Title: Testing General Relativity with Weak Gravitational Lensing

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Abstract: Weak gravitational lensing is a powerful probe of modifications of General Relativity on cosmological scales, since such modifications can affect both how matter produces gravitational potential wells and how photons move within these wells. I will discuss alternative theories of gravitation and how we may constrain such theories using weak lensing observables, including those that could be obtained with the balloon-borne High Altitude Lensing Observatory (HALO). I will also discuss the "parametrized-post-Friedmannian" approach for obtaining model-independent constraints, in which new parameters are introduced to characterize the departure from General Relativity on large scales.

Testing GR on cosmological scales with weak gravitational lensing

Ali Vanderveld (Caltech & JPL)

Perimeter Institute

October 27th, 2009

Agenda

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- Weak gravitational lensing –

  what, how, and why

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- The "parameterized post-Friedmannian" framework –

  model-independent constraints on modified gravity from weak lensing

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- The "parameterized post-Friedmannian" framework –

  model-independent constraints on modified gravity from weak lensing

- The High Altitude Lensing Observatory –

  a new concept for a balloon-borne weak lensing survey

Weak lensing

Matter acts like a lens

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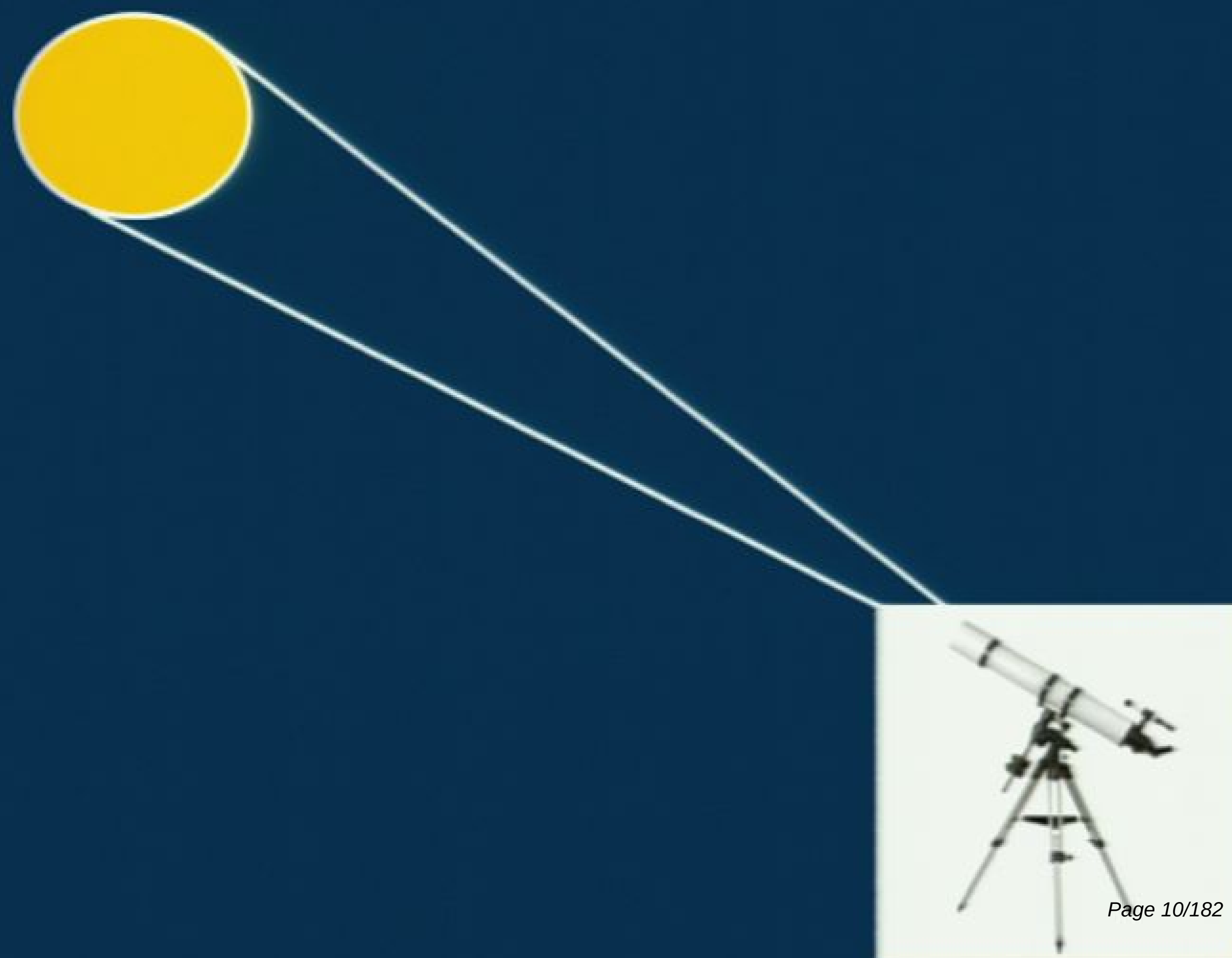

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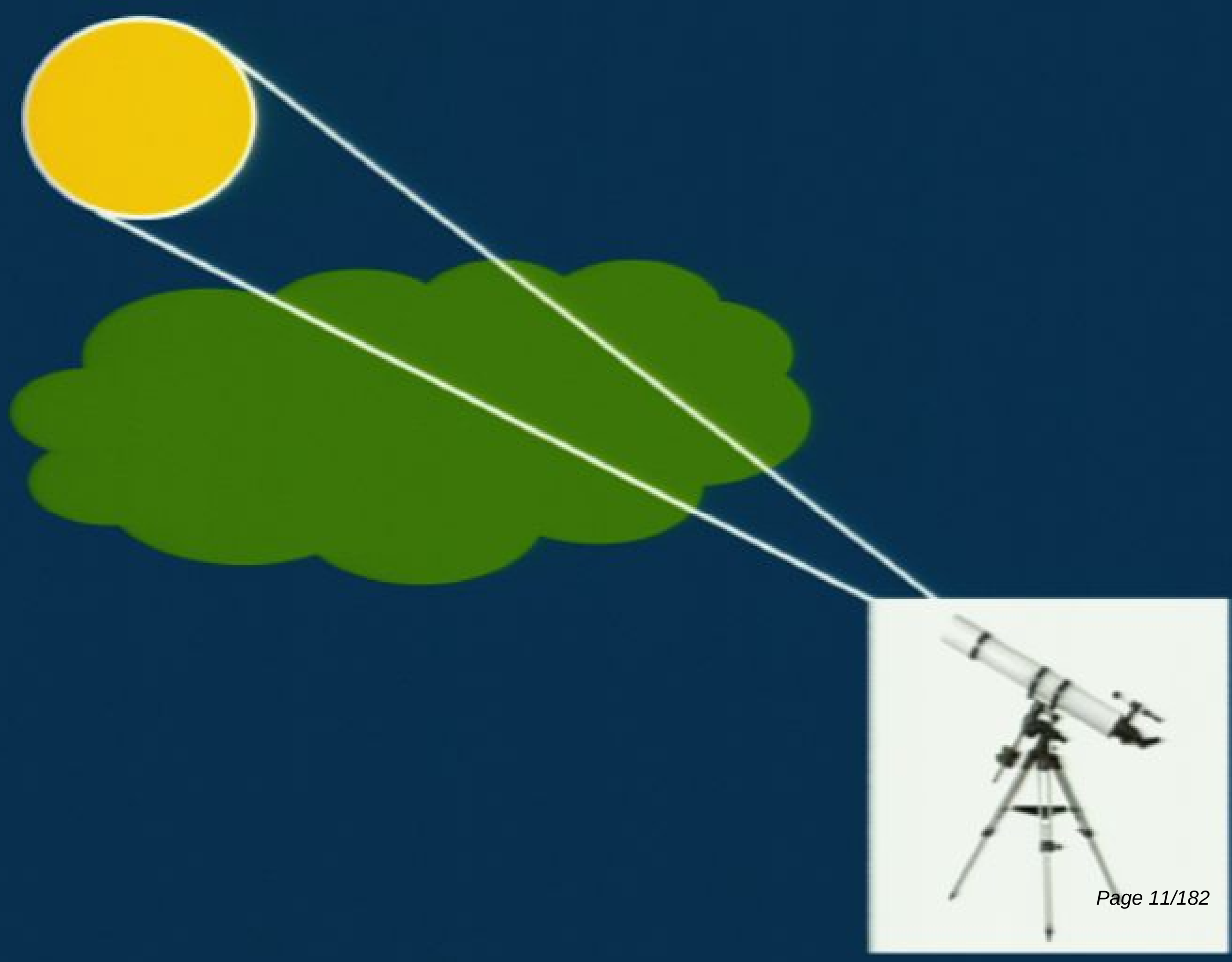

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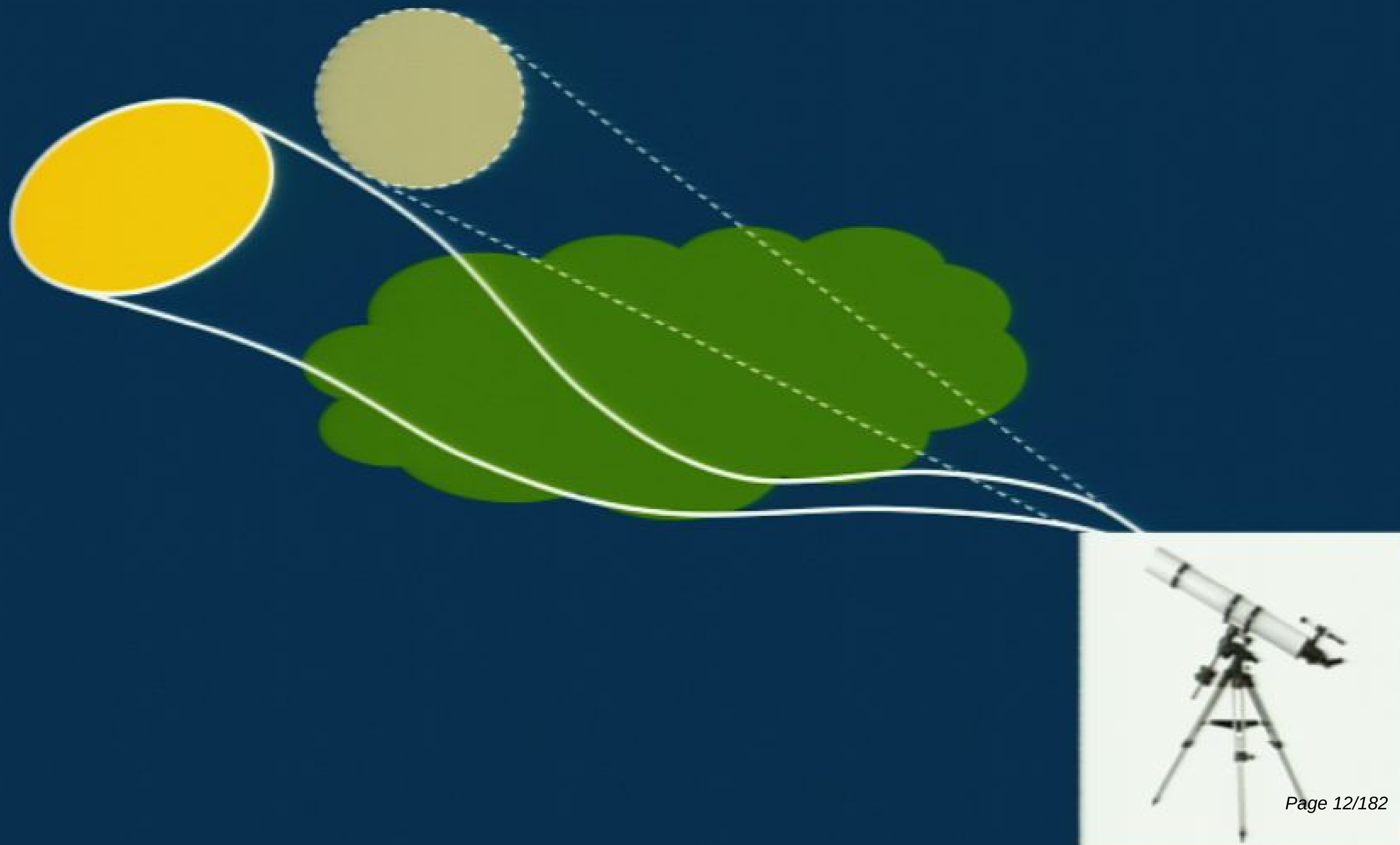
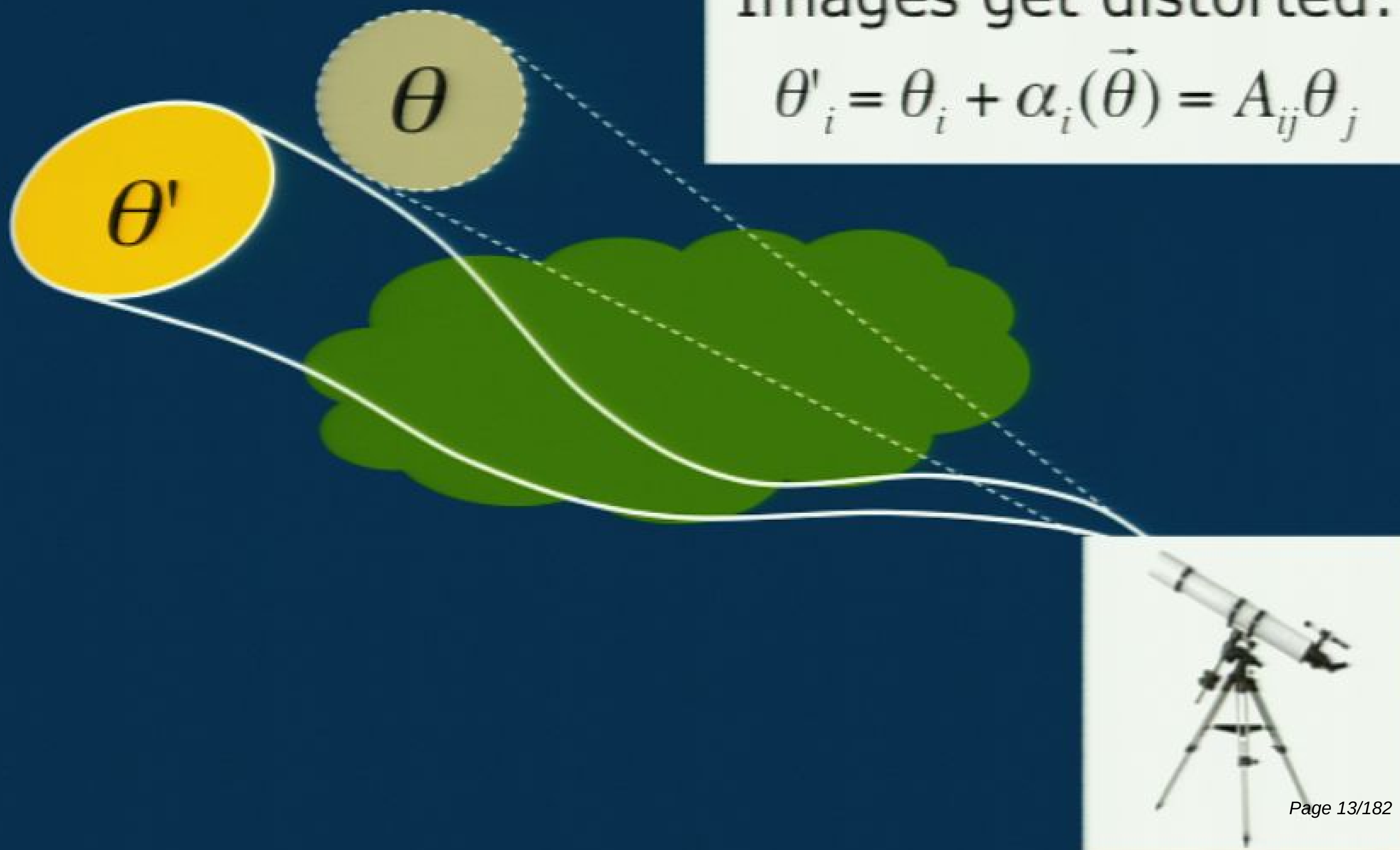


Matter acts like a lens

Images get distorted:

$$\theta'_i = \theta_i + \alpha_i(\vec{\theta}) = A_{ij}\theta_j$$



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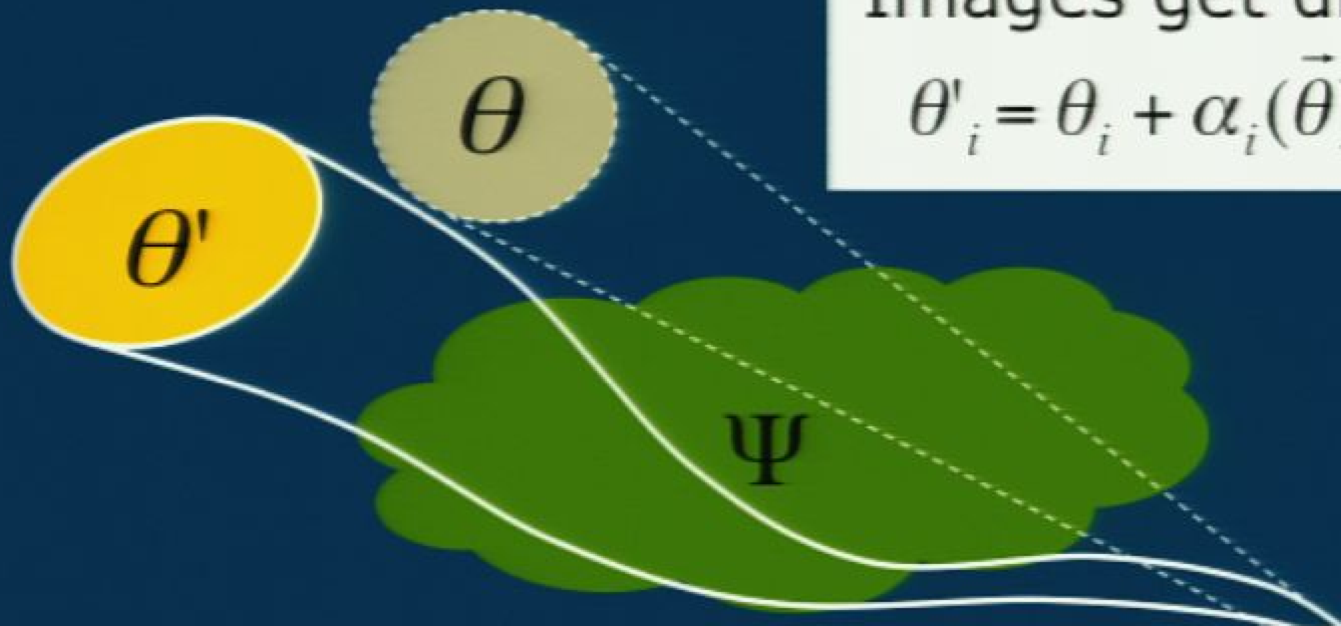

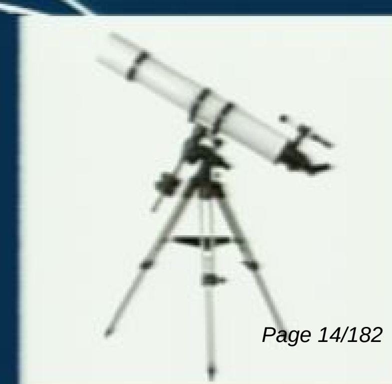

$$A_{ij} = \delta_{ij} + \frac{\partial^2 \Psi}{\partial\theta^i \partial\theta^j}$$

* In GR, to linear order

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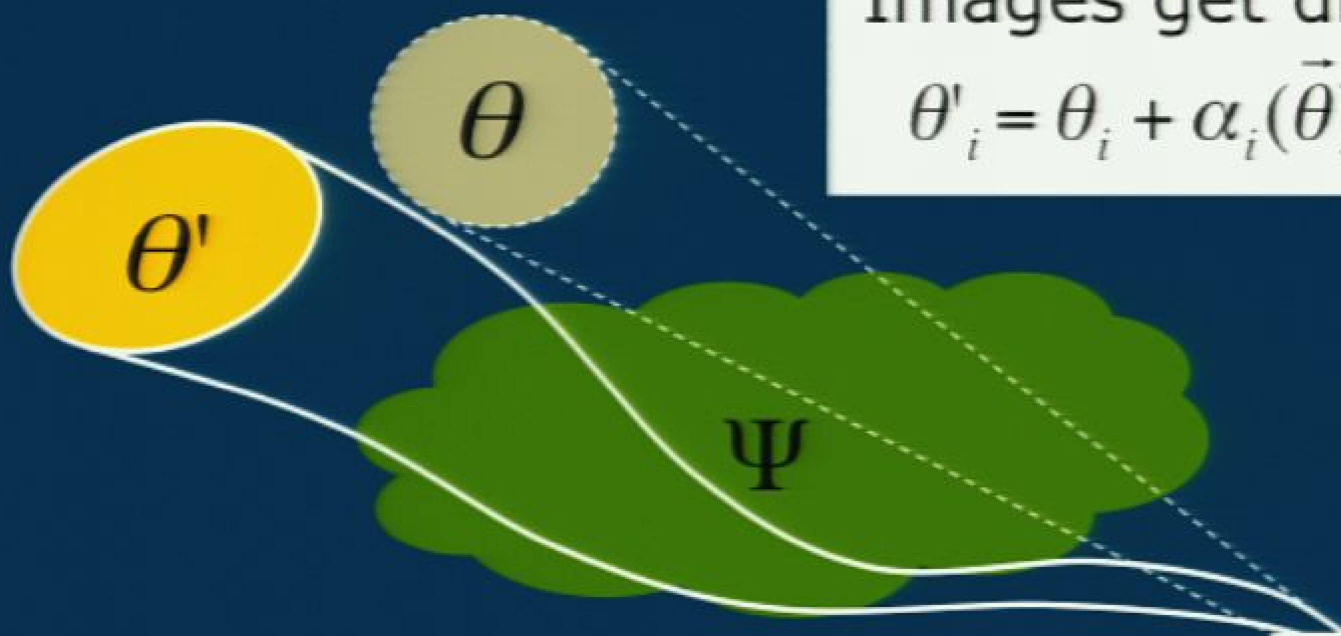

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Why should we care?

From matter distribution to galaxy distortions

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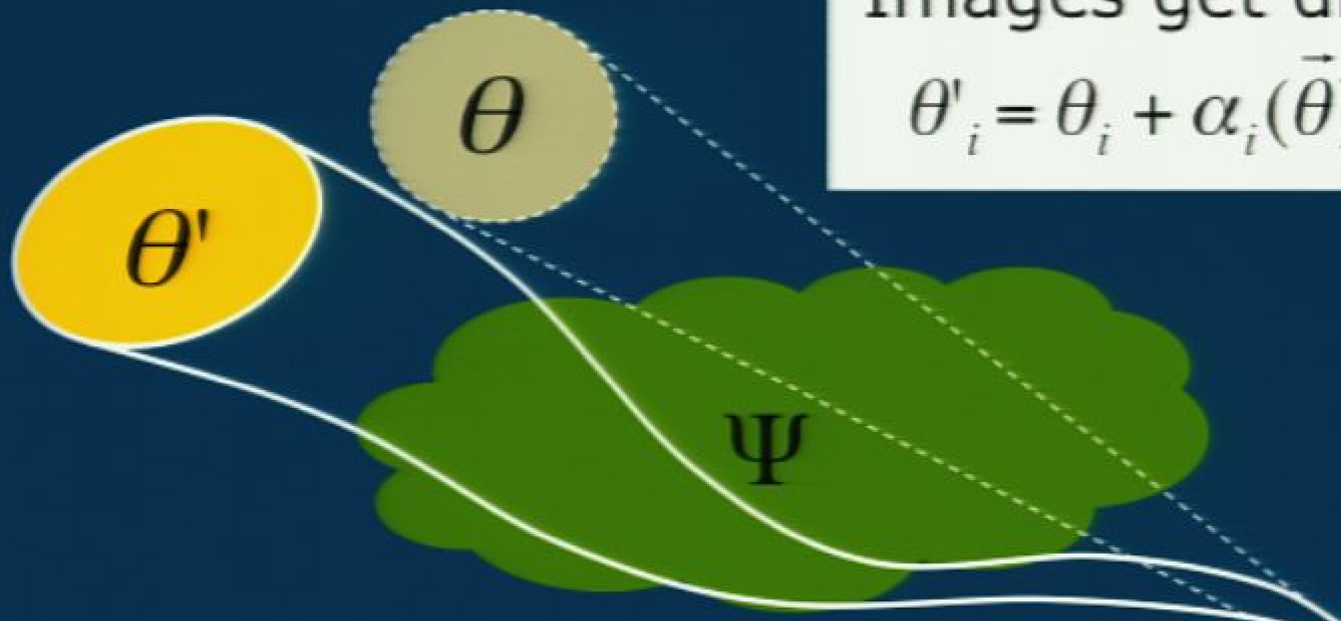

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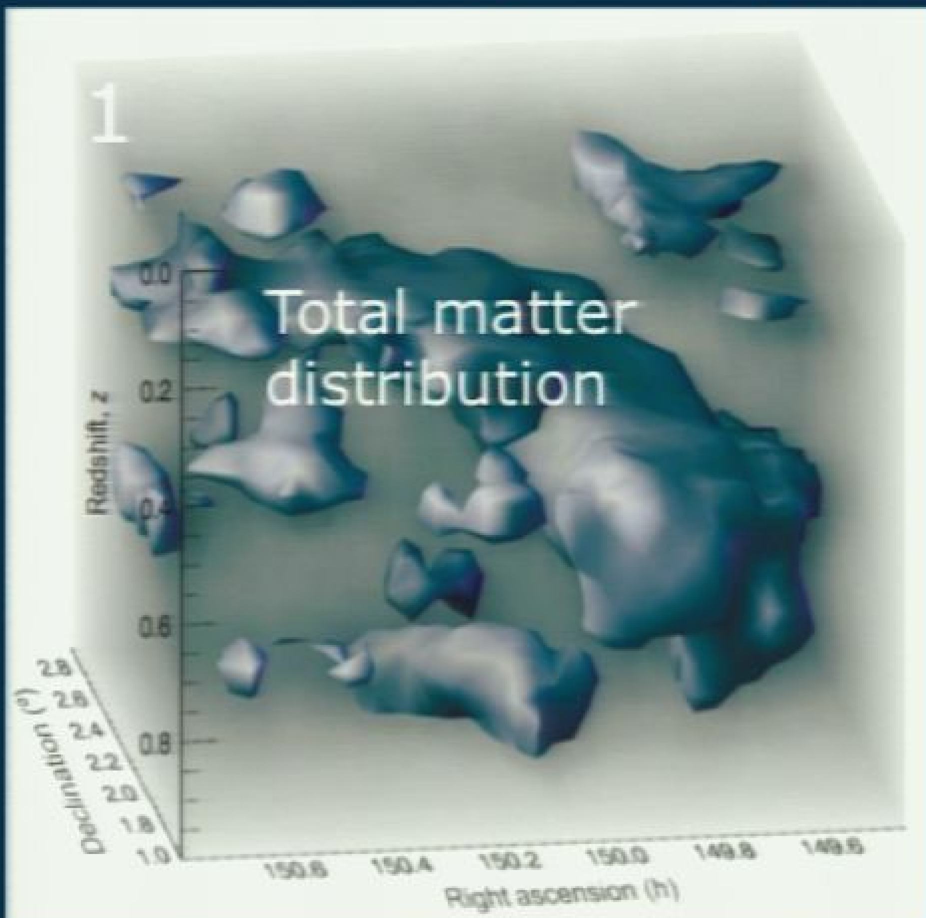

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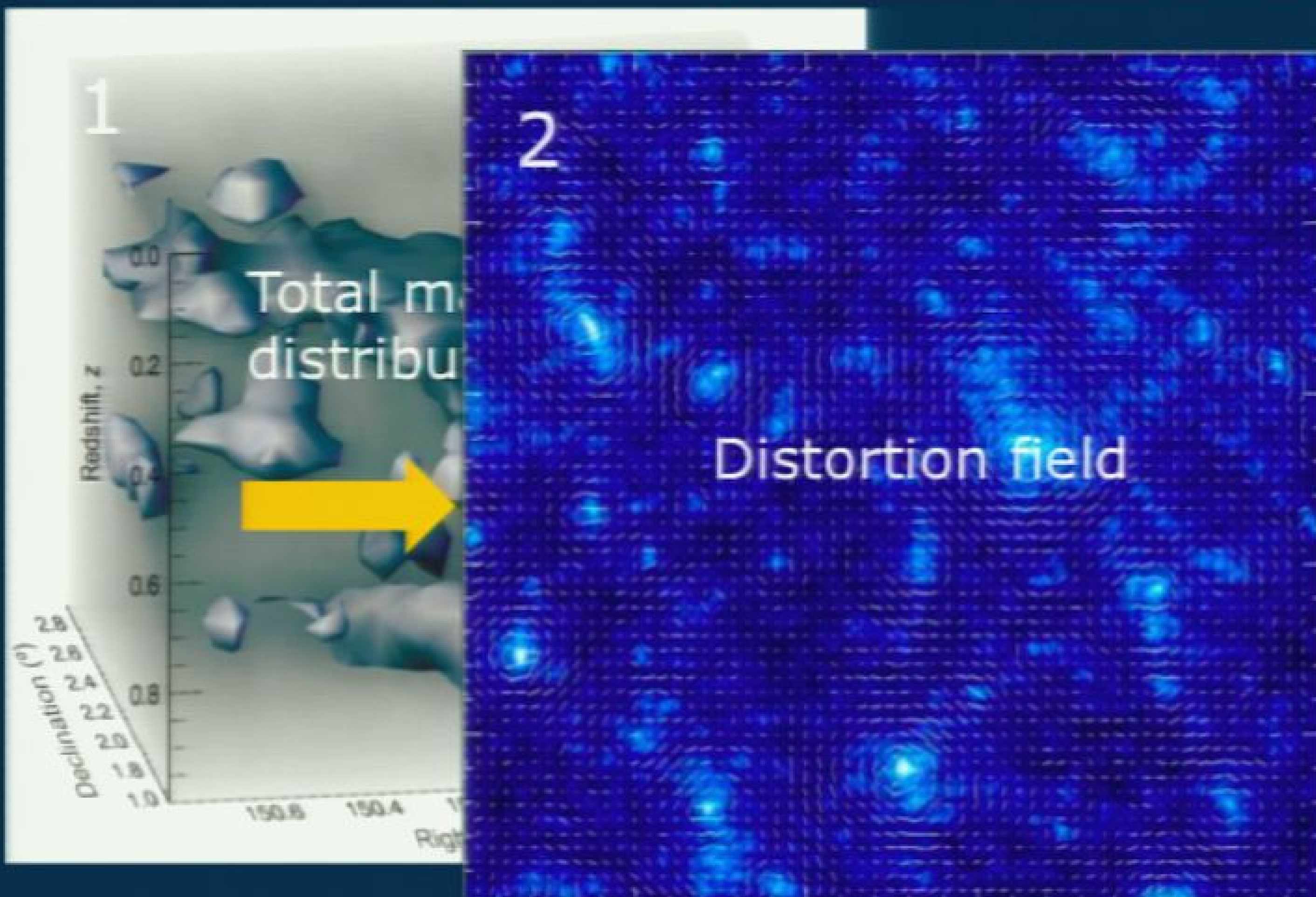

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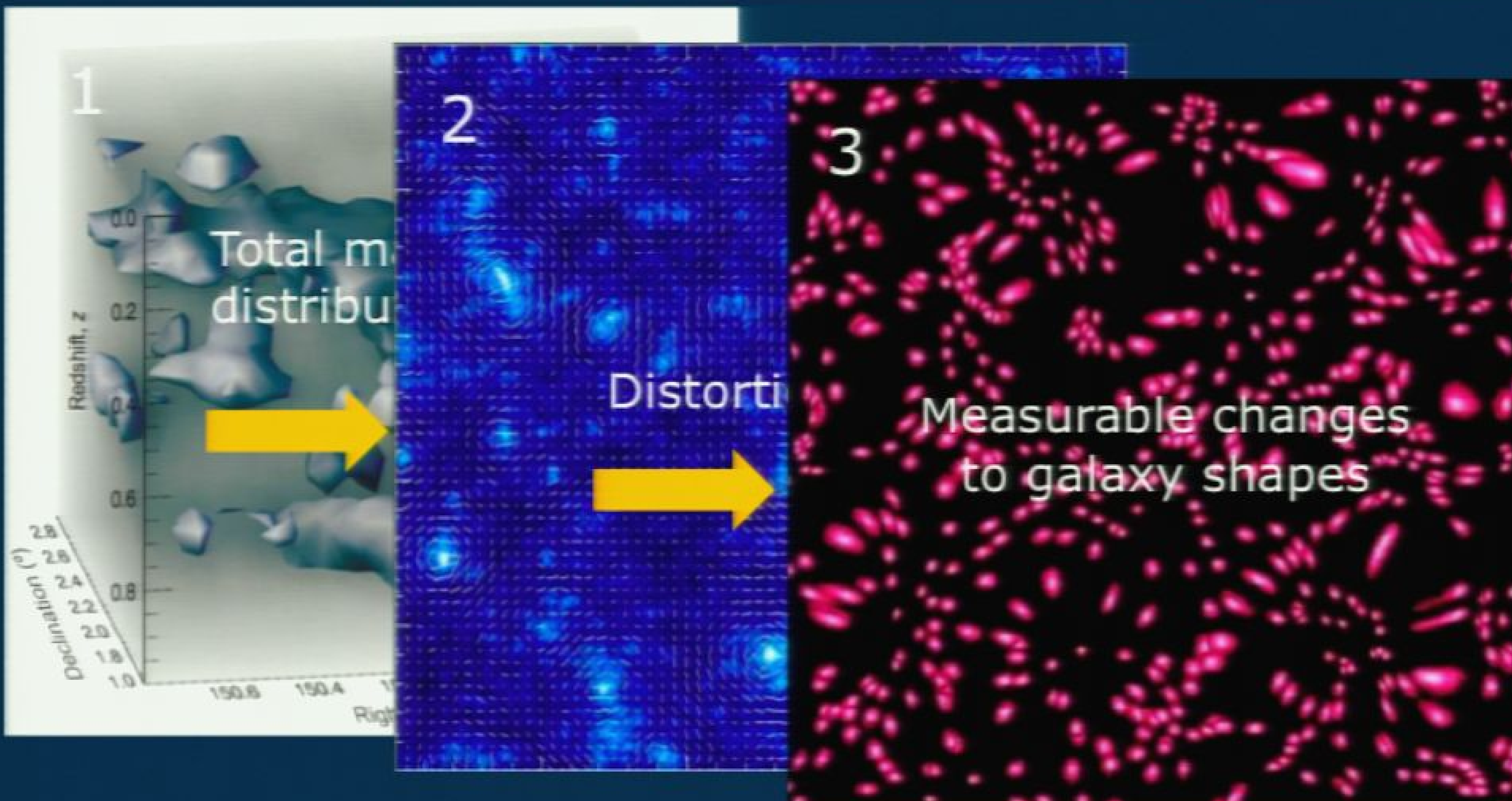

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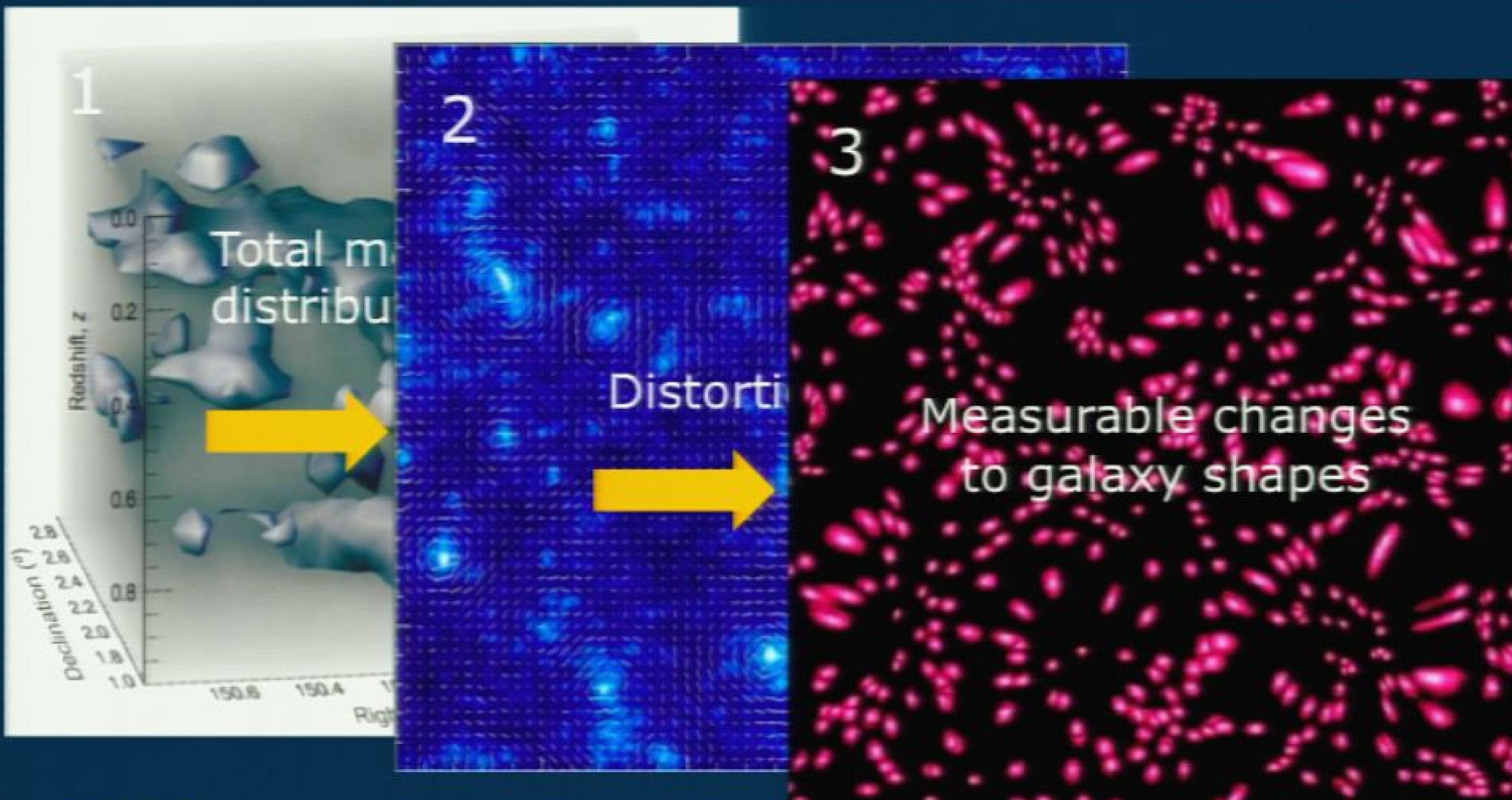

Goal –

to unravel this process to get from 3 back to 1

From galaxy shapes to matter distribution

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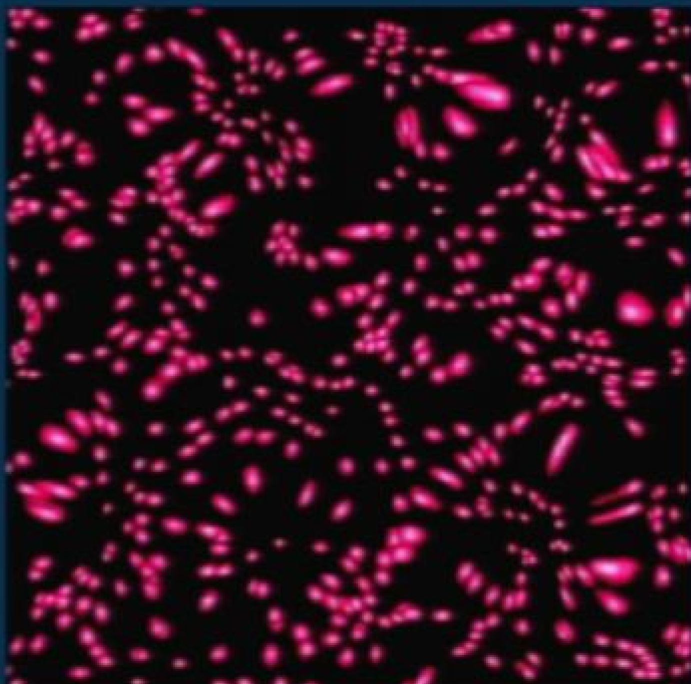

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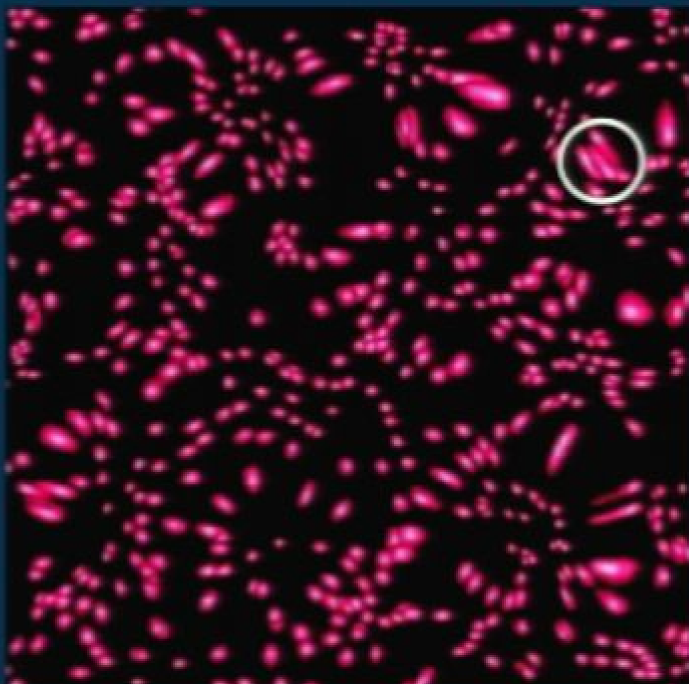

Galaxy ellipticity is an estimator of the shear:

$$\langle e_i \rangle \approx 2\gamma_i$$

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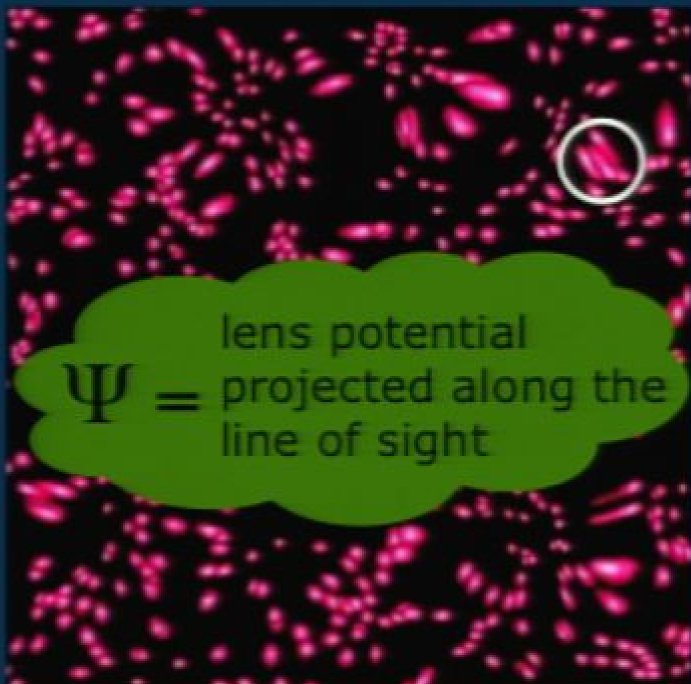

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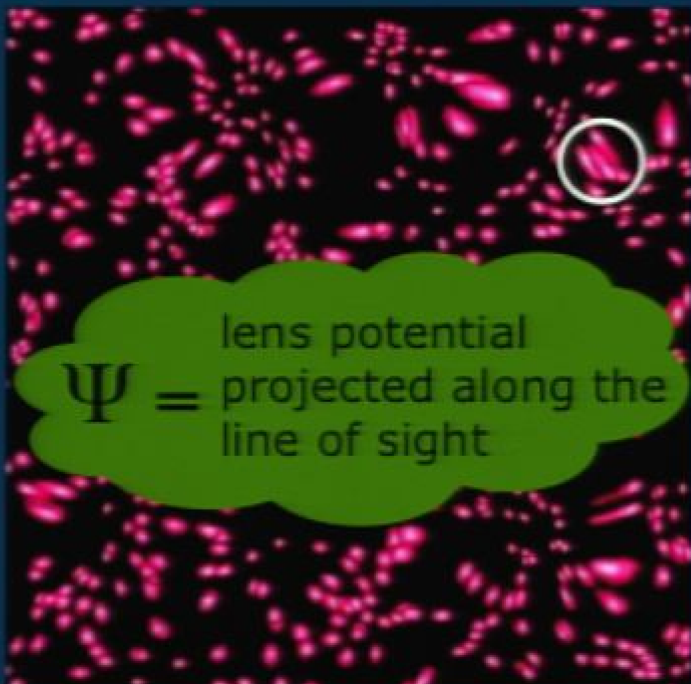

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The shear is a component of the distortion tensor:

$$A_{ij} = \delta_{ij} + \frac{\partial^2 \Psi}{\partial \theta^i \partial \theta^j}$$

$$\equiv \begin{pmatrix} 1+\kappa+\gamma_1 & \gamma_2 \\ \gamma_2 & 1+\kappa-\gamma_1 \end{pmatrix}$$

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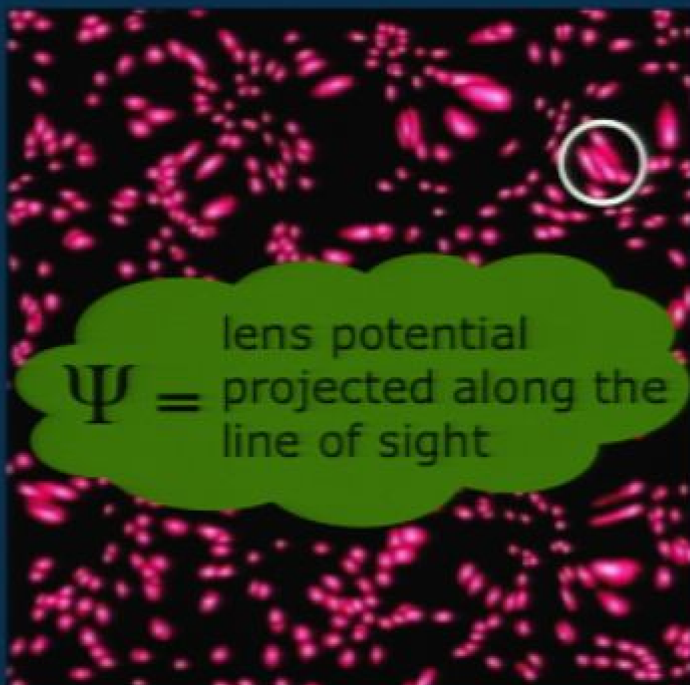

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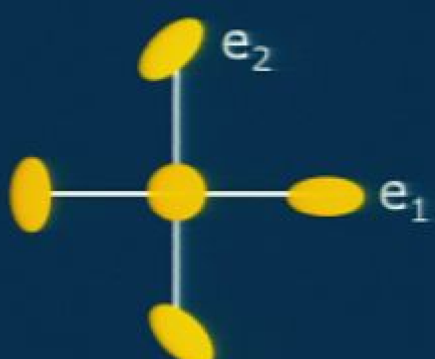

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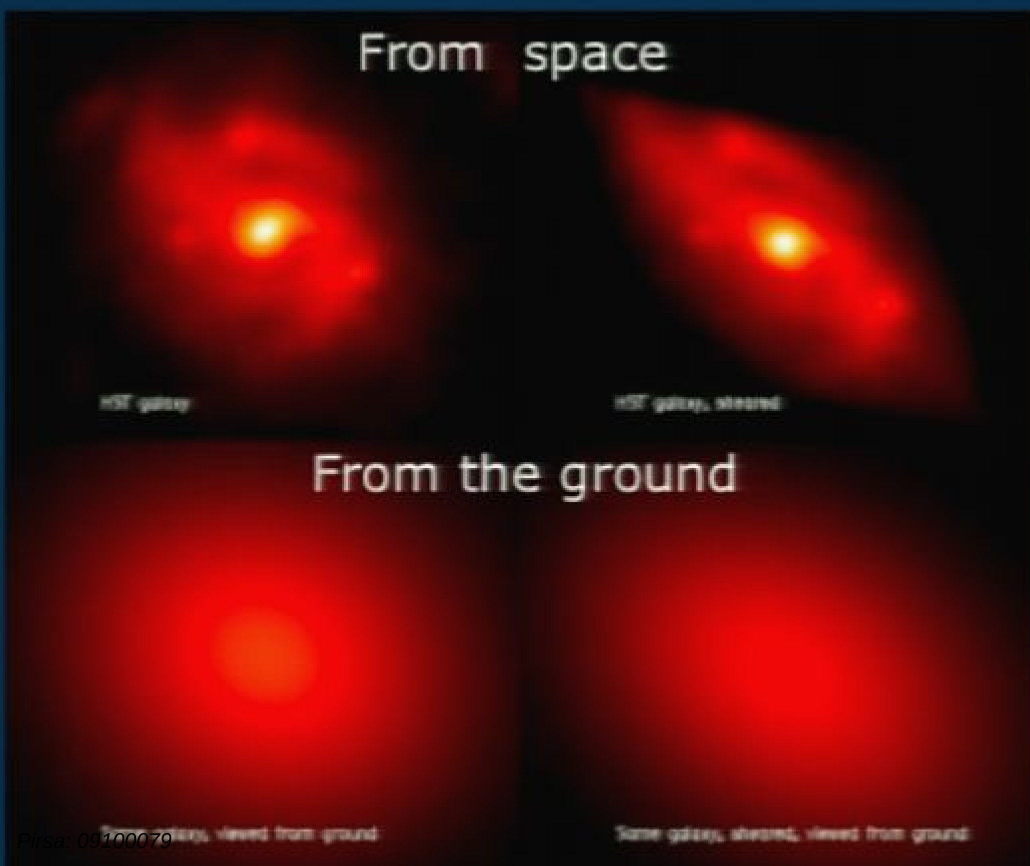

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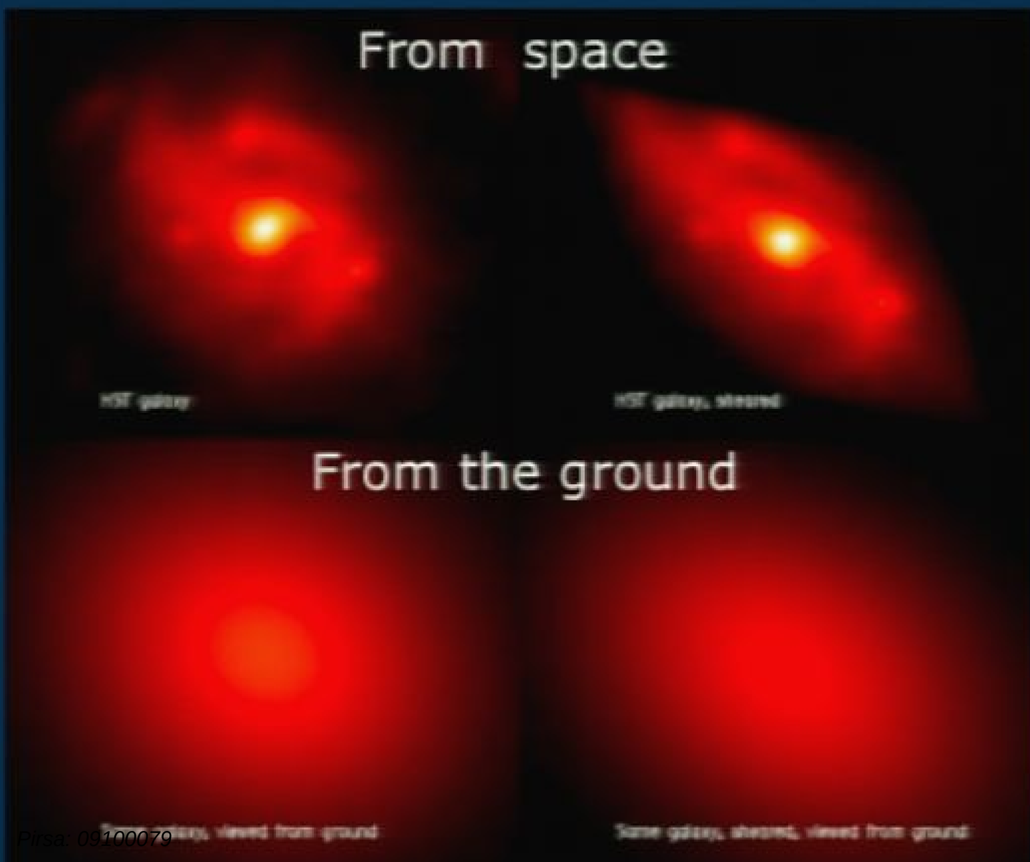

- Atmospheric seeing
- Intrinsic alignments (Hirata & Seljak 2004)

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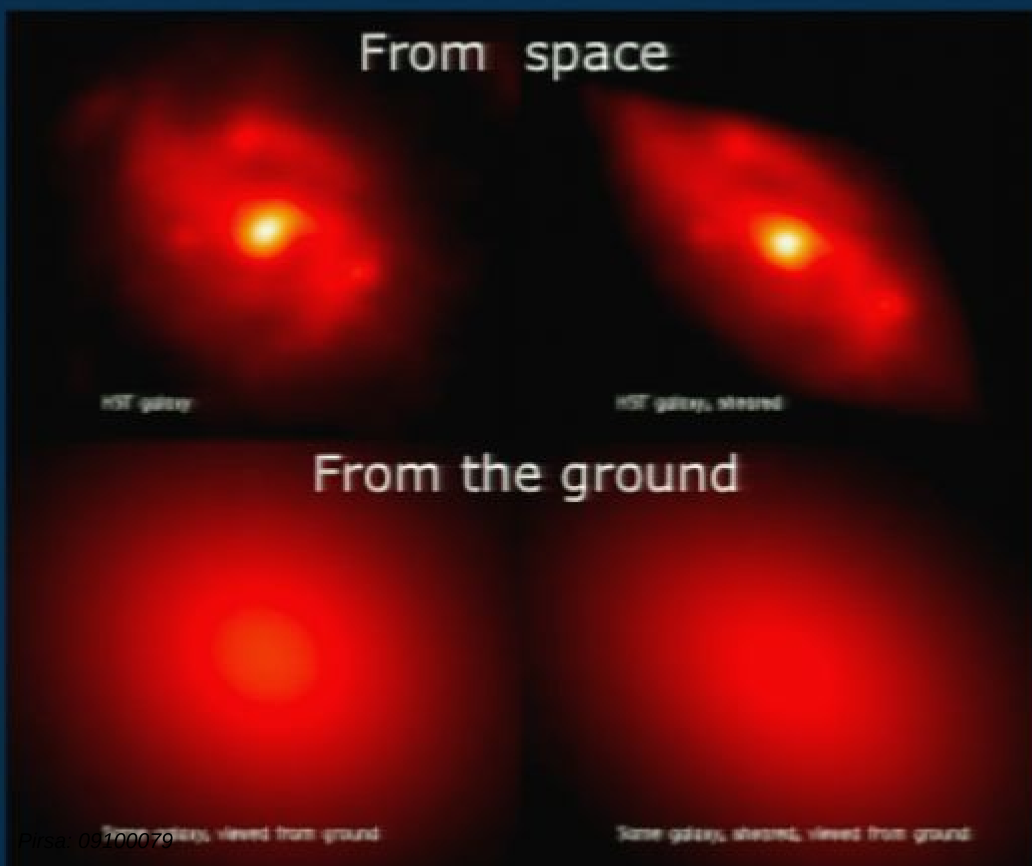

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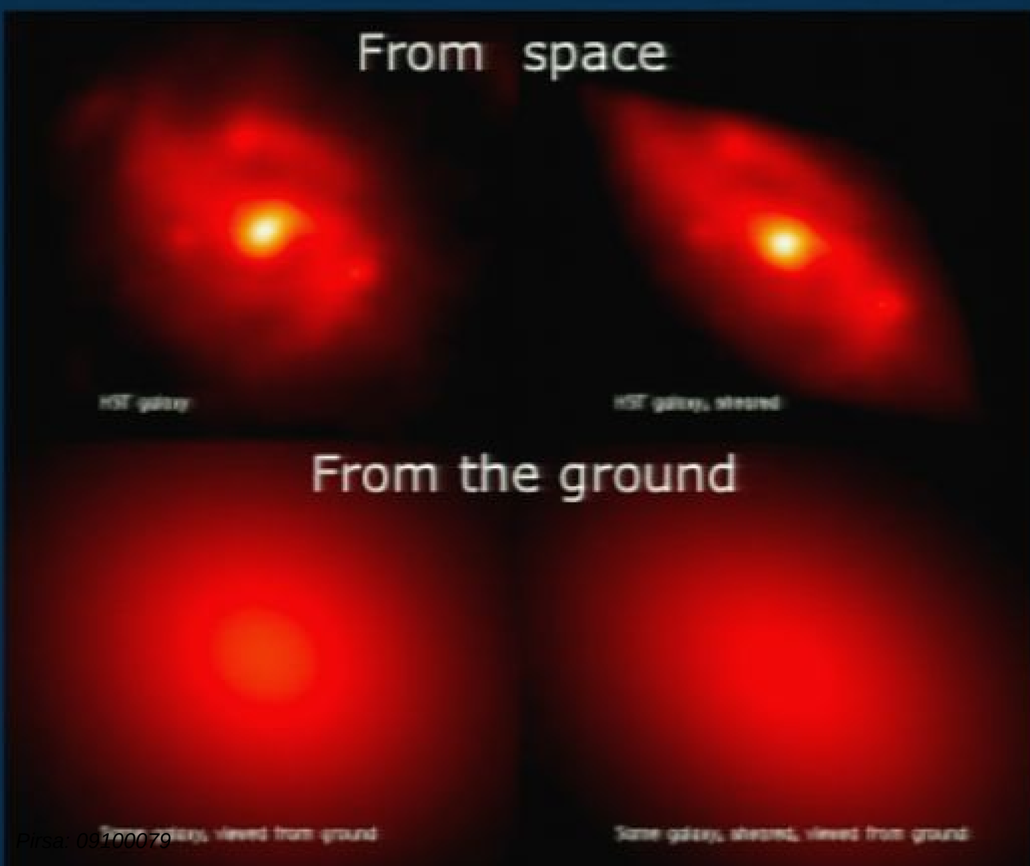

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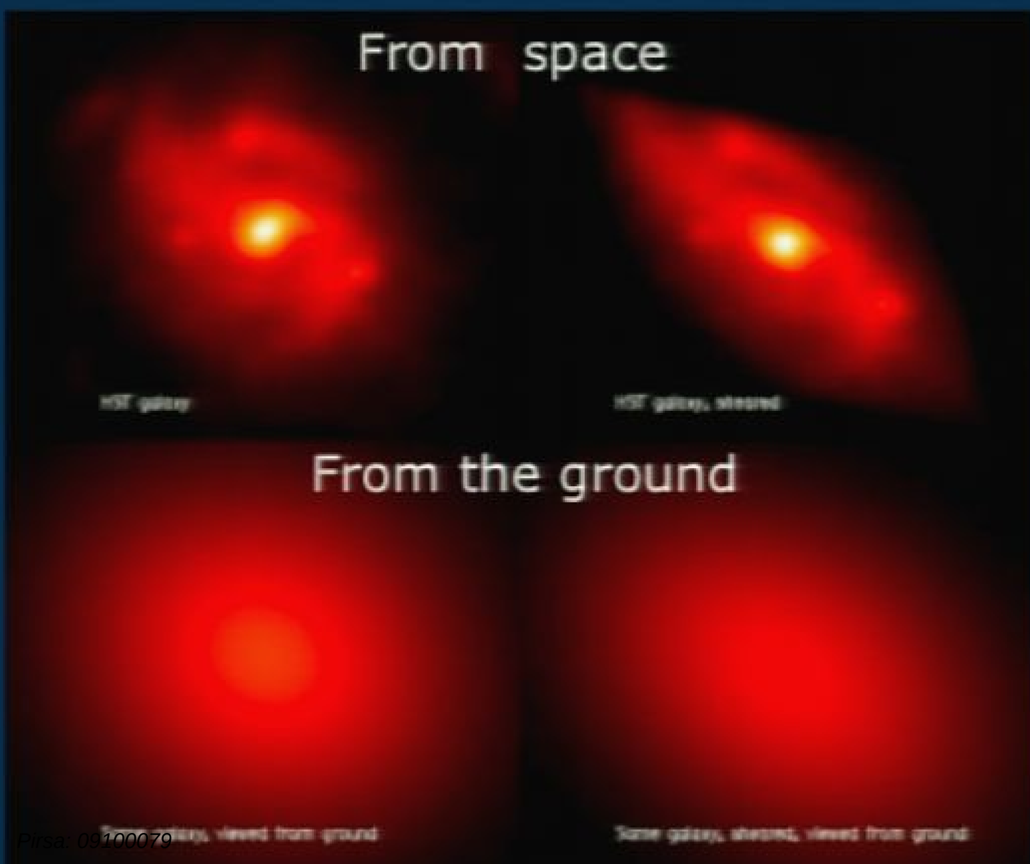

- Atmospheric seeing
- Intrinsic alignments (Hirata & Seljak 2004)
- Instrumental point spread function
- Detector effects, e.g. charge transfer inefficiency (Massey et al. 2009)
- Lossy data compression (Bernstein et al. 2009, AV et al. in prep)

Survey simulations

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Weak lensing image simulation housed @ Caltech (Dobke et al. 2009)

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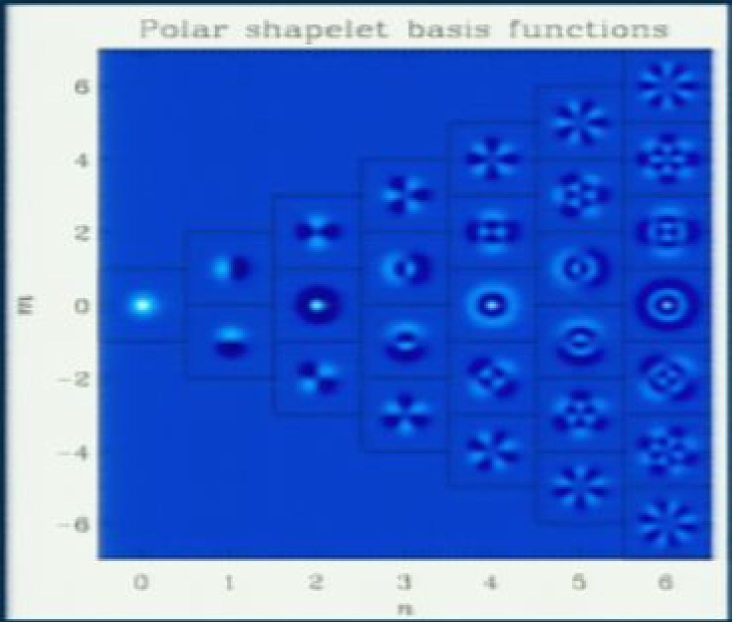

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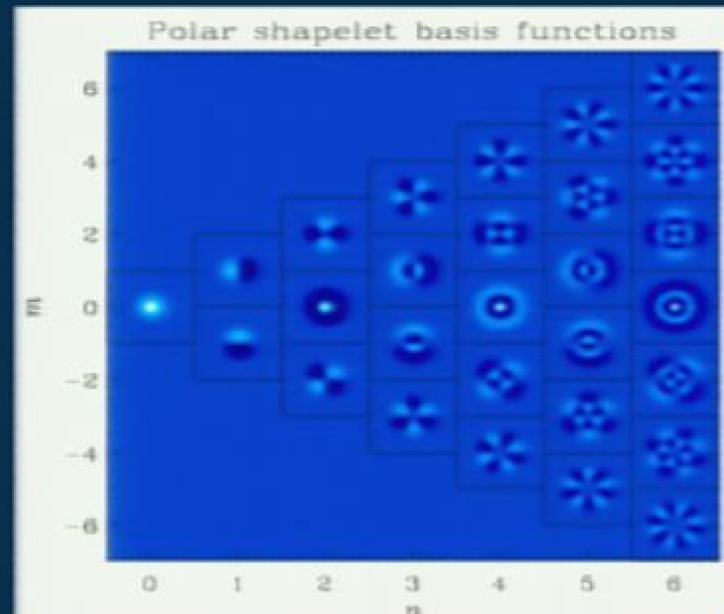

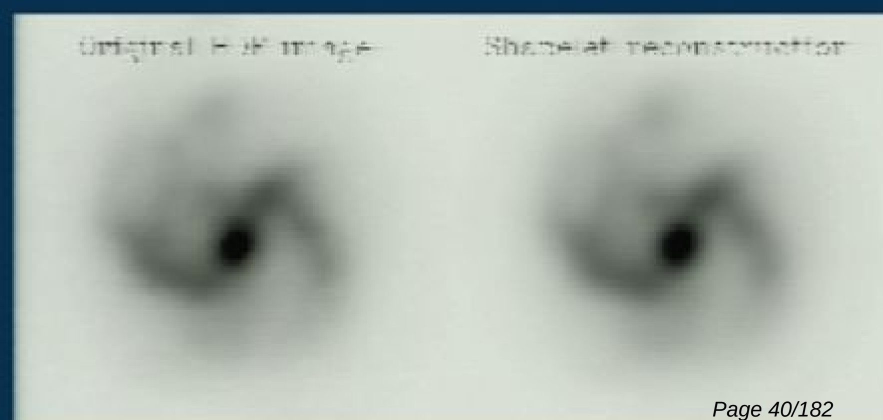

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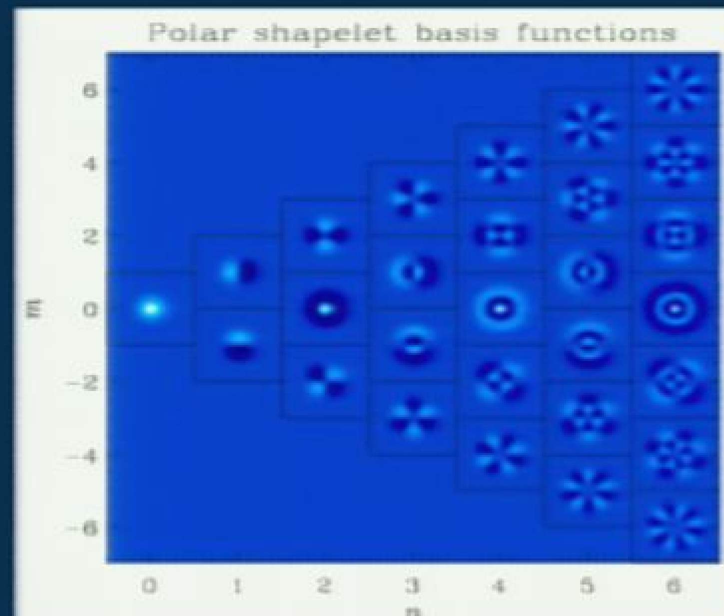

Parameter file input:	Description:
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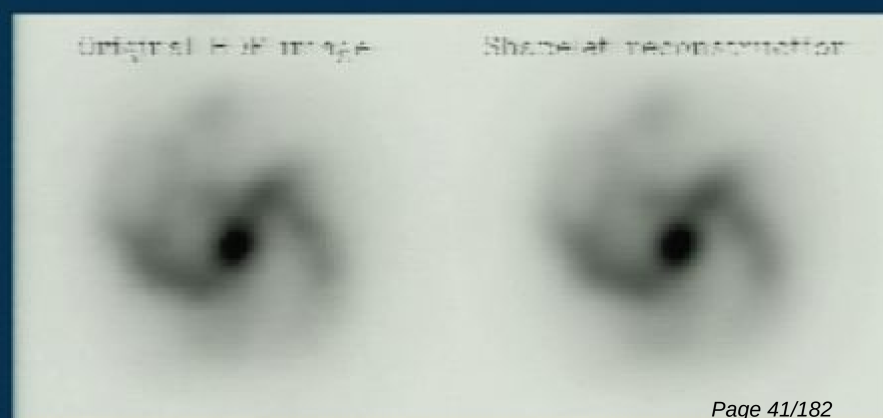
random_seed	A random seed for all random selections
gamma	The user specified weak lensing shear
output_file_pref	Selection of output image file names
n_star	Number of field stars to be added
n_gal	Number of field galaxies
filter_files	Path to user's transition filter files
ee50	The half light radius of the PSF



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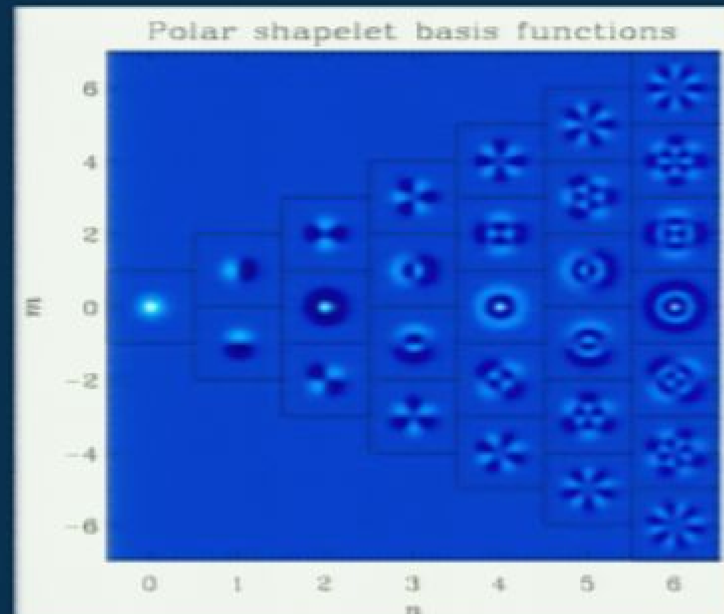

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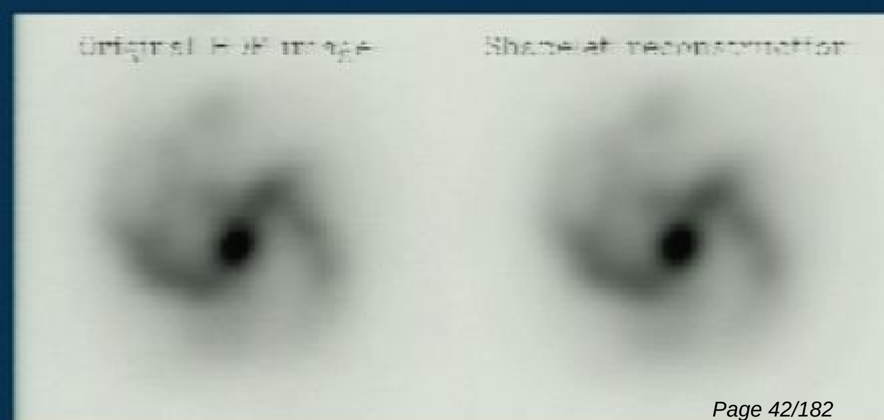

Weak lensing science

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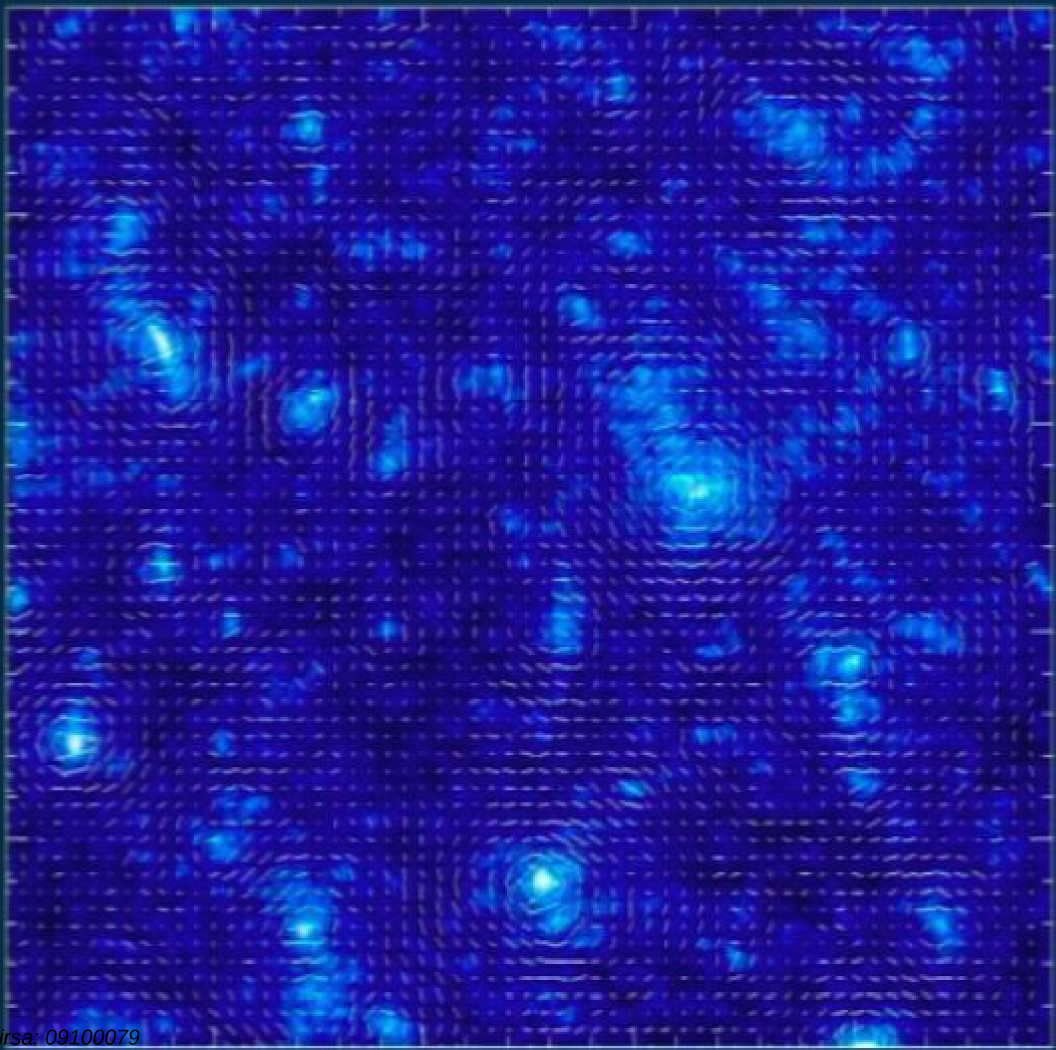
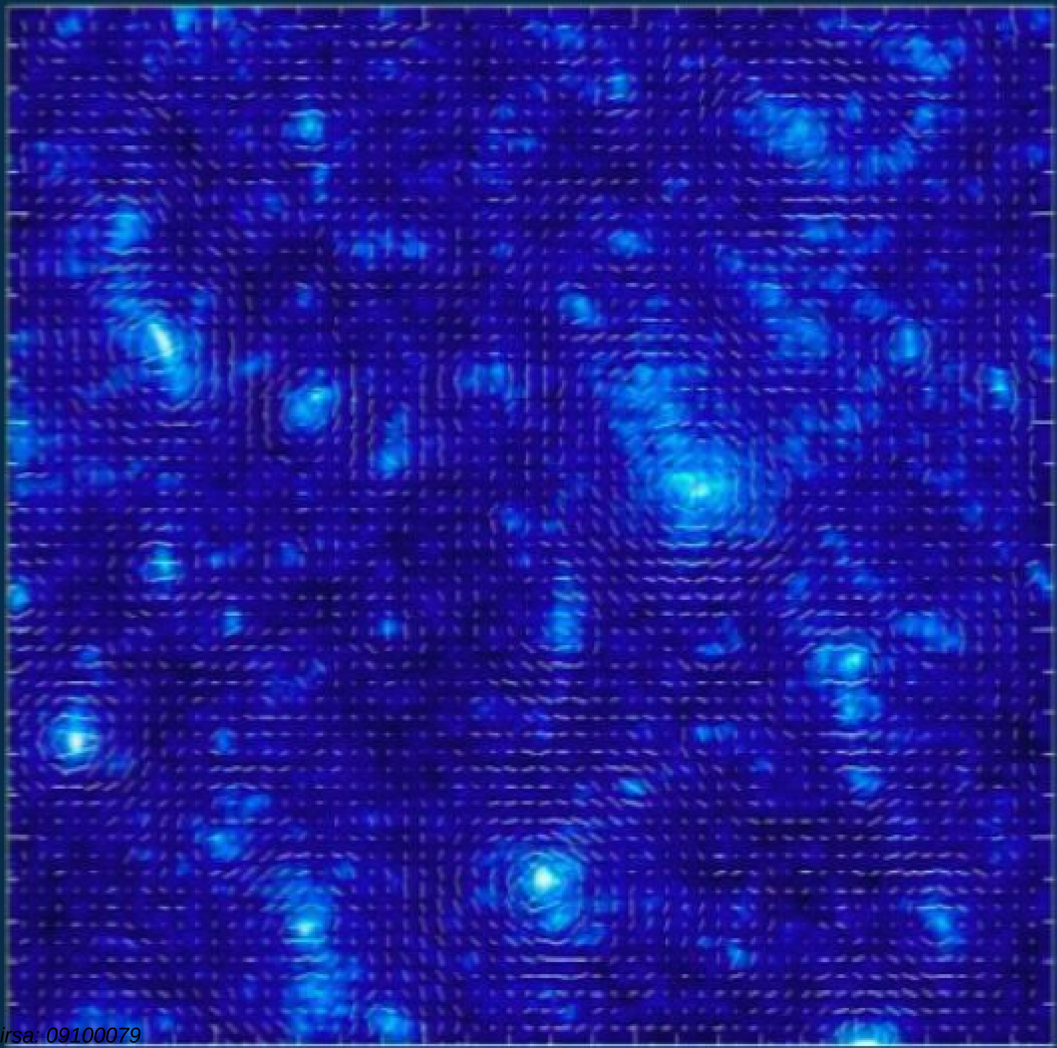


Numerical simulation (Jain, Seljak & White 2000)

Weak lensing science



The shear map (with redshifts) and its statistics tell us about:

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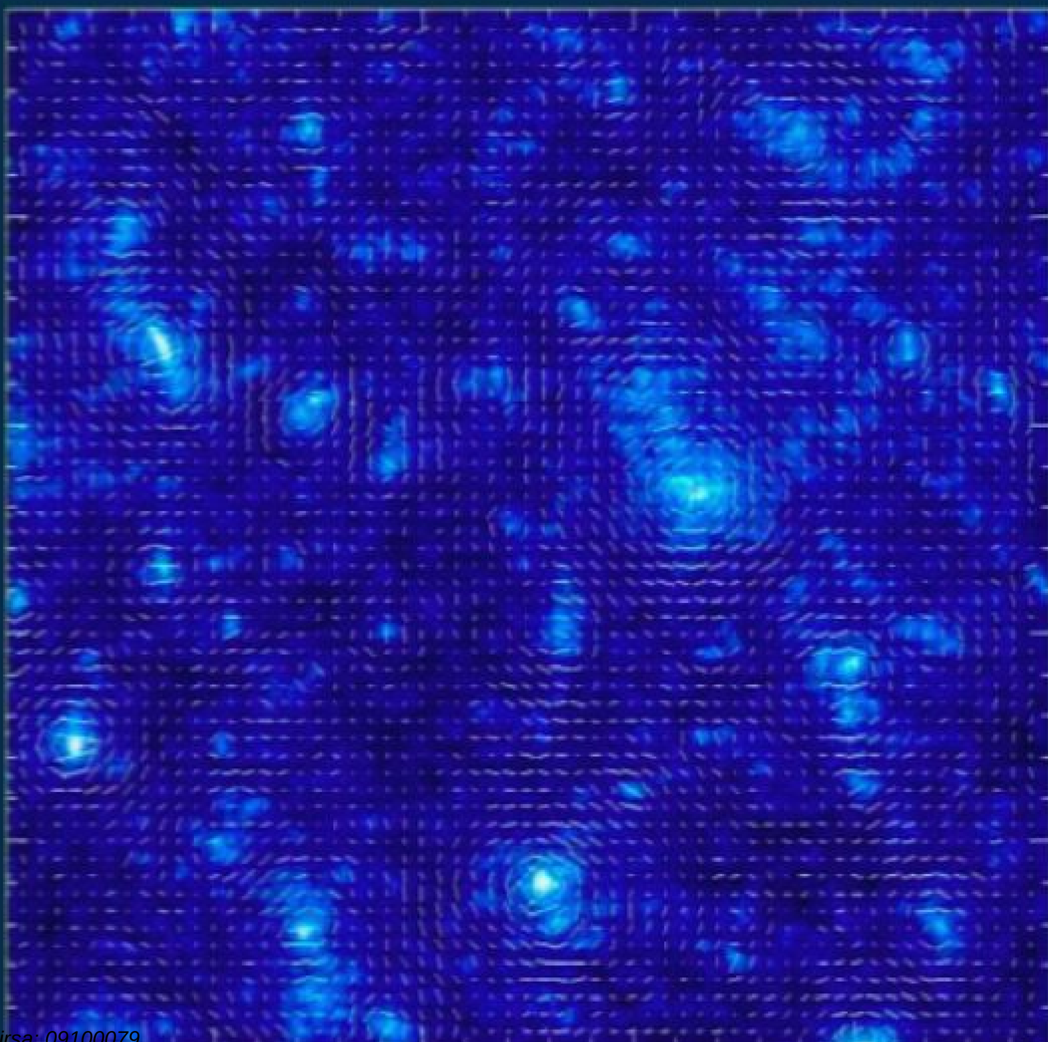

The shear map (with redshifts) and its statistics tell us about:

• the large scale matter distribution

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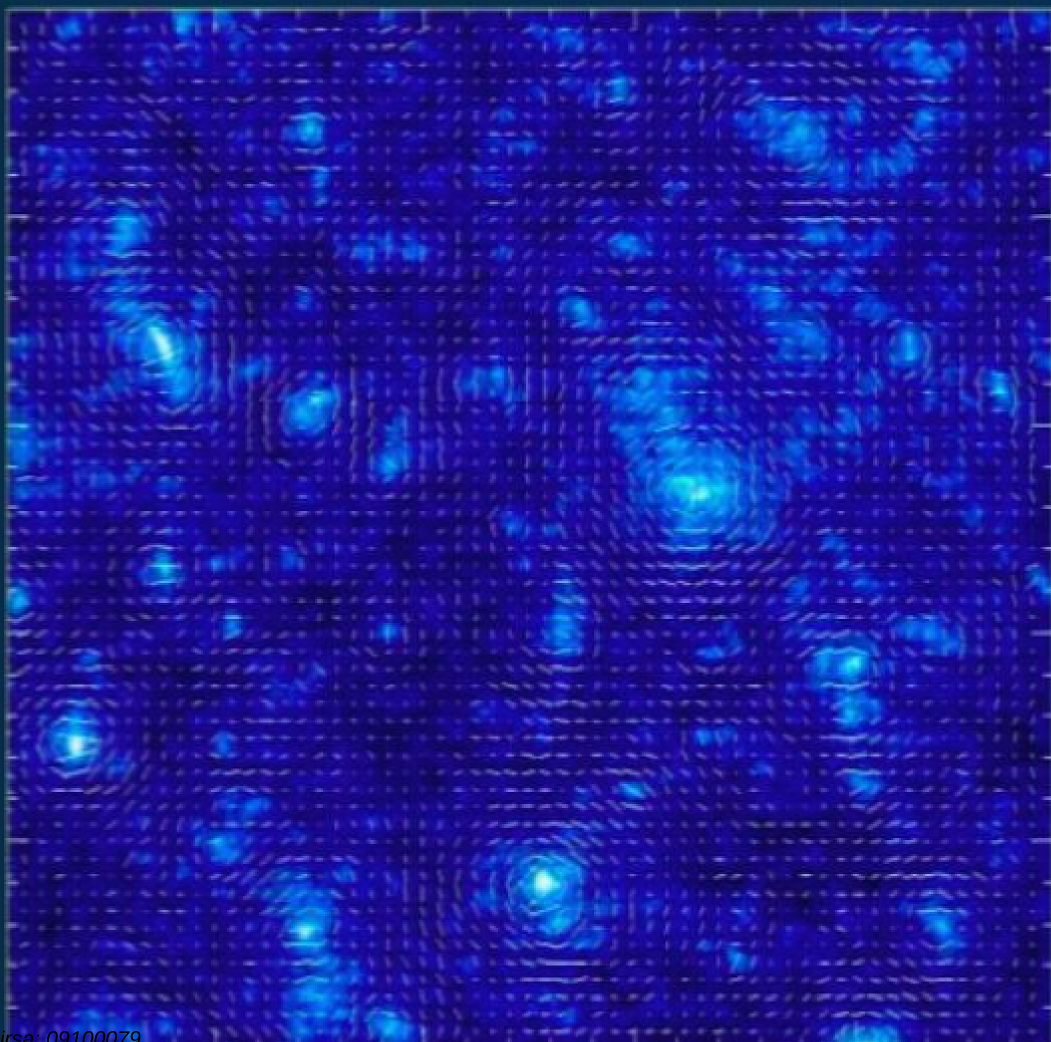

The shear map (with redshifts) and its statistics tell us about:

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- the evolution of large scale structure

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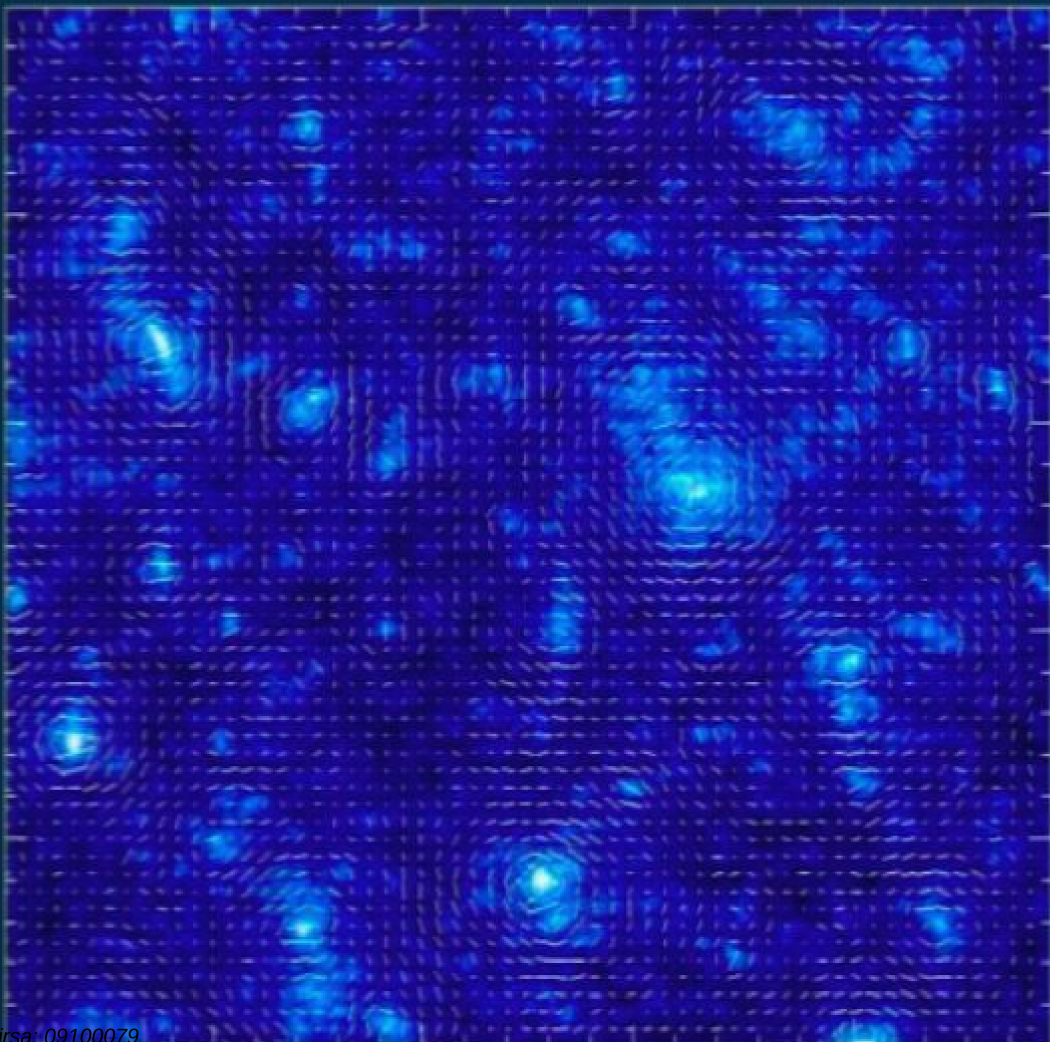

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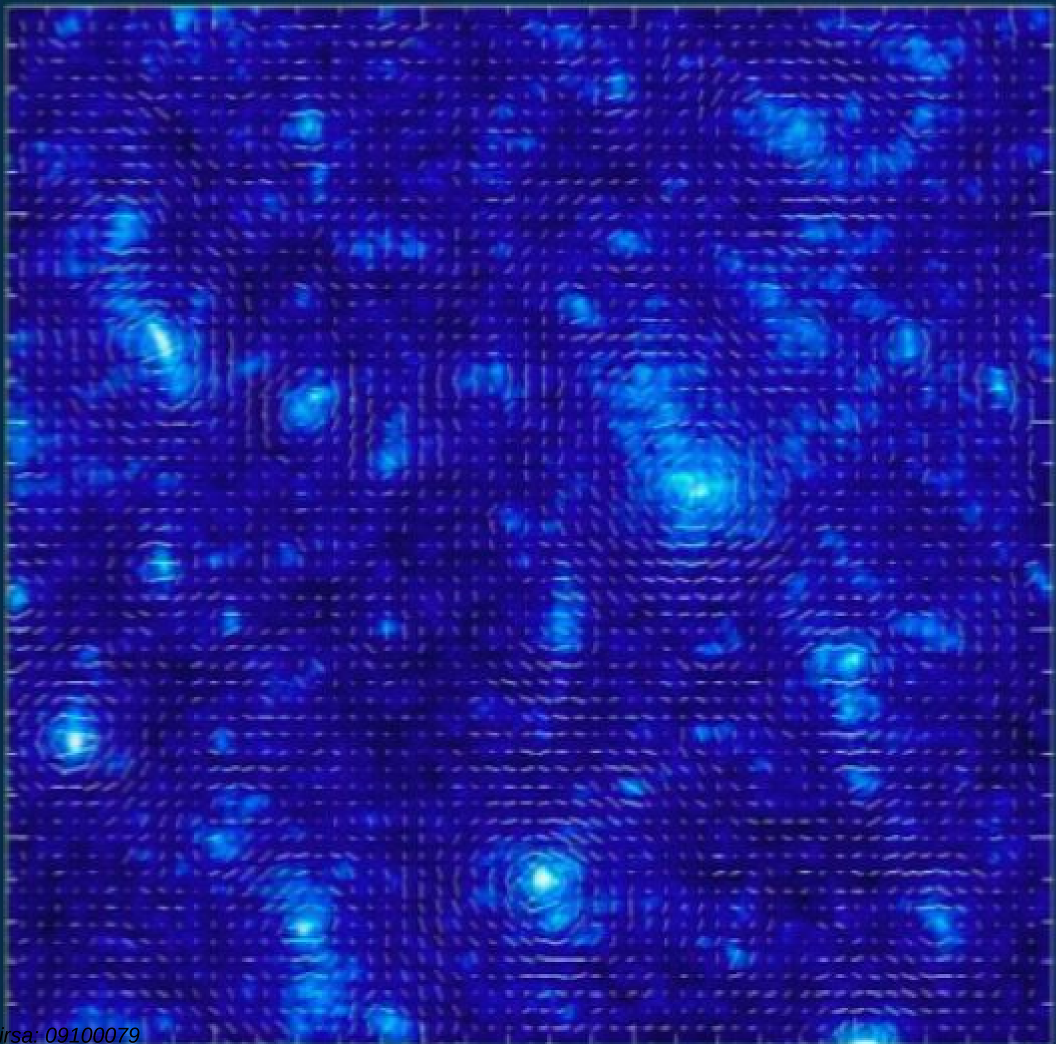

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- the large scale matter distribution
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- non-Gaussianity

Numerical simulation (Jain, Seljak & White 2000)

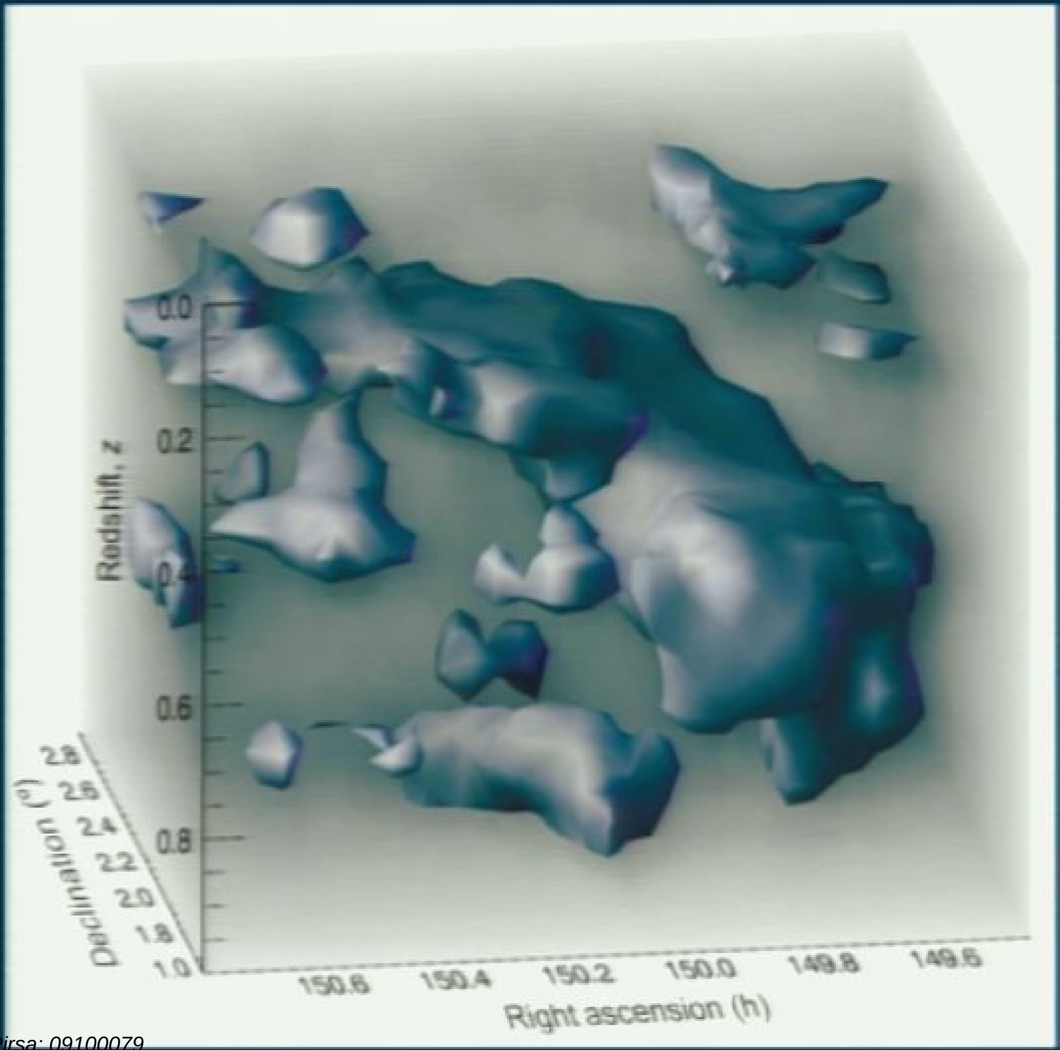
Dark matter maps

Dark matter maps

COSMOS –
2° square survey

- Imaging with ACS I band
- Redshifts from the ground

Dark matter maps



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Massey et al. 2007

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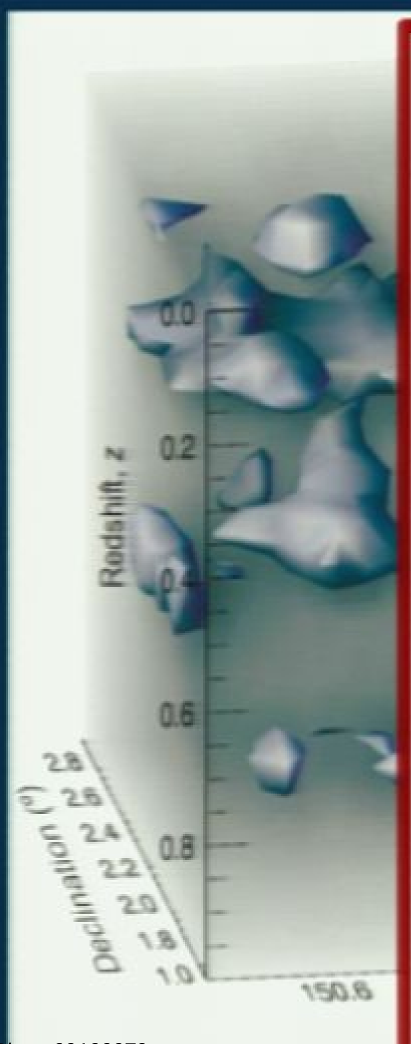

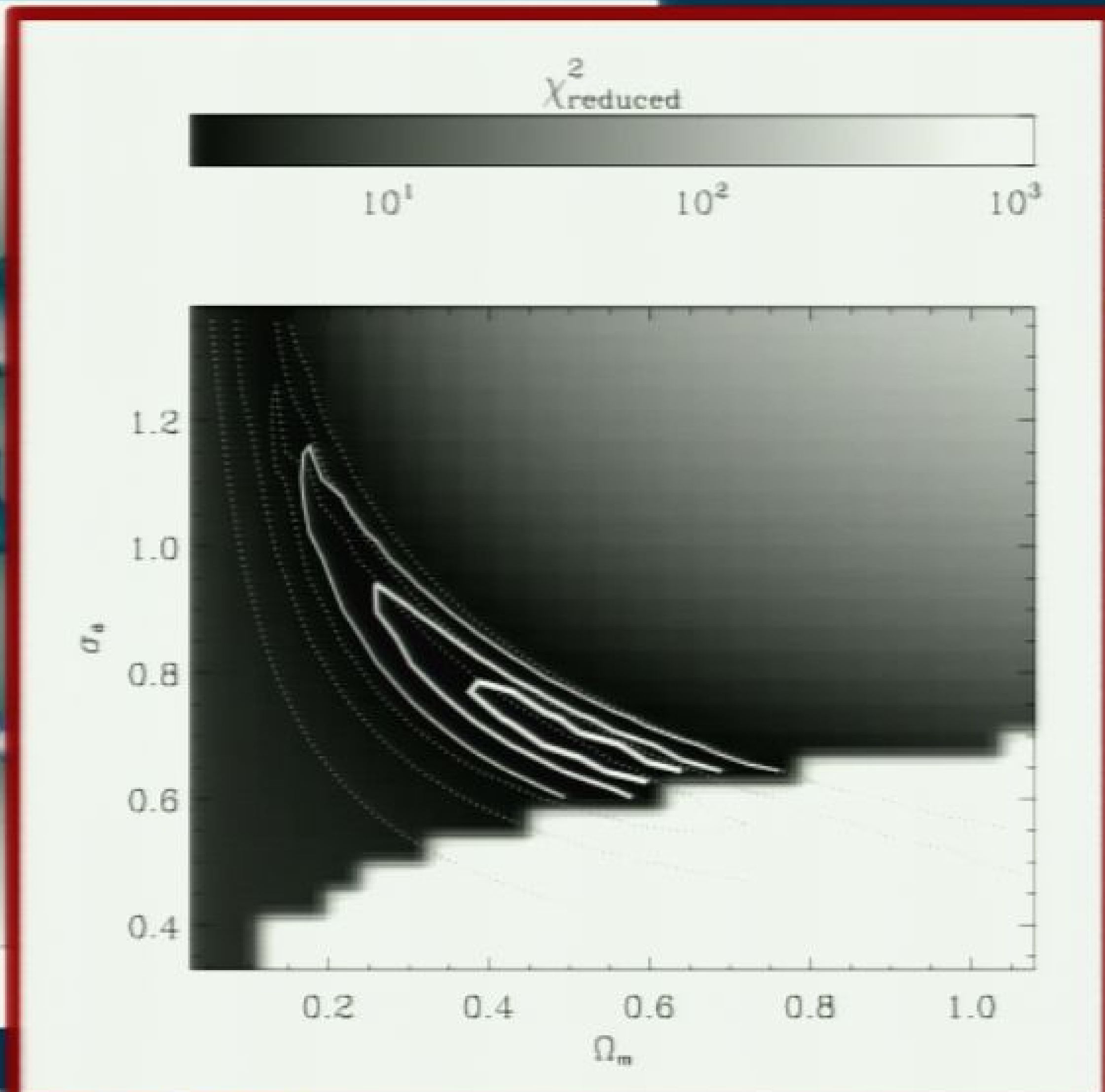

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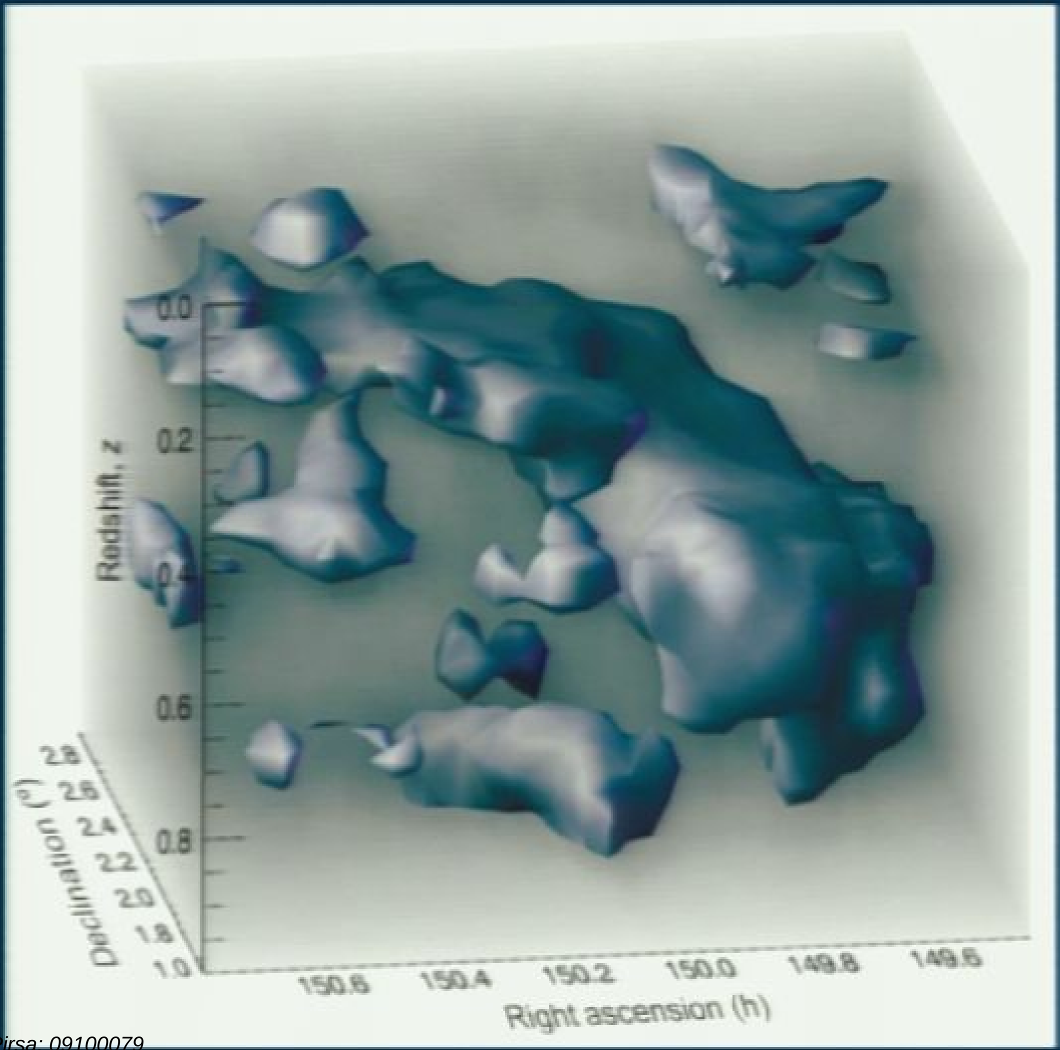

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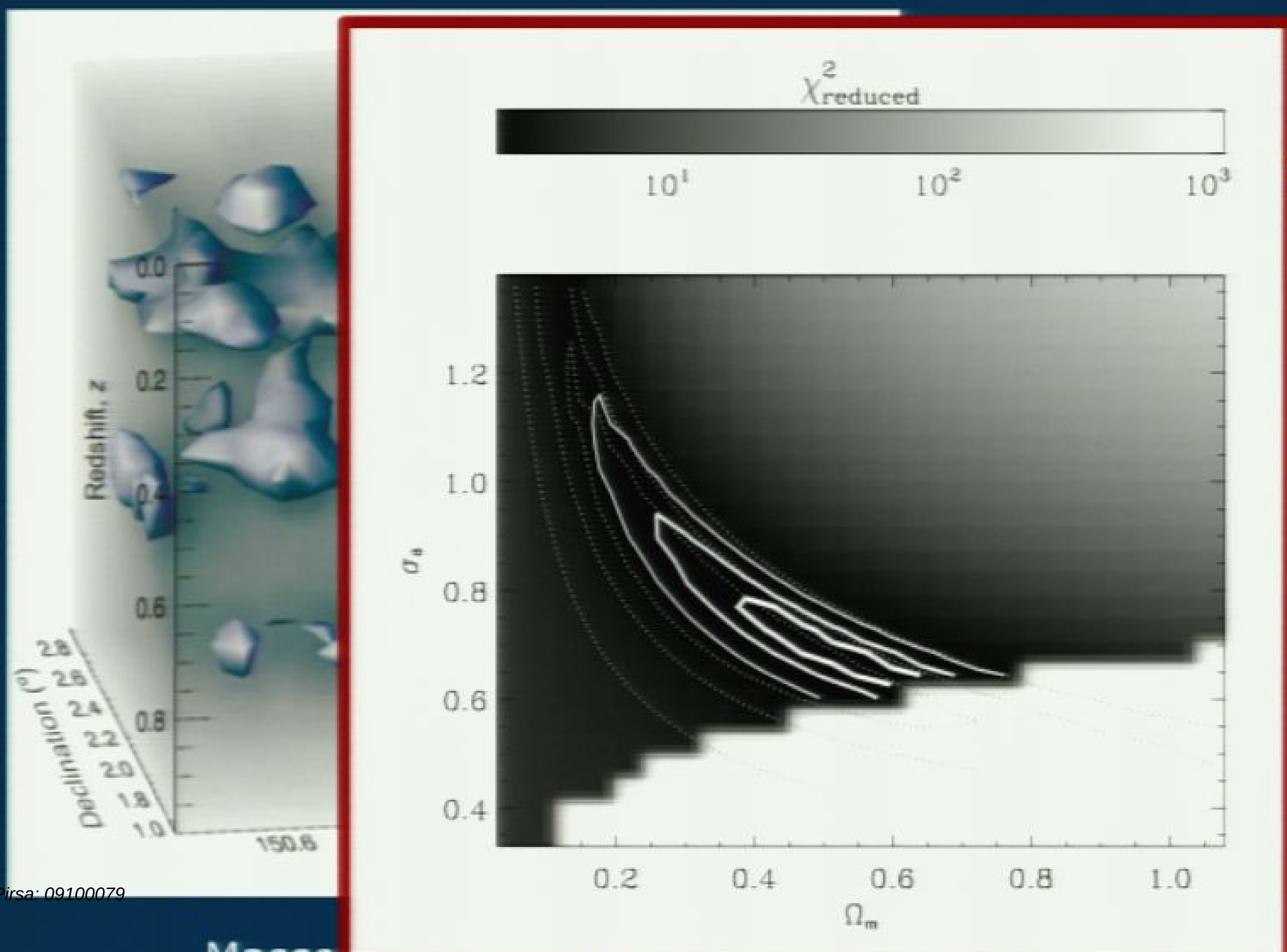

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Dark energy constraints

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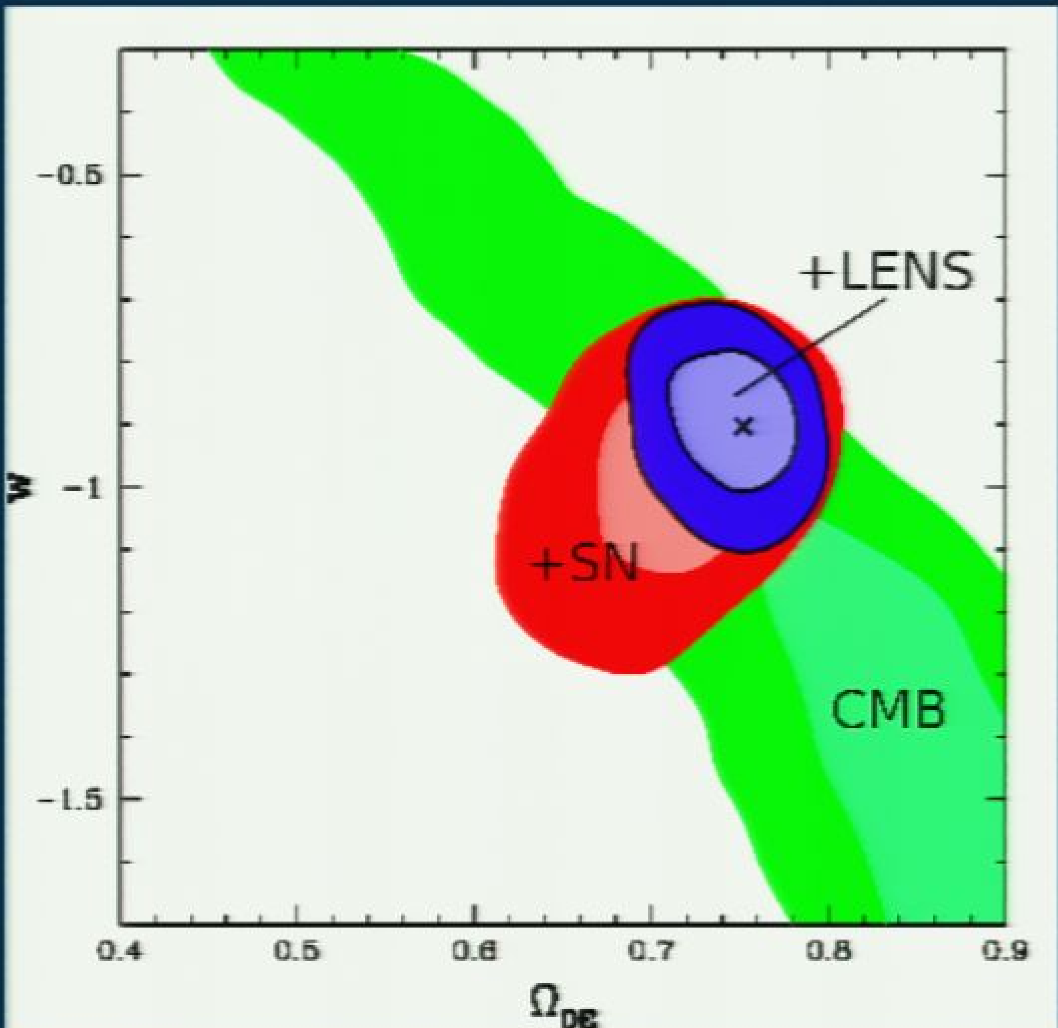
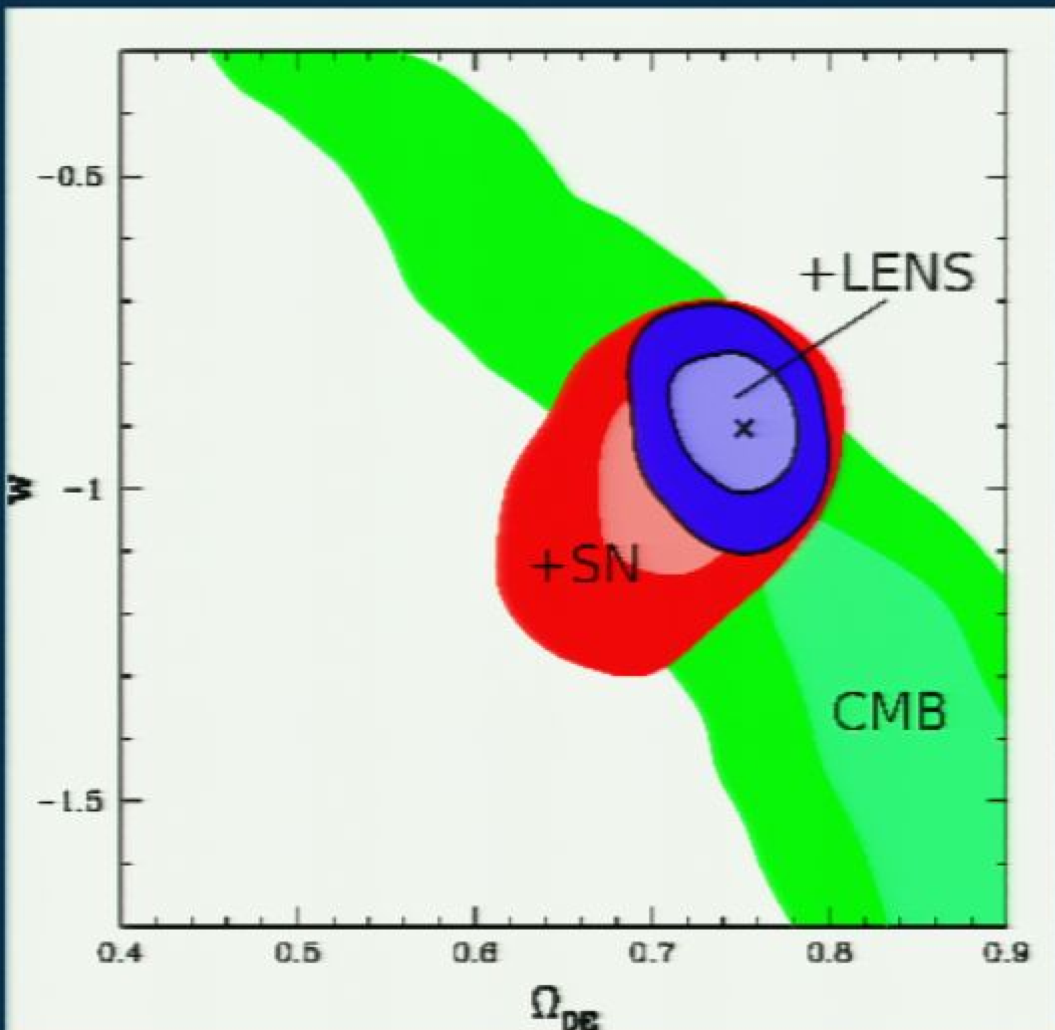


Jarvis et al. 2006 (CTIO)

Dark energy constraints



Dark Energy Task Force: "Weak lensing is potentially the most powerful probe of dark energy. The ultimate limit would be set by the extent to which the systematics can be controlled."
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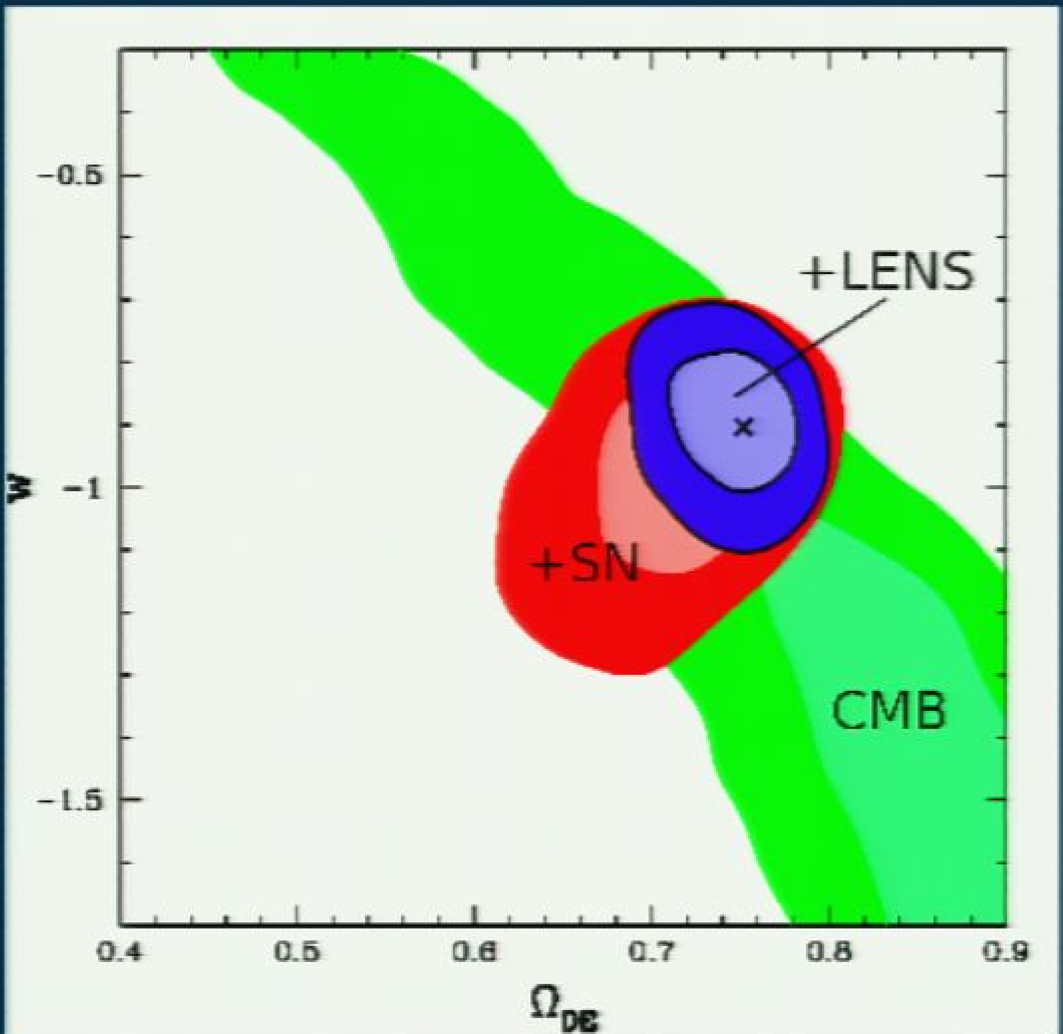

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Can also constrain modifications to General Relativity

Testing GR

Motivation for modifying GR on large scales

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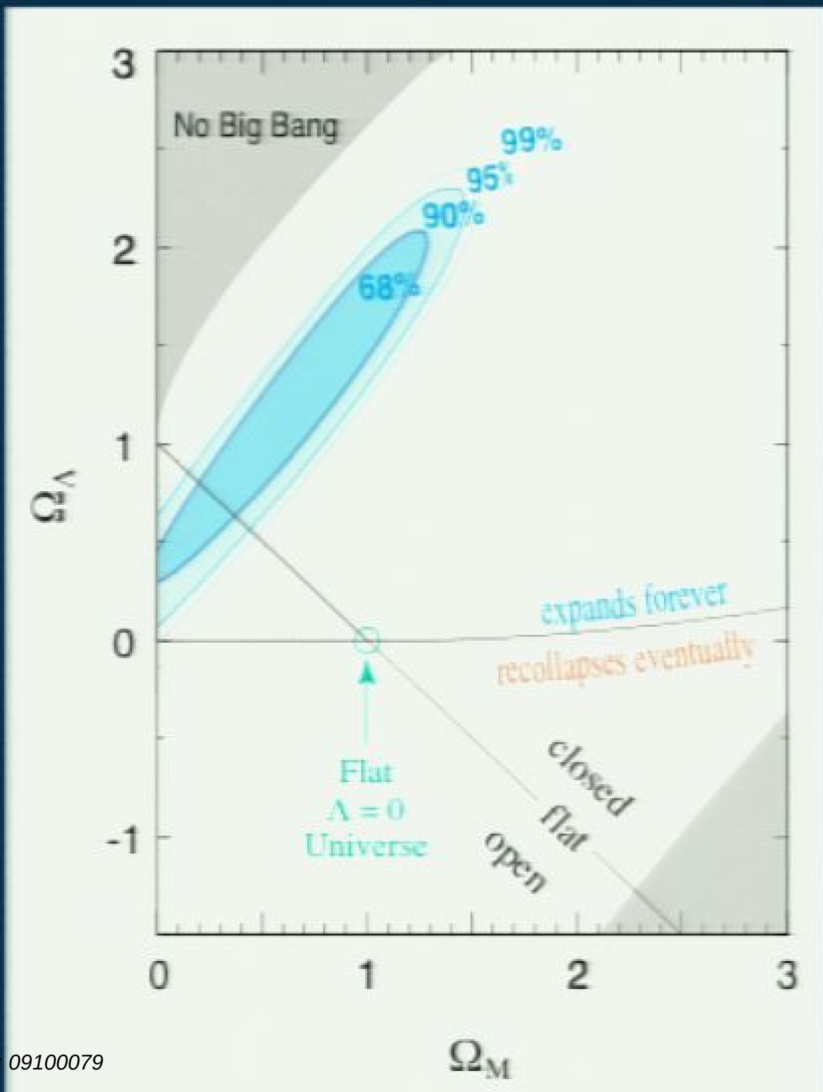

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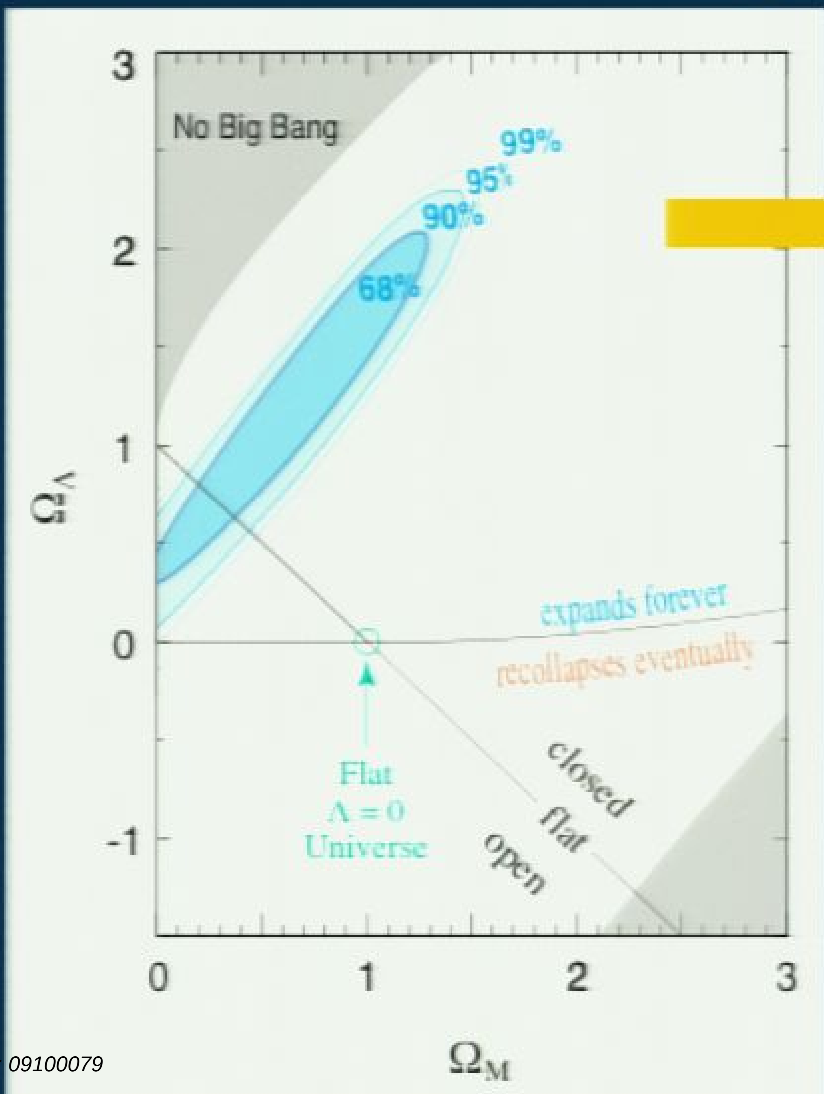

Accelerated expansion contradicts GR in a matter-dominated universe

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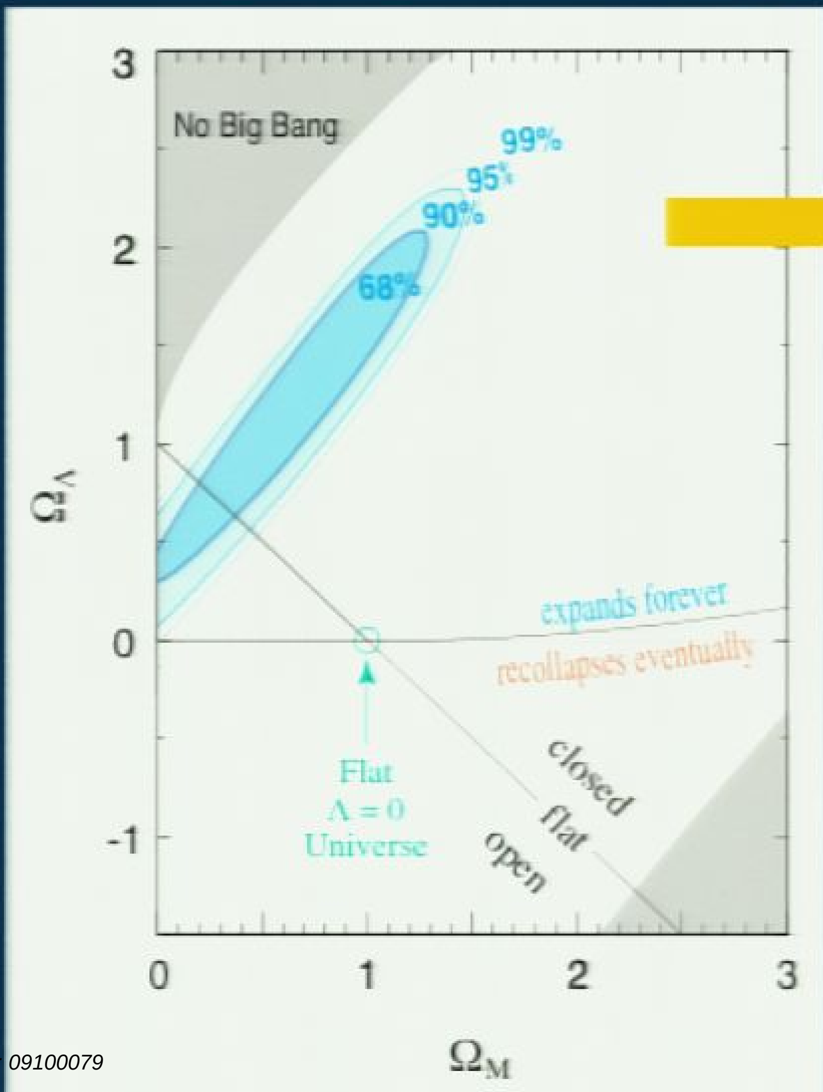
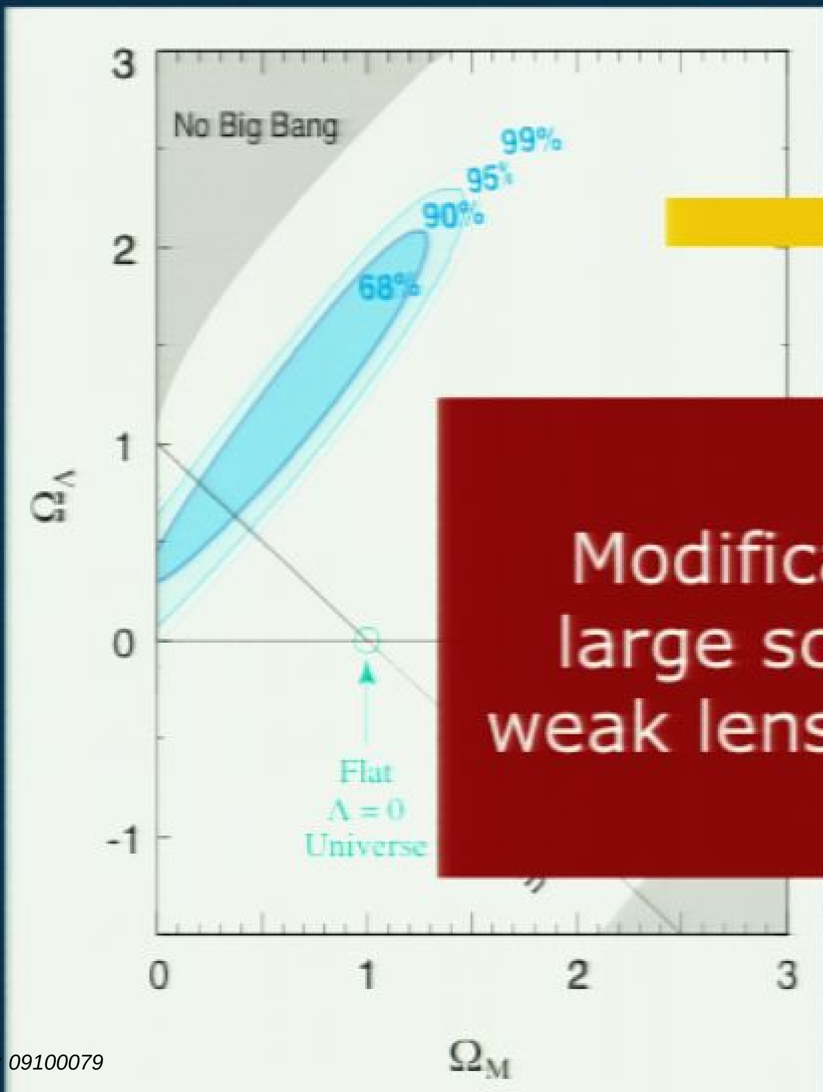


Accelerated expansion contradicts GR in a matter-dominated universe

But we want to keep gravity the same within the Solar System

Motivation for modifying GR on large scales



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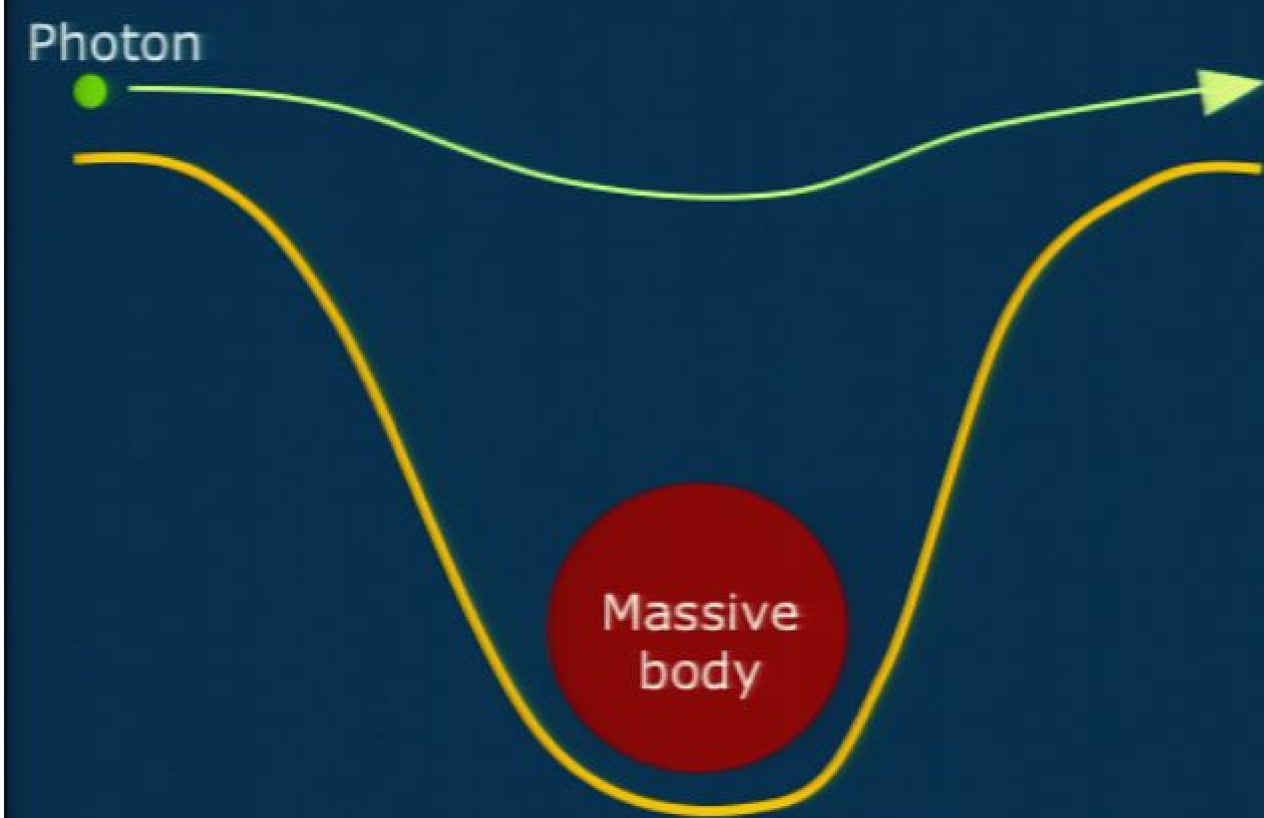
Modifications to GR on large scales will impact weak lensing observables…

Lensing in GR



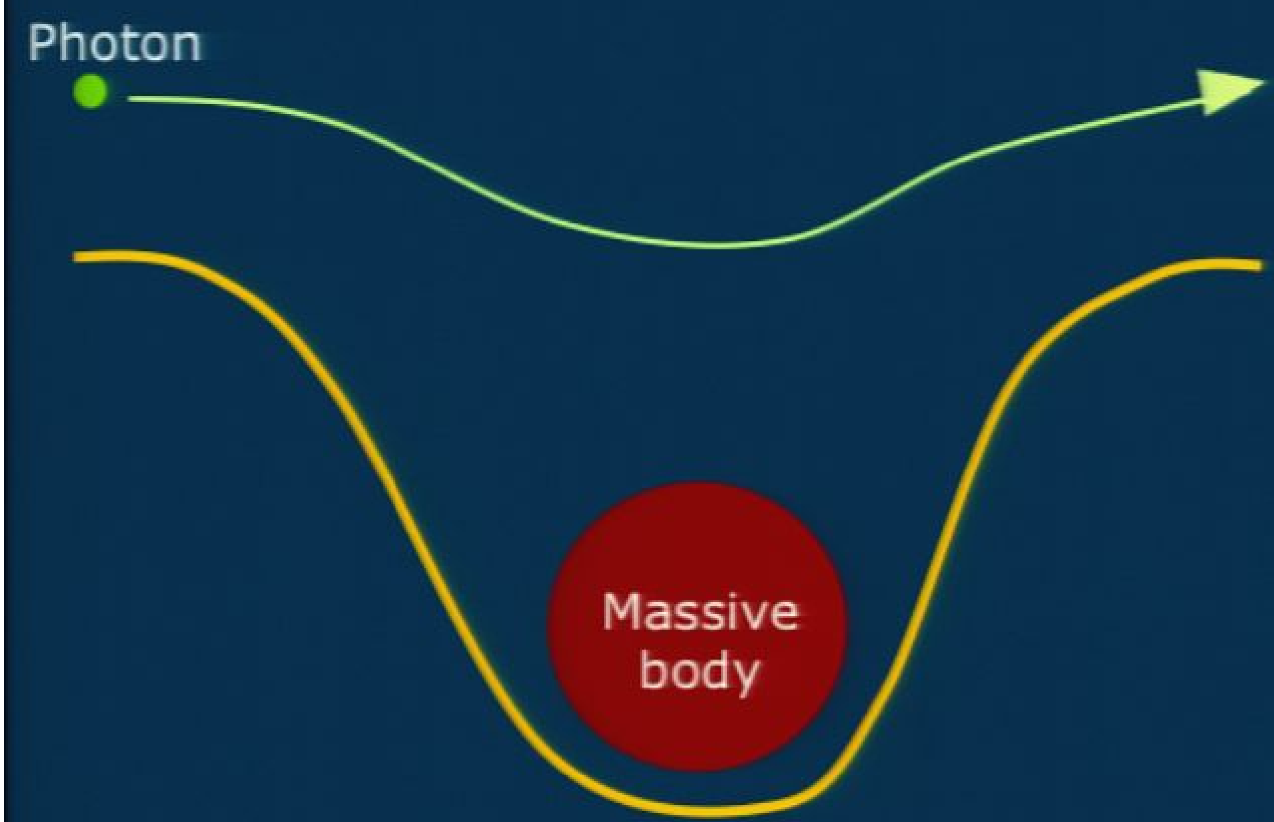
The potential is a function of the matter distribution:

$$\Phi = F(\rho)$$

The light bending angle is a function of this potential:

$$\Theta = G(\Phi)$$

Lensing in modified gravity



The potential is a function of the matter distribution:

$$\Phi = \bar{F}(\rho)$$

The light bending angle is a function of this potential:

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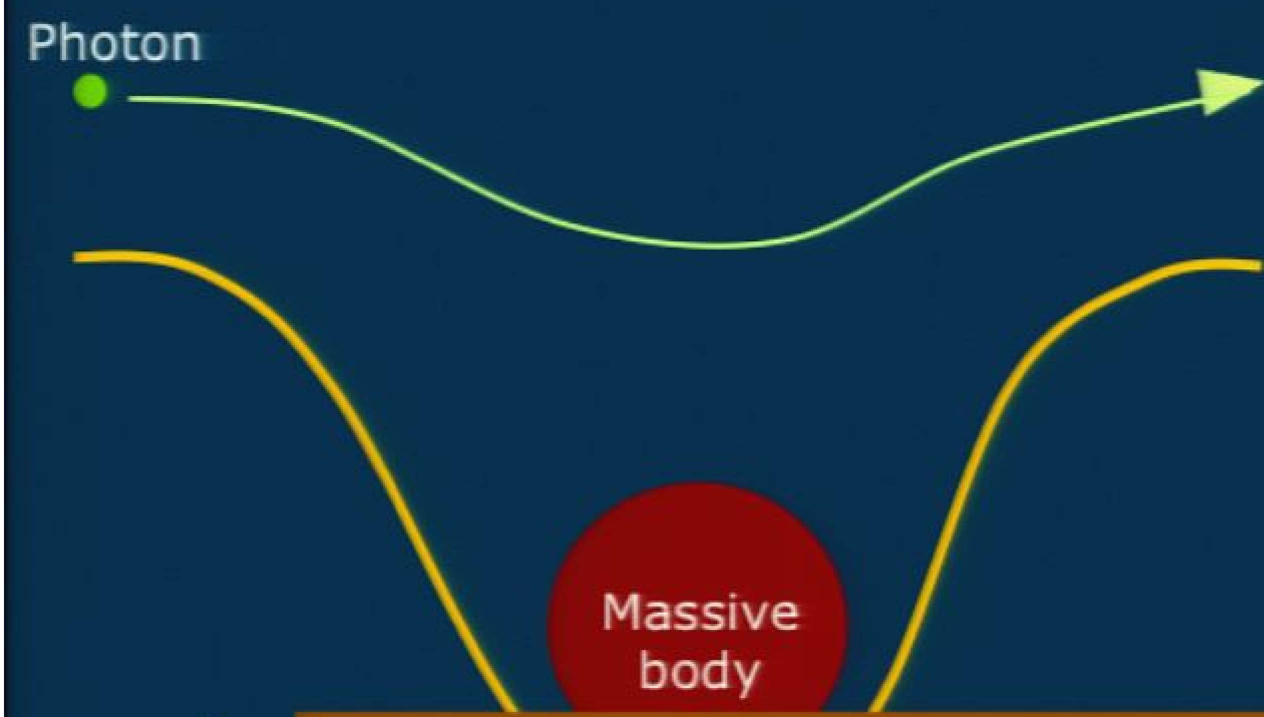

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$$(\Phi)$$

Modifying GR can change how:

- matter produces potentials
- photons move in those potentials

Modified gravity theories

Modified gravity theories

- Brans-Dicke
- Tensor-scalar
- Tensor-vector-scalar
- DGP
- Supergravity
- Brane-induced gravity
- Conformal gravity
- F(R)
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- Torsion gravity
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Very large theory space

want model-independent tests of generic deviations from GR

Lessons from “small” scales

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The parameterized post-Newtonian (**PPN**) formalism – in the weak-field regime, the gravitational potentials of GR are modified, for instance like:

$$ds^2 = -(1 - 2U + 2\beta U^2)dt^2 + (1 + 2\gamma U + \frac{3}{2}\varepsilon U^2)d\vec{x}^2$$

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Can do similar "PPF" expansion about FRW background on cosmological scales

PPN parameters

Parameter	What it measures relative to GR	Value in GR	Value in semi-conservative theories	Value in fully conservative theories
γ	How much space-curvature produced by unit rest mass?	1	γ	γ
β	How much "nonlinearity" in the superposition law for gravity?	1	β	β
ξ	Preferred-location effects?	0	ξ	ξ
α_1	Preferred-frame effects?	0	α_1	0
α_2		0	α_2	0
α_3		0	0	0
α_3	Violation of conservation	0	0	0
ζ_1	of total momentum?	0	0	0
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Solar System constraints:

- Light deflection due to the sun $\gamma - 1 = (-1.7 \pm 4.5) \times 10^{-4}$ (VLBI)
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Are these parameters the same on all scales?

The PPF framework

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Important scales:

- Superhorizon – must match expansion history
- Small scales – must match GR
- Intermediate linear regime – important for weak lensing

PPF weak lensing

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The metric:

$$ds^2 = a^2(\tau)[-(1 - 2U + 2\beta U^2)d\tau^2 + (1 + 2\gamma U + \frac{3}{2}\varepsilon U^2)d\vec{x}^2]$$

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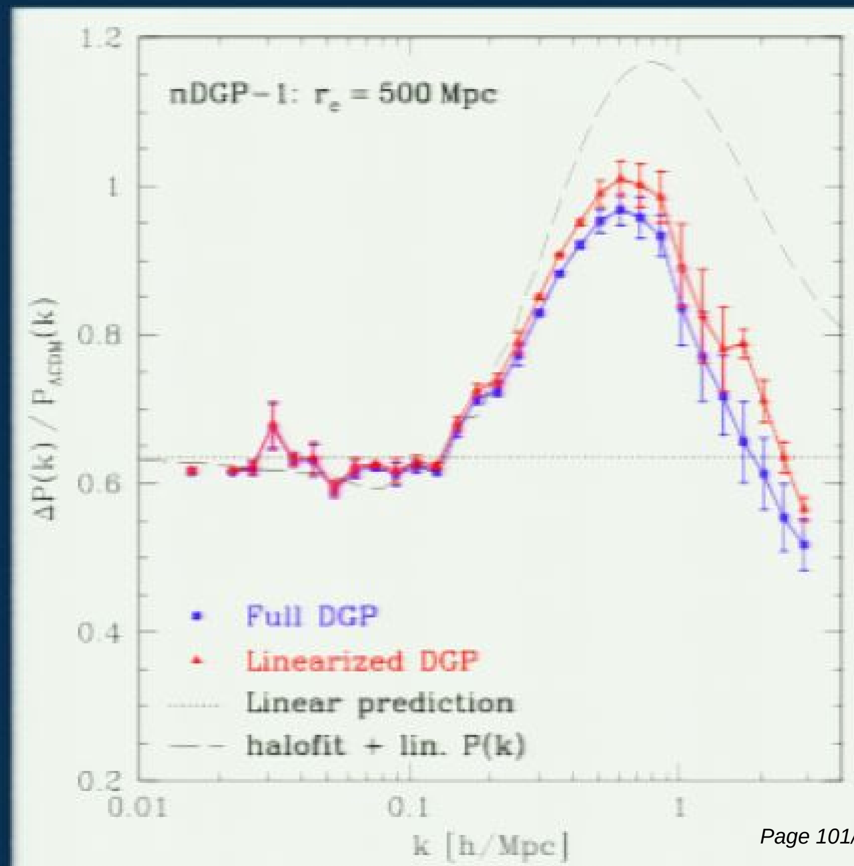

Post-post-Newtonian light deflection

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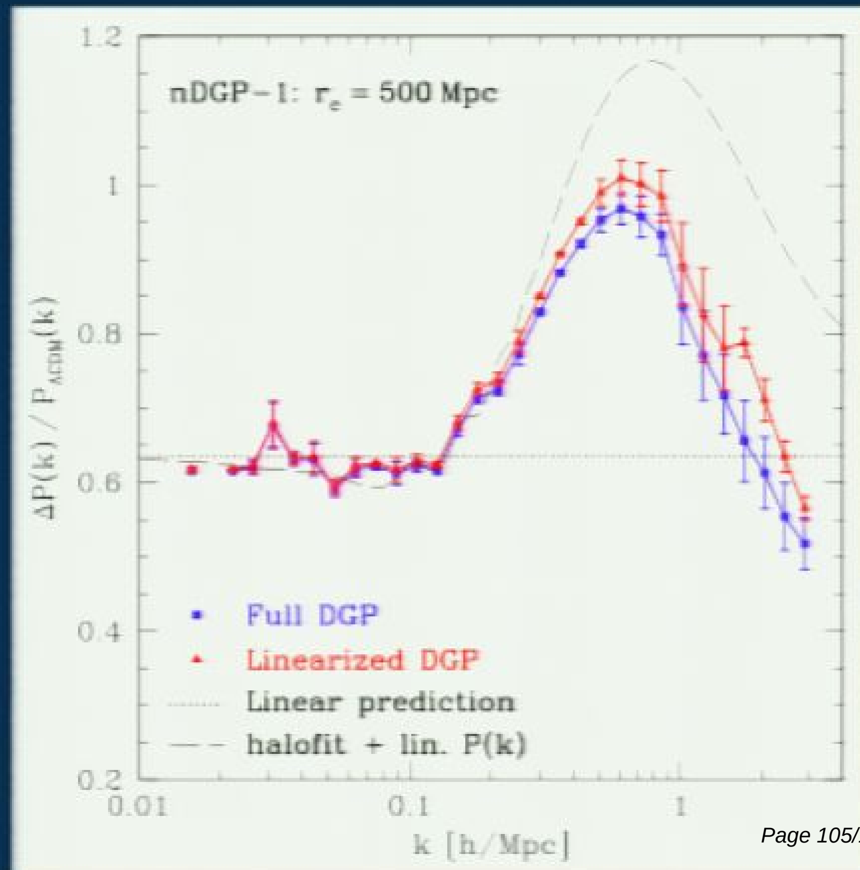

Schmidt 2009

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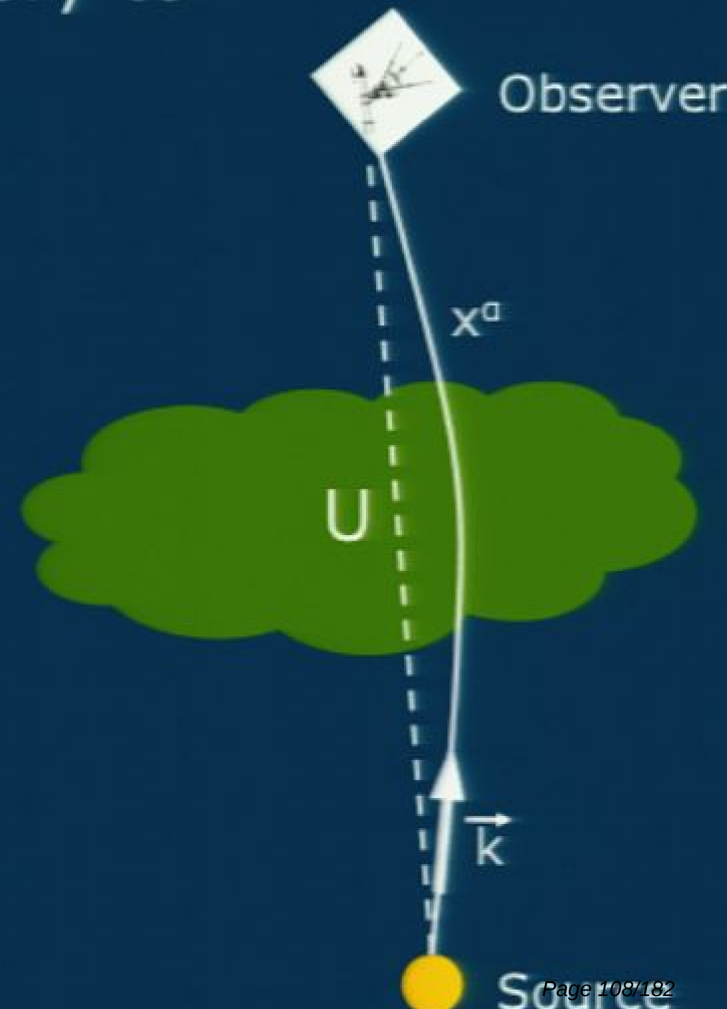

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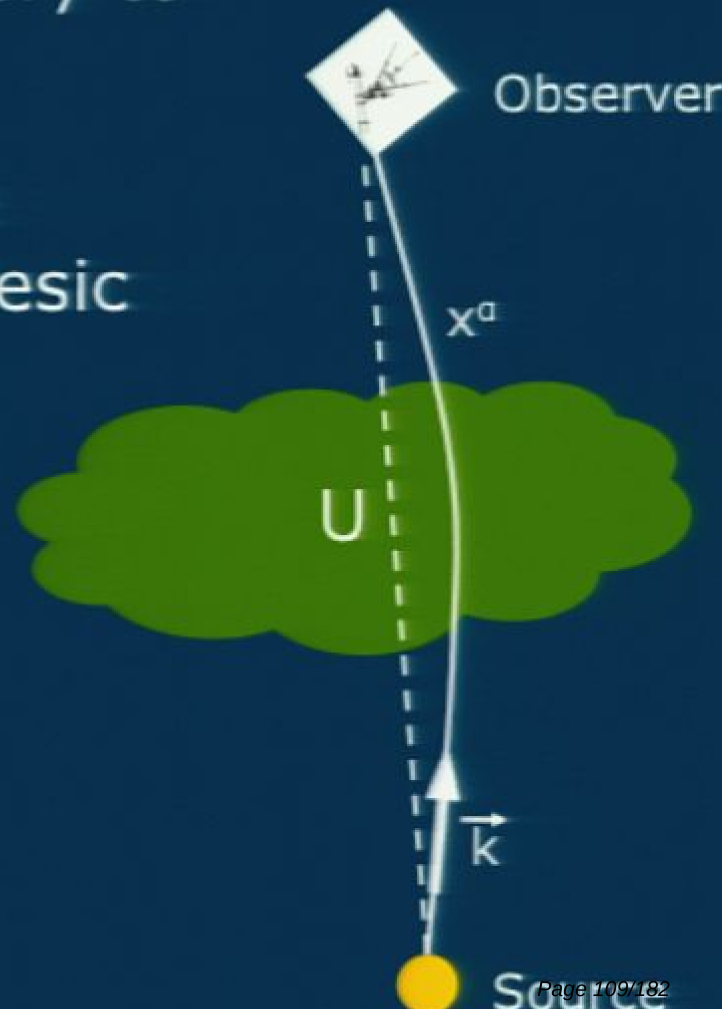
From the metric we compute the connection and get the null geodesic equation:

$$\frac{dk^\alpha}{d\lambda} = -\Gamma^\alpha_{\mu\nu} k^\mu k^\nu$$



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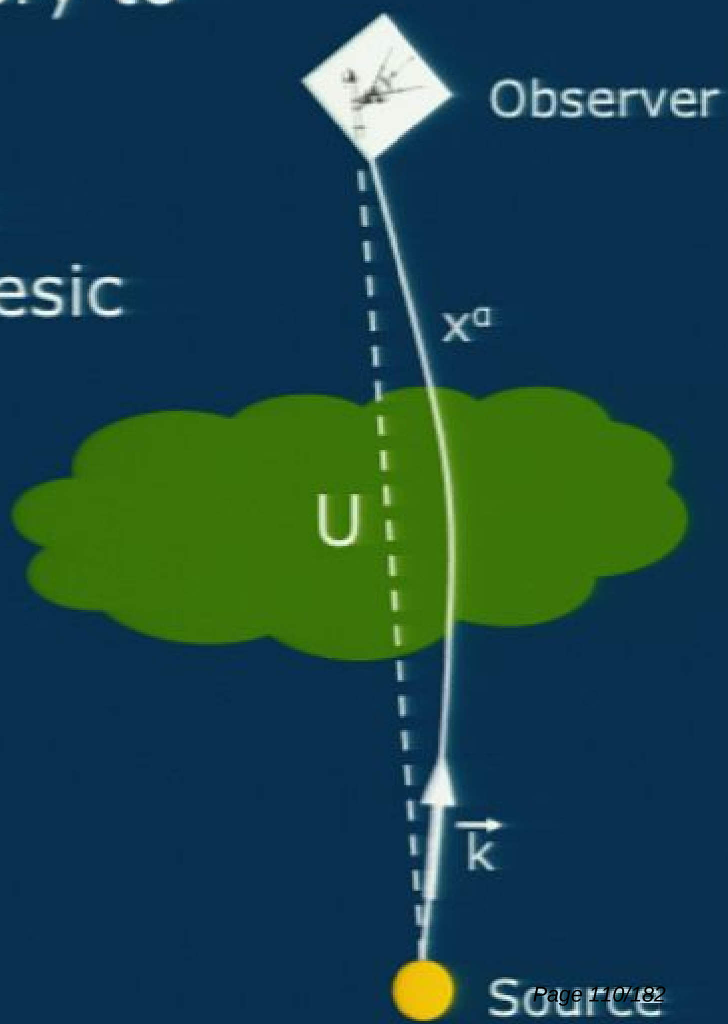

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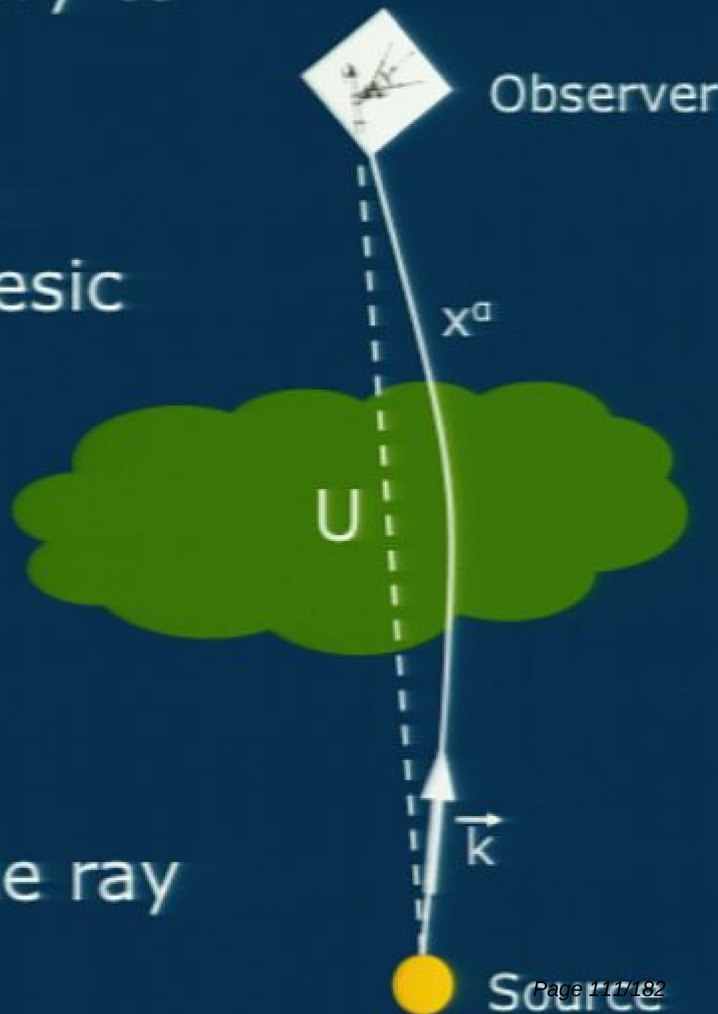
➡ Integrating this gives us the ray trajectory x



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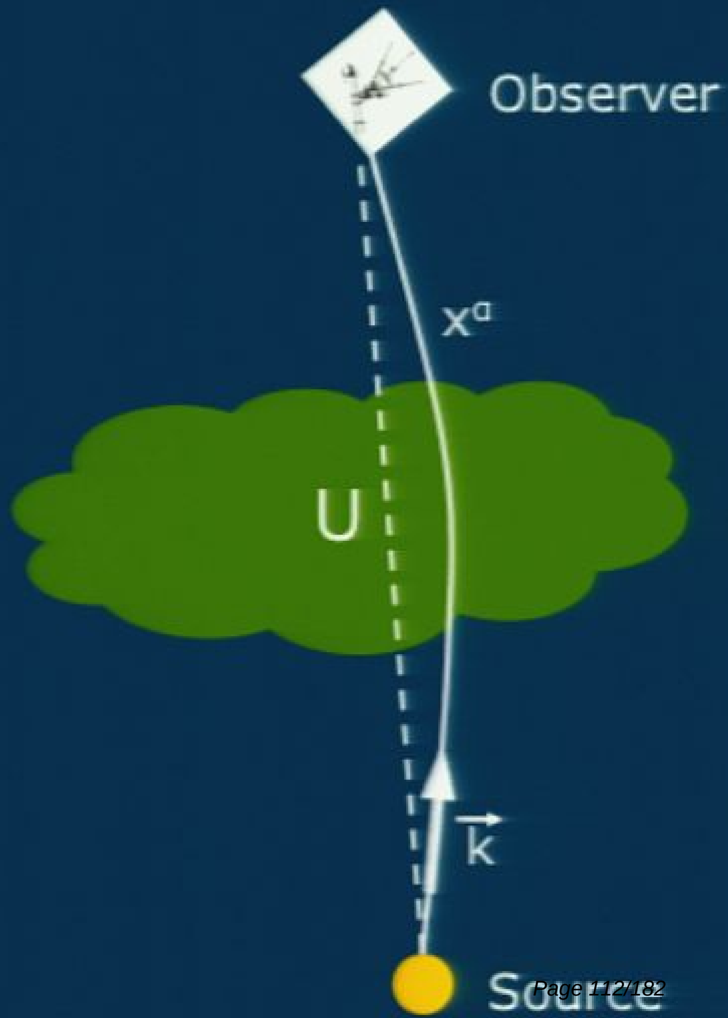

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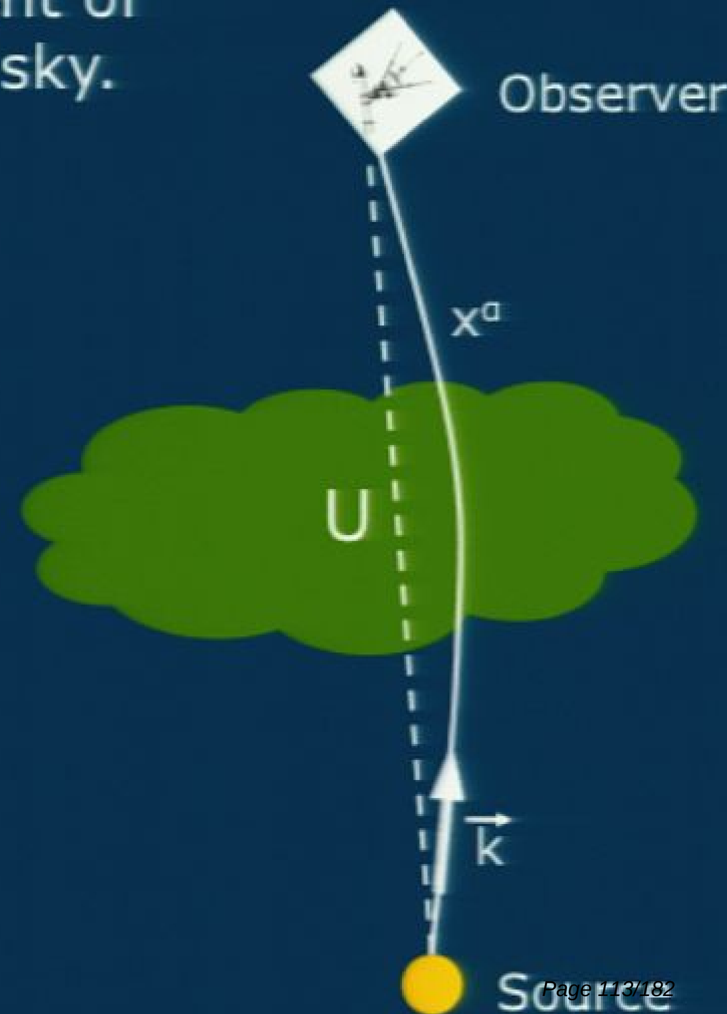
The deflection angle α_i is the component of the trajectory shift in the plane of the sky.



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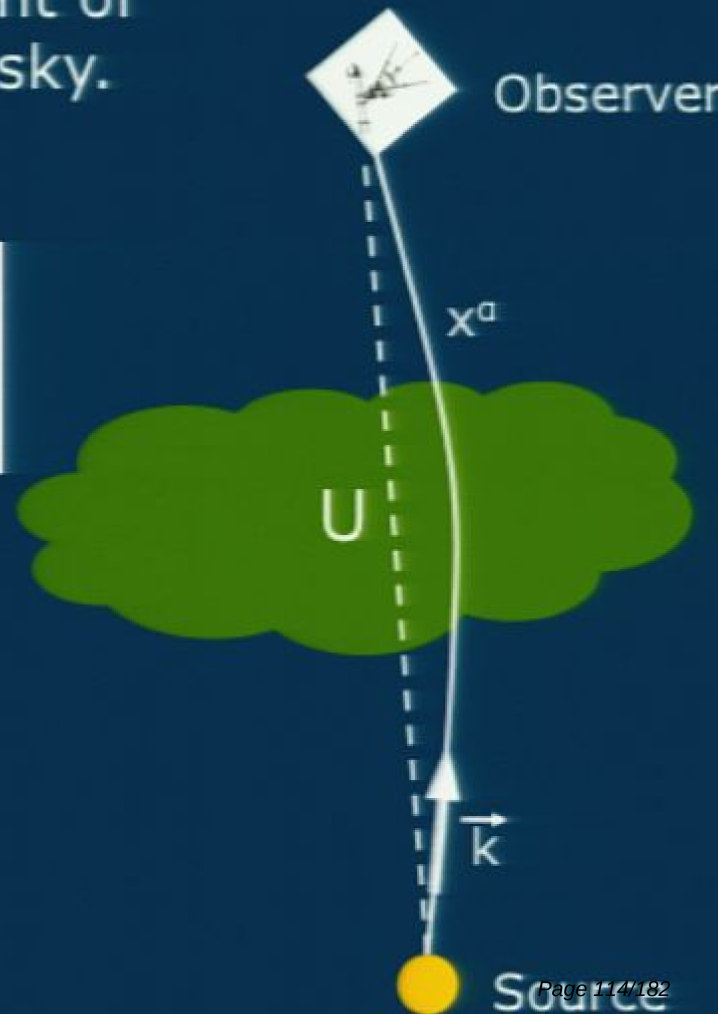

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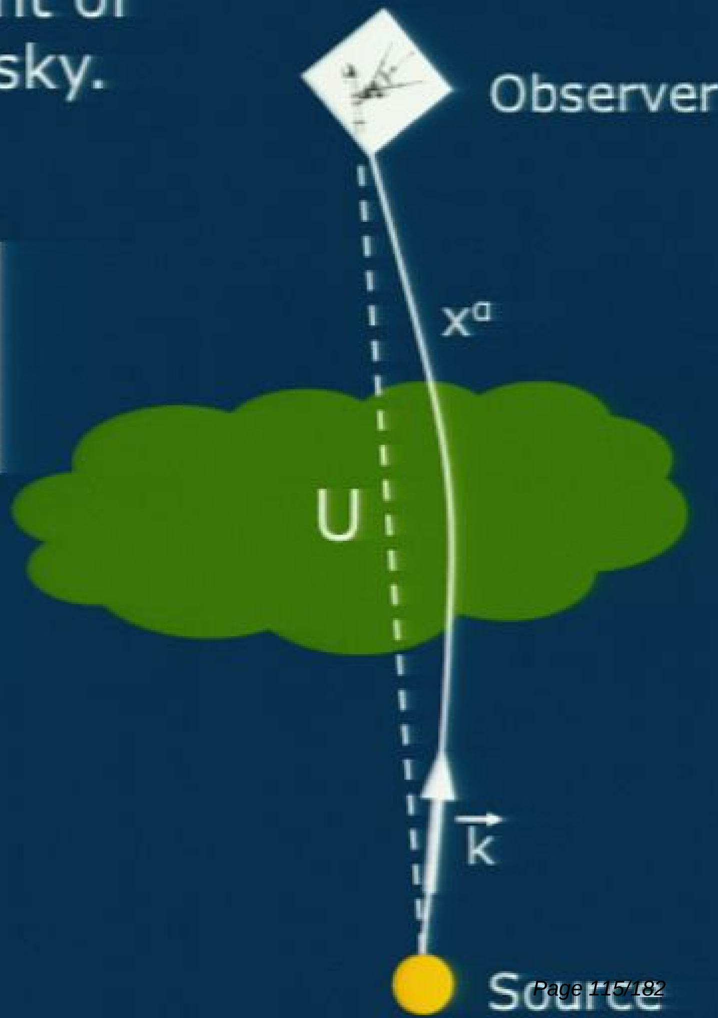

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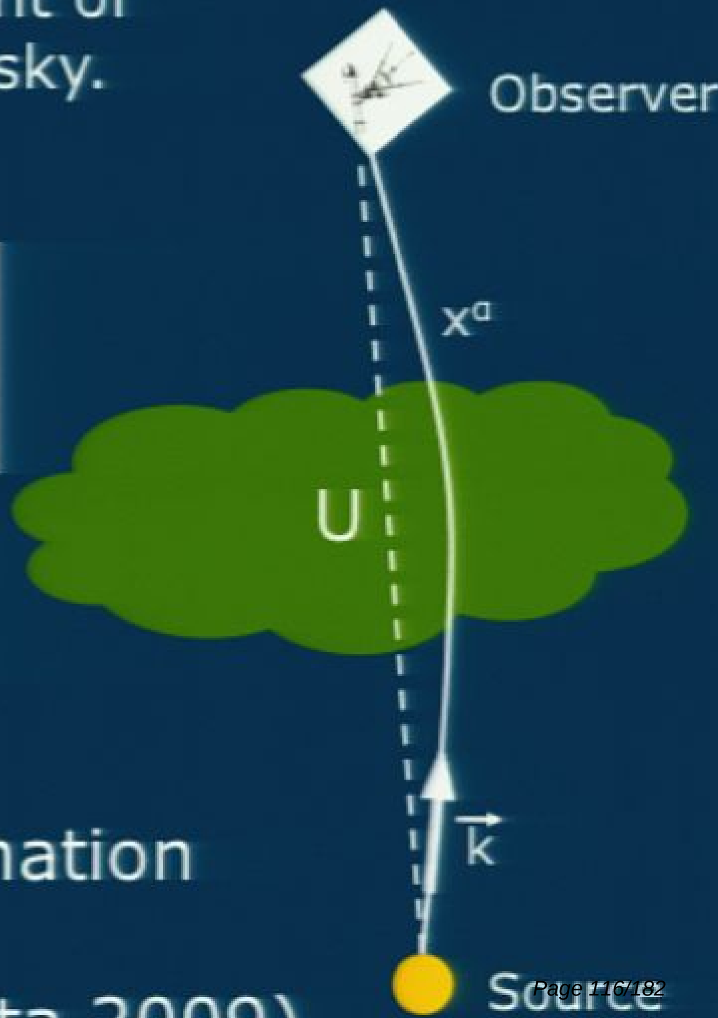

Nonlinear effects:

- Correction to Born approximation
- Lens-lens coupling
- etc. (see e.g. Krause & Hirata 2009)

The convergence

$$\kappa = \int_0^w dw' \left(\frac{w - w'}{w} \right) w' \left\{ \left(\frac{1 + \gamma}{2} \right) \nabla^2 U \right.$$

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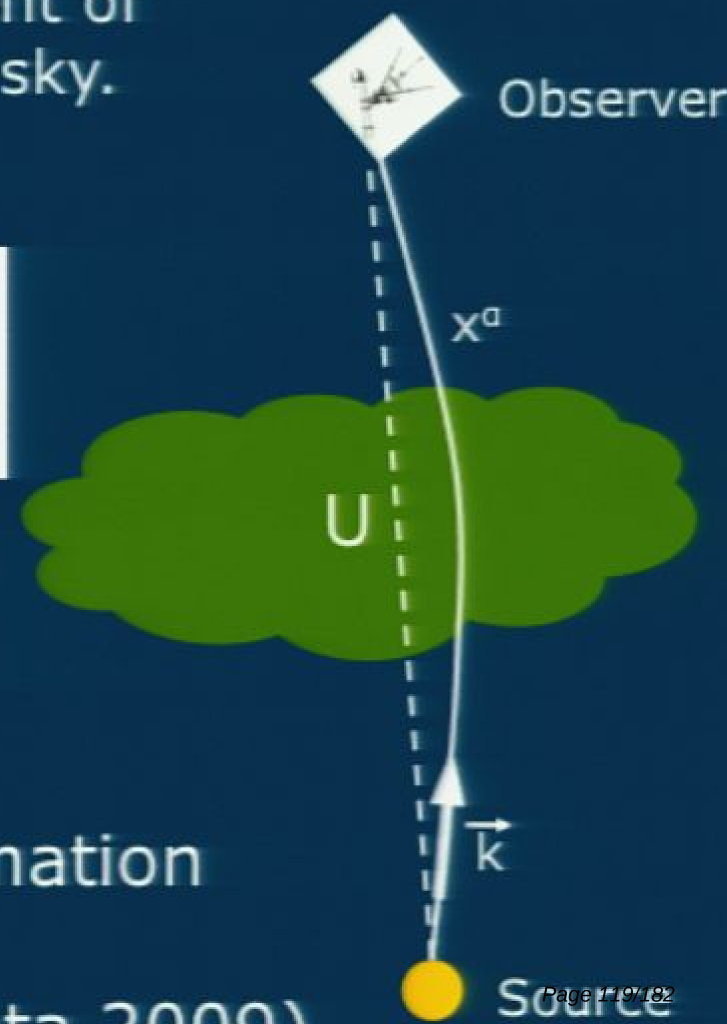

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k²U²

$+$ β-independent second-order terms... $\}$

Linear piece ⟹ constrain γ with power spectrum

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Nonlinear piece ➡ constrain β, ε with bispectrum

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Assumed scale-independent, and time-dependent in same way as Λ

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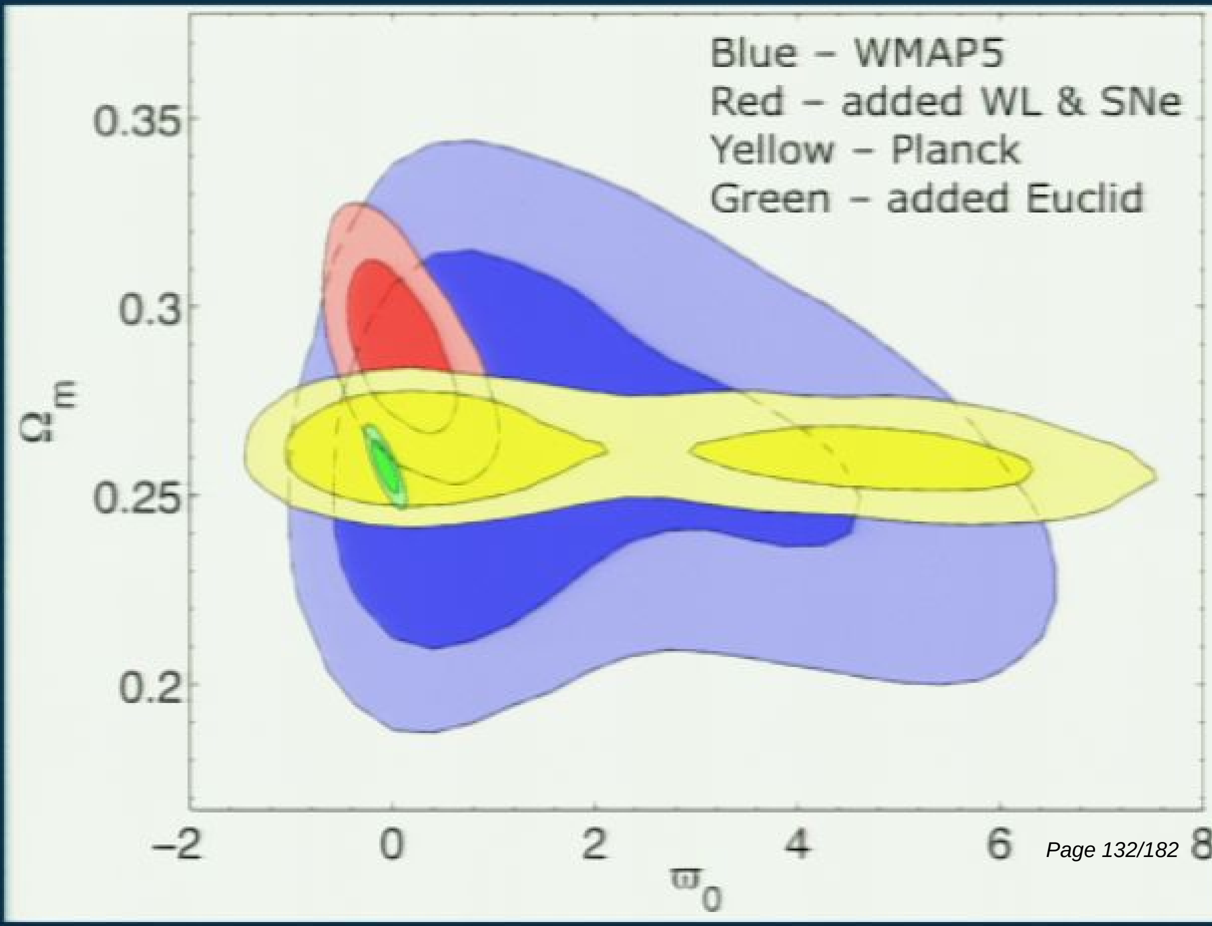

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Bean 2009: Assumed constant in redshift bins

$$\eta(k,a) = \phi(k,a)/\psi(k,a)$$

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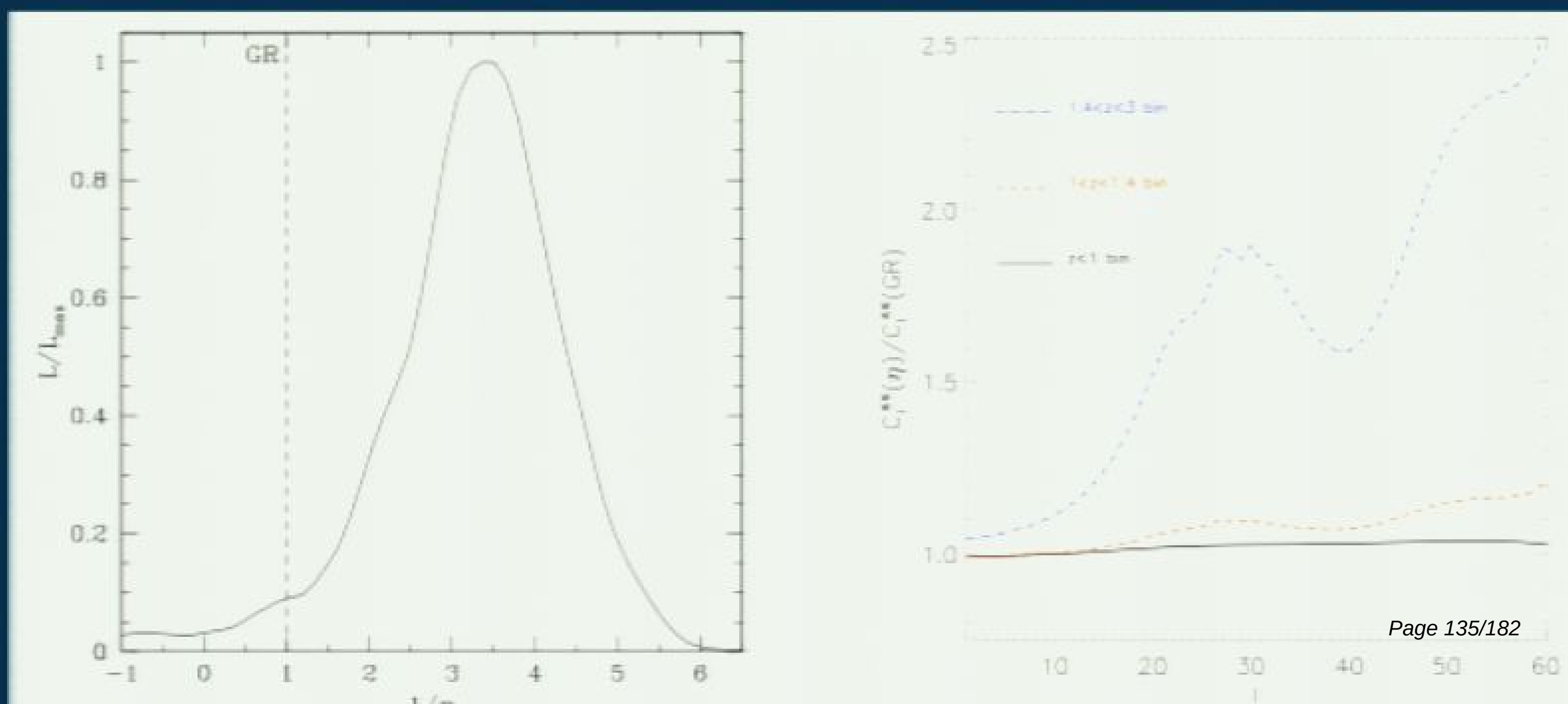

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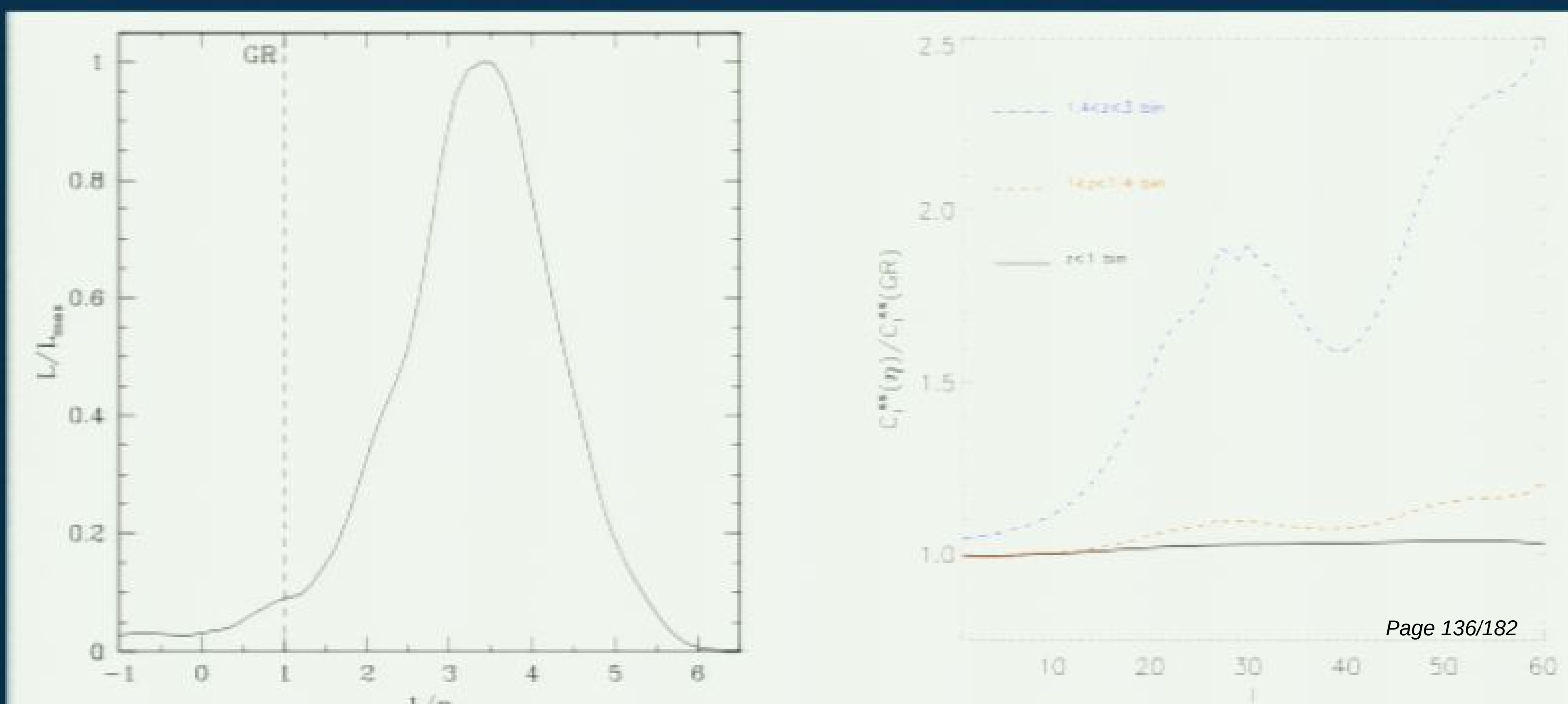

Constraining beta and epsilon

(AV & Caldwell in prep)

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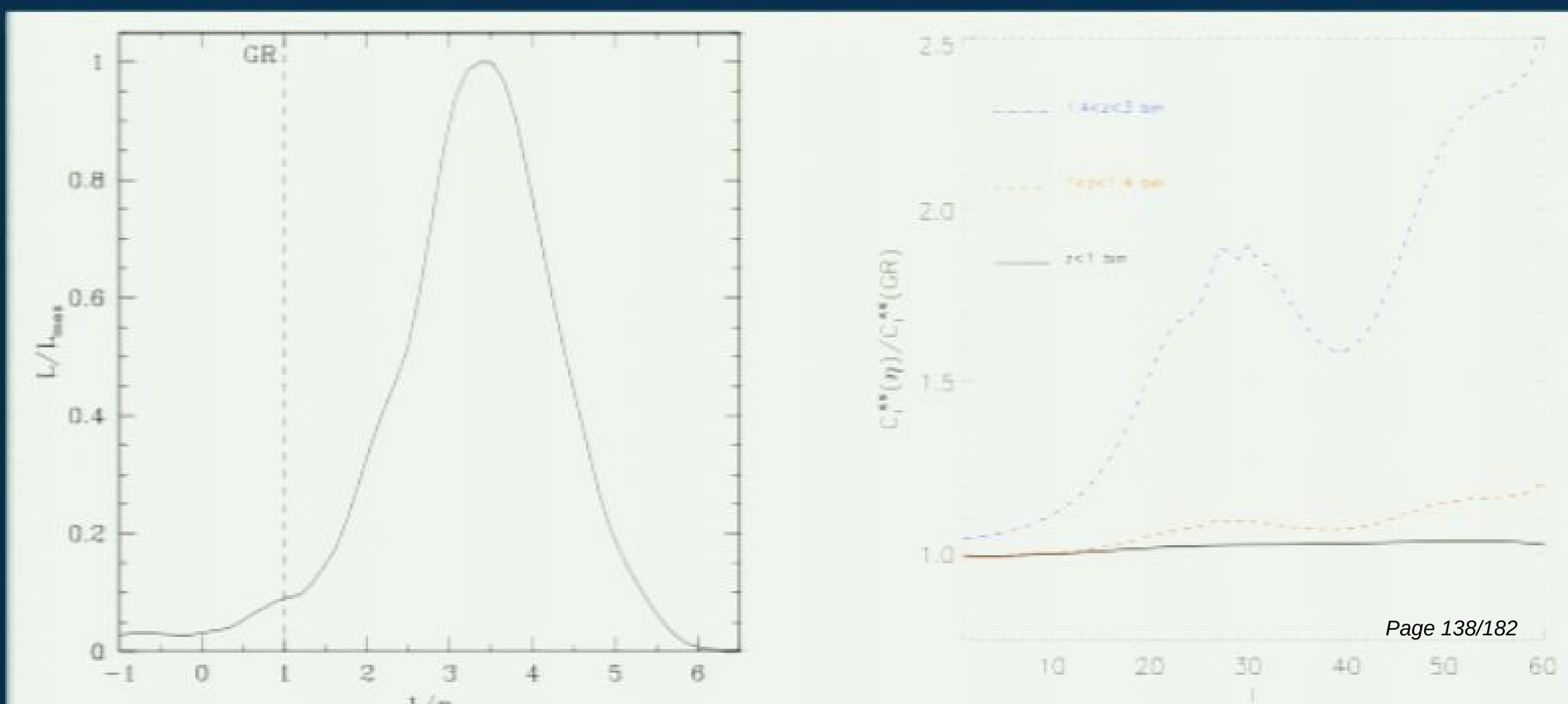

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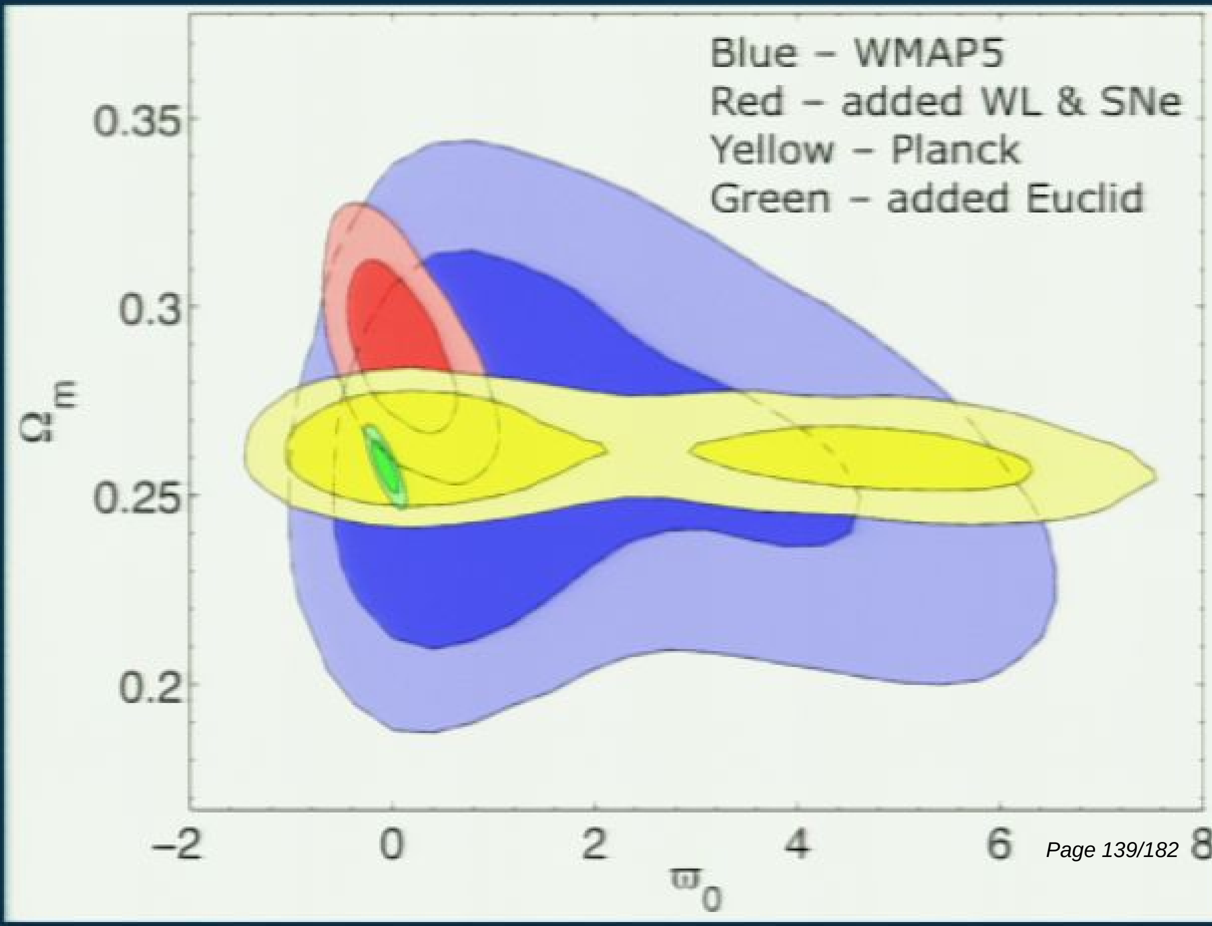

Constraining gamma

$$ds^2 = a^2 \left[-(1+2\psi)\, d\tau^2 + (1-2\phi)\, d\vec{x}^2 \right]$$ (this talk: $\gamma = \phi/\psi$)

Bean 2009: Assumed constant in redshift bins

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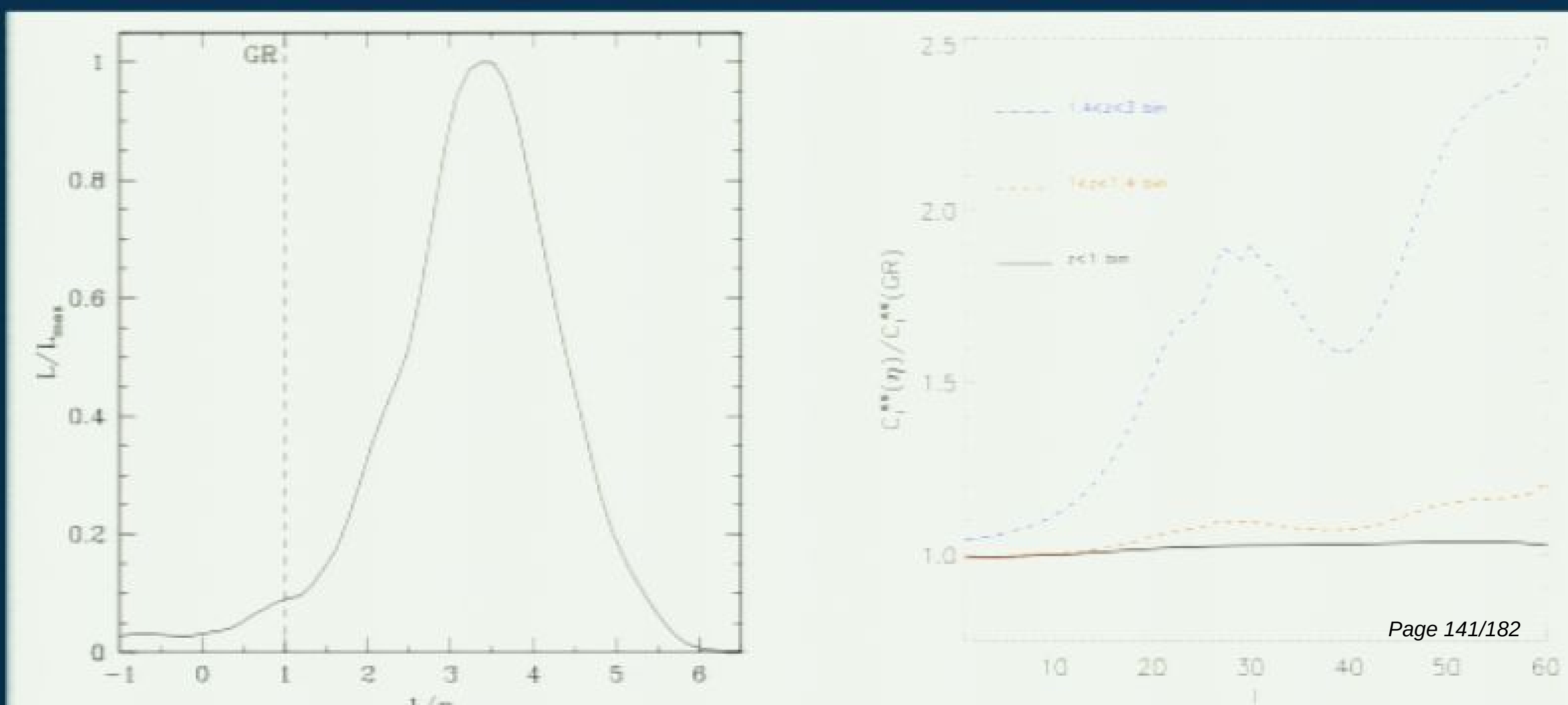

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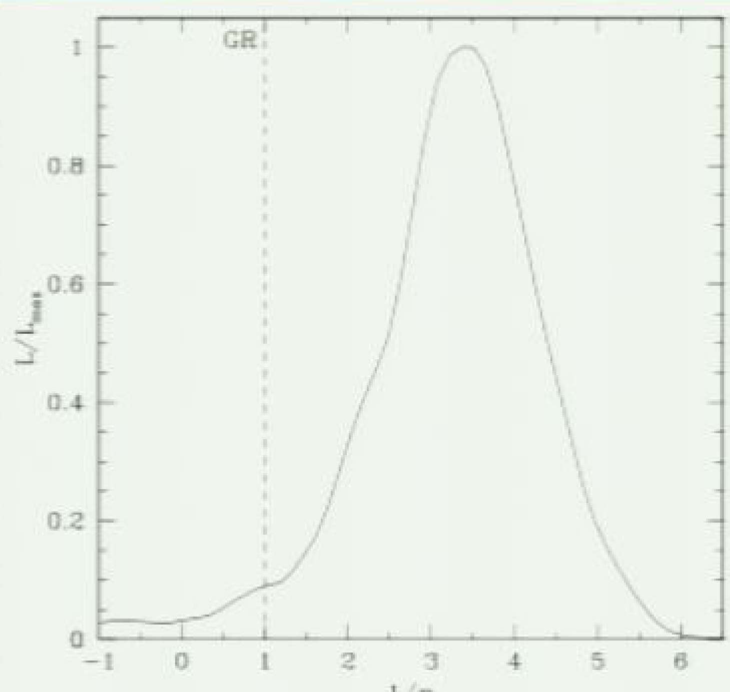
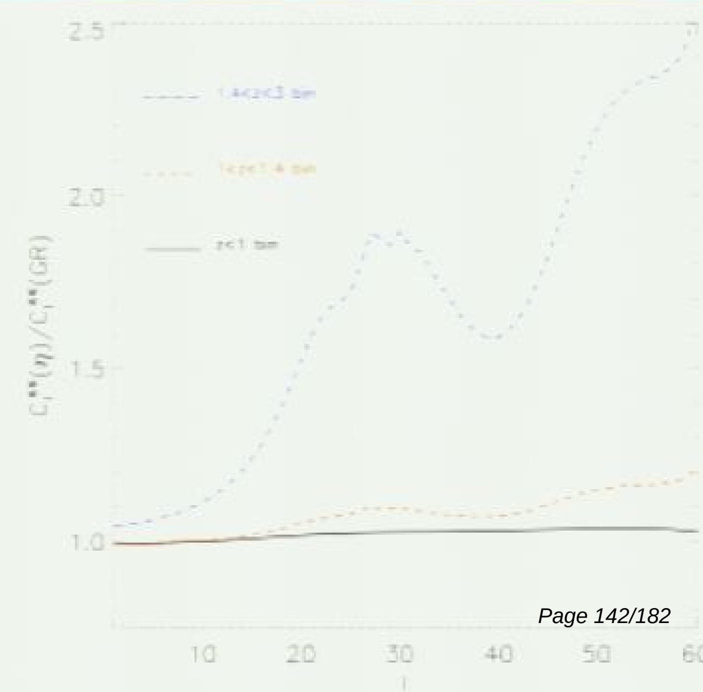
Too much shear at high z?





Constraining beta and epsilon

(AV & Caldwell in prep)

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Non-GR values for beta and epsilon change the bispectrum...

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The (far) future of weak lensing

Weak lensing requirements

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Weak lensing requirements

To get accurate shear measurements, we need:

- Accurate galaxy shape measurements
  - Small and stable PSF
  - Low detector systematics
  - Sufficient nearby stars to calibrate the PSF
- Accurate redshifts
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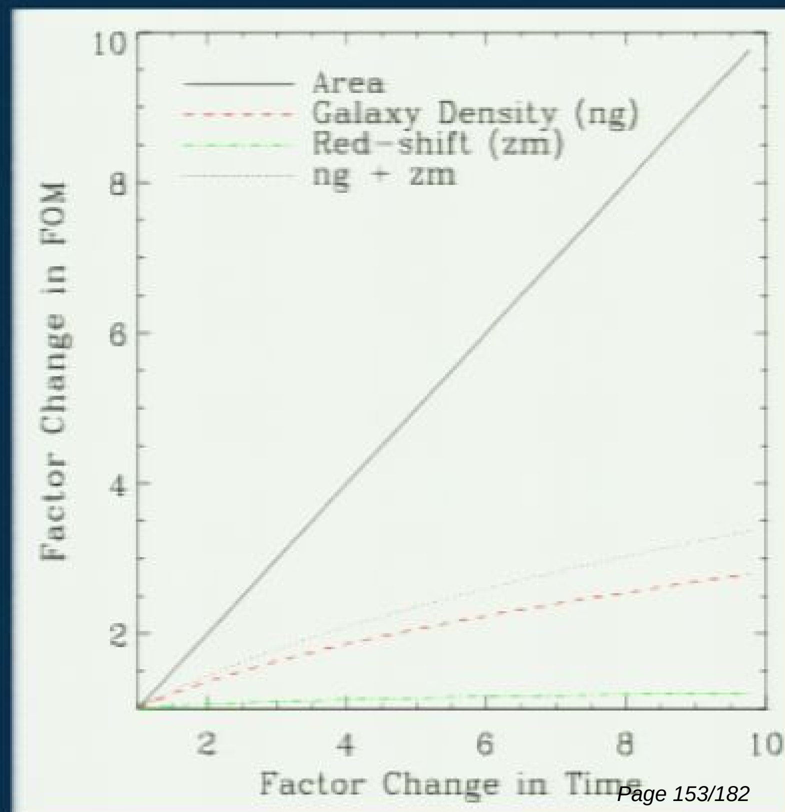

Future possibilities

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- High Altitude Lensing Observatory –
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The High Altitude Lensing Observatory

HALO

PI: Jason Rhodes

Jeff Booth (JPL), Kurt Liewer (JPL), Michael Seiffert (JPL),Wesley Traub (JPL), Richard Key (JPL), Ali Vanderveld (Caltech/JPL), Adam Amara (ETH Zurich), Richard Ellis (Caltech), Richard Massey (University of Edinburgh), Satoshi Miyazaki (NOAJ Japan), Harry Teplitz (Spitzer Science Center, Caltech), Calvin Barth Netterfield (University of Toronto), Alexandre Refregier (CEA Saclay, Paris), Roger Smith (Caltech)

Weak lensing past & future

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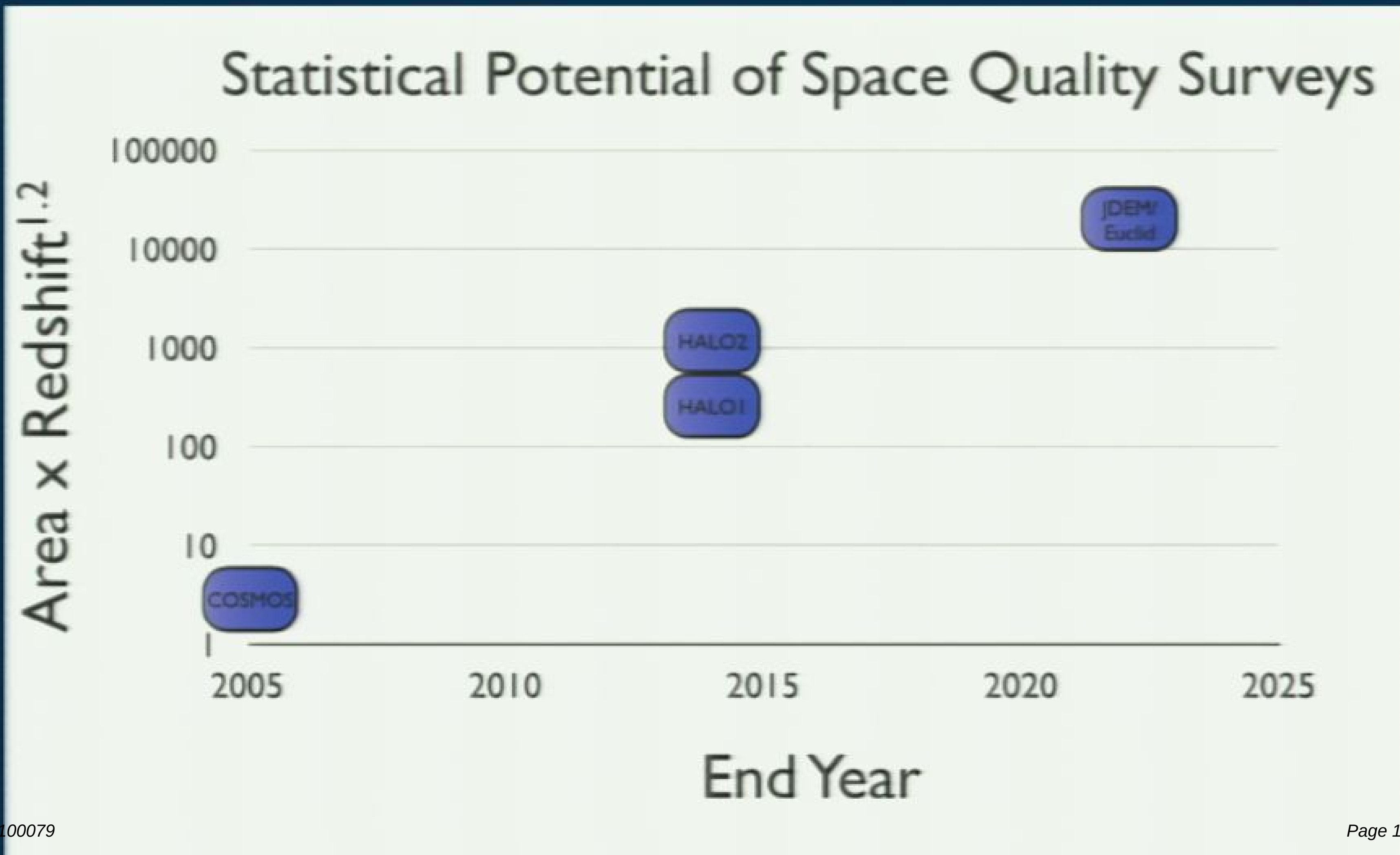
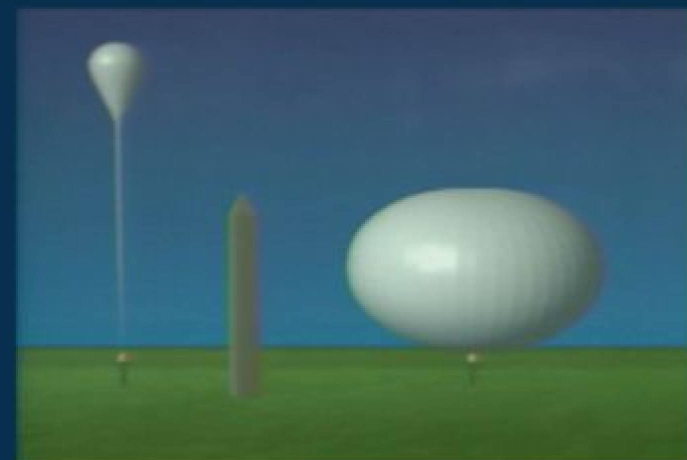


Using a balloon

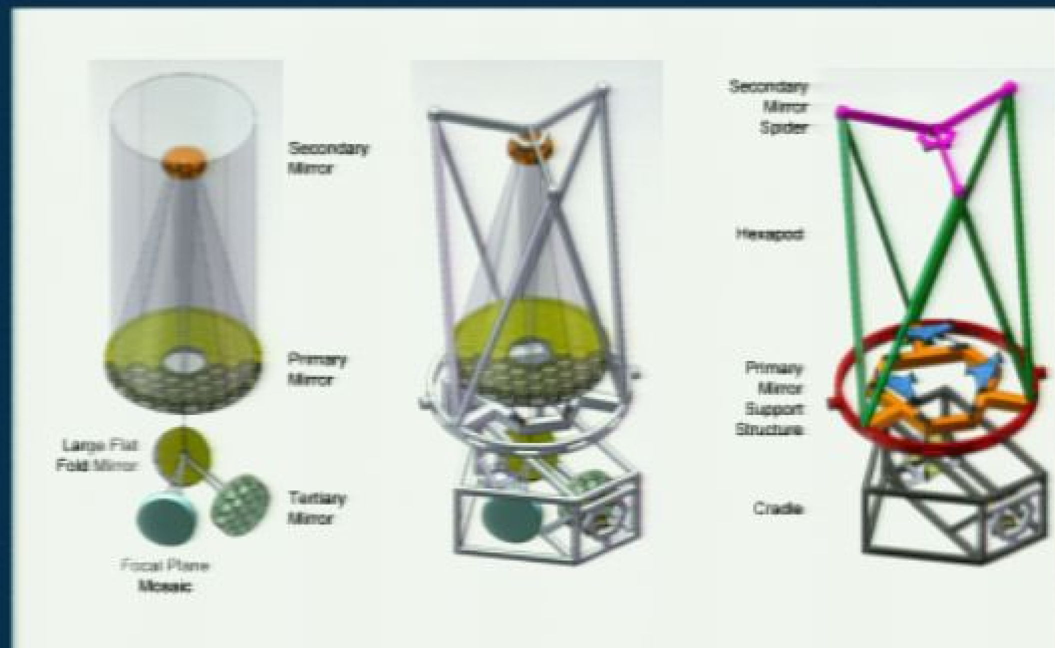
- NASA's Ultra Long Duration Balloon program
- 7 million cubic foot balloon flown (14 and 22 MCF planned) – BIG!
- 14 MCF have ~2000 pound payload
- 20 day circumnavigations from Australia baselined for science within a few years



Columbia Scientific Balloon Facility

HALO

- 15-20 day flight Australia to Australia (can stop in South America if needed)
- 1.2m lightweight primary mirror
- 48 2k×4k Hamamatsu CCDs
- Single wide optical filter
- Photo zs from ground
- Solar panel to recharge batteries
- 1000 kg



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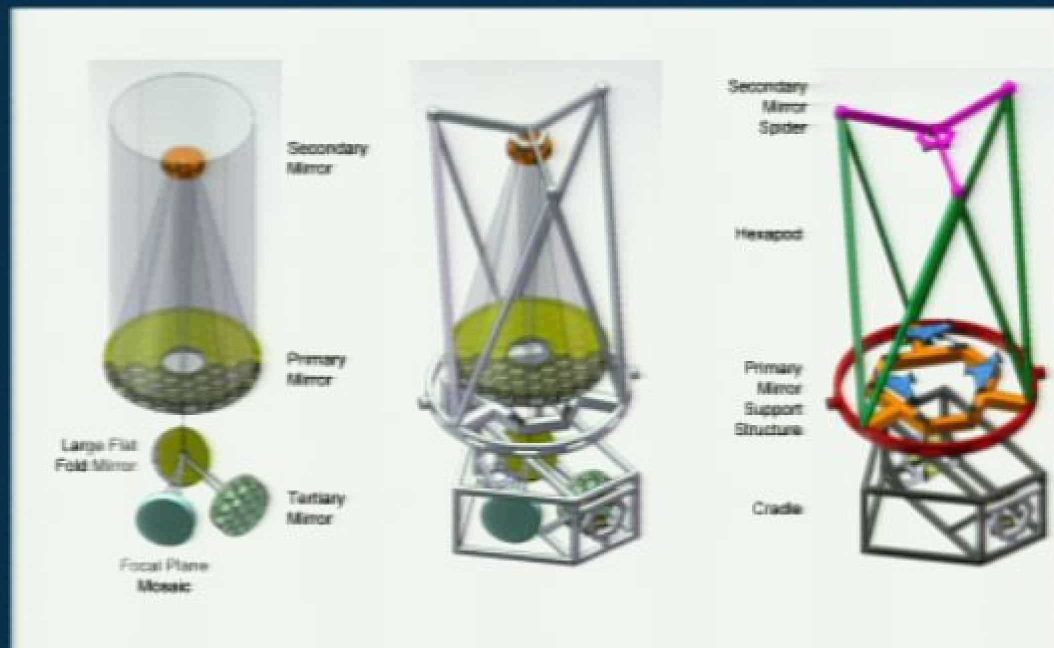

Need to pick up the disk drives (2 Tb) afterwards to do the science

Key parameters

Survey area	200+ square degrees
PSF Stability	0.1" RMS with 0.15" pixels
Wavelength coverage	500-720nm
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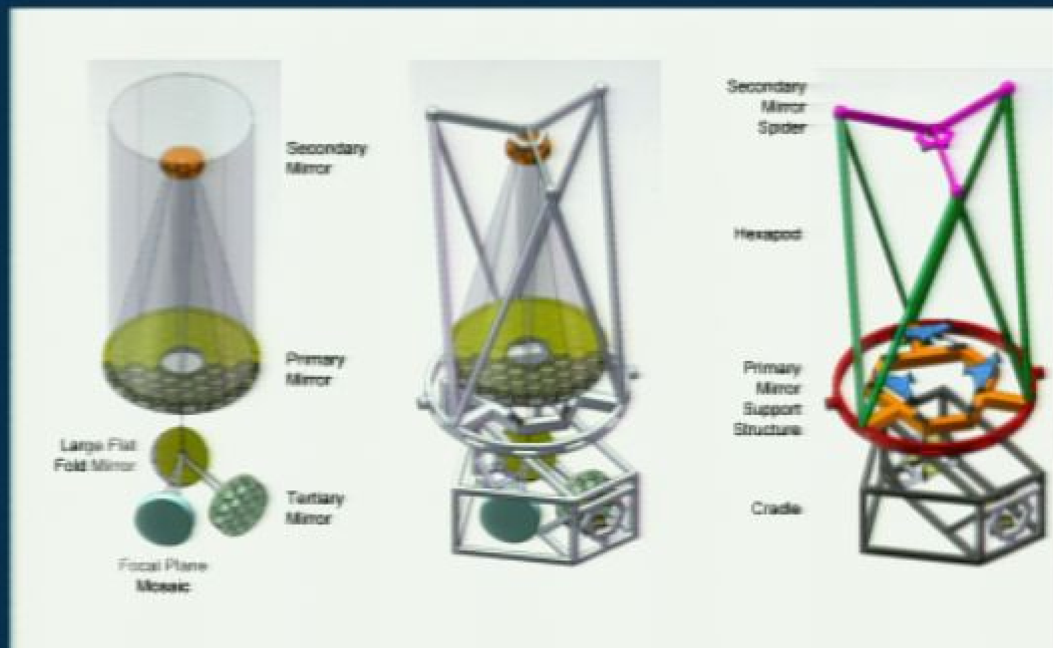

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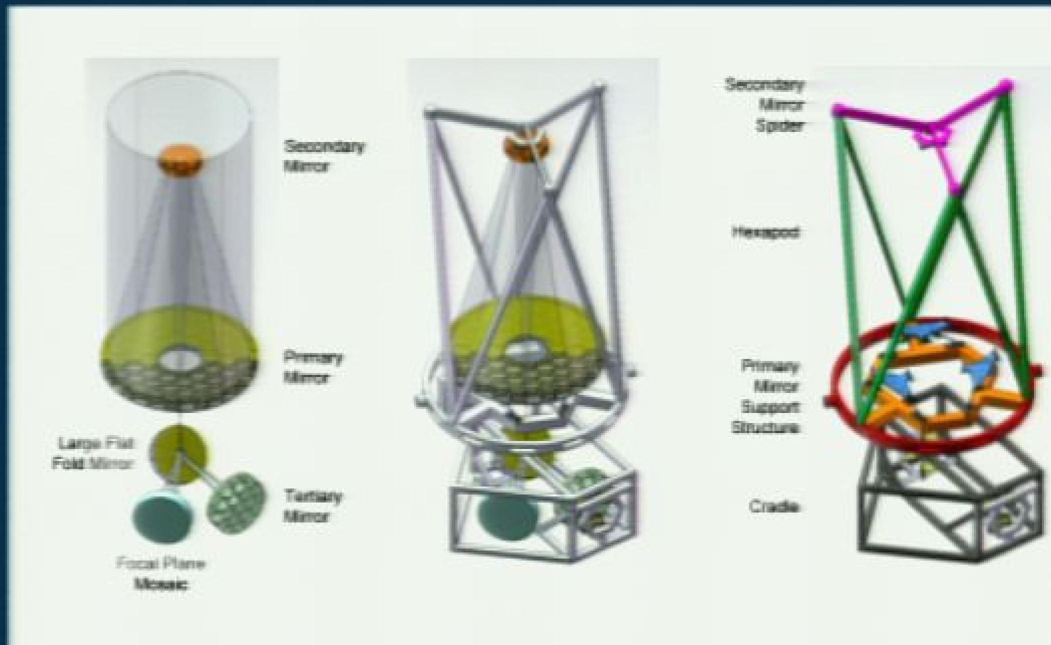

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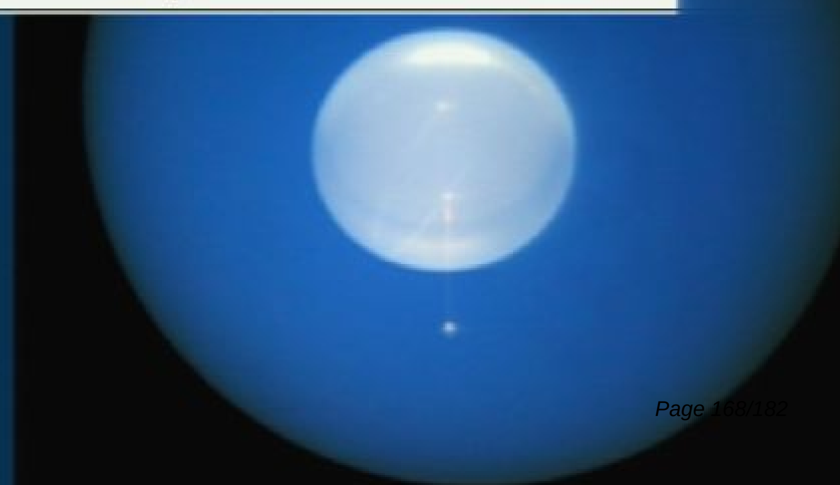

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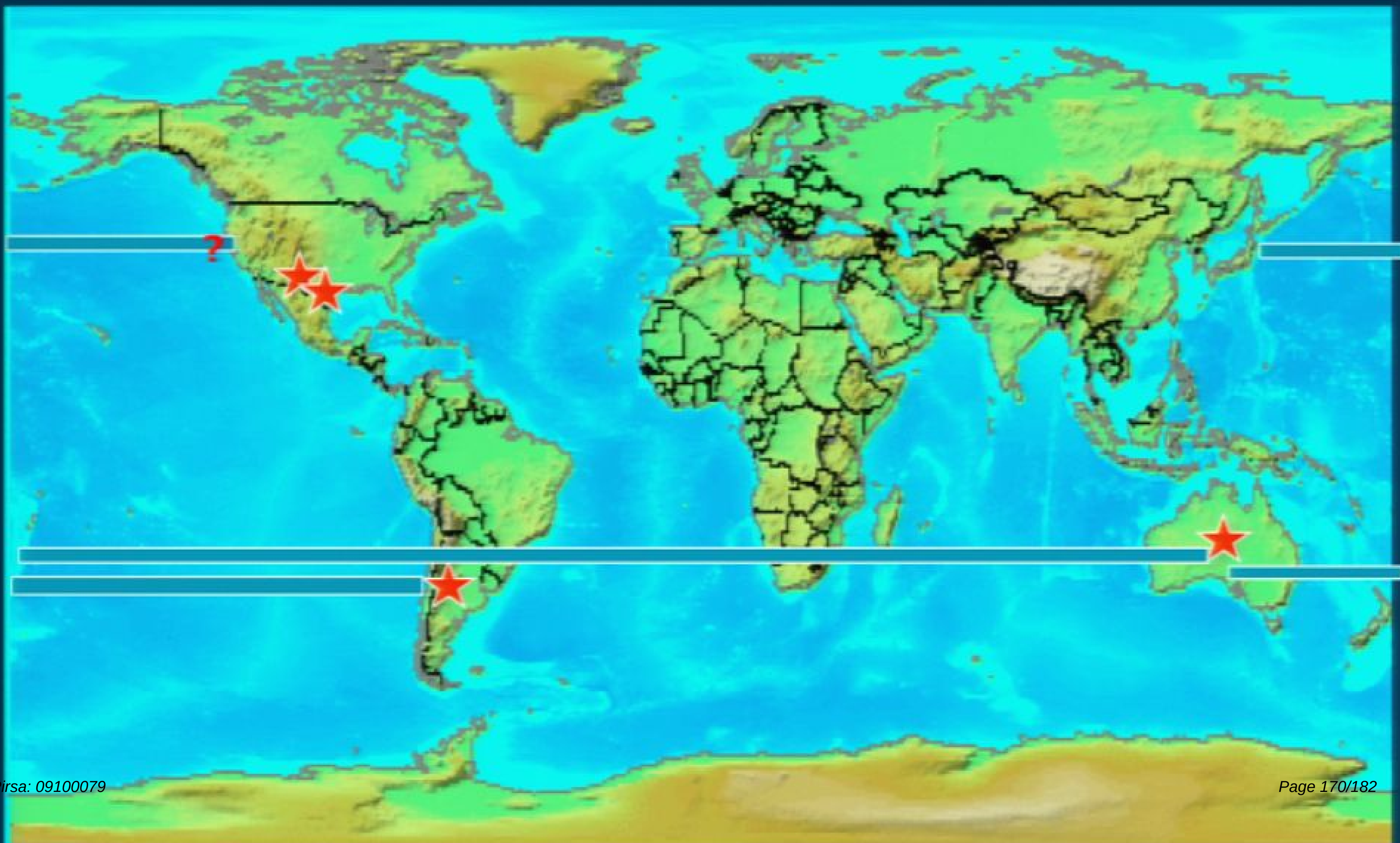
Potential launch sites



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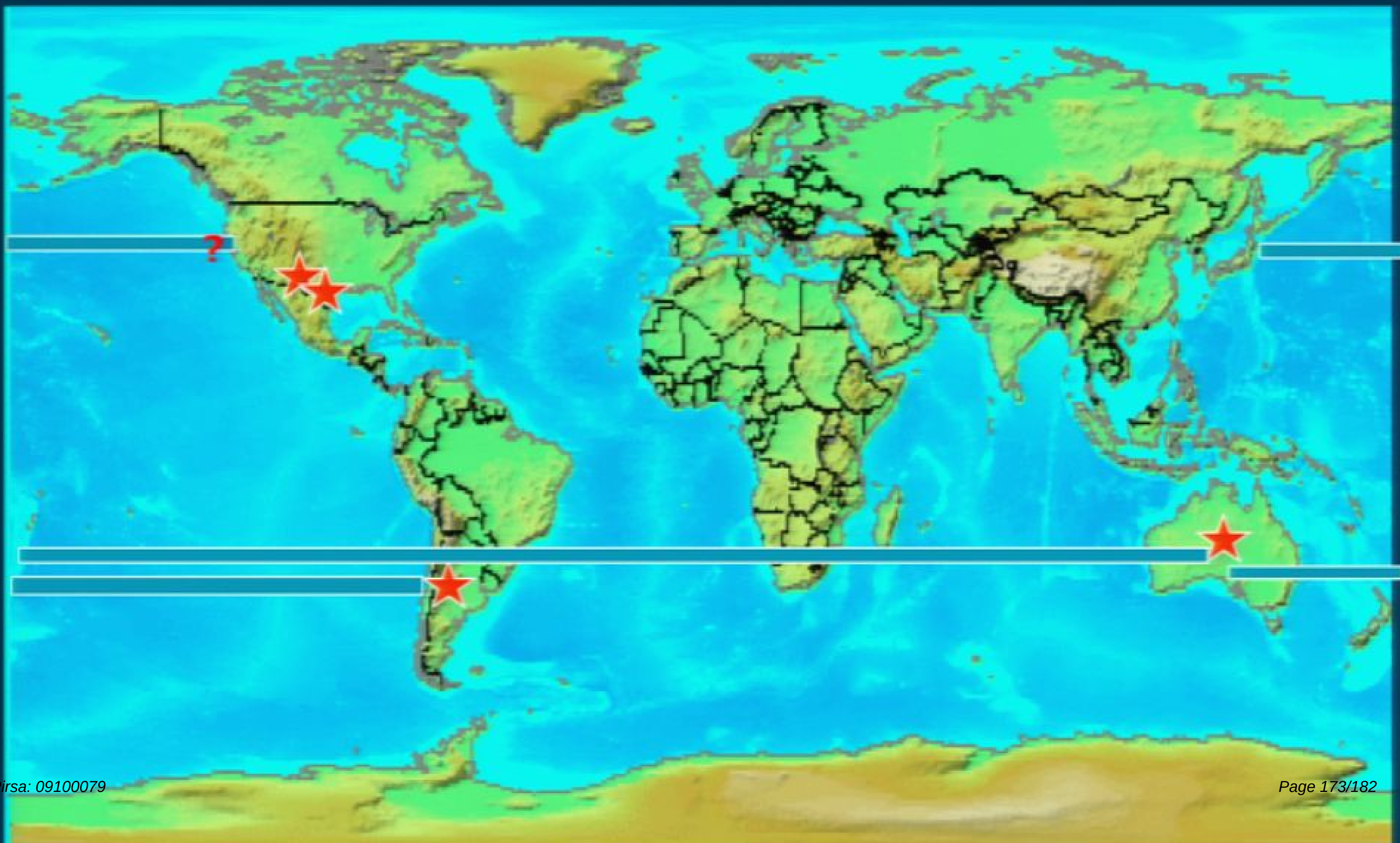

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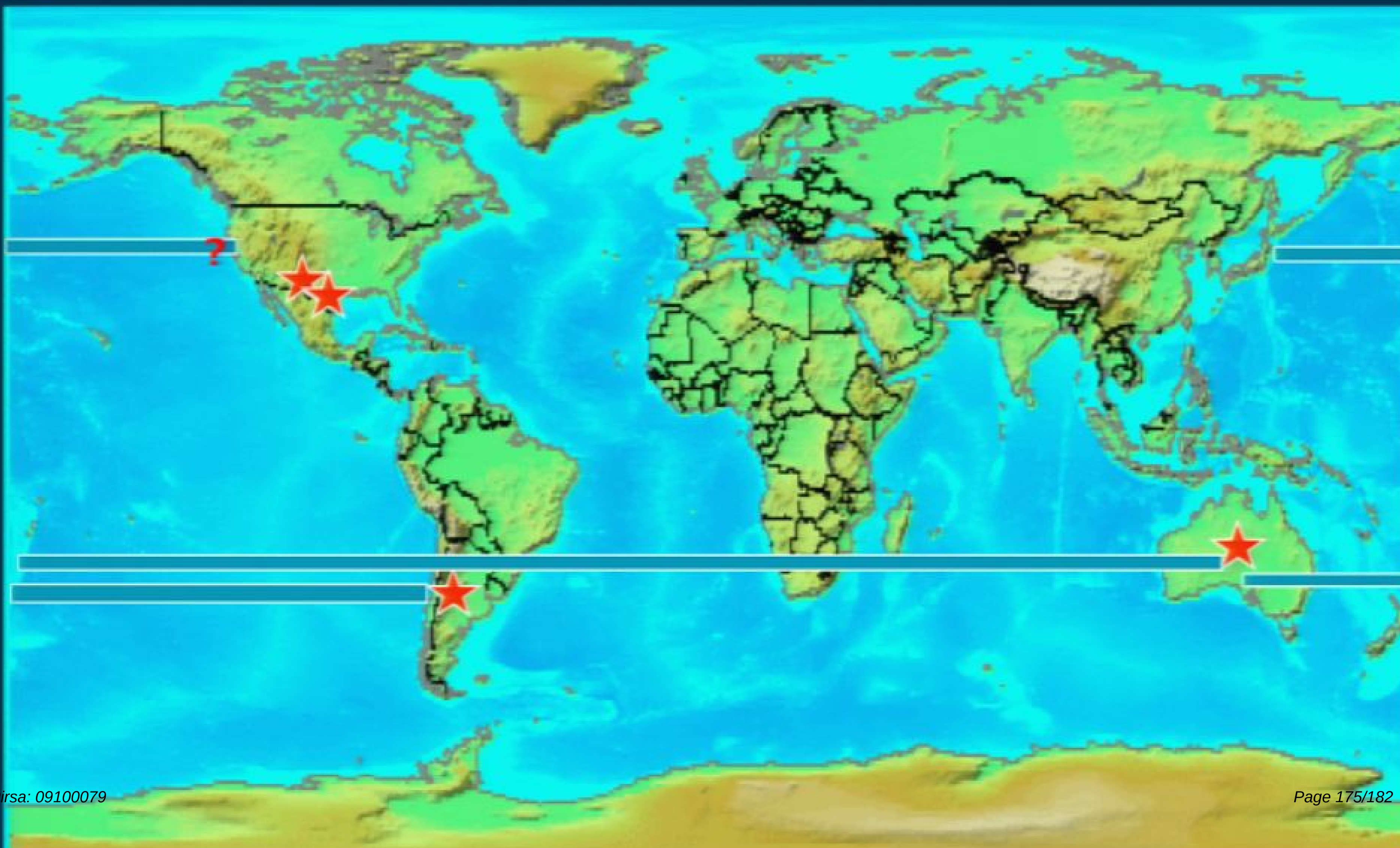

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Technical:

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Programmatic:

- Technical requirements imply risk
- High cost relative to typical balloon missions and the balloon budget – external partners
- 14MCF and 22MCF and Australian launch need to be demonstrated

Timeline

March 2010- Proposal due to NASA ROSES/APRA

October 2010- Selections

2010-2011 – Development

2011-2012- Construction

2013 – Integration at JPL

2014- Overnight Test Flight at Ft. Sumner (US)

Late 2014/early 2015- Science flight at Alice Springs, Australia

Science reach

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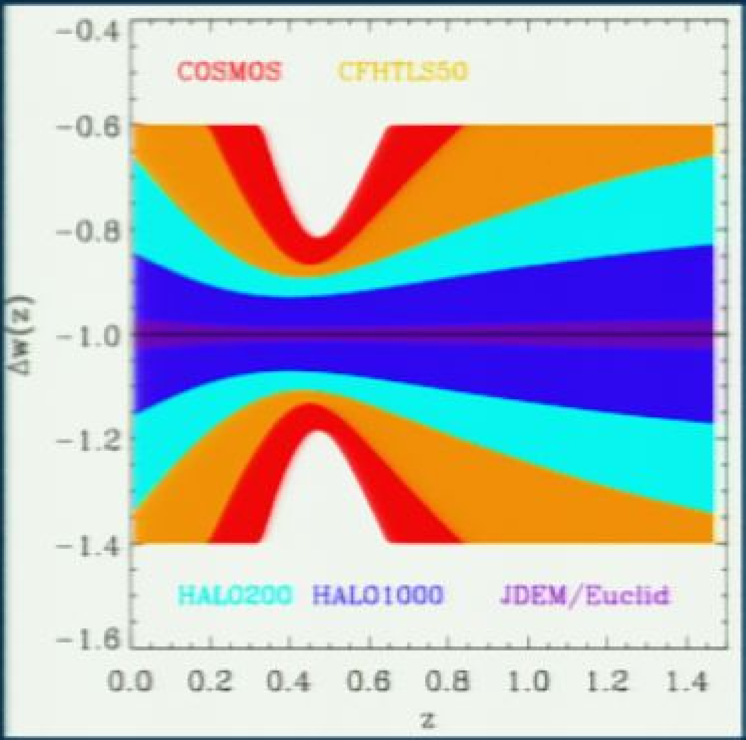
Understand dark matter:

- Amount and distribution
- Weak and strong lensing

Explore dark energy and modified gravity:

- Examine expansion history
- Growth of structure



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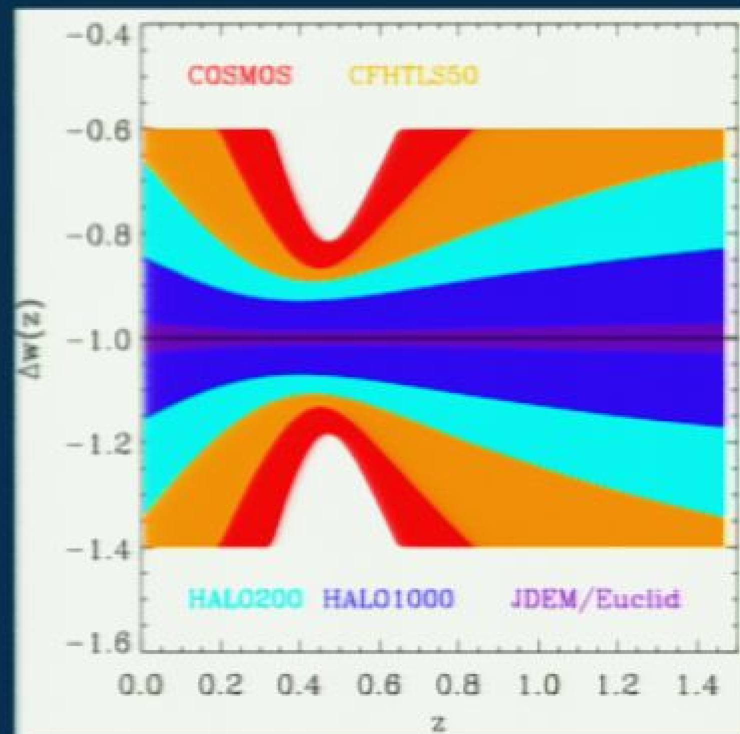

Ancillary science:

- Galaxy morphology and evolution
- Stellar counts
- Surface brightness fluctuations

Conclusions

- Weak gravitational lensing is an excellent cosmological tool
- In particular, it is an excellent probe of modified gravity and dark energy
- The PPF formalism gives model-independent constraints on modifications of General Relativity
- Future space-quality data from HALO can make this possible