Searching for Inflationary Gravitational Waves with Large-Scale Structure

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with
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Motivation

- Gravitational waves (tensor modes) are a unique window into the early universe:
  - Inflation
  - Phase transitions
  - Potential signatures of quantum gravity
- Once generated, they essentially propagate unperturbed towards us
  - exceptionally "clean" probe

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Gravitational waves from inflation

- Detecting primordial gravitational waves: *decisive probe of inflation*

$$k^3 P_t(k) = \frac{2}{\pi^2} \frac{H^2}{M_{\rm Pl}^2}\Big|_{k=aH}$$

- Amplitude of GW is set only by expansion rate during inflation, and $H^2 \propto V(\phi)$
- Thus, we can use it to measure the *energy scale of inflation* (anywhere from 10^3 to 10^{19} GeV)

Searching for GW

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- Let us classify observables by their behavior under *rotation on the sky*:
    - Spin 0 ("2-scalar"): density, temperature, ...
    - Spin 1 ("2-vector"): "arrow" on the sky
    - Spin 2: polarization; galaxy shapes

Searching for GW

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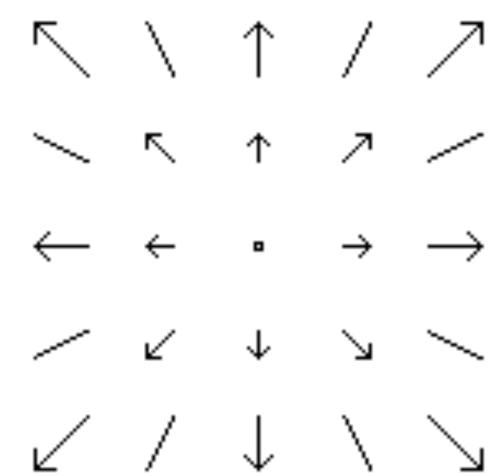
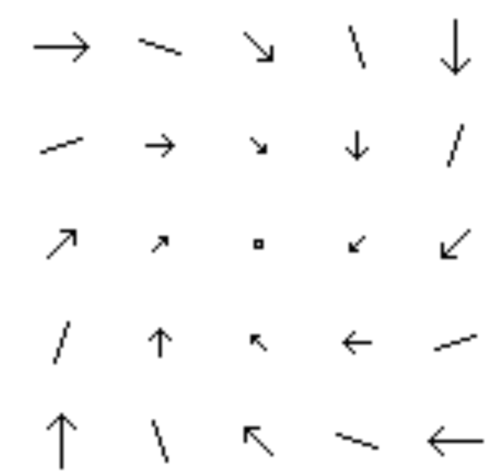
- Vector and tensor observables do: via E/B decomposition
- E (gradient) type: *even parity, scalar perturbations contribute*
- B (curl) type: *odd parity, no scalar contribution*

Spin 1:



E



B

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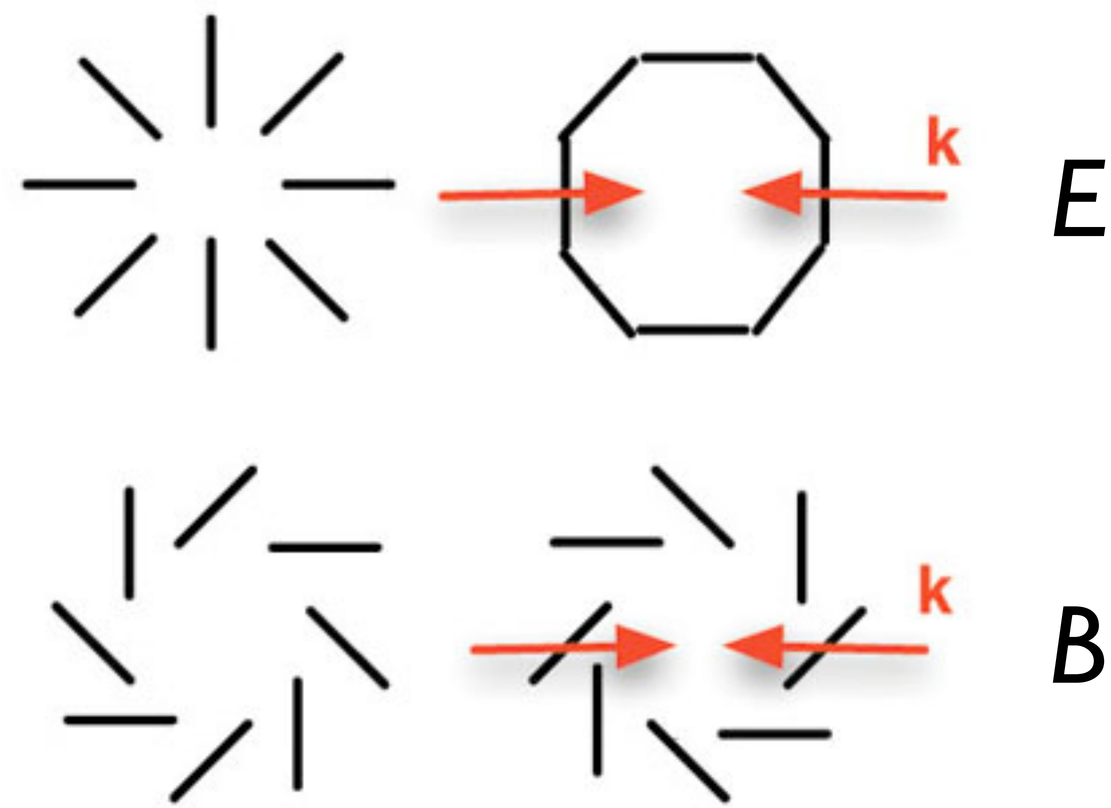

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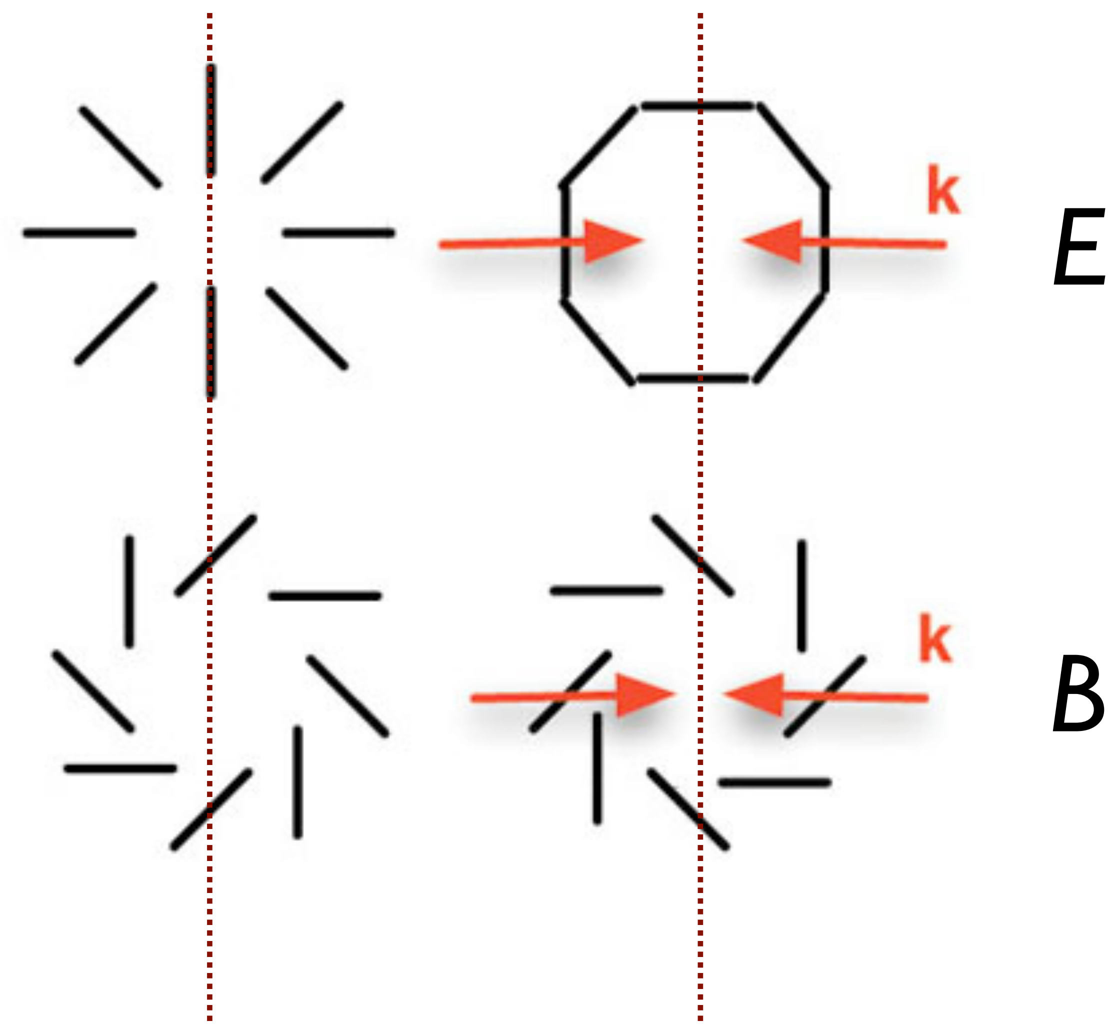

Searching for GW

- Reason: tensor modes have two polarization states
    - If one state generates P-even pattern, the other will generate P-odd

- Density perturbations on the other hand can create only one type of pattern

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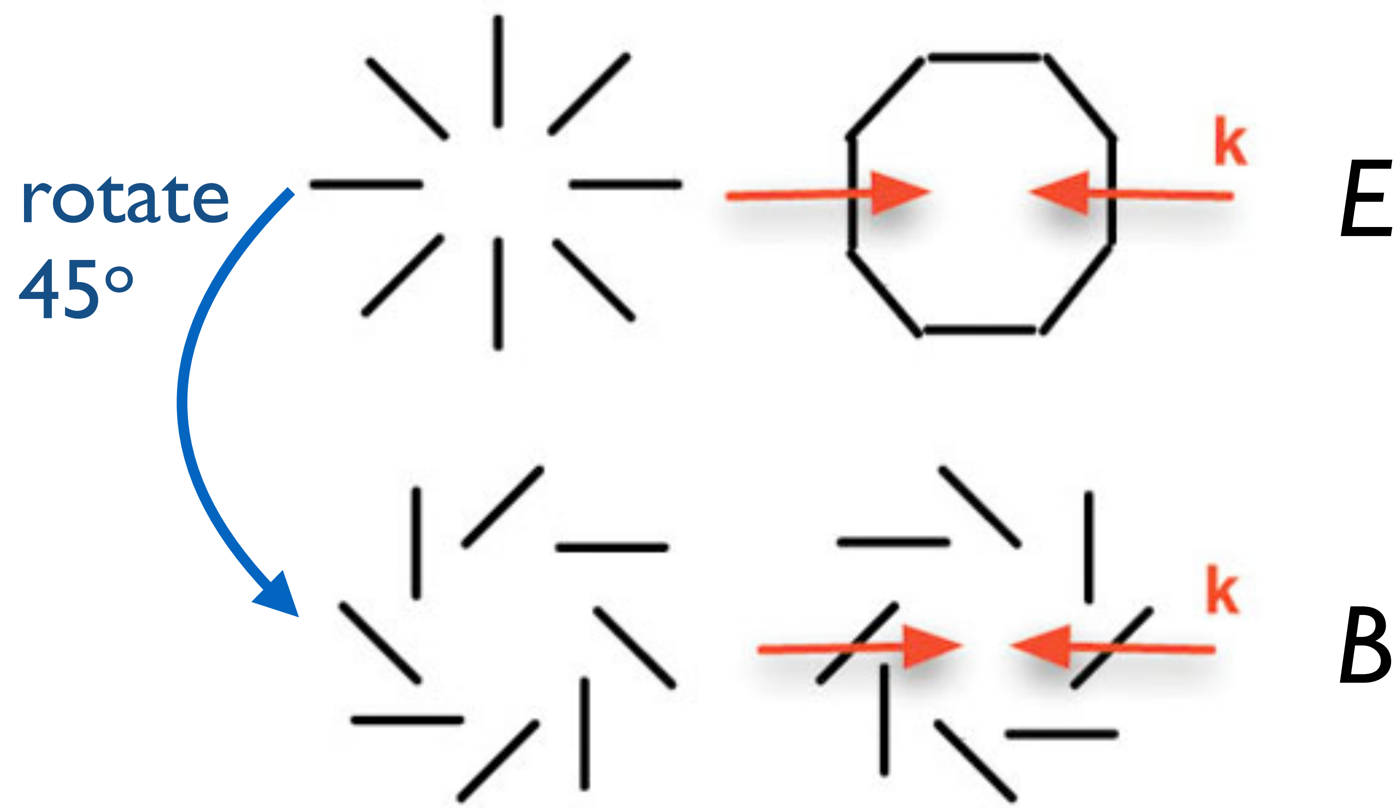
(galaxy shapes, polarization)



Can we independently confirm CMB detection of tensor modes ?

- Dust contamination is clearly an issue for CMB measurements - it will only get more difficult when pushing sensitivity to lower values
- Are there any observables in the large-scale structure that can probe gravitational waves ?
  - *Cross-correlation LSS-CMB* should be exceptionally clean
  - We want a spin-1 or spin-2 observable

Galaxy shape correlations

- Large-scale imaging surveys (DES, HSC, Euclid, LSST) will measure shapes for billions of galaxies
- The shape (ellipticity) of a galaxy is a spin-2 observable, like polarization
- Intrinsic galaxy shapes are weakly correlated over large distances; apparent correlations are (mostly) due to gravitational lensing

Gravitational lensing by tensor modes

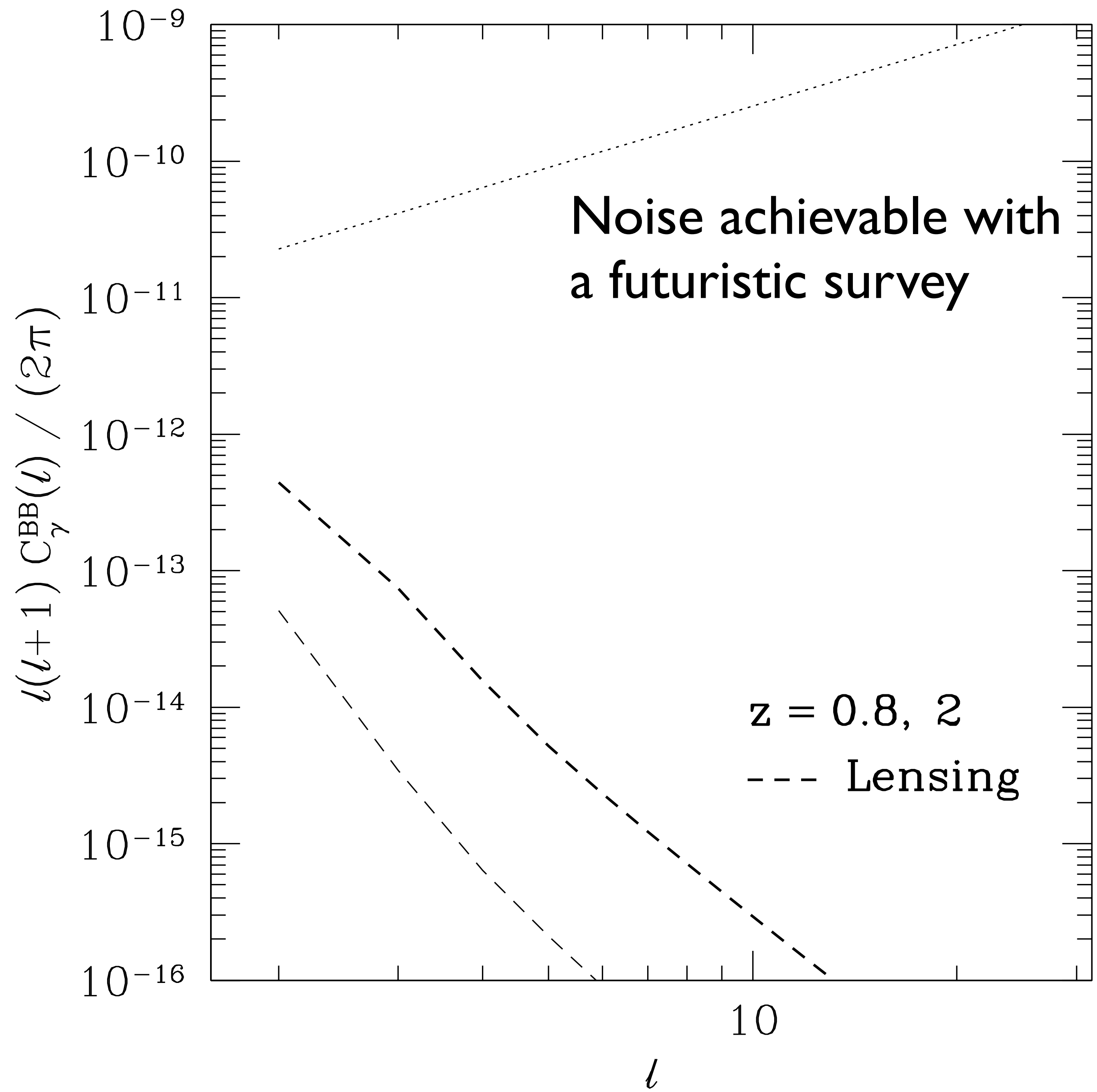
- The most well-known contribution to galaxy shape correlations is *gravitational lensing (shear)*

- GW transverse to the line of sight contribute to shear

Dodelson, Rozo, Stebbins 2003
FS, Jeong, 2012b

Gravitational lensing by tensor modes

- The signal, unfortunately, is *very* small
- Too small…



Dodelson, Rozo, Stebbins 2003
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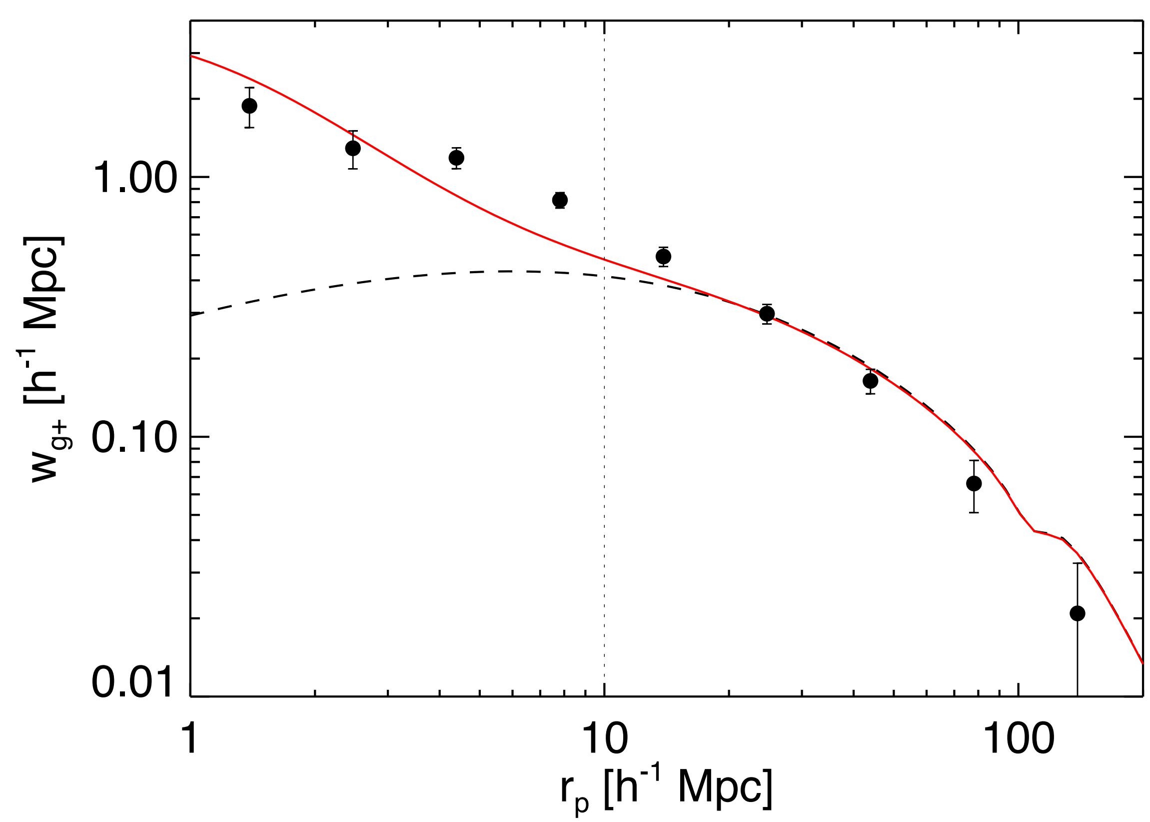
Tidal alignment contribution to galaxy shape correlations

- Tidal alignments known to be typically smaller than lensing signal for scalar perturbations
- What about tensor modes ? Do they produce tidal alignment ?
- *Very difficult problem:* impact of horizon-scale modes on nonlinear structure

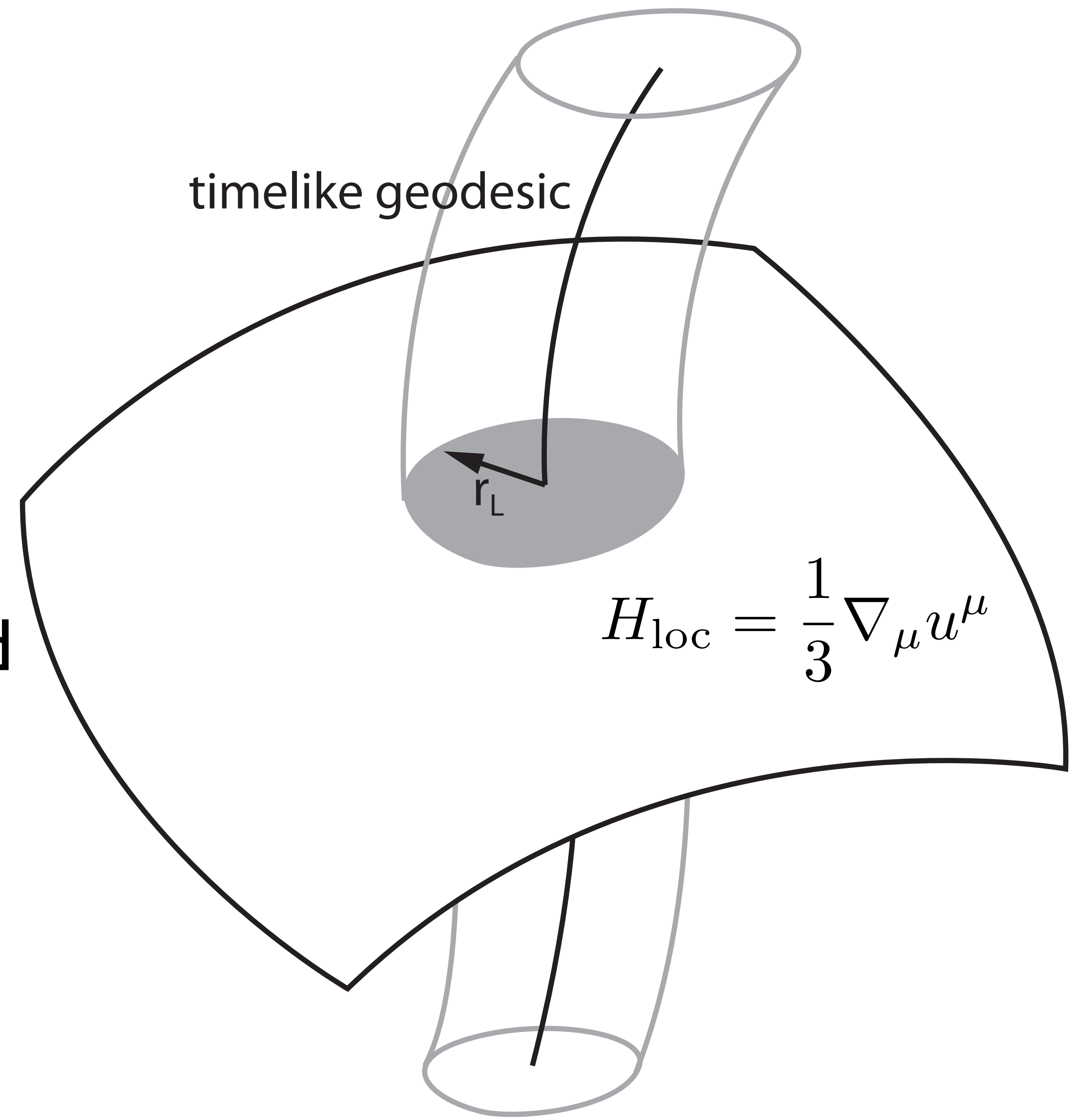


Okumura & Jing (2009)
Blazek et al. (2011)

Impact of GW on galaxies

Dai, Pajer, FS, 2015a
Pajer, FS, Zaldarriaga, 2013a,b

- Consider wordline of a small patch within the Universe
- *Conformal Fermi frame:* constructed so that close to the wordline, the spacetime looks close to an unperturbed universe at all times



$$g_{\mu\nu}^{\rm CFC} = a_{\rm loc}^2(\tau)\left[\eta_{\mu\nu} + h_{\mu\nu}^{\rm CFC}\right]$$

$$h_{\mu\nu}^{\rm CFC} = \mathcal{O}(x^i x^j)$$

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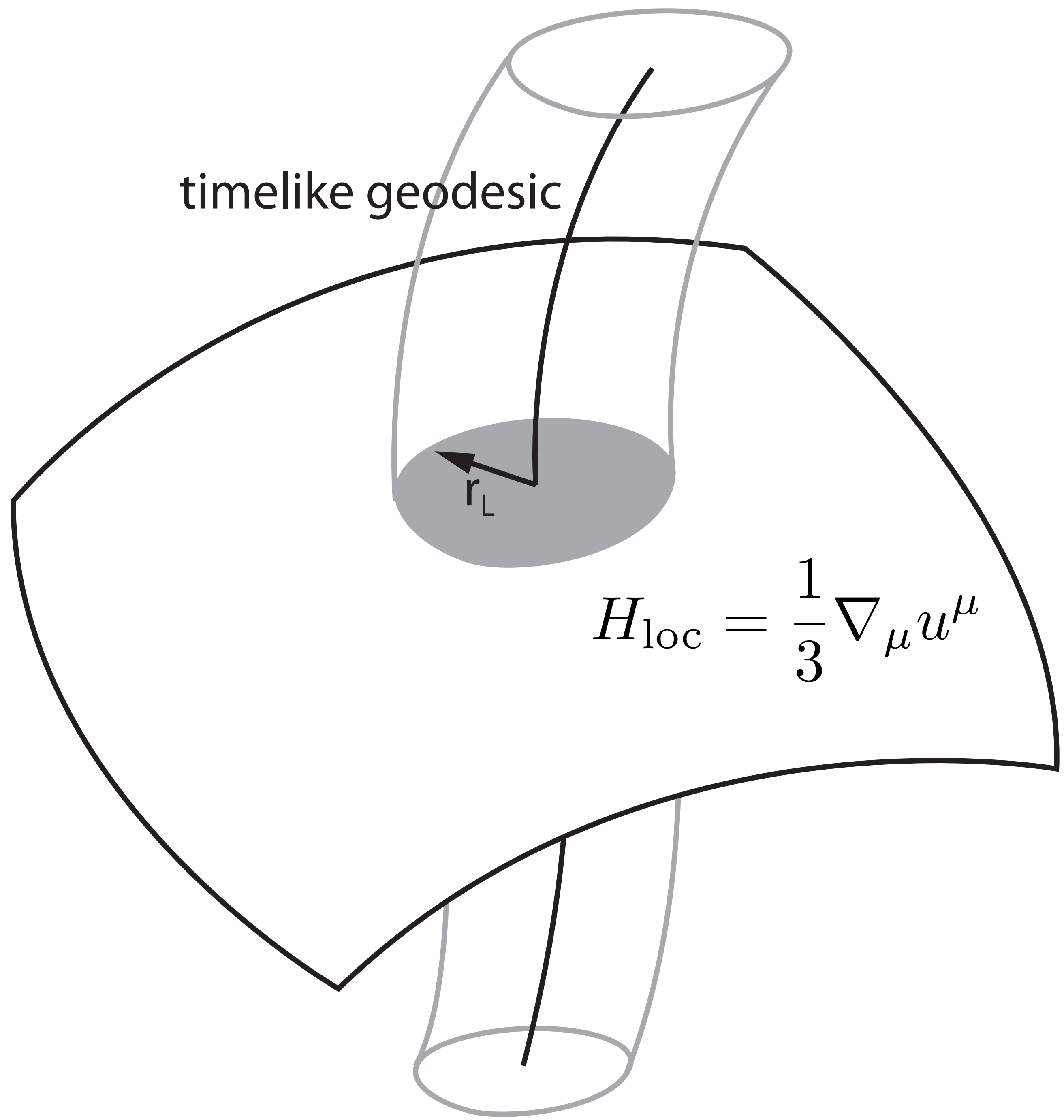
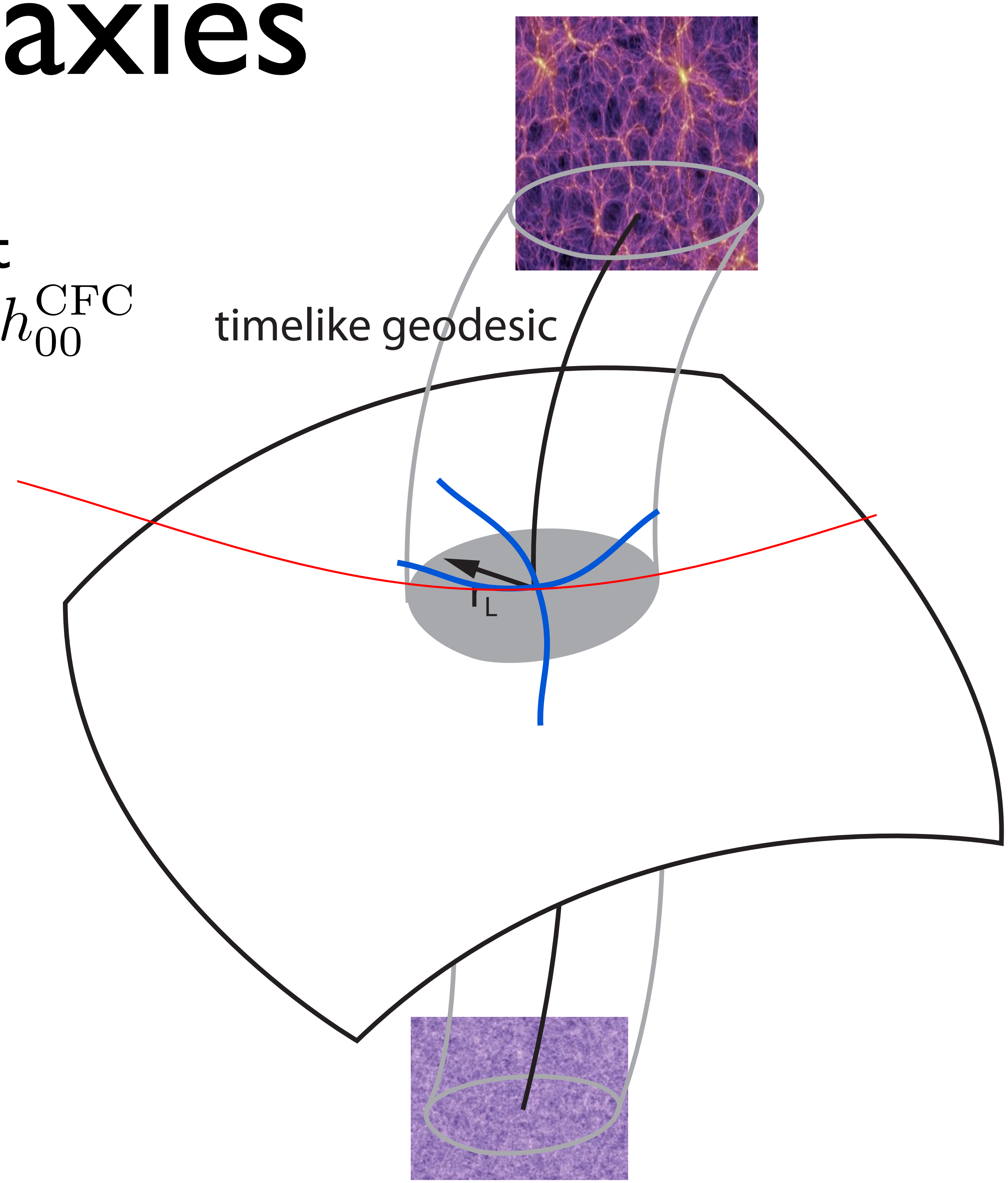
- Consider wordline of a small patch within the Universe
- *Conformal Fermi frame:* constructed so that close to the wordline, the spacetime looks close to an unperturbed universe at all times
- natural frame to describe local gravitational experiments in cosmology



Impact of GW on galaxies

- In the conformal Fermi frame, GW induces a tidal field once it enters the horizon, encoded in h_{00}^{CFC}
  - The same effect that moves the mirrors of a GW detector



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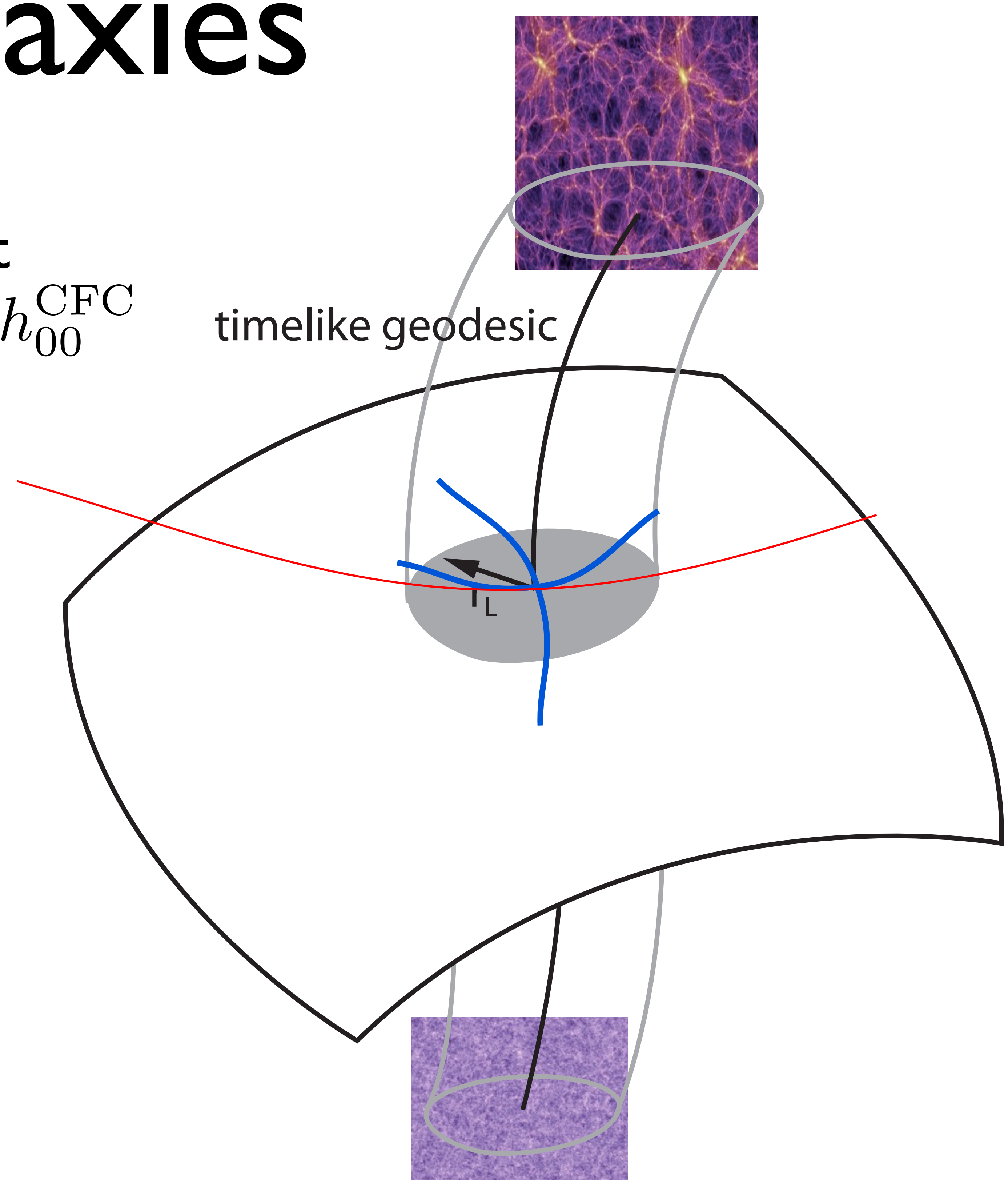
- In the conformal Fermi frame, GW induces a tidal field once it enters the horizon, encoded in h_{00}^{CFC}
  - The same effect that moves the mirrors of a GW detector
- This affects the formation of large-scale structure
- In perturbation theory, we can calculate exactly what that effect is



GW effects in perturbation theory

Matter density perturbation →

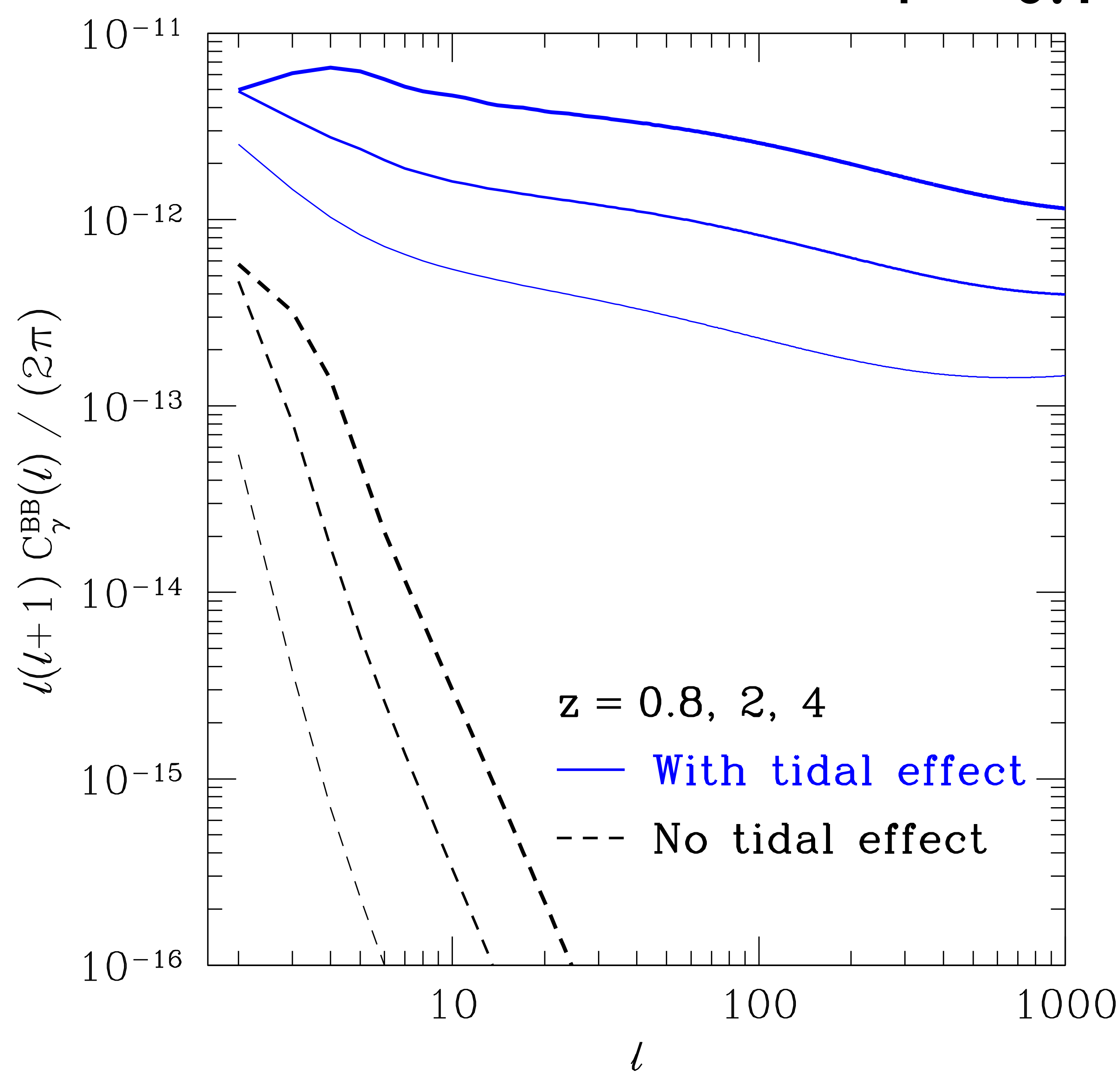
$$\delta(\mathbf{x},t)\Big|_h = \alpha(t)\, h_{ij}(\mathbf{x},t)\frac{\partial^i\partial^j}{\nabla^2}\delta_{\rm lin}(\mathbf{x},t)$$

- Tensor tidal field ~α h_{ij} couples to scalar tidal field
- α approaches constant as tensor mode has decayed away - *observable effects at low redshift even when GW has long disappeared*
- "Memory" effect - only happens because GW were superhorizon

Signatures of GW tidal alignments

- B-mode shape correlations
- Tidal effect is much larger than "lensing" contribution
- The exact opposite of scalar perturbations!

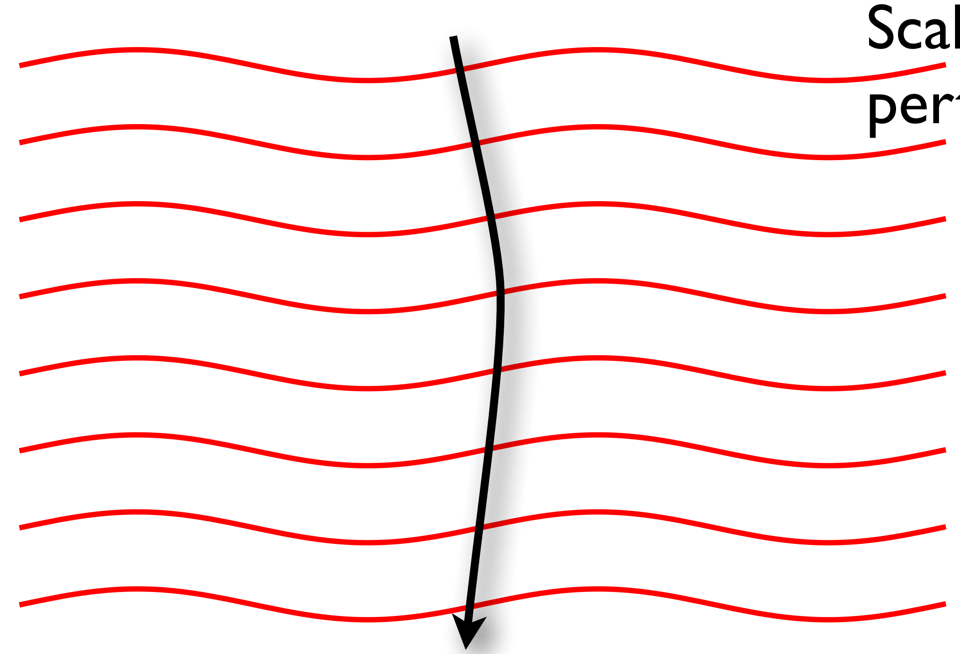
r = 0.1



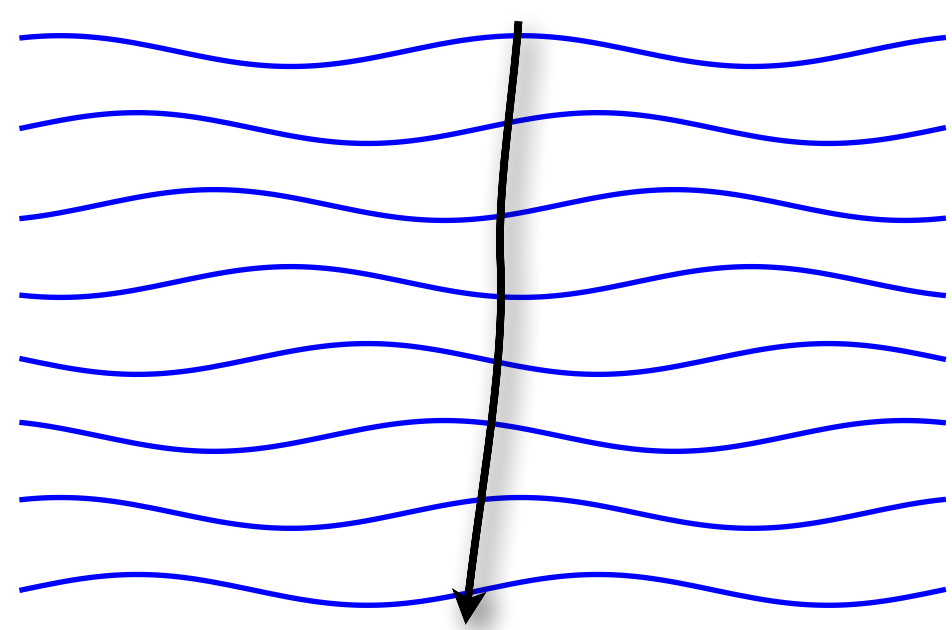
FS, Pajer, Zaldarriaga, 2013
FS, Jeong, 2012b

Why is intrinsic alignment so large for GW ?

- Actually, the correct question is: *why is the GW lensing contribution so small ?*
- Cancelation of lensing effect along the line of sight because GW propagate



Scalar perturbations



GW

Signatures of GW tidal alignments

- Still very small signal - difficult to measure even for EUCLID
- Depends sensitively on how strong galaxies align with tidal fields
- One of the few possible ways to independently confirm detection of GW in CMB

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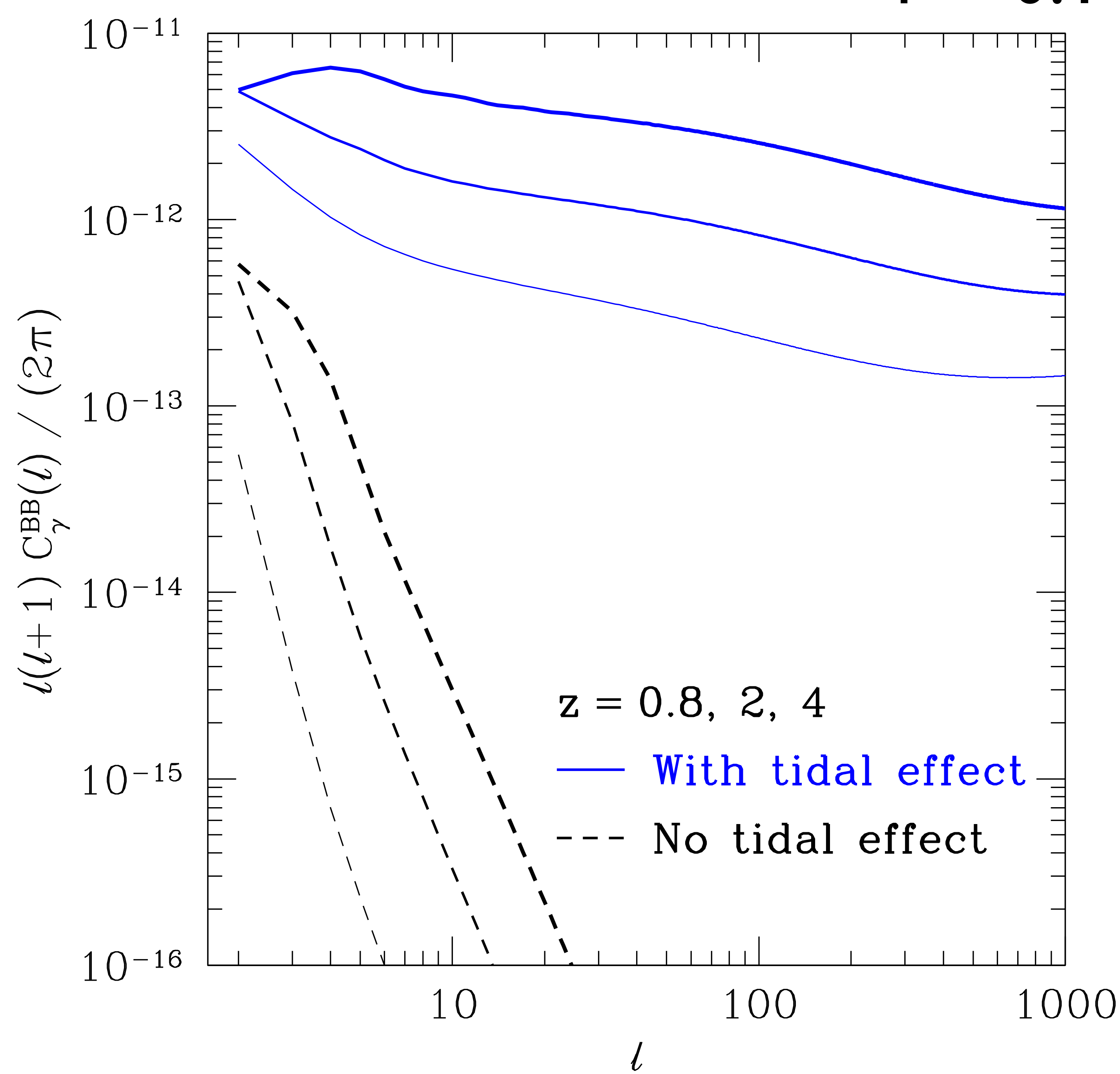

FS, Pajer, Zaldarriaga, 2013
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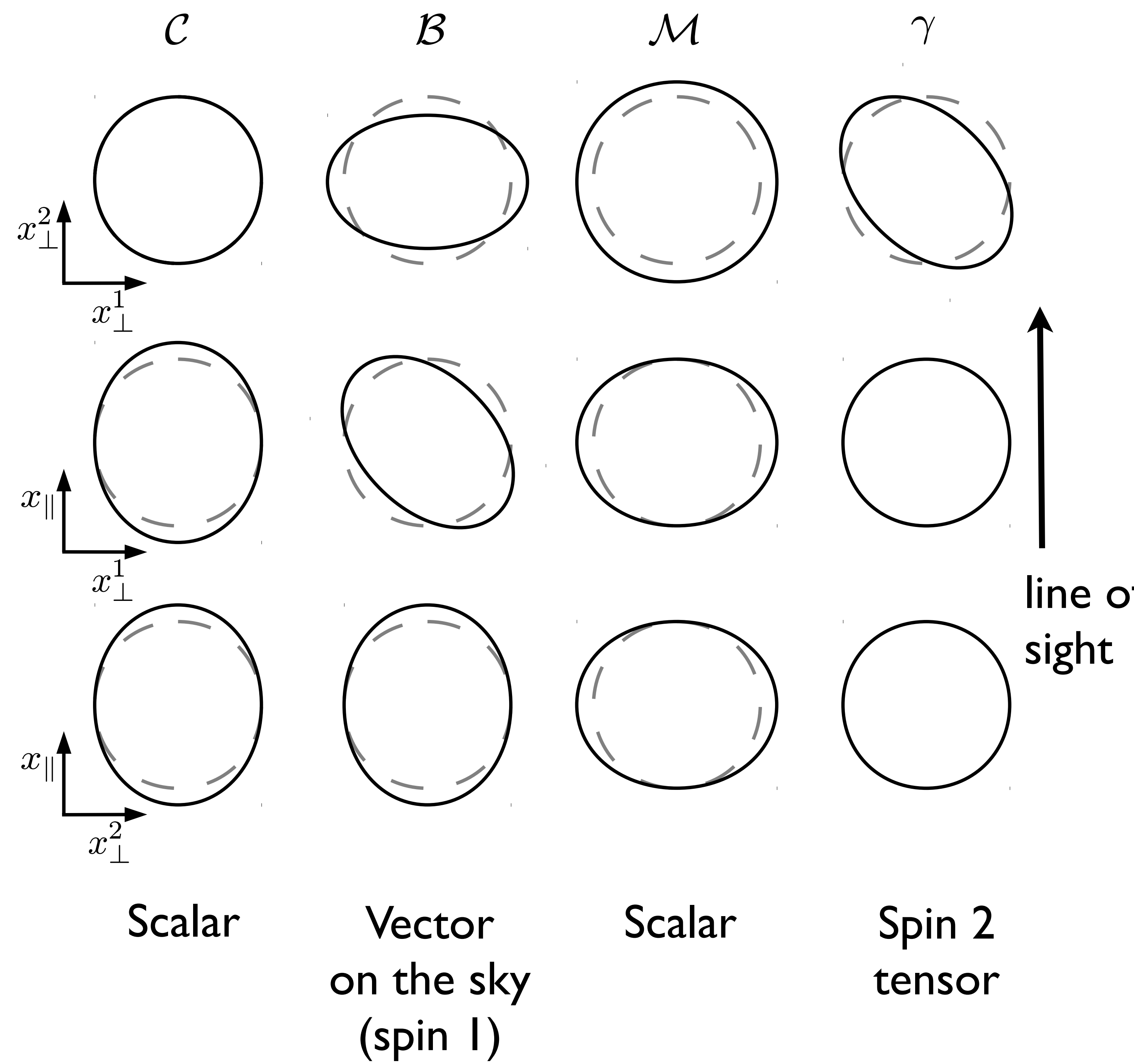
From 2D to 3D

- So far, considered shapes of galaxies
- What if we have 3D observations ?
- Examples:
  - galaxies with spatially resolved spectra
  - measurement of 3D small-scale correlation function (21cm background)
- Distortions of a "standard ruler" in 3 dimensions

From 2D to 3D

- A ruler is defined by two endpoints in 3D space (4 angles, 2 redshifts)
- In principle we can thus measure *6 independent d.o.f.* from the distortion of the ruler
- This the most general "*weak lensing in 3 dimensions*"



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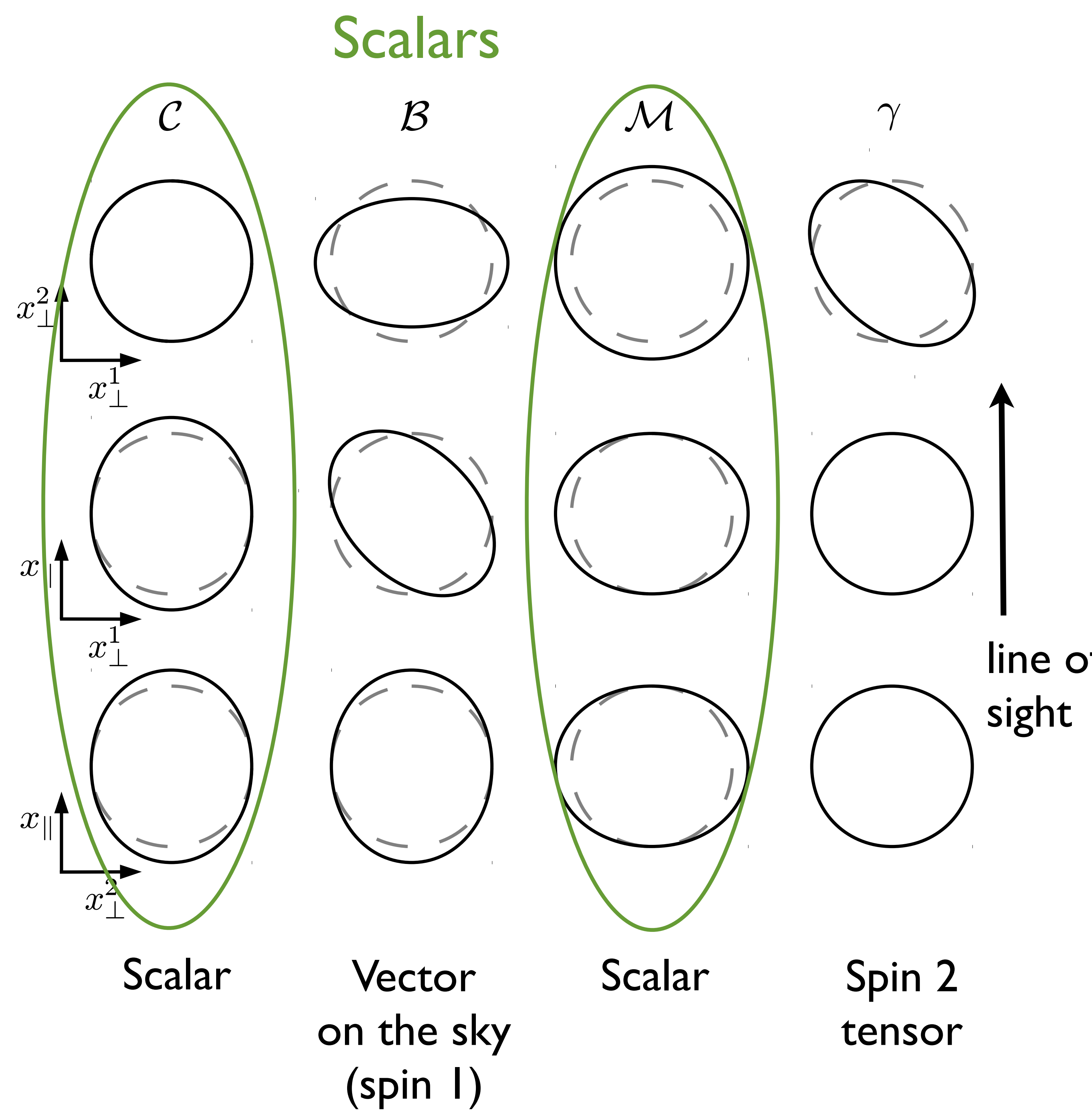

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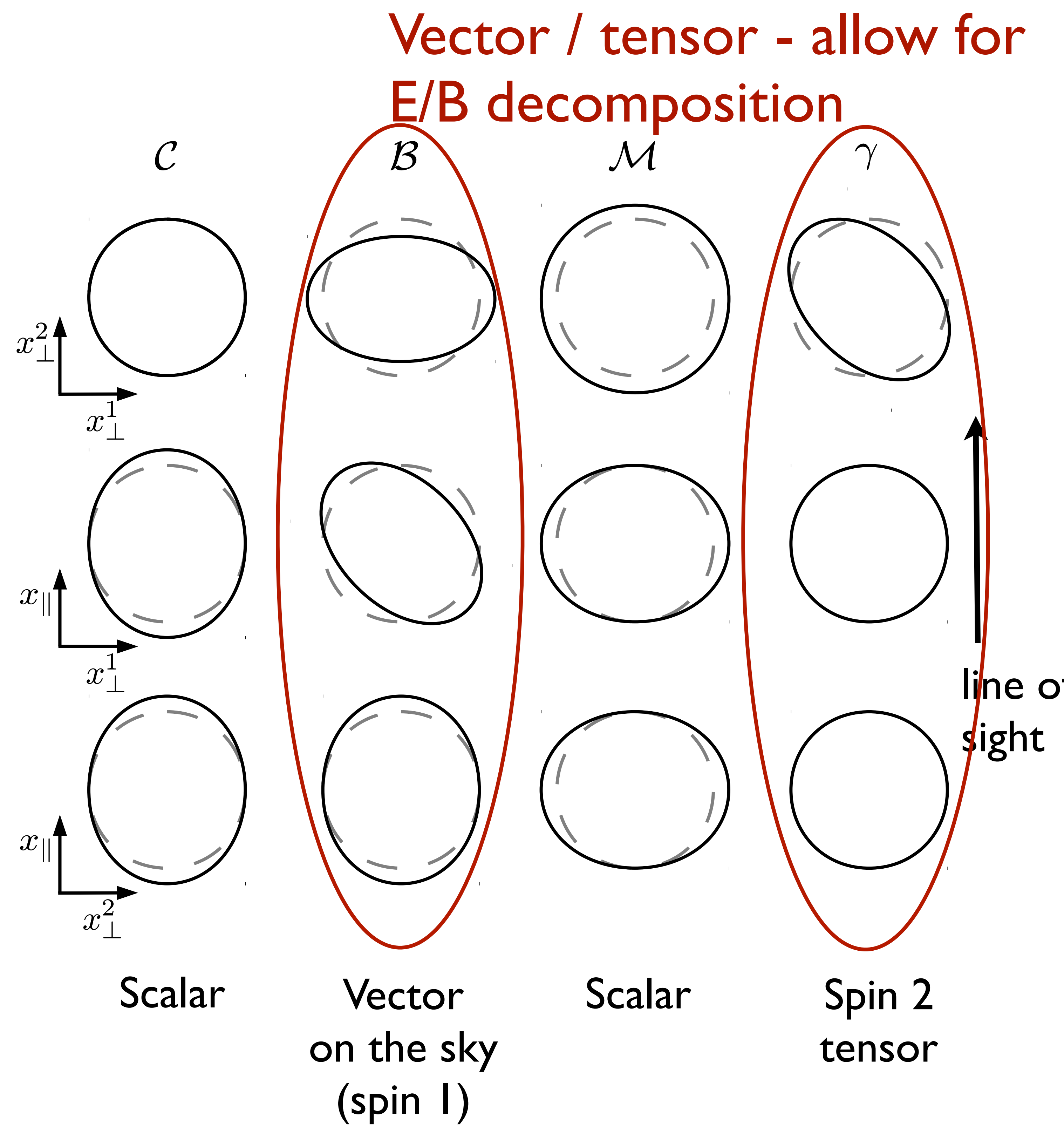
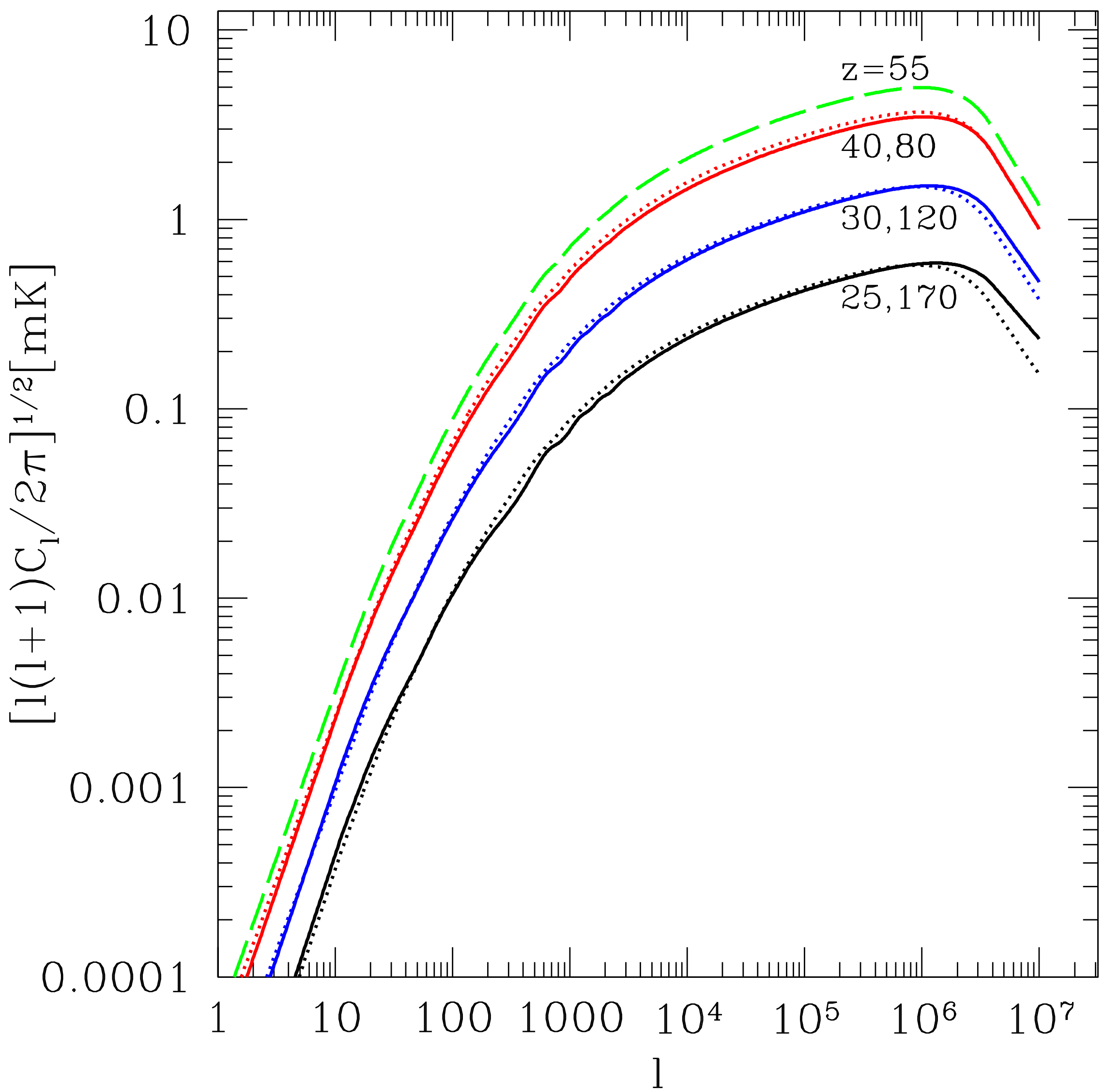


Example: 21cm emission

- Before reionization (z >~ 10), HI can be observed in 21cm spin-flip transition
- Cold gas (T ~ 100K): Jeans scale extremely small; undamped linear P(k) out to k ~ pc^{-1}
- Number of modes available beats any other probe
- Issue: galactic foregrounds; enormous sensitivity needed to probe fluctuations

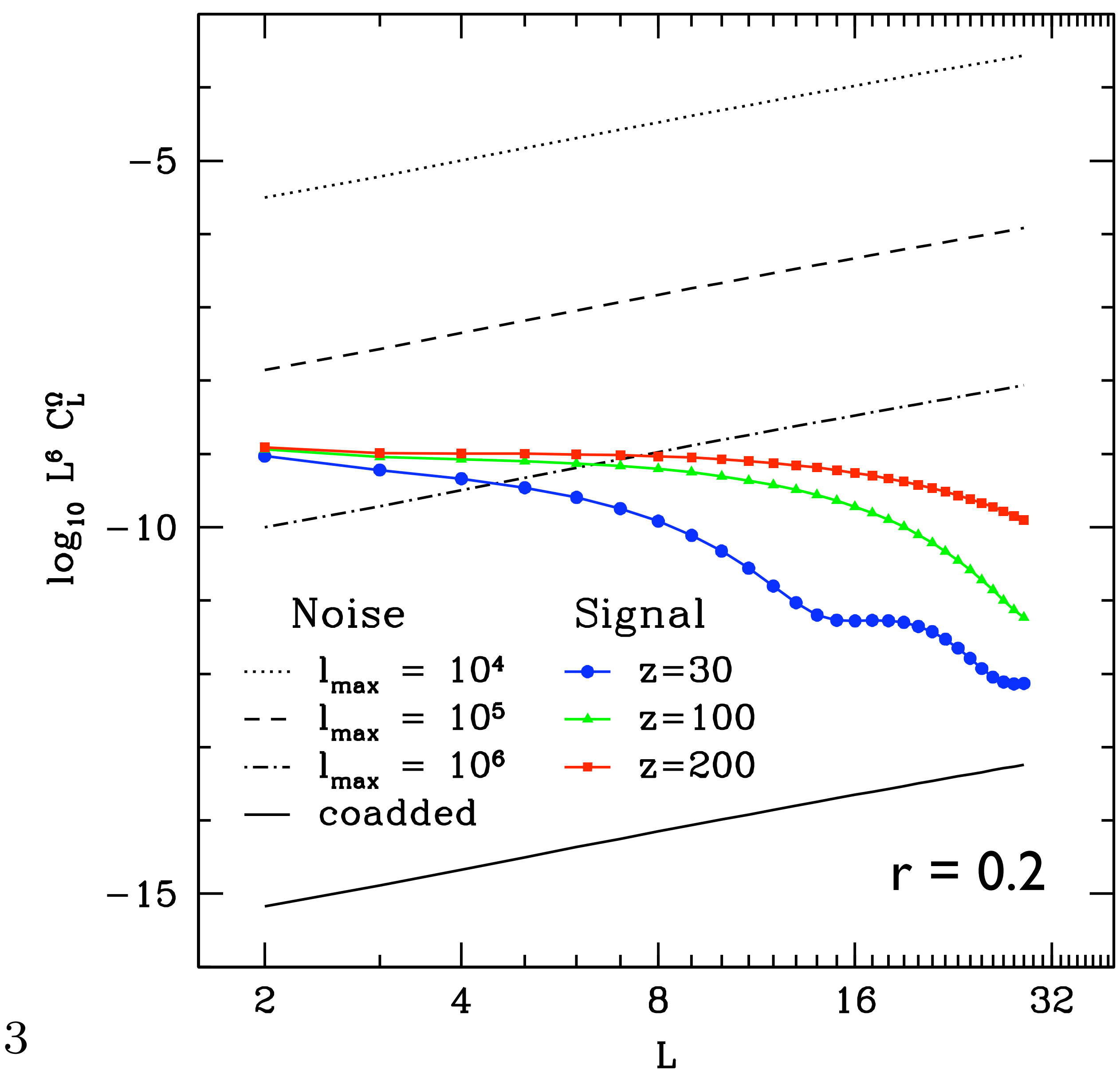


Loeb & Zaldarriaga, 2004

21cm emission from the “dark ages”

- Reconstruction of GW lensing from B-mode shear (4-pt function)
- Vector $\mathcal{B}$ not considered here - but possibly easier to measure
- Possibly the ultimate probe of GW ? Mode counting yields

$$r \simeq 10^{-6} \left(L_{\min}/2\right) \left(l_{\max}/10^6\right)^{-3}$$



L. Book, MK, FS
1112.0567

Summary

- Detecting *primordial GW* from inflation is still one of the primary goals of cosmology
- Large-scale structure can potentially confirm a future CMB detection with *shear correlations* - thanks to *tidal alignment* by GW
  - Especially important given the higher than expected CMB contamination by dust polarization
- ... or detect even smaller amplitudes with far-future *21cm surveys*

Contaminations by scalar perturbations

- At second order, scalar perturbations lead to B modes
- Non-linear corrections to light propagation ("Born")
- Non-linearities in shear estimation ("red. shear")