Programma per Giovani Ricercatori
"Rita Levi Montalcini"

Synergistic cosmology across the spectrum

Stefano Camera

Dipartimento di Fisica, Università degli Studi di Torino, Italy

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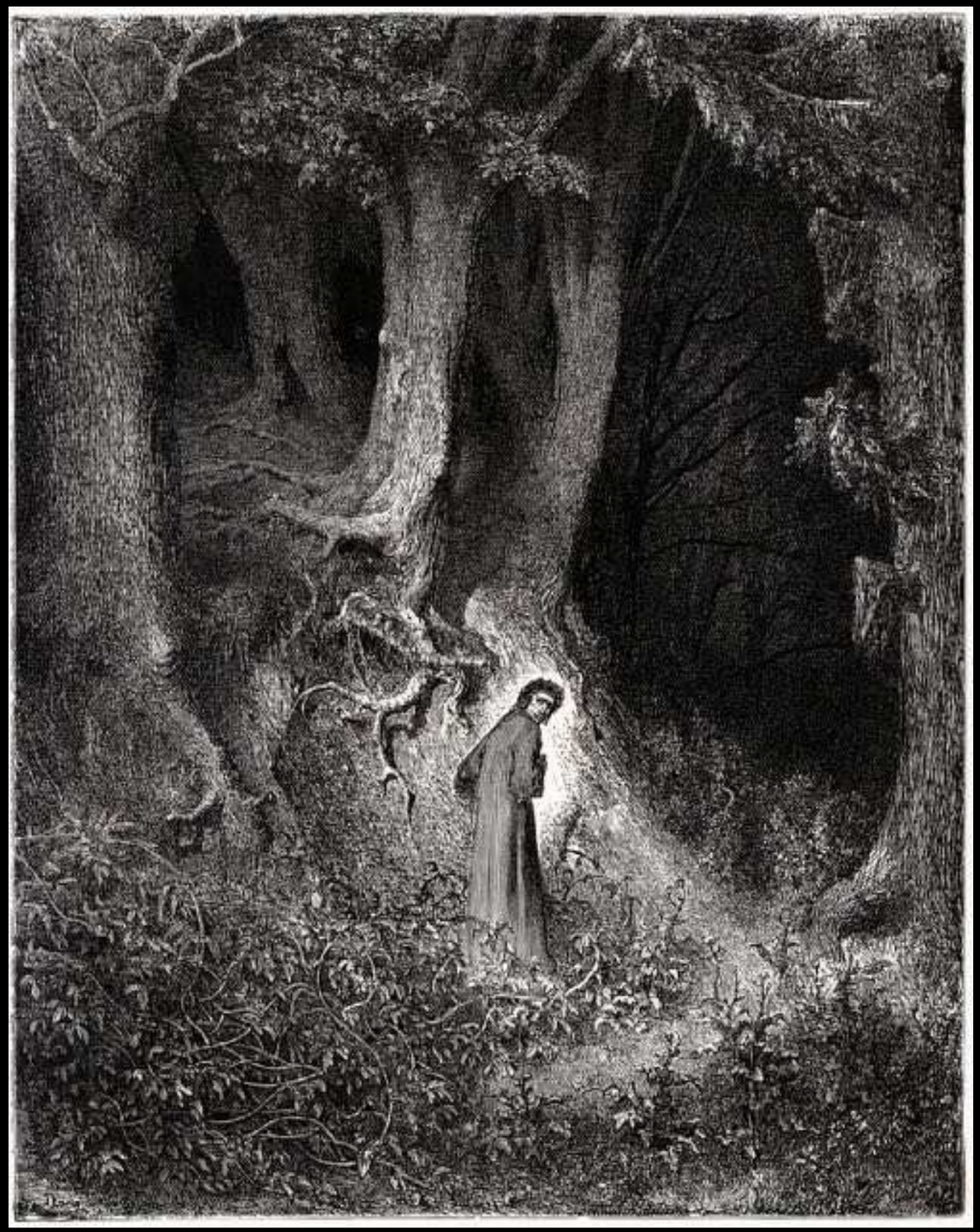
Fundamental Cosmology



Lion

Panther

She-wolf

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FUNDAMENTAL COSMOLOGY

Dark matter

Dark energy

Inflation

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:

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SYNERGIES

PRIMORDIAL INFLATION EXPLORER
PIXIE
NASA • GSFC • BATC

herschel
Unveiling the cool and dusty Universe

jwst
Observing t

DARK ENERGY SURVEY

CFHTLENS

planck
Looking back at the dawn of time

COrE
Cosmic Origins Explorer

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

SKA
SQUARE KILOMETRE ARRAY

SKA AFRICA
SQUARE KILOMETRE ARRAY

ACTPol

SOUTH POLE TELESCOPE

Pan-STARRS

VIPERS
VIMOS PUBLIC EXTRAGALACTIC REDSHIFT SURVEY

SLOAN DIGITAL SKY SURVEY

ultraviolet
x-rays
gamma rays

integral
...ing out the extremes
...e Universe

Fermi
Gamma ray
Space Telescope
European Space Agency

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Outline

- Synergies: Why and how?
- Synergies
- Synergies vs C e:

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Correlations

- Cosmological perturbation
  [temperature anisotropies, density fluctuations…]
  $f(t, \mathbf{x})$

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

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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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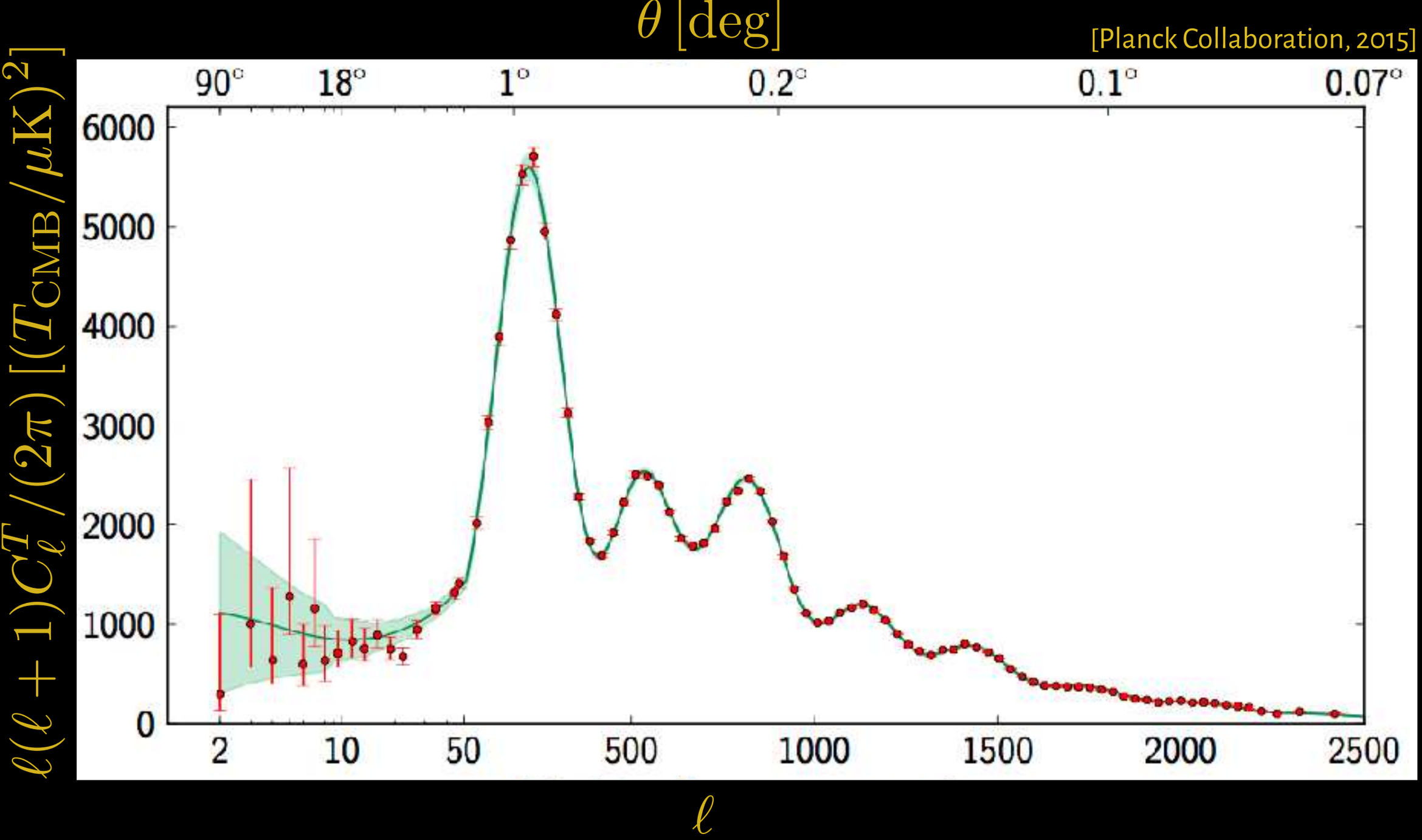
Correlations



[Planck Collaboration, 2015]

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Correlations

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- Example #2: Matter power spectrum

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

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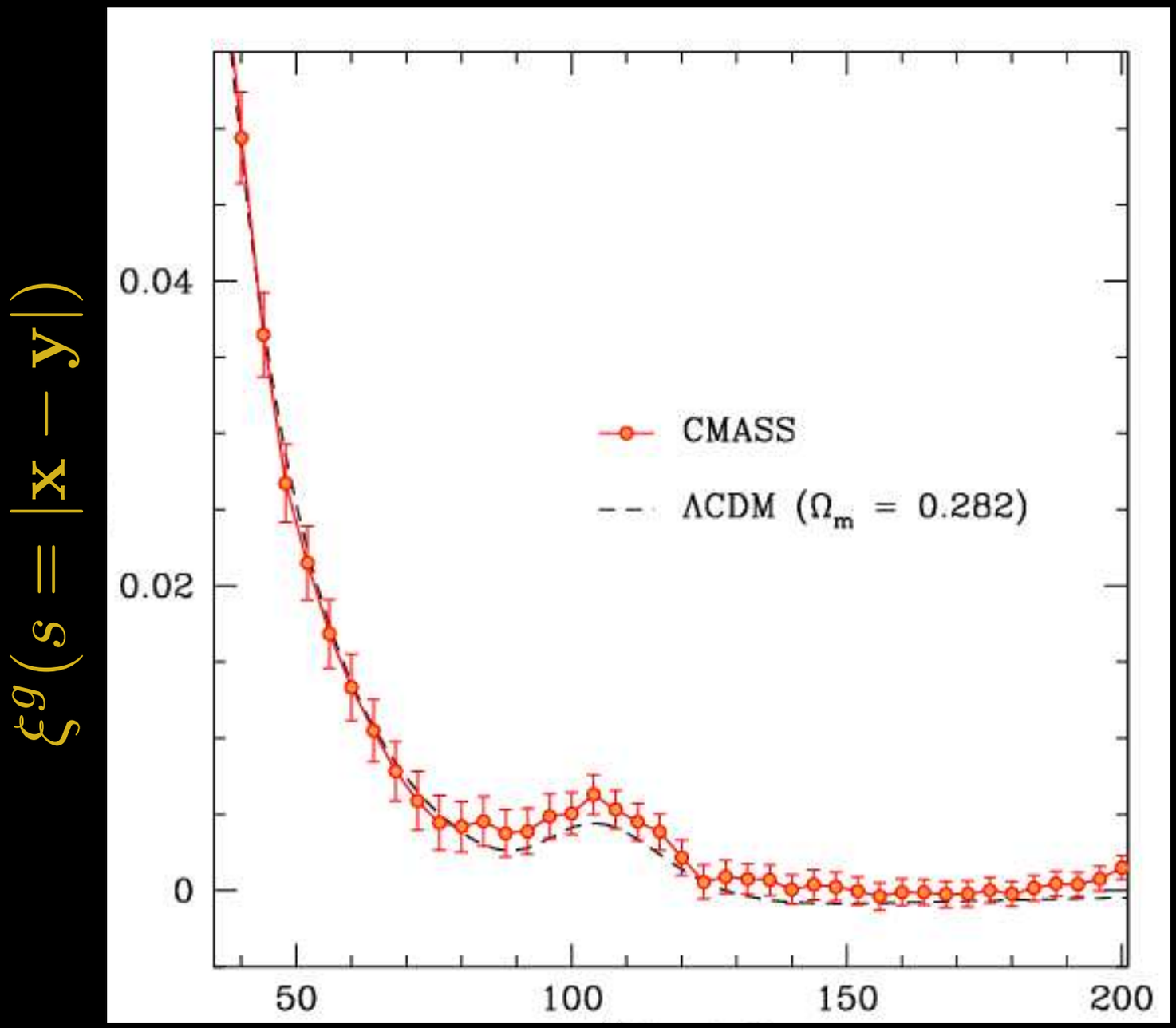
Correlations

[SDSS-III BOSS Collaboration, 2012]



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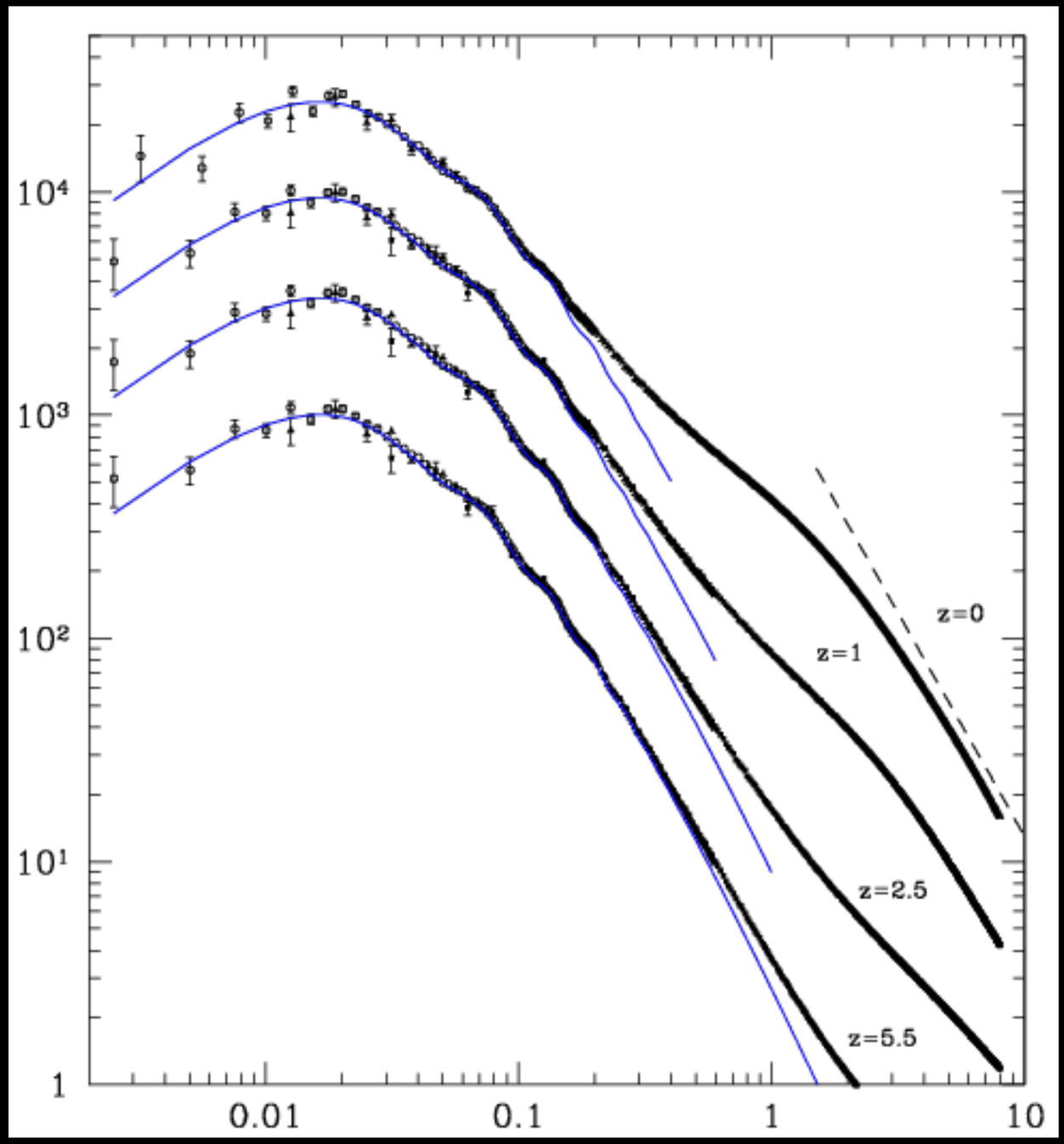
Correlations

[Klypin et al., 2016]



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Cross-Correlations

- Cosmological perturbation $f(t, \mathbf{x})$
- Correlation function $\xi^{fg}(t, |\mathbf{x} - \mathbf{y}|) = \langle f(t, \mathbf{x}) g(t, \mathbf{y}) \rangle$
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WHY!?

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Cross-Correlations

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- Power spectrum $\langle \hat{f}_k(t) \hat{g}^\star_{k'}(t) \rangle = \delta_D(\mathbf{k}-\mathbf{k}') P^{fg}(k,t)$
- Measurement
  [noise, systematic effects, 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?
- Synergies vs Noise: Indirect search of particle dark matter signatures
- Synergies vs Cosmic Variance: Multi-tracing galaxy number counts

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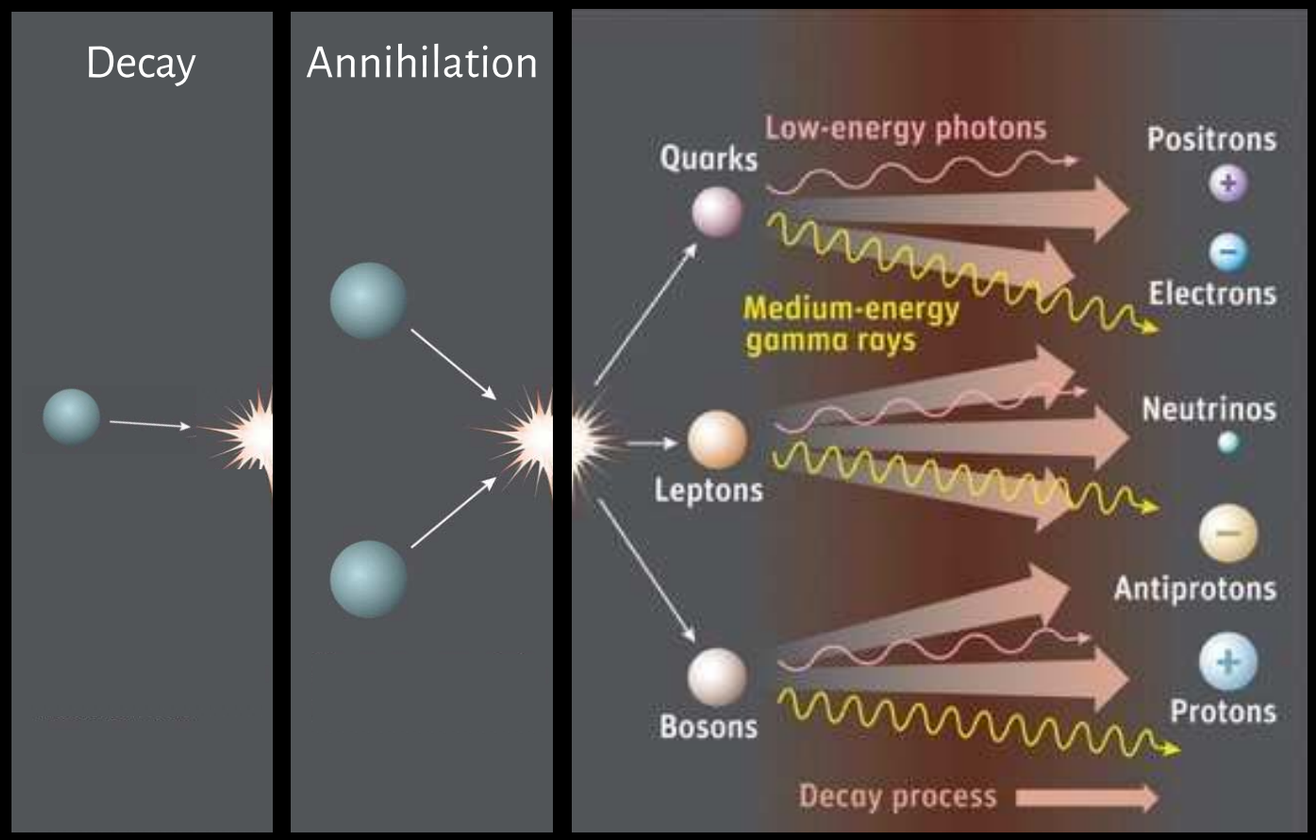
Particle Dark Matter

- Particle dark matter established ingredient of concordance cosmology
- Weakly interacting massive particles (WIMPs)
  - Indirect detection experimentrs: WIMP-sourced cosmic & gamma rays



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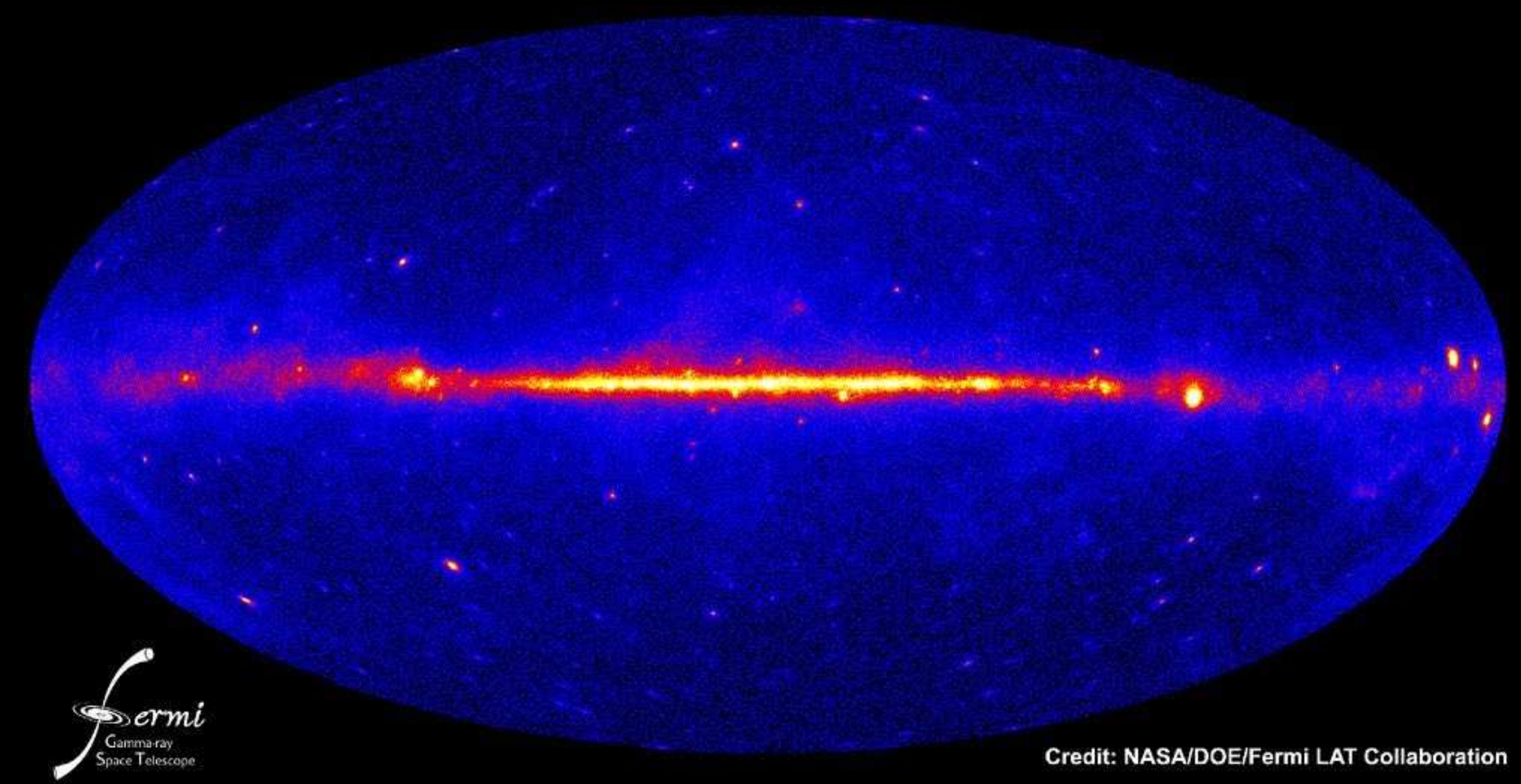
DM-Sourced Gamma Rays



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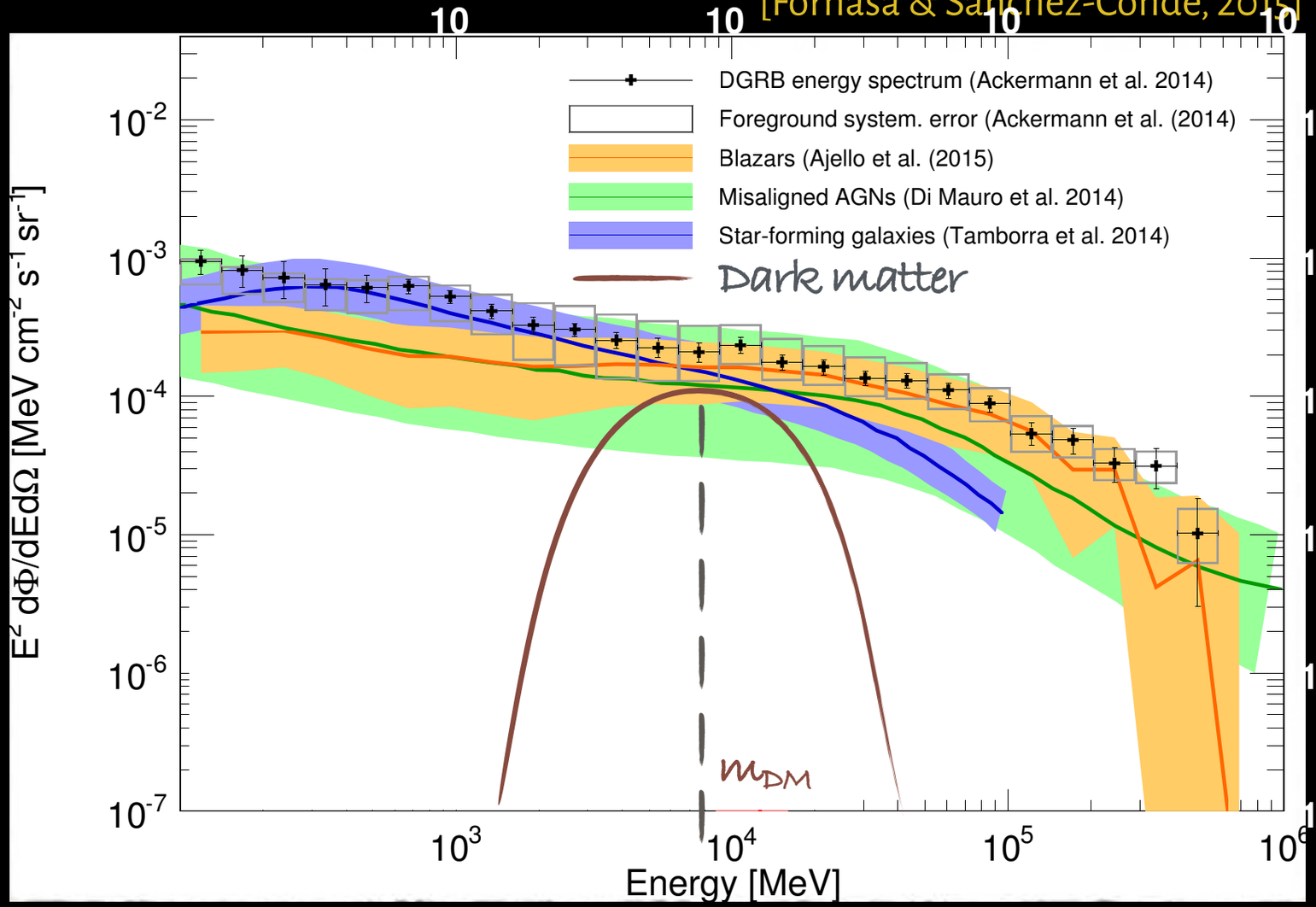
DM-Sourced Gamma Rays

- Hunting down signals of annihilations/decays of dark matter particles
  - Gamma-ray energy spectrum

[Fornasa & Sánchez-Conde, 2015]



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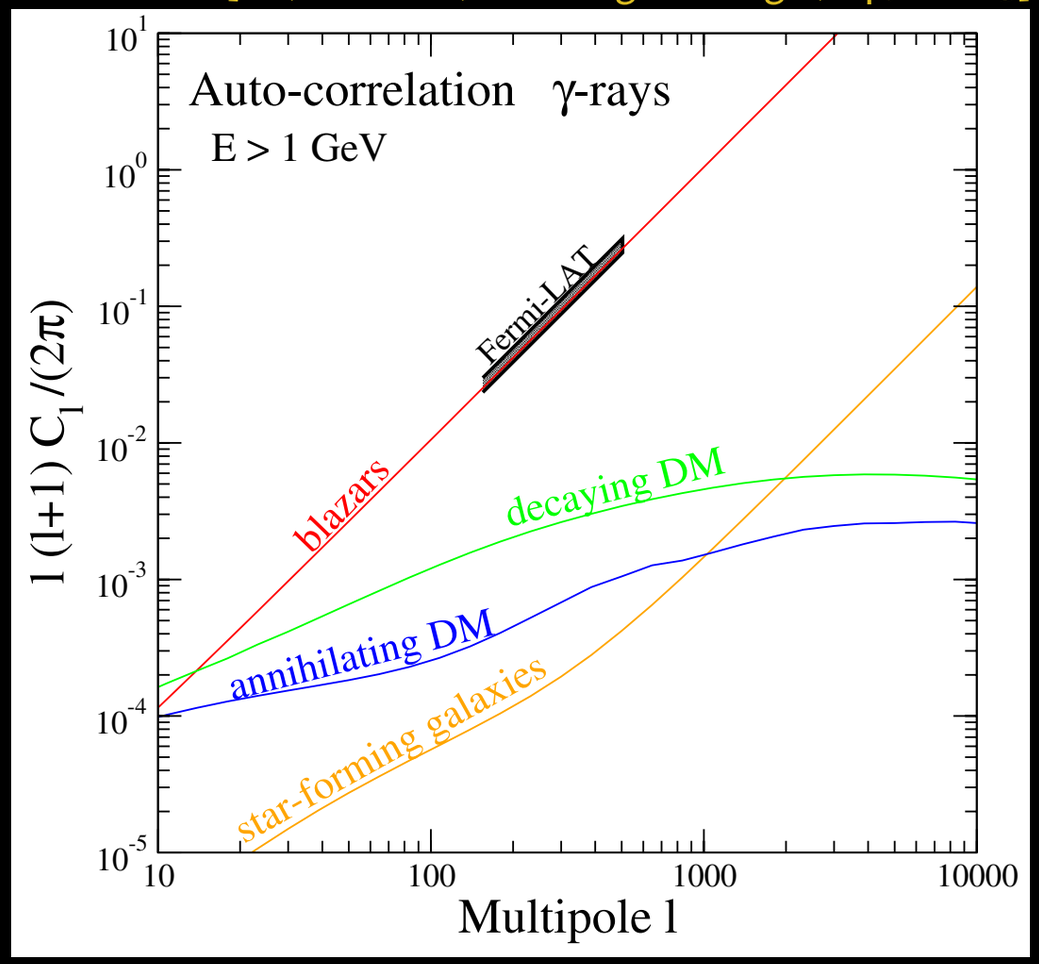
DM-Sourced Gamma Rays

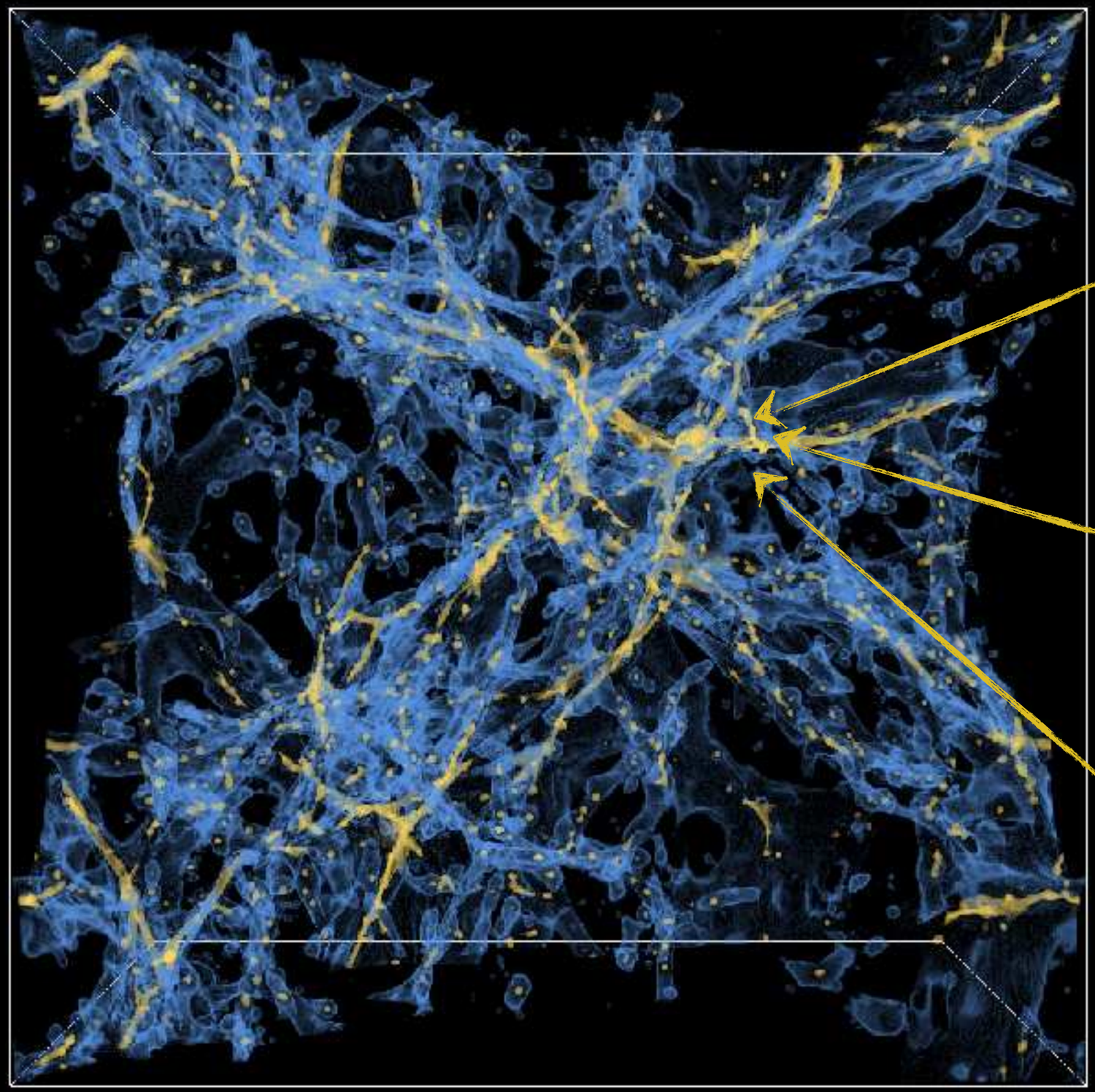
- Hunting down signals of annihilations/decays of dark matter particles
  - Gamma-ray anisotropies angular spectrum

[SC, Fornasa, Fornengo & Regis, ApJL 2013]



Direct Gravitational Probes

[Lukic et al.; Image: Casey Stark]



Potential wells of the cosmic large-scale structure

Gamma rays from astrophysical sources hosted within the dark matter halo

Gamma rays from annihilations/decays of dark matter particles forming the halo

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DIRECT GRAVITATIONAL PROBES

- Find an optimal tracer of the cosmic dark matter distribution on large scale to filter out astrophysical non-thermal emission from the dark matter gamma-ray signal

- Main tracers of the cosmic large-scale structure:

  - Weak gravitational lensing (cosmic shear, CMB lensing...)

    [SC, Fornasa, Fornengo & Regis, ApJL 2013;
    Fornengo, Perrotto, Regis & SC, ApJL 2015; Shirasaki et al. 2013; 2015]

  - Clustering of structures (galaxies, galaxy clusters...)

    [Fornengo & Regis, 2014; Ando et al., 2014; Xia et al., ApJS 2015;
    Regis et al., PRL 2015; Shirasaki et al., 2015, Branchini, SC et al., ApJS 2017]

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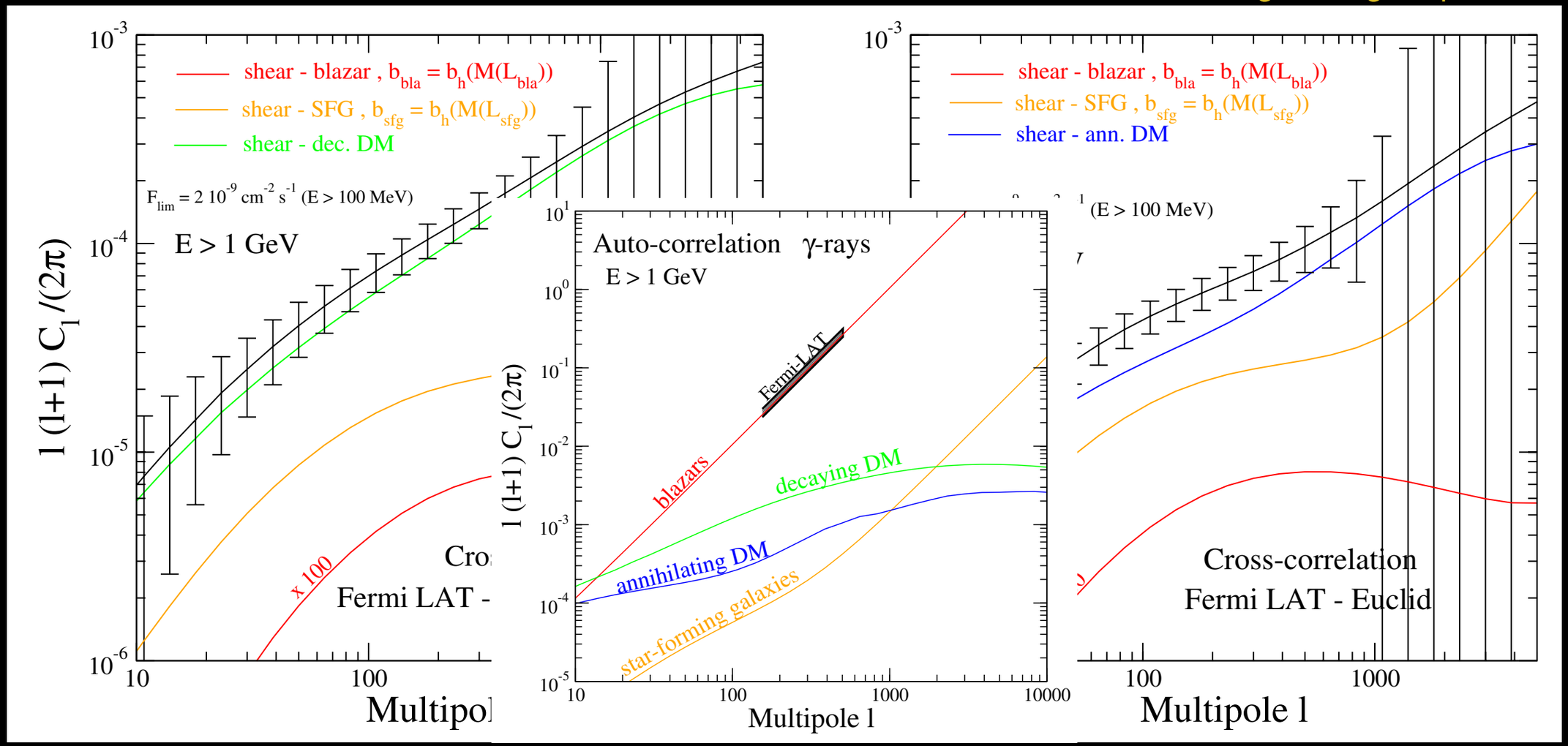
GAMMA RAYS & WEAK LENSING

euclid

Fermi Gamma-ray Space Telescope

[SC, Fornasa, Fornengo & Regis, ApJL 2013]



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GAMMA RAYS & WEAK LENSING

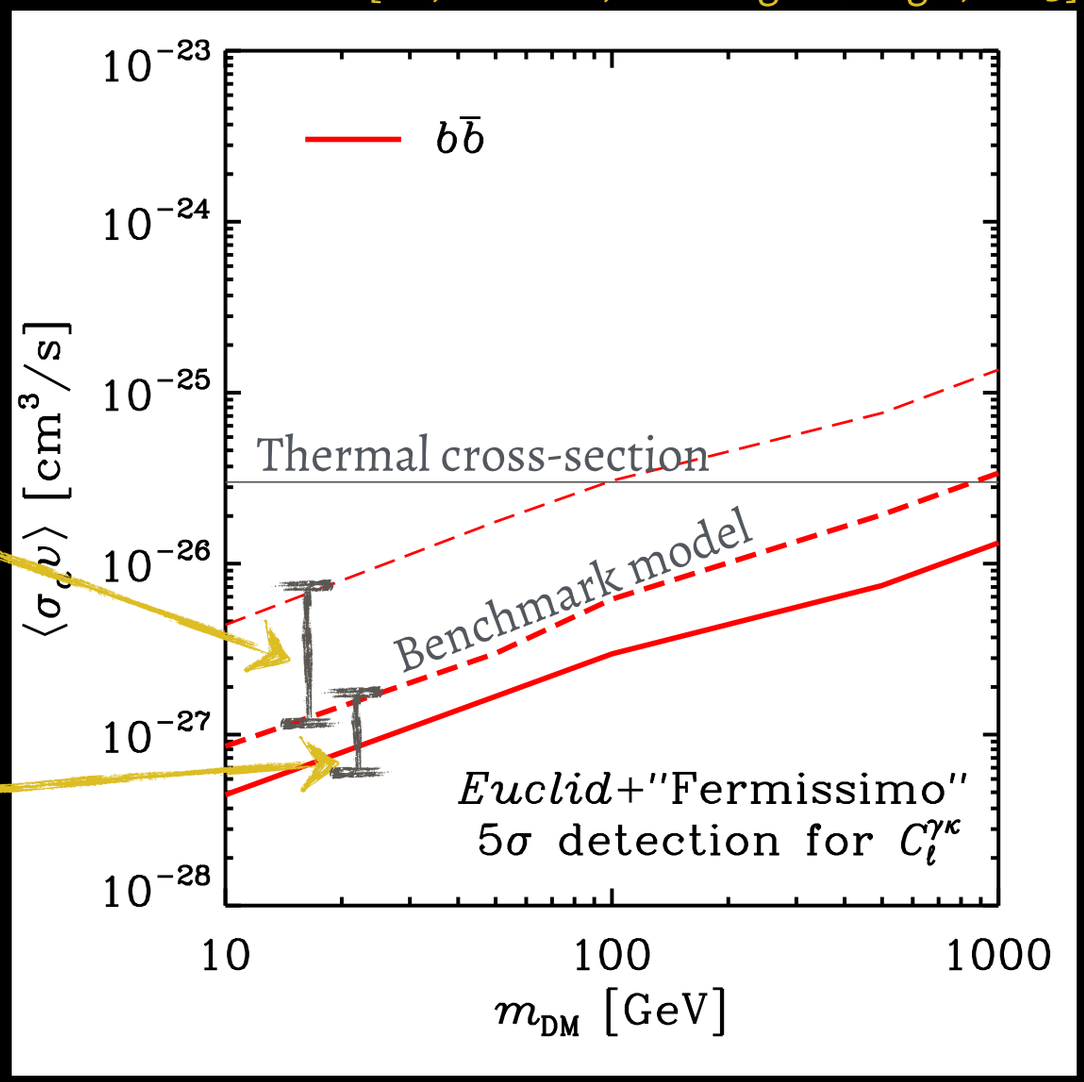
euclid

Fermi Gamma-ray Space Telescope

[SC, Fornasa, Fornengo & Regis, 2015]

Uncertainty on dark matter properties

Uncertainty on unresolved astrophysical emission



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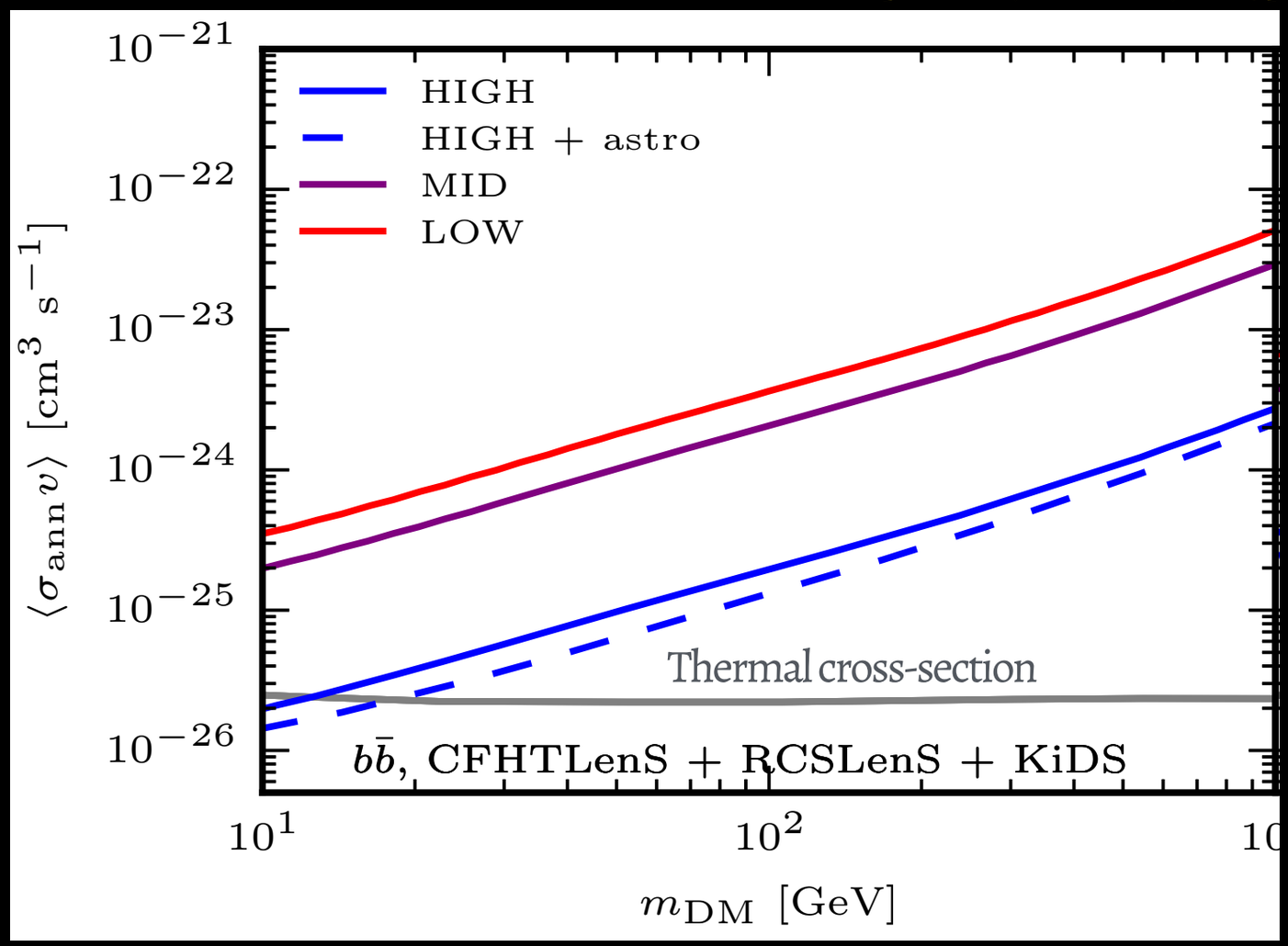
GAMMA RAYS & WEAK LENSING

KiDS

Fermi Gamma-ray Space Telescope

[Tröster, SC et al., 2017]



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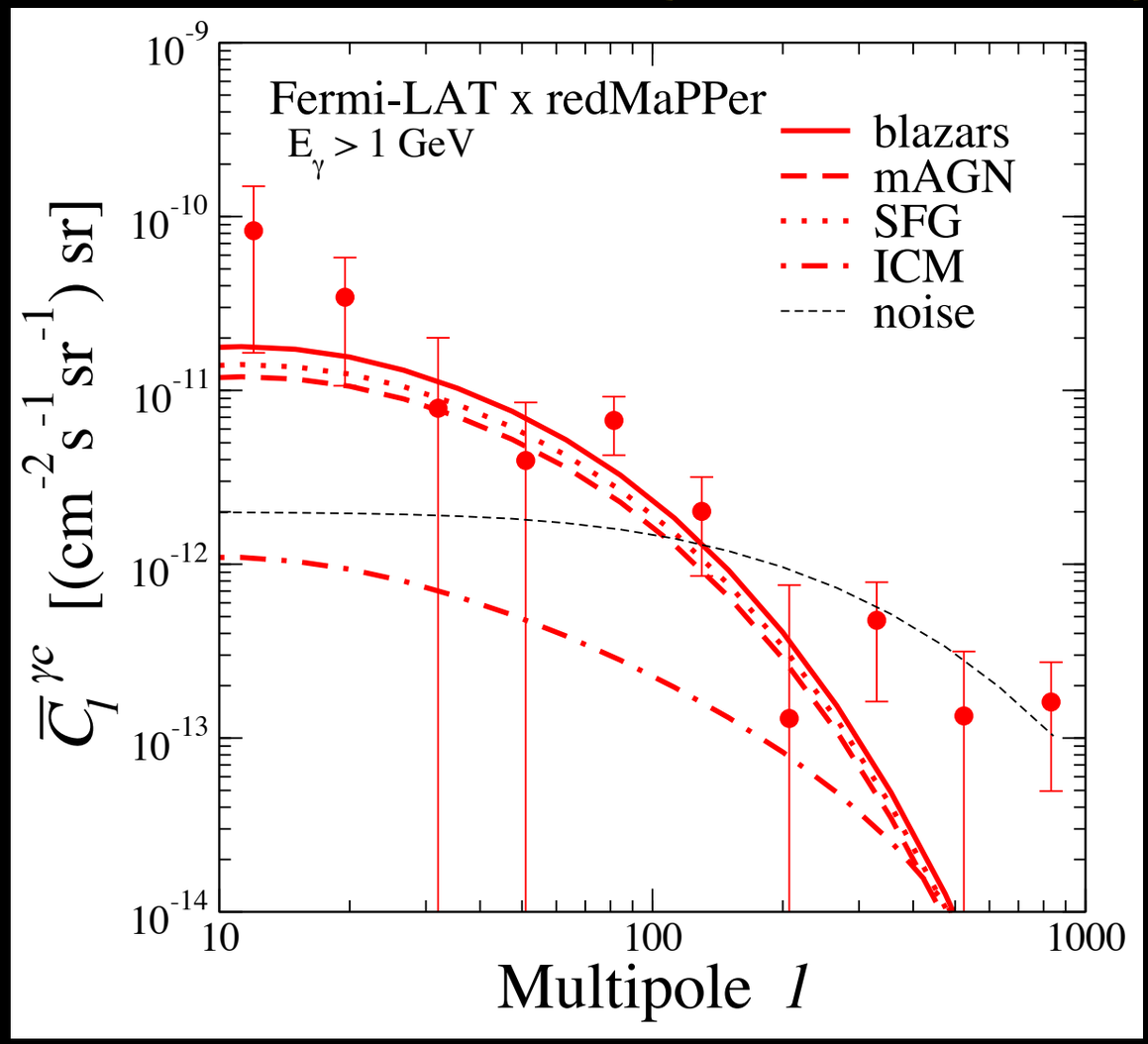
Gamma Rays & Clusters

SLOAN DIGITAL SKY SURVEY

Fermi Gamma-ray Space Telescope

[Branchini, SC et al., 2017]



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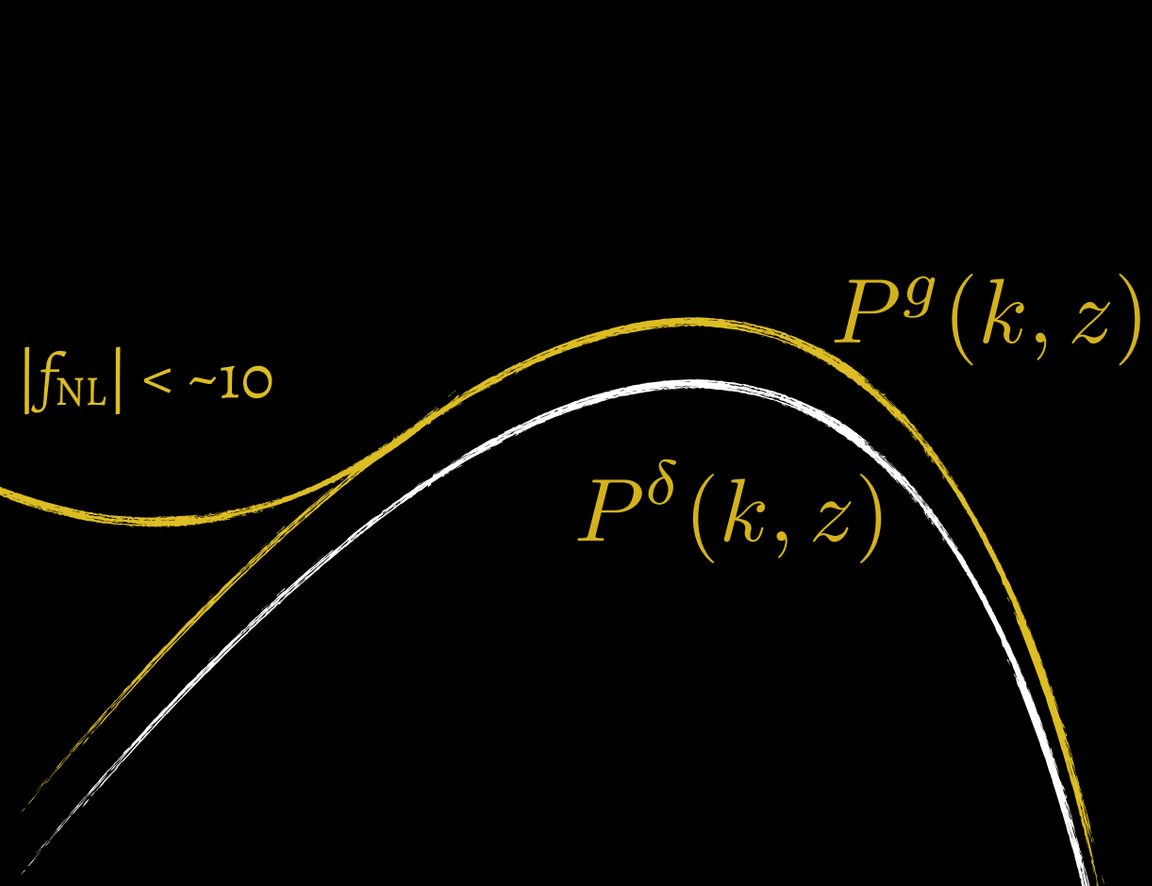
Galaxy Number Counts

- Proxy of the matter power spectrum

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

- Primordial non-Gaussianity
  - One of inflation's 4 'smoking guns'
  - Tightest available constraints from CMB: $|f_{\rm NL}| < \sim 10$

$$f_{\rm NL} > 0$$



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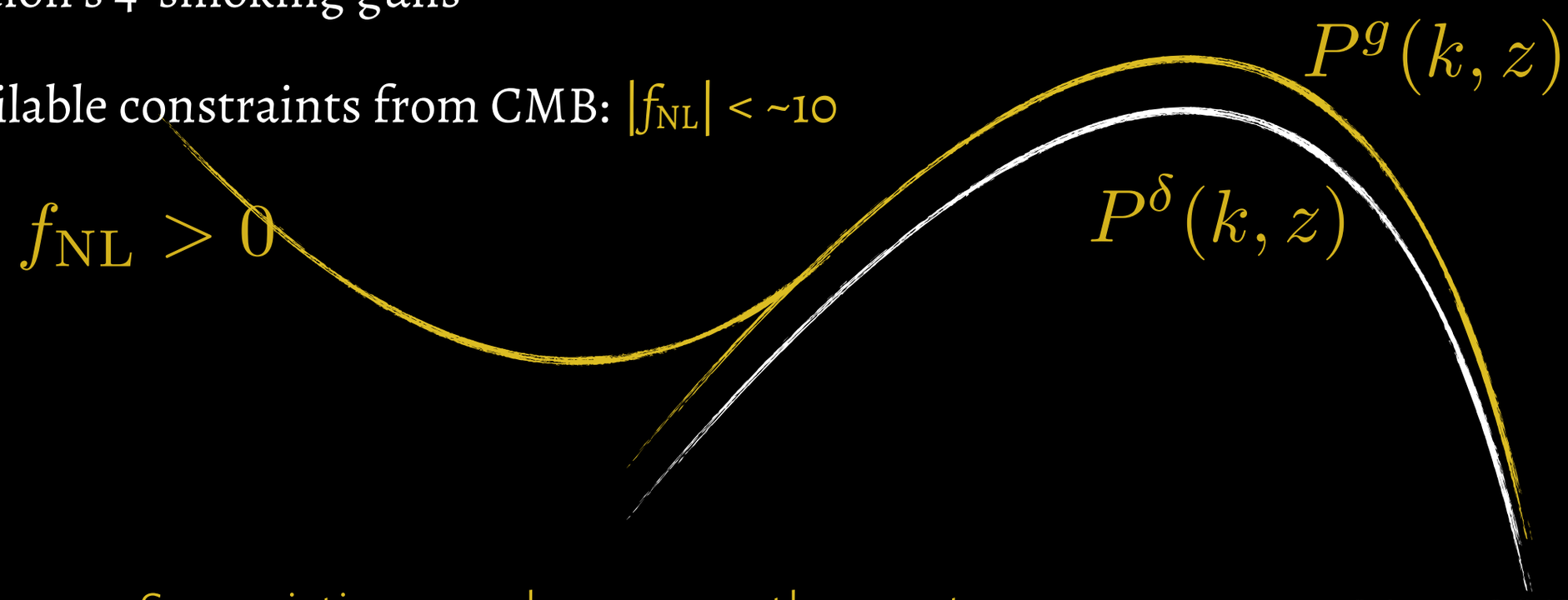

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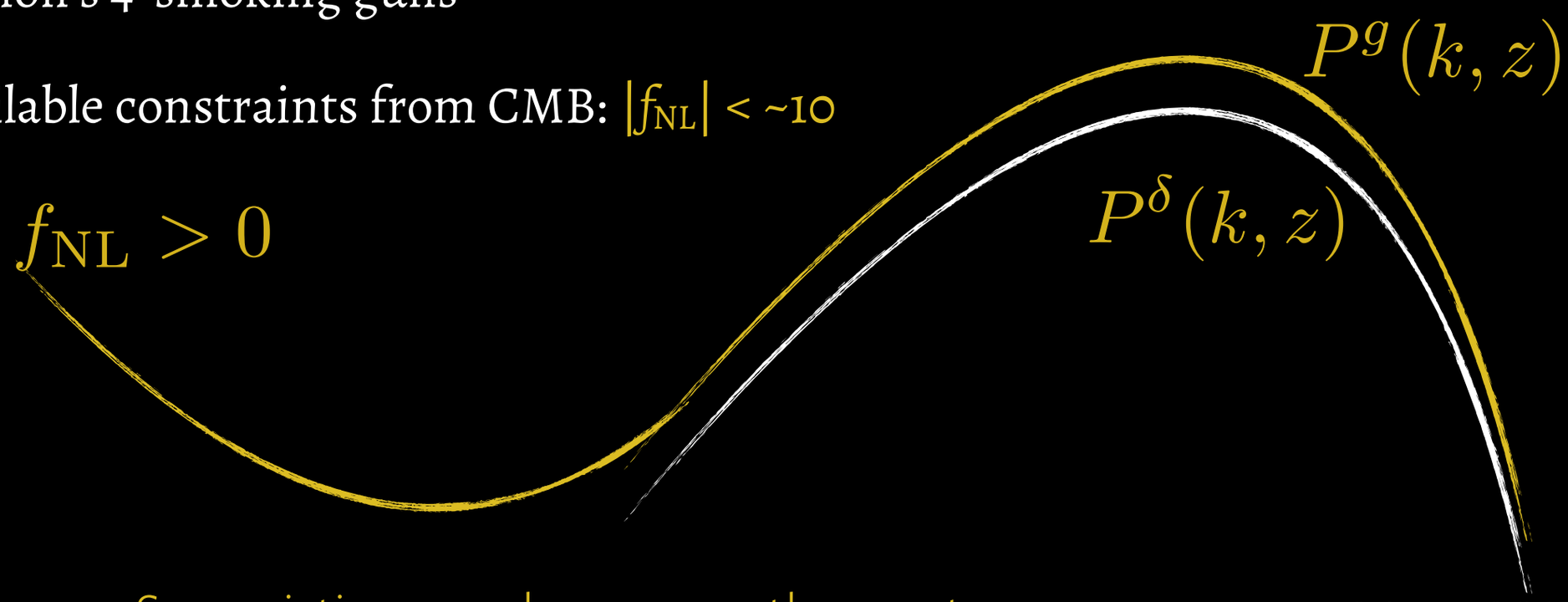

MANCHESTER 1824

The University of Manchester

Galaxy Number Counts

- Proxy of the matter power spectrum

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

MANCHESTER 1824

The University of Manchester

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]

MANCHESTER 1824

The University of Manchester

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

- Newtonian density fluctuations
- Redshift-space distortions
- Lensing
- Gravitational redshift, time delay, Sachs-Wolfe and integrated Sachs-Wolfe

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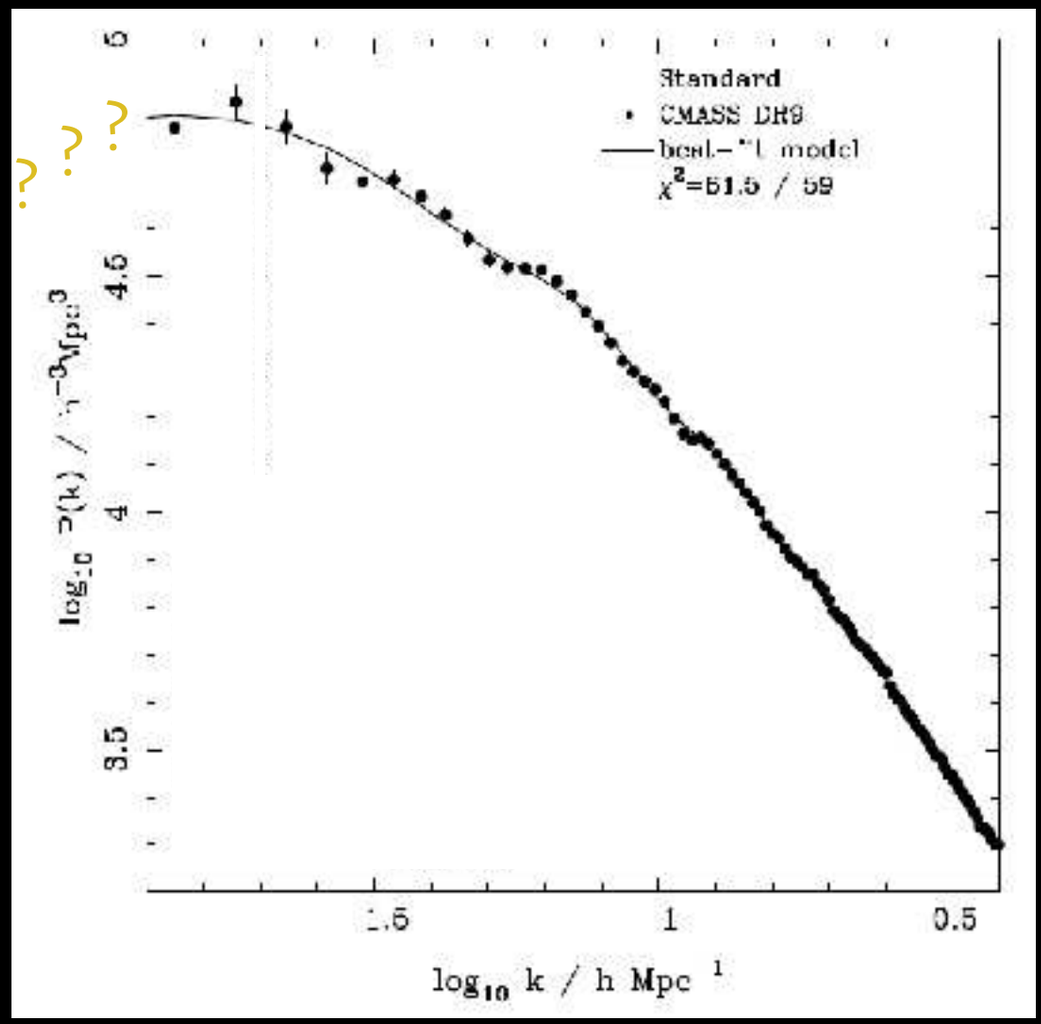
ACCESSING THE LARGEST SCALES

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

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

? ? ? ? ? ? ? ?

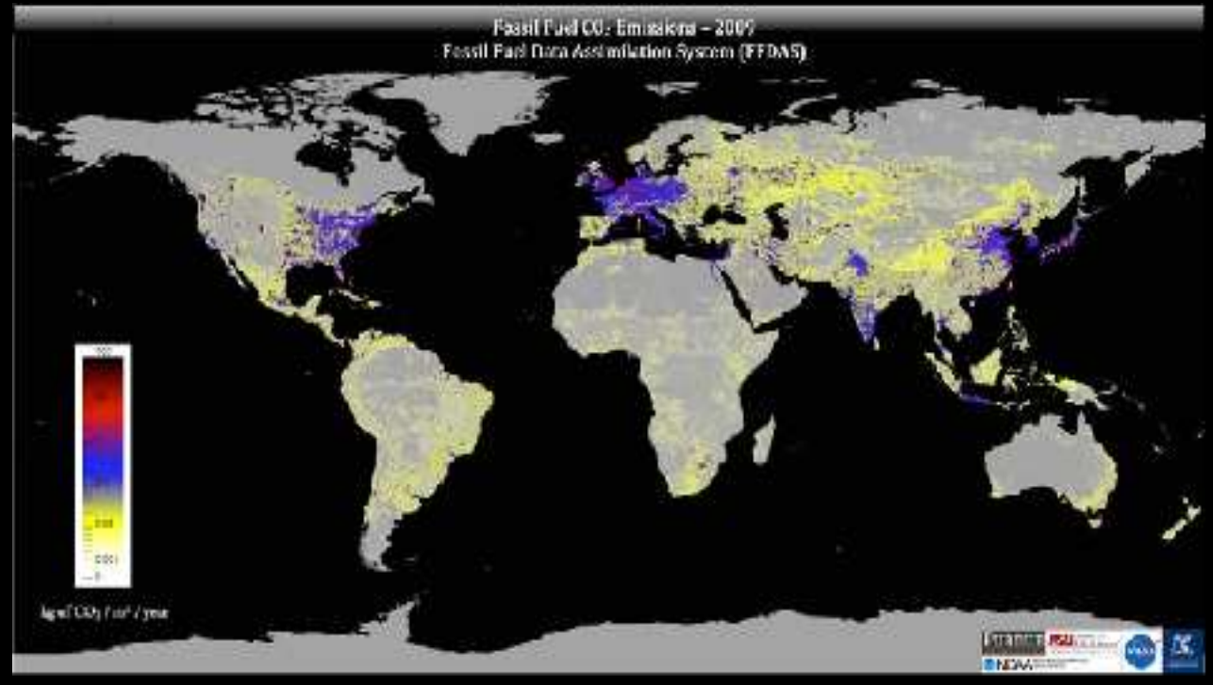
[SDSS-III BOSS Collaboration, 2012]



Multi-Tracer Technique

- Comparing the relative clustering of different populations of tracers

[Seljak, 2009; Seljak & McDonald, 2009]



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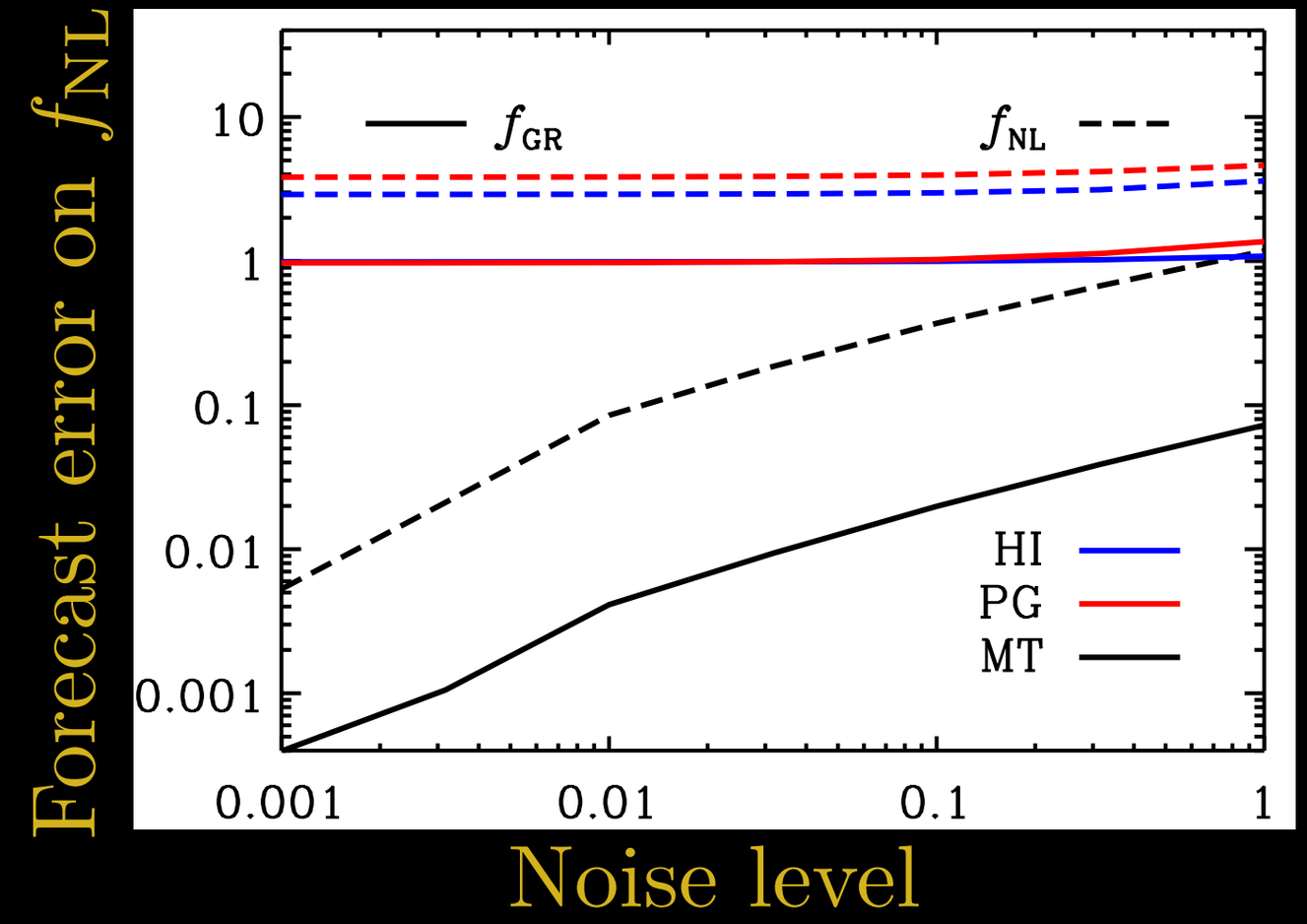
[Seljak, 2009; Seljak & McDonald, 2009]

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



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Summary

- Great time for synergies among cosmological surveys at various wavelengths

- Cross-correlations valuable for:

  - Cross-checking validity of cosmological results

  - Accessing signal buried in noise or cosmic variance
    [e.g. particle dark matter signatures, multi-tracing for non-Gaussianity]

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