Records from Primordial Gravitational Waves and Cosmic Acceleration in CMB polarization

Carlo Baccigalupi
SISSA, Trieste
VI Challenges of New Physics in Space,
Campos de Jordao, Brazil, May 25-29, 2015

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Part I: physical processes and cosmological relevance
Part II: status of observations

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Outline

- Introduction to SISSA
- CMB anisotropies
- Initial conditions and Gravitational Waves
- Large Scale Structure and Dark Energy
- Concluding remarks, I

The International School for Advanced Studies, Trieste, Italy

- Main goal: training PhD students to research
- Interdisciplinary:
  - physics (Astrophysics, Astroparticle, Elementary Particles, Condensed Matters, Statistical Physics),
  - Mathematics,
  - Neuro-sciences
- About 100 professors, 100 Post-Docs, 200 PhD students
- Located in Trieste, Italy, one of the places with the highest density of scientific institutions: the international center for theoretical physics, the University of Trieste, the Astronomical observatory in Trieste, research area laboratories

ma per seguir virtute e canoscenza
SISSA

The SISSA cosmology group: data analysis for CMB experiments

- PolarBear (Fabbian, Puglisi):
  - Map-making
  - Foreground control and cleaning, B mode power spectrum measurements
- Planck:
  - INAF-OATs and SISSA run the Low Frequency Instrument Data Processing Centre,
  - Component Separation for CMB and characterization (Basak, Bielewicz, Castex, Paci)
- EBEX (Castex, Puglisi)
  - Analysis of maps, support for foreground cleaning and power spectrum estimation
- CMB satellite/ground-based network proposals
  - Data analysis simulations

SISSA

The SISSA cosmology group: CMB-LSS Cross-Correlations

- Euclid:
  - CMB-N-body lensing simulations: geodesics (Calabrese, Fabbian)
  - CMB-N-body lensing simulations of cross-correlartions (Bianchini, Calabrese)
- Herschel:
  - Galaxy formation and evolution (Lapi et al. for the Galaxy Formation group)
  - Cross-correlation with Planck (Bianchini, Bielewicz, Lapi et al. for the Galaxy formation group)

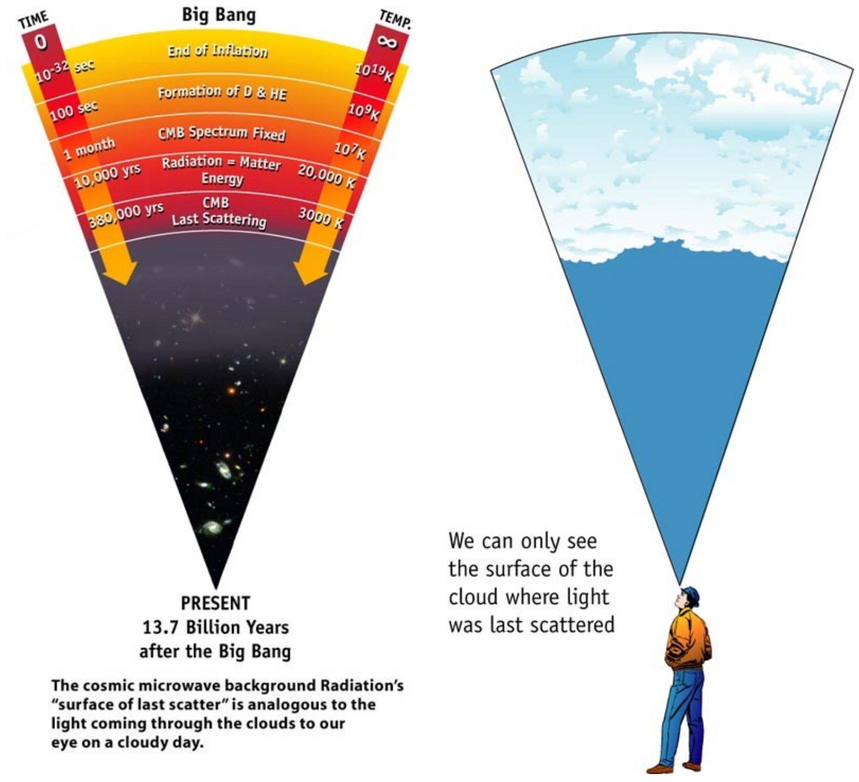
CMB anisotropies

CMB: where and when?

- Opacity:

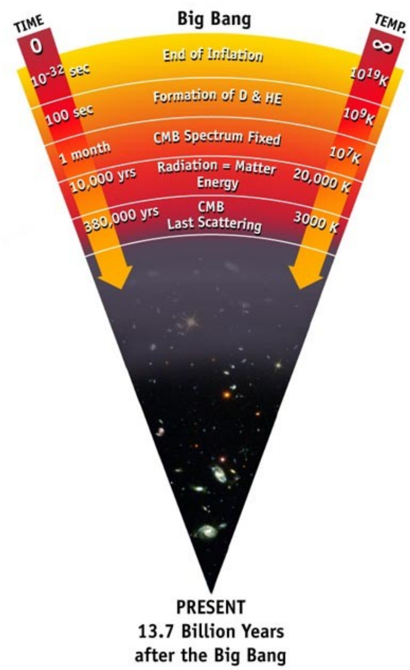
  $\lambda = 1/n\sigma \ll$ horizon

  where the horizon is the distance at which information get at each time, inverse of the Hubble expansion rate
- Decoupling: $\lambda \approx$ horizon
- Free streaming: $\lambda \gg$ horizon
- Cosmological expansion, Thomson cross section and electron abundance conspire to activate decoupling about 380000 years after the Big Bang, at about 3000 K CMB photon temperature

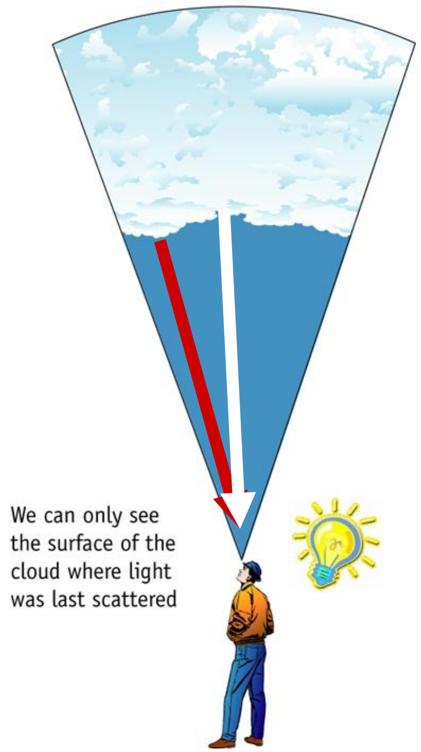


A postcard from the big bang

- From the Stephan Boltzmann law, regions at high temperature should carry high density
- The latter is activated by perturbations which are intrinsic of the fluid as well as of spacetime
- Thus, the maps of the CMB temperature is a kind of snapshot of primordial cosmological perturbations

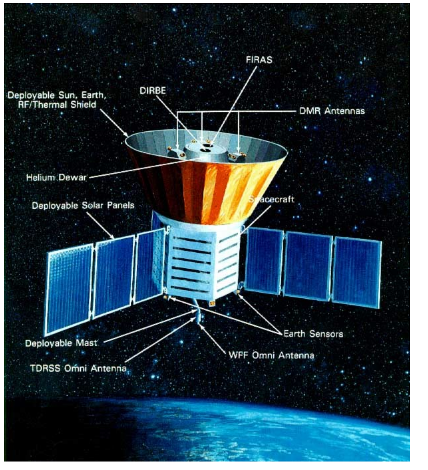


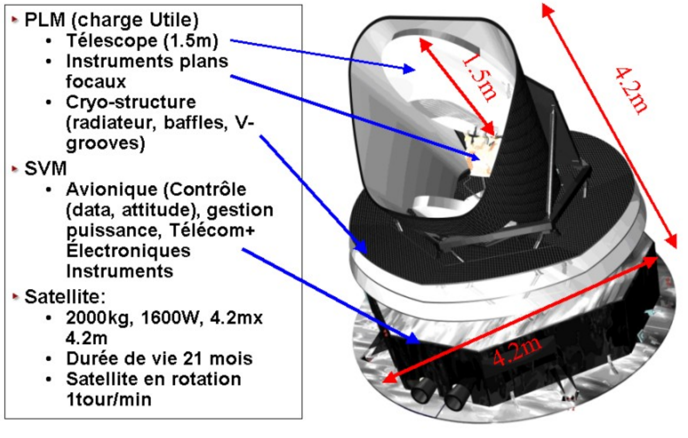
The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.

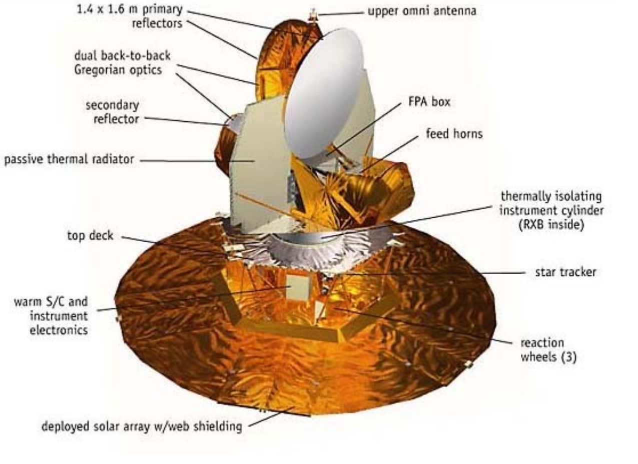


From COBE to the Wilkinson Microwave Anisotropy Probe (WMAP) to Planck

- About 40 years of scientific and technological progresses
- Lots of experiments, people
- See lambda.gfsc.nasa.gov







CMB physics: Boltzmann equation

$$\frac{d\ \text{photons}}{dt} = \text{gravity + Compton scattering}$$

$$\frac{d\ \text{baryons+leptons}}{dt} = \text{gravity + Compton scattering}$$

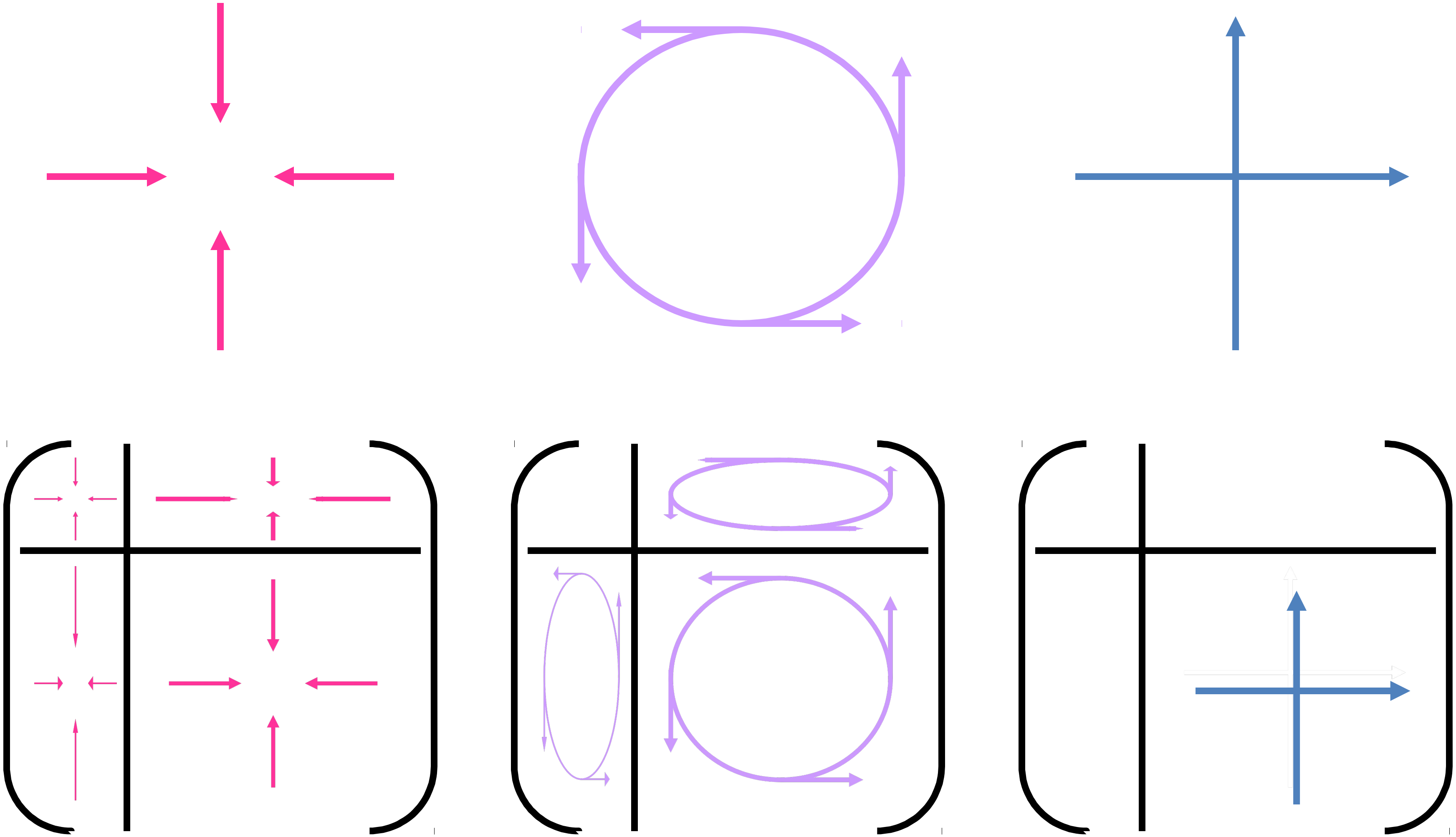
CMB physics: Boltzmann equation

$$\frac{d\ \text{neutrinos}}{dt} = \text{gravity} + \text{weak interaction}$$

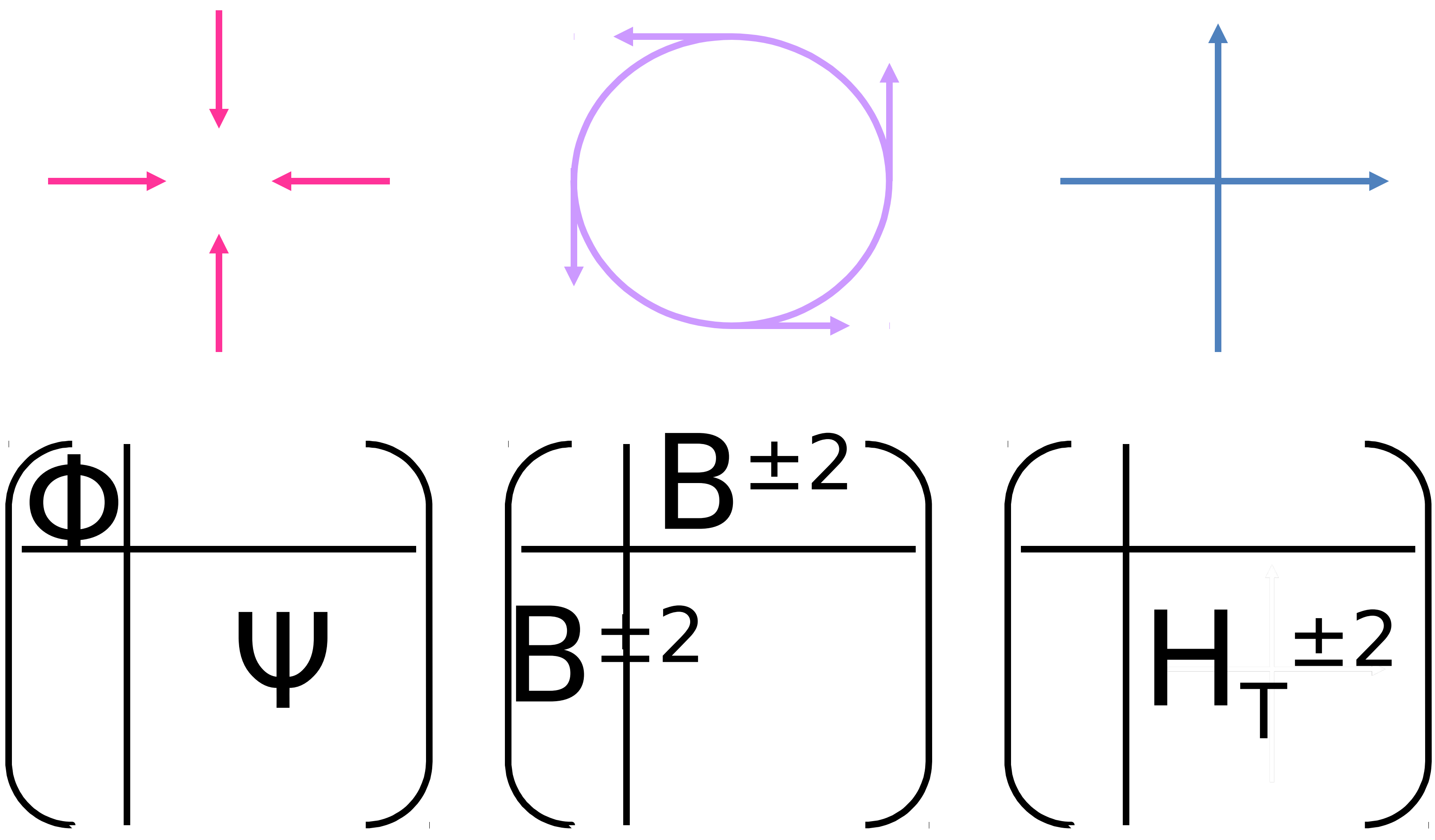
$$\frac{d\ \text{dark matter}}{dt} = \text{gravity} + \text{weak interaction (?)}$$

gravity = photons + neutrinos + baryons + leptons + dark matter

CMB physics: gravity

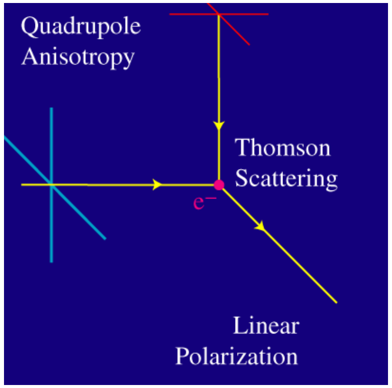


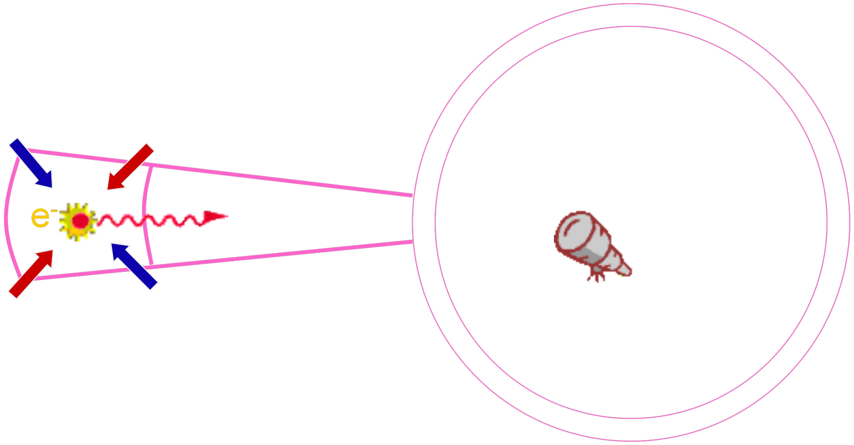
CMB physics: gravity



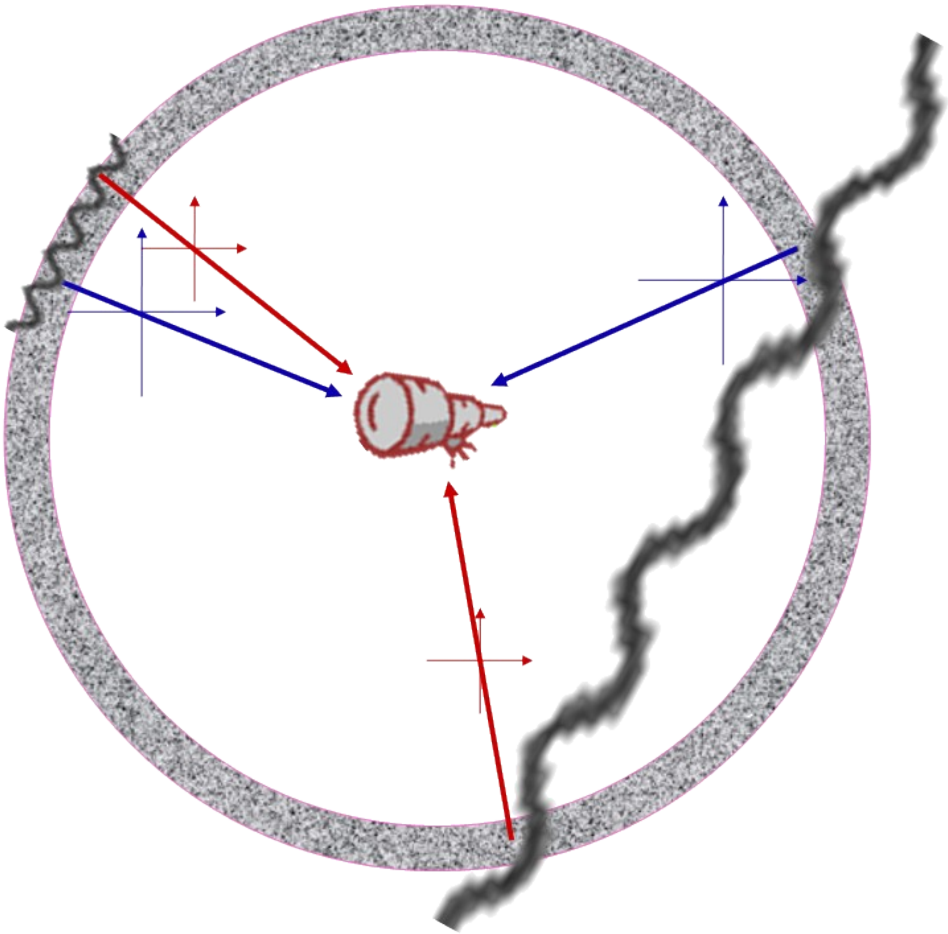
CMB Physics: Compton scattering

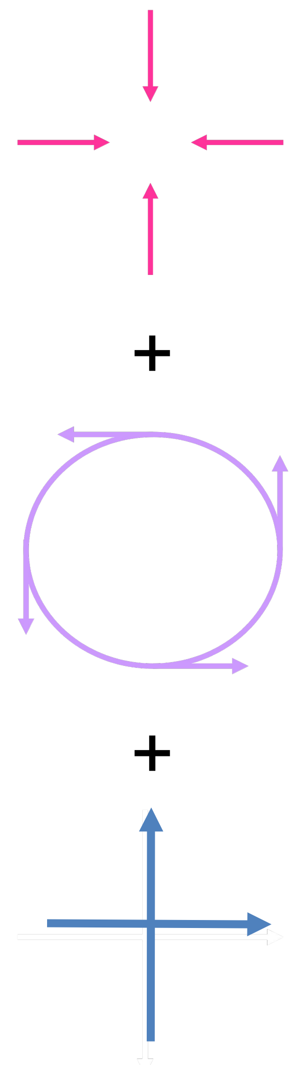
- Compton scattering is anisotropic
- An anisotropic incident intensity determines a linear polarization in the outgoing radiation
- At decoupling that happens due to the finite width of last scattering and the cosmological local quadrupole



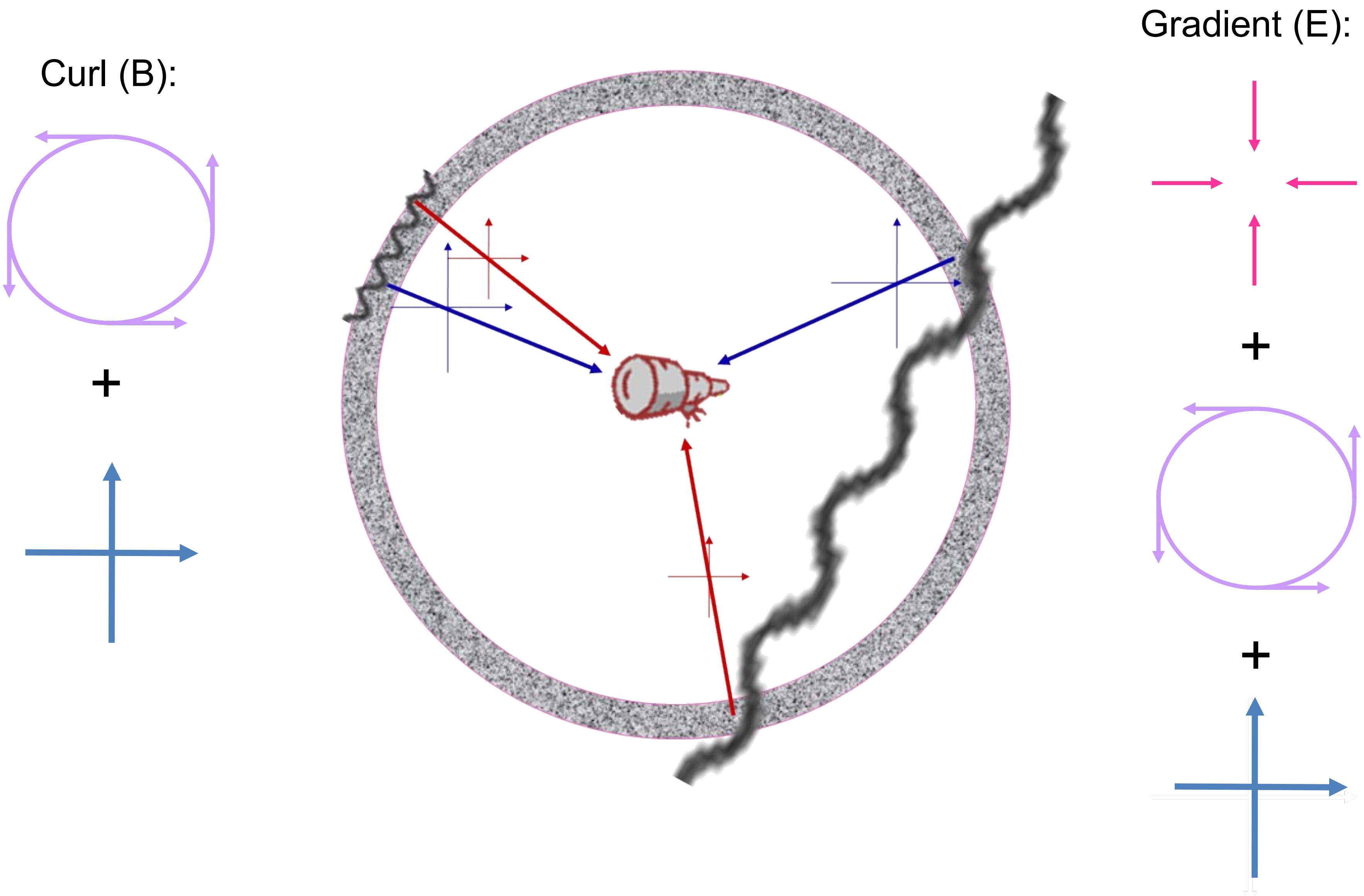


CMB anisotropy: Total Intensity





CMB anisotropy: polarization



Anisotropies

$T(\theta,\varphi)$, $Q(\theta,\varphi)$, $U(\theta,\varphi)$, $V(\theta,\varphi)$

spherical harmonics

$X(\theta,\varphi)=\Sigma_{lm}\, a_{lm}{}^{X}\, Y^{s}{}_{lm}(\theta,\varphi)$

X=T,E,B

s=0 for T, 2 for Q and U

E and B modes have opposite parity

Angular power spectrum

$T(\theta,\varphi)$, $Q(\theta,\varphi)$, $U(\theta,\varphi)$, $V(\theta,\varphi)$

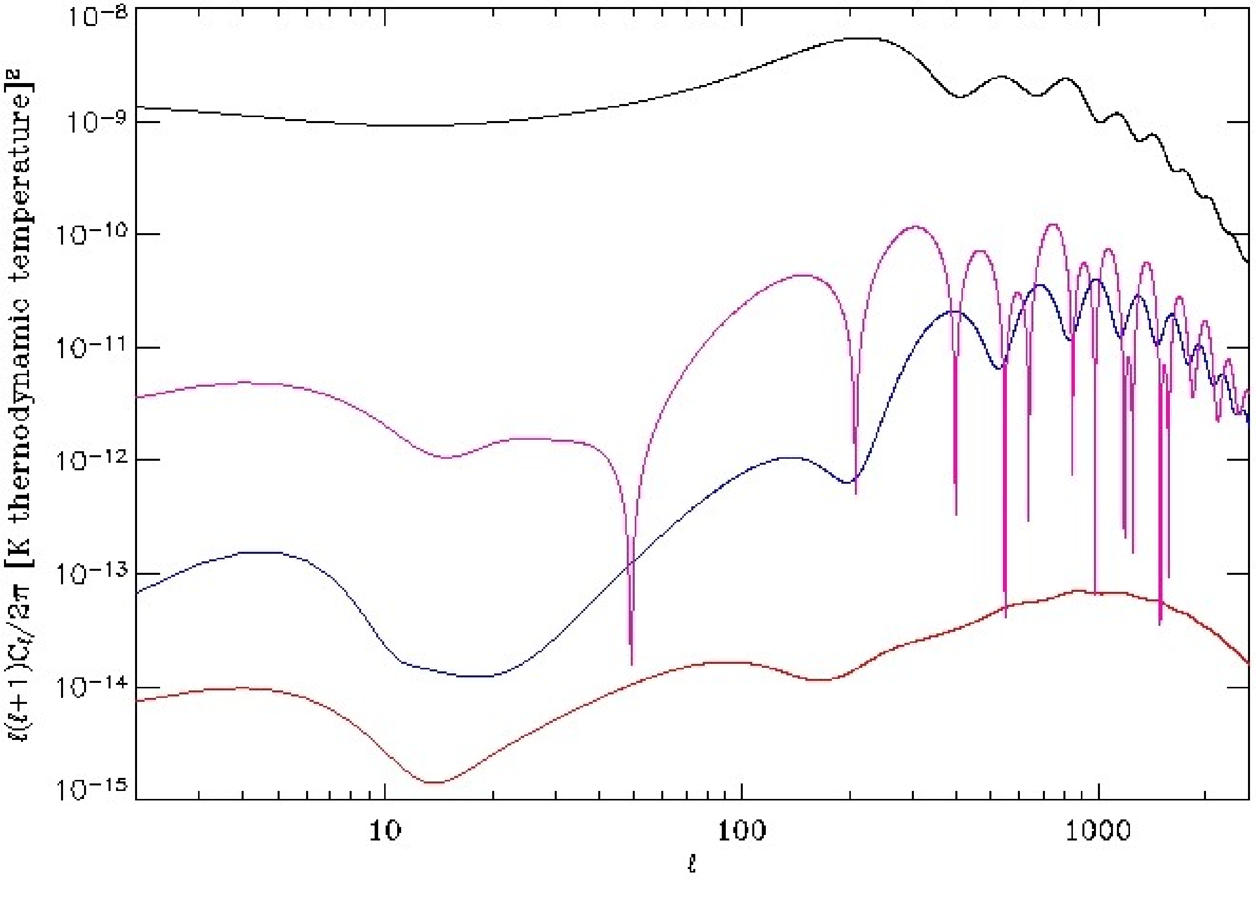
spherical harmonics

a^X_{lm}, $X=T,E,B$

information compression

$C_l = \Sigma_m [(a_{lm}{}^X)(a_{lm}{}^Y)^*]/(2l+1)$

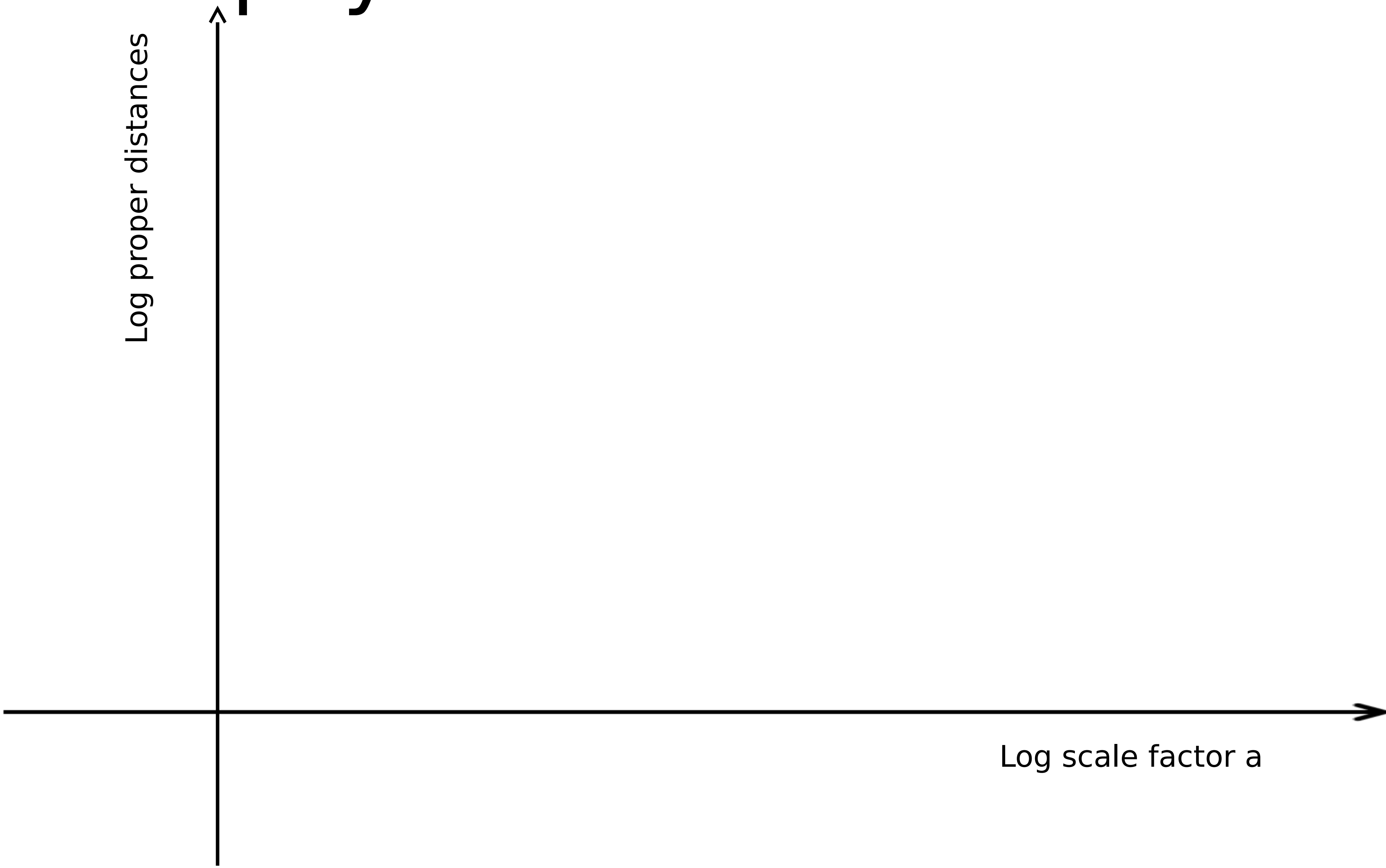
CMB angular power spectrum



Angle ≈ 200/l degrees

Initial conditions and Gravitational Waves

CMB physics: initial conditions



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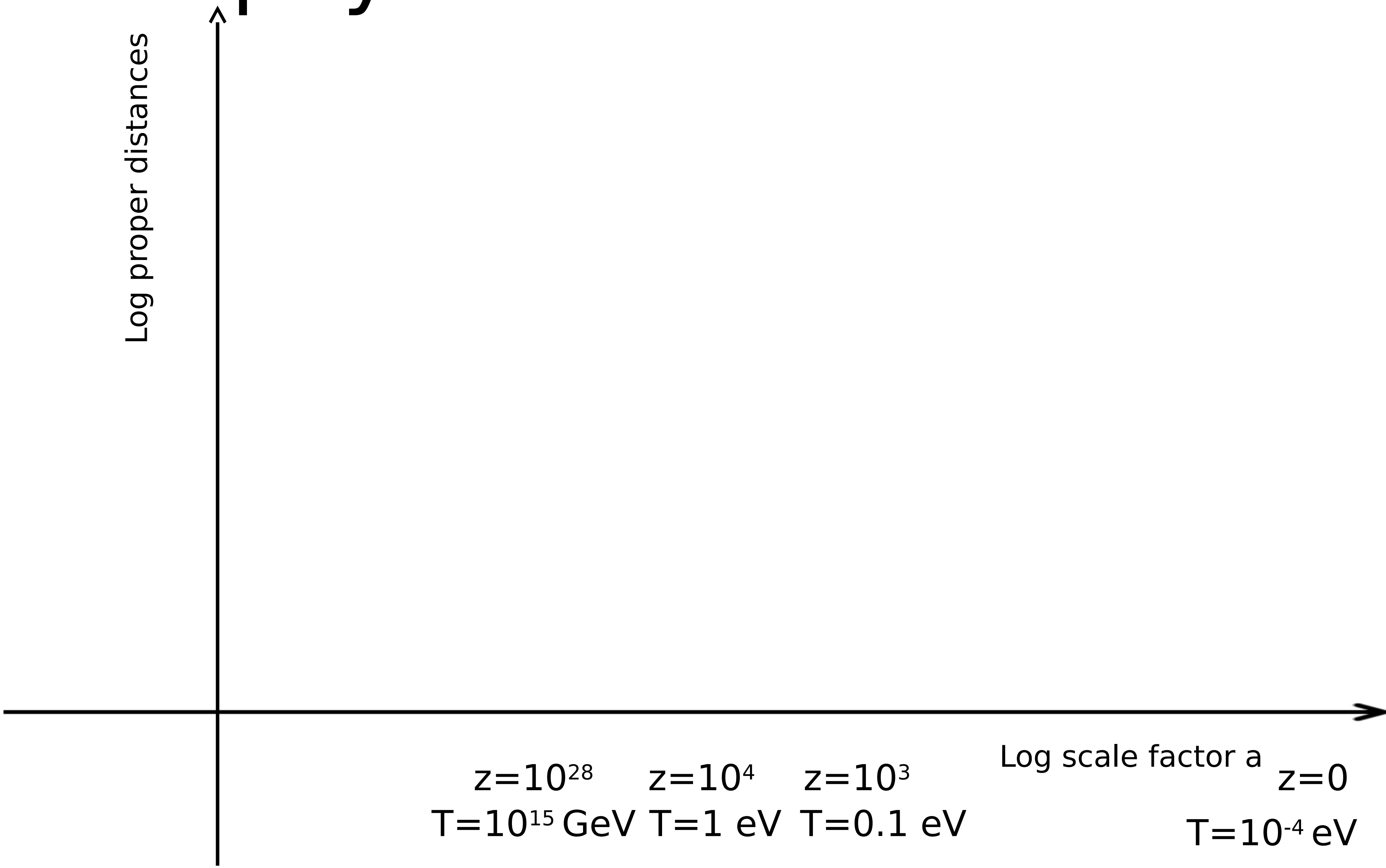

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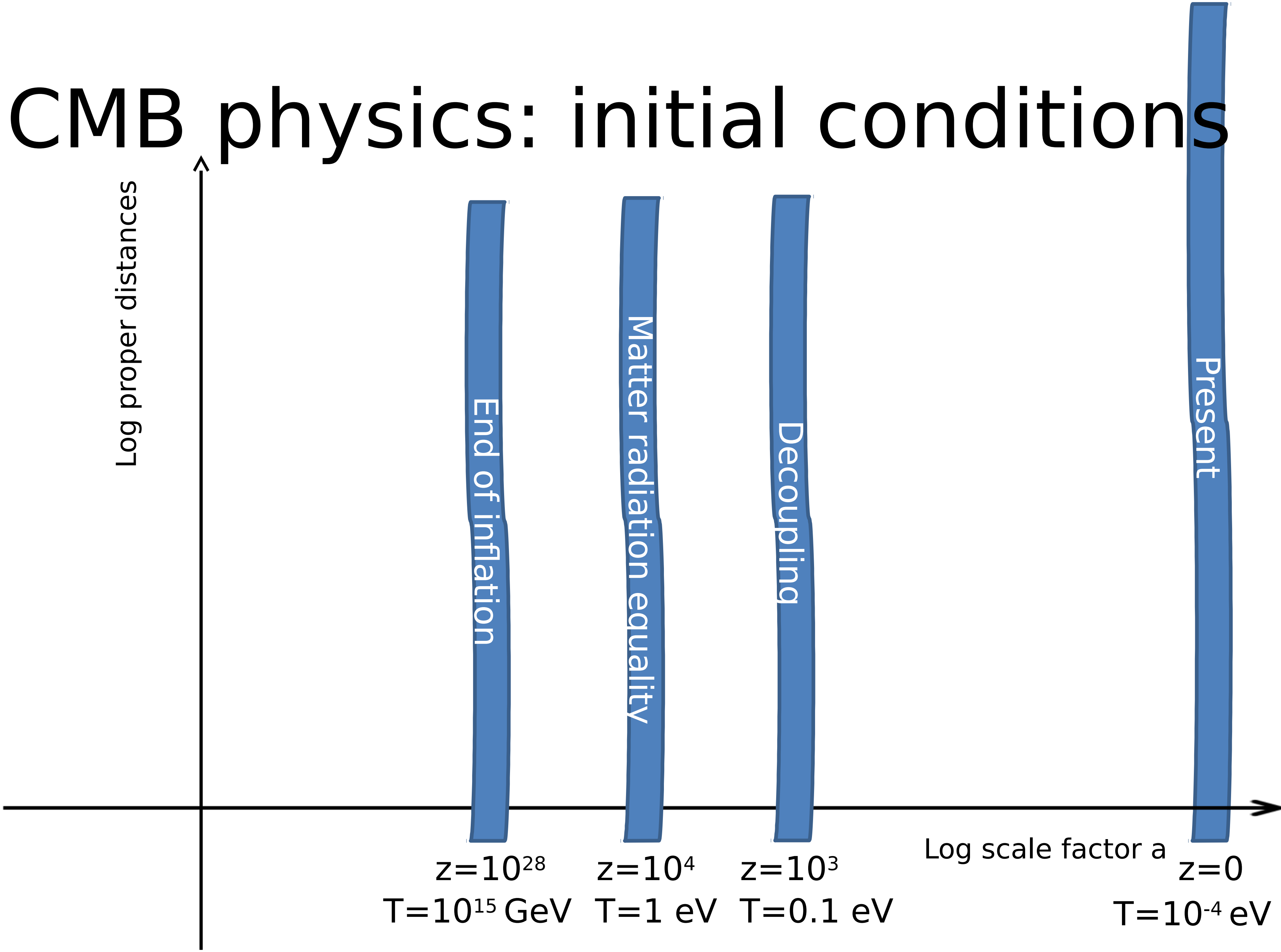

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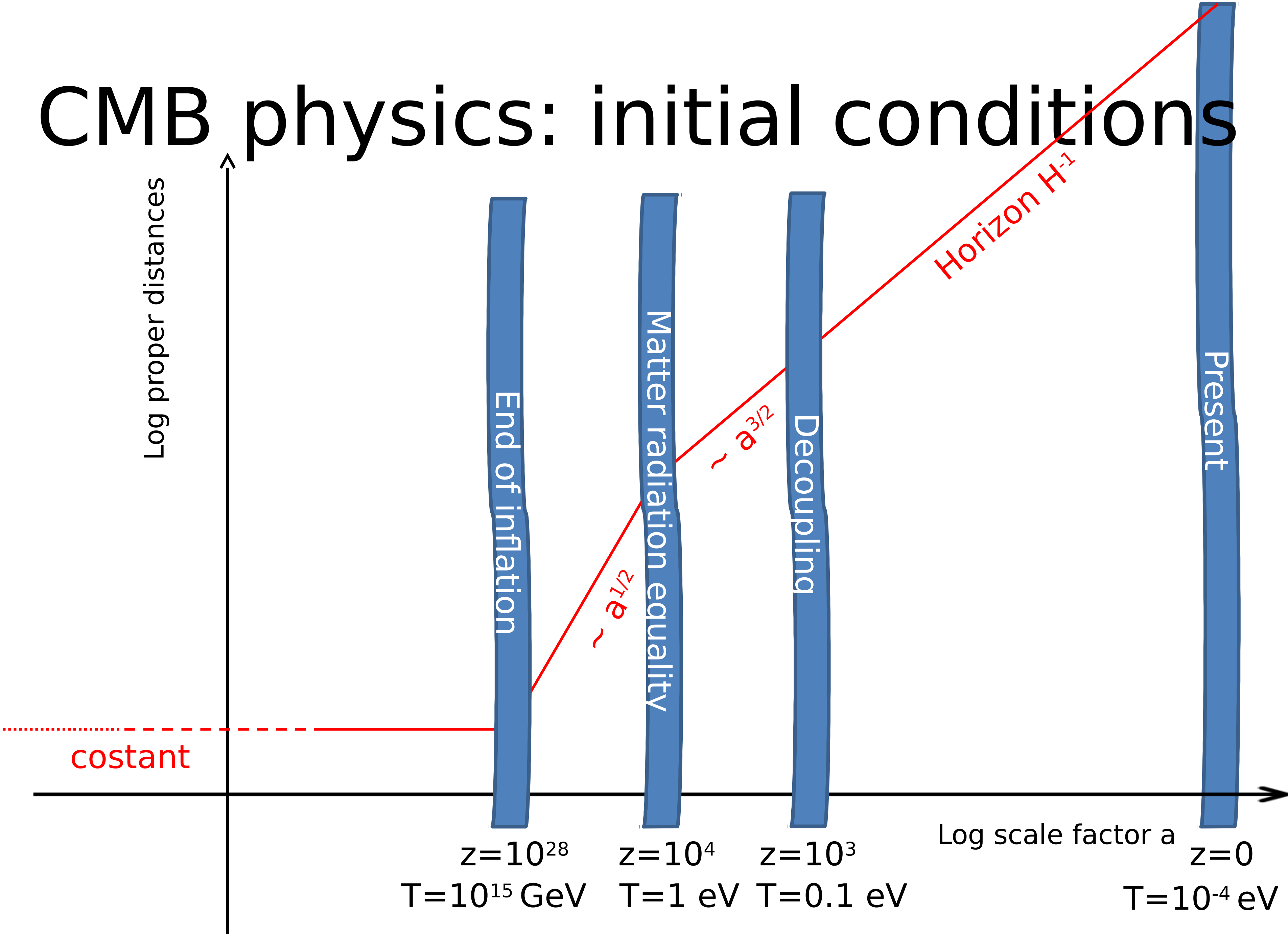

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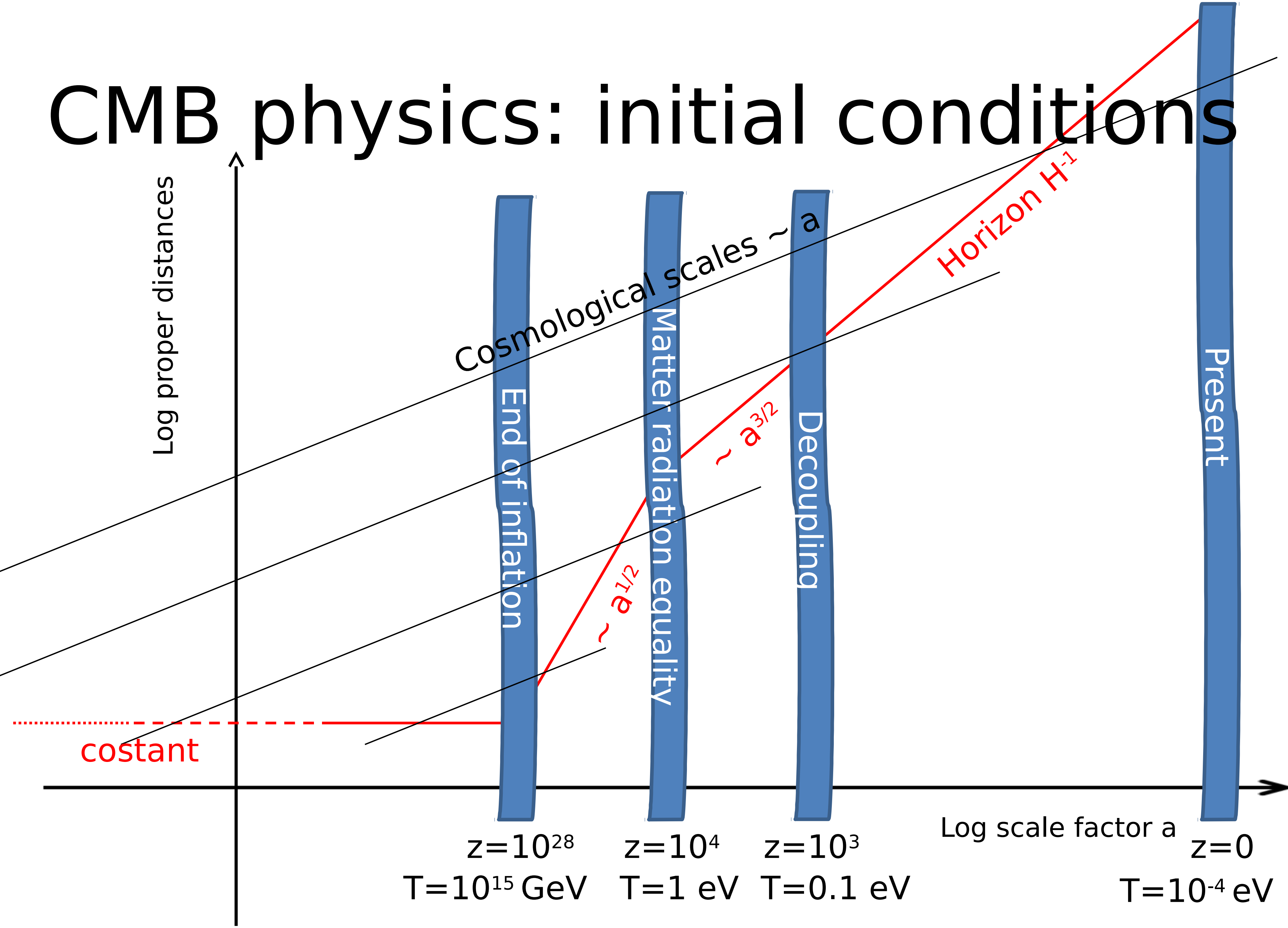


CMB physics: initial conditions

End of inflation

$\Delta(\vec{x}, t)$

Fluctuations are in the linear regime: $\Delta \ll 1$

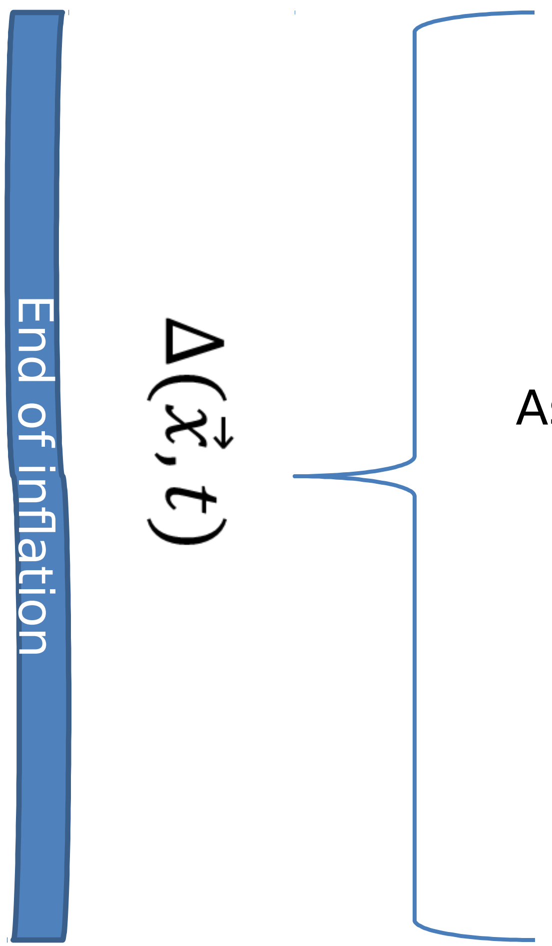
Fourier decomposition: $\Delta(\vec{x}, t) \rightarrow \Delta(\vec{k}, t)$

Assumed statistics:

$$< \Delta(\vec{k}, t)\overline{\Delta}(\vec{k}', t) > = P_{\Delta}(\vec{k}, t)\, \delta(\vec{k} - \vec{k}')$$

Gaussianity

CMB physics: initial conditions



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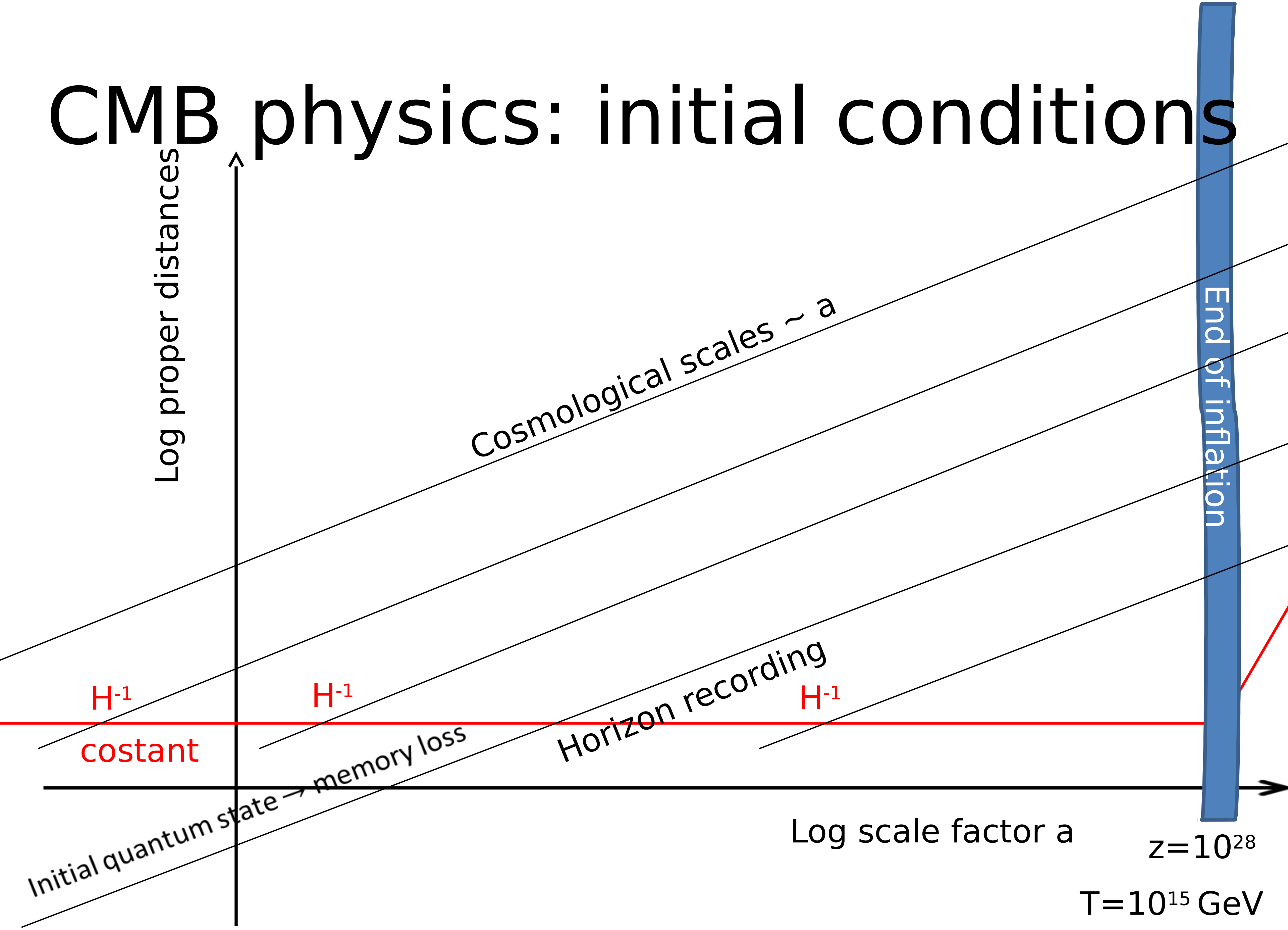
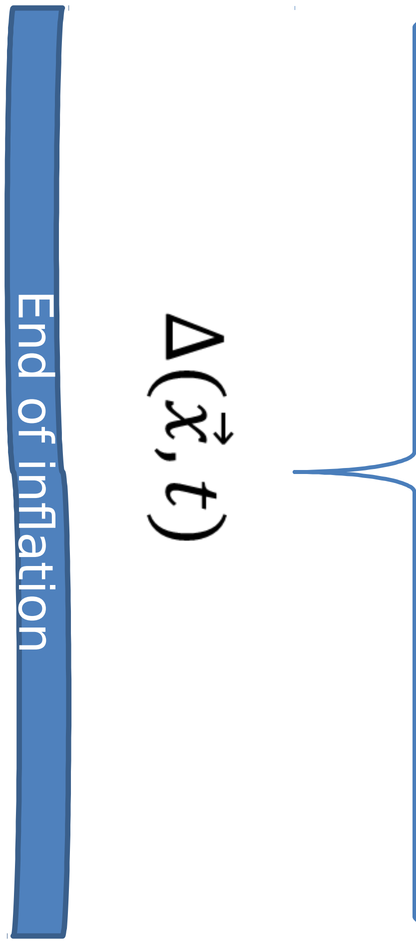
Gaussianity

& Isotropy

CMB physics: initial conditions



CMB physics: initial conditions



Harrison Zel-dovich spectrum:

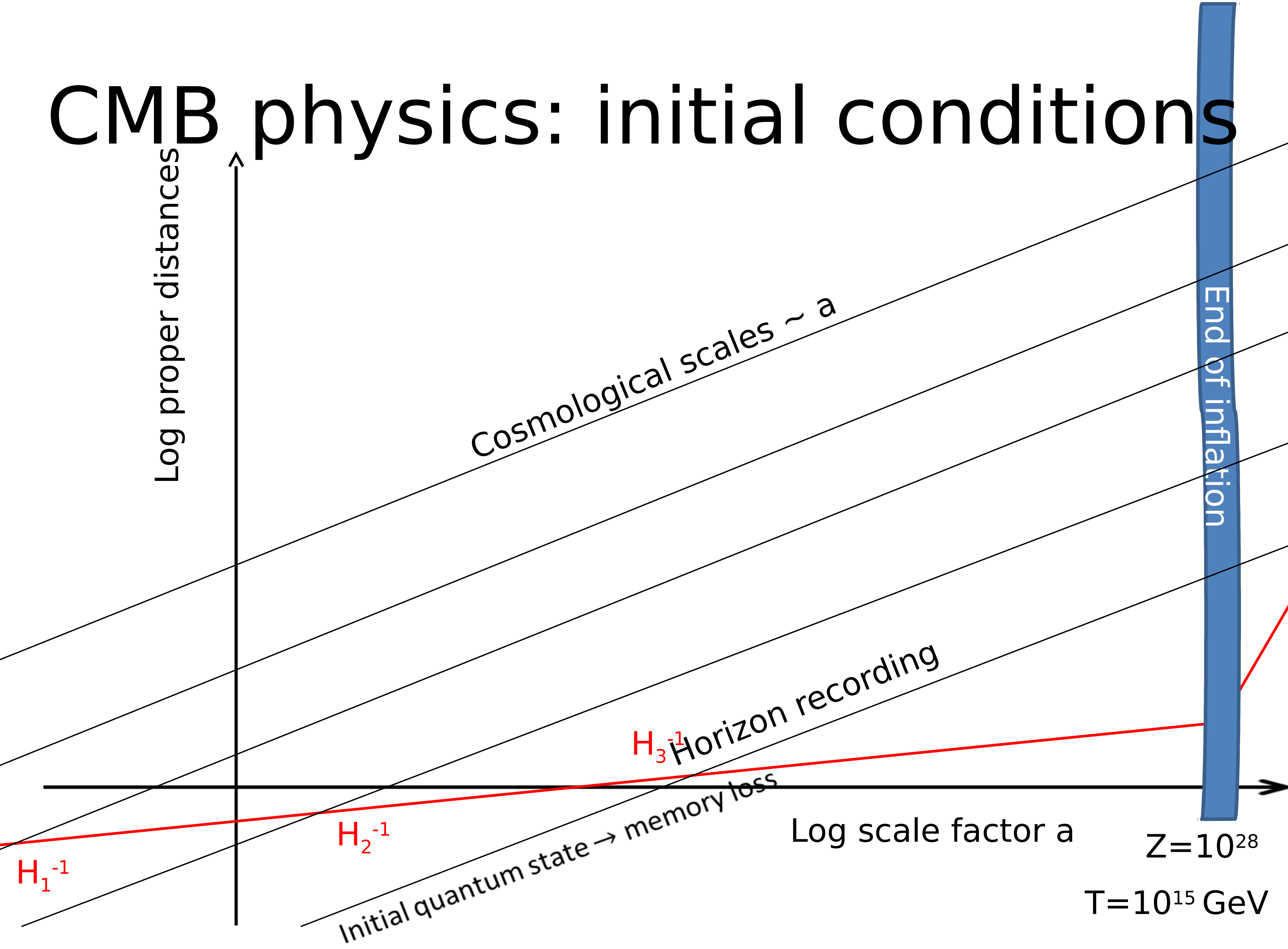
$$< |\Delta(\vec{x}, t)|^2 >= \frac{1}{2\pi^2} \int \frac{dk}{k} k^3 P_\Delta(k, t)$$

Harrison Zel’dovich spectrum, also known as scale invariant:

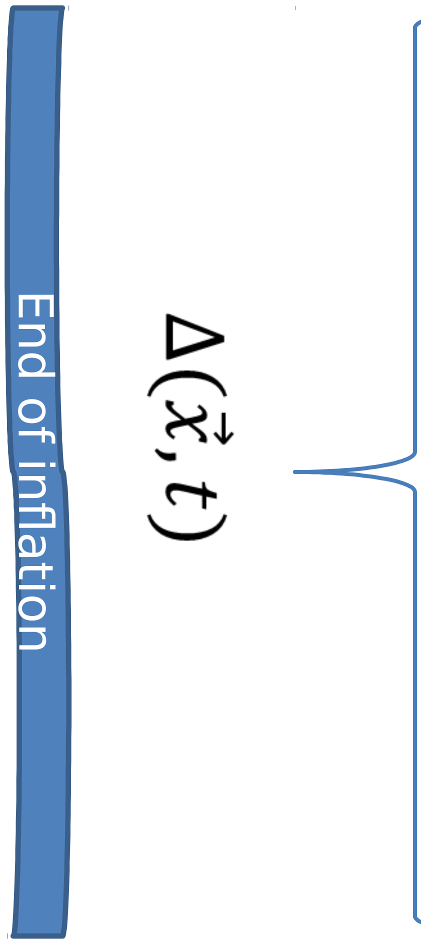
$$k^3 P_\Delta(k, t) = constant\ at\ horizon\ crossing, \Leftrightarrow \frac{a}{k} = H^{-1}$$

$$at\ a\ fixed\ time\ for\ all\ scales, P_\Delta(k) = normalizaton\ \times k$$

CMB physics: initial conditions



CMB physics: initial conditions



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$$at\ a\ fixed\ time\ for\ all\ scales, P_\Delta(k) = normalizaton\ \times k$$

$$P_\Delta(k) = normalizaton\ \times k^{n_s}$$

Inflation predicts $n_s < 1$

CMB physics: initial conditions

$$\Delta(\vec{x},t)$$

Questioning Gaussianity:

$$< \Delta(\vec{k},t)\bar{\Delta}(\vec{k}',t) > = P_{\Delta}(k,t)\ \delta(\vec{k}-\vec{k}')$$

Finite correlation:

$$< \Delta(\vec{k},t)\bar{\Delta}(\vec{k}',t) > = P_{\Delta}(k,t)\ e^{-(\vec{k}-\vec{k'})^2/2\sigma}$$

Usually expressed in terms of second order correction:

$$\Phi = \Phi(\Phi_G) \approx \Phi_G + f_{NL}\Phi_G{}^2$$

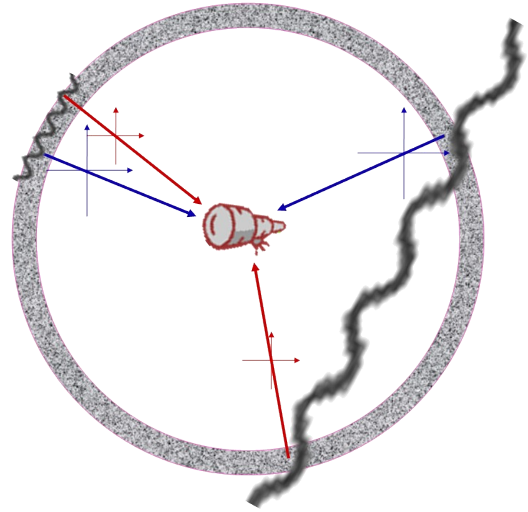
CMB physics: initial conditions

Non-scalar metric modes:

Vectors decay

Scalars and tensors keep constant

For total intensity, tensors they contribute on all scales:



CMB physics: initial conditions

End of inflation

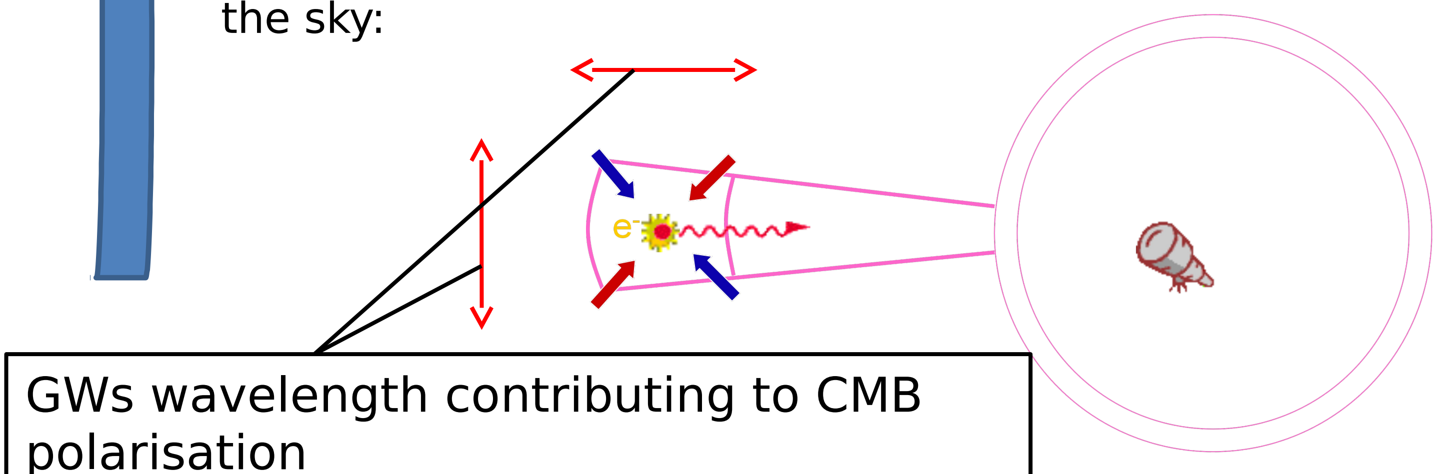
Non-scalar metric modes:

Vectors decay — Scalars and tensors keep constant

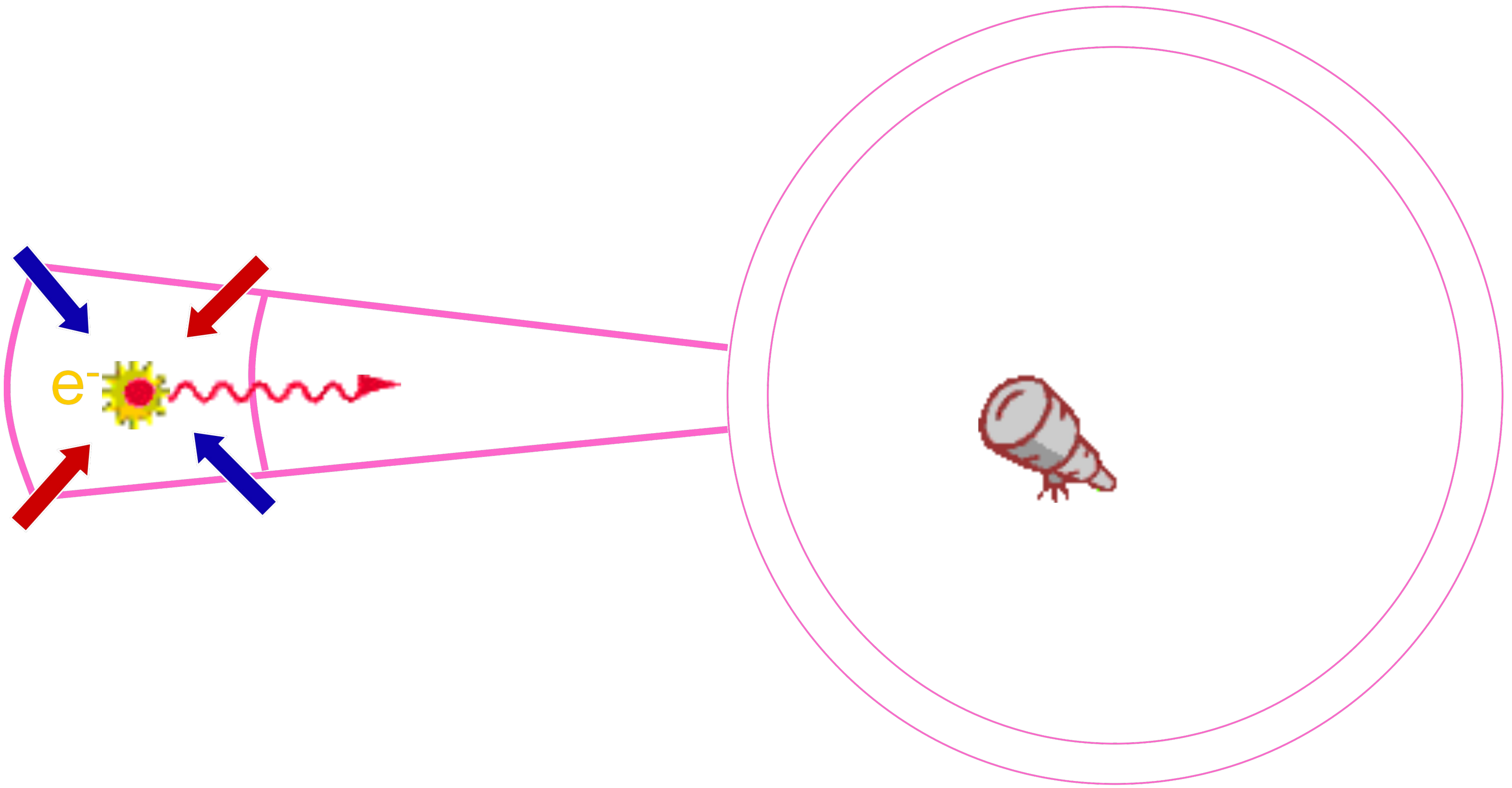
Tensors are not substained by radiation pressure when sub-horizon, implying rapid diffusion damping

Super-horizon tensor perturbation cannot be recorded in polarisation

Polarisation CMB anisotropies from tensors peak on the angular scale corresponding to the width of the last scattering region, about 1 degree in the sky:



The B-modes record GWs mono-chromatically in angle



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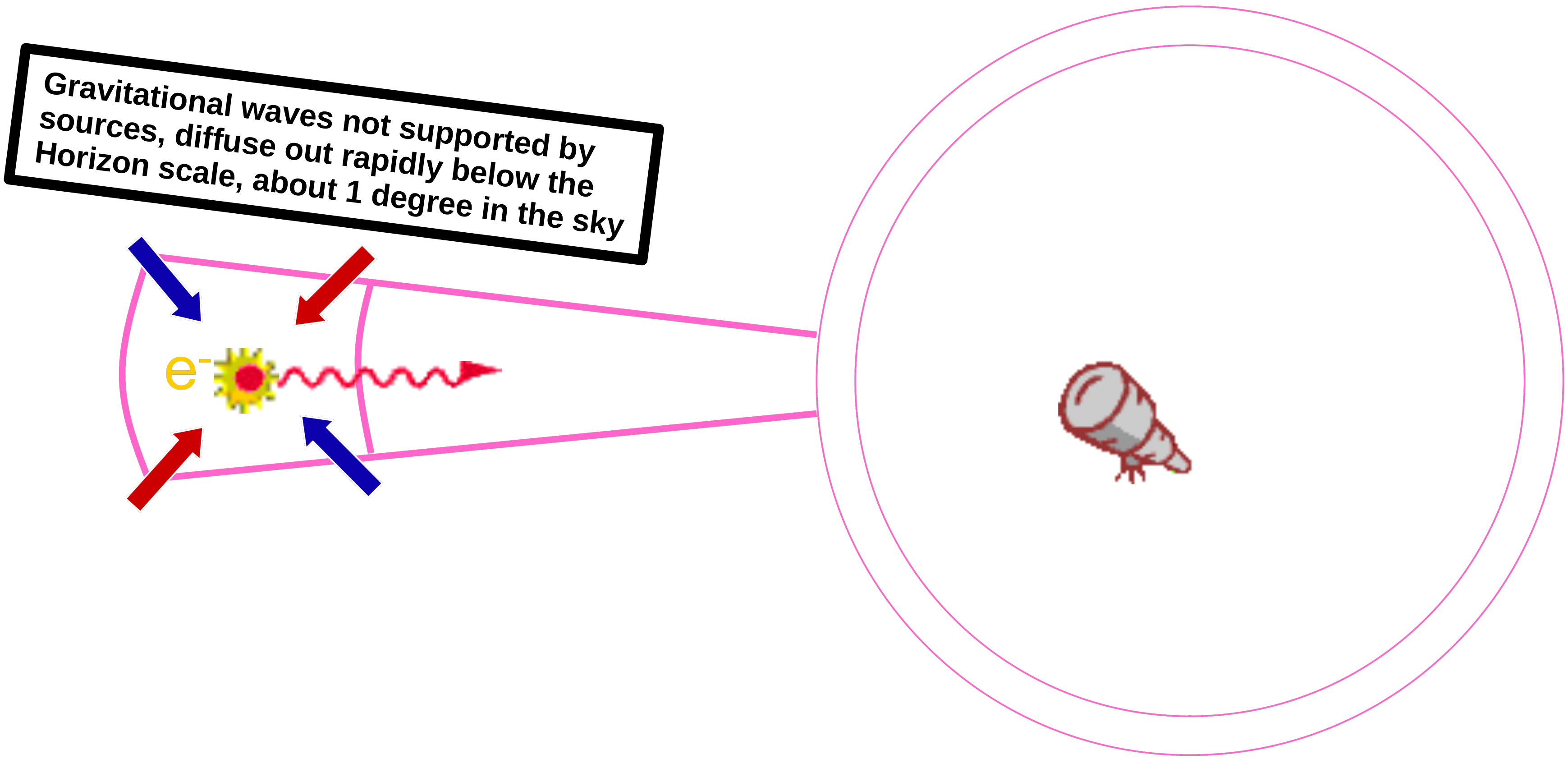

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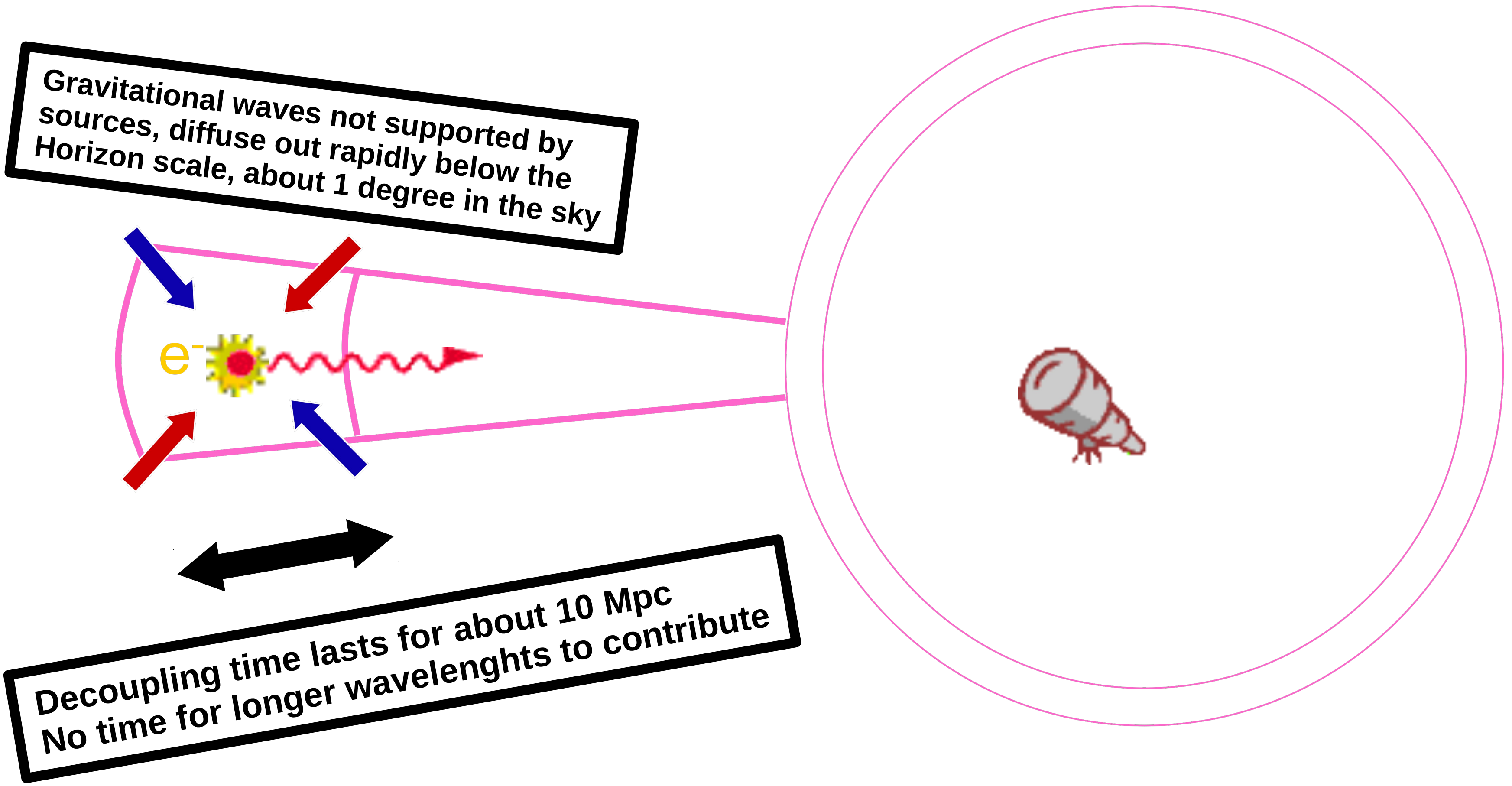

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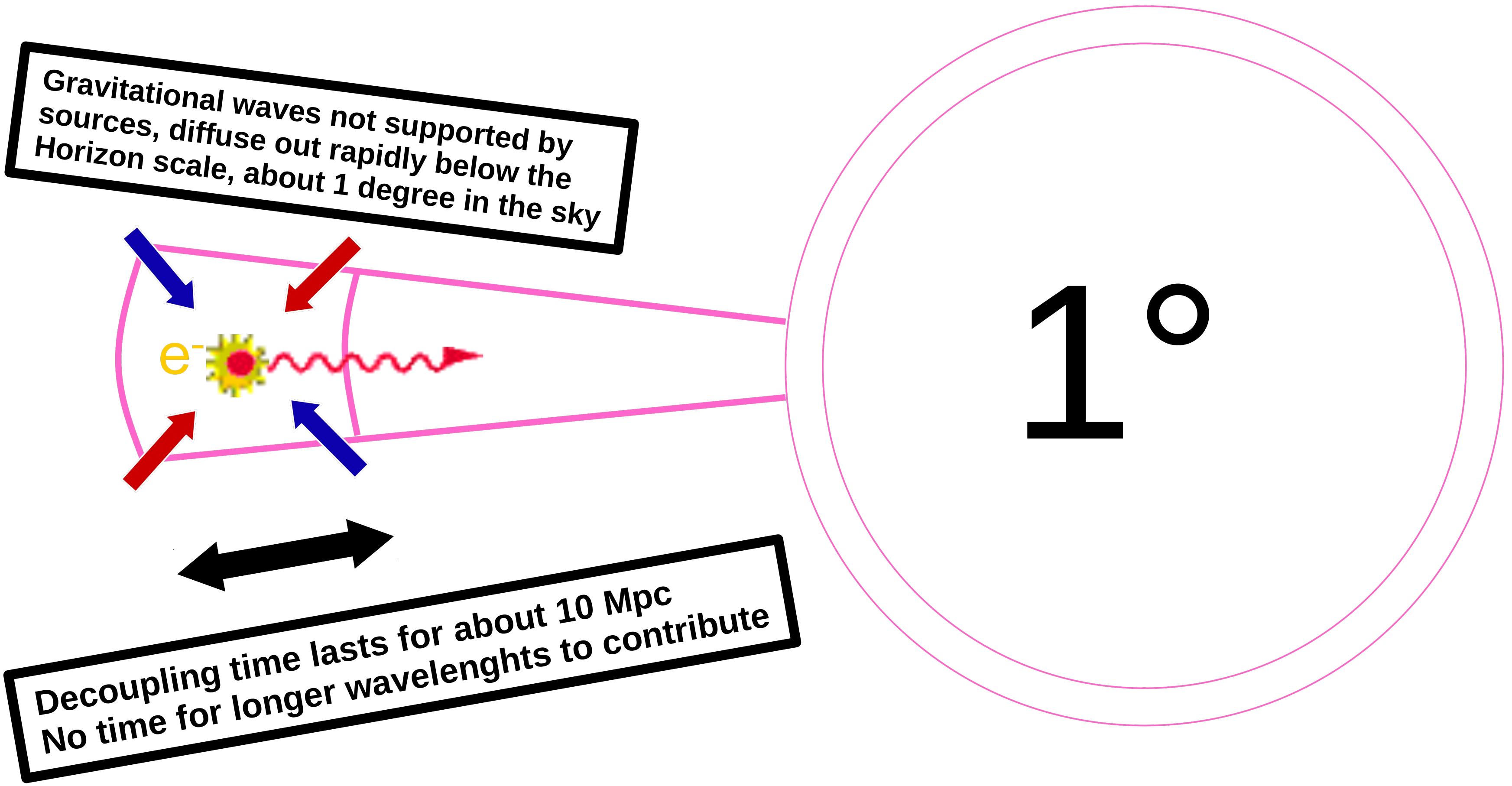
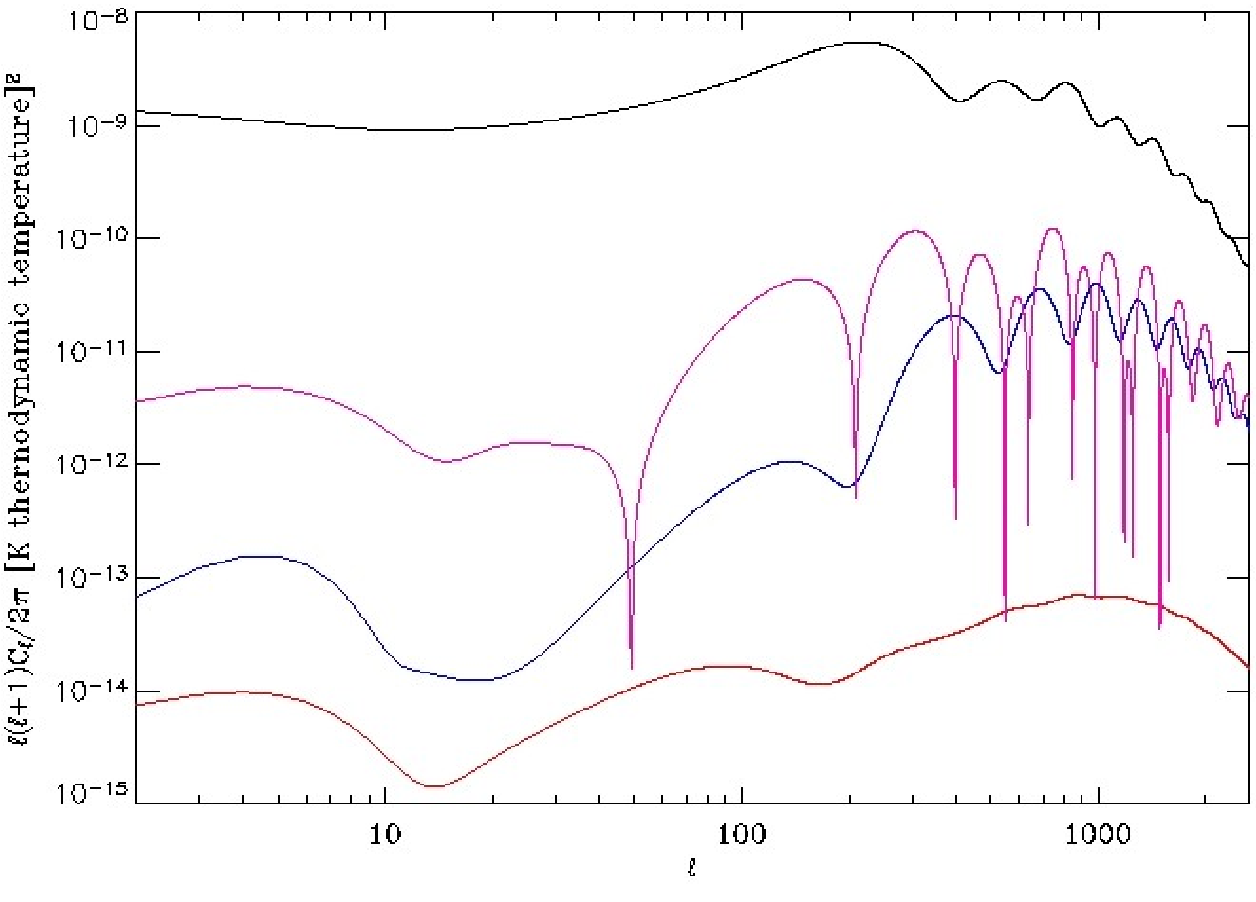
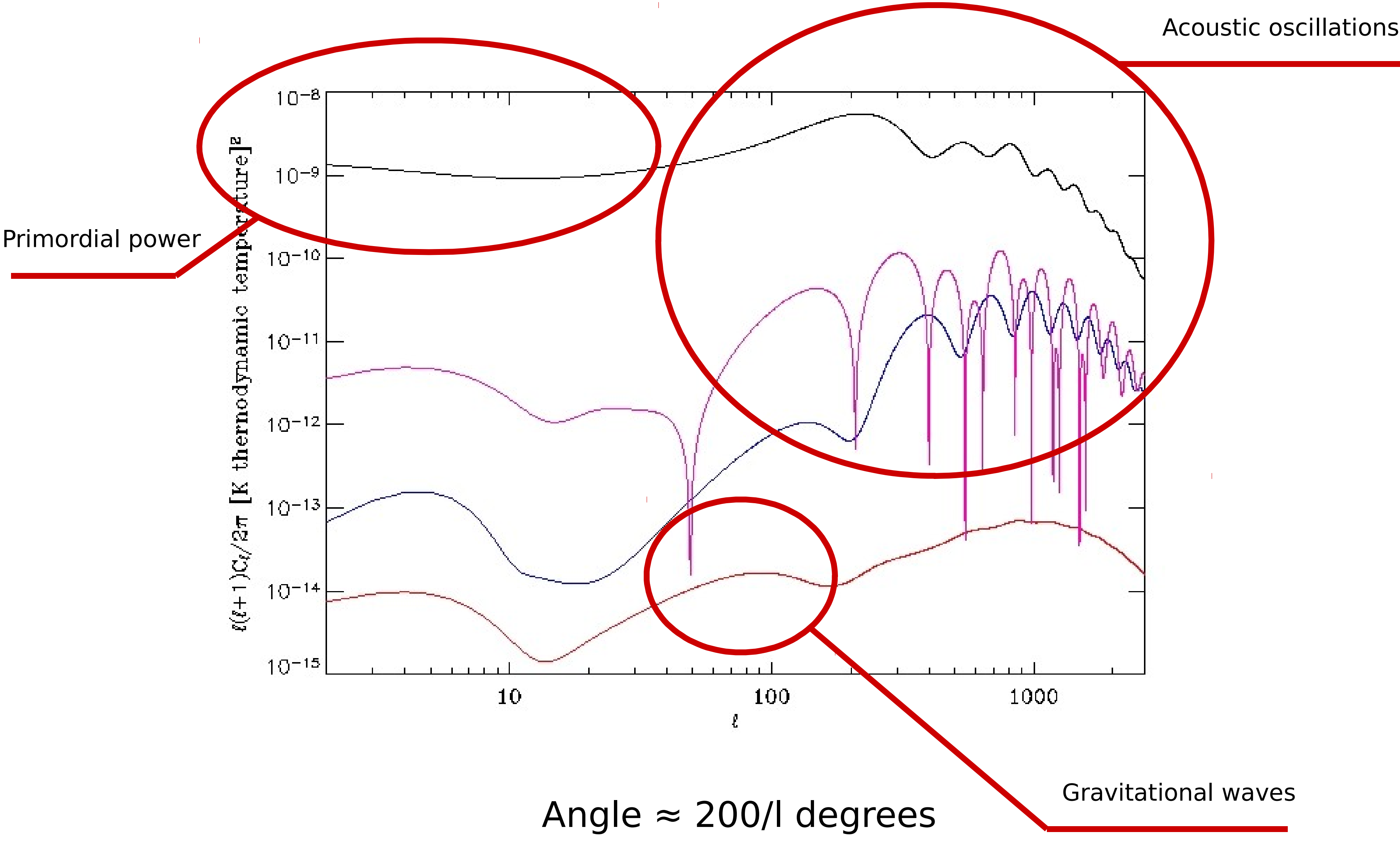


CMB angular power spectrum



Angle ≈ 200/l degrees

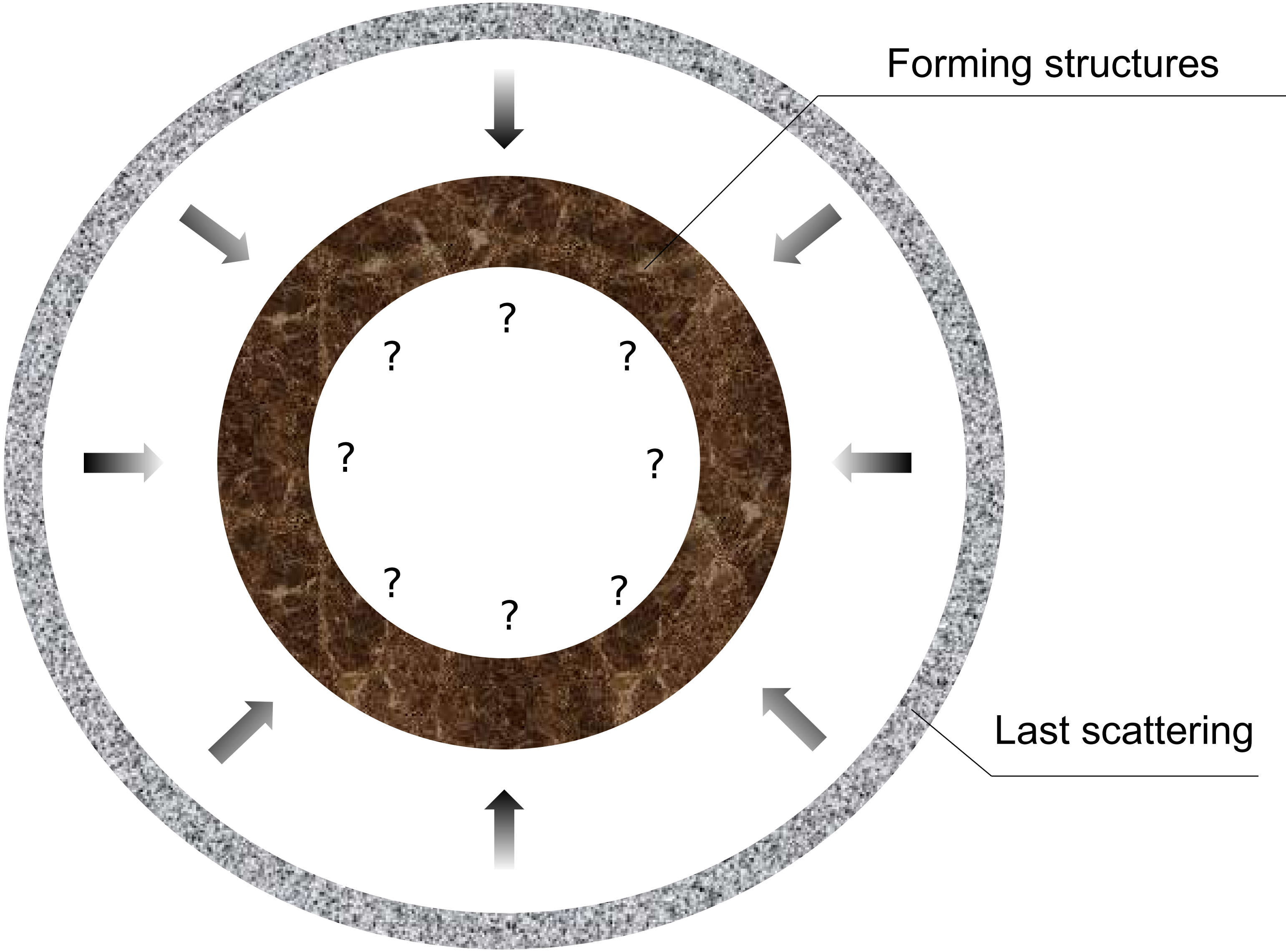
CMB angular power spectrum



Angle ≈ 200/l degrees

Large Scale Structure and Dark Energy

LSS effects on CMB



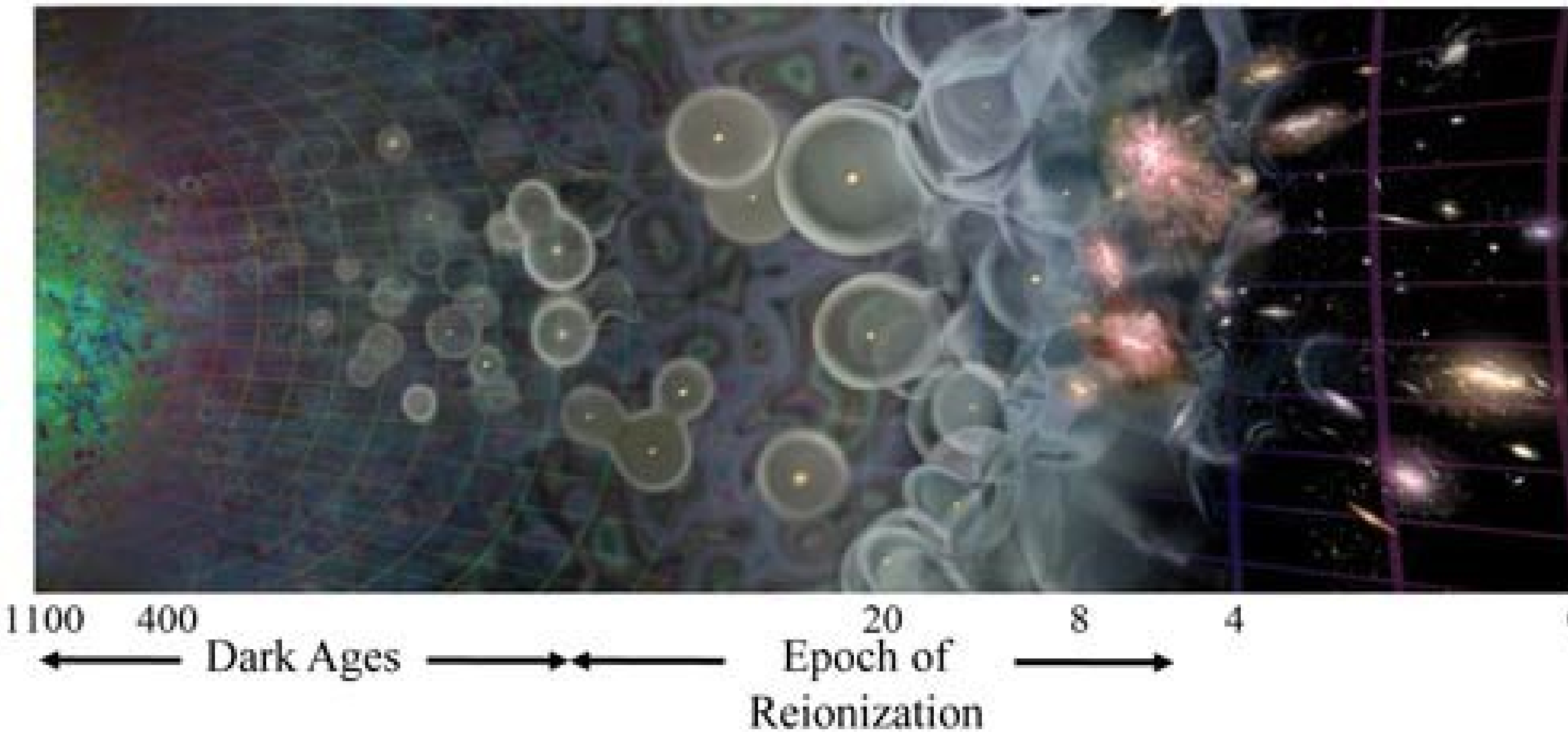
Categories for LSS effects on CMB

- Re-scattering
- Gravitation

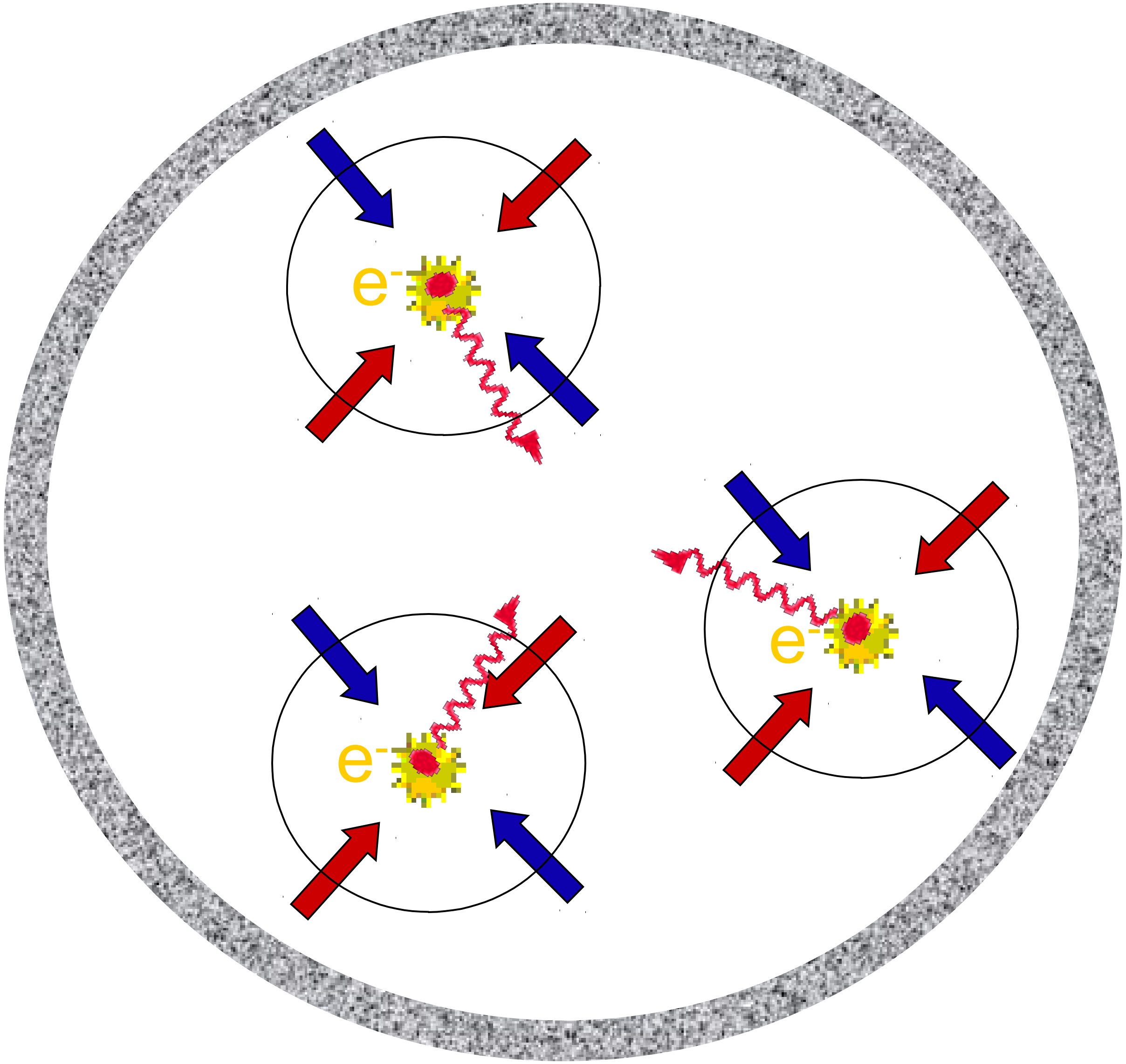
Categories for LSS effects on CMB

- Re-scattering
  - Re-ionization
- Gravitation
  - Time evolution of the metric tensor
  - Deflection

Reionization



CMB anisotropy: reionization



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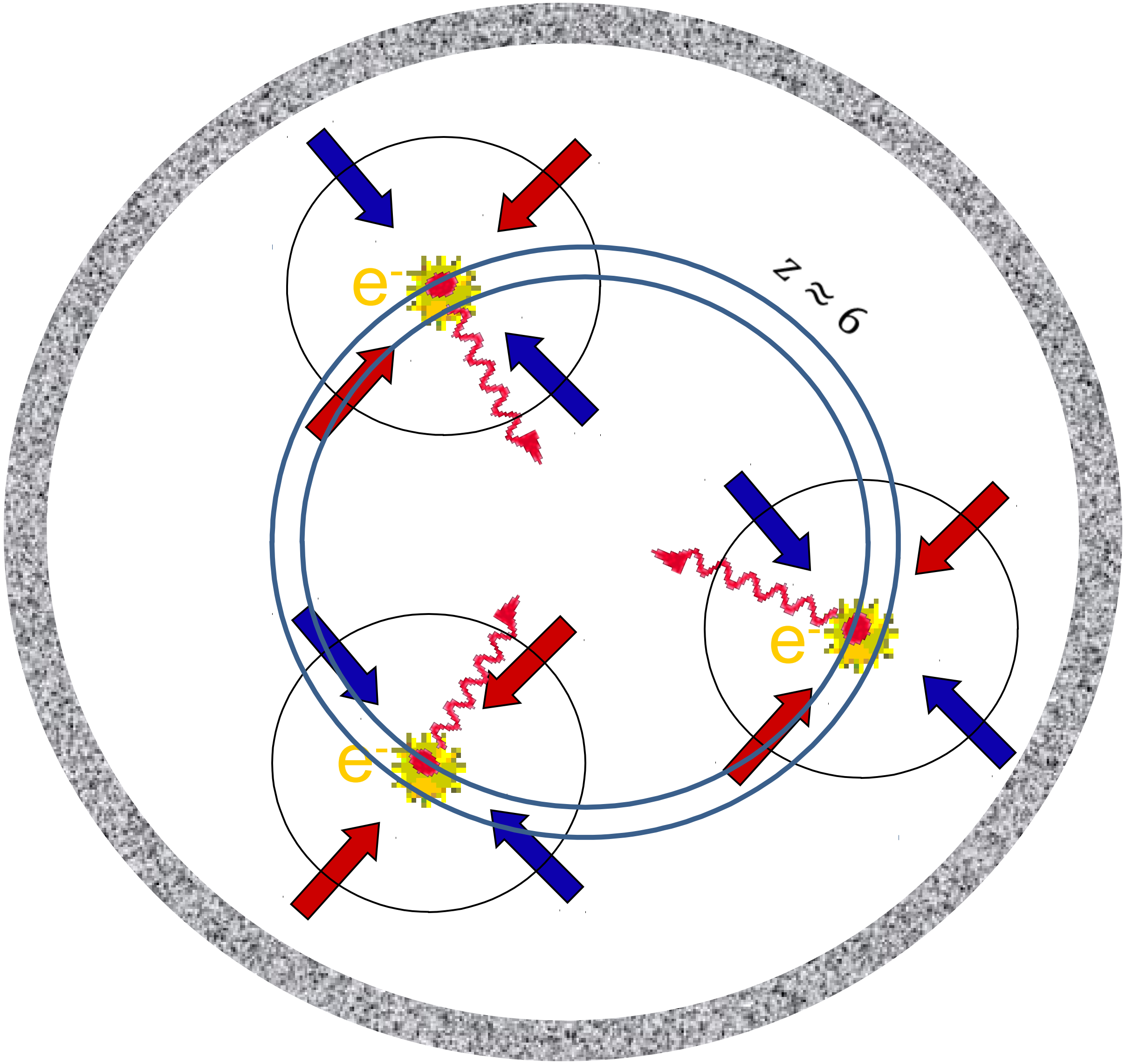

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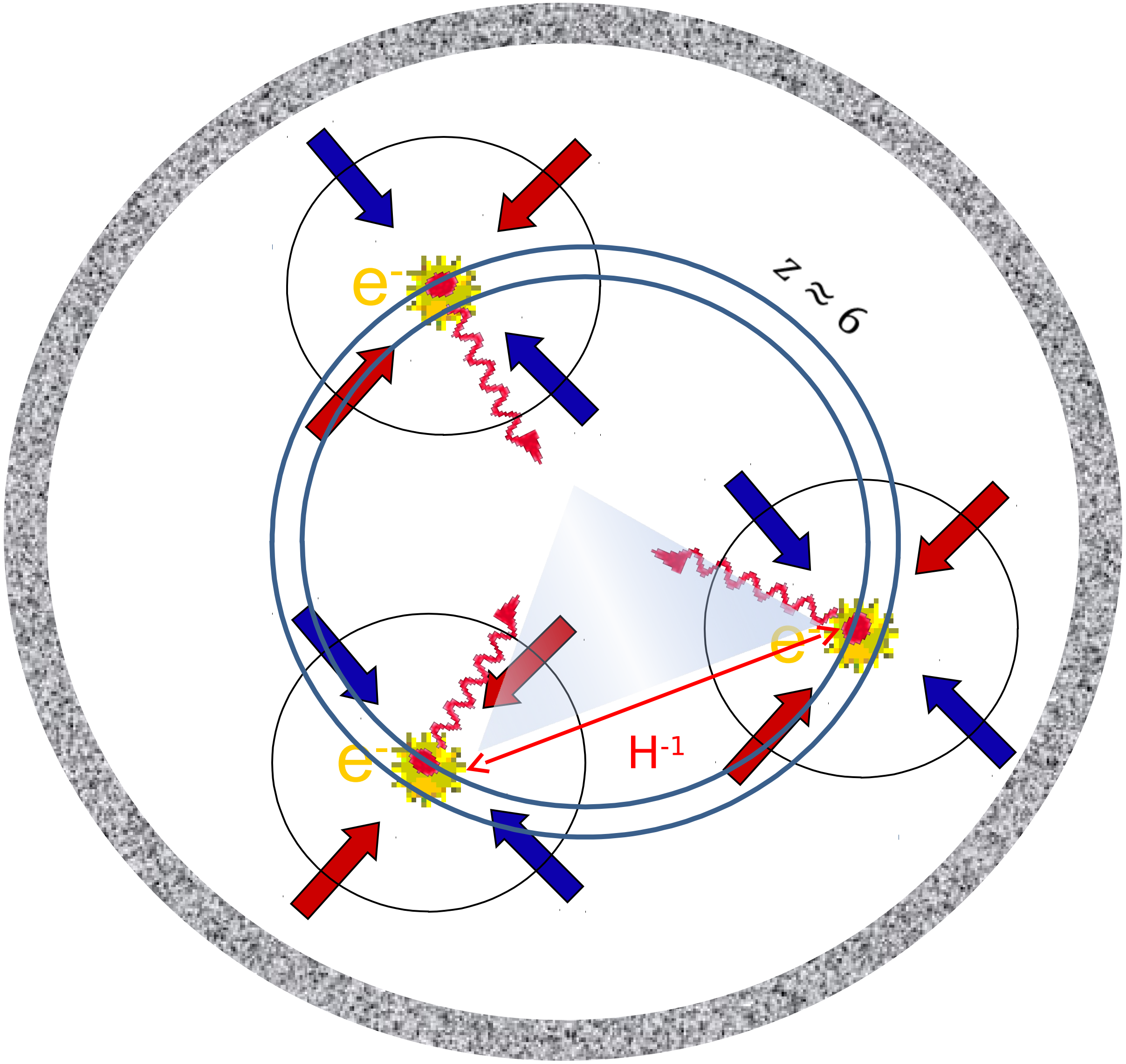
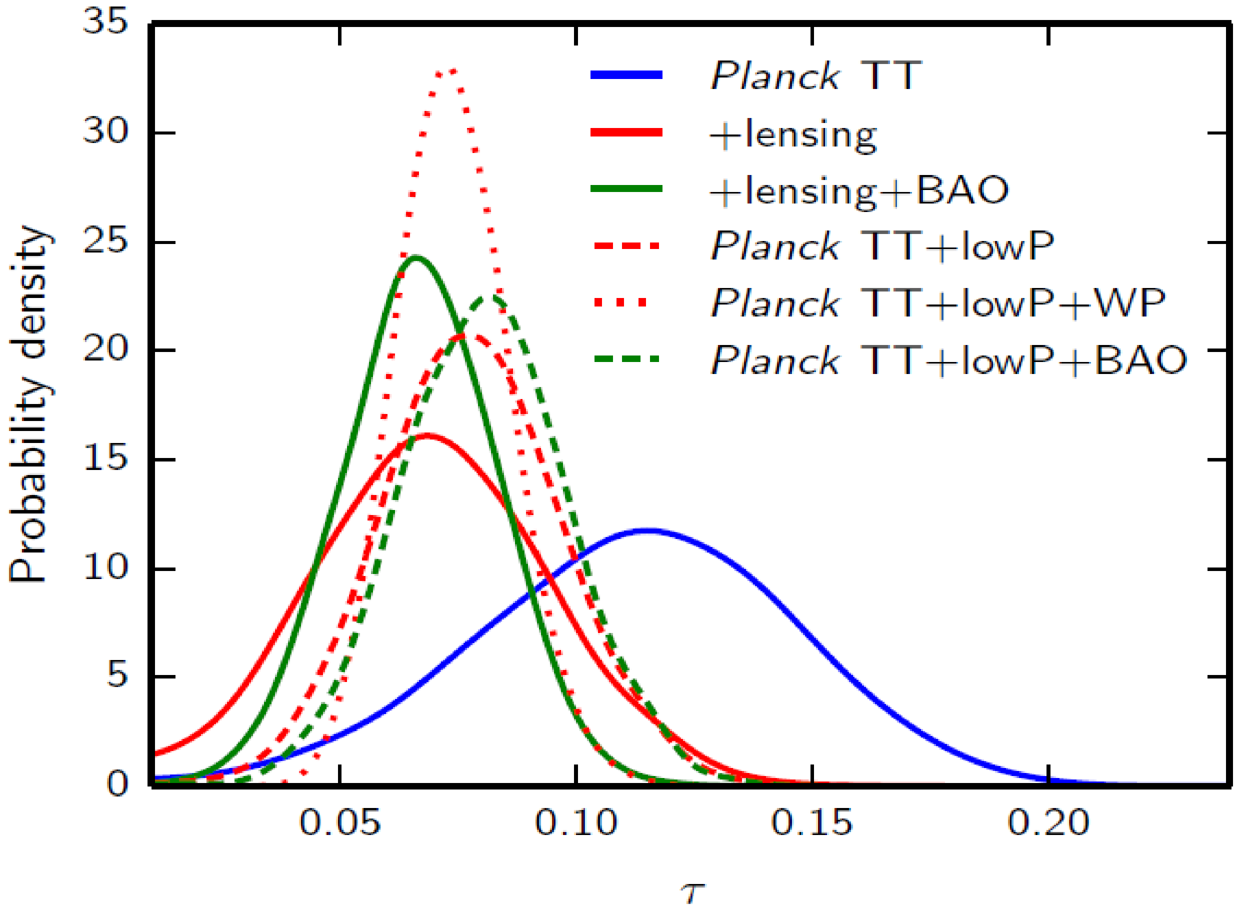
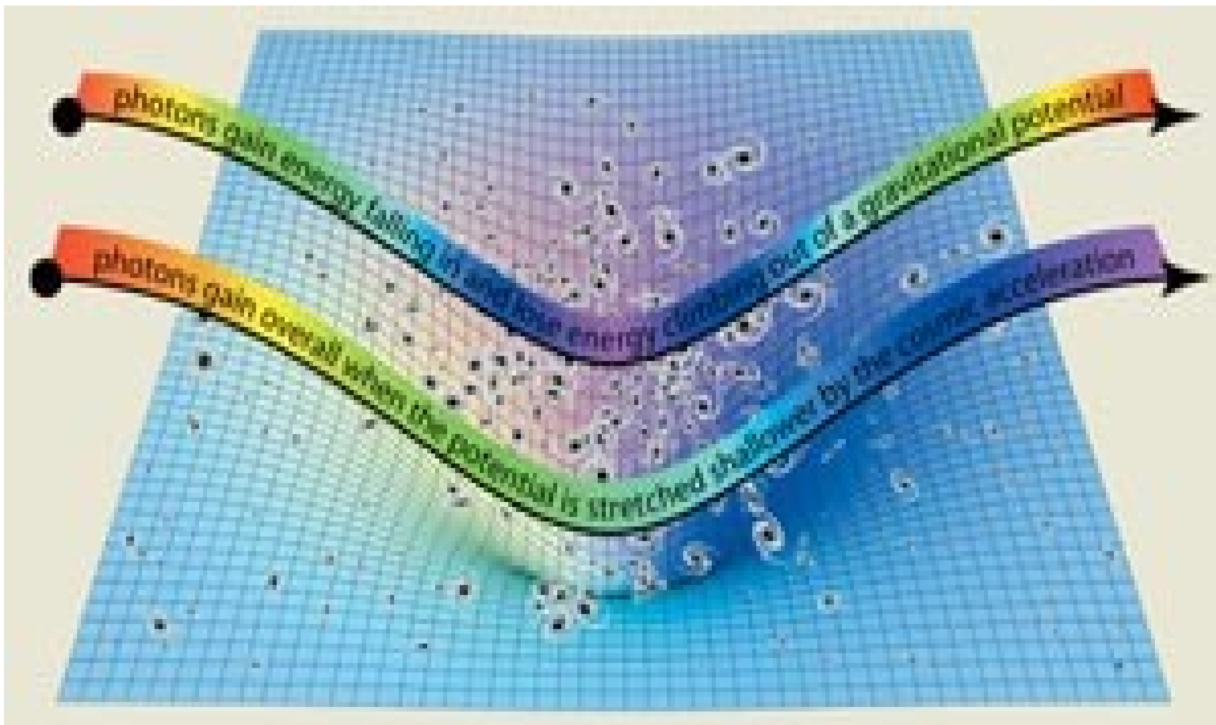


Planck 2015: reionization epoch



Integrated Sachs-Wolfe



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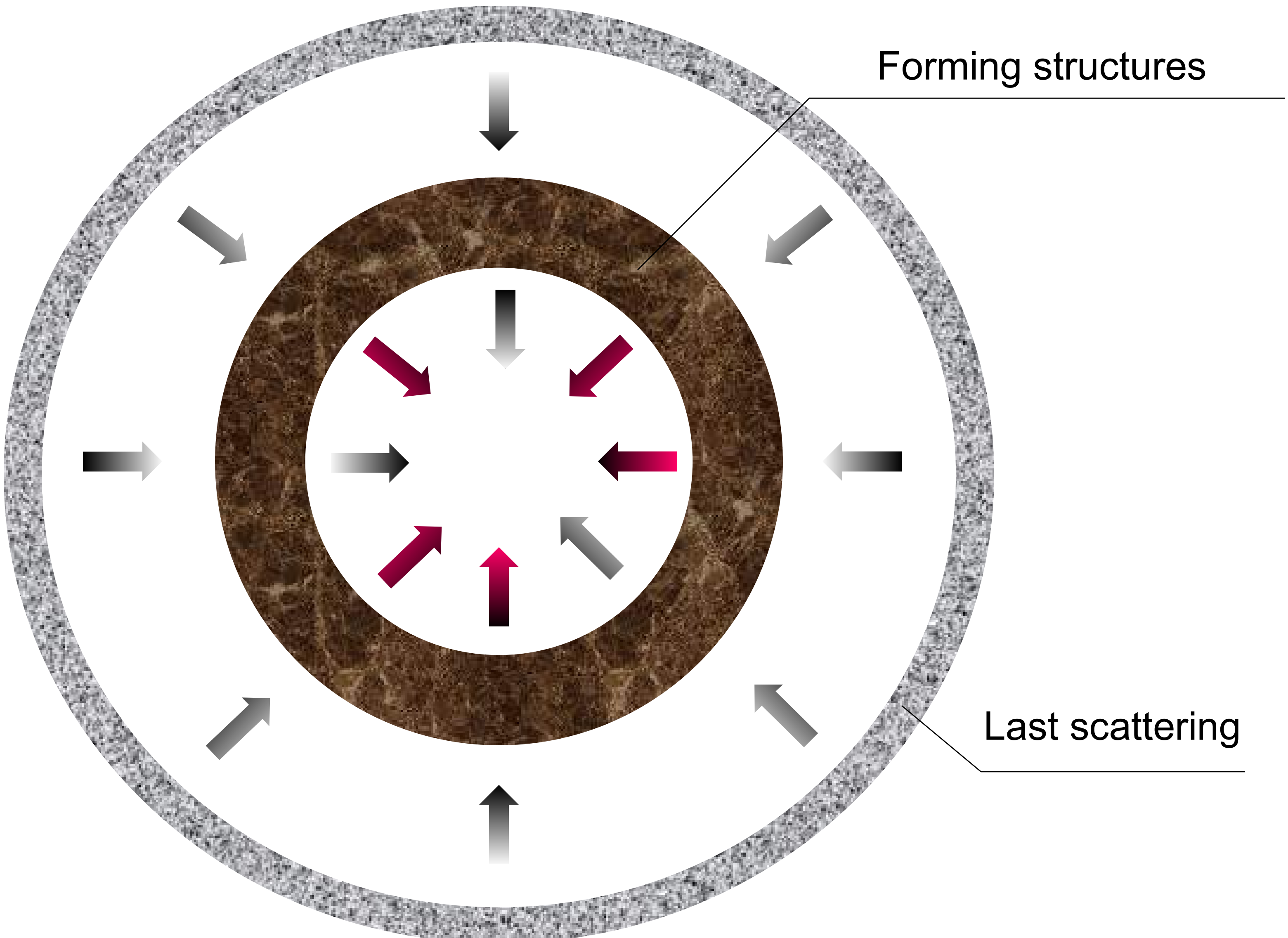
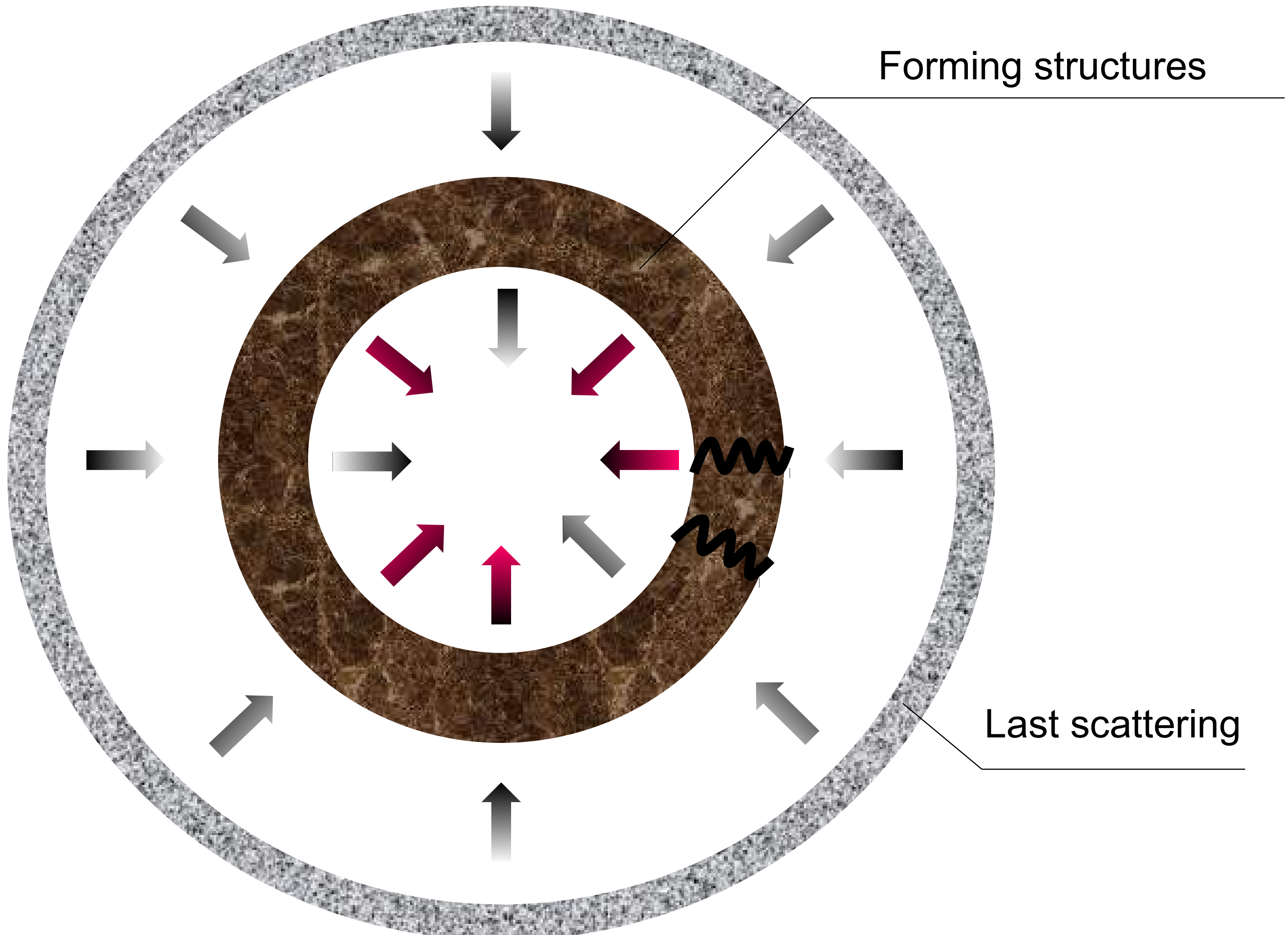


Sachs & Wolfe 1967

Integrated Sachs-Wolfe



Sachs & Wolfe 1967

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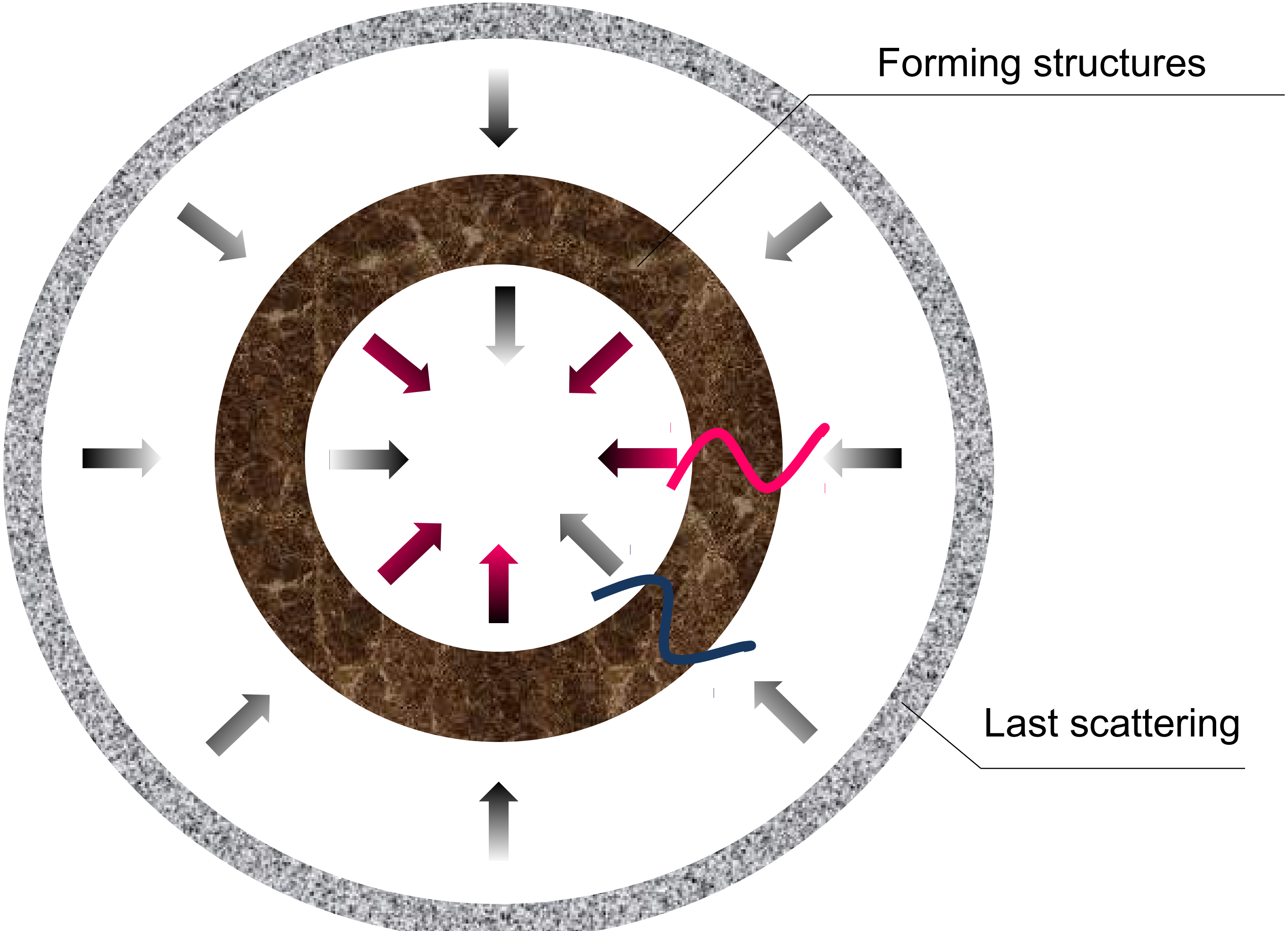

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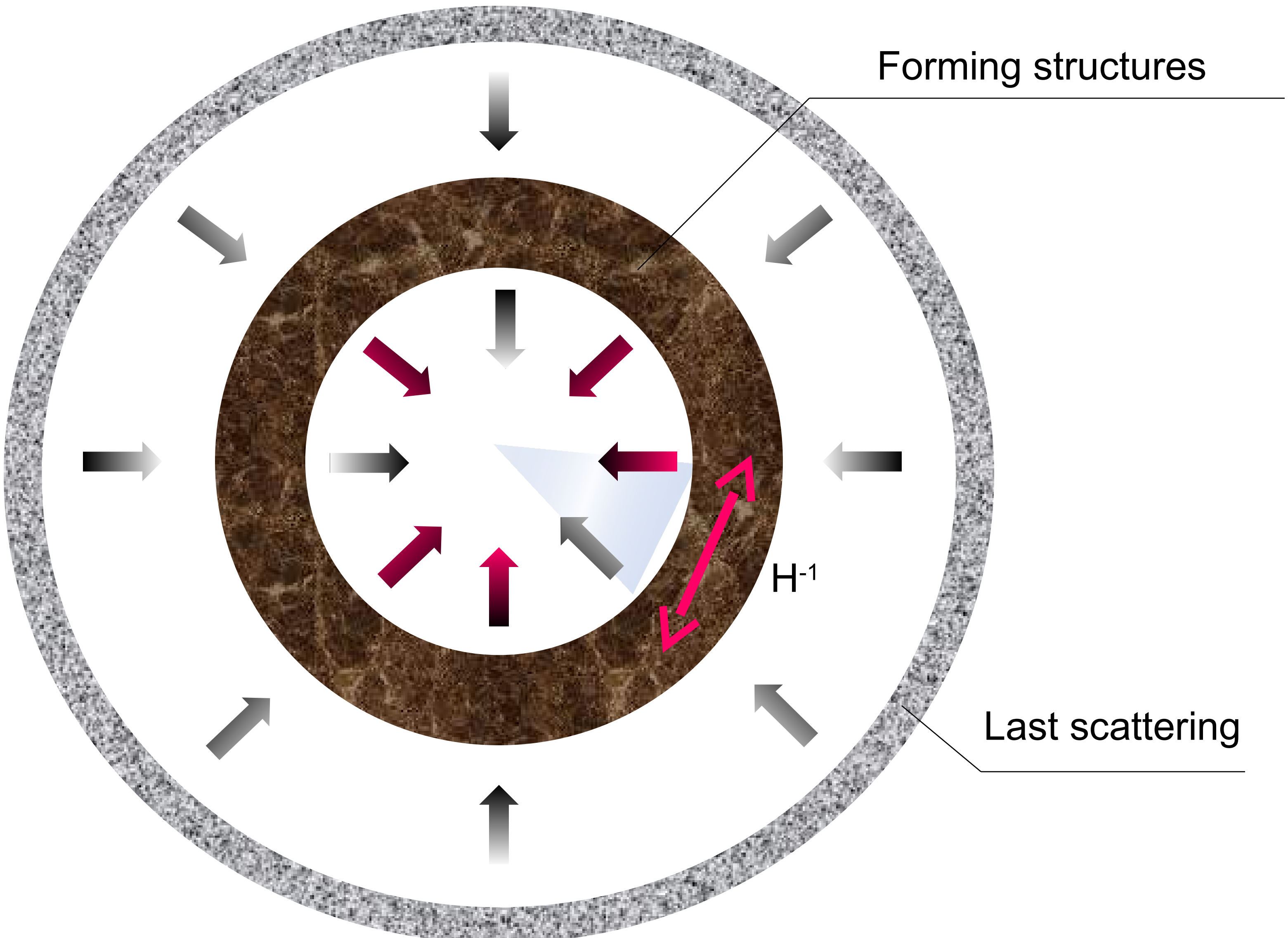

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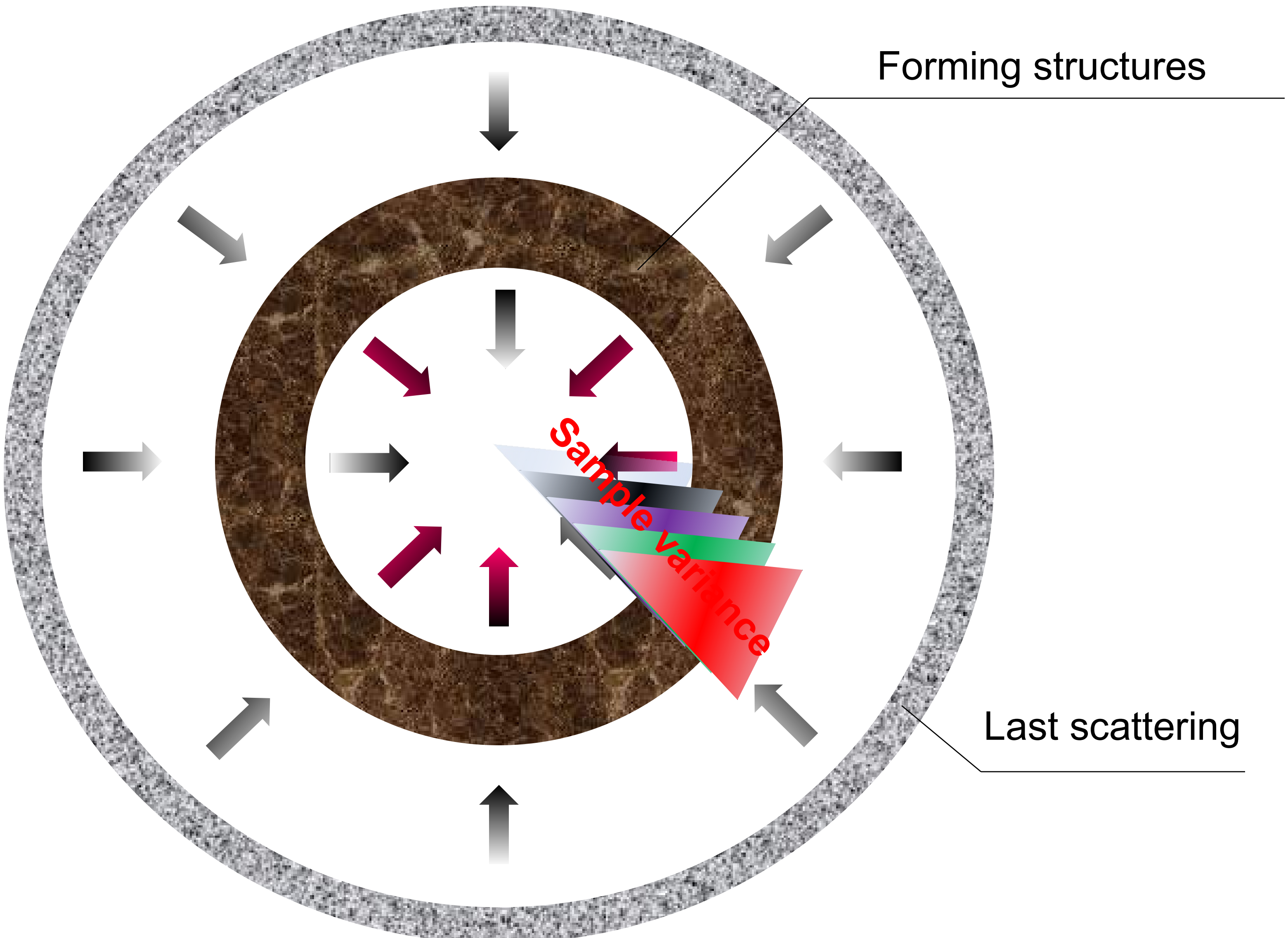

Sachs & Wolfe 1967

Cross-correlating with LSS

$$\frac{\Delta T}{T}^{\rm ISW}(\hat{\rm n}) = -2\int \dot{\Phi}[\eta, \hat{\rm n}(\eta_0 - \eta)]d\eta \qquad \delta_{\rm g}(\hat{\rm n}_1) = \int f(z)\delta_{\rm m}(\hat{\rm n}_1, z)dz = \int b_{\rm g}(z)\frac{dN}{dz}(z)\delta_{\rm m}(\hat{\rm n}_1, z)dz$$

$$C^{\rm gT}(\theta) \equiv \left\langle \frac{\Delta T}{T}(\hat{\rm n}_1)\delta_{\rm g}(\hat{\rm n}_2)\right\rangle = \sum_{\ell=2}^{\infty}\frac{2\ell+1}{4\pi}C_\ell^{\rm gT}P_\ell[\cos(\theta)]\exp[-0.5(\theta_s\ell)^2]$$

$$C_\ell^{\rm gT} = \frac{2}{\pi}\int k^2 dk P(k) I_\ell^{\rm ISW}(k) I_\ell^{\rm g}(k)$$

$$I_\ell^{\rm ISW}(k) = -2\int \frac{d\Phi(k)}{dz} j_\ell[k\chi(z)]dz \qquad I_\ell^{\rm g}(k) = \int b_{\rm g}(z)\frac{dN}{dz}(z)\delta_{\rm m}(k,z) j_\ell[k\chi(z)]dz$$

Cross-correlating with LSS

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Perturbation **statistics and dynamics** → early Universe

Cross-correlating with LSS

$$\frac{\Delta T}{T}^{\rm ISW}(\hat{\rm n}) = -2\int \dot{\Phi}[\eta, \hat{\rm n}(\eta_0-\eta)]d\eta \qquad \delta_{\rm g}(\hat{\rm n}_1) = \int f(z)\delta_{\rm m}(\hat{\rm n}_1, z)dz = \int b_{\rm g}(z)\frac{dN}{dz}(z)\delta_{\rm m}(\hat{\rm n}_1, z)dz$$

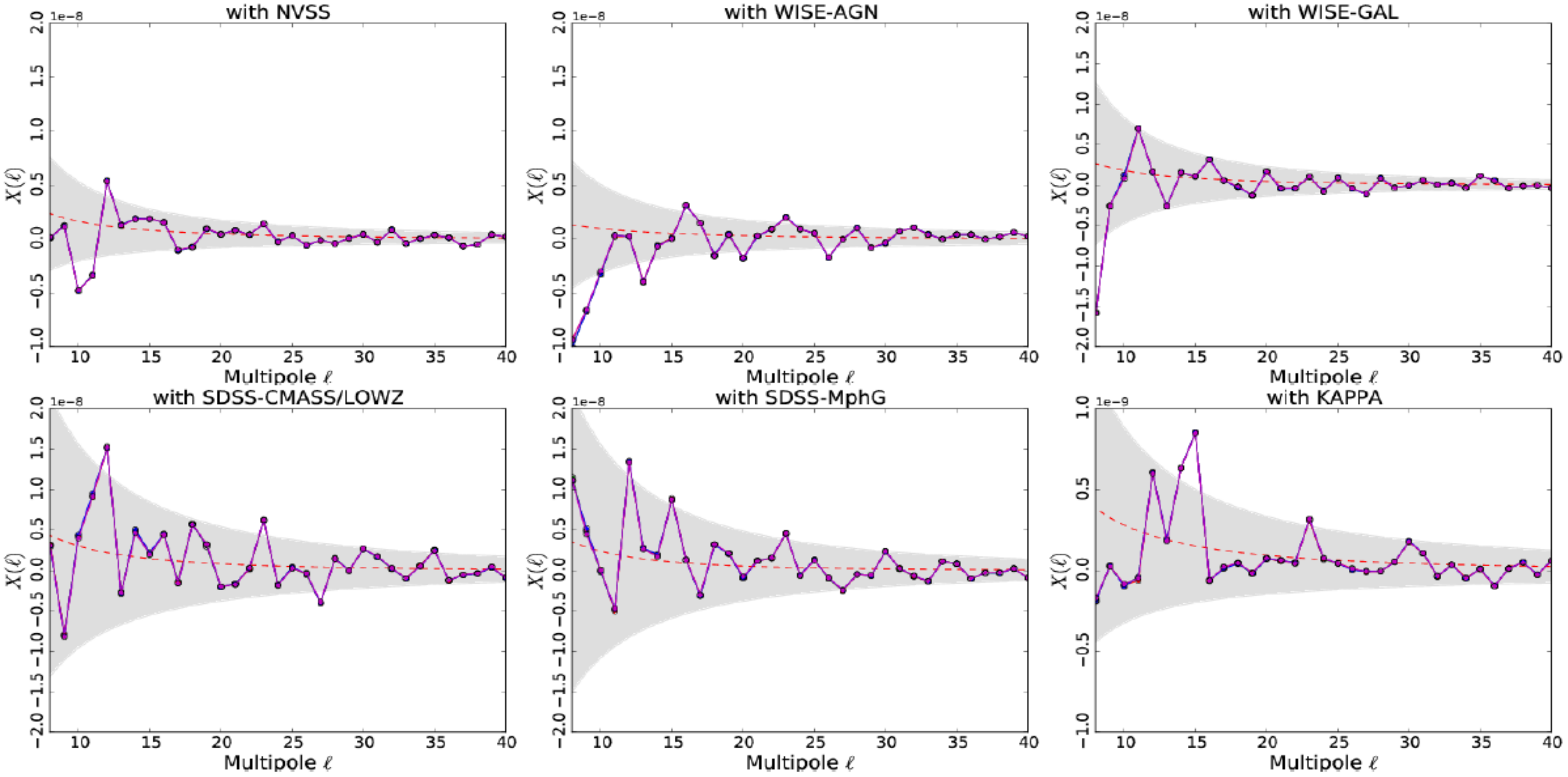
$$C^{\rm gT}(\theta) \equiv \left\langle \frac{\Delta T}{T}(\hat{\rm n}_1)\delta_{\rm g}(\hat{\rm n}_2)\right\rangle = \sum_{\ell=2}^{\infty}\frac{2\ell+1}{4\pi}C_\ell^{\rm gT}P_\ell[\cos(\theta)]\exp[-0.5(\theta_s\ell)^2]$$

$$C_\ell^{\rm gT} = \frac{2}{\pi}\int k^2 dk P(k) I_\ell^{\rm ISW}(k) I_\ell^{\rm g}(k)$$

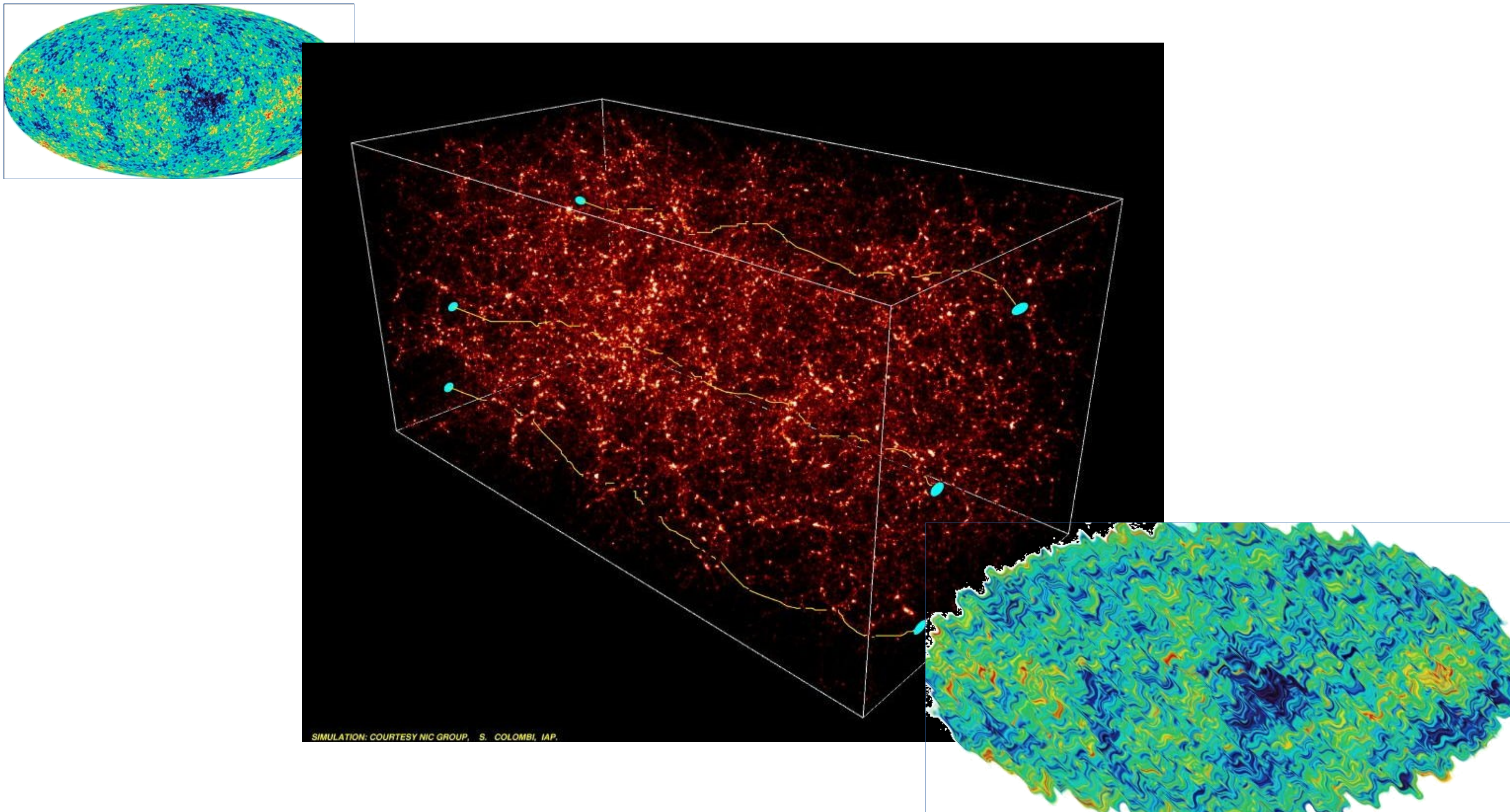
$$I_\ell^{\rm ISW}(k) = -2\int \frac{d\Phi(k)}{dz} j_\ell[k\chi(z)]dz \qquad I_\ell^{\rm g}(k) = \int b_{\rm g}(z)\frac{dN}{dz}(z)\delta_{\rm m}(k,z) j_\ell[k\chi(z)]dz$$

Geometry and **perturbation dynamics** → dark energy effects

Planck 2015: non-zero ISW-LSS Cross-Spectra at 4σ

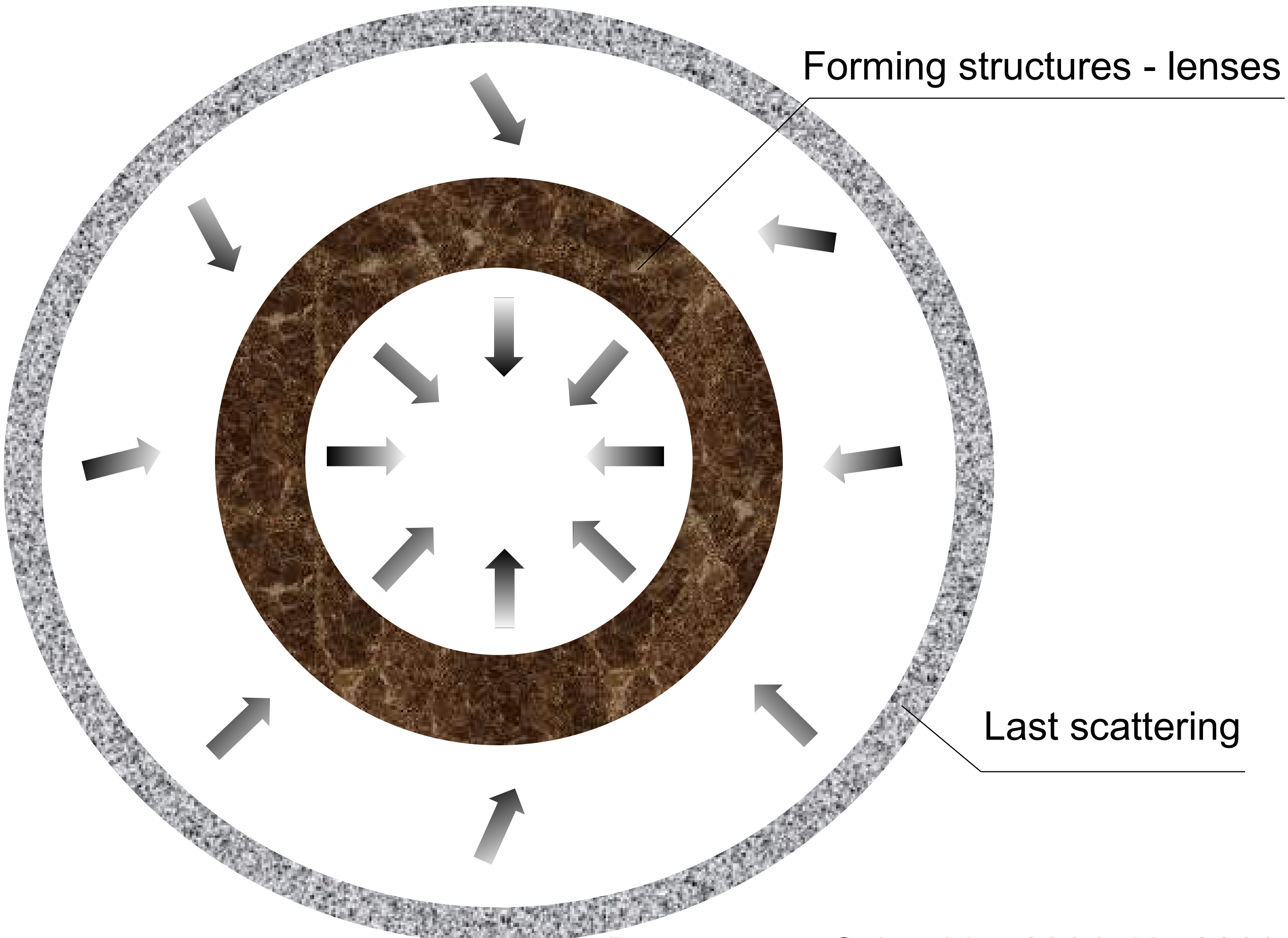


CMB lensing



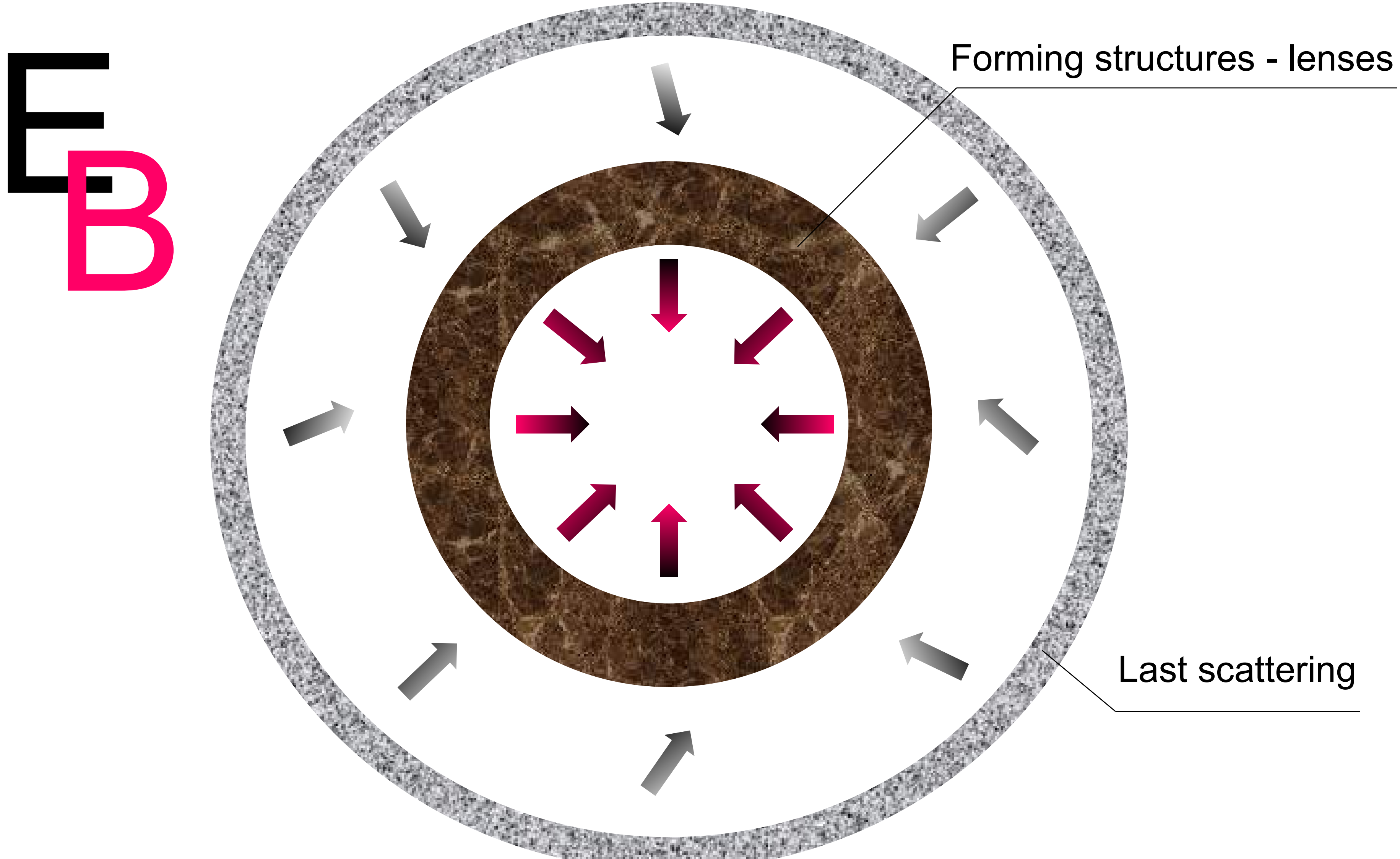
CMB lensing

T



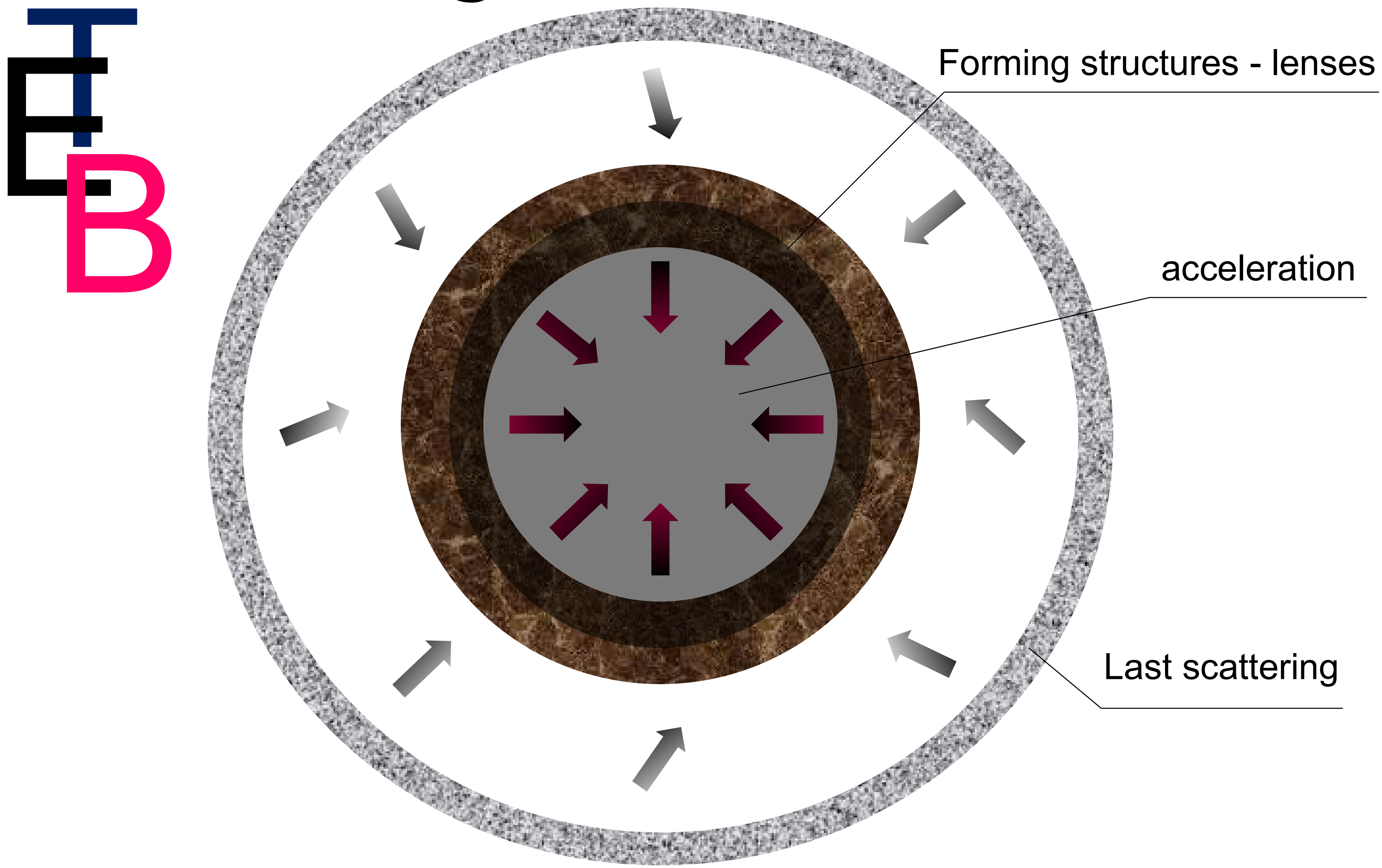
Bartelmann, Schneider 2001, Hu 2000

CMB lensing



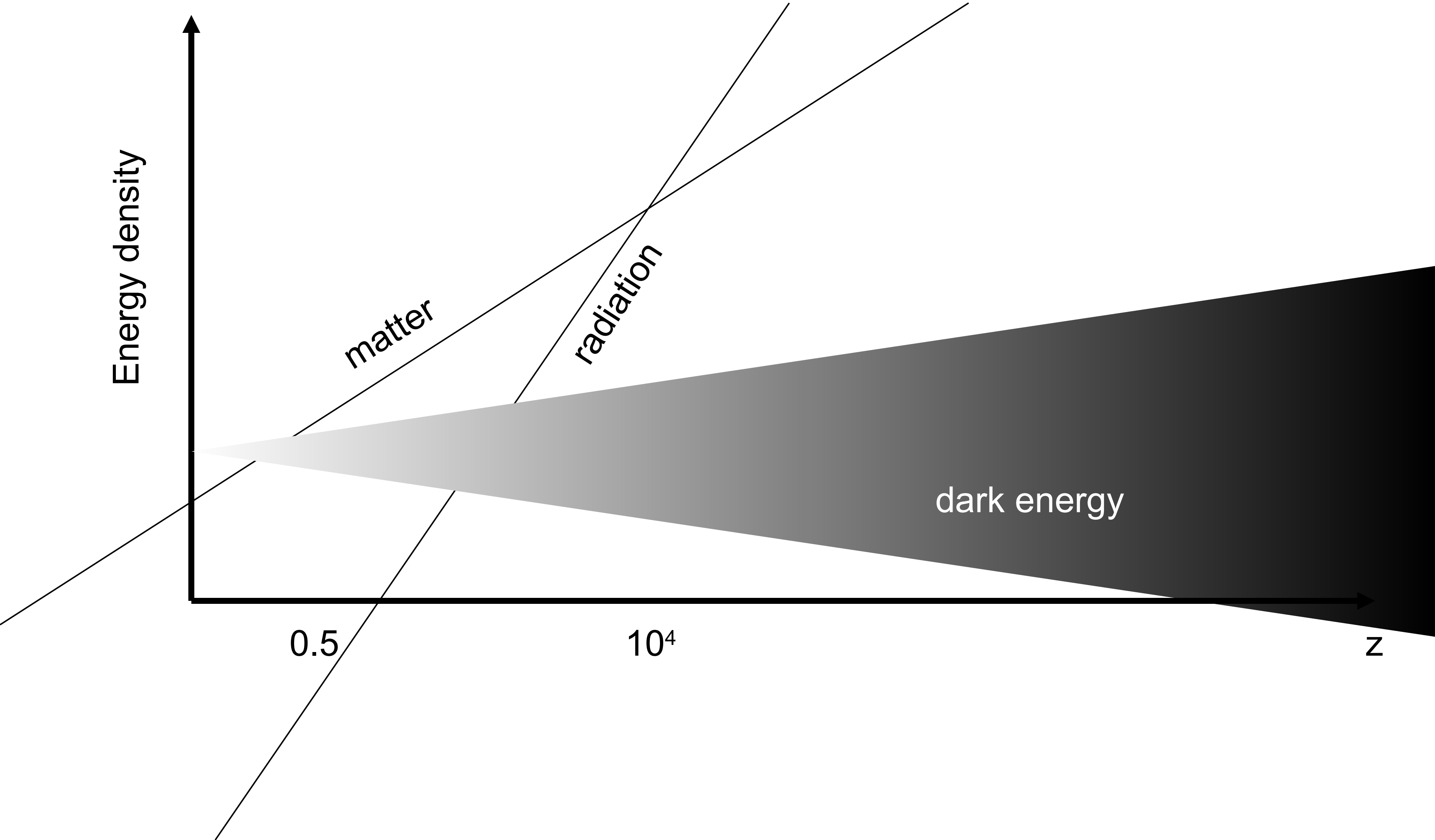
Kamionkowski, Kosowsky & Stebbins, Zaldarriaga & Seljak1998

CMB lensing

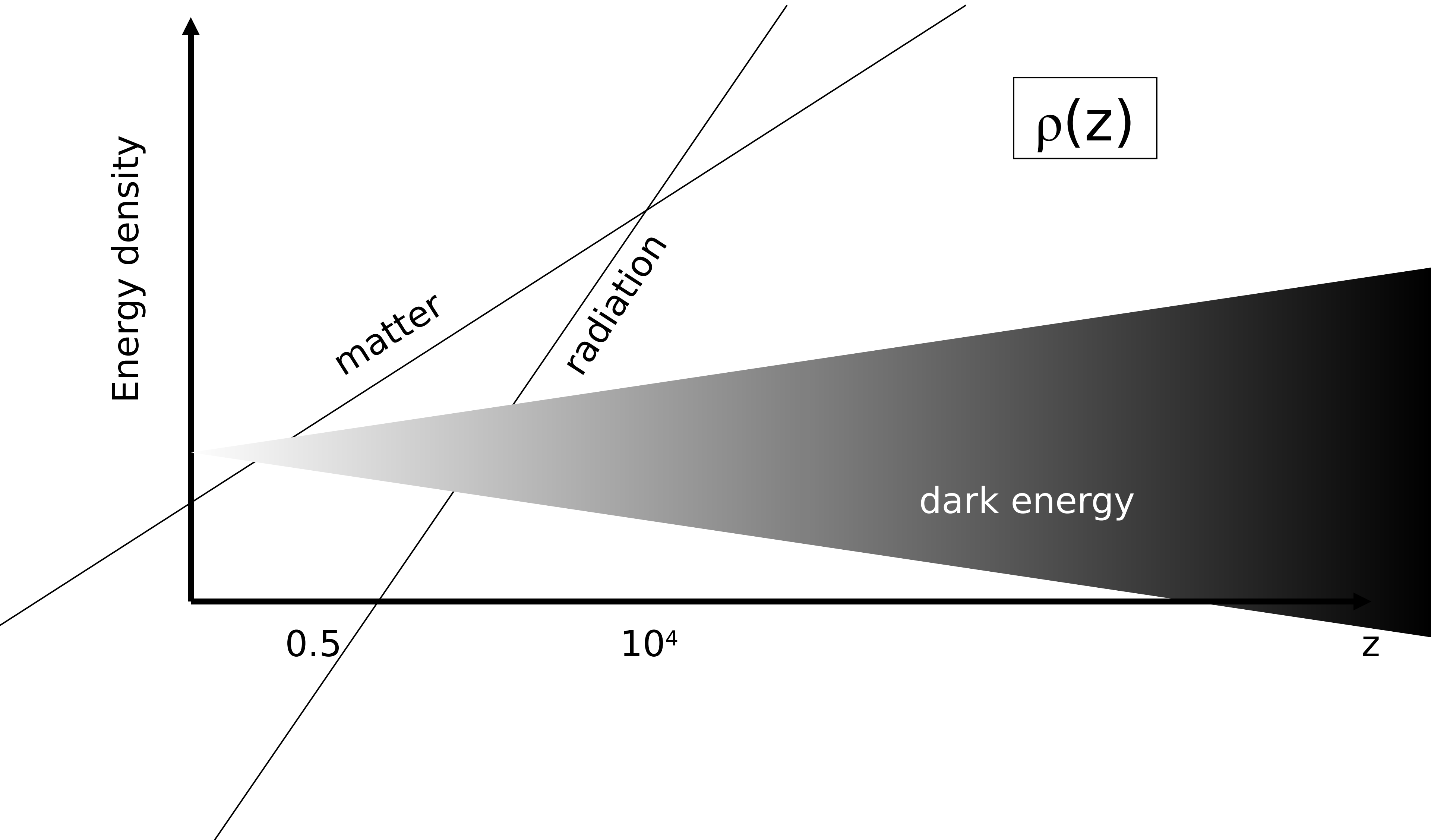


T
E
B
Forming structures - lenses
acceleration
Last scattering

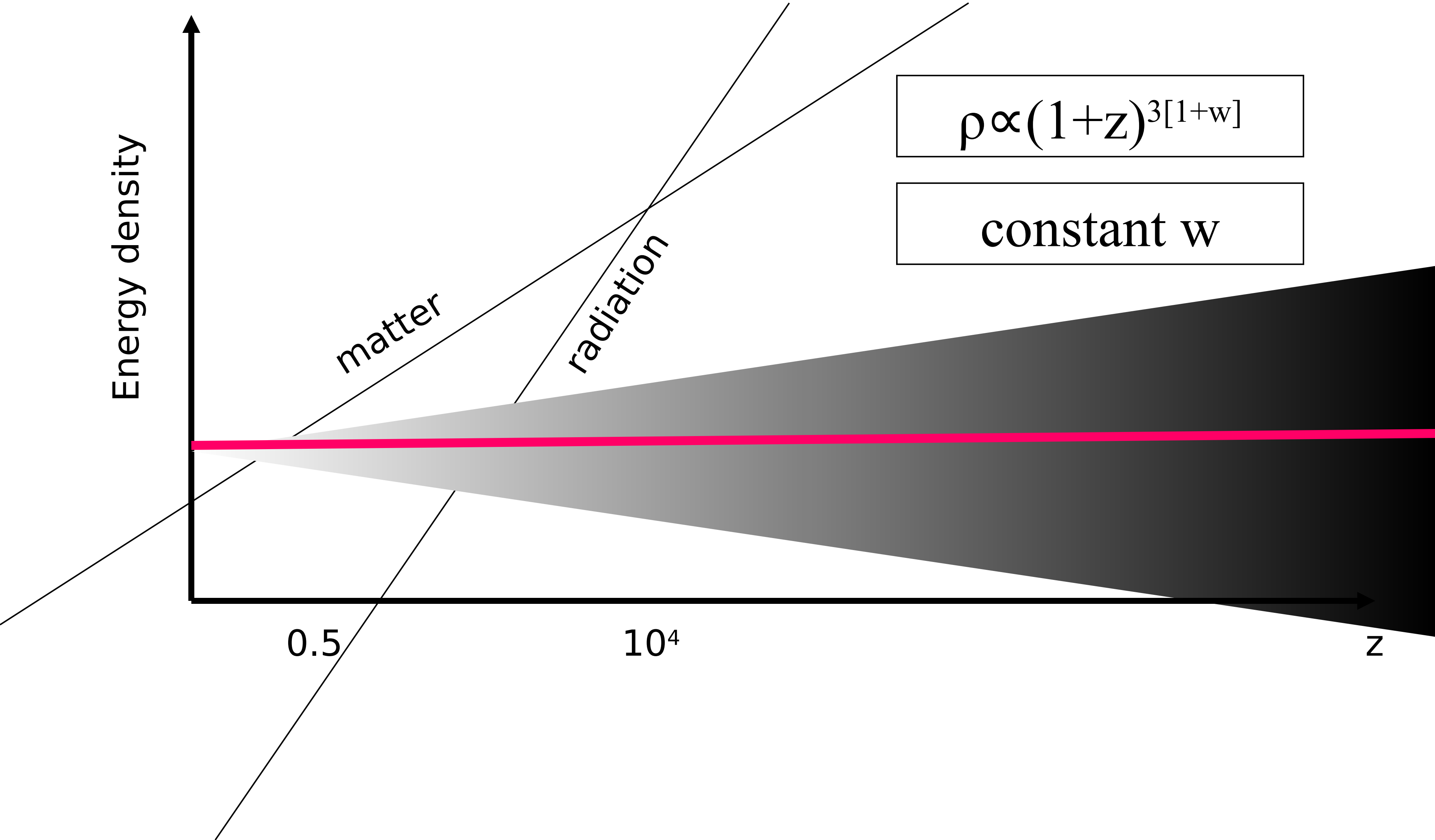
The promise of CMB lensing



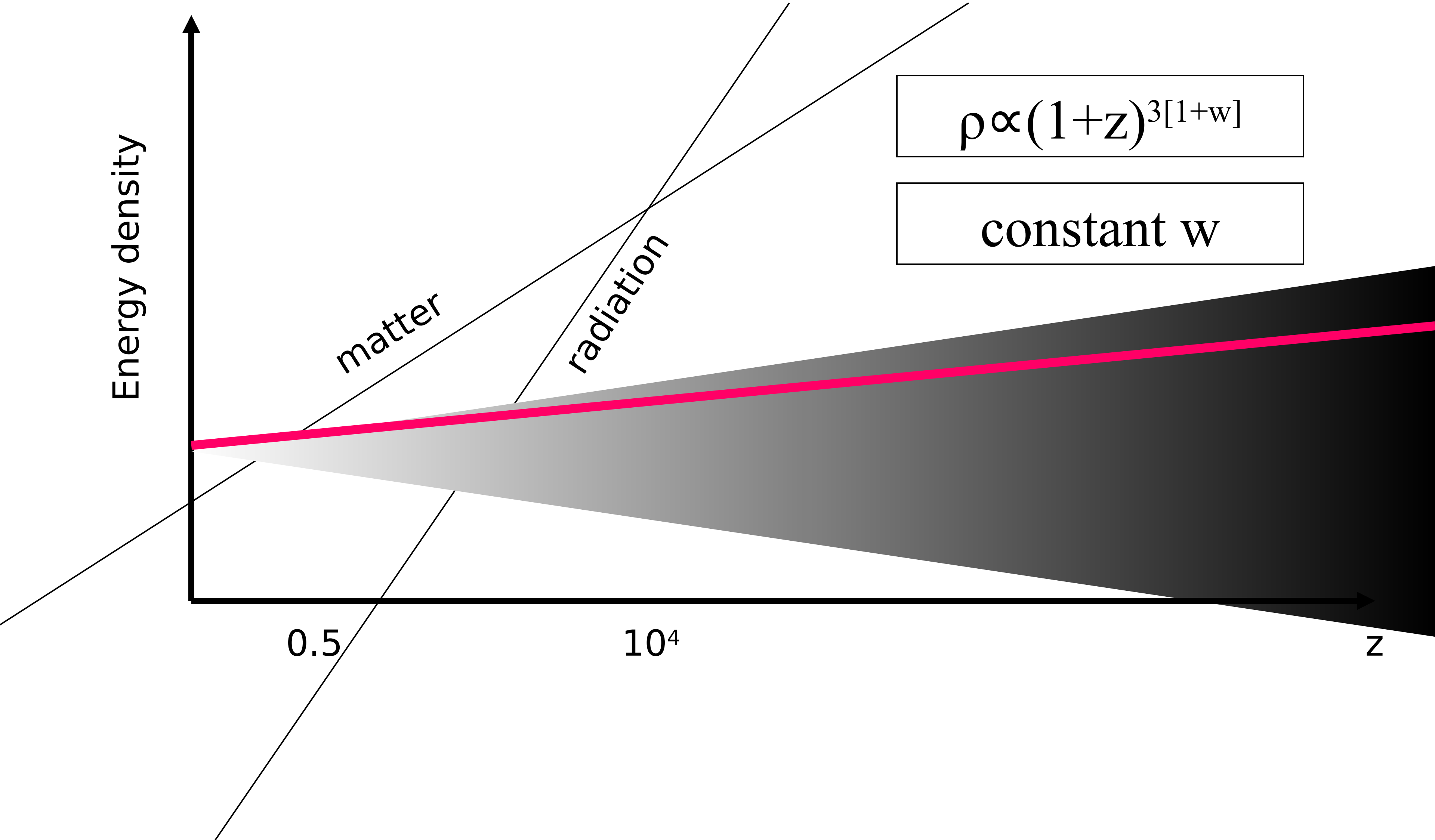
Dark energy density



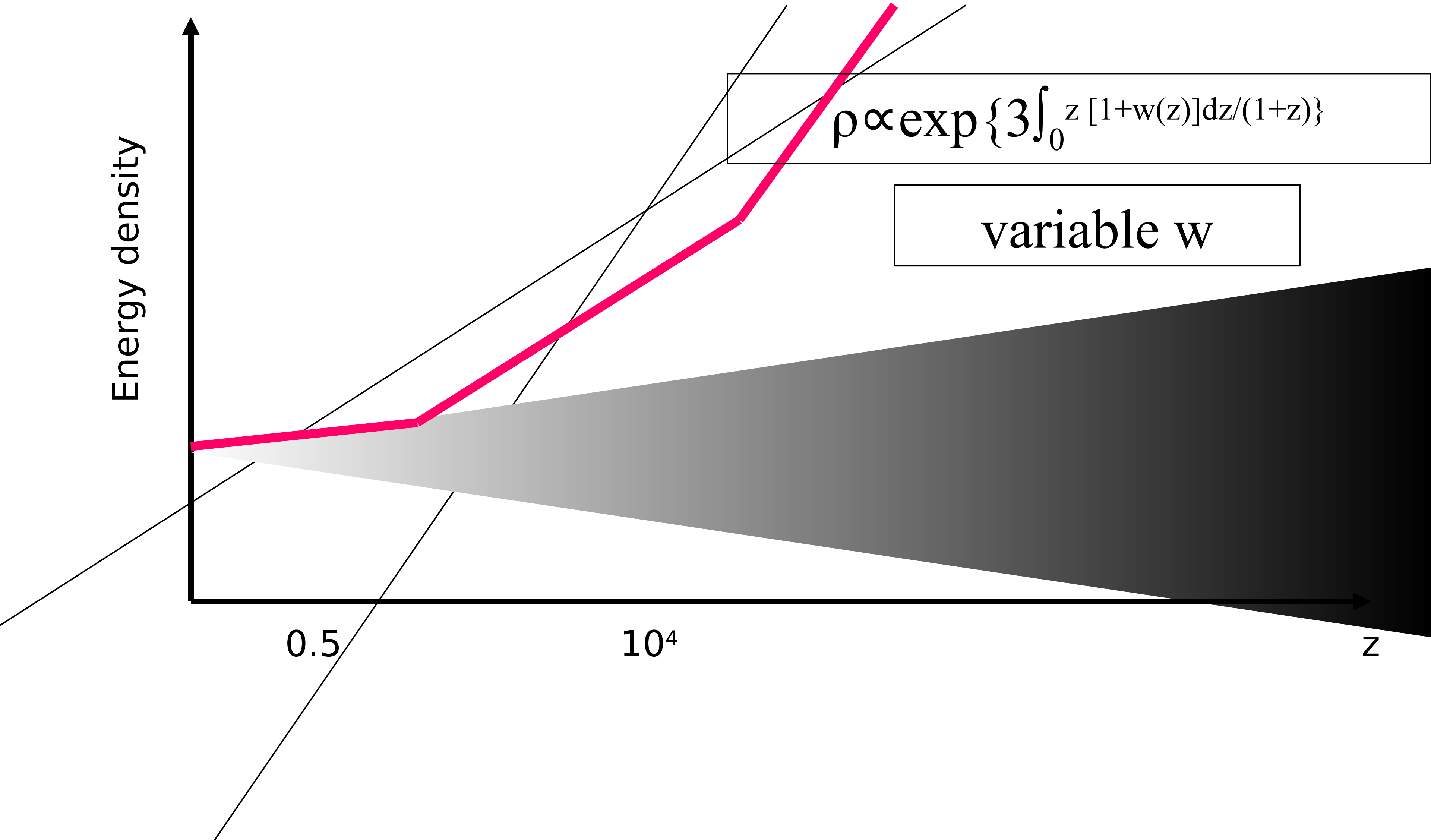
Constant Dark Energy (Λ)



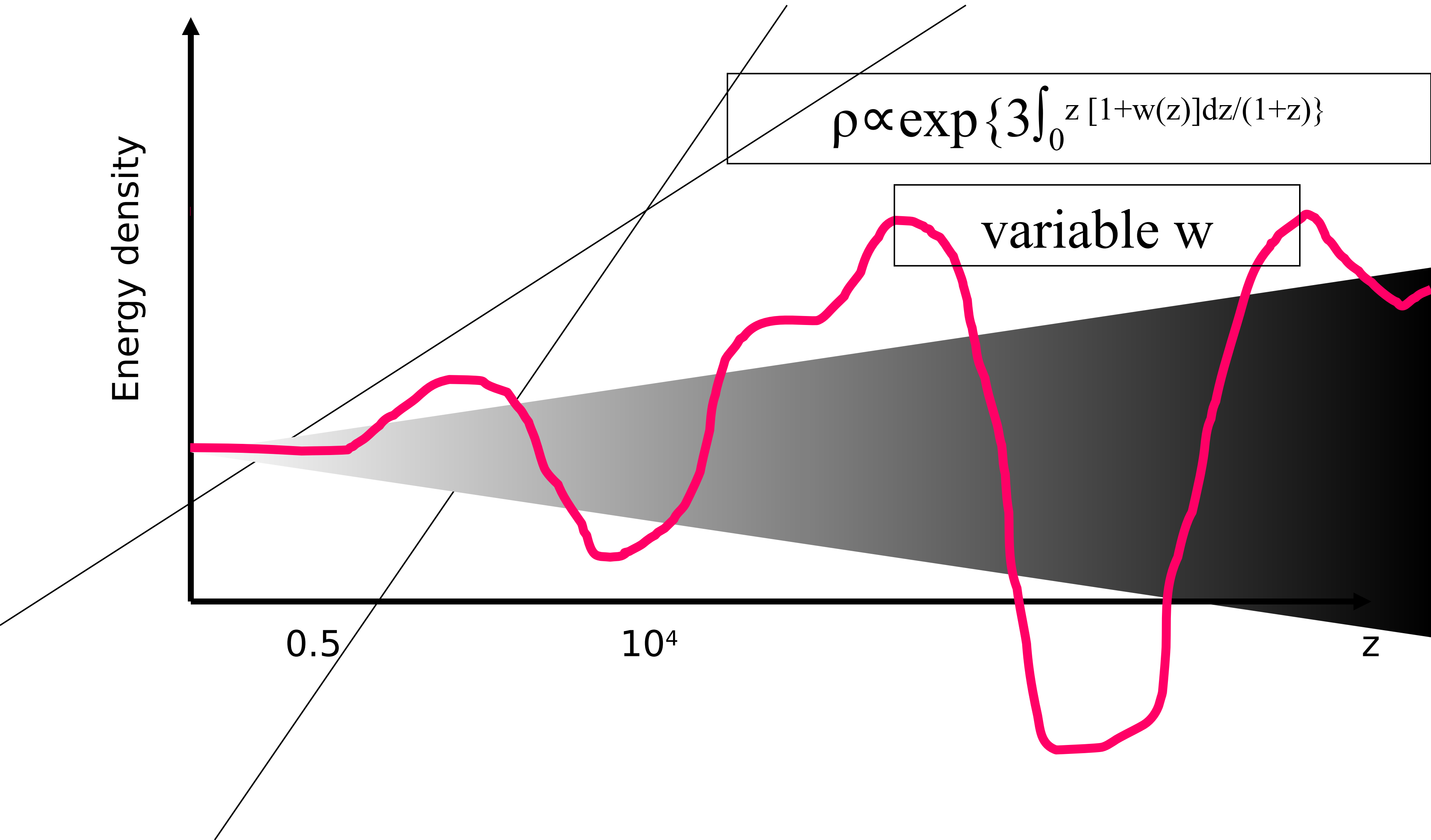
Scaling Dark Energy



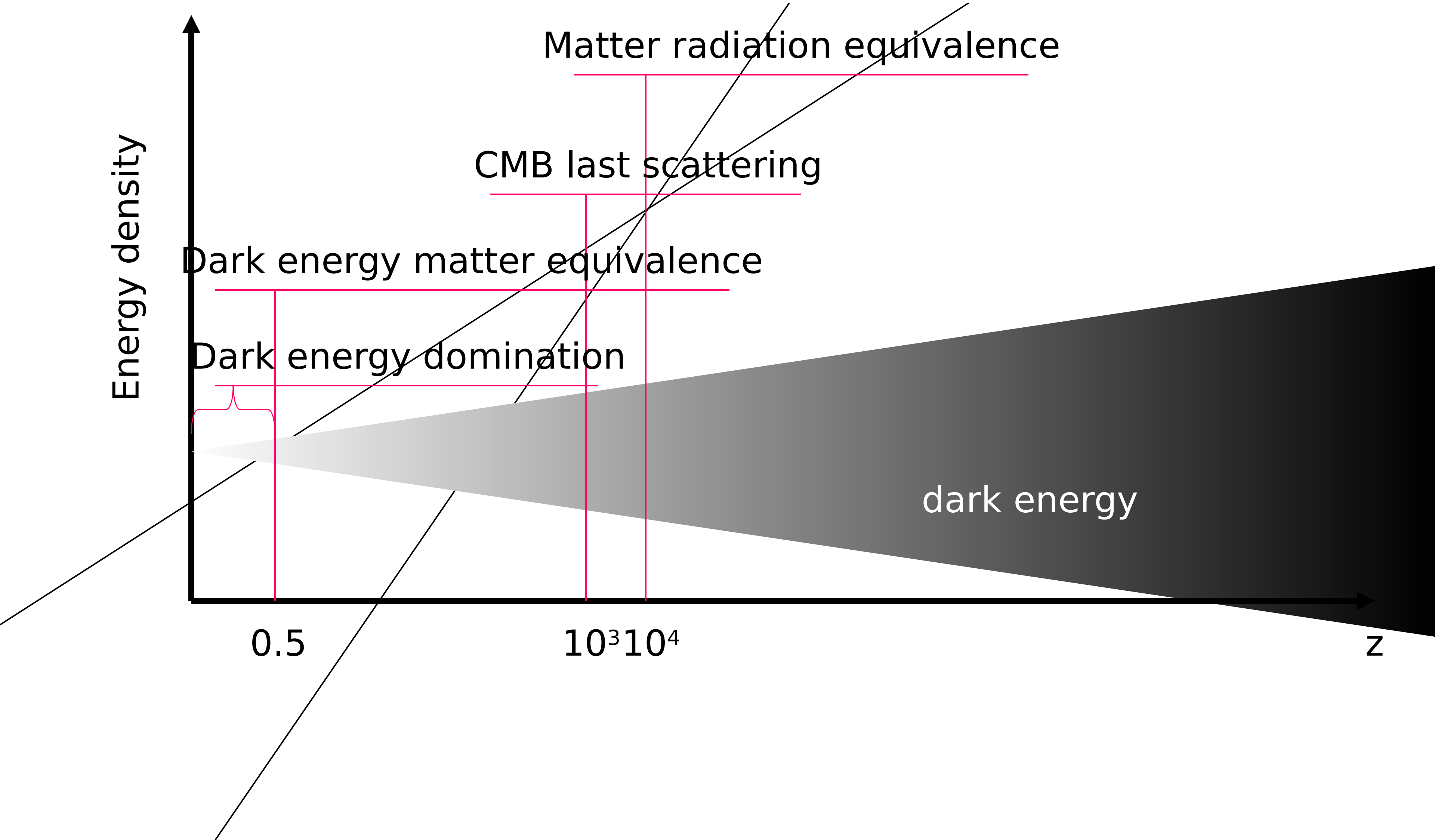
Early Dark Energy



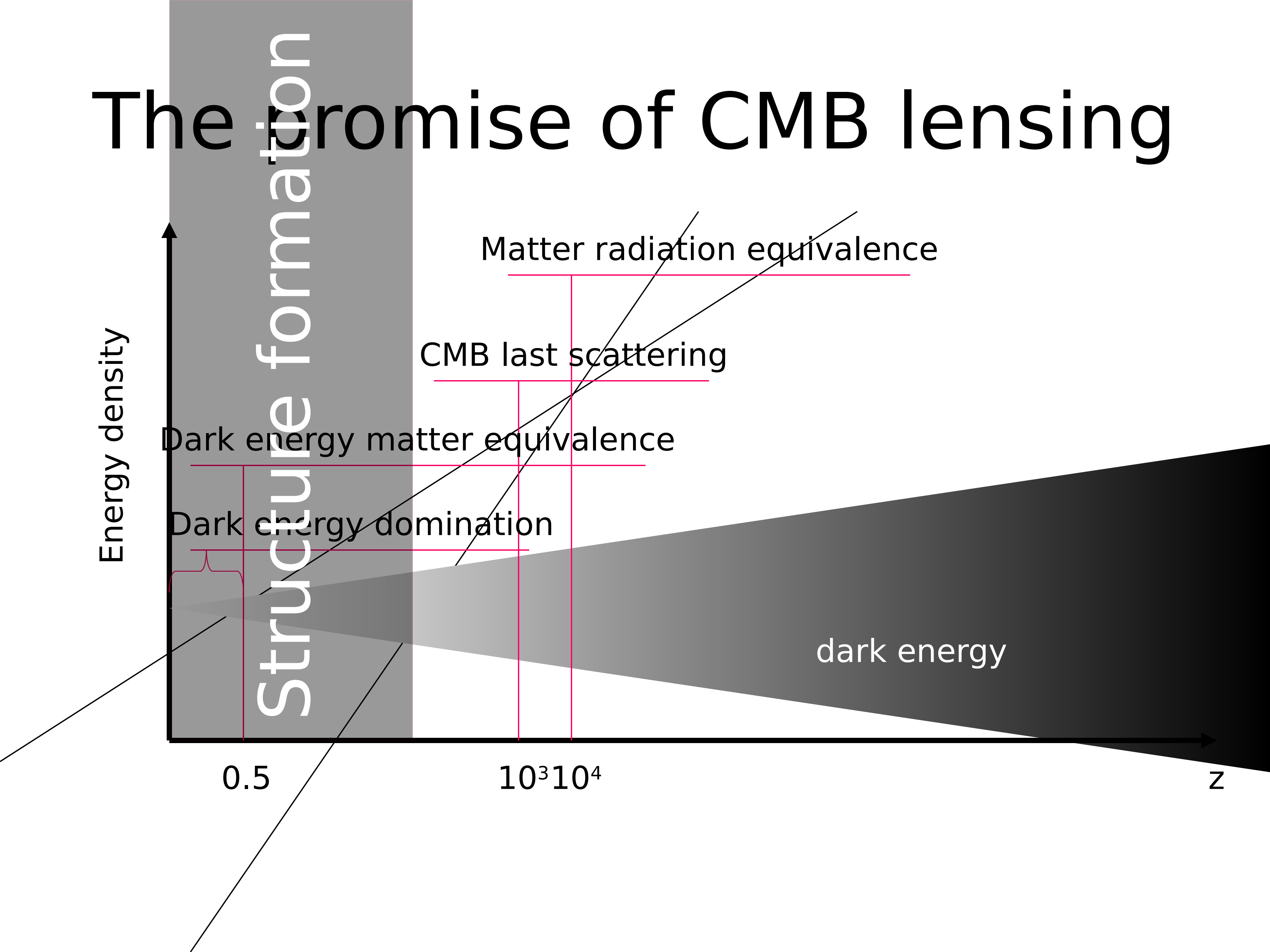
Messy Dark Energy



The promise of CMB lensing

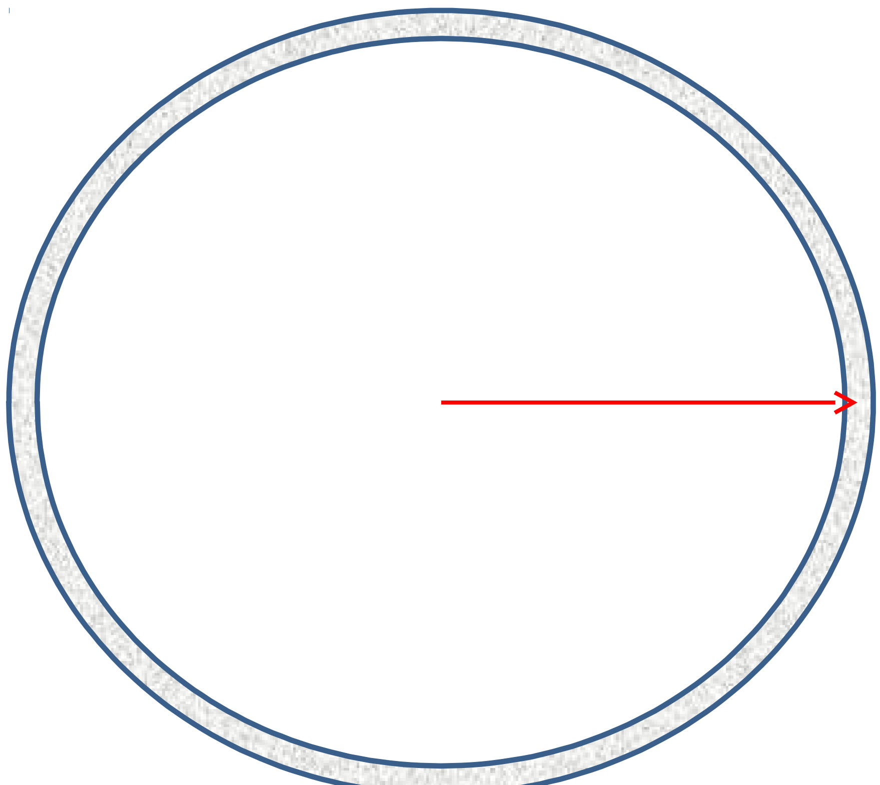


The promise of CMB lensing



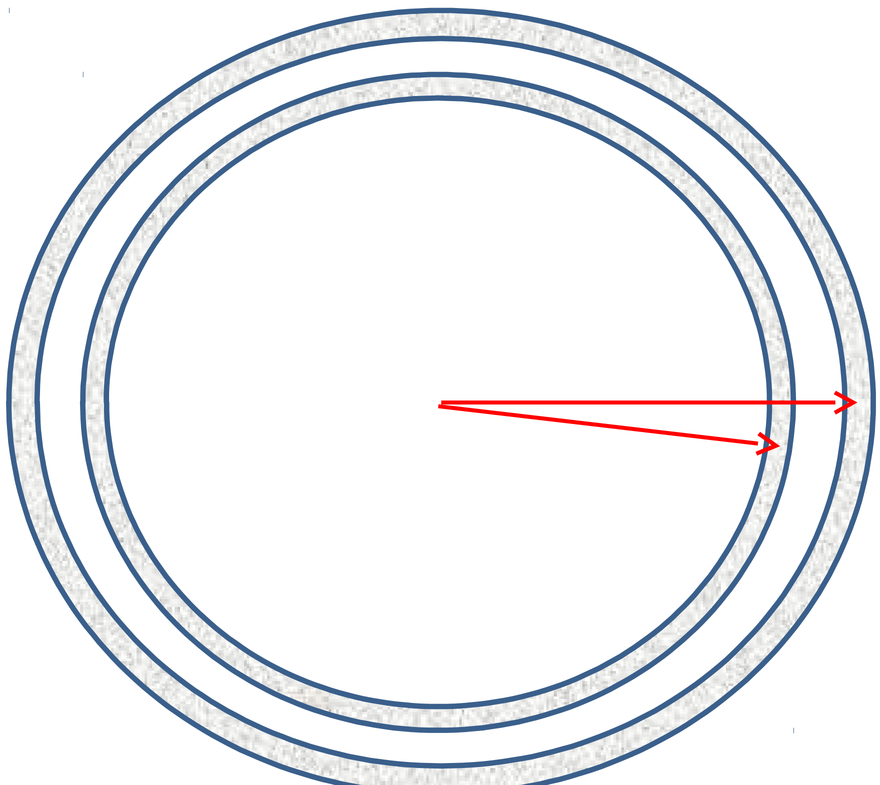
Constraining the expansion with distances

$$D = H_0^{-1} \int_0^z \frac{dz}{\left[\sum_i \Omega_i (1+z)^{3(1+w_i)}\right]^{1/2}}$$



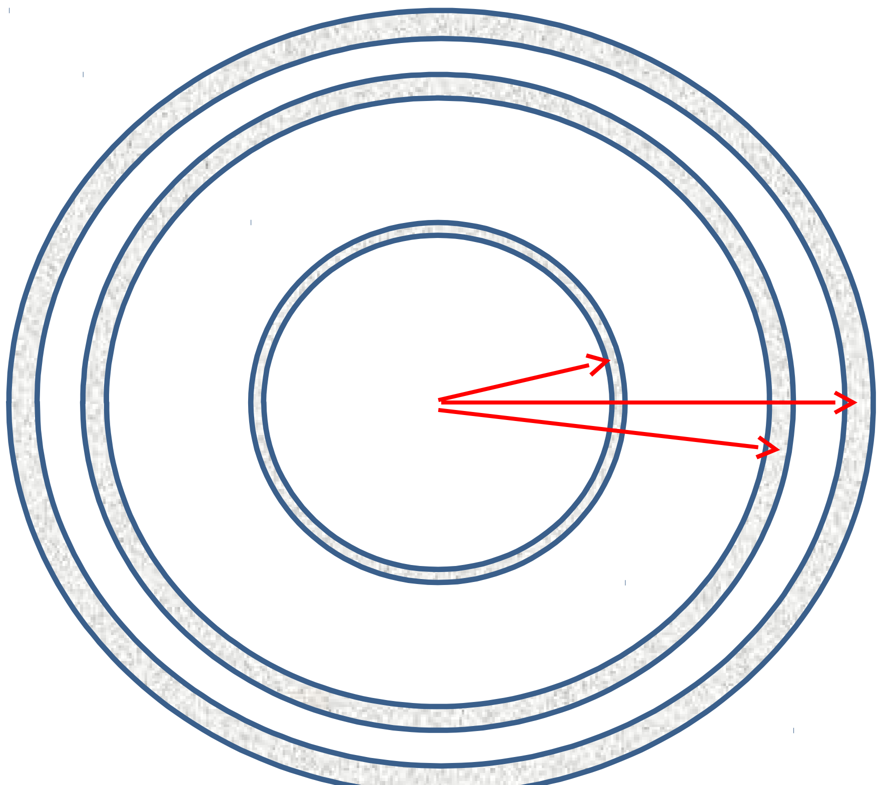
Constraining the expansion with distances

$$D = H_0^{-1} \int_0^z \frac{dz}{[\Sigma_{i} \Omega_i (1+z)^{3(1+w_i)}]^{1/2}}$$

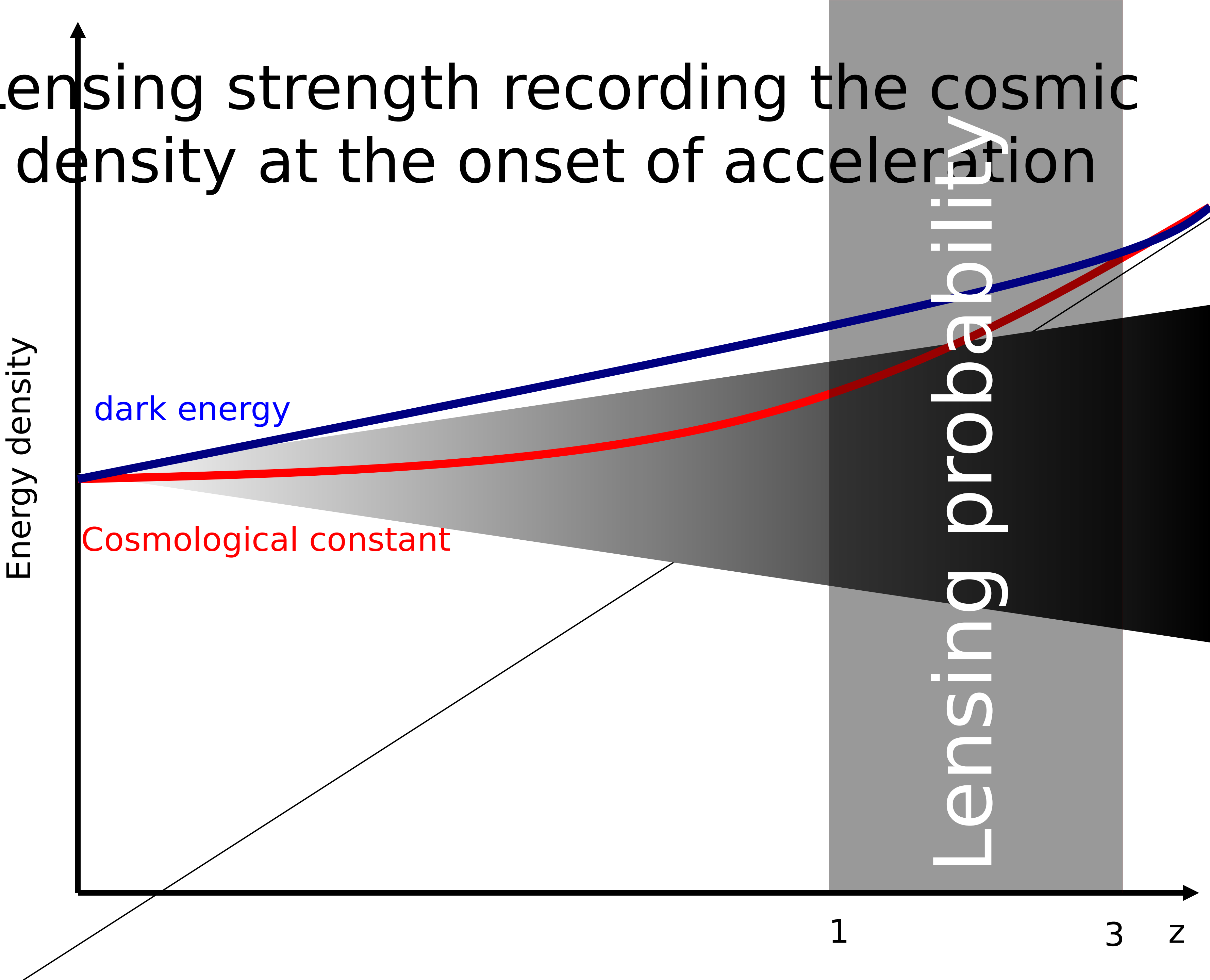


Constraining the expansion with distances

$$D = H_0^{-1} \int_0^z \frac{dz}{\left[\sum_i \Omega_i (1+z)^{3(1+w_i)}\right]^{1/2}}$$



Lensing strength recording the cosmic density at the onset of acceleration



CMB lensing

$$\phi(\hat{n}) = \int_0^{\chi_\infty} d\chi D(\chi) \left[\Psi(\hat{n},\chi) - \Phi(\hat{n},\chi)\right] \int_\chi^{\chi_\infty} d\chi' \frac{D(\chi'-\chi)}{D(\chi')} g(\chi')$$

$$\begin{aligned} C_l^{\phi\phi} &= \frac{32}{\pi} \int_0^{\chi_\infty} d\chi\, g'(\chi) \int_0^{\chi_\infty} d\chi' g'(\chi') \int k^2 dk\, u_l[k\, D(\chi)] u_l[k\, D(\chi')] \cdot \\ &\cdot \left[\frac{1}{4}\langle \Psi(k,\chi)\Psi(k,\chi')\rangle + \frac{1}{4}\langle \Phi(k,\chi)\Phi(k,\chi')\rangle - \frac{1}{2}\langle \Psi(k,\chi)\Phi(k,\chi')\rangle\right] \end{aligned}$$

$$\begin{aligned} C_l^{\Theta\phi} = \frac{2}{\pi} \int_0^{\chi_\infty} d\chi\, g'(\chi) \int_0^{\chi_\infty} d\chi' \int k^2\, dk\, u_l(k\, D(\chi)) u_l(k\, D(\chi')) \cdot \\ \cdot \left[\langle \Psi(k,\chi)\dot{\Psi}(k,\chi')\rangle + \langle \Phi(k,\chi)\dot{\Phi}(k,\chi')\rangle - \langle \Psi(k,\chi)\dot{\Phi}(k,\chi')\rangle - \langle \dot{\Psi}(k,\chi')\Phi(k,\chi)\rangle\right] \end{aligned}$$

Acquaviva et al. 2004

CMB lensing

$$\phi(\hat{n}) = \int_0^{\chi_\infty} d\chi D(\chi) \left[\Psi(\hat{n},\chi) - \Phi(\hat{n},\chi)\right] \int_\chi^{\chi_\infty} d\chi' \frac{D(\chi'-\chi)}{D(\chi')} g(\chi')$$

$$C_l^{\phi\phi} = \frac{32}{\pi}\int_0^{\chi_\infty} d\chi\, g'(\chi) \int_0^{\chi_\infty} d\chi' g'(\chi') \int k^2 dk\, u_l[k\,D(\chi)] u_l[k\,D(\chi')] \cdot \left[\frac{1}{4}\langle\Psi(k,\chi)\Psi(k,\chi')\rangle + \frac{1}{4}\langle\Phi(k,\chi)\Phi(k,\chi')\rangle - \frac{1}{2}\langle\Psi(k,\chi)\Phi(k,\chi')\rangle\right]$$

$$C_l^{\Theta\phi} = \frac{2}{\pi}\int_0^{\chi_\infty} d\chi\, g'(\chi) \int_0^{\chi_\infty} d\chi' \int k^2\, dk\, u_l(k\,D(\chi)) u_l(k\,D(\chi')) \cdot \left[\langle\Psi(k,\chi)\dot{\Psi}(k,\chi')\rangle + \langle\Phi(k,\chi)\dot{\Phi}(k,\chi')\rangle - \langle\Psi(k,\chi)\dot{\Phi}(k,\chi')\rangle - \langle\dot{\Psi}(k,\chi')\Phi(k,\chi)\rangle\right]$$

Geometry

Acquaviva et al. 2004

CMB lensing

$$\phi(\hat{n}) = \int_0^{\chi_\infty} d\chi D(\chi) [\Psi(\hat{n},\chi) - \Phi(\hat{n},\chi)] \int_\chi^{\chi_\infty} d\chi' \frac{D(\chi'-\chi)}{D(\chi')} g(\chi')$$

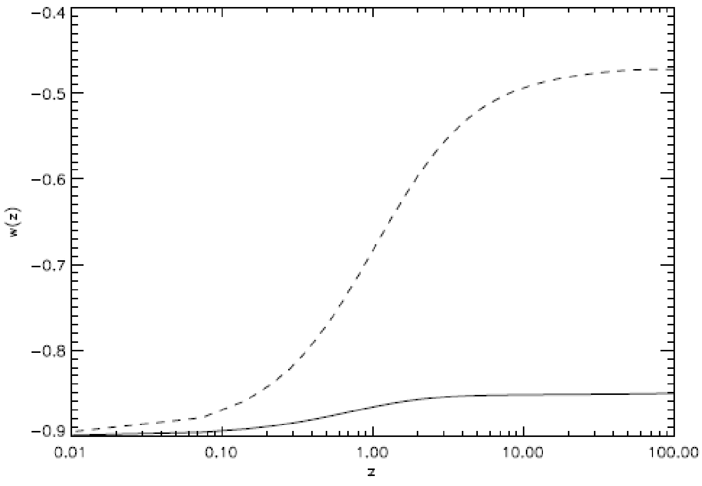
$$C_l^{\phi\phi} = \frac{32}{\pi} \int_0^{\chi_\infty} d\chi\, g'(\chi) \int_0^{\chi_\infty} d\chi' g'(\chi') \int k^2 dk\, u_l[k\,D(\chi)] u_l[k\,D(\chi')] \cdot \cdot \left[\frac{1}{4}\langle\Psi(k,\chi)\Psi(k,\chi')\rangle + \frac{1}{4}\langle\Phi(k,\chi)\Phi(k,\chi')\rangle - \frac{1}{2}\langle\Psi(k,\chi)\Phi(k,\chi')\rangle\right]$$

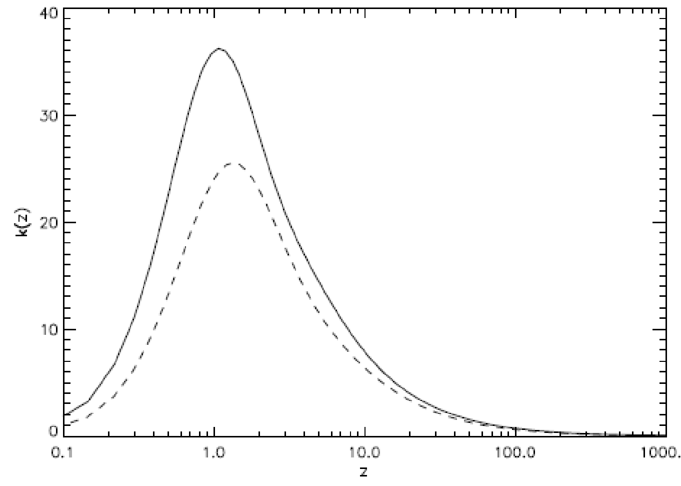
$$C_l^{\Theta\phi} = \frac{2}{\pi} \int_0^{\chi_\infty} d\chi\, g'(\chi) \int_0^{\chi_\infty} d\chi' \int k^2\, dk\, u_l(k\,D(\chi)) u_l(k\,D(\chi')) \cdot \cdot \left[\langle\Psi(k,\chi)\dot{\Psi}(k,\chi')\rangle + \langle\Phi(k,\chi)\dot{\Phi}(k,\chi')\rangle - \langle\Psi(k,\chi)\dot{\Phi}(k,\chi')\rangle - \langle\dot{\Psi}(k,\chi')\Phi(k,\chi)\rangle\right]$$

Perturbation dynamics

Acquaviva et al. 2004

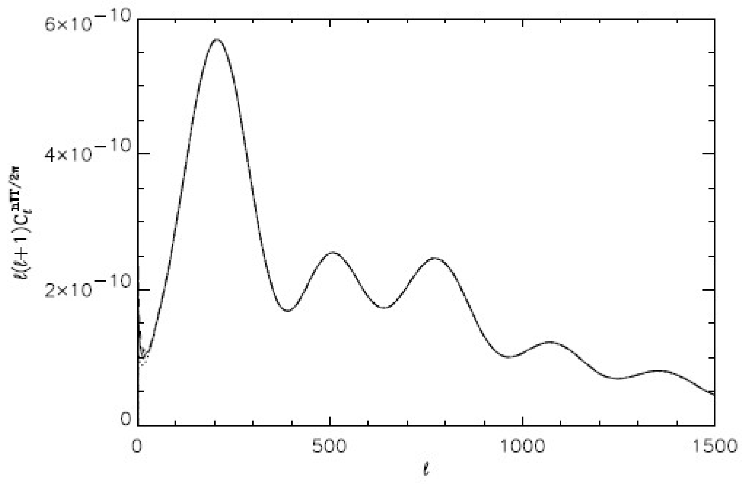
Early dark energy and CMB lensing

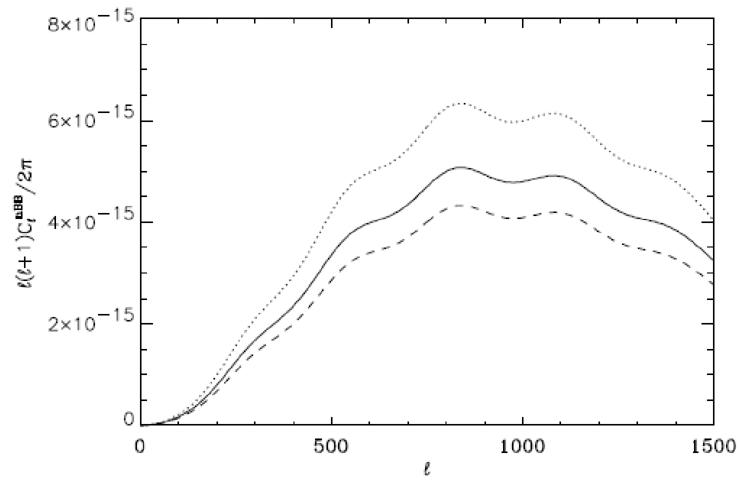




Acquaviva & Baccigalupi 2006

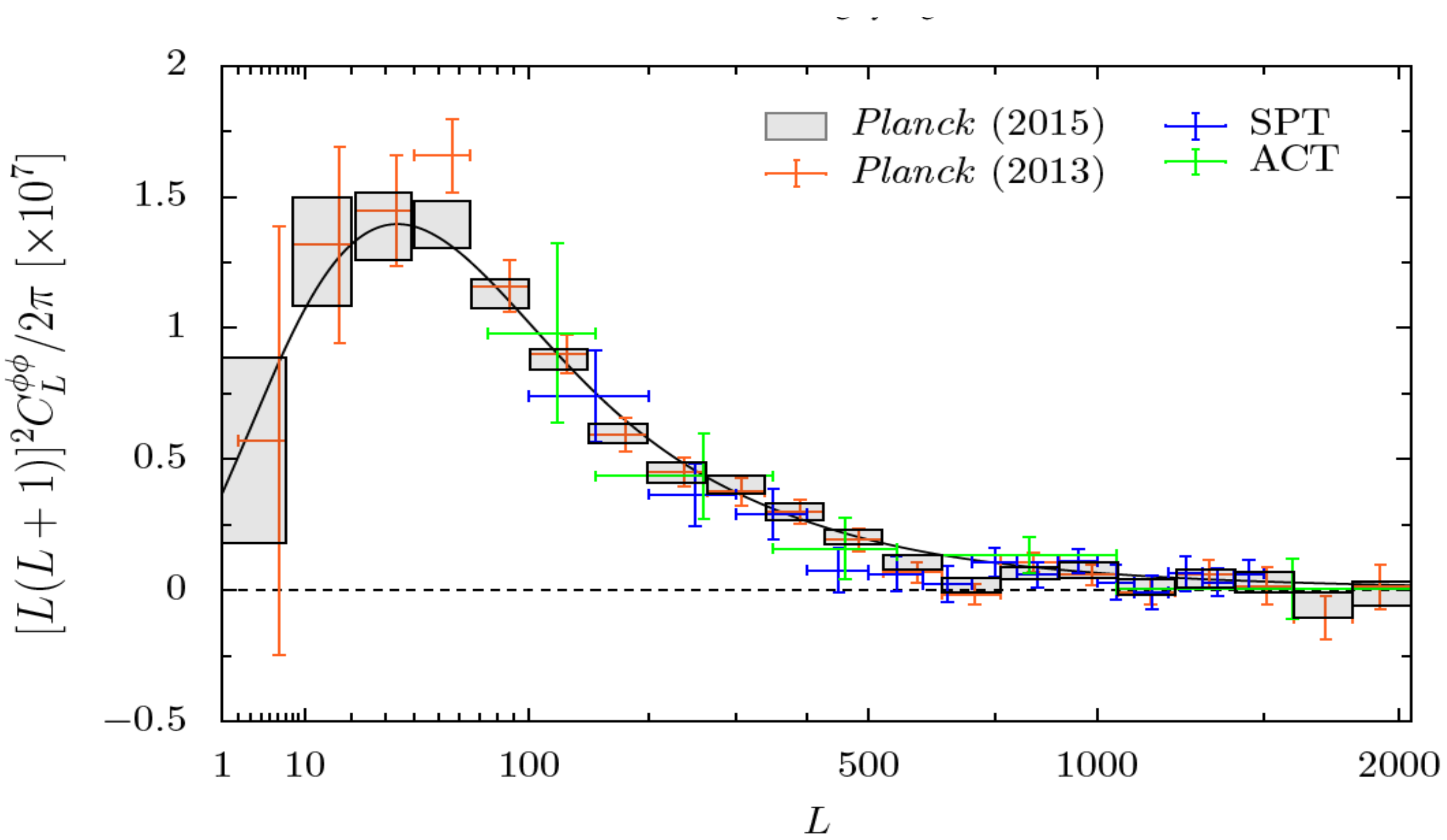
CMBreaking projection degeneracy



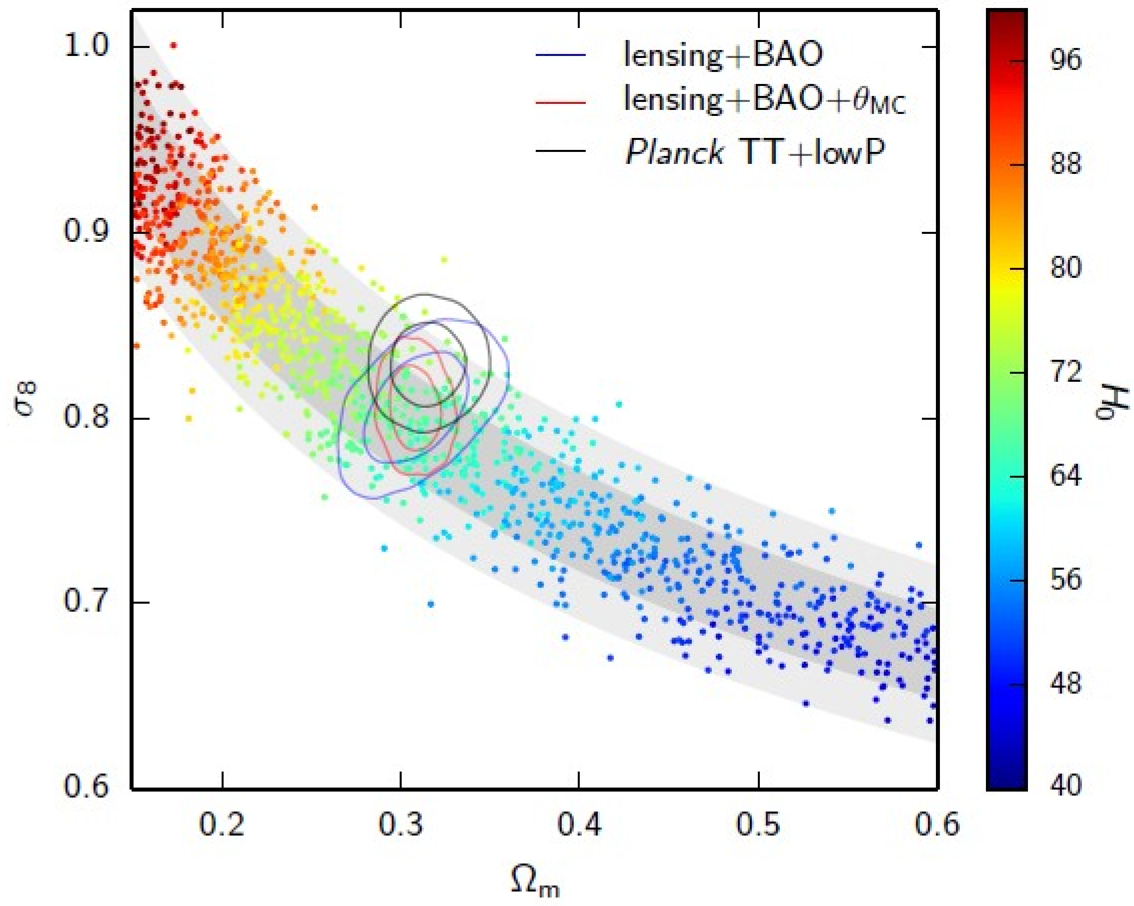


Acquaviva & Baccigalupi 2006

Planck lensing 2015



Planck lensing 2015



Lensing-LSS Cross-Correlations

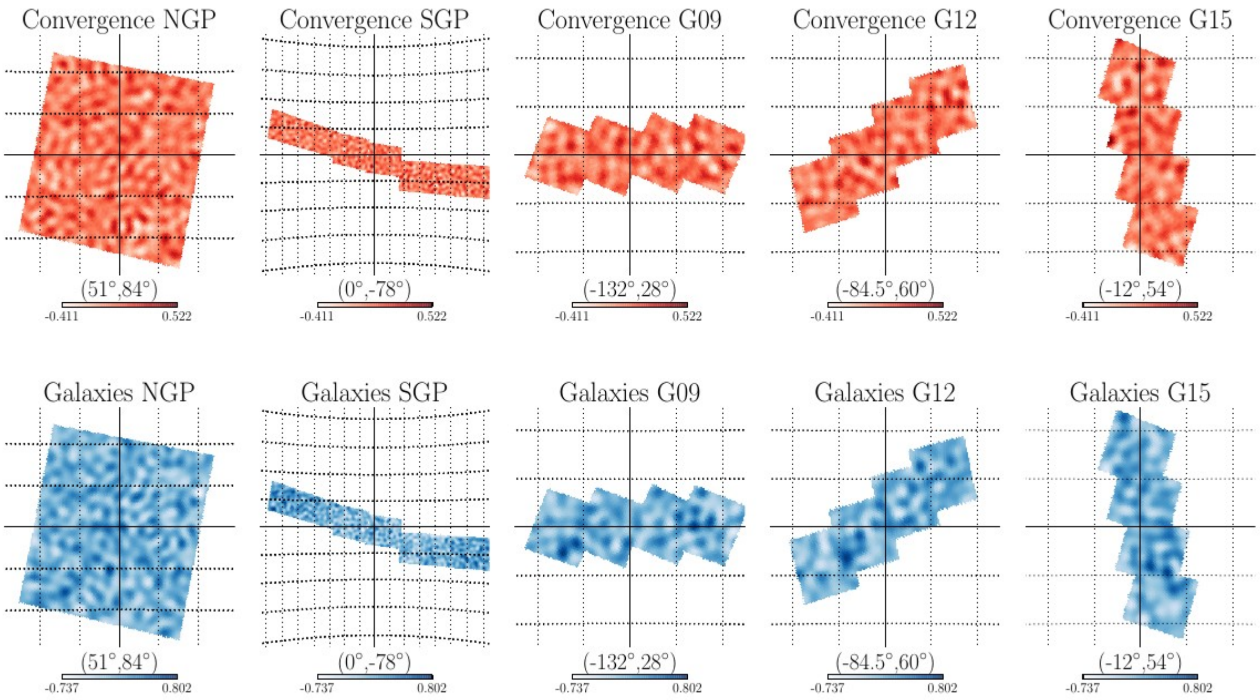


Fig. 5.— Convergence maps (upper row) and galaxy overdensity maps (lower row) in the H-ATLAS fields: noise-dominated multipoles $\ell > 400$ have been filtered out. Galactic longitude and latitude (l, b) of patches centers are provided in brackets. The grid overlay has spacing of 3° in each box.

Bianchini et al. 2014, 2015 in preparation

Lensing-LSS Cross-Correlations

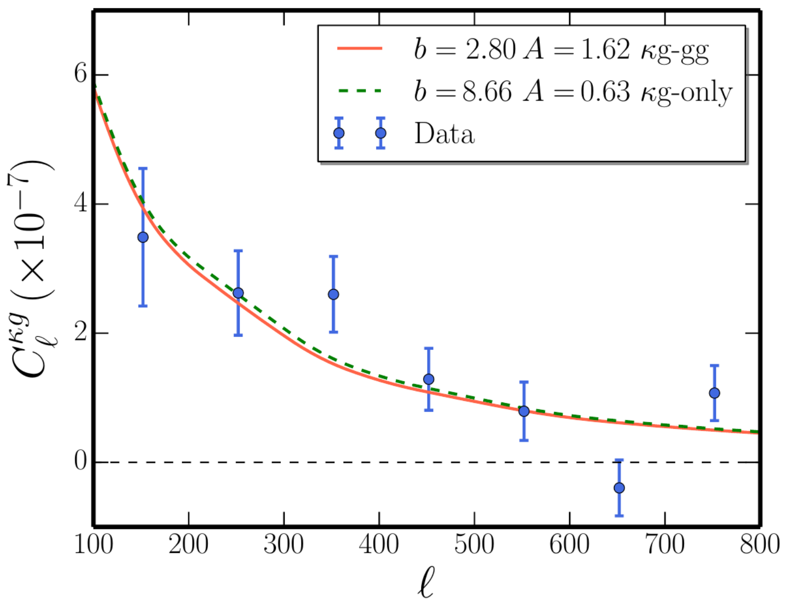
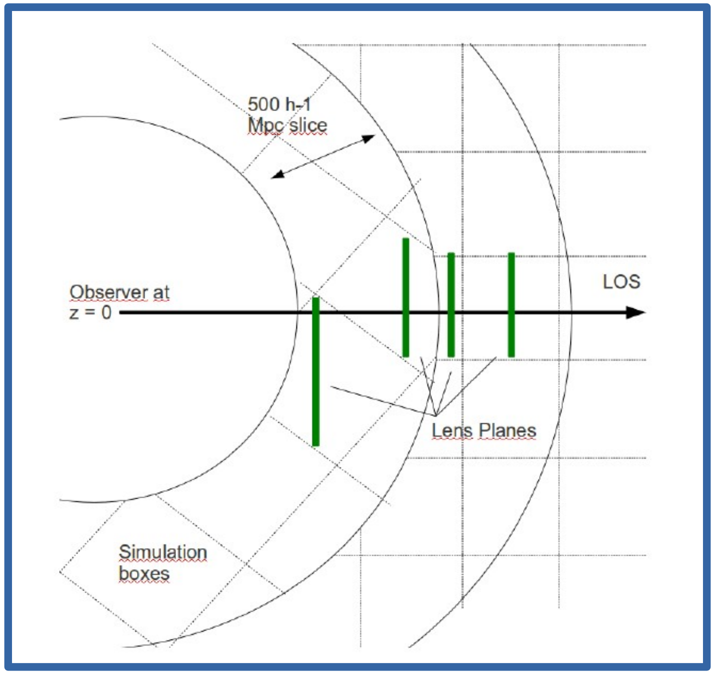
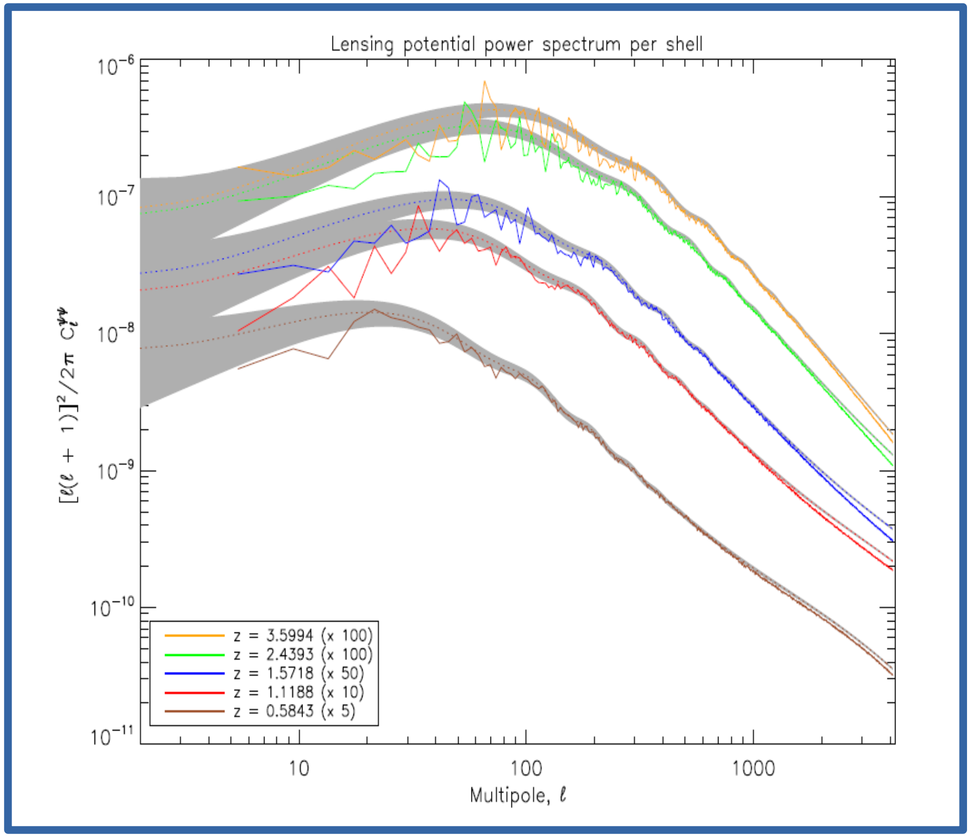


Fig. 9.— The CMB convergence - galaxy density cross-spectrum as measured from *Planck* and *Herschel* data. The data points are shown in blue, with error bars computed using the full covariance matrix obtained from Monte Carlo realizations of convergence maps. The theoretical spectra calculated with the bias values inferred from the likelihood analysis (as described in text) using the cross-correlation data only (solid red line) and the cross-correlation together with the galaxy auto-correlation data (dot-dashed green line) are also shown; we fix $\alpha = 3$ in this analysis. The null (no correlation) hypothesis is rejected at the $20\,\sigma$ level.

Bianchini et al. 2014, 2015 in preparation

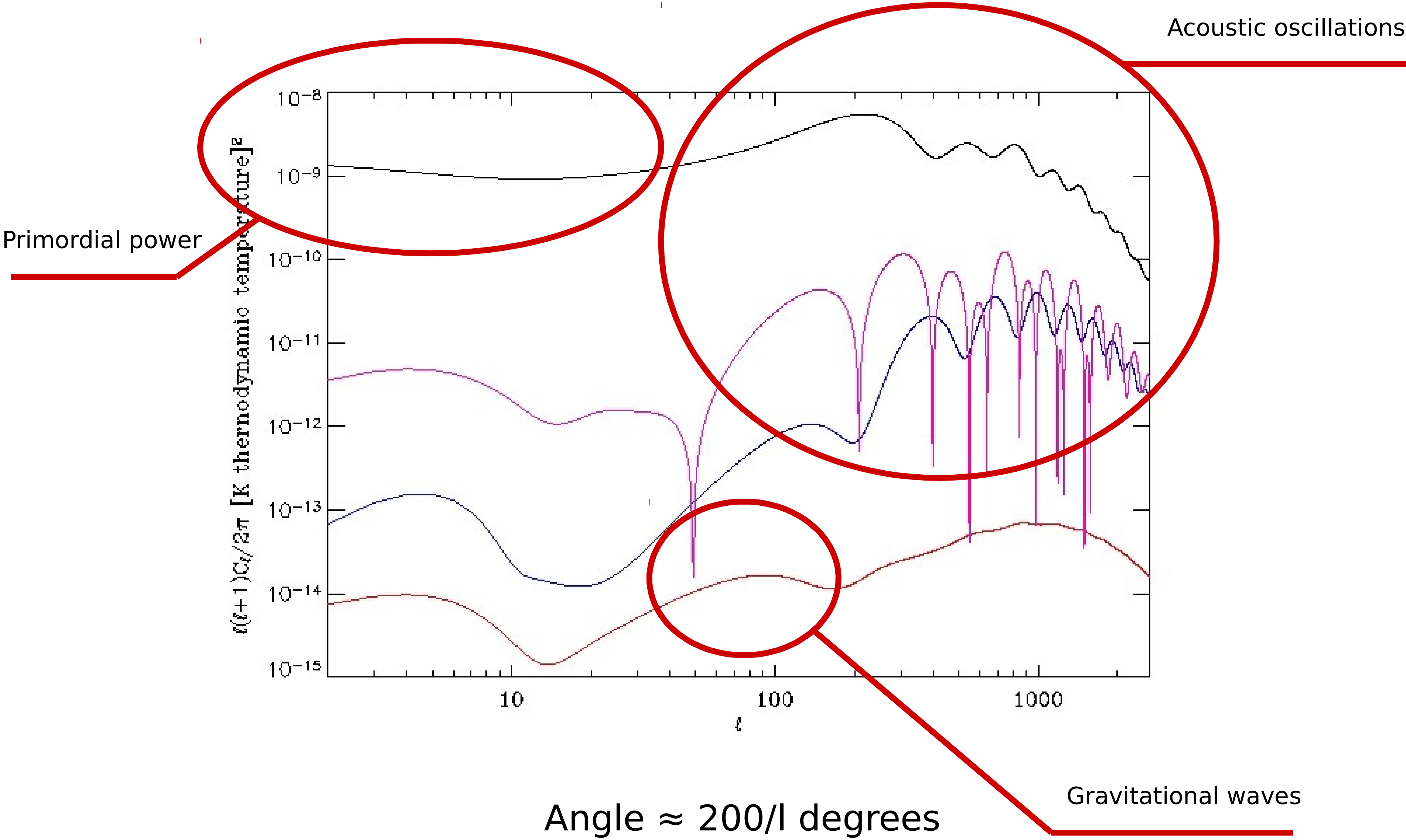
CMB-N-body Lensing





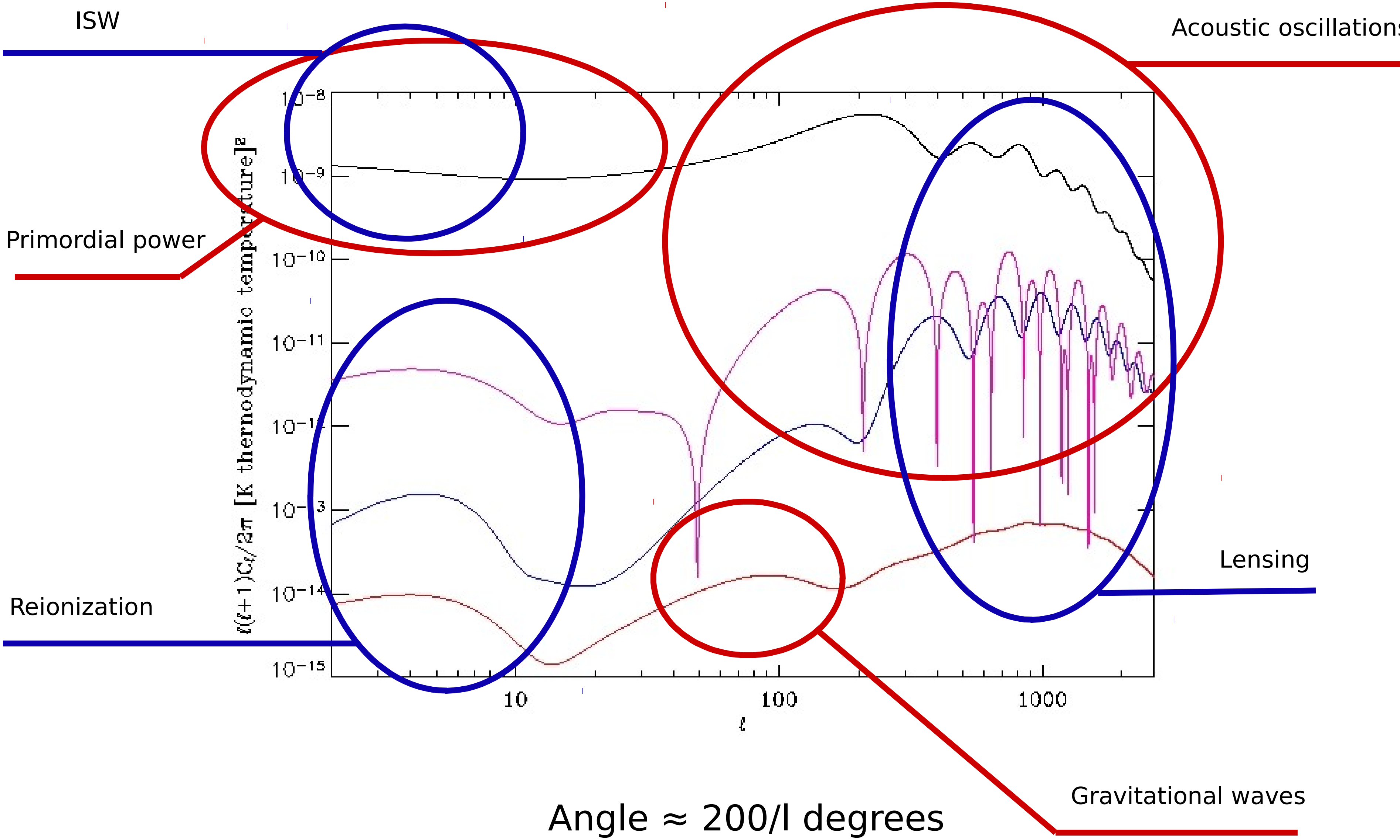
Calabrese et al. 2014, 2015 in preparation

CMB angular power spectrum



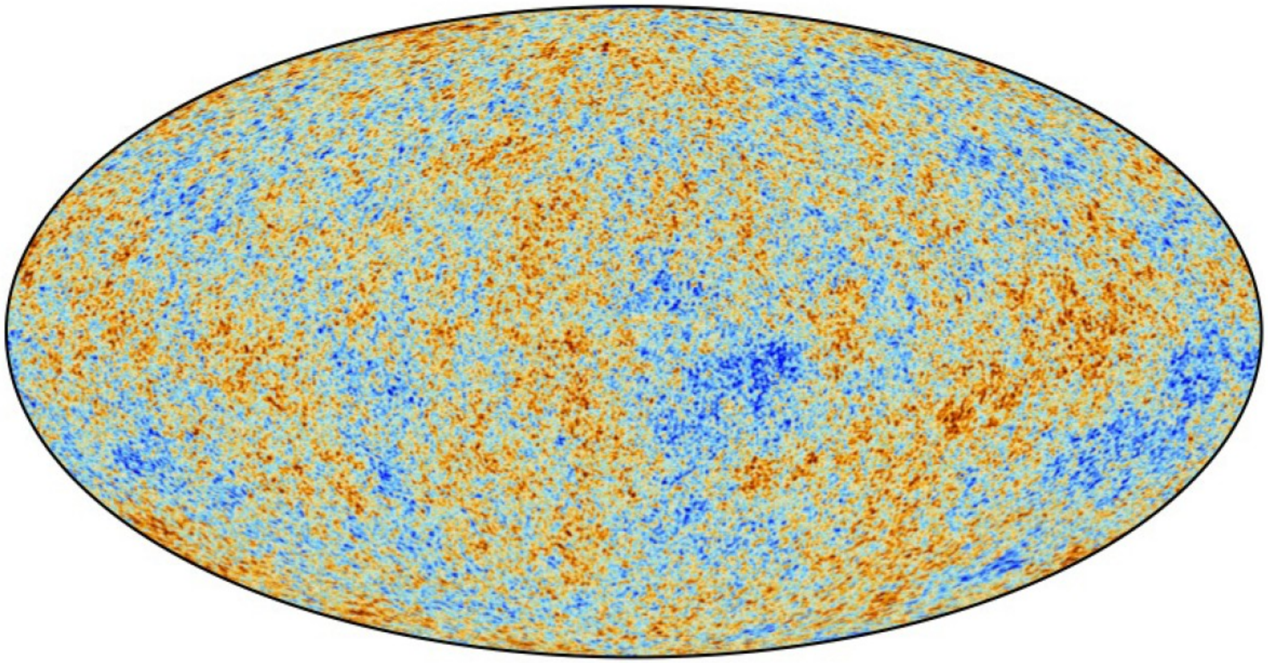
Angle ≈ 200/l degrees

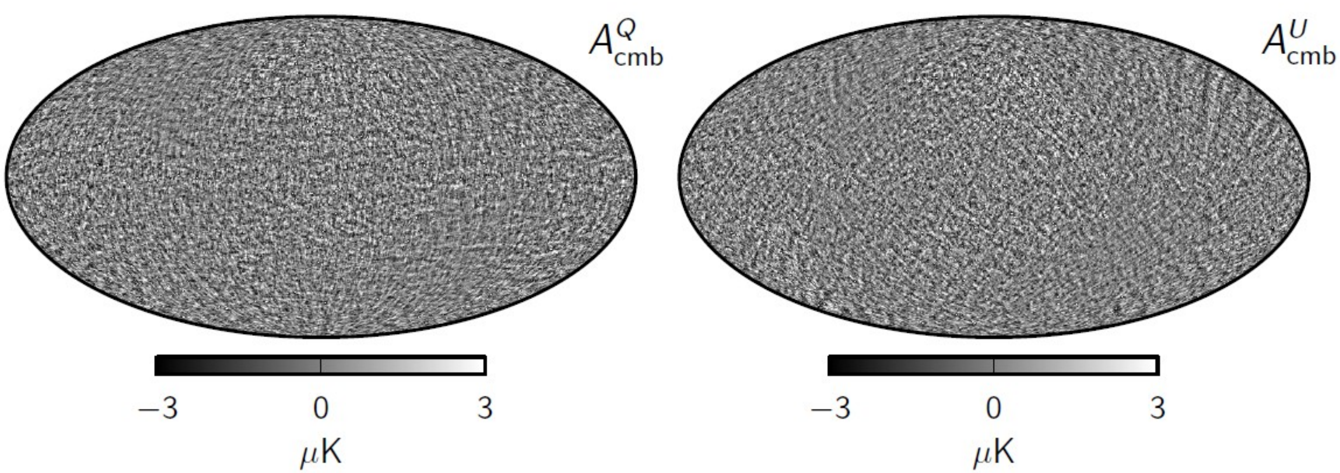
CMB angular power spectrum



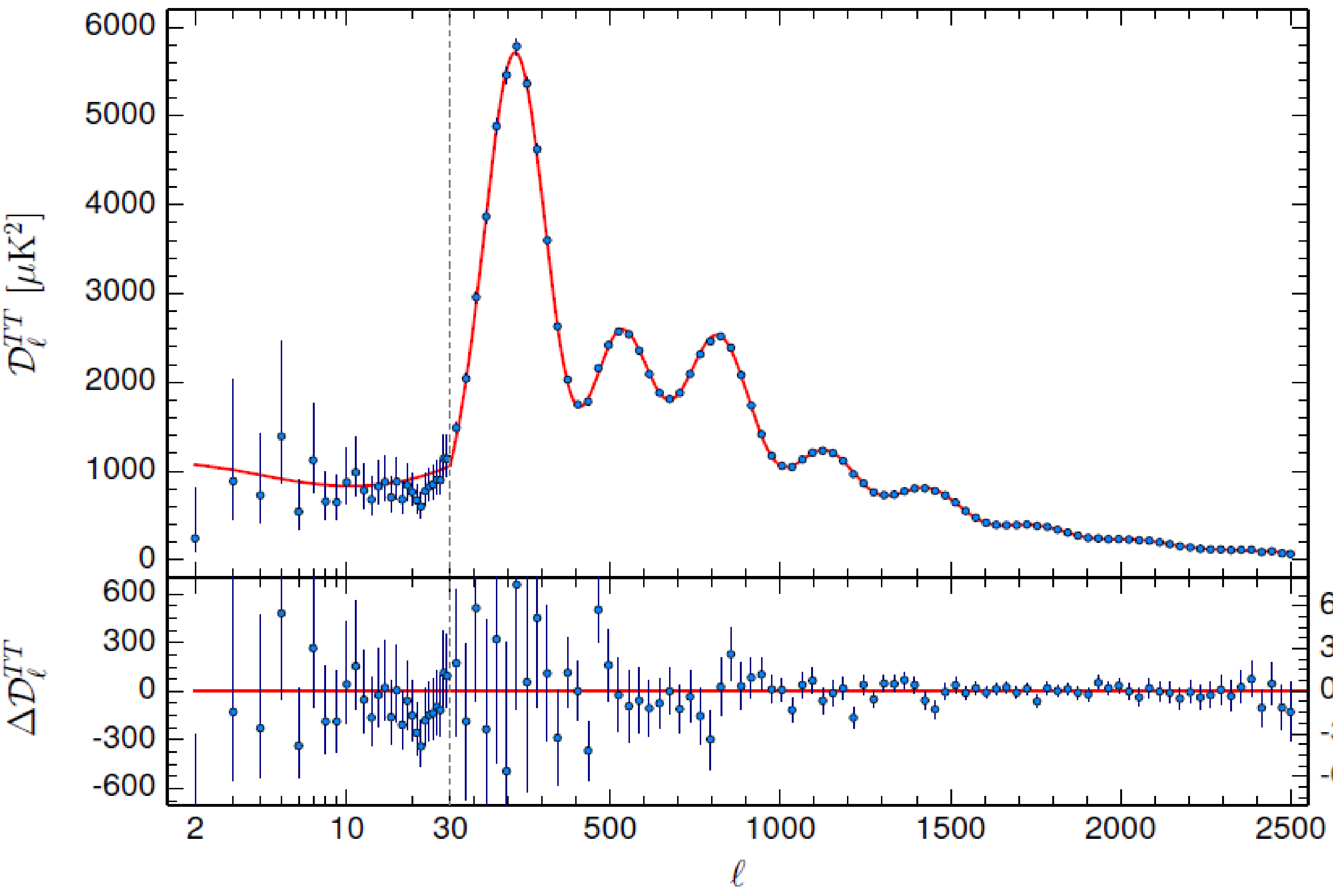
Angle ≈ 200/l degrees

Planck 2015 CMB

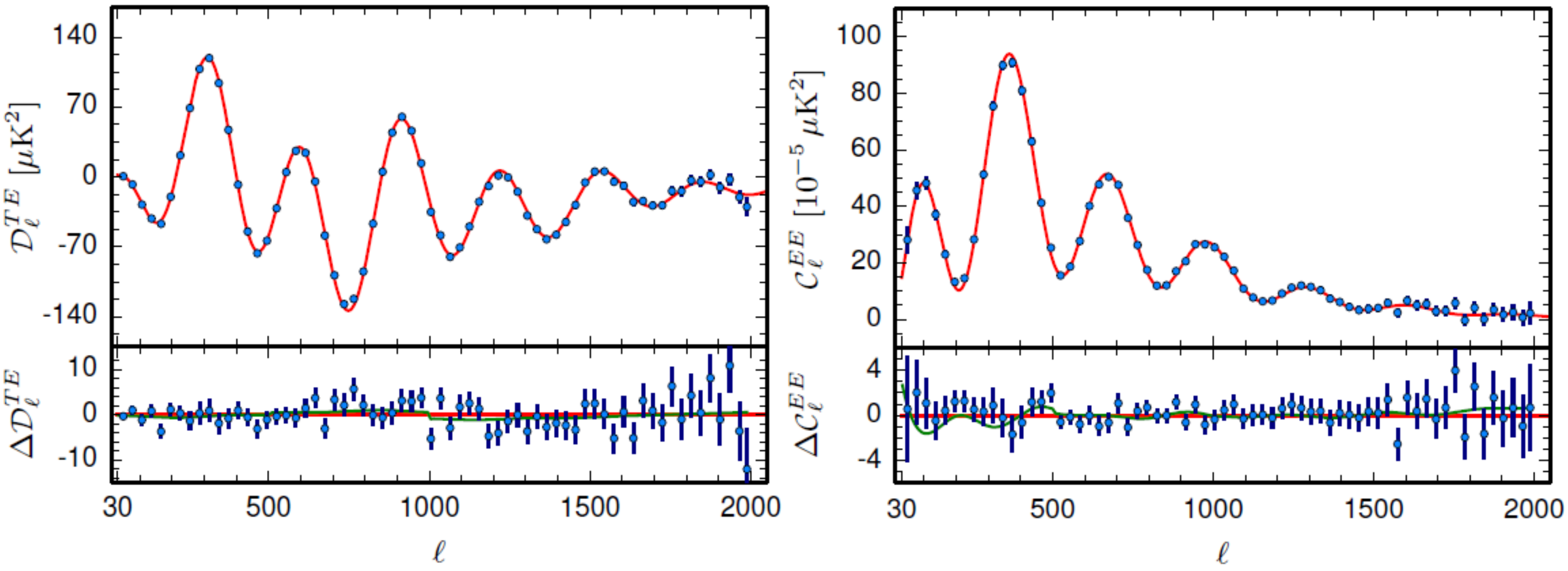




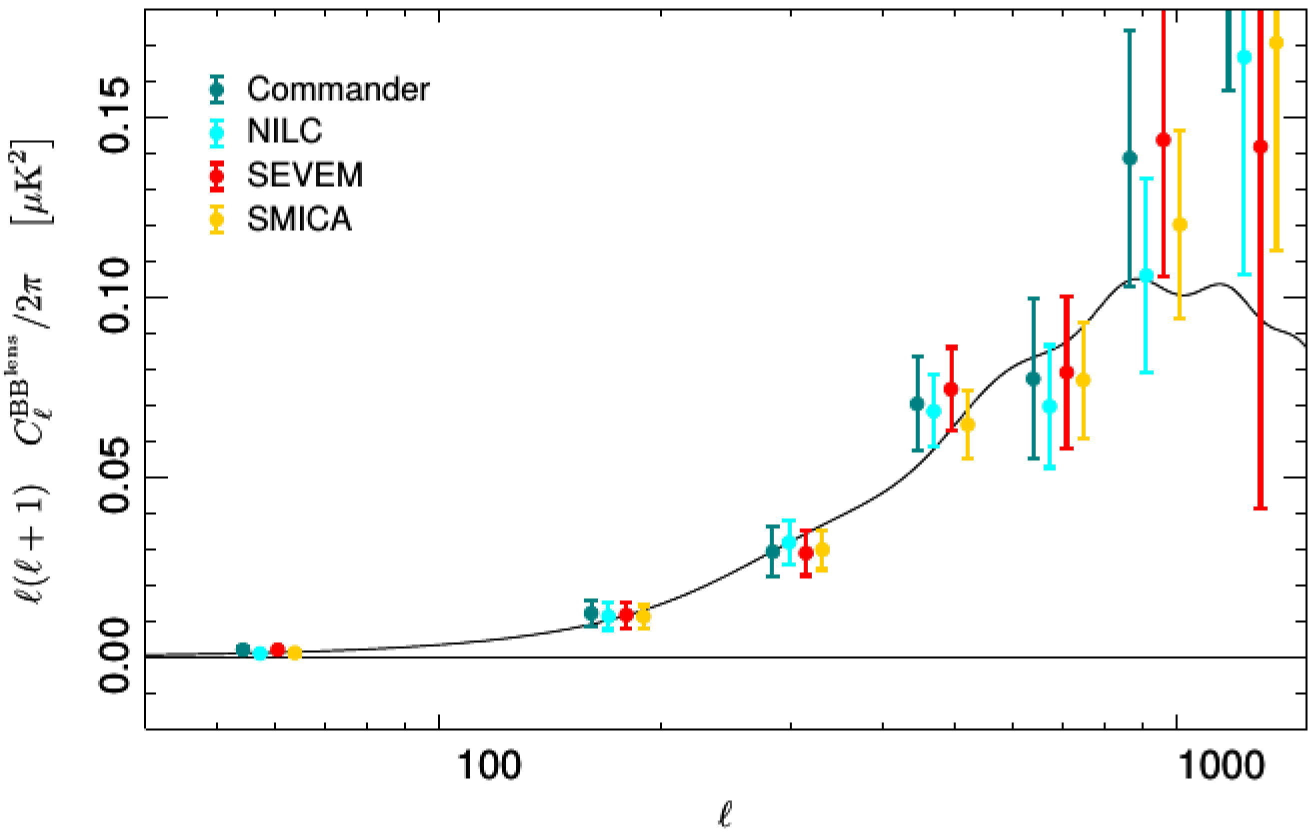
Planck 2015 TT power spectrum



Planck 2015
TE and EE power spectra



Planck 2015 BB power spectra



Concluding remarks, I

- Effects from the Early Universe and Large Scale Structure affect large parts of CMB anisotropies, and directly compete for detection, for example in the B-modes
- Measurements of the abundance of primordial Gravitational Waves, and constraints on the Dark Energy dynamics must proceed jointly in the analysis of data from operating and future high resolution and sensitivity probes, LSS surveys
- Cross-correlation studies gathering relevance, large scale simulations CMB LSS experiments being implemented
- ...

Planck

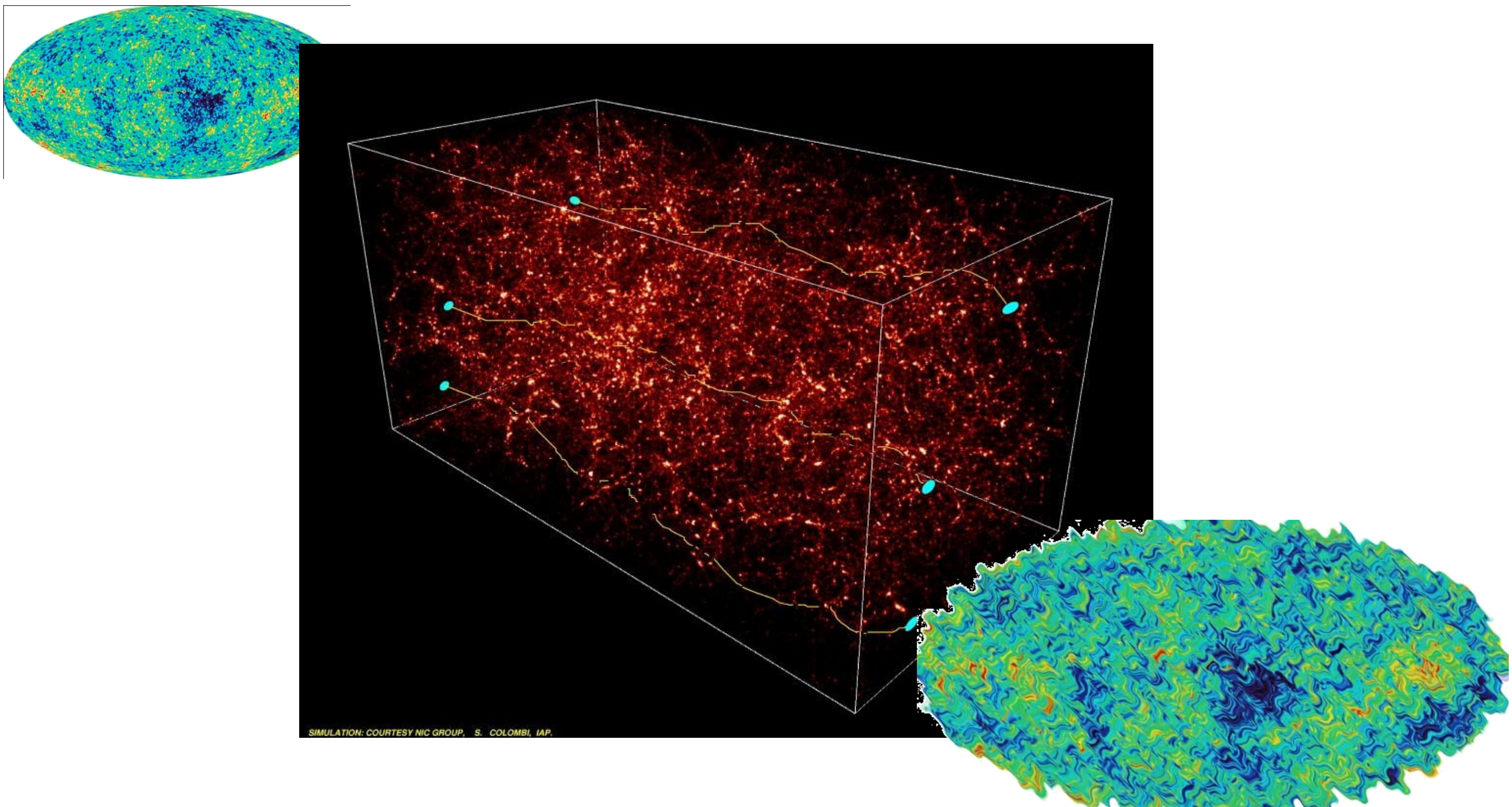
The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

Backup slides

Extension I:
CMB-N-body lensing

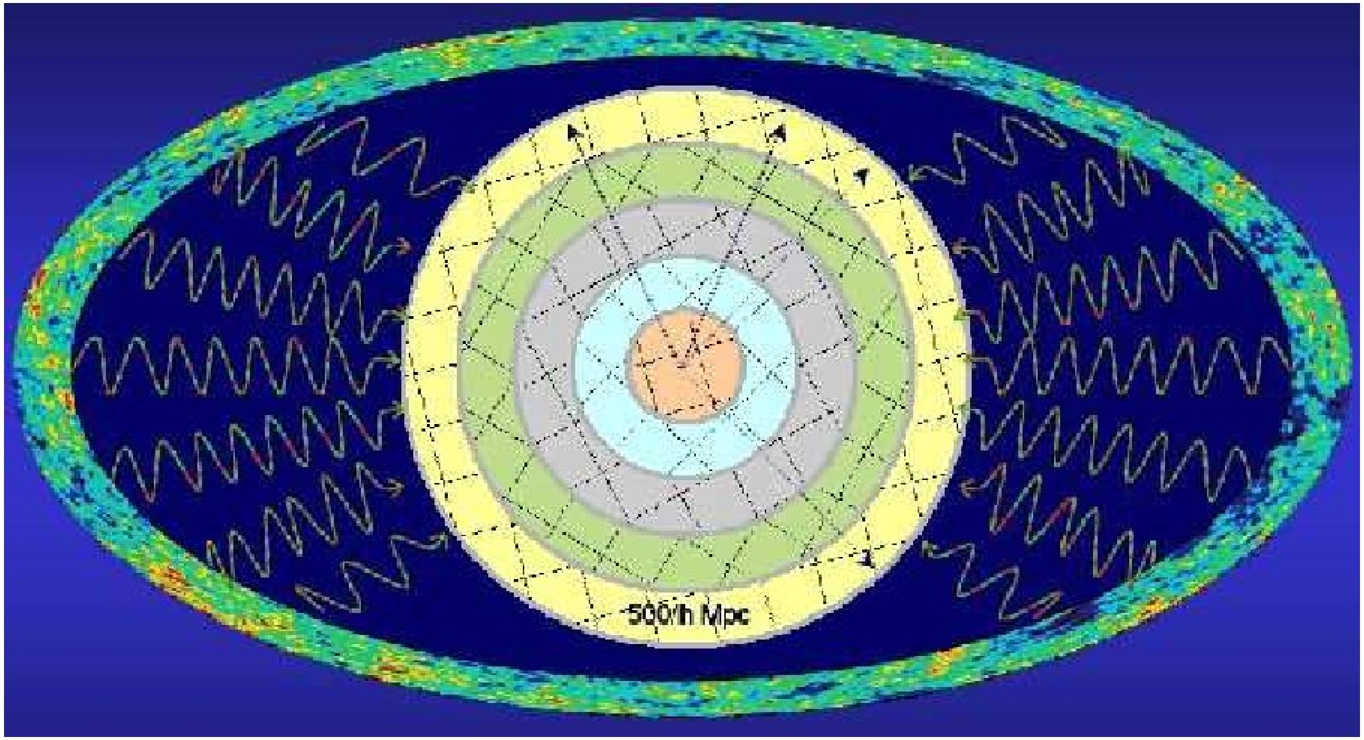
CMB-N-Body lensing



CMB-N-body lensing: do we really need it?

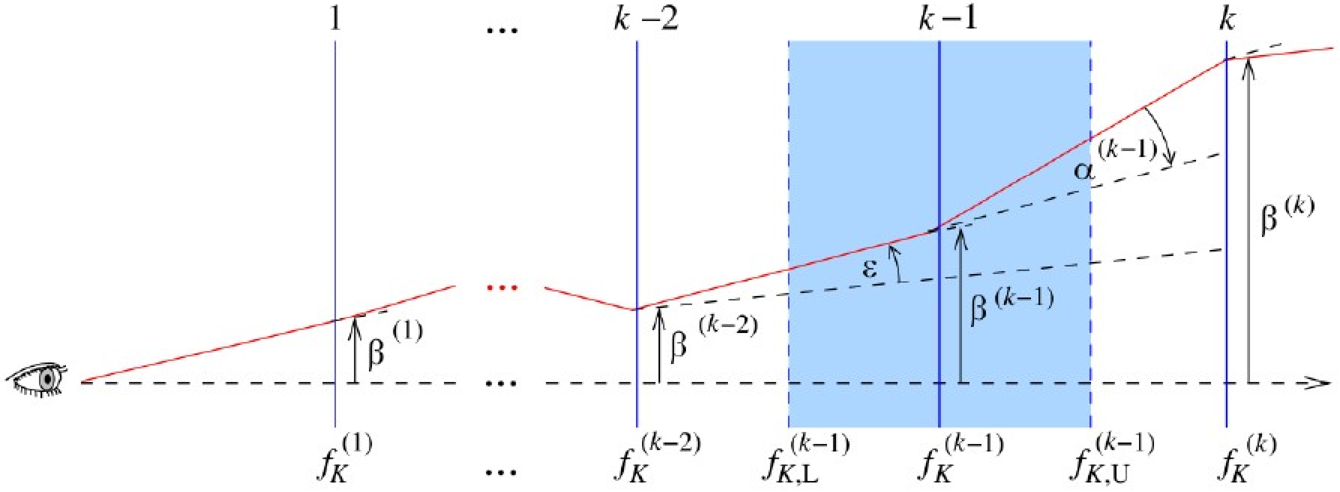
- Do we have a satisfactory statistics in semi-analytic prescriptions for CMB lensing?
- Do we have an understanding of mildly and full non-linear Dark Matter clustering in Dark Energy models?
- Can we learn about simulations trying to get the signal right in particular at high resolution?
- Do we need simulations for understanding cross-correlation studies?
- ...

CMB-N-body lensing



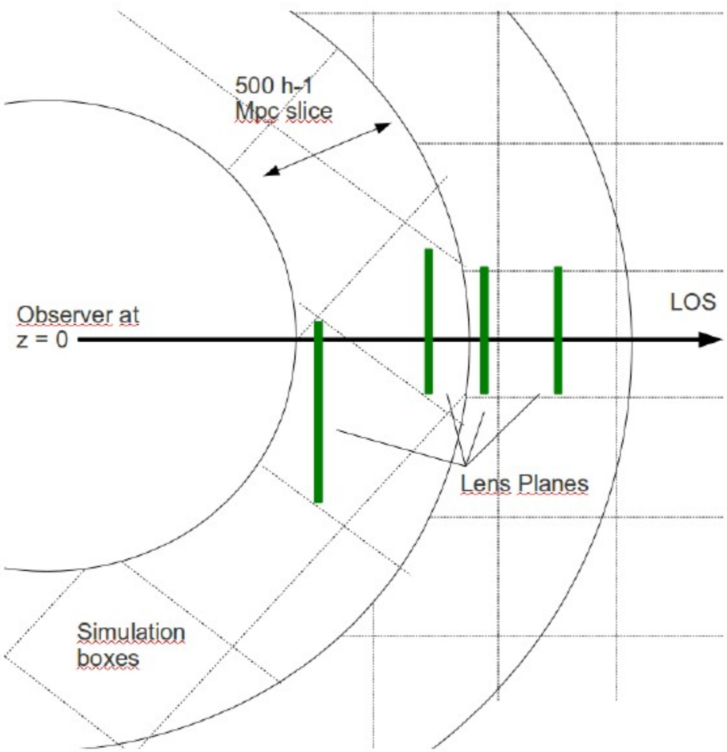
Carbone et al. 2008, 2009, 2013

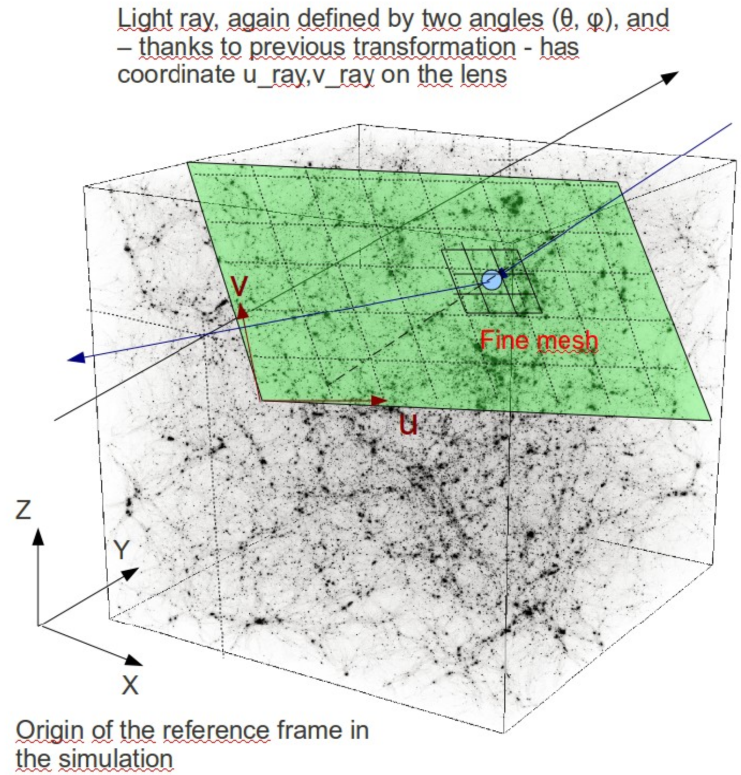
CMB-N-body lensing ray-tracing: Born or non-Born?



Hilbert et al. 2009

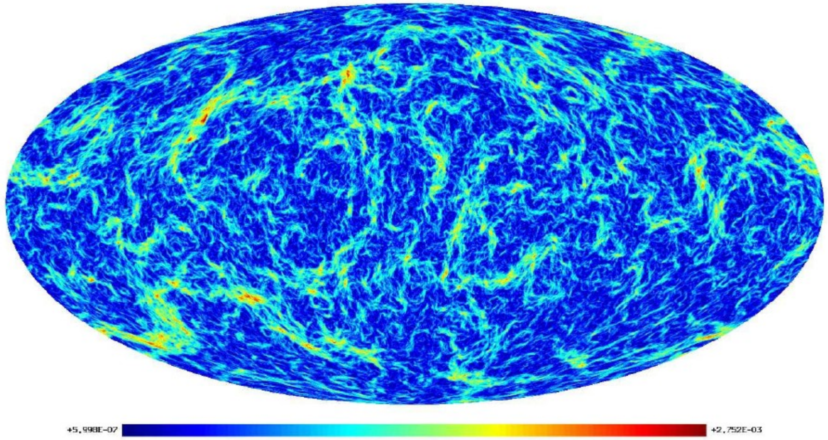
CMB-N-body lensing ray tracing

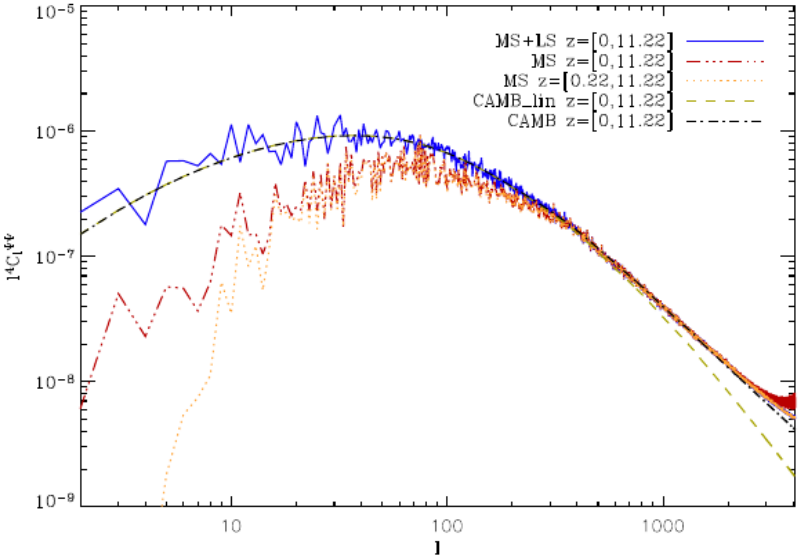




Hilbert et al. 2009, Calabrese et al. 2013

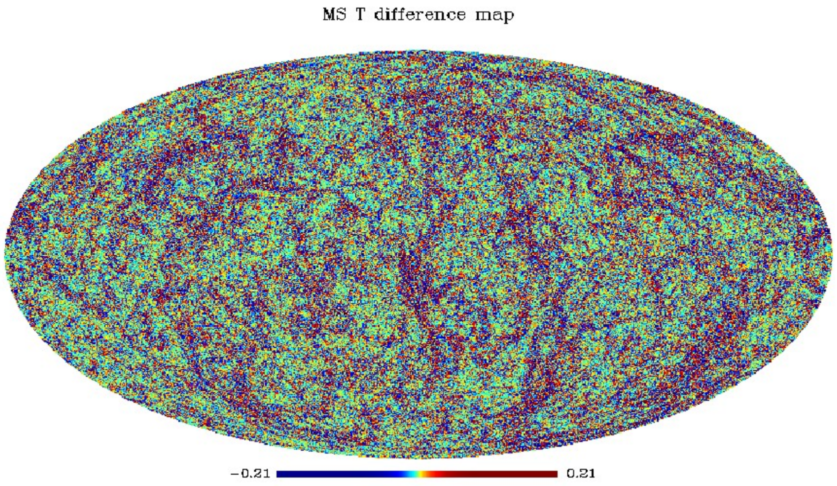
CMB-N-body lensing

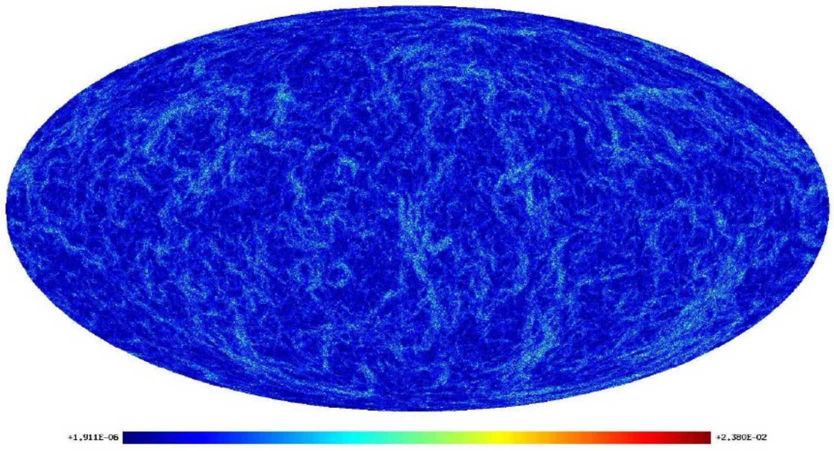




Carbone et al. 2008, 2009, 2013

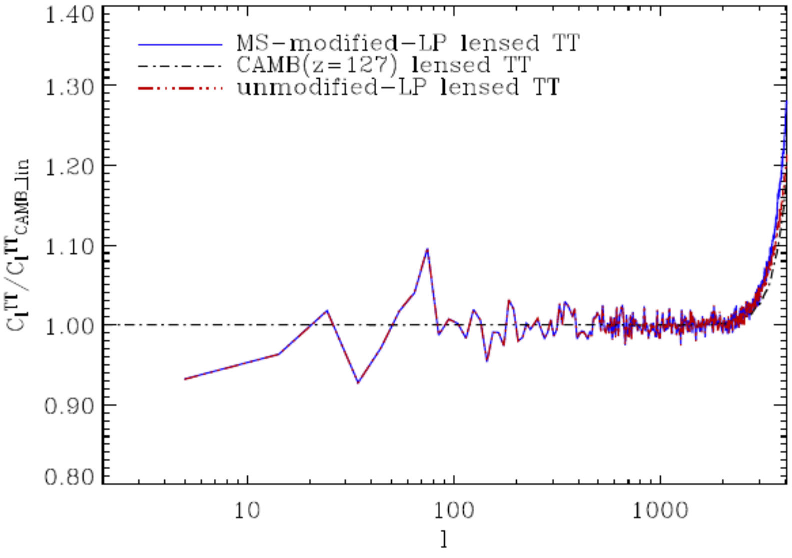
CMB-N-body lensing

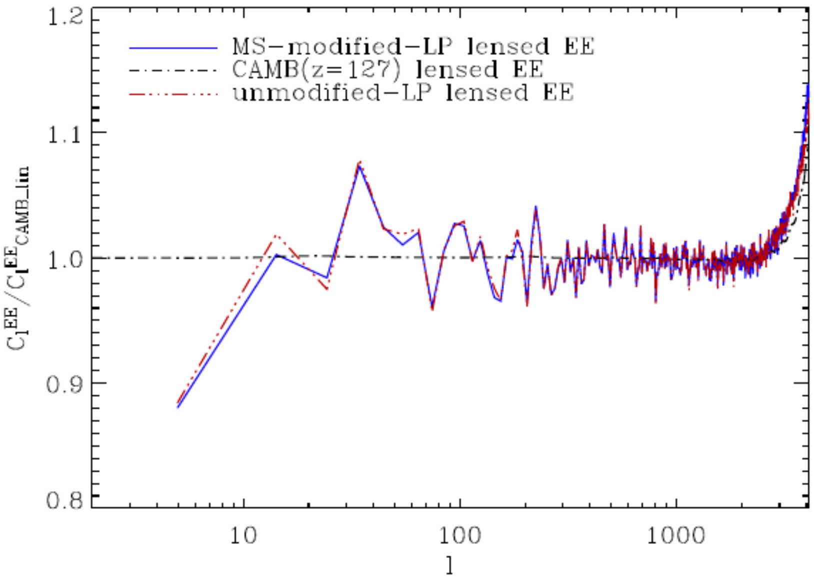




Carbone et al. 2008, 2009, 2013

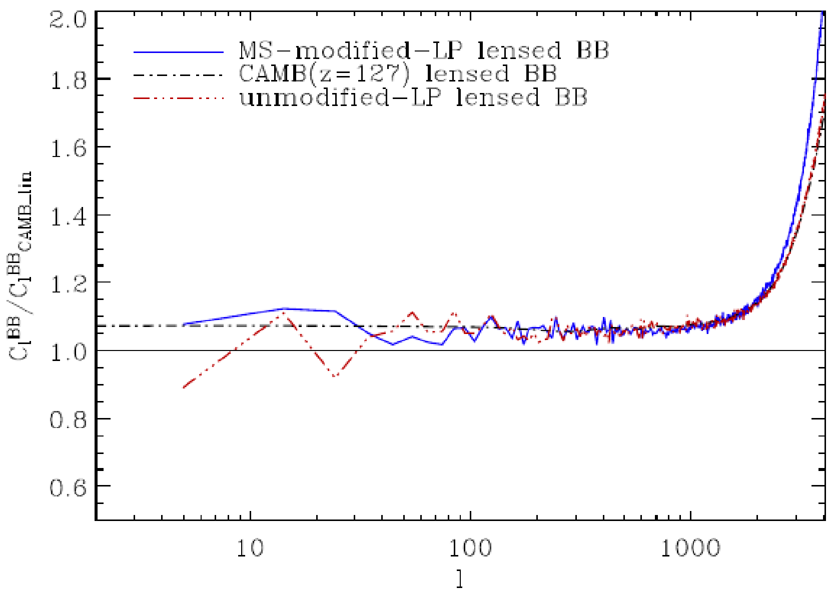
CMB-N-body lensing

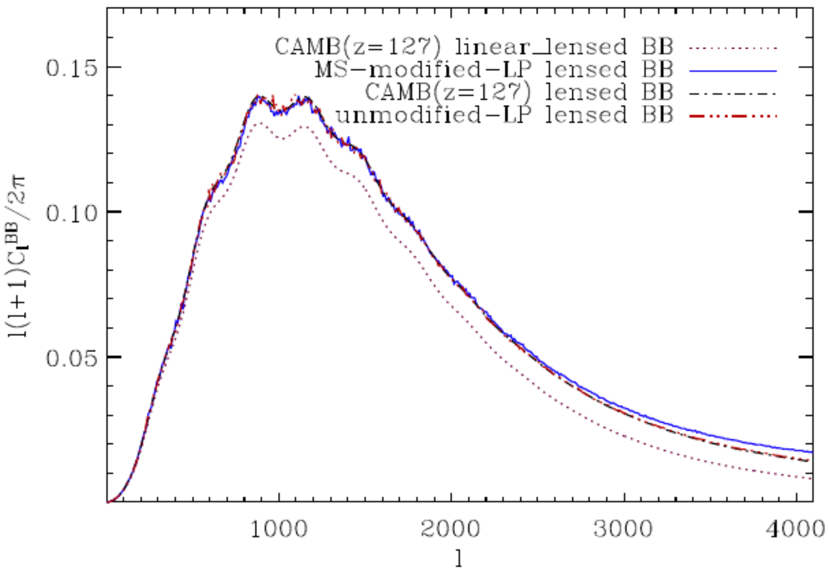




Carbone et al. 2008, 2009, 2013

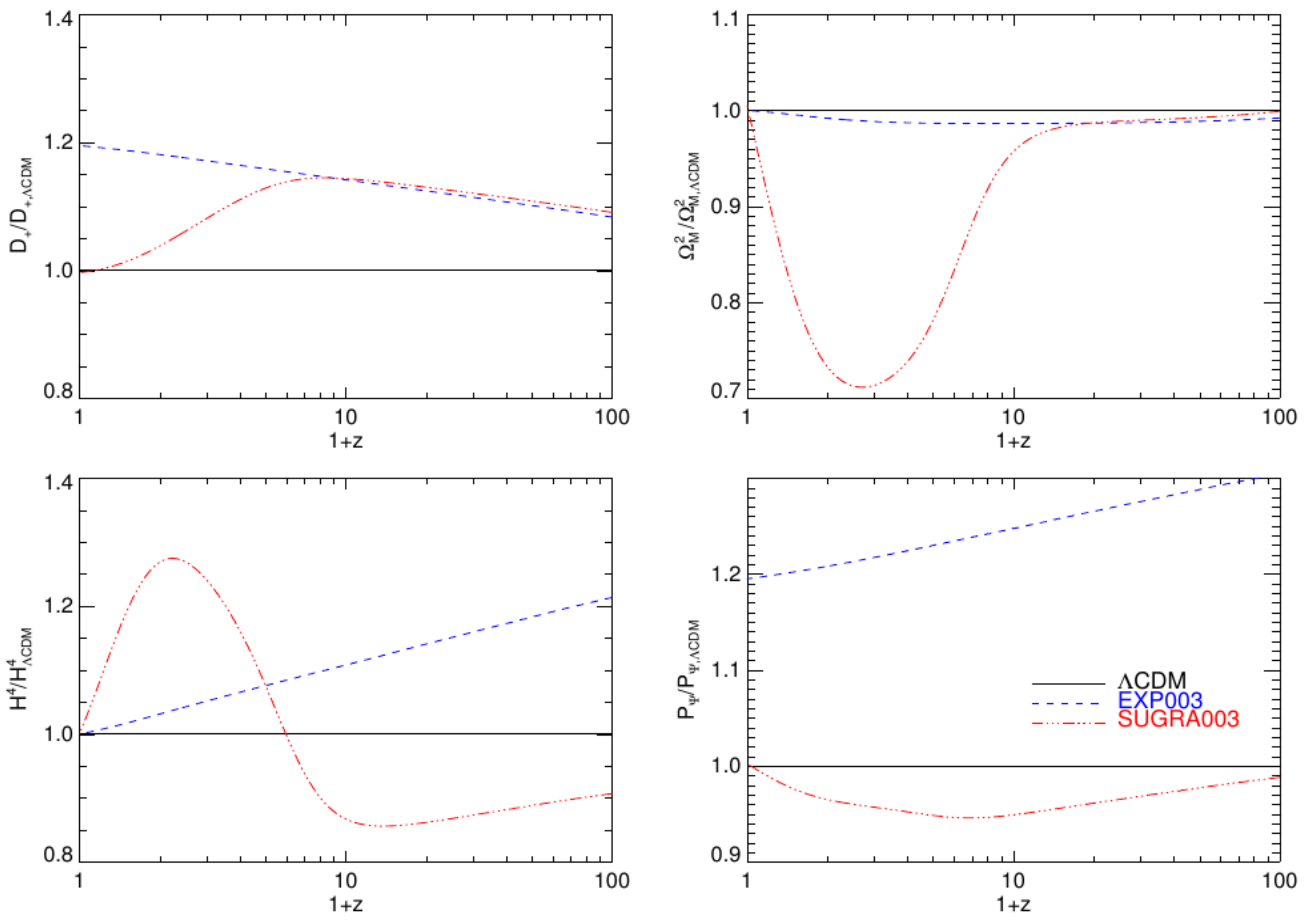
CMB-N-body lensing





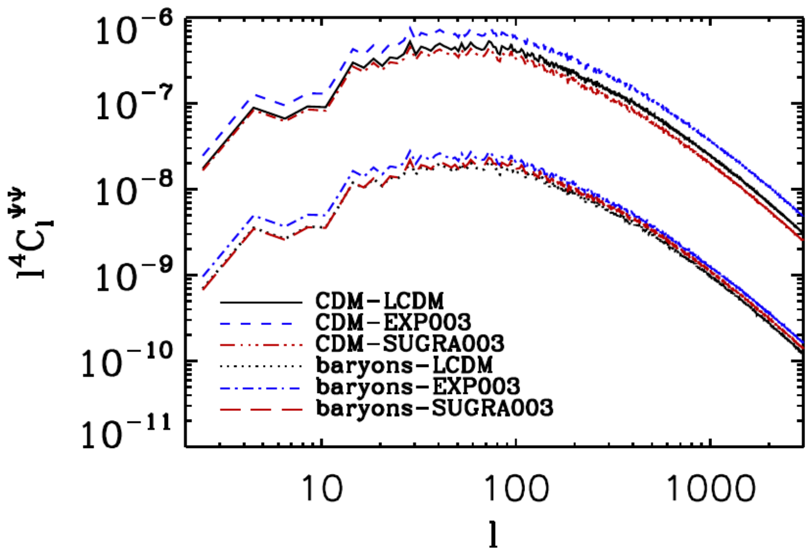
Carbone et al. 2008, 2009, 2013

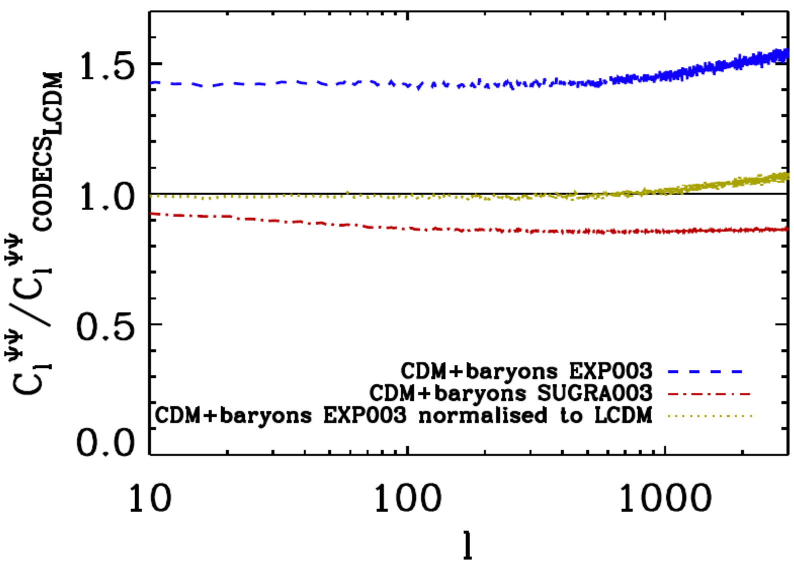
•CMB-N-body lensing: first inspection of non-LCDM cosmologies



Baldi et al. 2012, Carbone et al. 2013

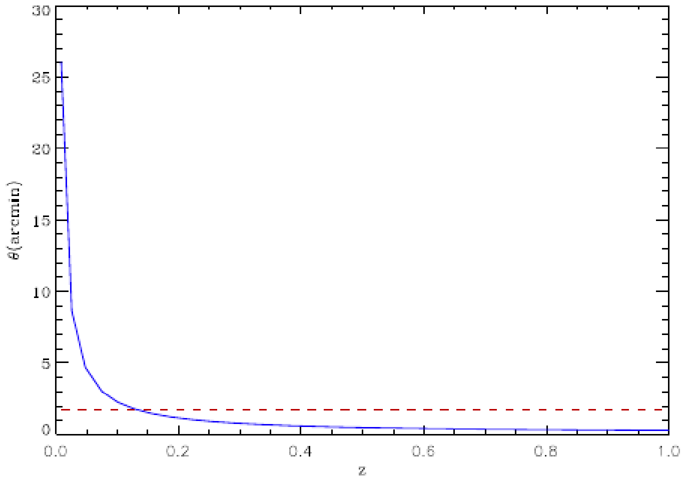
CMB-N-body lensing: first inspection of non-LCDM cosmologies

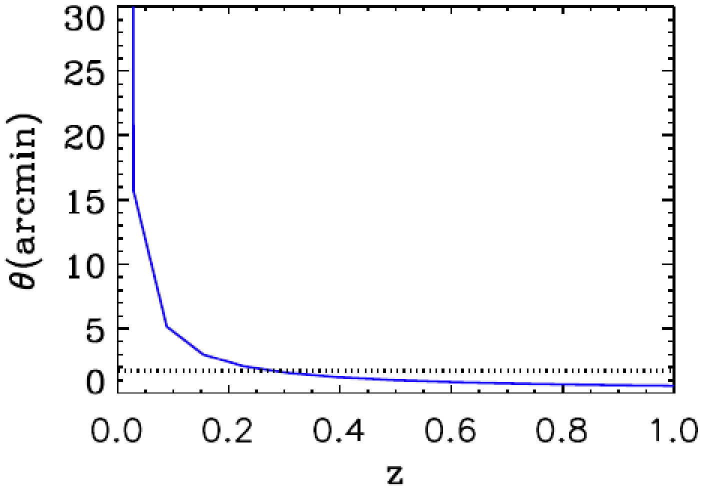




Baldi et al. 2012, Carbone et al. 2013

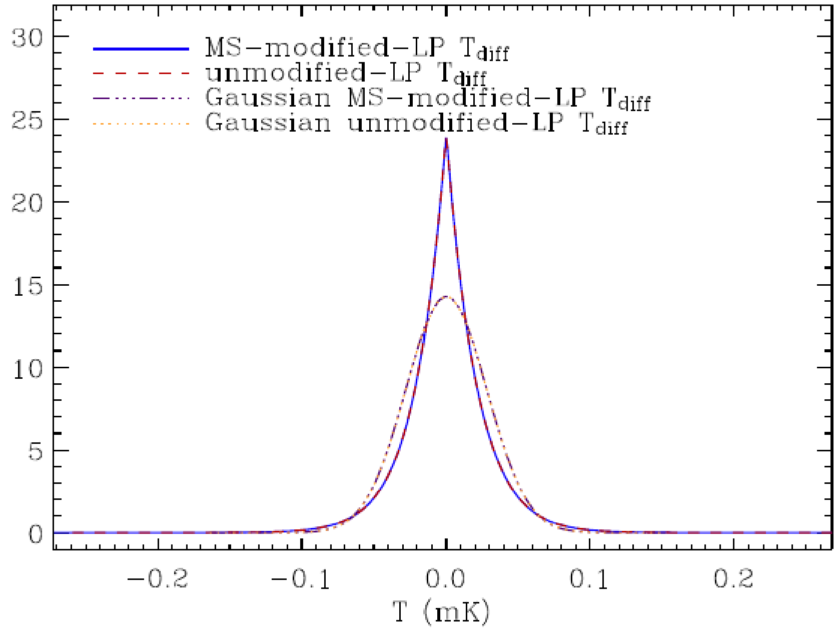
CMB-N-body lensing: gridding issues





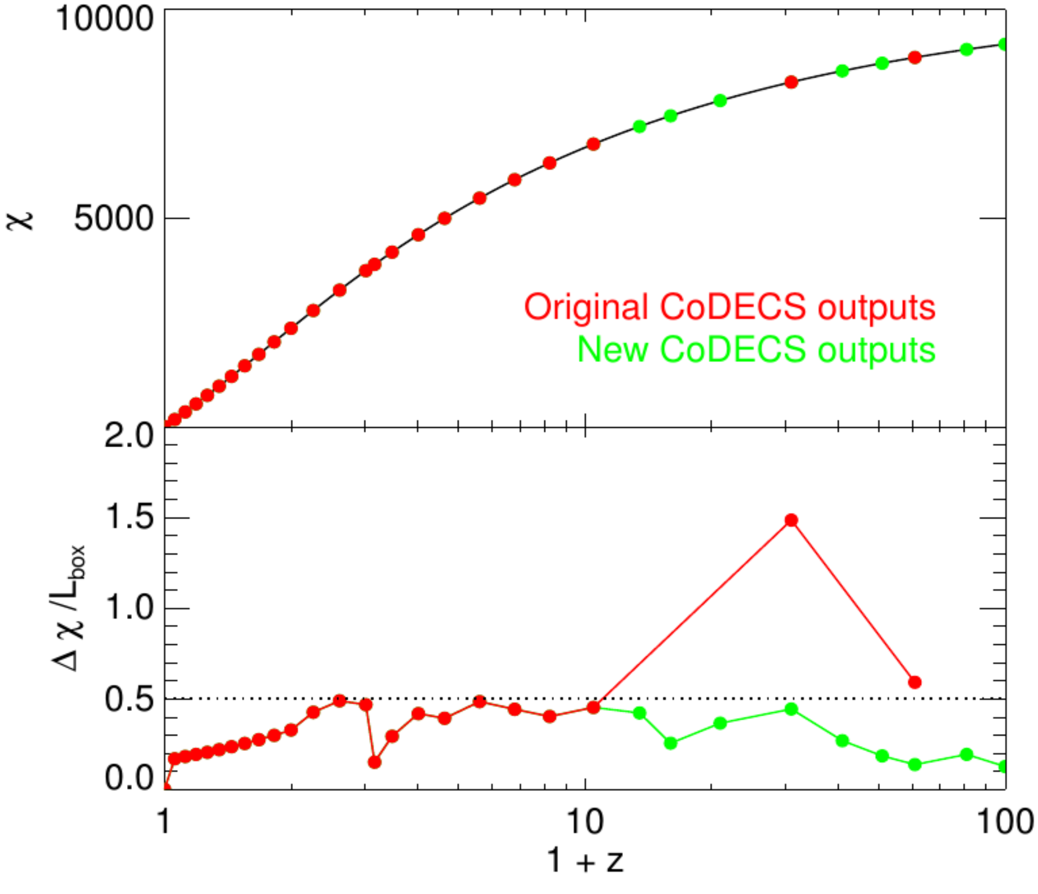
Carbone et al. 2008, 2009, 2013

CMB-N-body lensing: skewed statistics in the CMB lensed/non-lensed maps



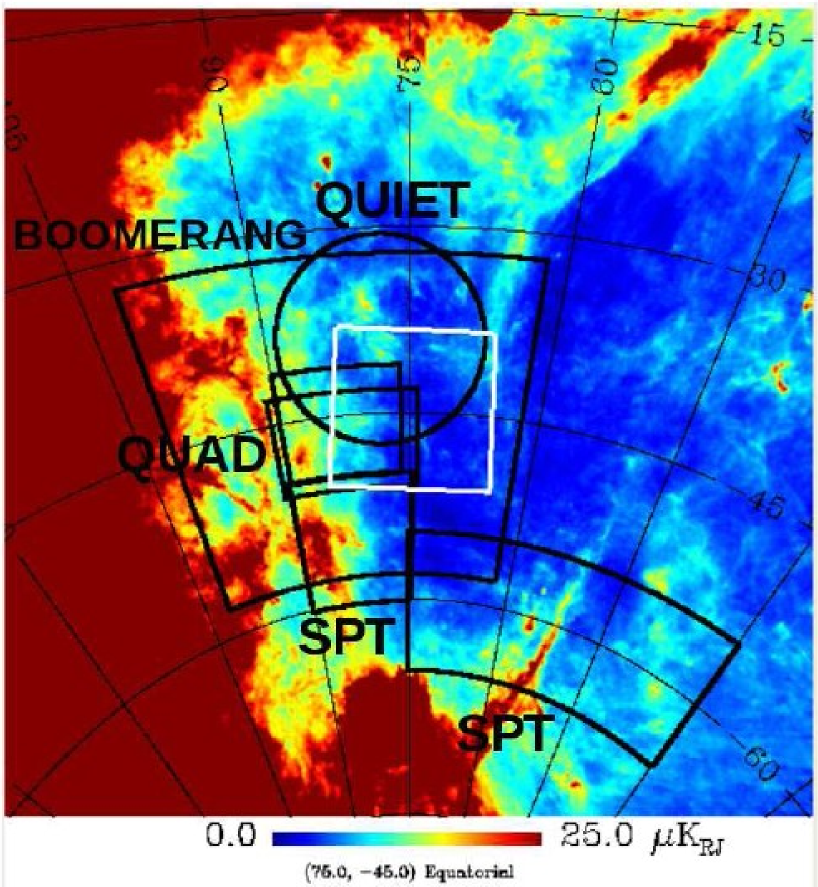
Carbone et al. 2008, 2009, 2013

CMB-N-body lensing: learning lessons on N-body



Carbone et al. 2008, 2009, 2013

CMB lensing and sub-orbital CMB probes: extraction



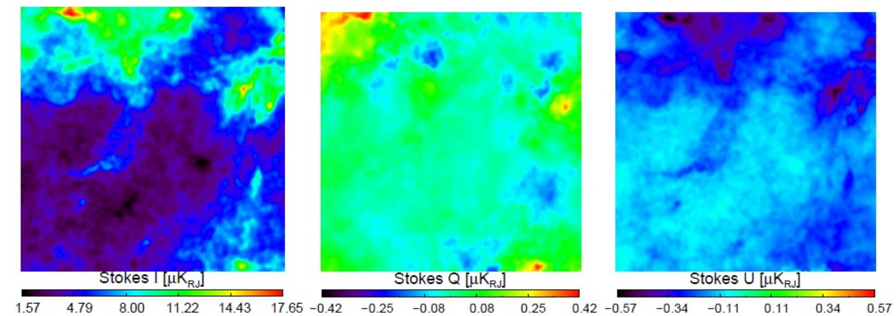


Figure 2. Dust simulation (Stokes I, Q, and U) at 150 GHz, with a polarization fraction $p = 0.036$, on a $13° \times 13°$ patch centred on $(l,b)=(250°,-38°)$.

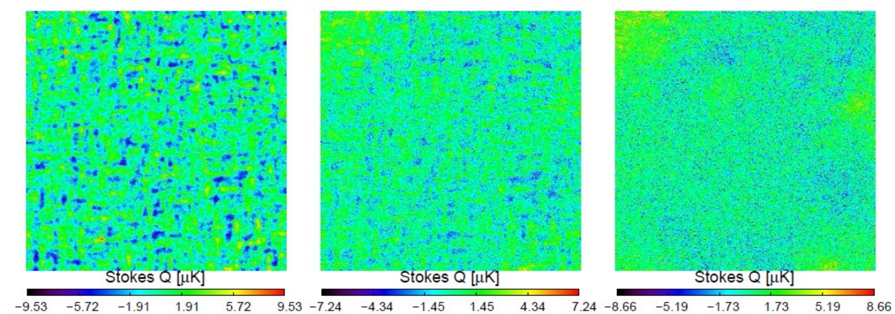
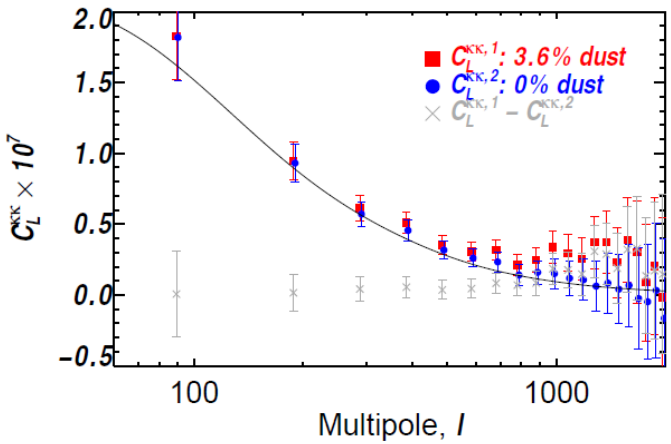
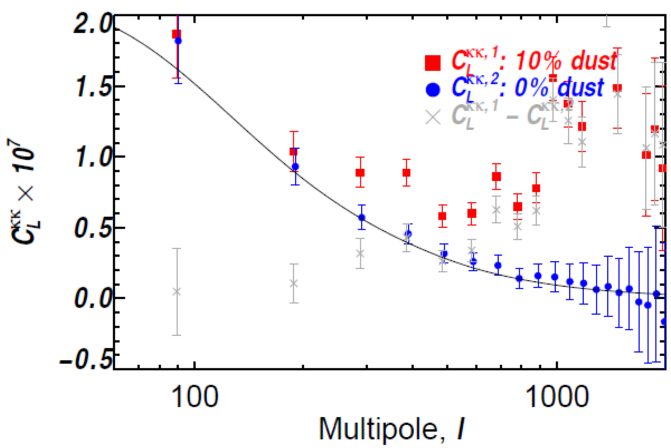


Figure 3. From left to right, we show our CMB+dust+noise simulations at 150, 250 and 410 GHz for a dust polarization fraction $p = 0.1$. The 150 GHz channel is CMB dominated, while the 410 GHz channel is dust dominated. The 250 GHz channel provides information about the dust spectral index.

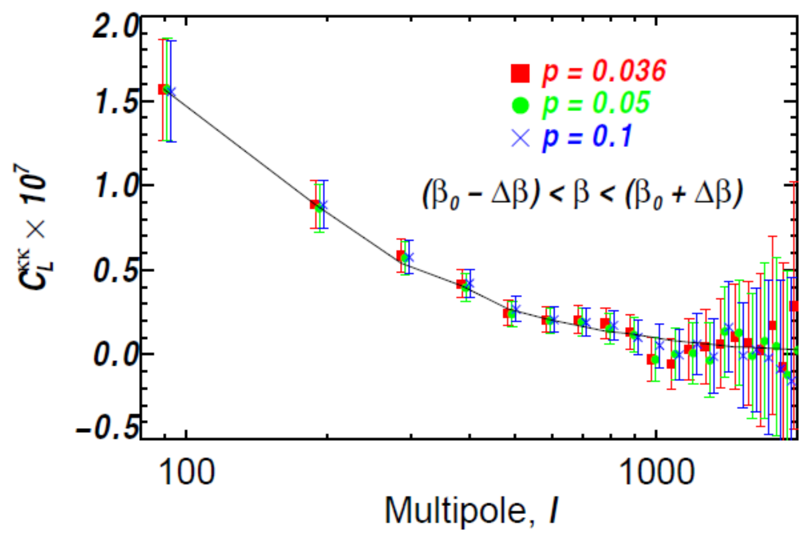
Fantaye et al. 2012

CMB lensing and sub-orbital CMB probes: extraction





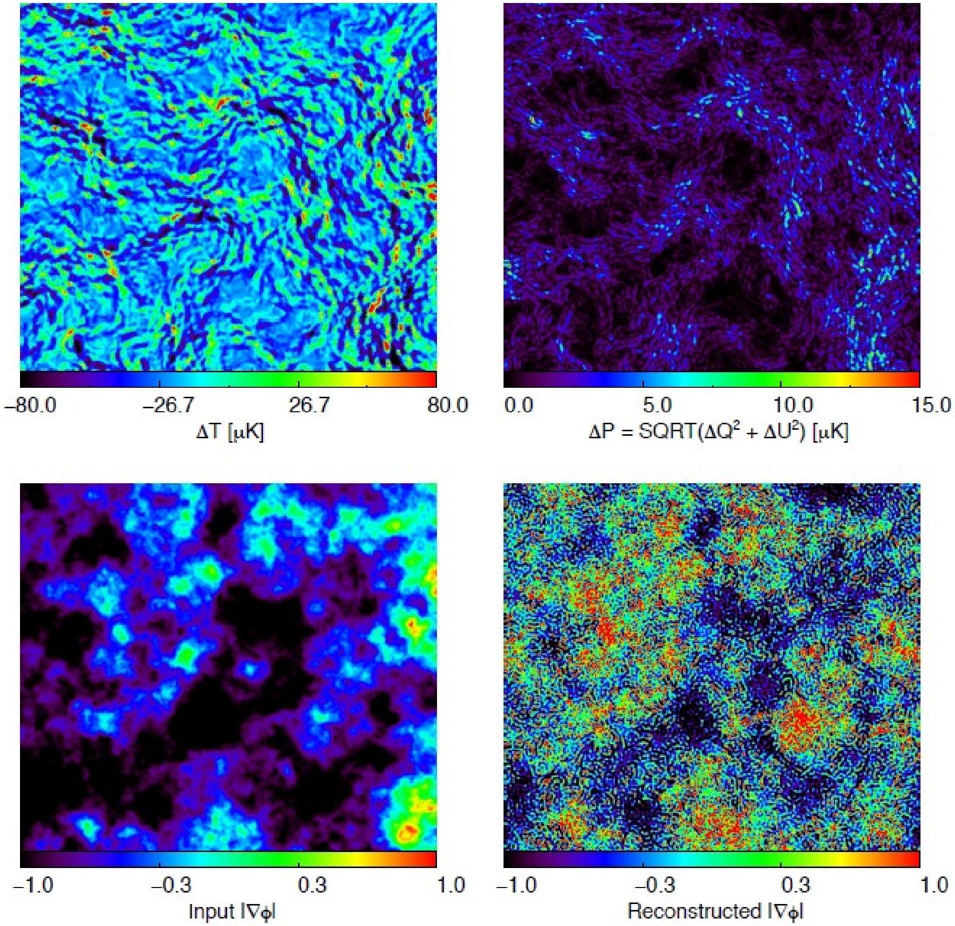
Convergence estimation
Without foreground cleaning



Convergence estimation
With foreground cleaning

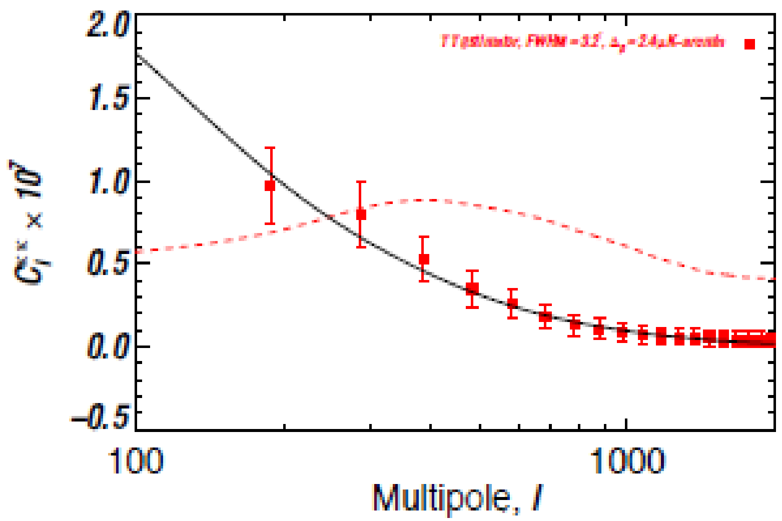
Fantaye et al. 2012

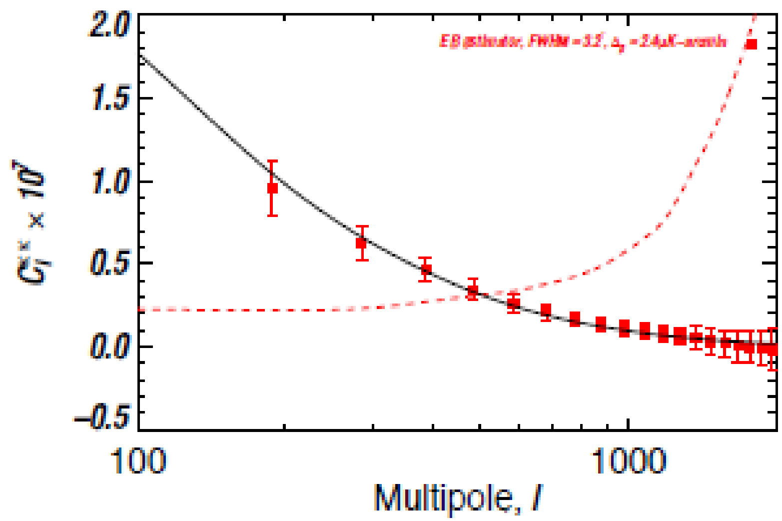
CMB-N-body lensing reconstruction



Antolini, et al. 2014

CMB-N-body lensing reconstruction





Antolini, et al. 2014

Concluding remarks

- Is lensing relevant for Dark Energy?
- Does the signal keep its promise?
- Do we need CMB-N-body lensing?
- Do we have the technology for simulating it?
- Do we have a complete understanding of the effects of details in the simulations in the signal we see?
- Can we start simulating cross-correlation studies on the way to Euclid?
- ...

Concluding remarks

- Is lensing relevant for Dark Energy? **Yes, it is.**
- Does the signal keep its promise? **Yes, it does.**
- Do we need CMB-N-body lensing? **Well...yes.**
- Do we have the technology for simulating it? **Yes...still limited by present simulations, but it works.**
- Do we have a complete understanding of the effects of details in the simulations in the signal we see? **No. We still need to distinguish between physical effects/N-body details/gridding issues at high resolution.**
- Can we start simulating cross-correlation studies on the way to Euclid? **Oh yes, we should...**
- ...

Extension II:
A mini-Dark Energy Course

Fighting the cosmological constant

$$G_{\mu\nu}=8\pi T_{\mu\nu}$$

Fighting the cosmological constant

geometry

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi T_{\mu\nu} + V g_{\mu\nu}$$

quantum vacuum

Fighting the cosmological constant

Λ:???

Fighting the cosmological constant

$V : M^4_{Planck}$???

Fighting the cosmological constant

Λ:???

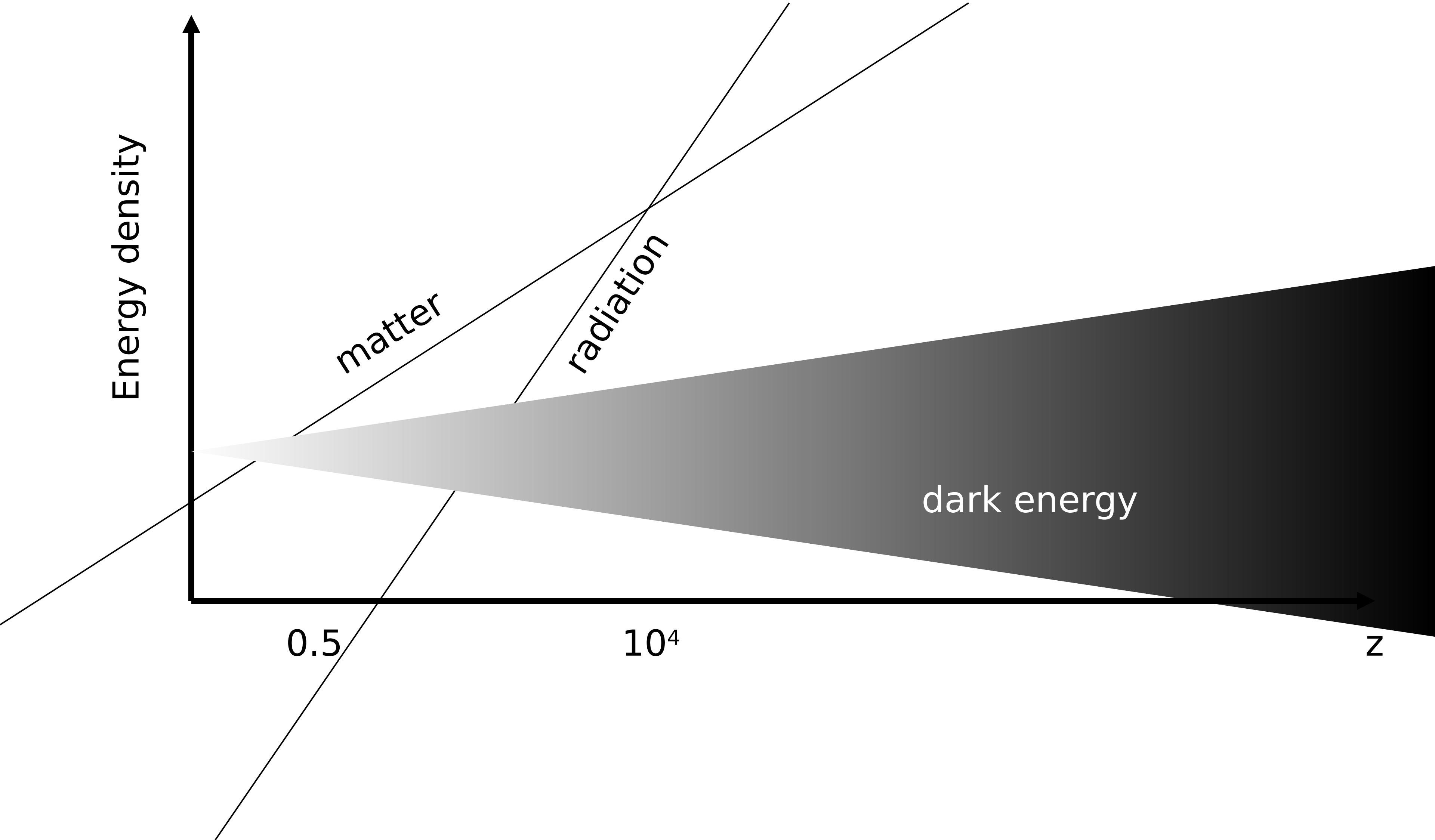
$$|\Lambda\text{-}V|/M^4_{Planck} = 10^{-123}$$

V:M^4_{Planck} ???

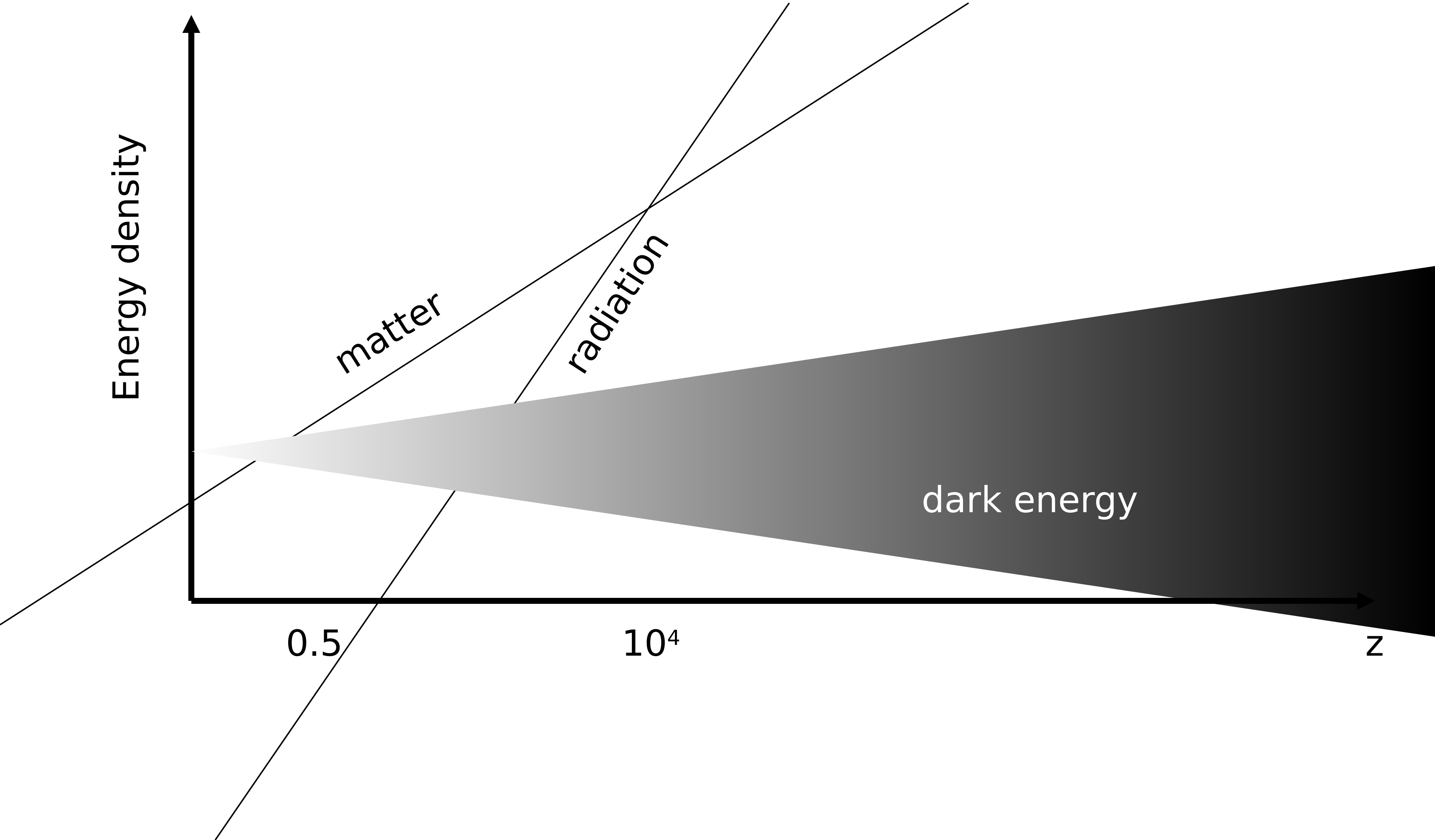
$(Boh?)^2$

- Why so small with respect to any other known energy scale in physics?
- Why comparable to the matter energy density today?

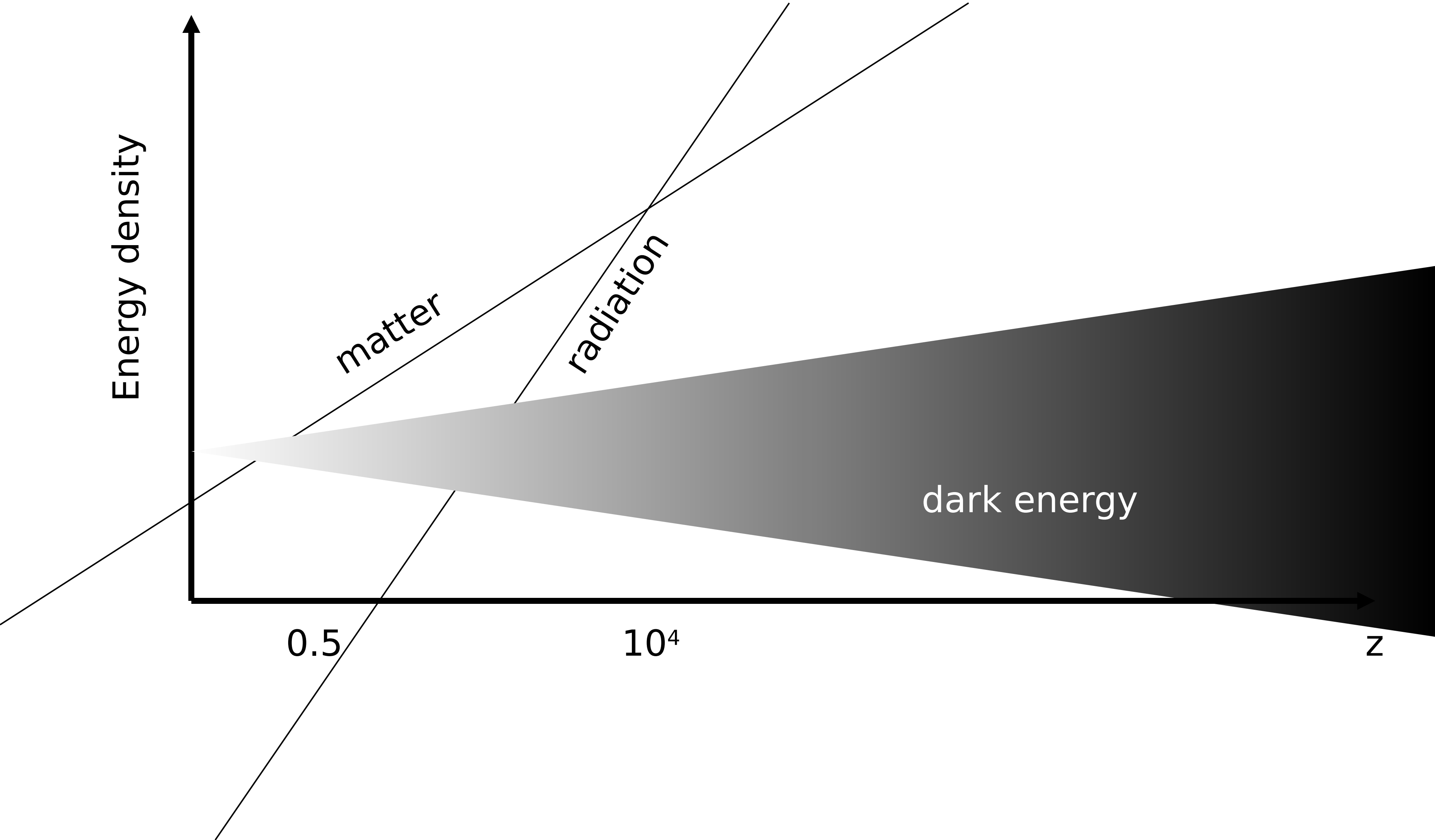
Dark Energy



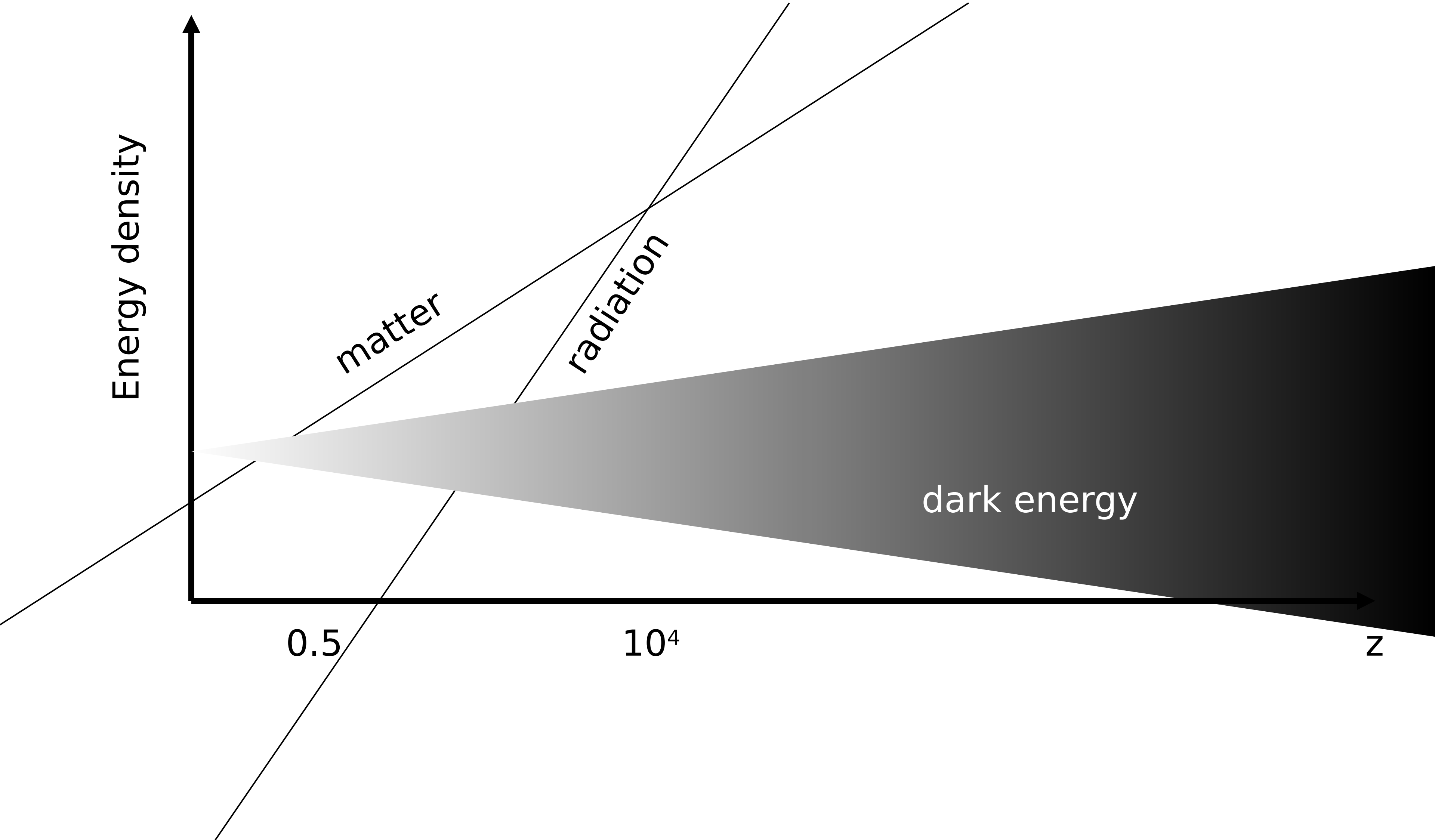
Dark Energy



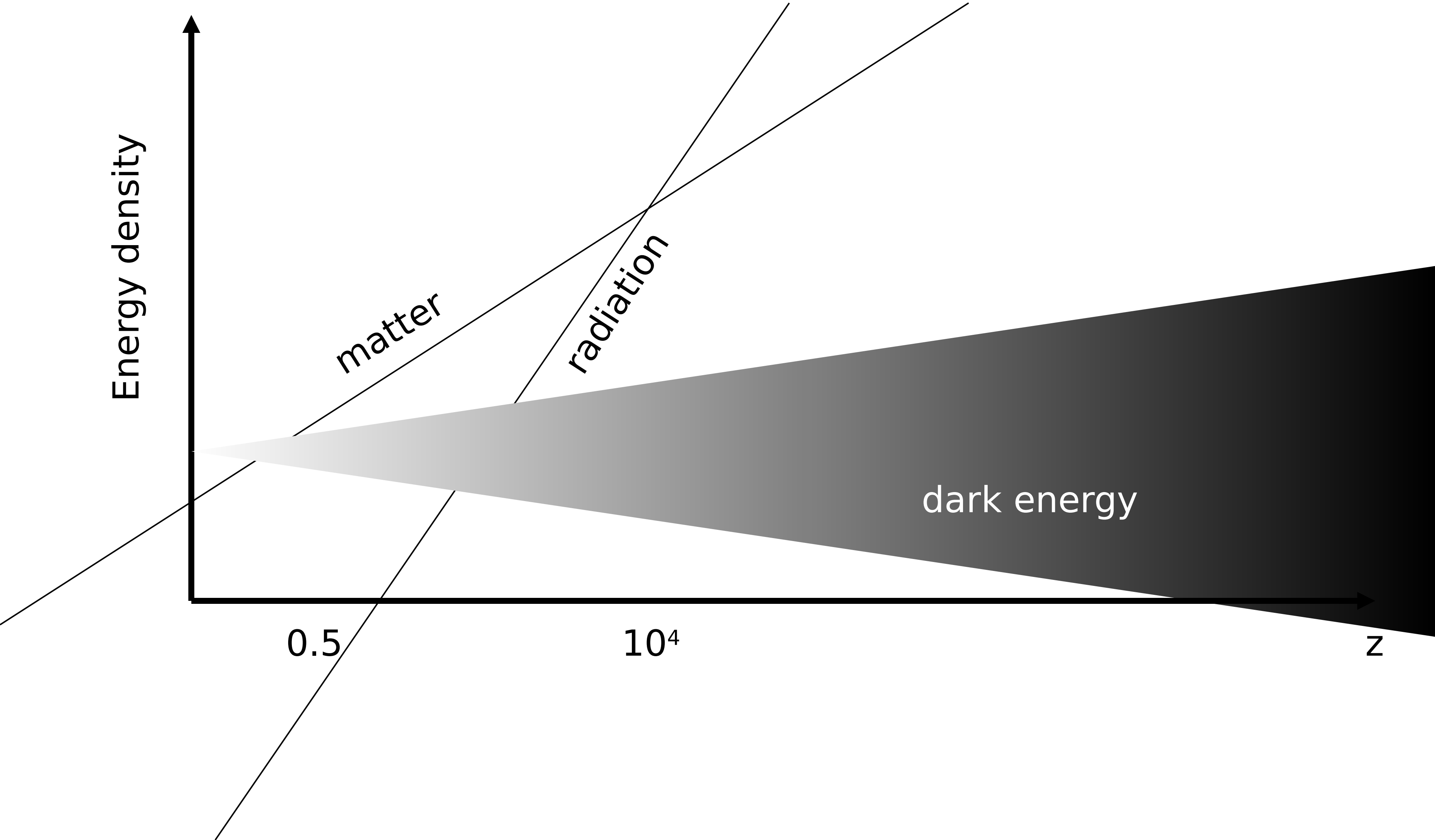
Dark Energy



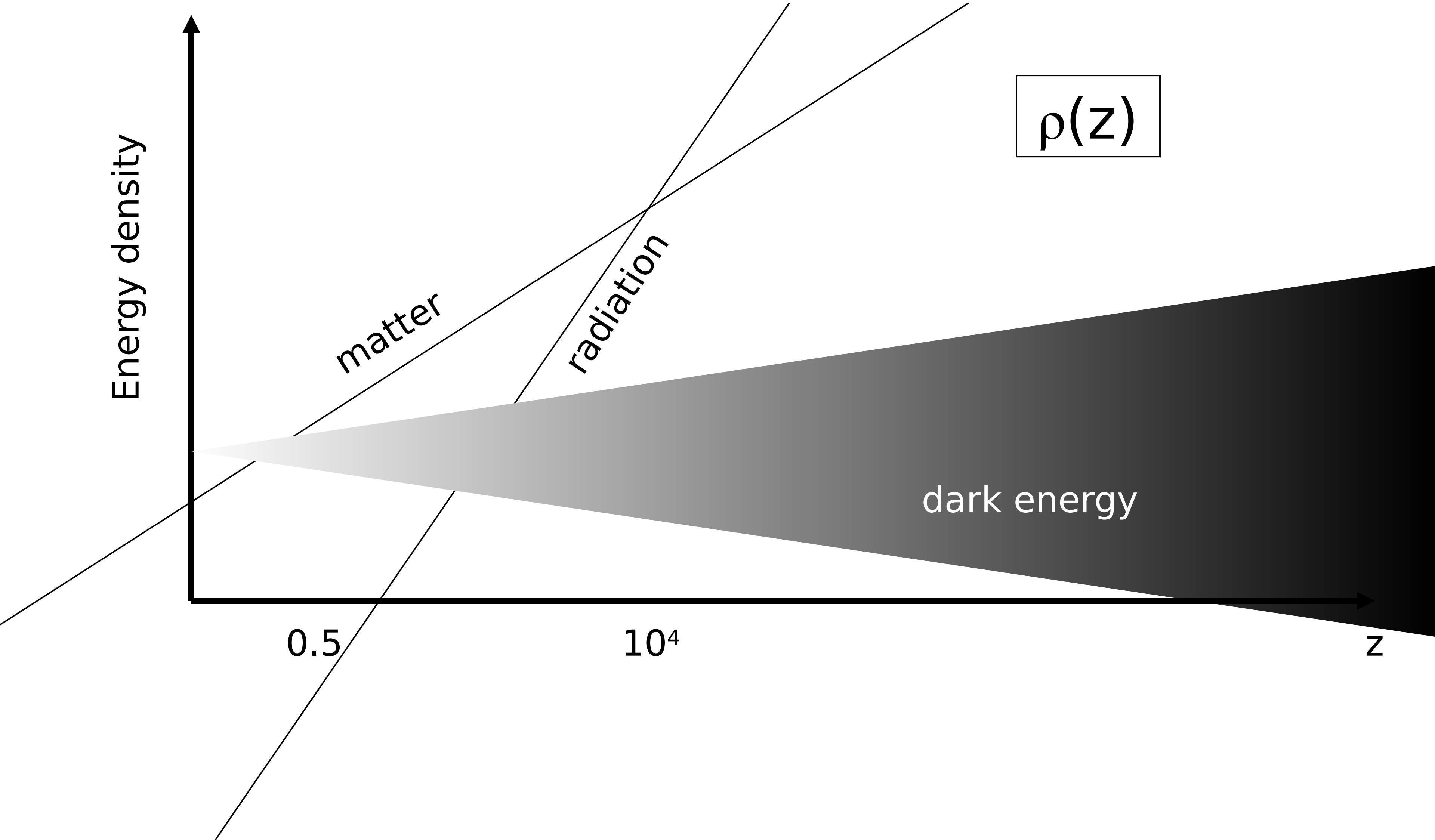
Dark Energy



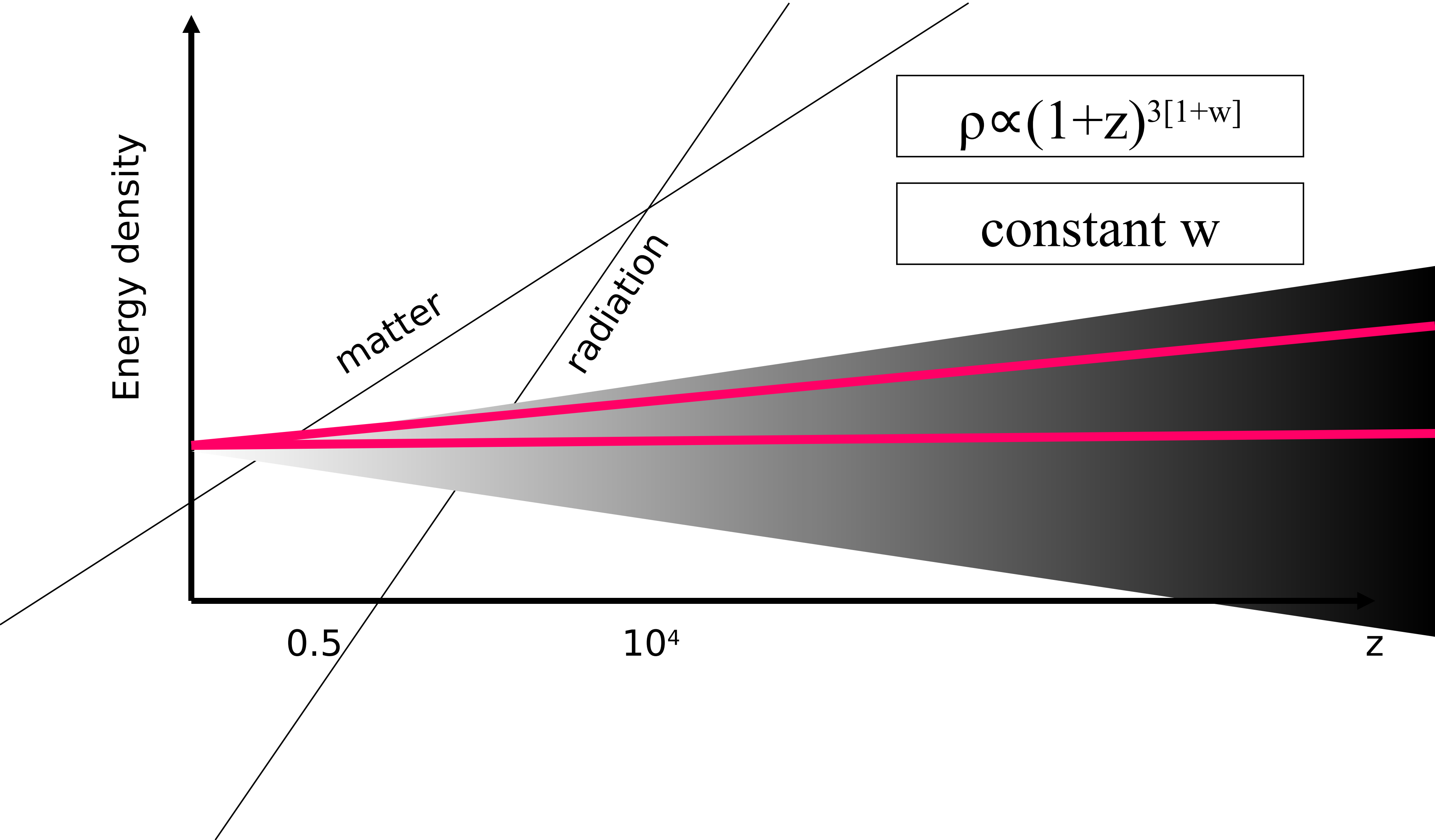
Dark Energy



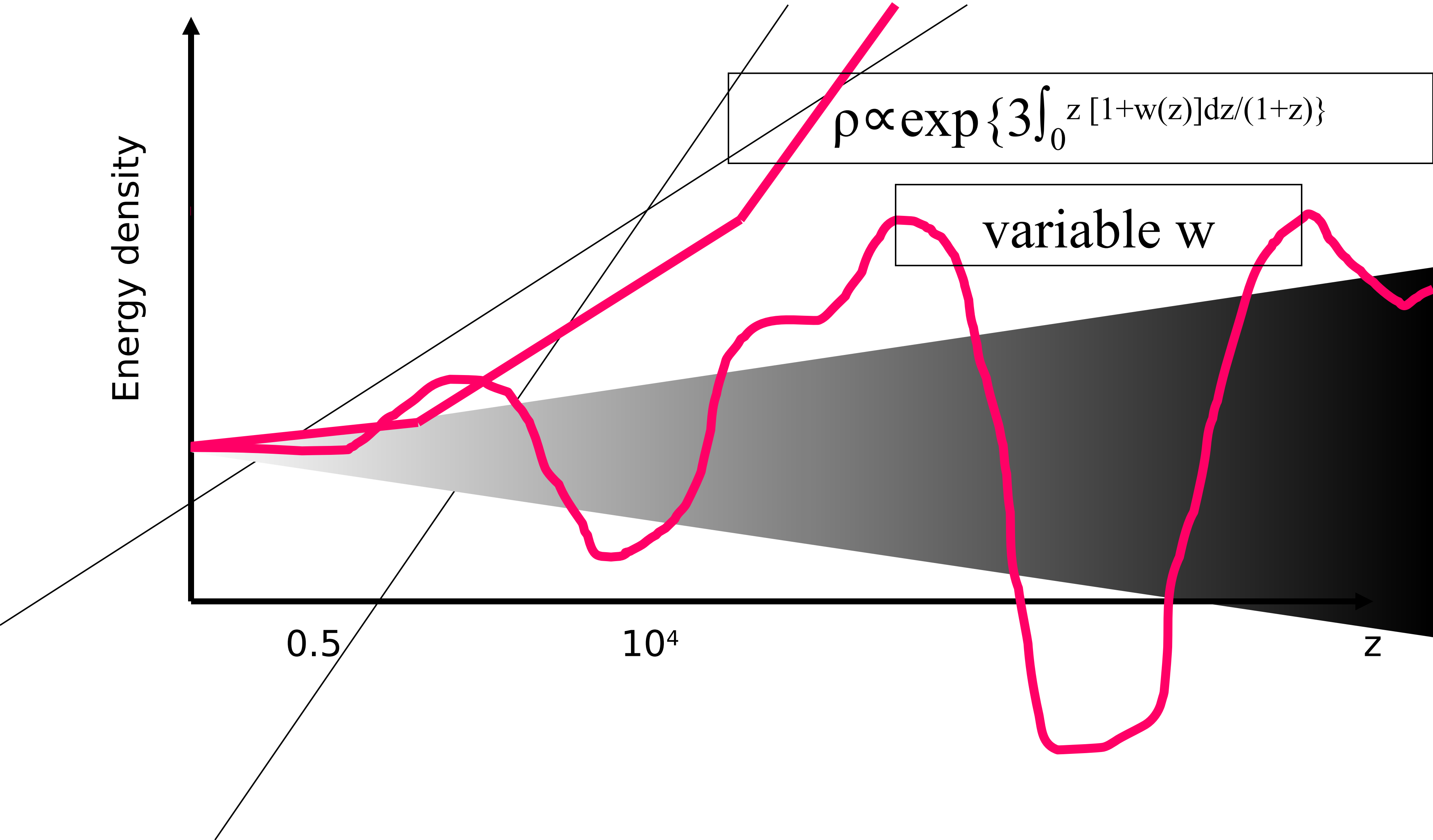
Parametrizing cosmic acceleration is ...



...parametrizing cosmic density

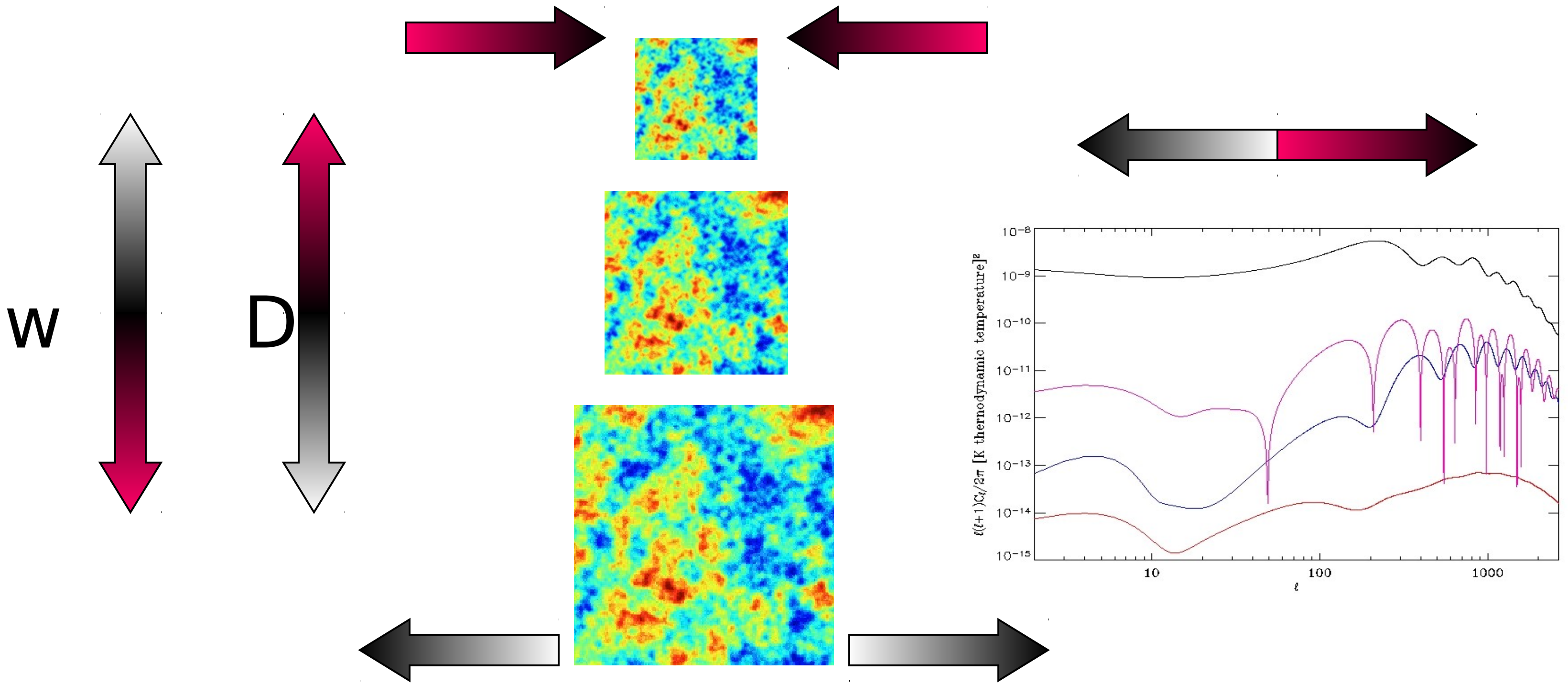


Parametrizing cosmic density



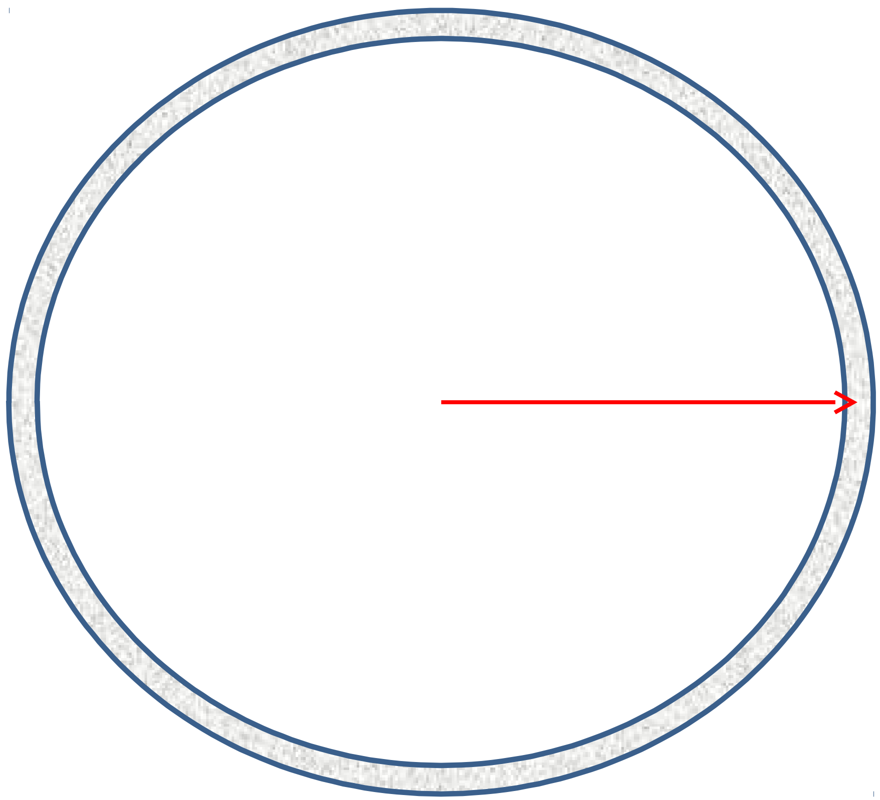
Cosmological expansion and CMB: projection

$$D = H_0^{-1} \int_0^z \frac{dz}{\left[\sum_i \Omega_i (1+z)^{3(1+w_i)}\right]^{1/2}}$$



Constraining the expansion with distances

$$D = H_0^{-1} \int_0^z \frac{dz}{[\Sigma_i \Omega_i (1+z)^{3(1+w_i)}]^{1/2}}$$



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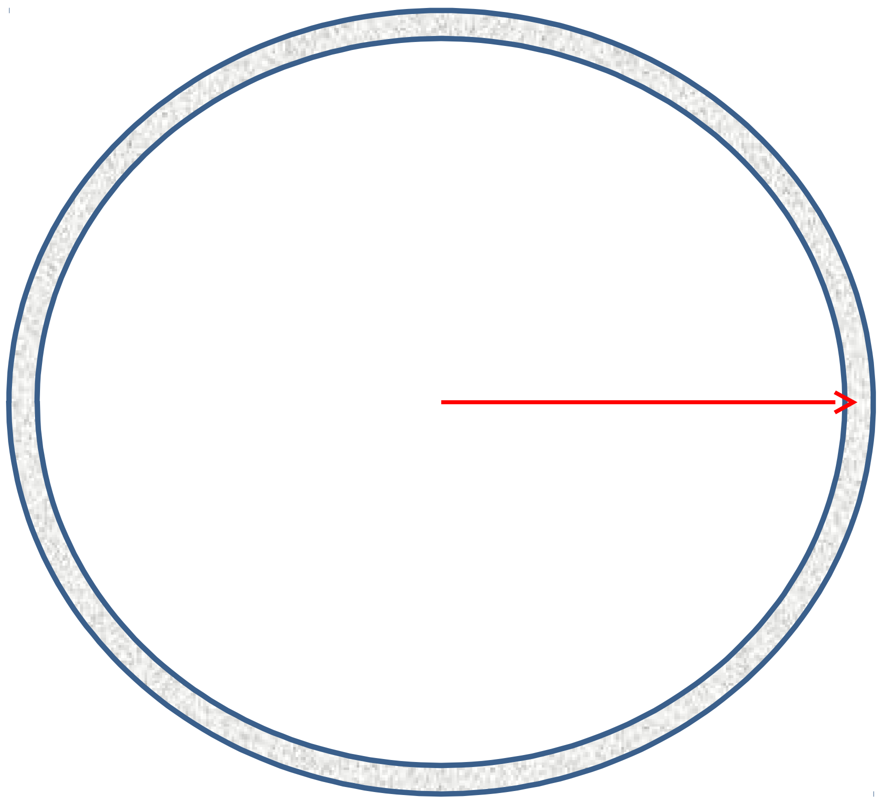

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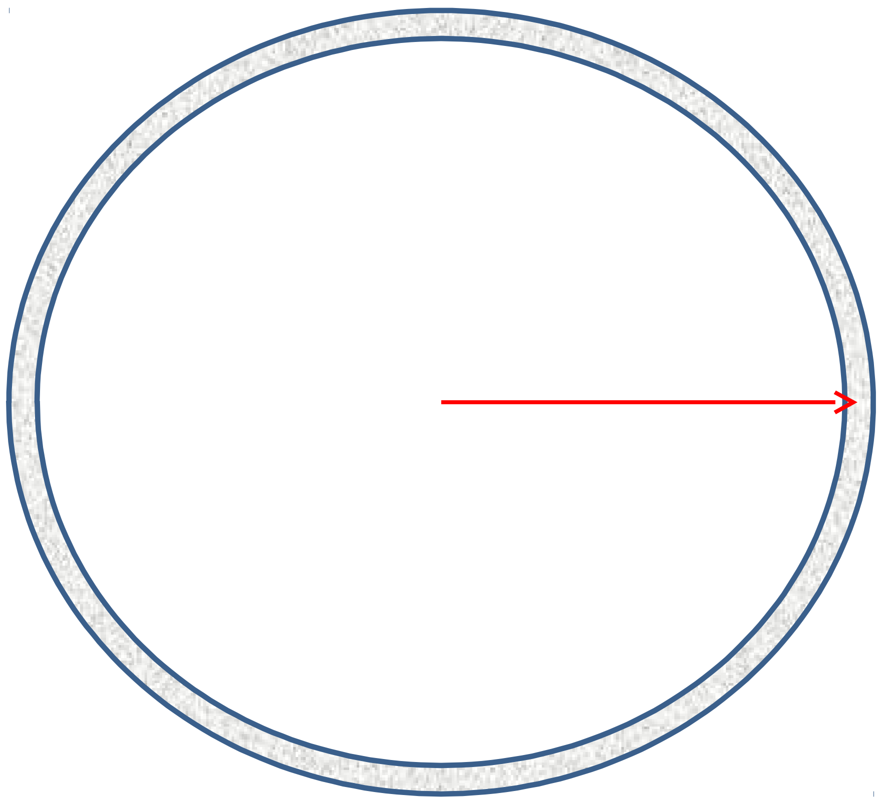
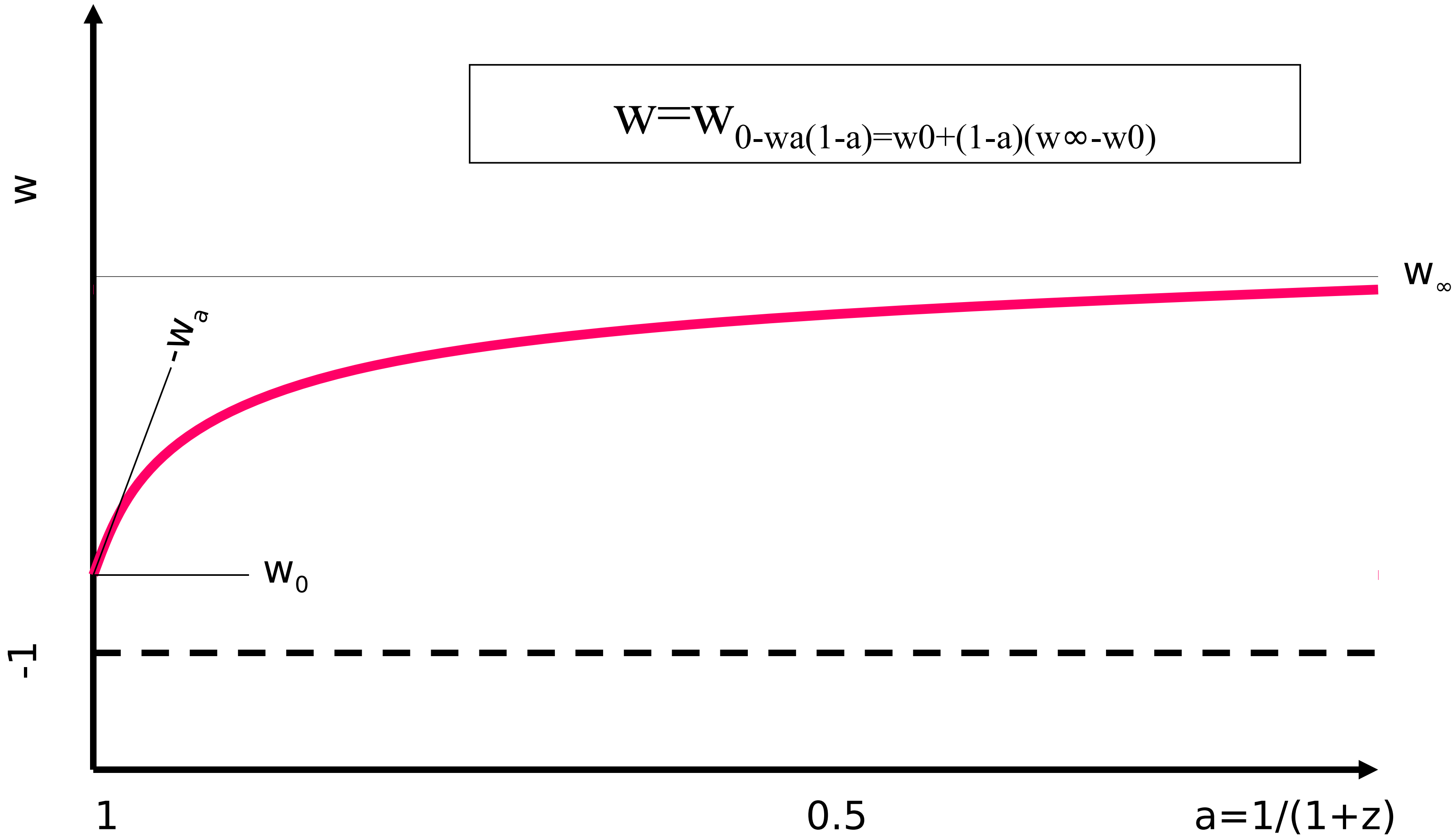
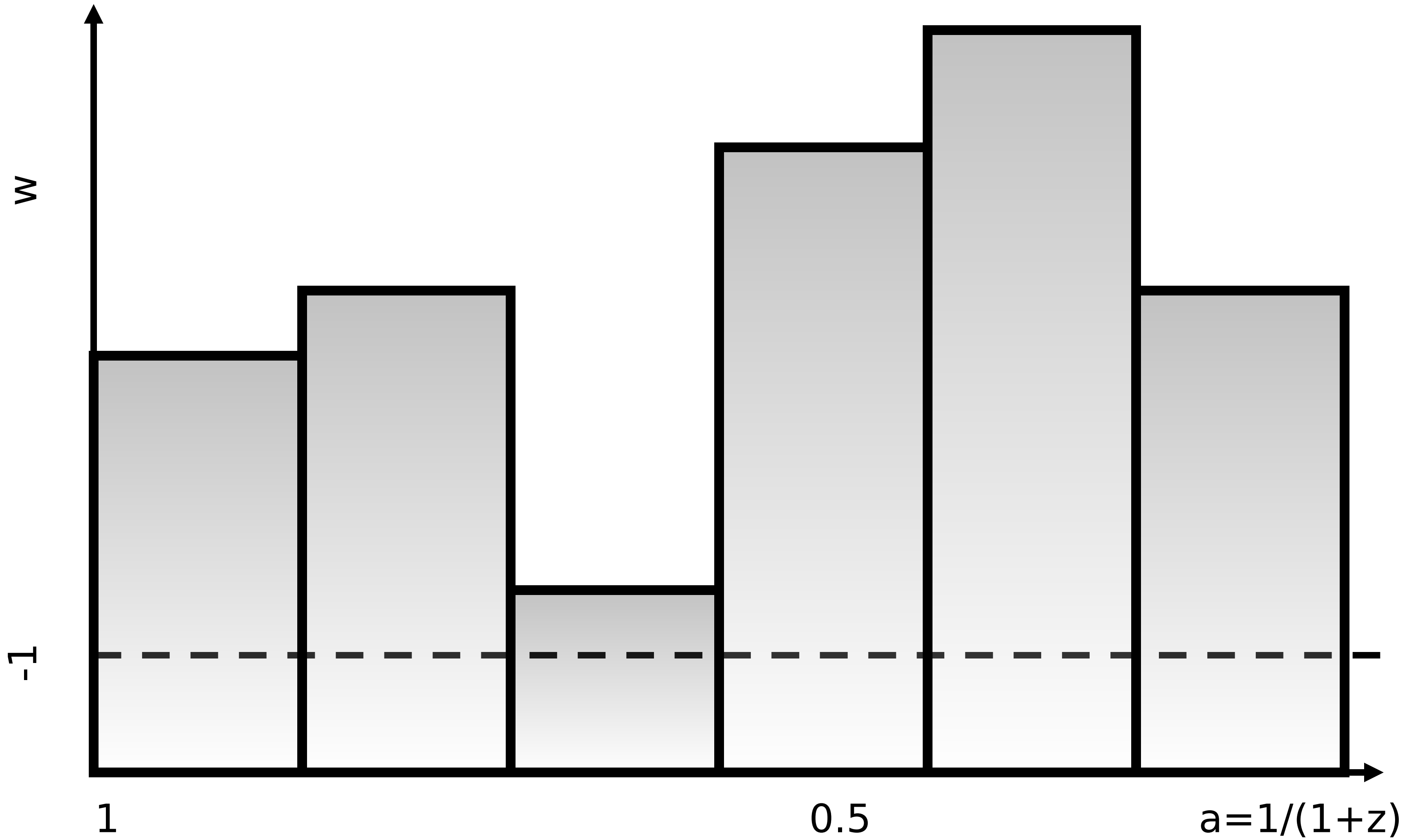


Constraining Dark Energy: models



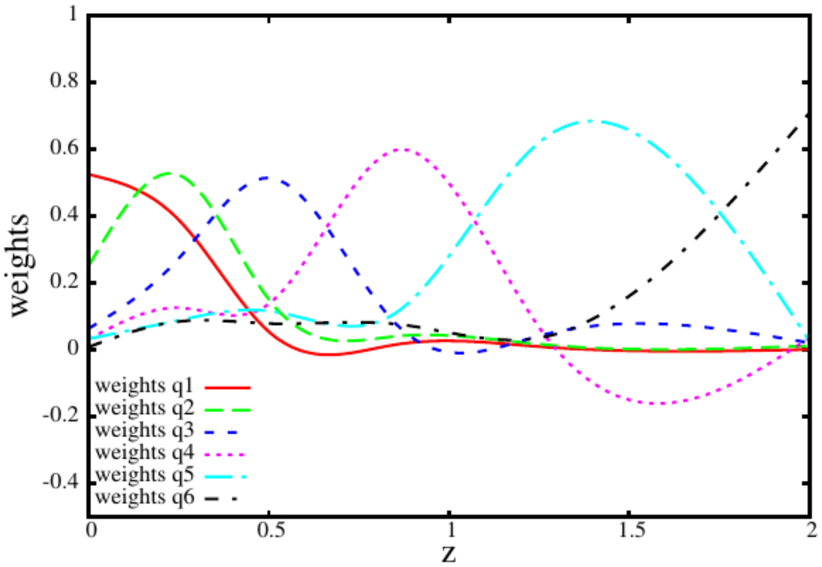
Chevallier & Polarski 2001, Linder 200

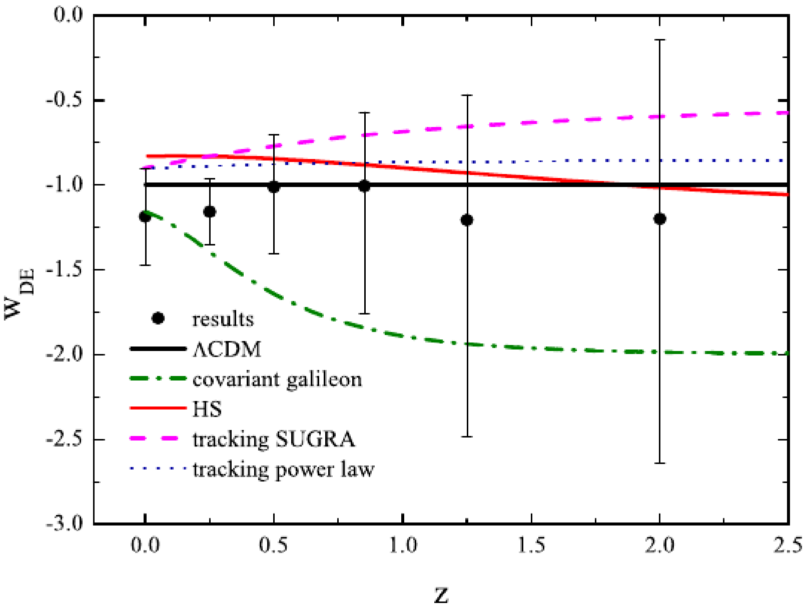
Constraining Dark Energy: binning



Crittenden & Pogosian 2006, Dick et al. 2006,Said et al. 2

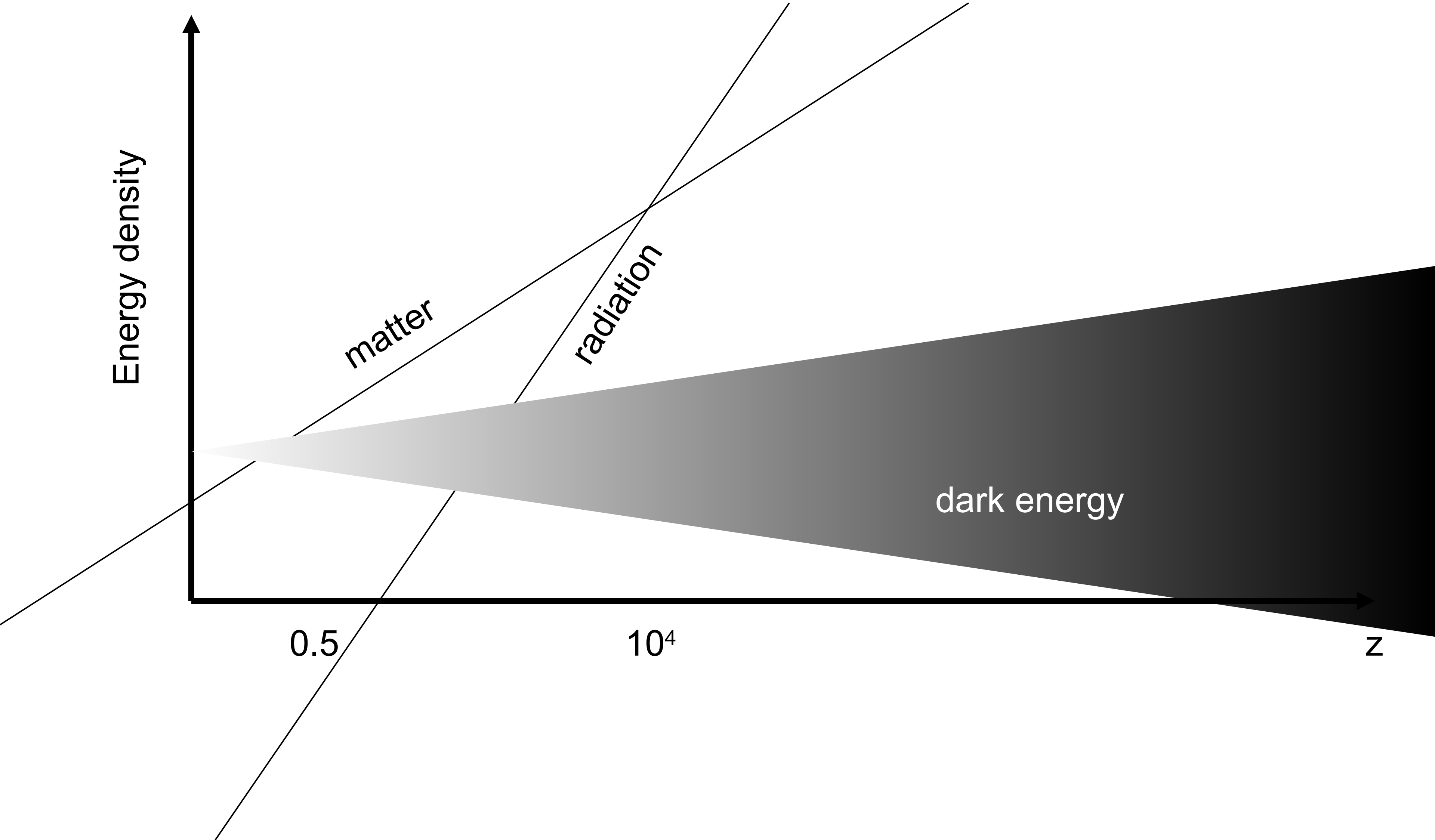
Constraining Dark Energy: latest pre-Planck constraints



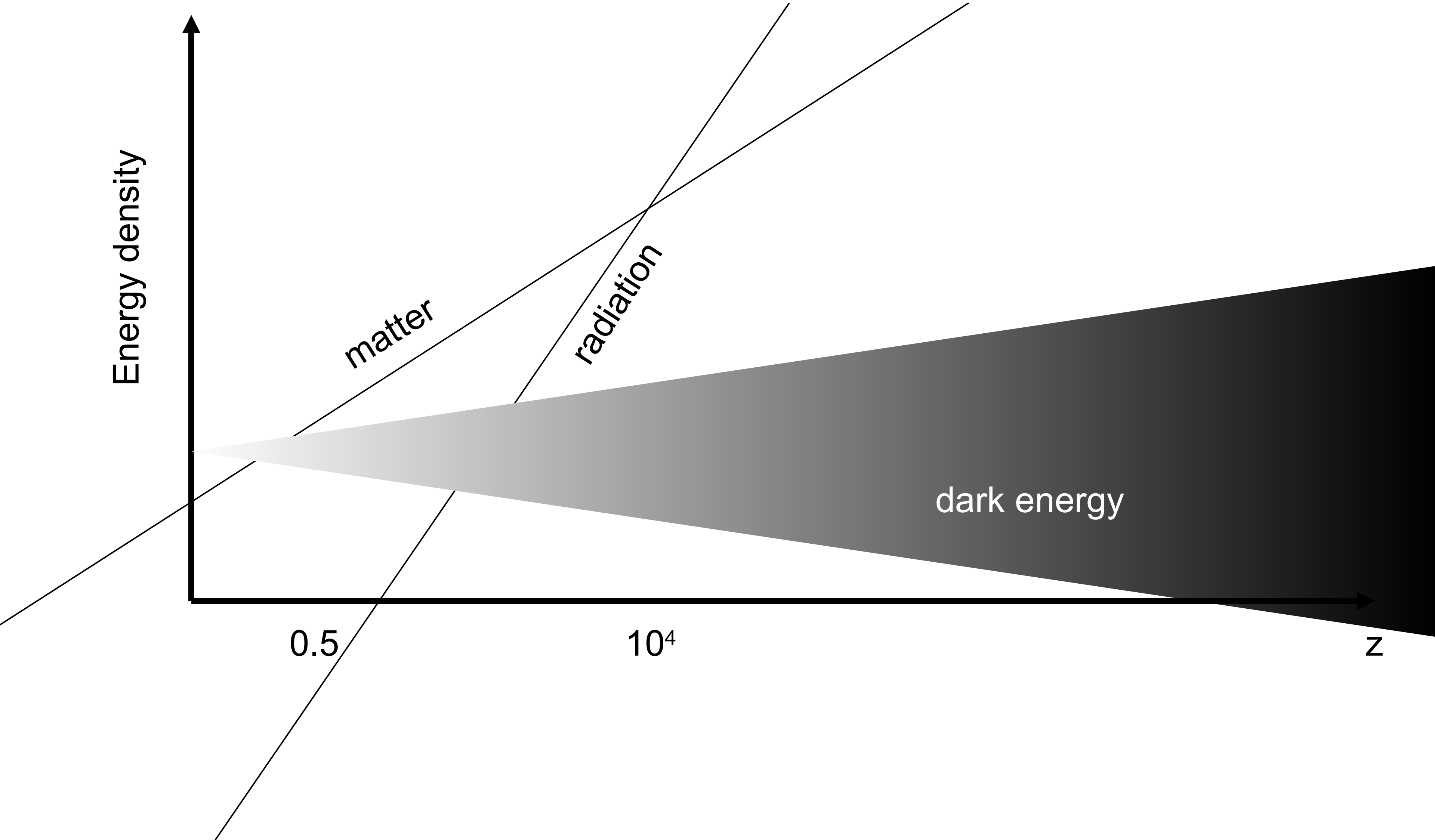


Said et al. 2013

The promise of CMB lensing



The promise of CMB lensing



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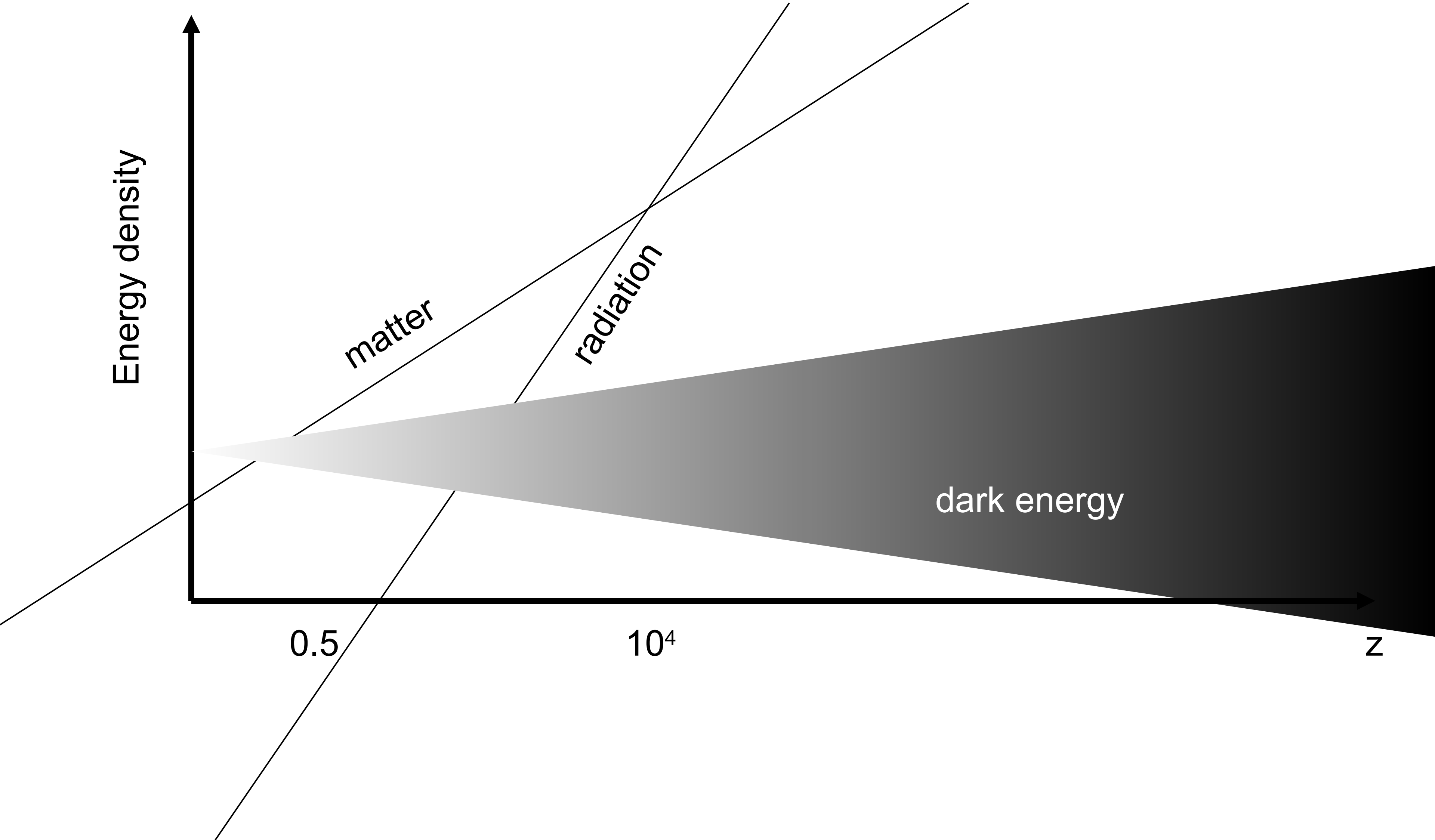

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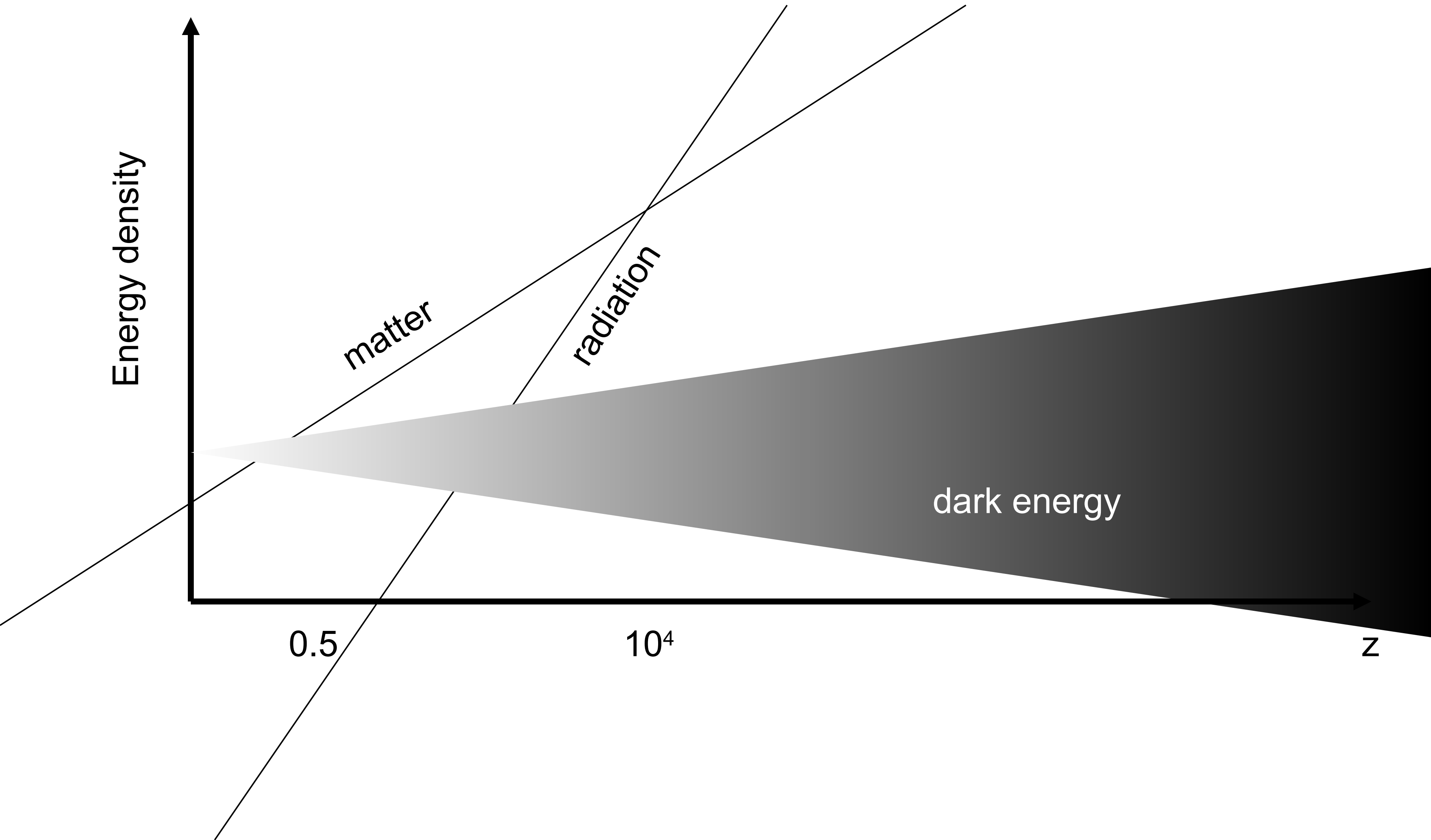
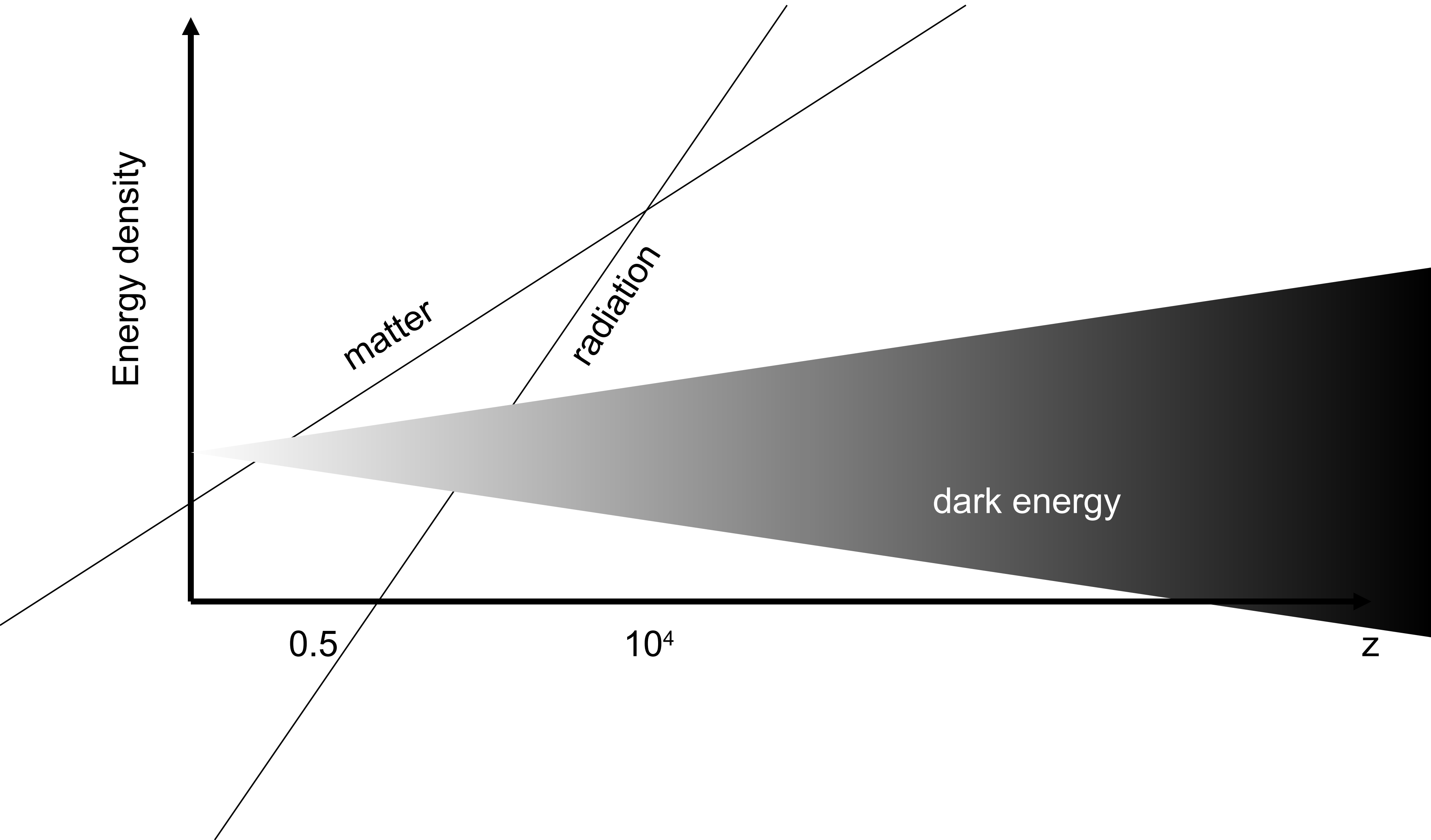


The promise of CMB lensing



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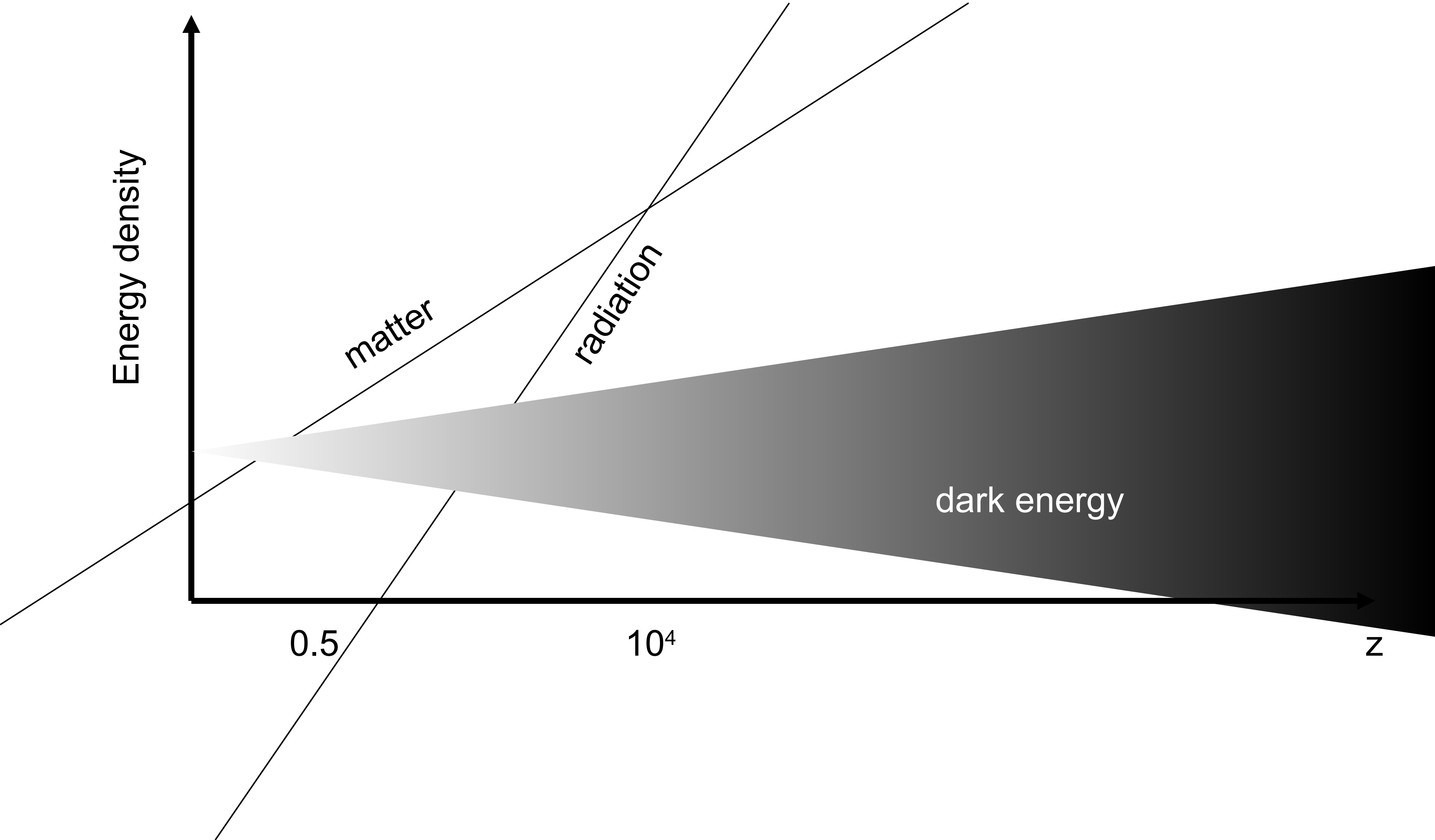

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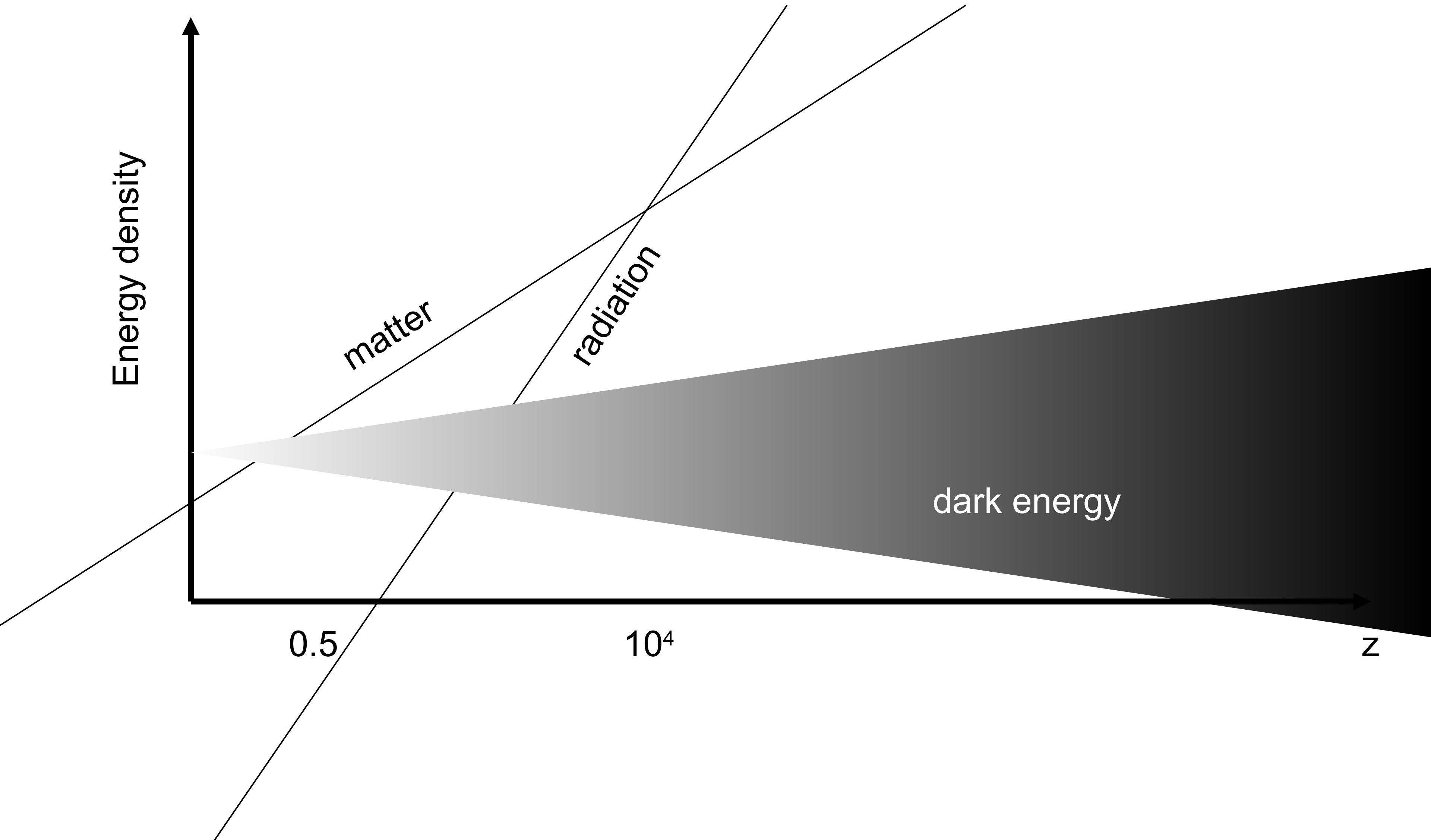
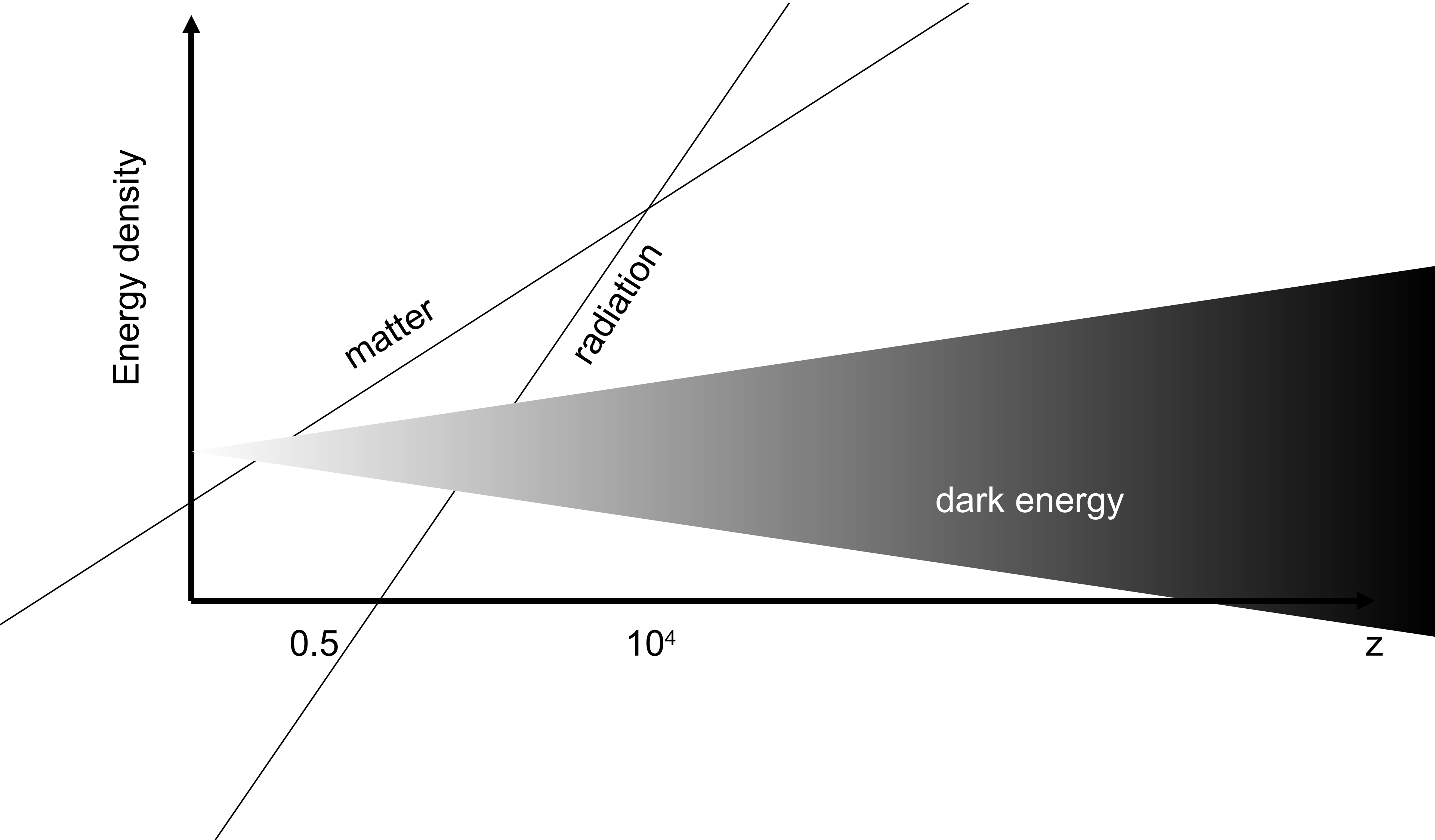
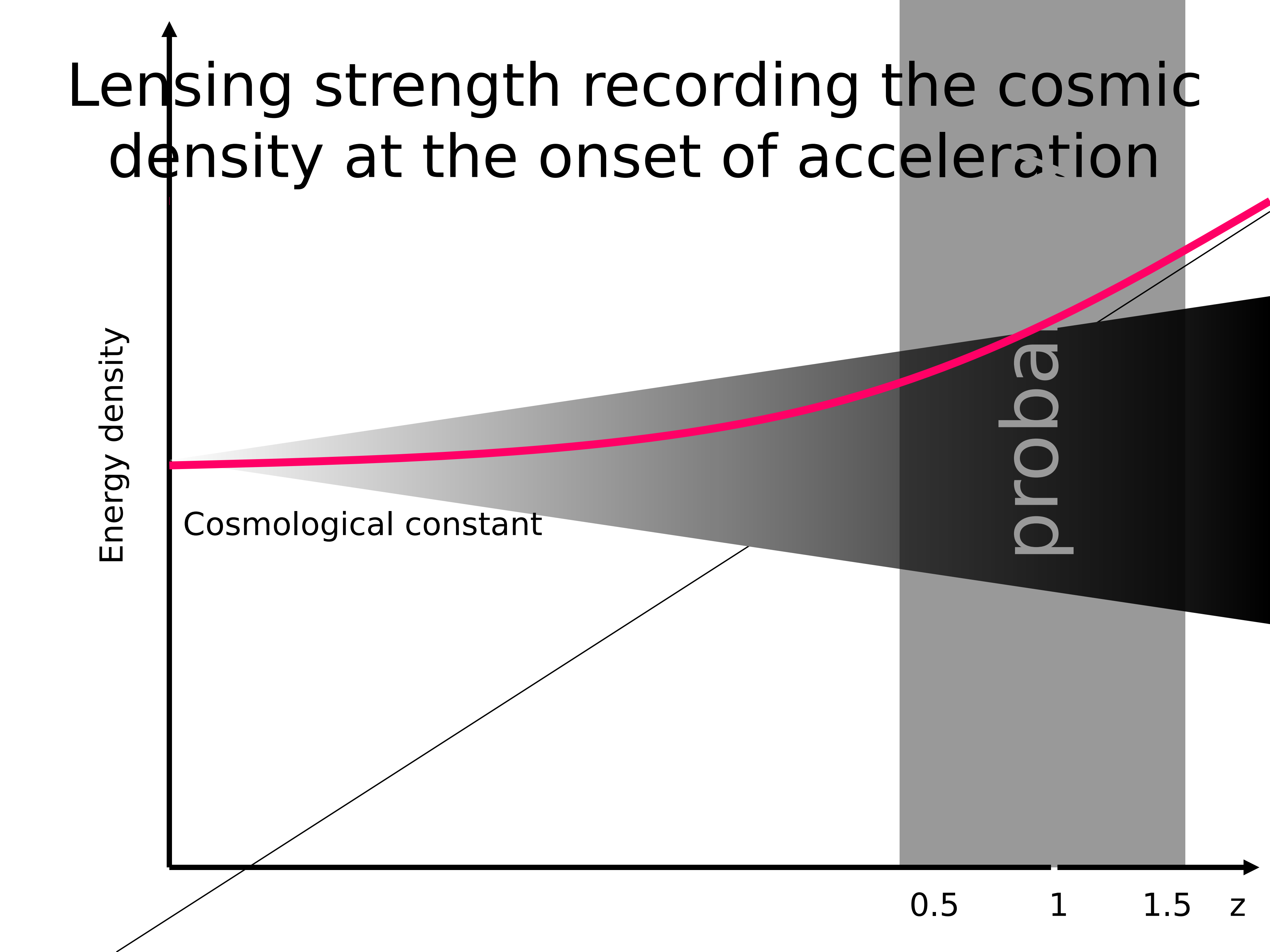
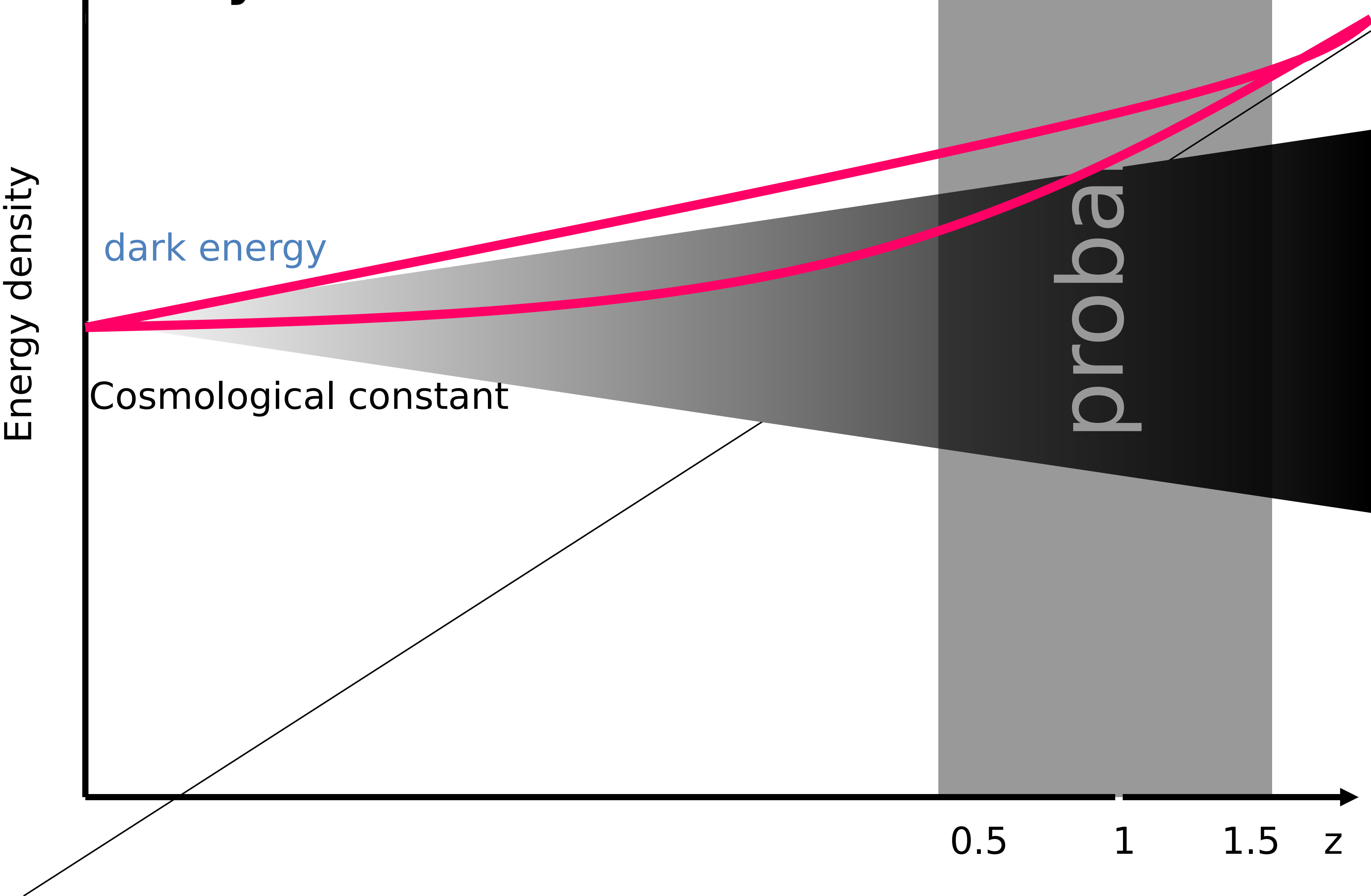


The promise of CMB lensing



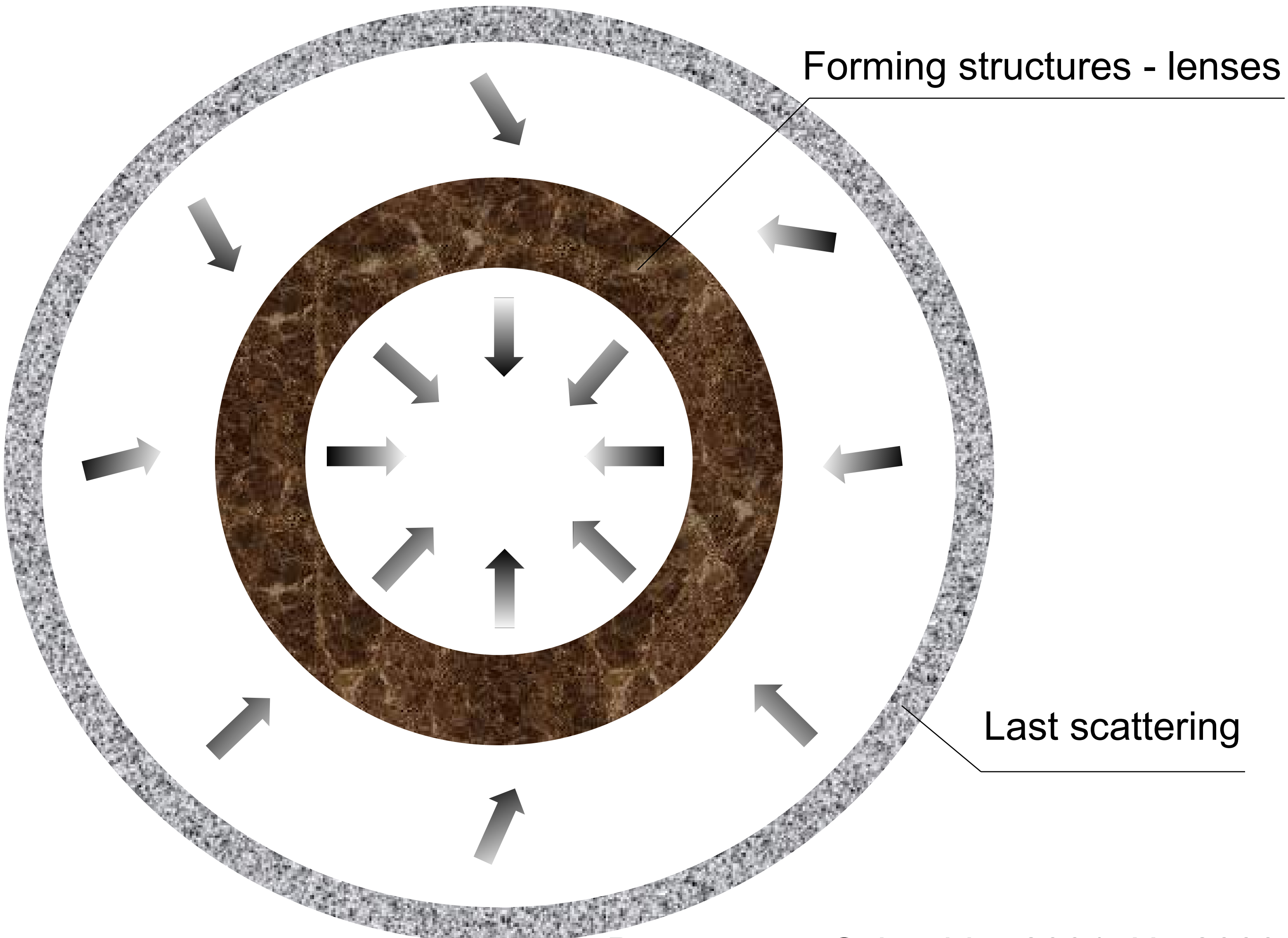

Lensing strength recording the cosmic density at the onset of acceleration
Energy density
Cosmological constant
proba
0.5
1
1.5
z

Lensing strength recording the cosmic density at the onset of acceleration



CMB lensing

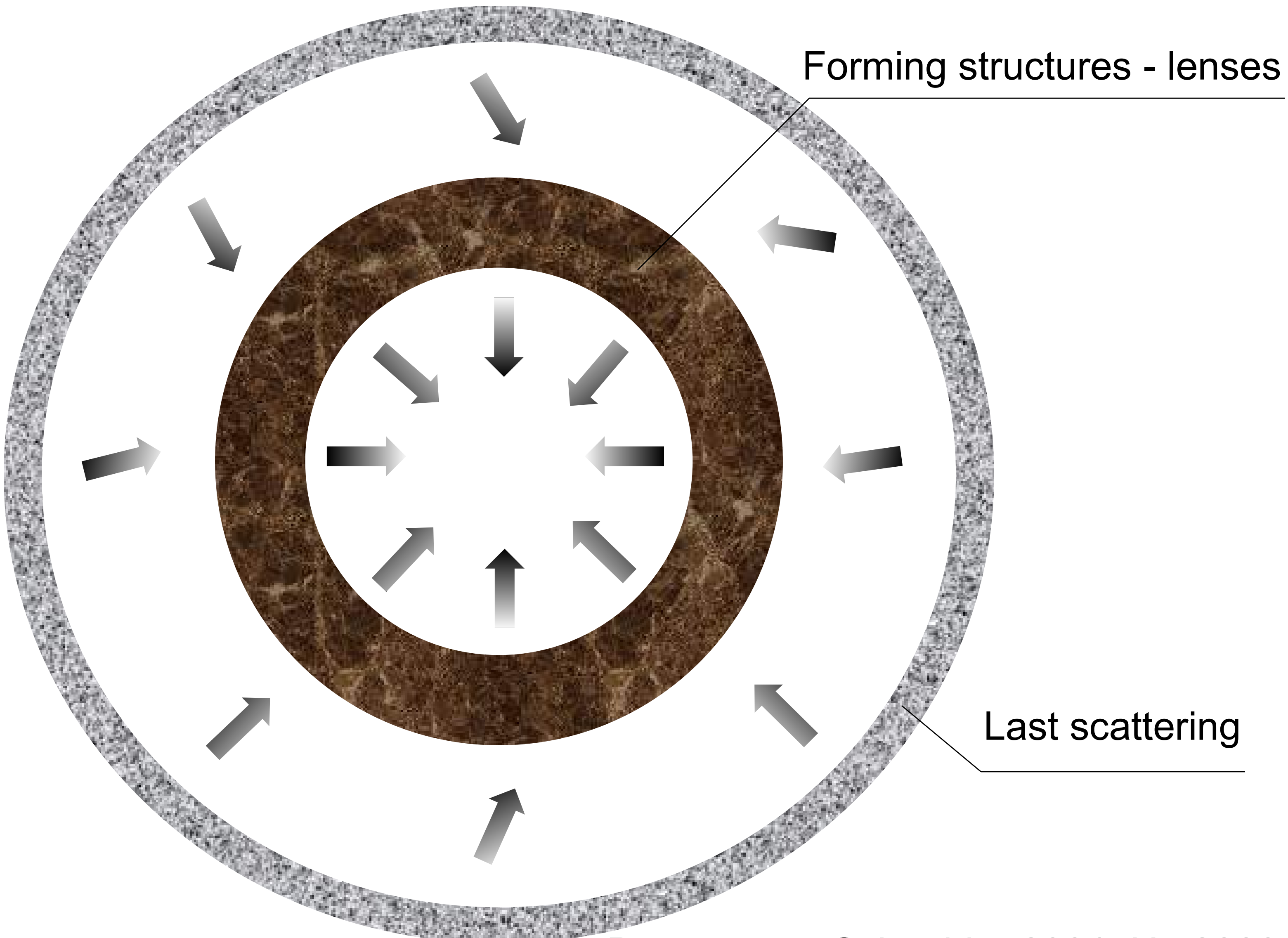
T



Bartelmann, Schneider 2001, Hu 2000

CMB lensing

T



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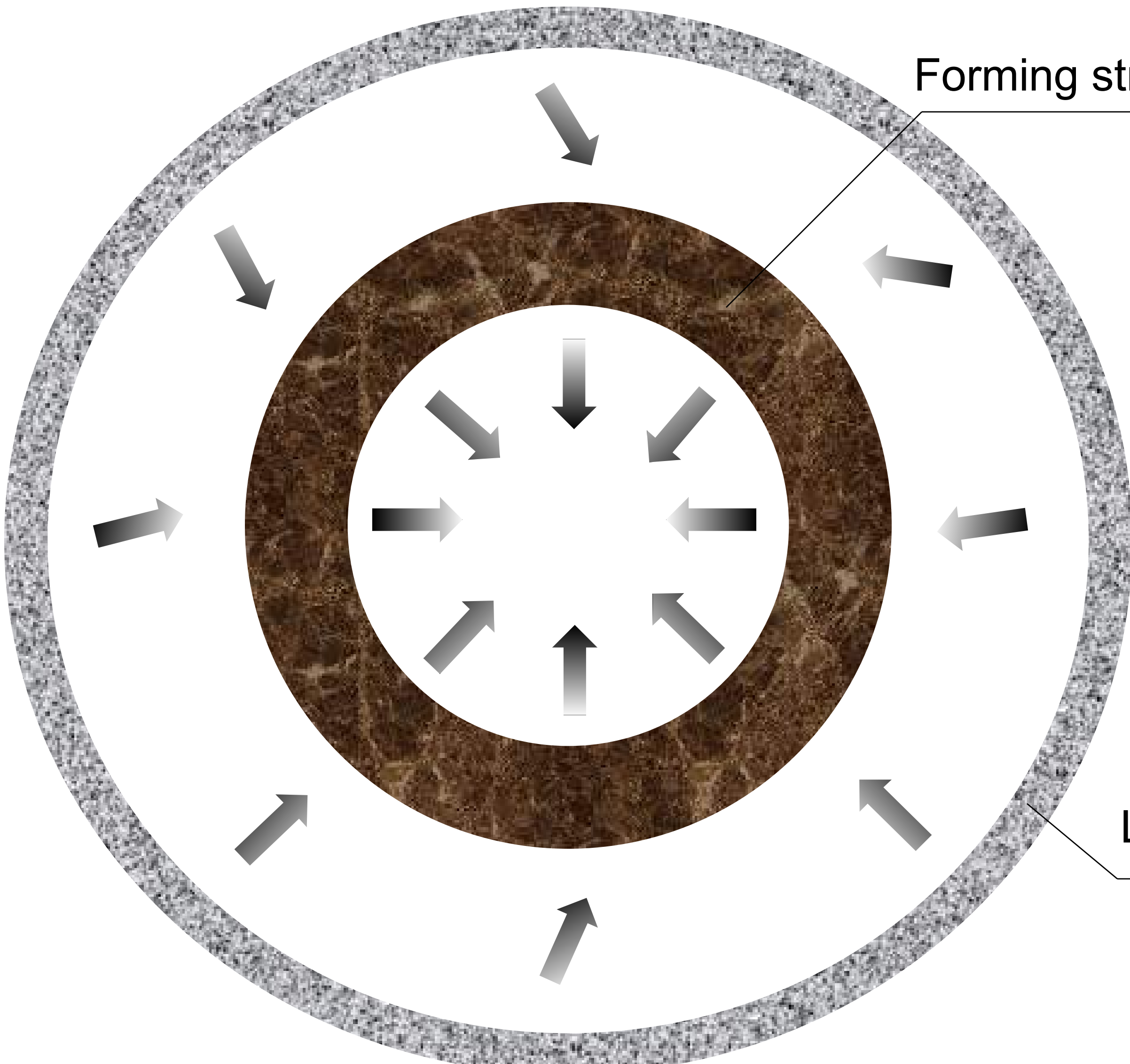
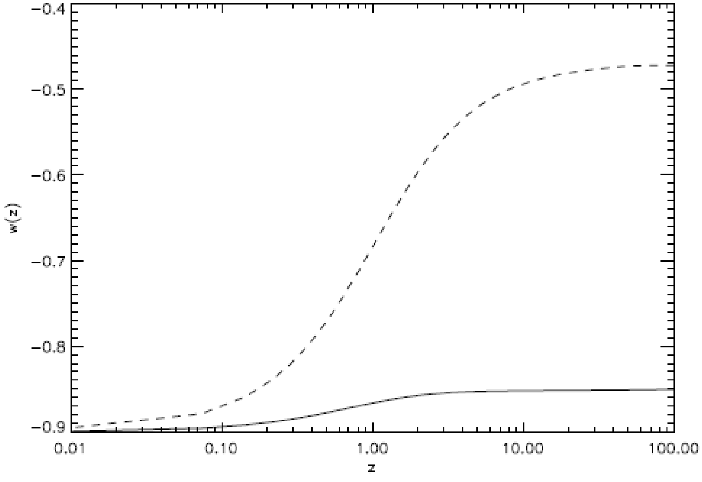
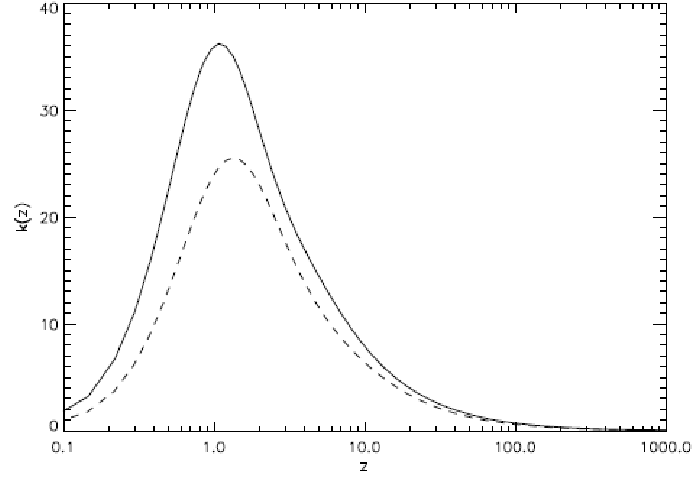


Bartelmann, Schneider 2001, Hu 2000

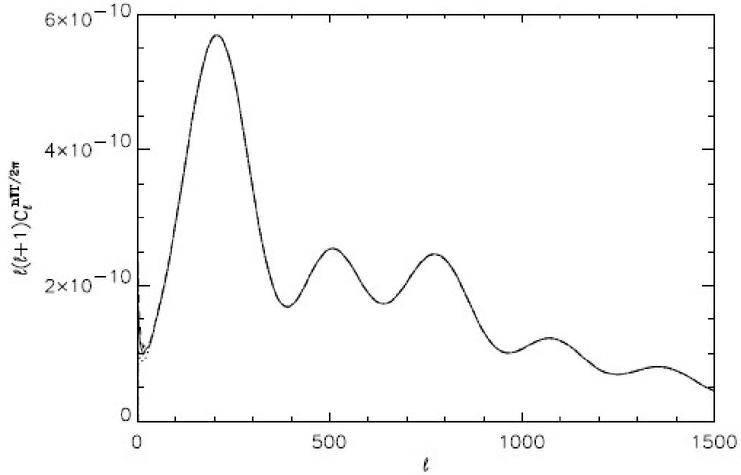
Early dark energy and CMB lensing

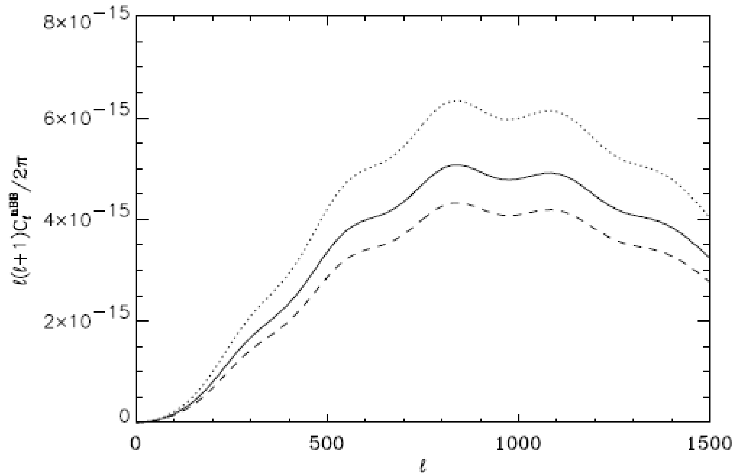




Acquaviva & Baccigalupi 2006

CMBreaking projection degeneracy





Acquaviva & Baccigalupi 2006

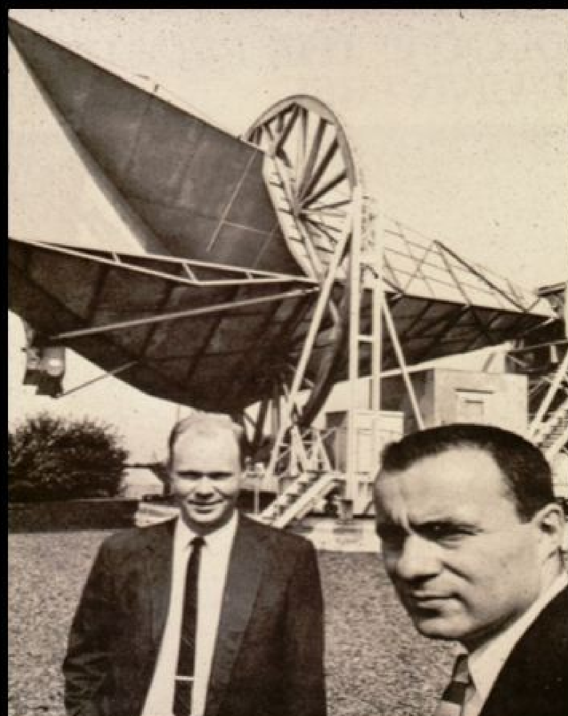
Expanding universe => CMB

- compression in the early stages of an expanding universe causes lots of radiation arising from thermonuclear explosions
- Reactions are rapid enough to achieve thermalization and a black body spectrum
- It is possible to compute the rarefaction caused by the expansion since that epoch
- The relic radiation is predicted to peak in microwaves, temperature of a few Kelvin, known today as the Cosmic Microwave Background (CMB, Gamow et al. 1948)

George Gamow, three years old in Odessa, Ukraine, 1907

Discovery

Arno Penzias and Robert Wilson



Early 1960s - Penzias and Wilson are hired by Bell Labs to evaluate the performance of the new radio telescope to be used in trans-Atlantic telephone communications.

They find a small, unexplained signal regardless of the direction the telescope is pointed. It is not enough to be a problem, but they are curious.

1964 - They become aware that the noise in their telescope is the cosmic background radiation predicted by the Big Bang theory.

COsmic Background Explorer