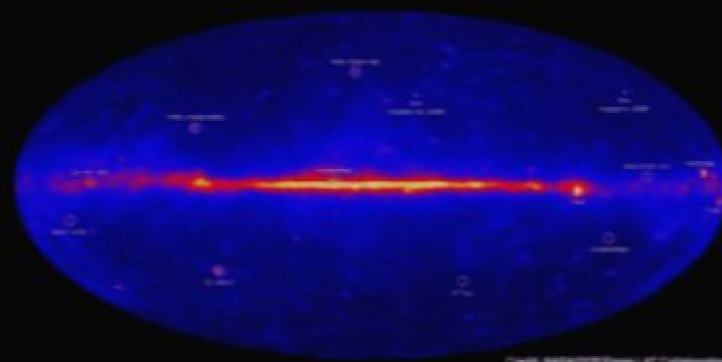
Title: Dark matter under different angles

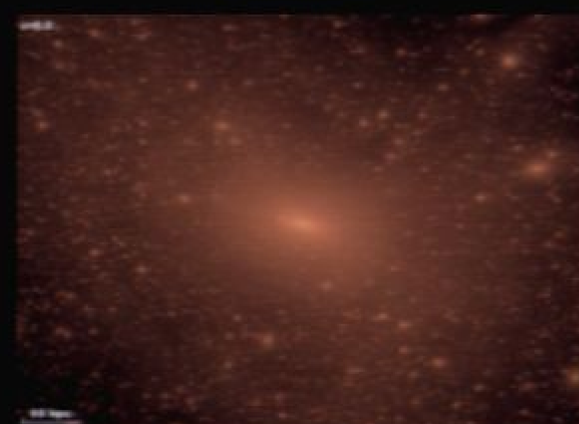
Date: Dec 07, 2009 02:00 PM

URL: http://pirsa.org/09120024

Abstract: Most often, the dark matter puzzle is analyzed along a single perspective, thus trying to answer a single question. Either "what is the dark matter?", focusing on its microscopic nature, or "how is dark matter distributed in the universe?" focusing on the large scale structure of the universe, or still "how does it affect what we observe in the sky?". Both my scientific interests and some random fluctuations at the beginning of my career have conspired so that I would take on projects in all these fields.
Leaving aside the ambition -- and the impossible task -- to be comprehensive, I will review some interesting aspects of these fields and some of my contributions, ranging from using astrophysical cross-correlations to put constraints on the neutrino masses, to the interplay between Higgs searches at colliders and dark matter experiments, to using gamma ray observations to detect and measure properties of extra dimensions.

Dark Matter under different angles



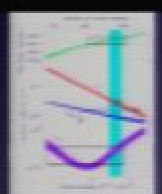


Alberto Vallinotto
Fermilab

Evidence for dark matter

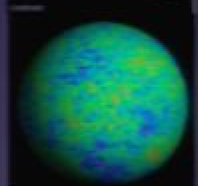
Cluster Dynamics

Galaxies' Rotation Curves



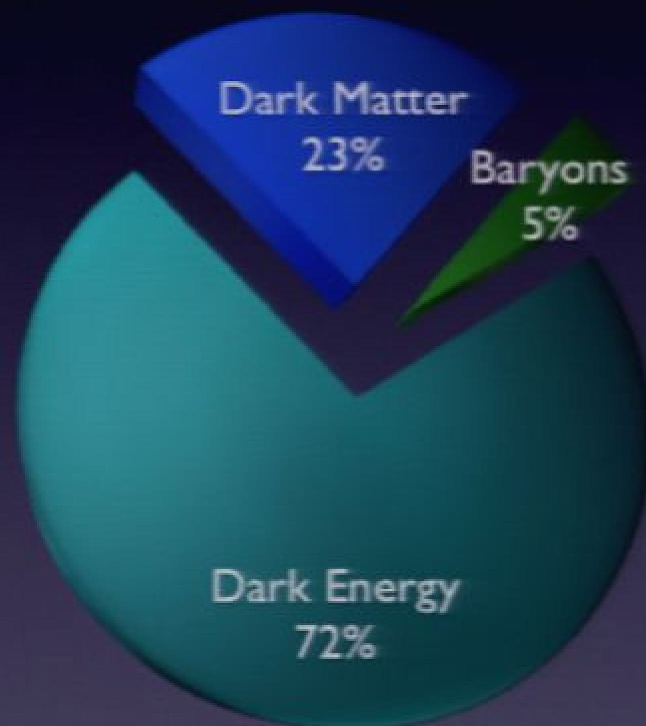
Big Bang Nucleosynthesis

Gravitational Lensing



Cosmic Microwave Background

Bullet cluster



Different questions, different fields

- What is dark matter?
- How was dark matter distributed "initially"?
- How is dark matter distributed "now"?
  - How does it affect what we observe?

Different questions, different fields

- What is dark matter? → Particle astrophysics

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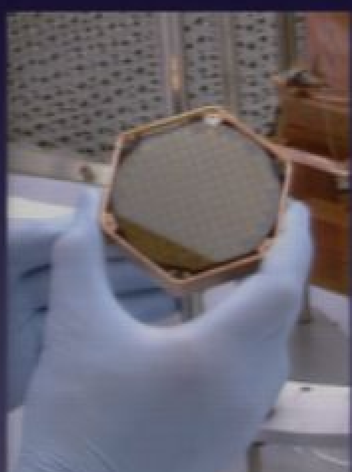
Complementary Experimental Techniques

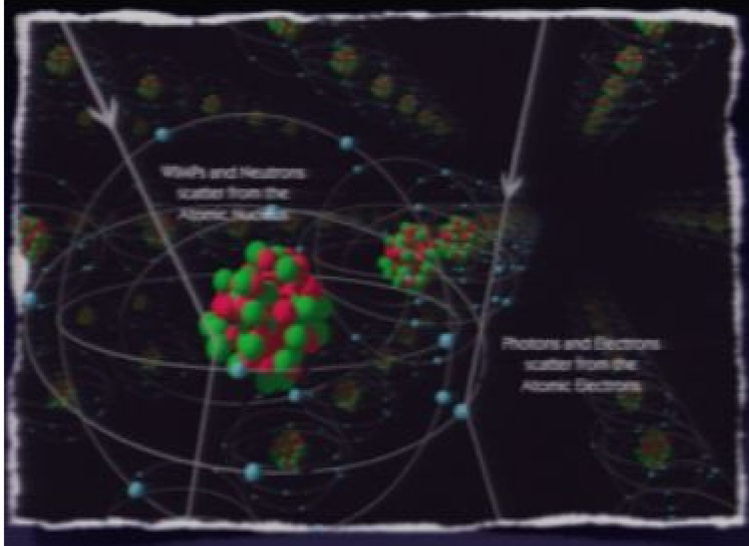
Indirect Detection

Collider Searches



Direct Detection

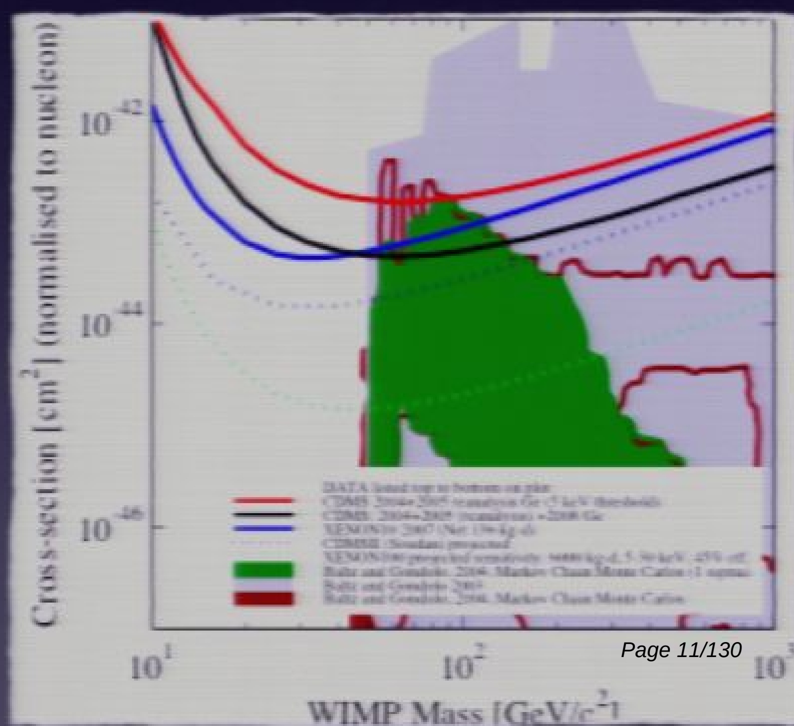
Experimental Techniques: Direct Detection



Idea: to measure the recoil energy of a wimp-nucleus collision

Potential problems:

- Backgrounds
- Very low interaction rates
- Large volume and costs



Experimental Techniques: Indirect Detection

Idea: to detect products of dark matter annihilation

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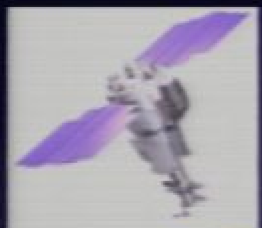
Electron/ Positions



Antiprotons

Gamma's

Neutrinos

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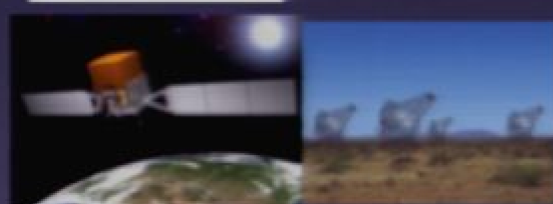

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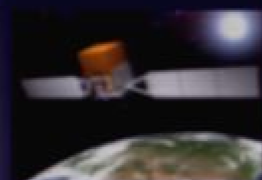


Antiprotons

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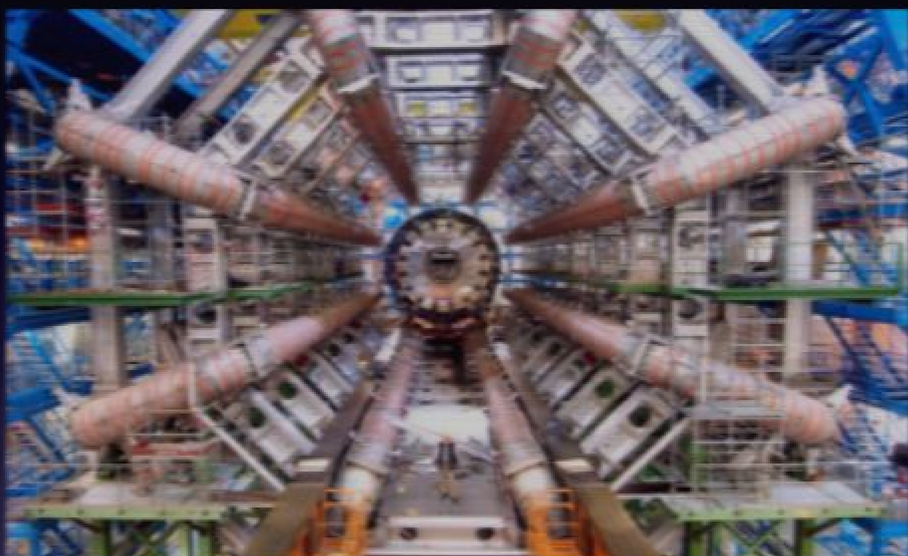
Drawbacks: astrophysical uncertainties

- Injection spectrum
- Propagation

Experimental Techniques: Collider Searches



Idea: colliders (will) probe extensions the standard model.
In principle can shed light on the nature of dark matter.

Model building

From theory to the data

- Build an extension of the SM with a DM candidate and check that it does not violate any of the constrains from the data.
- Possibly, predict new observational signatures.

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- Popular lately, thanks to the massive increase in data available mostly from indirect detection and colliders (near future).

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Cosmological constraints

Whenever a model for dark matter is built, the candidate should be

weakly interacting

(meta)stable

cold, massive, slow

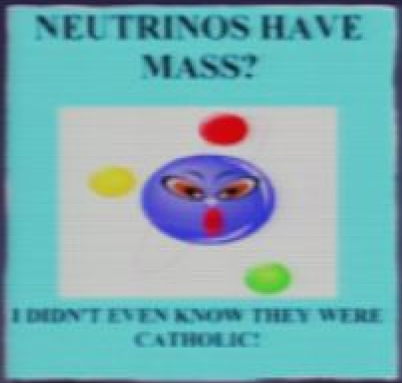
neutral

consistent with BBN

First candidates

Baryons (Machos)

Neutrinos (non-sterile)



First candidates

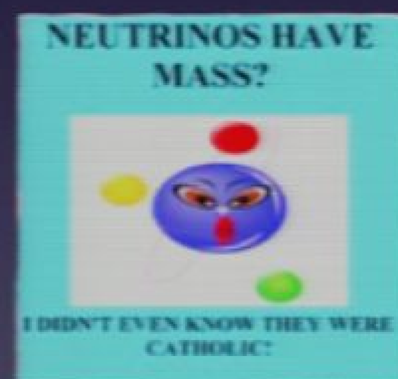
FAIL

Large fractions of baryonic dark matter is inconsistent with BBN, CMB, BAO and microlensing

FAIL

sterile)

Massive neutrinos
(a few eV or more)
erase structure on small scales



Many candidates for one job

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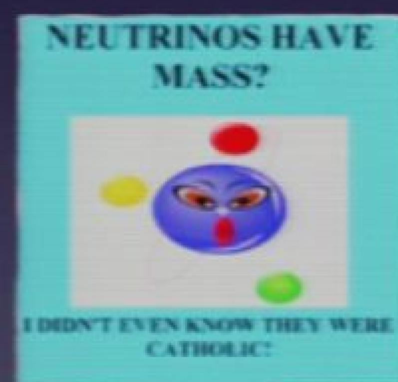


Many candidates for one job

From theory to the data: the Wimp forest

Example: the *Wimp Forest* or "Spectroscopy of Extra Dimensions"

Kaluza-Klein theories naturally provide a dark matter candidate, the Lightest Kaluza-Klein Particle (LKP), that

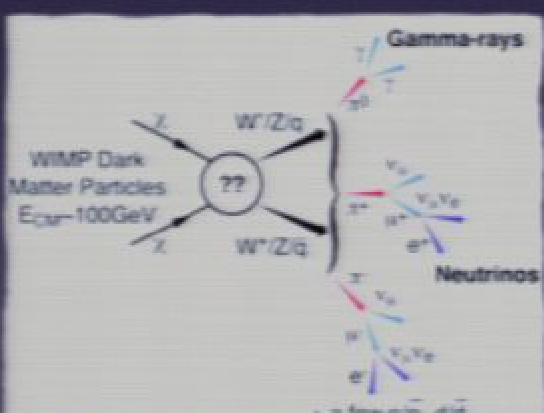
- ✓ does not overclose the universe
- ✓ is stable
- ✓ is cold and massive (~100 GeV)
- ✓ is neutral
- ✓ does not screw up BBN

[Bertone, Jackson, Shaughnessy, Tait, AV, 2009]

Indirect detection of γ's: continuum + lines

Continuum spectrum

- Secondary γ's from quark or gauge boson fragmentation, or
- from final state radiation from charged leptons.
- Almost featureless but with sharp cutoff at wimp mass.

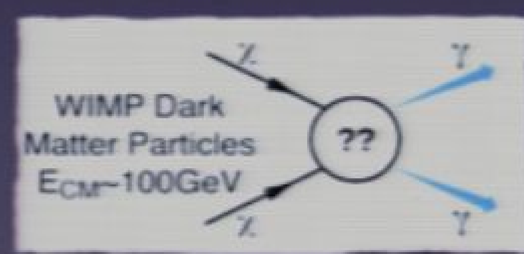


Lines

- Loop-induced processes give γ+X
- Spectral lines at

$$E_\gamma = m_{\rm DM}\left(1 - \frac{M_X^2}{4m_{\rm DM}^2}\right)$$

- Smoking gun signature of dark matter



The Kaluza-Klein Zoo

5D KK model

- UED compactified on a circle
- KK modes identified by one index, i.e. $B^{(i)}$
- LKP is the KK partner of the hypercharge gauge boson $B^{(1)}$
- ✓ LKP is lepton-friendly (good for Pamela)
- LKP mass can reach 1TeV

References: Bertone et al. (PRD 2003),
Bergstrom et al. (PRL, 2004),
Bergstrom et al. (JCAP 2004).

6D KK (Chiral Square)

- UED compactified on a square with two adjacent sides identified

$$(y,0) \equiv (0,y) \qquad (y,L) \equiv (L,y)$$

- KK modes identified by 2 indeces, i.e. $B^{(i,j)}$
- LKP's are the two KK partner of hypercharge gauge boson

$$B^{(1,0)}, \quad B^{(0,1)}$$

- LKP is lepton-unfriendly
- Favors lighter LKP (up to 450 GeV)

References: Dobrescu and Ponton (JHEP, 2004),
Dobrescu et al. (JCAP, 2007)

The Kaluza-Klein Zoo

5D KK model

- Particles are even (odd) if i is even (odd)
- Particle masses are

$$M^2_{(j)} = M^2_0 + \pi \frac{j^2}{L^2}$$

- LKP's can only pair-annihilate into SM particles

6D KK (Chiral Square)

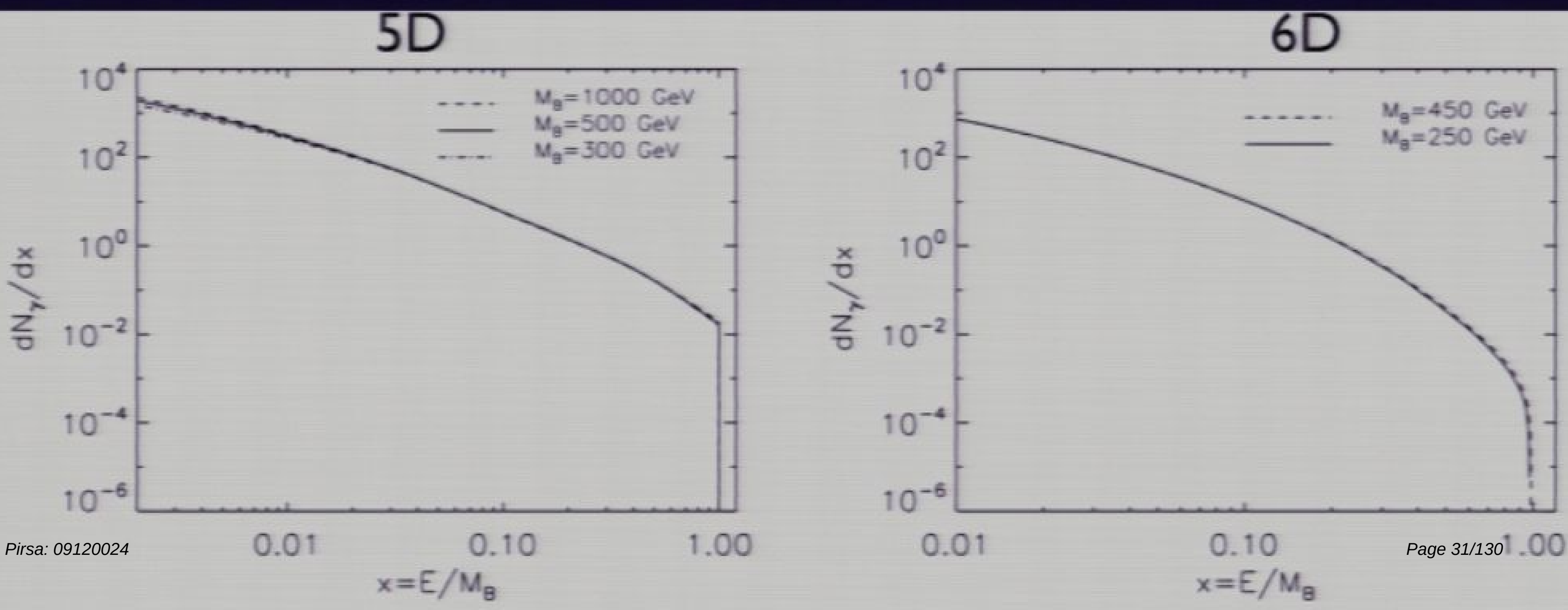
- Particles are even (odd) if (i+j) is even (odd)
- Particle masses are

$$M^2_{(j,k)} = M^2_0 + \pi^2 \frac{j^2 + k^2}{L^2}$$

- In models with 2 or more UED the LKP is kinematically allowed to pair-annihilate into other KK-particles and γ.
- These lines are well separated from the γγ and Zγ lines and potentially carry a wealth of information.
- "Spectroscopy of UED" if the x-section and continuum are favorable.

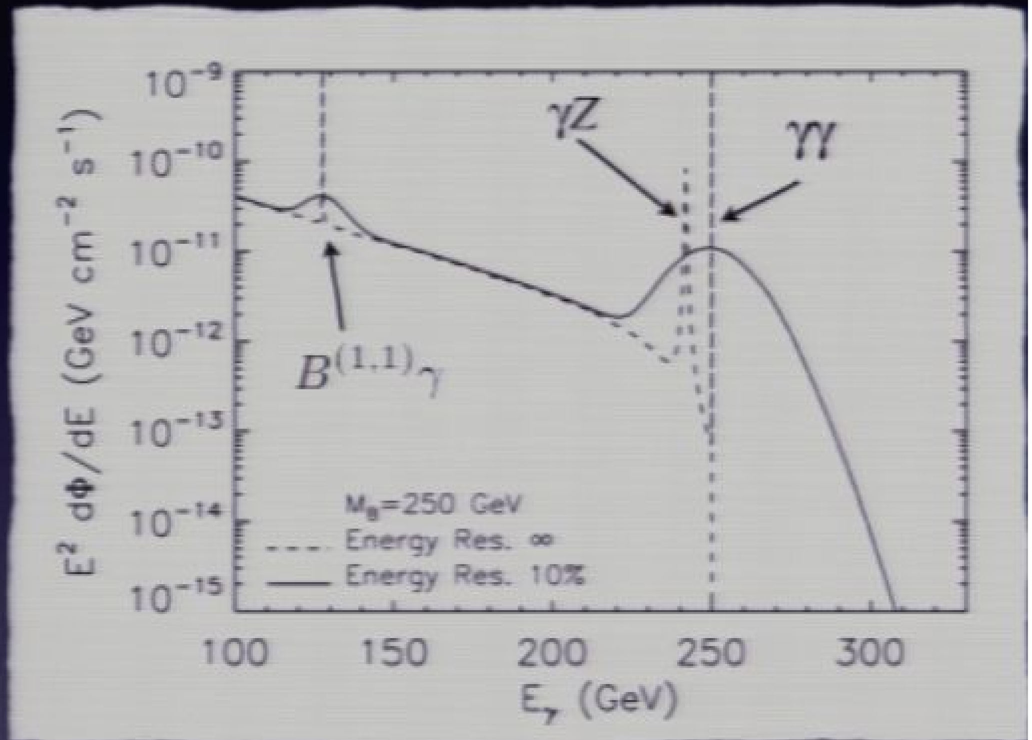
Continuum Spectrum

- Chiral square case characterized by pair-annihilation into W's (~50%), H's (~25%) and Z's (~25%), which then decay.
- Spectrum of secondary photons (from FSR and π^0 decays) is softer than in the 5D (lepton-friendly) case. The latter often quoted for PAMELA.
- Calculation carried out with MicrOmegas.



The Chiral Square Spectrum

- Three lines and two distinctive bumps.
- 10% energy resolution is insufficient to resolve $Z\gamma$ and $\gamma\gamma$ lines.
- The $B^{(1,1)}\gamma$ bump is well separated from the other.
- Contributing factors:
  - Large x-section.
  - Large $M_{B(1,1)}$
  - Small continuum.



[Bertone, Jackson, Shaughnessy, Tait, AV, PRD 80, 023512 (2009)]

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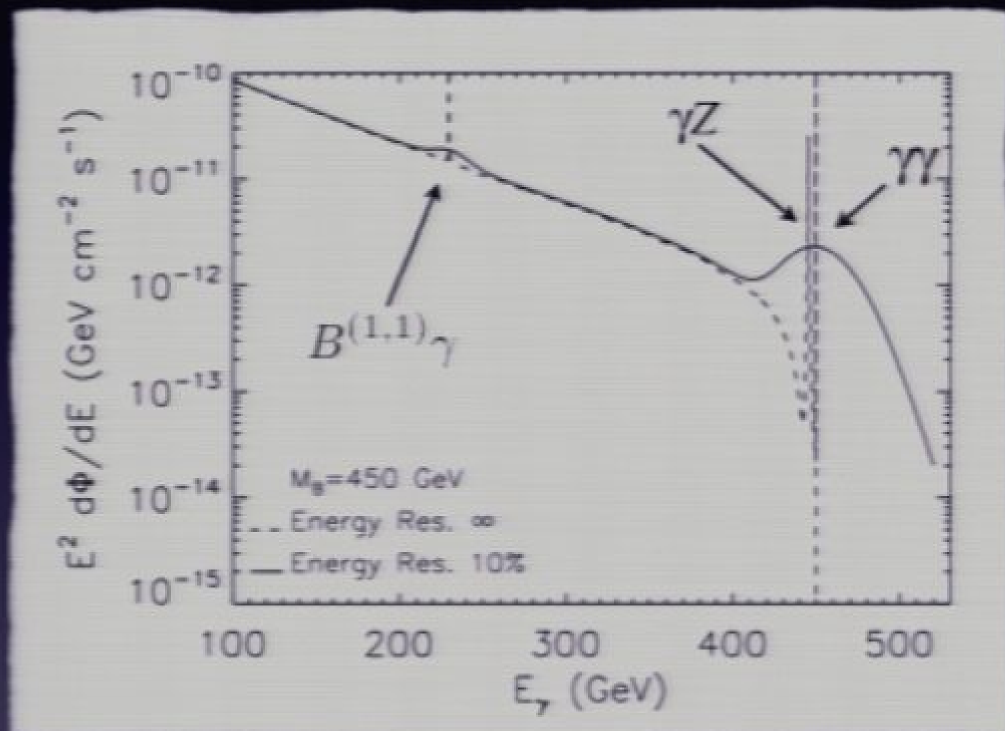

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The 5D KK Spectrum

- Three lines but only one bump.
- 10% energy resolution is insufficient to resolve $Z\gamma$ and $\gamma\gamma$ lines and kills the $H\gamma$ one.
- Contributing factors:
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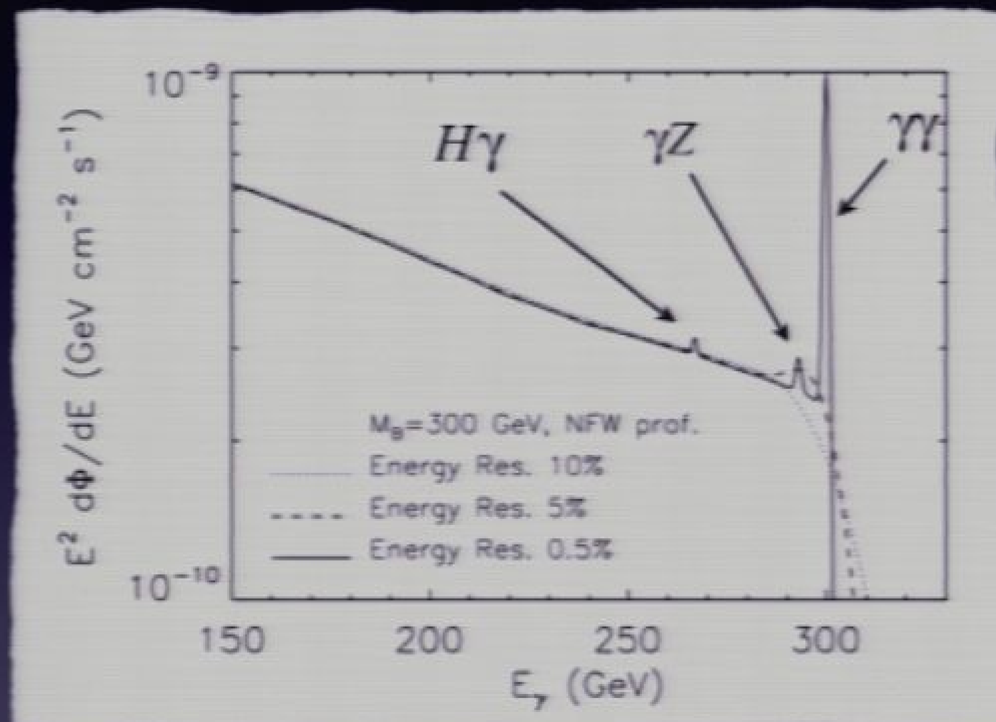
  - Higgs mass smaller than $M_{B(1,1)}$
  - Large continuum.



[Bertone, Jackson, Shaughnessy, Tait, AV, *in prep.*]

Bottom Line

- KK extensions of the SM with more than one extra dimension exhibit one or more extra lines, well separated from $\gamma\gamma$.
- This "forest" of lines may be detectable with the right combination of xsection and continuum and can potentially provide a lot of information.
- However, this is not the only model characterized by a two bump feature.
- Detection of a single bump and no drop off could also hint toward a Wimp forest scenario.

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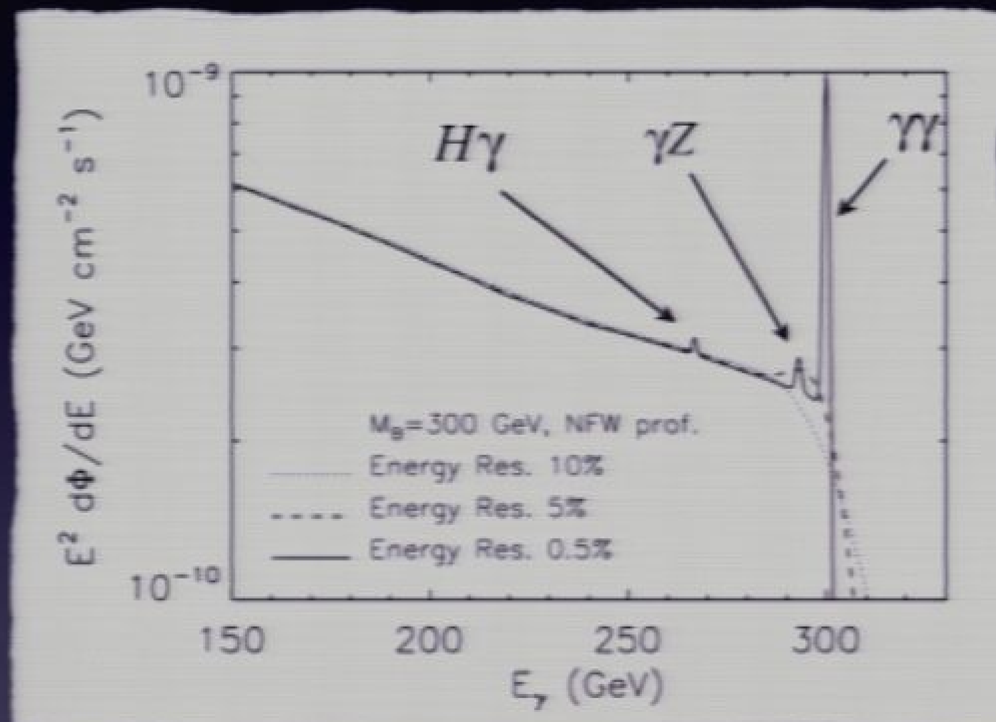

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From the data to theory: the interplay of different experimental techniques

The *interplay* between different experimental techniques

Whenever the standard model lagrangian is *extended* to include a dark matter candidate...

Indirect Detection

Direct Detection

Collider searches

Theoretical *predictions* are not independent

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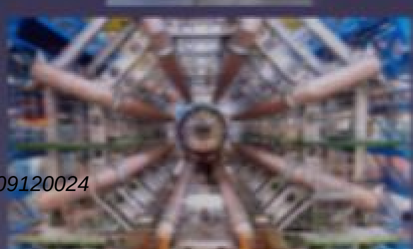

Collider searches

Multimessenger approach

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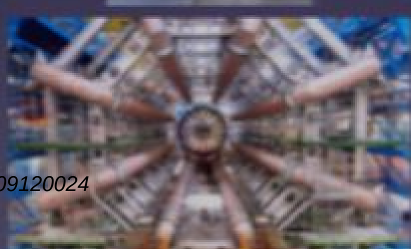

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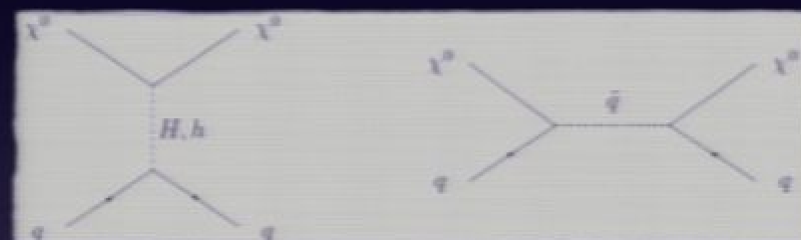

Same processes contribute to both: the results are expected to be correlated

Neutralinos

- Supersymmetry relates fermions and bosons

$$Q|\text{fermion}\rangle = |\text{boson}\rangle \qquad Q|\text{boson}\rangle = |\text{fermion}\rangle$$

- It introduces R parity. The corresponding (multiplicative) quantum number is conserved.

$$R = (-1)^{3B+L+2S}$$

- As a consequence of R parity, the lightest supersymmetric particle (LSP) is stable.

Standard Model particles and fields		Supersymmetric partners			
		Interaction eigenstates		Mass eigenstates	
Symbol	Name	Symbol	Name	Symbol	Name
$q = d, c, b, u, s, t$	quark	$\tilde{q}_L, \tilde{q}_R$	squark	$\tilde{q}_1, \tilde{q}_2$	squark
$l = e, \mu, \tau$	lepton	$\tilde{l}_L, \tilde{l}_R$	slepton	$\tilde{l}_1, \tilde{l}_2$	slepton
$\nu = \nu_e, \nu_\mu, \nu_\tau$	neutrino	$\tilde{\nu}$	sneutrino	$\tilde{\nu}$	sneutrino
g	gluon	$\tilde{g}$	gluino	$\tilde{g}$	gluino
$W^\pm$	W-boson	$\tilde{W}^\pm$	wino		
H^-	Higgs boson	$\tilde{H}_1^-$	higgsino	$\tilde{\chi}_{1,2}^\pm$	chargino
H^+	Higgs boson	$\tilde{H}_2^+$	higgsino		
B	B-field	$\tilde{B}$	bino		
W^3	W^3-field	$\tilde{W}^3$	wino		
H_1^0	Higgs boson			$\tilde{\chi}_{1,2,3,4}^0$	neutralino
H_2^0	Higgs boson	$\tilde{H}_1^0$	higgsino		
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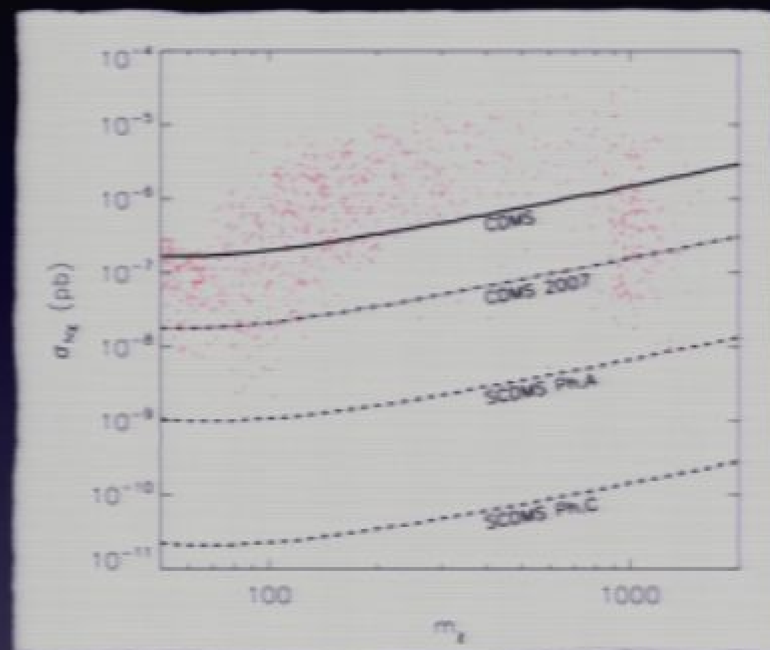
B	B-field	$\tilde{B}$	bino		
W^3	W^3-field	$\tilde{W}^3$	wino		
H_1^0	Higgs boson			$\tilde{\chi}_{1,2,3,4}^0$	neutralino
H_2^0	Higgs boson	$\tilde{H}_1^0$	higgsino		
H_3^0	Higgs boson	$\tilde{H}_2^0$	higgsino		

Charged

Ruled out by direct detection

The interplay between direct detection and colliders

- Assume the MSSM as the extension of the standard model.
- Consider a *specific* channel for a collider experiment.
- What are the prospects for one class of experiments given the results of the other?



Models consistent with Wmap relic density and within Tevatron reach for 3σ discovery of Higgs Boson in the channel

$$p\bar{p} \to A/H + X \to \tau^+\tau^- + X$$

[Carena, Hooper, AV, PRD 75, 055010 (2007)]

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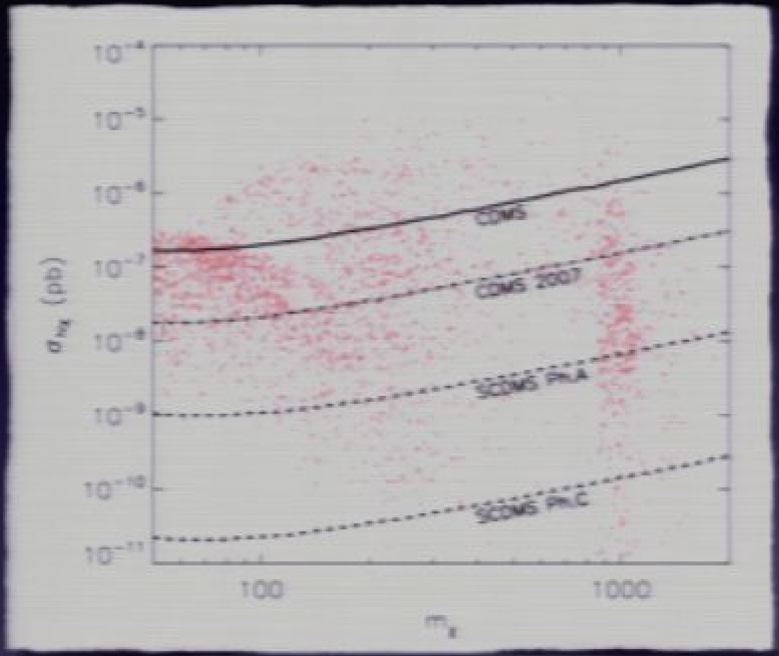

Models consistent with Wmap relic density and within LHC reach for 3σ discovery of Higgs Boson in the channel

$$pp \rightarrow A/H + X \rightarrow \tau^+\tau^- + X$$

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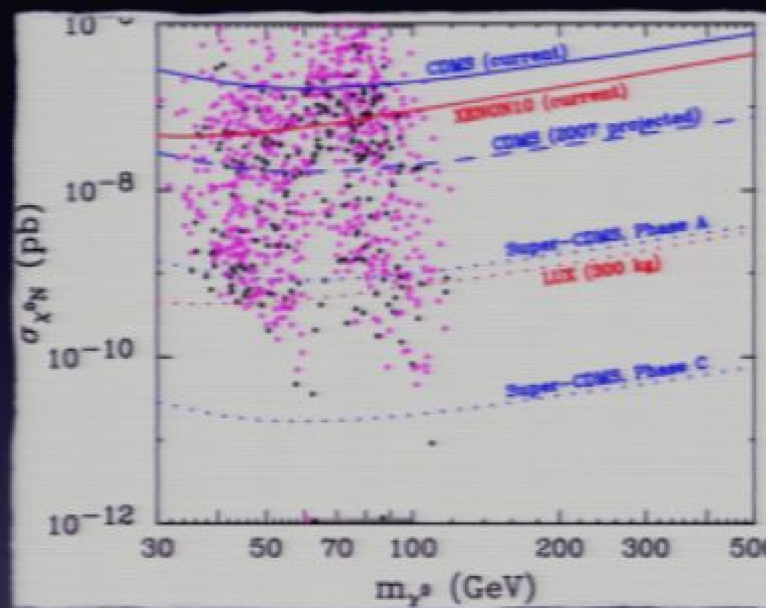


Models within 8fb Tevatron reach for 3σ discovery of chargino in the trilepton channel

$$q\bar{q} \rightarrow \tilde{\chi}_2^0 + \tilde{\chi}_1^{\pm} \rightarrow 2l + \bar{l} + 2\tilde{\chi}_1^0 + \nu_l$$

[Hooper, Plehn, AV, PRD 75, 055010 (2007)]

Bottom Line

- These projects were a nice "warm up"...
- ... but to efficiently constrain the MSSM parameter space using all available data, MCMC are the best tool (cfr *Sfitter*).
- The amount of experimental data becoming available makes these the most exciting times for particle astrophysics.
- A neat example: dark matter satellites.

Structure, dark matter and indirect detection

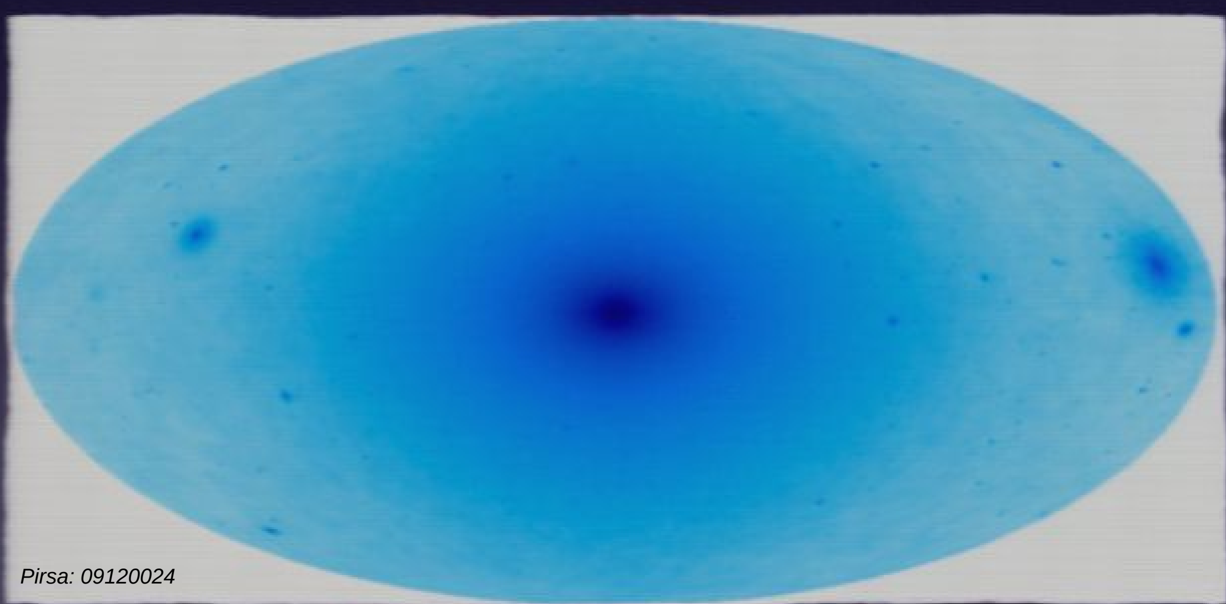
The issue of missing subhalos/ dark matter clumps is the point of contact between the particle astrophysics and the structure formation perspectives on dark matter.

- Subhalos are predicted by numerical simulation.
- Not as many as the one predicted have been observed.

[Diemand et al., 2008]

Structure, dark matter and indirect detection

- Subhalos are elusive and tricky to detect (high M/L ratio): it's a tough life to be a wimp clump seeking attention...
- Given a reasonable cross section for DM annihilation, they should become visible in the γ-ray sky.



Map of ρ^2 integrated along the line-of-sight, no Sommerfeld enhancement.

[Kuhlen et al. 2008]

Different questions, different fields

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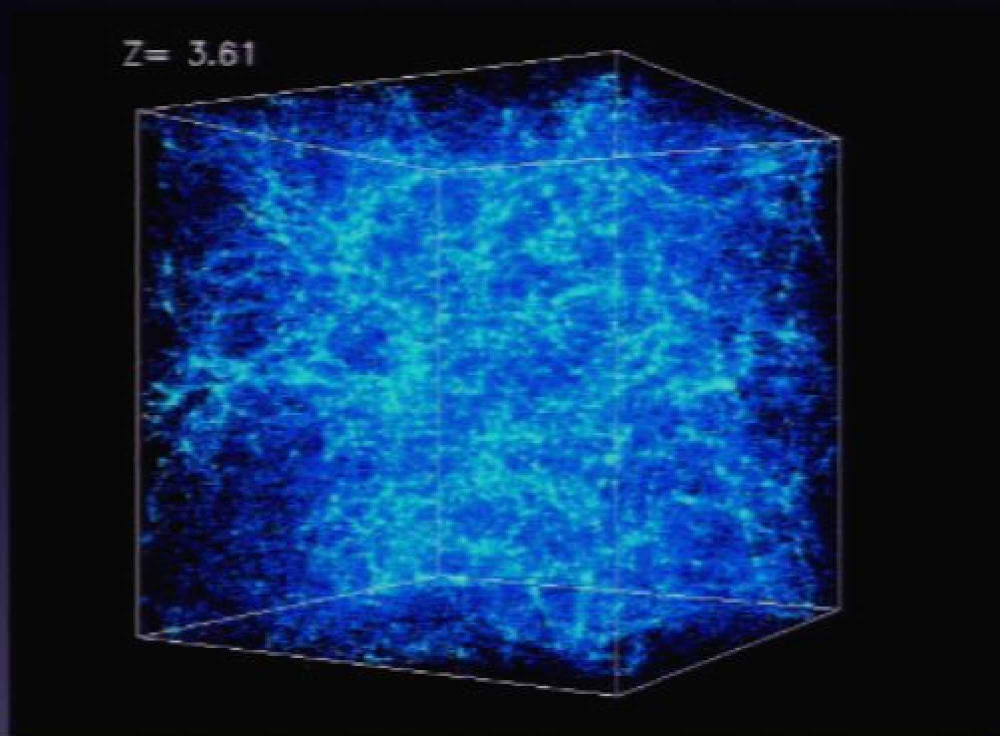
Dark matter, large scales

- Structure forms through gravitational collapse...
- ... starting from initial conditions consistent with CMB.



[Kravtsov, 2005]

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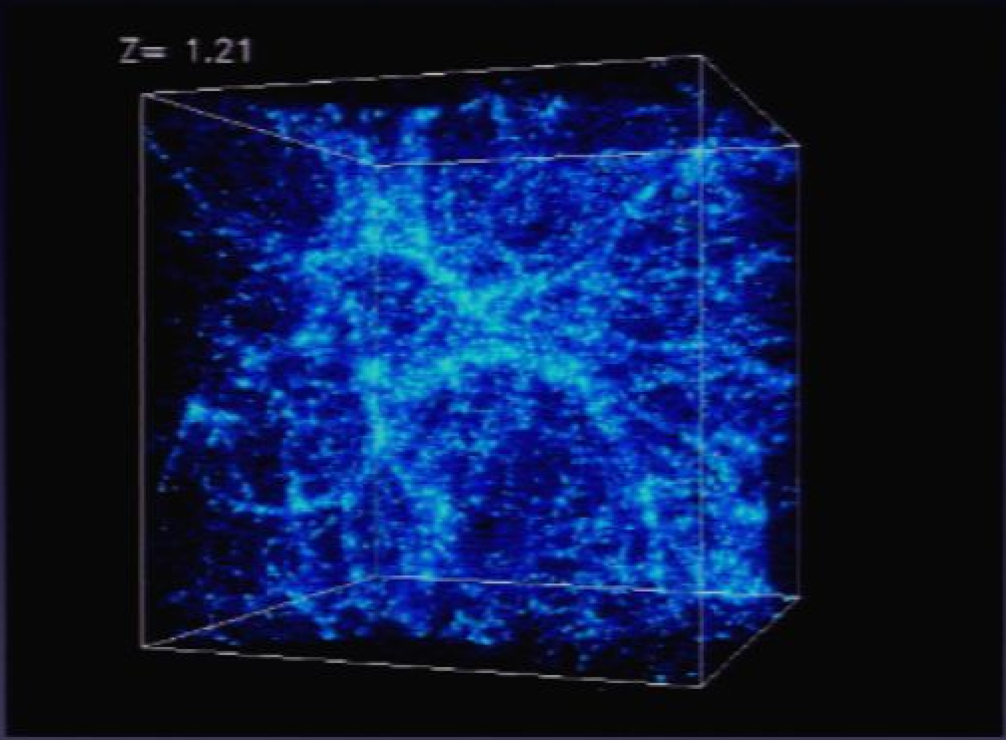

[Kravtsov, 2005]

Dark matter, large scales

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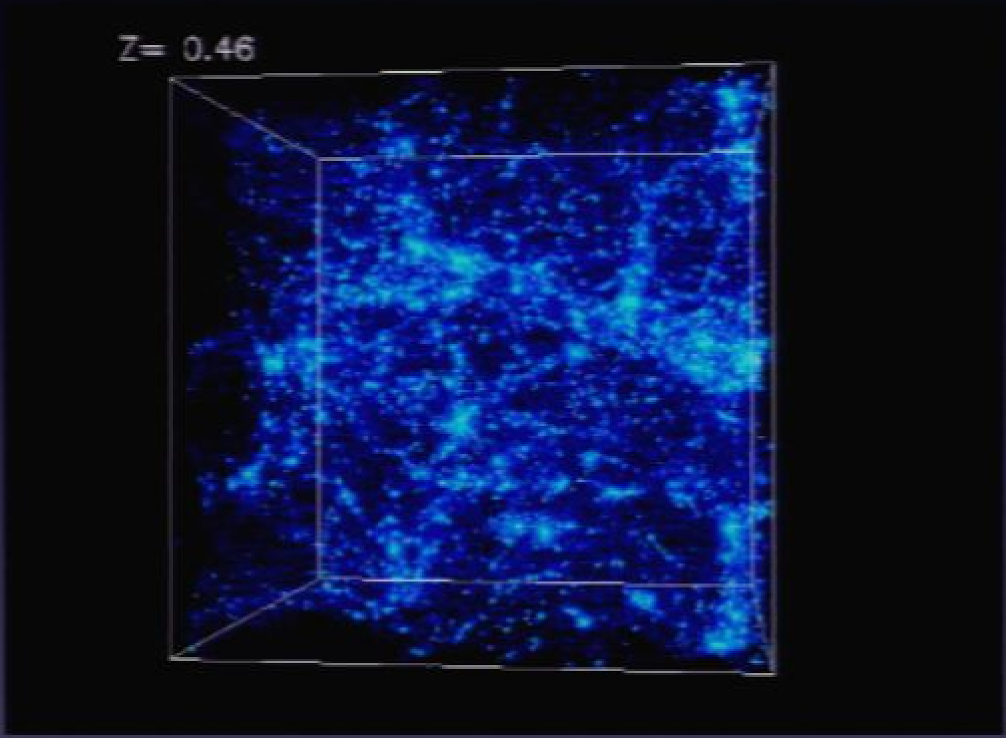

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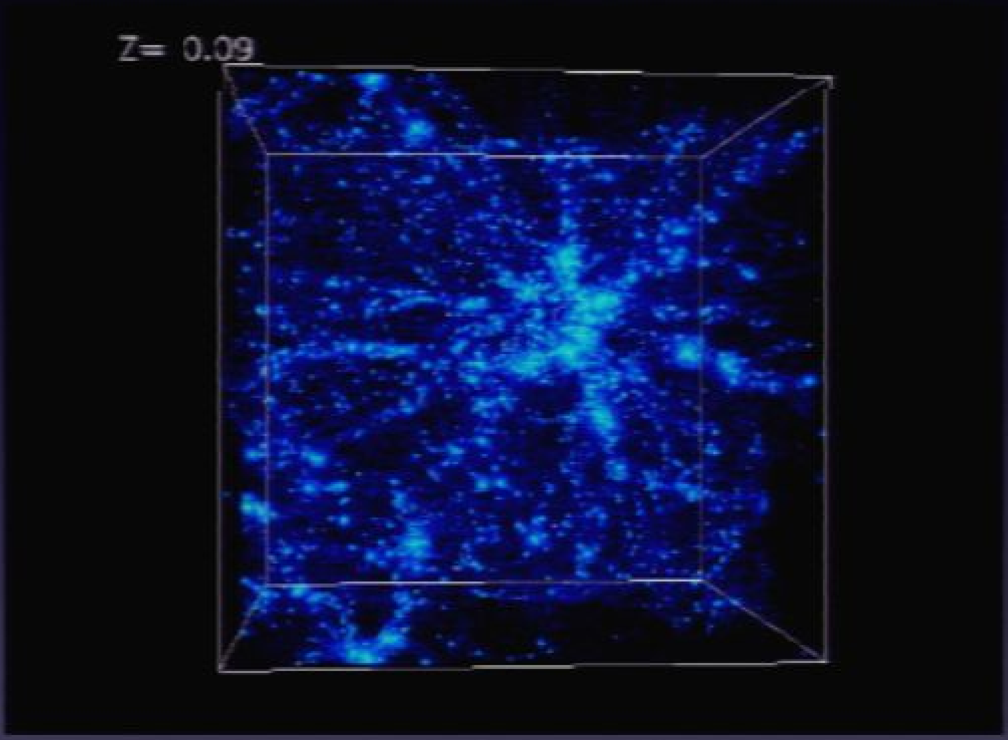

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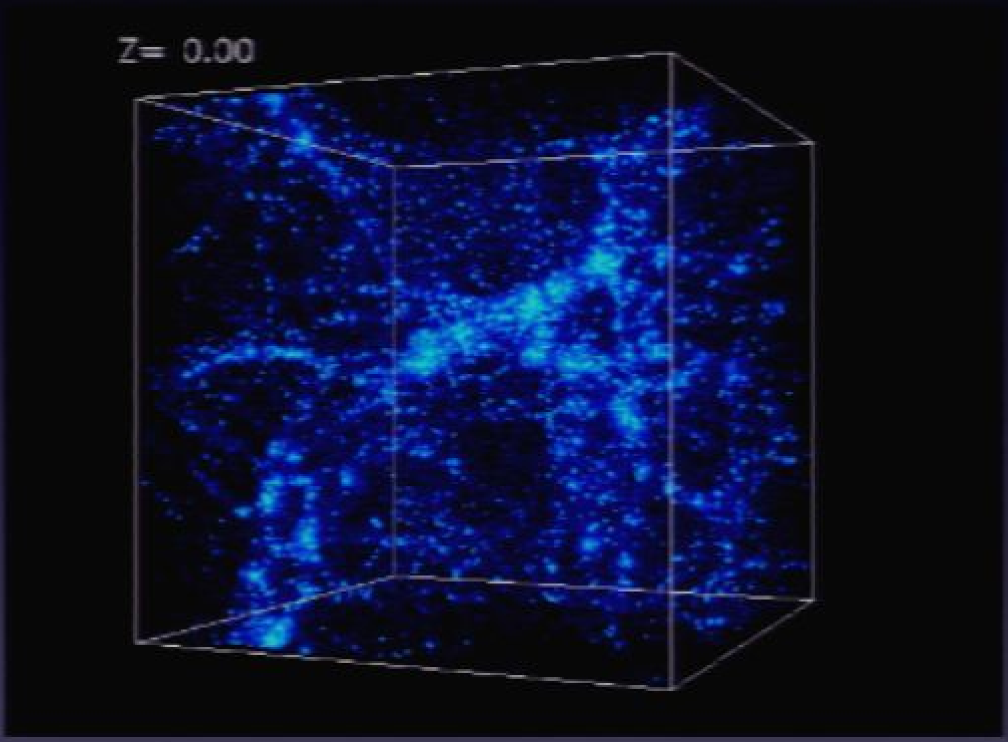
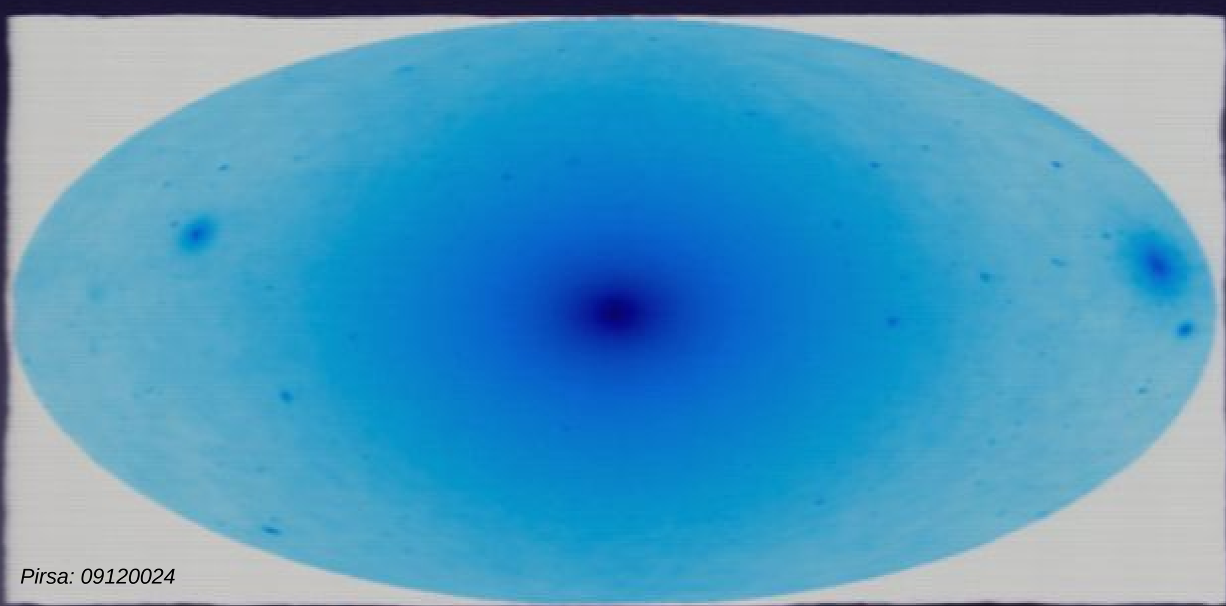


[Kravtsov, 2005]

Structure, dark matter and indirect detection

- Subhalos are elusive and tricky to detect (high M/L ratio): it's a tough life to be a wimp clump seeking attention...
- Given a reasonable cross section for DM annihilation, they should become visible in the γ-ray sky.

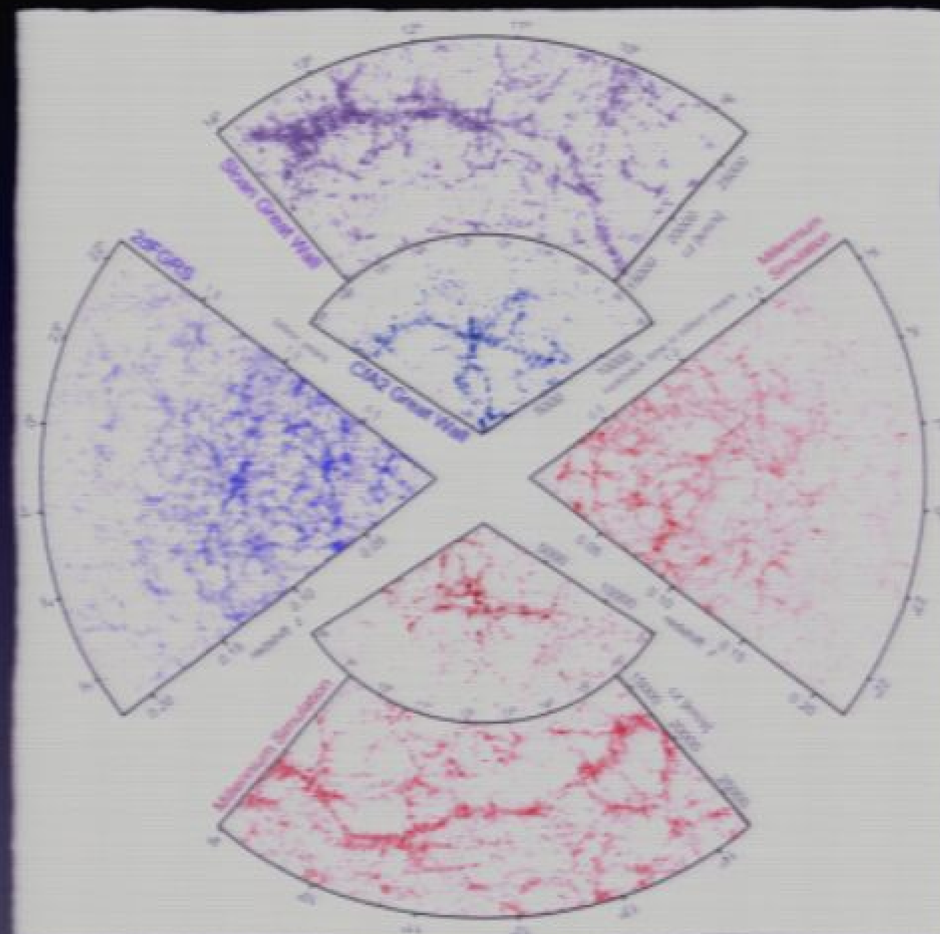


Map of ρ^2 integrated along the line-of-sight, no Sommerfeld enhancement.

[Kuhlen et al. 2008]

Dark matter, large scales

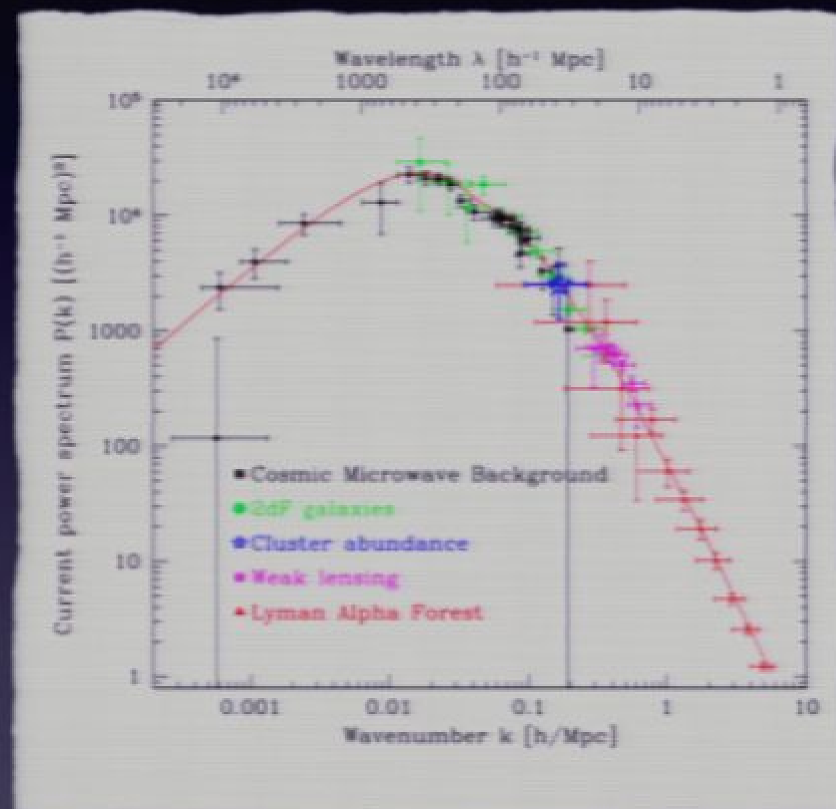
- Structure forms through gravitational collapse...
- ... starting from initial conditions consistent with CMB.
- Simulations results are consistent with observational evidence from LSS surveys on large scales.
- We look at the universe through an inhomogeneous medium.



[Springel et al., 2005]

Dark matter, large scales

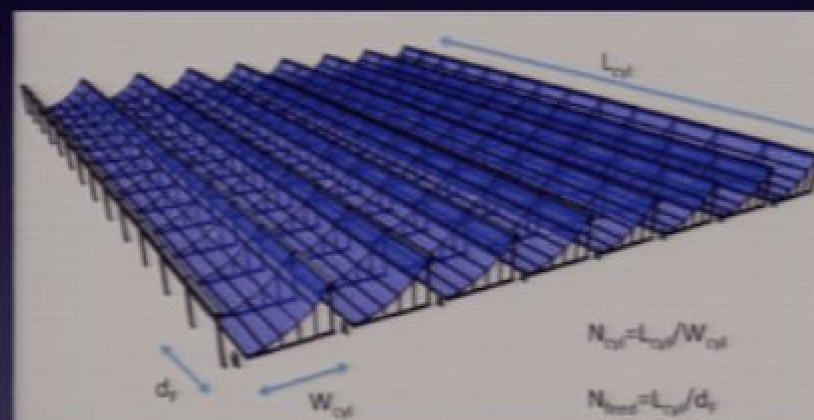
- Cosmological perturbation theory provides a theoretical framework for the prediction and the analysis of the properties of the dark matter field distribution.
- Being dark, we cannot "see" DM.
- Two ways to probe its distribution in the universe:
  - Using "tracers": intuitively, overdensities in the DM field should be matched by overdensities in other "visible" stuff
    - Galaxies, quasars and clusters
    - Neutral Hydrogen (Lyman-α, 21cm)
    - CMB temperature
  - Measuring the distorsion of images by the DM grav. field.
- Different tracers allow to probe the DM field on different scales.
- Different tracers are "biased" in different ways.



[Tegmark, 2002]

Large scales 21cm surveys

- 21-cm radiation survey at low redshift (z=0-4) using a packed rectangular CRT array should allow a low cost way to image the large scale structure of the universe.
- Cheap/competitive way to do dark energy measurements through BAO [Chang et al., 2008; Seo et al., 2009]...
- ... provided foreground subtraction is carried out correctly.



[Seo et al., 2009]

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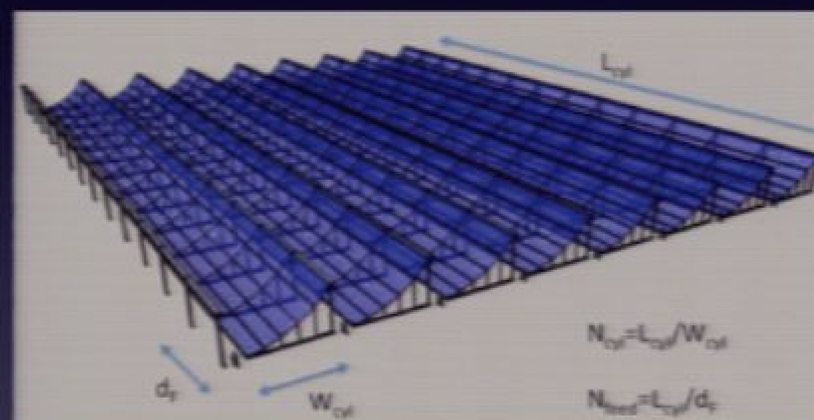
Very high future potential!

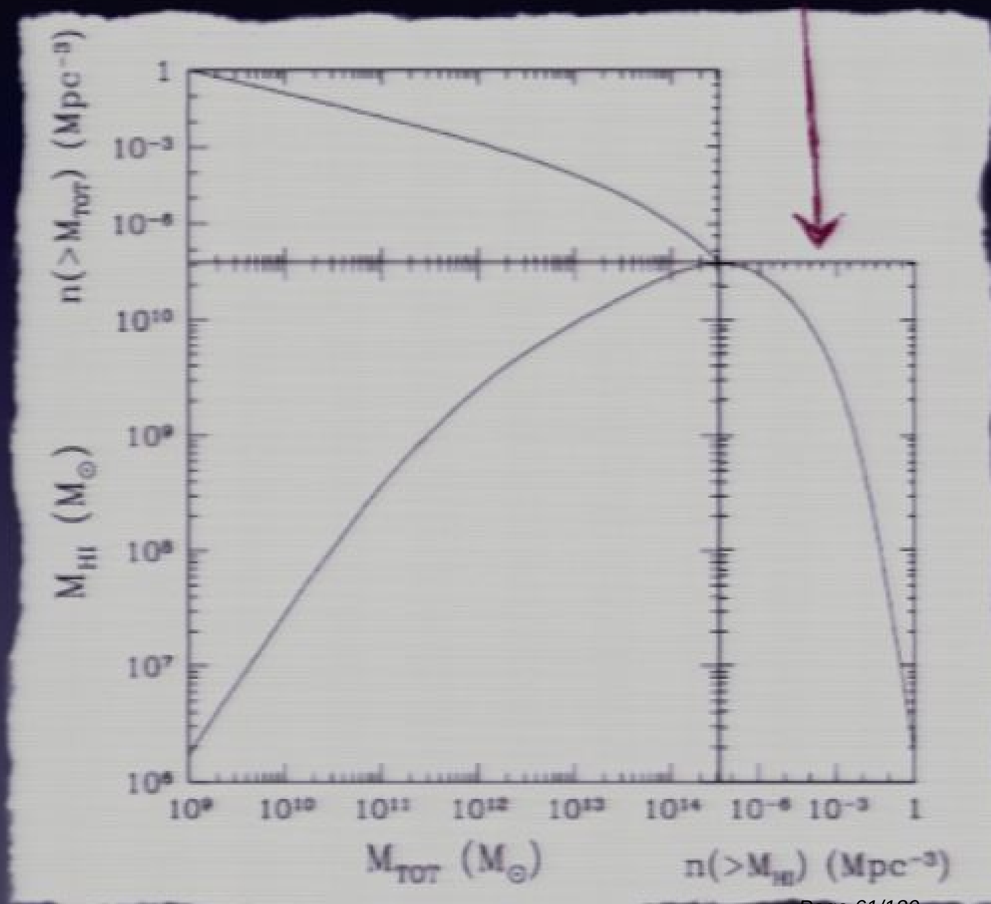


[Seo et al., 2009]

Large scales HI bias

- To carry out a 21-cm survey of LSS, it is necessary to know how well HI traces the dark matter field.
- In particular, we need to know whether the HI bias
  - evolves with redshift,
  - shows scale dependence.
- First, we build the HI mass function $M_{HI}(M_{TOT})$.

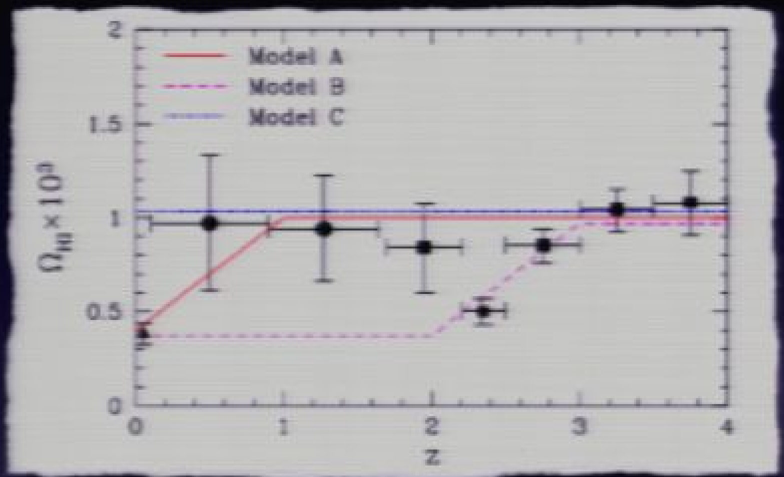
[Zwaan et al., 2005]



[Marin, Gnedin, Seo, AV, 2009]

Large scales HI bias

- Next, we need a prescription to evolve the HI mass function. We build it out of two elements.
- The (poorly measured) evolution of $\Omega_{HI}(z)$. We consider three limiting cases (A, B, C).
- Two limiting ways of assigning the total HI to halos:
  - Fix the number density (PME)
  - Fix the halo mass (PNE).



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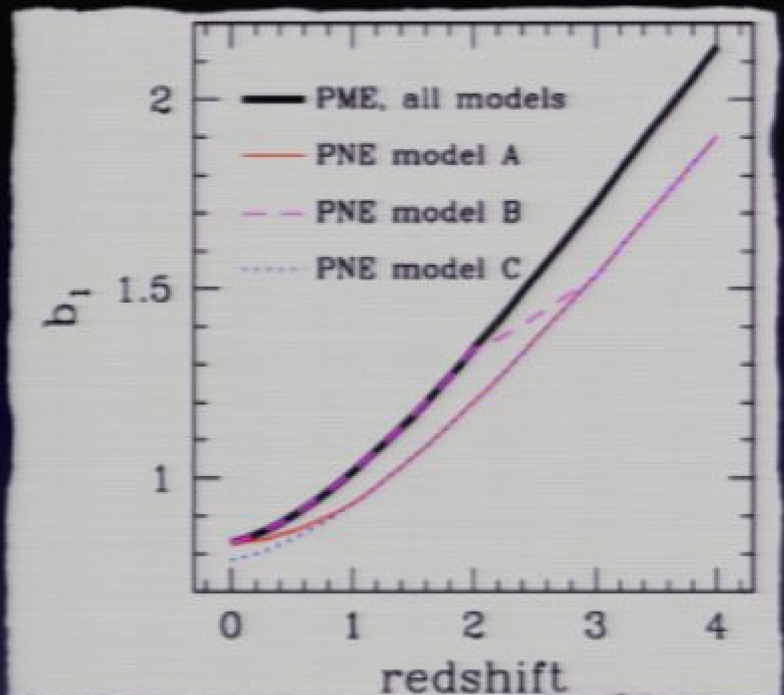

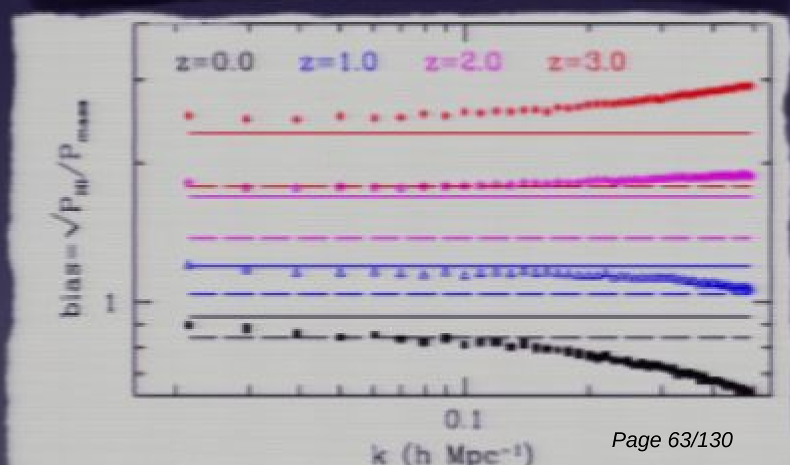

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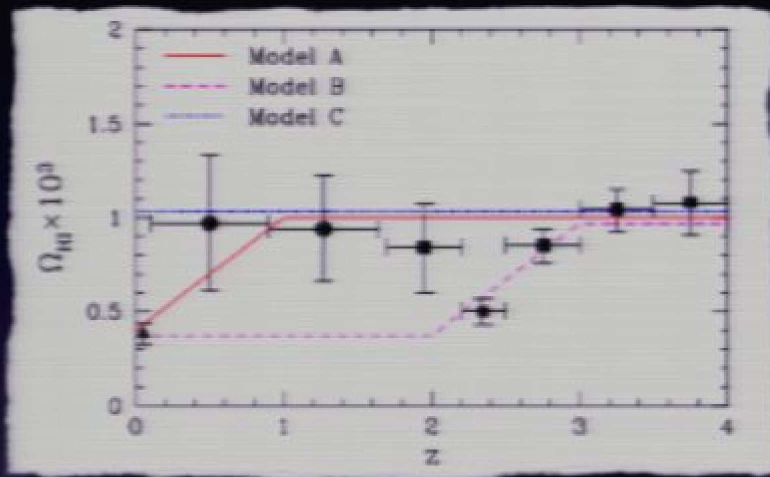

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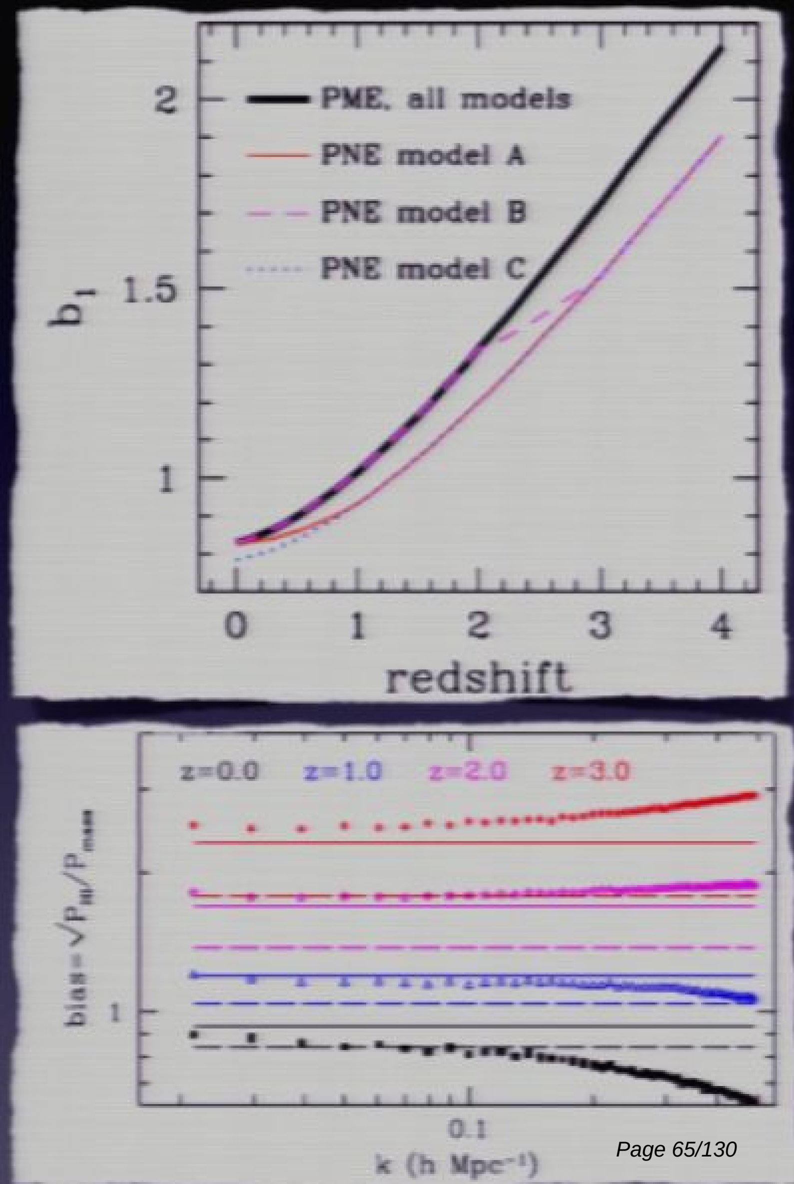


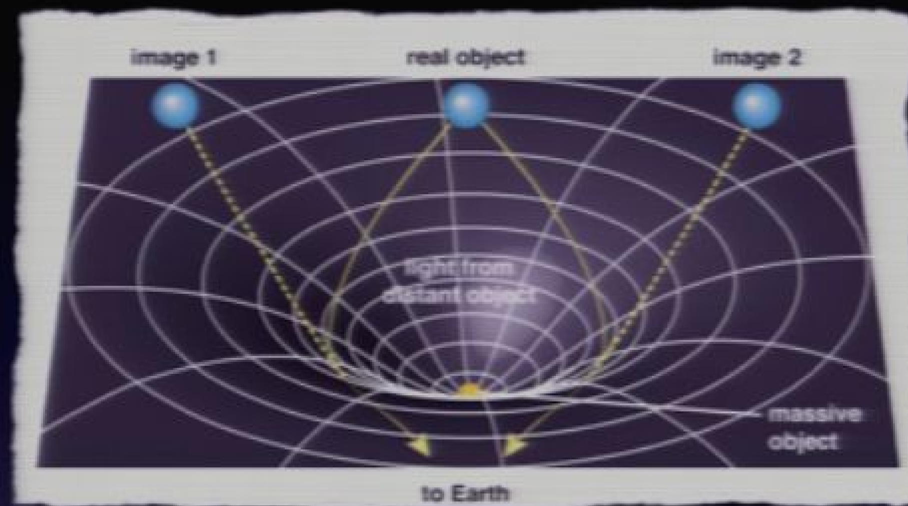
[Marin, Gnedin, Seo, AV, 2009]

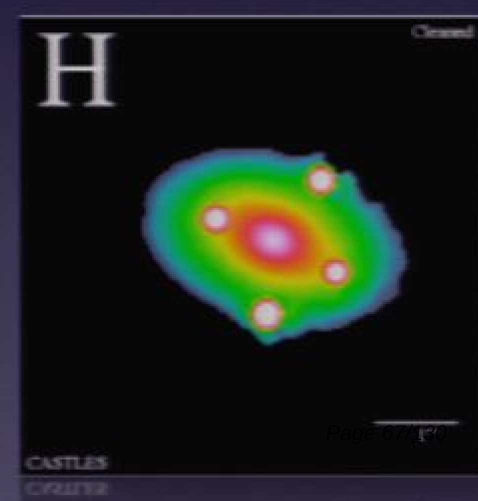
Gravitational Lensing

Looking at the sky through an inhomogeneous medium

Gravitational Lensing

- Photons travel on geodesics.
- Geodesics are determined by the distribution of matter/energy between source and observer.





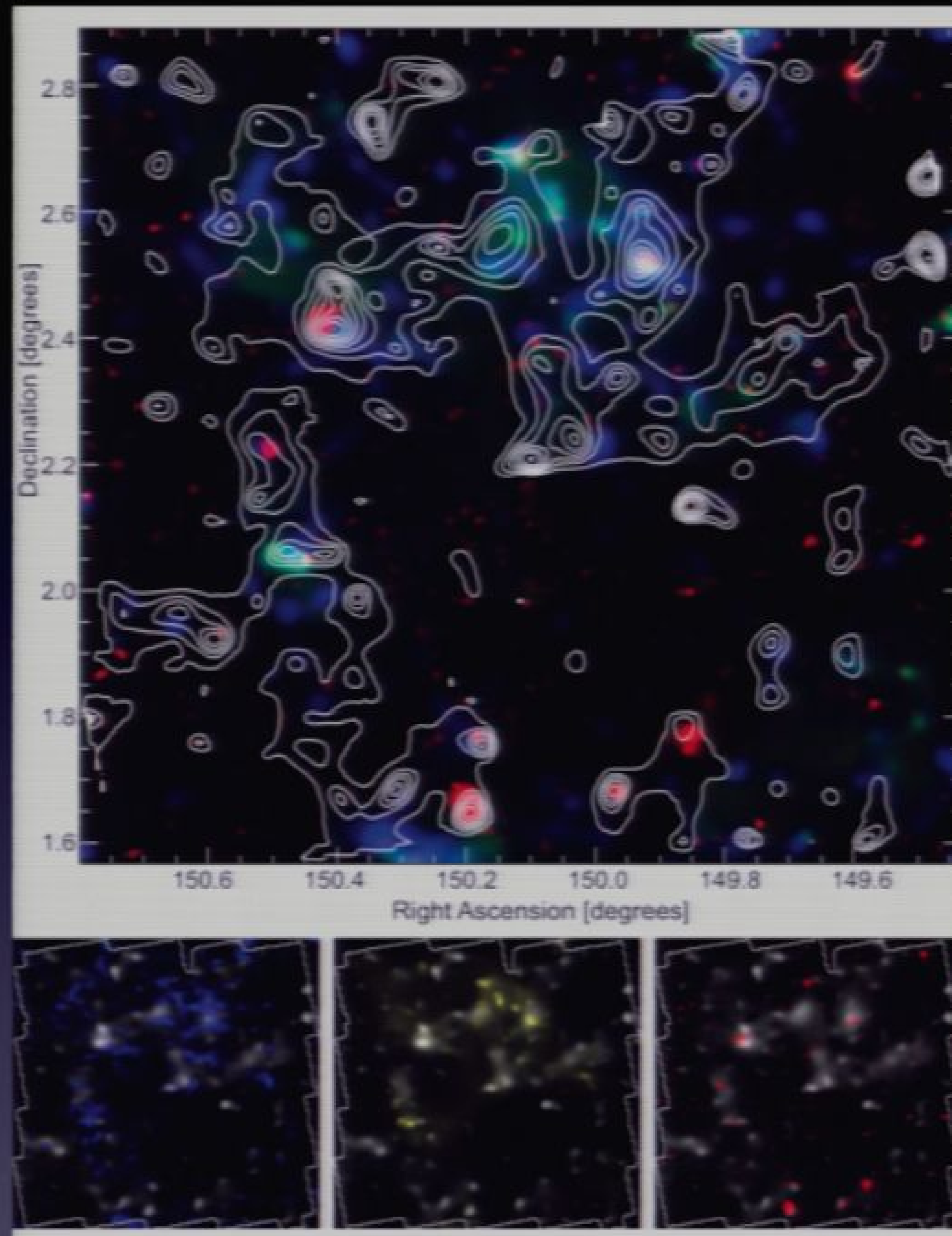
The twofold role of lensing

Lensing (de)magnifies objects' brightnesses (magnification bias) and distorts and displaces images (smoothing) → Noise

If the impact of lensing can be assessed, we can then obtain information about the intervening dark matter distribution → Information

Example

One slice of COSMOS weak lensing mass reconstruction



Stellar Mass

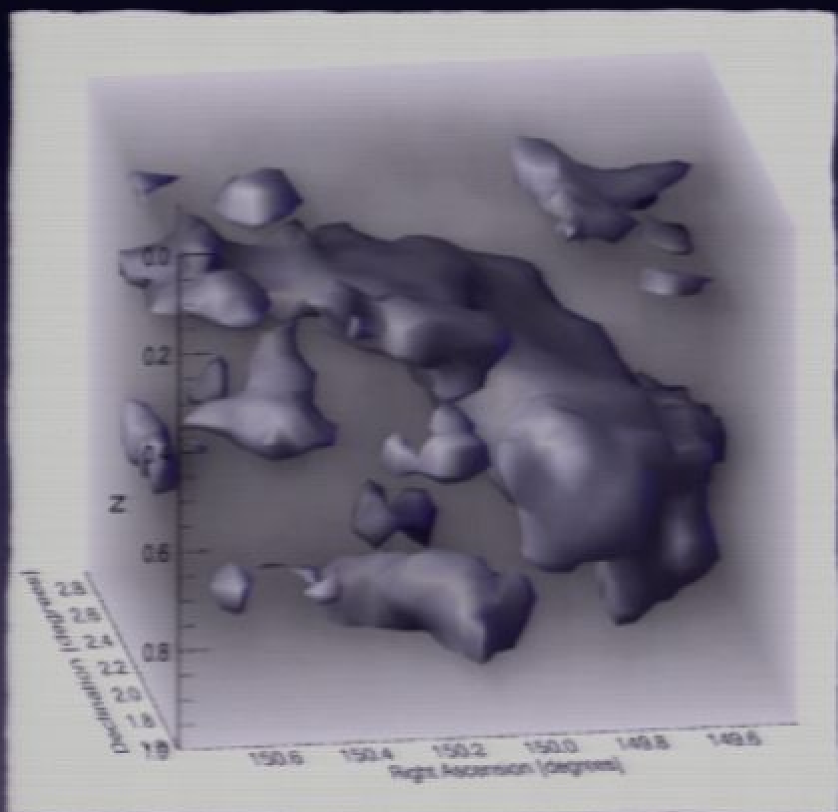
Galaxies' number density

X-ray gas

[Massey et al., 2007]

Example

Full 3D mass reconstruction
(isodensity surface)



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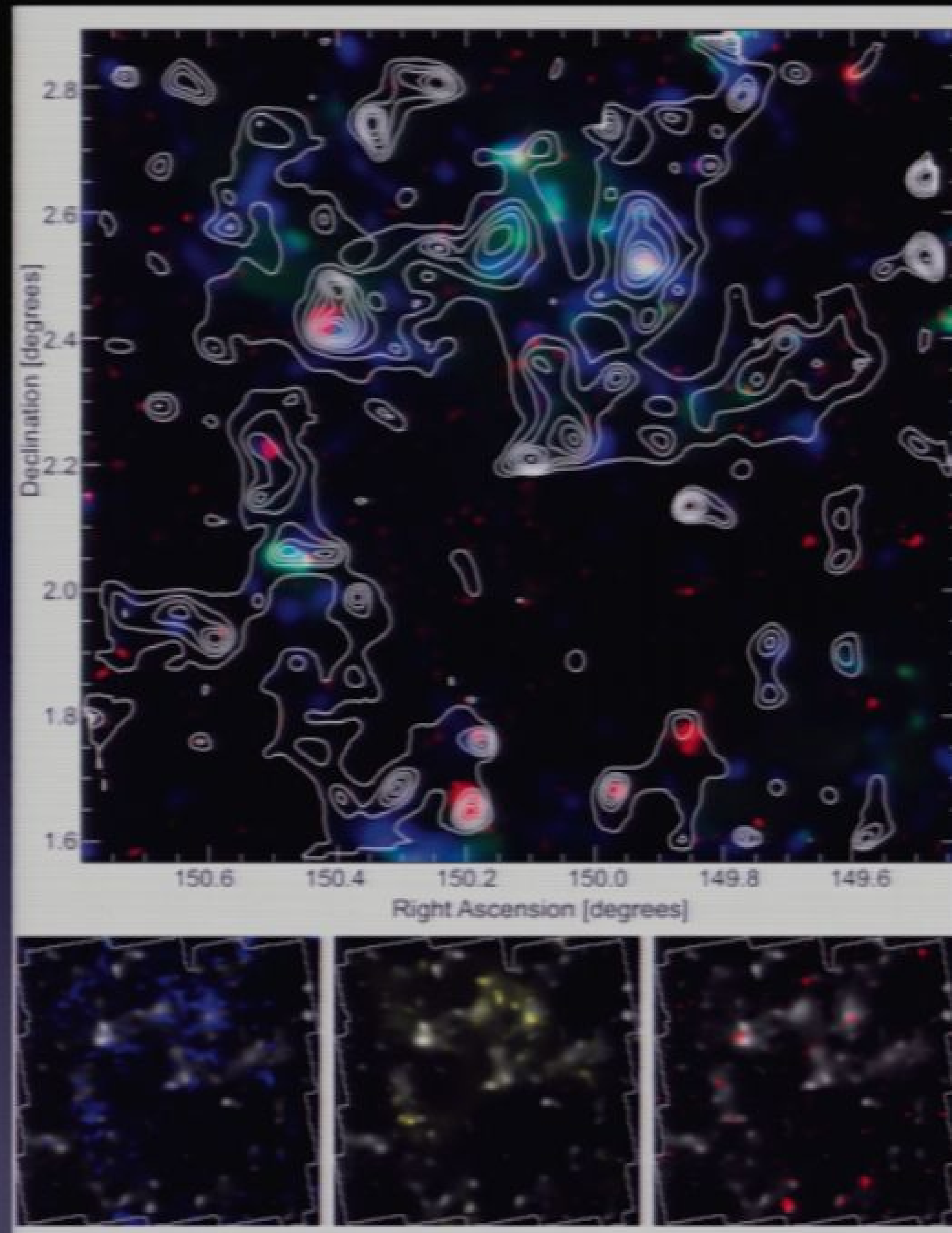

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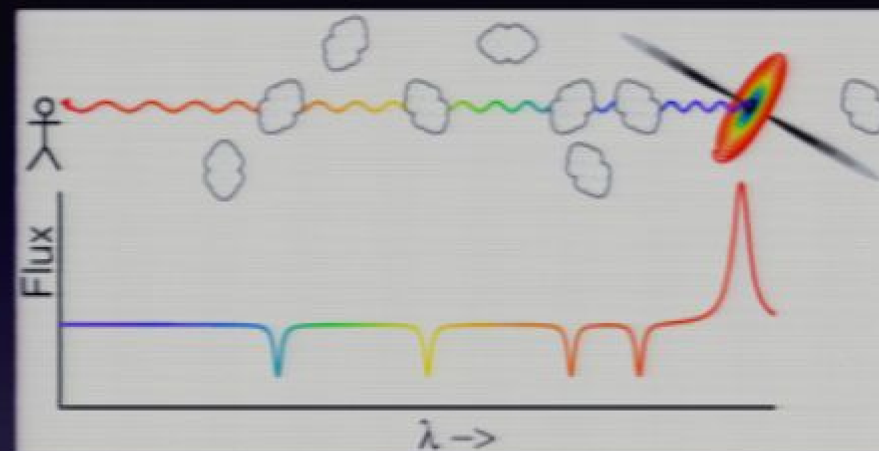
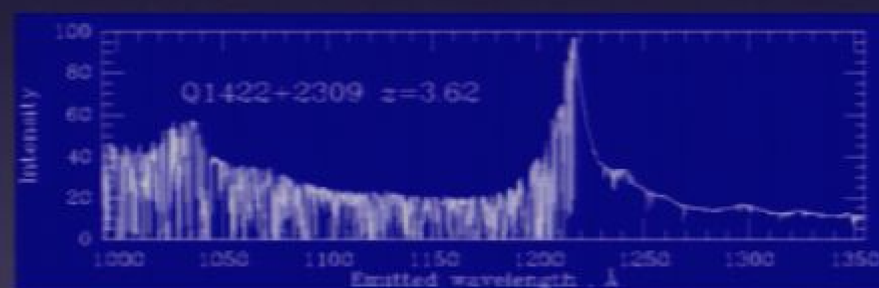
Information from weak lensing: the cross-correlation of the Lyman-α forest and CMB lensing

Lyman-α forest and CMB lensing cross-correlation

- Quasar emits light which, as it travels through the universe, is redshifted.
- Whenever light travels through a gas cloud, a fraction of it (that at the cloud's redshift has the appropriate frequency) is scattered through Lyman-α transition in neutral hydrogen.



- The quasar spectra is then characterized by a "forest" of "absorption" lines.
- The forest is a map of neutral H along the los.
- Understanding the forest requires understanding and modeling the physics of the IGM.



- Fluctuations in the flux are related to overdensities

$$\mathcal{F} = \exp\left[-A(1+\delta)^{\beta}\right]$$

- On large scales (> 1 Mpc) the Lyman-α forest can be used as a dark matter tracer [Viel et al. 2001]

$$\delta_{\rm IGM} \approx \delta$$

$$\delta\mathcal{F}^r(\vec{n}) = \int_{\chi_s}^{\chi_Q} d\chi\, \delta\mathcal{F}^r(\vec{n},\chi) \approx \int_{\chi_s}^{\chi_Q} d\chi\, (\ldots)\, \delta^r(\vec{n},\chi)$$

- The flux-matter relation has many sources of

Lyman-α forest and CMB lensing cross-correlation

- Weak lensing depends to the distribution of matter between the observer and the source.
- Quadratic optimal estimators allow the reconstruction of the CMB lensing convergence field [Hu and Okamoto (2000), Hirata and Seljak (2003)].

$$\kappa(\hat{n}, \chi_F) = \frac{3H_0^2\Omega_m}{2c^2}\int_0^{\chi_F} d\chi\, W_L(\chi, \chi_F)\frac{\delta(\hat{n}, \chi)}{a(\chi)}$$

Original vs reconstructed deflection field. [Hirata and Seljak, 2003]

Lyman-α forest and CMB lensing
cross-correlation

Does it make sense to cross-correlate these 2 observables?

Lyman-α forest and CMB lensing cross-correlation

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✓ κ depends on the dark matter overdensity integrated along the los.

✓ The flux is proportional to the matter fluctuations along the los.

Lyman-α forest and CMB lensing cross-correlation

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- ✓ κ depends on the dark matter overdensity integrated along the los.
- ✓ The flux is proportional to the matter fluctuations along the los.

Yes

What can we hope to learn from this?

- Get a handle on Lyman-α flux-dark matter bias.
- Use this cross correlation as a tool to measure cosmological parameters and make tests.

Physical meaning of the observables

$\langle \delta \mathcal{F} \kappa \rangle$ correlates the integrated fluctuation in the flux along the los with the CMB convergence.

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$\langle \delta \mathcal{F}^2 \kappa \rangle$ correlates the flux variance integrated along the los with the CMB convergence.

- Sensitive to intermediate to small scales.
- Sensitive to the enhanced growth of structure in overdense regions [Zaldarriaga, Seljak, Hui, 2001].

It is "just" a matter of evaluating a couple of integrals...

$$\langle \delta \mathcal{F}^r(\hat{n}) \kappa(\hat{n}) \rangle = \frac{3 H_0^2 \Omega_m}{2c^2} \int_0^{\chi_F} d\chi_c \frac{W_L(\chi_c, \chi_F)}{a(\chi_c)} \int_{\chi_i}^{\chi_Q} d\chi_q \, (-A\beta)^r \, \langle \delta^r(\hat{n}, \chi_q) \, \delta(\hat{n}, \chi_c) \rangle$$

"Just" a couple of integrals...

- Things become complicated when we take into account the finite resolution of the observational programs.

- The nature of the observables naturally breaks the spherical symmetry of the problem.

$$W_\alpha = \exp\left[-\frac{k_\parallel^2}{k_L^2}\right]$$

$$W_\kappa = \exp\left[-\frac{\vec{k}_\perp^2}{k_C^2}\right]$$

Cutoff scales

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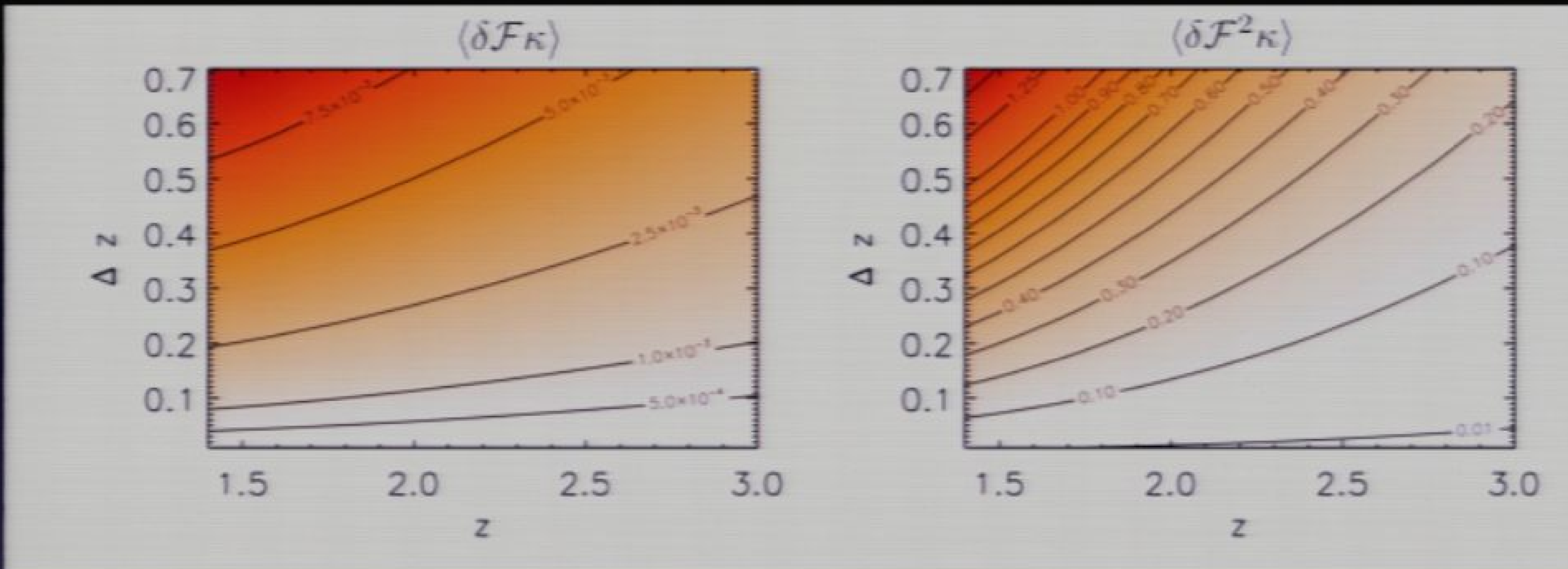
Cutoff scales

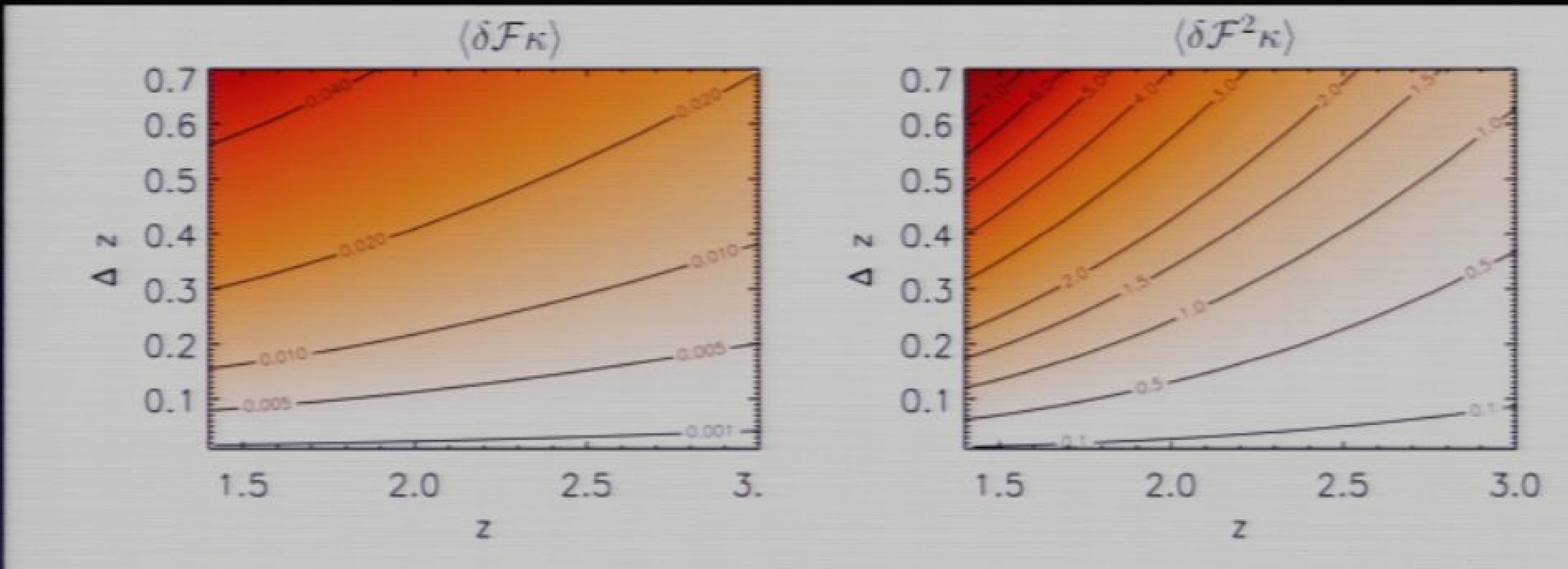
Results: correlators (BOSS+Planck)



[AV, Das, Spergel, Viel, 2009]

- Turn off IGM physics (A=β=1)
- $k_L = 4.8\,h\,\mathrm{Mpc}^{-1}$ (SDSS-III), $k_C = 0.021\,h\,\mathrm{Mpc}^{-1}$ (Planck)
- Signal decreases with increasing z: probing less collapsed regions
- Signal for $\langle\delta\mathcal{F}\kappa\rangle$ is smaller than the one for $\langle\delta\mathcal{F}^2\kappa\rangle$.

Results: correlators (BOSS+*ActPol*)



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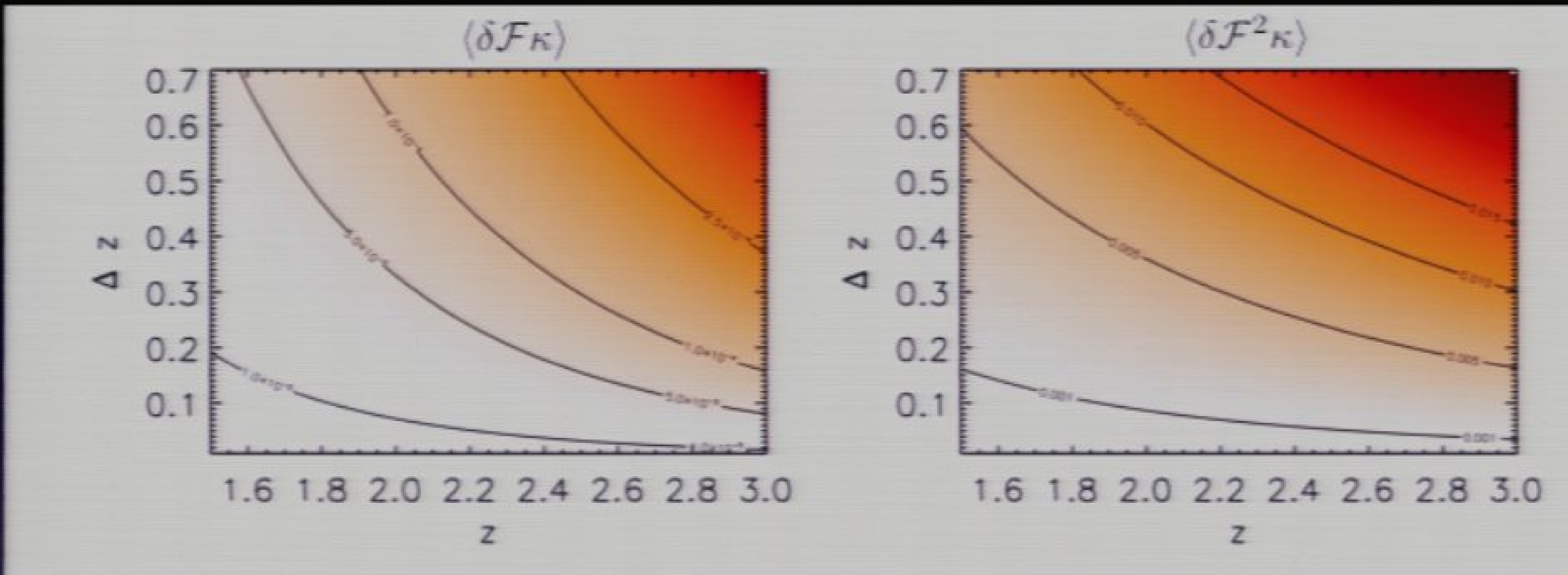

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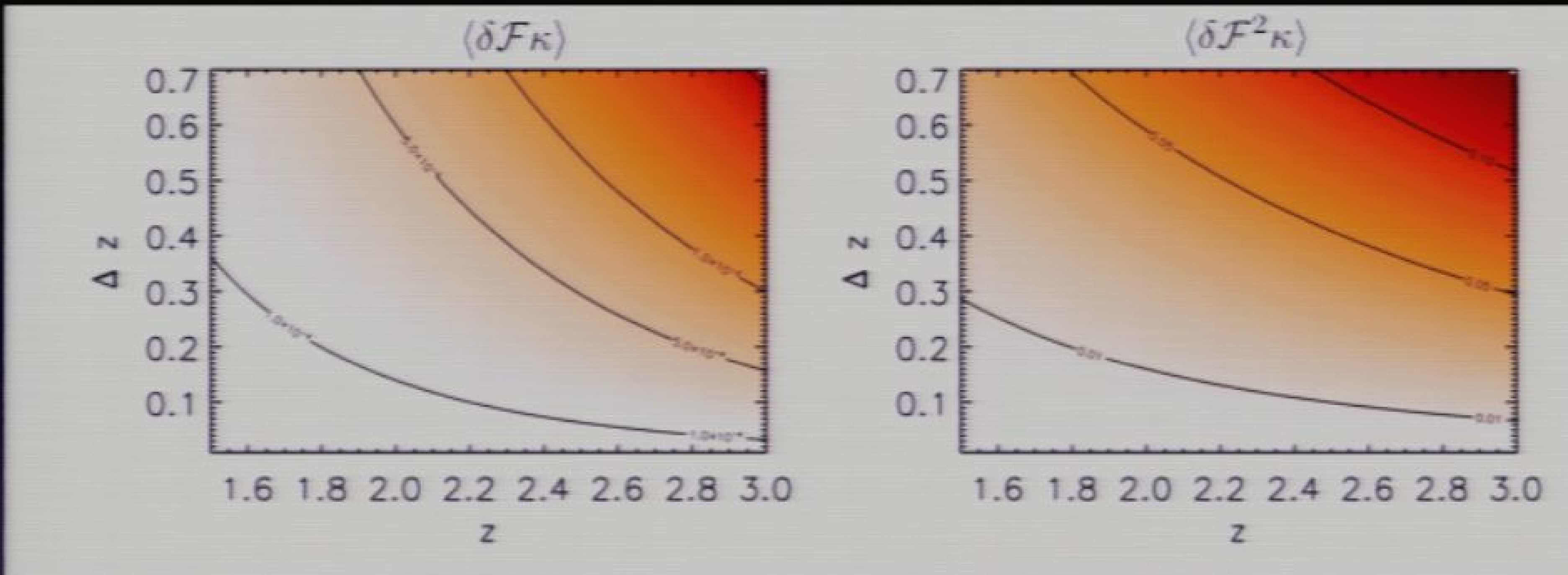

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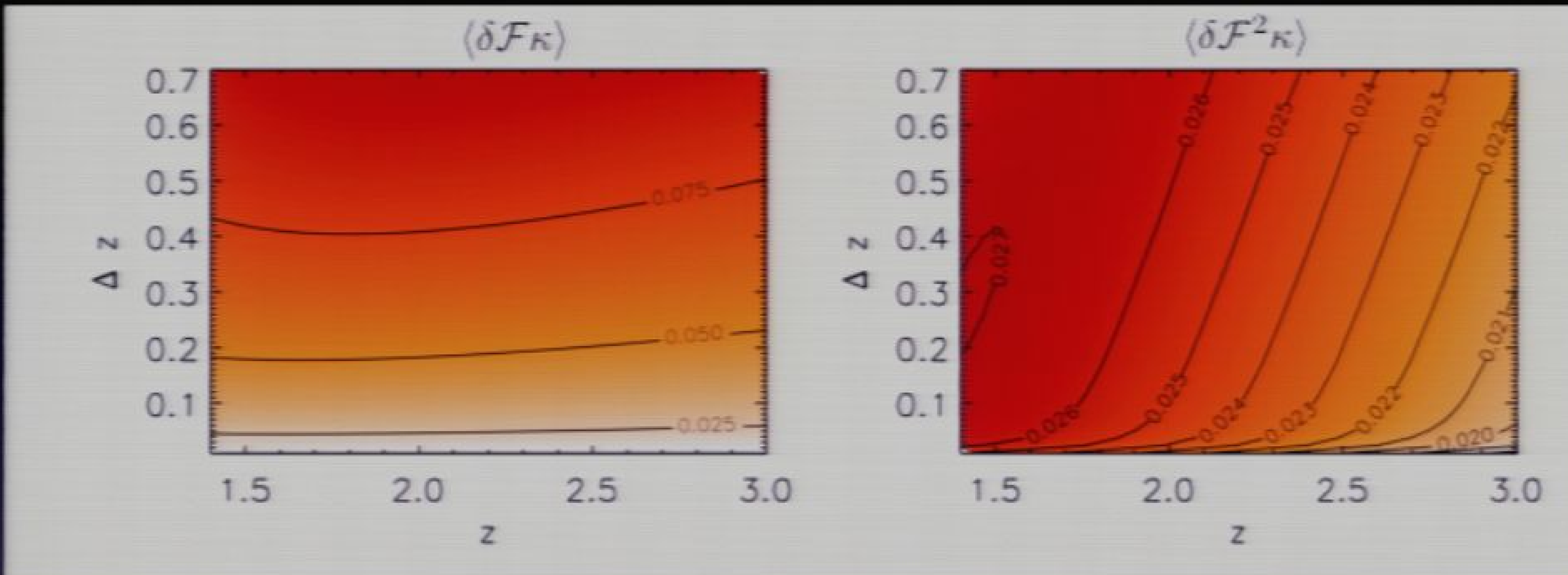
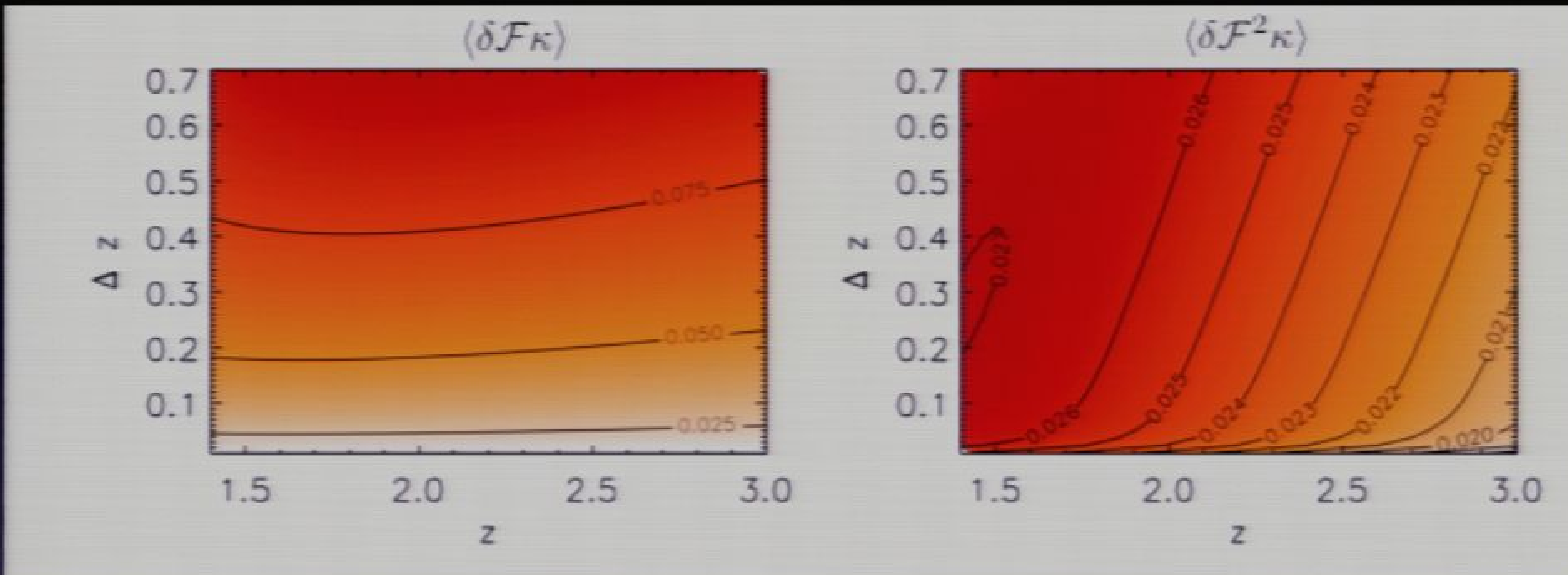
Results: detectability (BOSS+Planck)



[AV, Das, Spergel, Viel, 2009]

- S/N for single line-of-sight. $1.6 \cdot 10^5$ los for Boss, ~10^6 los for BigBoss.
- Estimates for total S/N are ~30 (75) for $\langle \delta\mathcal{F}\kappa \rangle$ and ~9.6 (24) for $\langle \delta\mathcal{F}^2\kappa \rangle$ when Planck dataset is xcorrelated with Boss (BigBoss).
- The growth of structure enters twice for $\langle \delta\mathcal{F}^2\kappa \rangle$: once for the long-wavelengths and once for the short wavelengths. The variance is dominated by long wavelengths only.

Results: detectability (BOSS+*ActPol*)



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- S/N for single line-of-sight. $1.6 \cdot 10^5$ los for Boss, ~10^6 los for BigBoss.
- Estimates for total S/N are ~50 (130) for $\langle \delta \mathcal{F} \kappa \rangle$ and ~20 (50) for $\langle \delta \mathcal{F}^2 \kappa \rangle$ when ActPol dataset is xcorrelated with Boss (BigBoss).
- S/N does not depend on the redshift evolution of A and β.

Caveats

- Numerical results currently do not take into account non-linear effects due to gravitational collapse
  - Extension is straightforward
  - Signal is expected to increase, S/N is hard to say.
- All results do not take into account small scales (<1 Mpc) IGM physics and use "gaussian approximation" to evaluate the correlators' variance
  - Final answer will come from numerical simulations

Cosmological application: neutrino masses

$\langle \delta \mathcal{F}^2 \kappa \rangle$ is sensitive to intermediate to small scales and to the power spectrum normalization σ_8.

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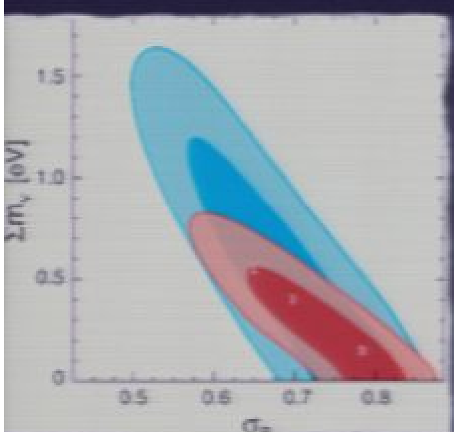

$\sum m_\nu$ and σ_8 are not independent if they are to be consistent with CMB measurements.

[Komatsu et al., 2008]

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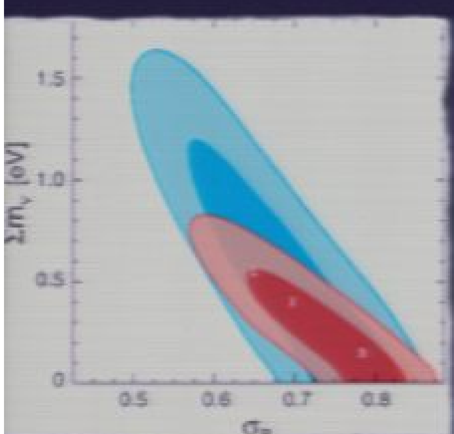
We can use $\langle \delta\mathcal{F}^2\kappa \rangle$ to put limits on the neutrino mass



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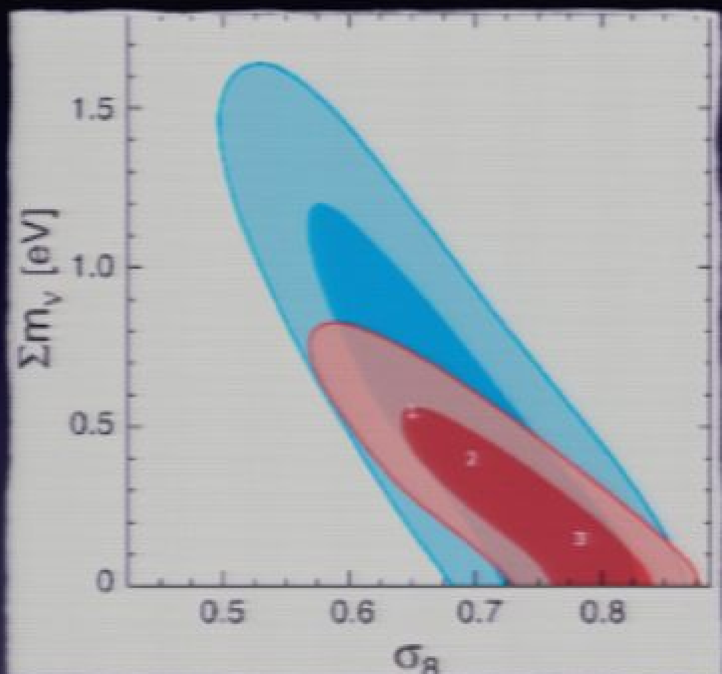

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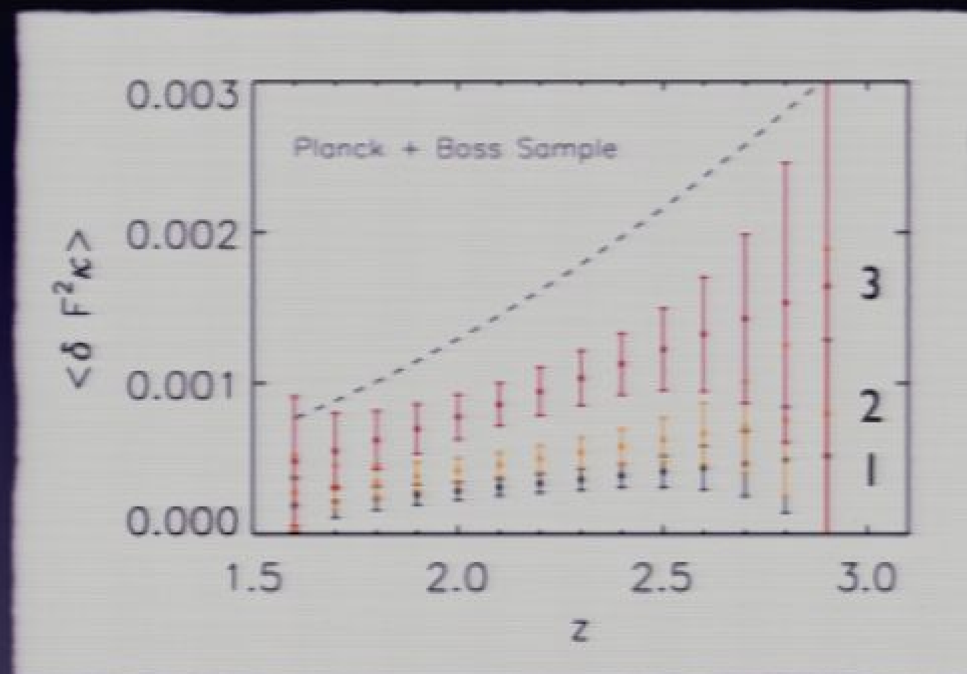


[AV, Viel, Das, Spergel, 2009]

- Caveat: non-linear effects due to gravitational collapse need to be taken into account.

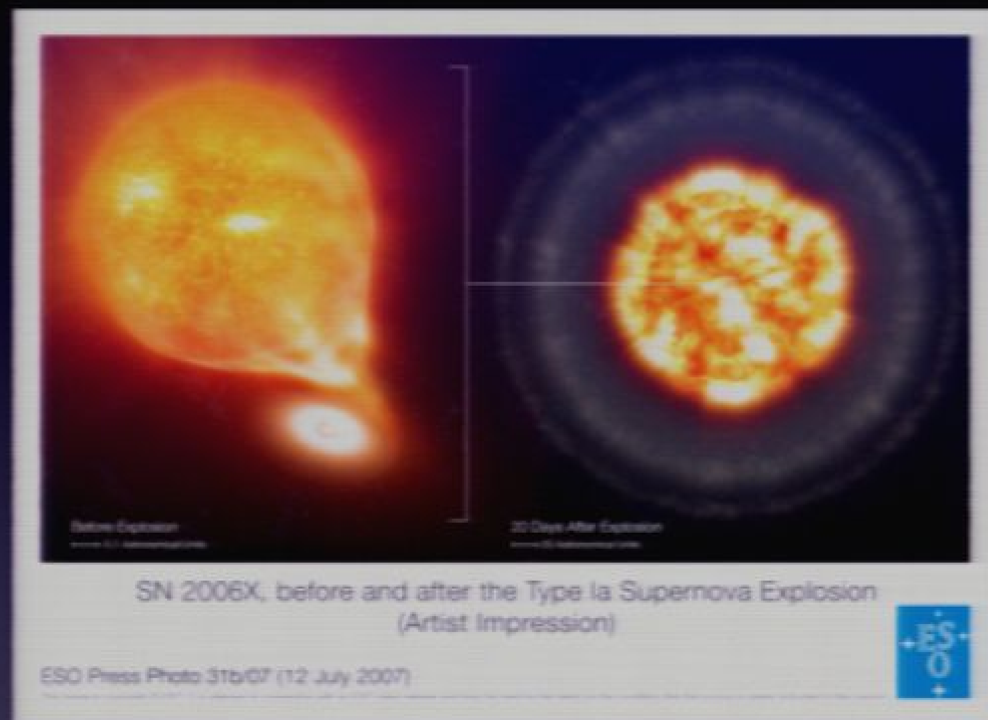
Bottom line

- The xcorrelation between the Lyman-α forest and the CMB lensing convergence will be detectable with very near future data sets (Planck + SDSS-III)
- It will allow to probe
  - How well Lyman-α flux traces dark matter
  - Growth of structure at the Lyman-α redshifts
  - Matter power spectrum on intermediate-to-small scales
  - Scale dependent modifications of gravity
- Numerical simulations will be crucial for a better understanding.

Information from weak lensing: Type Ia Supernovae

Type Ia Supernovae

- SNIa are thought to be born from white dwarves - red giants binary systems.



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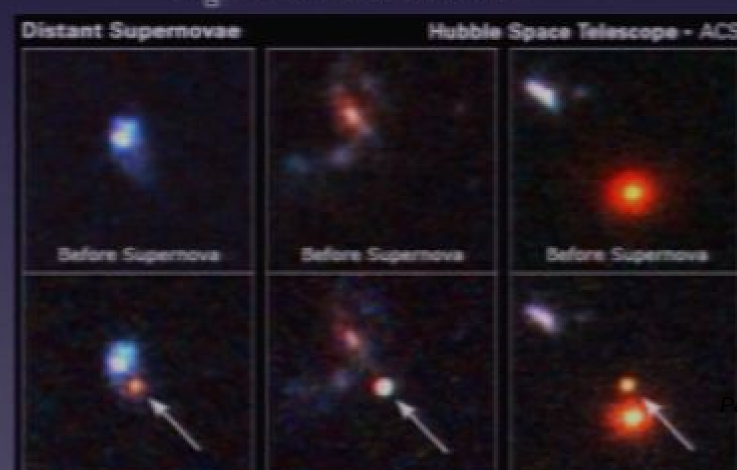
- Type Ia Supernovae are detected through image subtraction.

SN1994D imaged with HST.
High-Z SN Search Team



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- SNIa are thought to be born from white dwarves - red giants binary systems.
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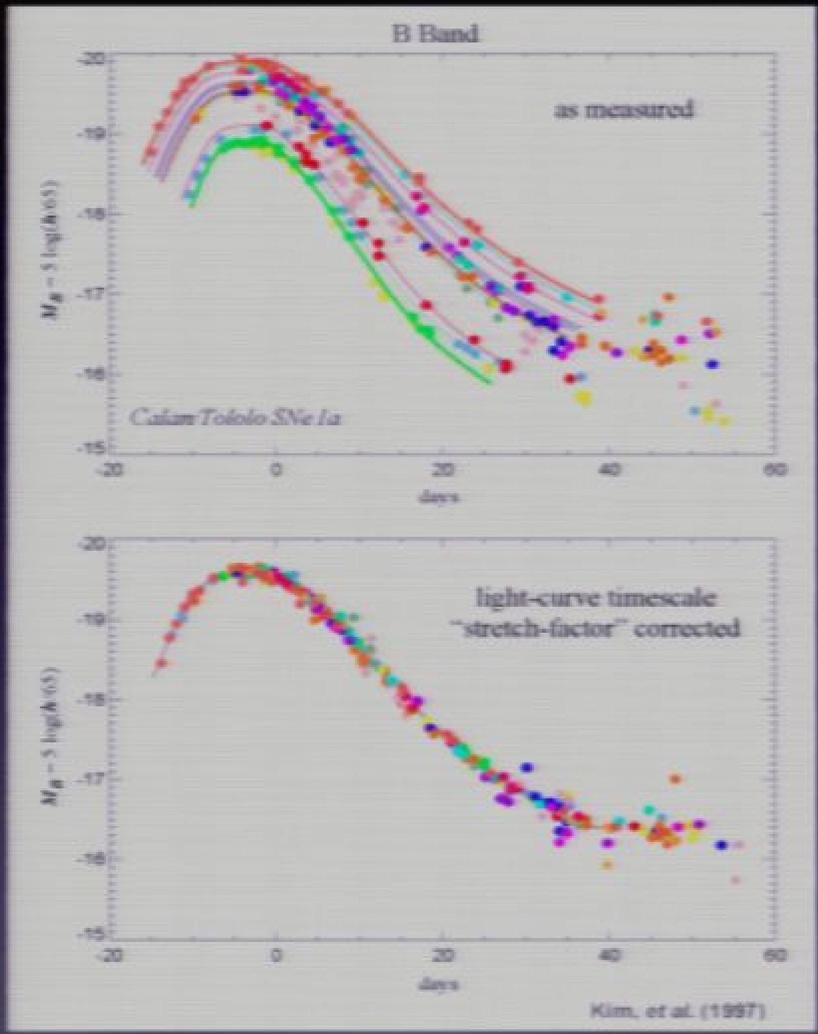
- The have self-similar light curves, that makes them standardizable candles.



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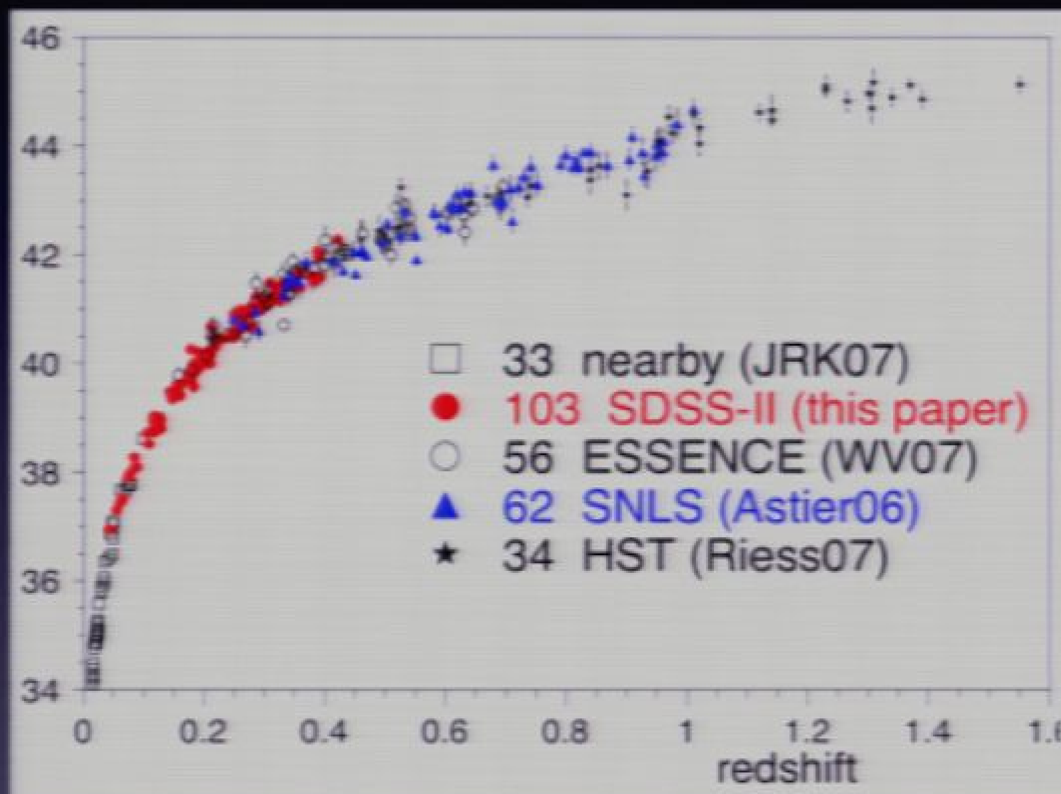

[Kessler et al., 2009]

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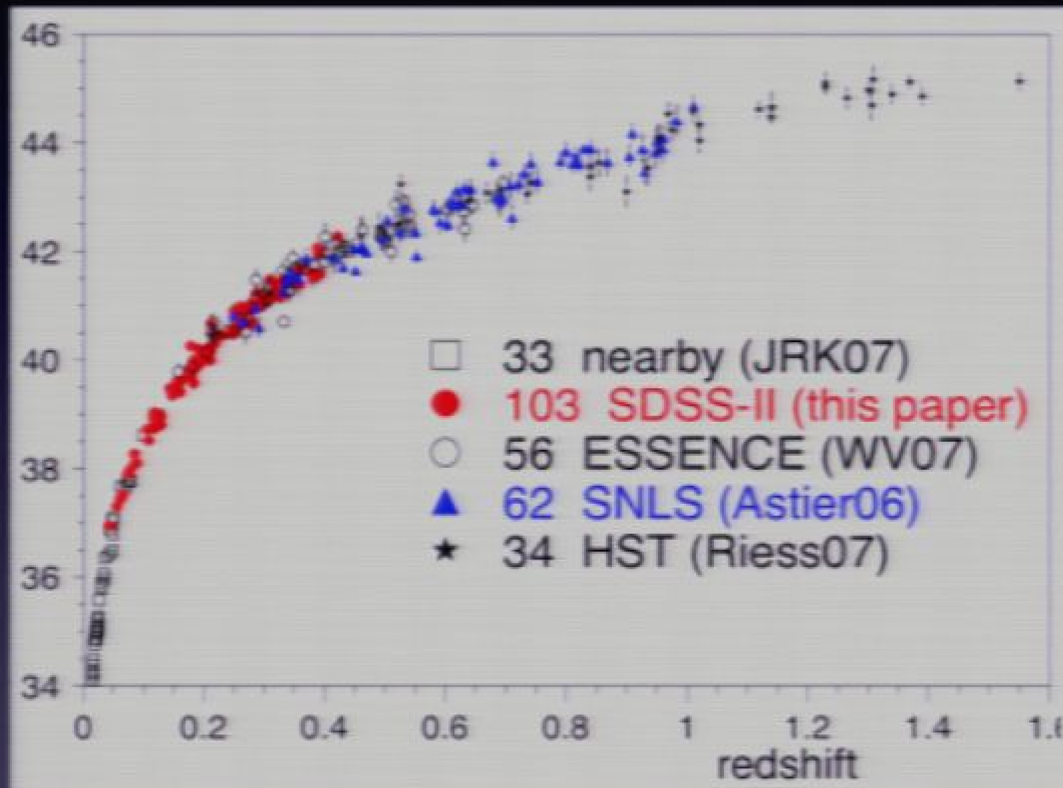


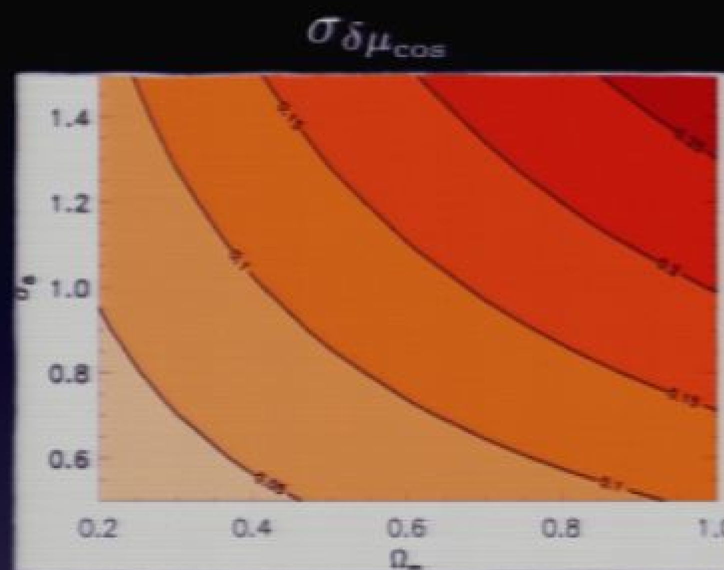
[Kessler et al., 2009]

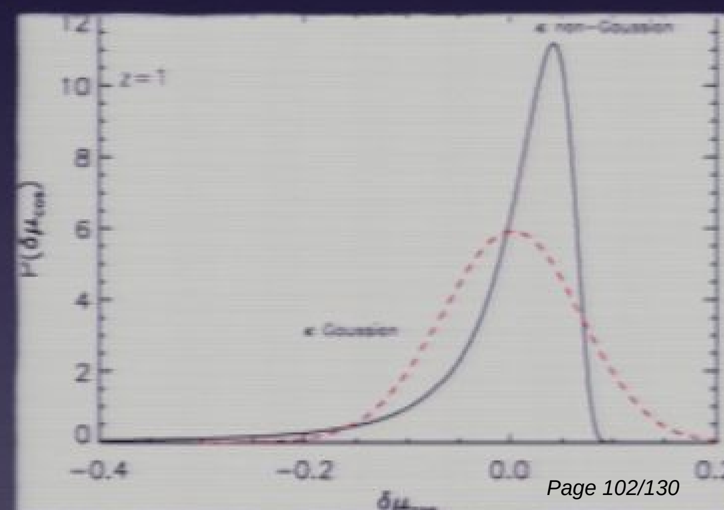
Weak lensing of SNIa

- Weak lensing alters the luminosity of SNIa's.
- The average value of μ probes the FRW background expansion [Holz and Linder, 2004].
- The scatter of μ is sensitive to an intrinsic component $\delta\mu_{\rm i}$ and to a lensing contribution $\delta\mu_{\rm cos}$.

$$\mu = \mu_0 + \delta\mu_{\rm i} + \delta\mu_{\rm cos}$$

- The characteristics of the lensing contribution depend on the "clumpiness" of large scale structure, σ_8.



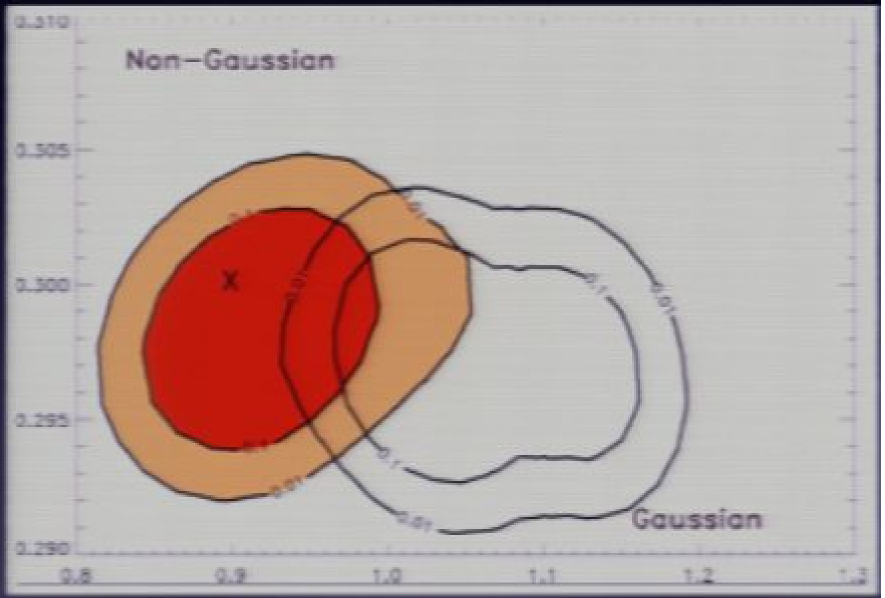


[Dodelson AV 2005]

Weak lensing of SNIa

- Buried in the SNIa scatter together with an intrinsic component there is a random component that depends on σ_8.
- This information can be mined using *knowledge of the pdf* of $\delta\mu_{\cos}$ and a Montecarlo technique.
- Added bonus: this information comes for free, and it is independent from other LSS probes.

2000 SNIa, z∈[0.5,1.7]



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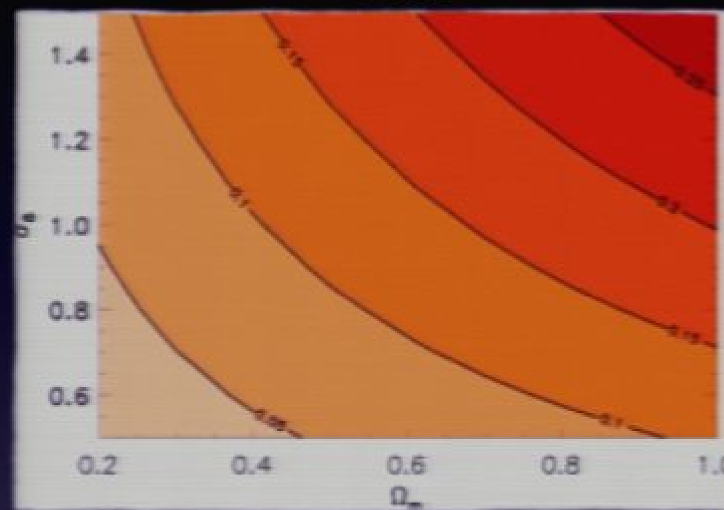
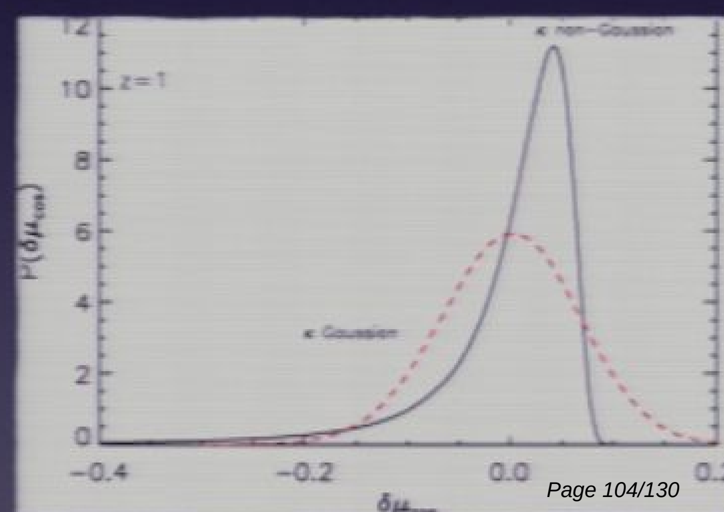
$\sigma_{\delta\mu_{\rm cos}}$





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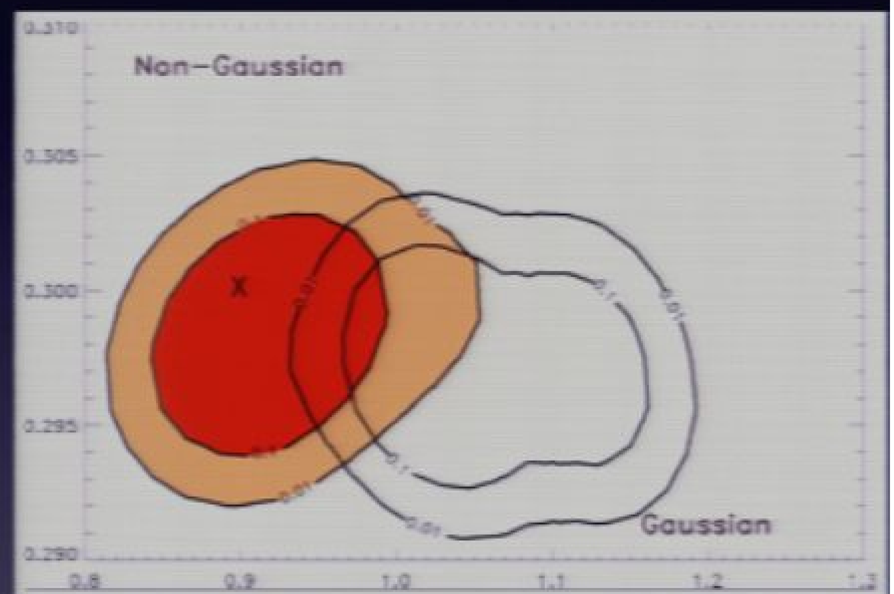
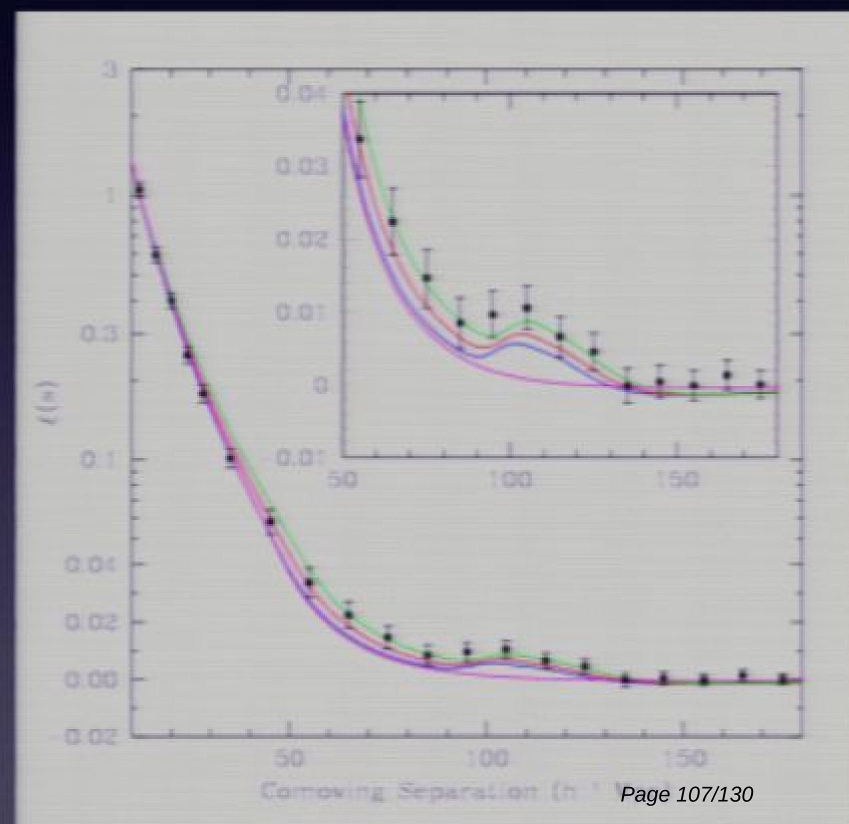


[Dodelson, AV, 2005]

Noise from weak lensing: Baryon Acoustic Oscillation, CMB and everything in between

Baryon Acoustic Oscillations

- We don't really see "shells" in the sky.
- However, if the correlation function of matter overdensities is measured, we expect an extra correlation at the scale of the shell.
- BAO allow to measure Ω_m and Ω_b.
- They are standard rulers, and as such the ideal tool to probe the expansion history of the universe.
- If galaxy overdensities are a good tracer of DM overdensities, then BAO can be measured through galaxies' correlation function.

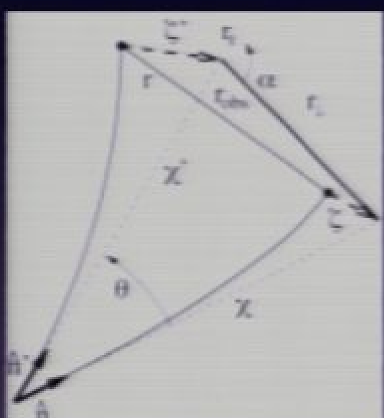


Weak lensing induced noise

Lensing acts on observations in two ways

Smoothing

DM distribution bends geodesics



* observed and true positions no longer coincide.
* applies to pointlike sources and diffuse backgrounds.
* small but difficult to compensate or avoid.

Magnification bias

Lensing alters objects'

* luminosity by squeezing/ stretching geodesics bundles.
* density by squeezing/stretching patches of sky.
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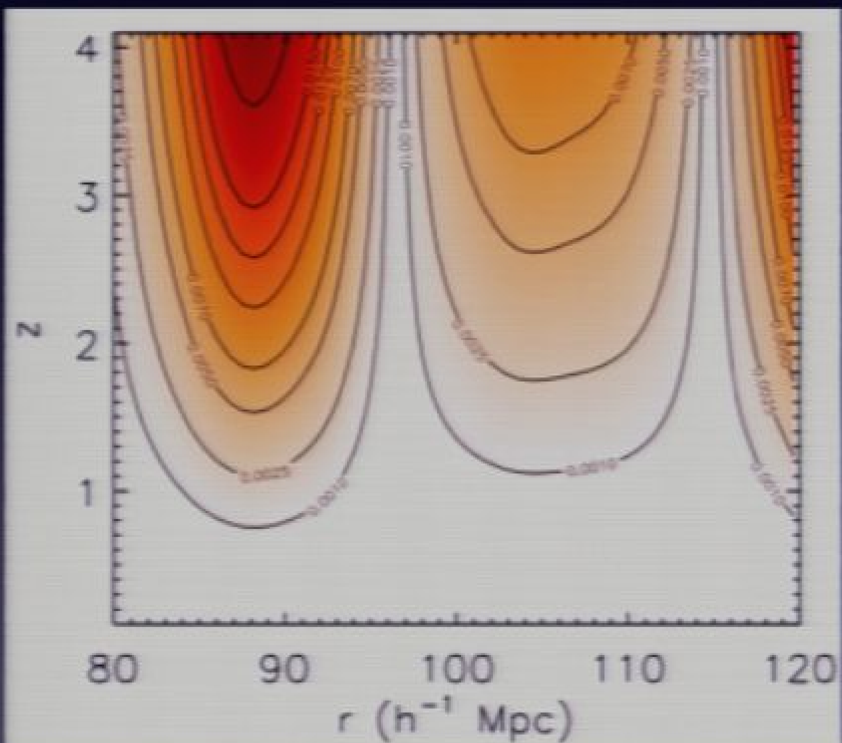

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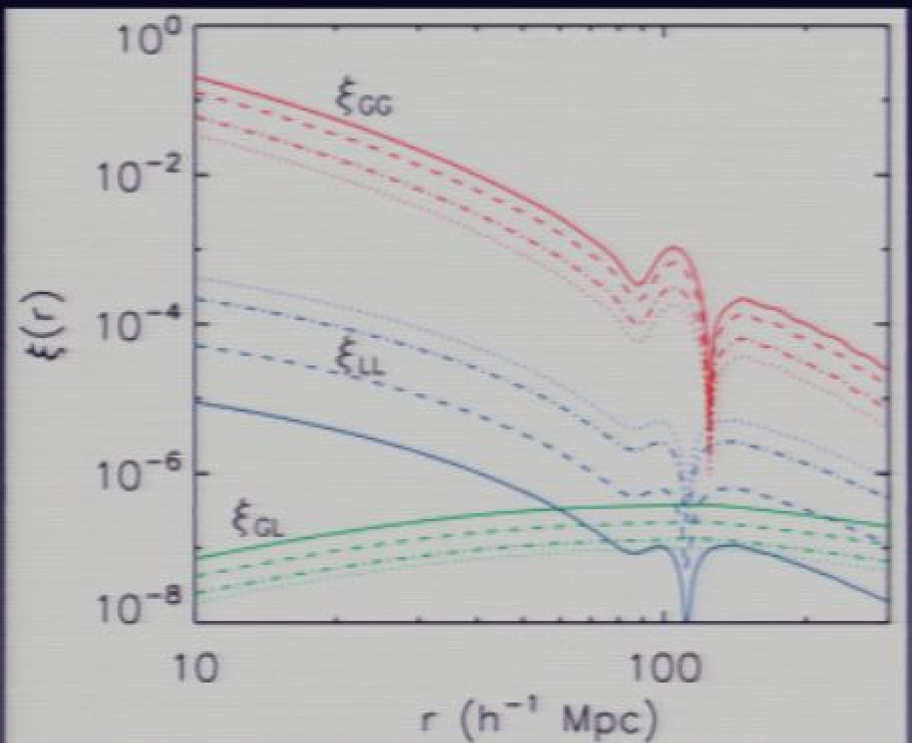

[AV, Dodelson, Schimd, Uzan, 2007]

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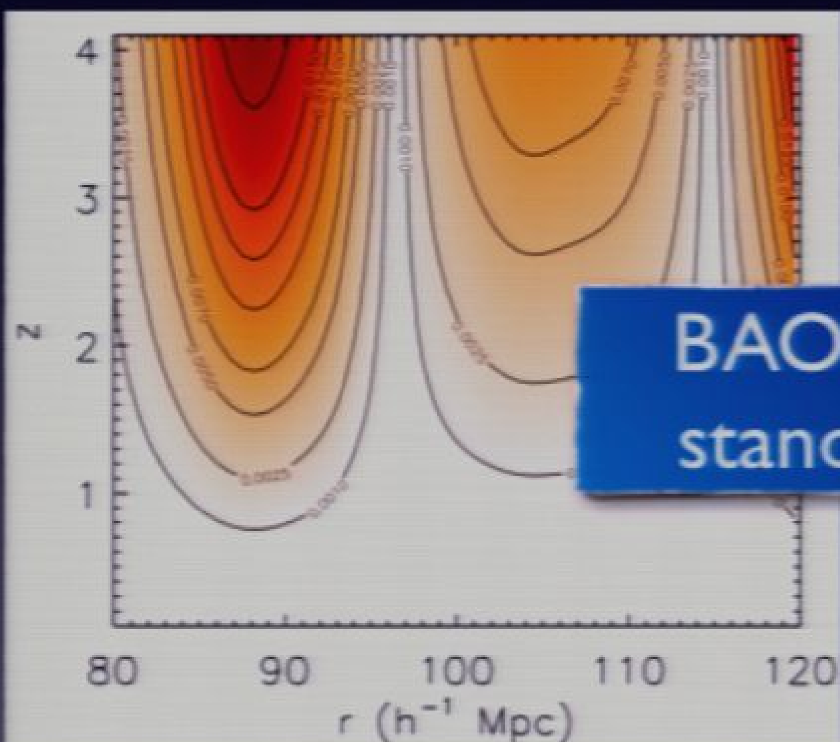

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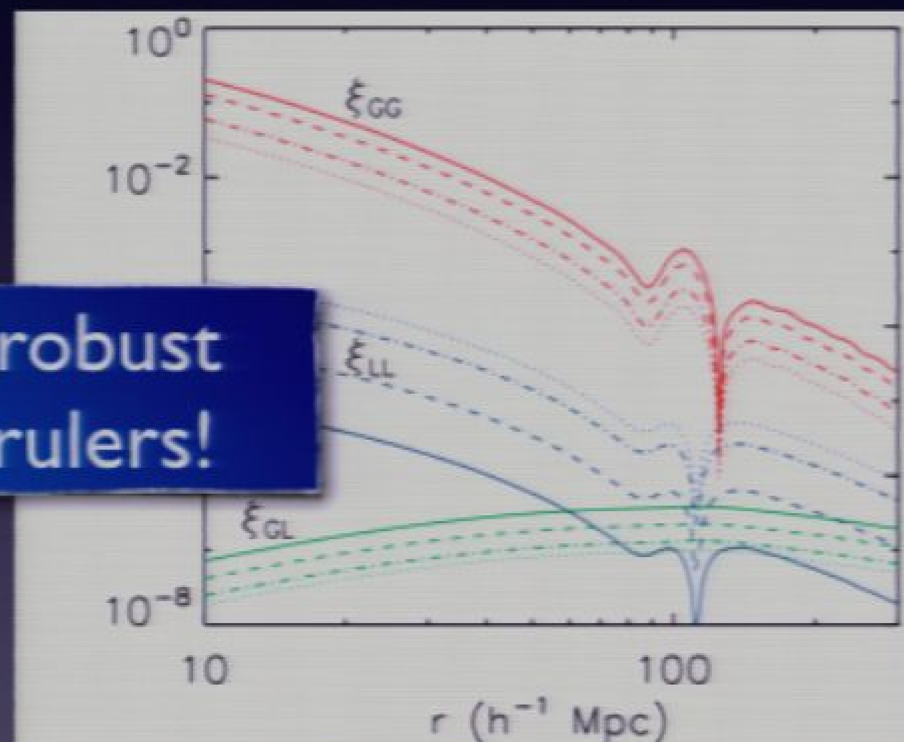

BAO are robust standard rulers!

[AV, Dodelson, Schimd, Uzan, 2007]

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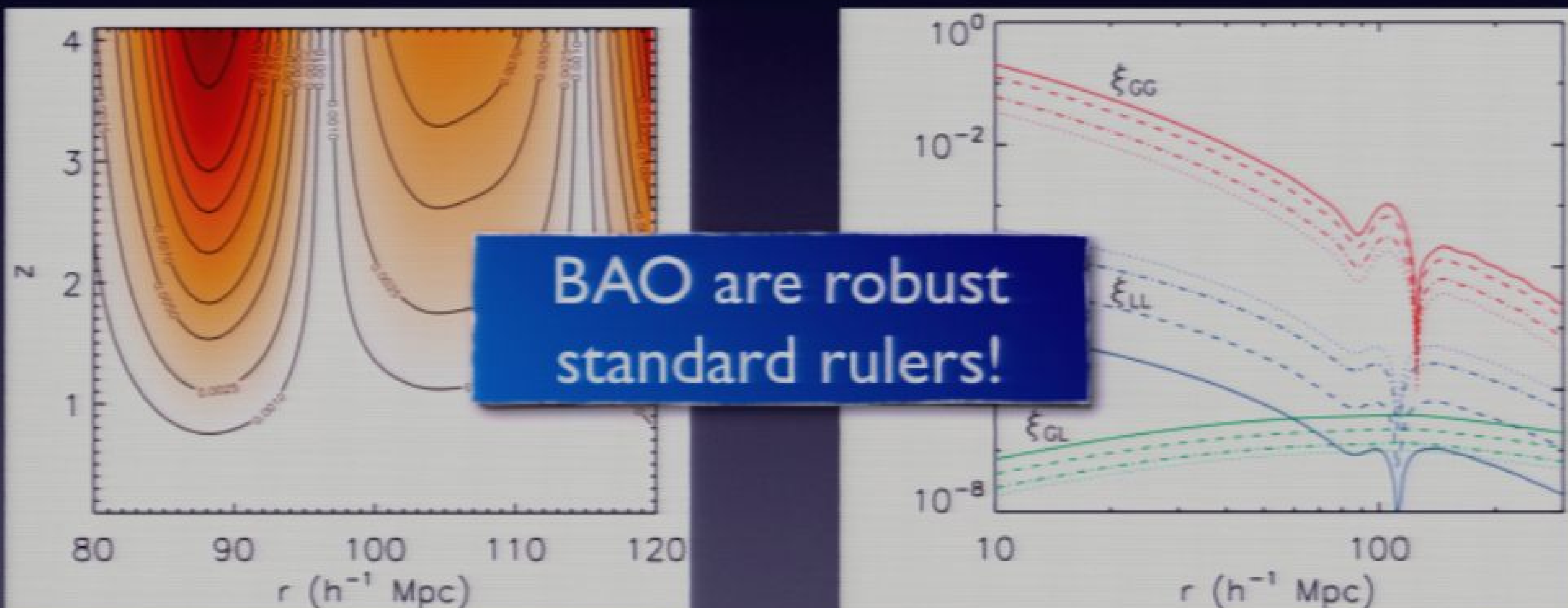

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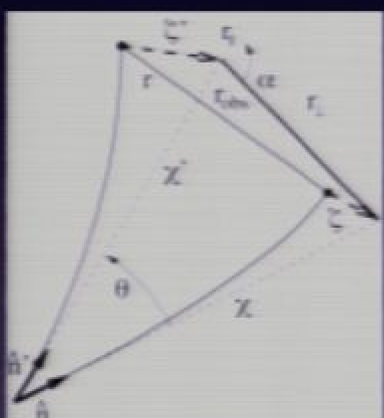

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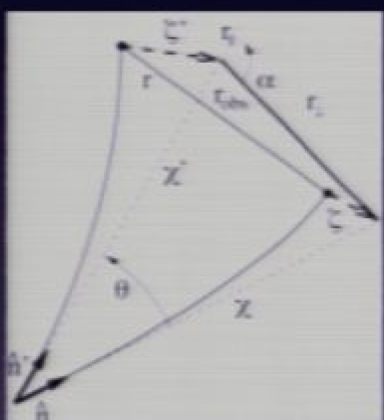

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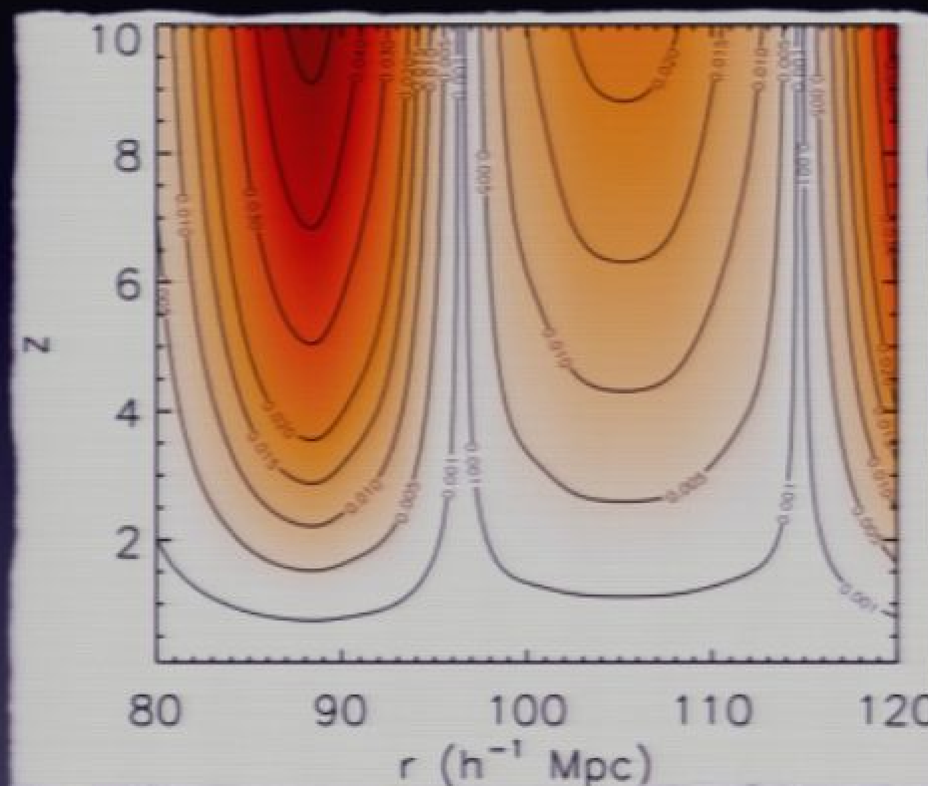
Lensing induced contributions to correlation functions

✦ The contribution to cosmological correlation functions of the bending of geodesics due to the intervening dark matter distribution is almost completely unavoidable.

✓ However, it is normally quite small.

✦ General effect, acts on any cosmological observables.

- BAO measured through galaxies, QSO and low redshift 21-cm surveys.



[Dodelson, Schmidt, AV, 2008]

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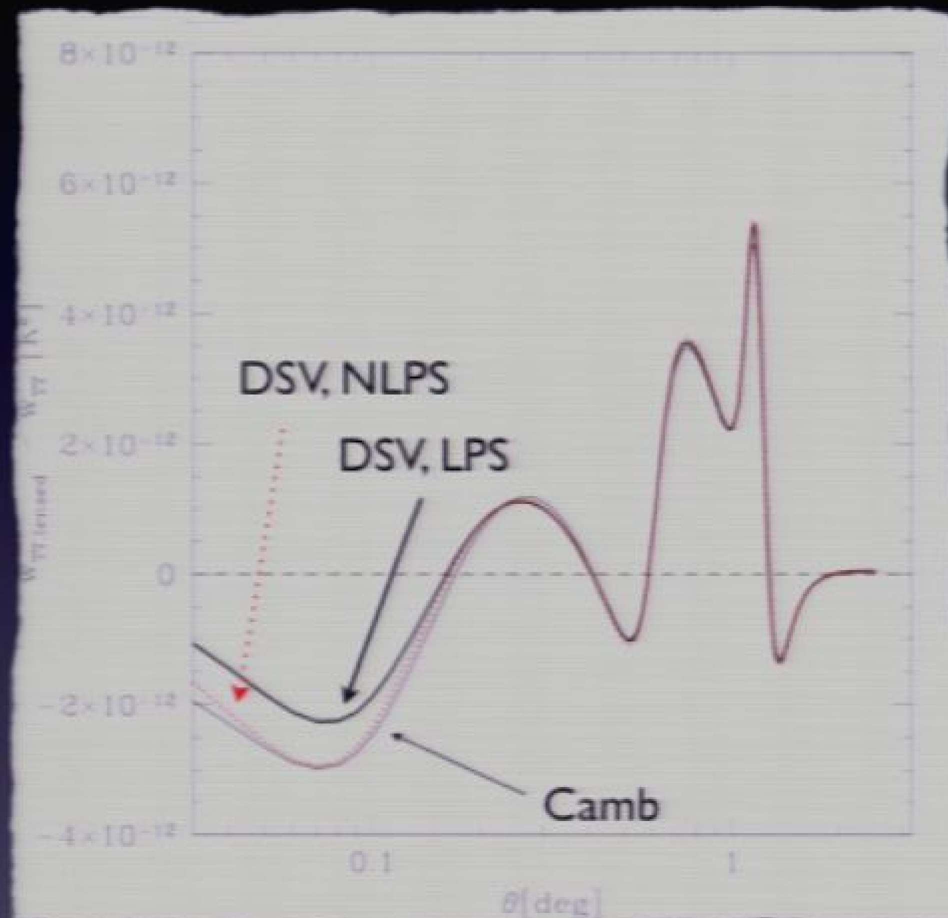
  - CMB in configuration space.



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Magnification bias effect on galaxies 3-pt correlation function

- The effect of magnification bias is potentially relevant galaxies' 3PCF.
- It strongly depends on the configuration of the triangles, but it can reach 5-10% and have an effect on the measurement of non-gaussianity.
- Can affect the reduced three point function

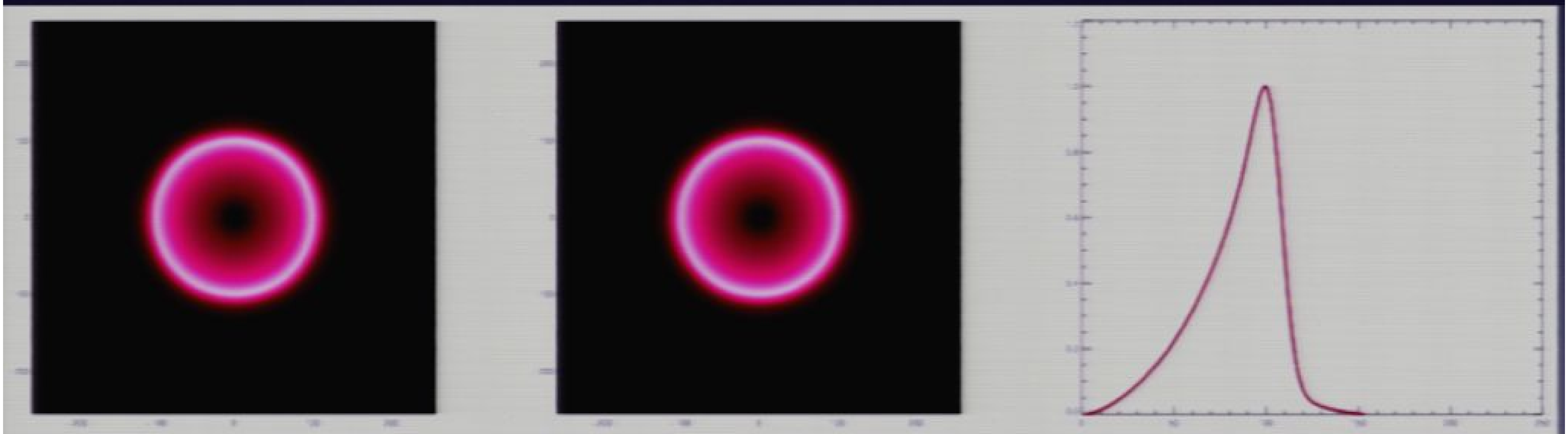
$$Q_\zeta(\vec{x}_1,\vec{x}_2,\vec{x}_3) = \frac{\zeta(\vec{x}_1,\vec{x}_2,\vec{x}_3)}{\xi(\vec{x}_1,\vec{x}_2)+\xi(\vec{x}_2,\vec{x}_3)+\xi(\vec{x}_3,\vec{x}_1)}$$

Conclusions

- Apologies to the experts!
- Data from current and near future experiments make these the most exciting times for cosmology...
- ... especially when looking at dark matter under many different angles.

Baryon Acoustic Oscillations

- Baryons + photons wave expands at $c_s = \sqrt{\dfrac{4\rho_\gamma}{3(4\rho_\gamma + 3\rho_b)}}$



[White, 2006]

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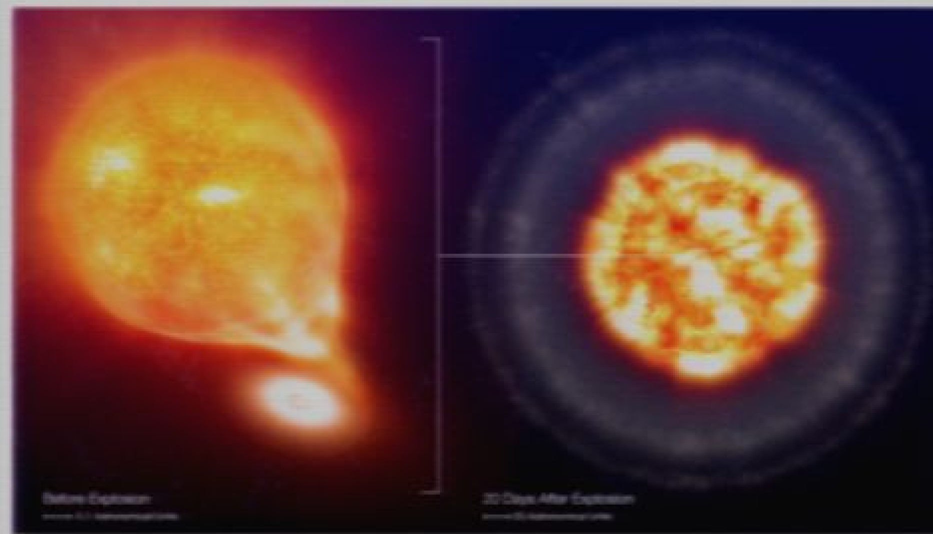


SN 2006X, before and after the Type Ia Supernova Explosion (Artist Impression)

ESO Press Photo 31b/07 (12 July 2007)

Cosmological application: neutrino masses

$\langle \delta\mathcal{F}^2\kappa \rangle$ is sensitive to intermediate to small scales and to the power spectrum normalization σ_8.

Physical meaning of the observables

$\langle \delta \mathcal{F} \kappa \rangle$ correlates the integrated fluctuation in the flux along the los with the CMB convergence.

- Sensitive to intermediate to large scales.
- Sensitive to the matter fluctuations in the forest responsible for the lensing of CMB along the los.

Lyman-α forest and CMB lensing cross-correlation

Does it make sense to cross-correlate these 2 observables?

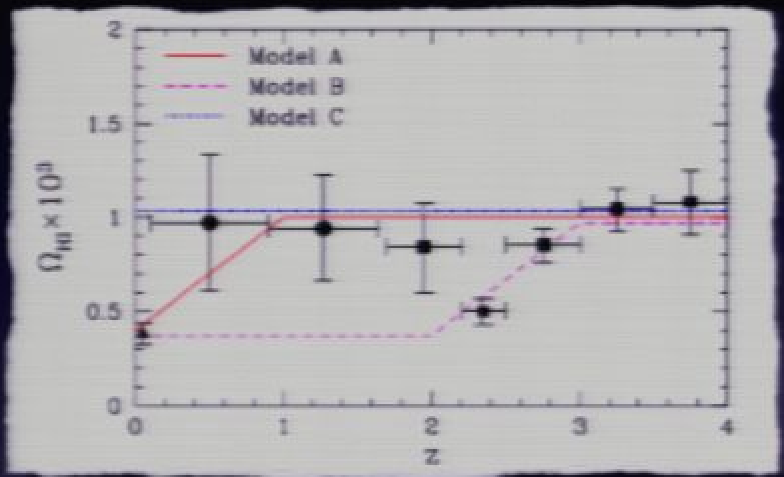
✓ κ depends on the dark matter overdensity integrated along the los.

✓ The flux is proportional to the matter fluctuations along the los.

Yes

Large scales HI bias

- Next, we need a prescription to evolve the HI mass function. We build it out of two elements.



- The (poorly measured) evolution of $\Omega_{HI}(z)$. We consider three limiting cases (A, B, C).

- Two limiting ways of assigning the total HI to halos:

  - Fix the number density (PME)

  - Fix the halo mass (PNE).

Neutralinos

- Supersymmetry relates fermions and bosons

$$Q|\text{fermion}\rangle = |\text{boson}\rangle \qquad Q|\text{boson}\rangle = |\text{fermion}\rangle$$

- It introduces R parity. The corresponding (multiplicative) quantum number is conserved.

$$R = (-1)^{3B+L+2S}$$

- As a consequence of R parity, the lightest supersymmetric particle (LSP) is stable.

Standard Model particles and fields		Supersymmetric partners			
		Interaction eigenstates		Mass eigenstates	
Symbol	Name	Symbol	Name	Symbol	Name
$q = d, c, b, u, s, t$	quark	$\tilde{q}_L, \tilde{q}_R$	squark	$\tilde{q}_1, \tilde{q}_2$	squark
$l = e, \mu, \tau$	lepton	$\tilde{l}_L, \tilde{l}_R$	slepton	$\tilde{l}_1, \tilde{l}_2$	slepton
$\nu = \nu_e, \nu_\mu, \nu_\tau$	neutrino	$\tilde{\nu}$	sneutrino	$\tilde{\nu}$	sneutrino
g	gluon	$\tilde{g}$	gluino	$\tilde{g}$	gluino
$W^\pm$	W-boson	$\tilde{W}^\pm$	wino		
H^-	Higgs boson	$\tilde{H}_1^-$	higgsino	$\tilde{\chi}^\pm_{1,2}$	chargino
H^+	Higgs boson	$\tilde{H}_2^+$	higgsino		
B	B-field	$\tilde{B}$	bino		
W^3	W^3-field	$\tilde{W}^3$	wino		
H_1^0	Higgs boson			$\tilde{\chi}^0_{1,2,3,4}$	neutralino
H_2^0	Higgs boson	$\tilde{H}_1^0$	higgsino		
H_3^0	Higgs boson	$\tilde{H}_2^0$	higgsino		

Charged

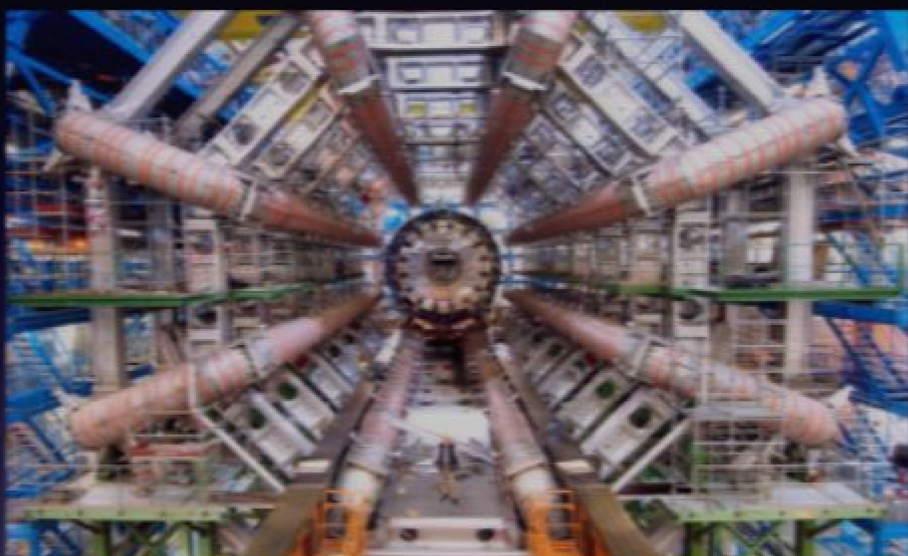
Example: the *Wimp Forest* or "Spectroscopy of Extra Dimensions"

Kaluza-Klein theories naturally provide a dark matter candidate, the Lightest Kaluza-Klein Particle (LKP), that

- ✓ does not overclose the universe
- ✓ is stable
- ✓ is cold and massive (~100 GeV)
- ✓ is neutral
- ✓ does not screw up BBN

[Bertone, Jackson, Shaughnessy, Tait, AV, 2009]

Experimental Techniques: Collider Searches

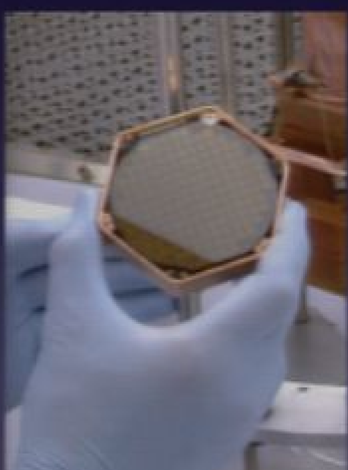


Idea: colliders (will) probe extensions the standard model.
In principle can shed light on the nature of dark matter.

Complementary Experimental Techniques

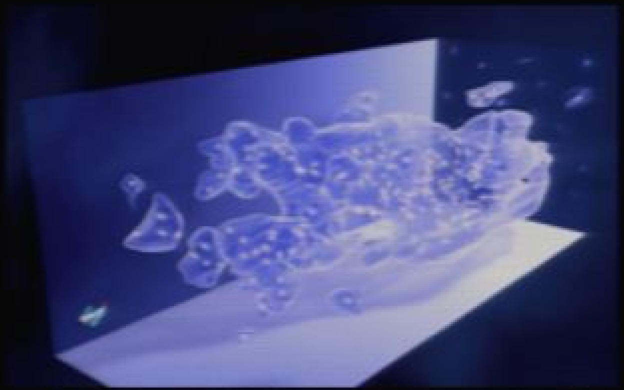
Indirect Detection

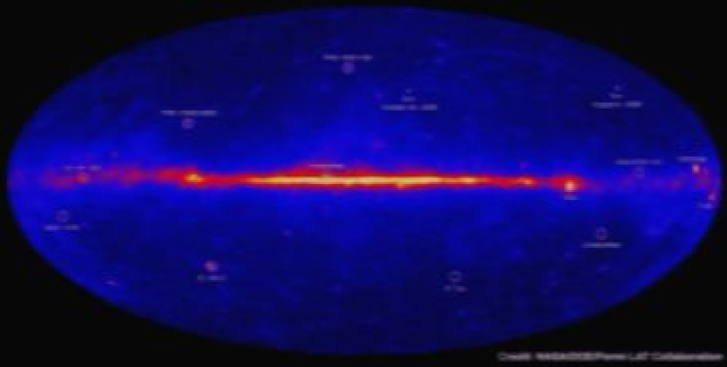
Collider Searches



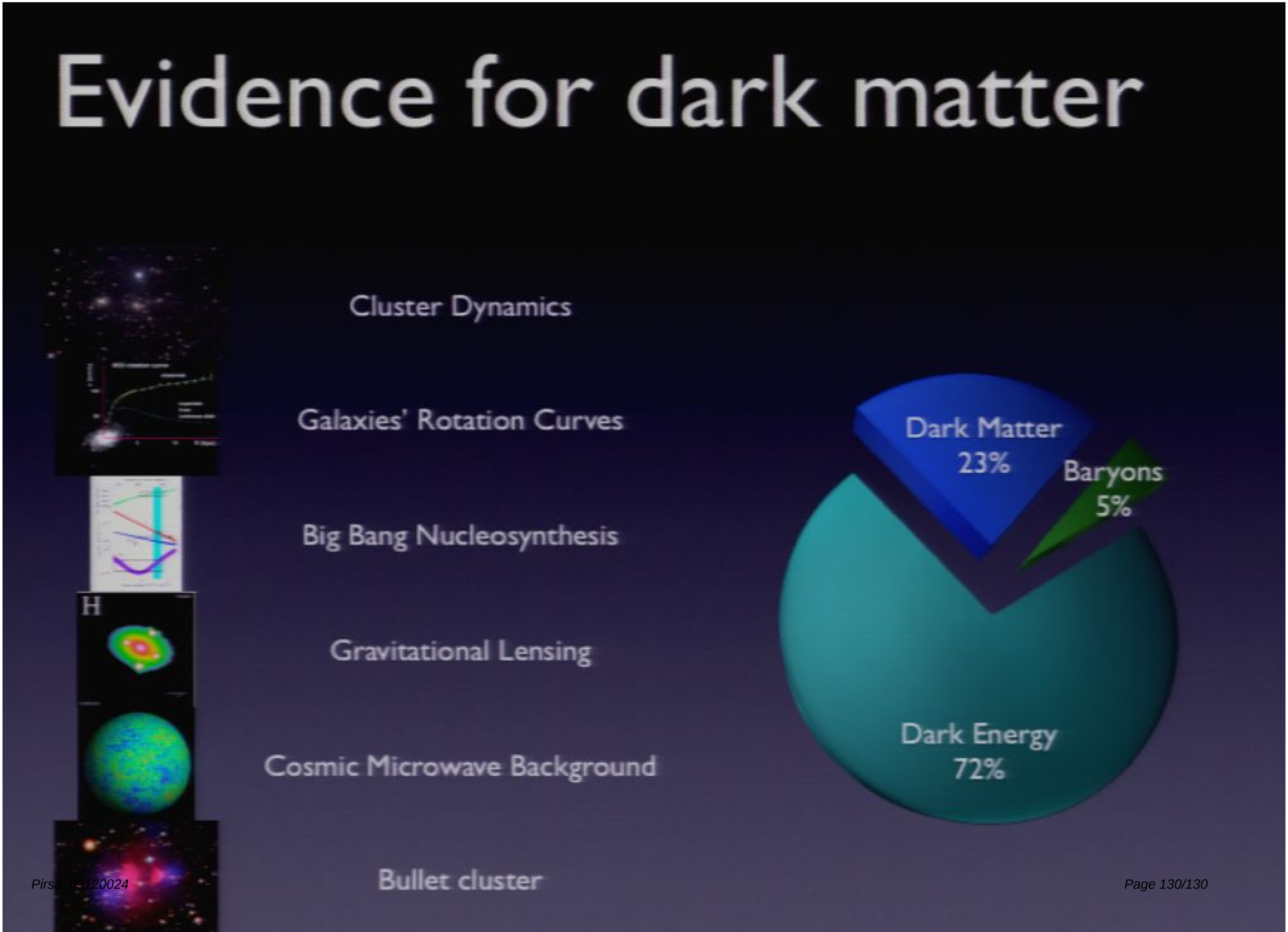
Direct Detection

Dark Matter under different angles





Alberto Vallinotto
Fermilab


Evidence for dark matter
Cluster Dynamics
Galaxies' Rotation Curves
Big Bang Nucleosynthesis
Gravitational Lensing
Cosmic Microwave Background
Bullet cluster
Dark Matter
23%
Baryons
5%
Dark Energy
72%