Cosmology in the Era of Big Surveys

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Outline

Cosmology

- Concordance (ΛCDM) model
- Cosmological probes - Planck results!

Weak gravitational lensing

- Cosmological information
- Systematics and limitations

Intrinsic alignment of galaxies

- Impact on cosmology
- Self-calibration techniques

The Szekeres metric

- Interpretations of data

Cosmology: A History Lesson

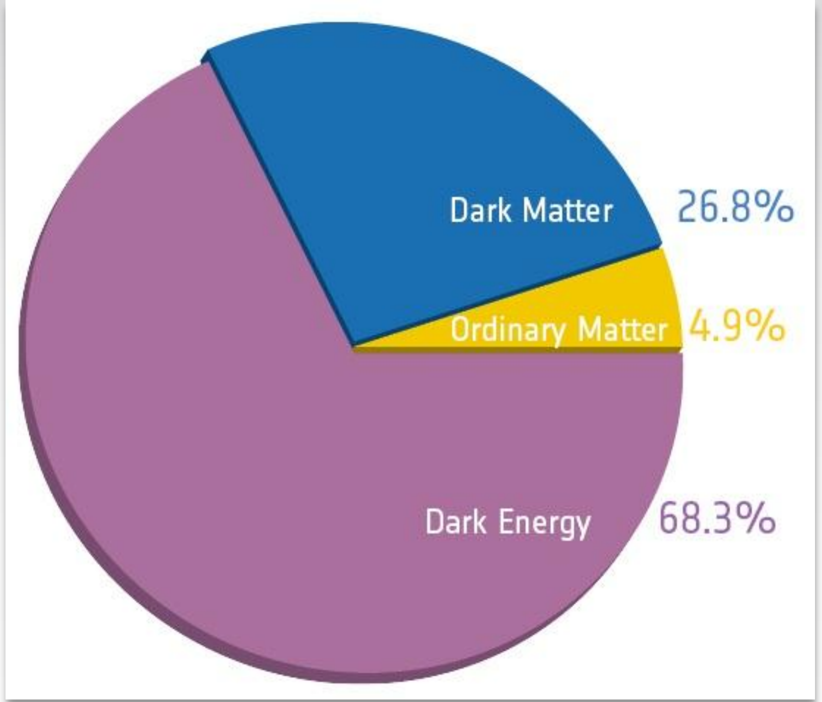
ΛCDM

Concordance model of cosmology

- Lambda (dark energy) + Cold Dark Matter in a perturbed FLRW metric
- Extremely successful!

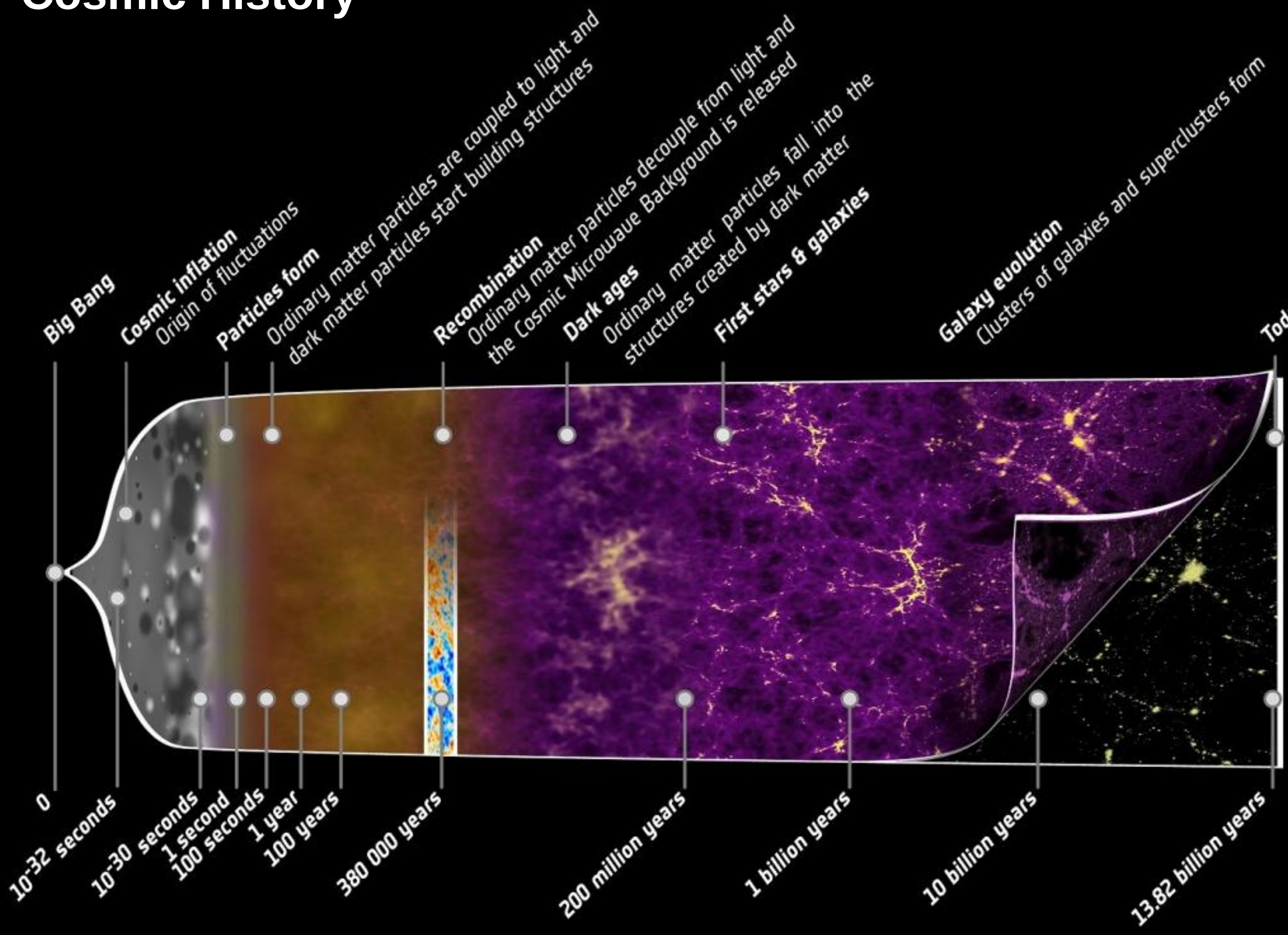
Agreement across data sets

- Cosmic microwave background (CMB)
- Supernovae Ia
- Baryon acoustic oscillations (BAO)
- Gravitational lensing
- And more…



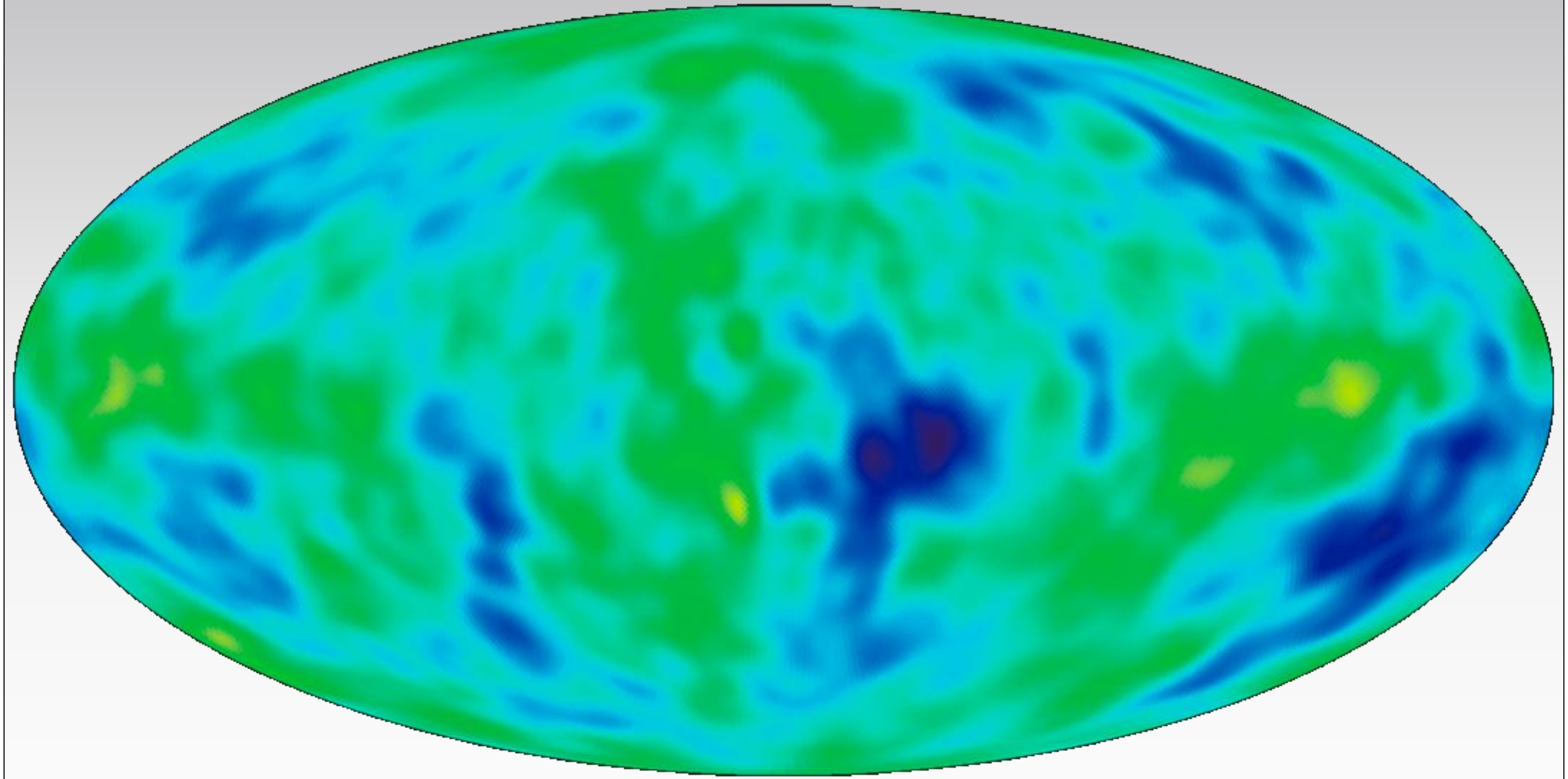
Credit: ESA and the Planck Collaboration

Cosmic History



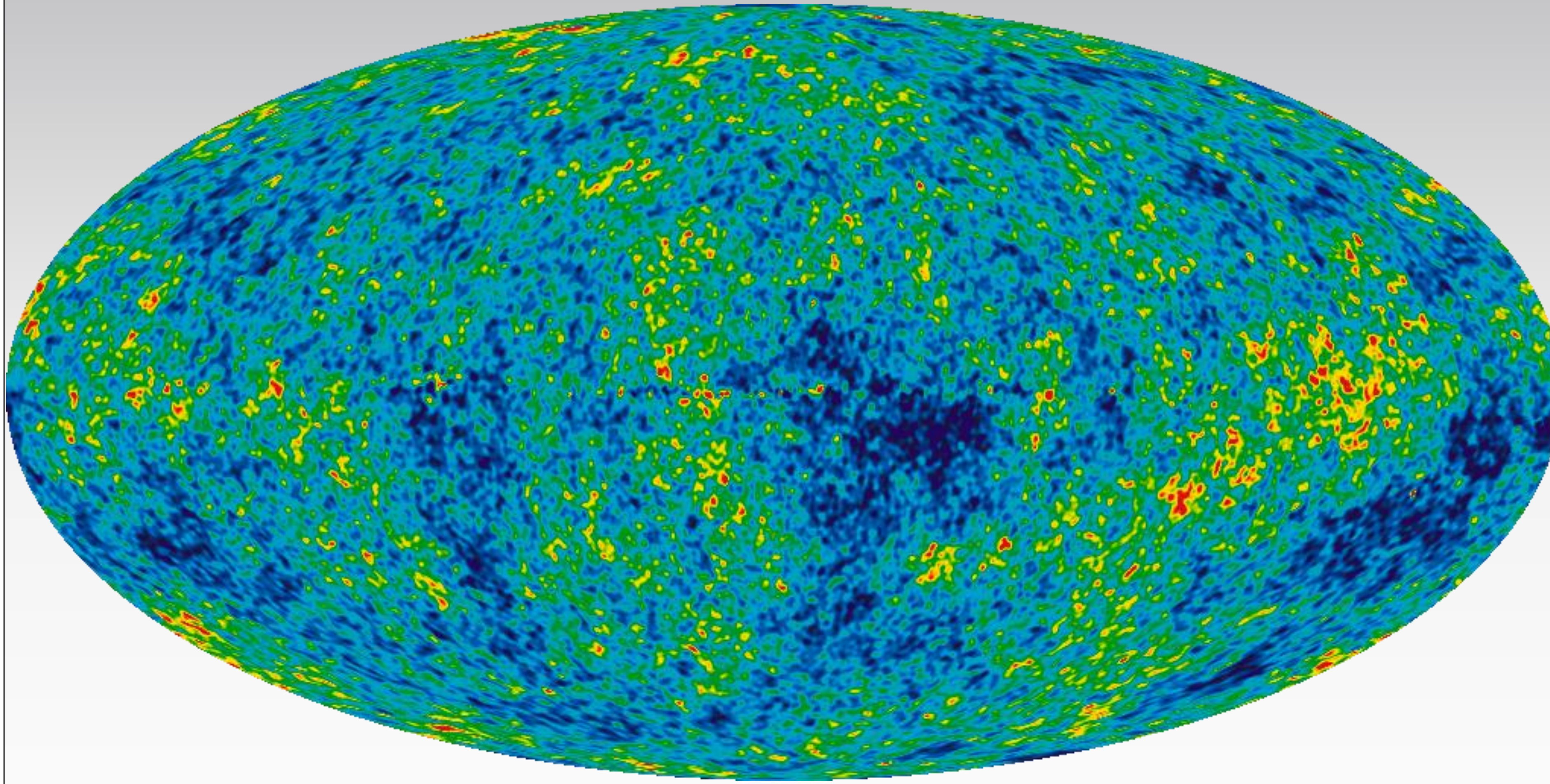
Credit: ESA – C. Carreau

COBE CMB temperature map



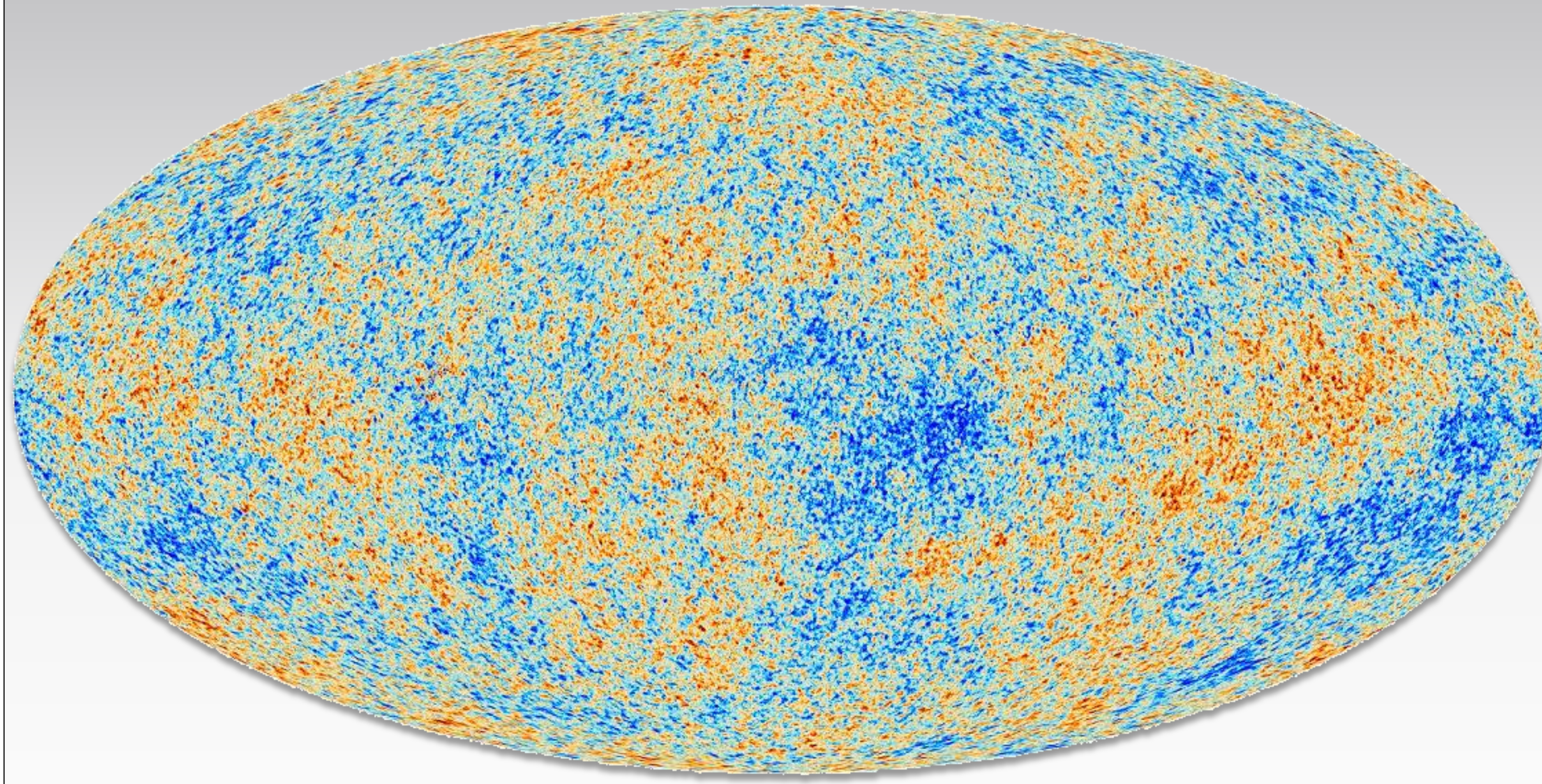
Credit: NASA / WMAP Science Team

WMAP 9yr CMB temperature map



Credit: NASA / WMAP Science Team

Planck 2013 CMB temperature map



Credit: Planck Collaboration, submitted A&A (2013)

ΛCDM – precise constraints

New Planck results (+WMAP polarization)

- 0.05%-5% precision in parameter constraints

Exciting possibilities…

Systematic limitations

- Understanding the physics

Testing our interpretations

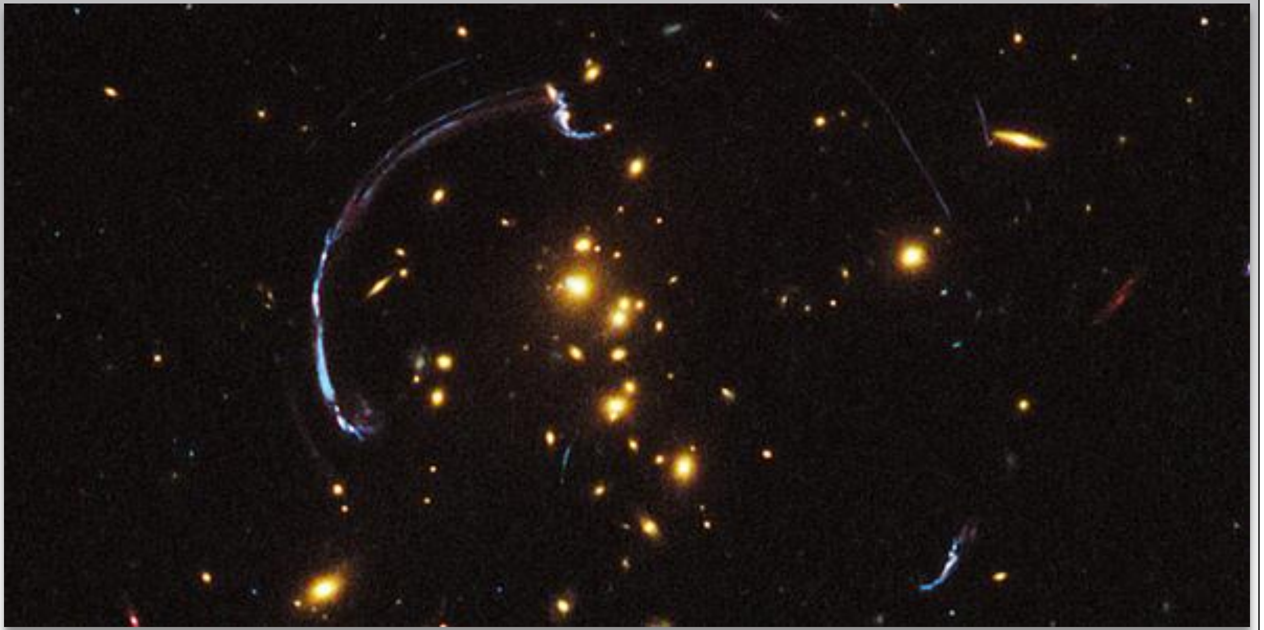
- Exploring new physics

	Planck+WP	
Parameter	Best fit	68% limits
Ω_Λ	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8347	0.829 ± 0.012
H_0	67.04	67.3 ± 1.2
Age/Gyr	13.8242	13.817 ± 0.048
z_*	1090.48	1090.43 ± 0.54

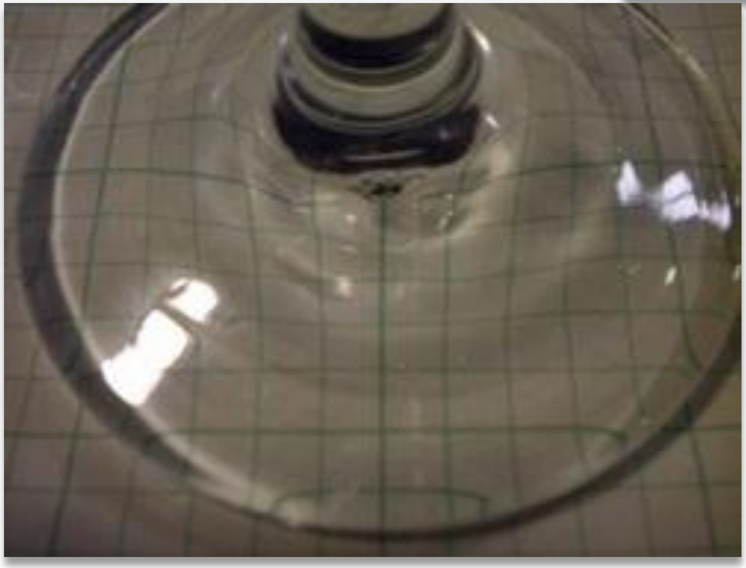
Credit: Planck Collaboration, submitted A&A (2013)

Weak Gravitational Lensing: Cosmic Shear

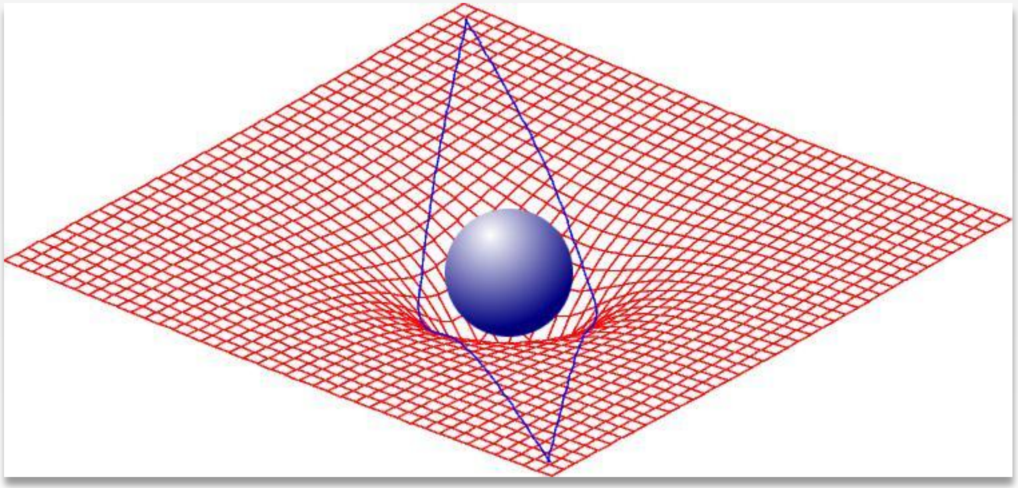
Gravitational lensing



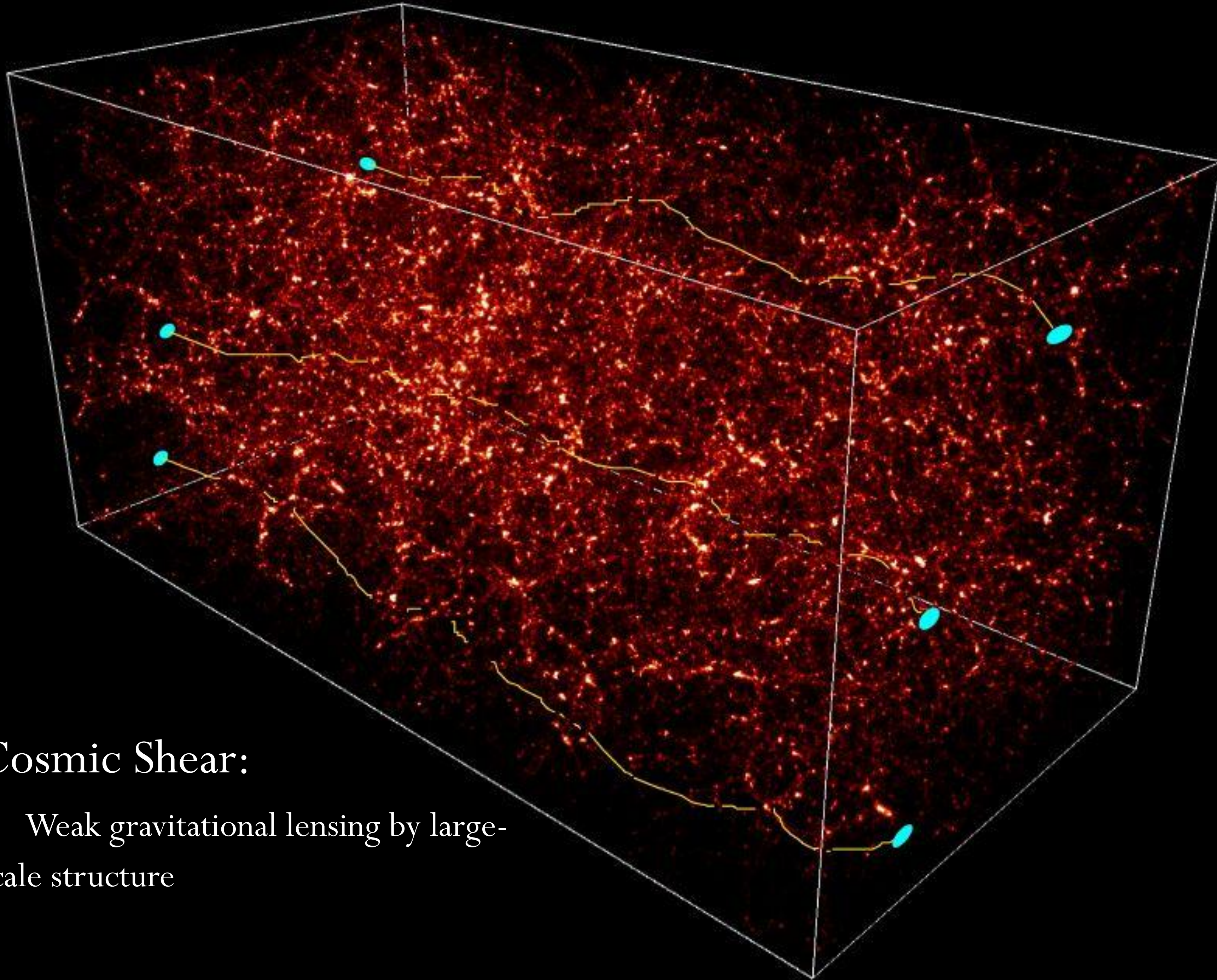
Credit: NASA/ESA/J. Rigby/K. Sharon



Credit: APS



Credit: ITA, Bartelmann



Cosmic Shear:

Weak gravitational lensing by large-scale structure

SIMULATION: COURTESY NIC GROUP, S. COLOMBI, IAP.

Weak gravitational lensing (cosmic shear)

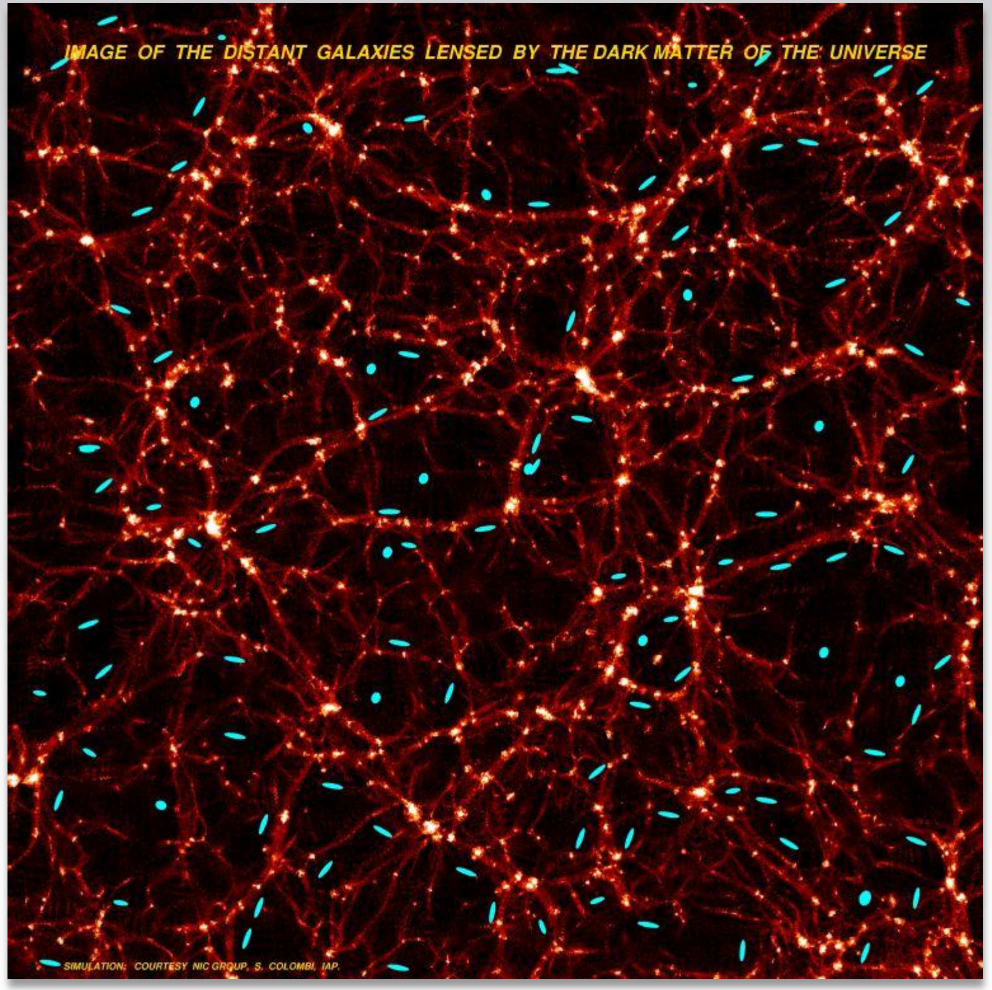
Powerful probe for cosmology

- Map dark matter
- Large-scale structure

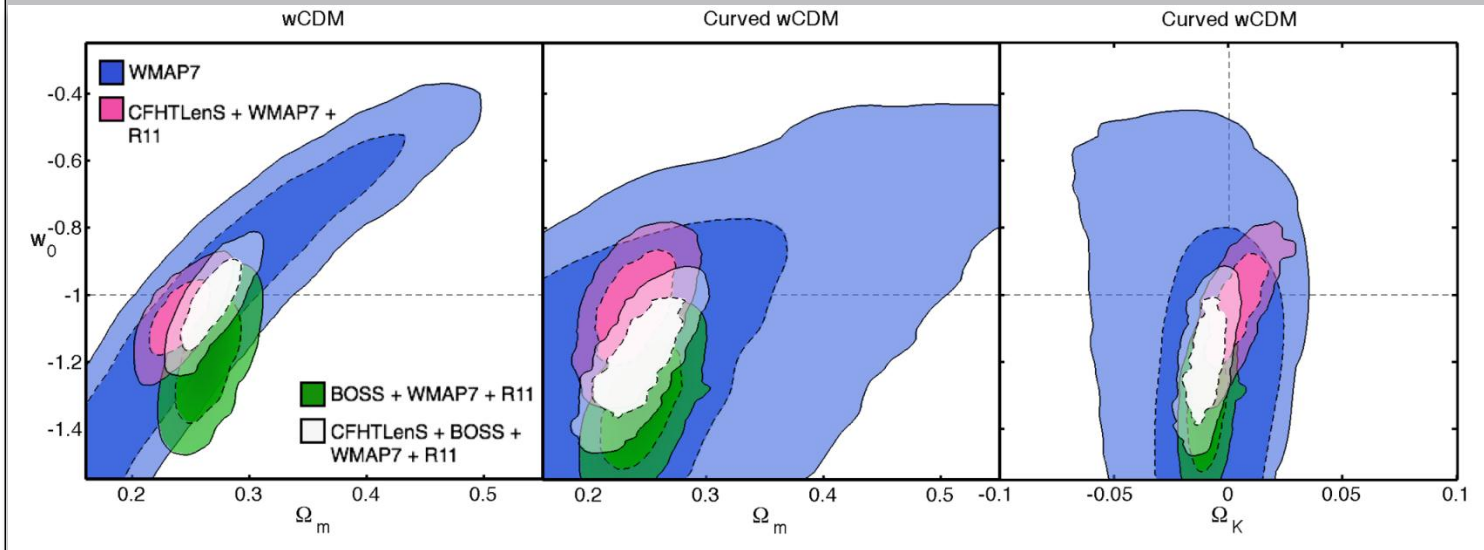
Parameter constraints

- Factor of 2-4 improvement:
  - DE eqn. of state
  - Matter fluctuation amp.

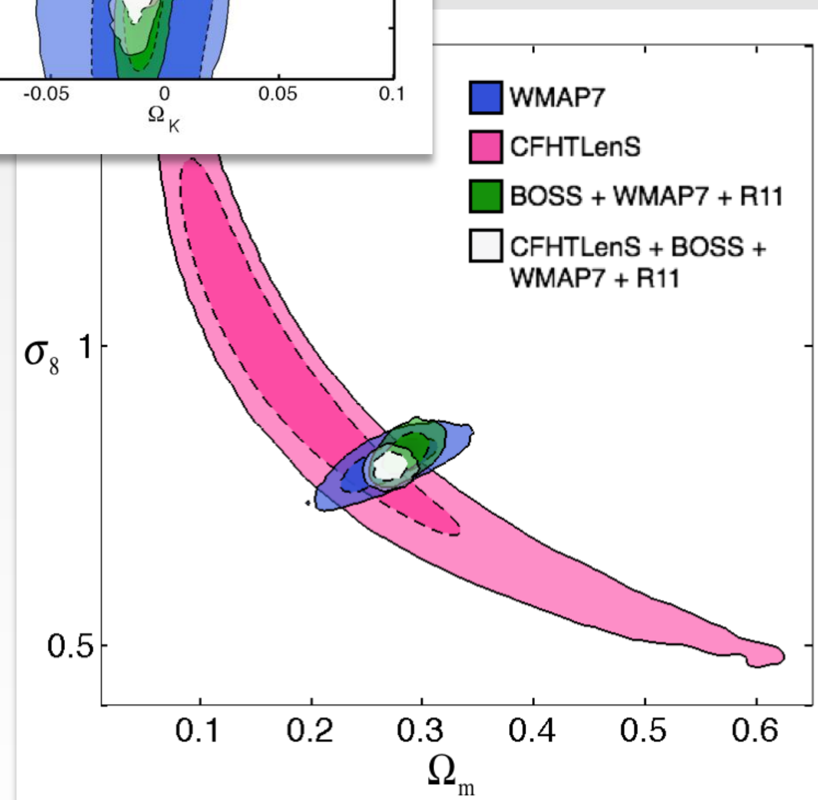
Test of gravity on large scale



Cosmological constraints from CFHTLenS



For more: Heymans et al., submitted MNRAS (2013)



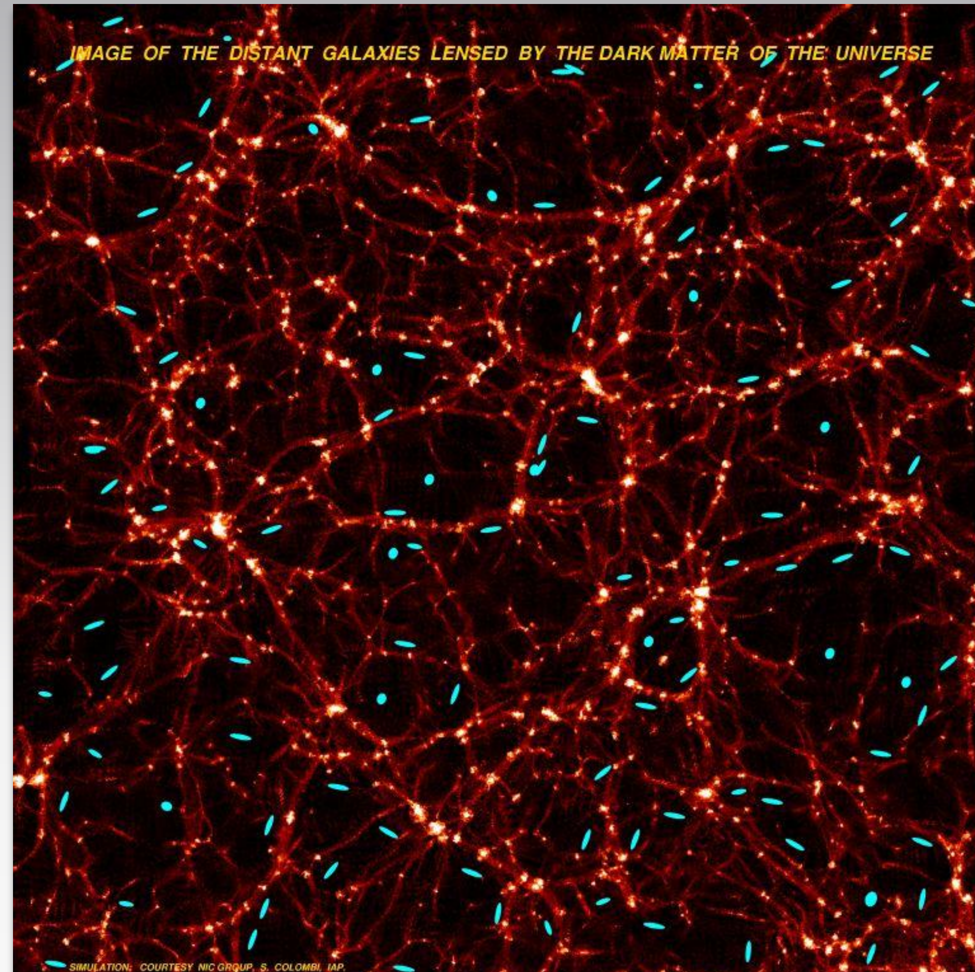
Complementary

- Weak lensing measures different info.

It will get much better…

- Exciting planned lensing missions
- DES, LSST, Euclid, etc…

Measuring cosmic shear



Cosmic shear is weak (lensing)

- Quantified by ellipticity
- …intrinsic alignment

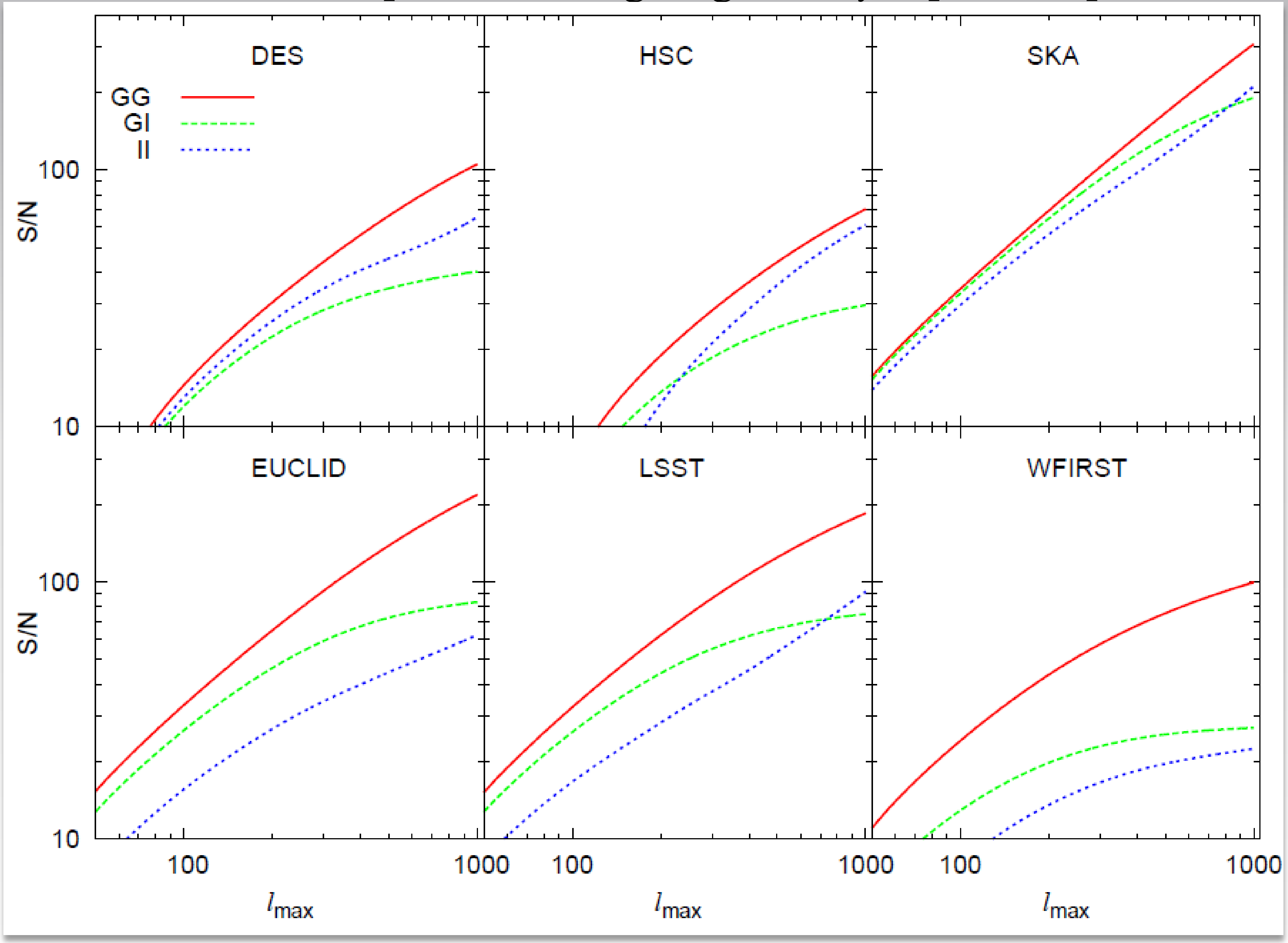
Statistical correlation of shapes

- Average 10^6-10^9 galaxies
- Like CMB temperature

Power spectrum (galaxy pairs)

- Measures correlation power at different angular scales
- Bispectrum (galaxy triplets) – even more information
  - Improved constraints
  - Info. on non-Gaussianities

S/N of future and planned/ongoing surveys (power spectra)



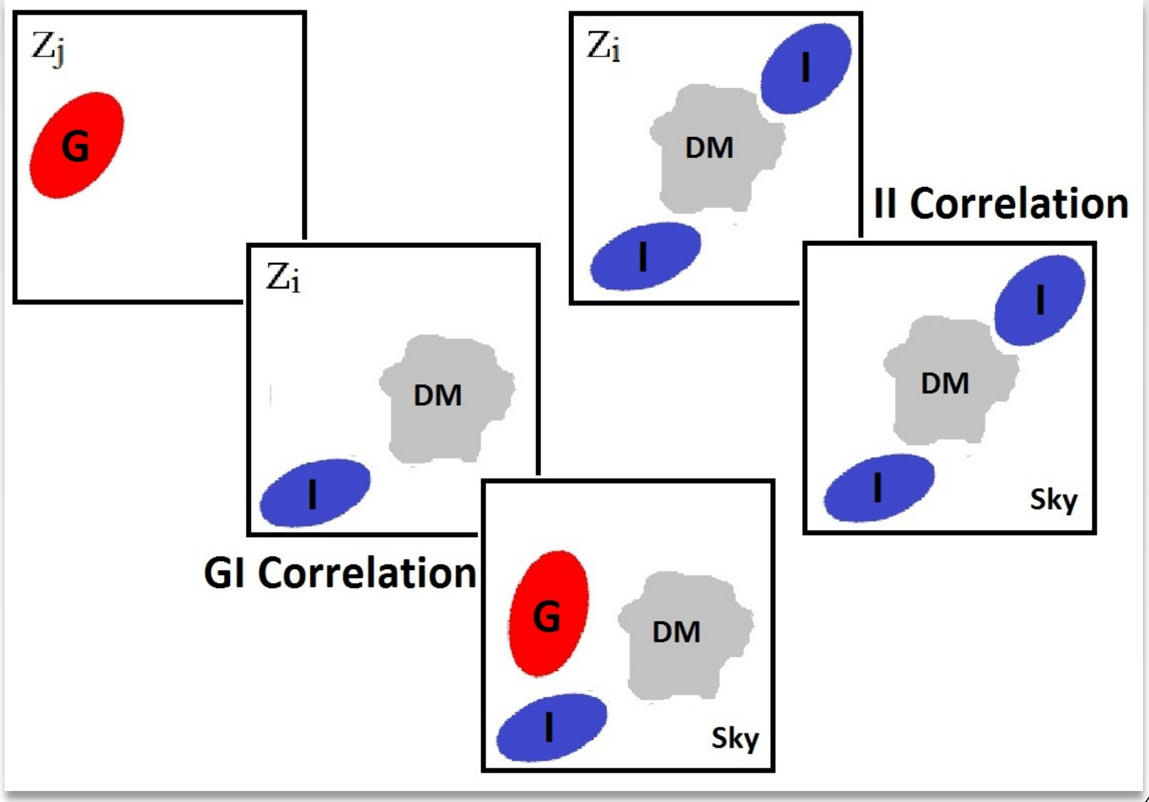
Intrinsic Alignment of Galaxies

Intrinsic alignment of galaxies (IA)

- Large systematic effect in shear measurements
- Dark energy equation of state biased by up to 50% (Bridle & King 2007)
- Contaminates 2-pt weak lensing signal by up to 10% (Mandelbaum et al. 2007)
  - 3-pt weak lensing signal by up to 15-20% (Semboloni et al. 2008)
- Essential to remove for planned survey goals!

Two 2-pt correlations

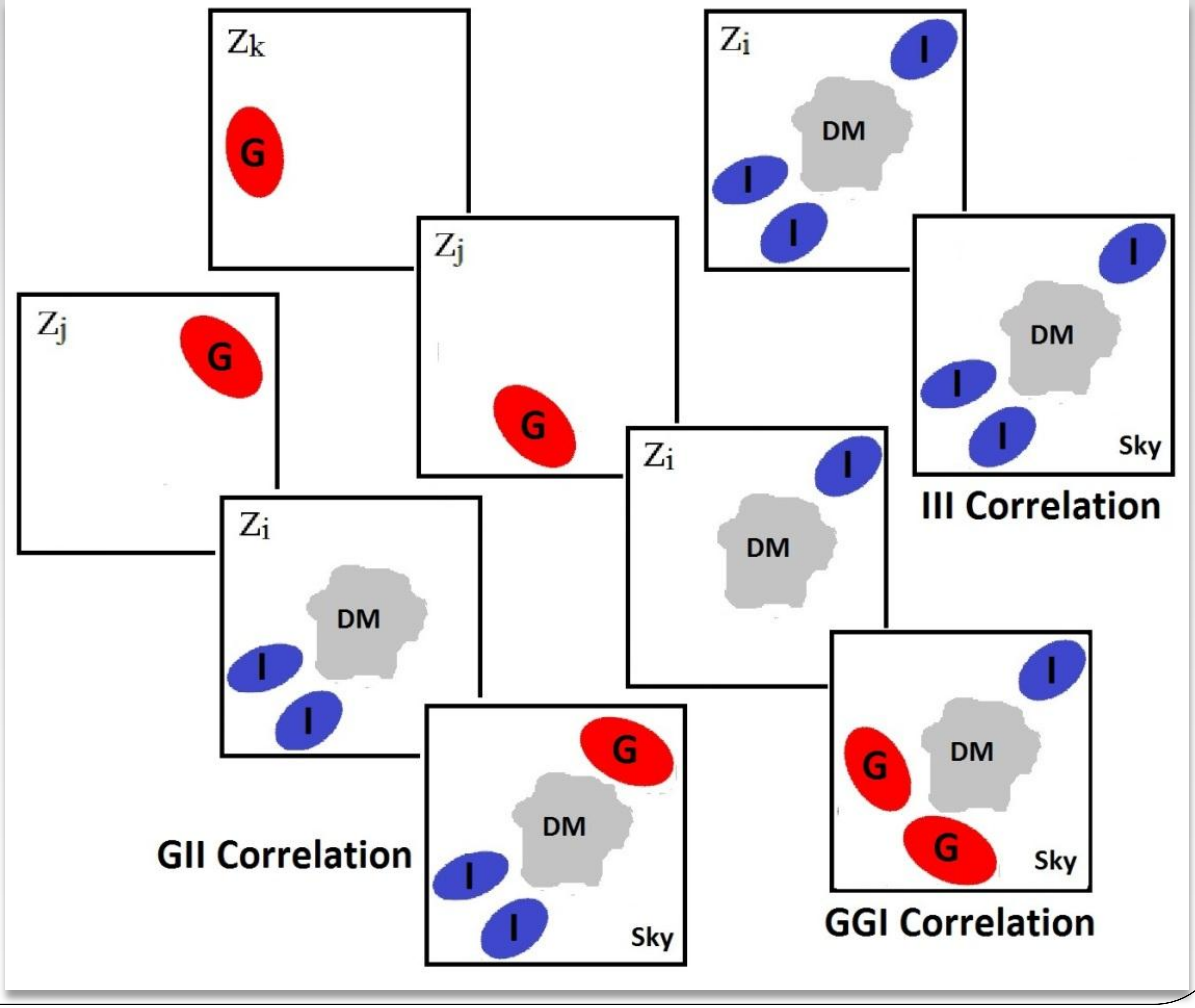
- II - Only 'close' pairs
  - Positive correlation
  - Boosts signal
- GI - All pairs
  - Negative correlation
  - Reduces signal



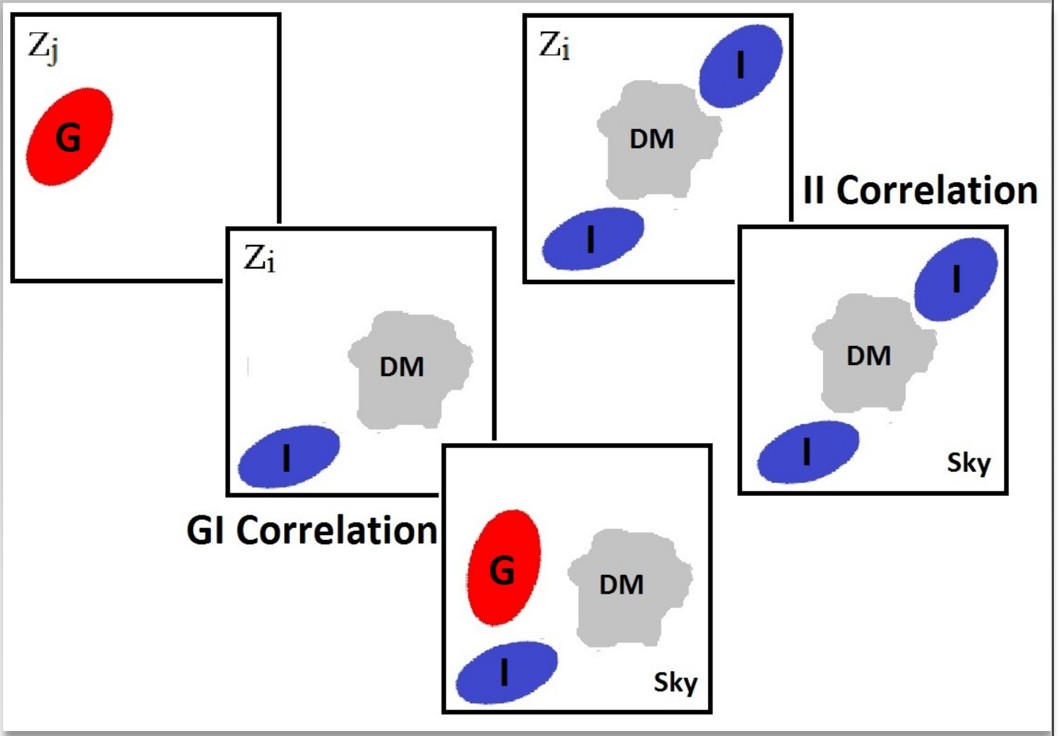
Intrinsic alignment of galaxies (IA)

Three 3 pt. correlations

- III - Only ‘close’ triplets
- GII - All triplets
- GGI - All triplets



Mitigating intrinsic alignment



Redshift bin tomography

- Greatly reduce II corr.
- No impact on GI corr.

(Refregier 2003)

Template/model fitting

- Dep. on choice of model

(King 2005, Joachimi & Bridle 2010)

Nulling techniques

- Geometric nulling of IA
- Loss of statistical power

(Joachimi & Schneider 2008,2009,2010)

Self-calibration techniques

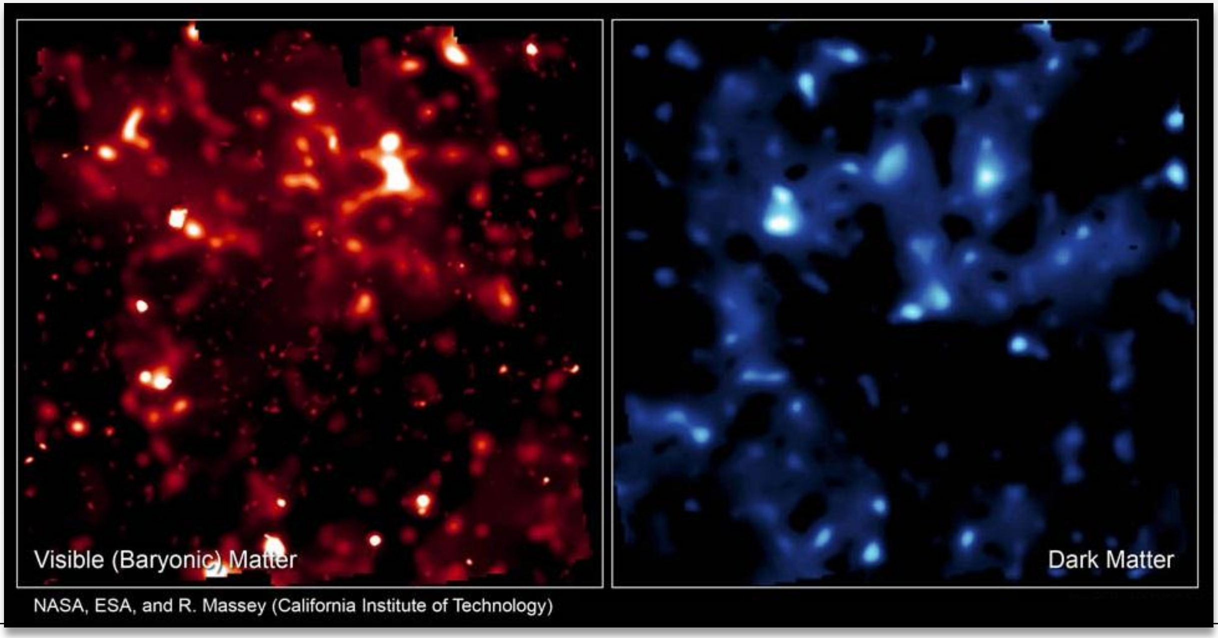
- Combines tomography + nulling
- …But works for GI and no power loss

(Zhang 2010a, 2010b, MAT & Ishak 2012a,2012b,2012c)

Weak lensing surveys

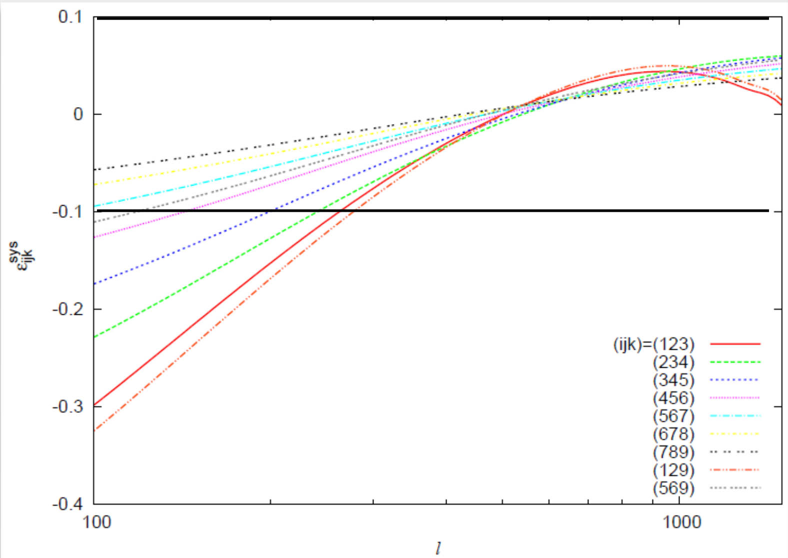
Two primary observables

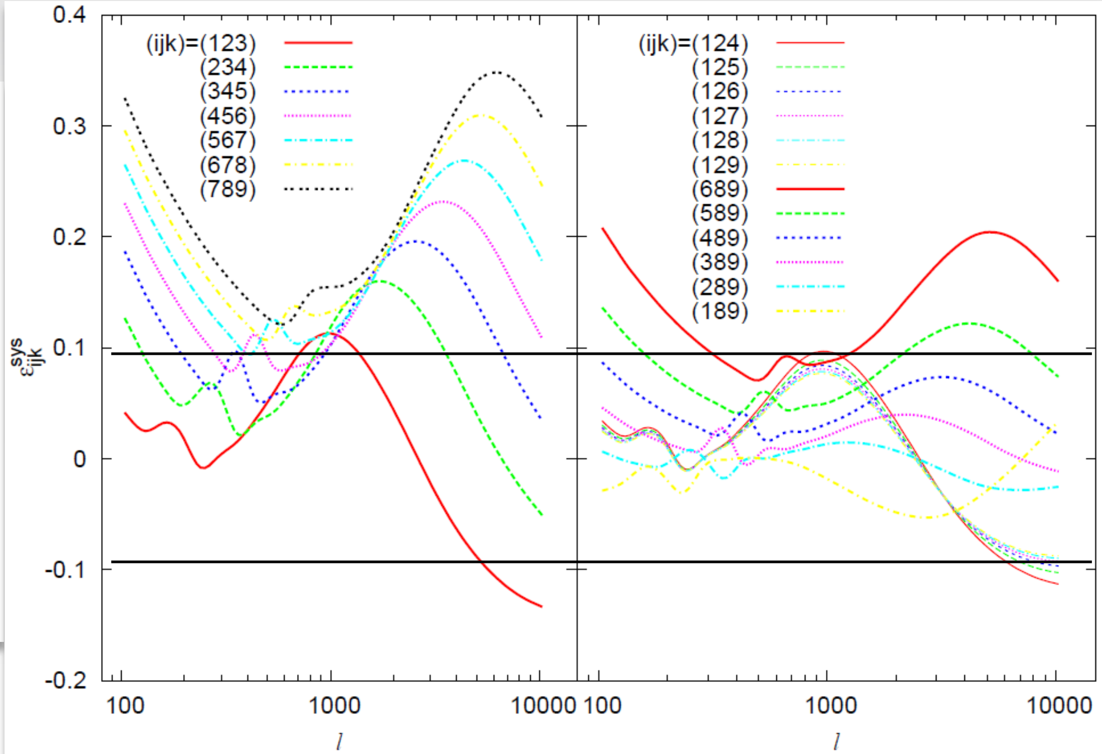
- Galaxy shape → shear/convergence (G+I)
- Galaxy number → galaxy surface density (g)
- Also photo-z (redshift or distance) and position on the sky
- Galaxies split into redshift bins
  - Cross-correlations between redshift bins (galaxies are spatially distant)
  - Auto-correlations within a single redshift bin (galaxies are spatially close)



Self-calibration of IA cross-correlations

- Pure IA correlations negligible
- Standard galaxy bias model
- Build relationship between lensing-IA and galaxy density-IA corr.
- Galaxy density-IA corr. isolated from galaxy shape-density corr.
- Can now isolate the IA contamination from the lensing signal



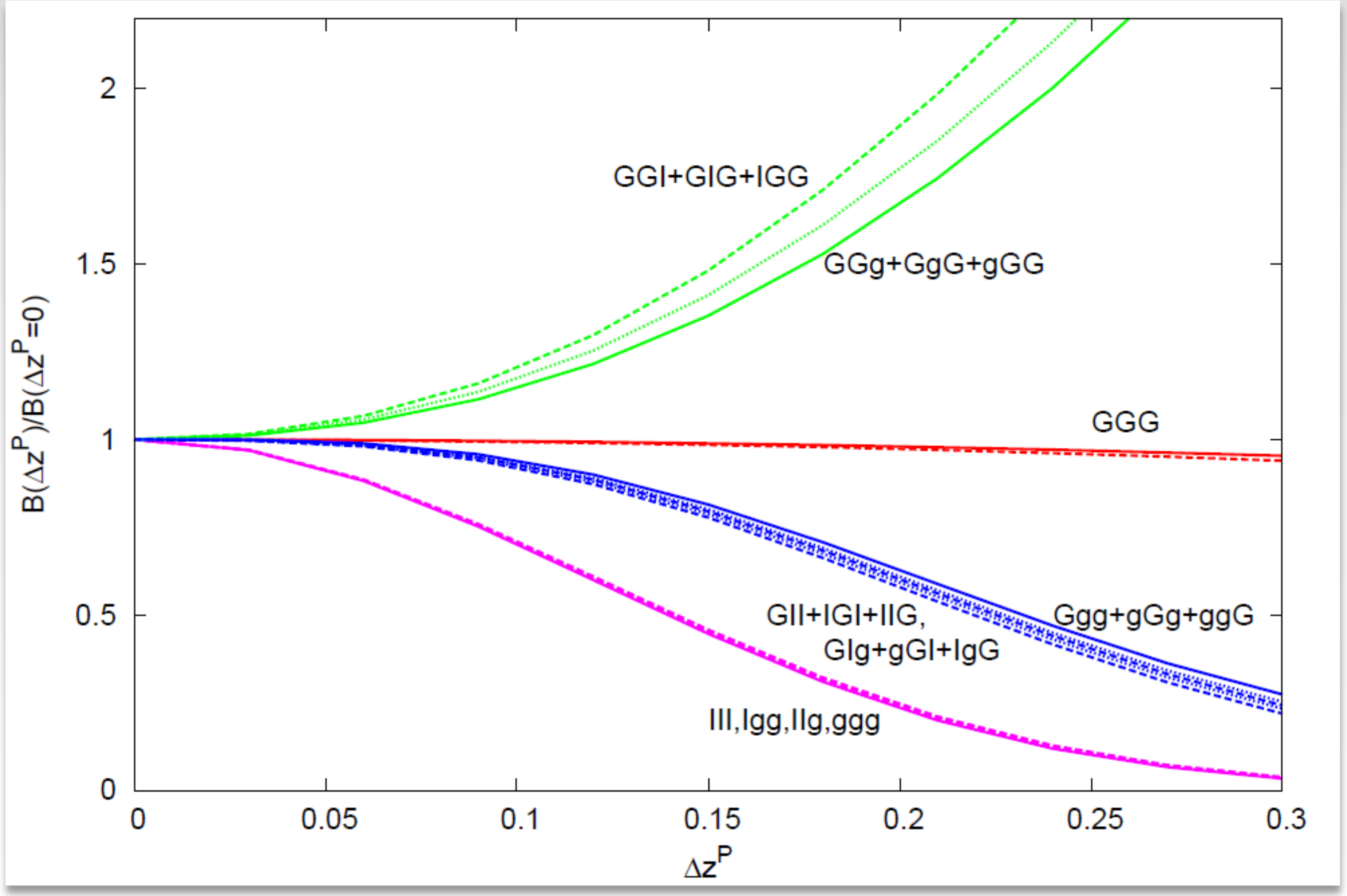


Left: GII self-calibration systematic error

Right: GGI self-calibration systematic error

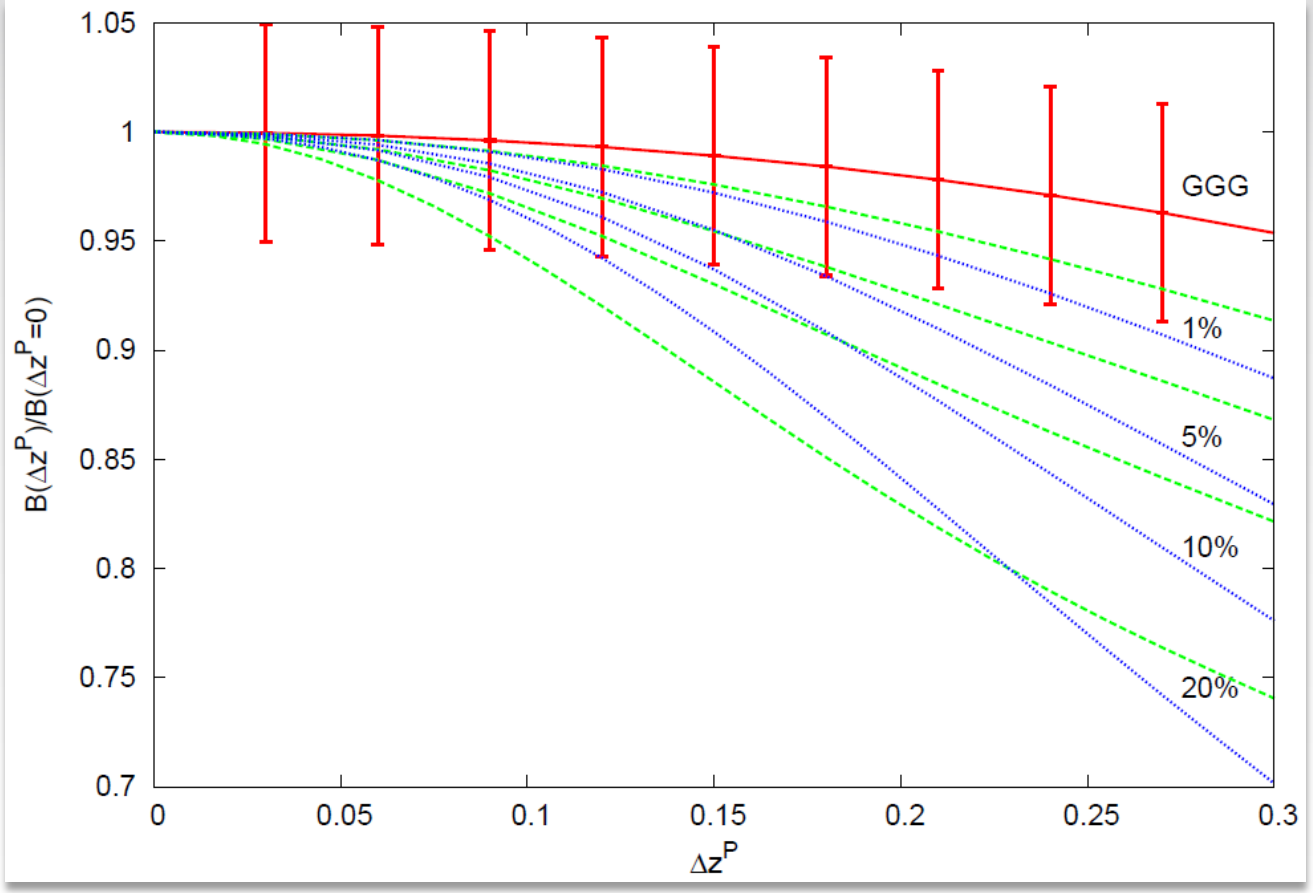
Self-calibration of IA auto-correlations

- Use distinct separation dependence of IA and shear signal
- Derive scaling relationships between IA-lensing and gal. density-lensing
- Isolate individual IA-lensing corr. from pure lensing signal
- More difficult in practice than previous self-calibration technique



Self-calibration of IA auto-correlations

- Requires measurement of shear bispectrum at 7 or more separations
- Conservative photo-z error + expected IA contamination (10-15%)
- Constraint of IA relationships possible
- Allows us to isolate individual IA and cosmic shear auto-correlations



Must correct for IA contamination in future surveys

- 10% or more bias in cosmological information

IA self-calibration techniques

- Reduction of IA contamination by up to factor of 10 in cross-correlations
  - 10+% bias in cosmological information becomes percent level
  - Errors introduced by self-calibration negligible
  - Little/no loss in lensing signal
- Recover IA correlations for use in other studies
  - Large scale structure formation
- Applicable in any weak lensing survey
  - DES, EUCLID, HSC, JWST, LSST, Pan-STARRS, WFIRST…

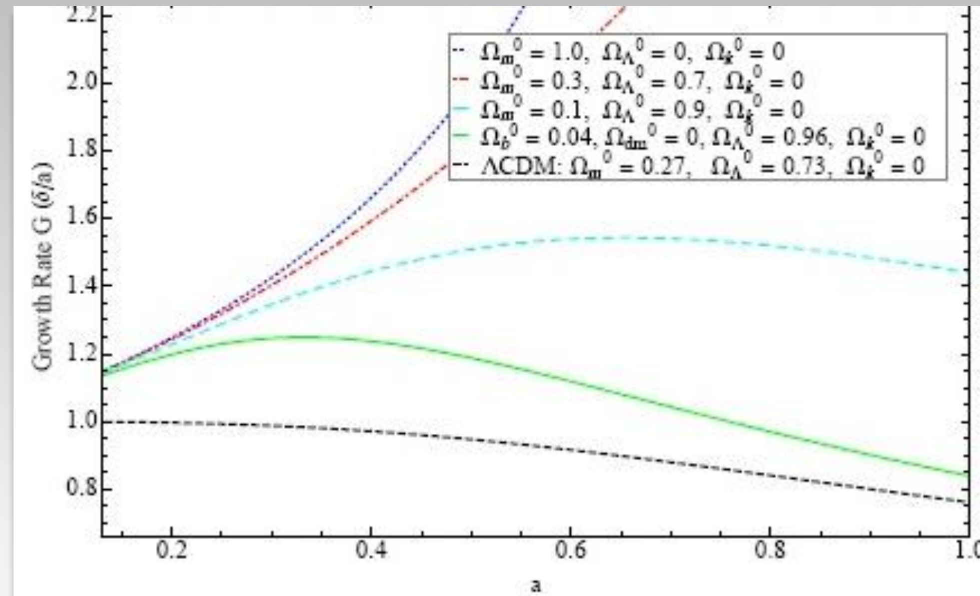
For more information: MAT & Ishak, MNRAS, 419, 1804 (2012)

MAT & Ishak, MNRAS, 423, 1663 (2012)

MAT & Ishak, MNRAS, 427, 442 (2012)

New Interpretations?

FLRW metric vs Szekeres metric



FLRW metric

- Exact sol'n of Einstein's eqs.
- Homogeneous & isotropic
- Uses linear perturbations to produce structure formation

$$\ddot{\delta} + 2\frac{\dot{a}}{a}\dot{\delta} - 4\pi G\bar{\rho}\,\delta = 0$$

Szekeres metric

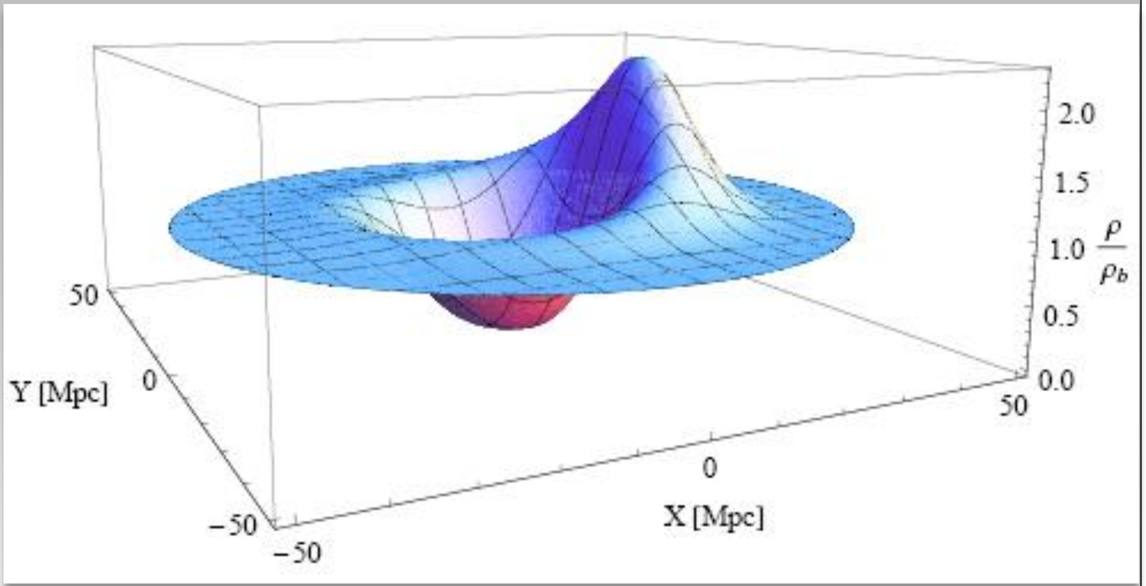
- Exact sol'n of Einstein's field eqs.
- Inhomogeneous & anisotropic
- Can be expressed in form of ***exact*** non-linear perturbations
- Enhanced growth of structure compared to FLRW and ΛCDM
- FLRW is a natural limit to the Szekeres metric (class I)

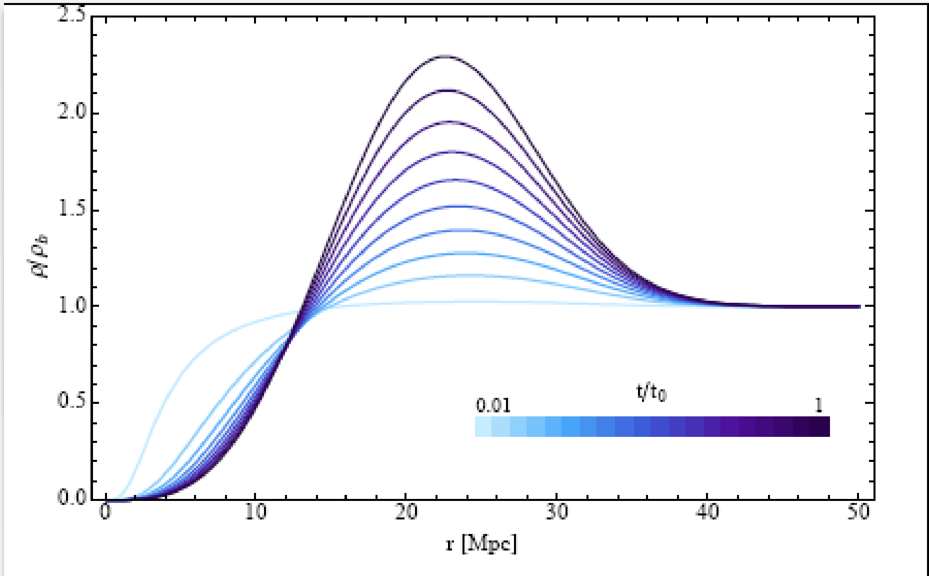
$$\ddot{\delta} + 2\frac{\dot{a}}{a}\dot{\delta} - \frac{3M}{a^3}\delta - \frac{2}{1+\delta}\dot{\delta}^2 - \frac{3M}{a^3}\delta^2 = 0$$

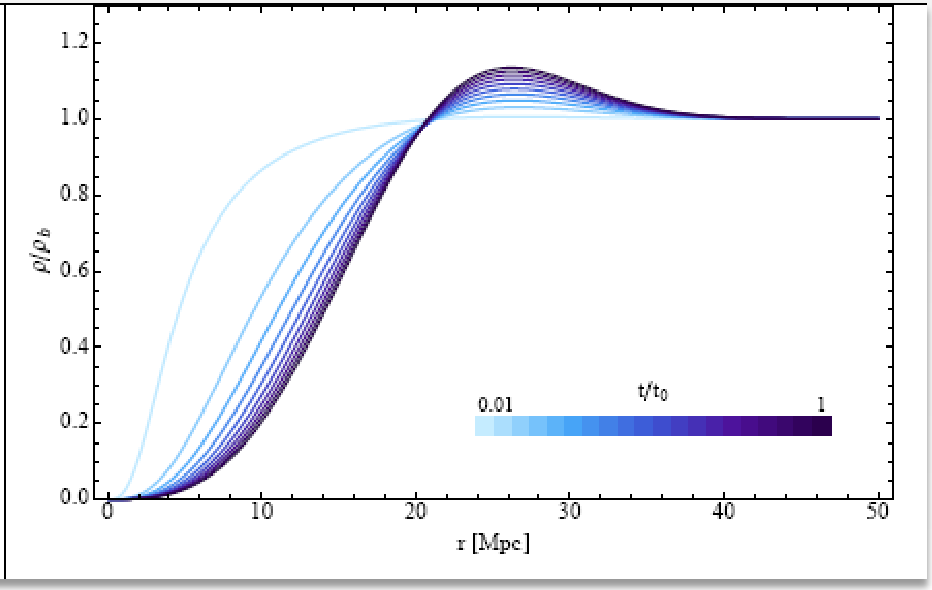
Modeling exact structures (class I)

Void + super-cluster

- Exact Szekeres metric
- Structure evolution







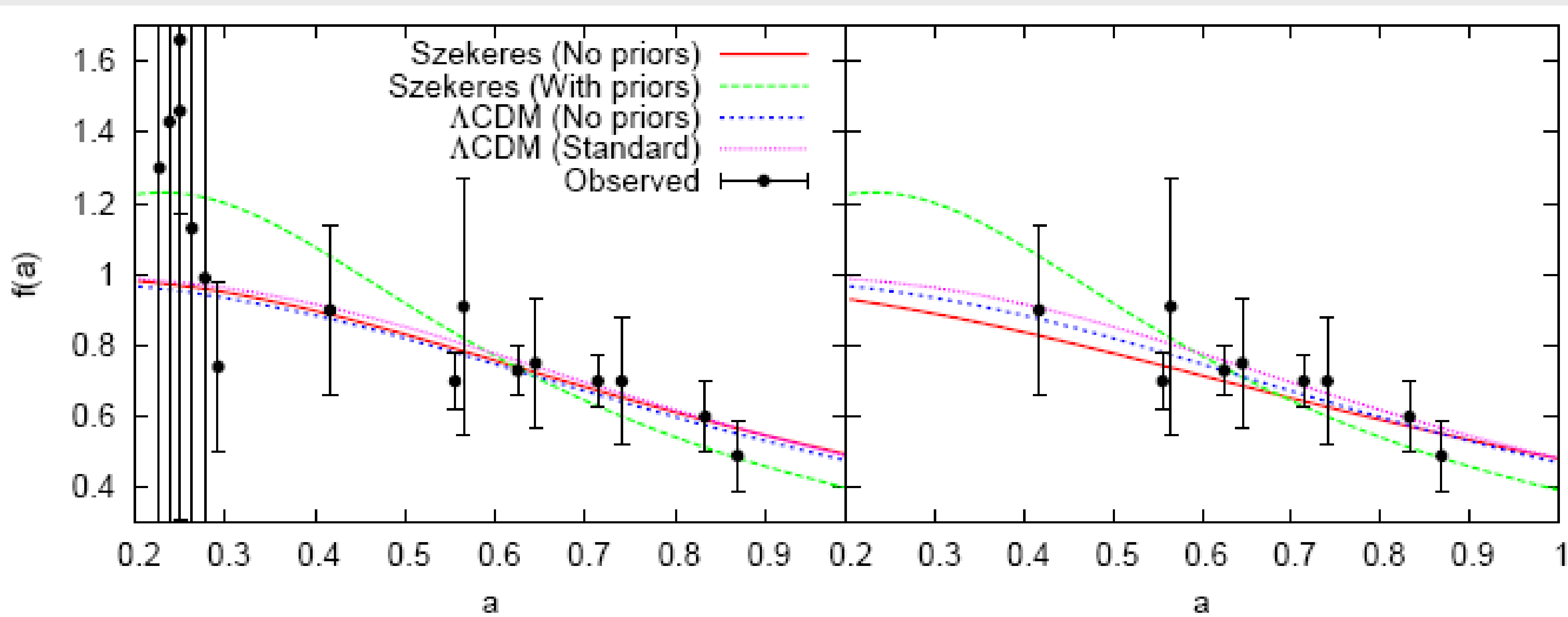
Comparing to ΛCDM (class II)

Fitting Szekeres and ΛCDM to growth data

- Comparable fitting ability
- Different interpretation?

(Peel, Ishak & MAT 2012)

	$L\alpha$?	Without priors Ω_m^0	Ω_Λ^0	Ω_k^0	(χ^2)	With priors Ω_m^0	Ω_Λ^0	Ω_k^0	(χ^2)
Szekeres	No	0.12	0.59	0.29	(0.22)	0.05	0.98	-0.03	(0.62)
	Yes	0.11	0.69	0.20	(0.39)	0.05	0.98	-0.03	(0.63)
ΛCDM	No	0.29	0.56	0.15	(0.21)	0.27	0.73	0.00	(0.32)
	Yes	0.26	0.69	0.05	(0.39)	0.27	0.73	0.00	(0.43)



Cosmological constraints are becoming very precise

- Situation will still greatly improve over the next decade
  - Large lensing surveys will complement current CMB constrains
- Systematics a barrier: exciting opportunities
- Precision results will let us explore alternative interpretations

IA self-calibration techniques look to be very successful

- Could reduce a 10-20% systematic bias to the percent level

Szekeres models

- Fully general solution, can build exact physical structures
- Enhanced growth of structure compared to FLRW and ΛCDM
- Comparable fitting power to growth data
  - Szekeres and FLRW indicate possible different interpretations of that data
  - This is very preliminary work, though, and requires more study…

Cosmology, Relativity and Astrophysics group at UTD

- Professor Mustapha Ishak, Austin Peel (PhD student)
- www.utdallas.edu/~mishak/cosmogroup/

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Texas Symposium on Relativistic Astrophysics

- Dec. 8-13, 2013 in Dallas at the Fairmont Hotel
- nsm.utdallas.edu/texas2013/

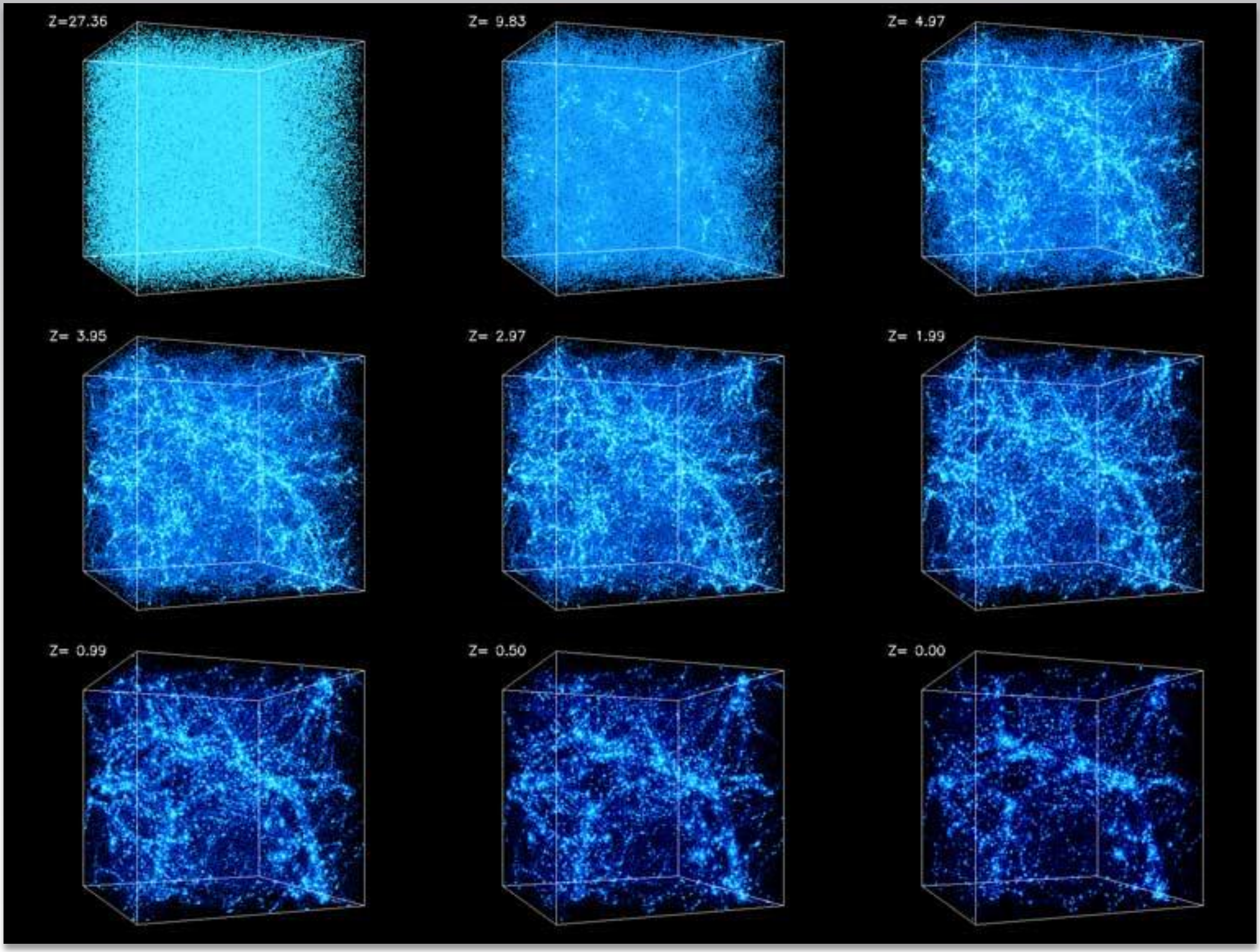
For more information: MAT & Ishak, MNRAS, 419, 1804 (2012)

MAT & Ishak, MNRAS, 423, 1663 (2012)

MAT & Ishak, MNRAS, 427, 442 (2012)

Peel, Ishak & MAT, PRD, 86,123508 (2012)

Cosmic Evolution



Credit: Center for Cosmological Physics