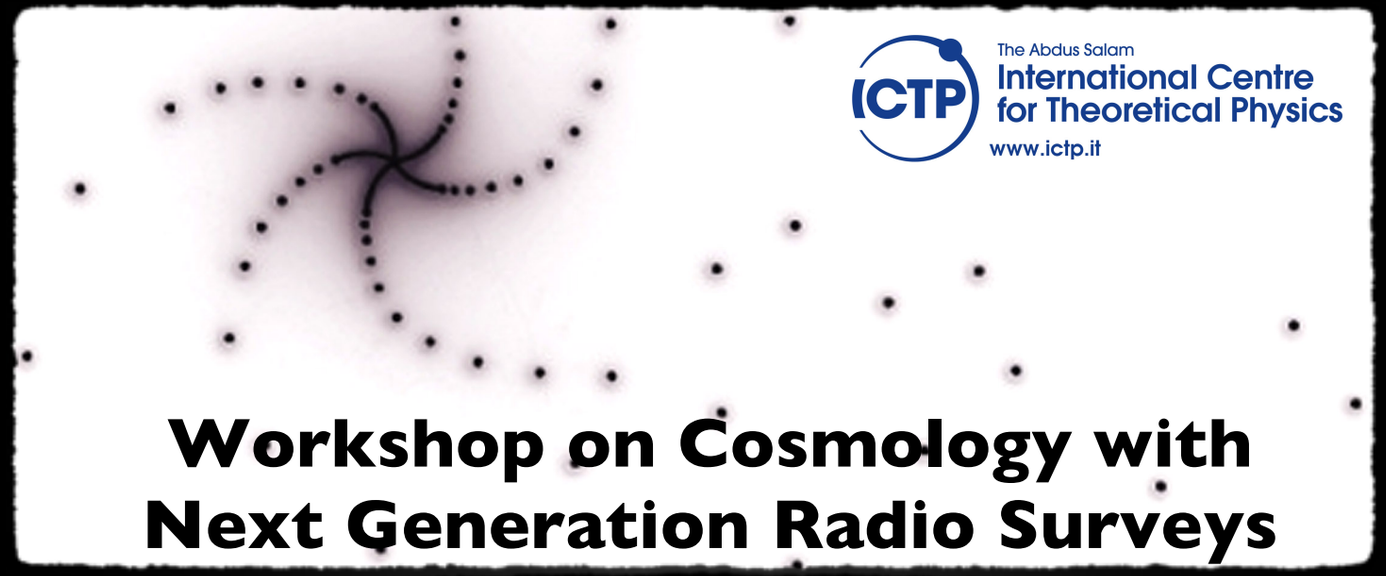

The Abdus Salam International Centre for Theoretical Physics
www.ictp.it

Workshop on Cosmology with Next Generation Radio Surveys

Multi-Wavelength Synergies with Radio Surveys

Stefano Camera

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Jodrell Bank Centre for Astrophysics, The University of Manchester, UK

The University of Manchester

Outline

- Synergies: Why and How?
- Synergies vs Systematics: Radio-Optical Synergies for Cosmic Shear
- Synergies vs Cosmic Variance: Multi-Tracing Galaxy Number Counts

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Outline

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Synergies

Definition of *synergy* in English:

synergy

Pronunciation: /ˈsɪnədʒi/ (?)

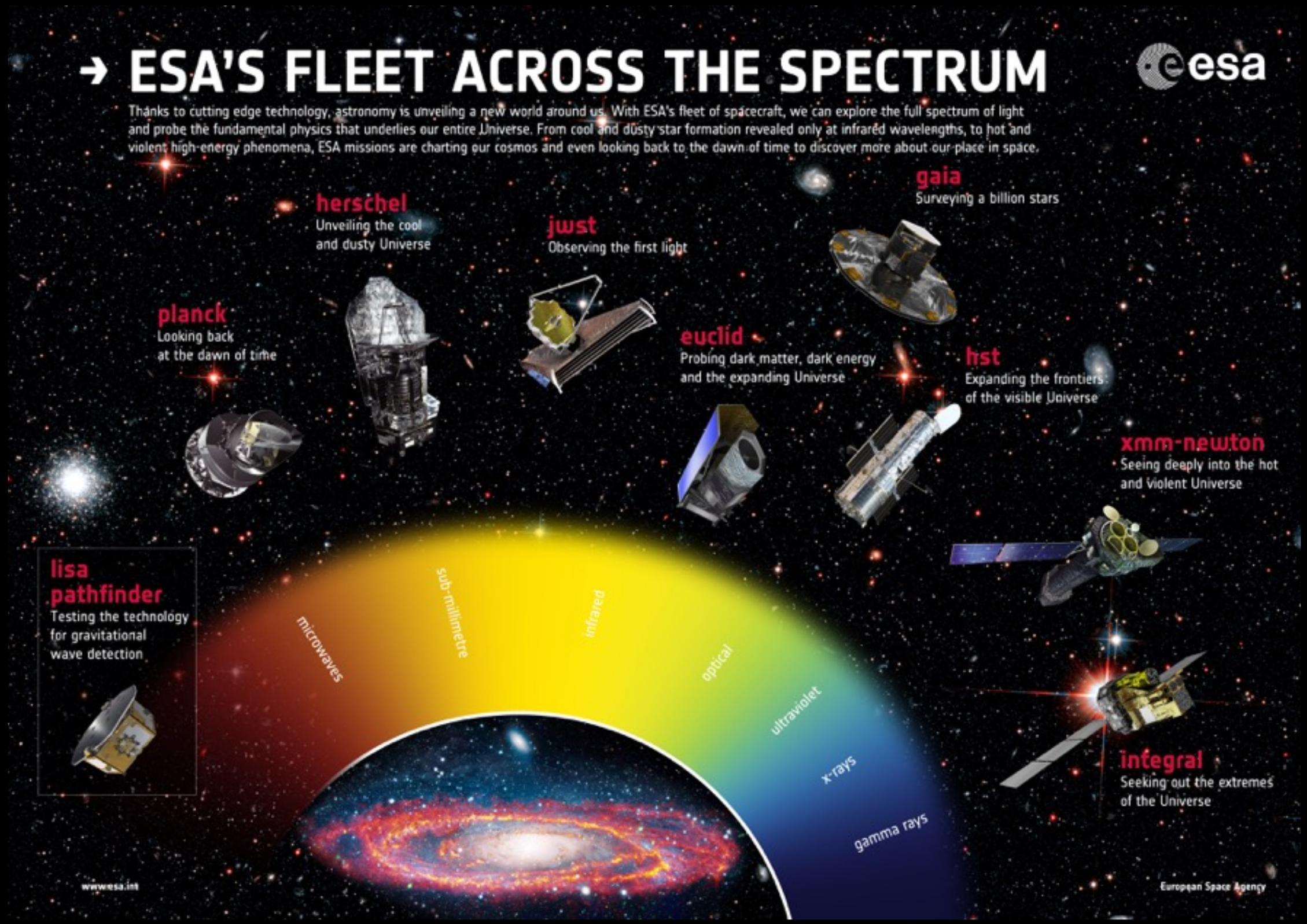
(also **synergism** /ˈsɪnədʒɪz(ə)m/)

NOUN

[MASS NOUN]

The interaction or cooperation of two or more organizations, substances, or other agents to produce a combined effect greater than the sum of their separate effects:

Synergies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Unveiling the cool and dusty Universe
jwst
Observing the first light
gaia
Surveying a billion stars
planck
Looking back at the dawn of time
euclid
Probing dark matter, dark energy and the expanding Universe
hst
Expanding the frontiers of the visible Universe
xmm-newton
Seeing deeply into the hot and violent Universe
lisa pathfinder
Testing the technology for gravitational wave detection
microwaves
sub-millimetre
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integral
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Synergies


PRIMORDIAL INFLATION EXPLORER
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CFHTLENS
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Looking back at the dawn of time
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hst
Expanding the frontiers of the visible Universe
COrE
Cosmic Origins Explorer
xmm-newton
Seeing deeply into the hot and Violent Universe
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ATACAMA COSMOLOGY TELESCOPE
ACTPol
Pan-STARRS
VIPERS
VIMOS PUBLIC EXTRAGALACTIC REDSHIFT SURVEY
SOUTH POLE TELESCOPE
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ultraviolet
x-rays
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infegral
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e Universe
Fermi
Gamma-ray Space Telescope
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European Space Agency

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Correlations

- Cosmological perturbation $f(t, \mathbf{x})$
- Correlation function $\xi^f(t, |\mathbf{x} - \mathbf{y}|) = \langle f(t, \mathbf{x}) f(t, \mathbf{y}) \rangle$
- Power spectrum $\langle \hat{f}_k(t) \hat{f}^\star_{k'}(t) \rangle = \delta_D(\mathbf{k} - \mathbf{k}') P^f(k, t)$

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- Example #1: Cosmic microwave background temperature anisotropies

$$f(t, \mathbf{x}) \to \frac{\delta T(t_{\rm rec}, \vec{\theta})}{T_{\rm CMB}}$$

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- Example #1: Cosmic microwave background temperature anisotropies

$$\hat{f}_k(t) \to a_{\ell m}$$

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$$\langle a_{\ell m} a^\star_{\ell' m'} \rangle = \delta_K^{\ell\ell', mm'} C_\ell^T$$

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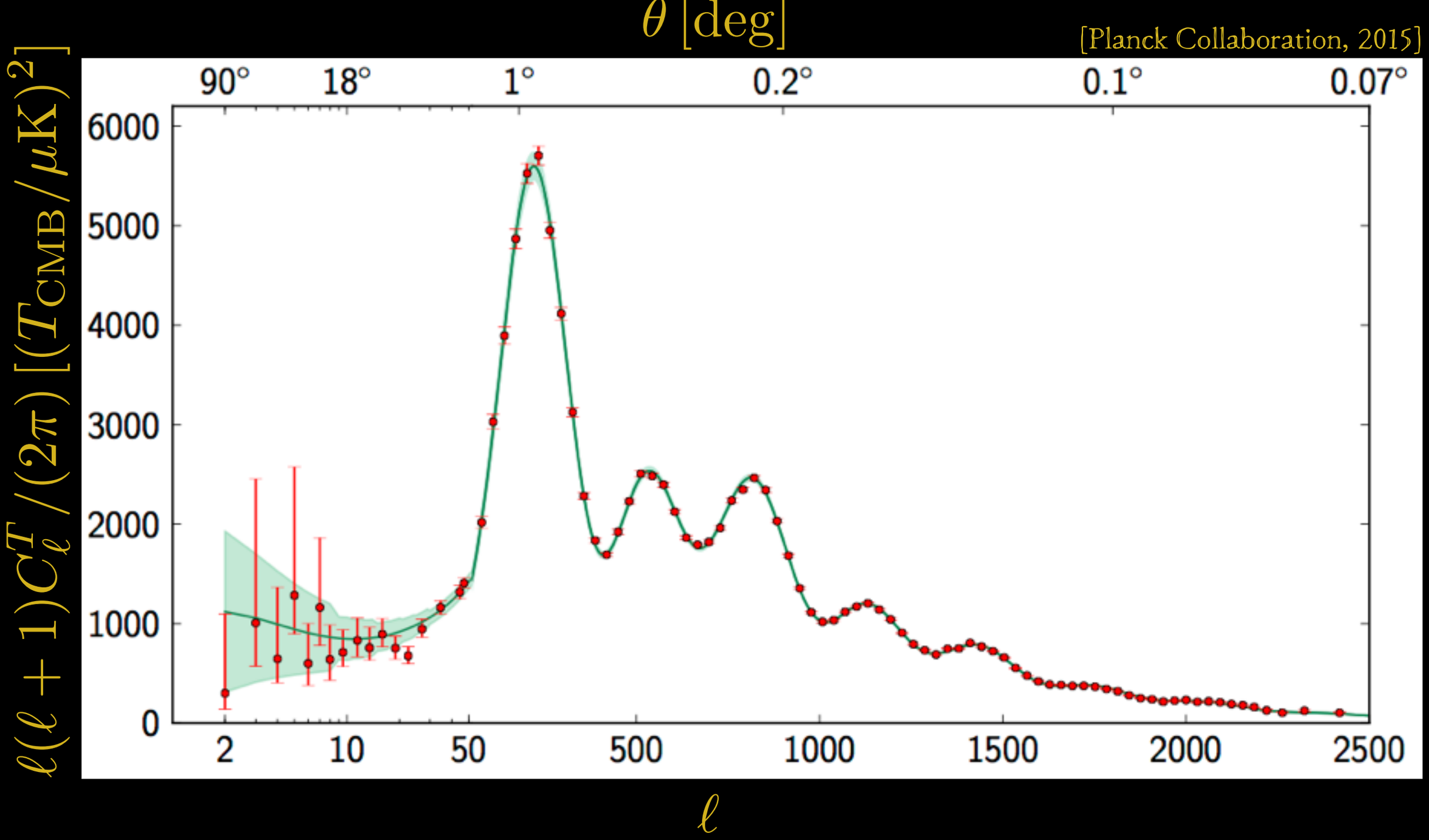
Correlations

[Planck Collaboration, 2015]



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Correlations

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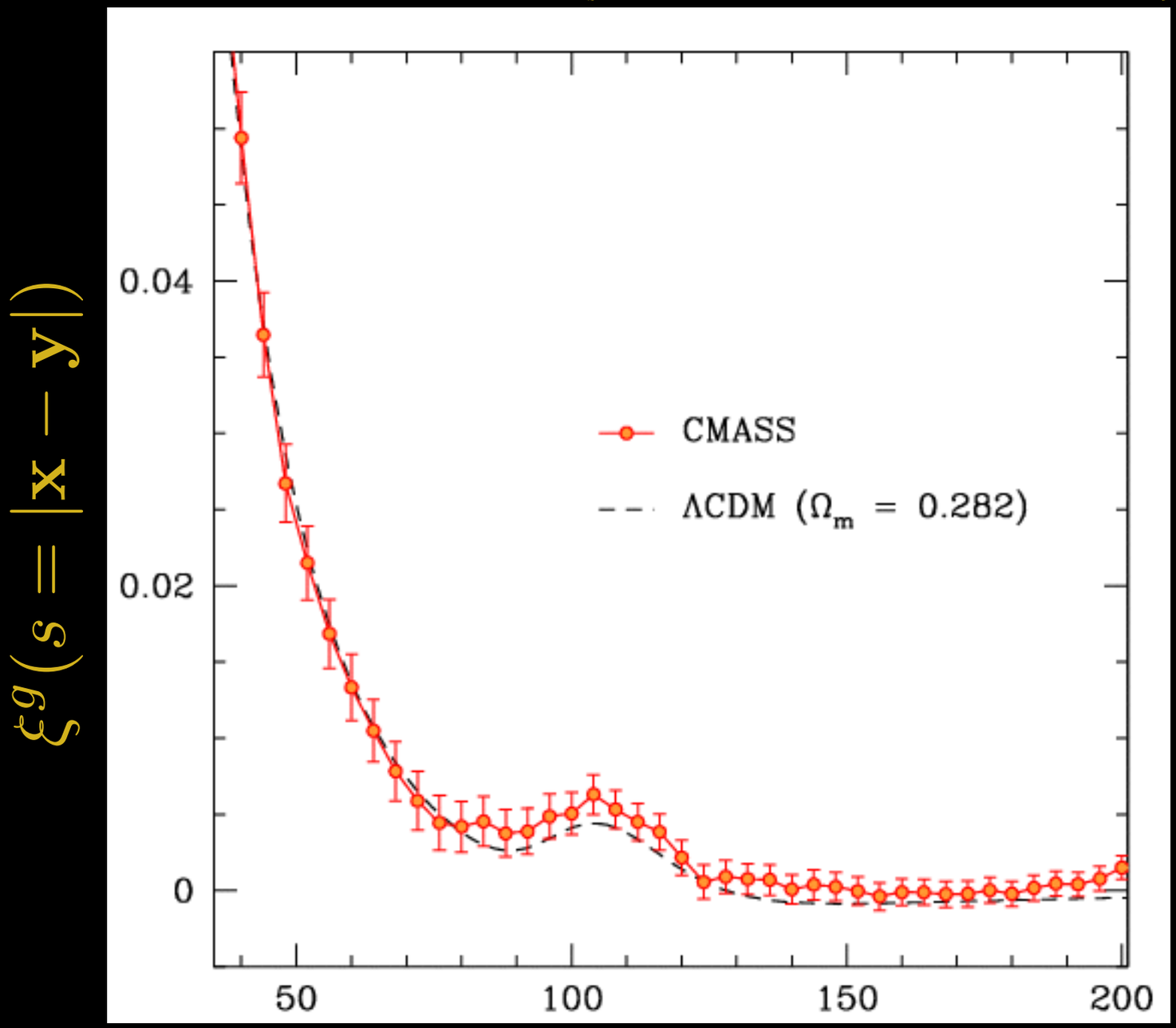
- Power spectrum $\langle \hat{f}_k(t) \hat{f}^\star_{k'}(t) \rangle = \delta_D(\mathbf{k} - \mathbf{k}') P^f(k, t)$
- Example #2: Matter power spectrum

$$f(t, \mathbf{x}) \to \delta_g(t, \mathbf{x}) = b_g(t) \delta(t, \mathbf{x})$$

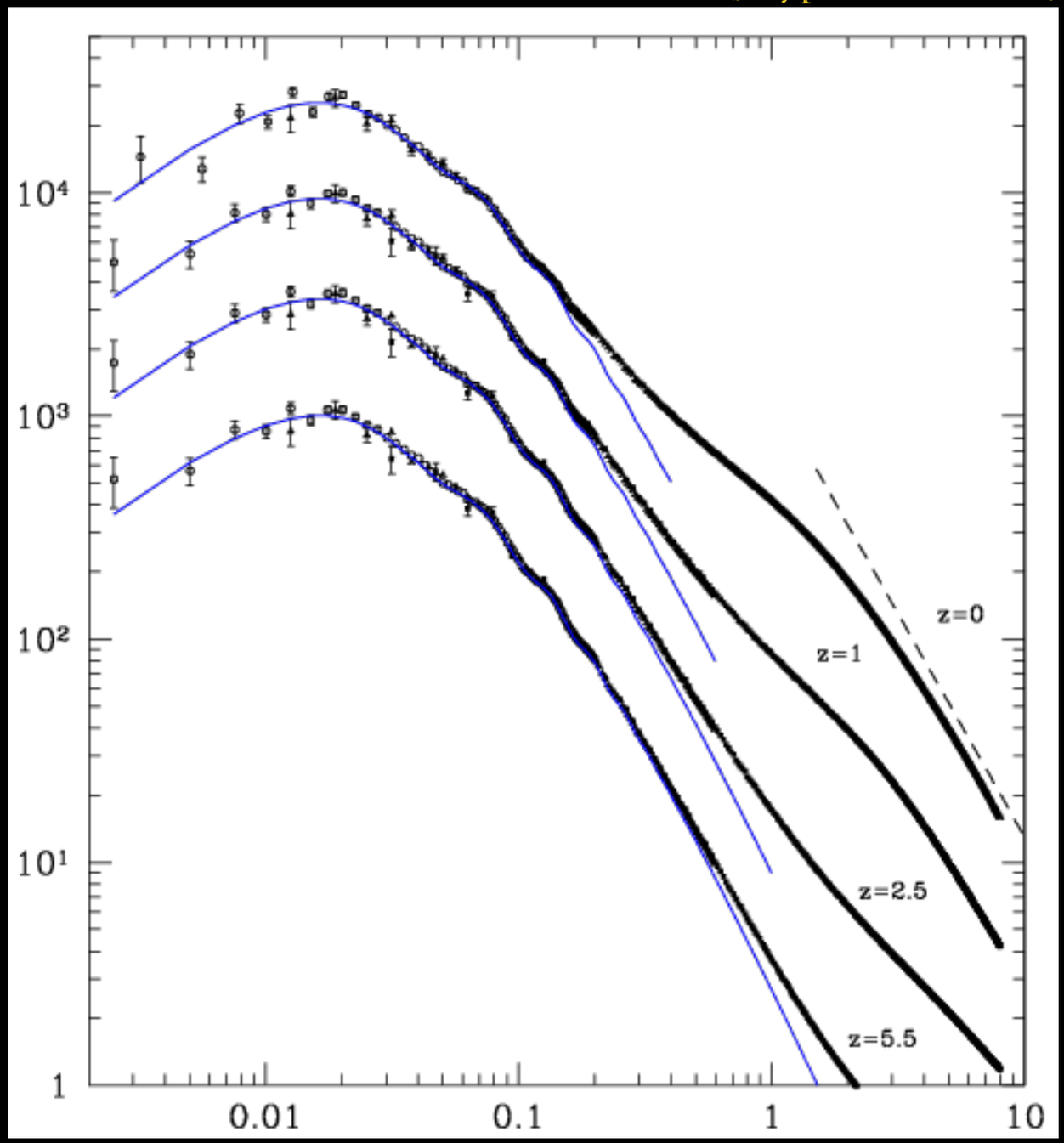
Correlations

[SDSS-III BOSS Collaboration, 2012]



Correlations

[Klypin et al., 2016]



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Cross-Correlations

- Cosmological perturbation $f(t, \mathbf{x})$
- Correlation function $\xi^{fg}(t, |\mathbf{x} - \mathbf{y}|) = \langle f(t, \mathbf{x}) g(t, \mathbf{y}) \rangle$
- Power spectrum $\langle \hat{f}_k(t) \hat{g}^\star_{k'}(t) \rangle = \delta_D(\mathbf{k} - \mathbf{k}') P^{fg}(k, t)$

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Cross-Correlations

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- Power spectrum $\langle \hat{f}_k(t) \hat{g}^\star_{k'}(t) \rangle = \delta_D(\mathbf{k} - \mathbf{k}') P^{fg}(k, t)$

WHY!?

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Cross-Correlations

- Cosmological perturbation $f(t, \mathbf{x})$
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- Power spectrum $\langle \hat{f}_k(t) \hat{g}^\star_{k'}(t) \rangle = \delta_D(\mathbf{k} - \mathbf{k}') P^{fg}(k, t)$
- Measurement
  [systematic effects, noise, cosmic variance…]

$$\Delta C_\ell^{f,\mathrm{obs}} = \sqrt{\frac{2}{(2\ell+1) f_\mathrm{sky}}} \left(C_\ell^f + C_\ell^{f,\mathrm{sys}} + \mathcal{N}_\ell^f \right)$$

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Outline

- Synergies: Why and How?
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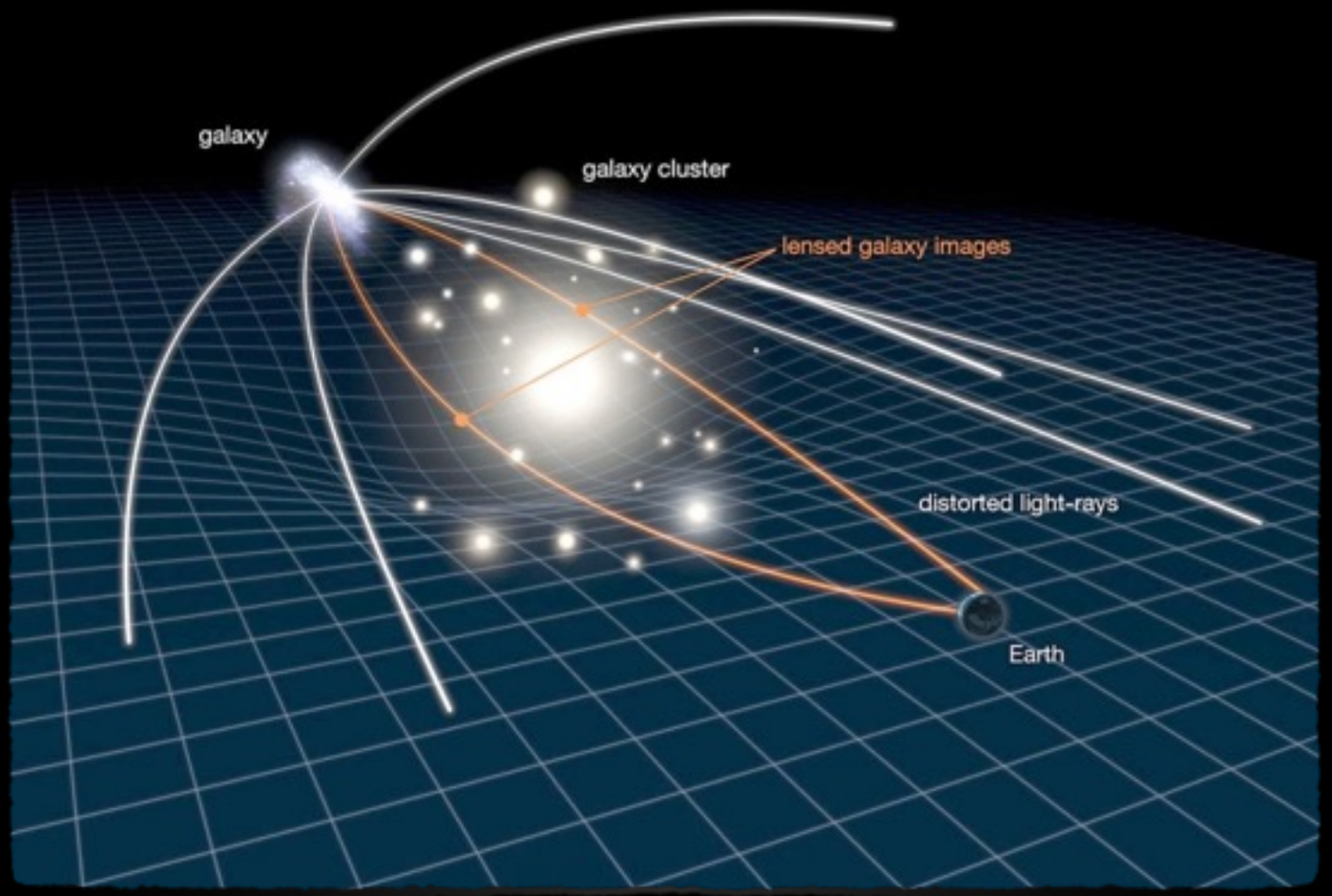
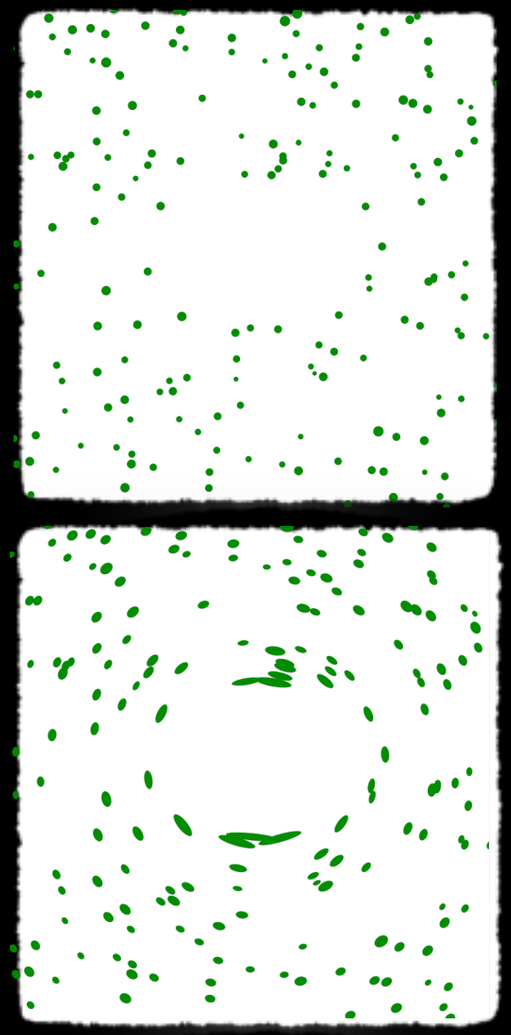
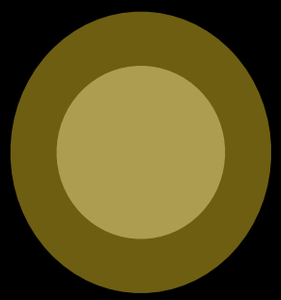
Cosmic Shear

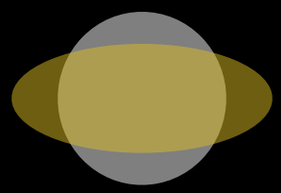




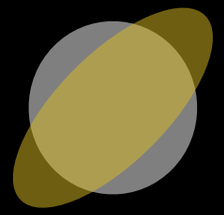
convergence



shear +



shear ×



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Cosmic Shear

- Cosmological perturbation $f(t, \mathbf{x}) \to \gamma(z, \vec{\theta})$
- Correlation function $\xi_\pm(z, z'; \theta)$
- Power spectrum $C_\ell^\gamma(z, z')$

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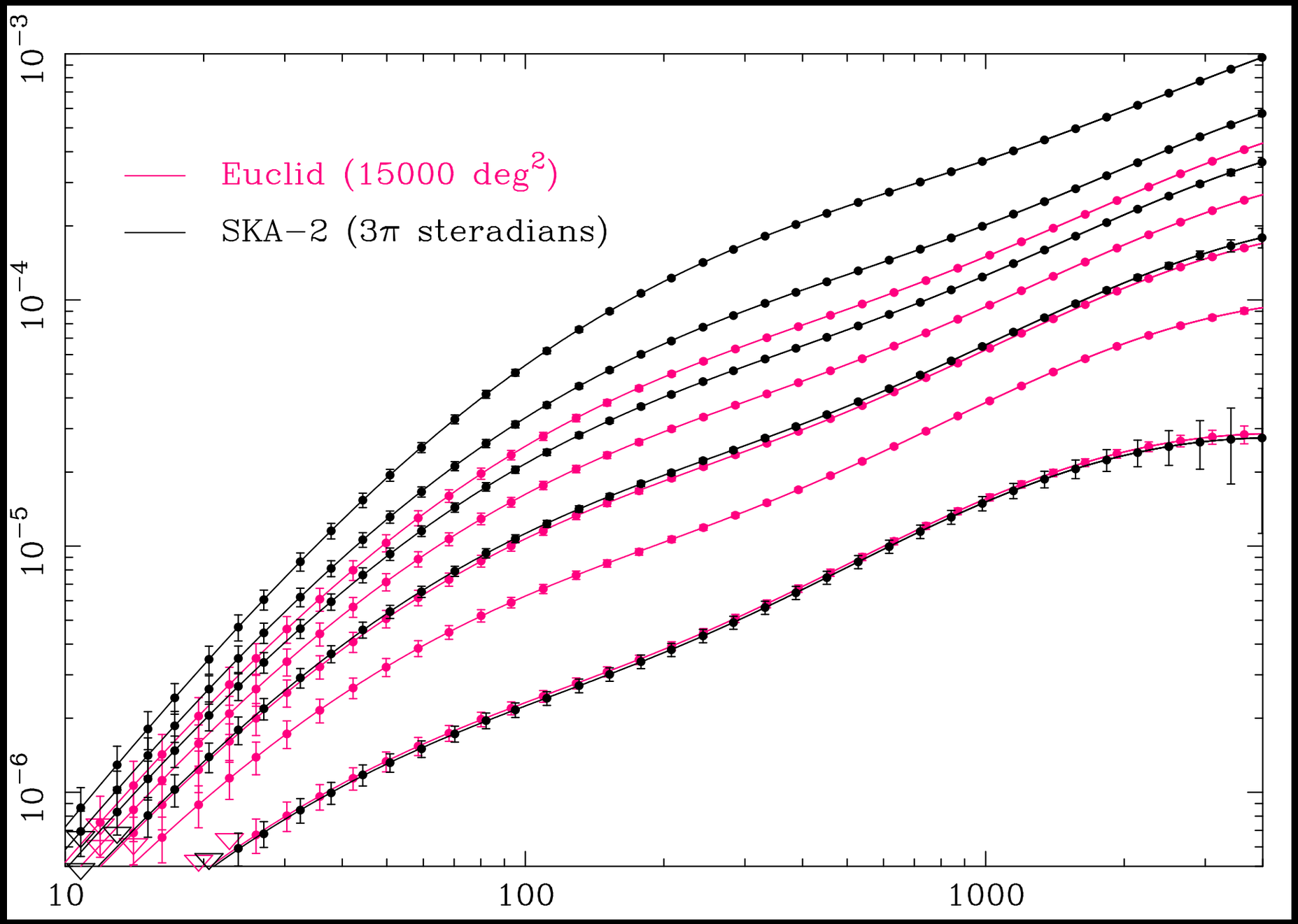
Cosmic Shear

[Brown, SC et al., 2015]



Cosmic Shear

Cosmology from Cosmic Shear with DES Science Verification Data

The Dark Energy Survey Collaboration: T. Abbott[1], F. B. Abdalla[2], S. Allam[3], A. Amara[4], J. Annis[3], R. Armstrong[5], D. Bacon[6], M. Banerji[7,8], A. H. Bauer[9], E. Baxter[10], M. R. Becker[11,12], A. Benoit-Lévy[2], R. A. Bernstein[13], G. M. Bernstein[10], E. Bertin[14,15], J. Blazek[16], C. Bonnett[17], S. L. Bridle[18], D. Brooks[2], C. Bruderer[4], E. Buckley-Geer[3], D. L. Burke[11,19], M. T. Busha[11,12], D. Capozzi[6], A. Carnero Rosell[20,21], M. Carrasco Kind[22,23], J. Carretero[9,17], F. J. Castander[9], C. Chang[4], J. Clampitt[10], M. Crocce[9], C. E. Cunha[11], C. B. D'Andrea[6], L. N. da Costa[21,20], R. Das[24], D. L. DePoy[25], S. Desai[26,27], H. T. Diehl[3], J. P. Dietrich[28,26], S. Dodelson[3,29], P. Doel[2], A. Drlica-Wagner[3], G. Efstathiou[7,8], T. F. Eifler[30,10], B. Erickson[24], J. Estrada[3], A. E. Evrard[24,31], A. Fausti Neto[21], E. Fernandez[17], D. A. Finley[3], B. Flaugher[3], P. Fosalba[9], O. Friedrich[32,28], J. Frieman[29,3], C. Gangkofner[26,27], J. García-Bellido[46], E. Gaztanaga[9], D. W. Gerdes[24], D. Gruen[32,28], R. A. Gruendl[22,23], G. Gutierrez[3], W. Hartley[4], M. Hirsch[2], K. Honscheid[16,34], E. M. Huff[16,34], B. Jain[10], D. J. James[1], M. Jarvis[10], T. Kacprzak[4], S. Kent[3], D. Kirk[2], E. Krause[11], A. Kravtsov[29], K. Kuehn[35], N. Kuropatkin[3], J. Kwan[36], O. Lahav[2], B. Leistedt[2], T. S. Li[25], M. Lima[21,37], H. Lin[3], N. MacCrann[18] ⋆, M. March[10], J. L. Marshall[25], P. Martini[16,38], R. G. McMahon[7,8], P. Melchior[34,16], C. J. Miller[31,24], R. Miquel[39,17], J. J. Mohr[32,27,26], E. Neilsen[3], R. C. Nichol[6], A. Nicola[4], B. Nord[3], R. Ogando[21,20], A. Palmese[2], H.V. Peiris[2], A. A. Plazas[30], A. Refregier[4], N. Roe[40], A. K. Romer[41], A. Roodman[19,11], B. Rowe[2], E. S. Rykoff[11,19], C. Sabiu[42], I. Sadeh[2], M. Sako[10], S. Samuroff[18], C. Sánchez[17], E. Sanchez[33], H. Seo[16], I. Sevilla-Noarbe[33,23], E. Sheldon[43], R. C. Smith[1], M. Soares-Santos[3], F. Sobreira[3,21], E. Suchyta[34,16], M. E. C. Swanson[22], G. Tarle[24], J. Thaler[44], D. Thomas[6,45], M. A. Troxel[18], V. Vikram[36], A. R. Walker[1], R. H. Wechsler[19,11,12], J. Weller[32,26,28], Y. Zhang[24], J. Zuntz[18] †

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If you can think of something, it will probably be a lensing systematics.

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Cosmic Shear

- Cosmological perturbation $f(t, \mathbf{x}) \to \gamma(z, \vec{\theta})$
- Correlation function $\xi_\pm(z, z'; \theta)$
- Power spectrum $C_\ell^\gamma(z, z')$

$$\gamma^{\rm obs}(z, \vec{\theta}) = \gamma(z, \vec{\theta}) + \gamma^{\rm sys}(z, \vec{\theta})$$

$$\langle \gamma^{\rm obs} \gamma^{\rm obs} \rangle = \langle \gamma\gamma \rangle + \cancel{2 \langle \gamma^{\rm sys} \gamma \rangle} + \langle \gamma^{\rm sys} \gamma^{\rm sys} \rangle$$

J. Zuntz[18]† If you can think of something, it will probably be a lensing systematics.

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$$\left\langle \gamma^{\rm obs}_{(r)} \gamma^{\rm obs}_{(o)} \right\rangle = \langle \gamma\gamma \rangle + \cancel{\left\langle \gamma^{\rm sys}_{(r)} \gamma_{(o)} \right\rangle} + \cancel{\left\langle \gamma_{(r)} \gamma^{\rm sys}_{(o)} \right\rangle} + \cancel{\left\langle \gamma^{\rm sys}_{(r)} \gamma^{\rm sys}_{(o)} \right\rangle}$$

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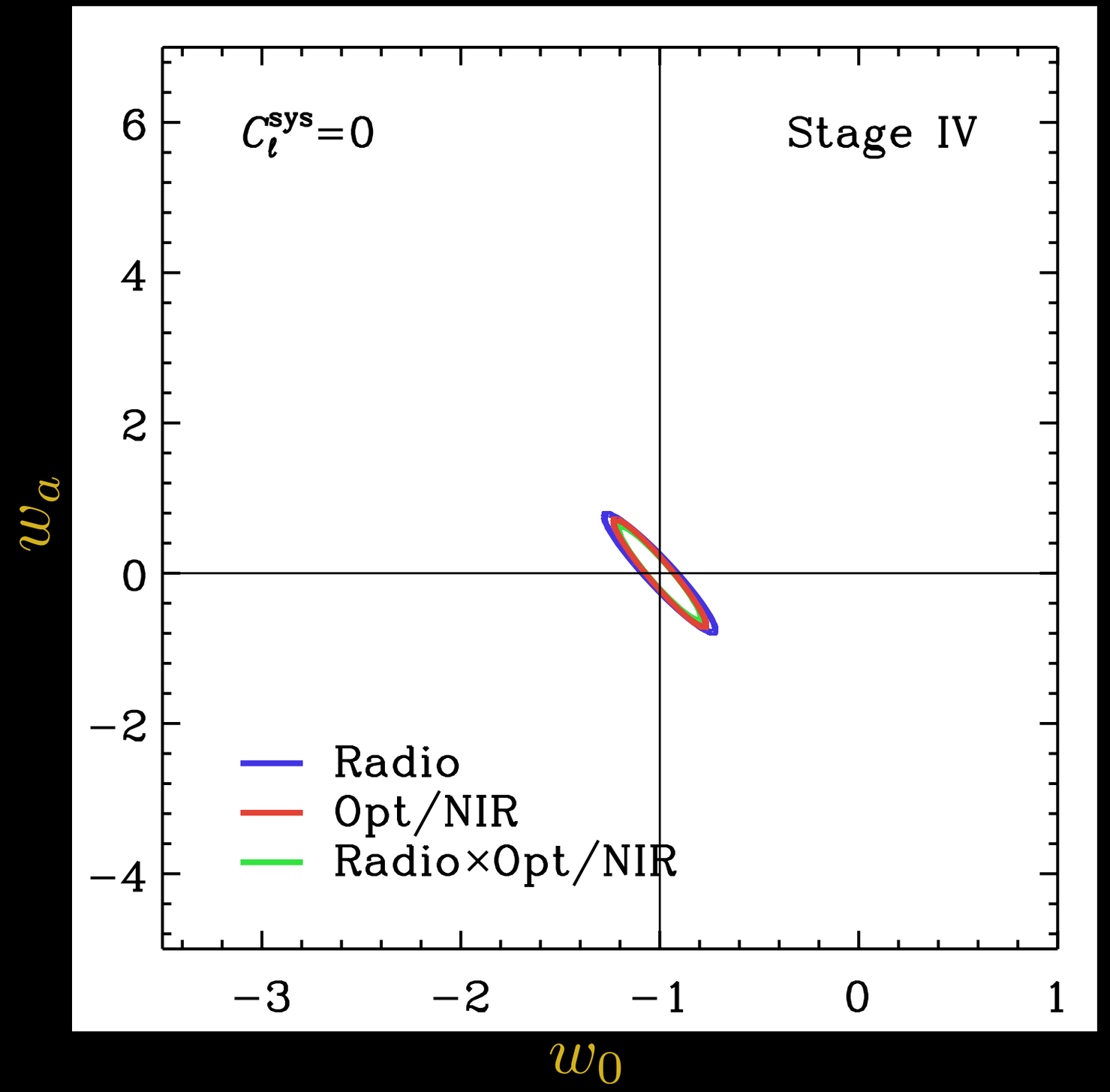
Cosmic Shear



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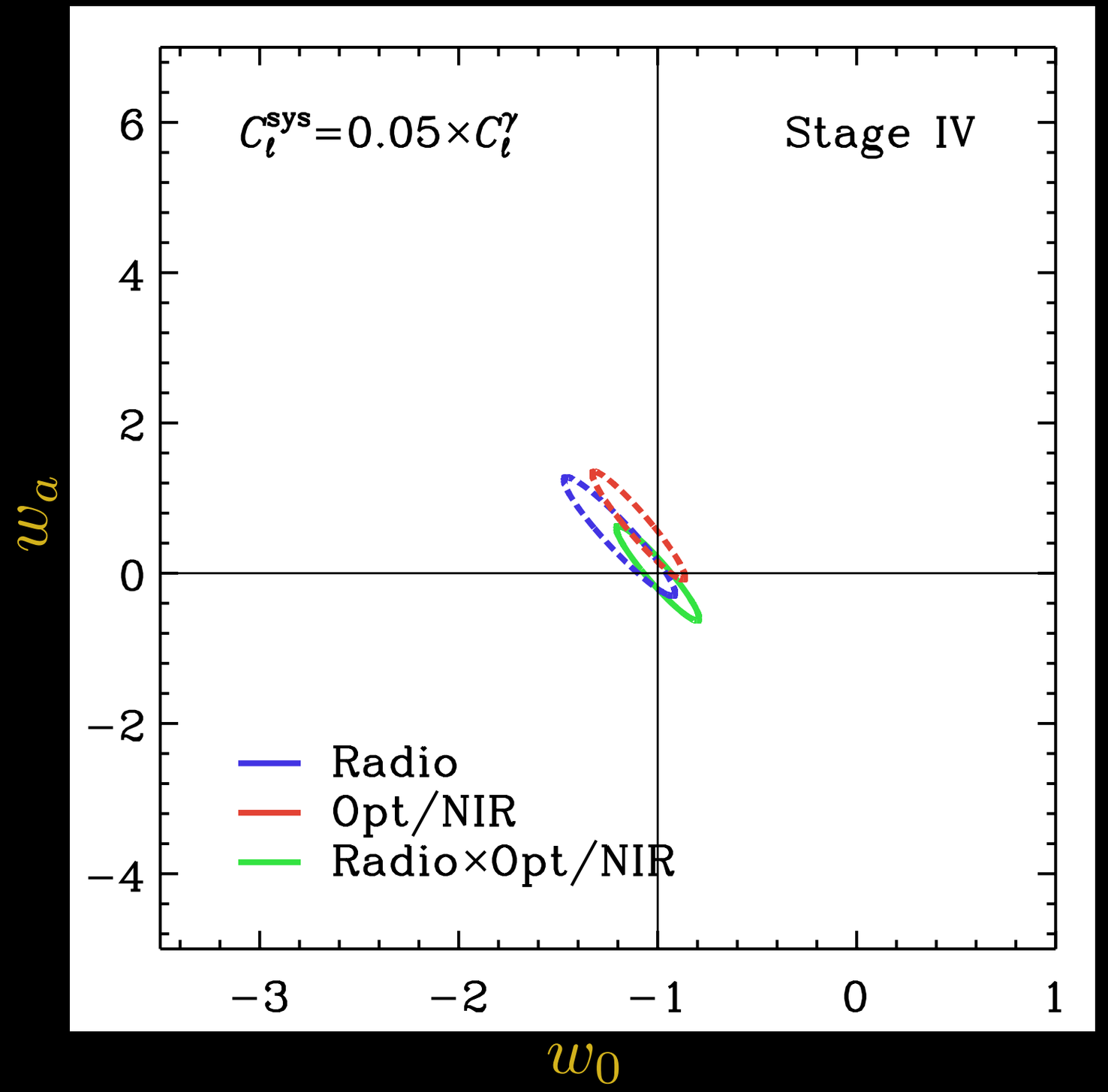

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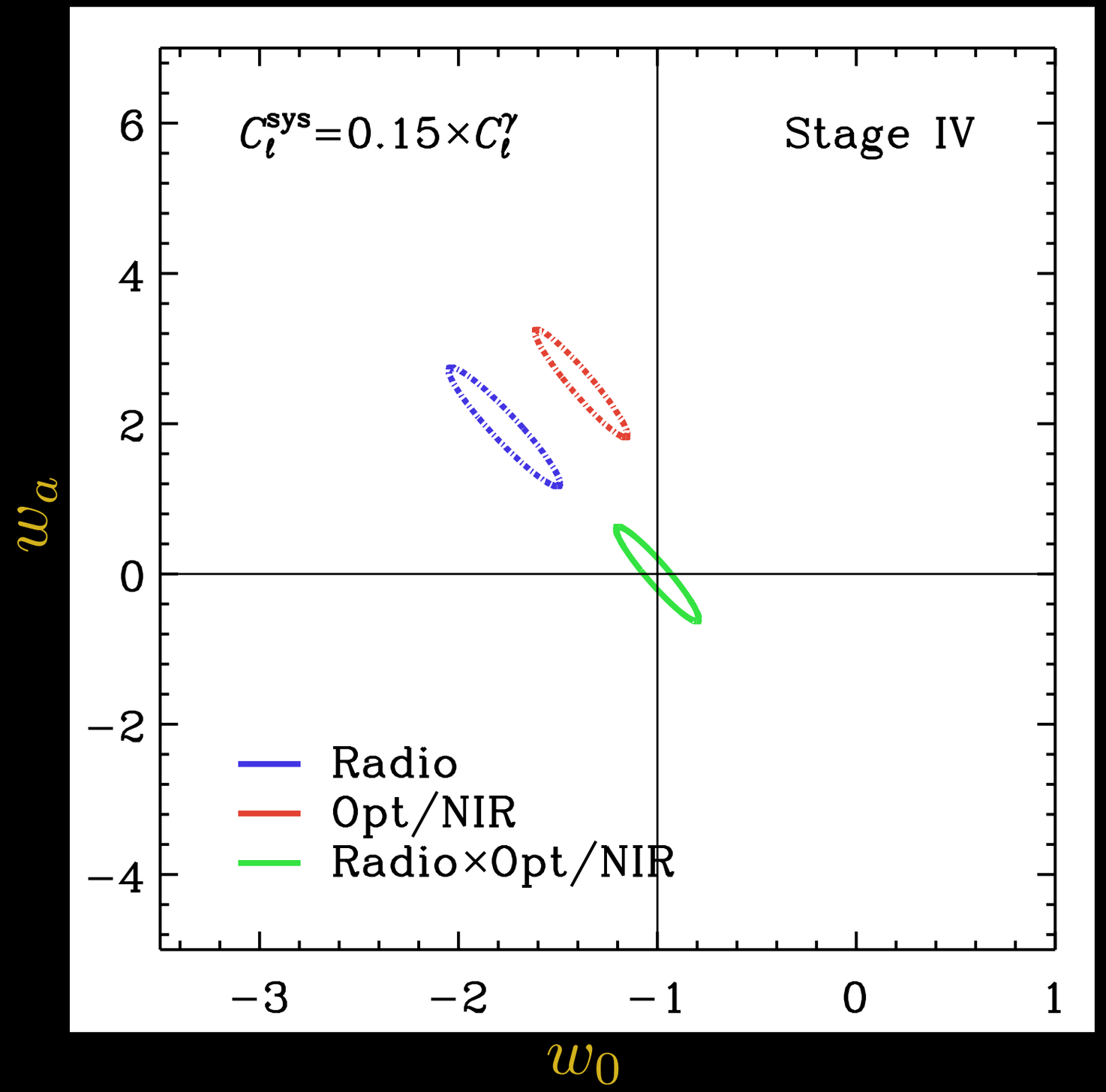
Cosmic Shear



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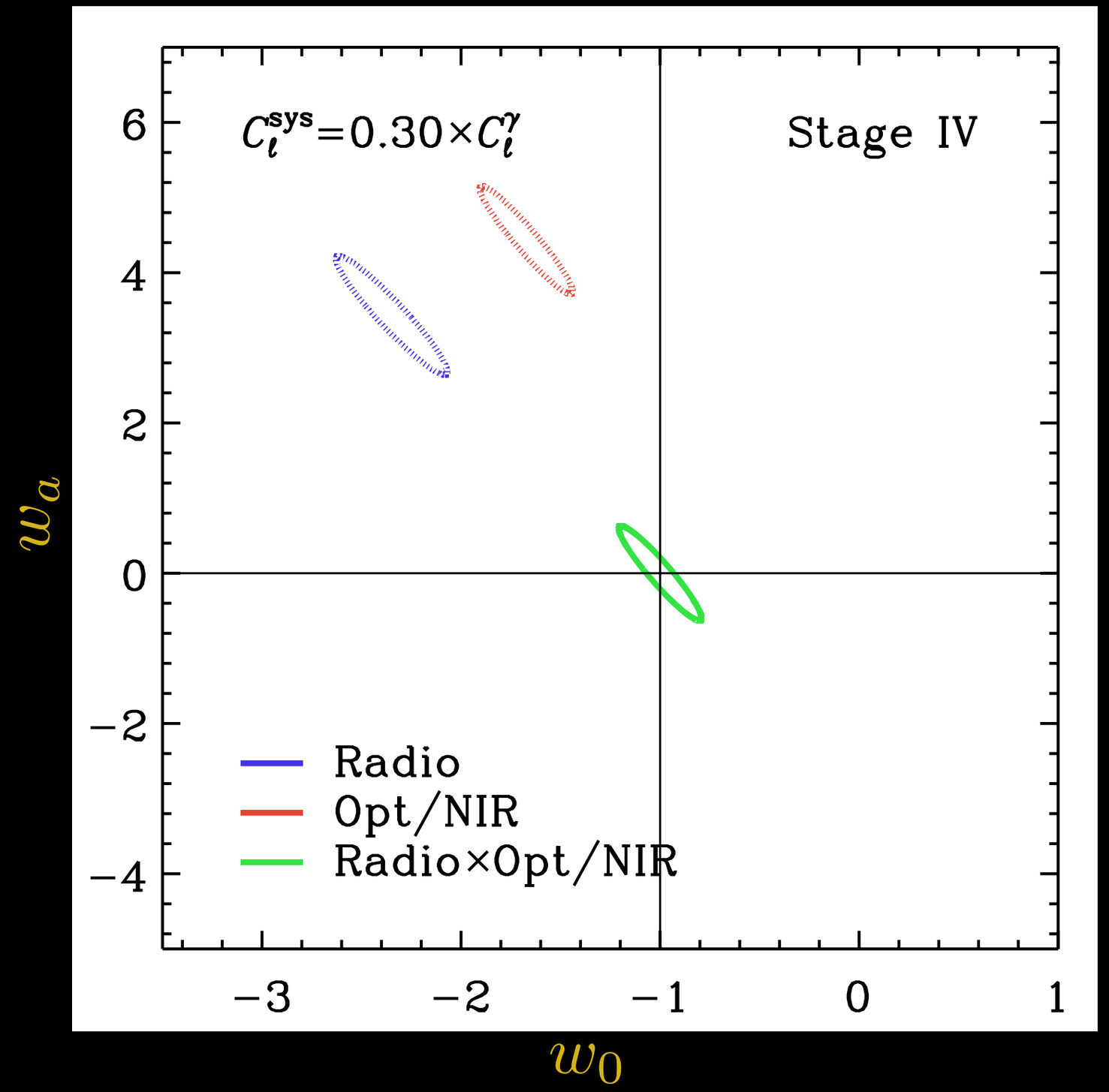
Cosmic Shear



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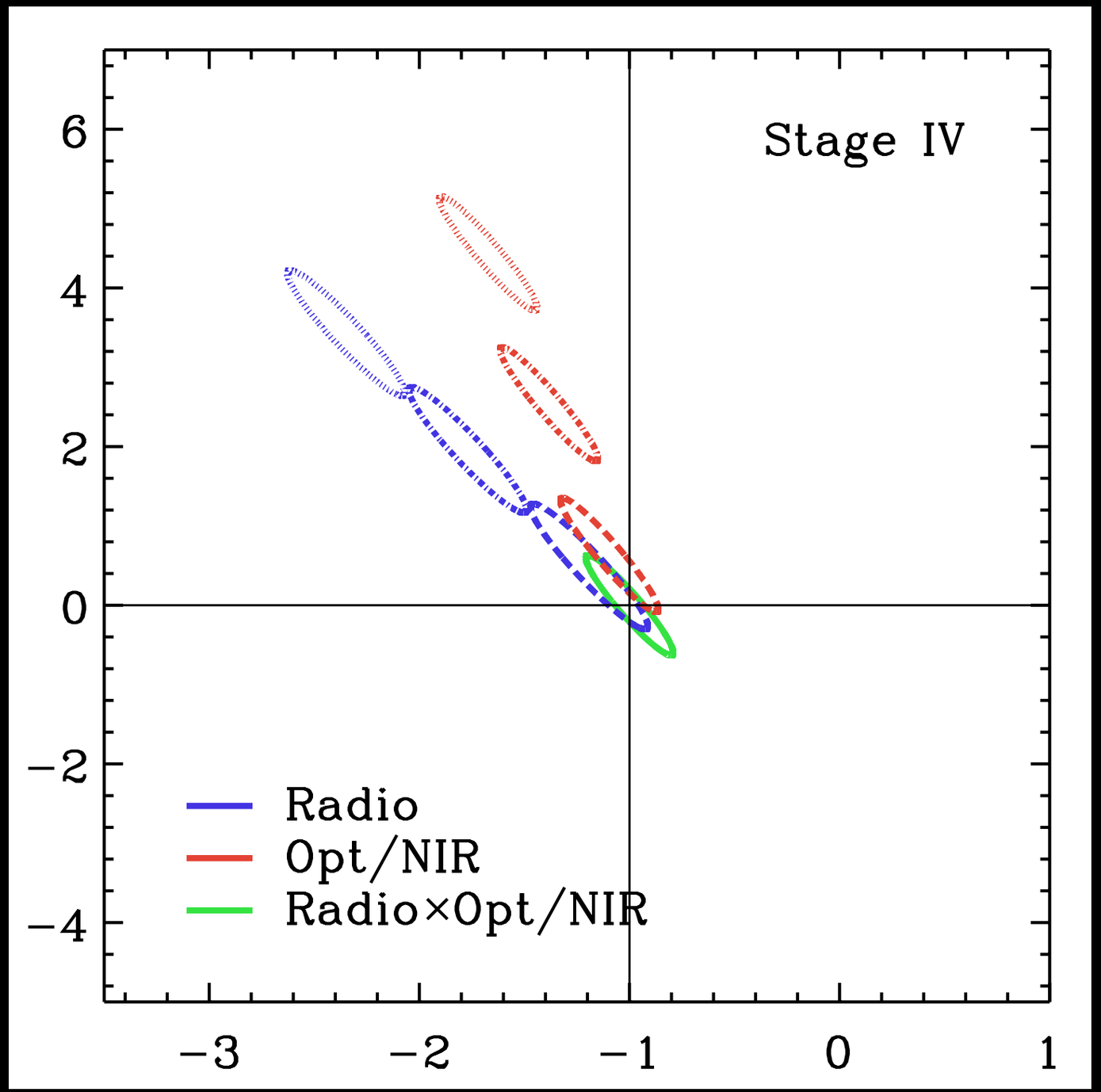
Cosmic Shear

[SC, Harrison, Bonaldi & Brown, 2016]



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$$\left\langle \gamma^{\rm obs}_{(r)} \gamma^{\rm obs}_{(o)} \right\rangle = \left(1 + \gamma^{\rm mul}_{(r)} \gamma^{\rm mul}_{(o)}\right) \langle \gamma\gamma \rangle + \cancel{\left\langle \gamma^{\rm add}_{(r)} \gamma^{\rm add}_{(o)} \right\rangle}$$

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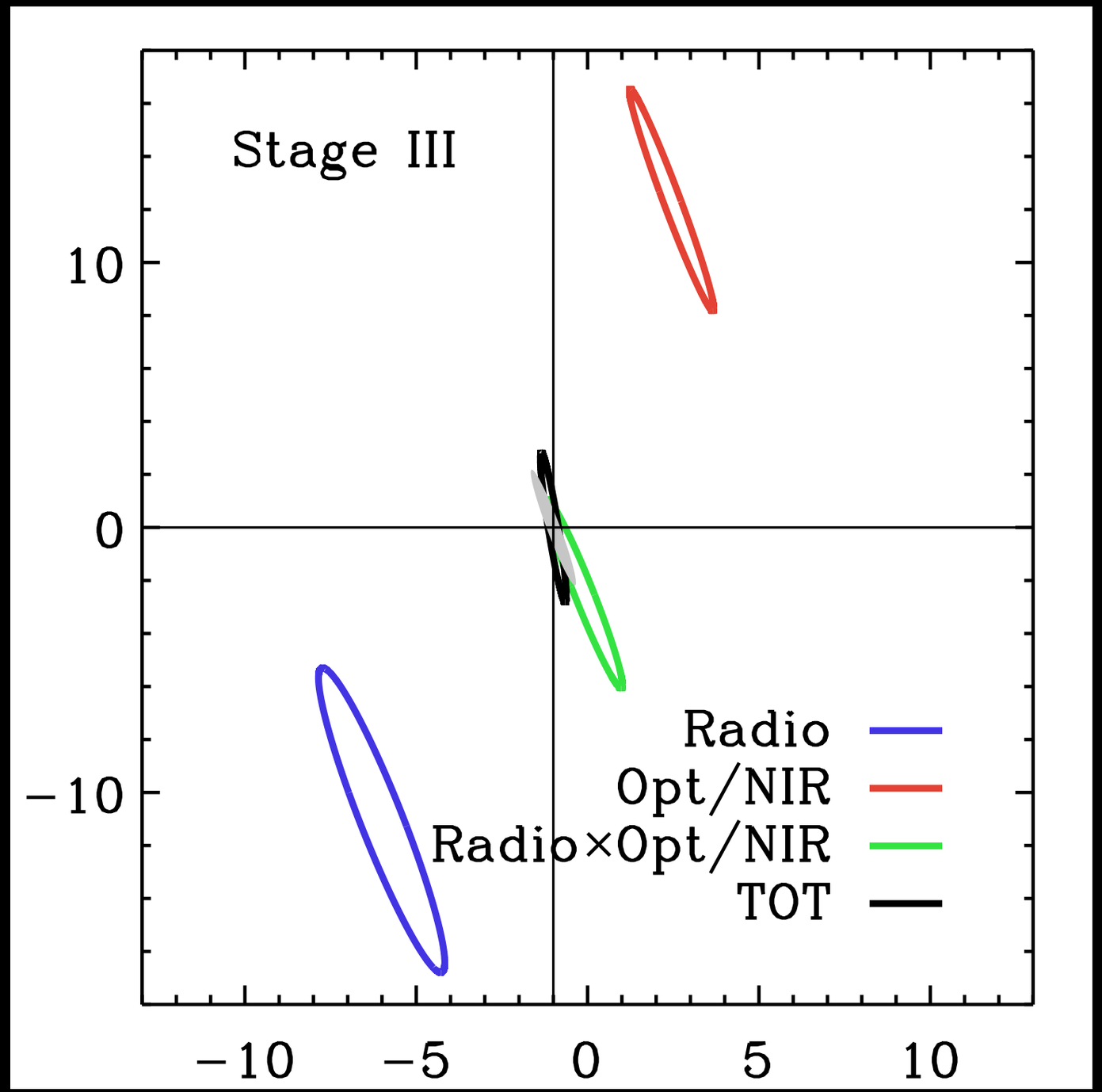
Cosmic Shear

[SC, Harrison, Bonaldi & Brown, 2016]



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Outline

- **Synergies:** Why and How?
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- **Synergies vs Cosmic Variance:** Multi-Tracing Galaxy Number Counts

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Galaxy Number Counts

- Proxy of the matter power spectrum

$$f(t,\mathbf{x}) \to \delta_g(t,\mathbf{x}) = b_g(t)\delta(t,\mathbf{x})$$

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Galaxy Number Counts

- Proxy of the matter power spectrum

$$f(t,\mathbf{x}) \to \delta_g(z,\hat{\mathbf{n}}) = \frac{n_g(z,\hat{\mathbf{n}}) - \bar{n}_g(z)}{\bar{n}_g(z)}$$

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Galaxy Number Counts

- Proxy of the matter power spectrum

$$f(t,\mathbf{x}) \to \delta_g(z,\hat{\mathbf{n}}) = \frac{N_g(z,\hat{\mathbf{n}}) - \bar{N}_g(z)}{\bar{N}_g(z)}$$

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Galaxy Number Counts

- Proxy of the matter power spectrum

$$\frac{N_g(z,\hat{\mathbf{n}}) - \bar{N}_g(z)}{\bar{N}_g(z)} \propto \frac{\delta\rho(z,\hat{\mathbf{n}})}{\bar{\rho}(\bar{z})} - \frac{\mathrm{d}\bar{\rho}}{\mathrm{d}\bar{z}}\frac{\delta z(z,\hat{\mathbf{n}})}{\bar{\rho}(\bar{z})} + \frac{\delta V(z,\hat{\mathbf{n}})}{V(z)}$$

[Yoo, 2010; Bonvin & Durrer, 2011;
Challinor & Lewis, 2011; Bertacca et al., 2012]

  - Newtonian density fluctuations
  - redshift space distortions
  - lensing
  - gravitational redshift, time delays, Sachs-Wolfe and integrated Sachs-Wolfe

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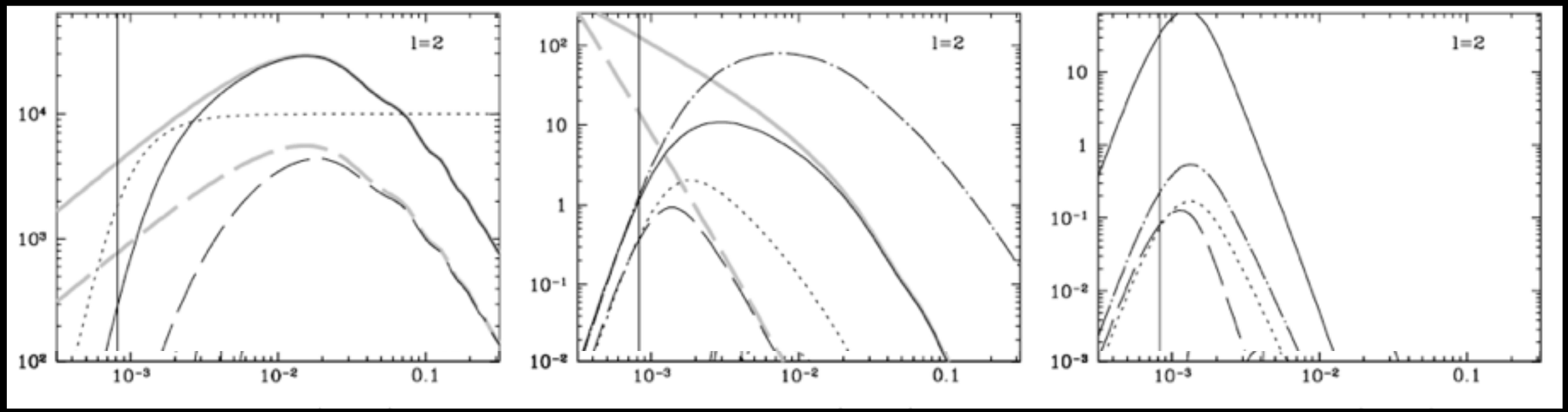
Galaxy Number Counts

- Relativistic corrections

[Yoo & Desjaques, 2013]



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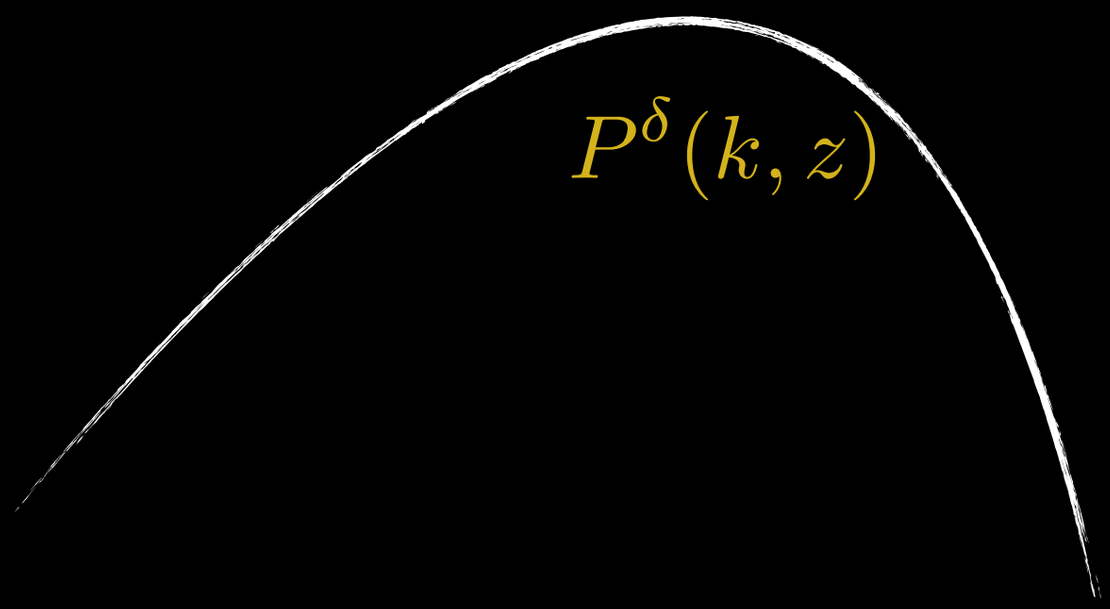
Galaxy Number Counts

- Relativistic corrections
- Primordial non-Gaussianity
- Predicted in many scenarios of inflation
- Tightest available constraints from CMB



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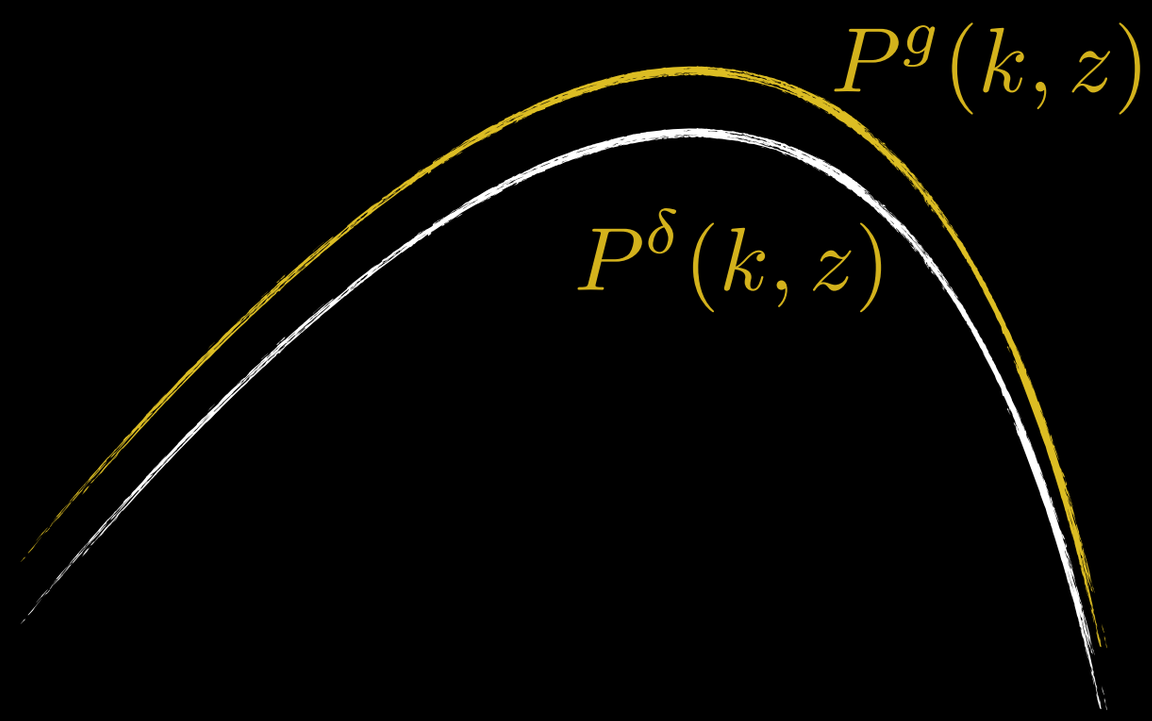

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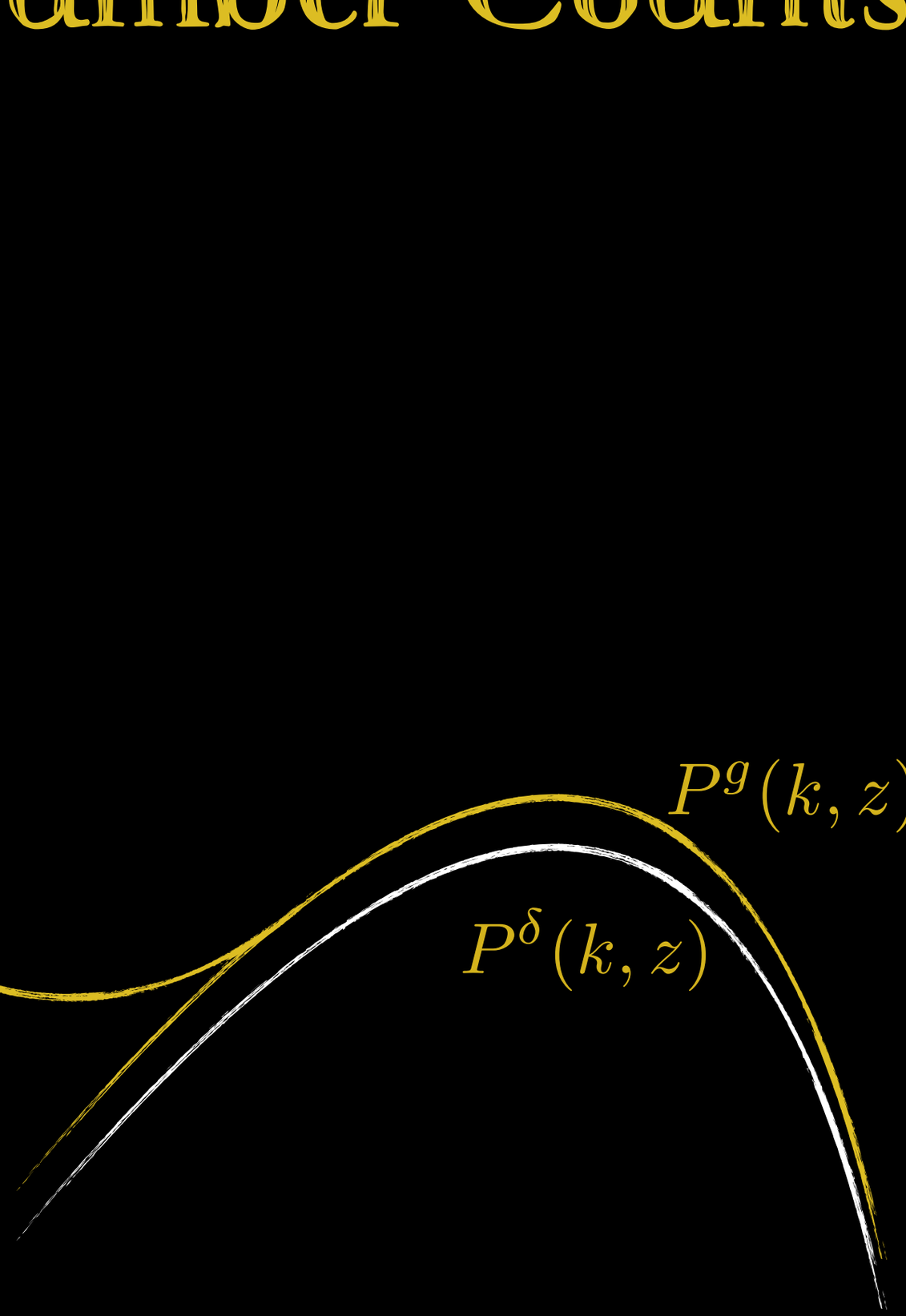
$f_{\rm NL} > 0$



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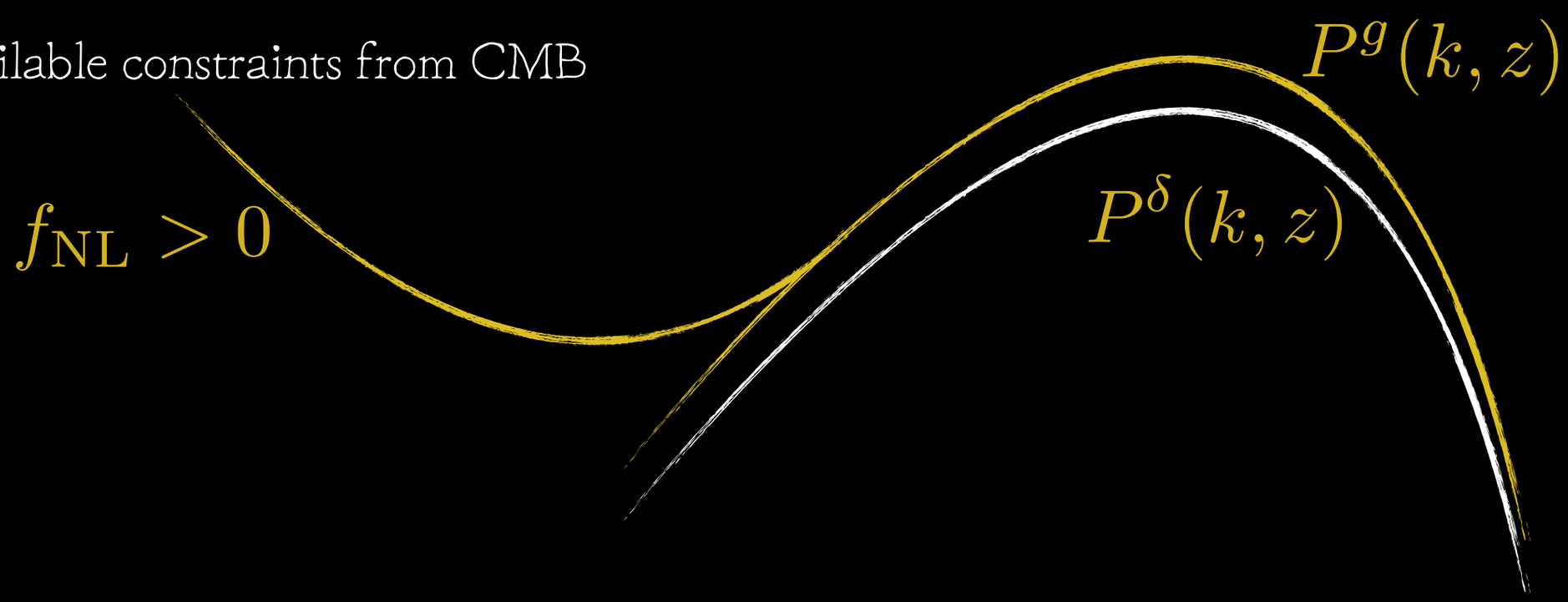

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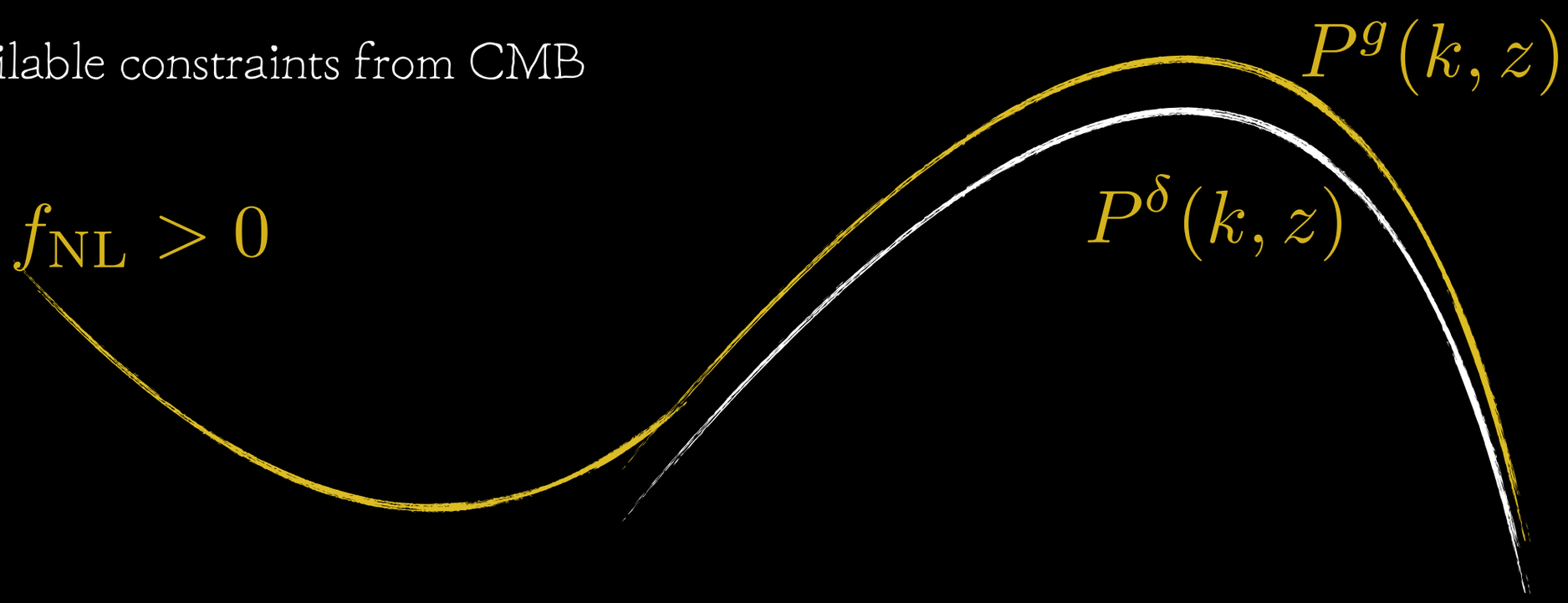

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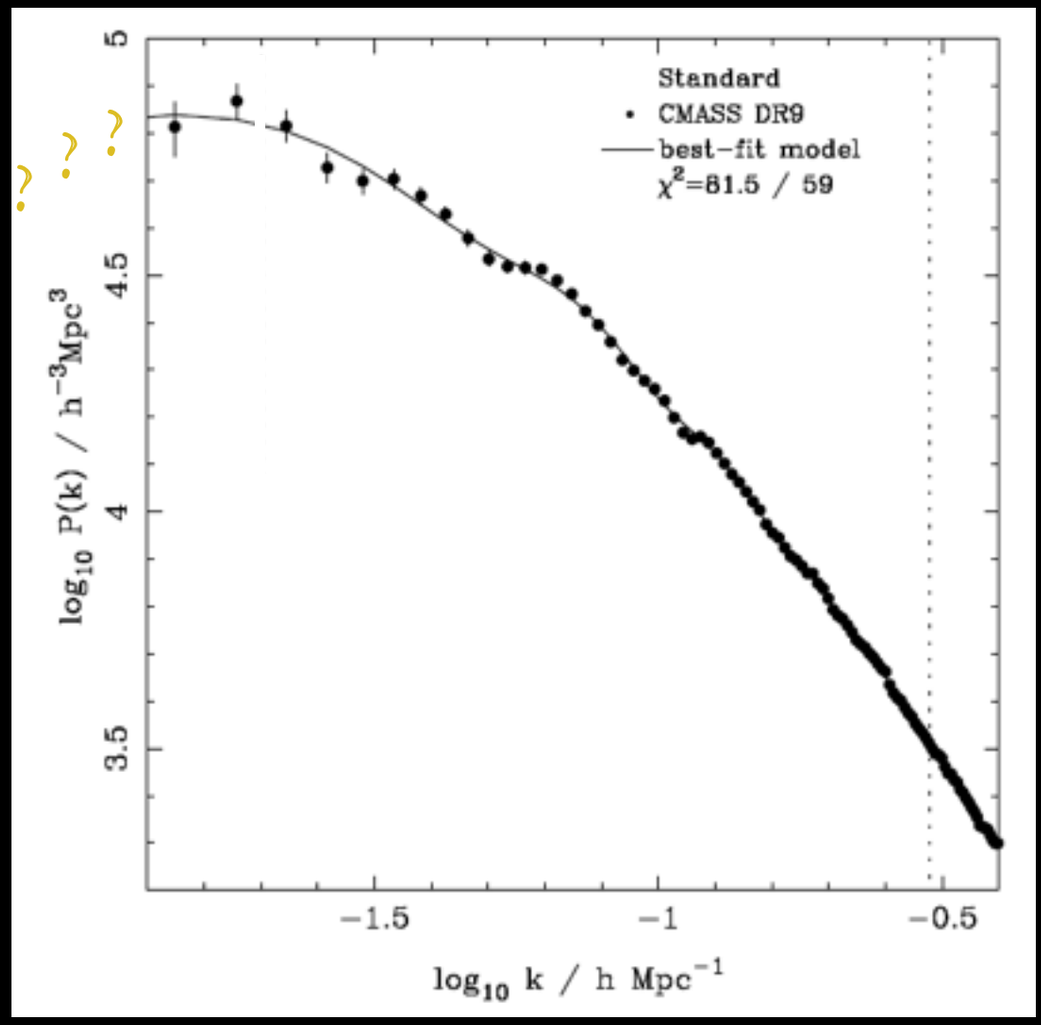
Accessing the Largest Scales

- Probe huge volumes
  [high sensitivity at high-z over large sky areas]

- Beat cosmic variance
  [we have only one Universe to observe!]

? ? ? ? ? ? ?

[SDSS-III BOSS Collaboration, 2012]



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Multi-Tracer Technique

- Comparing the relative clustering of different populations of tracers

[Seljak, 2009; Seljak & McDonald, 2009]

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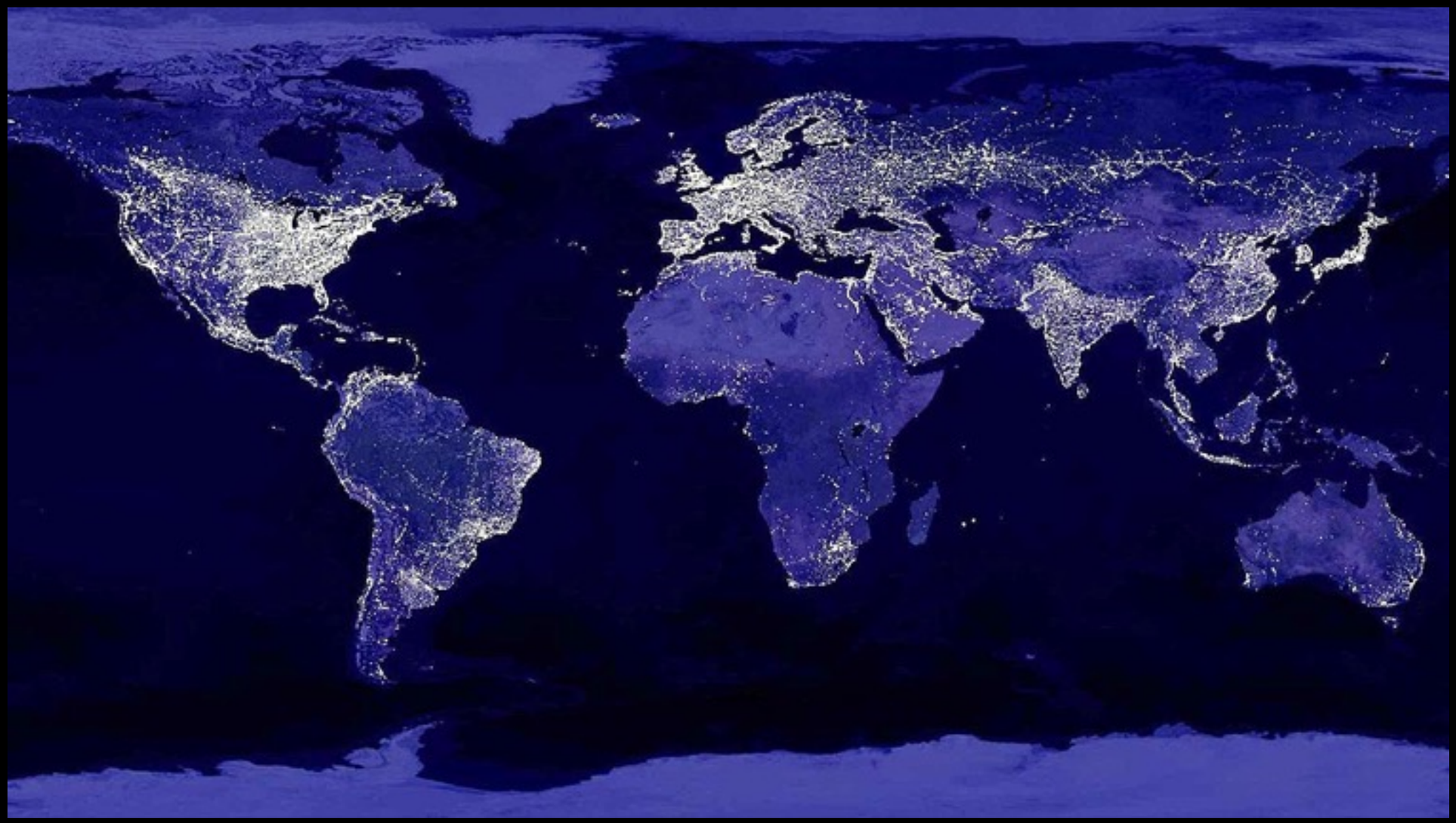

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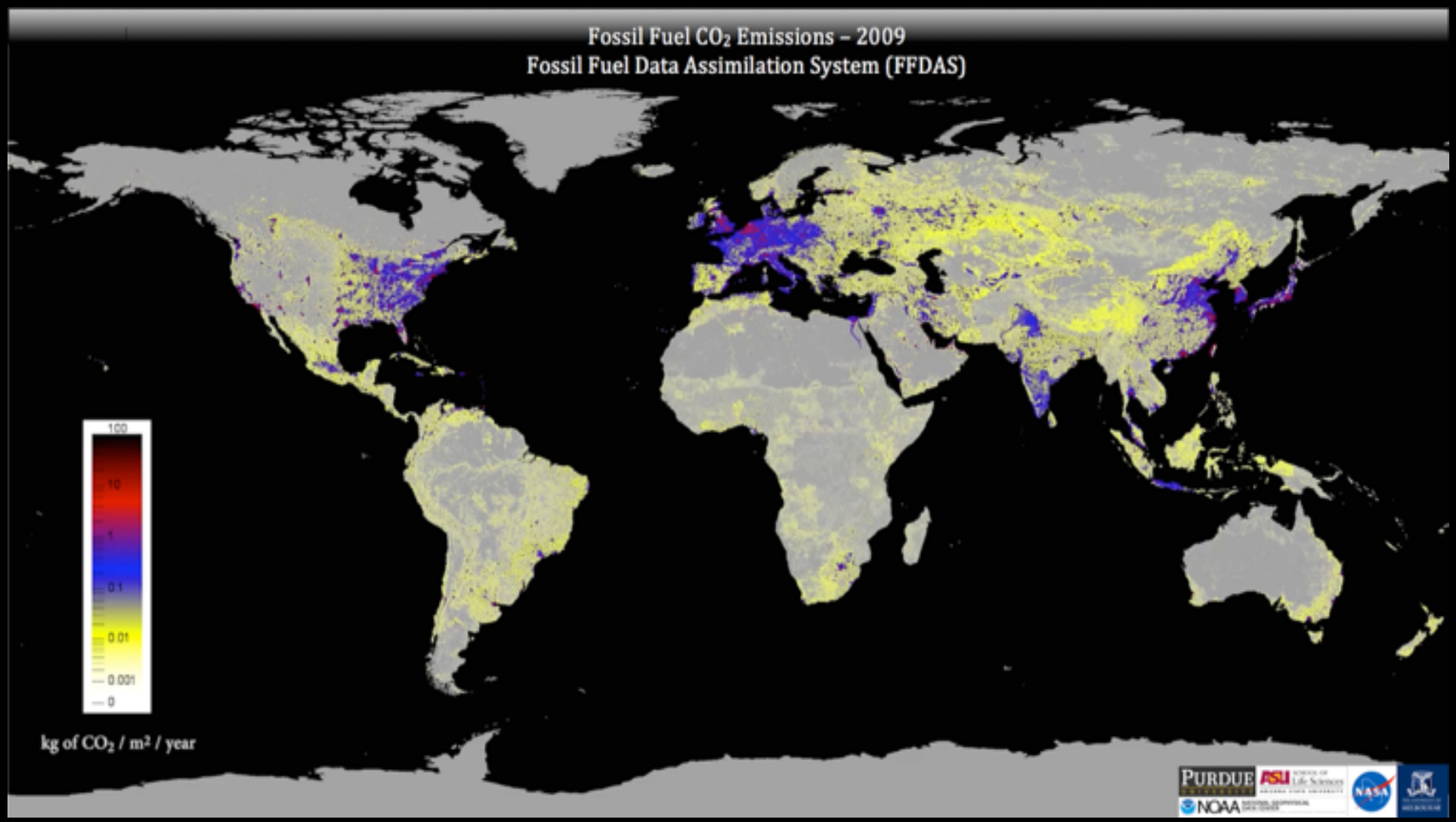

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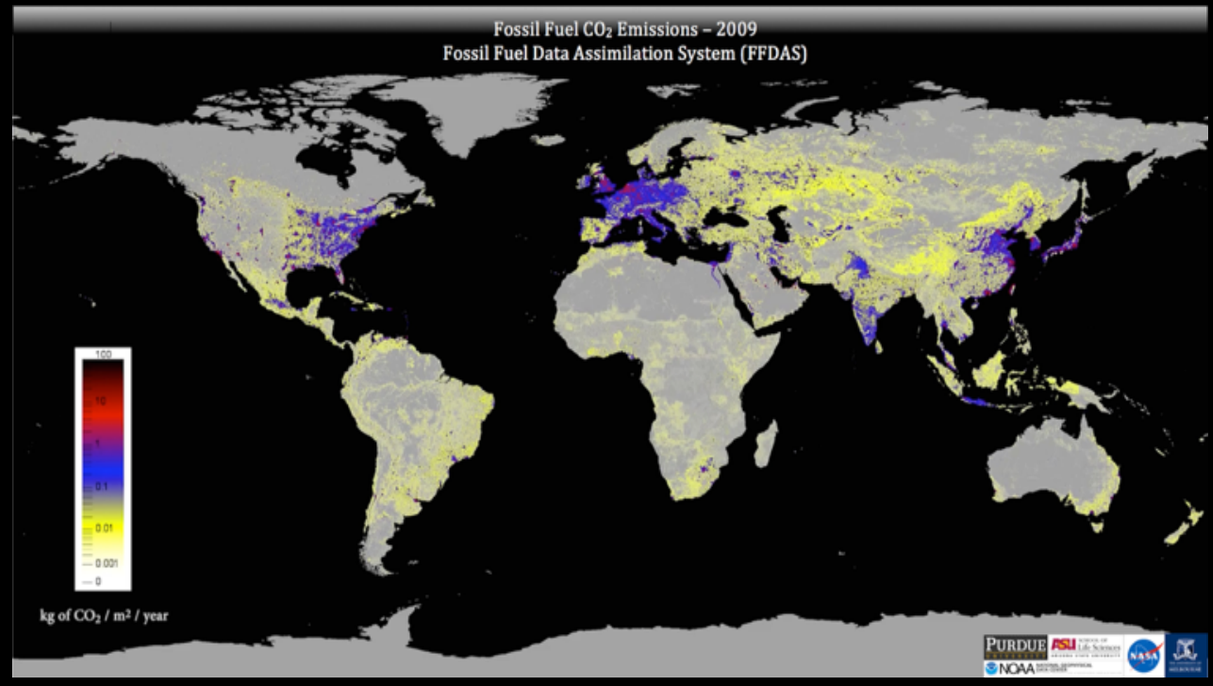

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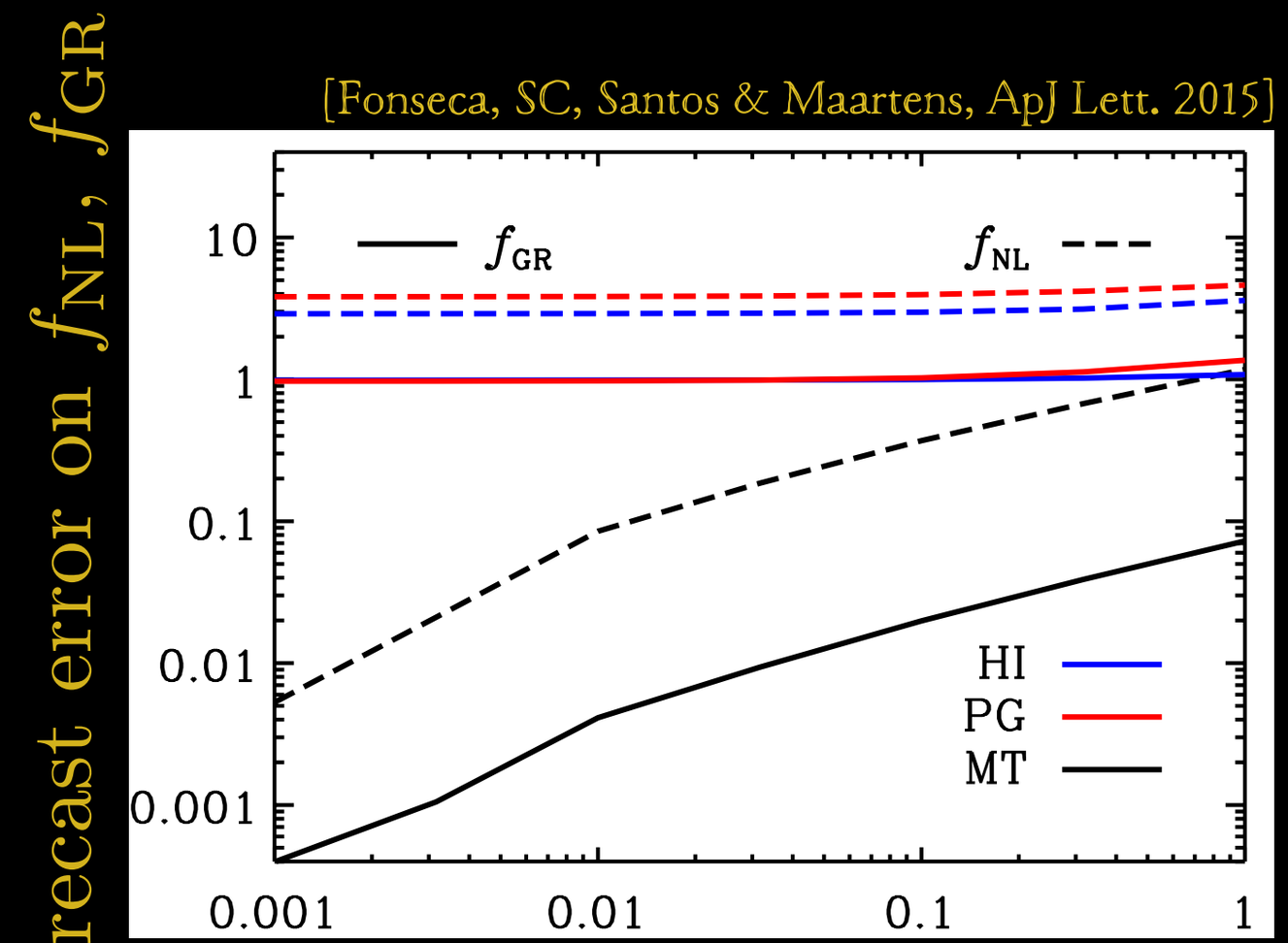
[Seljak, 2009; Seljak & McDonald, 2009]

[Fonseca, SC, Santos & Maartens, ApJ Lett. 2015]



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Horizon Scales Matter!

- Neglecting horizon-scale effect could undermine future cosmological experiments' accuracy

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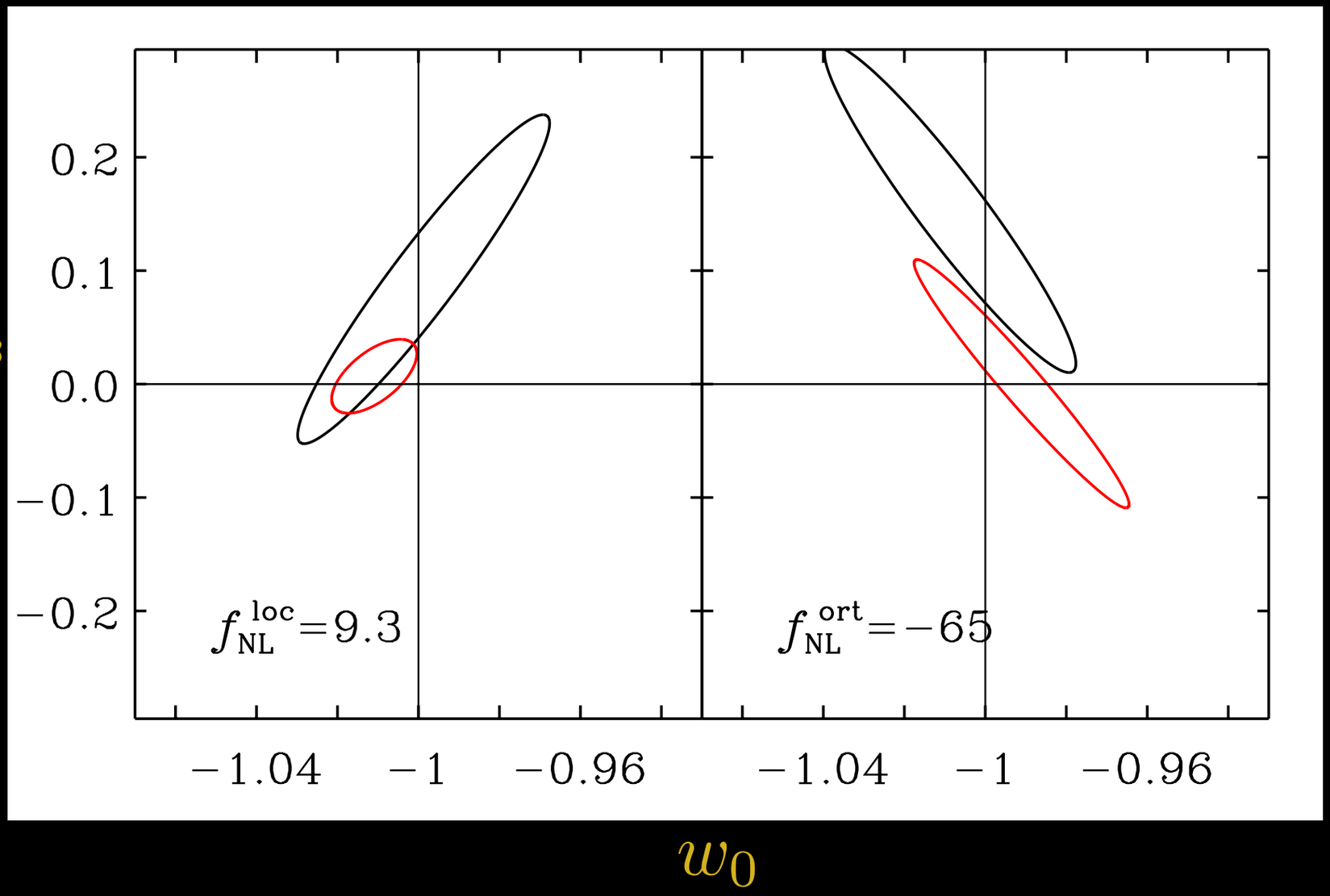
Horizon Scales Matter!

- Neglecting primordial non-Gaussianity

[SC, Carbone, Fedeli & Moscardini, 2015]

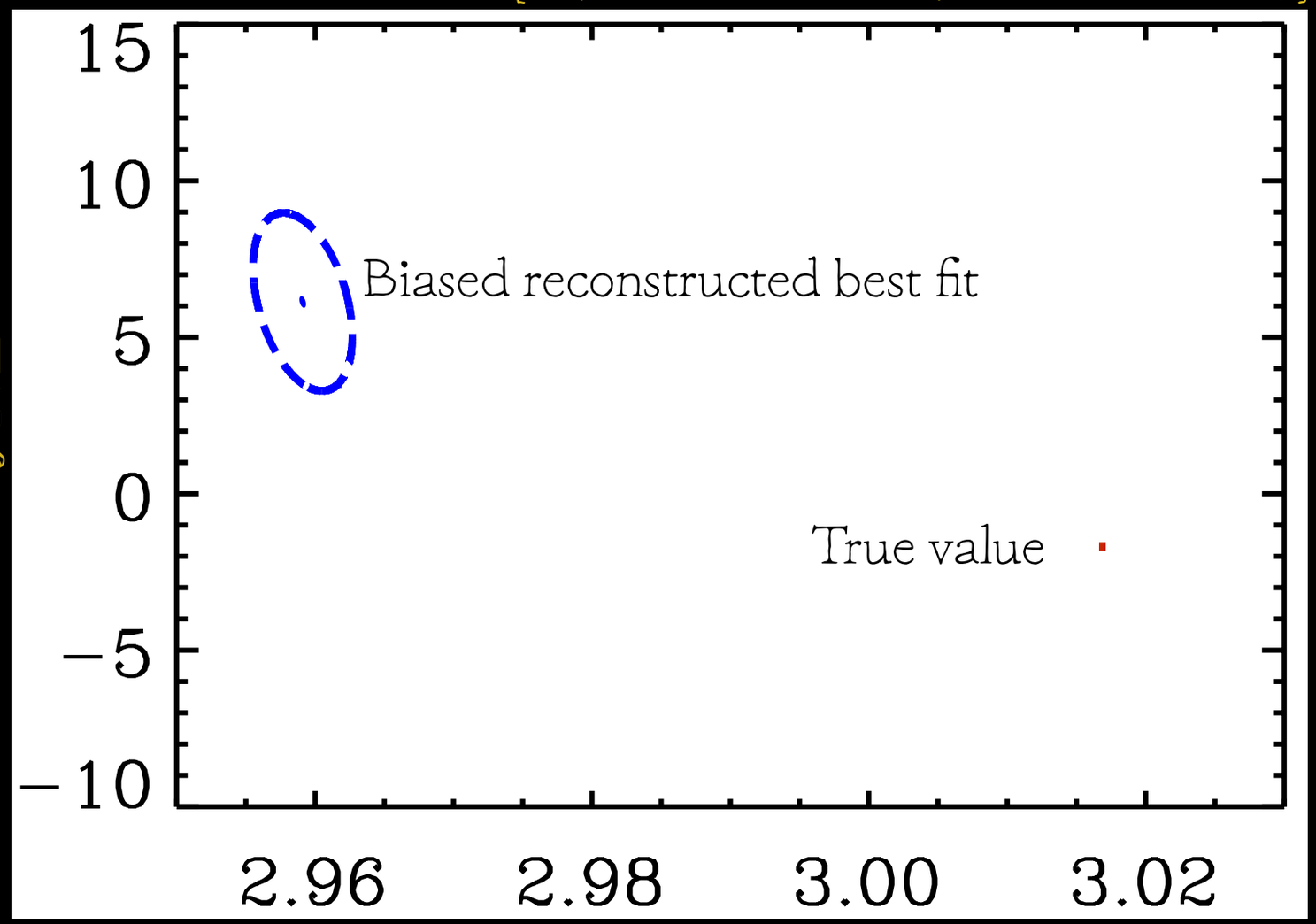


euclid

Horizon Scales Matter!

- Neglecting relativistic effects

[SC, Maartens & Santos, MNRAS Lett. 2015]



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Summary

- Great time for synergies between radio surveys and cosmological experiments at other wavelengths

- Cross-correlations valuable for:

  - Cross-check validity of cosmological results

  - Removing/alleviating contamination from systematic effects
    [e.g. radio-optical cosmic shear]

  - Helping in accessing signal buried in noise/cosmic variance
    [e.g. multi-tracer technique for horizon-scale effects]

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Thank You!