COSMOLOGY WITH STANDARD SIRENS

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OUTLINE

- Gravitational Wave (GW) Standard Sirens
- Probes of the Universe's Geometry
- Probes of the Growth of Large-Scale Structures
- Challenges & New Horizons

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GW STANDARD SIRENS

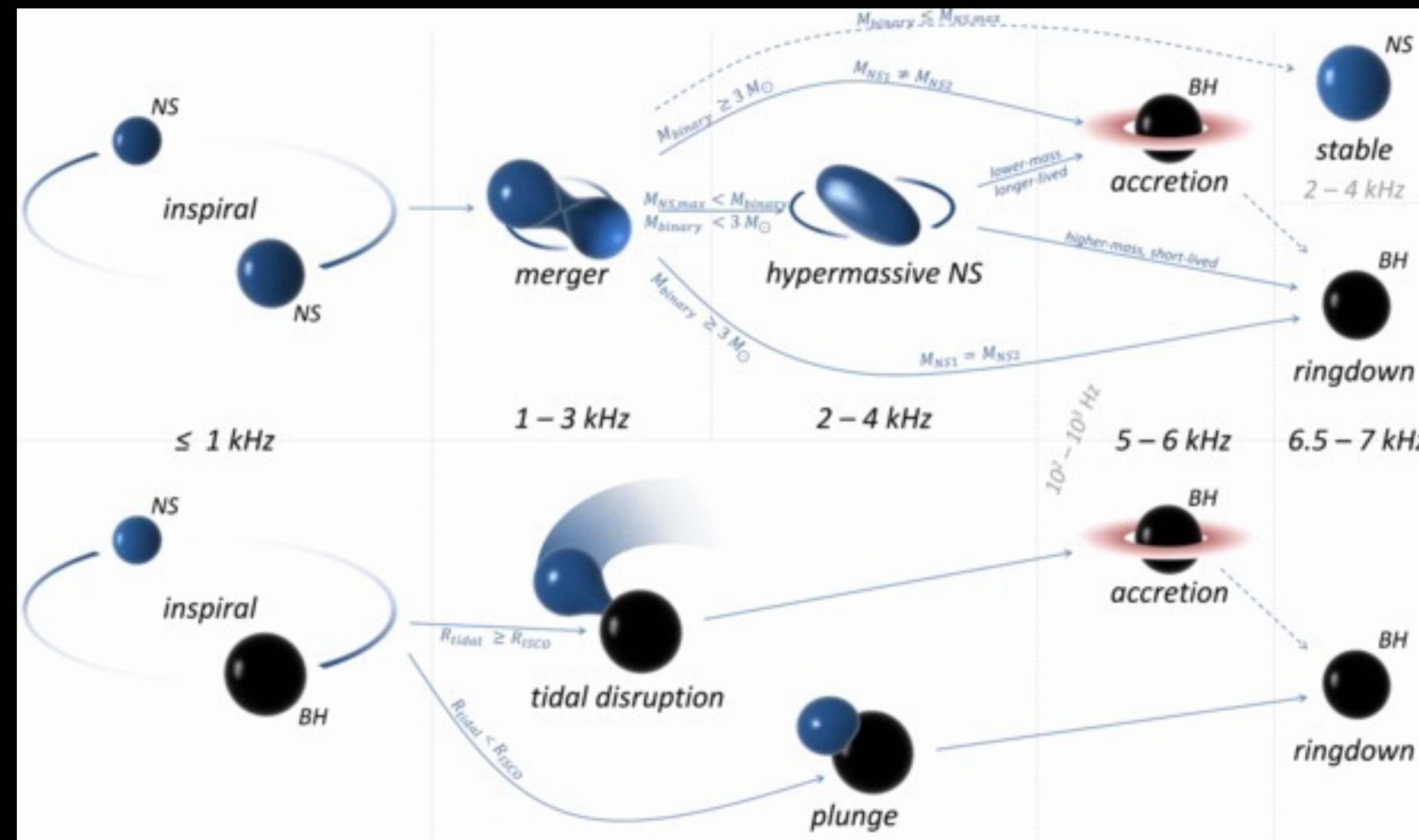
BINARY-SOURCE GW

- In-spirals and mergers of compact binary sources
  - A binary is a nearly perfect quadrupole radiator
  - Waveform phase depends only on the physics of the system

$$\Phi\left(m_1, m_2; \vec{S}_1, \vec{S}_2; t\right)$$

  - Binary black holes (BH) in-spirals are theoretically clear [Schutz 1986, 2002; Holz & Hughes 2005; Dalal *et al.*, 2006; Arun *et al.*, 2007]
  - Binary BH in-spirals are well-modelled

BINARY-SOURCE GW



LIGO ET

- Stellar-mass binaries

eLISA

- Binary black holes (BH) in-spirals are theoretically clear

[Schutz 1986, 2002; Holz & Hughes 2005; Dalal

- Binary BH in-spirals are

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BINARY-SOURCE GW

- A measured binary GW signal (schematically)

$$h_{\rm meas} = \frac{G\mathcal{M}_z^{5/3}}{d_L(z)} f(t)^{2/3} \mathcal{F}(\text{angles}) \cos\left[\Phi\left(m_1, m_2, \vec{S}_1, \vec{S}_2; t\right)\right]$$

Luminosity distance

Geometry of the system

Masses and spins of mergers

BINARY-SOURCE GW

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- Redshifted 'chirp mass'

$$\mathcal{M}_z = (1+z)\frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$

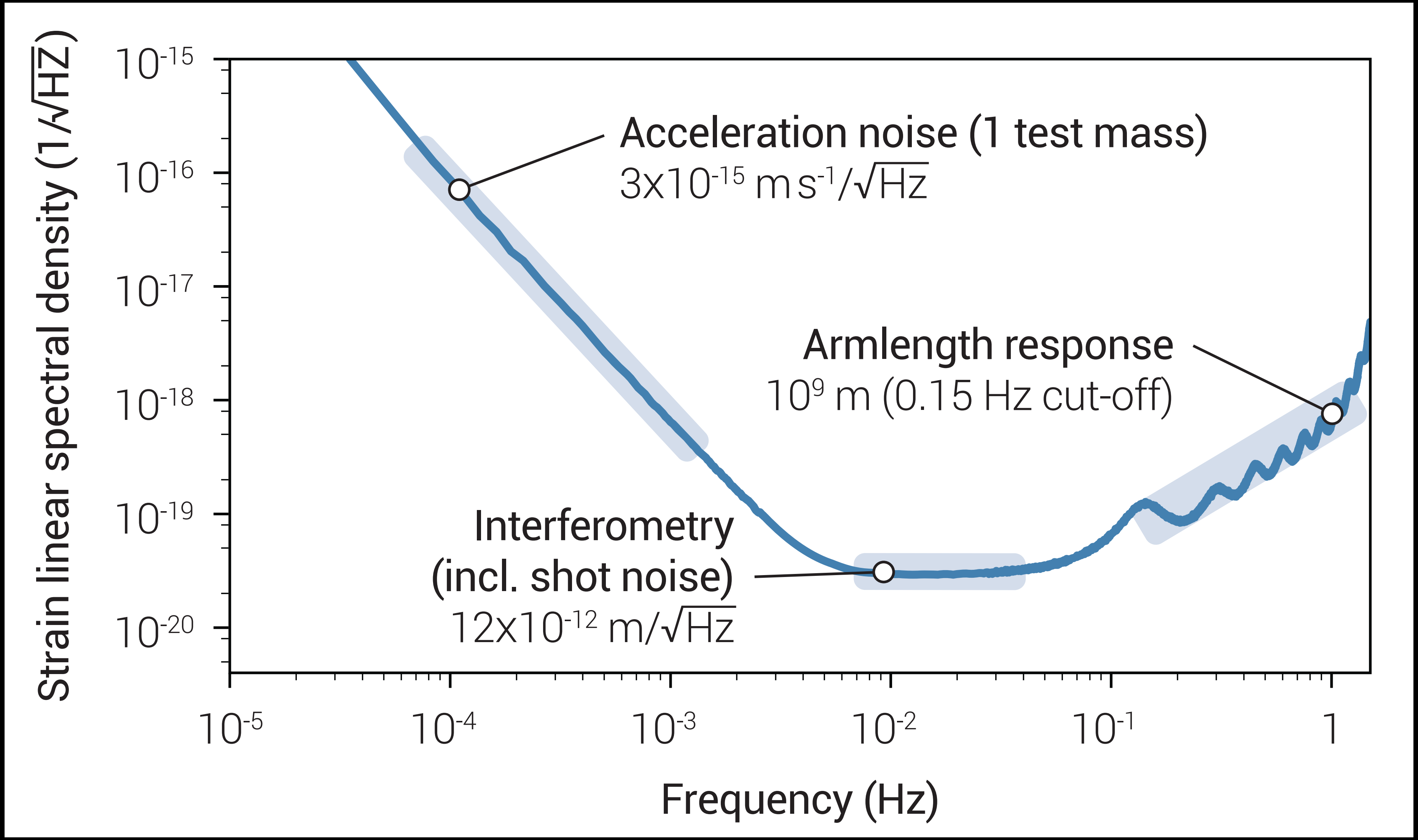
- GW frequency

$$f(t) = \frac{1}{2\pi}\frac{\mathrm{d}\Phi}{\mathrm{d}t}$$

STANDARD SIRENS

- How to make binary in-spirals standard sirens?

[eLISA Withe Paper, 2013]



STANDARD SIRENS

- How to make binary in-spirals standard sirens?
  - Chirp mass determined to high precision
    (It sets the rate at which the frequency changes)
  - Masses and spins measured through the waveform phase
    (Data analysis based on matching the data to a model for Φ)
  - Angular localisation available within 1–10 square degrees
    (Depending on number and baselines of GW detectors)

[eLISA Withe Paper, 2013]

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STANDARD SIRENS

$$h_{\rm meas} = \frac{G\mathcal{M}_z^{5/3}}{d_L(z)} f(t)^{2/3} \mathcal{F}(\text{angles}) \cos\left[\Phi\left(m_1, m_2; \vec{S}_1, \vec{S}_2; t\right)\right]$$

- Caveat!

$$\mathrm{BS}_1[m_1, m_2; t(0)] \Leftrightarrow \mathrm{BS}_2\left[\frac{m_1}{1+z}, \frac{m_2}{1+z}; t(z)\right]$$

- Need *EM counterparts* for *distance–redshift* relation

EM COUNTERPARTS

- How to identify host galaxies?

  [Begelman, Blandford & Rees, 1980; Kocsis, Haiman & Loeb, 2012]

  - Use modulation to infer sky position better

    [Takahashi & Nakamura, 2005]

  - Exploit next-generation galaxy surveys
    (Euclid, LSST in the optical/near-IR; the SKA in the radio)

    [Metzger & Berger, 2012]

  - Locate morphologically promising galaxies
    (E.g. merging galaxies, tidal tails &c.)

  - Statistical tests for concordance between multiple sources

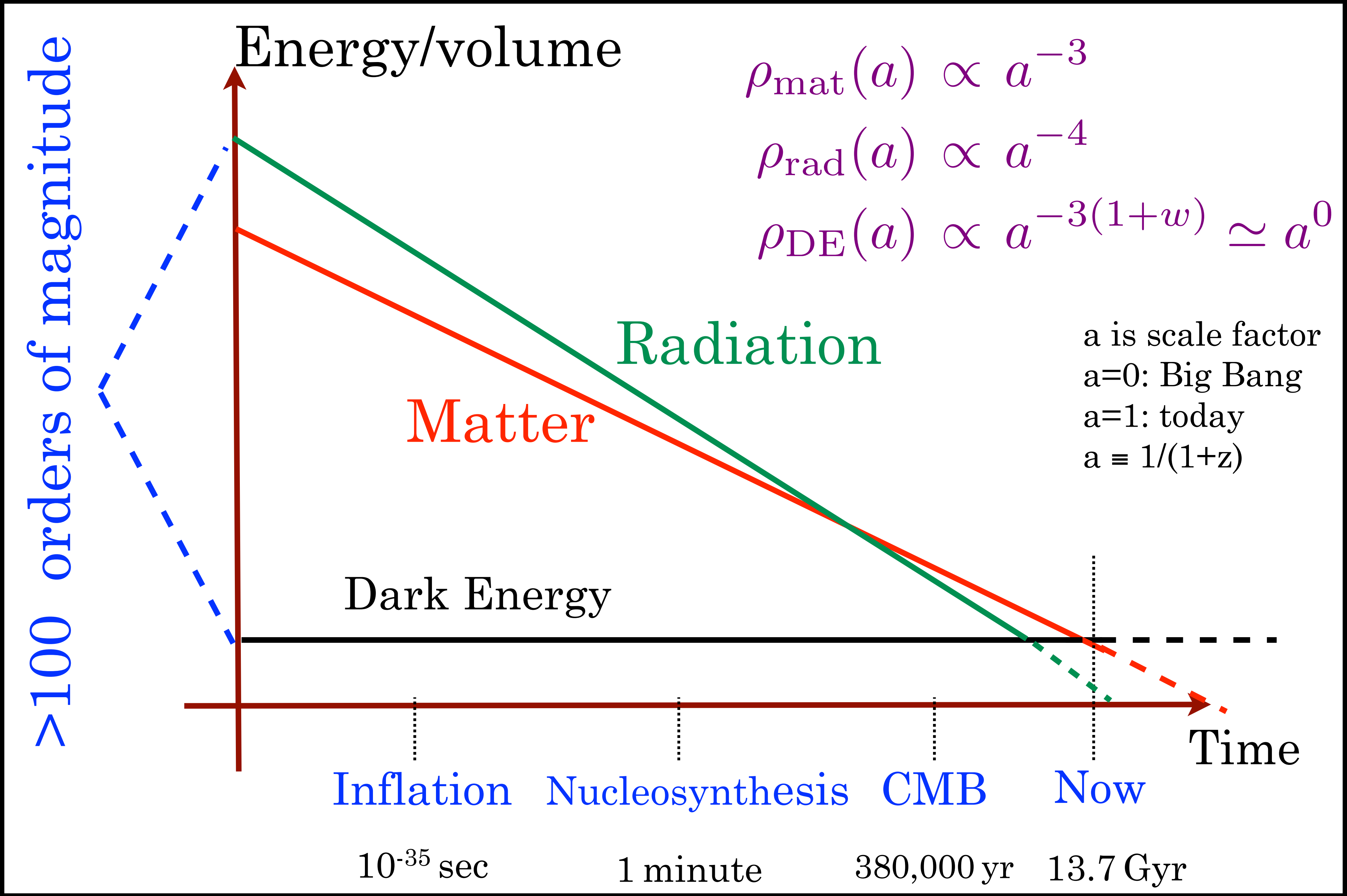
PROBES OF GEOMETRY

ALL THERE IS

- The Universe's geometry and ultimate fate are determined by its content

THE DARK UNIVERSE

[Huterer @ COSMO-15, 2015]



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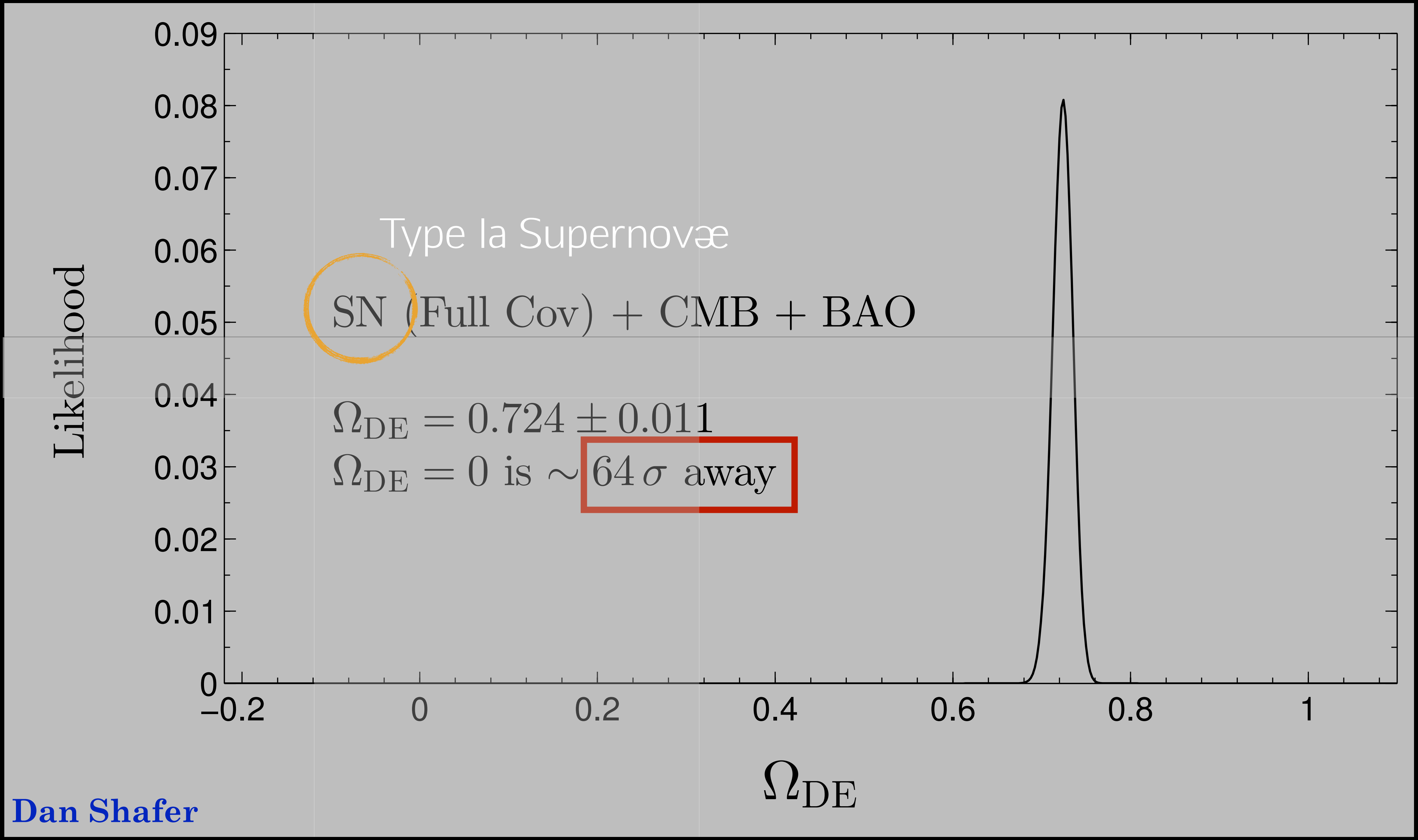
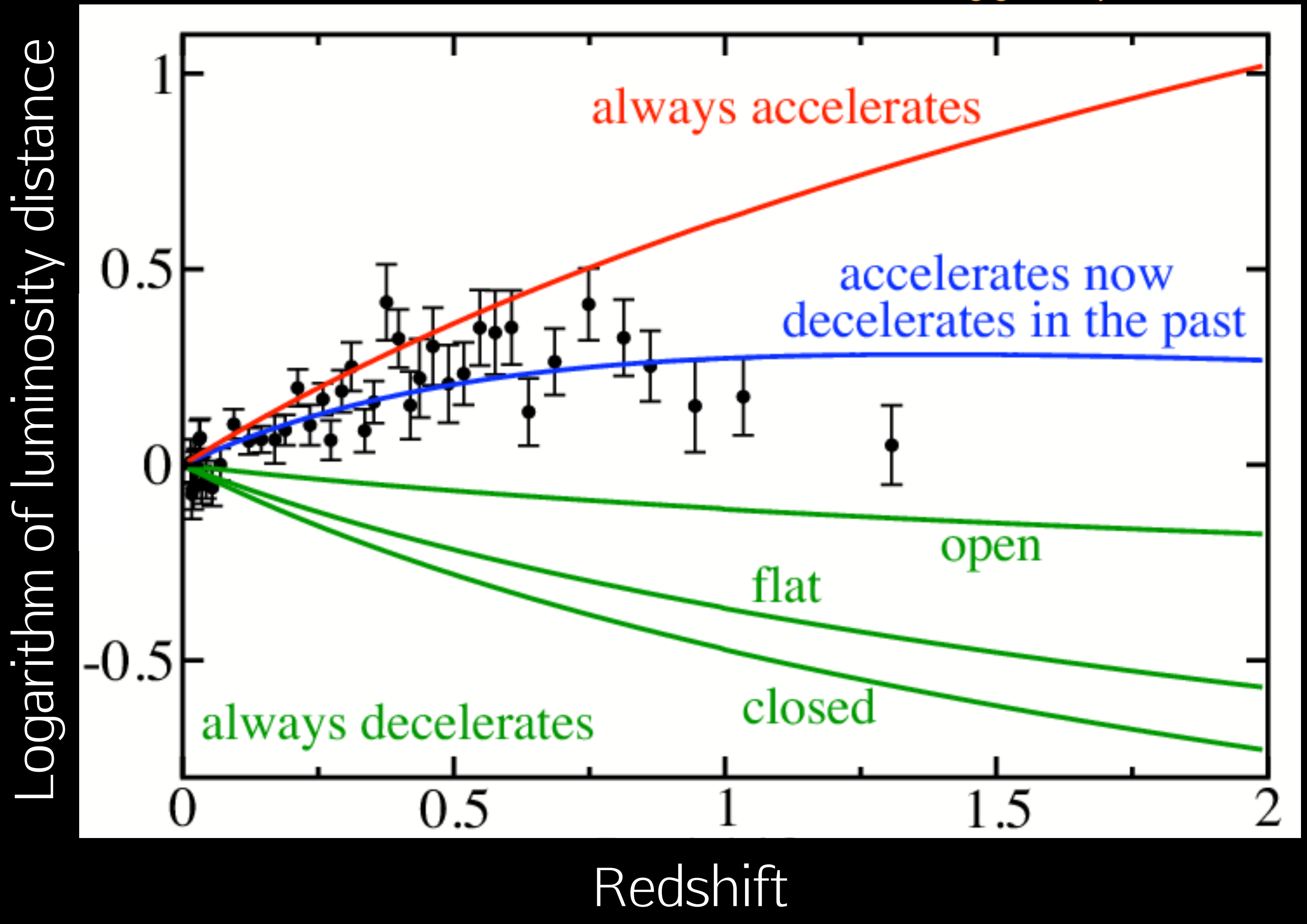


DISTANCE MODULUS

- Type Ia supernovæ are standard(isable) candles

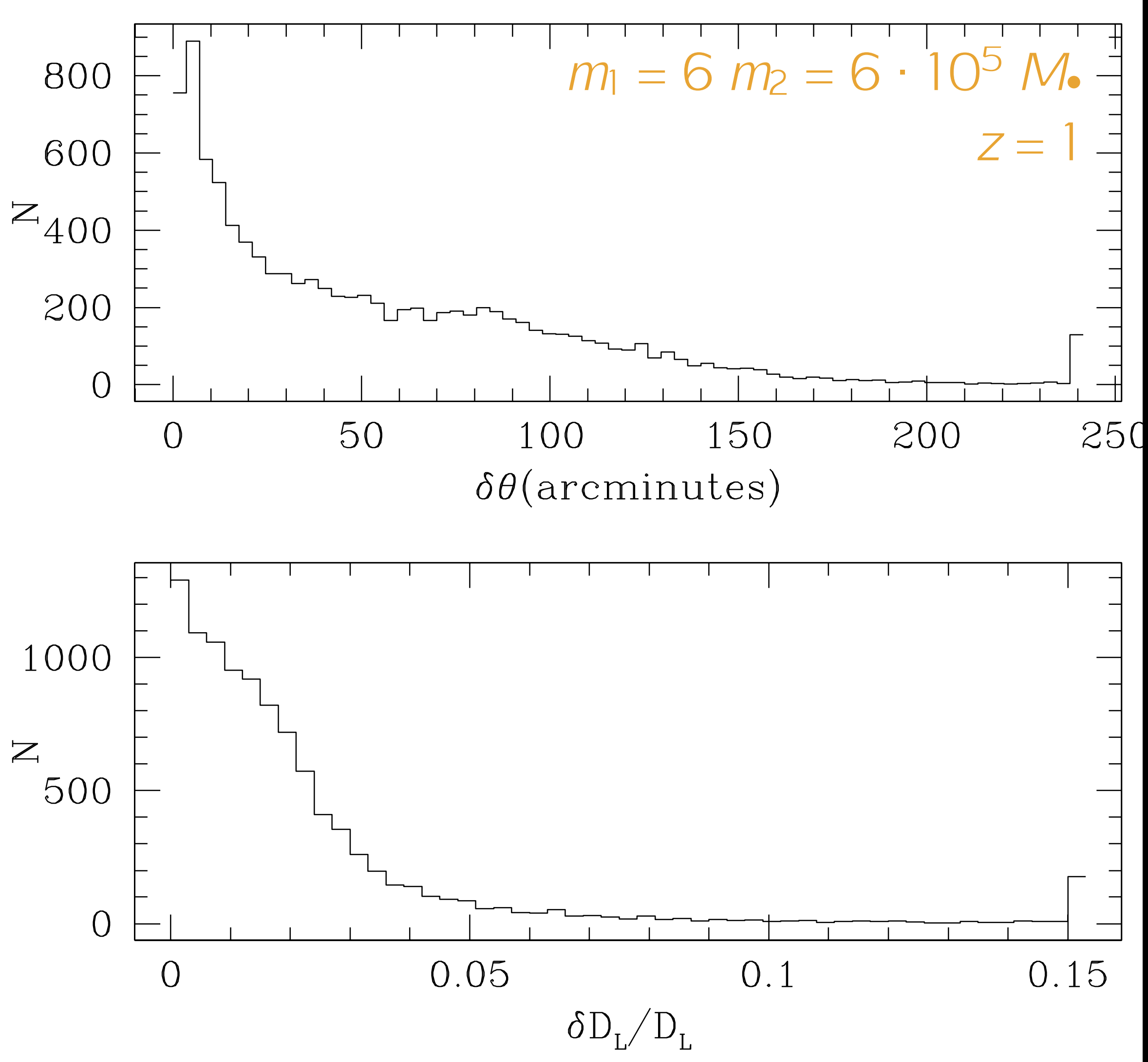
[Union2 SN Cosmology Project, 2011]



DISTANCE MODULUS

- GW from binary in-spirals are standard sirens

[Holz & Hughes, 2005]



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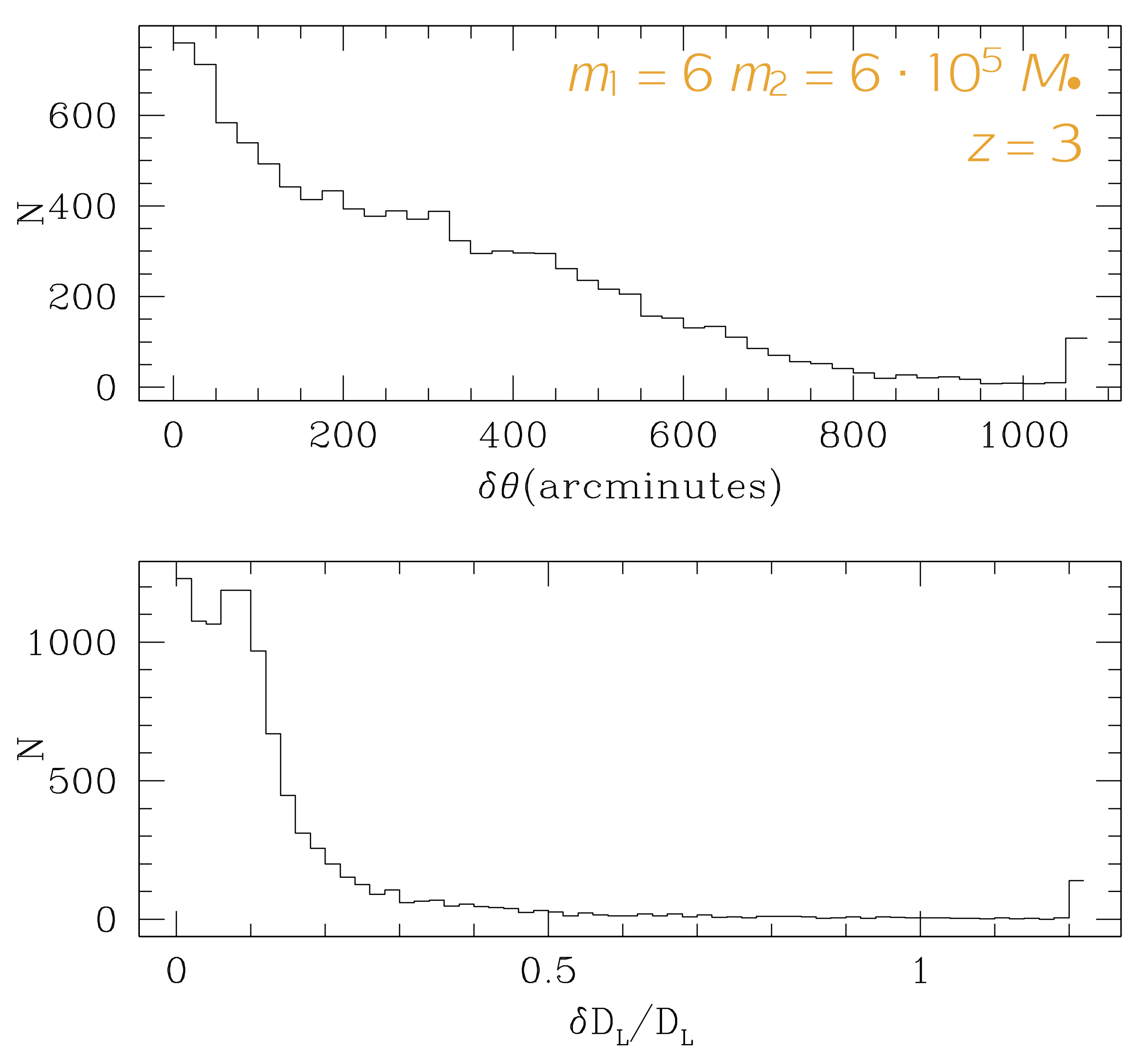
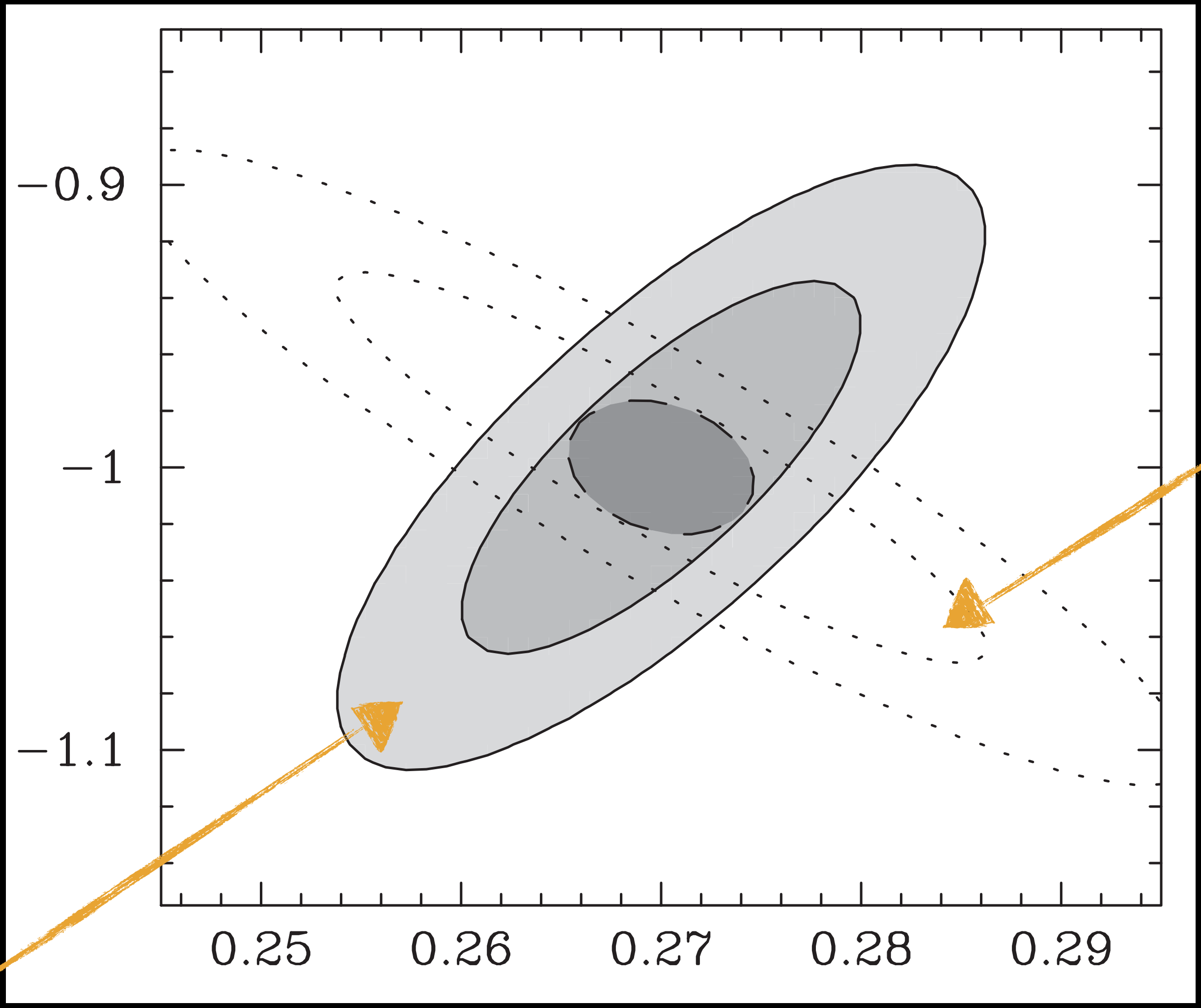


DISTANCE MODULUS

- Constraints on dark energy equation of state

[Dalal *et al.*, 2006]



Dark energy equation of state

Total matter fraction

3,000 SNAP
Type Ia Supernovæ

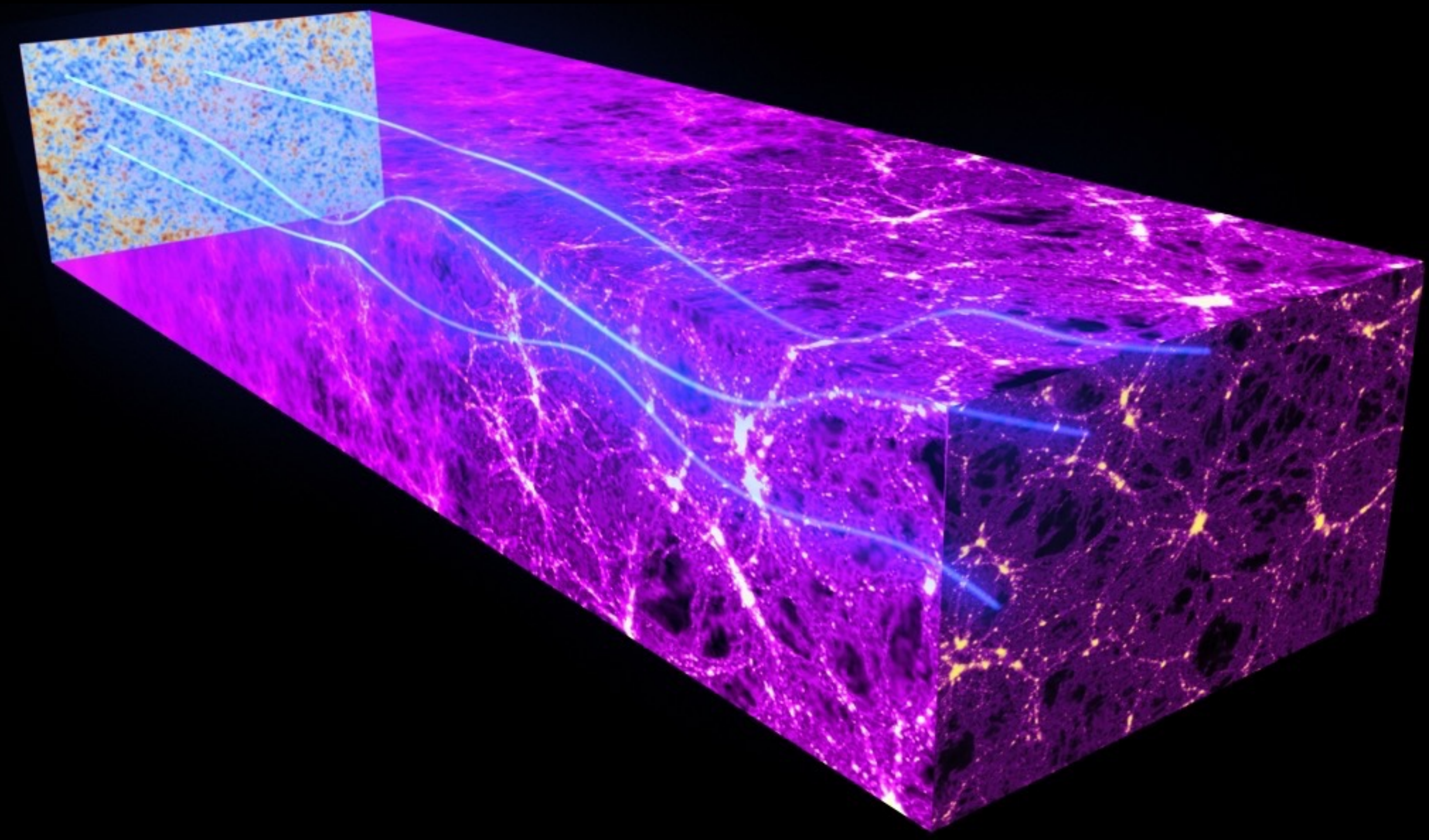
100 LISA
GW BH in-spirals

PROBES OF GROWTH

A CLUMPY UNIVERSE

- Photons *do not experience* a *homogeneous* Universe!

$$\mathrm{d}s^2 = -\mathrm{d}t^2[1+2\Phi(\mathbf{x},t)] + a^2(t)\delta^K_{ij}\mathrm{d}x^i\mathrm{d}x^j[1-2\Phi(\mathbf{x},t)]$$



EFFECTS OF PERTURBATIONS

- Two main effects:

[Bonvin, Durrer & Gasparini, 2006;
Hui & Greene, 2006]

  - Redshift perturbations
    (Affect GW frequency and redshifted chirp mass)

  - Distance perturbations *(Affect luminosity distance)*

$$d_L(z_S) = \left[(1+z_S)\int_0^{z_S} \frac{\mathrm{d}z}{H(z)}\right]$$

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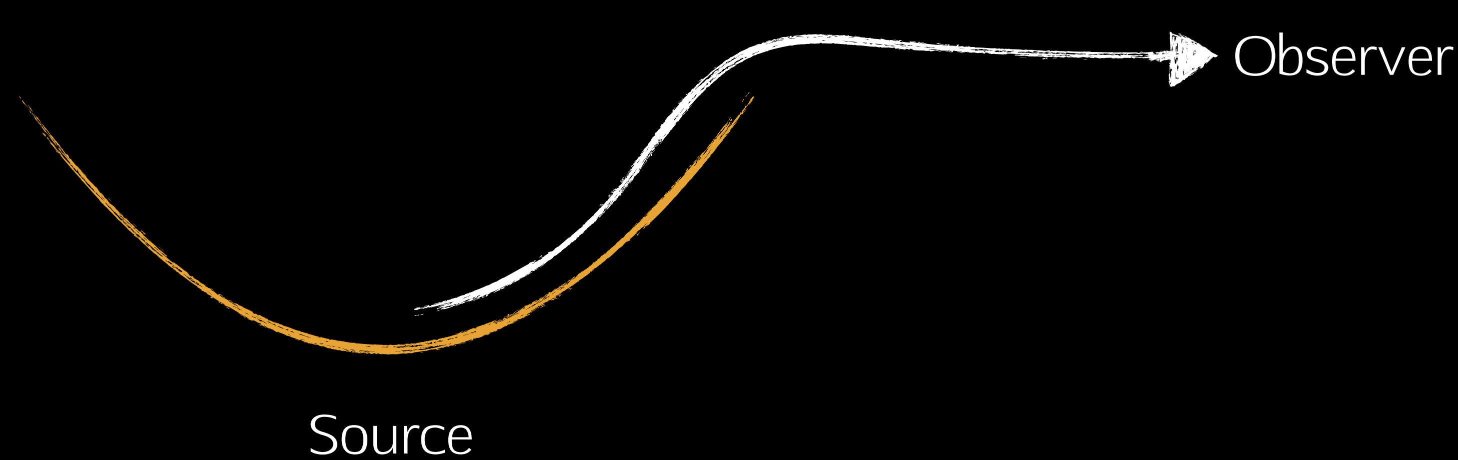

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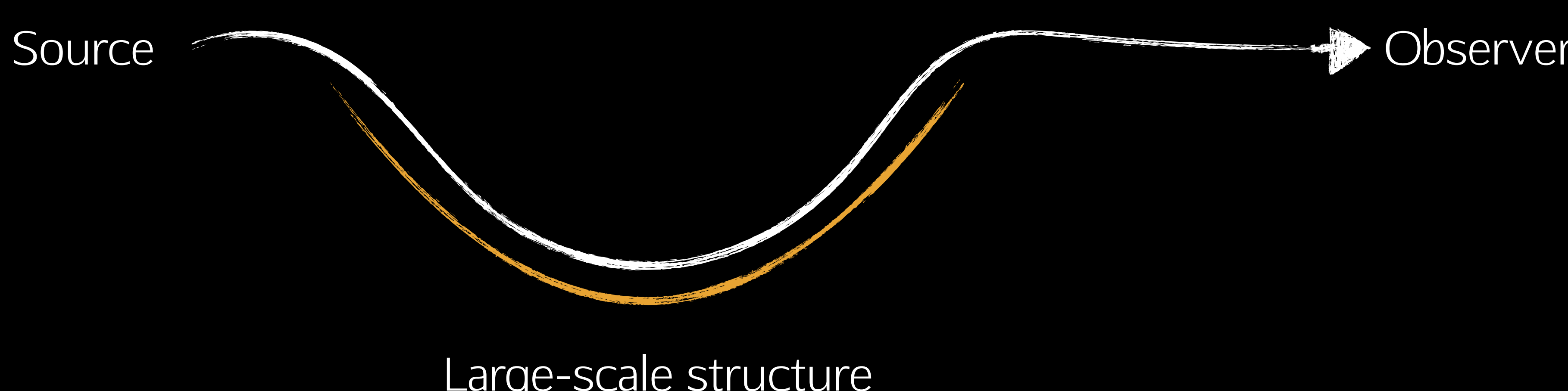

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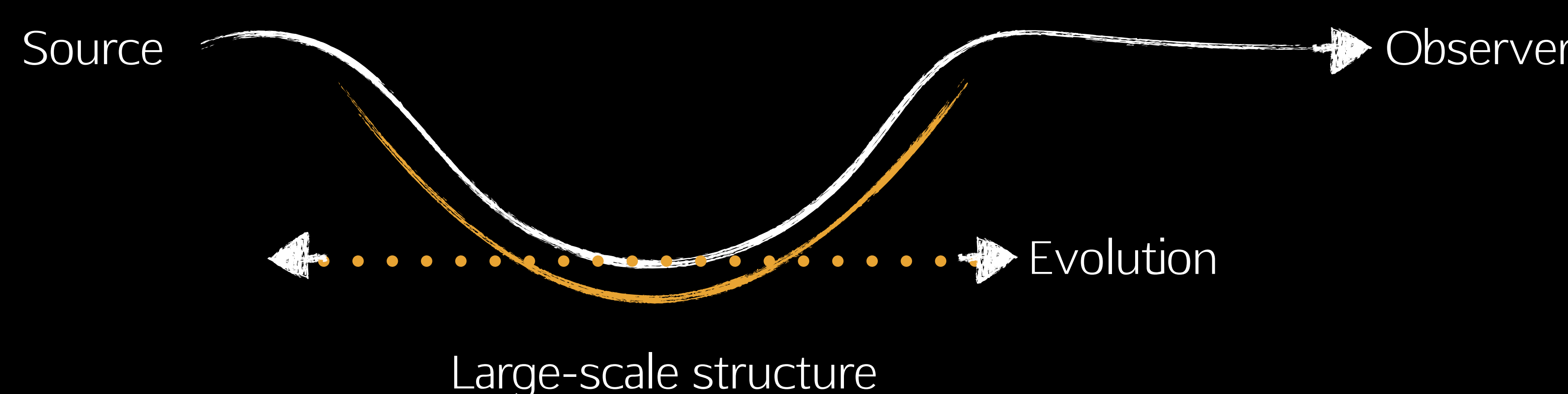

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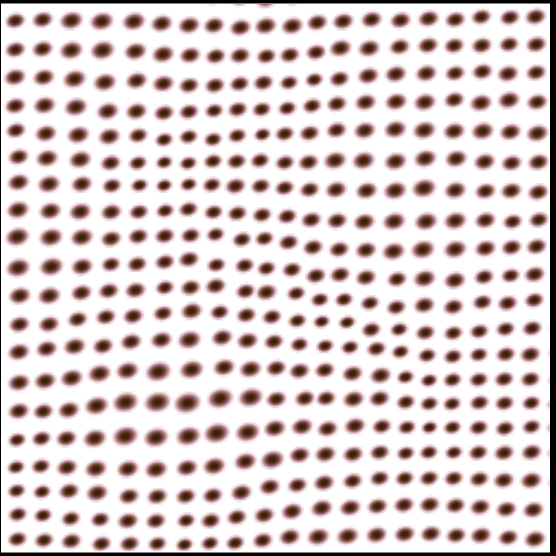
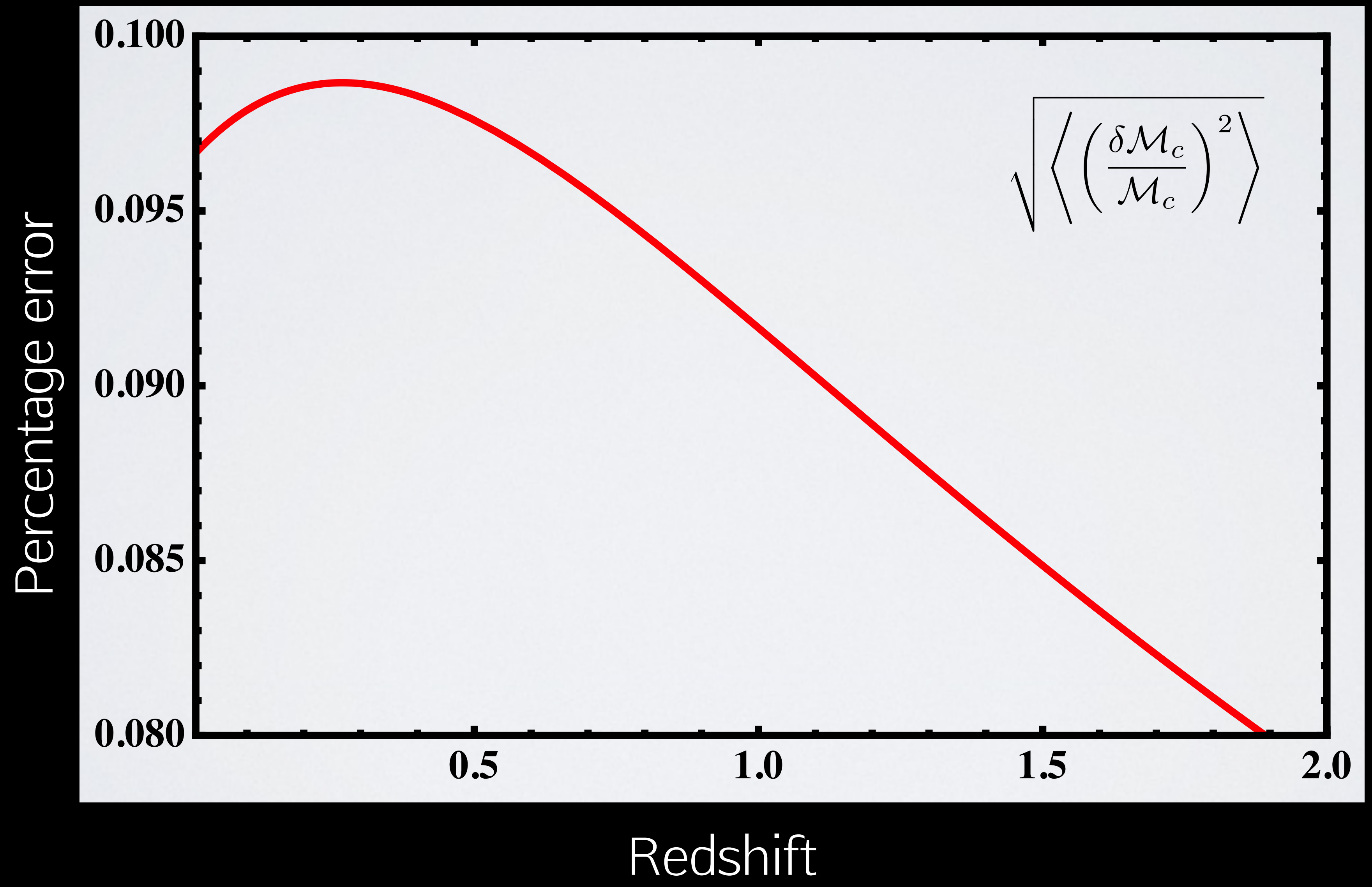


INDUCED ERRORS

$< 10^{-3}$

- Dominant error on *chirp mass* due to *velocities*

[Bonvin @ 1st eLISA CosWG WS, 2015]



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INDUCED ERRORS

- Dominant errors on *luminosity distance*
  - At *low*-redshift due to *velocities*

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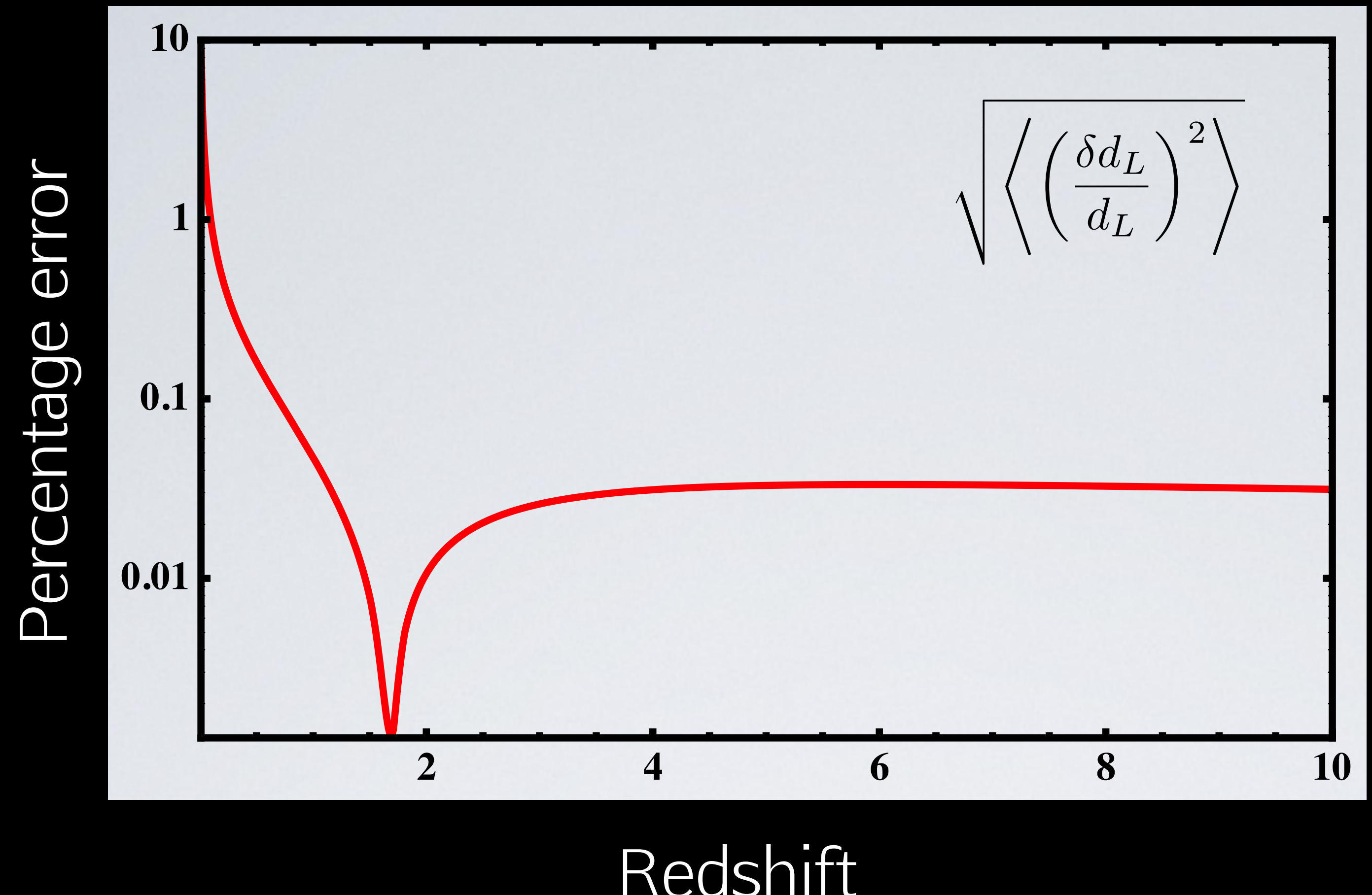

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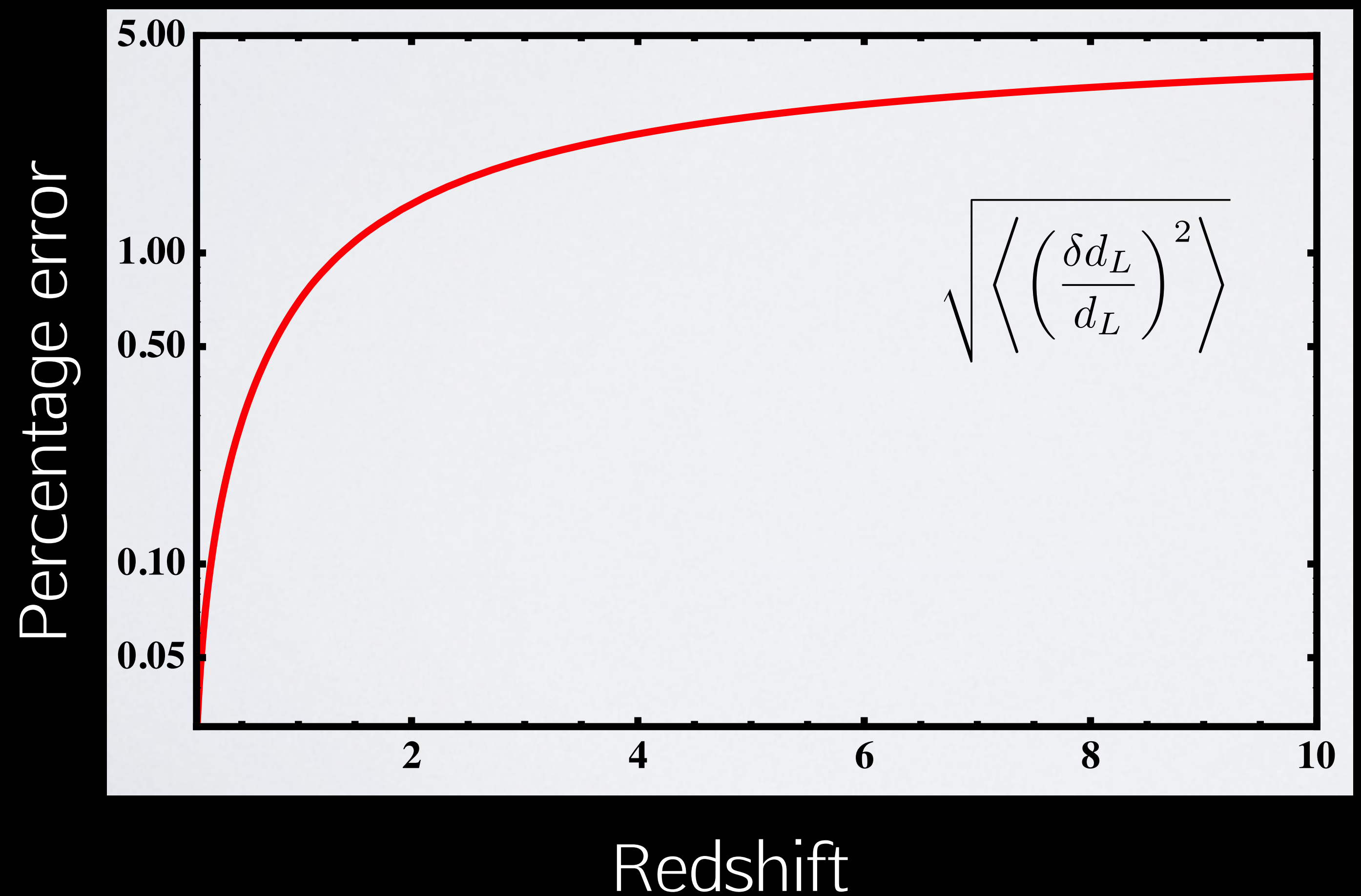
- Dominant errors on *luminosity distance*
  - At *high*-redshift due to *lensing*

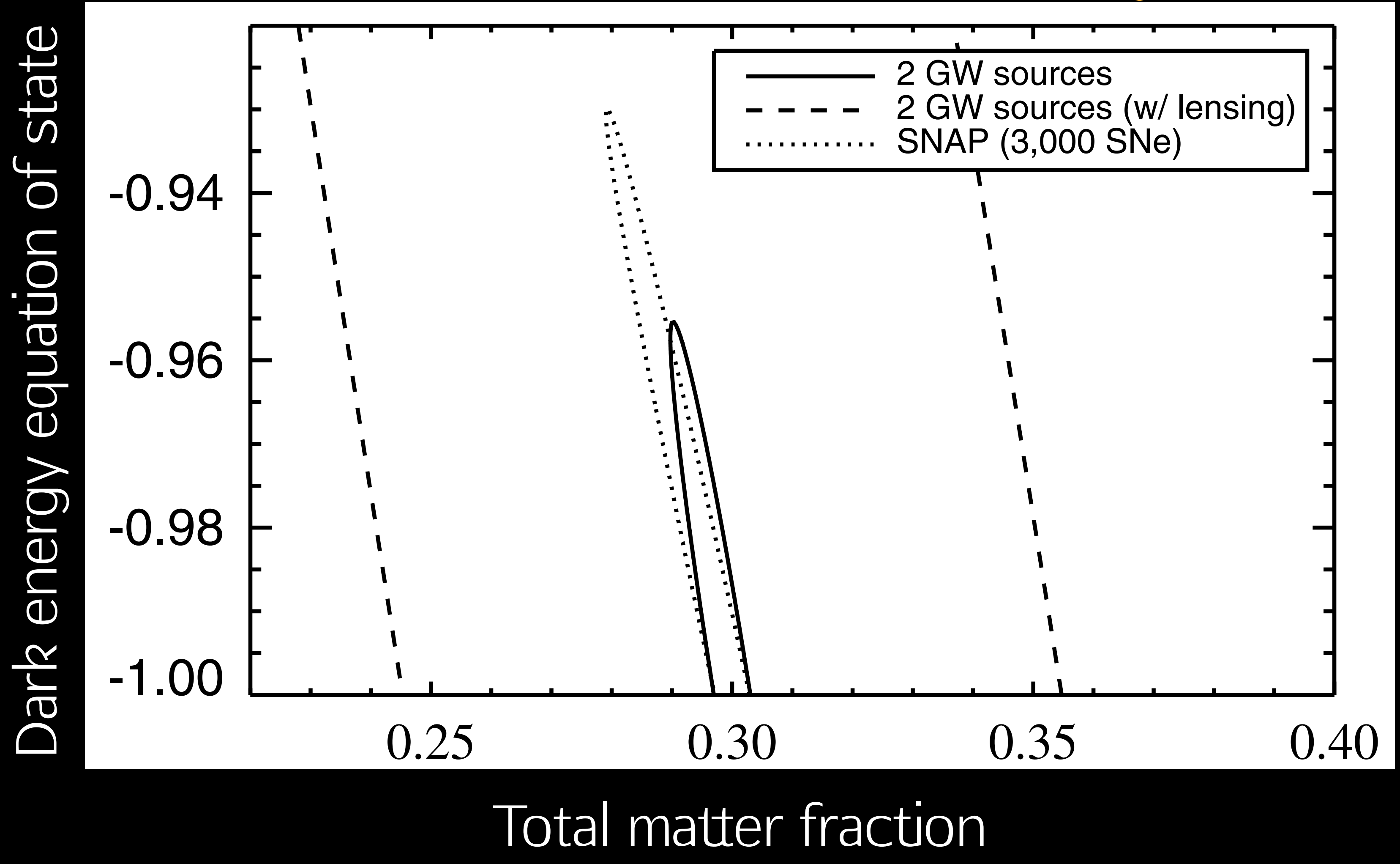
[Bonvin @ 1st eLISA CosWG WS, 2015]



LENSING PROS & CONS

- Lensing *magnification* degrades measurements of the *luminosity distance*

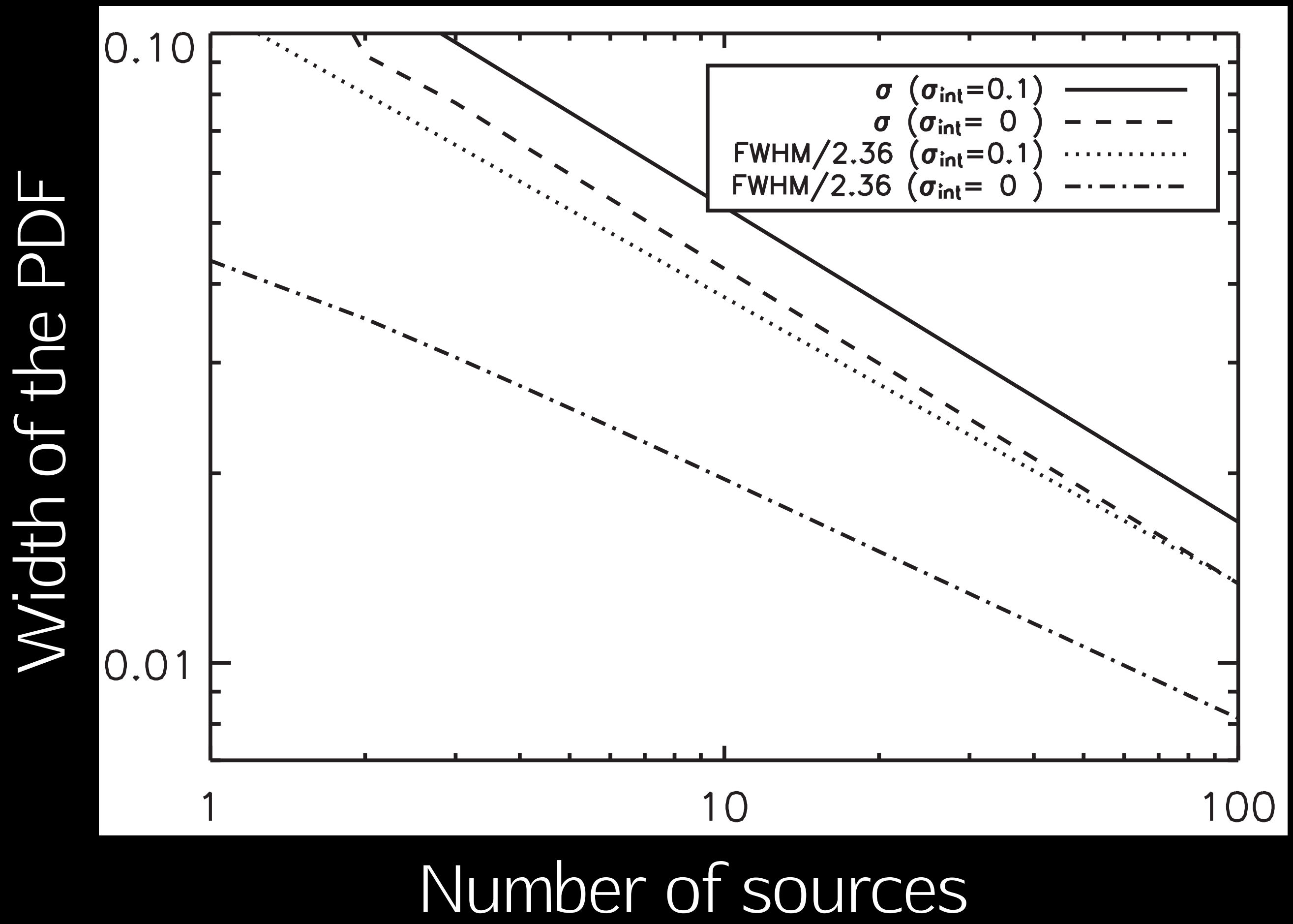
[Holz & Hughes, 2005]



LENSING PROS & CONS

- Lensing *magnification* conserves surface brightness
- For a sufficient number of sources it can be averaged out

[Holz & Linder, 2006]



LENSING PROS & CONS

- Lensing *magnification* power spectrum

$$C_\ell^\mu = 4\pi \int \mathrm{d}\ln k\,[\mathcal{W}_\ell(k)]^2 \Delta_\delta^2(k)$$

Power spectrum
of density perturbations
(depends on growth)

Weak lensing
efficiency function
(depends on geometry)

LENSING PROS & CONS

- Lensing *magnification* power spectrum

$$C_\ell^\mu = 4\pi \int \mathrm{d}\ln k \, [\mathcal{W}_\ell(k)]^2 \Delta_\delta^2(k)$$

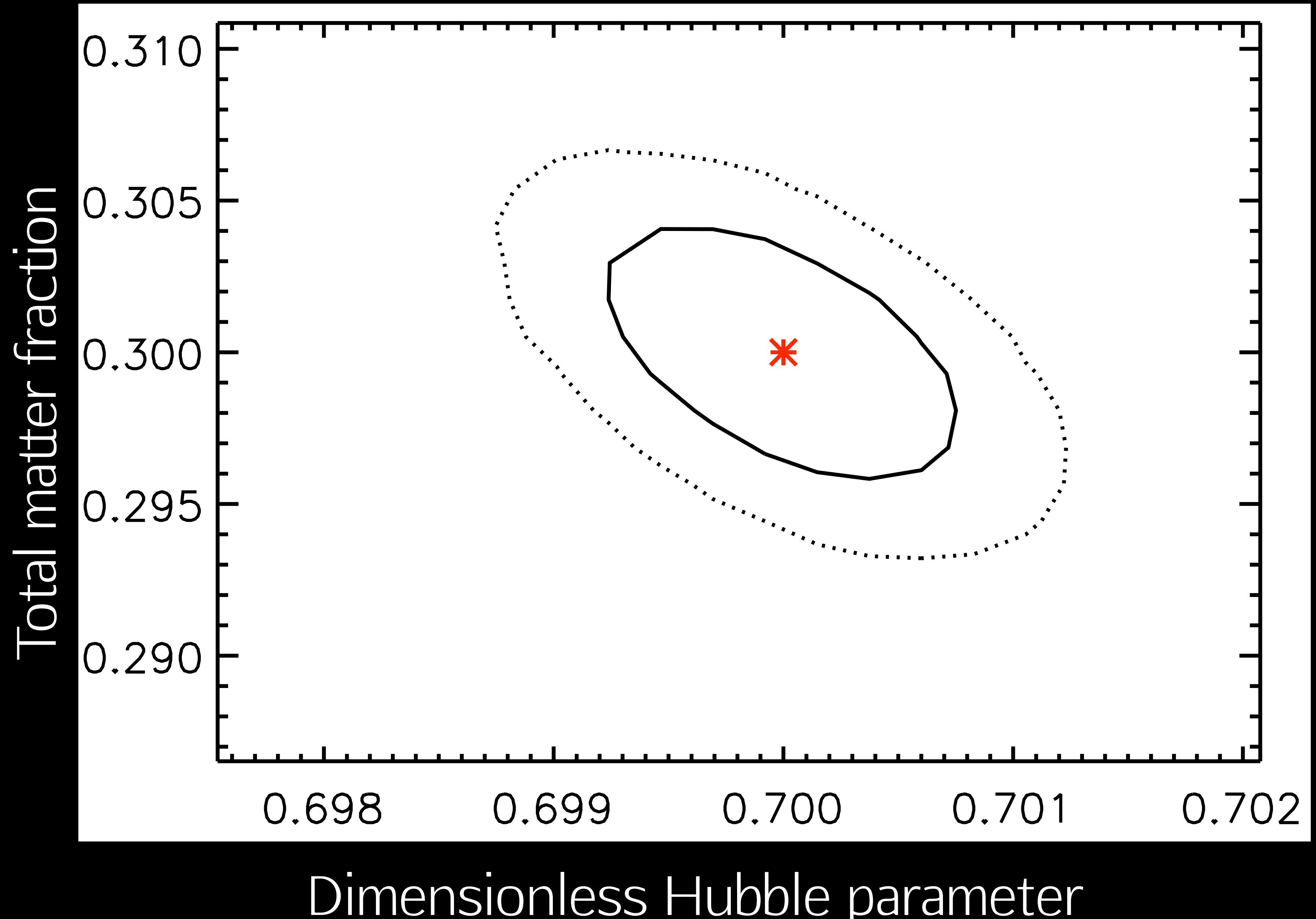
- Error on its measurement

$$\mathcal{N}^\mu \simeq \frac{1}{N_\mathrm{sources}} \left(\frac{\delta d_L}{d_L} \right)^2$$

LENSING PROS & CONS

- Lensing *magnification* power spectrum

[Cutler & Holz, 2009]



CHALLENGES & NEW HORIZONS

NO EM COUNTERPARTS

- Cosmology with GW standard sirens alone?
  - Constraining the binary source redshift range with the observed chirp mass distribution
    (Bayesian analysis of measured-vs-expected chirp mass)
    [Markovic, 1993; Chernoff & Finn, 1993]
  - Observing tidal effects on GWs
    (Appearing at 5th post-Newtonian order)
    [Messenger & Read, 2011]
  - Combining luminosity distance and cosmological phase shift
    (Large number of sources, e.g. neutron-star binaries)
    [Nishizawa *et al.*, 2012]

NO EM COUNTERPARTS

- *Bayesian analysis* of the chirp mass distribution
  - Assume a constant chirp mass and extract candidate source redshifts by comparing with a redshifted chirp mass
  - Large number of detections: 3rd-generation GW detectors!

[Taylor, Gair & Mandel, 2011]

$$\frac{\Delta H_0}{H_0} \simeq 10\%$$

NO EM COUNTERPARTS

- *Tidal effects* on GWs
  - Waveform phase from orbital evolution

$$\Phi = \Phi_{\rm PPN} + \Phi_{\rm tidal}$$

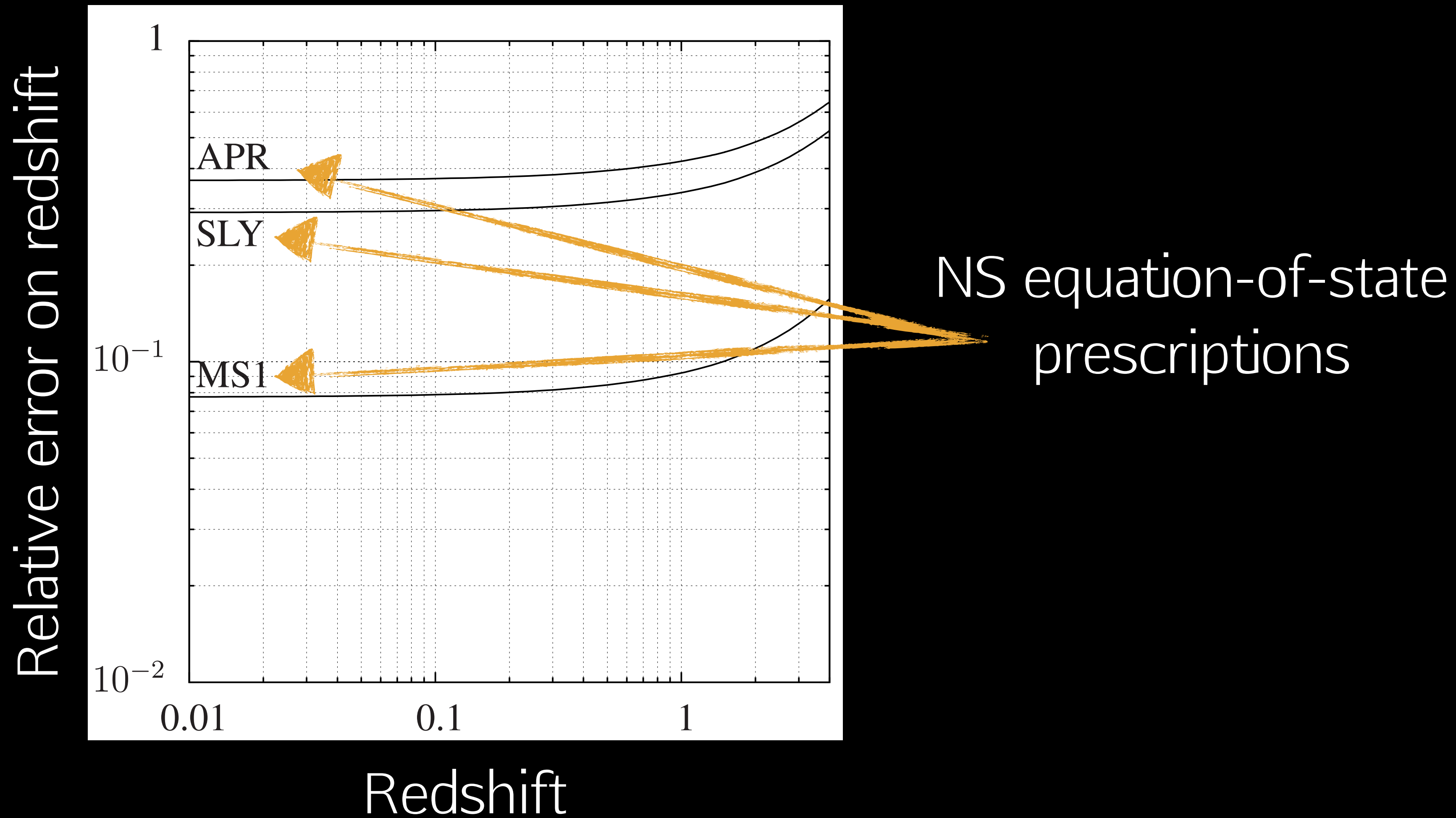
Standard 1st-order post-Newtonian

5th-order post-Newtonian tidal contributions

NO EM COUNTERPARTS

- *Tidal effects* on GWs
  - Assumes a (perfect) knowledge of NS equation of state

[Messenger & Read, 2011]



NO EM COUNTERPARTS

- Luminosity distance and *cosmological phase shift*
  - Waveform phase from orbital evolution

$$\Phi\left[f, \mathcal{M}_z, t_c, \phi_c, X(z)\right]$$

Time and phase at coalescence

Correction due to cosmic evolution

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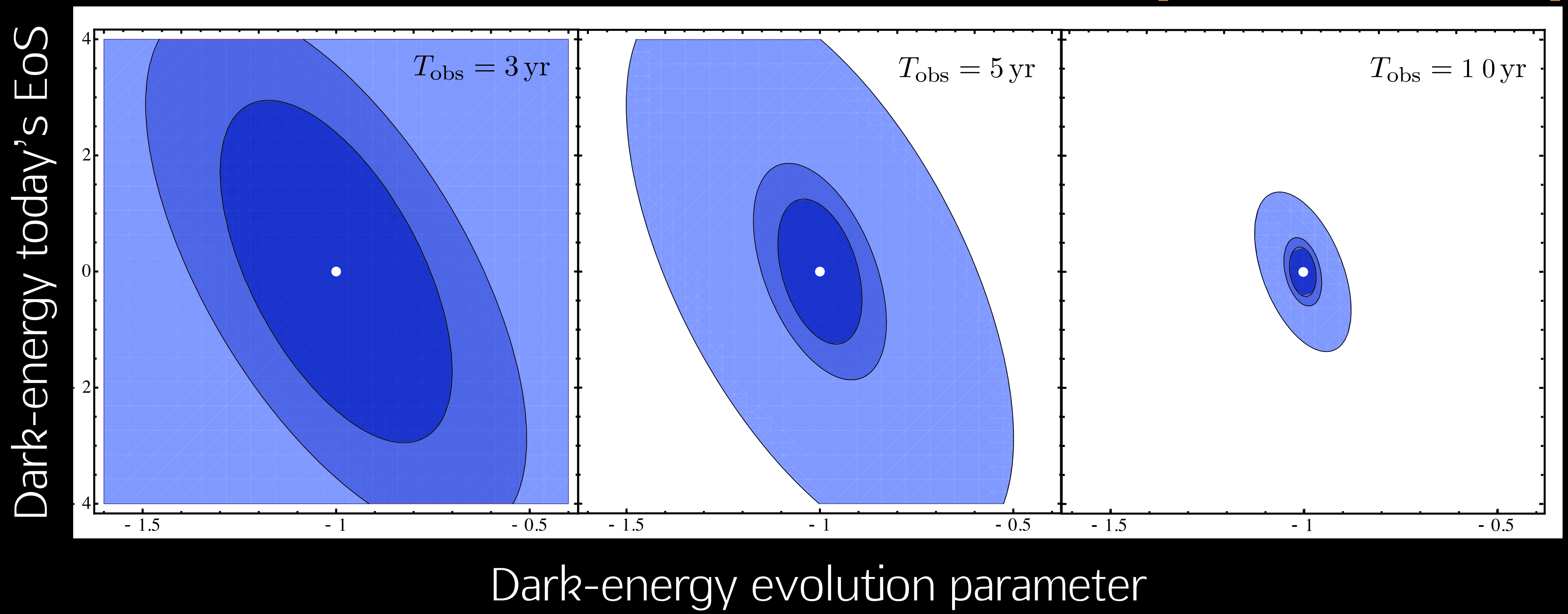
NO EM COUNTERPARTS

- Luminosity distance and *cosmological phase shift*
    - Constraints on dark energy equation of state

[Nishizawa *et al.*, 2012]



DE-LENSING

- Removing lensing-induced distance uncertainty by estimating magnification through *shear & flexion maps*

[Shapiro *et al.*, 2010; Hilbert, Gair & King, 2011]

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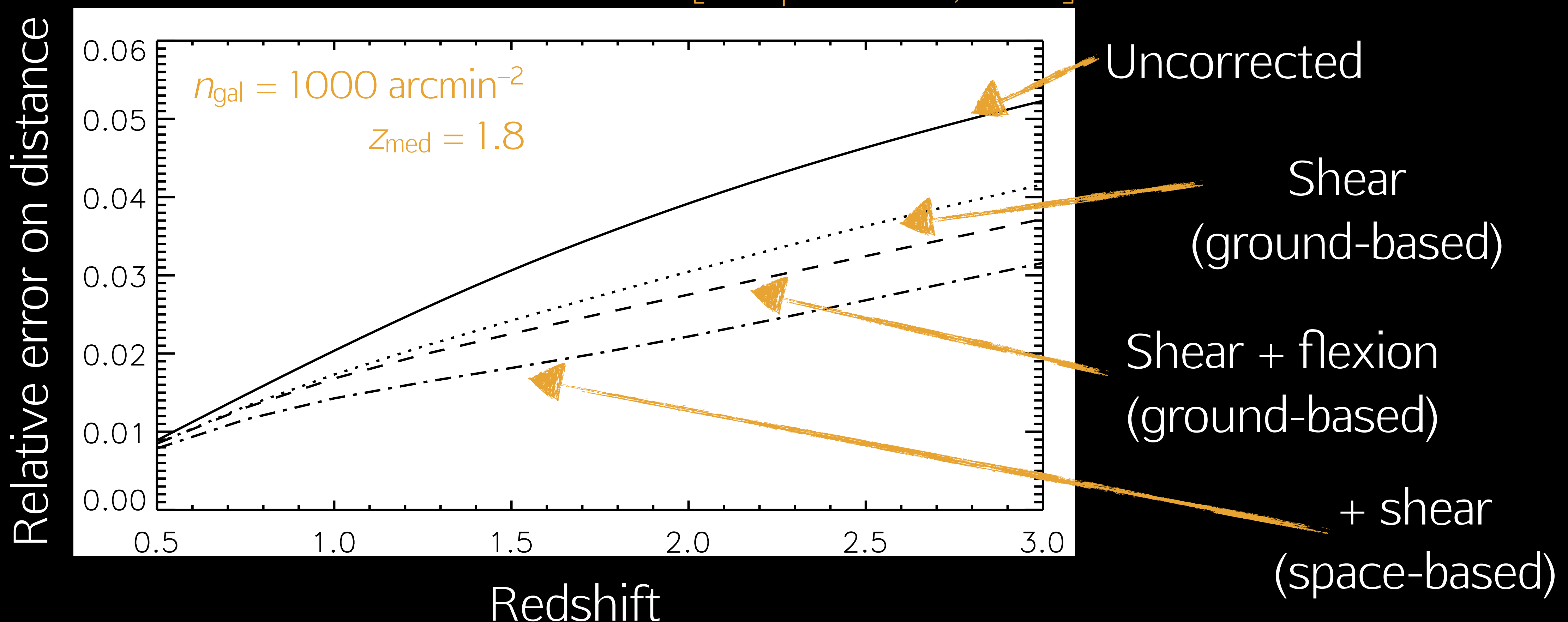

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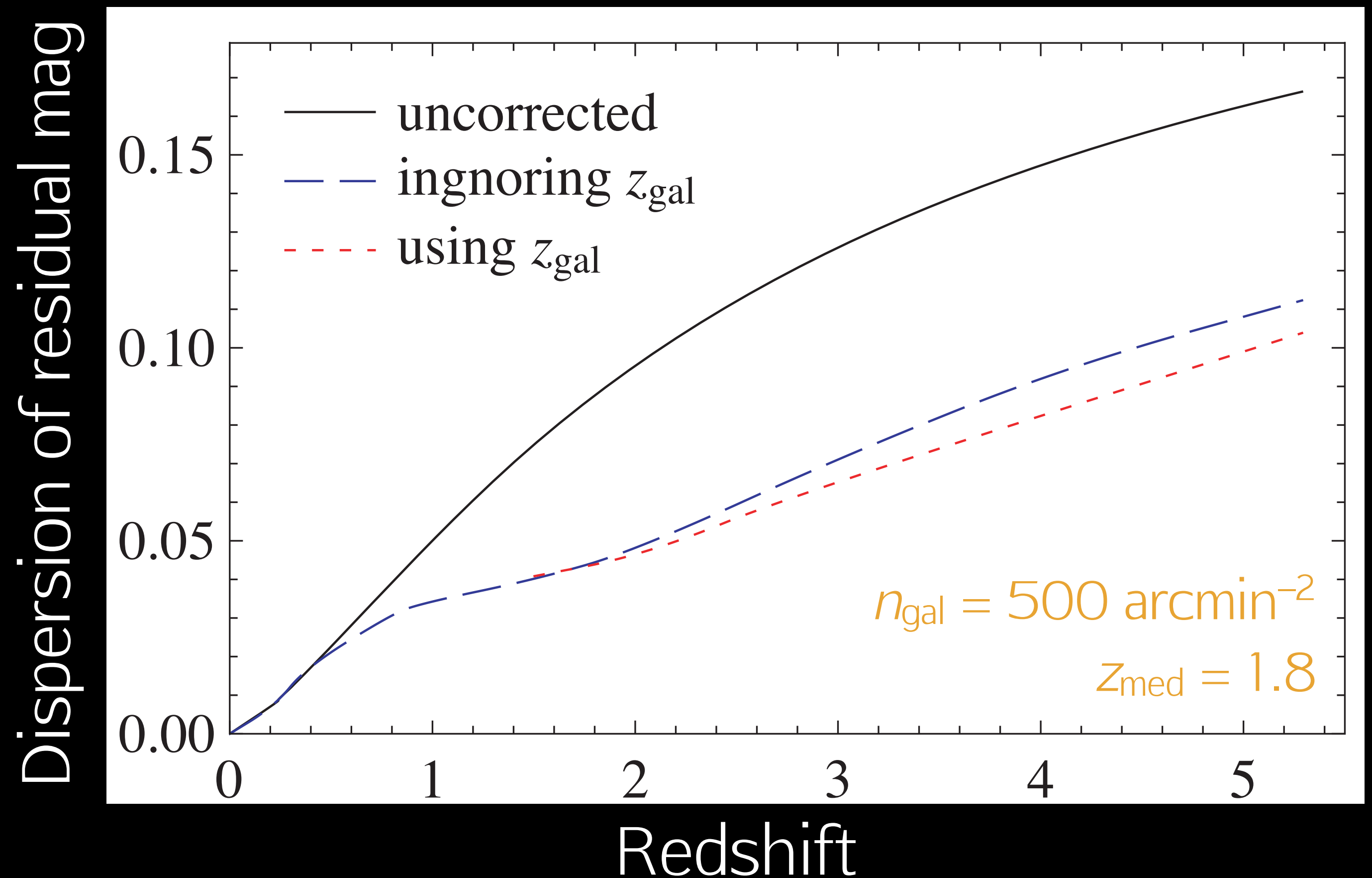

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BEYOND ΛCDM COSMOLOGY

- Use magnification angular power spectrum to detect deviations from concordance ΛCDM cosmology
    - *Dynamical dark energy*

[Chevallier & Polarski, 2001; Linder, 2003]

$$w_{\mathrm{DE}}(z) = w_0 + \frac{z}{1+z} w_a$$

- *Modified gravity*

[Zhao *et al.*, 2010]

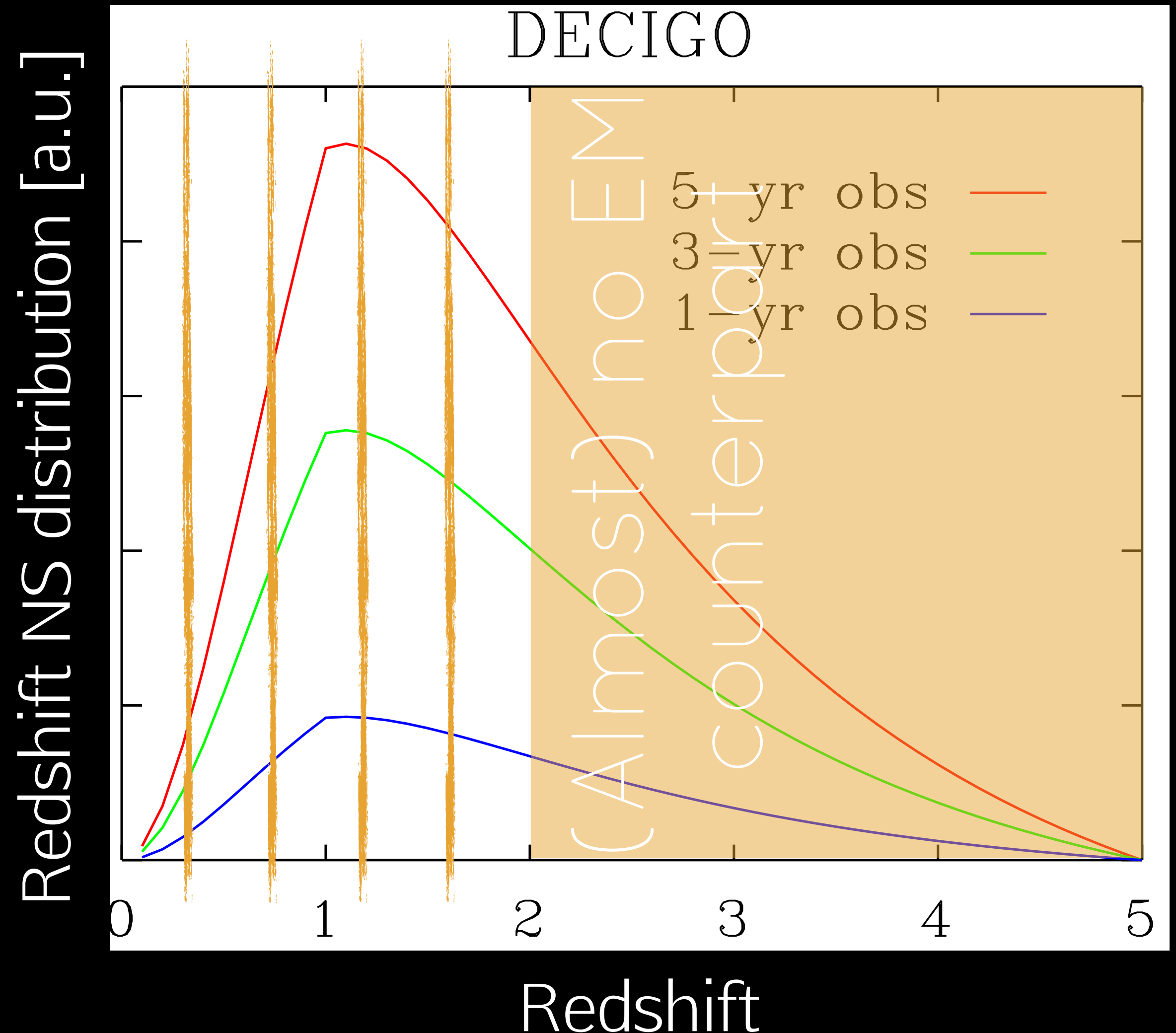
$$\nabla^2 \Phi = 4\pi G a^2 \rho \delta \mu(k, z)$$

$$\Psi = \Phi \eta(k, z)$$

BEYOND ΛCDM COSMOLOGY

- Implementation of *redshift tomography* for the magnification angular power spectrum

[Camera & Nishizawa, 2013]



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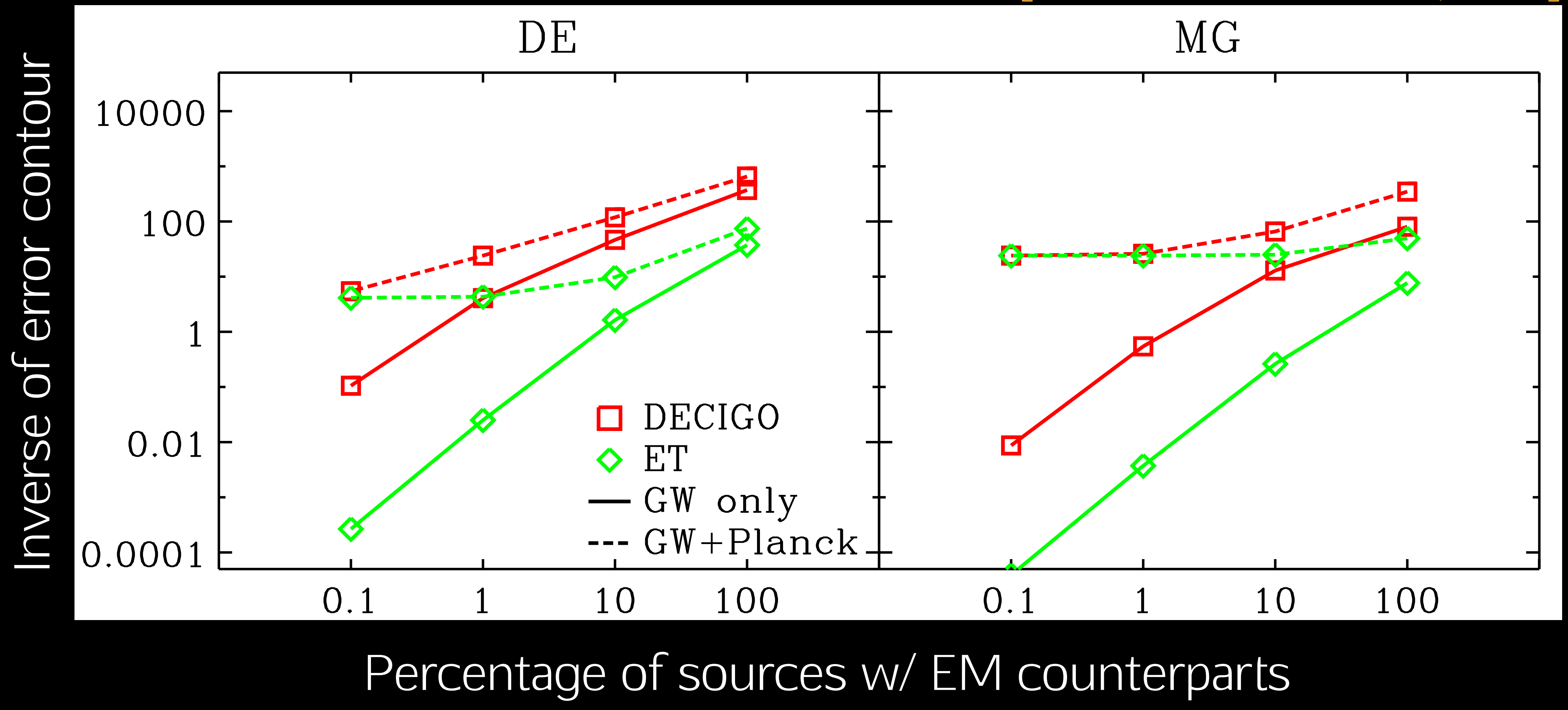

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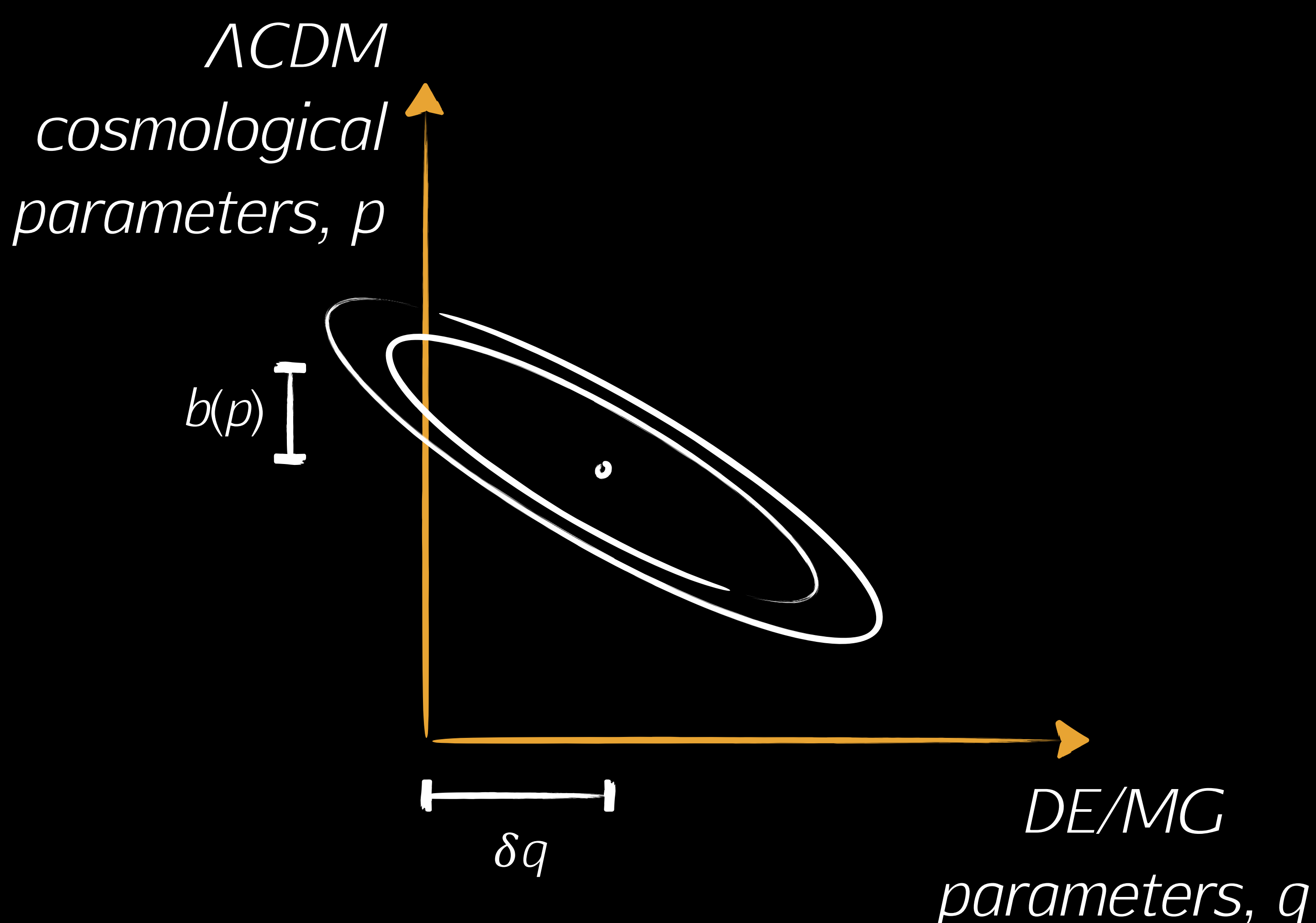
BEYOND ΛCDM COSMOLOGY

- Computation of the *Bayes factor* for eLISA &c.



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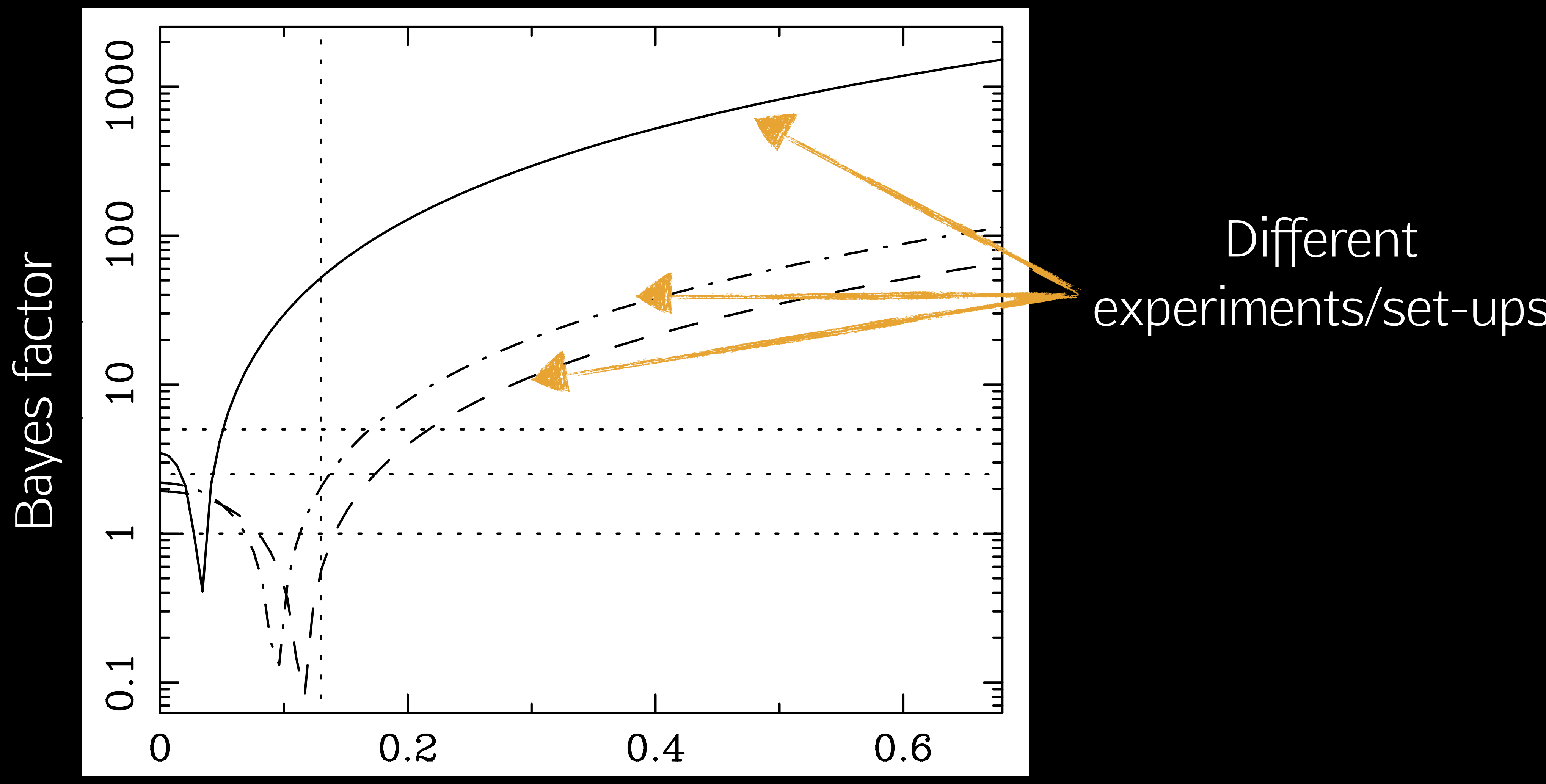

Shift in DE/MG extra-parameters

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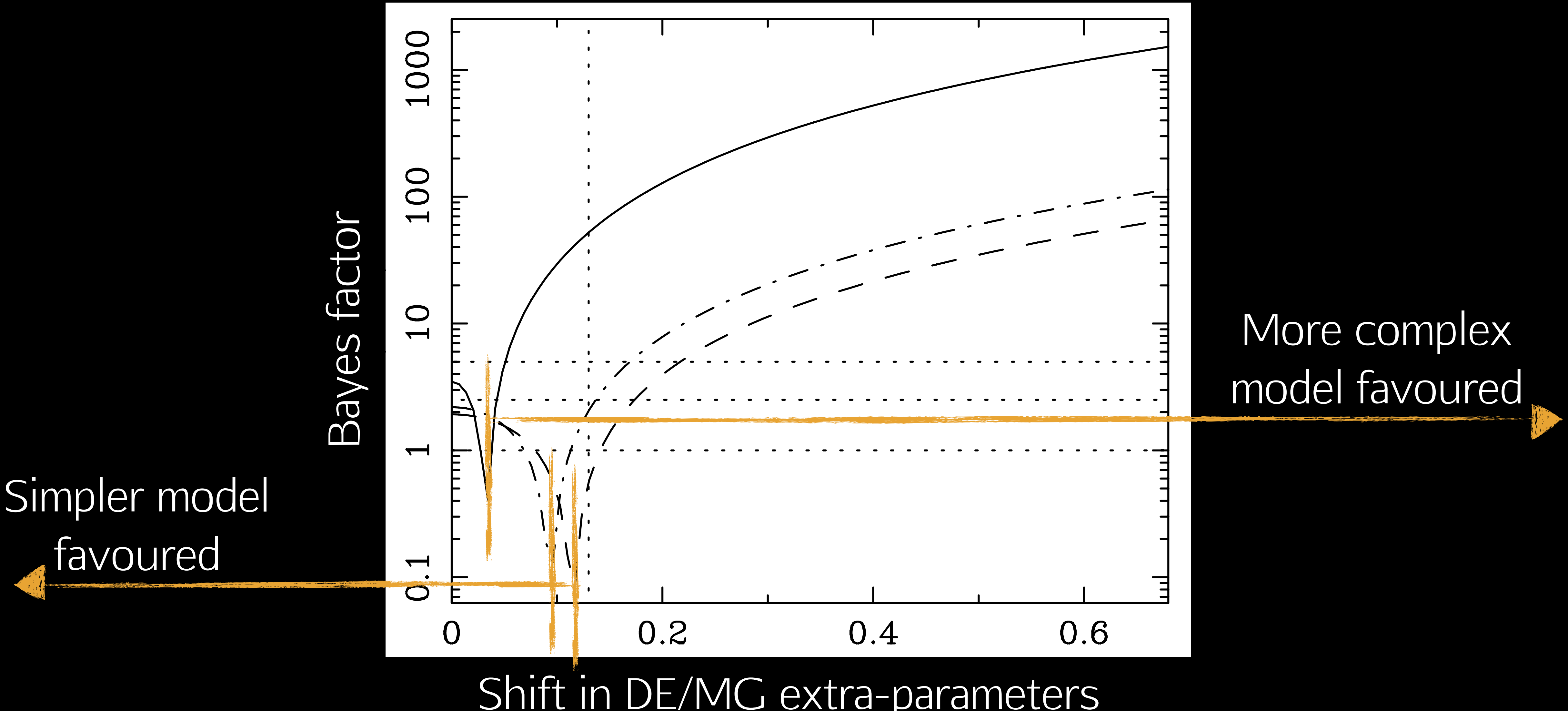

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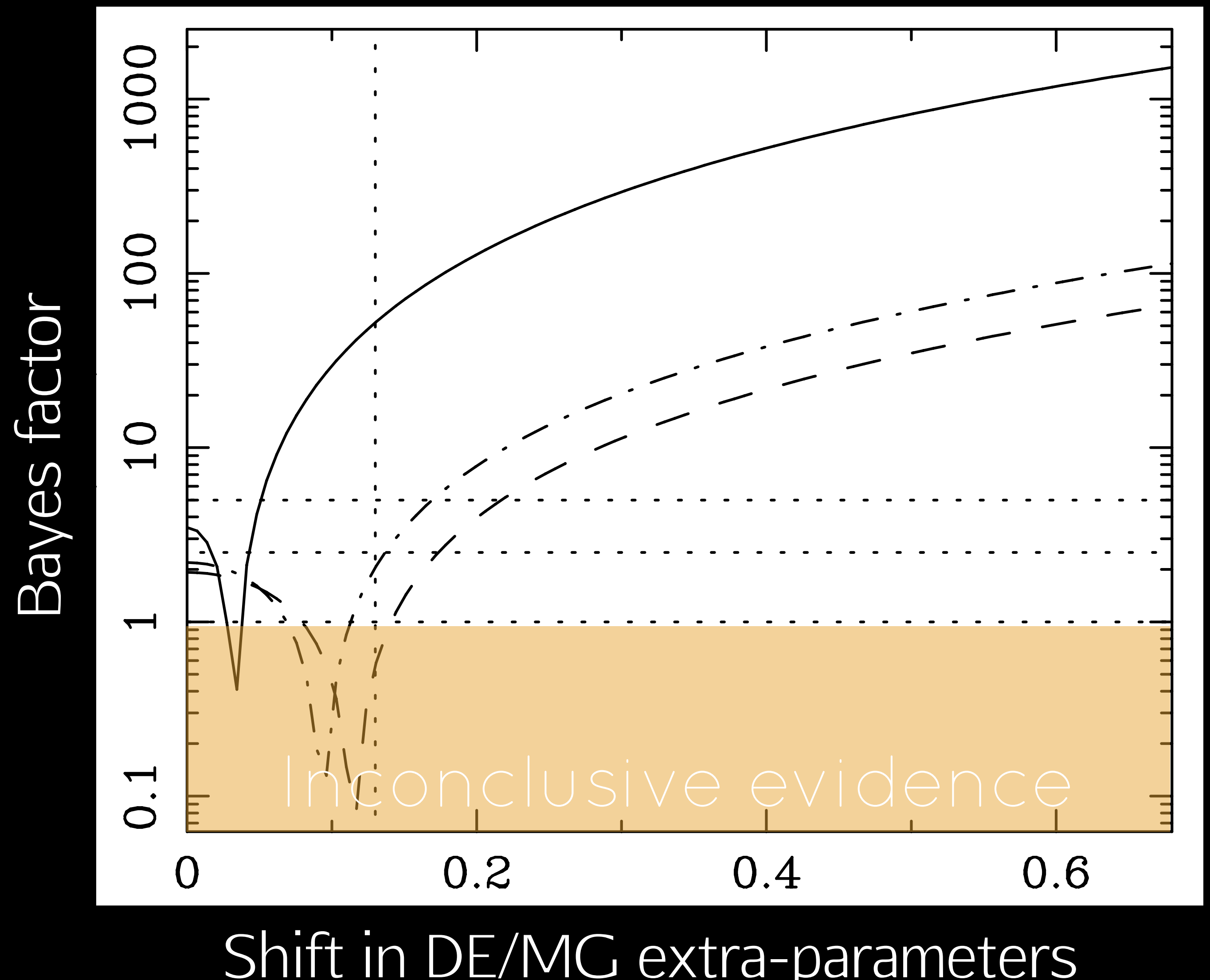

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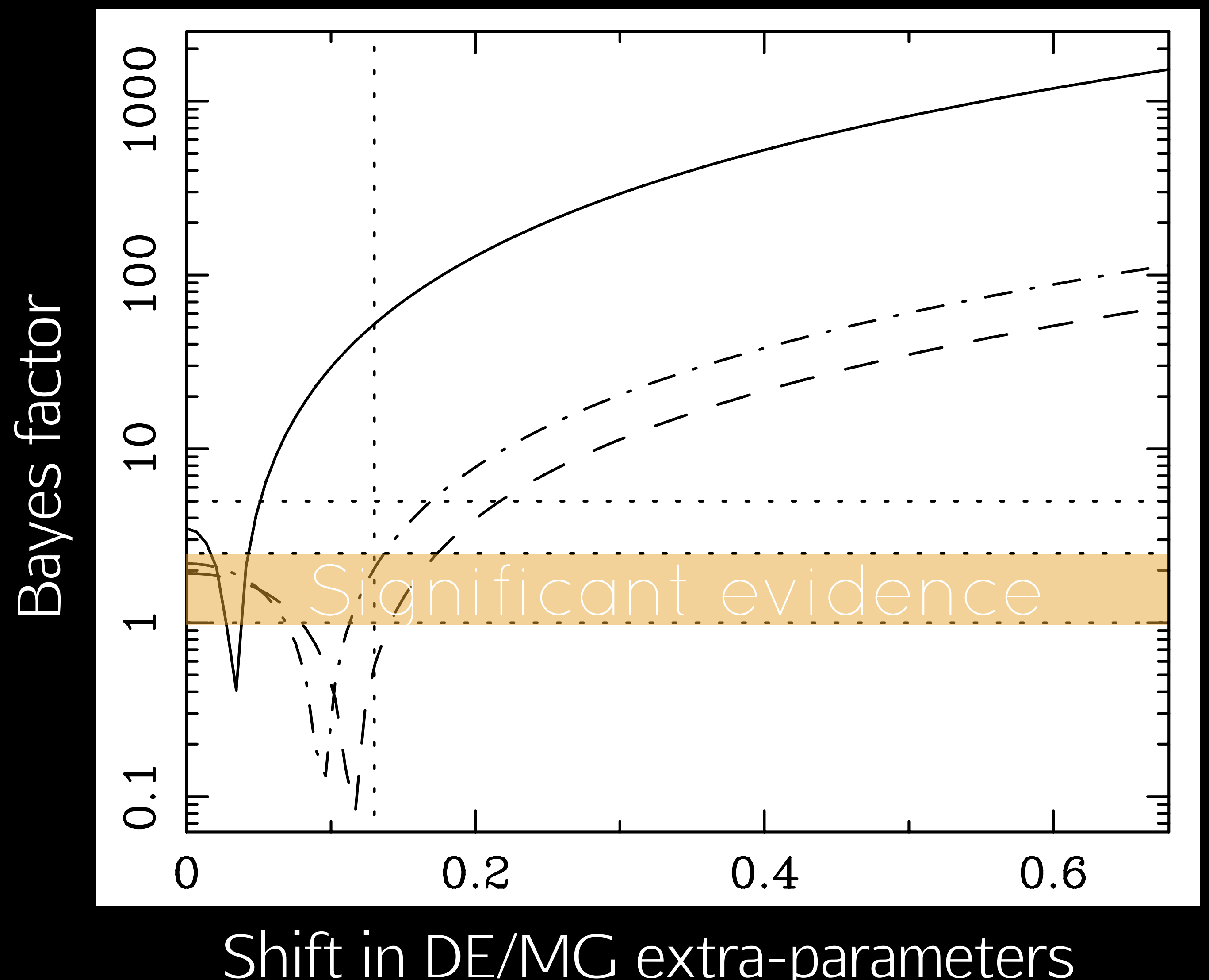

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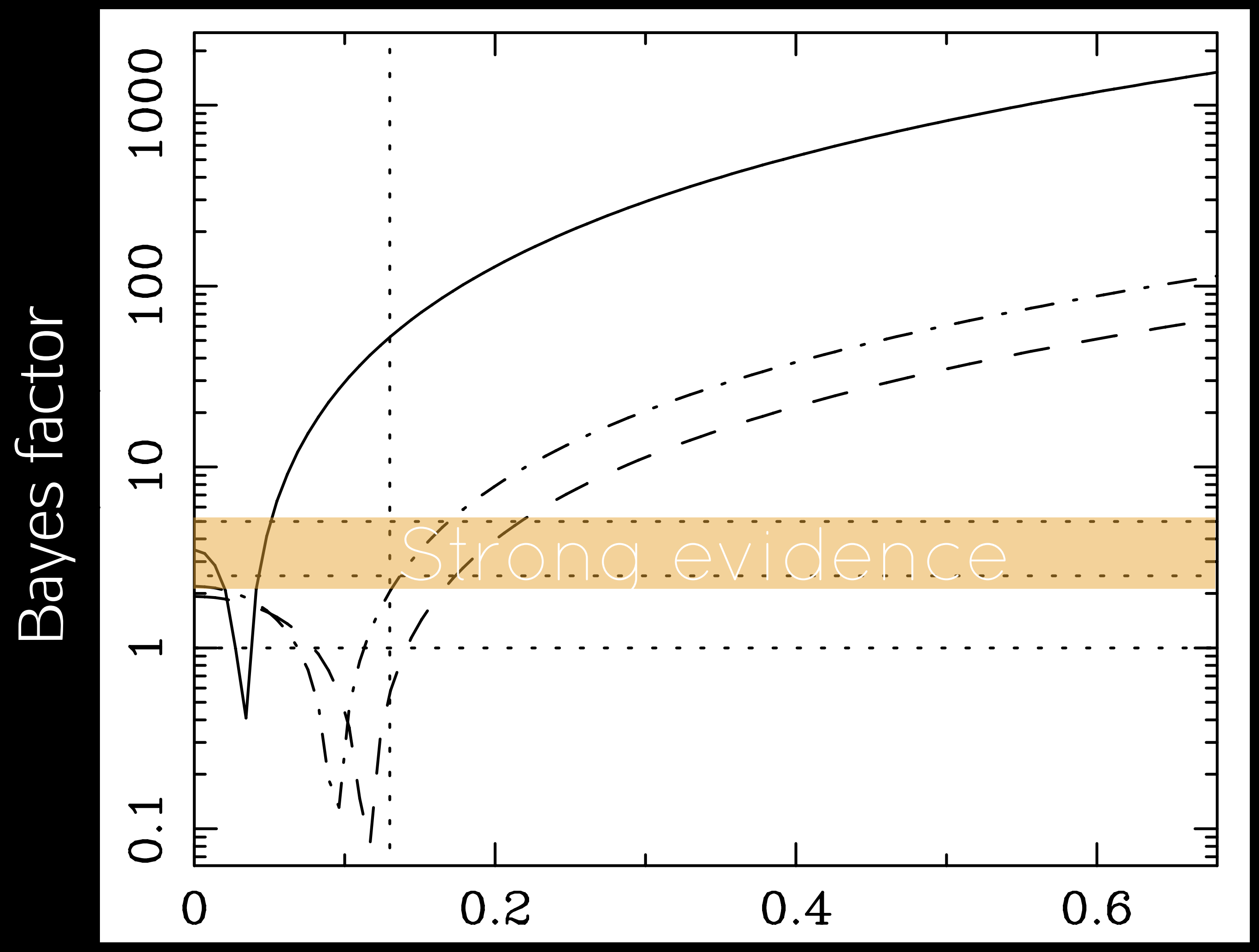

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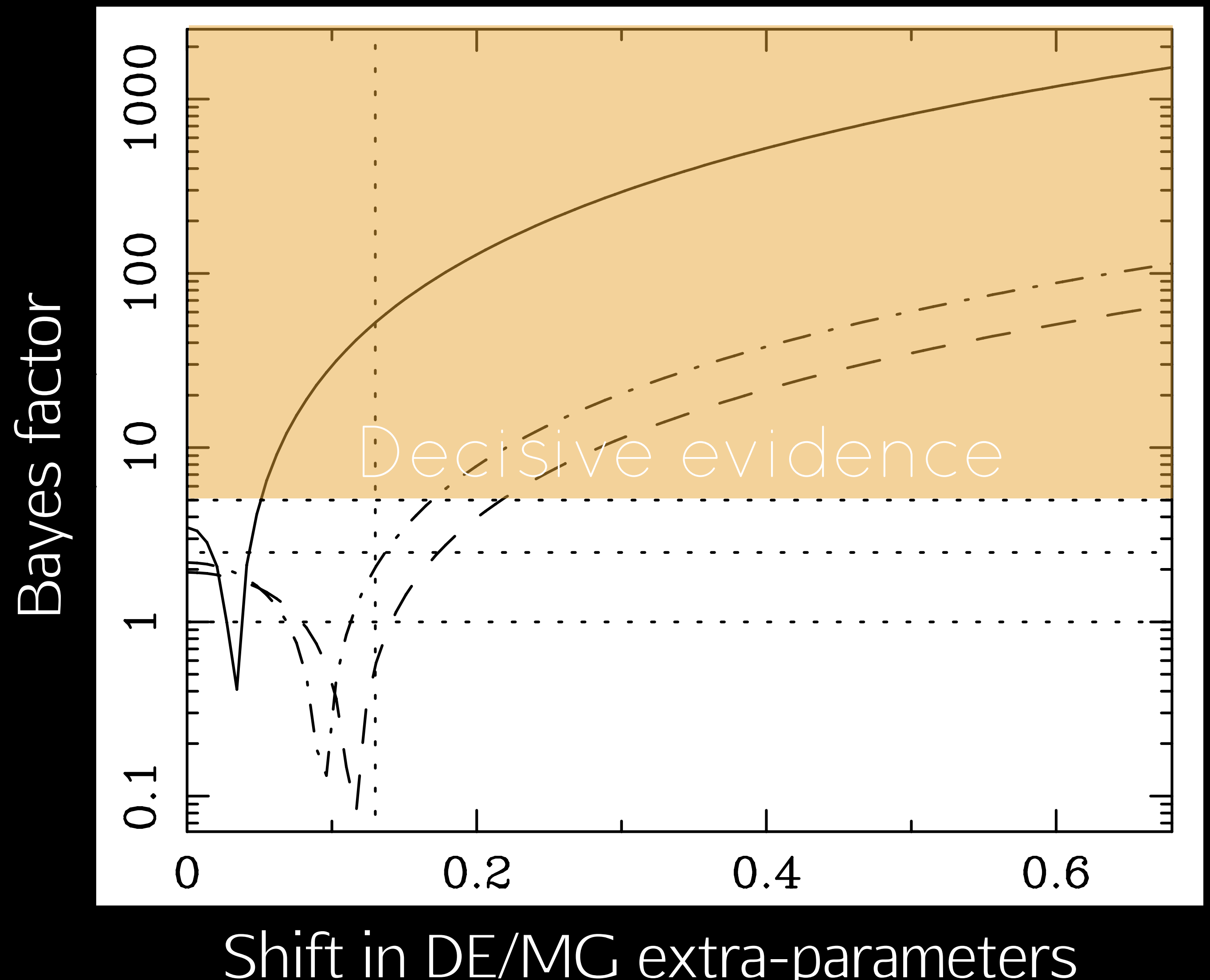

SUMMARY

- *Binary in-spirals can be used as GW standard sirens*
  - BH in-spirals best modelled and theoretically understood
  - NS mergers provide larger source samples
- *Gravity is 'scale free'*
  - Need to identify EM counterparts to infer source redshifts
  - Promising new approaches

SUMMARY

- *Perturbations along the l.o.s. degrade distance measurements*
  - Lensing magnification is the main contaminant
    - Need large number of sources to average lensing out
    - Combine magnification with shear/flexion maps to de-lens standard sirens
    - Magnification power spectrum powerful probe of the growth of structures
    - Potential for GW standard sirens to test alternative cosmologies!

THANK YOU!