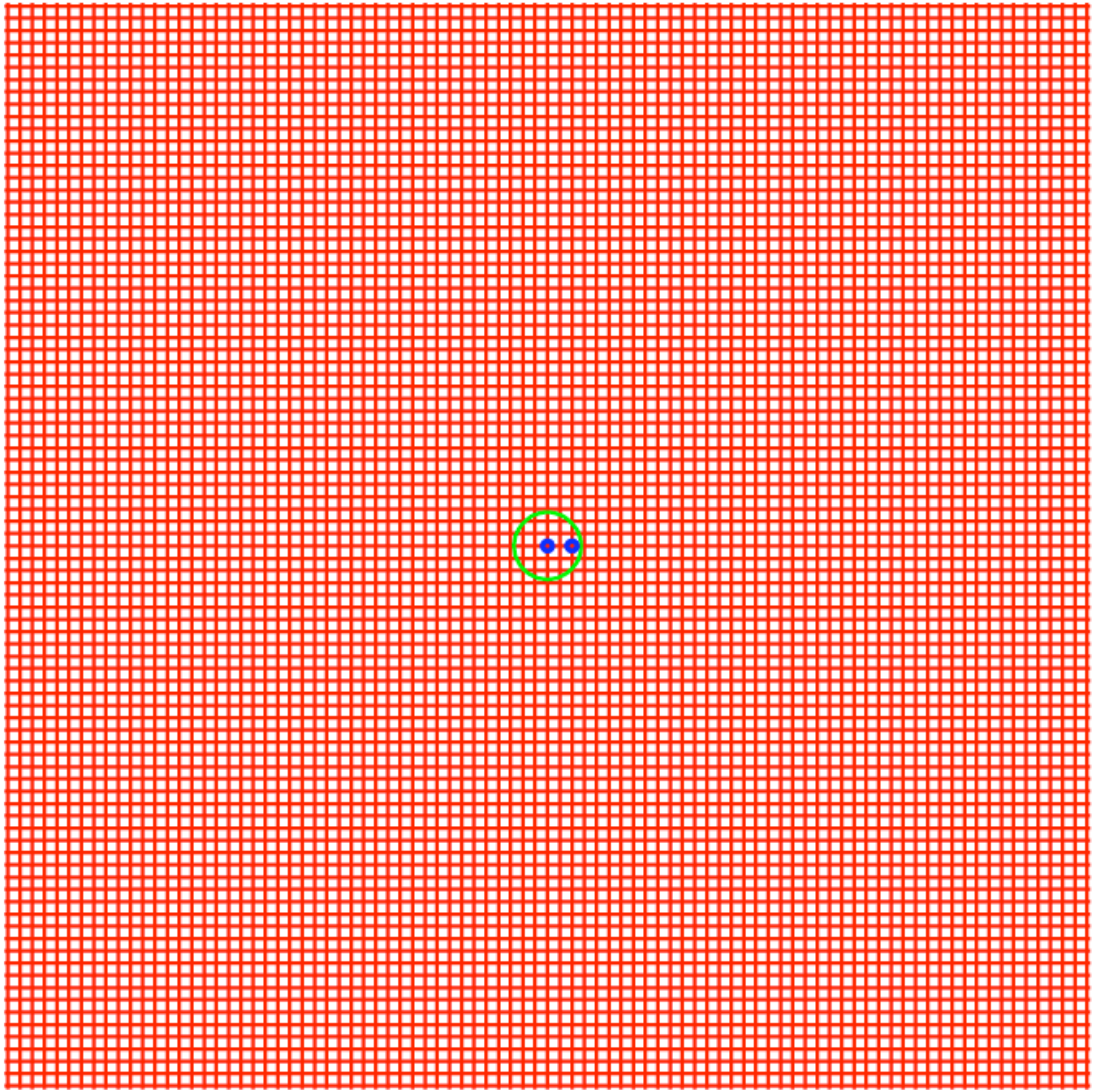
Legacy power of forthcoming surveys

We (and all of chemistry) are a small minority in the Universe.

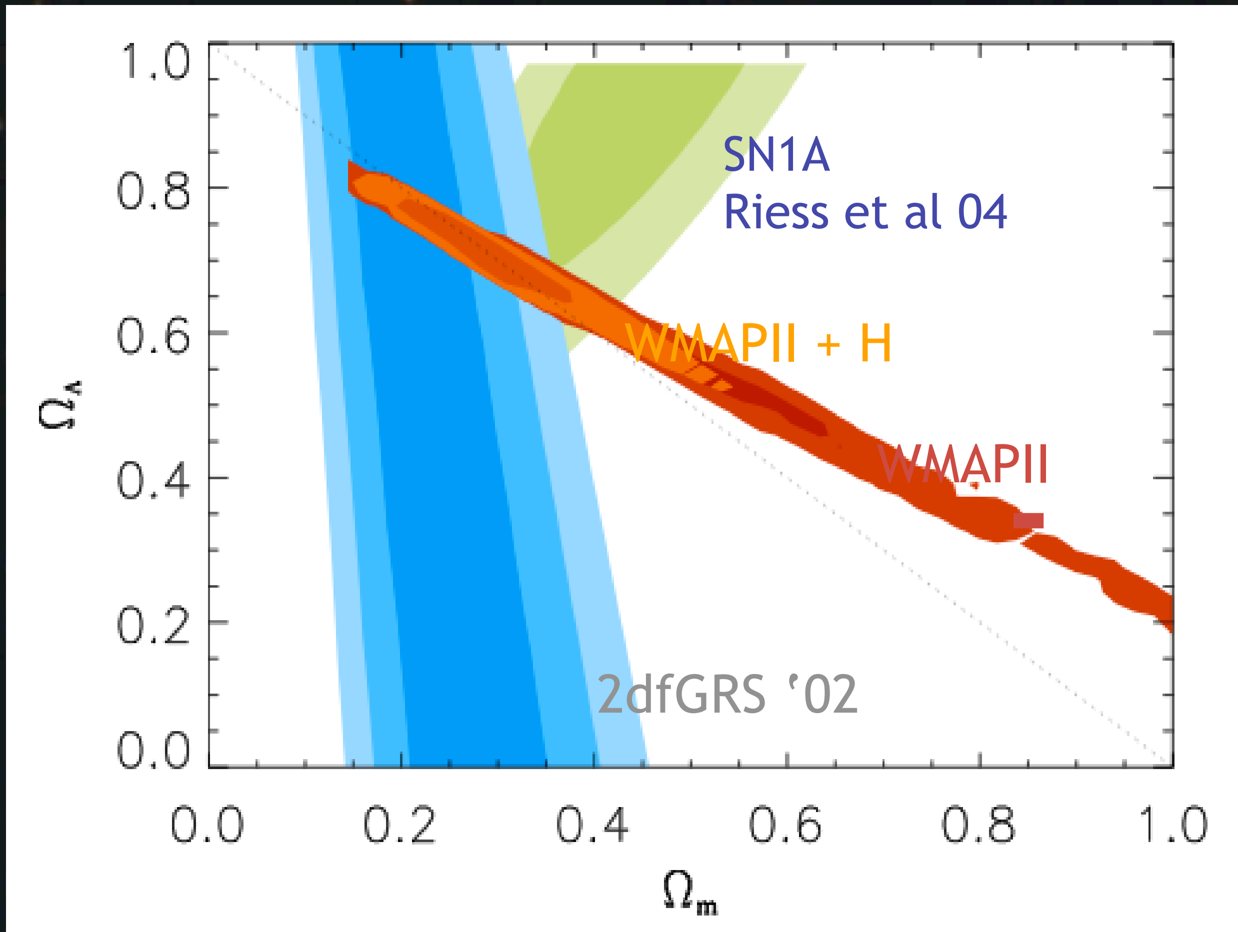




We do not know what 96% of the Universe is !



Observational status:

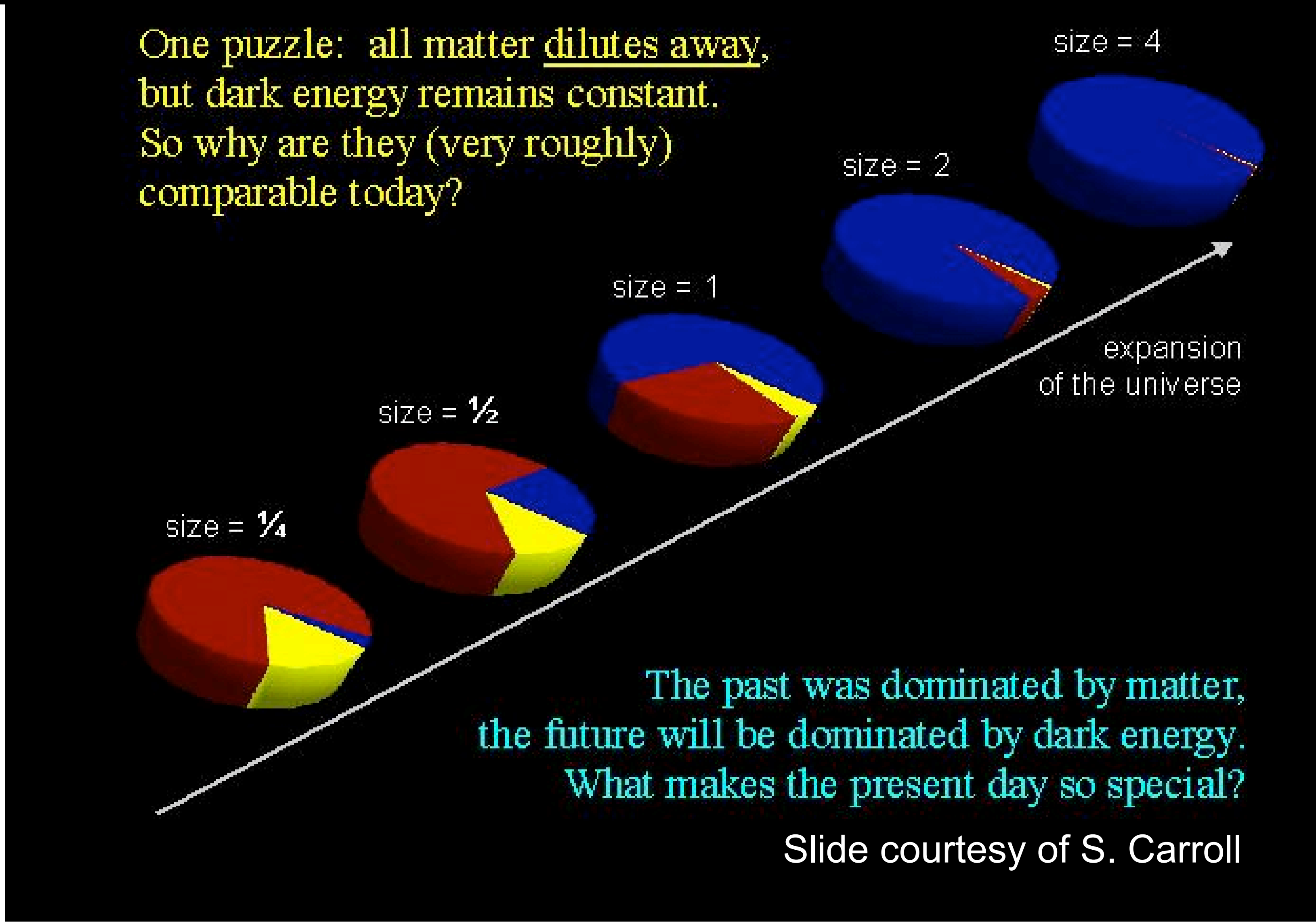


Einstein's Equations

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

Interpretation in terms of vacuum energy

The “why now” problem



Slide courtesy of S. Carroll

This is a preposterous universe.

- Why is the vacuum energy density so much smaller than it should be? Naive expectation:

$$\rho_{DE}^{(theory)} = 10^{120} \rho_{DE}^{(obs)}$$

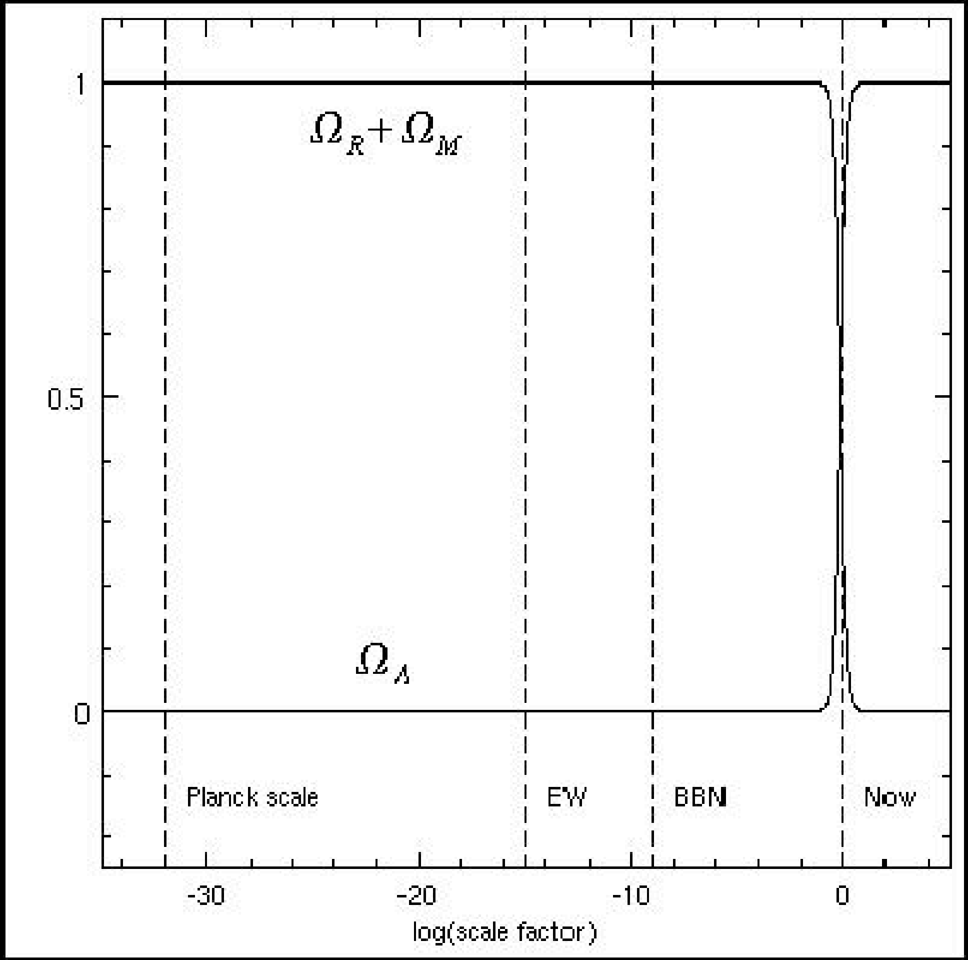
- What is the nonzero dark energy? A tiny vacuum energy, a dynamical field, or something even more dramatic?

- Why <u>now</u>? Remember $\rho_{DE} / \rho_M \sim a^3$. So why are they approximately equal today?

Slide courtesy of S. Carroll

And it's moving quickly:

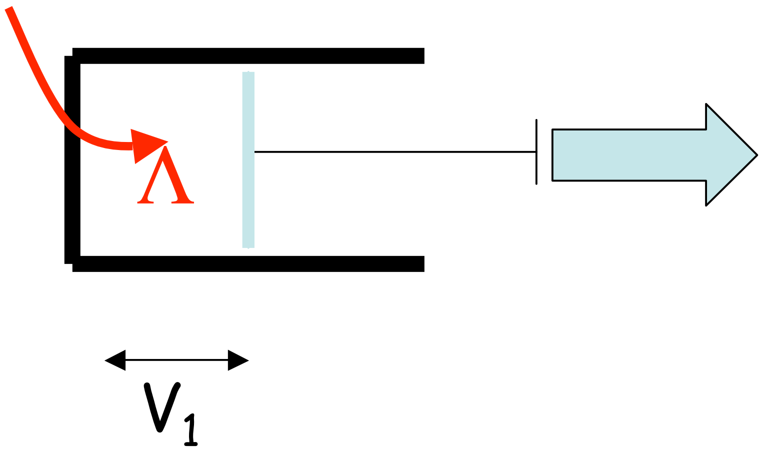
$$\frac{\Omega_\Lambda}{\Omega_M} \sim a^3$$



Vacuum energy Λ

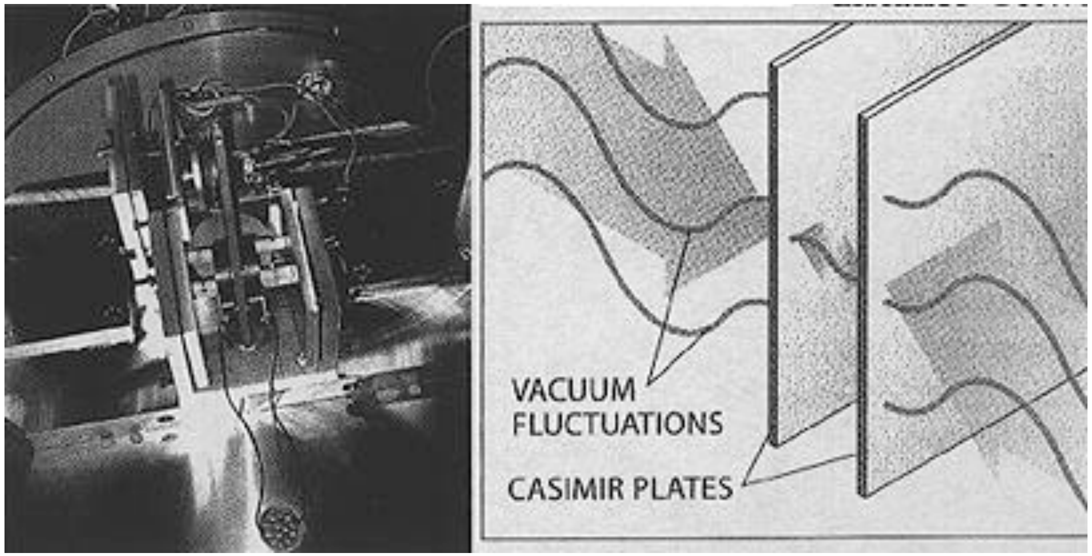
(also known as dark energy or cosmological constant)

vacuum



1917

$$E_1 = \rho_V V_1$$



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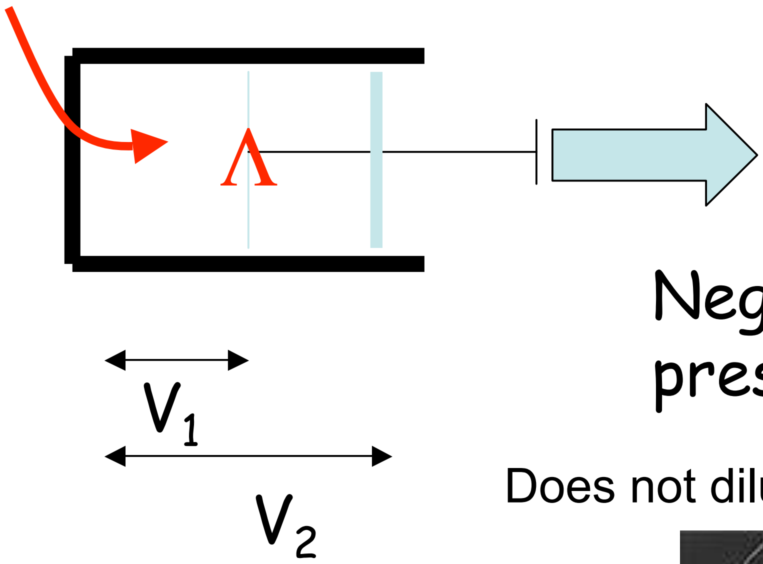


1917

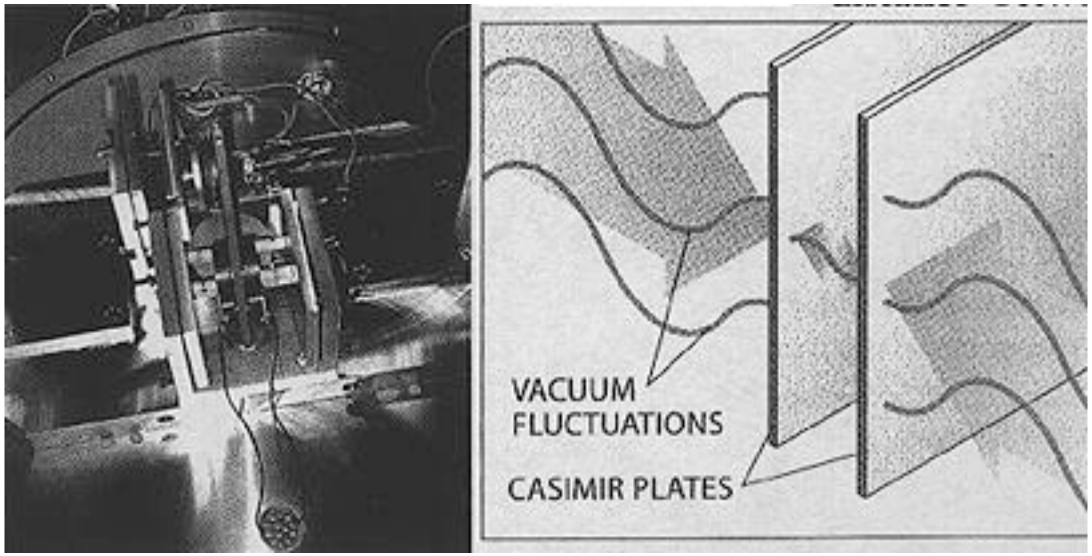
Negative pressure!

Does not dilute!

$E_1 = \rho_V V_1$

$E_2 = \rho_V V_2$

$E_2 > E_1$



The CC problem

QFT predict a huge cosmological constant from the energy of the quantum vacuum.

If the universe is described by an effective local quantum field theory down to the Planck scale, then we would expect a cosmological constant of the order of Mpl^4.

$$\rho_{DE}^{(theory)} = 10^{120} \rho_{DE}^{(obs)}$$

What cancels it out (almost but not completely)?
Fine tuning? Dynamical?

Preposterous Universe!

Compare DE with other major discoveries in physics

- ★ Constancy of the speed of light (1887)
- ★ Discovery of the μ-particle (1936)
- ★ Discovery of the Ω^- baryon (1964)
- ★ Cosmic Backgroud Radiation (1965)
- ★ W and Z bosons (1983)
- ☆ Higgs particle ?? (2010/2012 ??)

Courtesy of A. Casas

Compare DE with other major discoveries in physics

- ★ Constancy of the speed of light (1887)
- ★ Discovery of the μ-particle (1936)
- ★ Dark Energy
- ★ Discovery of the Ω^- baryon (1964)
- ★ Cosmic Backgroud Radiation (1965)
- ★ W and Z bosons (1983)
- ☆ Higgs particle ?? (2010/2012 ??)

Courtesy of A. Casas

Michelson & Morley result was against the theoretical expectations (theory of aether)

Nobody expected the muon **Who ordered the muon?** **(I.I. Rabi)**
but it does not challenge the theoretical framework

The DE discovery is also against the theoretical expectations

It likely requires a radical change in our pre-conceptions

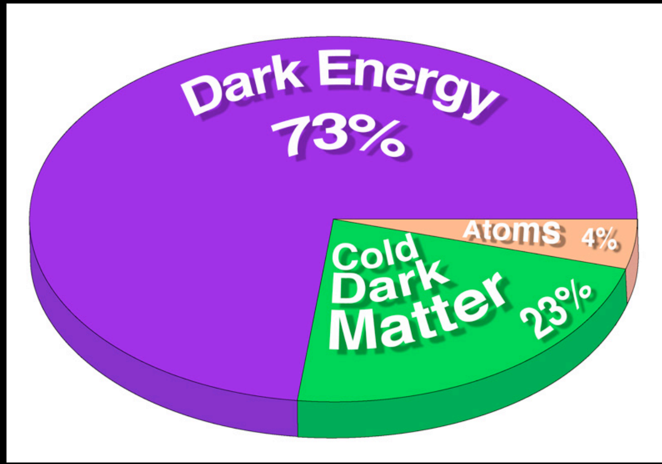
A continuation of the cosmological constant problem: why is Λ that small???

Courtesy of A. Casas

So.. Where do we go from here?

We have an inventory of what makes up the Universe but no understanding.

Connections with fundamental physics!



What may be going on?

Options include:

The vacuum energy is very different in other far far away parts of the Universe

We just got lucky…

A slowly varying dynamical component taking over (and it may not even be the first time)

Einstein was wrong

String theory?

The Challenges

Challenge n1: If it's Λ why is it that small?

On this issue astronomers have done their work already (I.e. Λ is non zero)
Now it is the job of theoretical physicists

Challenge n2: is it dynamical?

Astronomers: go measure it!

Theoretical physicists: which parameterization?

Challenge n3: are we sure we know gravity?

The Challenges

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Challenge n2: is it dynamical?

Astronomers: go measure it!

Theoretical physicists: which parameterization?

Challenge n3: are we sure we know gravity?

Challenge n2 is it Dynamical? What do you mean?

Think of inflation…. Or a slowly rolling scalar field…

$$p = \frac{1}{2}\dot{\phi}^2 - V(\phi) \qquad \rho = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

K.E. P.E.

$$\dot{\rho} + 3H(\rho + p) = 0$$ continuity

$$\ddot{\phi} + 3H\dot{\phi} = -V'(\phi)$$

$$w = \frac{p}{\rho} \longrightarrow a(t)$$

Challenge n2: is it dynamical?

Astronomers: go measure it!

CMB (only secondary anisotropies will now help: ACT, SPT, APEX, etc…)

SNe (SLNS, ESSENCE, SNAP, LSST, SDSSII, etc.)

Gravitational Lensing (DES, Panstarr, LSST, DUNE,…)

Galaxy Clusters (ACT, SPT, APEX…)

BAO… (DES, WFMOS, VISTA, AAO, BOSS, ADEPT, SPACE…)

And the acronyms keep coming….

Data challenge

"exponential world"

Systematics challenge.

"controlled errors are more important than how small they are"

THE SYMPTOMS

Or OBSERVATIONAL EFFECTS of DARK ENERGY

Recession velocity vs brightness of standard candles: dL(z)

CMB acoustic peaks: Da to last scattering

LSS:
- Da to z_{survey}
- perturbations amplitude today, to be compared with CMB
- (or Matter density today)

Leading observational techniques to go after dark energy

Supernovae (expansion history)

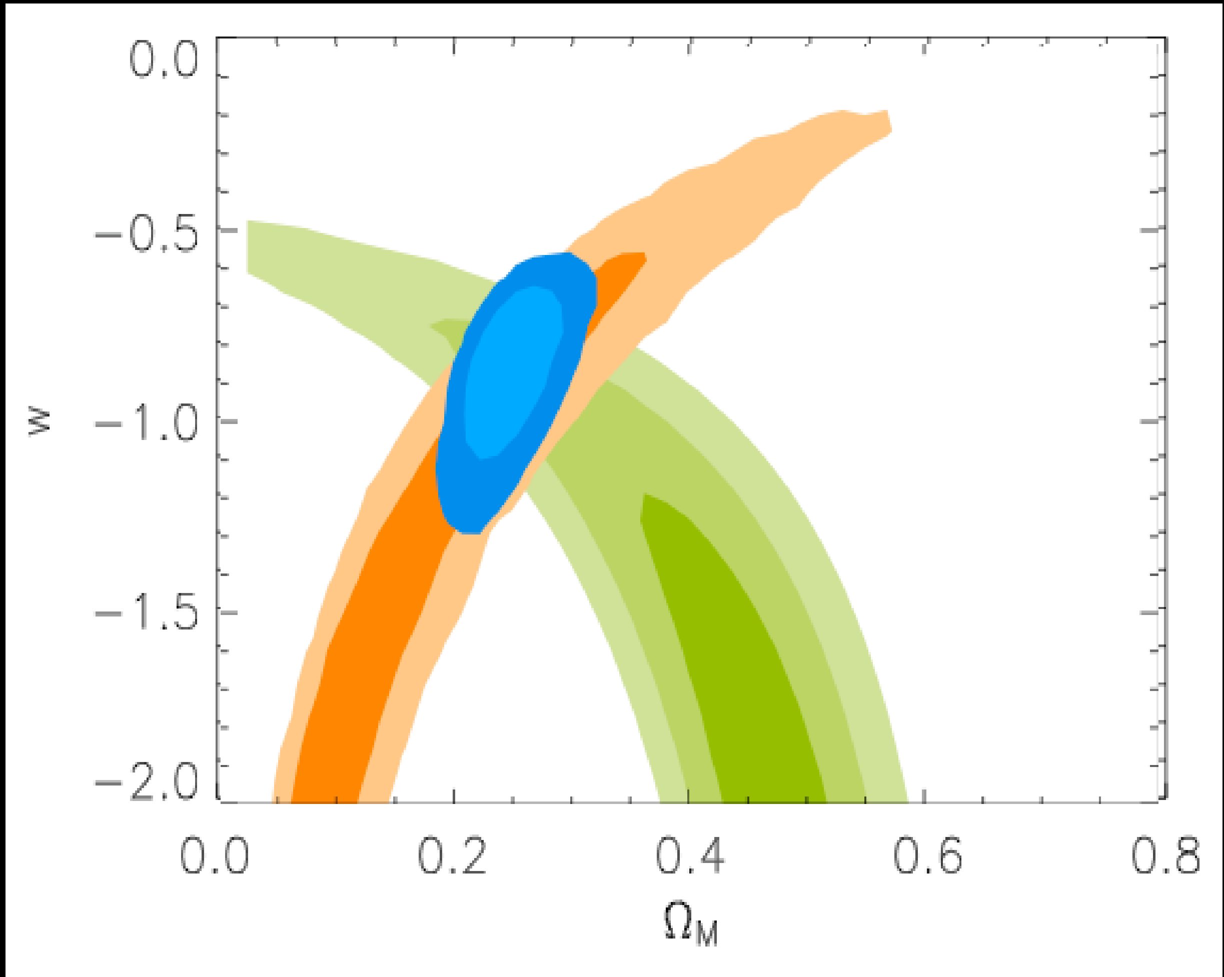
Galaxy clusters number counts (mostly growth of structure)

Weak Lensing (growth of structure and expansion history)

Baryonic Acoustic Oscillations (BAO) (expansion history)

Q: A combination of techniques will be best for
at least two reasons

Dark energy so far…



2dfGRS

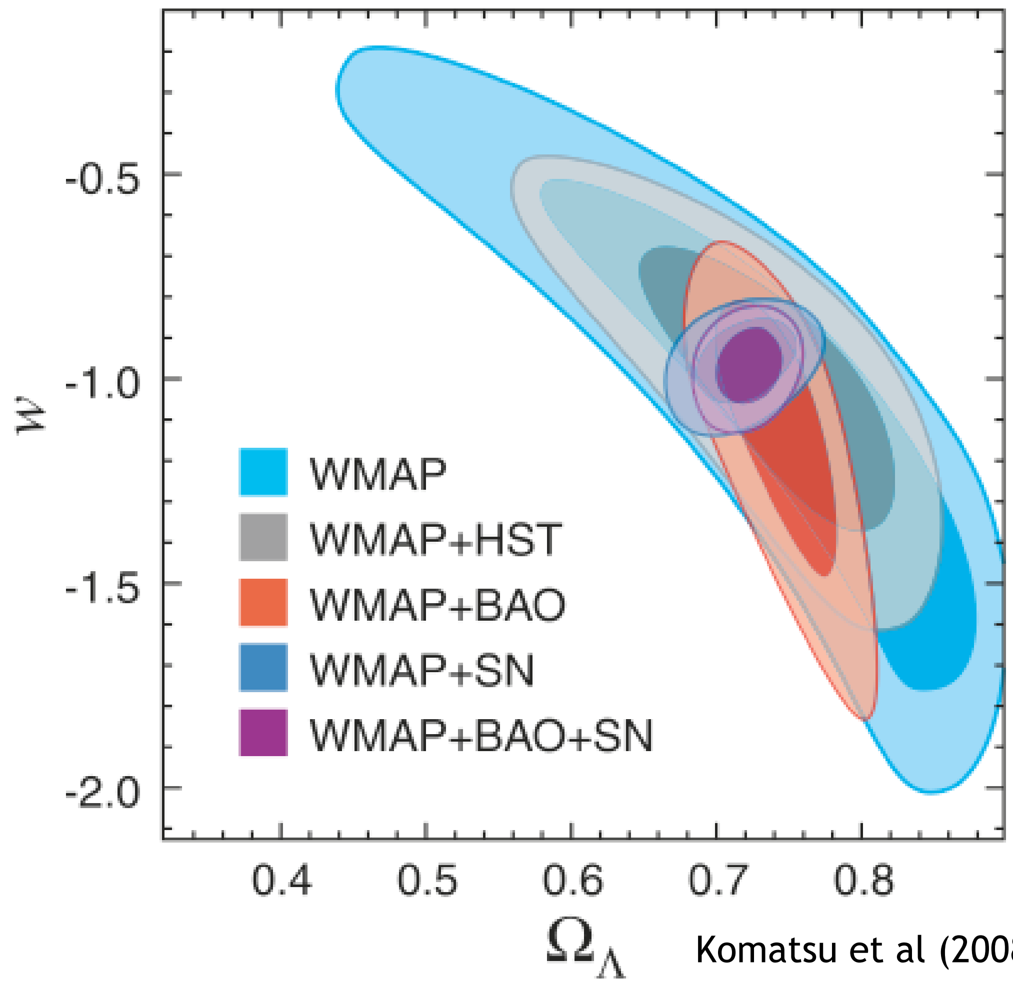
H prior

WMAPII

SN

(With DE clustering)

Dark energy



Komatsu et al (2008)

WMAP5

weak dark energy constraints from CMB?

A BUT The CMB encloses information about the growth of foreground structures: secondary CMB!

- Integrated Sachs Wolfe effect
- Secondary effects: Sunyaev Zeldovich(SZ), Kintetic SZ, Rees-Sciama, Lensing.

B **What if one could see the peaks pattern also at lower redshifts?** (and get other things for free)

C … resort to other probes

We test inflation by looking at the perturbations it generated

We can test about 10 efoldings by looking at cosmological structures
Despite Inflation happening 13.7 billion years ago and dark energy happening today, we seem to know much less about DE: we cannot see its perturbations and we can only see ~2 efoldings.
But we can follow the (recent) expansion history and the growth of cosmological structures

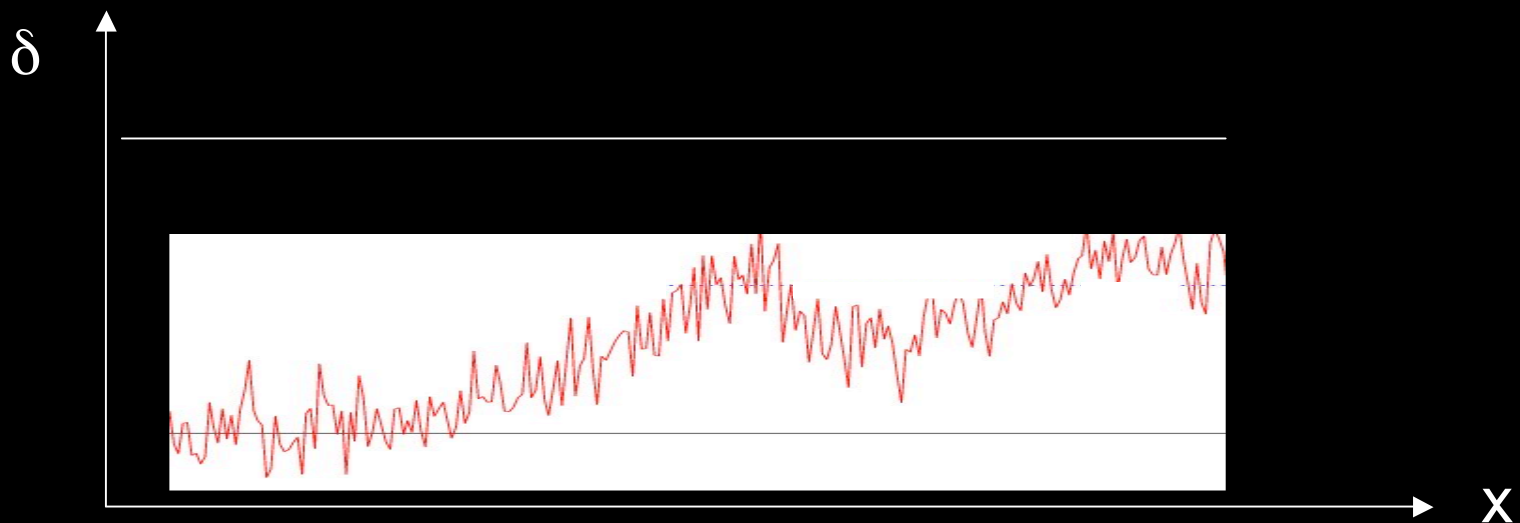
We test dark energy by looking at the expansion history (encoded also in the growth of cosmic structures)

Galaxy clusters number counts

Galaxy clusters are rare events:

$P(M,z) \propto \exp(-\delta^2/\sigma(M,z)^2)$

In here there is the growth of structure



Beware of systematics! "What's the mass of that cluster?"

Galaxy clusters number counts

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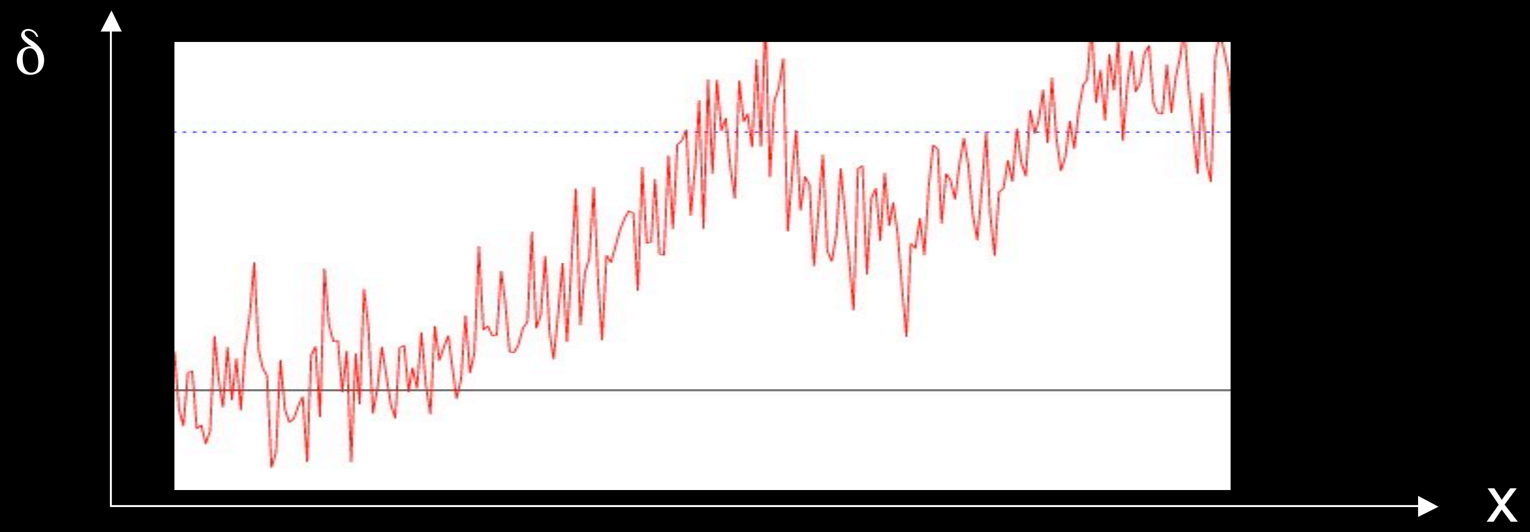

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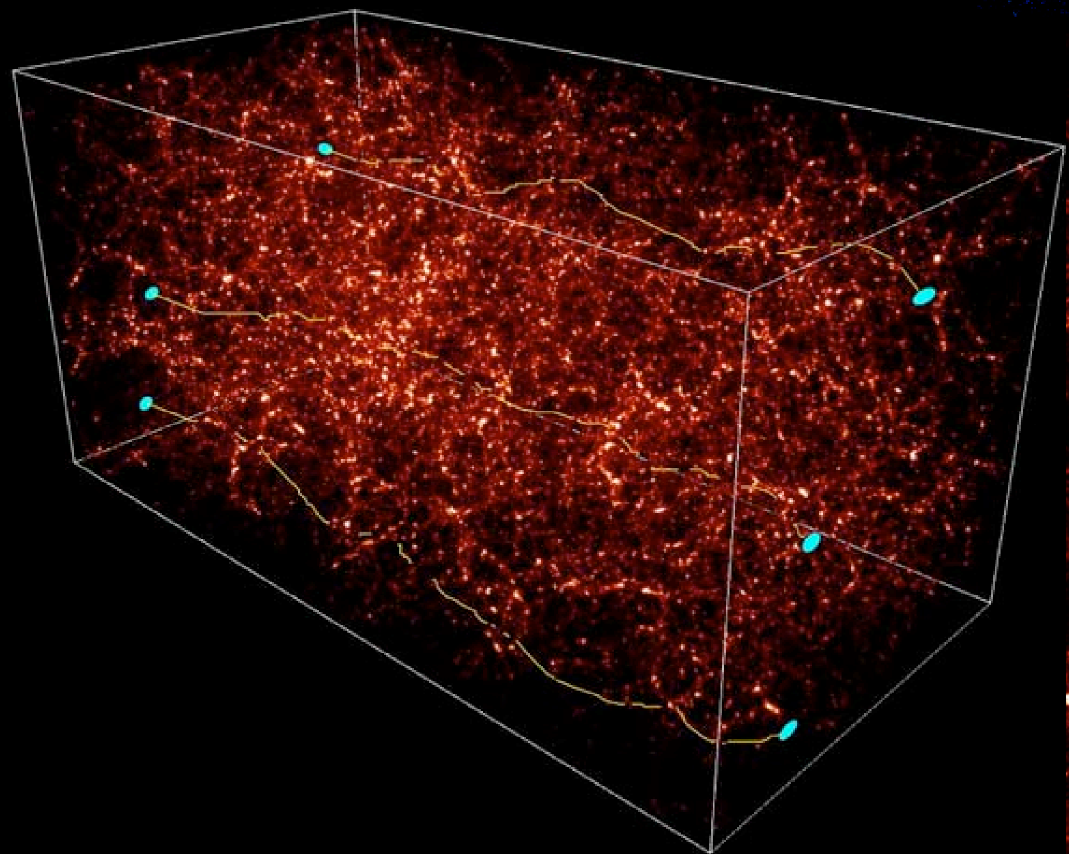
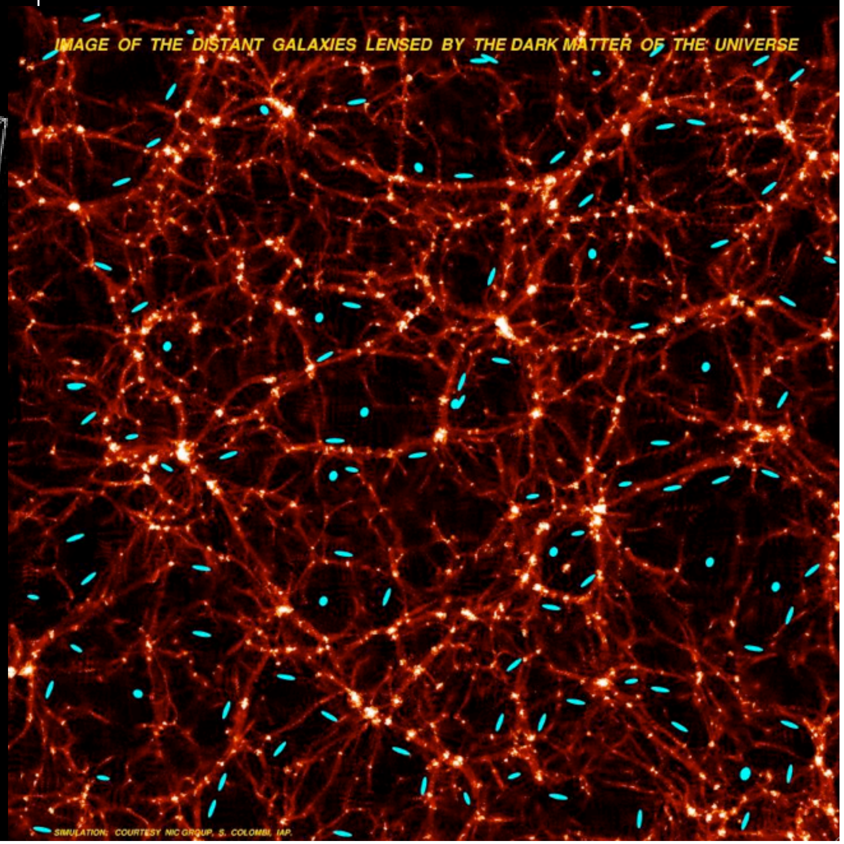
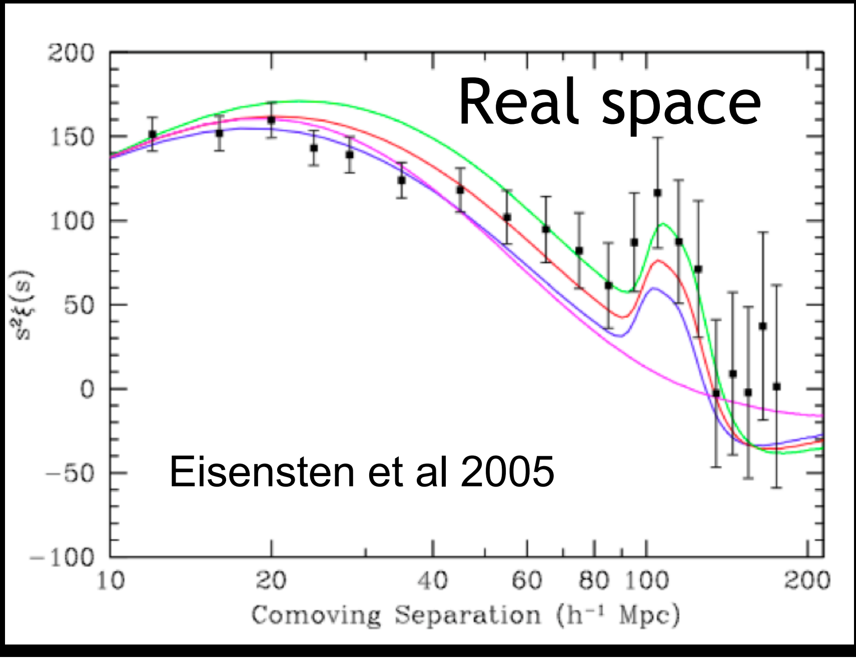
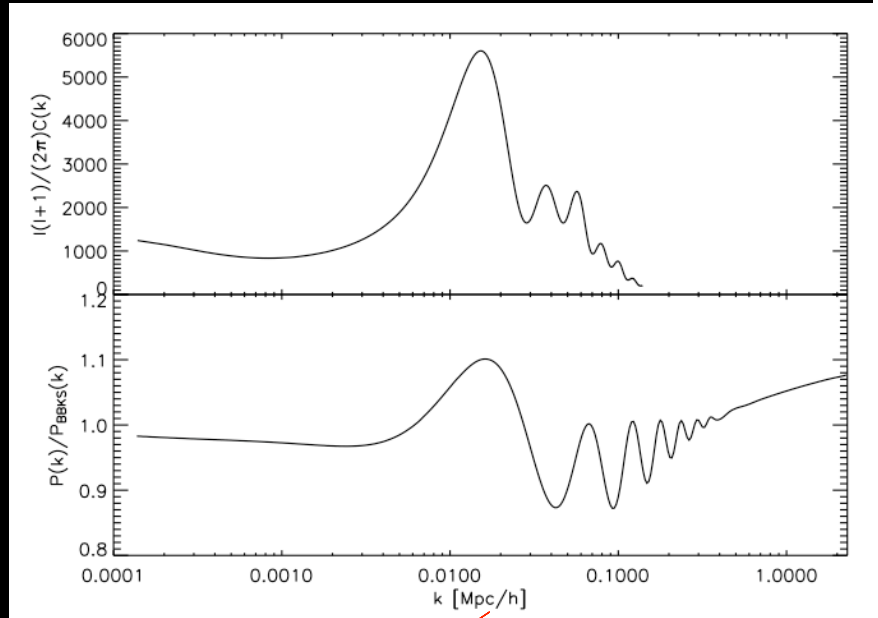
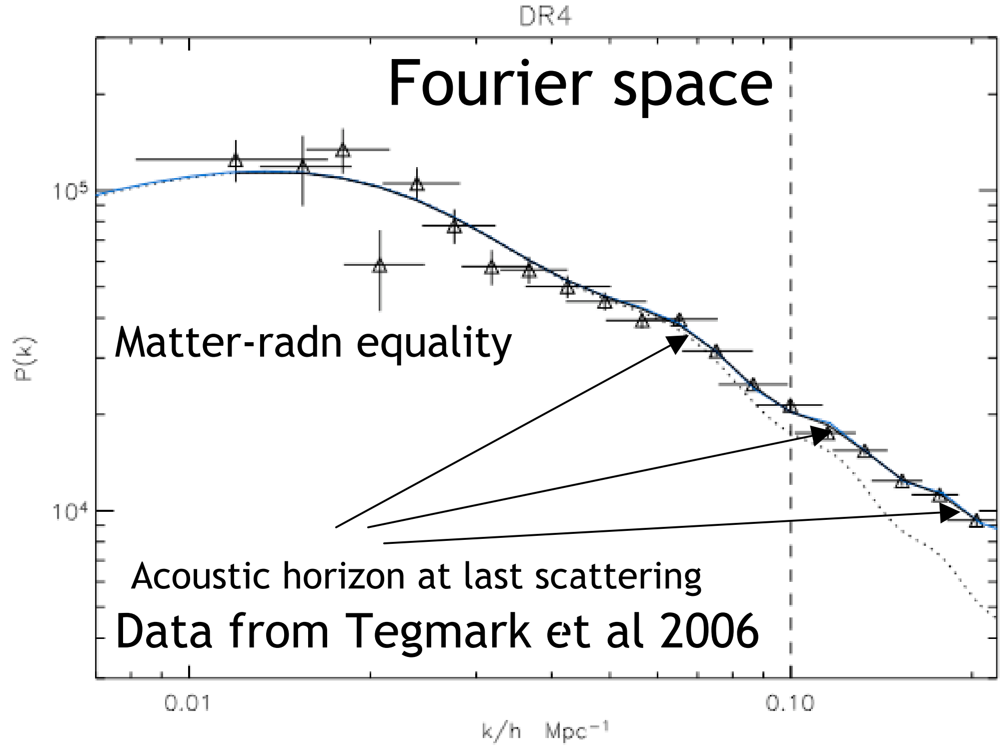
Weak lensing

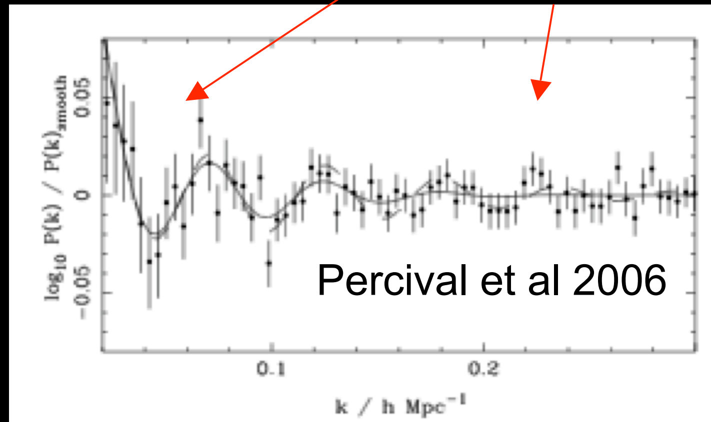












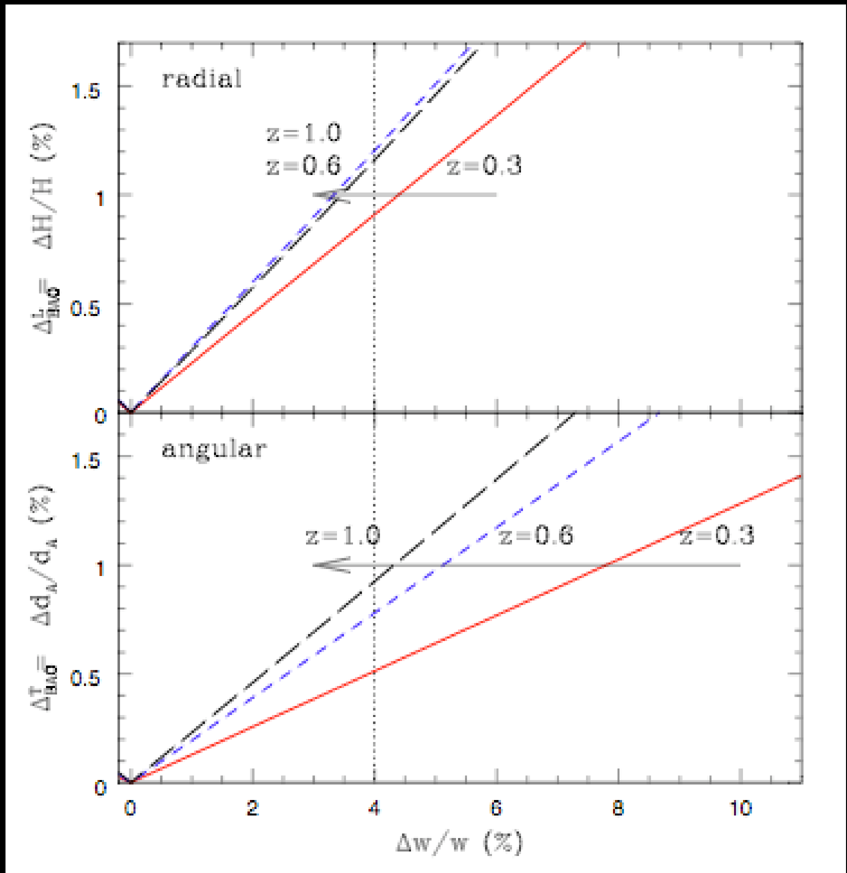
Divided by a smooth P(k)

Robust and insensitive to many systematics

2 measurements in one?

Challenge: scale of interest ~100 Mpc/h: large volumes!

Feature: measure BOTH dA and H(z) from 3D clustering



Line of sight (radial)

$$dr(z) = \frac{c}{H(z)}dz$$

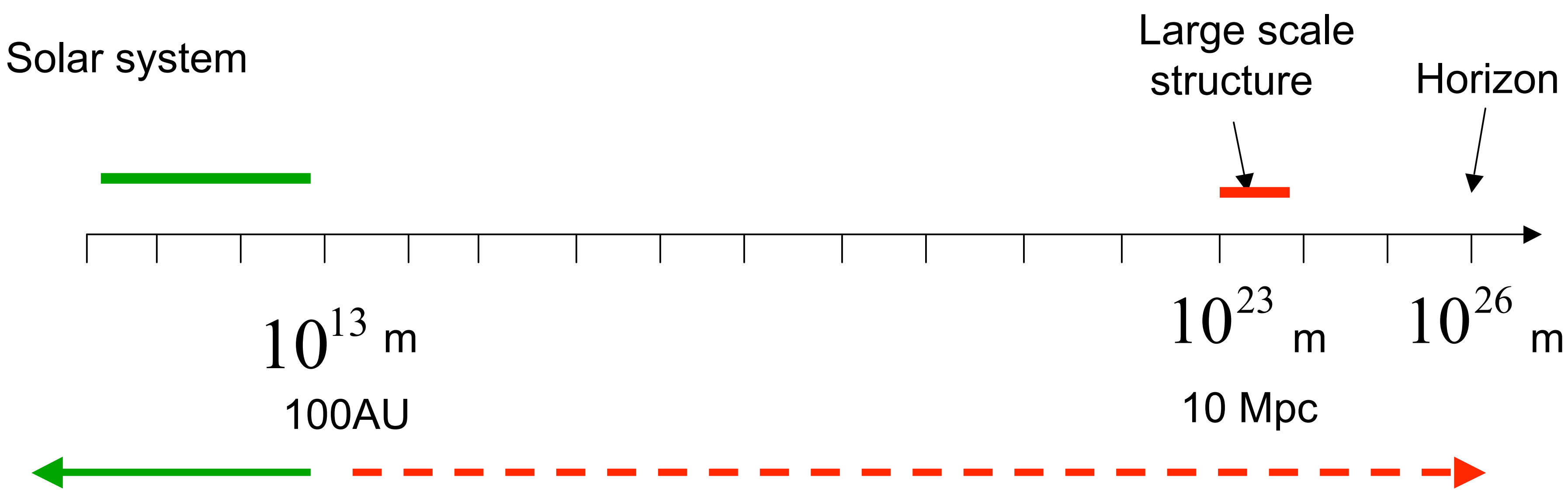
Plane of the sky (angular)

$$d_A(z) = \frac{c}{1+z}\int_0^z \frac{dz'}{H(z')}$$

Something on large scales?

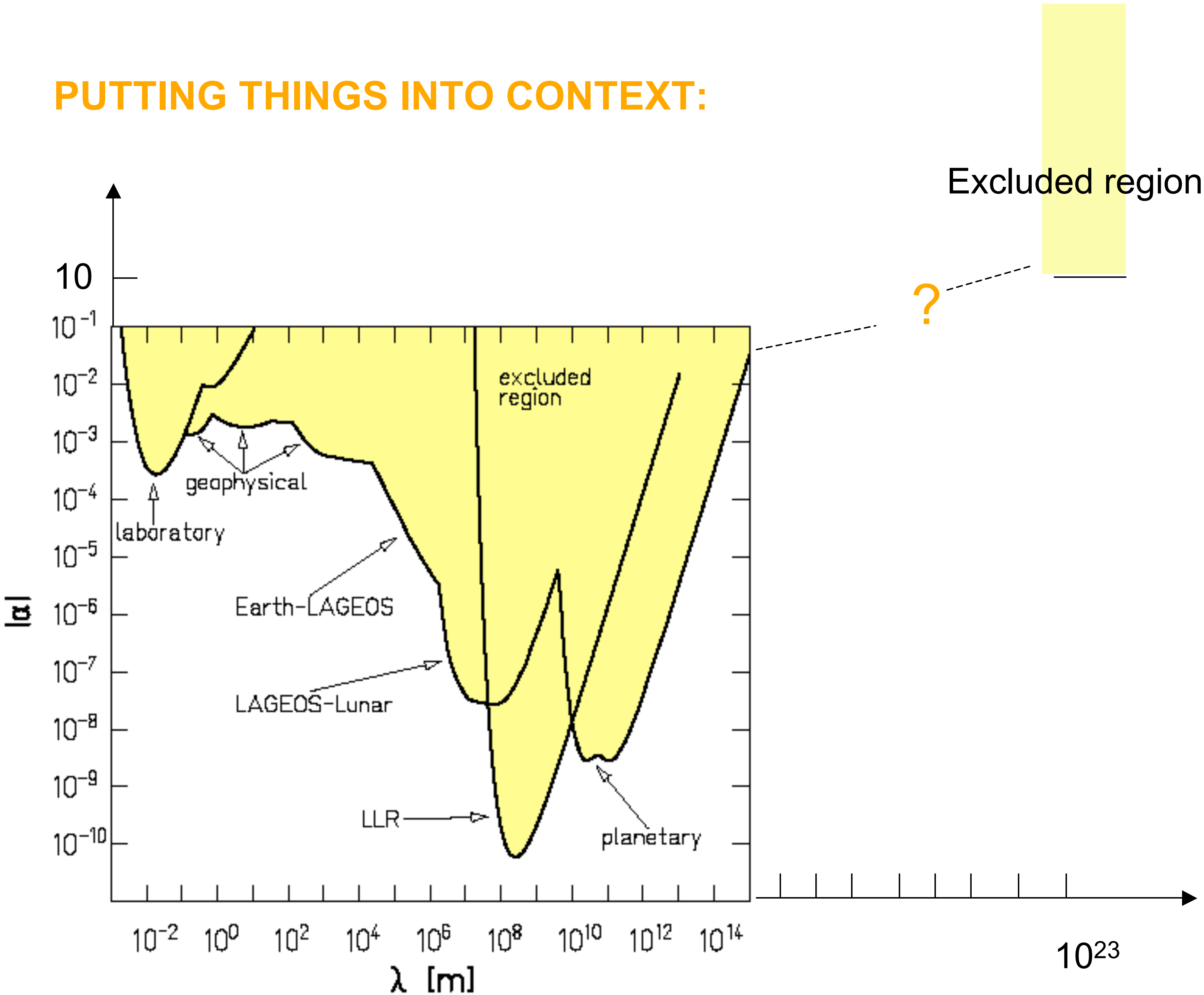
Dark energy shows its effects on scales comparable to the horizon… 10^{26} m

Precision test of the law of gravity have been carried out on scales< 10^{13} m



An enormous extrapolation is required

PUTTING THINGS INTO CONTEXT:



Adelberger, Hekel, Nelson, Ann.Rev.Nucl.Part.Sci. (2003) .

HOW TO MAKE A DIAGNOSIS?

Any modification of gravity of the form of f(R) can be written as a quintessence model for a(t)

This degeneracy is lifted when considering the growth of structure

Effort in determining what the growth of structure is in a given Dark Energy model!

combination of approaches!

COMPLEMENTARITY IS THE KEY!

The questions we want to ask:

Is it a cosmological constant?
A rolling scalar field? A fluid?
Is it a w= -1? w(z)?

Is it a breakdown of GR at horizon scales?

Backreaction…

Example:

Measurements of the growth of cosmological structures will help to disentangle the two cases.

Things could be "going wrong" in other ways

For not mentioning: control of systematics!

Summary: Much ado about nothing

The standard cosmological model is extremely successful, but….

Observations indicate that nothing weighs something (but much less than expected) and make the universe accelerate (other options are still Possible, inhomogeneities, gravity, but the result must "look like Λ").

What would it take to discriminate? discuss

Heroic observational effort is on going
(we'll learn not only about dark energy from it)

We HAVE TO ask: "how interesting it is really to add yet another significant figure to Λ or w ?" discuss

My personal view: The answer lies in the interface between Astronomy and Theoretical physics, if we take the "**Accelerating universe challenge**", there is no other way.

Challenges of the accelerating universe:

Zero-th order challenge: create a new culture of particle physicists and astronomers working together, theorists and experimentalists

First_order challenge: If it is Λ why is it so small?
On this issue astronomers have done their work already (I.e. Λ is non zero)
Now it is the job of theoretical physicists.

Second order challenge: is it dynamical? and if so how does it evolve?

Third order challenge: "could we have been wrong all along?"
did Einstein had the last word on gravity? Or FRW on the metric?

The data challenge: Avalanche of data coming soon
The systematics challenge: systematic errors in many cases will be the limit

Ground based, 8.4 m, all available sky every three nights

Weak lensing (but also, SN, variability, NEA, kuiper belts etc..)

Supernova acceleration probe

Space based, 2m telescope, started for SN but now lensing

3 filters, 1000 sq deg.

Funded surveys:

Survey	Telescope/ Instrument	Sky coverage	Filters	Depth	Period	Main goals
KIDS-Wide	VST/ Omegacam	1500 deg^2	ugriz	i_{AB}=22.9	2006-2009	WL ($z < 0.6$), DE, P(k), Bias High-z Univ.
UKIDSS-Large	UKIRT/ WFCam	4000 deg^2	YJHK	K=18.4	2006-2012	Clusters $z > 7$ Univ.
UKIDSS-Deep	UKIRT WFCam	3×10 deg^2	JK	K=21	2006-2012	Clusters High-z Univ.
UKIDSS-Ultra Deep	UKIRT WFCam	0.77 deg^2	JHK	K=25	2006-2012	Gal. Formation
WIRCam Deep Survey(CFHTLS)	CFHT/ WIRCam	4×0.75 deg^2	J/H/K	K_{AB}=23.6	2005-2008	High-z Univ. Clusters, P(k)
VISTA-Wide	VISTA	5000 deg^2	JHK	K=20.5	2006-2018	
VISTA-Deep	VISTA	250 deg^2	JHK	K=21.5	2006-2018	
VISTA-VeryDeep	VISTA	25 deg^2	JHK	K=22.5	2006-2018	
PanSTARRS	MaunaKea TBD	$\sim$30000 deg^2	giz	i_{AB}=24.	2008- 2012?	WL ($z < 0.7$), DE, P(k), Bias

Need accurate images of many many galaxies at z>1 and their redshift distribution (at least)

GRAVITATIONAL LENSING

Present status

Survey	Telescope	Sky coverage	n gal arcmin^{-2}	Mag	σ_8 ($\Omega_m = 0.3$)	w_0	Ref.
VLT-Descart	VLT	0.65 deg^2	21	$I_{AB} = 24.5$	1.05 ± 0.05		Maoli et al. 2001
Groth Strip	HST/WFPC2	0.05 deg^2	23	I=26	$0.90^{+0.25}_{-0.30}$		Rhodes et al. 2001
MDS	HST/WFPC2	0.36 deg^2	23	I=27	0.94 ± 0.17		Réfrégier et al. 2002
RCS	CFHT CTIO	16.4 deg^2+ 7.6 deg^2	9	R=24	$0.81^{+0.14}_{-0.19}$		Hoekstra et al. 2002a
Virmos-Descart	CFHT	8.5 deg^2	15	I_{AB}=24.5	0.98 ± 0.06	-	van Waerbeke et al. 2002
RCS	CFHT CTIO	45.4 deg^2+ 7.6 deg^2	9	R=24	$0.87^{+0.09}_{-0.12}$		Hoekstra et al. 2002b
COMBO-17	2.2m	1.25 deg^2	32	R=24.0	0.72 ± 0.09		Brown et al. 2003
Keck + WHT	Keck WHT	0.6 deg^2 1.0 deg^2	27.5 15	R=25.8 R=23.5	0.93 ± 0.13		Bacon et al. 2003
CTIO	CTIO	75 deg^2	7.5	R=23	$0.71^{+0.06}_{-0.08}$		Jarvis et al. 2003
SUBARU	SUBARU	2.1 deg^2	32	R=25.2	$0.78^{+0.55}_{-0.25}$		Hamana et al. 2003
COMBO-17	2.2m	1.25 deg^2	R	R=24.0	0.67 ± 0.10		Heymans et al. 2004
FIRST	VLA	10000 deg^2	0.01	1 mJy	1.0 ± 0.2		Chang et al. 2004
GEMS	HST/ ACS	0.22 deg^2	60	I=27.1	0.68 ± 0.13		Heymans et al. 2005
WHT + COMBO-17	WHT 2.2m	4.0 deg^2 + 1.25 deg^2	15 32	R_{AB}=25.8 R=24.0	 1.02 ± 0.15		Massey et al. 2005
Virmos-Descart	CFHT	8.5 deg^2	12.5	I_{AB}=24.5	0.83 ± 0.07	-	van Waerbeke et al. 2005
CTIO	CTIO	75 deg^2	7.5	R=23	$0.71^{+0.06}_{-0.08}$	$-0.89^{+0.16}_{-0.21}$	Jarvis et al. 2006
CFHTLS Deep+ Wide	CFHT	2.1 deg^2 + 22 deg^2	22 13	i_{AB}=25.5 i_{AB}=24.5	0.89 ± 0.06 0.86 ± 0.05	≤ -0.80	Semboloni et al. 2006a Hoekstra et al. 2006
GaBoDS	2.2m	15 deg^2	12.5	R=24.5	0.80 ± 0.10	-	Hetterscheidt et al. 2006
ACS parallel + GEMS+GOODS	HST/STIS HST/ACS	0.018 deg^2 0.027 deg^2	63 96	R=27.0 ? V=27.0	$0.52^{+0.13}_{-0.17}$		Schrabback et al. 2006

"detect potentially hazardous objects in the Solar System. But the wide-field, repetitive nature of the Pan-STARRS observations makes them ideal for a host of other astronomical purposes, ranging from Solar System astronomy to cosmology.

Panoramic Survey Telescope & Rapid Response System

(US air force, University of Hawii, & partners)

Ground based, 4, 1.8 m telescopes (only 1 to begin)

Each night 6000 square degrees one filter.
Plans for 4 filters eventually.

On - going

Survey	Telescope/ Instrument	Sky coverage	Filters	Depth	Period	Main goals
Deep Lens Survey	Mayall+ Blanco	7×4 deg^2	BVRz'	R=25.	2001-2005	WL DE, Clusters High-z Univ.
CFHTLS Deep	CFHT/ Megacam	4×1 deg^2	ugriz	i_{AB}=27	2003-2008	$0.3 < z < 1.$ SNIa DE Clusters, P(k) WL ($z < 2.0$) High-z Univ.
CFHTLS Wide	CFHT/ Megacam	3×50 deg^2	ugriz	i_{AB}=24.5	2003- 2008	WL ($z < 1$), DE, P(k), Bias
SDSS-II SN Survey	APO	250 deg^2	ugriz	r'=22.	2005-2008	$0.1 < z < 0.3 <$ SNIa DE
SUPRIME-33	SUBARU/ Suprime	33 deg^2	R	R=26	2003-?	WL ($z < 1.$), DE, P(k), Bias High-z Univ.
RCS2	CFHT/ Megacam	1000 deg^2	grz	$i_{AB} \simeq 22.5$	2003-?	WL ($z < 0.6$), DE, P(k), Clusters, Bias
CTIO-LS	CTIO	$12\times$ 2.5 deg^2	R	R=23	2002-2006	WL ($z < 0.6$)
COSMOS	HST/ACS	1×2 deg^2	I	I_{AB}=25.5	2003-?	WL ($z < 1$), DE, P(k), Clusters, Bias

Dark Energy Survey: DES (NOAO, NSF, Fermilab, DoE ....)

Ground based, 4 m telescope,
4 bands Photometry 5000 sq deg and
repeated 40 sq degrees;
300M galaxies z<1 (ETA: 2008-2012)

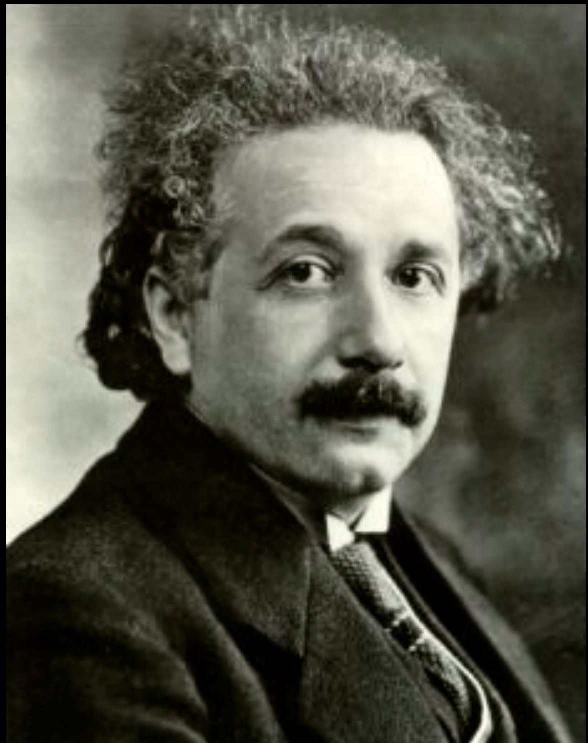
Blanco 4m on Cerro Tololo

Image credit: Roger Smith/NOAO/AURA/NSF

Photometric redshifts for SPT and ACT.
Weak lensing

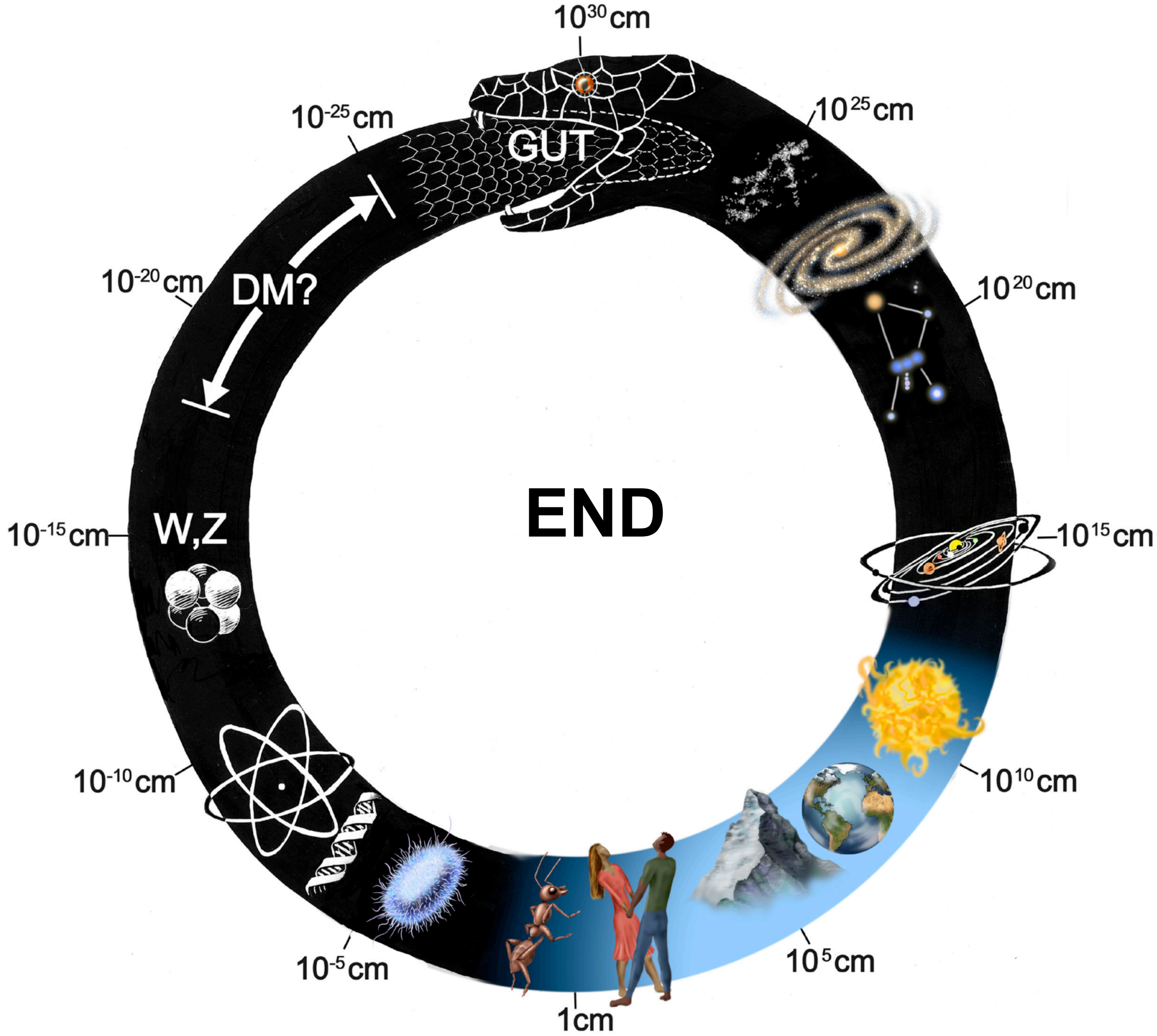
Planned surveys

Survey	Telescope/ Instrument	Sky coverage	Filters	Depth	Period	Main goals
VIKING	VISTA/	1500 deg^2	zYJHK	i_{AB}=22.9	2007-2010	WL ($z < 0.6$), DE, P(k), Bias High-z Univ.
Dark Energy Survey	CTIO DECam	5000 deg^2	griz	i_{AB}=24.5	2009-2014	WL ($z < 0.8$), DE, P(k),
DarkCam	VISTA	$\sim$10,000 deg^2	ugriz	i_{AB}=24.	2010-2014	WL ($z < 0.7$), DE, P(k),
HyperCam	SUBARU/ Suprime	$\sim$3500 deg^2	Vis.	?	>2012?	WL ($z < 2$), DE, P(k),
SNAP/JDEM	Space	100/1000/ deg^2 5000 deg^2	Vis.+NIR	-	>2013	WL ($z < 1.5$), DE, P(k), SNIa, Bias
DUNE	Space	$\sim$20000 deg^2	ugriz+NIR?	i=25.5	$\sim$2015?	WL ($z < 1$), SNIa, DE, P(k),
LSST	Ground TBD	20000 deg^2	ugrizy	i_{AB}=26.5	>2014	WL ($z < 2.$), DE, P(k)
Dome-C	SouthPole	? deg^2	?	?	$\sim$2012?	SNIa, DE



“In the middle of difficulty lies opportunity" ---

A. Einstein



Lectures and additional material will appear at

http://icc.ub.edu/~liciaverde/CLASHEP.html

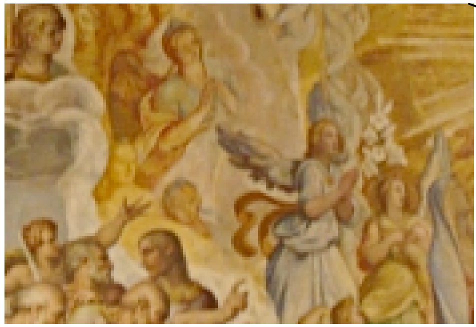
Why so weak dark energy constraints from CMB?

The limitation of the CMB in constraining dark energy is that the CMB is located at $z=1090$.

We need to look at the expansion history
(I.e. at least two snapshots of the Universe)

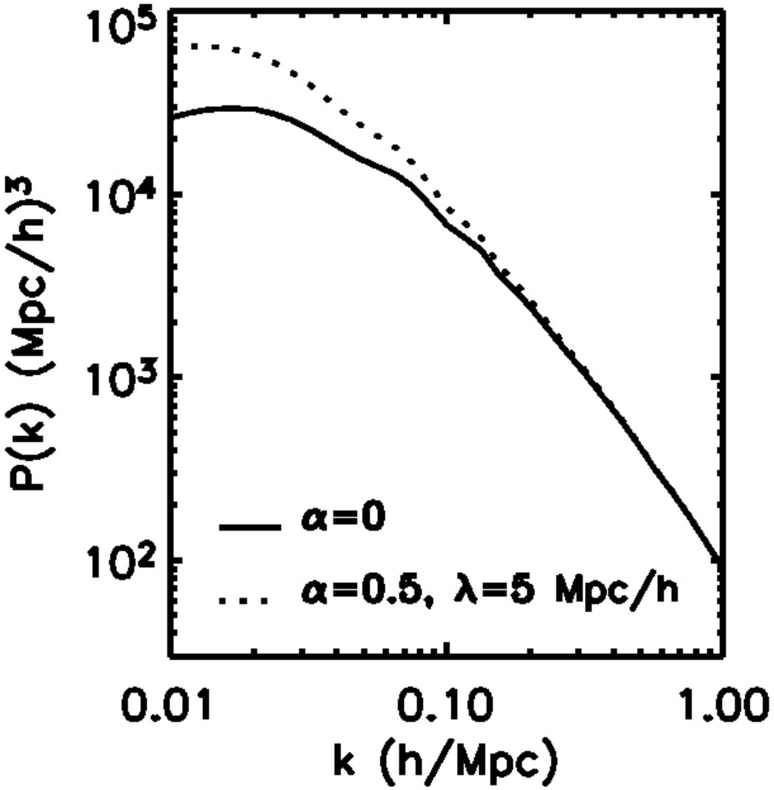
What if one could see the peaks pattern also at lower redshifts?

outline



Last Judgment, Vasari, Florence Duomo

$$\Phi(\vec{r}) = -G\int d^3r \frac{\rho(\vec{r}')}{|\vec{r}-\vec{r}'|}\left\{1+\alpha\left(1-e^{-|\vec{r}-\vec{r}'|/\lambda}\right)\right\}$$

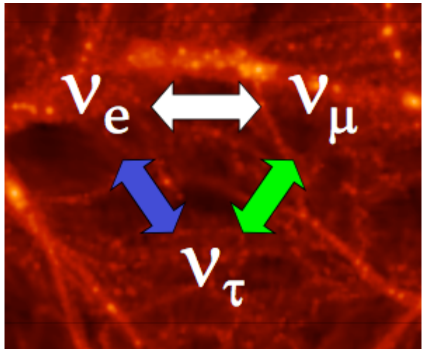


Velocities!

We also consider a power-law-like modification

From Sealfon, LV, Jimenez 04

Neutrino properties

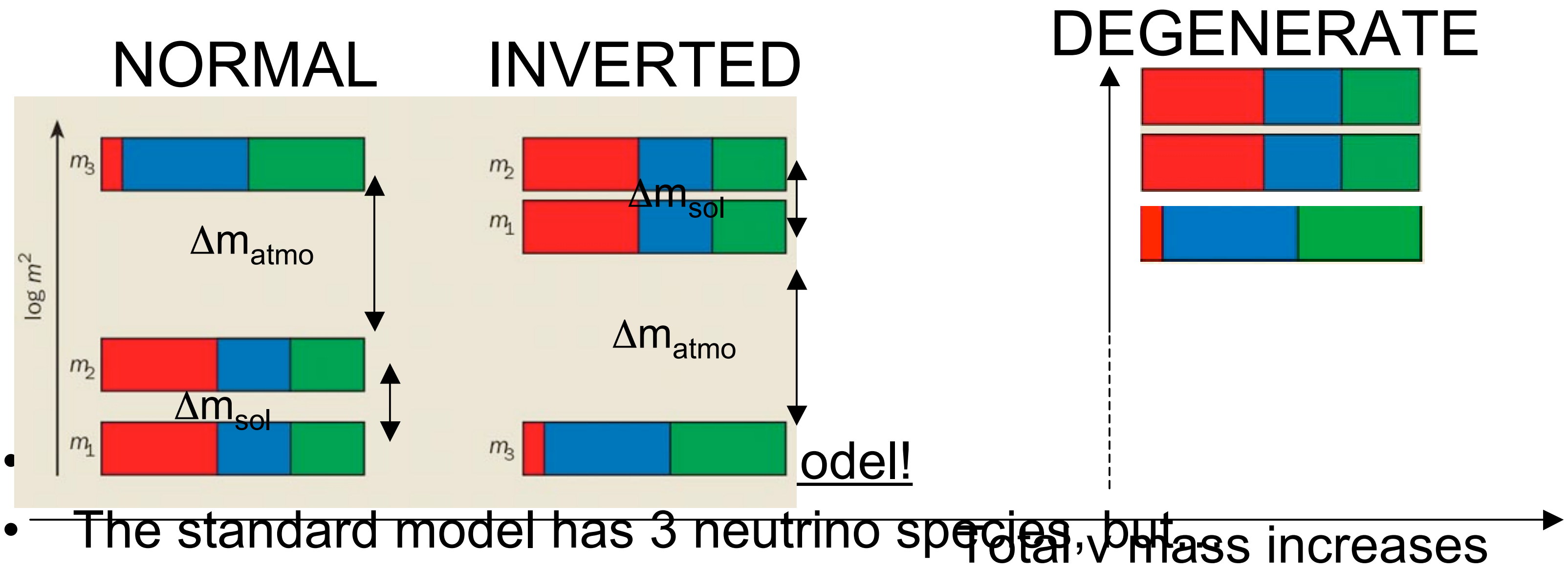


Neutrino mass eigenstates are not the same as flavor

- Oscillations indicate neutrinos have mass:

$$\Delta m^2_{21} \equiv \Delta m^2_{\rm sol} = 8.0^{+0.6}_{-0.4} \cdot 10^{-5} {\rm eV}^2 \qquad |\Delta m^2_{31}| \approx |\Delta m^2_{32}| \equiv \Delta m^2_{\rm atm} = 2.4^{+0.6}_{-0.5} \cdot 10^{-3} {\rm eV}^2$$

- Three possible hierarchies



- odel!
- The standard model has 3 neutrino species, but…

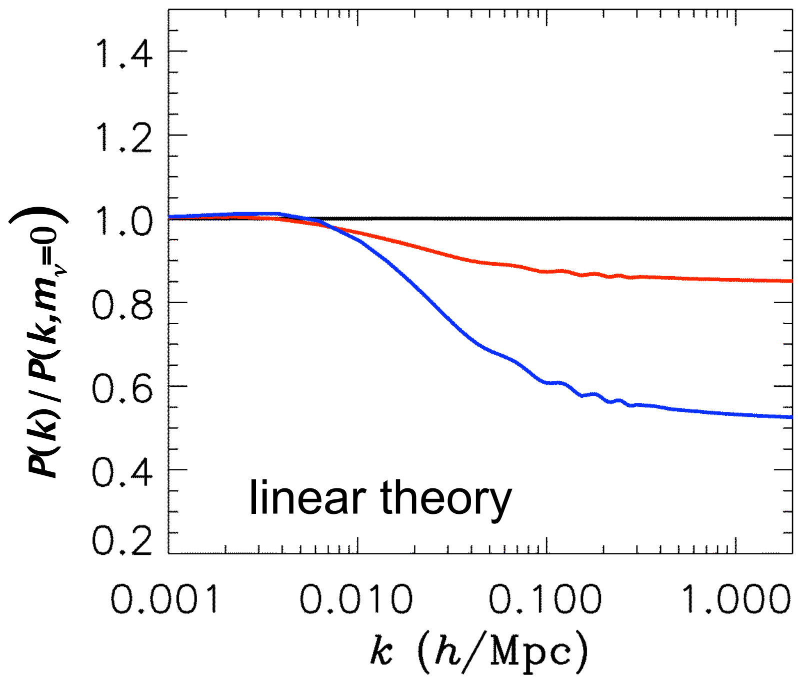
Physical effects

Total mass >~1 eV become non relativistic before recombination   CMB

Total mass <~1 eV become non relativistic after recombination:
alters matter-radn equality but effect can be "cancelled"
by other parameters   Degeneracy

After recombination

FINITE NEUTRINO MASSES SUPPRESS THE MATTER POWER SPECTRUM ON SCALES SMALLER THAN THE FREE-STREAMING LENGTH



Σm = 0 eV

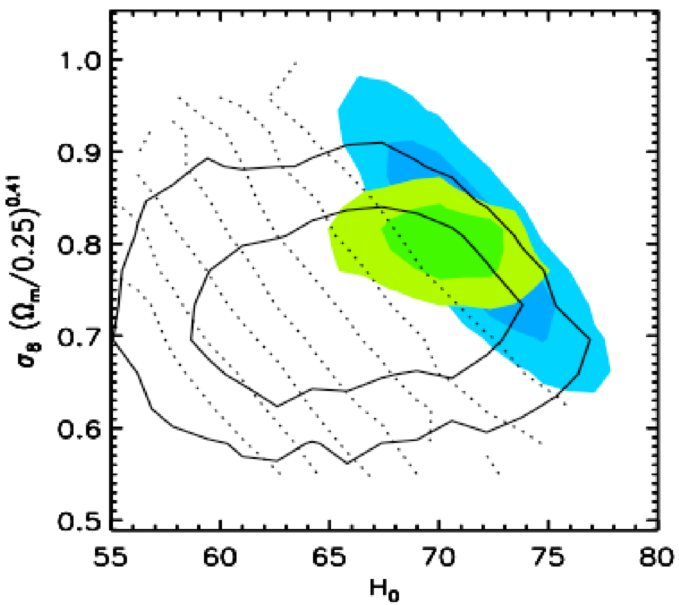
Σm = 0.3 eV

Σm = 1 eV

Physical effects cnt'

Beth Reid, LV, R. Jimenez, Olga Mena, arXiv:0910.0008

LCDM+ mν

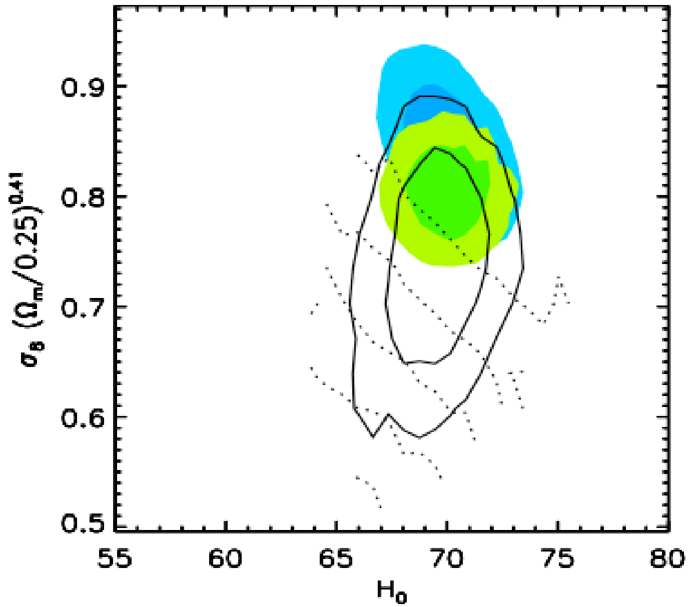


WMAP Mν=0

WMAP

·········· Constant Σmν

WMAP+maxBCG+H_0



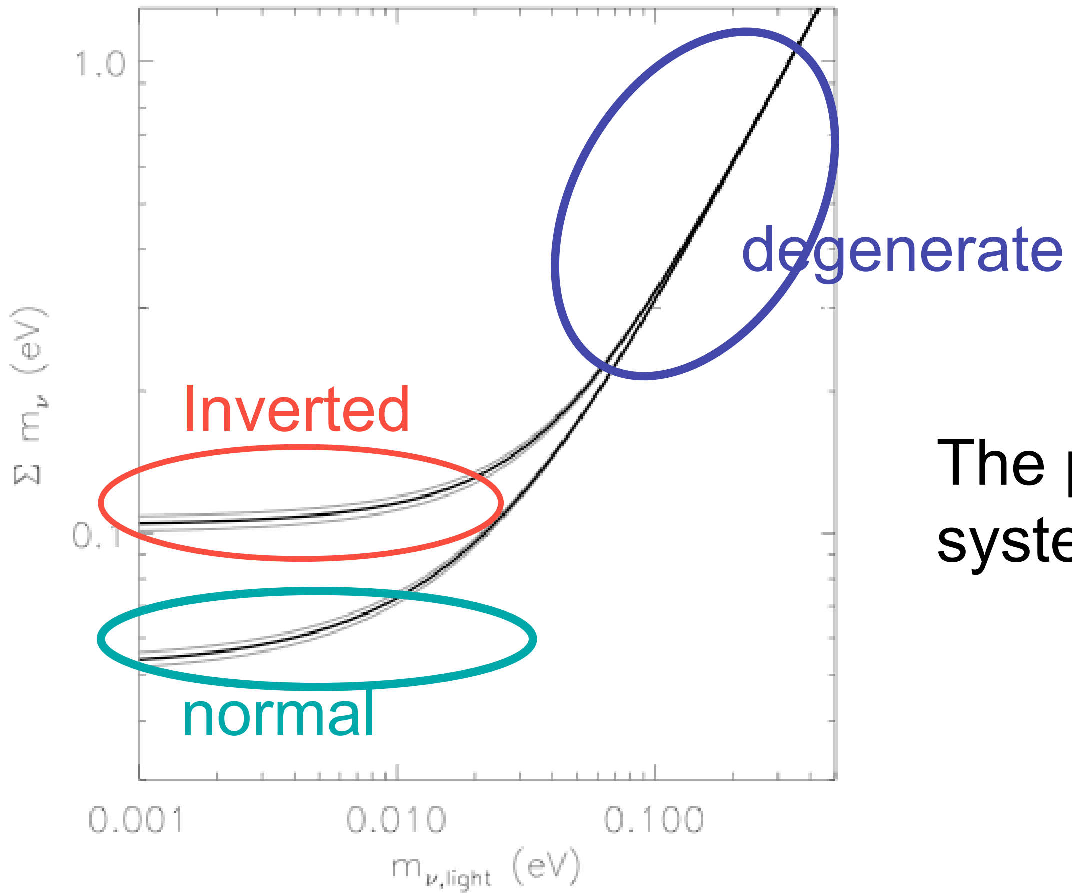
WMAP+BAO+SNe Mν=0

WMAP+BAO+SNe

·········· Constant Σmν

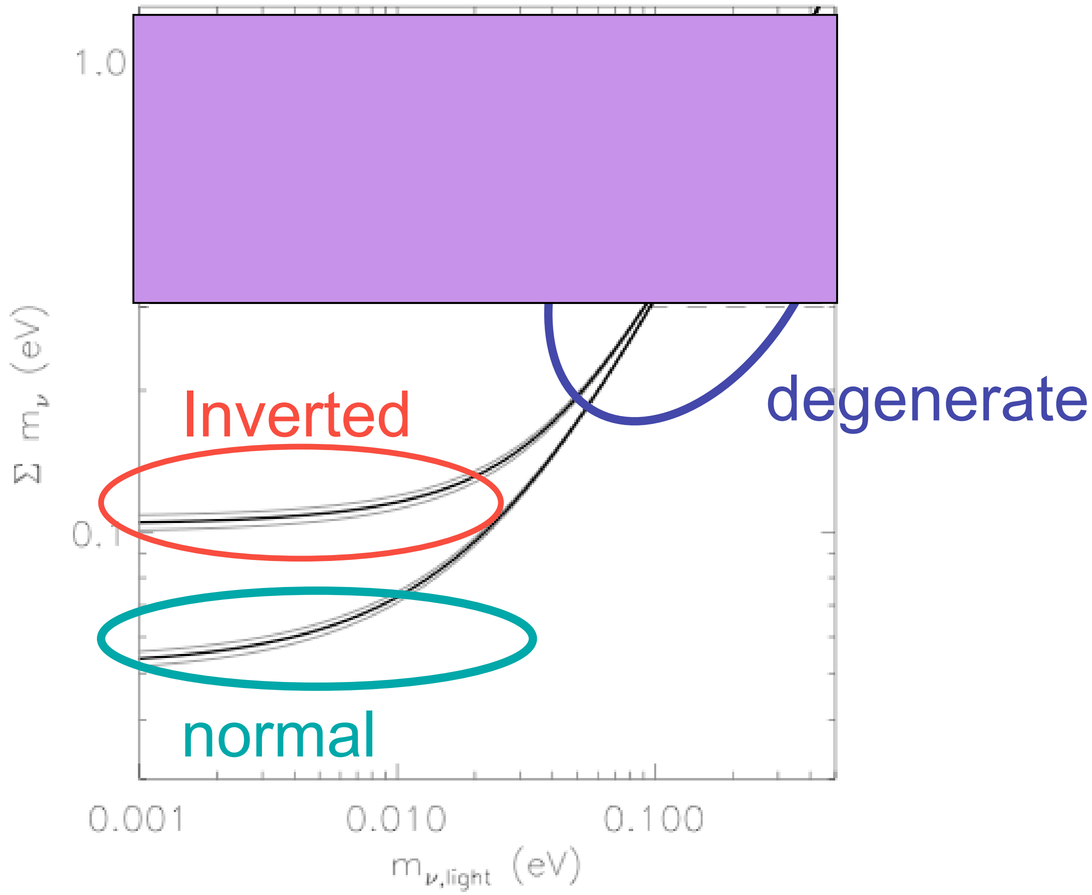
+maxBCG+H_0

Cosmology is key in determining the absolute mass scale



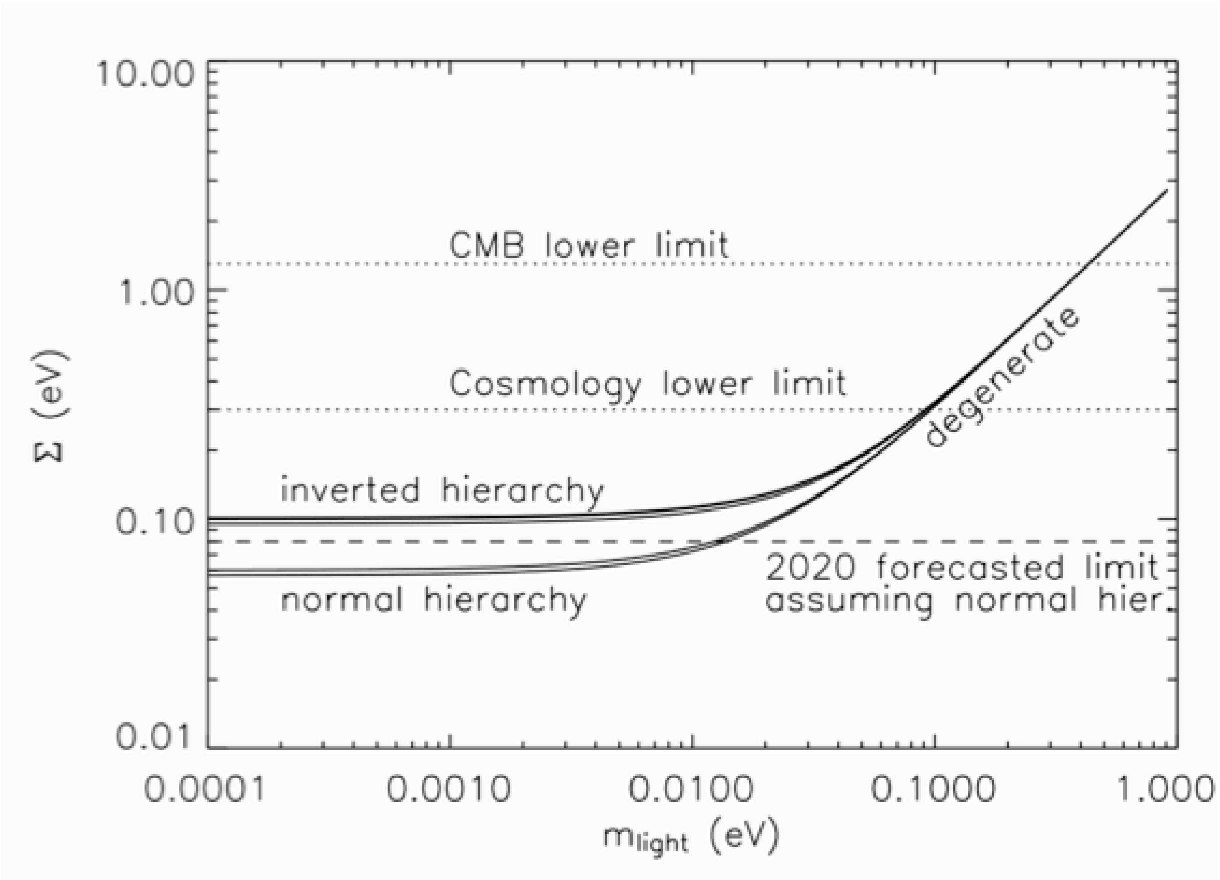
The problem is systematic errors

Cosmology is key in determining the absolute mass scale



Beth Reid, LV, R. Jimenez, Olga Mena, arXiv:0910.0008

Outlook towards the future



Can the hierarchy be determined?

Are neutrino Majorana or Dirac?

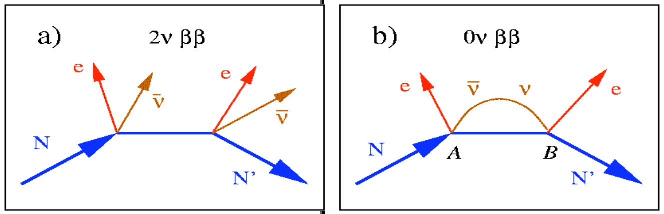
Jimenez, Kitching, Penya-Garay, Verde, arXiv:1003:5918

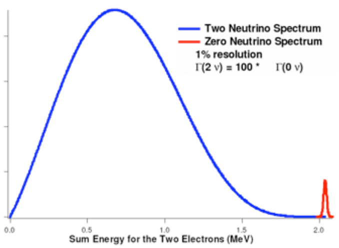
Dirac or Majorana? ⟺ hierarchy

Are neutrinos their own anti-particle?(are they Majorana or Dirac?)

$0\nu\beta\beta$ (next generation)

Yes

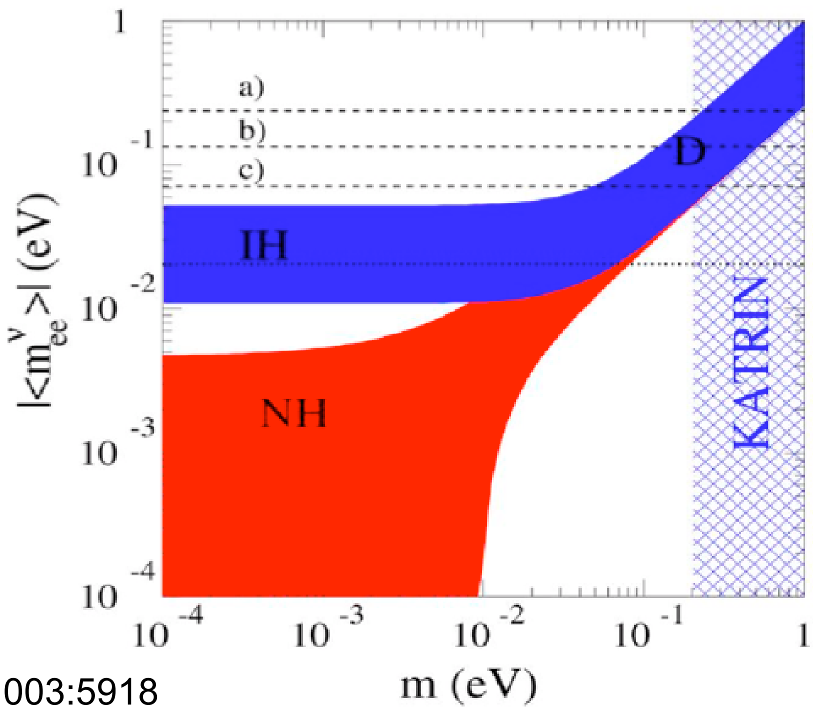




Majorana

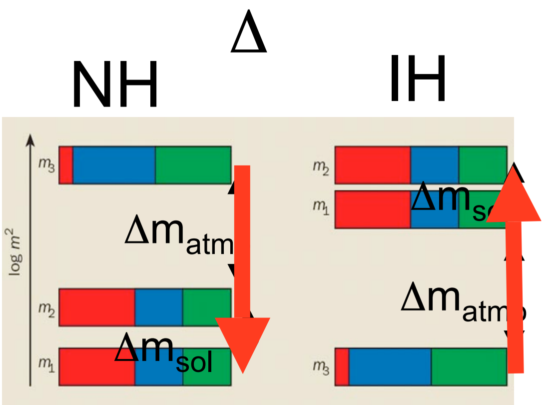
No

Because Dirac OR
because below threshold (still unknown)?

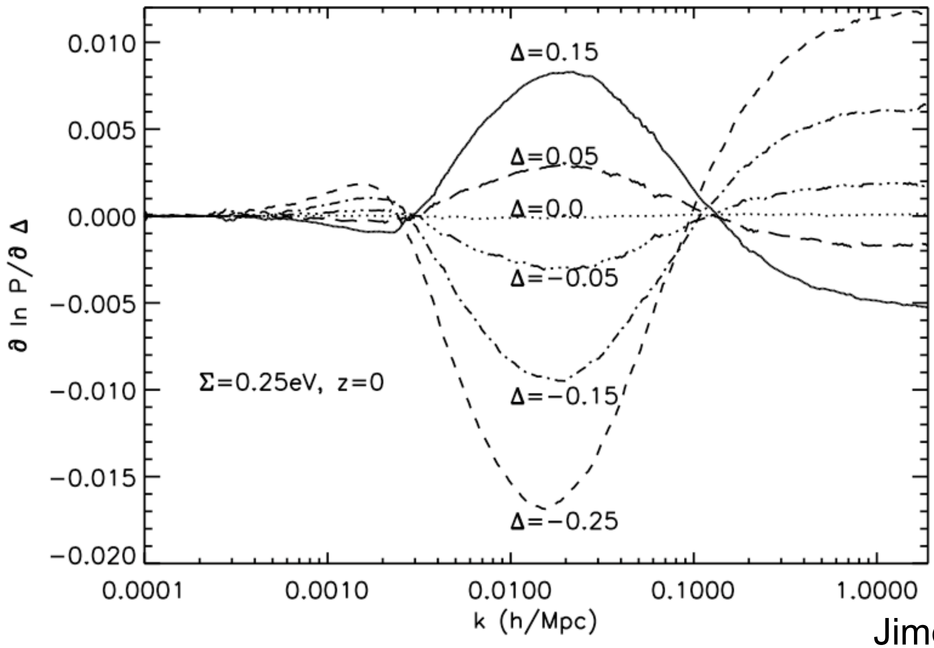


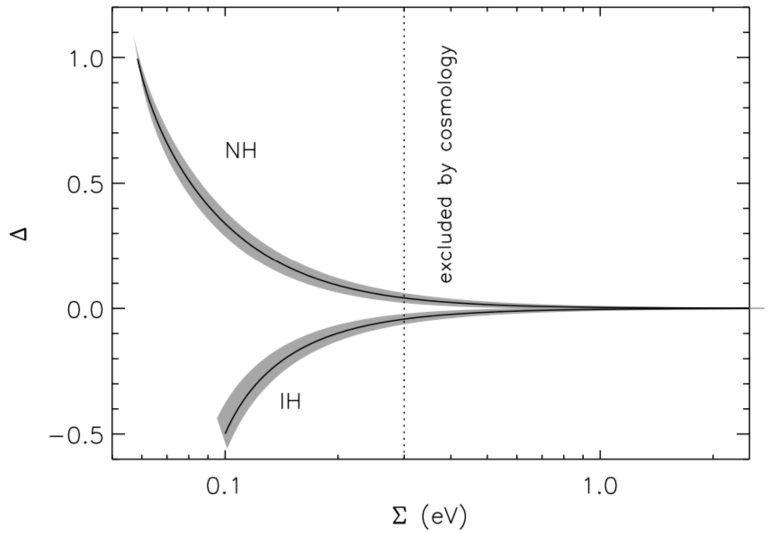
Jimenez, Kitching, Penya-Garay, Verde, arXiv:1003:5918

Hierarchy effect on the shape of the power spectrum



Neutrinos of different masses have different transition redshifts from relativistic to non-relativistic behavior, and their individual masses and their mass splitting change the details of the radiation-domination to matter- domination regime.

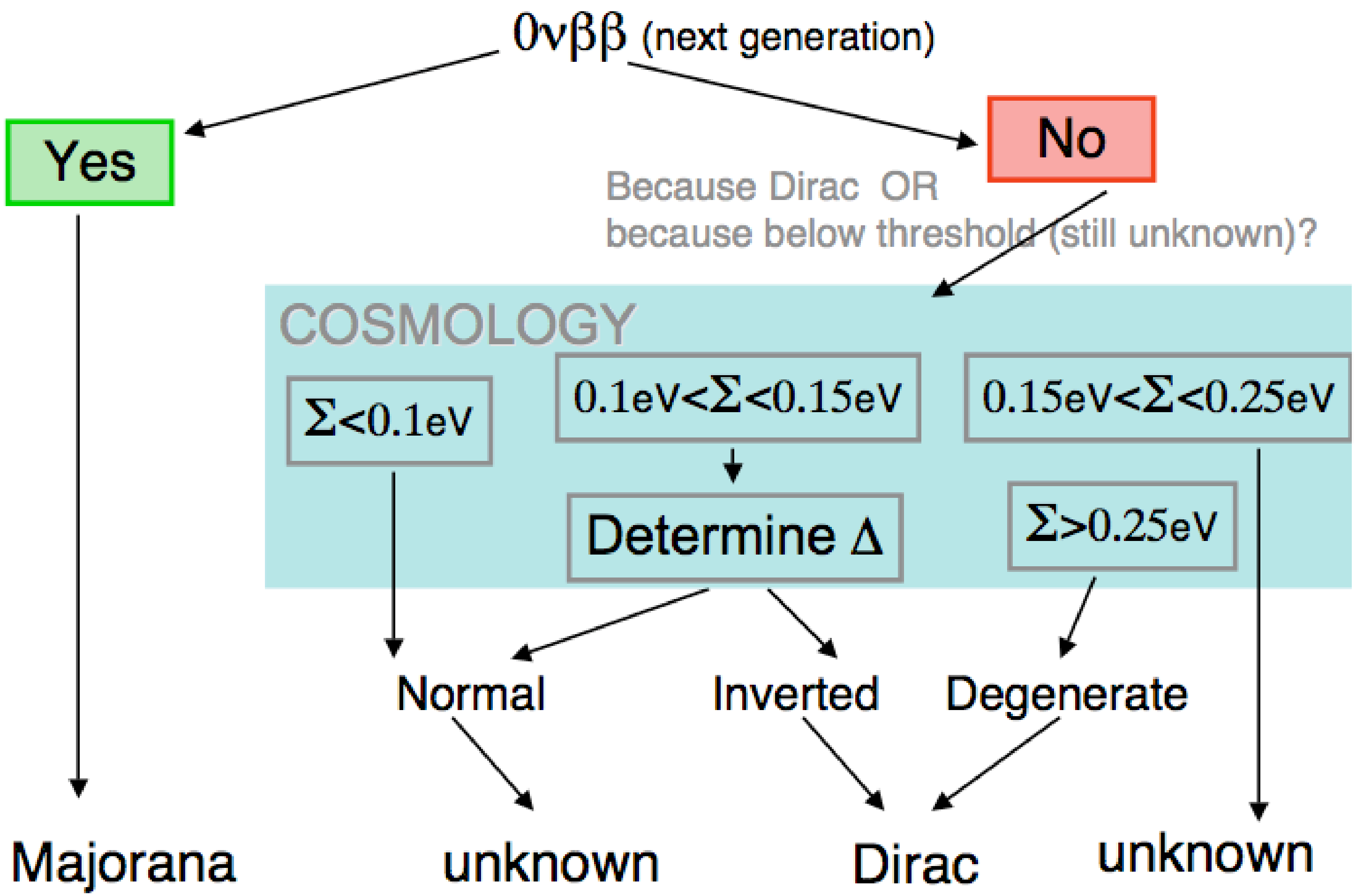




Jimenez, Kitching, Penya-Garay, Verde, arXiv:1003:5918

Future surveys can help!

Are neutrinos their own anti-particle?(are they Majorana or Dirac?)



Jimenez, Kitching, Penya-Garay, Verde, arXiv:1003:5918

Challenge n2: is it dynamical?

Theoretical physicists: which parameterization?

To give you a flavor, assume it is a slowly rolling potential and think about inflation

$$\varepsilon_1 = -\frac{\dot{H}}{H^2} = 1 - \frac{\ddot{a}}{a} H^{-2} = \frac{dH}{dz} \frac{(1+z)}{H}$$

Similar to horizon flow parameters

$$V(z) = (3 - \varepsilon_1) \frac{H^2}{\kappa} - \frac{1}{2} \rho_m$$

H(z)

$\dot{H}(z)$

$$K(z) = \varepsilon_1 \frac{H^2}{\kappa} - \frac{1}{2} \rho_m$$

Just integrate to get $\phi(z)$

But f you have a parameterization (or a model)

$$3H^2(z) - \frac{1}{2}(1+z)\frac{dH^2(z)}{dz} = \kappa \left(V(\alpha_i,\, z) + \frac{1}{2}\rho_m(z) \right) \equiv g(\alpha_i,\, z)$$

Can be integrated analytically!