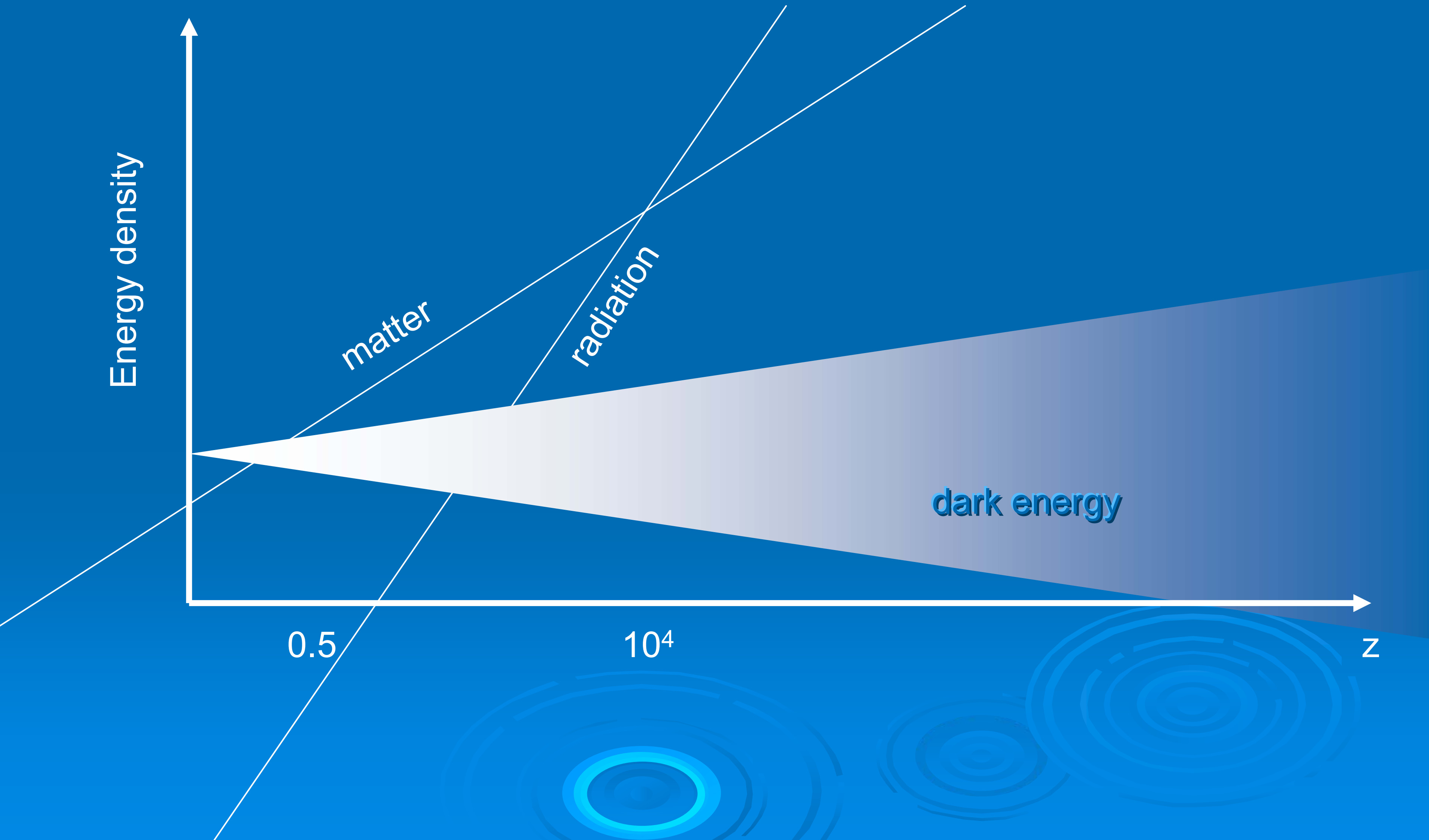
# Forthcoming CMB experiments and expectations for dark energy

Carlo Baccigalupi

# Outline

- "Classic" dark energy effects on CMB
- "Modern" CMB relevance for dark energy: the promise of lensing
- Lensing (B modes) in CMB (polarization) measuring the dark energy abundance at the onset of acceleration
- Expectations and challenges from future CMB probes

# Dark energy



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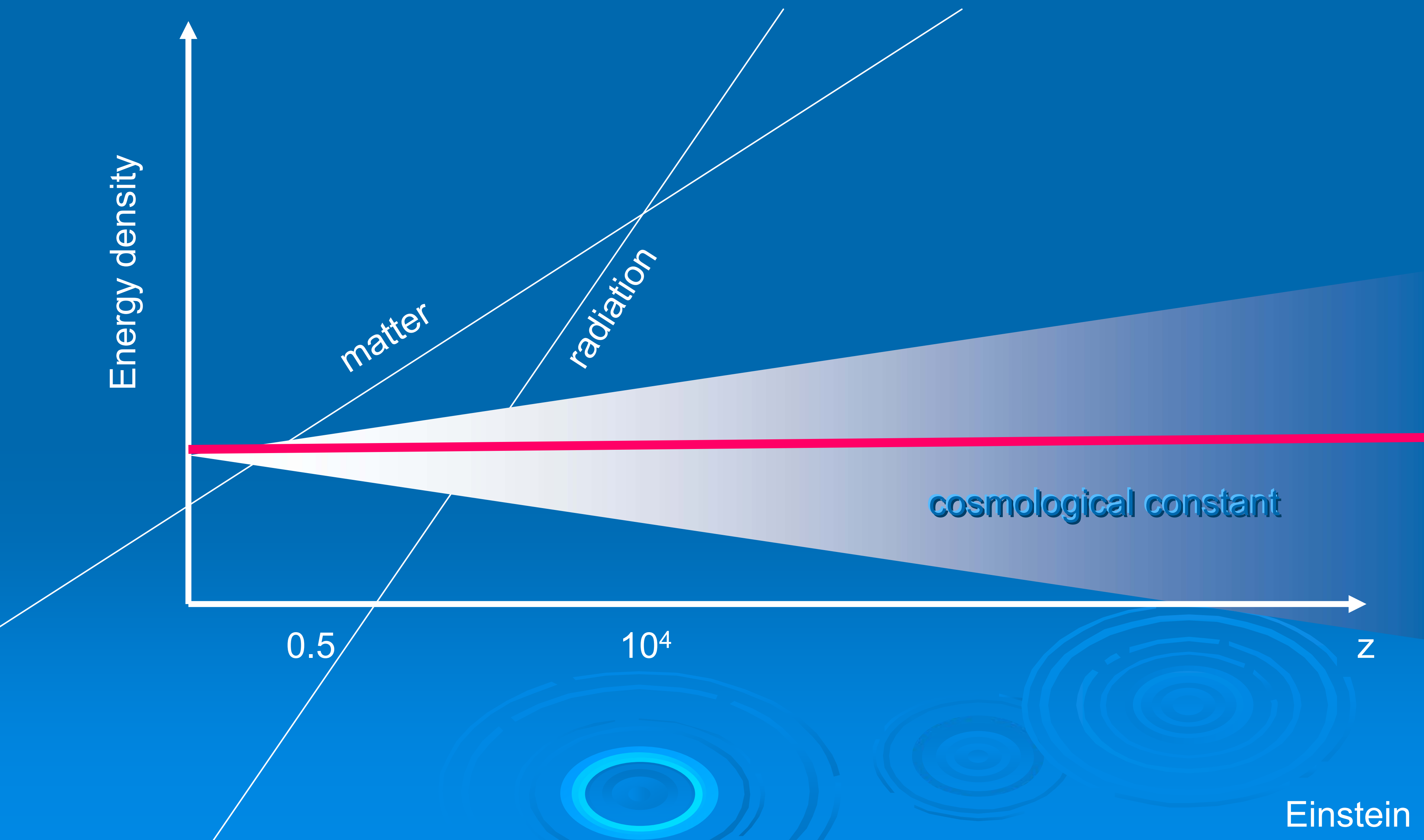
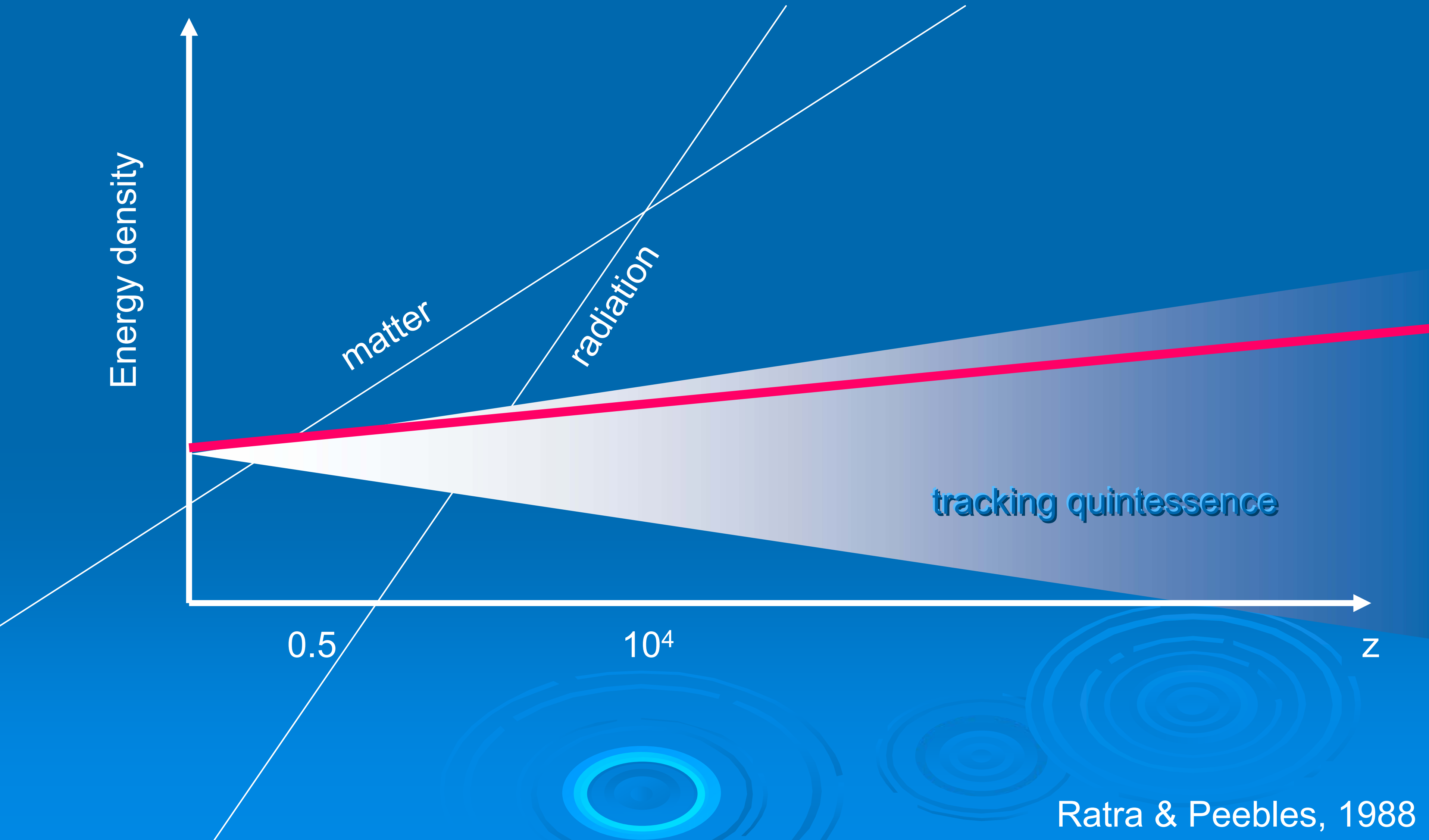
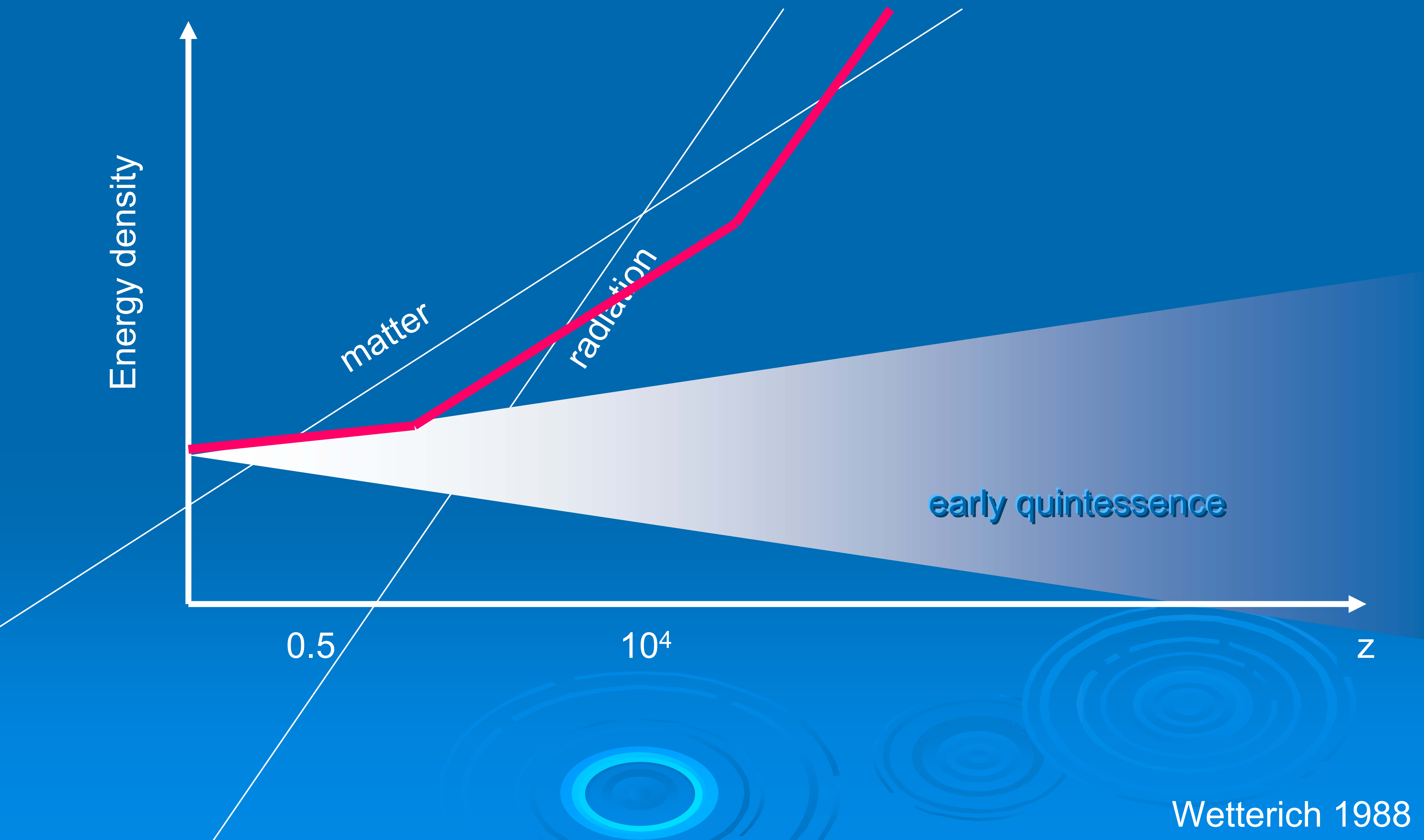

Energy density
matter
radiation
cosmological constant
0.5
10^4
z
Einstein

# Dark energy



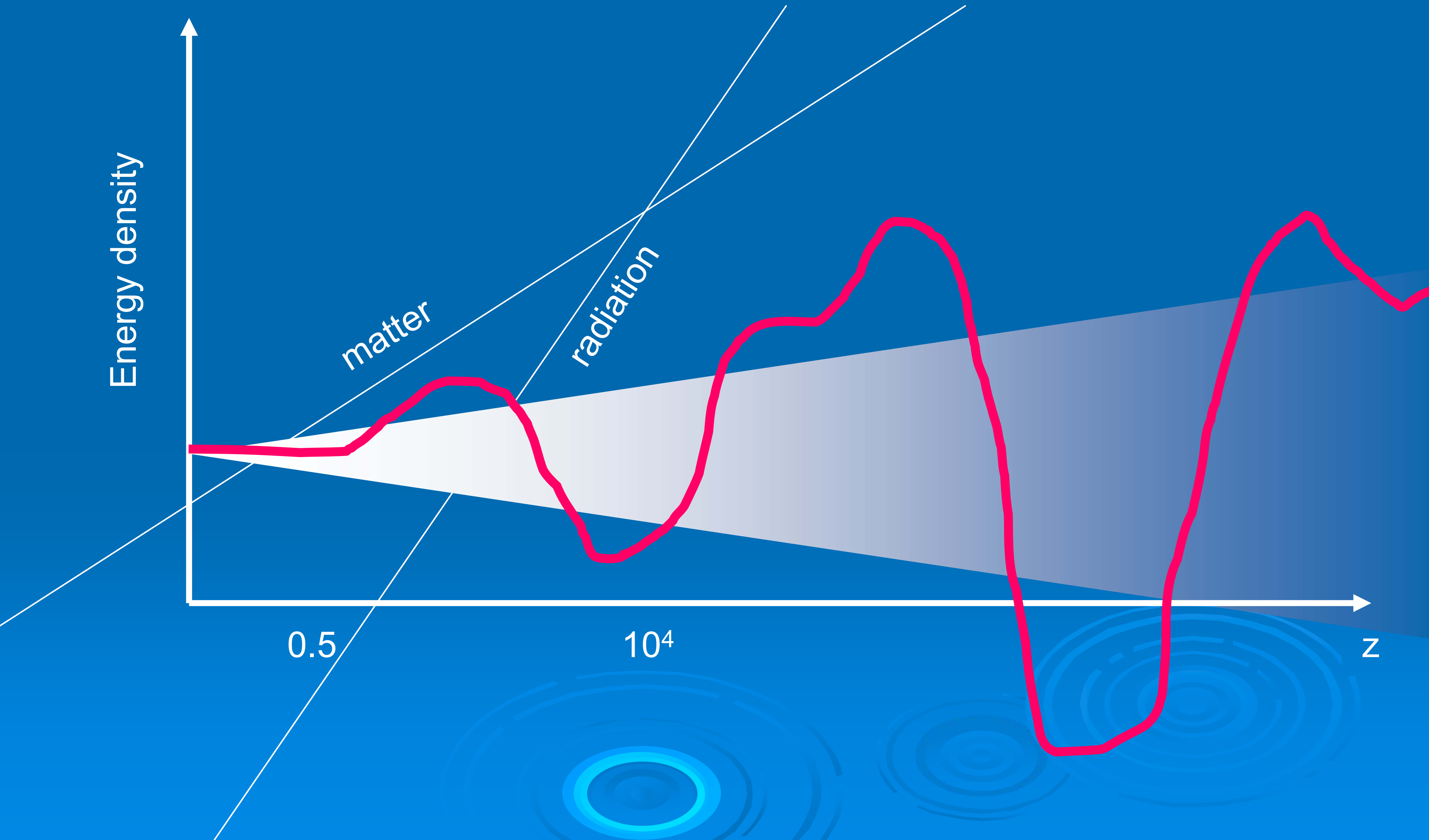

Ratra & Peebles, 1988

# Dark energy



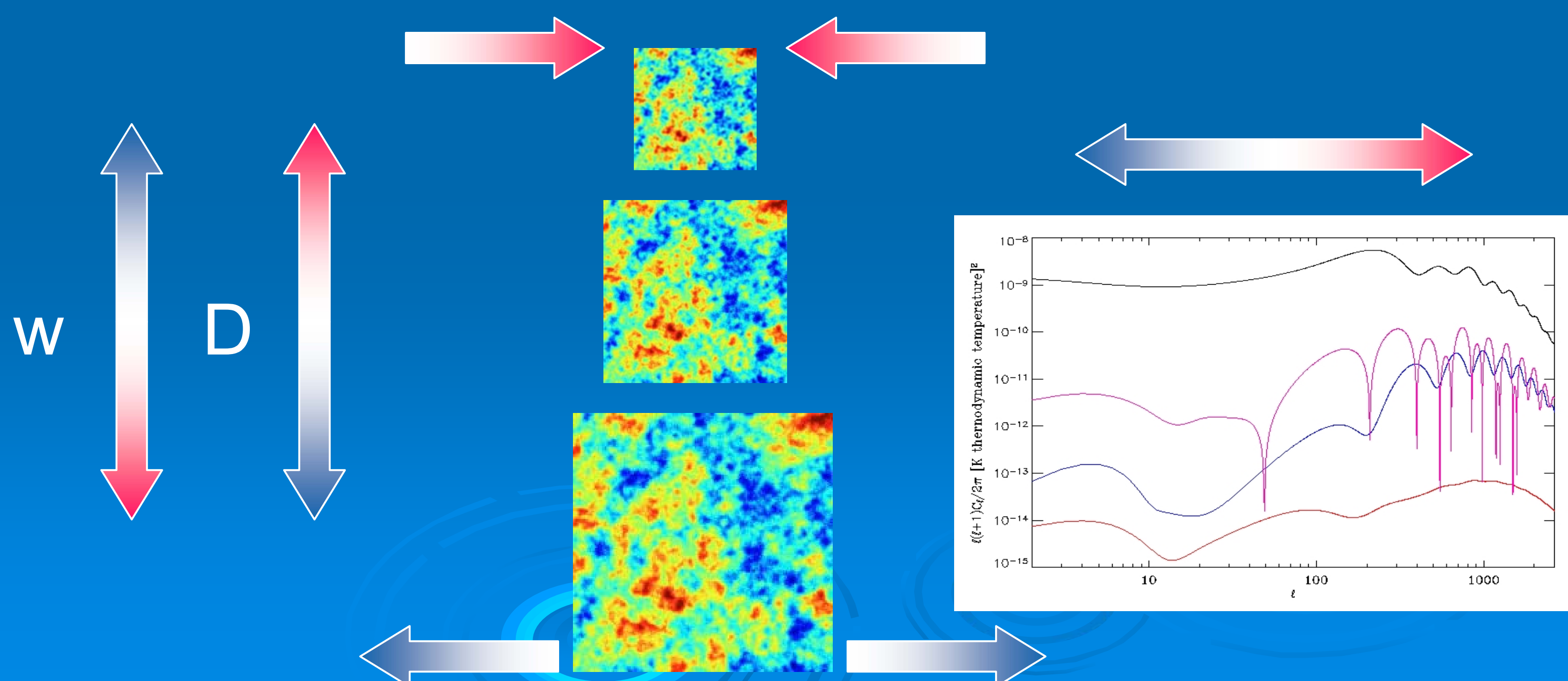

Wetterich 1988

# Dark energy



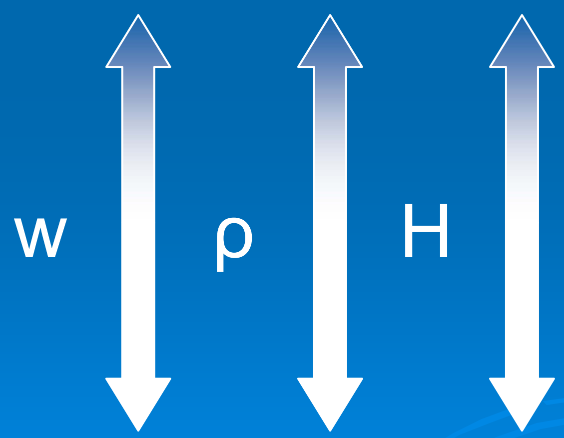
# "Classic" dark energy effects on CMB: projection

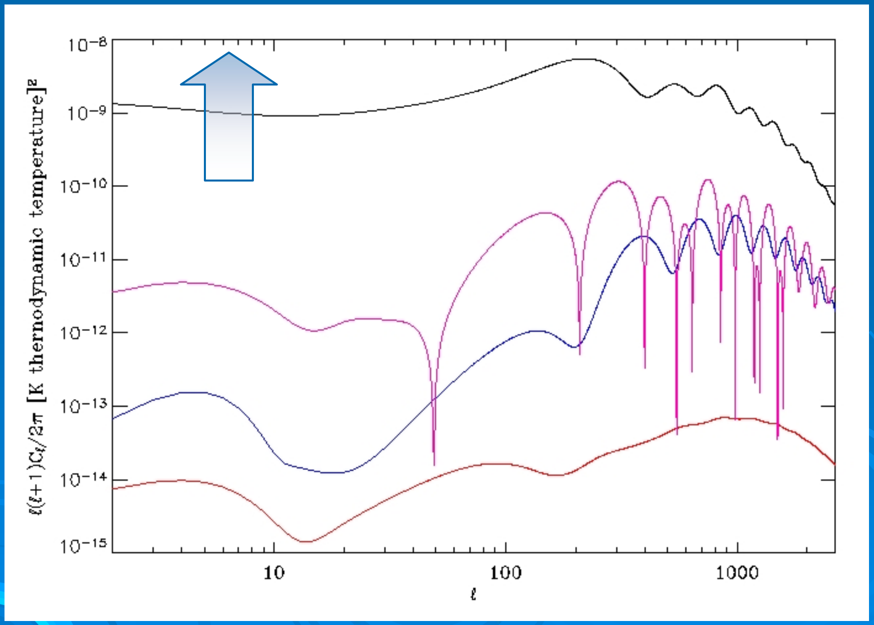
$$D = H_0^{-1} \int_0^z \frac{dz}{[\Sigma_i \Omega_i (1+z)^{3(1+w_i)}]^{1/2}}$$



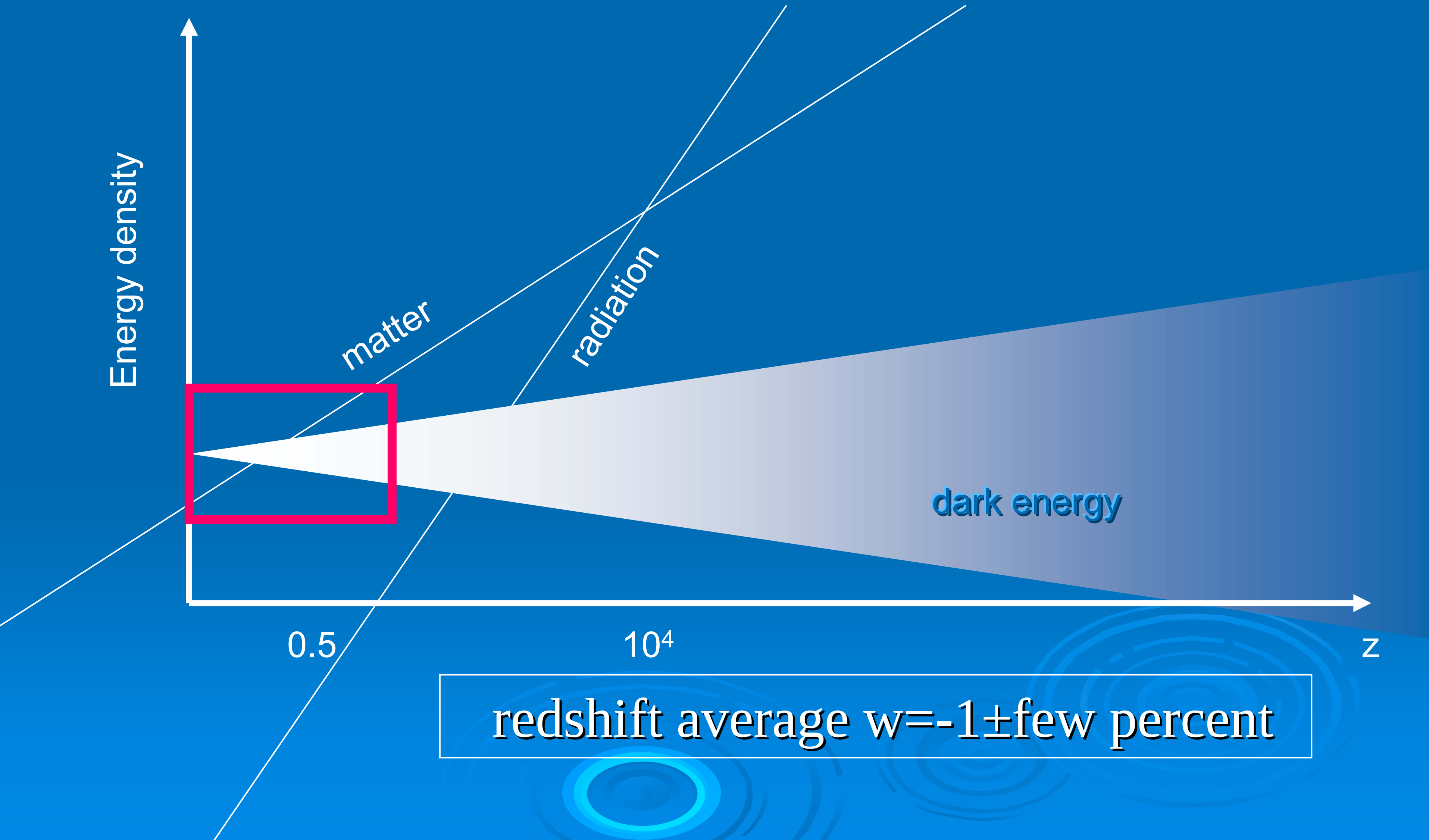
# "Classic" dark energy effects on CMB: integrated Sachs-Wolfe

Cosmological friction for cosmological perturbations $\propto$ H



# Present bounds include classic dark energy effects on CMB




redshift average w=-1±few percent

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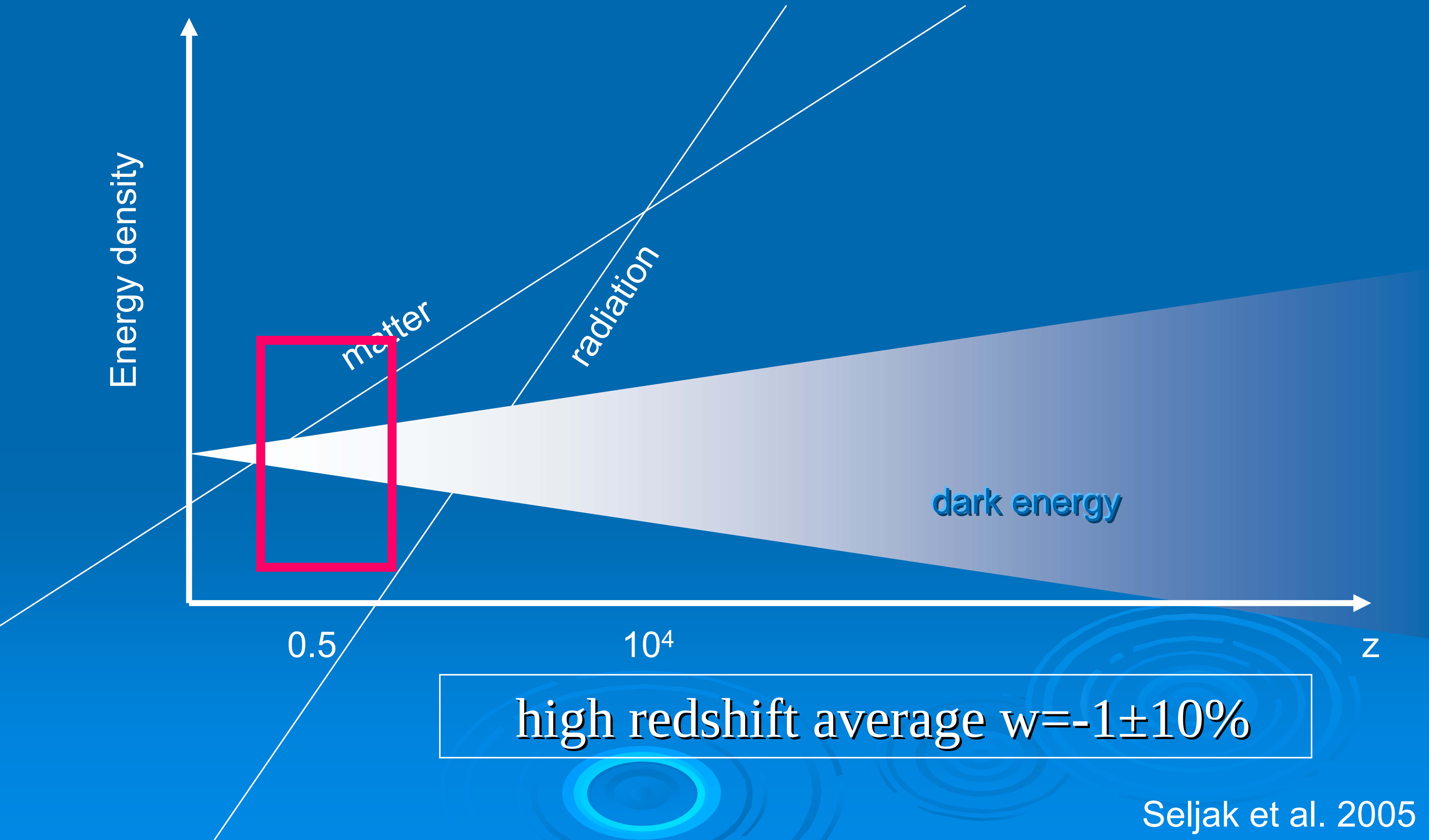
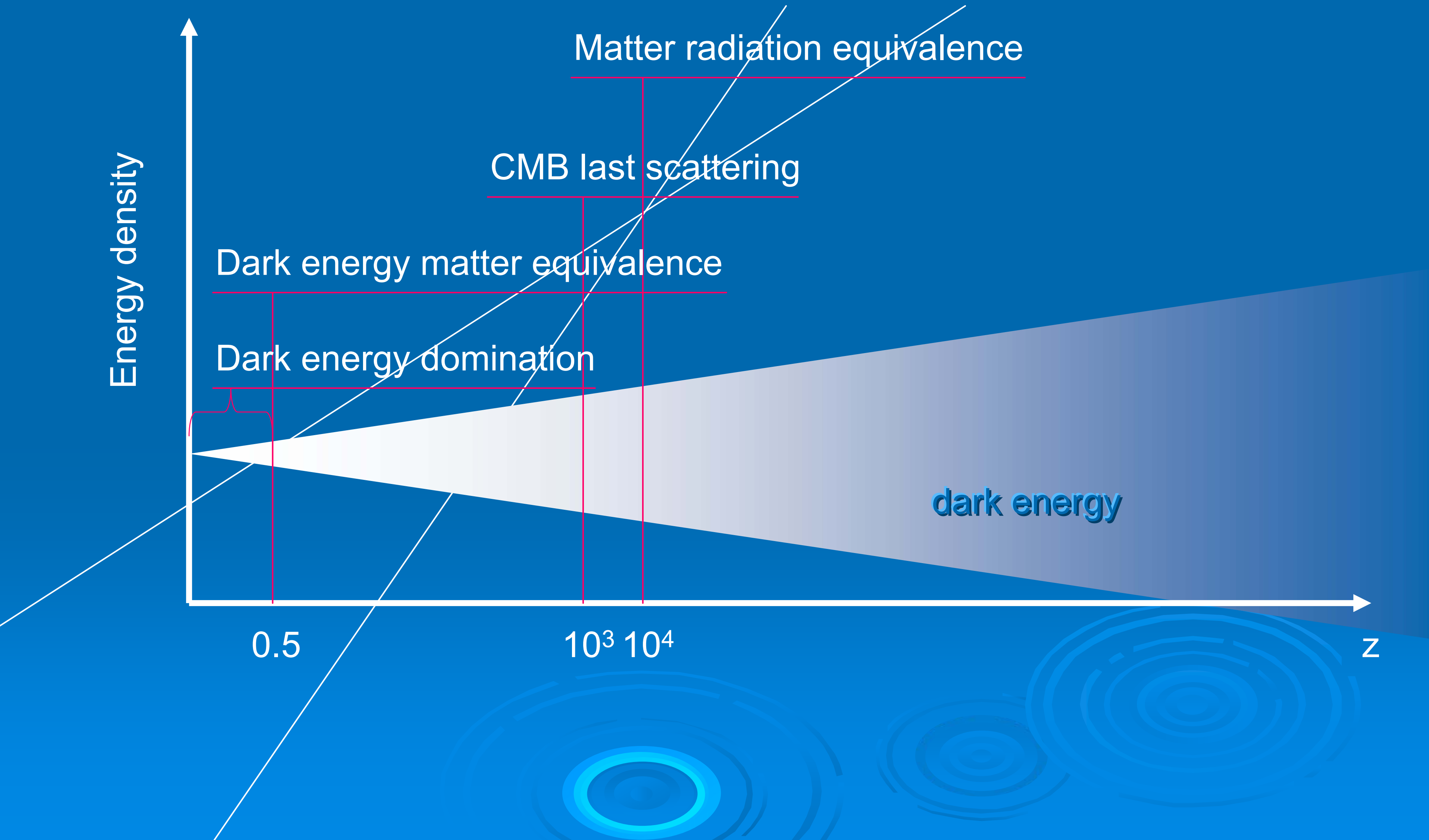



high redshift average $w=-1\pm10\%$

Seljak et al. 2005

# The "modern" era



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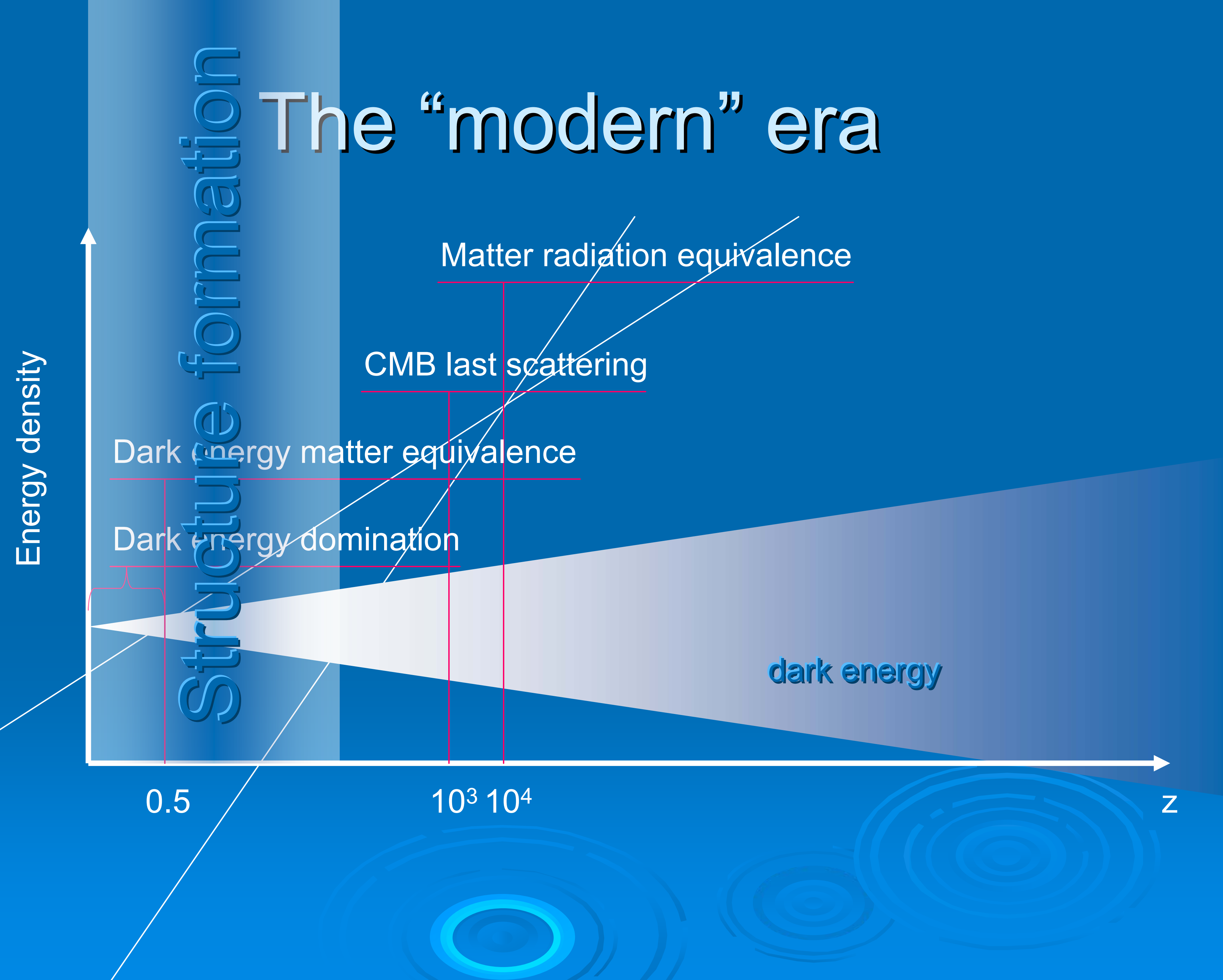

# The “modern” era: study the signatures of structure formation on the CMB

- Get the ISW effect with the highest accuracy by correlating CMB anisotropies with observed structures
- Study lensed CMB

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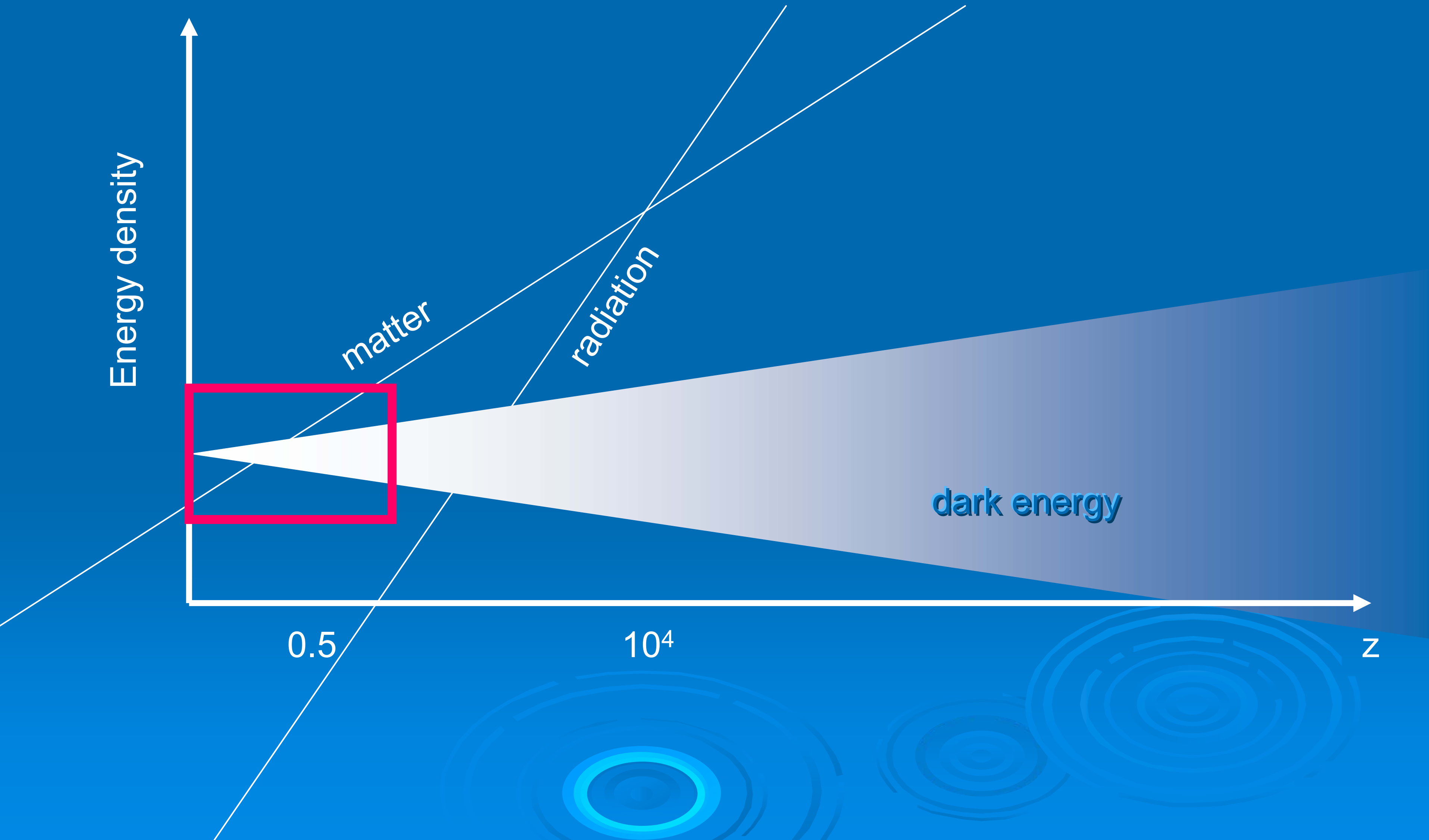
# The promise of lensing



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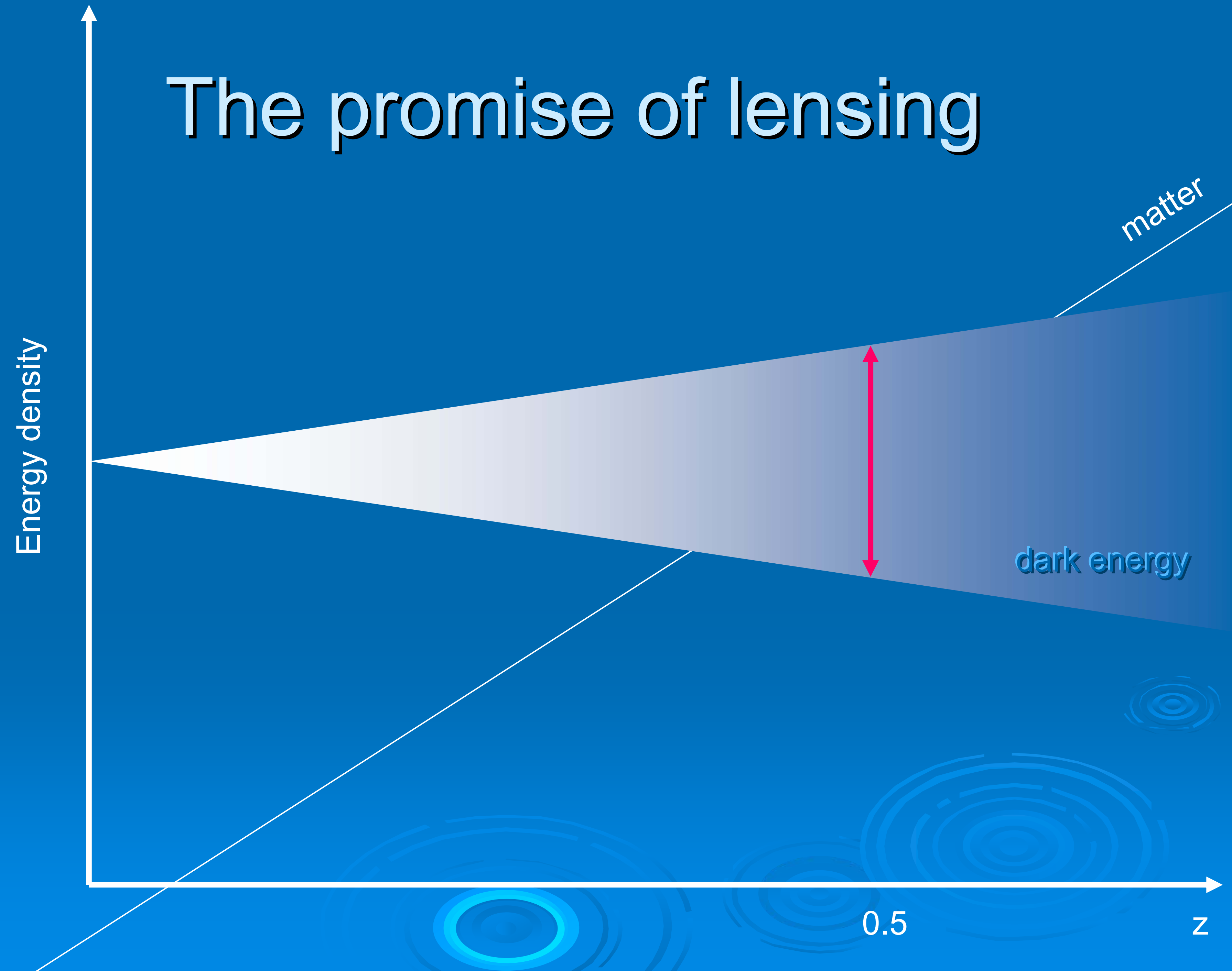

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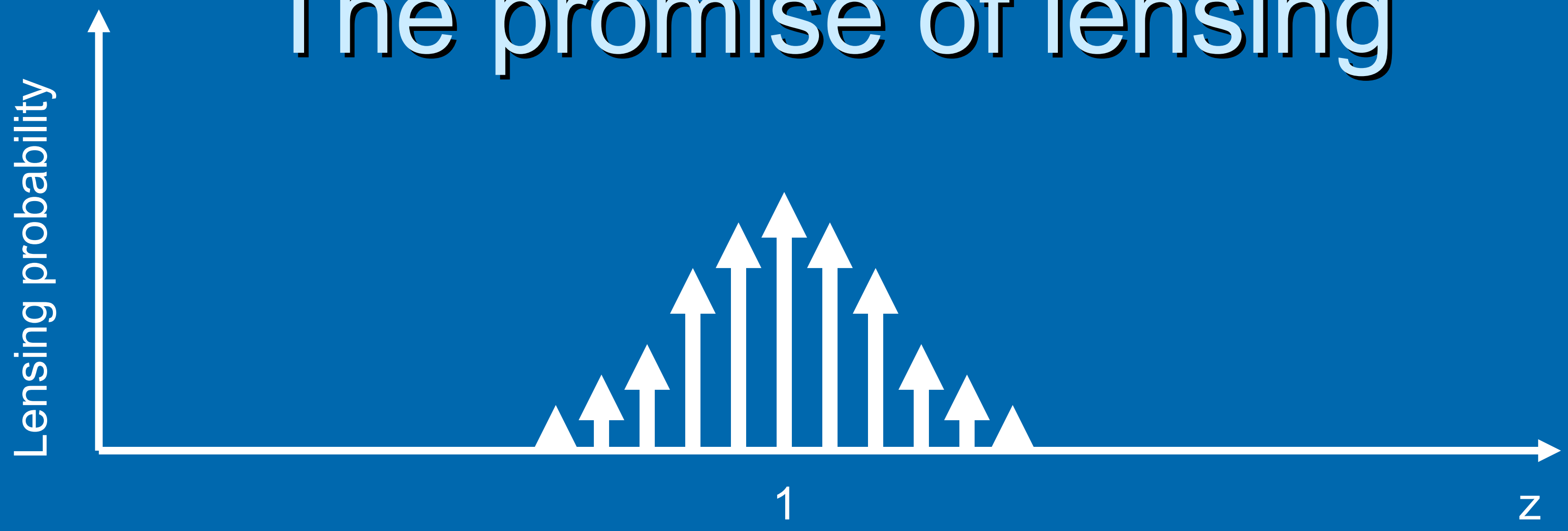
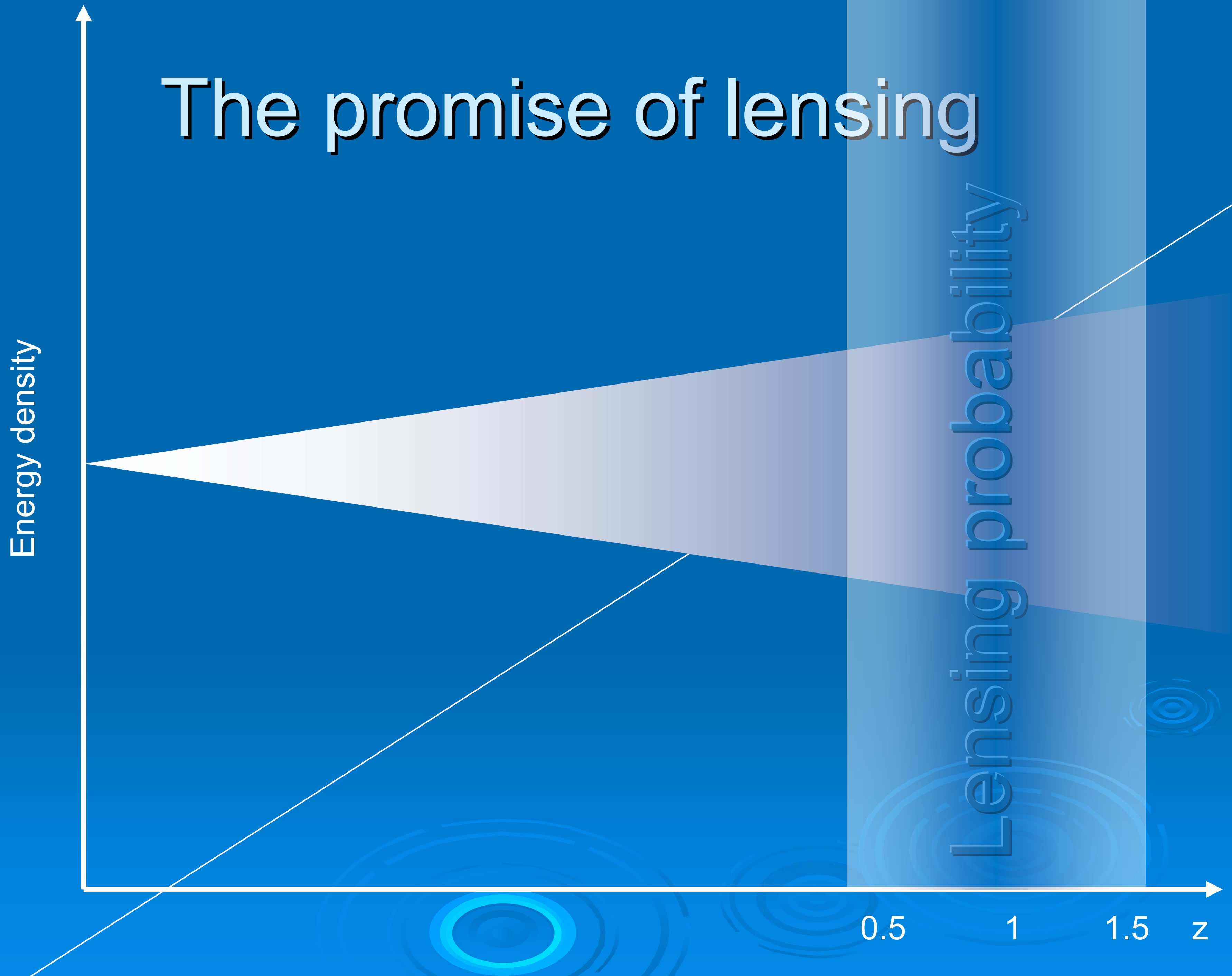



- By geometry, the lensing cross section is non-zero at intermediate distances between source and observer
- In the case of CMB as a source, the lensing power peaks at about z=1
- Any detected lensing in CMB anisotropy must be quite sensitive to the expansion rate at the onset of acceleration

# The promise of lensing



# How lensing modifies the CMB

- Most relevant on the angular scales subtended by lenses, from the arcminute to the degree
- It makes the CMB non-Gaussian
- It smooths acoustic peaks
- It activates a broad peak in the B modes of CMB polarization

Seljak & Zaldarriaga 1997, Spergel & Goldberg 1999, Hu 2000, Giovi et al. 2005

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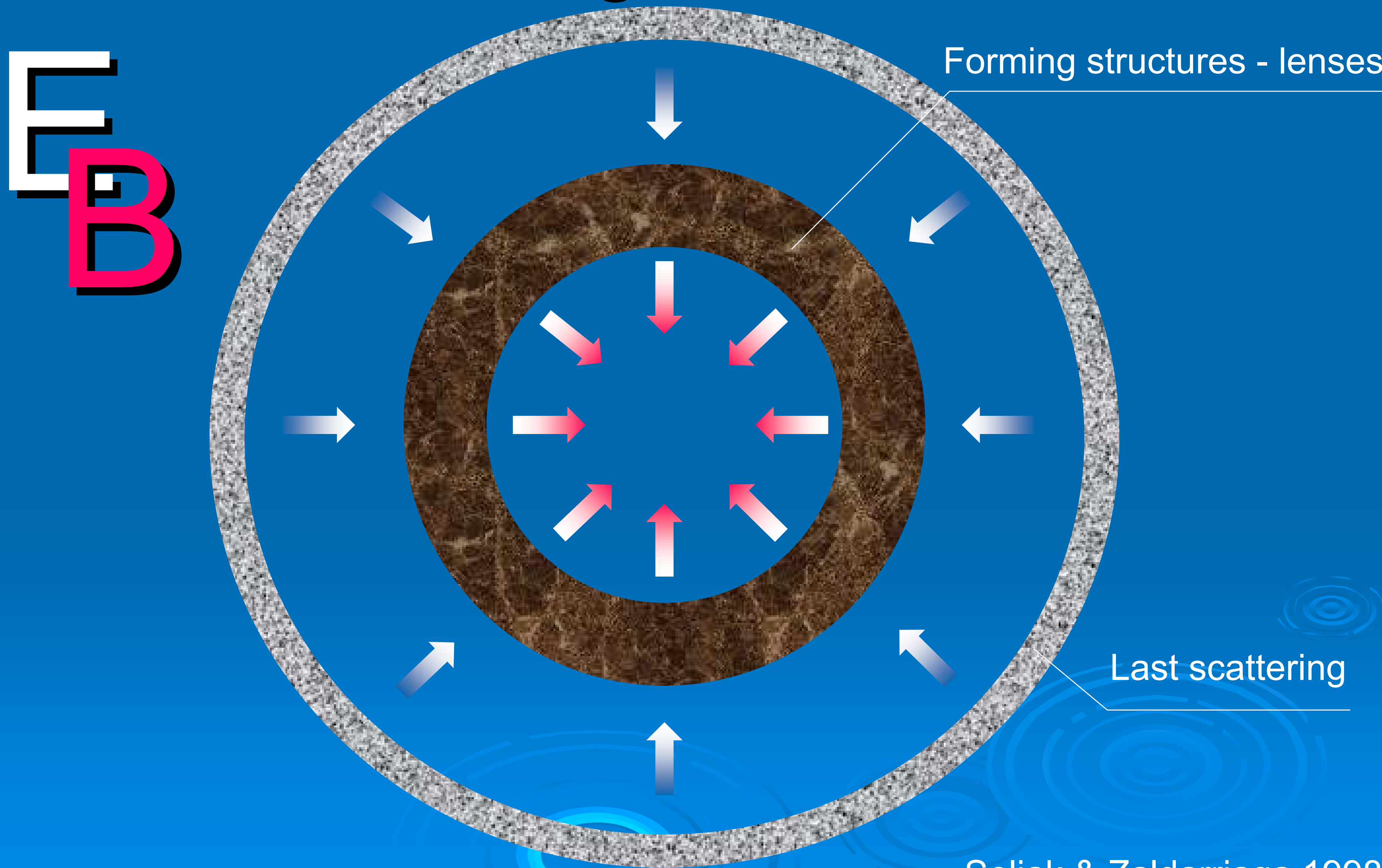
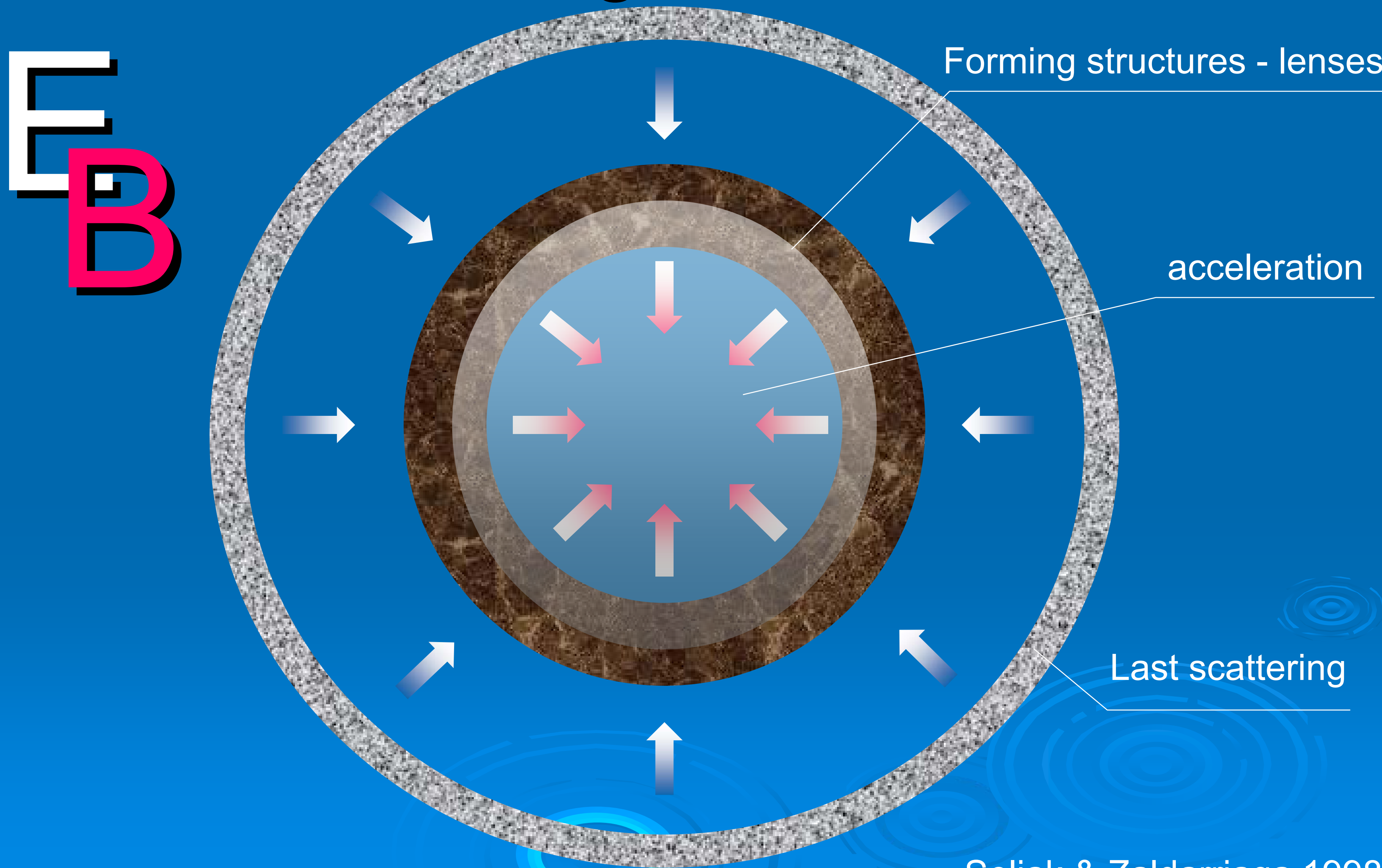
# Lensing B modes




Seljak & Zaldarriaga 1998

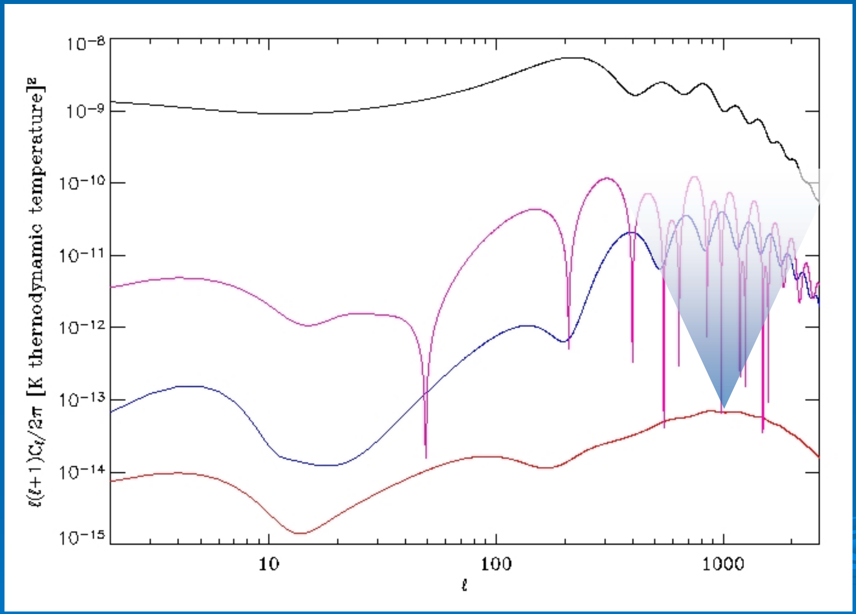
# Lensing B modes




Seljak & Zaldarriaga 1998

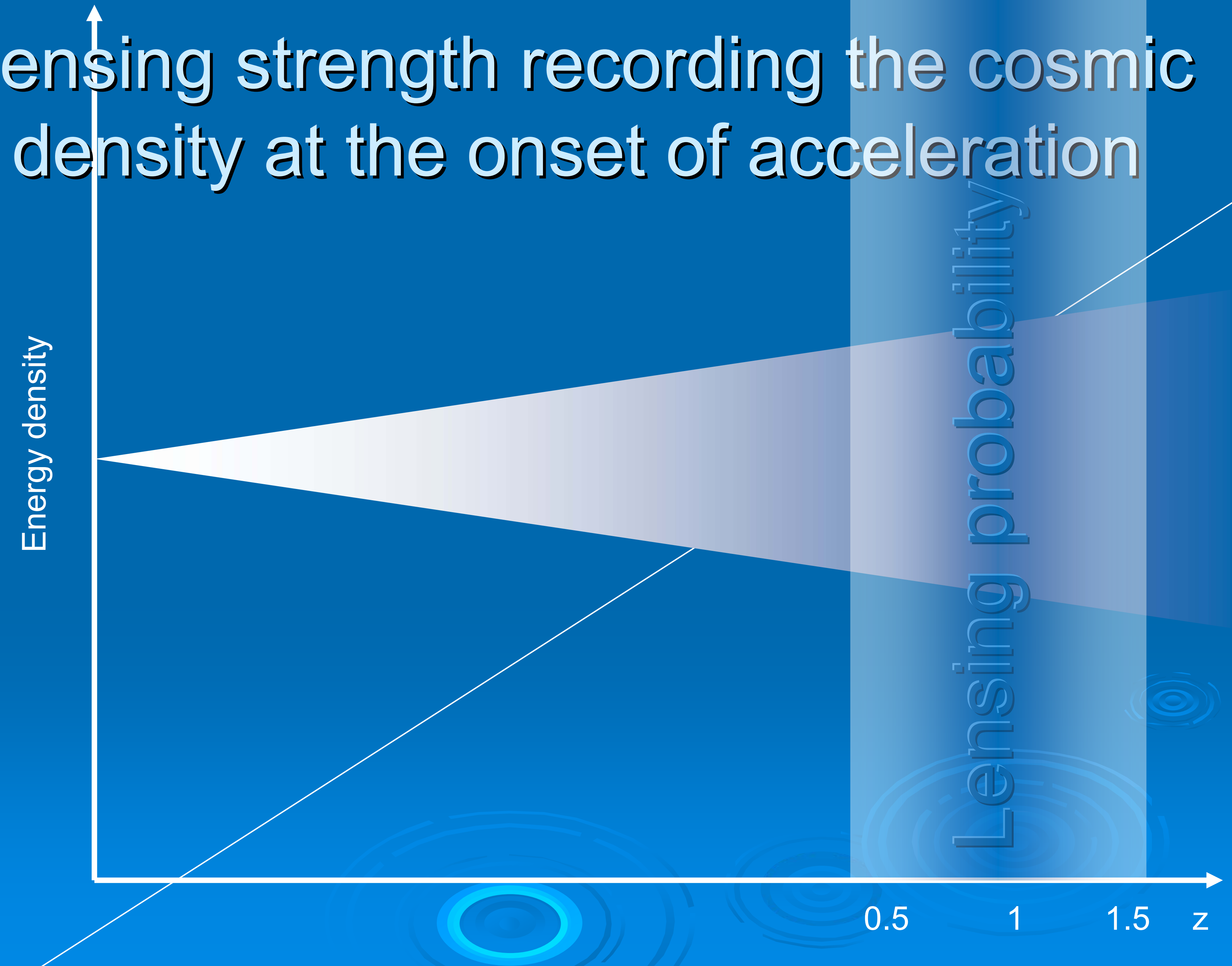
# CMB lensing: a science per se

- Lensing is a second order cosmological effect
- Lensing correlates scales
- The lensing pattern is non-Gaussian
- Statistical study in progress on the basis of large scale simulations of CMB lensing from N-body simulations




Smith et al. 2006, Lewis & Challinor 2006, Lewis 2005, …

# Lensing strength recording the cosmic density at the onset of acceleration



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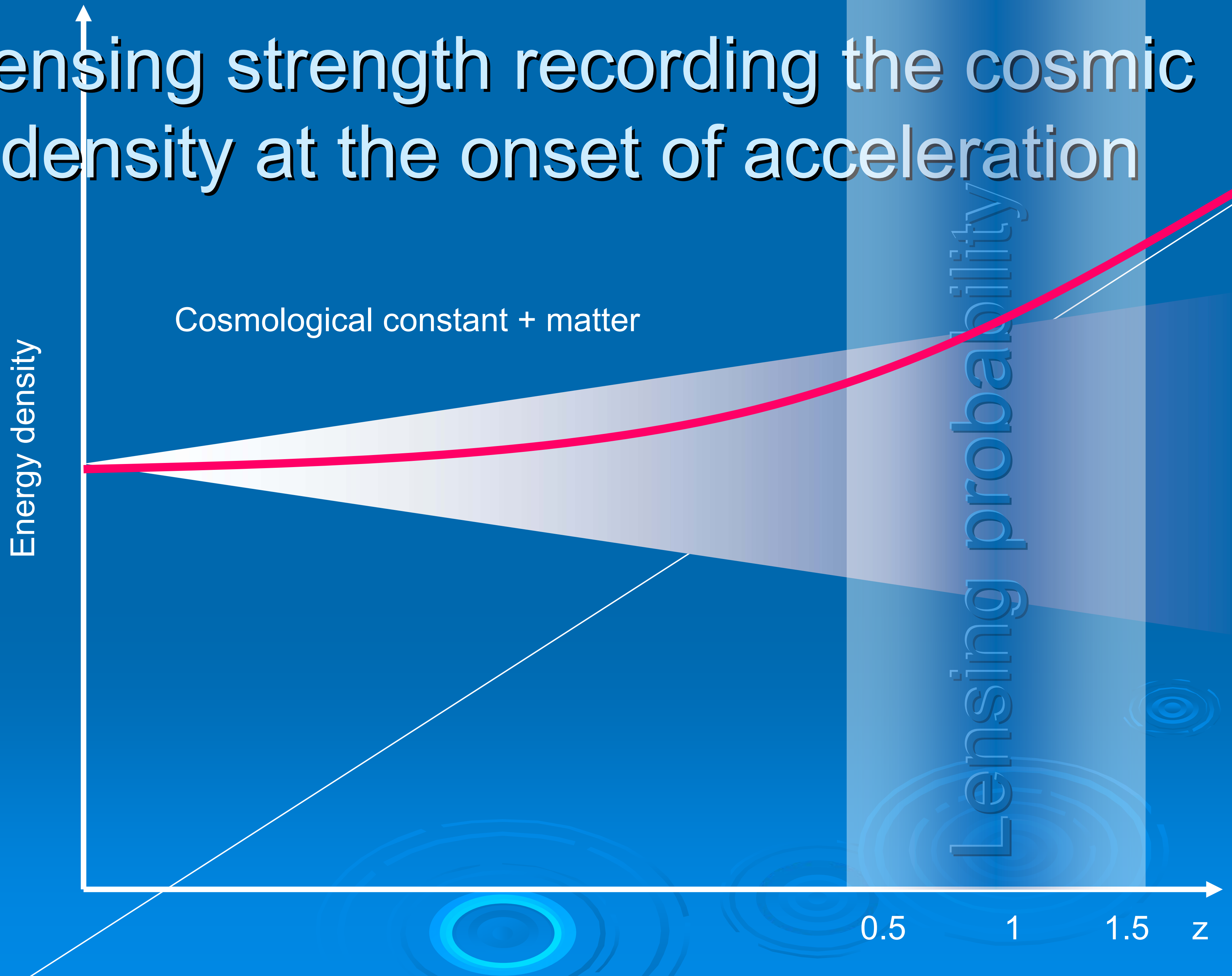

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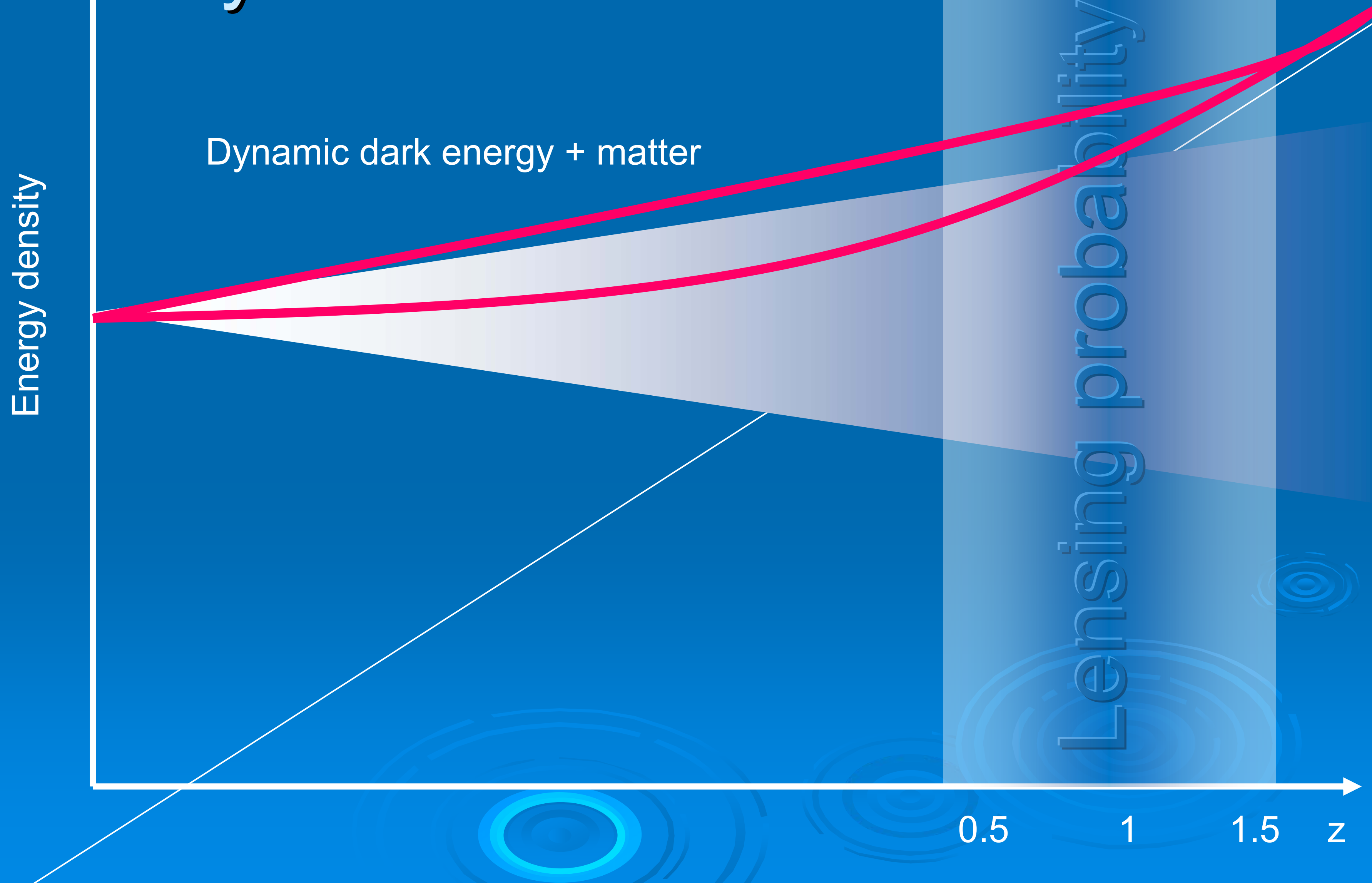
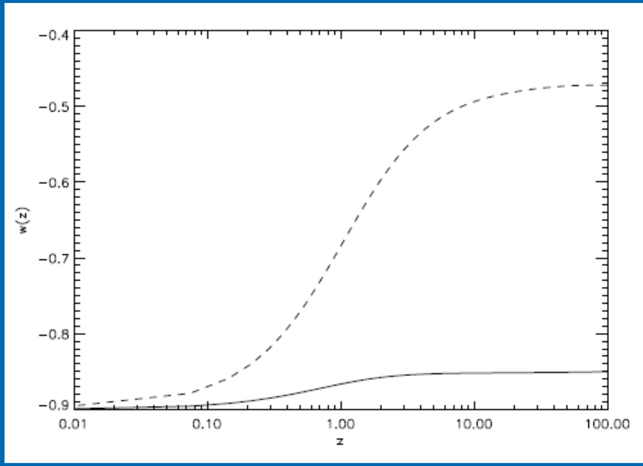
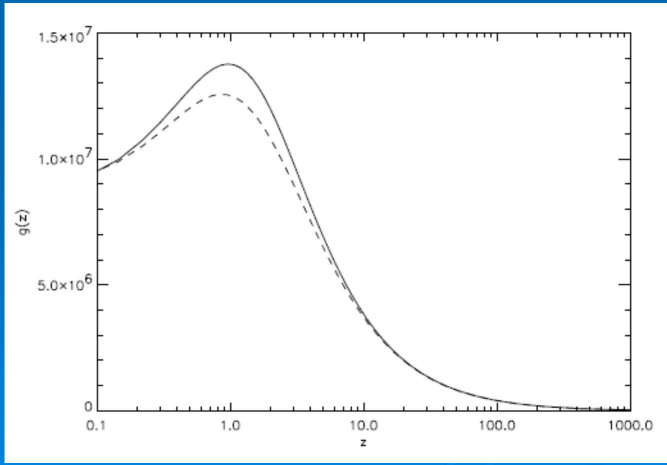
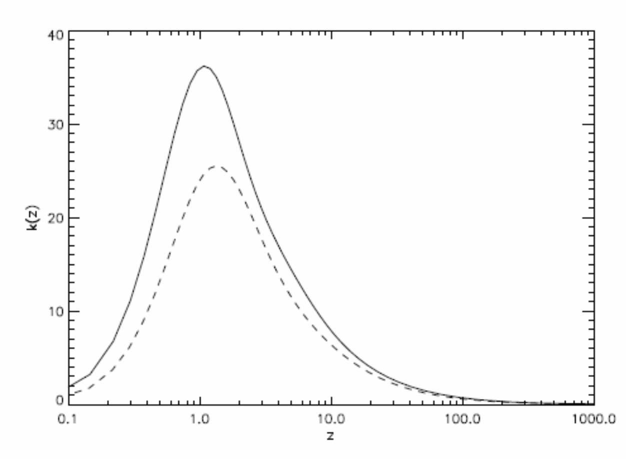


# Numerical experiments

- SUGRA vs. Ratra-Peebles quintessence
- Check structure formation, linear perturbation growth rate, …
- Perturbations and distances affected by geometry coherently…
- Effects sum up in the lensing kernel



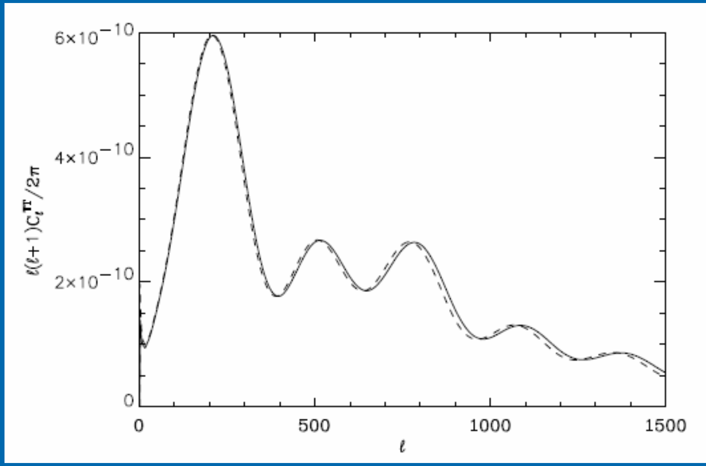



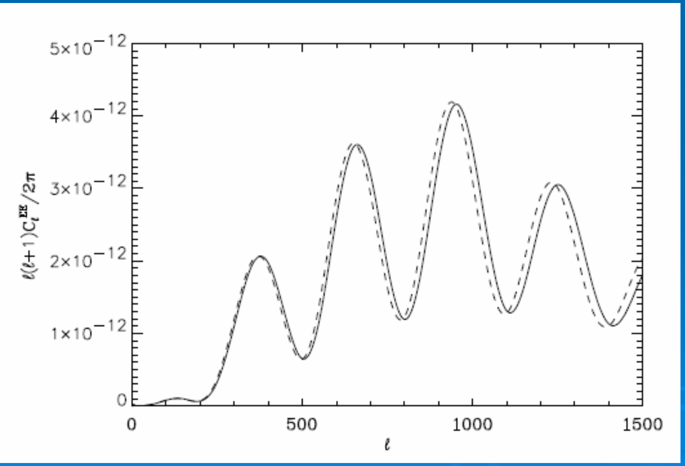



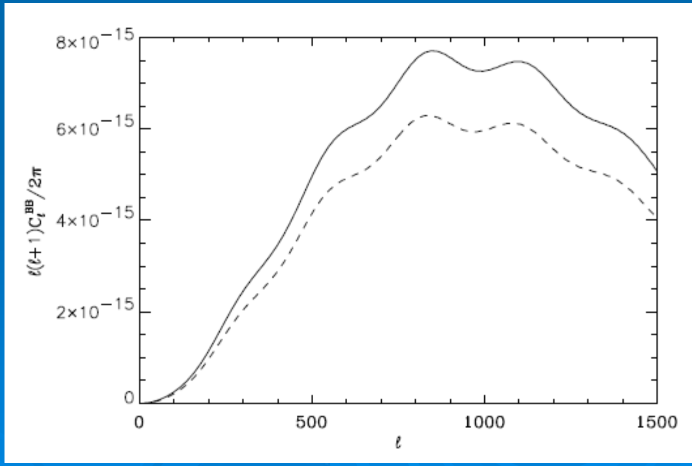

Acquaviva & Baccigalupi 2005

# Numerical experiments

- TT and EE spectra: slight projection shift
- BB amplitude: reflecting cosmic density at structure formation/onset of acceleration

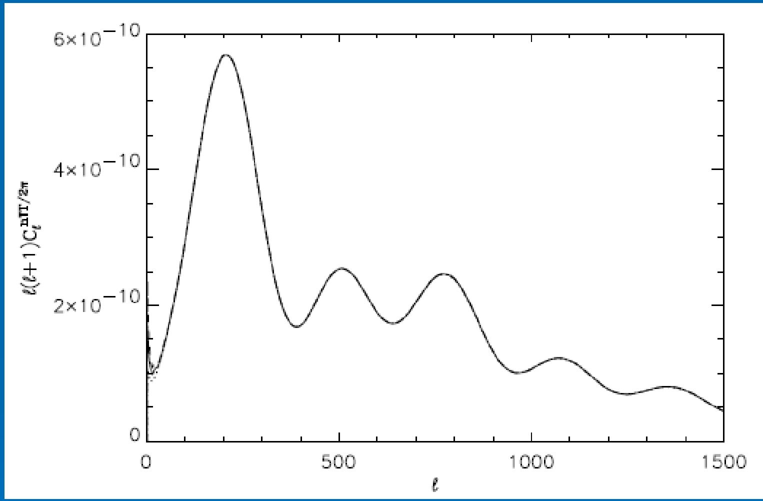


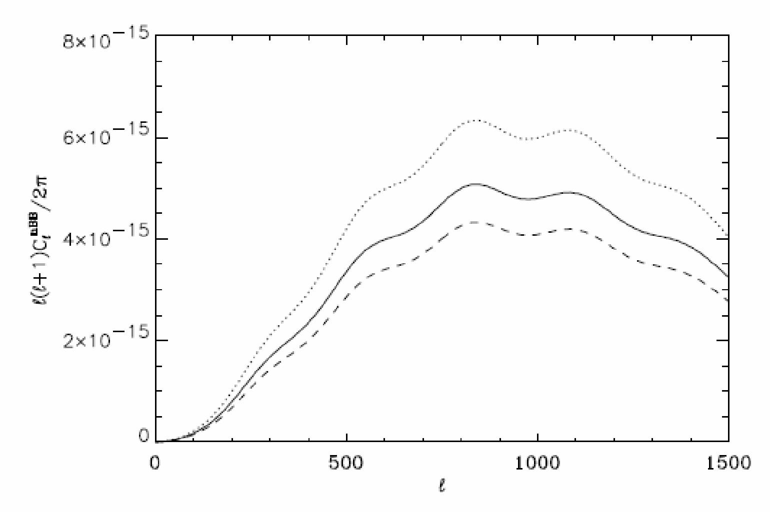




Acquaviva & Baccigalupi 2005

# Breaking projection degeneracy

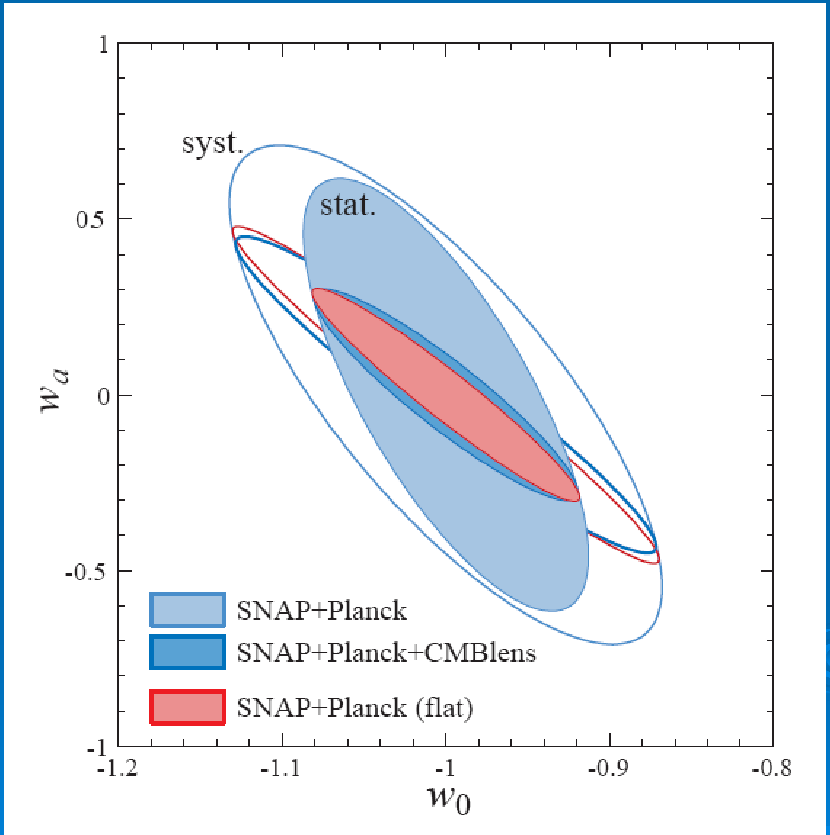



Acquaviva & Baccigalupi 2005

# Forecasts

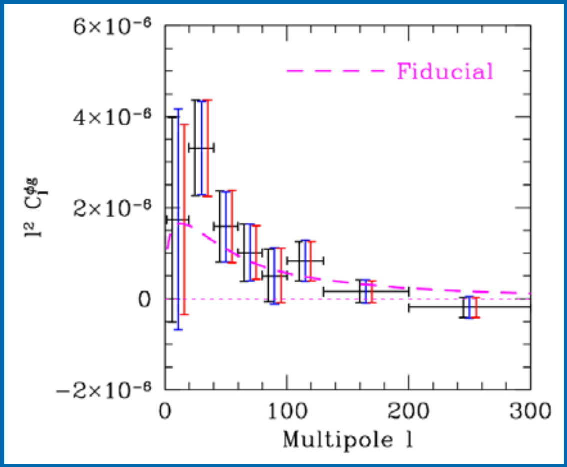
- Breaking of the projection degeneracy confirmed by independent analysis
- CMB lensing and future SNIa measurements can achieve measures of the curvature, present and first derivative of the dark energy equation of state

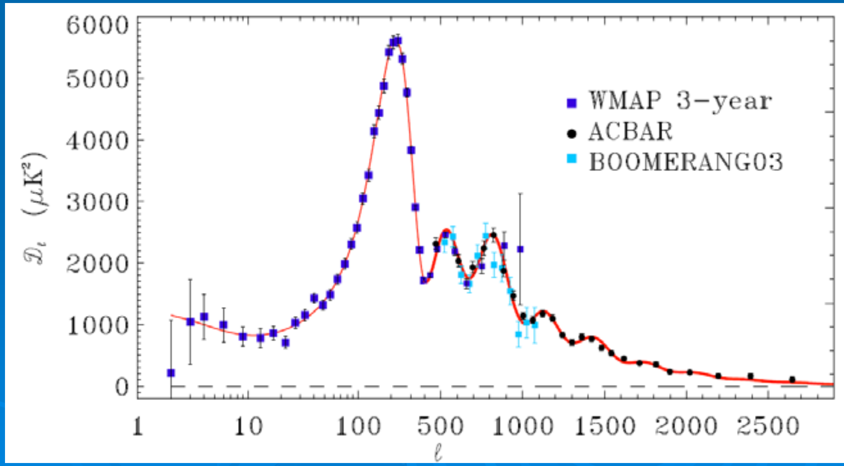



Hu et al. 2006

# Evidences for CMB lensing

- Correlation of WMAP with NVSS sources (Smith et al. 2007, Hirata et al. 2008)
- ACBAR finds a better $\chi^2$ if the lensing is taken into account in the likelihood analysis of power spectra (Reichardt et al. 2008)



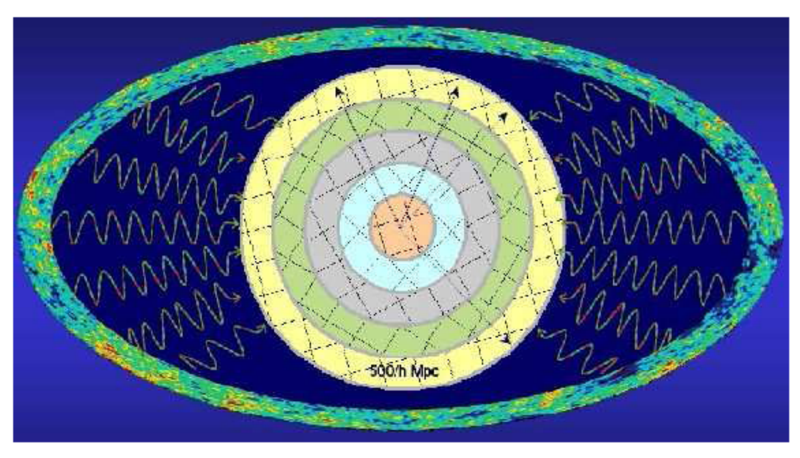



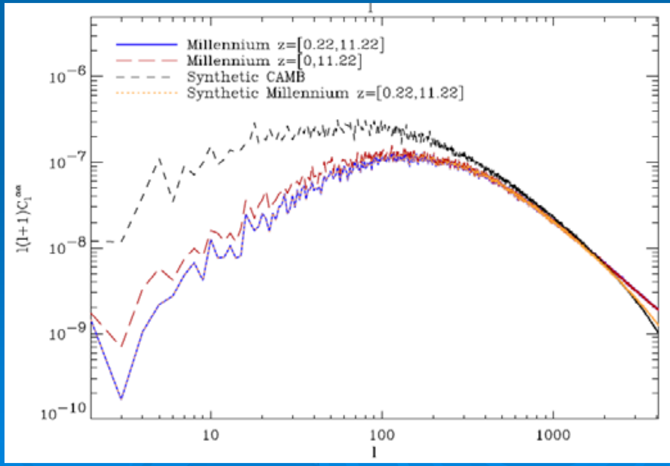
# The path to dark energy through CMB lensing requires…

- Simulating and studying the signal beyond the power spectrum
- Being able to separate it from foregrounds
- Good CMB experiments, for a complete list of those, see lambda.gfsc.nasa.gov

# CMB lensing simulations

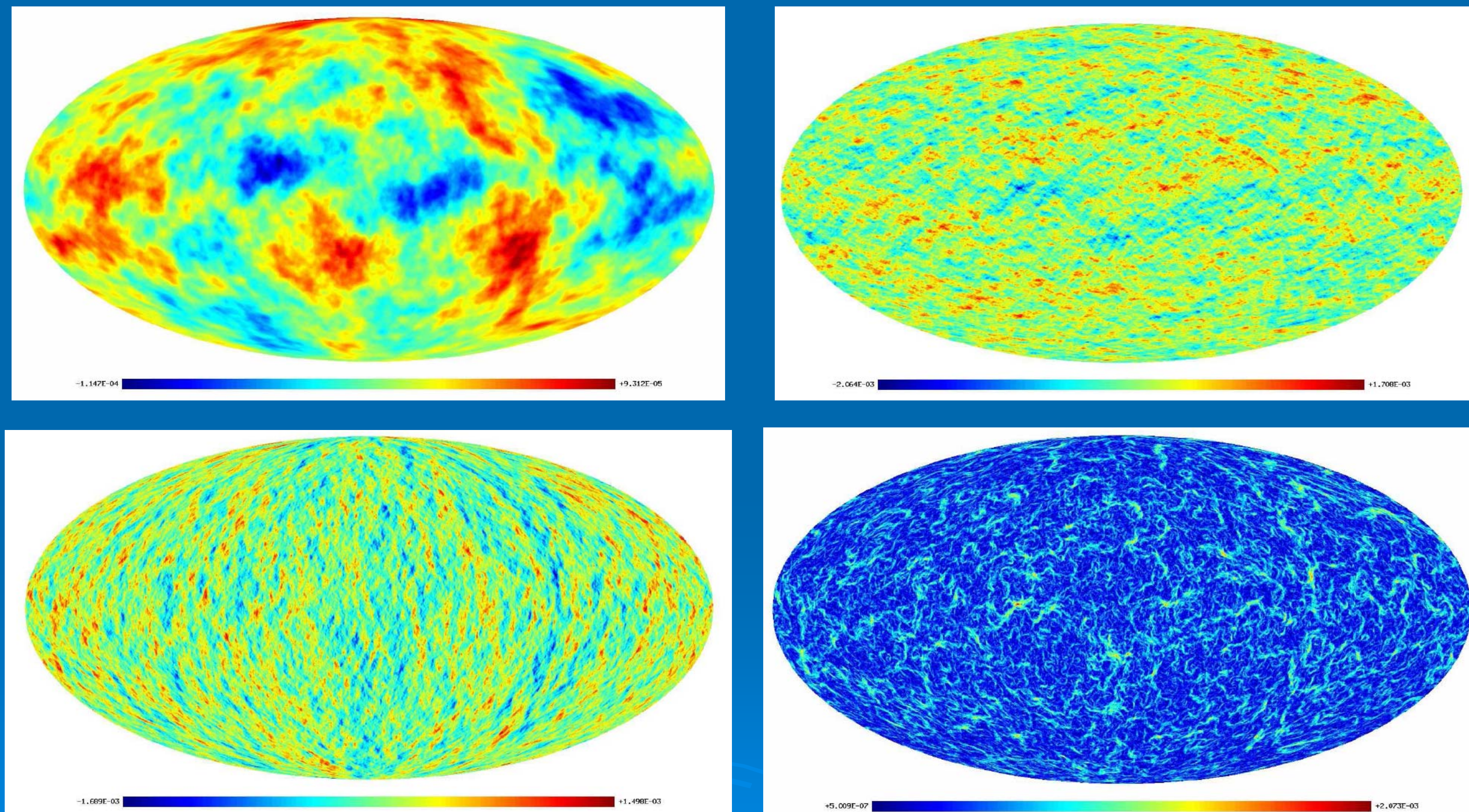
- Ray tracing through modern and large N-body simulations allows to simulate all sky CMB lensing
- The signal is being checked for effects due to the stacking of boxes, finite size of the simulations, at the power spectrum level with semi-analytic expectations



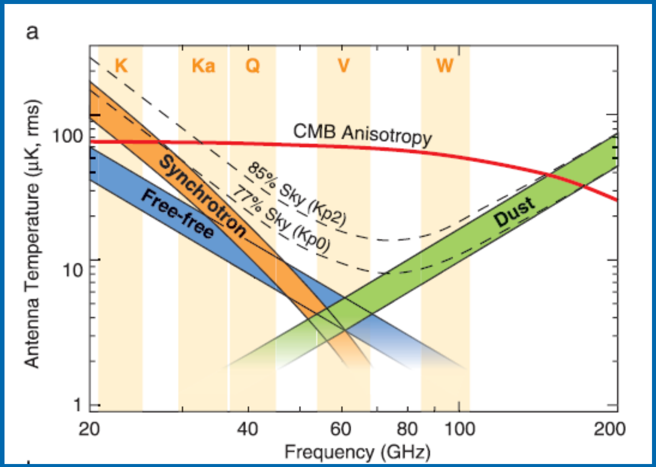

Carbone, CB, Bartelmann, Matarrese 2007, Das & Bode 2007, Fosalba et al. 2008

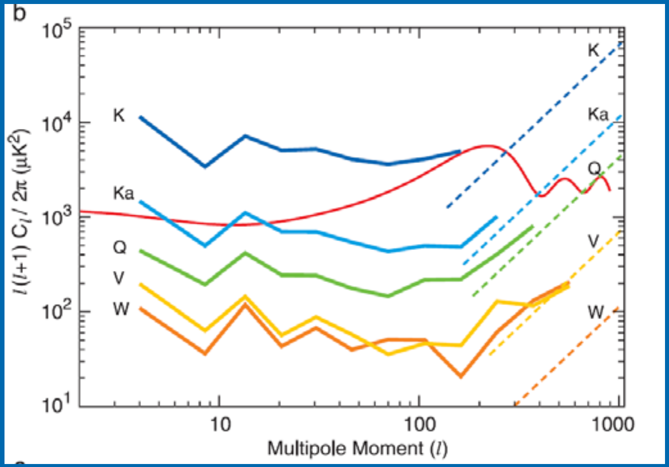
# CMB lensing simulations

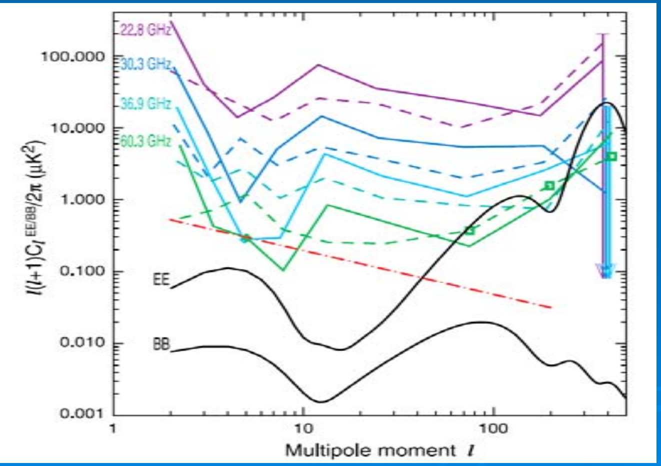


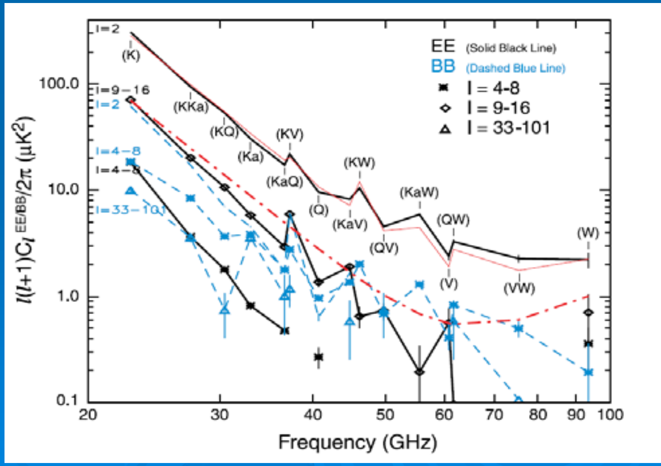

Carbone, CB, Bartelmann, Matarrese 2007

# Foreground fundamentals



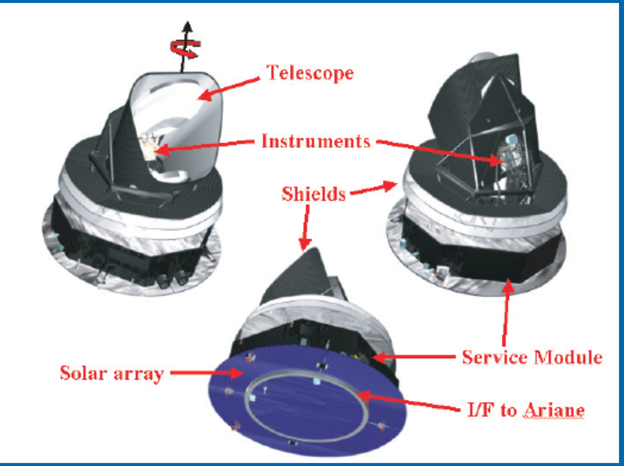



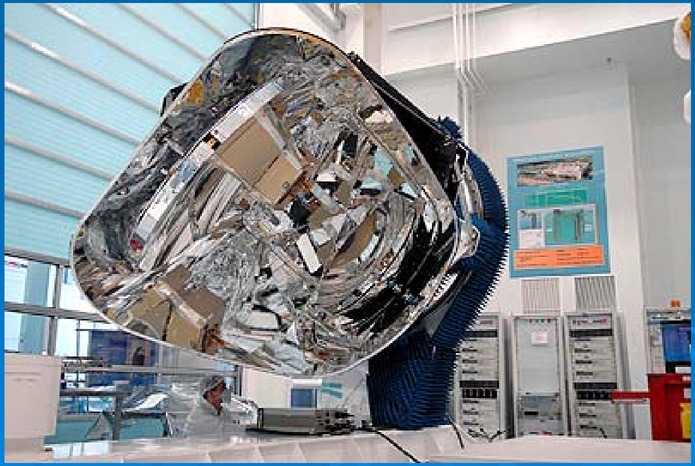




Bennett et al. 2003, Page et al. 2007, Gold et al. 2008

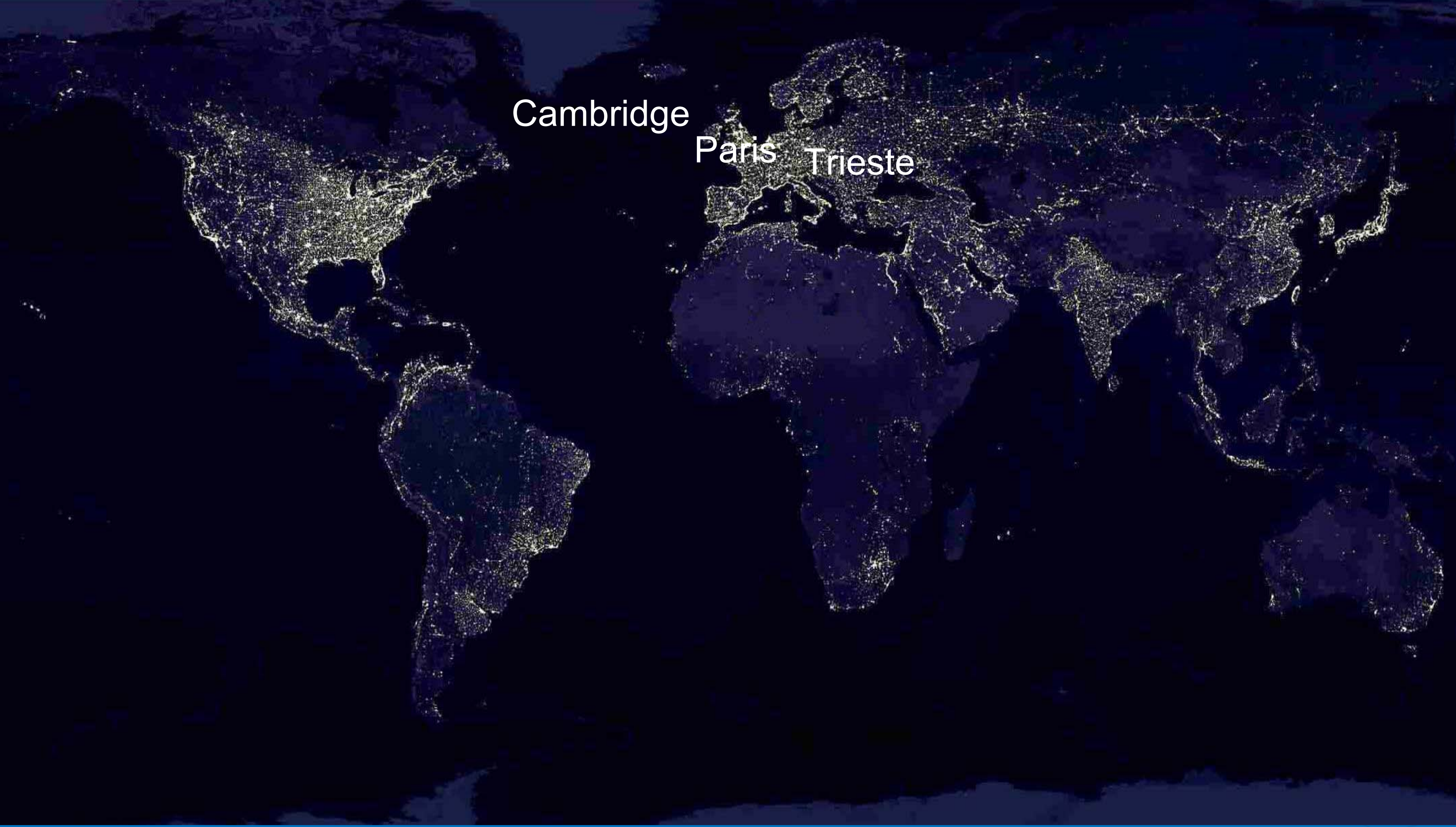
# Planck
# www.rssd.esa.int/Planck

- A third generation CMB probe, ESA medium size mission, NASA (JPL, Pasadena) contribution
- Over 400 members of the collaboration in EU and US
- Two data processing centers (DPCs): Paris + Cambridge (IaP + IoA, data from 100 to 857 GHz), Trieste (OAT + SISSA, data from 30 to 70 GHz)
- The analysis proceeds in parallel at the two DPCs from time ordered data to maps, and joins afterwards for component separation, angular power spectrum estimation, point source and cluster extraction, etc.
- Launch late 2008



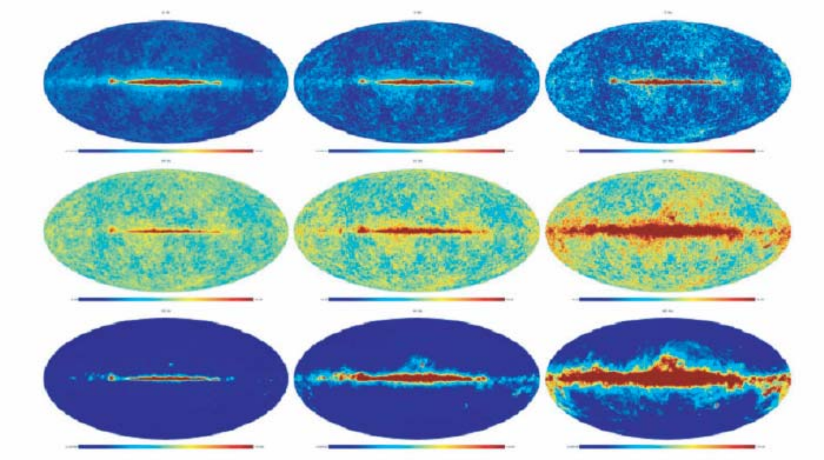

# Planck contributors




# Planck data processing sites

# Planck deliverables

- All sky maps in total intensity and polarization, at 9 frequencies between 30 and 857 GHz
- Angular resolution from 33' to 7' between 30 and 143 GHz, 5' at higher frequencies
- S/N ≈ 10 for CMB in total intensity, per resolution element
- Catalogues with tens of thousands of extra-Galactic sources

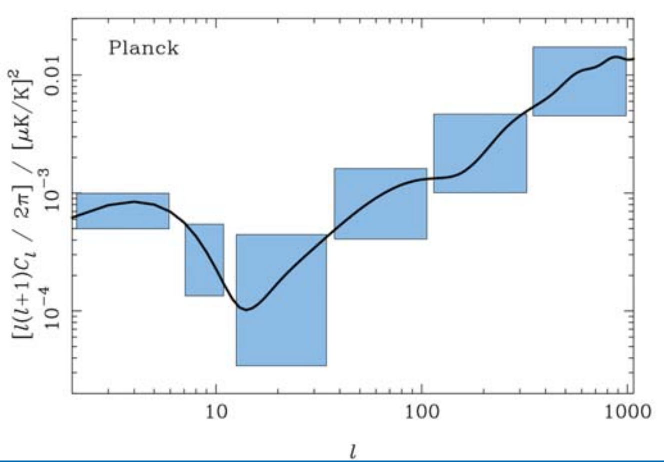


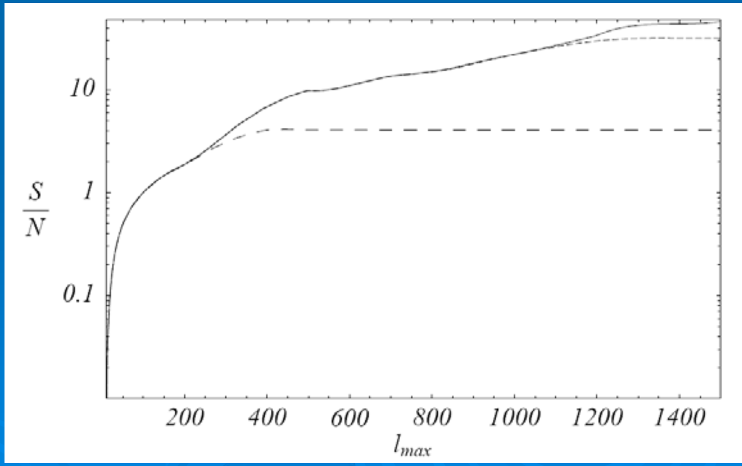
PLANCK GALAXY SURVEYS

| | FREQUENCY [GHz] | | | | |
|---|---|---|---|---|---|
| | 143 | 217 | 353 | 550 | 850 |
| Confusion limit [mJy, $3\sigma$] | 6.3 | 14.1 | 44.7 | 112 | 251 |
| *Planck* All Sky Survey sensitivity [mJy, $3\sigma$] | 26 | 37 | 75 | 180 | 300 |
| *Planck* Deep Survey sensitivity [mJy, $3\sigma$] | 10 | 18.4 | 49 | 170 | 280 |
| Number of galaxies [all sky] | 570 | 860 | 1700 | 4400 | 35000 |

# CMB lensing and Planck

- Even assuming no systematics and no foregrounds, the B modes from lensing are only marginally detectable
- Assuming the same hypotheses, the CMB lensing bispectrum should be detectable with good confidence

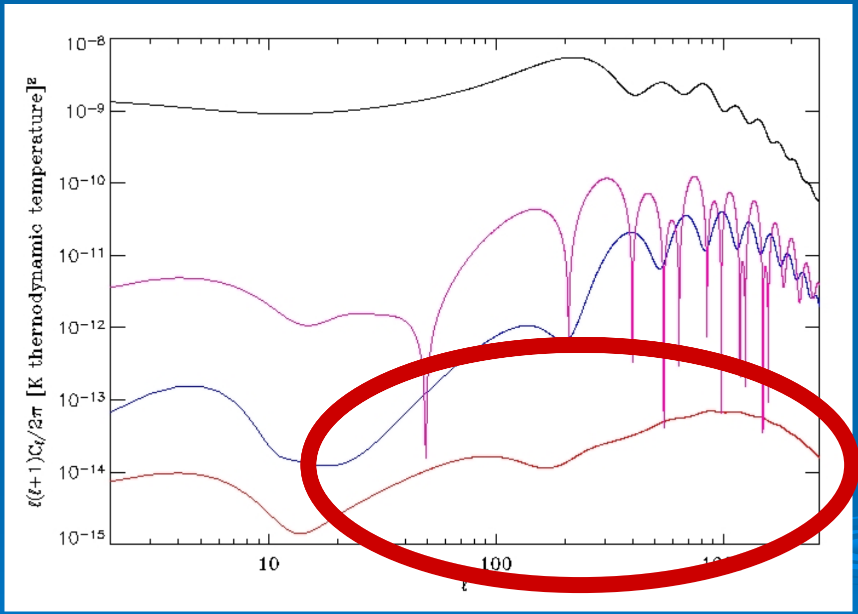



Giovi et al. 2005

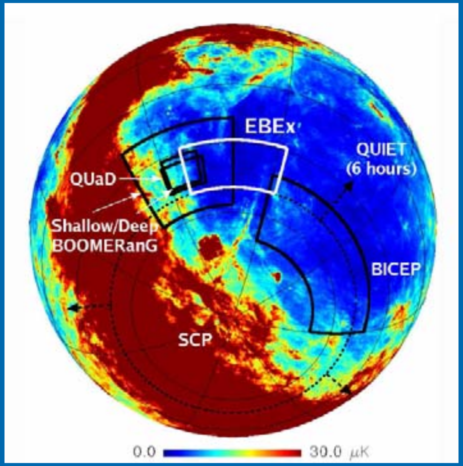
# B modes hunters

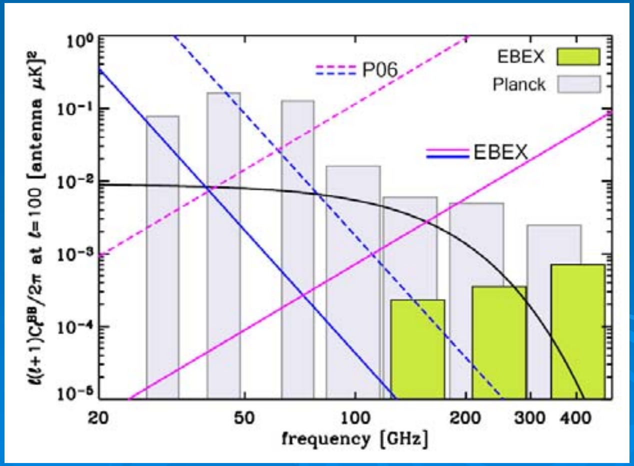
- Different technologies, ground based as well as balloon borne probes
- The instrumental sensitivity and angular resolution are high enough to get to a tensor to scalar ratio of about $10^{-2}$ via direct detection of cosmological B modes on the degree scale
- Some of the probes also are able to detect the lensing peak in the B modes
- All these experiments aim at the best measurement of CMB, although most important information is expected in particular for the B mode component of the diffuse Galactic emission
- The challenge of controlling instrumental systematics and foregrounds make these probes pathfinders for a future CMB polarization satellite



# EBEx

- 8 arcminute resolution, three frequencies, 150, 250 and 410 GHz
- Targeting a low foreground area in the antarctica flight, already probed by previous observations for total intensity and E mode polarization
- Foregrounds, dominated by Galactic dust at the EBEx frequencies, are estimated to be still comparable to the cosmological signal for B
- Band location and number of detectors per band have been optimized for foreground subtraction

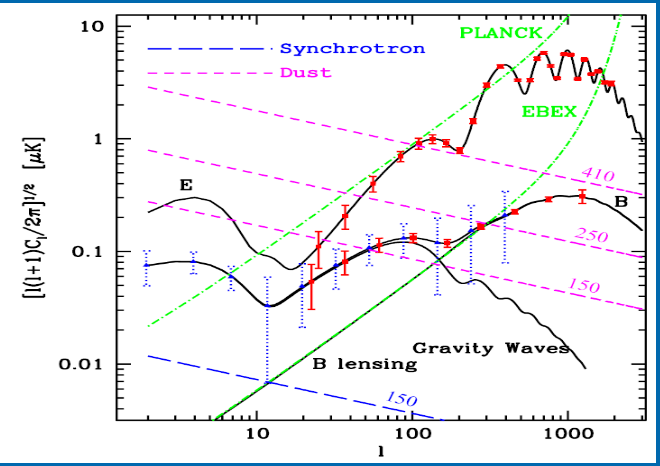


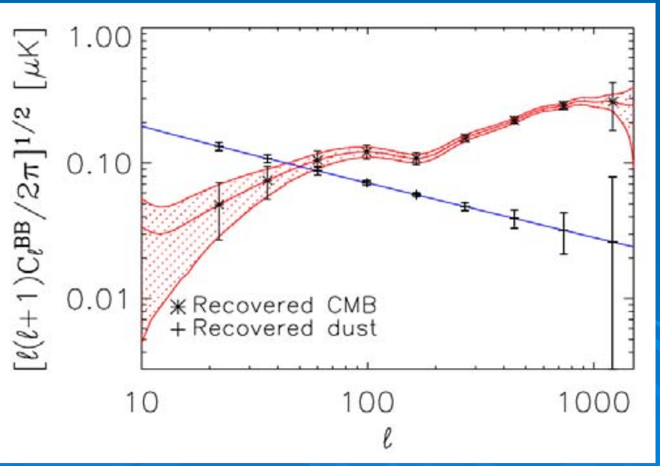

# EBEx contributors

# Expectations from EBEx

Zaldarriaga et al. 2005




- The detector sensitivity should allow a detection of the tensor to scalar ratio equal to 0.1 with a signal to noise ratio of about 5, or setting a two sigma upper limit of 0.02, plus a mapping of the lensing peak in B modes
- Together with the control of systematics, this all depends on an exquisite removal of the foreground emission




Stompor, Leach, Stivoli, CB 2008

# Conclusions

- The lensing power in the CMB is a tracer of the dark energy abundance at the onset of acceleration
- Within reach of forthcoming experiments, first evidences achieved by correlating CMB anisotropies with large scale structure
- Substantial (and new) studies for characterizing, foreground cleaning and extracting the signal from the data are ongoing and required to make it possible
- Complementary to galaxy lensing and BAOs