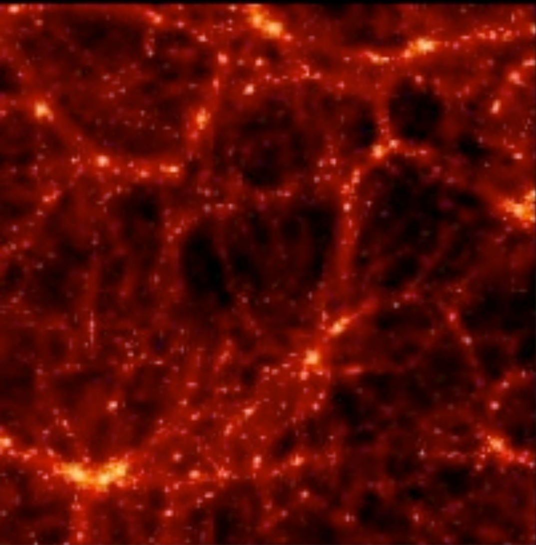

Licia Verde

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BARCELONA
UiO, Oslo, Norway

From precision ccosmology to accurate cosmology

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

icrea
Institució Catalana de Recerca i Estudis Avançats
ICCUB
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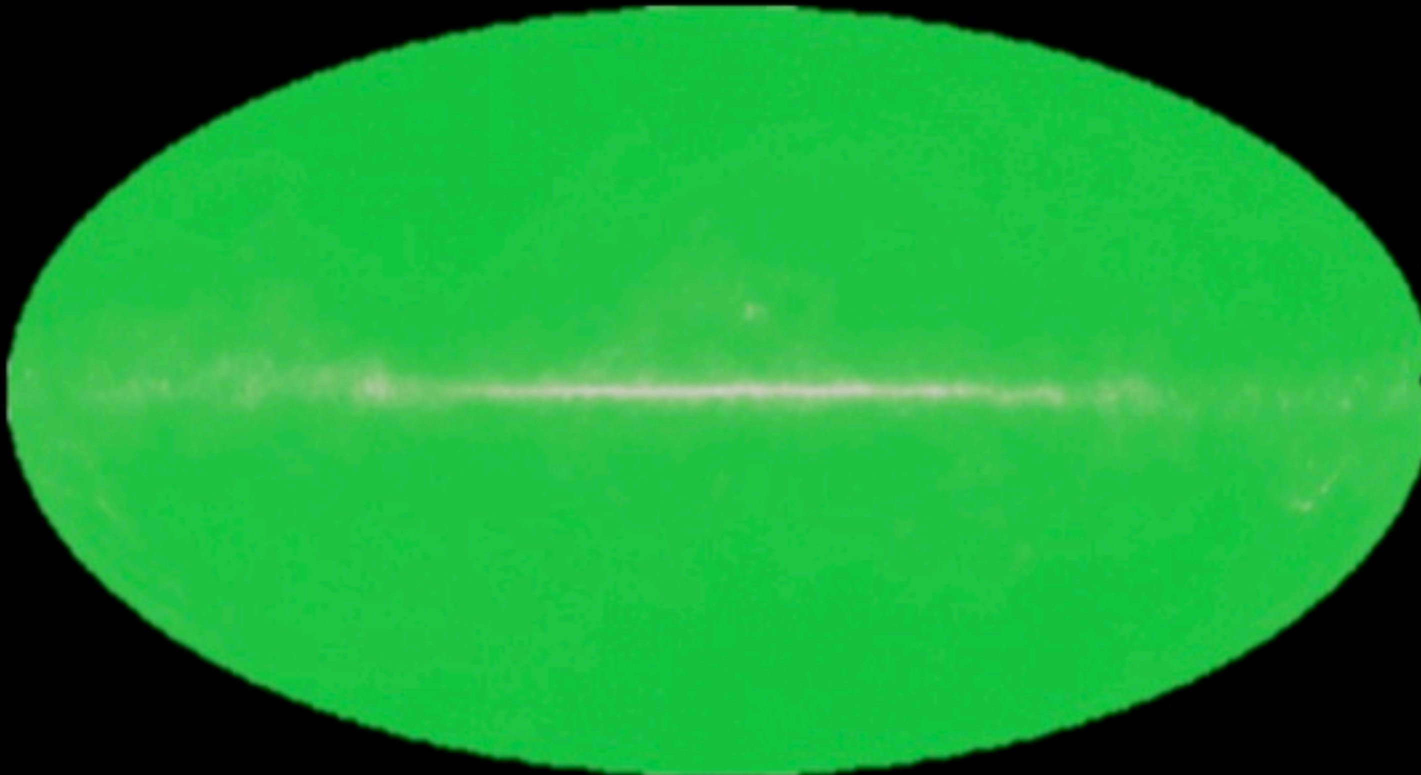
UNIVERSITAT DE BARCELONA
UNIVERSITAS OSLOENSIS MDCCCXI
erc

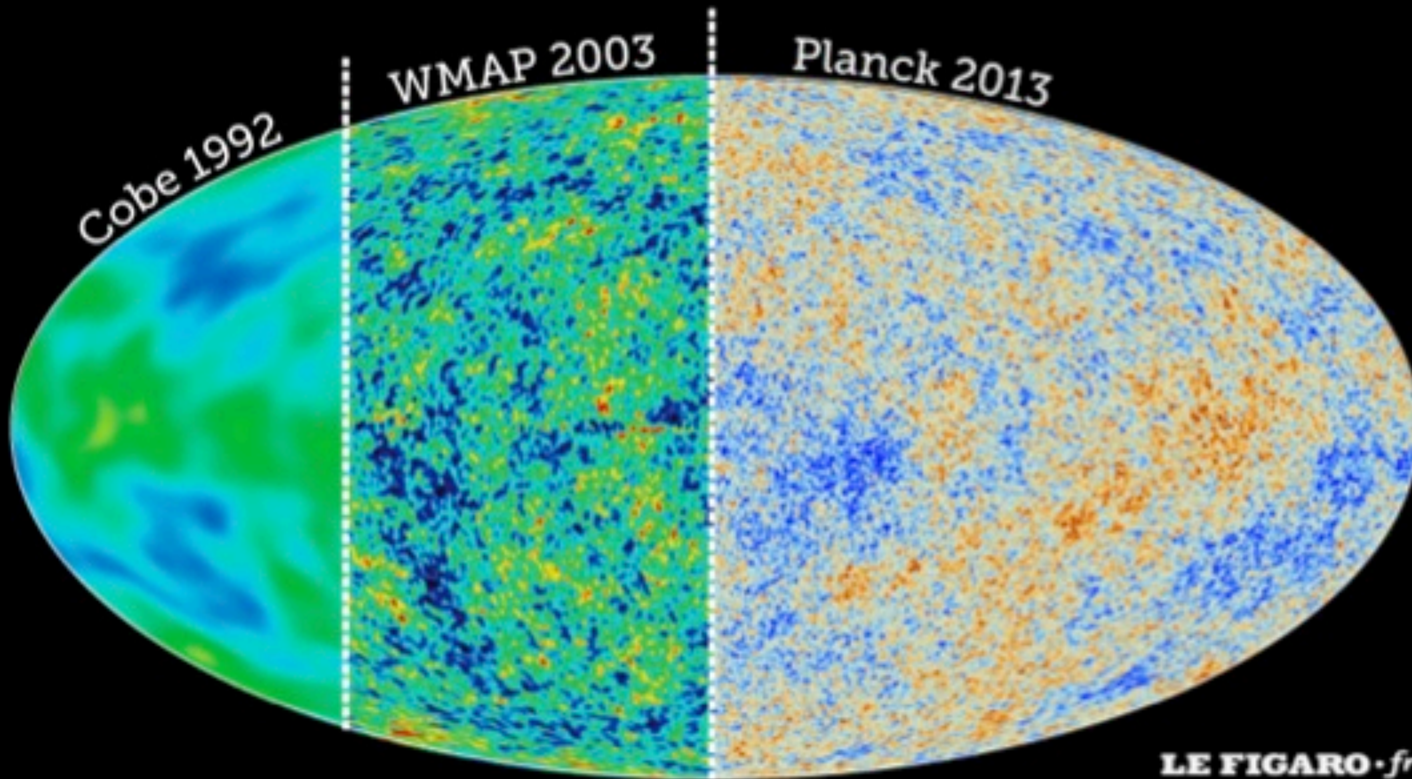
Context and overview

- Cosmology over the past 20 years has made the transition to *precision cosmology*
- Cosmology has moved from a *data-starved science* to a *data-driven science*
- Cosmology has now a *standard model.* The *standard cosmological model* only needs few parameters to describe origin composition and evolution of the Universe
- <u>Big difference between modeling and understanding</u>
- <u>Implies Challenges and opportunities</u>

The CMB turns 50



The CMB turns 50



Cosmology is special

We can't make experiments, only observations

We have to use the entire Universe as a detector:
the detector is given, we can't tinker with it.

The curse of cosmology

We only have one observable universe

We can only make observations (and only of the observable Universe) not experiments: we fit models (i.e. constrain numerical values of parameters) to the observations: (Almost) <u>any statement is model dependent</u>

*"Gastrophysics"** and non-linearities get in the way:
Different observations are more or less "trustable", it is however somewhat a question of personal taste (think about Standard & Poor's credit rating for countries)

Results will depend on the data you (are willing to) consider. (robustness?)

….And the Blessing

We can observe all there is to see

** Not a typo, means complex astrophysics that is poorly understood/hard to model*

….And the Blessing

We can observe all there is to see

And almost do

Ultimate survey

challenges

Big data….

Precision cosmology, accurate cosmology!

From precision cosmology to accurate cosmology

(Peebles 2002)

challenges

As the statistical errors shrink.....

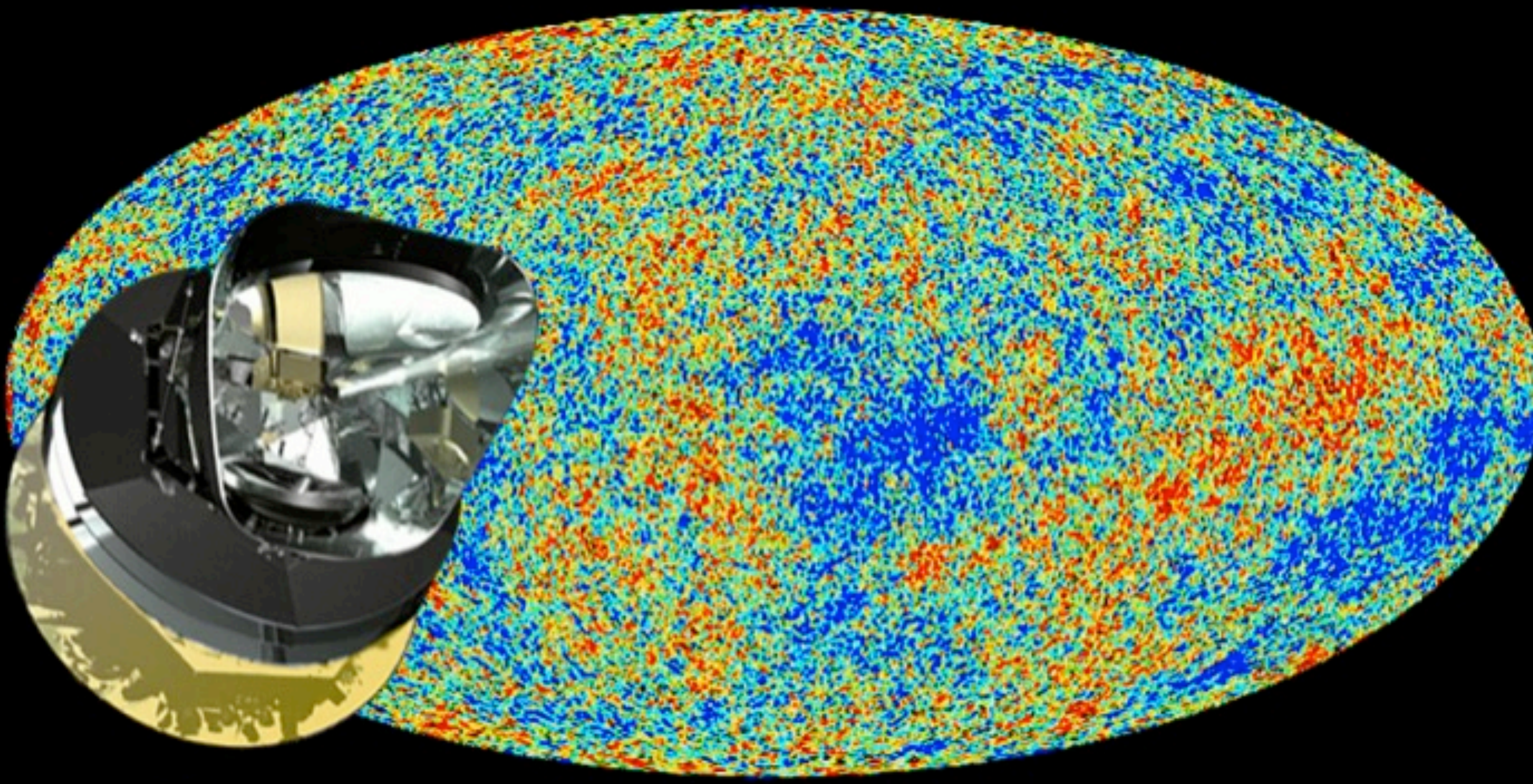
Systematic errors must be kept under exquisite control!

There is no systematic way to address systematic errors

The future is bright!

Ultimate surveys!

The future is here!



Planck 2015

DISCLAIMER

I am not part of the Planck collaboration

I cannot take any credit for the spectacular results
I have only access to public(published) information

but

I can give you an external point of view

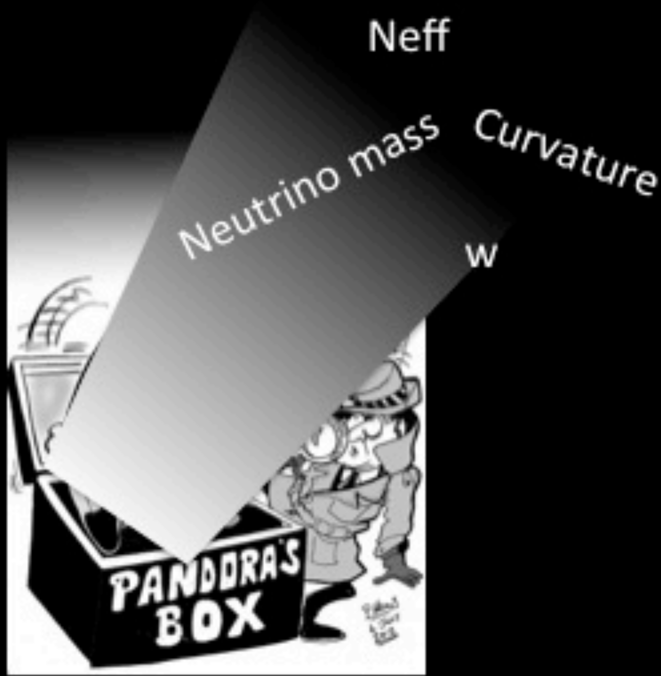
Wonderful agreement of new data with the ΛCDM model

STILL….

The model IS incomplete… Neutrinos have mass

The model is unsatisfactory

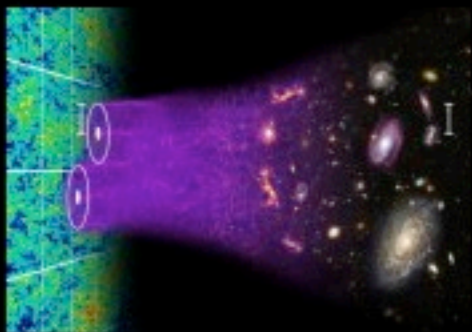
The cosmological constant problem
Inflation is more than n_s

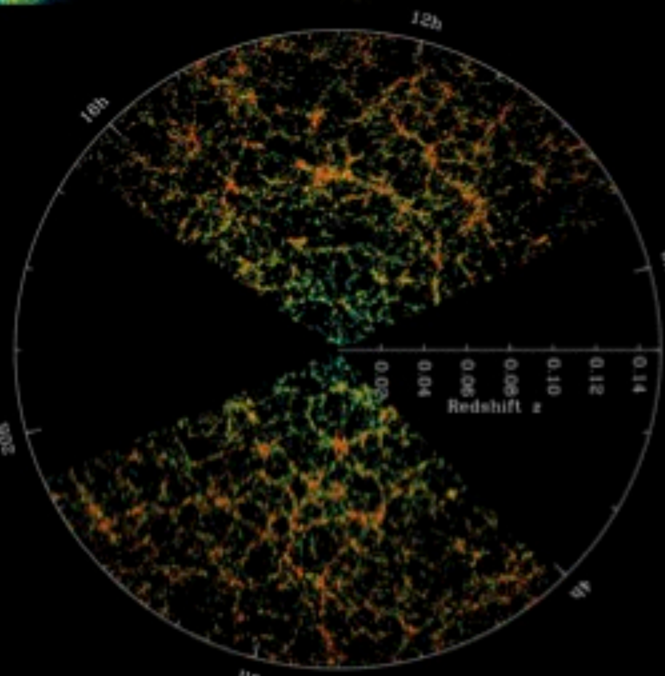


This drives a massive experimental effort

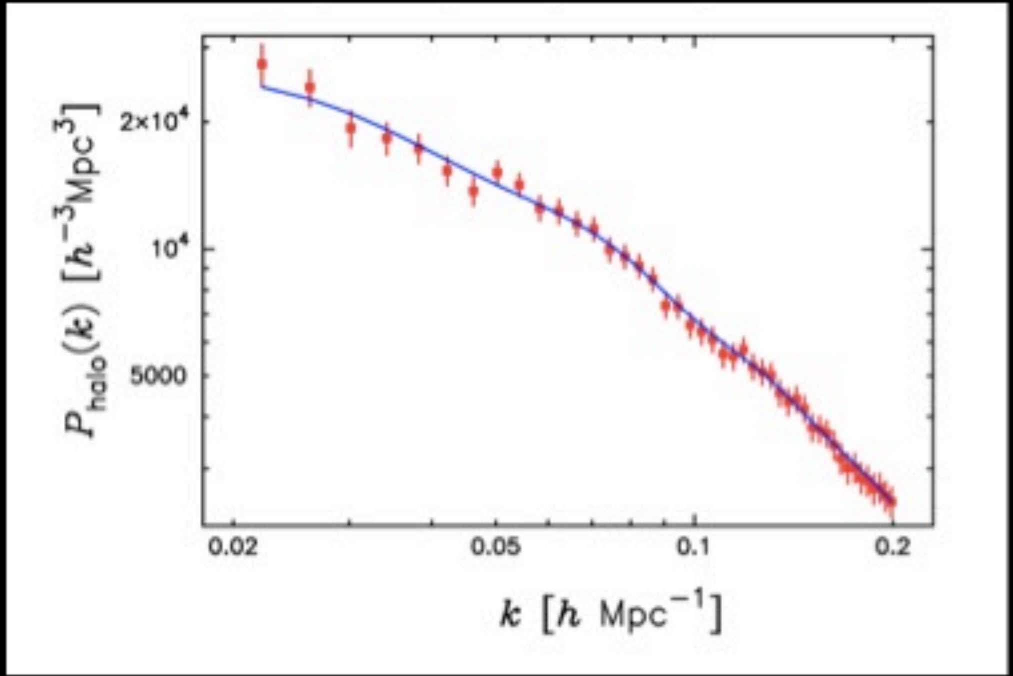
CMB primary temperature information content has been saturated

The near future IS large-scale structure





SDSS LRG galaxies power spectrum (Reid et al. 2010)



13 billion years of gravitational evolution

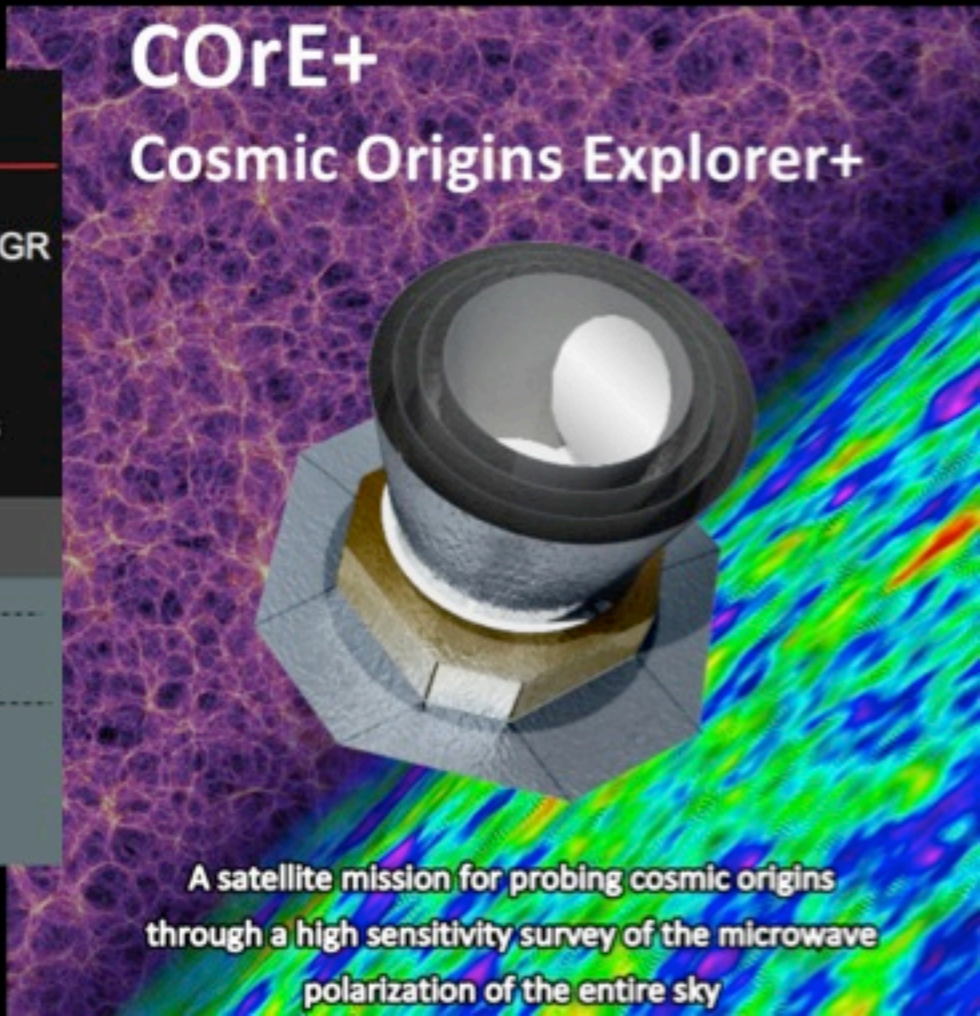
Longer-term timescale: CMB polarization

Inflation
and primordial Gravity waves

CMB polarization the only possible route

Windows into the primordial Universe

Recombination	380000 yrs	Atomic physics/GR
Nucleosynthesis	3 minutes	Nuclear phyiscs
LHC		TeV energies
inflation	10^{-30} s (?)	GUT?
Big BANG		



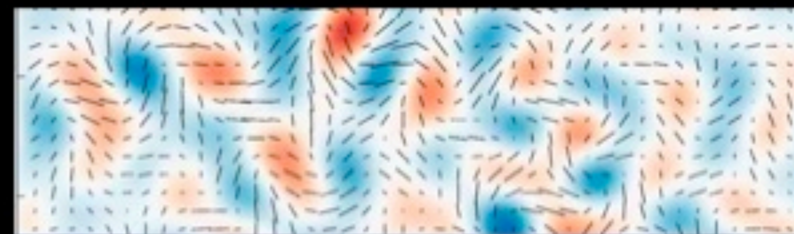
If the CMB temperature detection turns 50,

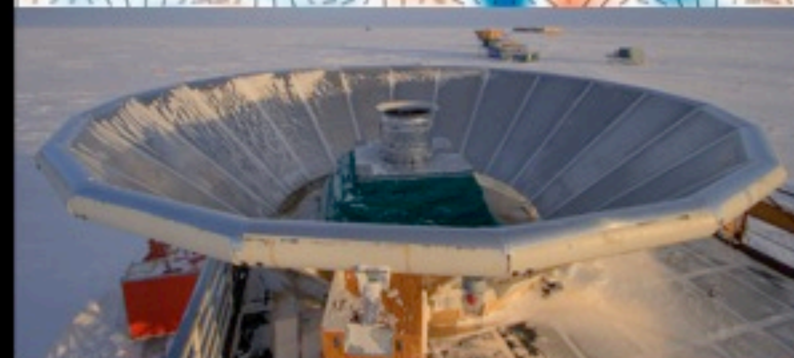
If the CMB temperature detection turns 50,

MID-LIFE CRISIS

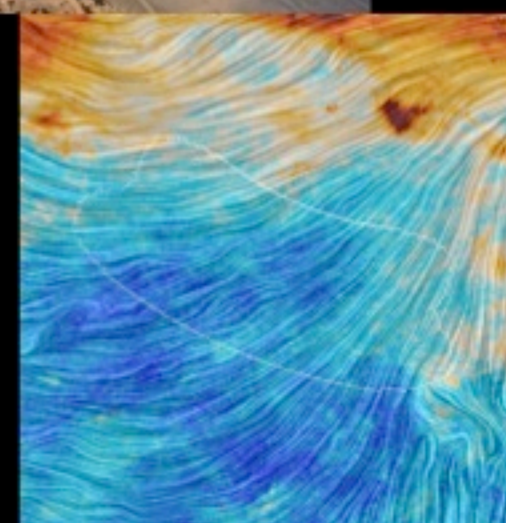
Face it. You're already everything you're ever going to be.

Inflation evidence….. BICEP curls

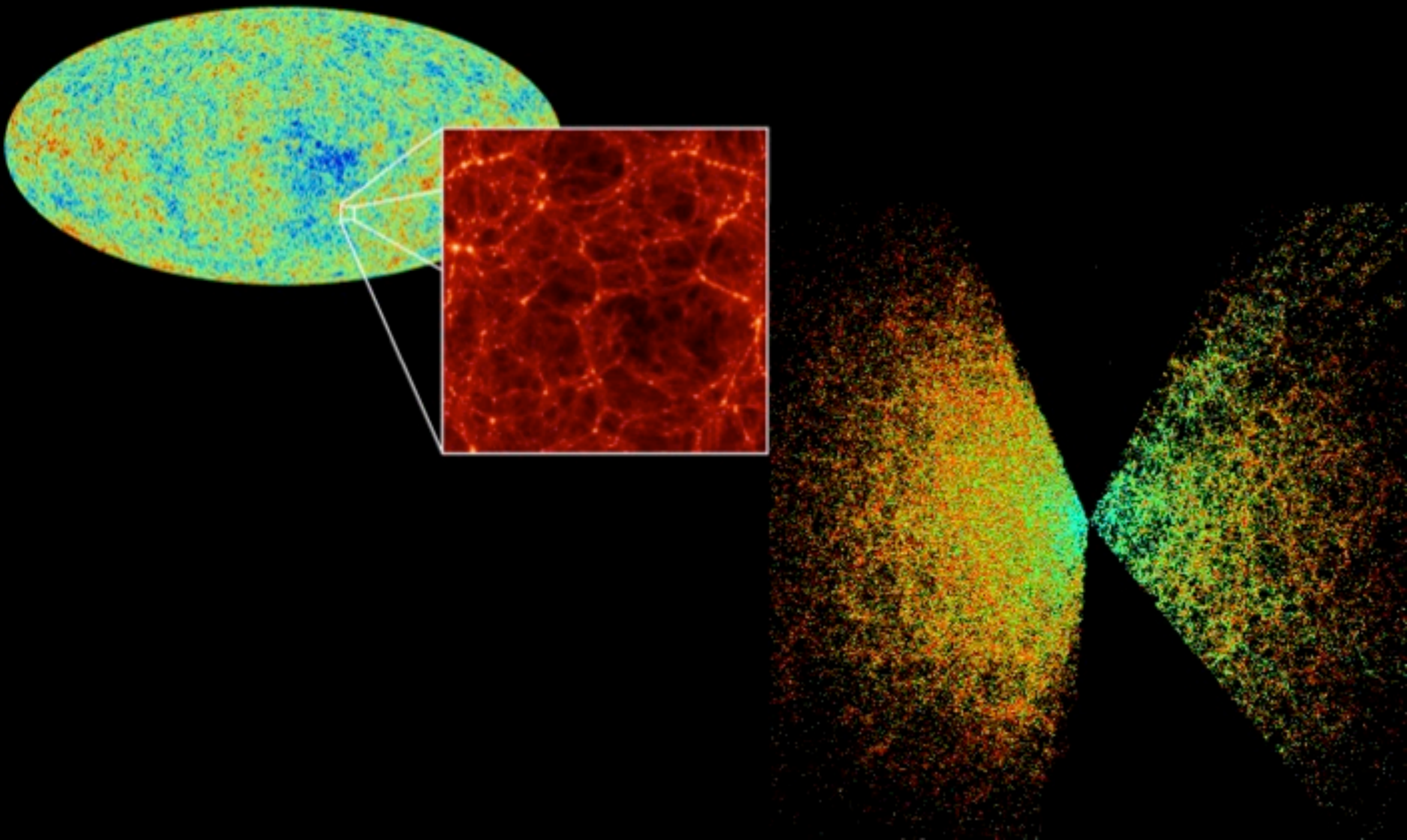




Reduced to dust!



NEXT: Explore low(er)-redshift Universe



Physical information from large-scale structure

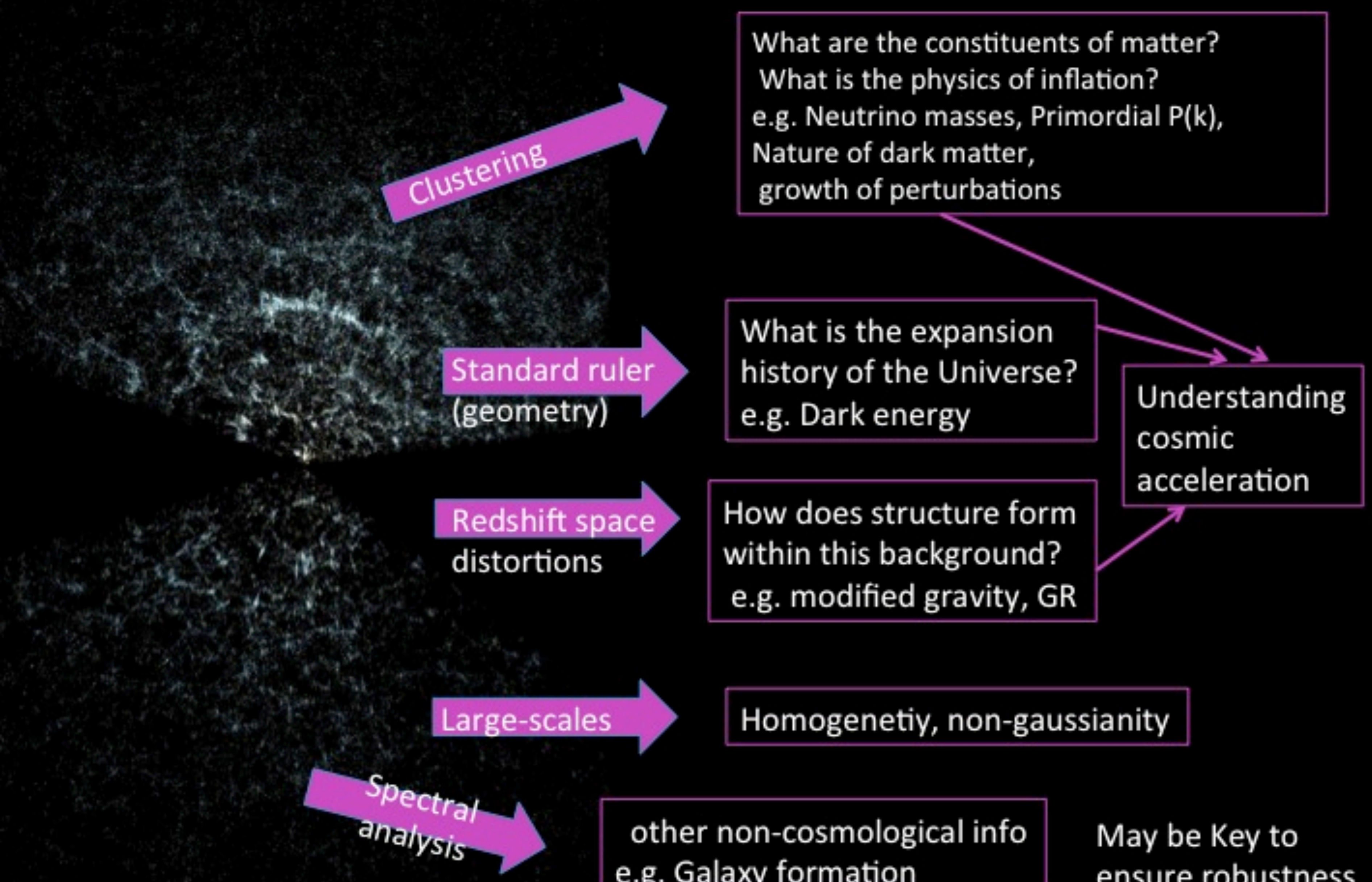
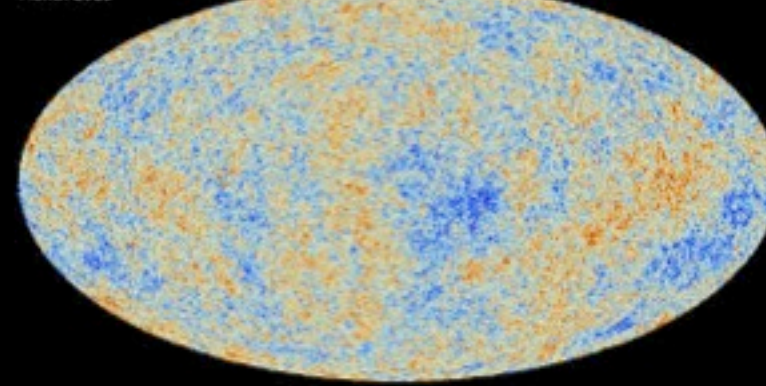


Fig. adapted from W. Percival

INCREASED PRECISION..



Planck 2013

Forthcoming new avalanche of data enables

PRECISION tests beyond the standard model

examples

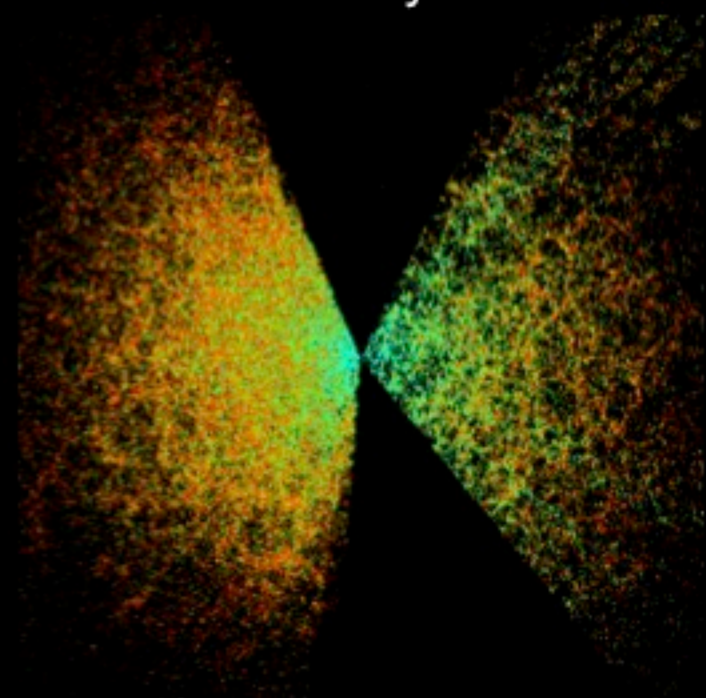
1) Neutrinos contribute at least to ~0.5% of the total matter density

Use the entire Universe as "detector"!

2) Nature of Dark energy

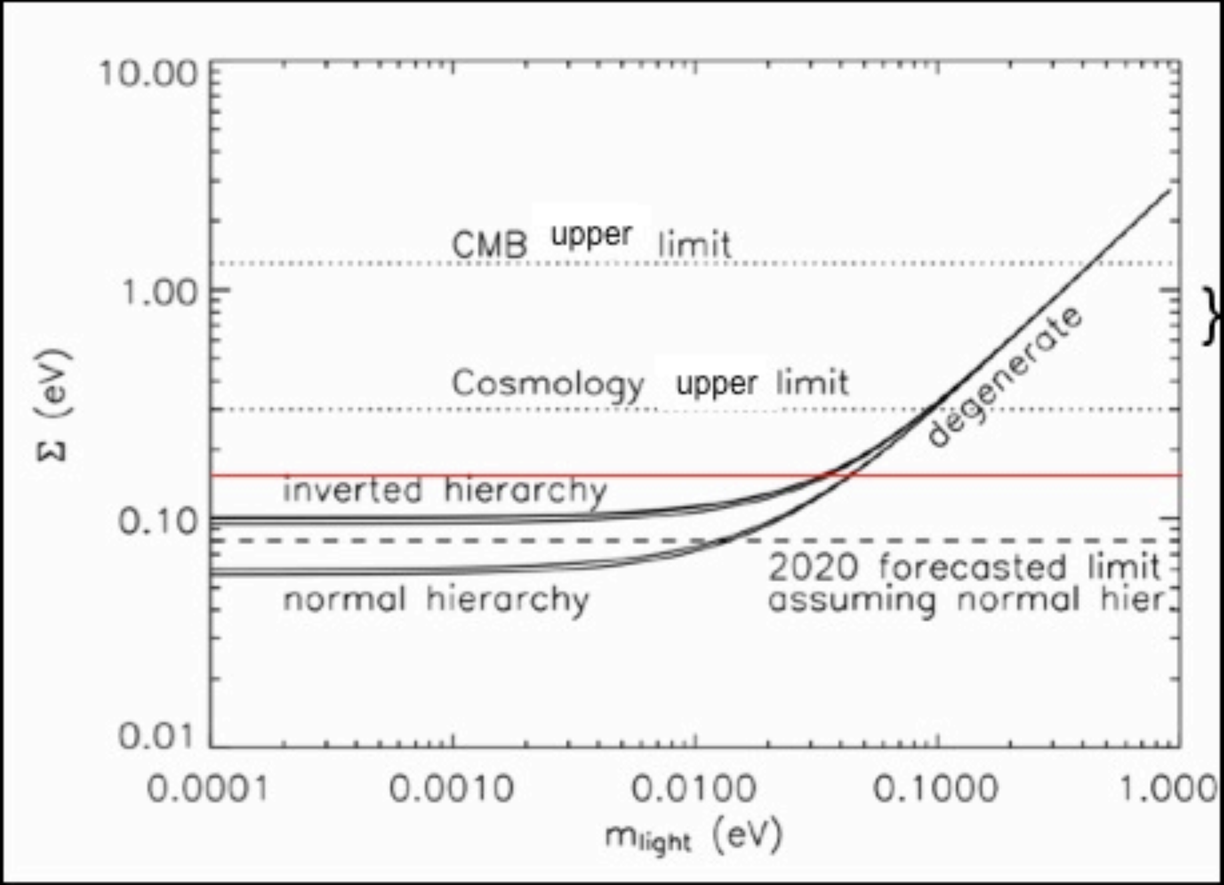
3) Nature of dark matter

4) Information about inflation: shape of
Primordial power spectrum, non-gaussianity



Etc...

Example: Neutrinos

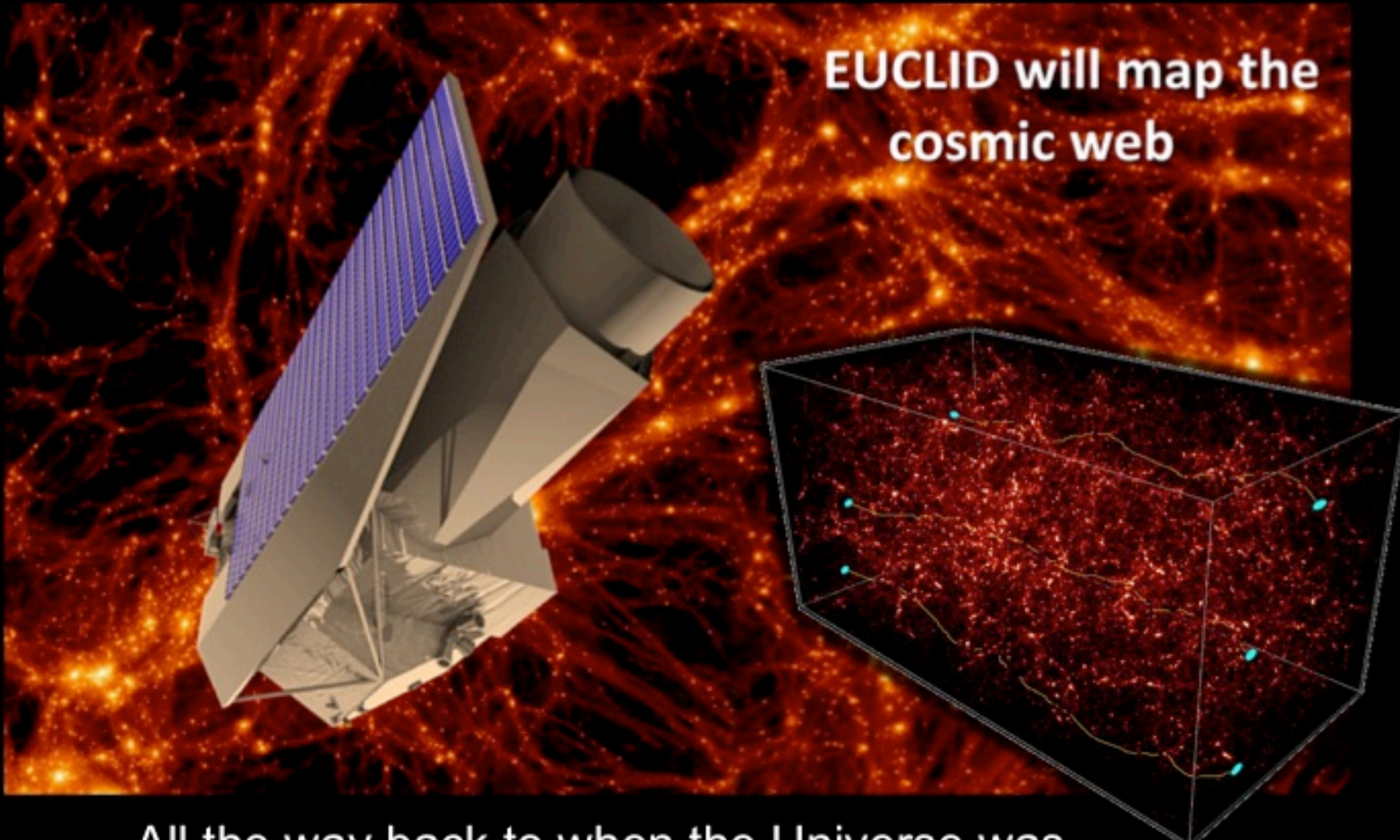


} KATRIN

Σ<0.3~0.14 (95%CL) in a minimal LCDM scenario

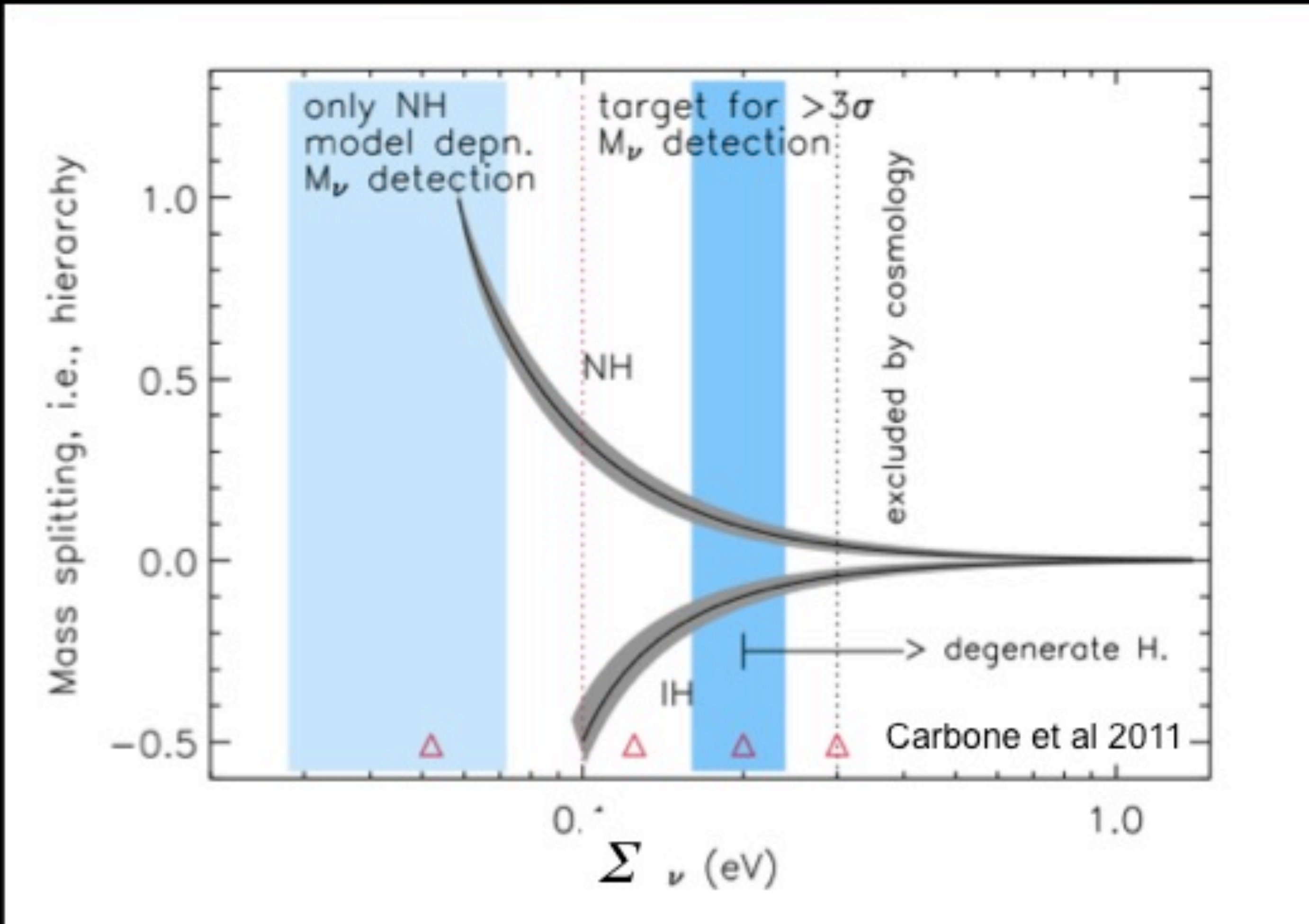
some recent heated discussion!

In the future



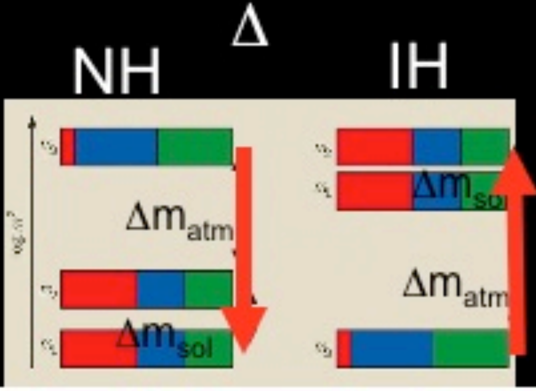
All the way back to when the Universe was 1/3 of current size and less than ¼ of current age

The Role of Euclid: forecasts



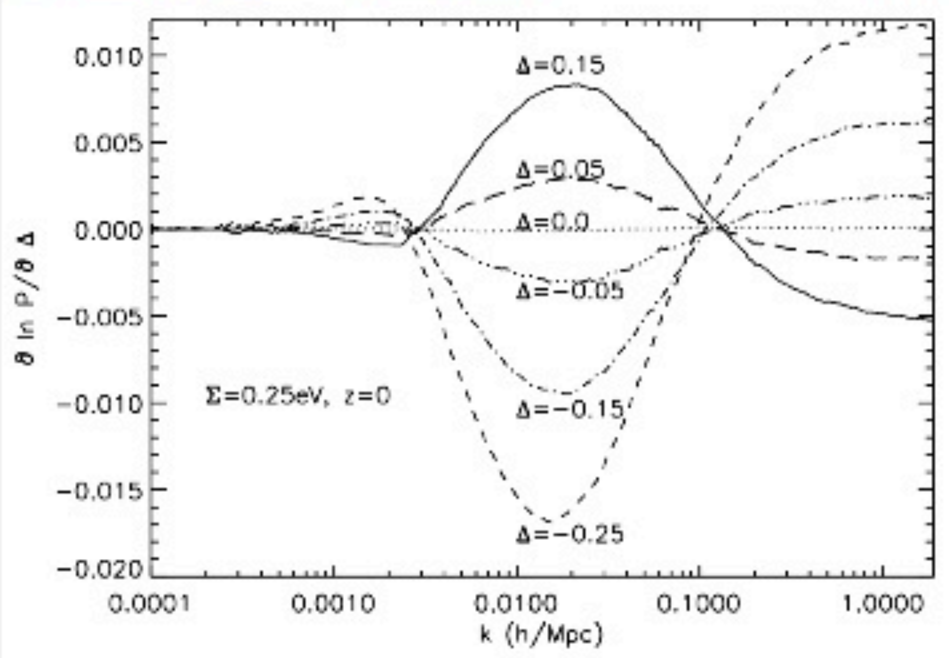
Detailed errors depend on what assumptions about underlying cosmology one is willing to make

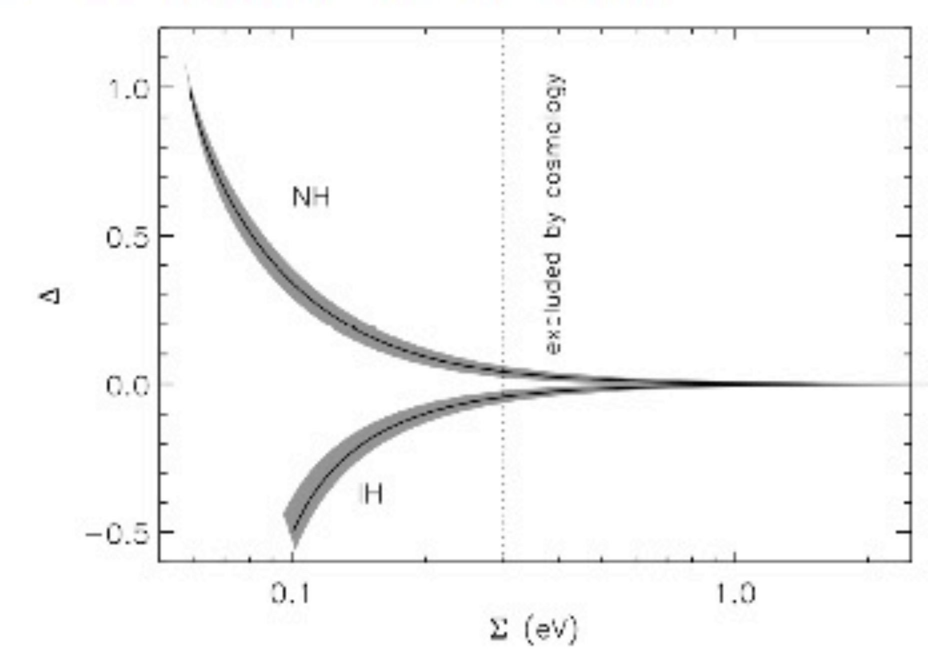
Hierarchy effect on the shape of the linear matter power spectrum



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.

$$\mathrm{NH}: \quad \Sigma = 2m + M \quad \Delta = (M - m)/\Sigma$$
$$\mathrm{IH}: \quad \Sigma = m + 2M \quad \Delta = (m - M)/\Sigma$$





Jimenez, Kitching, Penya-Garay, Verde, JACP2010

Cosmology is (mostly) sensitive to $|\Delta|$

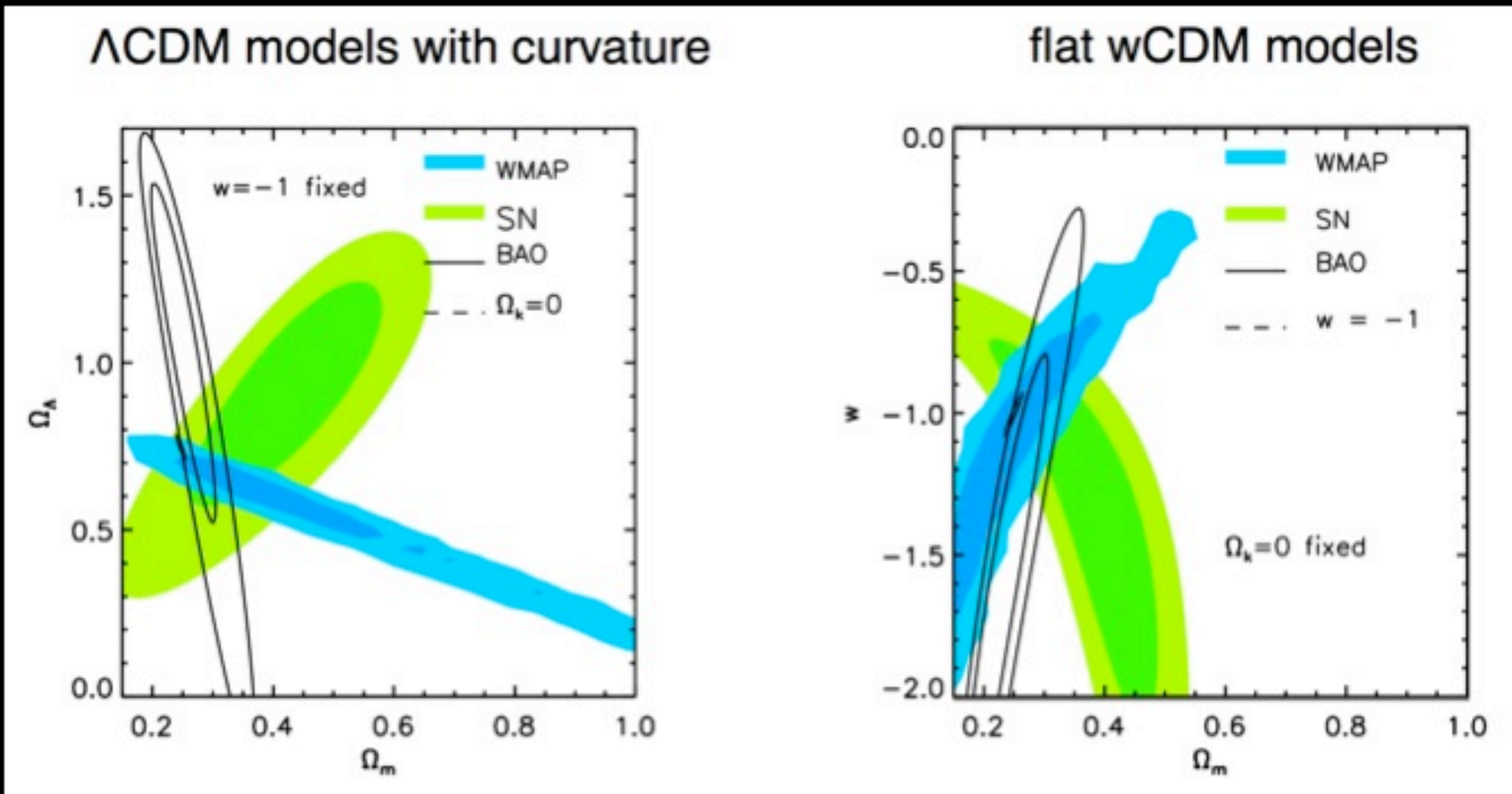
Still offers a powerful consistency check

What would it take to measure Δ?

Basically: the ultimate experiment

In combination with $\nu 0\beta\beta$ experiements can help answering:
Are neutrinos Dirac or Majorana?

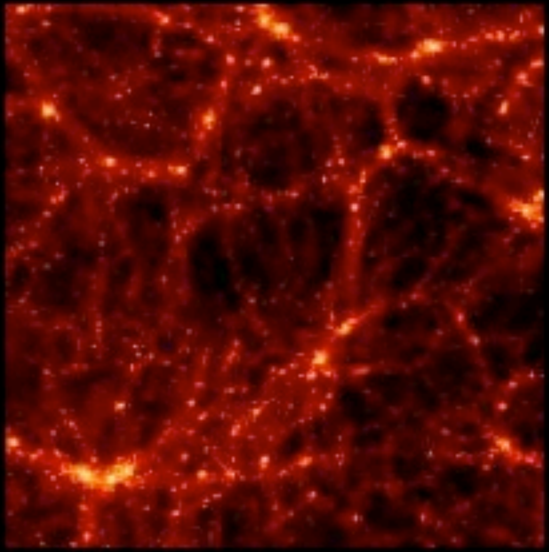
If only statistical errors



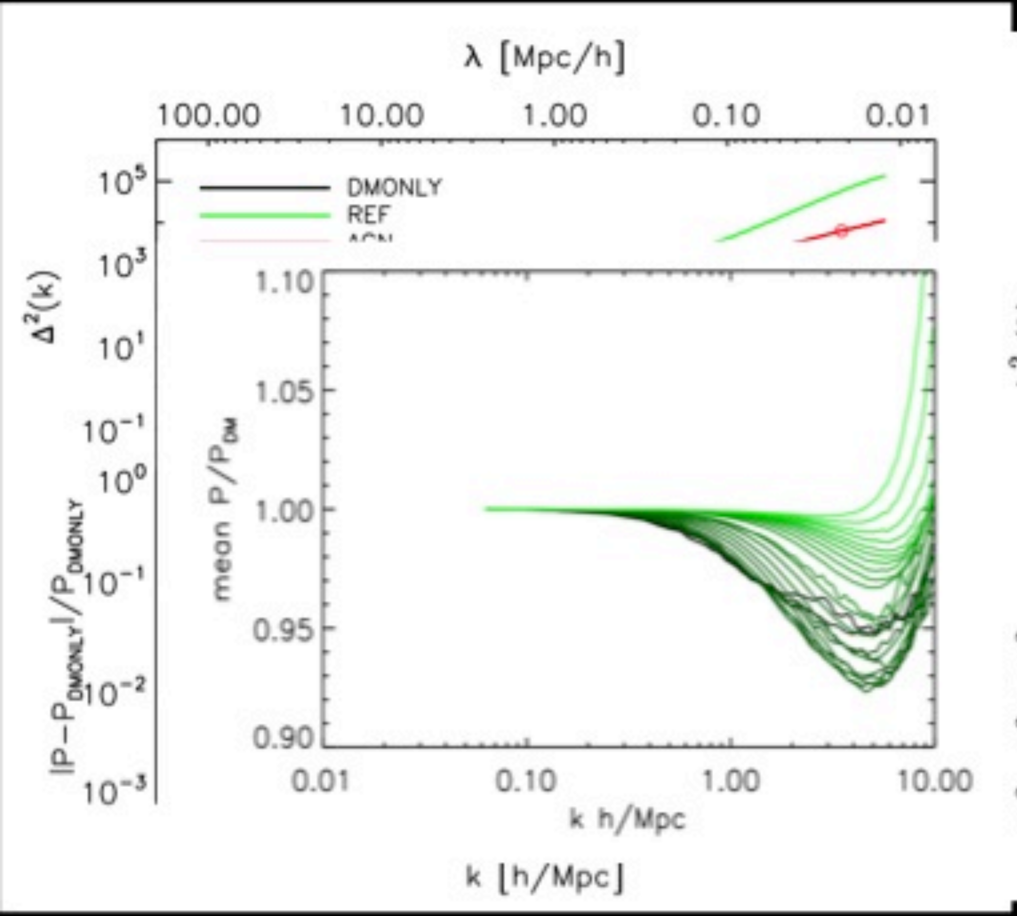
Percival et al 2009

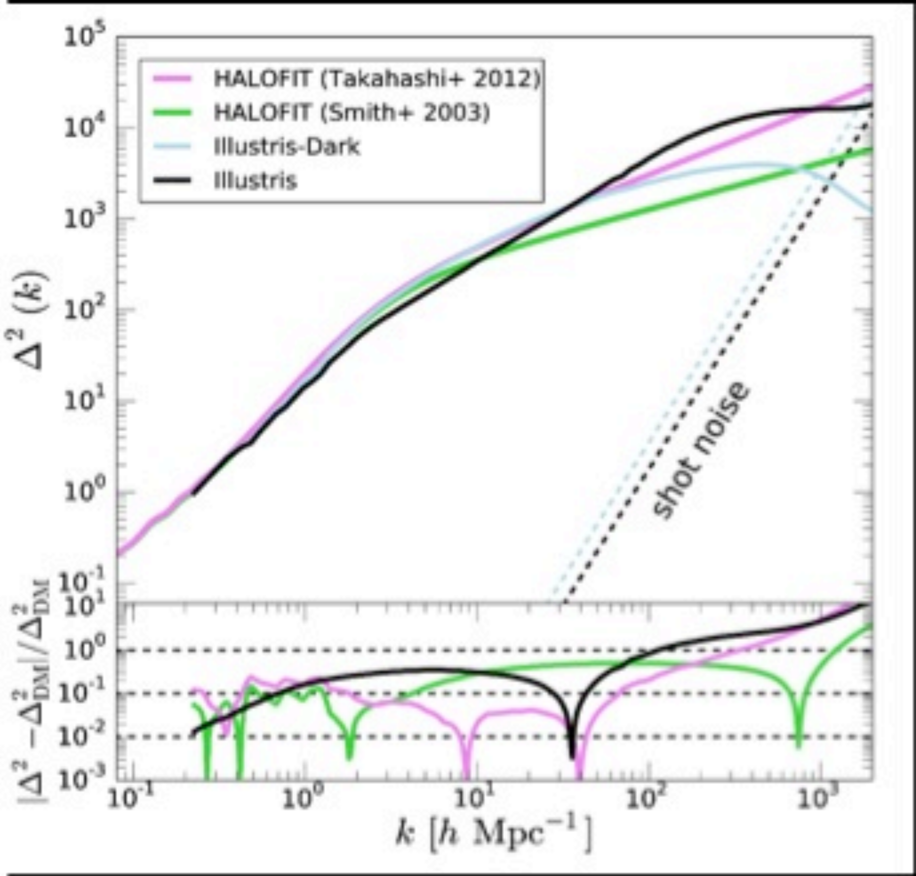
What about real world effects?

- Baryonic physics (lensing and galaxy surveys)
- Bias (galaxy surveys)
- redshift space (galaxy surveys)



Baryonic effects?





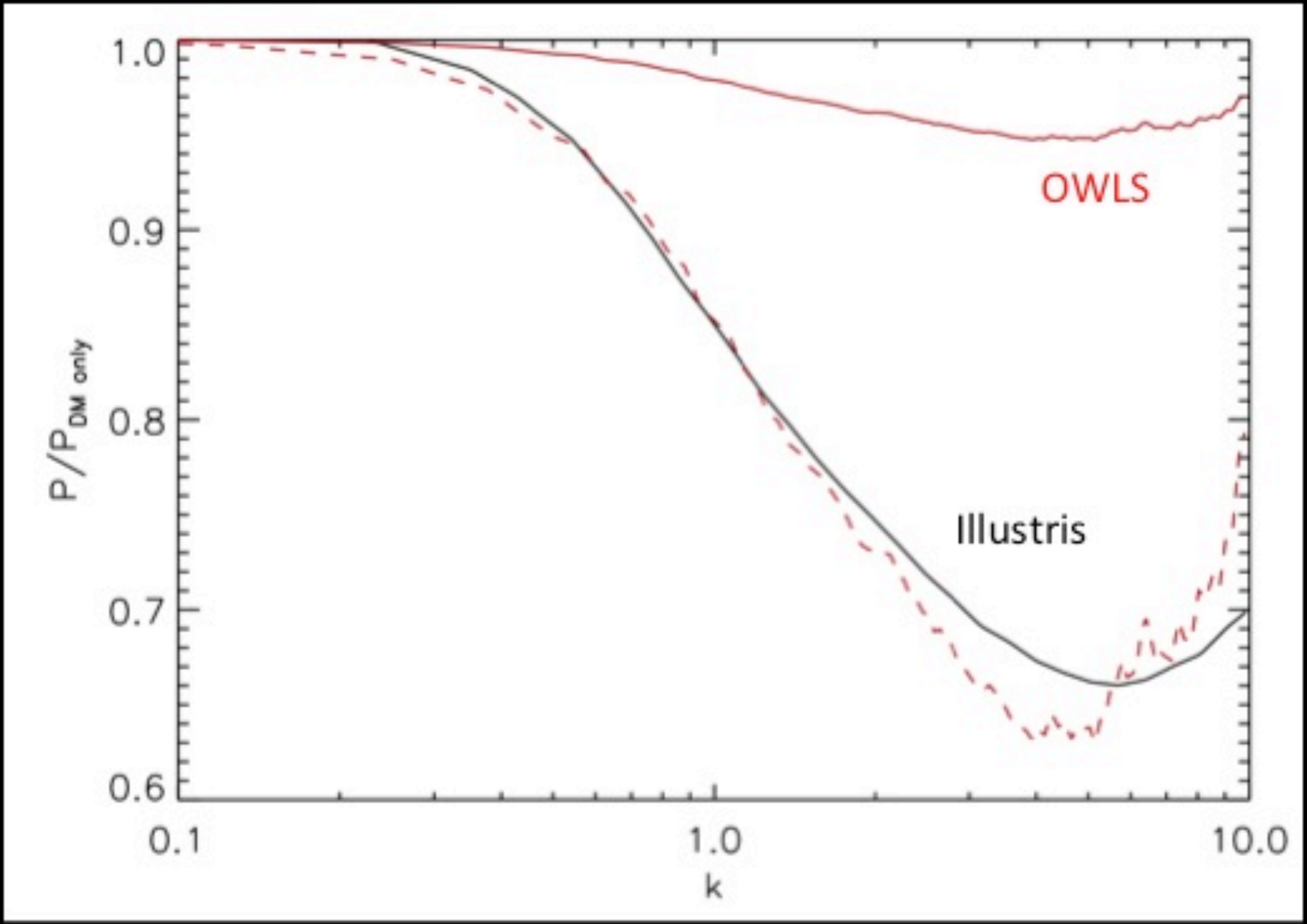
Vandaalen et al 2011

OWLS

Vogelseberger et al 2015

Illustris

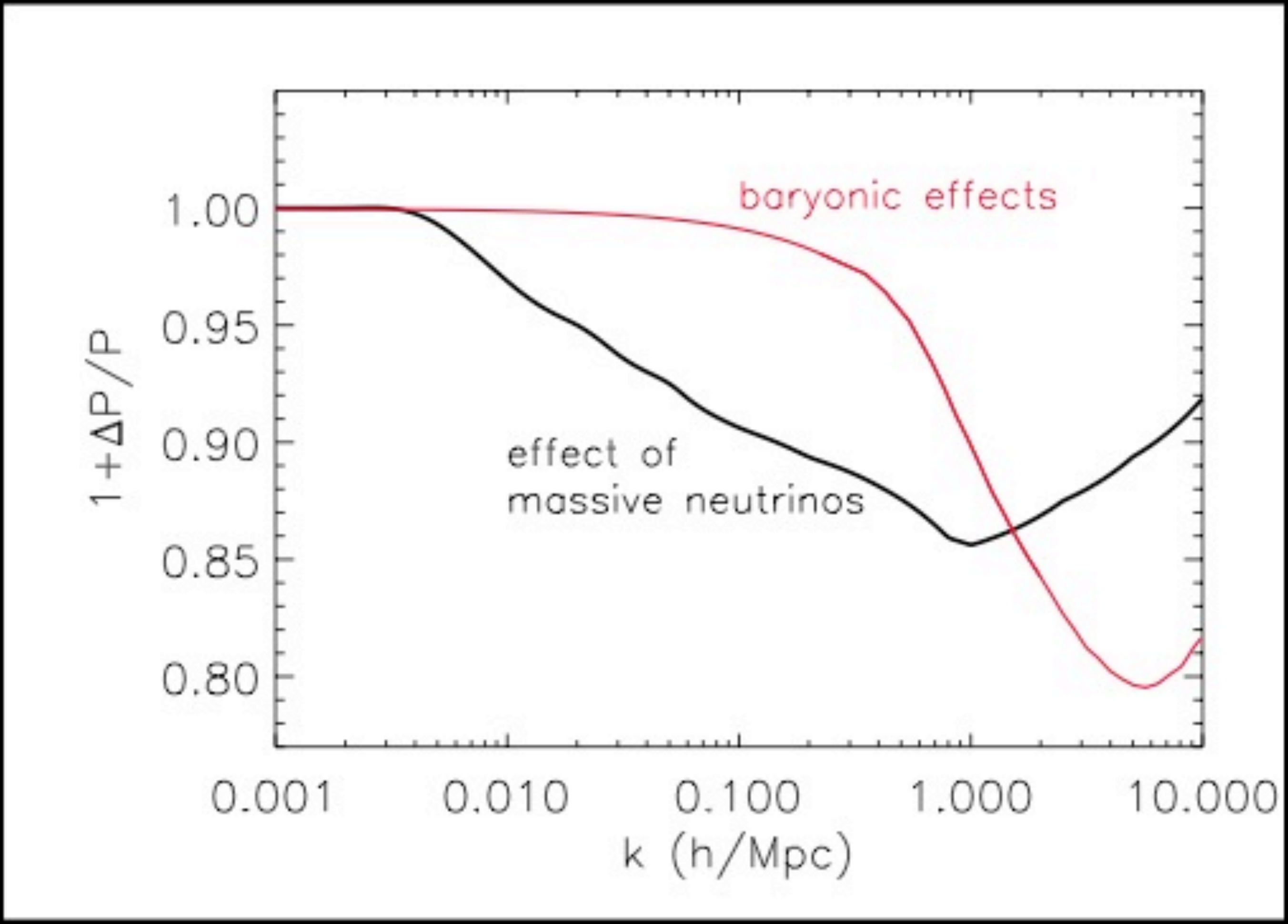
To worry or not to worry



OWLS effect x7

Thanks to M Vogelsberger for the black curve

To worry or not to worry



Designer statistics!

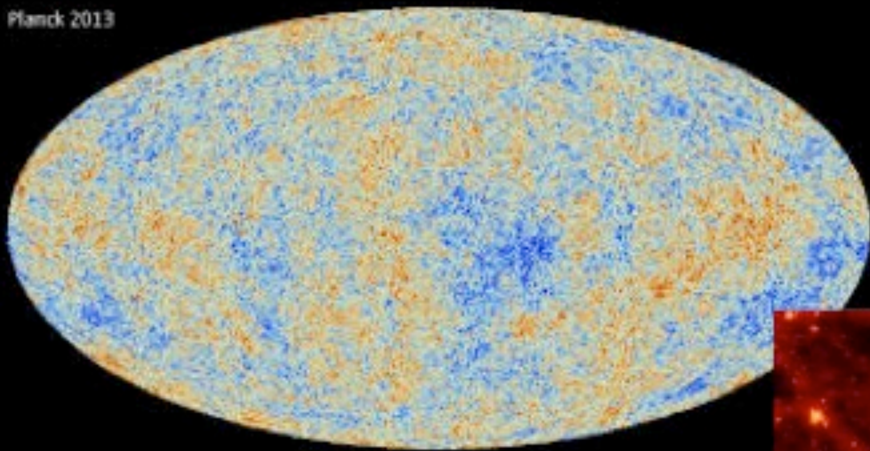
Heavens et al in prep.

BEWARE of Spherical cows

The modeling(s) we have in hand to describe real world effects are likely not sufficient for sub-percent accuracy

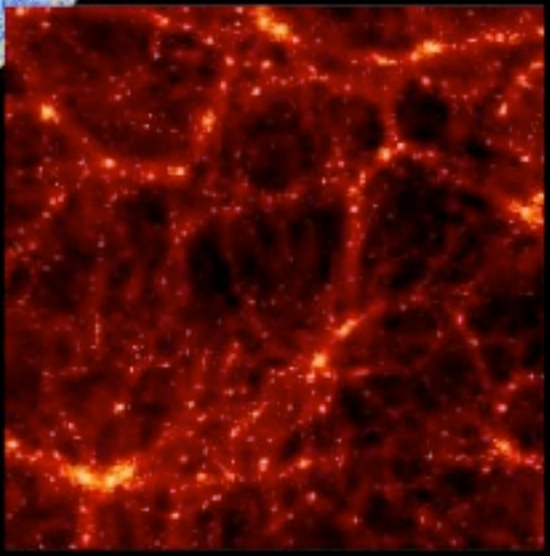
Example: galaxy bispectrum

Challenges and opportunities



Gaussian

gravity



Dark matter, not Gaussian

Bias
(and observational
issues)

Galaxies, not Gaussian

Sloan Digital Sky Survey Telescope 2.5 m at Apache Point (NM)

SDSS III

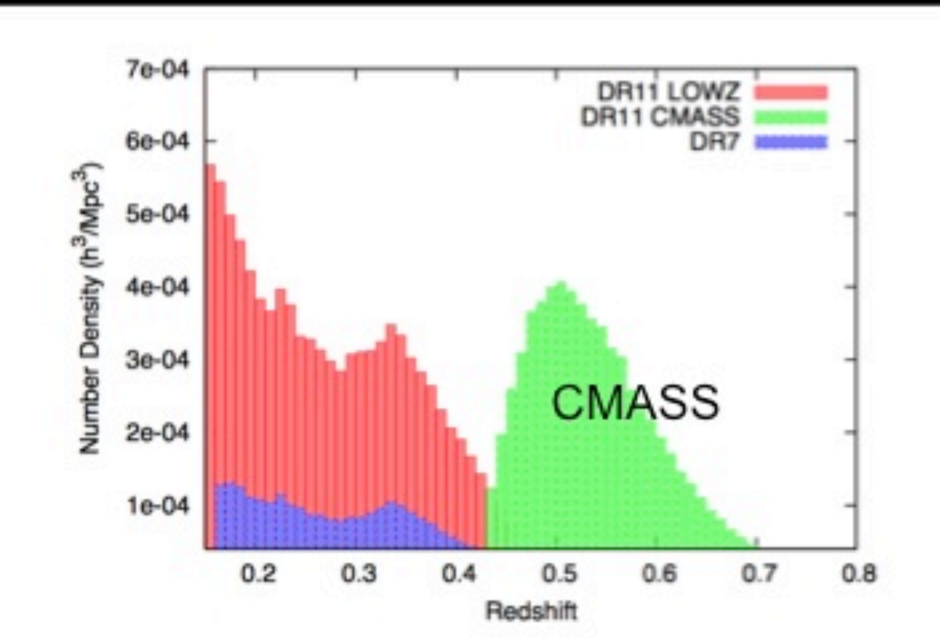
www.sdss3.org

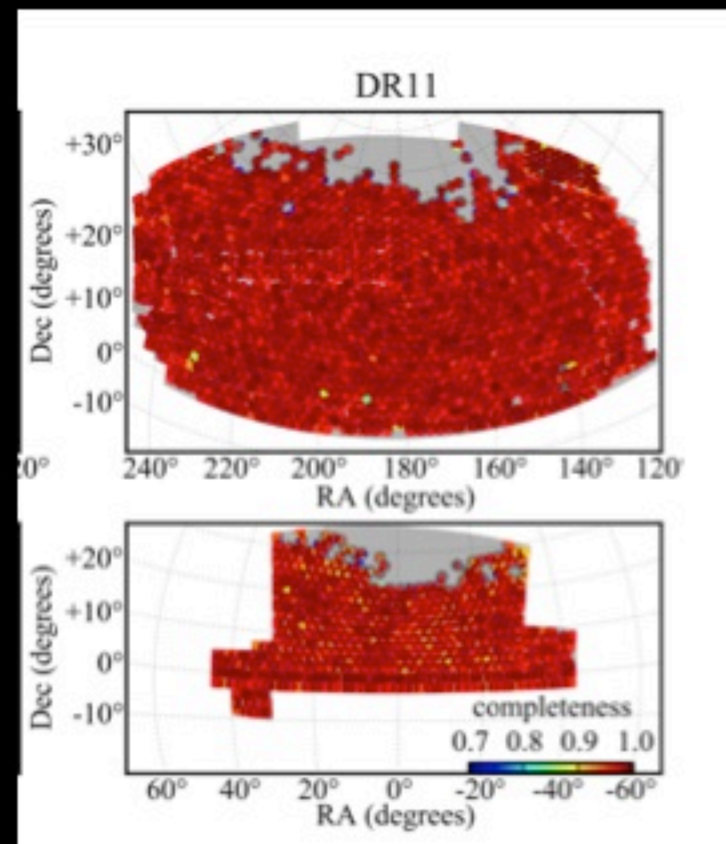
BOSS is made thinking of BAO

Galaxy redshift distribution
(Luminous red galaxies, LRG)

DR11

Distribution on the sky





Property	DR11 NGC	DR11 SGC	DR11 total
N_{gal}	556,896	186,907	743,803
Total area / deg^2	6,769	2,207	8,976
Veto area / deg^2	378	100	478
Used area / deg^2	6,391	2,107	8,498
Effective area / deg^2	6,308	2,069	8,377

zeff=0.57

Bispectrum

$$< \delta_{k_1} \delta_{k_2} \delta_{k_3} > = B(k_1, k_2, k_3) \delta^D (k_1 + k_2 + k_3)$$

In 2nd order tree level perturbation theory, for DM, for Gaussian initial conditions and for local quadratic bias this is

Shape Kernel

$$\langle \delta_{g\vec{k}_1} \delta_{g\vec{k}_2} \delta_{g\vec{k}_3} \rangle =$$
$$(2\pi)^3 \left\{ b_1^3 \left[P(\vec{k}_1) P(\vec{k}_2) 2J(\vec{k}_1, \vec{k}_2) + cyc. \right] + b_1^2 b_2 \left[P(\vec{k}_1) P(\vec{k}_2) + cyc. \right] \right\} \delta^D(\vec{k}_1 + \vec{k}_2 + \vec{k}_3).$$

And powerful test of gravitational instability (gravity) and bias

Acknowledgments and references: note the time-scales

An improved fitting formula for the dark matter bispectrum (2012)

Gil-Marín, Héctor; Wagner, Christian; Fragkoudi, Frantzeska; Jimenez, Raul; Verde, Licia

Dark matter and halo bispectrum in redshift space: theory and applications (2014)

Gil-Marín, Héctor; Wagner, Christian; Noreña, Jorge; Verde, Licia; Percival, Will

The power spectrum and bispectrum of SDSS DR11 BOSS galaxies I: bias and gravity (2015)

Gil-Marín, Héctor; Noreña, Jorge; Verde, Licia; Percival, Will J.; Wagner, Christian; et al.

The power spectrum and bispectrum of SDSS DR11 BOSS galaxies II: cosmological interpretation (2015)

Gil-Marín, Héctor; Verde, Licia; Noreña, Jorge; Cuesta, Antonio J.; Samushia, Lado; et al.

To be realistic…

- 1)Tree level perturbation theory is limited
- 2) Bias is likely not local,non-linear
- 3) There are redshift space distortions
- 4) Which are non-linear
- 5) A real survey has a mask and selection function
- 6) B's from different triplets are highly correlated
- 7) What's the PDF of B anyway?

To be realistic…

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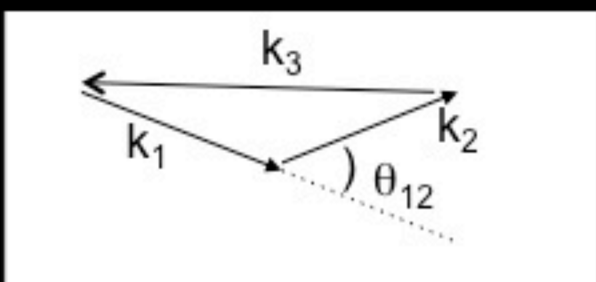
1,3,4 Calibrate on N body simulations find a fitting formula

$$Q_{123} \equiv \frac{B(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3)}{P(k_1)P(k_2) + P(k_1)P(k_3) + P(k_2)P(k_3)}$$

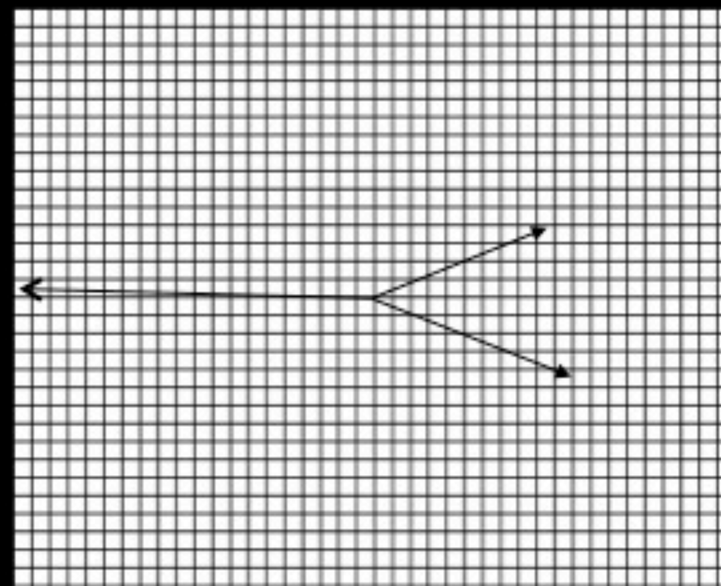
Use only a sub-set of shapes!

Triangles come in all shapes and sizes!

Nomenclature:



In a grid



Gil-Mańn, Wagner, Norena, LV, Percival, arXiv:1407.1836

Gil-Marin, Wagner, Fragkoudi , Jimenez LV, 2012

Simulations:

	A	B
L_b [Mpc/h]	2400	1875
N_p	768^3	1024^3
N_r	40	3
$k_N/4$ [h/Mpc]	0.25	0.43
softening ϵ [kpc/h]	90	40
PM grid	2048^3	2048^3
ErrTolForceAcc α	0.005	0.005
initial scale factor a_i	0.05	0.02
maximum $\Delta \log a$	0.025	0.025
ErrTolIntAccuracy η	0.025	0.025
# time steps	~ 1300	~ 2500

Run in the local cluster hipatia

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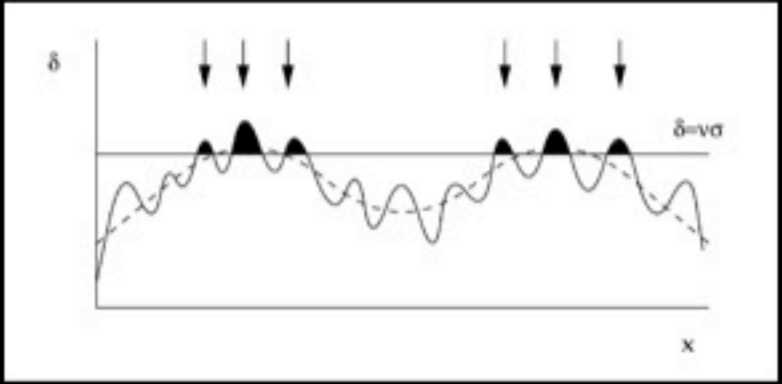
- 5) A real survey has a mask and selection function
- 6) B's from different triplets are highly correlated
- 7) What's the PDF of B anyway?

Bias model

Eulerian non-local bias model (local in Lagrangian space)

$$\delta_g(\mathbf{x}) = b_1\delta(\mathbf{x}) + \frac{1}{2}b_2[\delta(\mathbf{x})^2] + \frac{1}{2}[\frac{4}{7}(1-b_1)][s(\mathbf{x})^2]$$

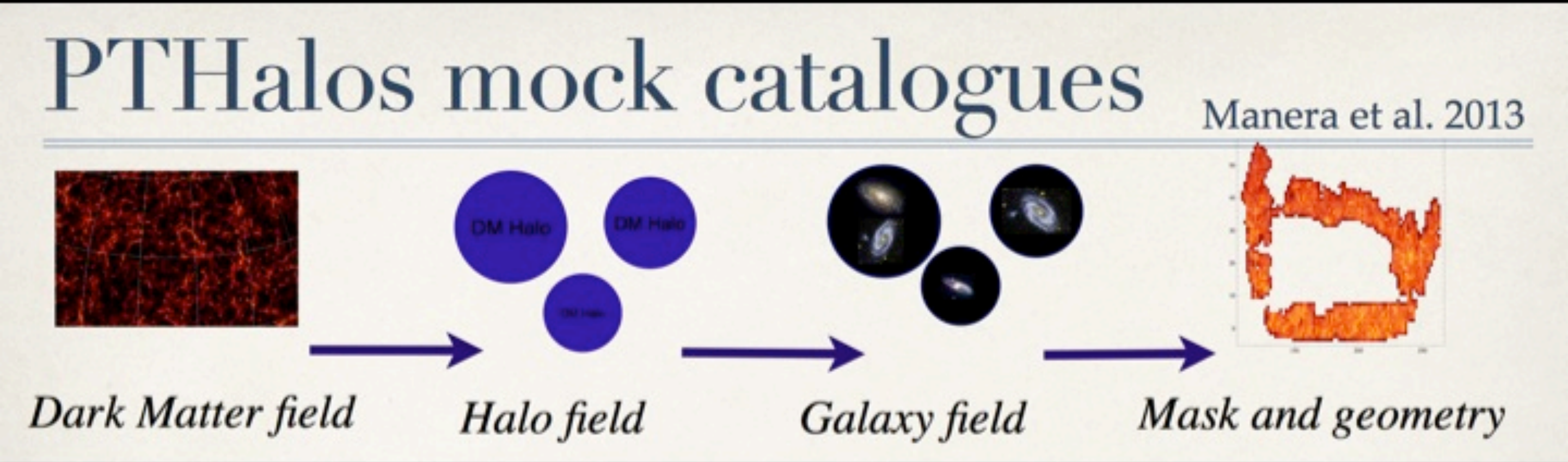
Tested on halo catalogs from N-body simulations



This is also a somwhat spherical cow

The role of Mocks

600+600 realizations of the N and S patches (virtual catalogs)



Use for testing pipeline, testing the modeling and
estimating the error distribution

Approach

We consider the monopole of the galaxy power spectrum and bispectrum (CMASS galaxies of DR11 of SDSSIII BOSS)

7 free indipendent parameters

- The bias parameters: b_1, b_2 (local Lagrangian bias, $b_{s2} = -4/7[b_1 - 1]$),
- Dark matter power spectrum amplitude, σ_8^2: $P_{lin}(k) \to \sigma_8^2 P_{lin}(k)$
- Growth rate of structure $f = \frac{d \log \delta}{d \log a}$
- Fingers of God damping functions: σ_{fog}^P, σ_{fog}^B
- Shot Noise term amplitude term, $A_{\rm noise}$: $A_{\rm noise} > 0$ (sub-Poisson); $A_{\rm noise} < 0$ (super-Poisson).

Of which we are interested in f and σ_8

Name of the game

- Use a model of the non-linear power spectrum monopole in redshift space

Which can be modeled very well on mildly non-linear scales

I spare you the details, the equations run over 2 pages.

- And of the Bispectrum monopole in redshift space (fit from simulations)
- And measure: b_1, b_2, f, σ_8, A_{noise}, σ_P , σ_B

↑

$d \ln \delta / d \ln a$

Test of gravity

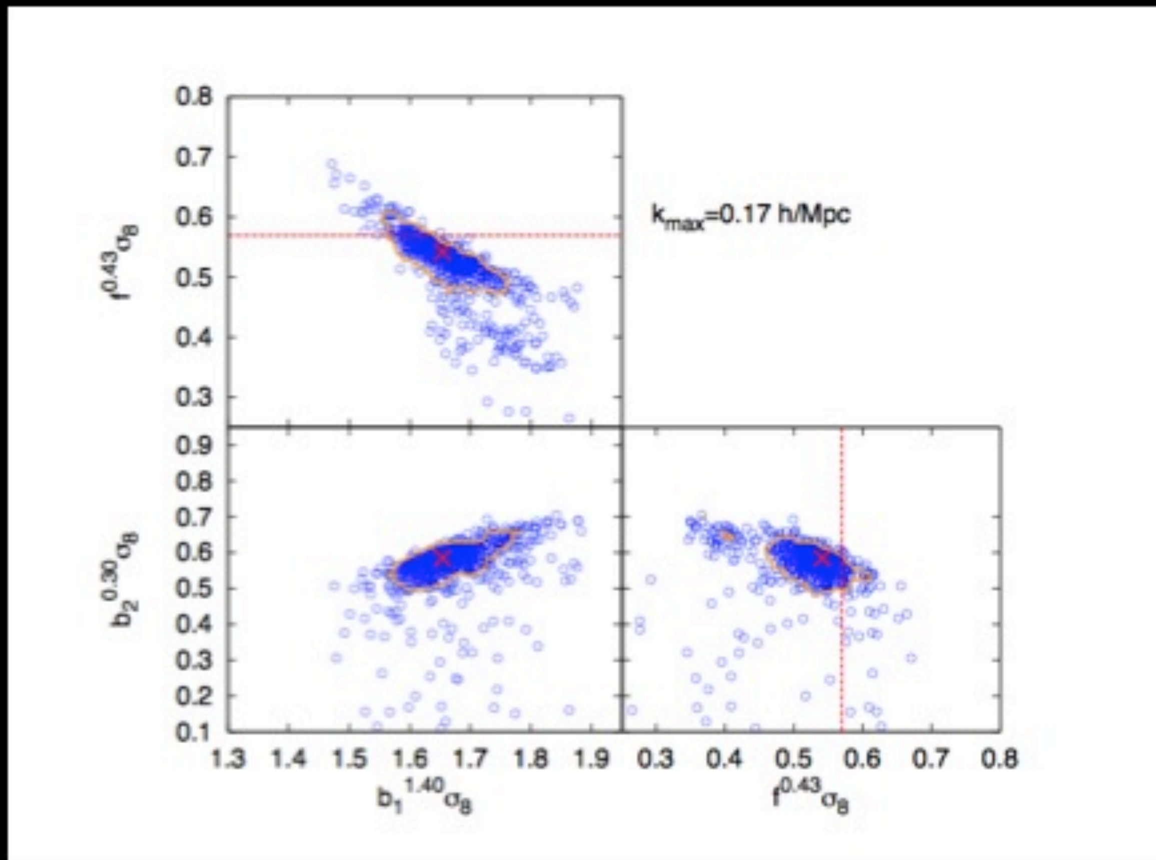
Very fashionable!

Note the nuisance parameters!

Battery of tests

	Recover input parameters?	
Real space dark matter	✓	
Redshft space dark matter	✓	
Real space halos	✓	
Redshift space halos	✗	Residual bias

In fact three (combinations) are constrained



Planck cosmology

Implications?

- BOSS galaxies are highly biased
- Their bias is NOT simple, linear, local (obvious in hindsight, but “scary”)
- Even more effort is needed to understand power spectrum and bispectrum of tracers in redshift space

The GR bispectrum kernel works!
….but this is not too stringent test for GR!

$$f^{0.43}\sigma_8 = 0.582 \pm 0.084 (0.584 \pm 0.051)$$

at z=0.57

Gil-Marín, LV, Noreña, Cuesta, Samushia, et al. MNRAS 2015

upshot

Selecting highly biased objects is good for BAO science, less good for other science

Bias and redshift space distortions-beyond the P(k)-are complicated!

Despite the effort, we are now becoming limited by systematics

Recall that primordial NG (~1 or below at z~1100)
will be a factor 10^3-10^4 smaller than the gravitational one (~few at z=0)
and possibly bias.
So bispectrum must be modeled at much better than 0.1%!!

It goes deeper than that

“We can’t live in a state of perpetual doubt, so we make up the best story possible and we live as if the story were true.”

Daniel Kahneman about theories

GR, big bang, choice of metric, nucelosynthesis, etc etc…

Cosmology tends to rely heavily on models (both for "signal" and "noise")

Essentially, all models are wrong , but some are useful
(Box and Draper 1987)

Systematics in the data
Systematics in the model (analysis)

Towards a systematic approach

Known knowns: model, marginalize over, nuisance parameters.

Known unknowns: systematic effects which are known, but not fully characterized "cancelling out systematics" , trading off precision for robustness, designer statistics etc.

Unknown knowns: assumptions that we know have not been tested, but that Nevertheless are being used. Theoretical systematics.
Model-independent , minimally parametric approaches, latent variables, etc.

Unknowns unknowns: "Hic sunt leones"

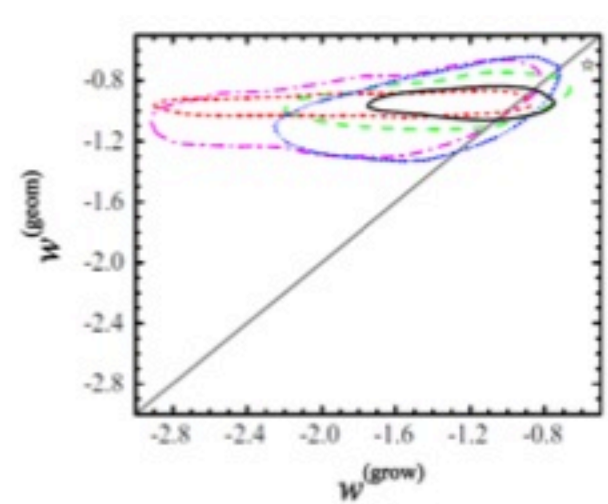
Big-data, COMPLEMENTARITY, model independence etc.

In its infancy…

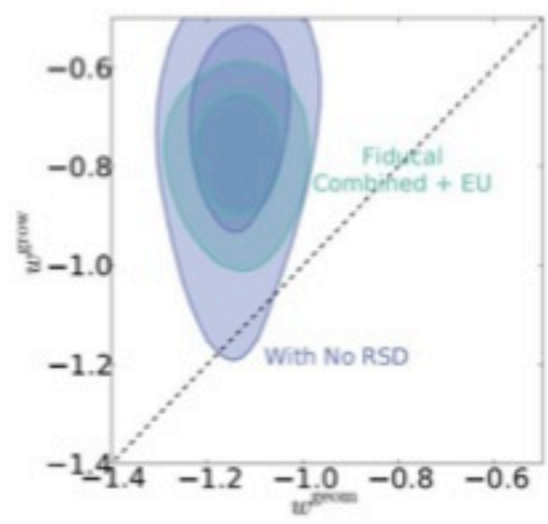
here's some exploratory examples

Example 1

Parameter splitting



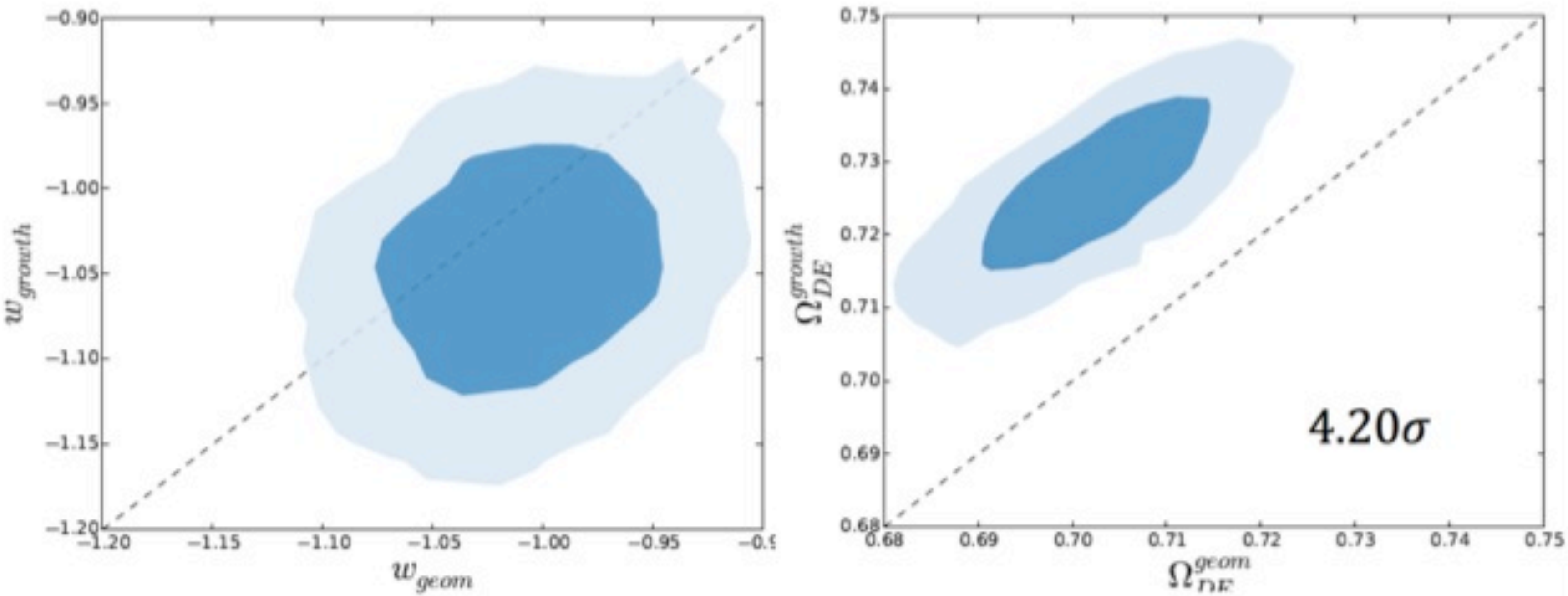
Wang et al. (2007)



Ruiz et al. (2014)

Puzzling:

Split both in Ω_{DE} and w

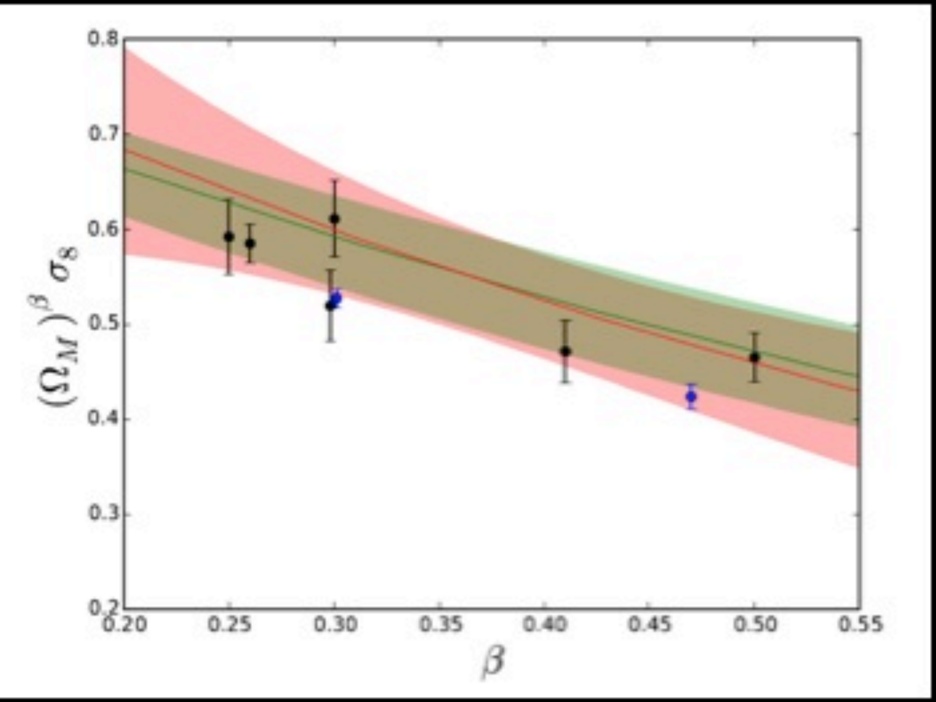


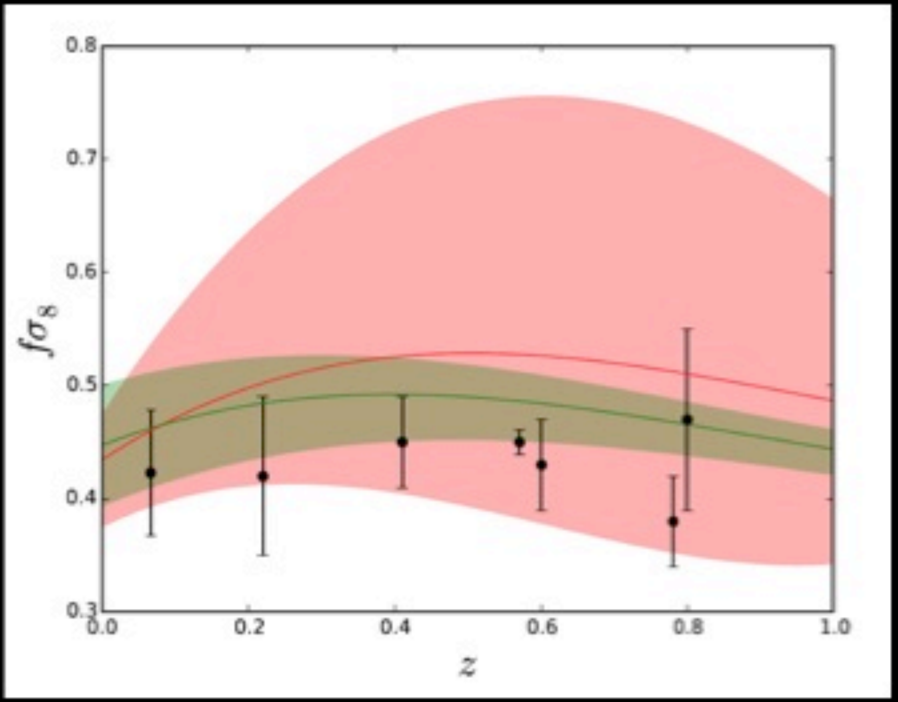
$$w_{geom} = -1.01 \pm 0.04$$
$$w_{growth} = -1.05 \pm 0.05$$

$$\Omega_{DE}^{geom} = 0.702 \pm 0.009$$
$$\Omega_{DE}^{growth} = 0.727 \pm 0.009$$

Bernal master thesis
(the first master thesis done by skype)

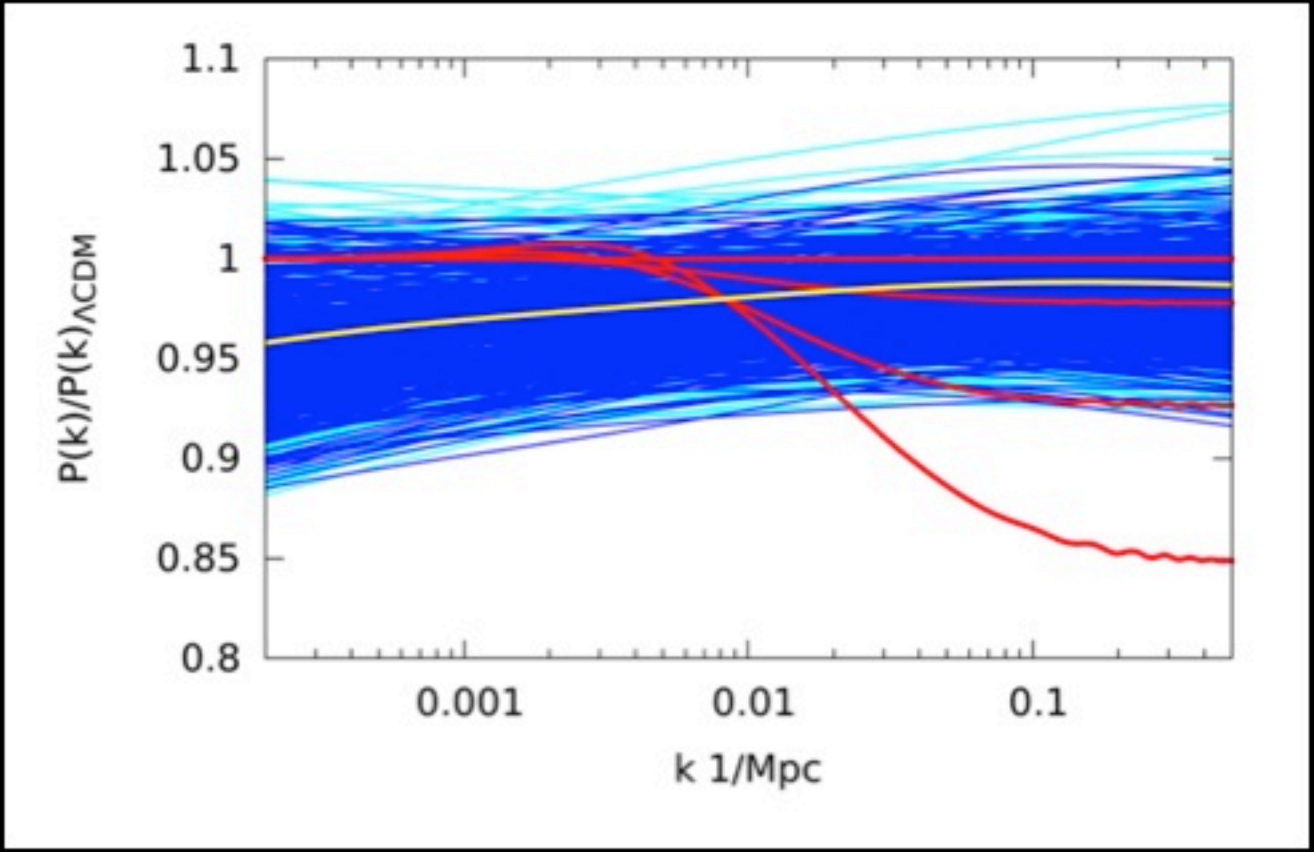
More than one culprit sharing responsibility





Bernal master thesis

Example2: non-parametric Weighting neutrinos



Planck+SDSSDR7+WiggleZ

Ravenni will be master thesis

3.Cancelling out systematics

In the exponential world statistical errors shrink, systematic errors are the big challenge!

Usual approach: treat as nuisance parameters and marginalize
this might not be satisfactory

The idea:

Say you have two measurements x, y, and two quantities of interest t_1 and t_2 that depend on nuisance parameter n as $x=t_1/n$ and $y=t_2n$

You use r=xy. Reduce the number of "data" points but is much more robust.

Few applications in the literature but no systematic treatment

with J. Norena, R. Jimenez, C. Penya-Garay, C. Gomez, MNRAS 2012

The setup

Have N observables O_i
that depend on m interesting quantities μ_i
and n nuisance quantities ν_i

$$O_i(\mu_1, \ldots, \mu_m, \nu_1, \ldots, \nu_n)$$

We are ignorant about mean values and errors of the nuisance parameters

Goal:

Find combinations of observables that are insensitive to nuisance parameters

$$f_k = f_k(O_1, ..., O_N) \; ;$$

$$\frac{df_k}{d\nu_i} = \sum_{j=1}^{N} \frac{\partial f_k}{\partial O_j} \frac{\partial O_j}{\partial \nu_i} = 0 \quad \text{for } i = 1, ..., n \, .$$

In math speak,
solve this

Reminds you of the renormalization group

Start simple: power-law dependence on ν_i

$$O_i - \hat{O}_i = g(\vec{\mu}) \prod_{j=1}^{n} (\nu_j - \hat{\nu}_j)^{a_{ij}}$$

The solution of the system of differential equations is of the form:

$$f_k = \prod_{i=1}^{N} (O_i - \hat{O}_i)^{b_i^k}$$

Which gives a system of linear algebraic equations for the unknown b_i^k

If M=N-n>0 then M non trivial solutions:

$$\sum_{i=1}^{m} a_{ij} b_i^k = 0\,.$$

i.e. N-n "combinations" of data

AND similarly for linear dependence….

Obvioulsy it follows that:

You can't do better than marginalization. But with marginalization you assume you know mean and errors of the nuisance parameters

You need more data (observables) than nuisance parameters.

If you have fewer observables than nuisance parameters exact solutions do not exist

However in some cases approximate solutions can be found

Of interest: observables have similar (but not identical) dependences on some of the nuisance parameters

In this case it is possible to…

minimize the impact of systematics

Minimize this!

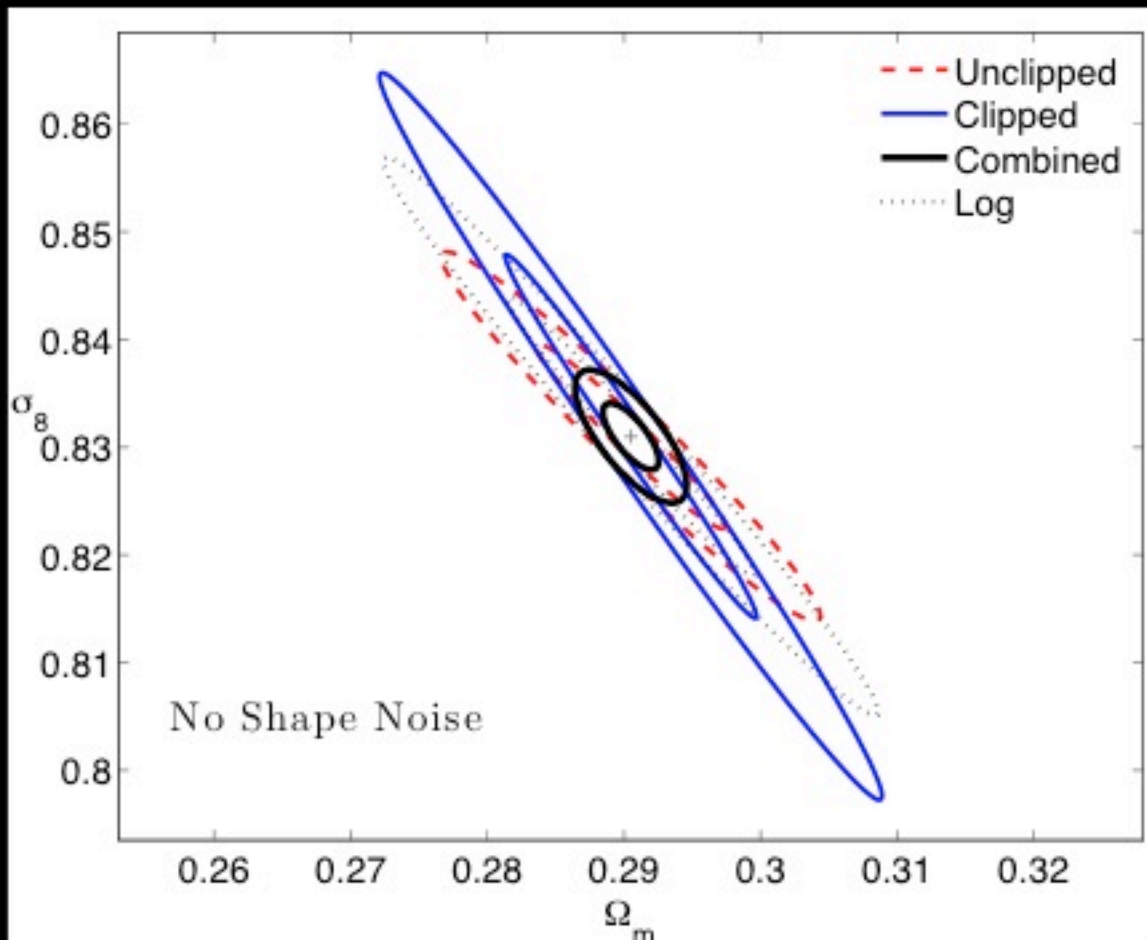
$$\mathcal{L}_k = \sum_{j=1}^{n} \left(\frac{\mathrm{d} f_k}{\mathrm{d}\nu_j} \right)^2 \Delta\nu_j^2 - \lambda_k \left(\sum_i (b_i^k)^2 - A_k^2 \right)$$

For power law case

$$\sum_{l=1}^{N} \mathcal{M}_{il} b_l^k = \sum_l \left[f_k^2 \sum_{j=1}^{n} \left(\frac{\Delta\nu_j}{\nu_j} \right)^2 a_{ij} a_{lj} \right] b_l^k = \lambda_k b_i^k$$

General and include previous cases

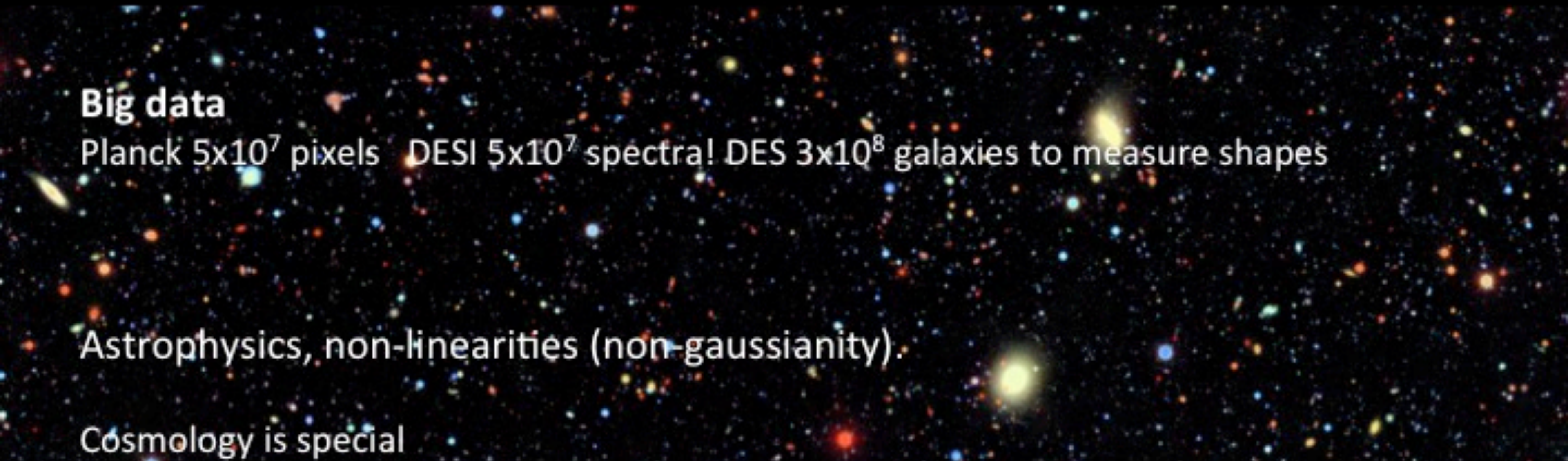
4. Clipping the convergence field and combining it with standard analysis



Simpson et al in preparation

Challenges and opportunities

The CMB was simple, well understood physics,
galaxies in the late-time universe are not simple nor well understood



Big data

Planck $5x10^7$ pixels DESI $5x10^7$ spectra! DES $3x10^8$ galaxies to measure shapes

Astrophysics, non-linearities (non-gaussianity).

Cosmology is special

Precision vs accuracy

Systematic errors will be the limiting factor

Analysis techniques must evolve and adapt

Conclusions

You can't do today's job with yesterday's tools and still be in business tomorrow

Conclusions: glass half empty

… the maximally boring universe…

The standard cosmological model has survived ever more stringent tests

Deviations from it are even more constrained

Eventually something will have to give, the model IS incomplete
(and the cosmological constant IS ugly..
And we have extrapolated the law of gravity some 13 orders of magnitude!!)

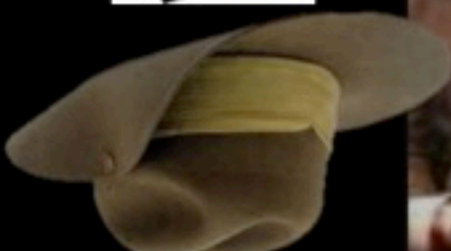
The point is how much smaller would the observational error bars have to be

Conclusions (glass half full)

- Precision cosmology means that we can start (or prepare for) constraining interesting physical quantities, and make model-independent tests.
- Neutrino properties: absolute mass scale, number of families, possibly hierarchy The (indirect) detection of neutrino masses is within the reach of forthcoming experiments (even for the minimum mass allowed by oscillations)
- Large future surveys means that sub % effects become detectable, which brings in a whole new set of challenges and opportunities (e.g., mass, hierarchy)
- Systematic and real-world effects are the challenge, need for in-build consistency checks!
- COMPLEMENTARITY is one of the keys

END

END



#AACChat