Analysis and physics of the Cosmic Microwave Background: a dark energy perspective

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These lectures are available in pdf format at people.sissa.it/~bacci/work/lectures

Outline

- Introduction and historical remarks
- Cosmological fossils
- CMB observables
- Status of CMB observations
- Planck & B mode hunters
- Dark Energy and CMB
- Classic and modern dark energy effects
- Conclusions and suggested reading

Introduction and historical remarks

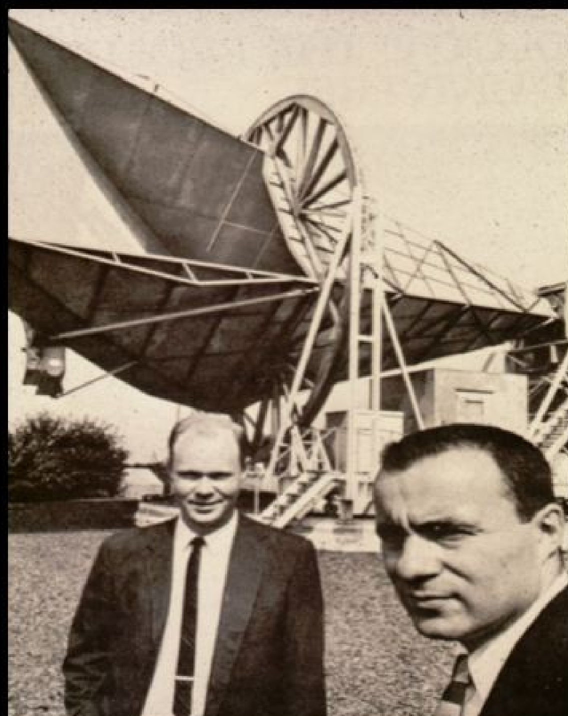
Expanding universe ⇒ CMB

- 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



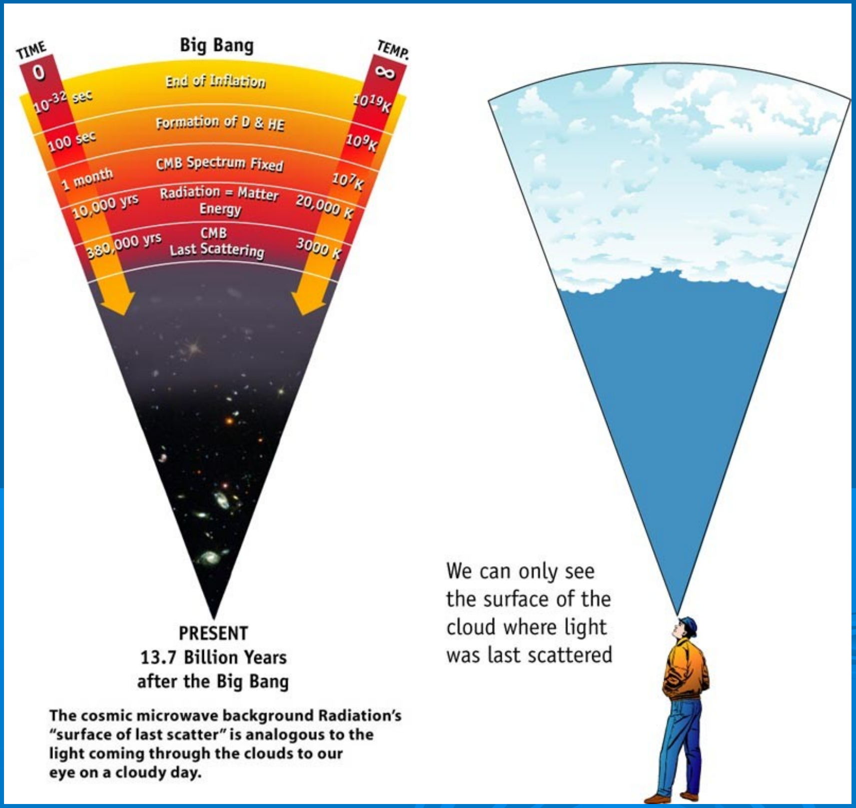
Early 1960s - Penzias and Wilson are hired by Bell Labs to evaluate the performance of the new radio telescope to be used in trans-Atlantic telephone communications.

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.

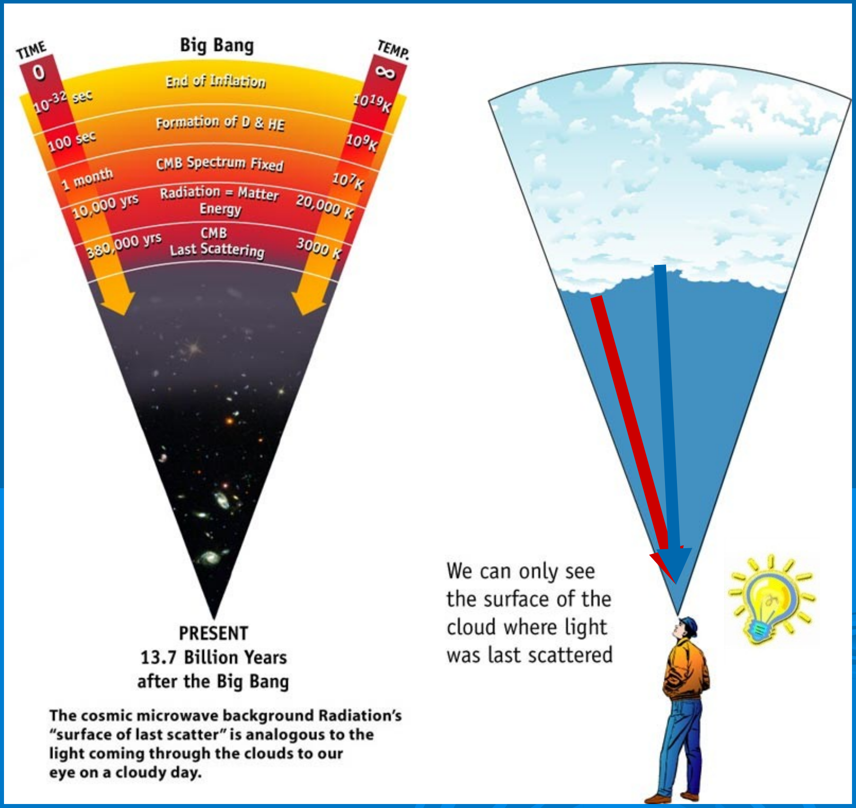
CMB: where and when?

- Opacity: $\lambda = (n_e \sigma_T)^{-1} \ll$ horizon
- 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



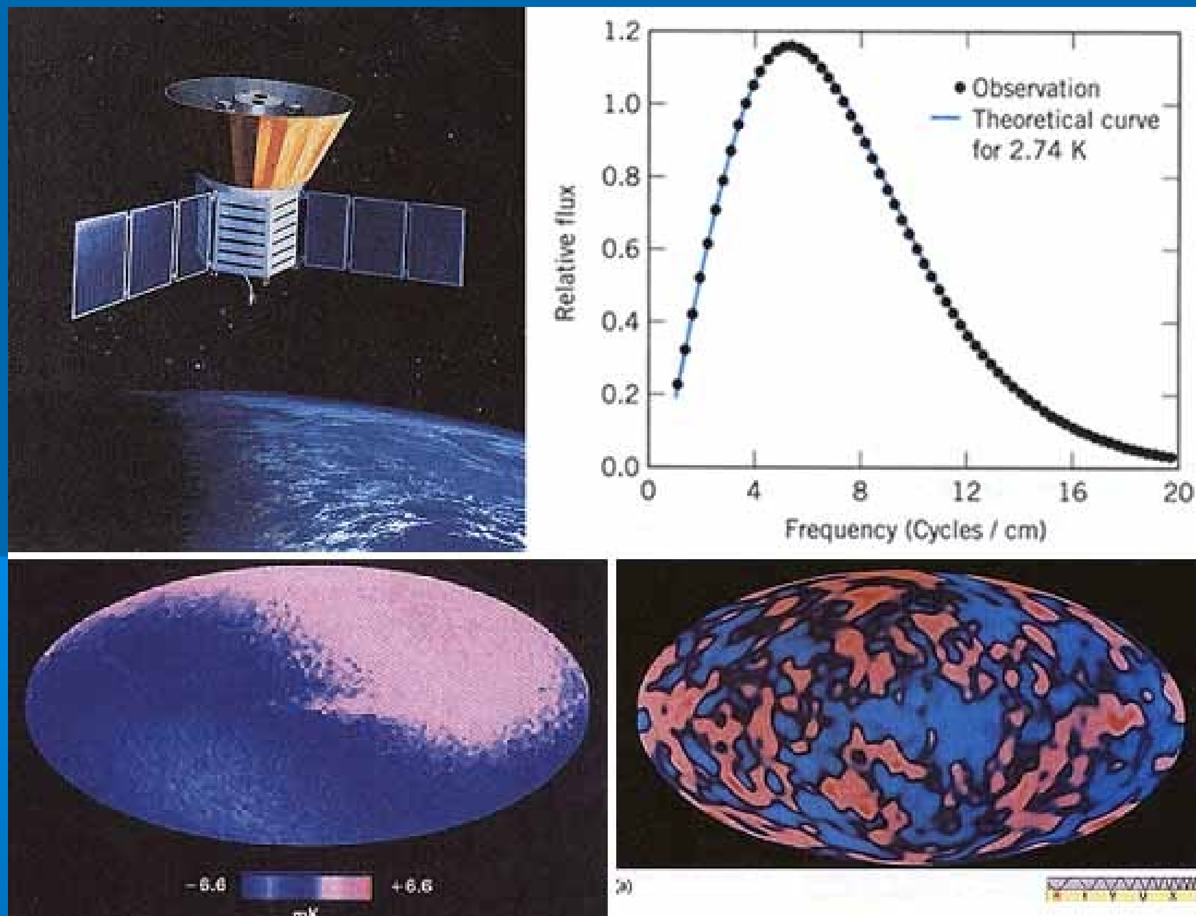
A postcard from the big bang

- 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



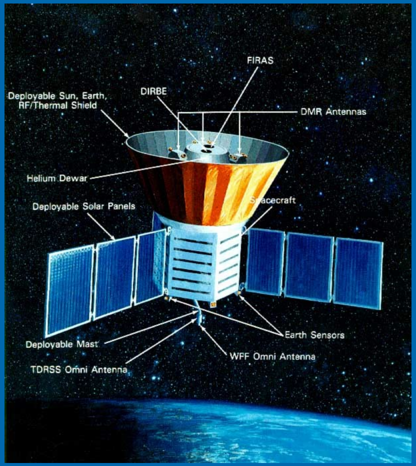
Animation from the NASA WMAP team

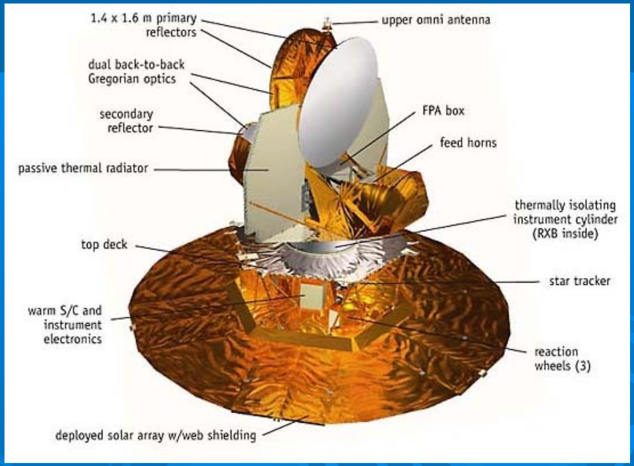
COsmic Background Explorer



From COBE to the Wilkinson Microwave Anisotropy Probe

- About 20 years of insight into one of the most important observables in physics
- Lots of experiments, from ground as well as the stratosphere
- A fantastic technological and data analysis progress, in parallel to theory
- lambda.gfsc.nasa.gov





Animation from the NASA WMAP team

Cosmological fossils

CMB physics: Boltzmann equation

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

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

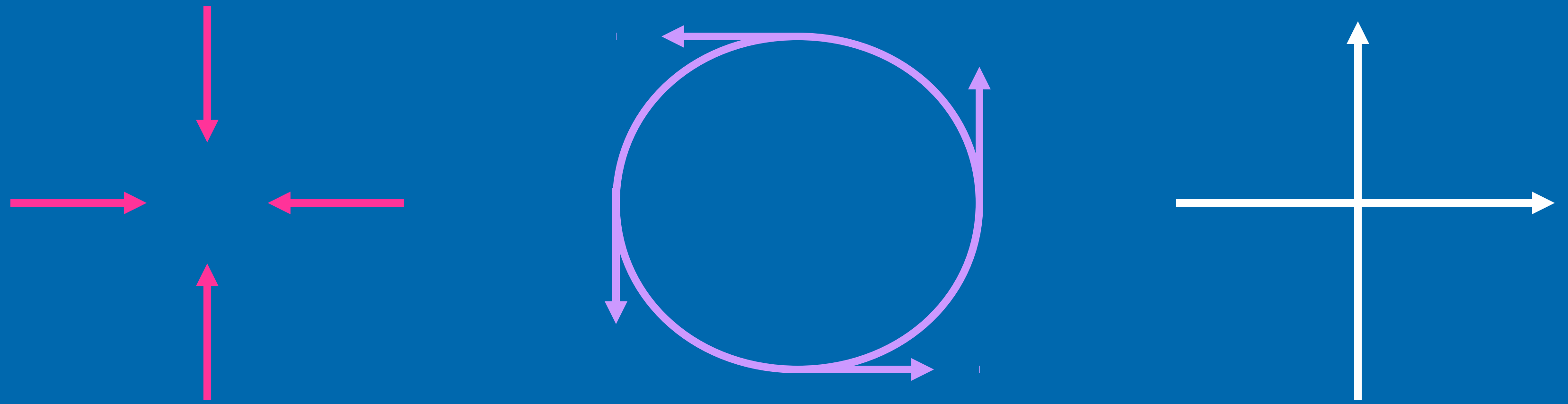
CMB physics: Boltzmann equation

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

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

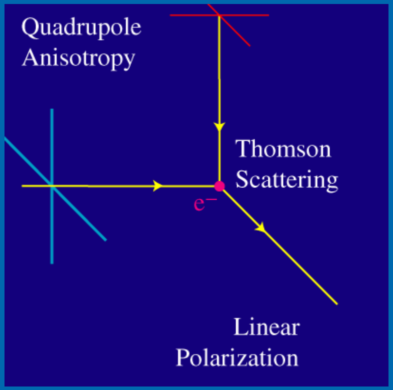
metric = photons + neutrinos + baryons + leptons + dark matter

CMB physics: metric



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



e-

CMB anisotropy: total intensity

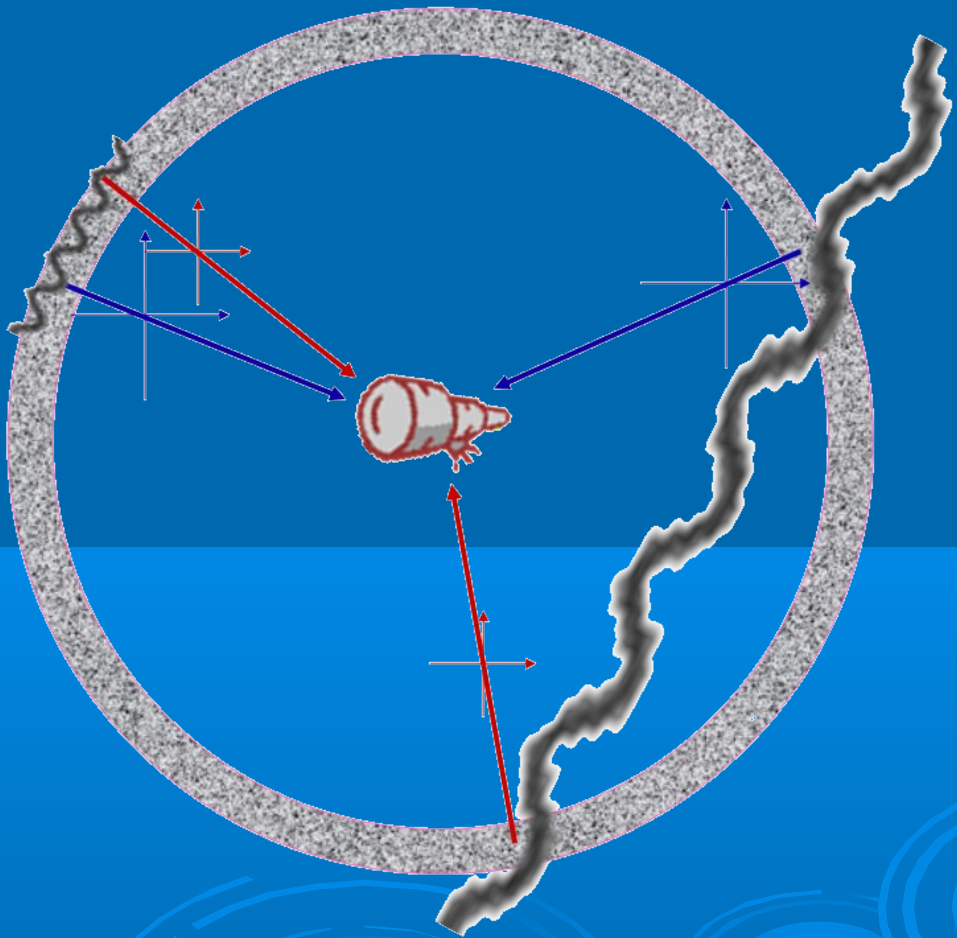
+

+

CMB anisotropy: polarization

Gradient (E):

Curl (B):

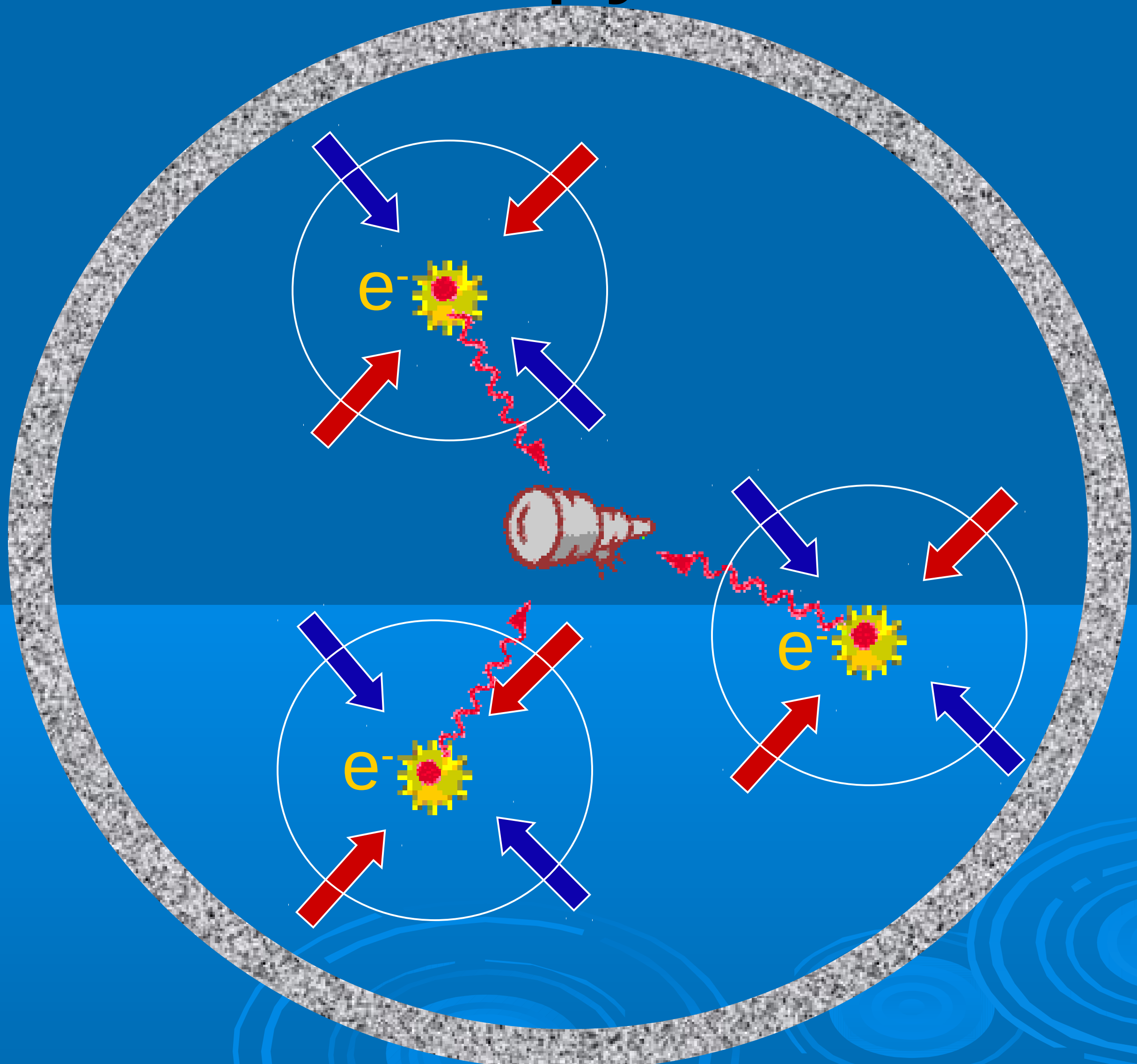


+

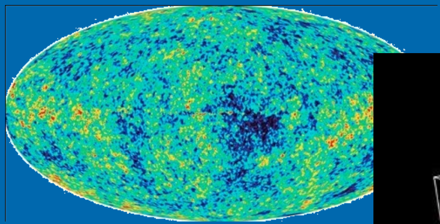
+

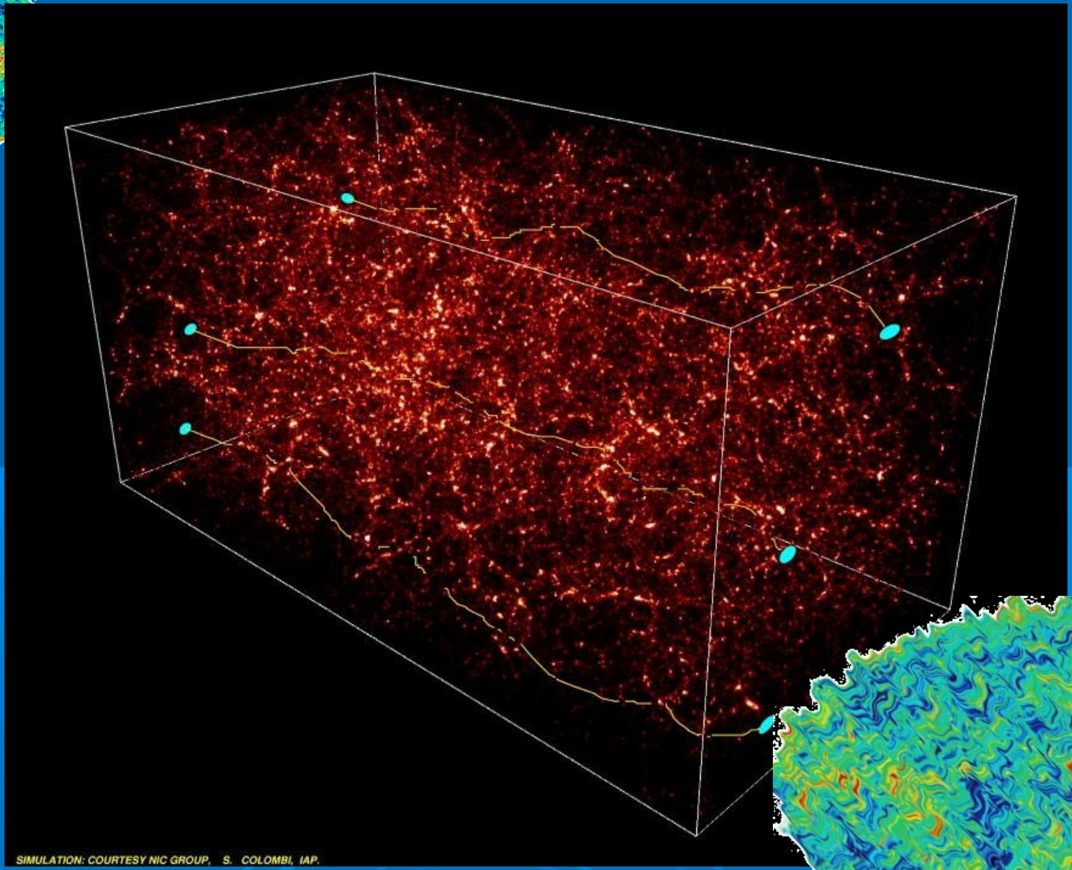
+

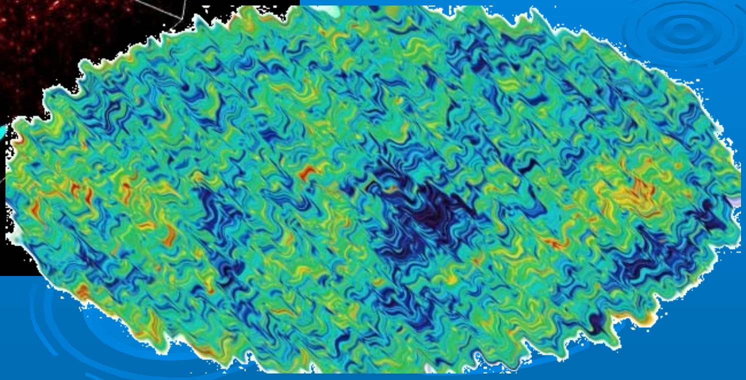
CMB anisotropy: reionization



CMB anisotropy: lensing







CMB observables

Anisotropies

T(θ,φ), Q(θ,φ), U(θ,φ), V(θ,φ)

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

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

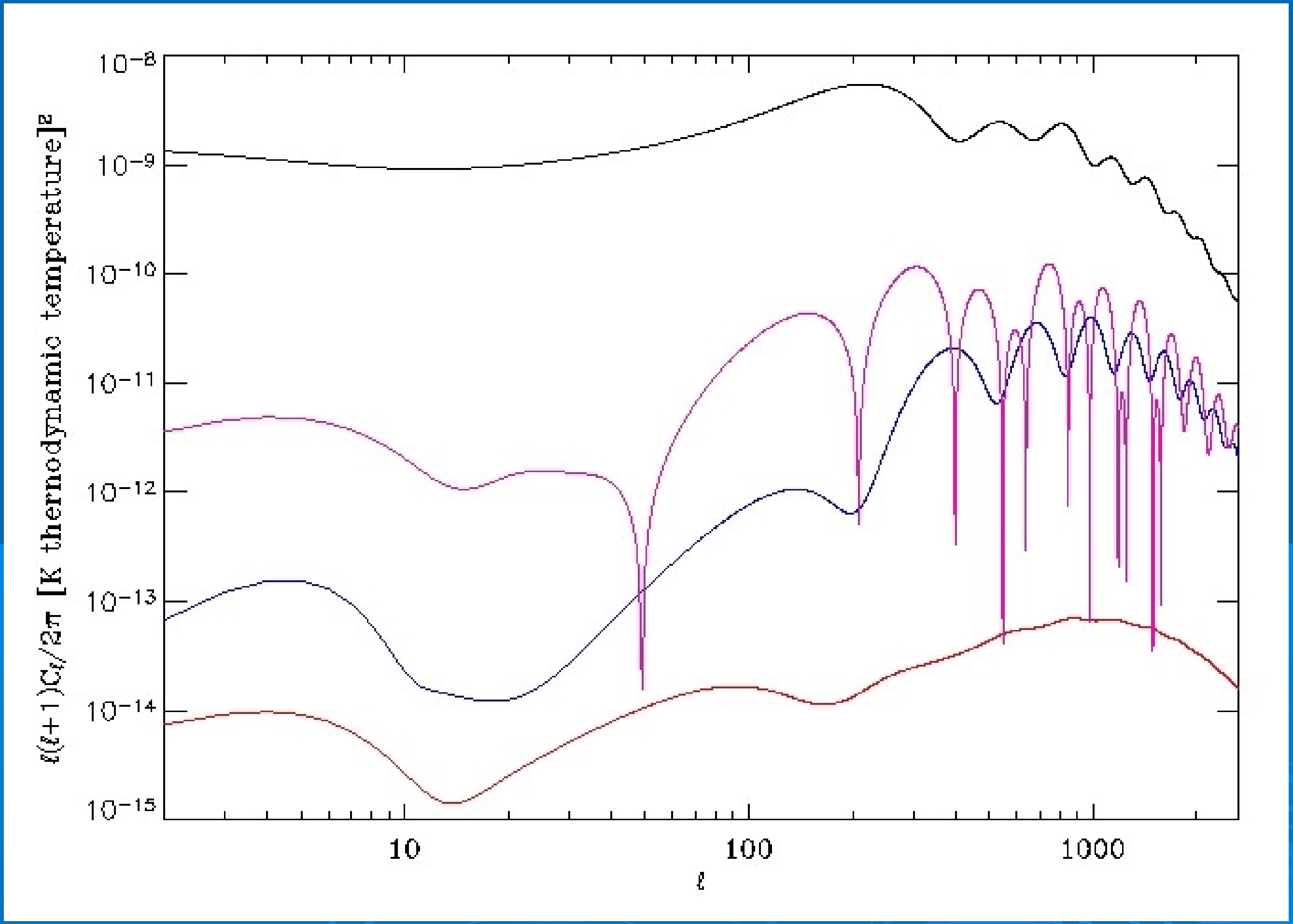
spherical harmonics

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

information compression

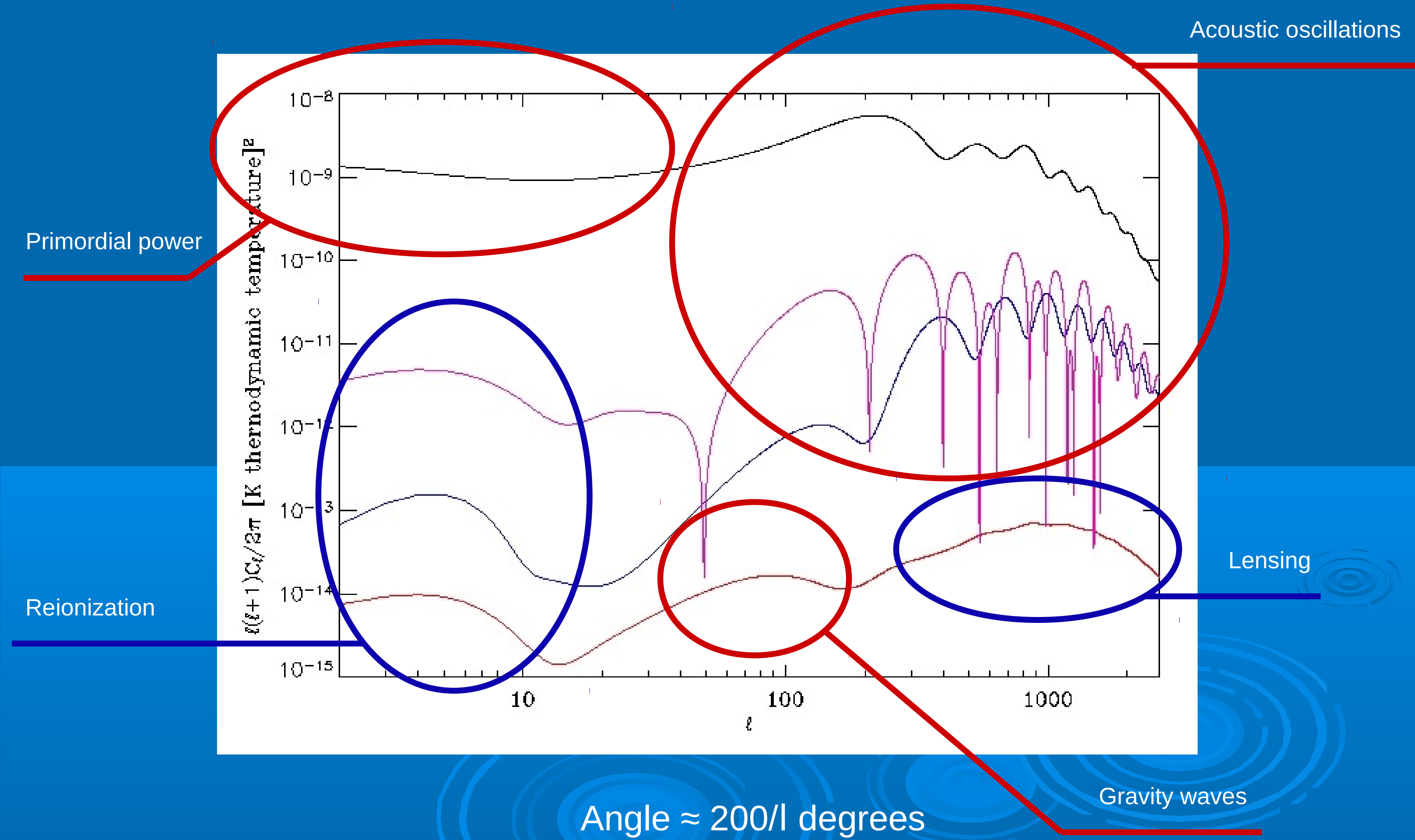
$C_l=\Sigma_m [(a_{lm}{}^X)(a_{lm}{}^Y)^*]/(2l+1)$

CMB angular power spectrum



Angle ≈ 200/l degrees

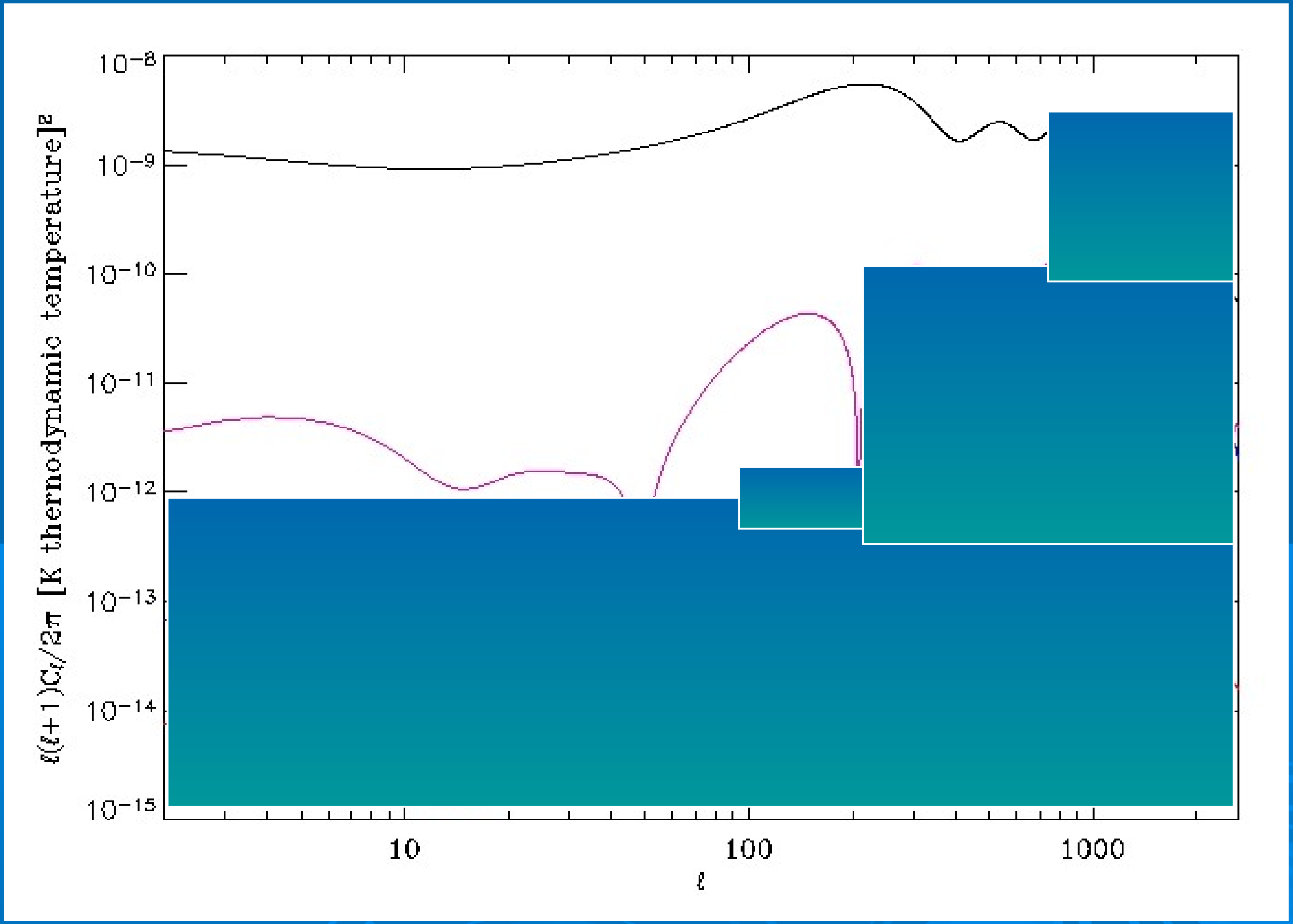
CMB angular power spectrum



Angle ≈ 200/l degrees

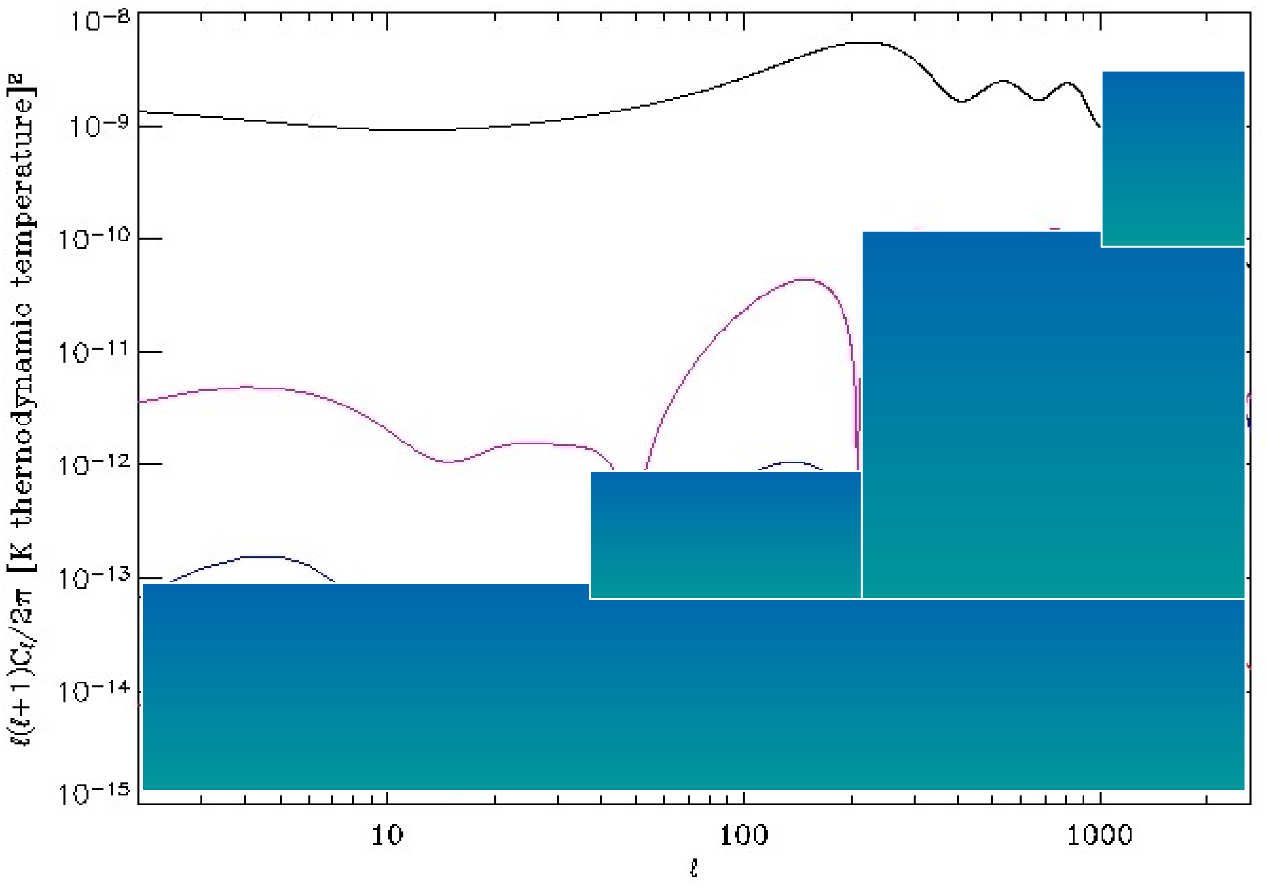
Status of the CMB observations

WMAP first year



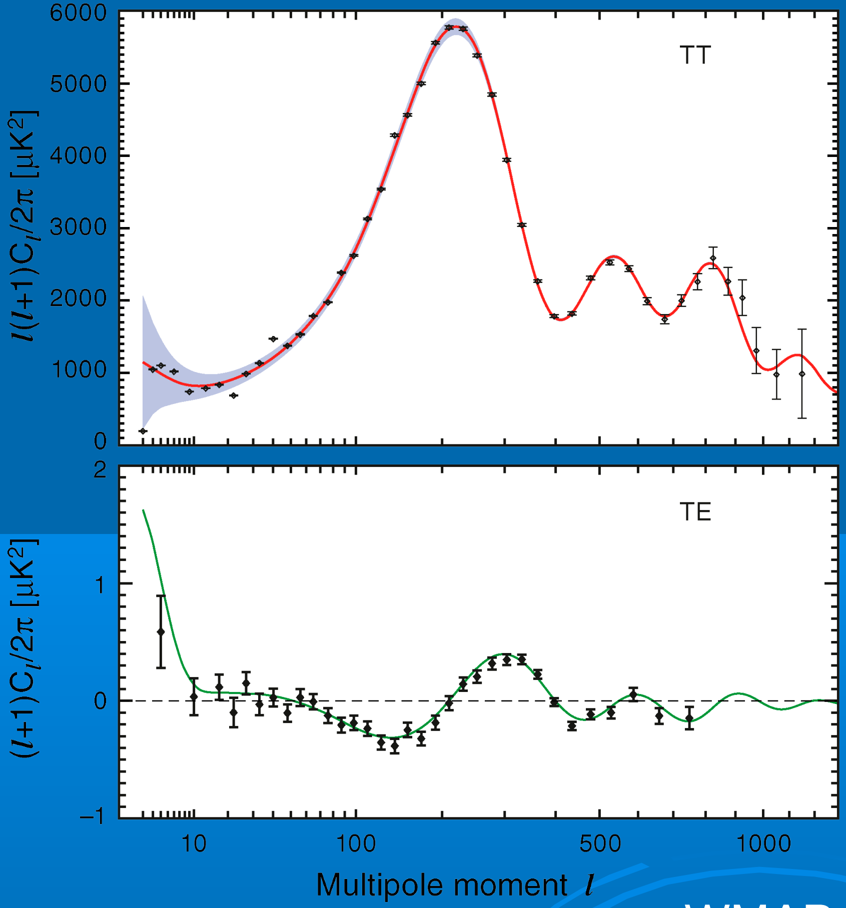
Angle ≈ 200/l degrees

WMAP seventh year

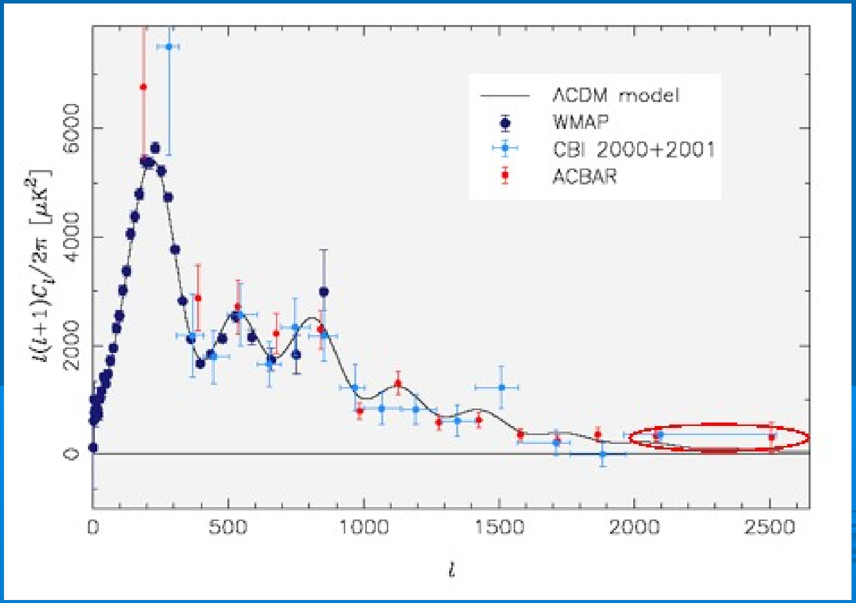


Angle ≈ 200/l degrees

CMB angular power spectrum

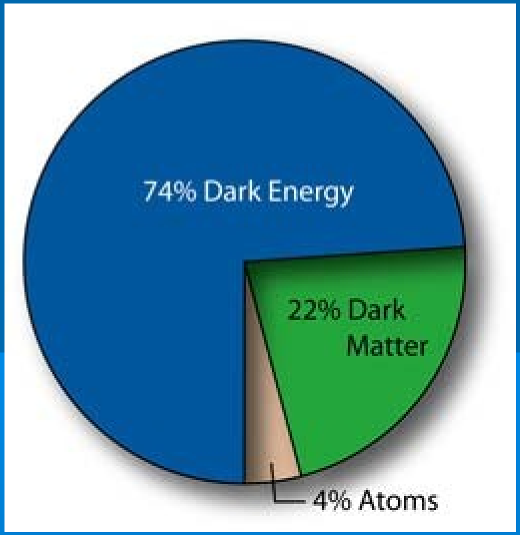


WMAP

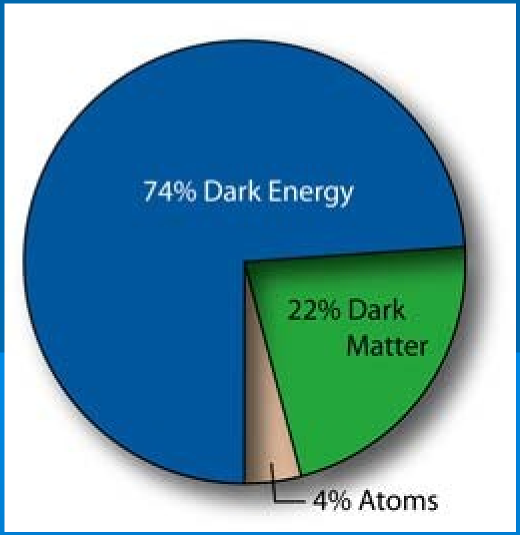


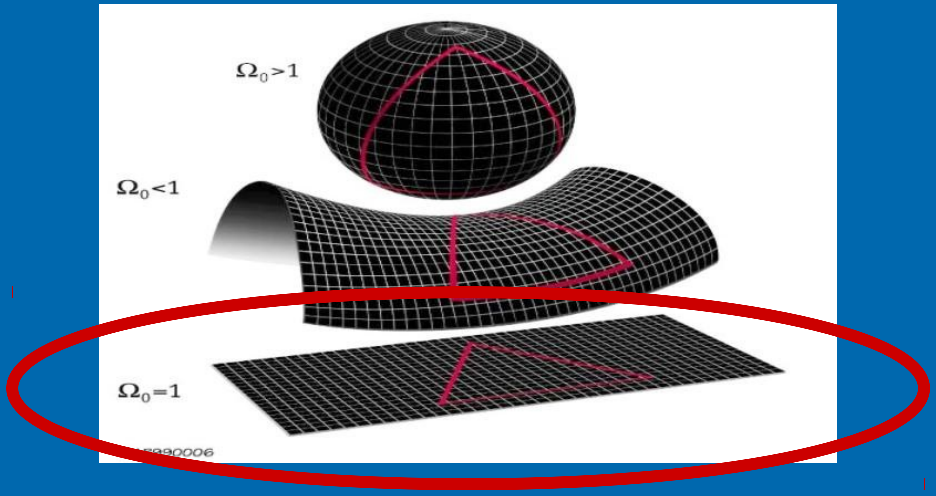
Small scales

Cosmological concordance model

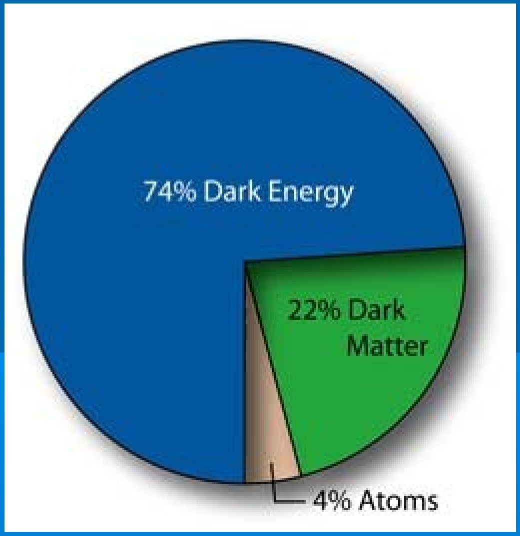


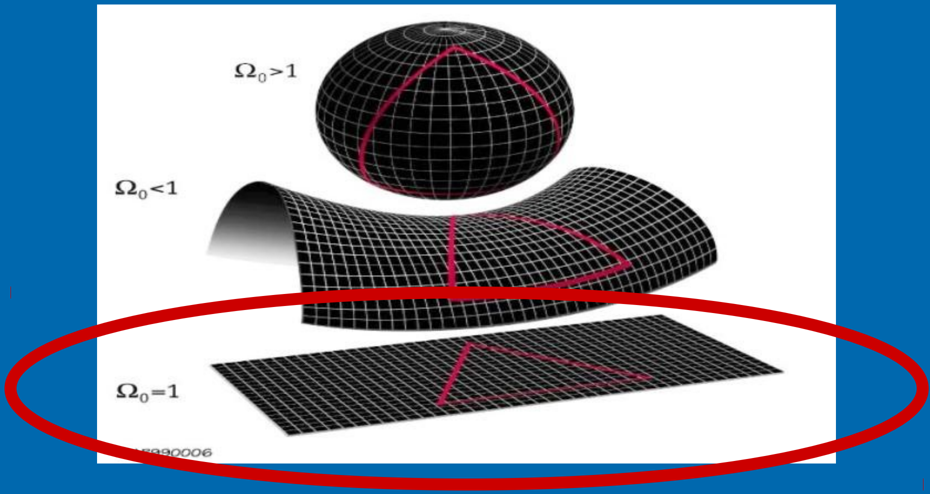
Cosmological concordance model

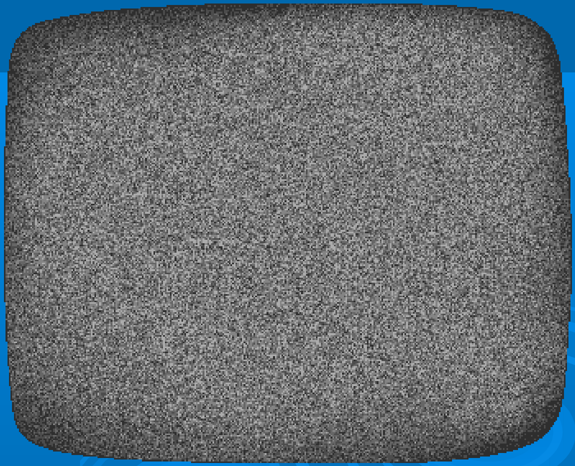




Cosmological concordance model

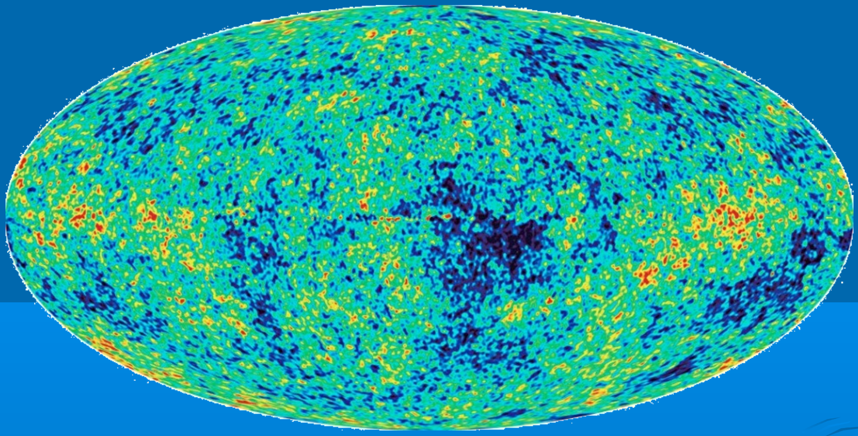






Are you happy?

- Dark components?
- B modes?
- Statistics beyond power spectrum?
- Lensing?
- Global topology?
- …



Other cosmological backgrounds?

- Neutrinos: abundance comparable to photons ☺, decoupling at MeV ☺, cold as photons ☹, weak interaction ☹
- Gravity waves: decoupling at Planck energy ☺, abundance unknown ☹, gravitational interaction ☹
- Morale: insist with the CMB, still for many years…that's the best we have for long…
- See lambda.gfsc.nasa.gov

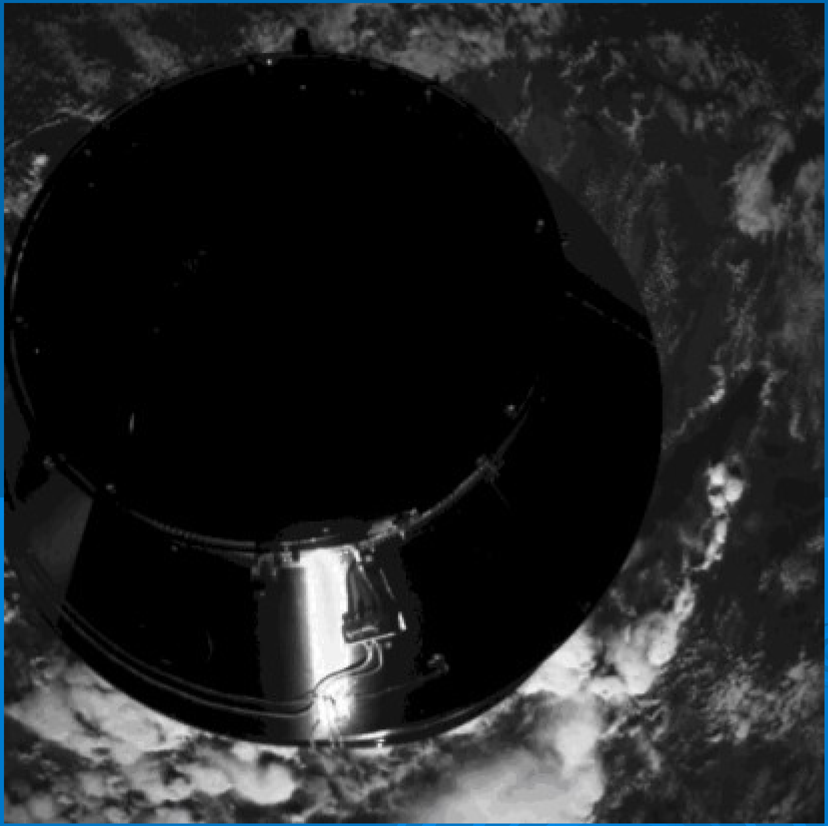
Planck and B mode hunters

Planck

- Hardware: 600 ME, third generation CMB probe, ESA medium size mission, NASA (JPL, Pasadena) contribution, radiometer and bolomoter technology
- Software from 400 collaboration members in EU and US
- Two data processing centers (DPCs): Paris + Cambridge (IaP + IoA), Trieste (OAT + SISSA)

Planck DPC facilities

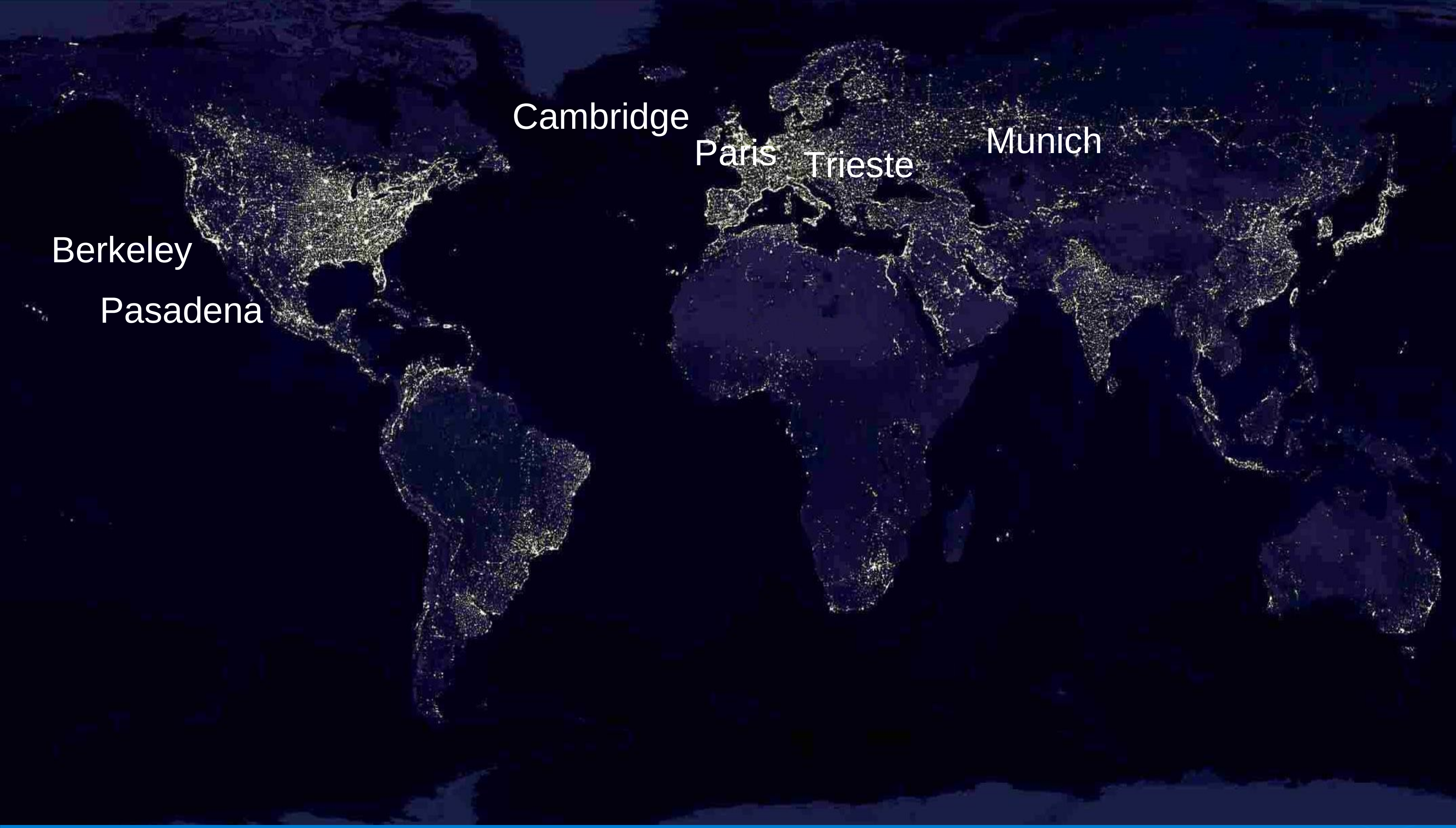
- DPC people physically in Trieste are about 20 at OATs and SISSA
- The data will be hosted on two computers, ENT (OATs, official products, 256 CPUs, hundreds of GB RAM, tens of TB disk space), HG1 (SISSA, simulations and scientific interpretation, 160 CPUs, hundreds of GB RAM, tens of TB disk space)



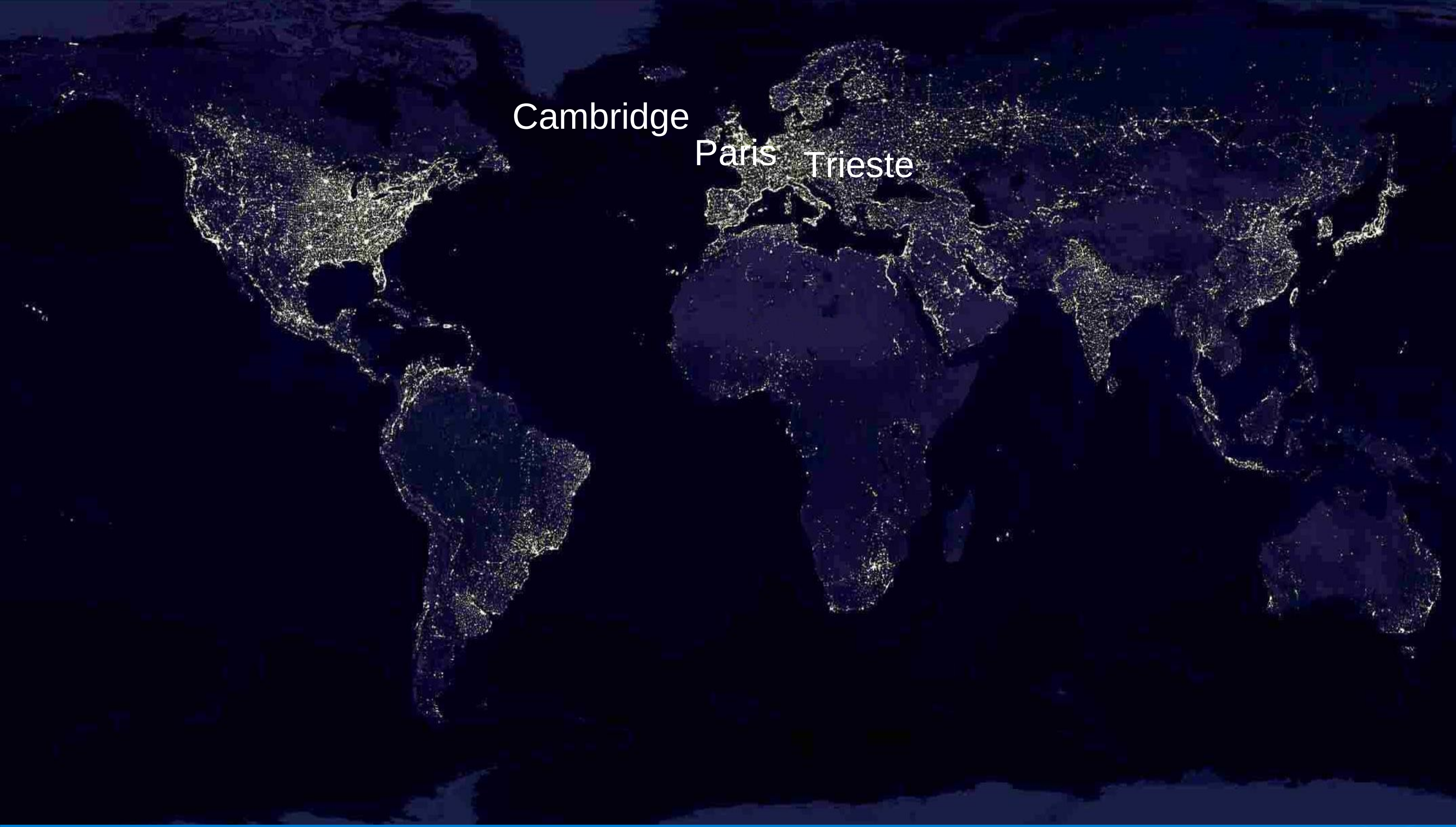
Planck milestones

- May 14th, 2009, launch, the High Frequency Instrument (HFI, bolometers) is on
- June 1st, 2009, active cryogenic systems are turned on
- June 8th, 2009, the Low Frequency Instrument (LFI, radiometers), is turned on
- Summer 2009, Planck gets to L2, survey begins, 14 months
- 2 years of proprietary period and data analysis
- Results end of 2011, 2012, 2013
- Mission duration doubled

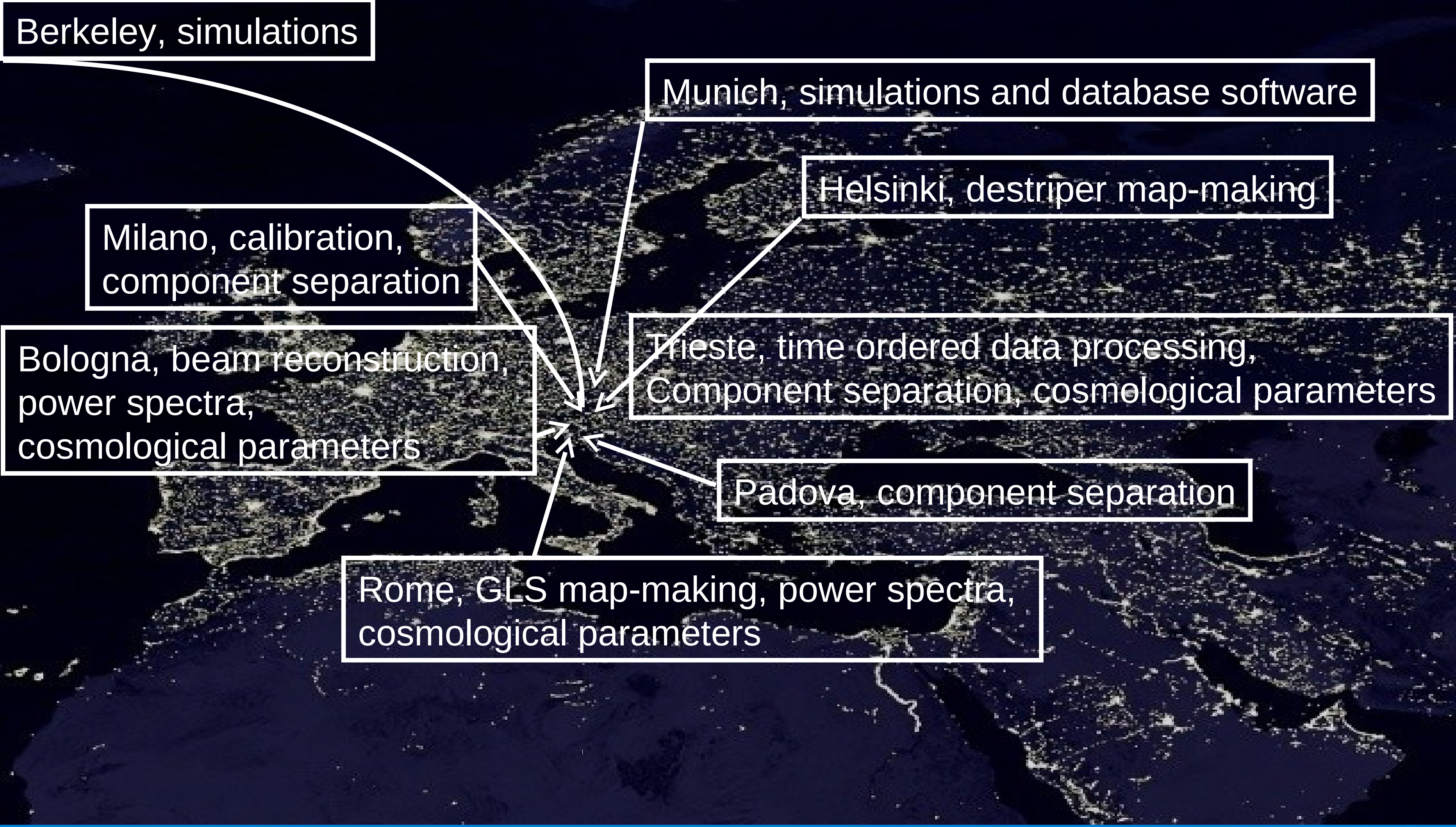
Planck contributors



Planck mission and data analysis simulations



Planck data processing centers



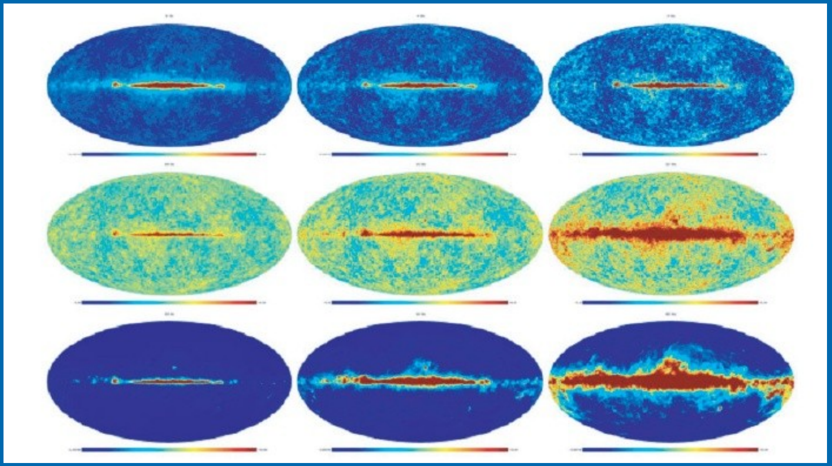
Structure of our DPC

DPC duties, data analysis levels

- Level 1, telemetry, timelines processing, calibration
- Level 2, map-making
- Level 3, component separation, power spectra estimation, cosmological parameters
- The analysis is conducted separately in the two DPCs up to level 2, and jointly for level 3

Planck data deliverables

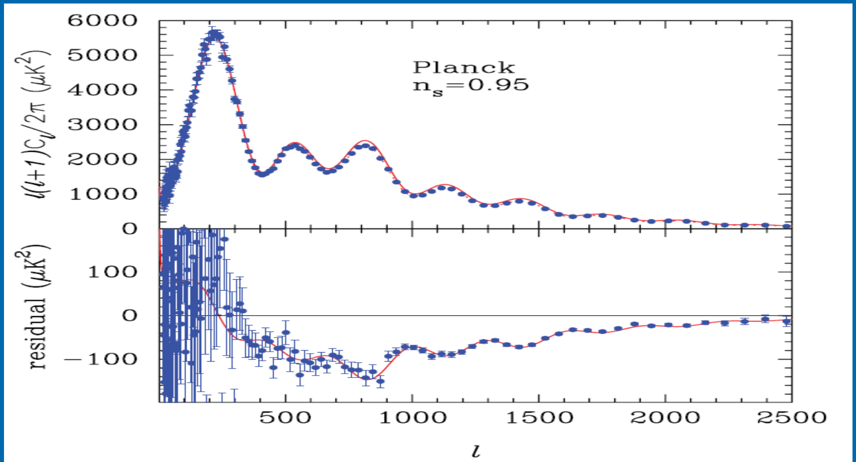
- All sky maps in total intensity and polarization, at 9 frequencies between 30 and 857 GHz
- Angular resolution from 33’ to 7’ between 30 and 143 GHz, 5’ at higher frequencies
- S/N ≈ 10 for CMB in total intensity, per resolution element
- Catalogues with tens of thousands of extra-Galactic sources

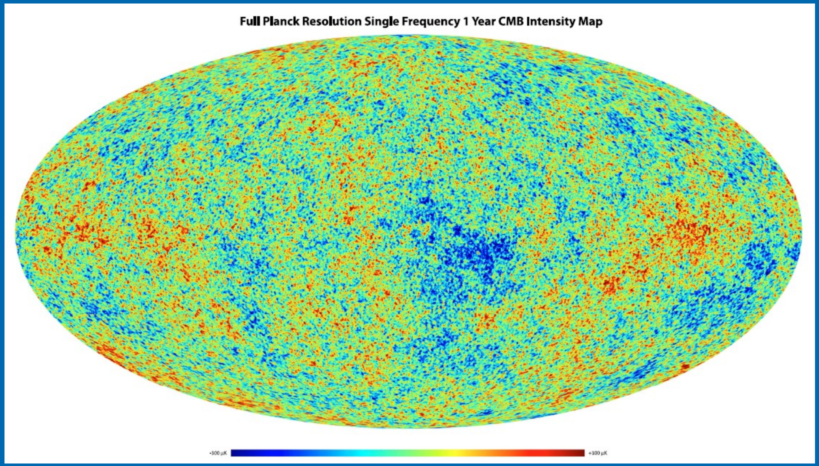


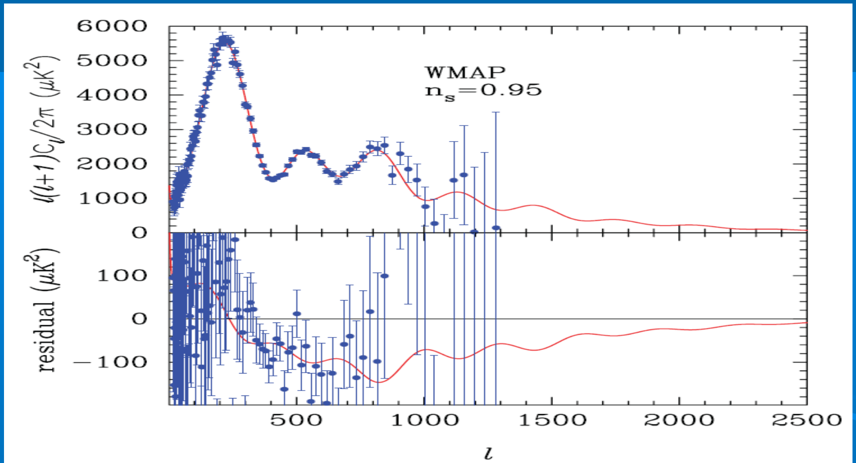
PLANCK GALAXY SURVEYS

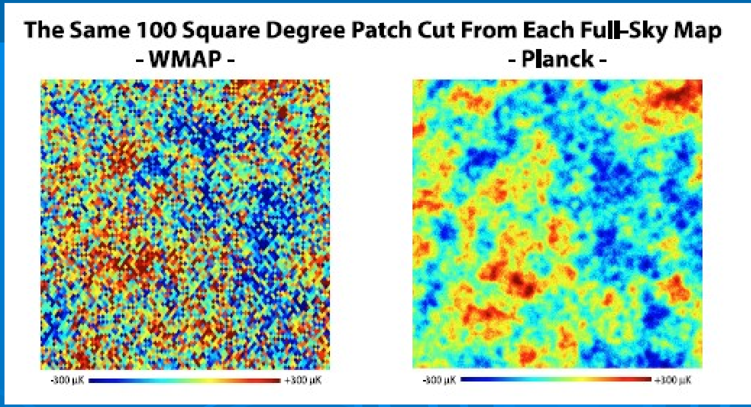
	FREQUENCY [GHz]				
	143	217	353	550	850
Confusion limit [mJy, 3σ]	6.3	14.1	44.7	112	251
Planck All Sky Survey sensitivity [mJy, 3σ]	26	37	75	180	300
Planck Deep Survey sensitivity [mJy, 3σ]	10	18.4	49	170	280
Number of galaxies [all sky]....................	570	860	1700	4400	35000

Planck scientific deliverables: CMB total intensity and the era of imaging

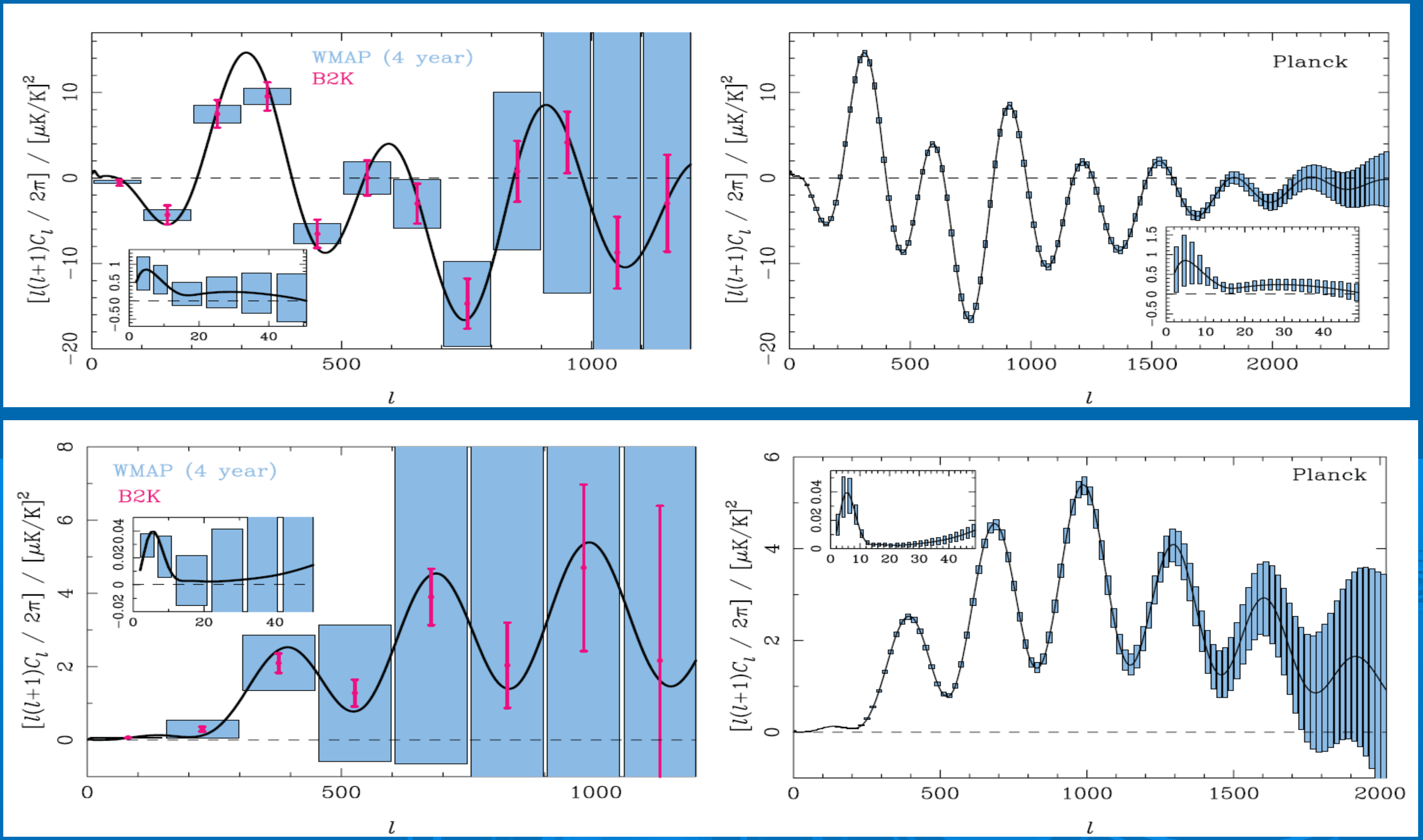




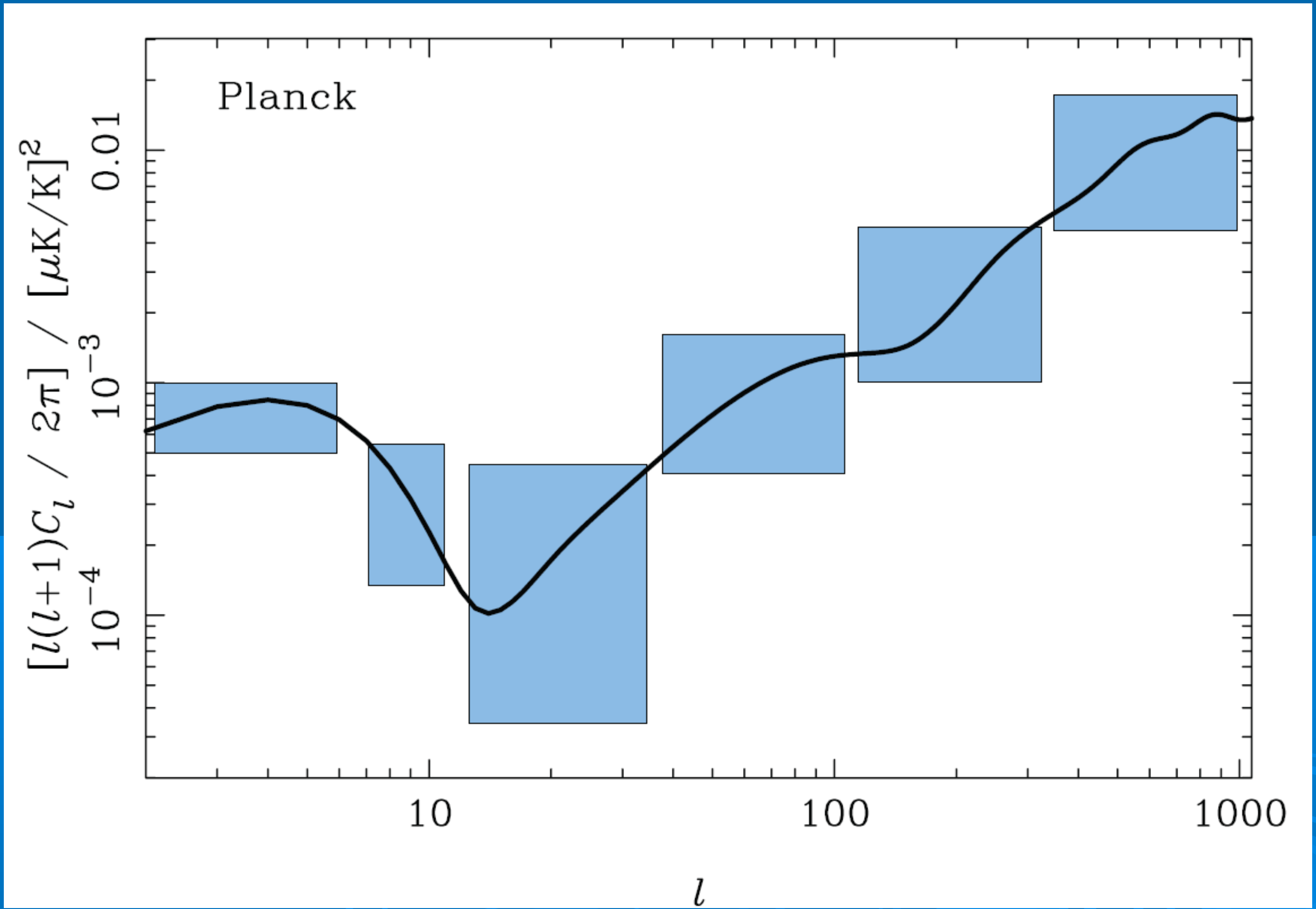




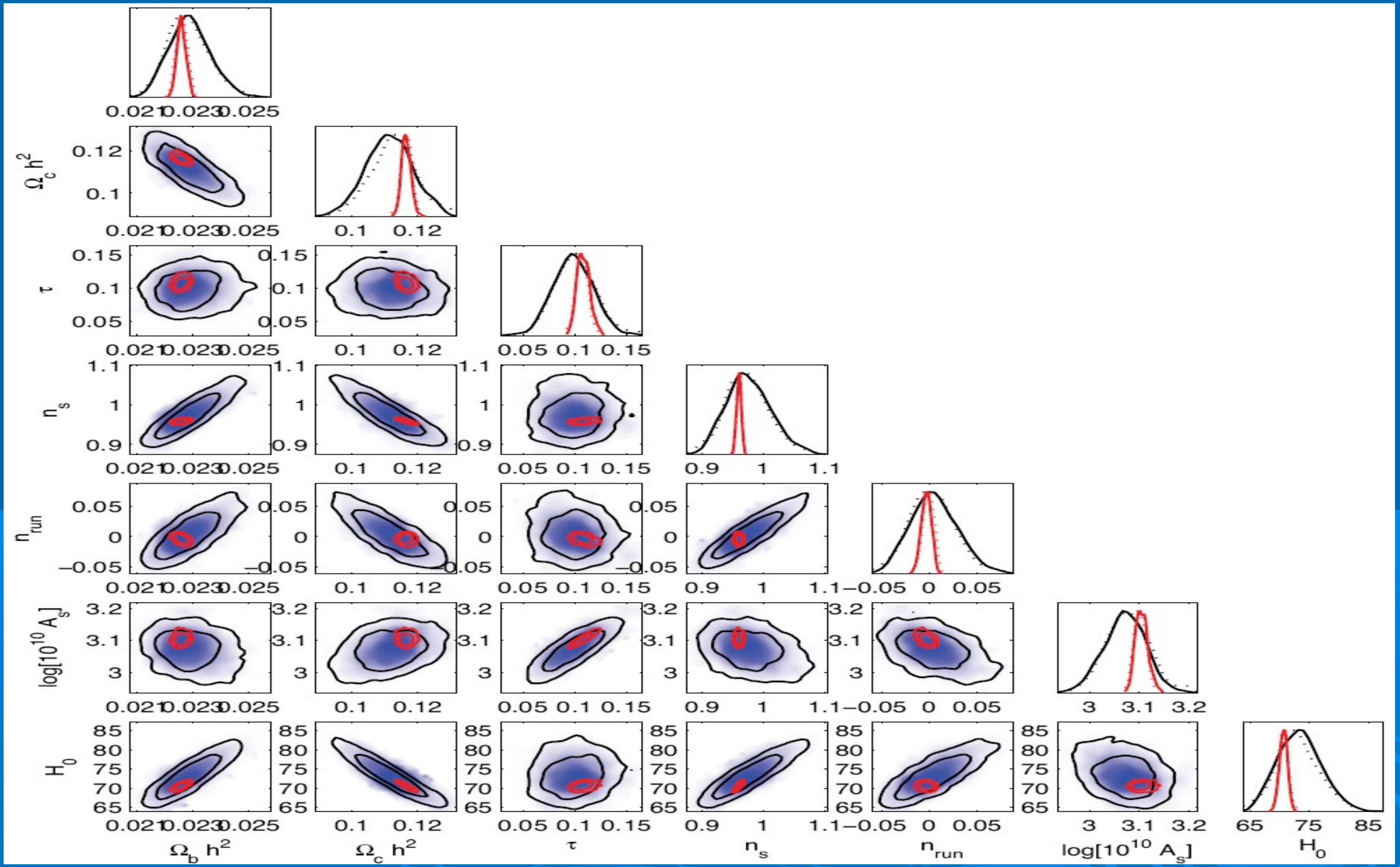
Planck scientific deliverables: CMB polarization



Planck and polarization CMB B modes



Planck scientific deliverables: cosmological parameters

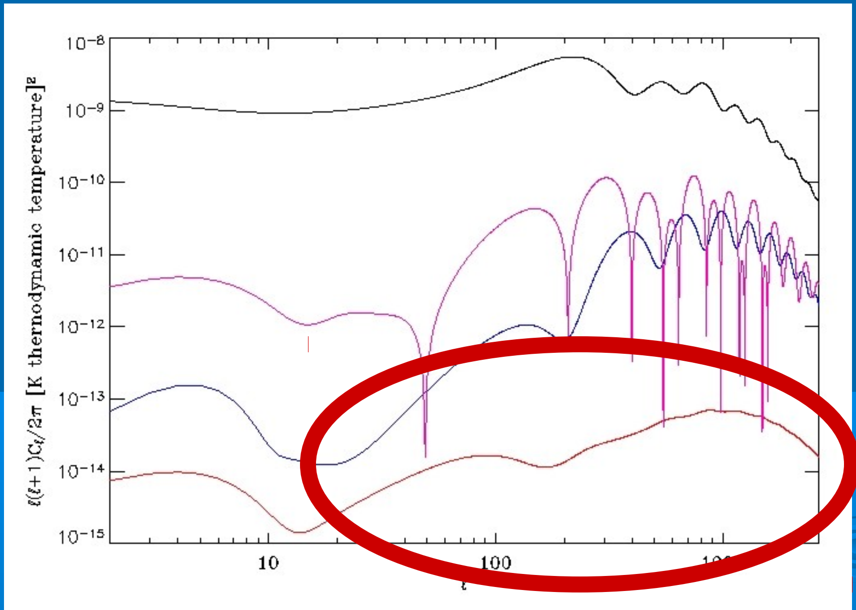


Non-CMB Planck scientific deliverables

- Thousands of galaxy clusters
- Tens of thousands of radio and infrared extra-Galactic sources
- Templates for the diffuse gas in the Galaxy, from 30 to 857 GHz
- …

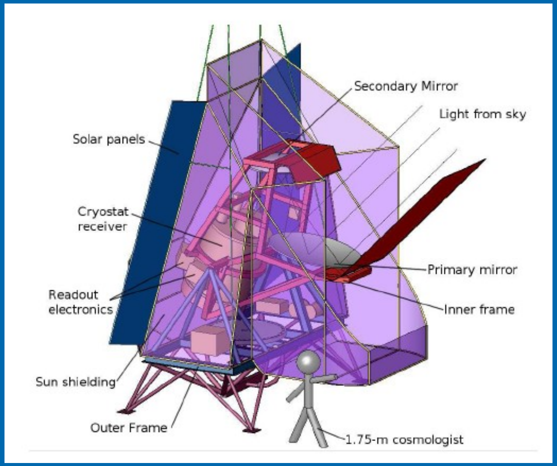
B modes hunters

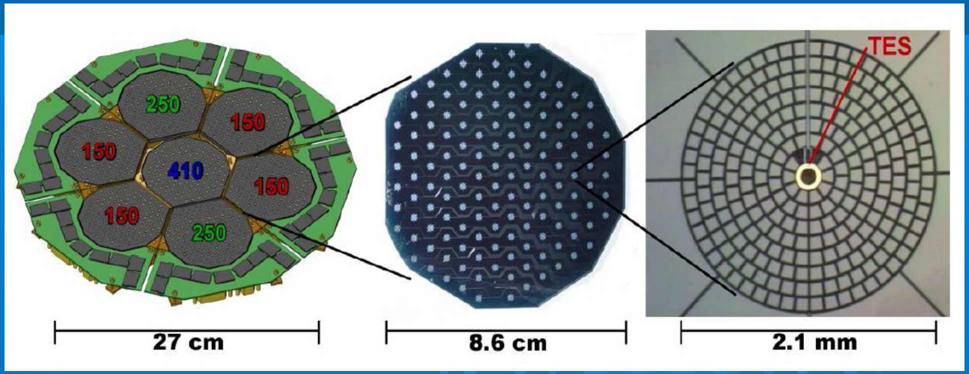
- Visit lambda.gfsc.nasa.gov for a complete list of all the ongoing and planned experiments
- Different technologies, ground based as well as balloon borne probes
- The instrumental sensitivity and angular resolution are high enough to get to a tensor to scalar ratio of about 10^{-2} via direct detection 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

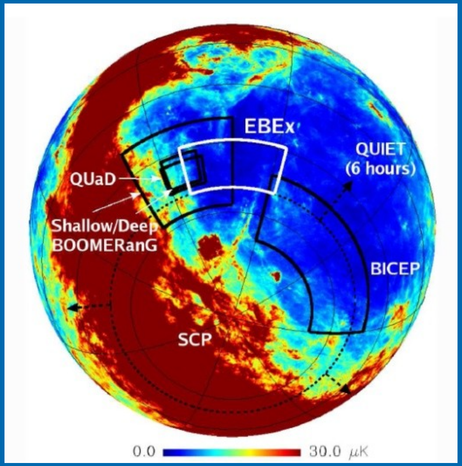
- Balloon borne
- Three frequency bands, 150, 250, 410 GHz
- About 1500 detectors
- 8 arcminutes angular resolution
- Sensitivity of 0.5 micro-K per resolution element
- Scheduled for flying from north america in May 2009, from Antarctica one year later

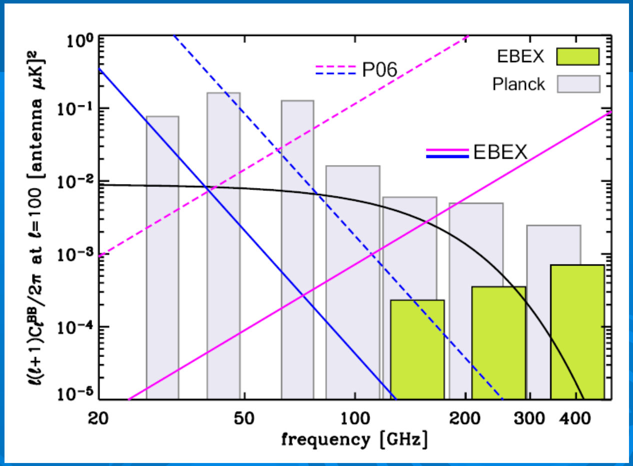




EBEX

- 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

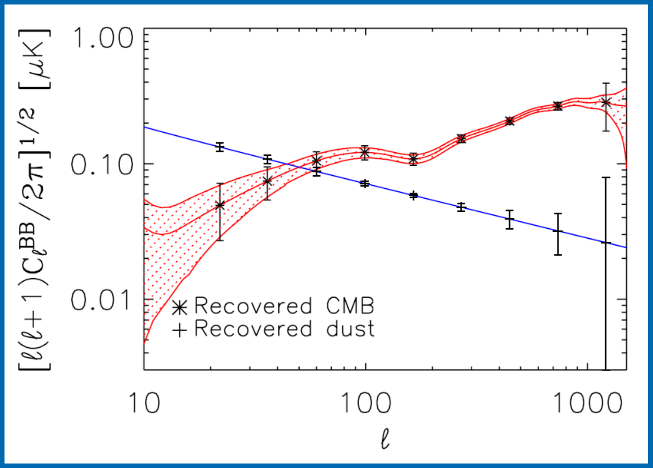


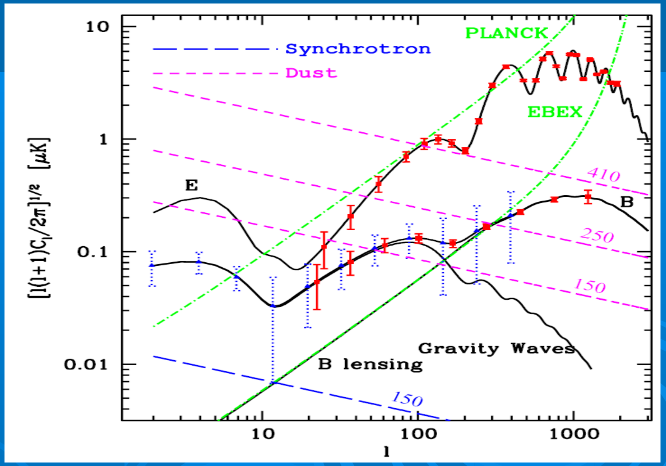


EBEX contributors

Expectations from EBEX

- Foreground parametrization and ICA foreground removal are going to be applied to the data to remove the contamination from the dust on the degree scale, also yielding most precious measures of the same Galactic signal for ongoing and future CMB probes
- 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





Conclusions

- The CMB will be the best signal from the early universe for long
- We have some knowledge of the two point correlation function, but most of the signal is presently unknown
- If detected, the hidden signatures might reveal mysteries for physics, like gravitational waves, or the machanism of cosmic acceleration
- We don’t know if we will ever see those things, systematics and foregrounds might prevent that
- But we’ve no other way to get close to the Big Bang, so let’s go for it and see how far we can go
- First go/no go criteria from Planck and other probes in just a few years, possible scenarios…

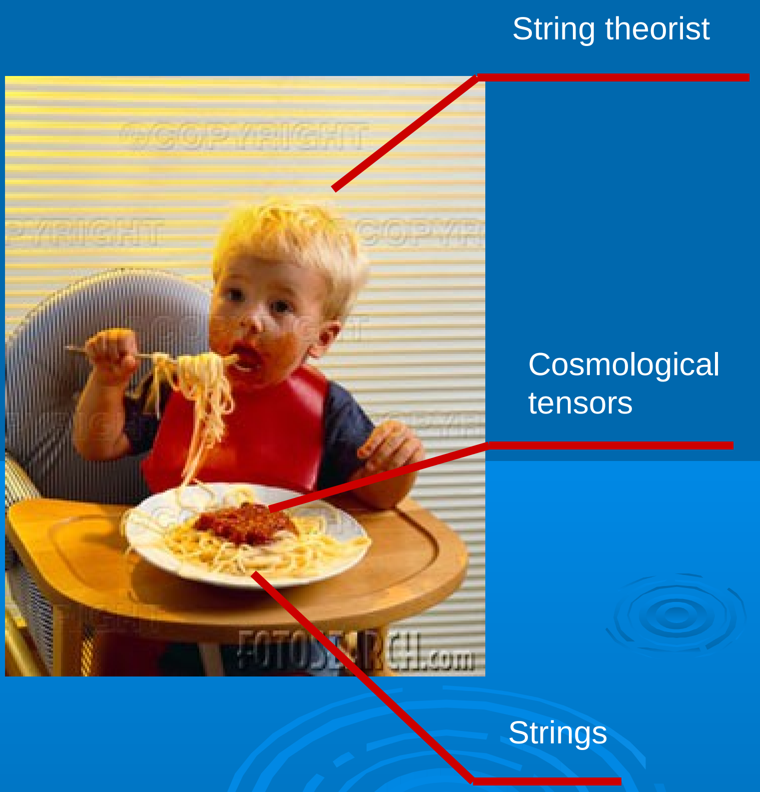
☹

- Polarized foreground too intense, no sufficient cleaning, systematics out of control
- Increase by one digit the cosmological parameters measurement, mostly from improvements in total intensity measurements
- Time scale: few years

String theorist

☺

- Modest or controllable foreground emission, systematics under control
- Inflation severely constrained by primordial non-Gaussianities
- Cosmological gravity waves discovered from CMB B modes! Expected precision down to one thousandth of the scalar amplitude
- Percent measurement of the dark energy abundance at the onset of acceleration, from CMB lensing
- Other surprises…?
- Time scale: from a few to 20 years



CMB as a dark energy probe

Outline

- Fighting against a cosmological constant
- Parametrizing cosmic acceleration
- The CMB role in the current dark energy bounds
- “Classic” dark energy effects on CMB
- “Modern” CMB relevance for dark energy: the promise of lensing
- Lensing B modes in CMB polarization
- Future CMB data and dark energy

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

Λ:???

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

Fighting the cosmological constant

Λ:???

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

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

Fighting the cosmological constant

Λ:???

percent precision

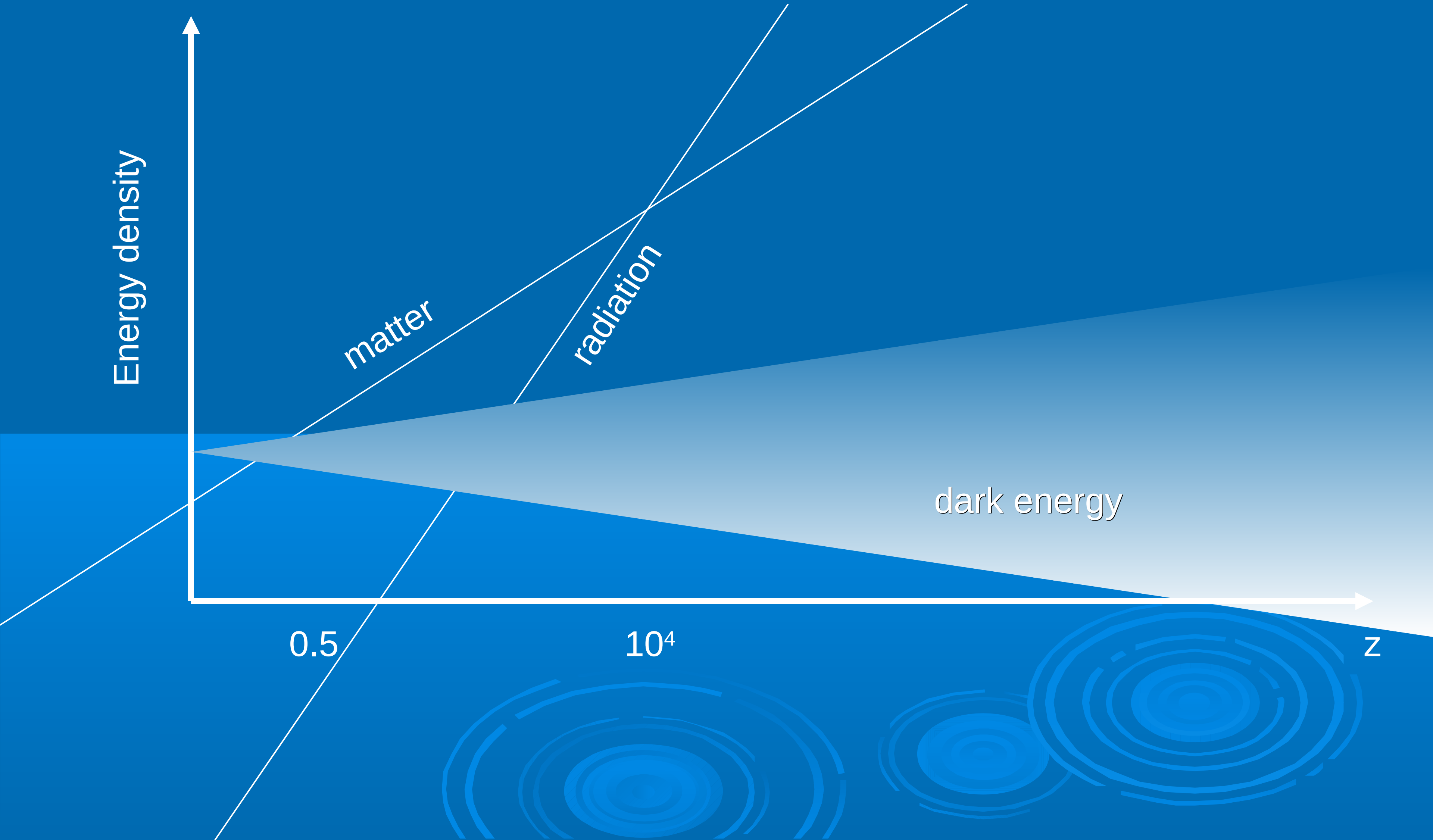
$$|\Lambda - V|/M^4_{Planck} = 10^{-123}$$

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

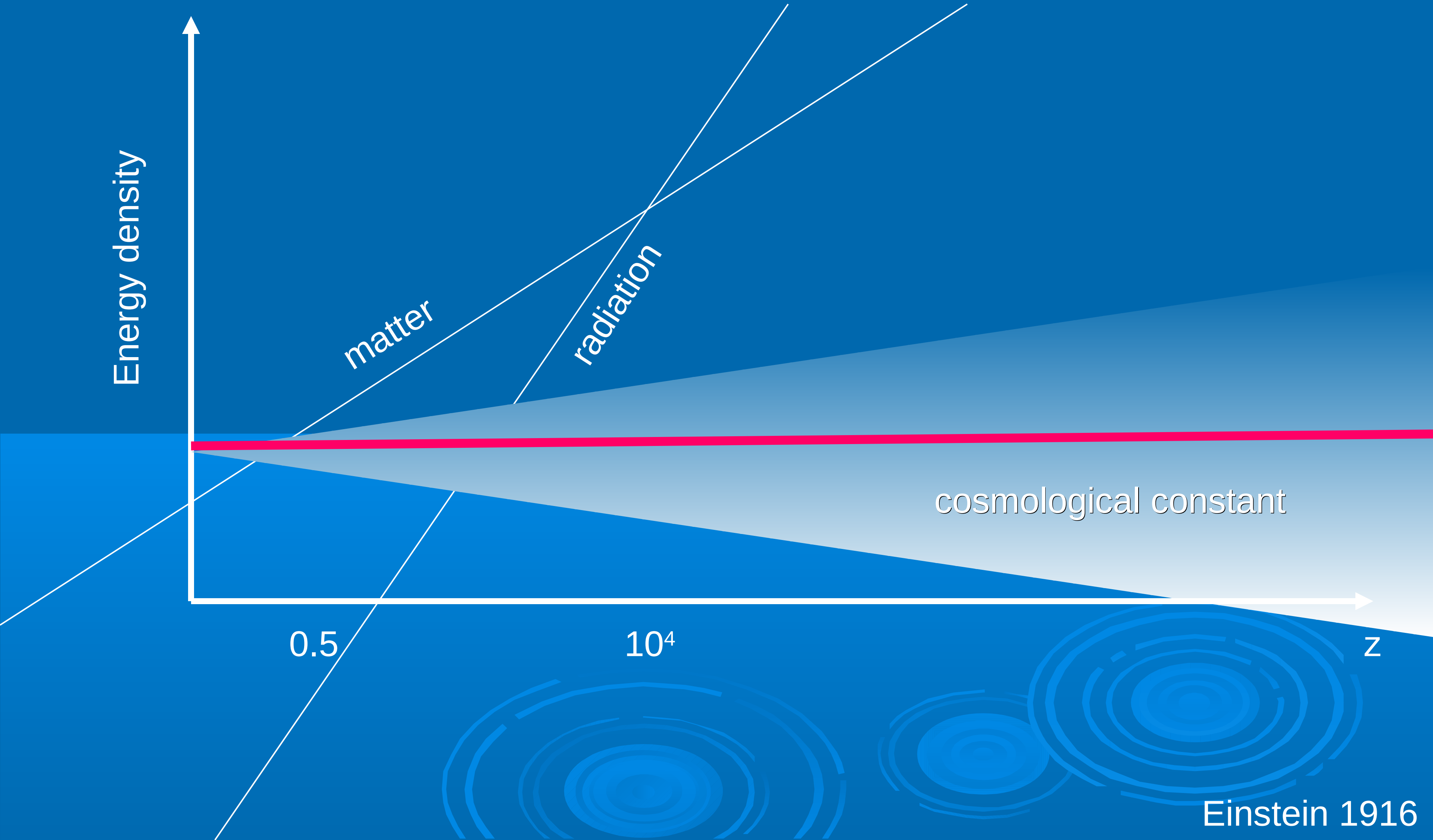
$(\text{Boh?})^2$

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

Dark energy

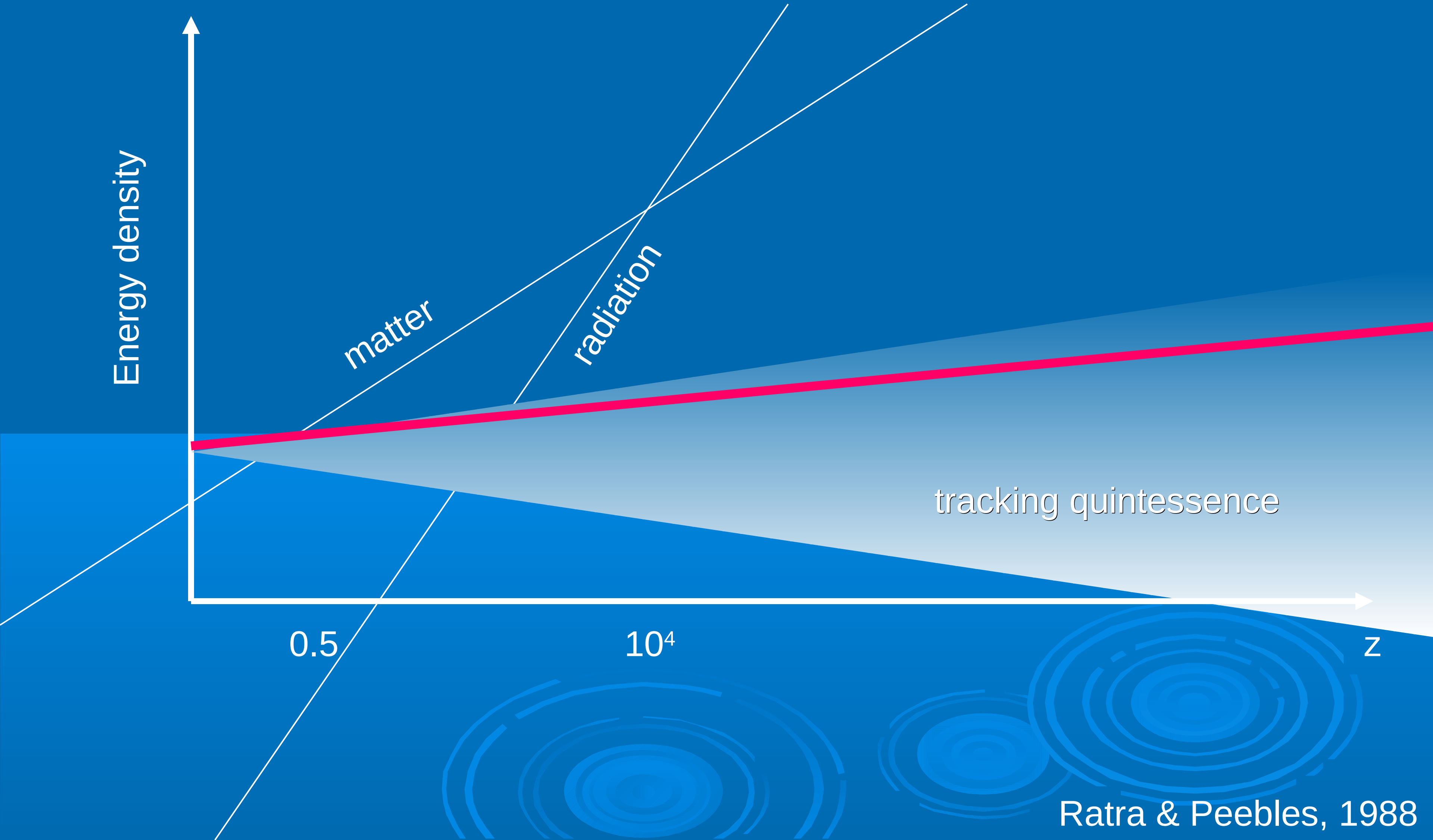


Dark energy



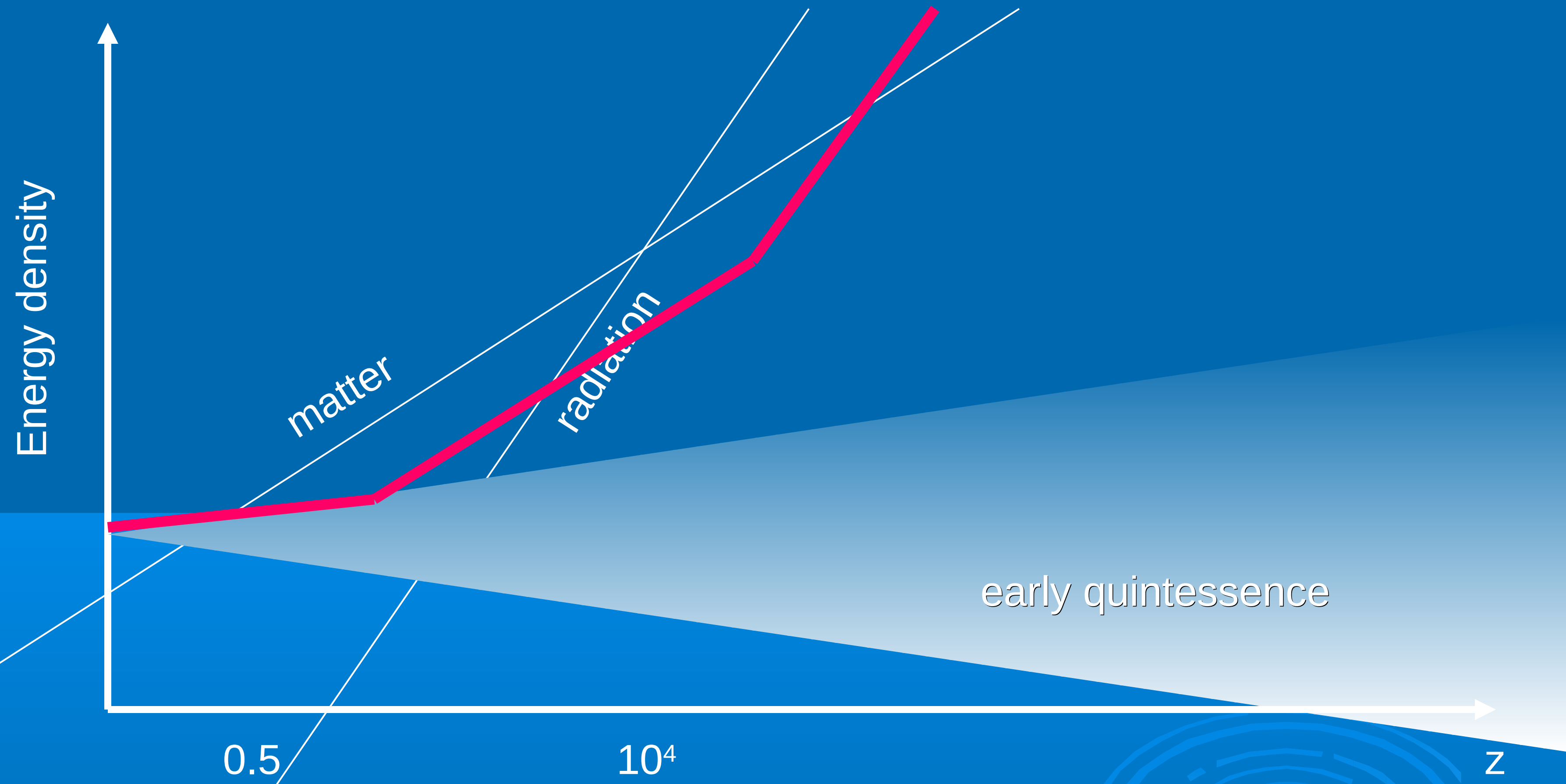
Einstein 1916

Dark energy



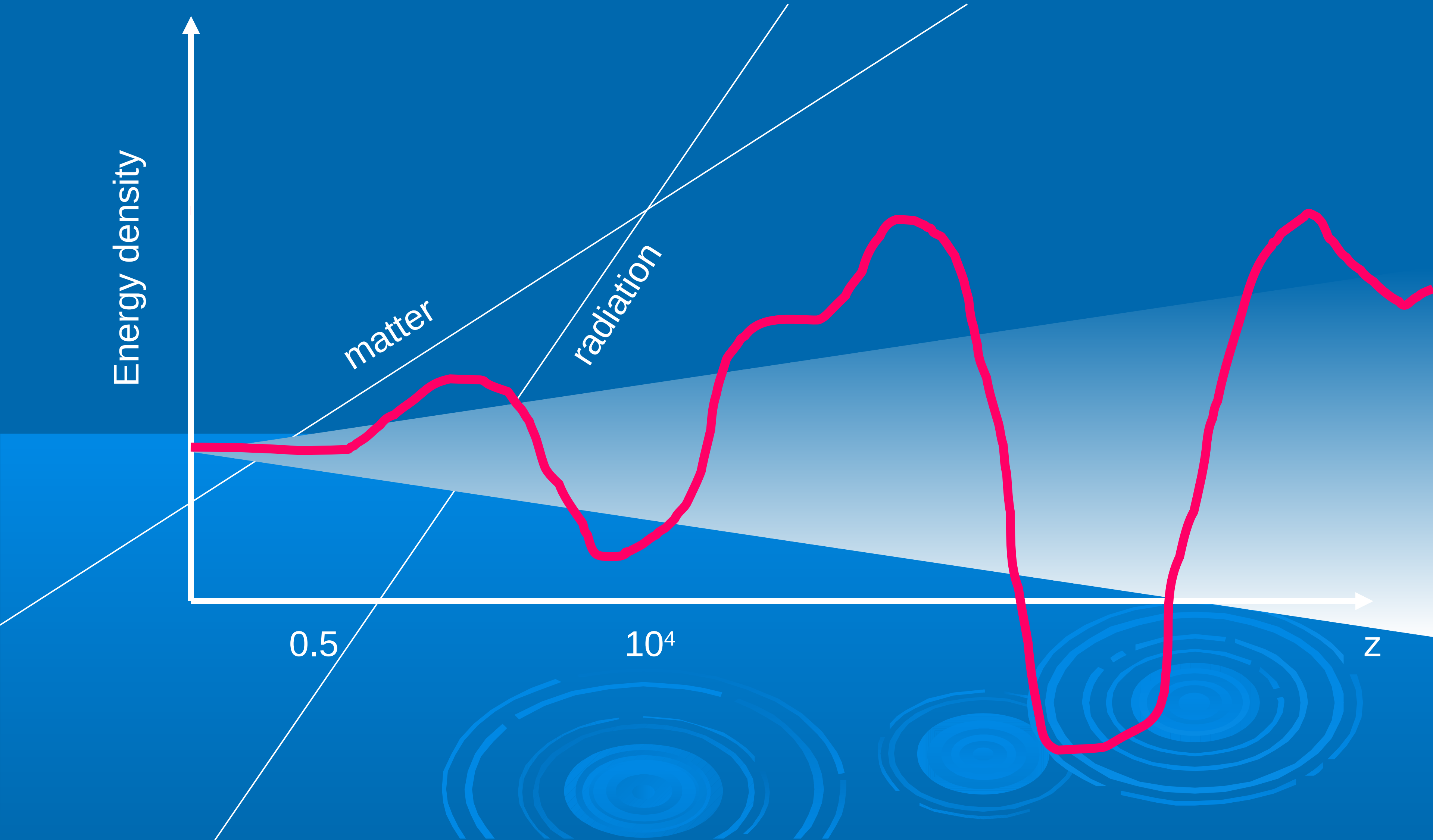
Ratra & Peebles, 1988

Dark energy

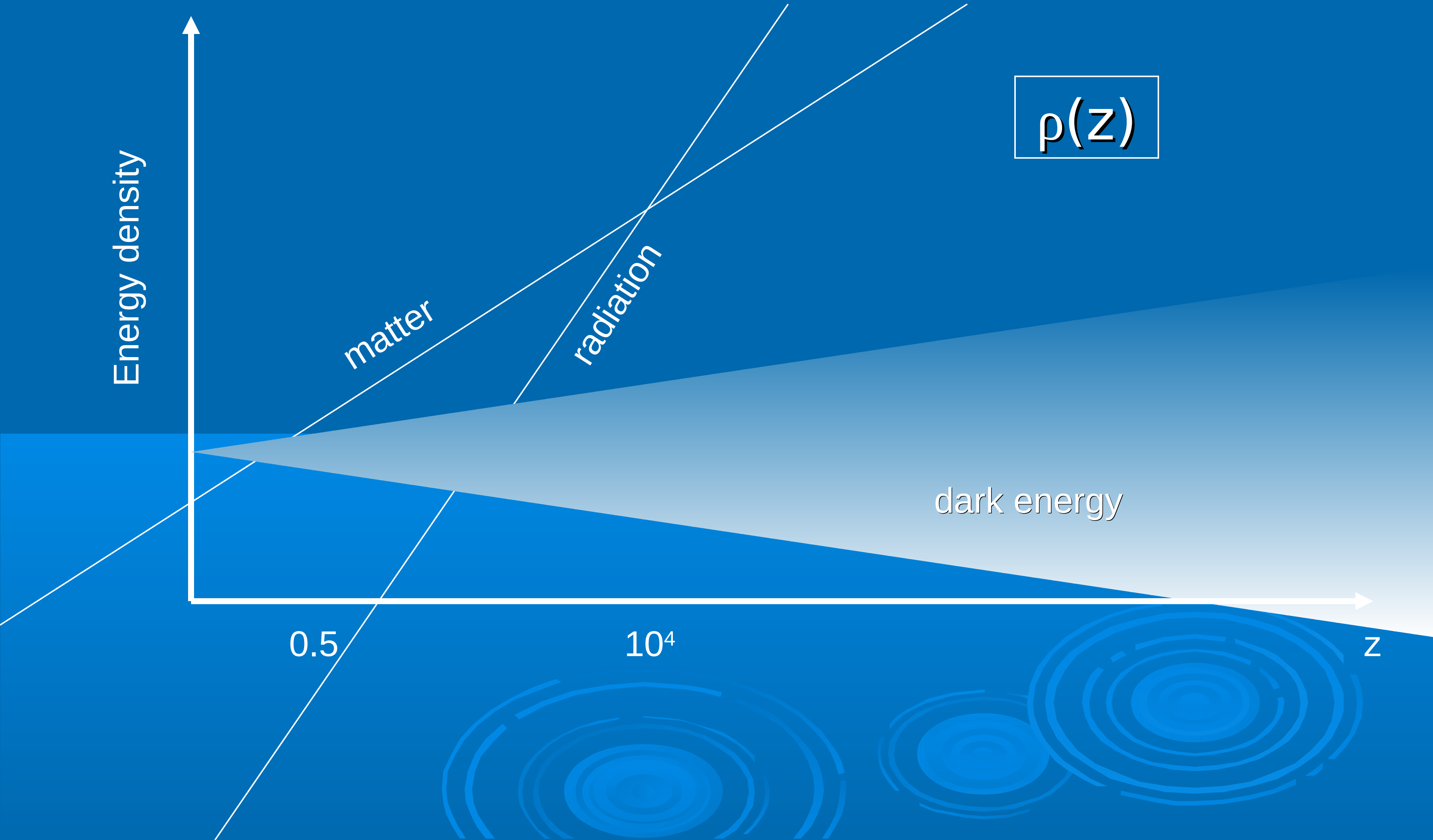


Wetterich 1988

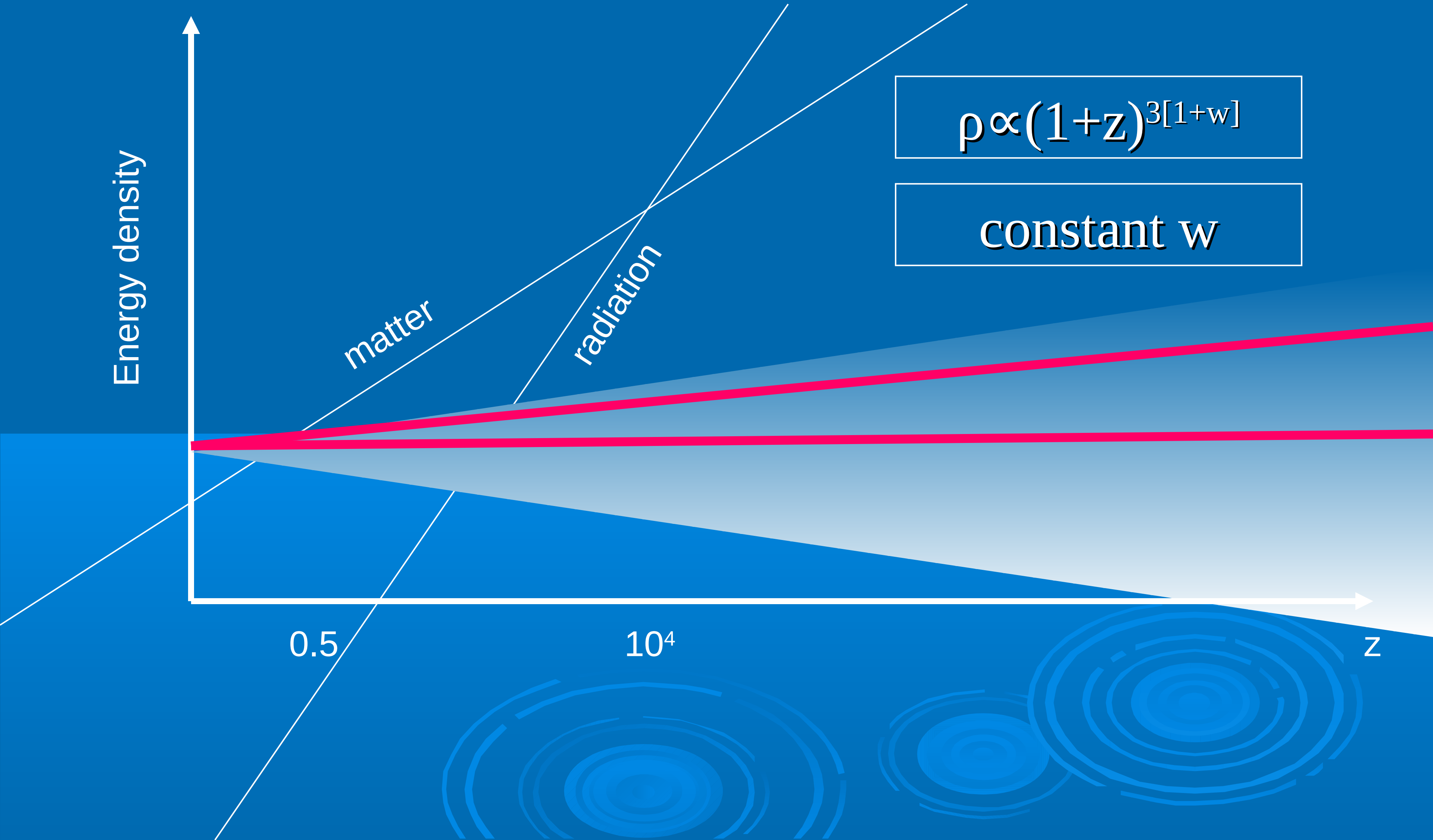
Dark energy



Parametrizing cosmic acceleration is …



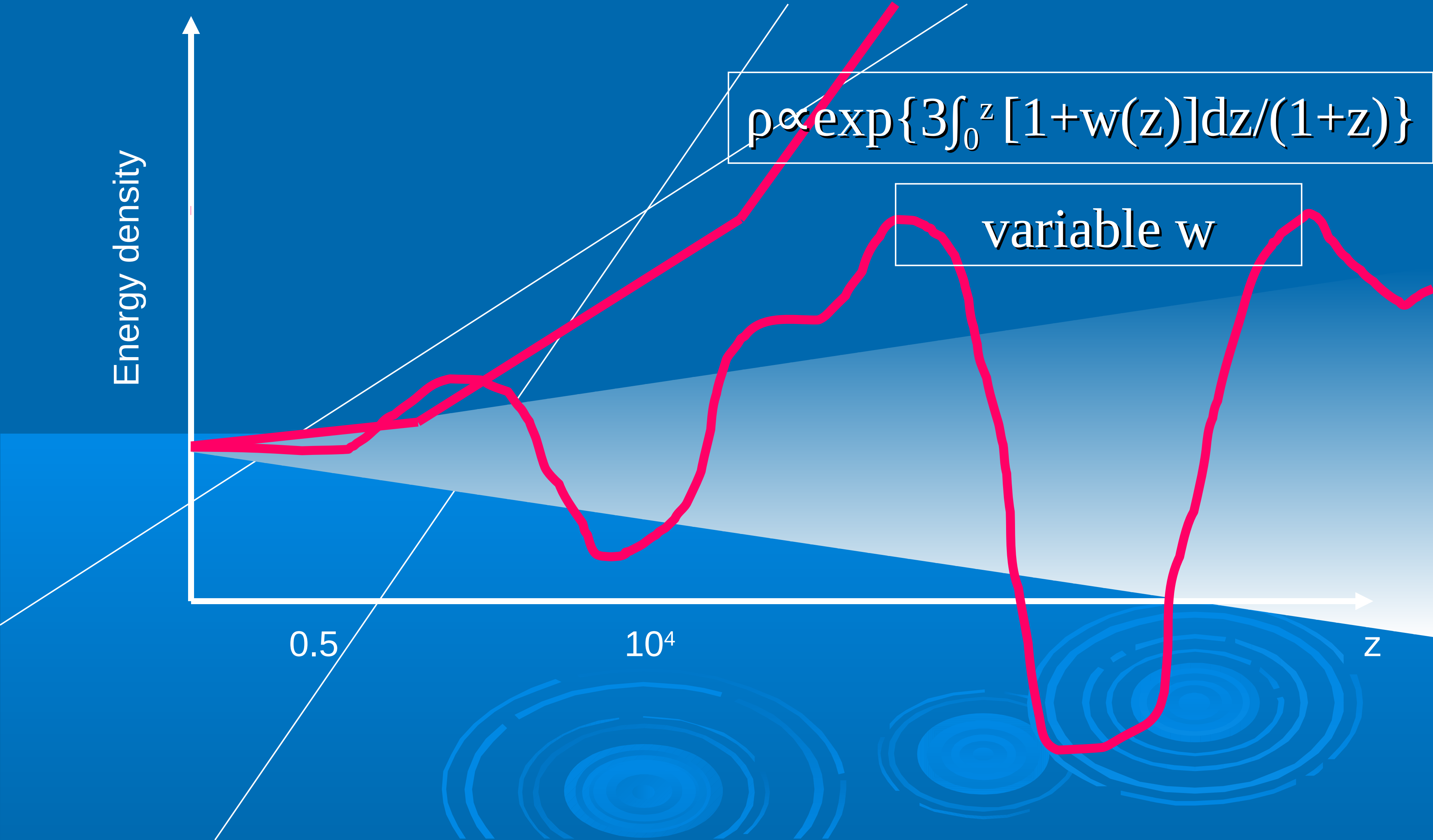
…parametrizing cosmic density



$$\rho \propto (1+z)^{3[1+w]}$$

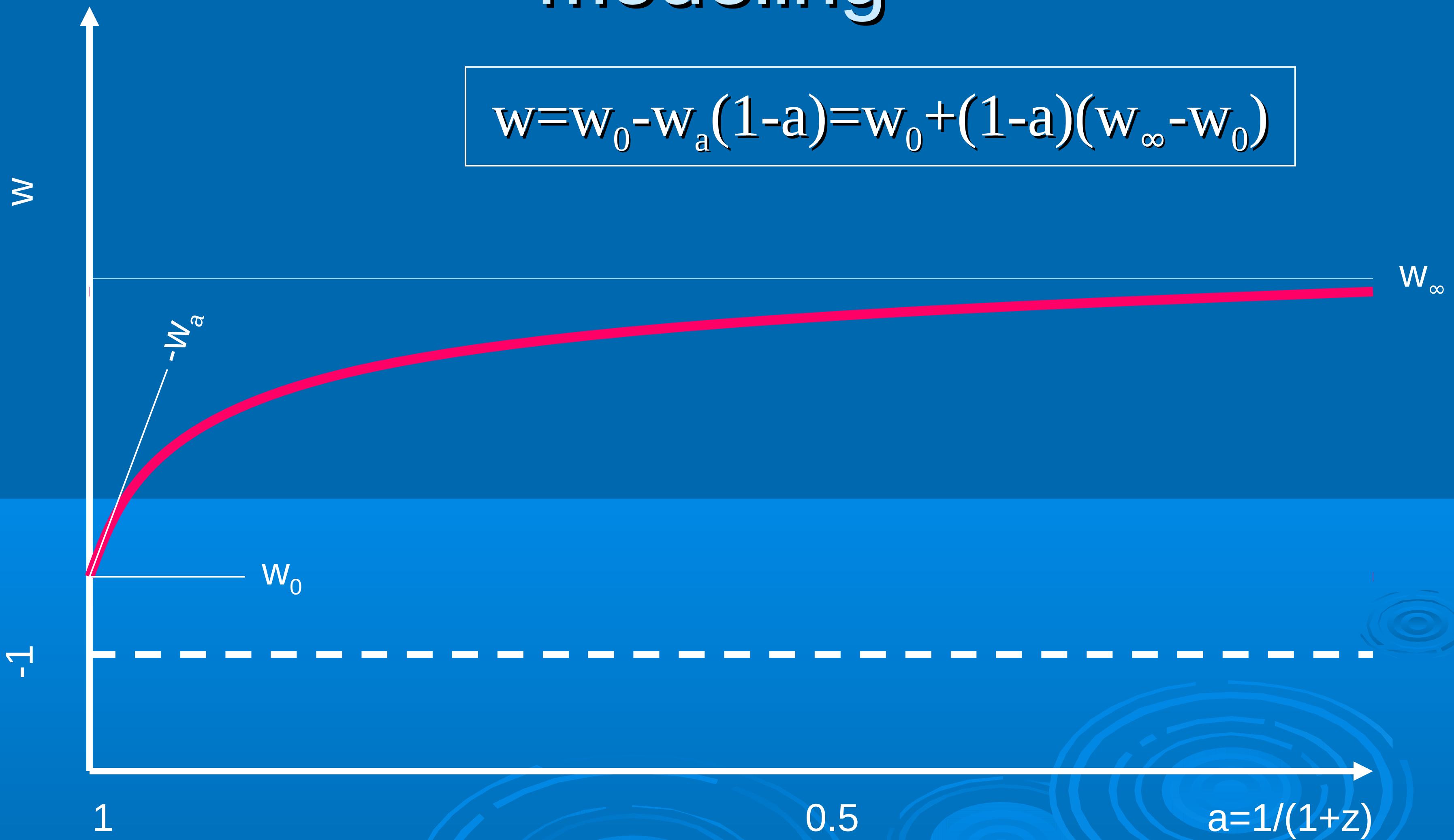
constant w

Parametrizing cosmic density



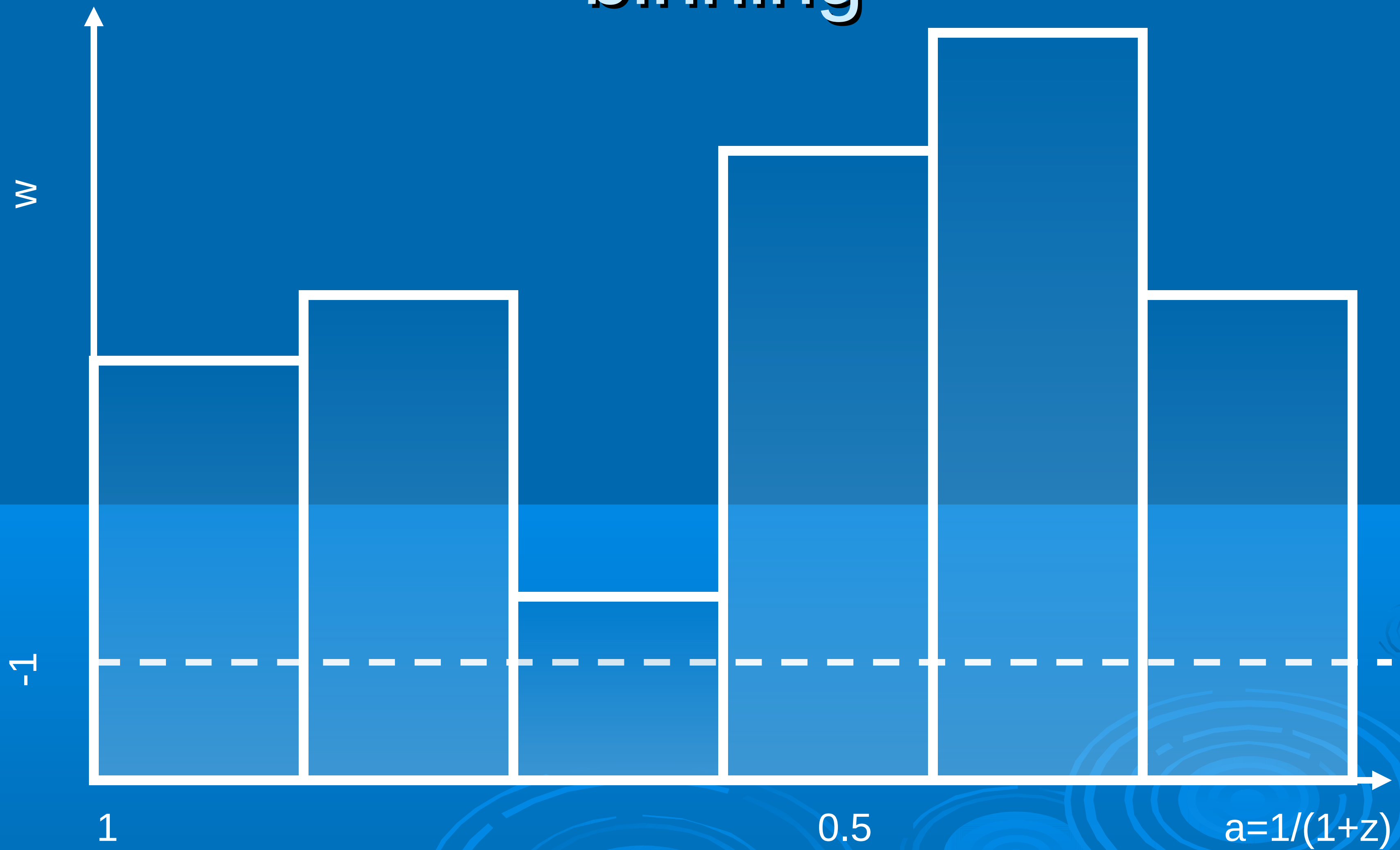
Parametrizing cosmic acceleration: modeling

$$w = w_0 - w_a(1-a) = w_0 + (1-a)(w_\infty - w_0)$$



Chevallier & Polarski 2001, Linder 2003

Parametrizing cosmic acceleration: binning

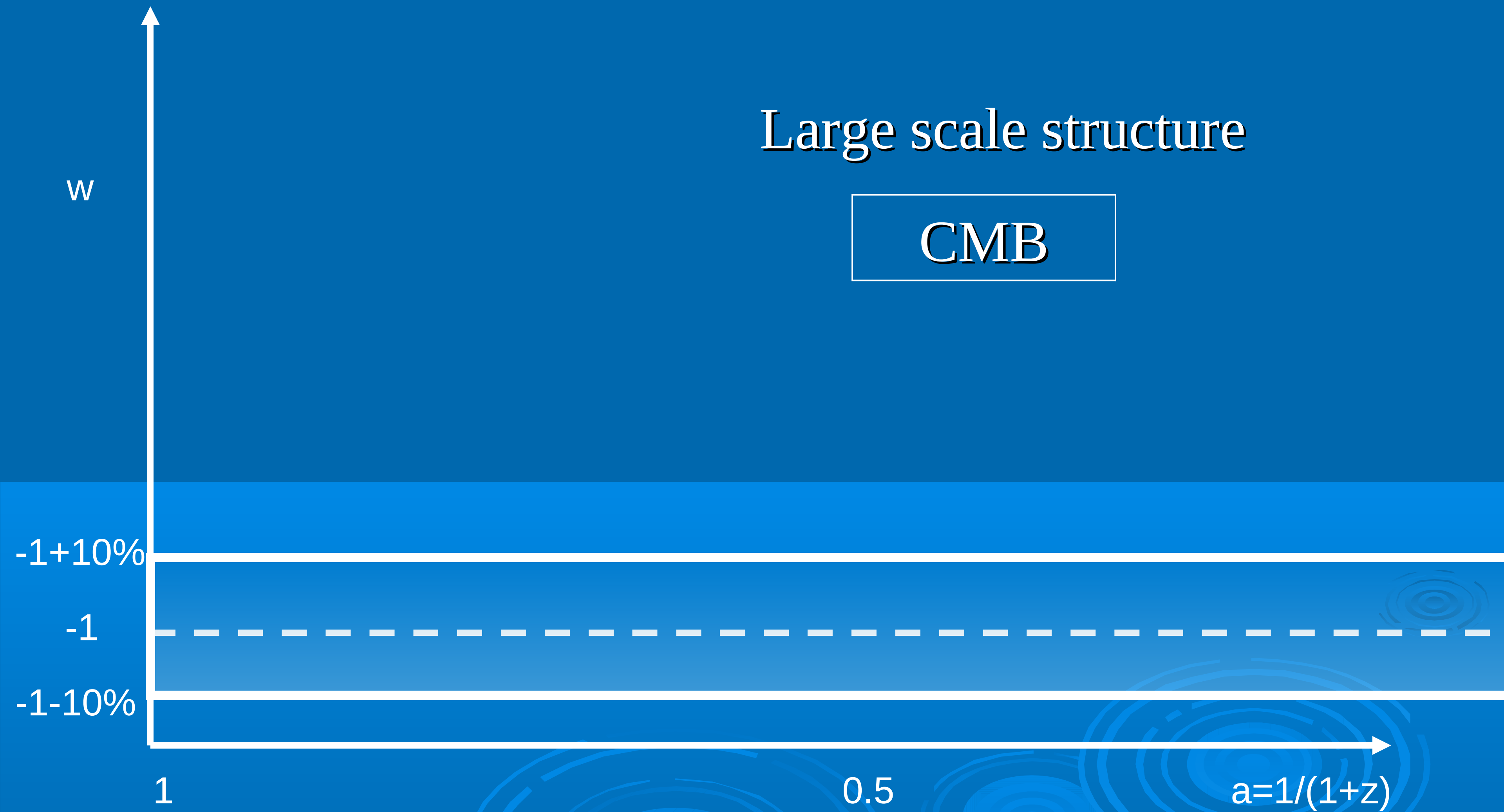


Crittenden & Pogosian 2006, Dick et al. 2006

Parametrizing cosmic acceleration: binning versus modeling

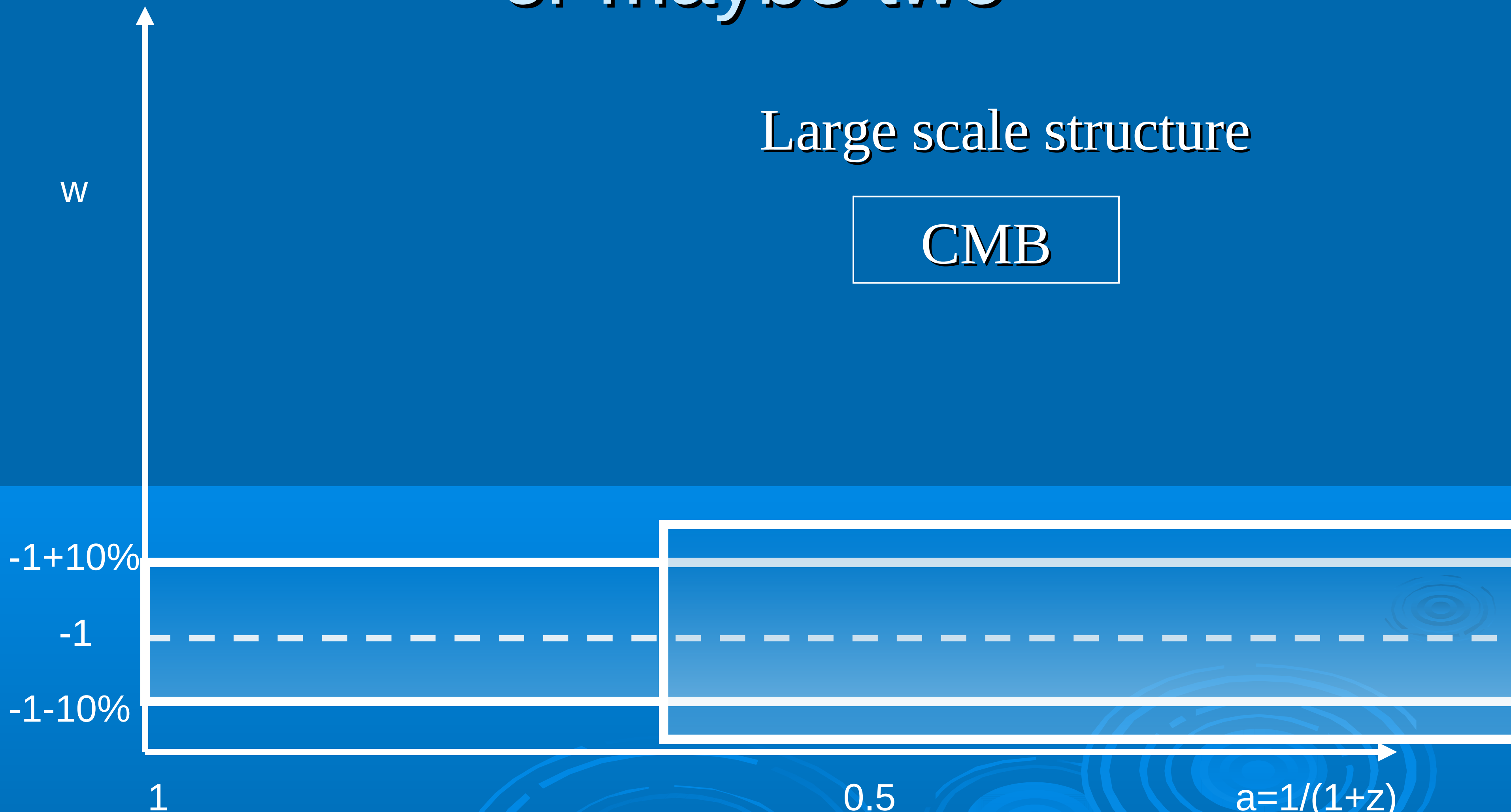
- Binning: model independent ☺, many parameters ☹
- Modeling: always a bias ☹, but a minimal model exists ☺, made by w_0 and its first time derivative
- Sticking with one particular model in between may be inconvenient, better relating that to one of the two approaches above

Present cosmological bounds: one bin



See Komatsu et al., 2011, and references therein

Present cosmological bounds: one bin, or maybe two



Seljak et al. 2005

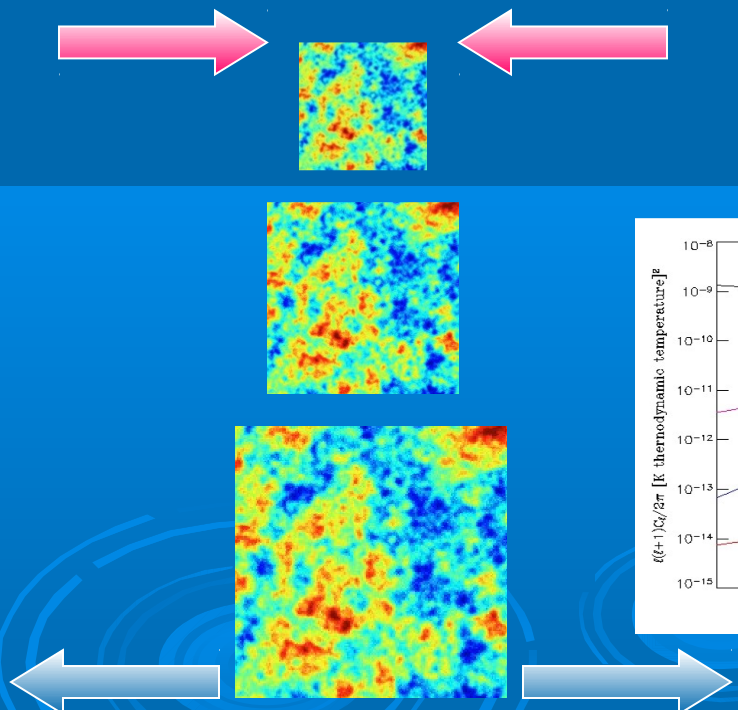
Classic and modern dark energy effects on CMB

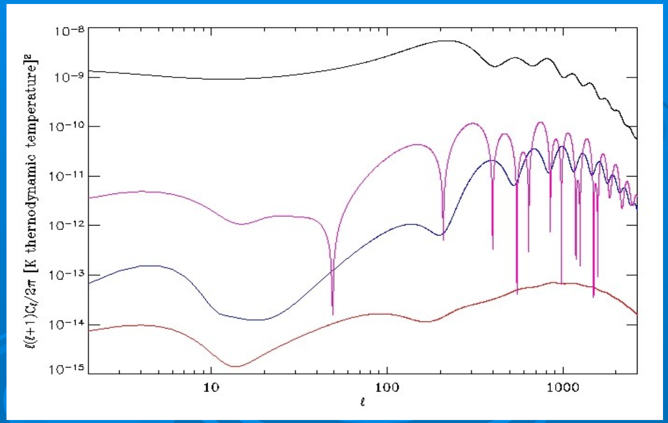
“Classic” dark energy effects on CMB: projection

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

w

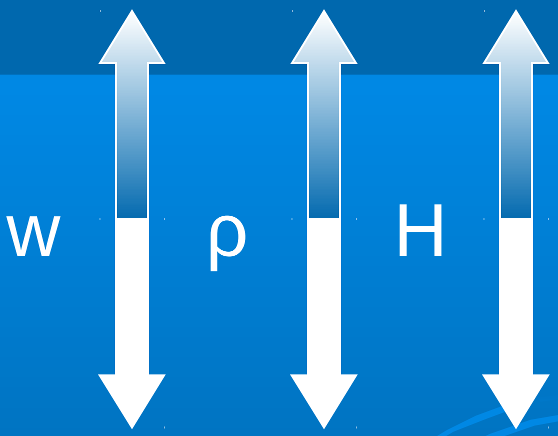
D

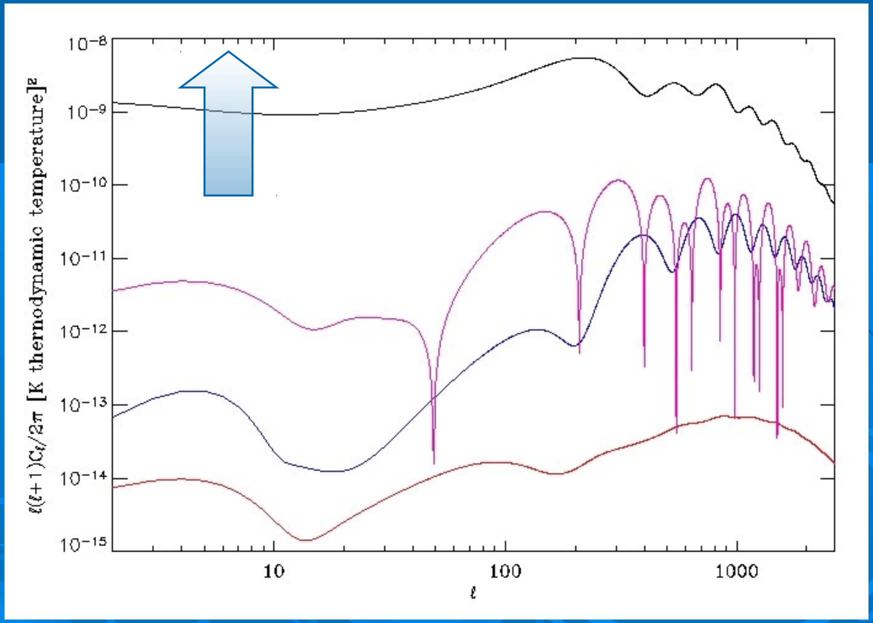




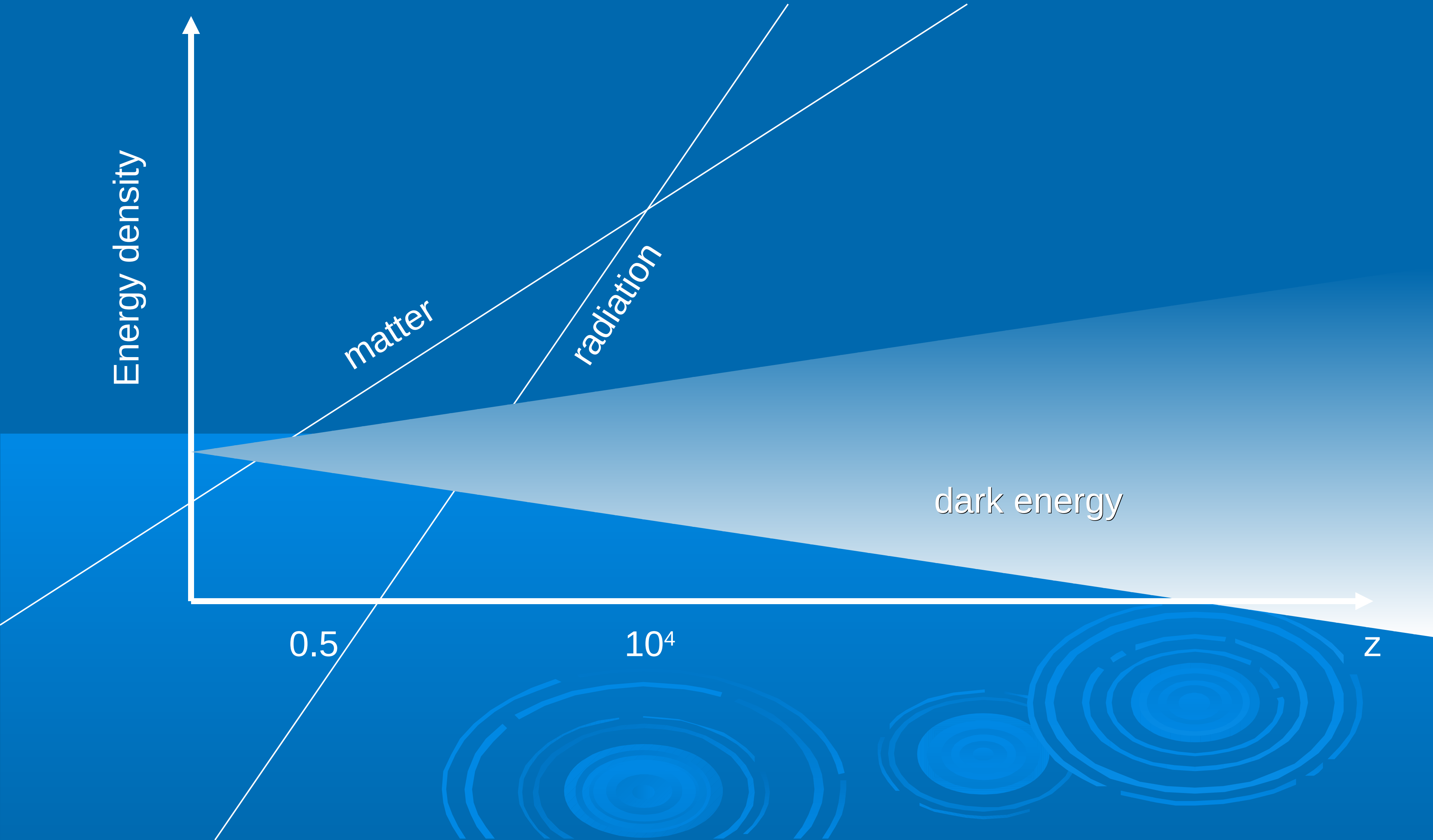
“Classic” dark energy effects on CMB: integrated Sachs-Wolfe

Cosmological friction for cosmological perturbations ∝ H

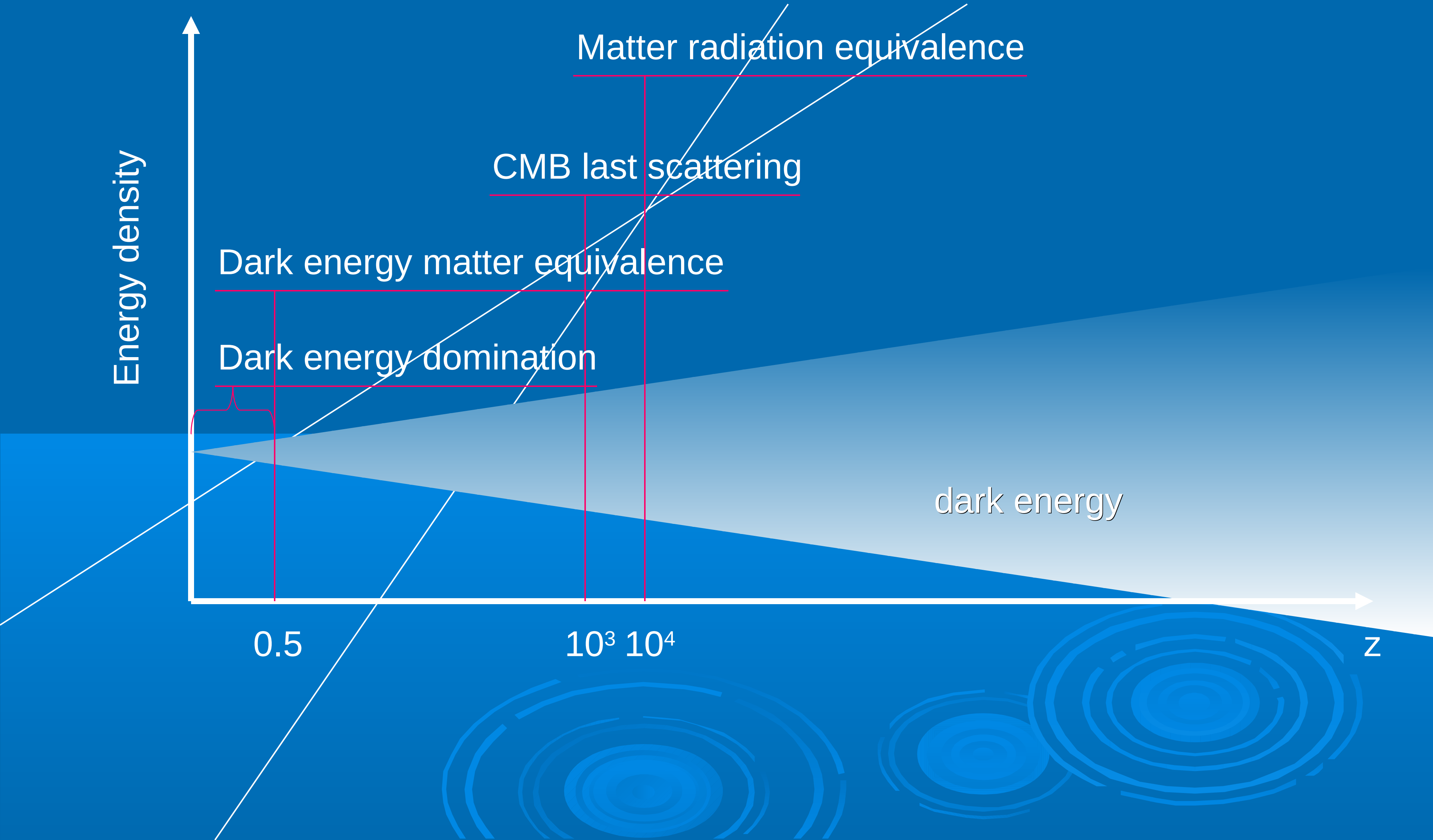




The “modern” era



The “modern” era



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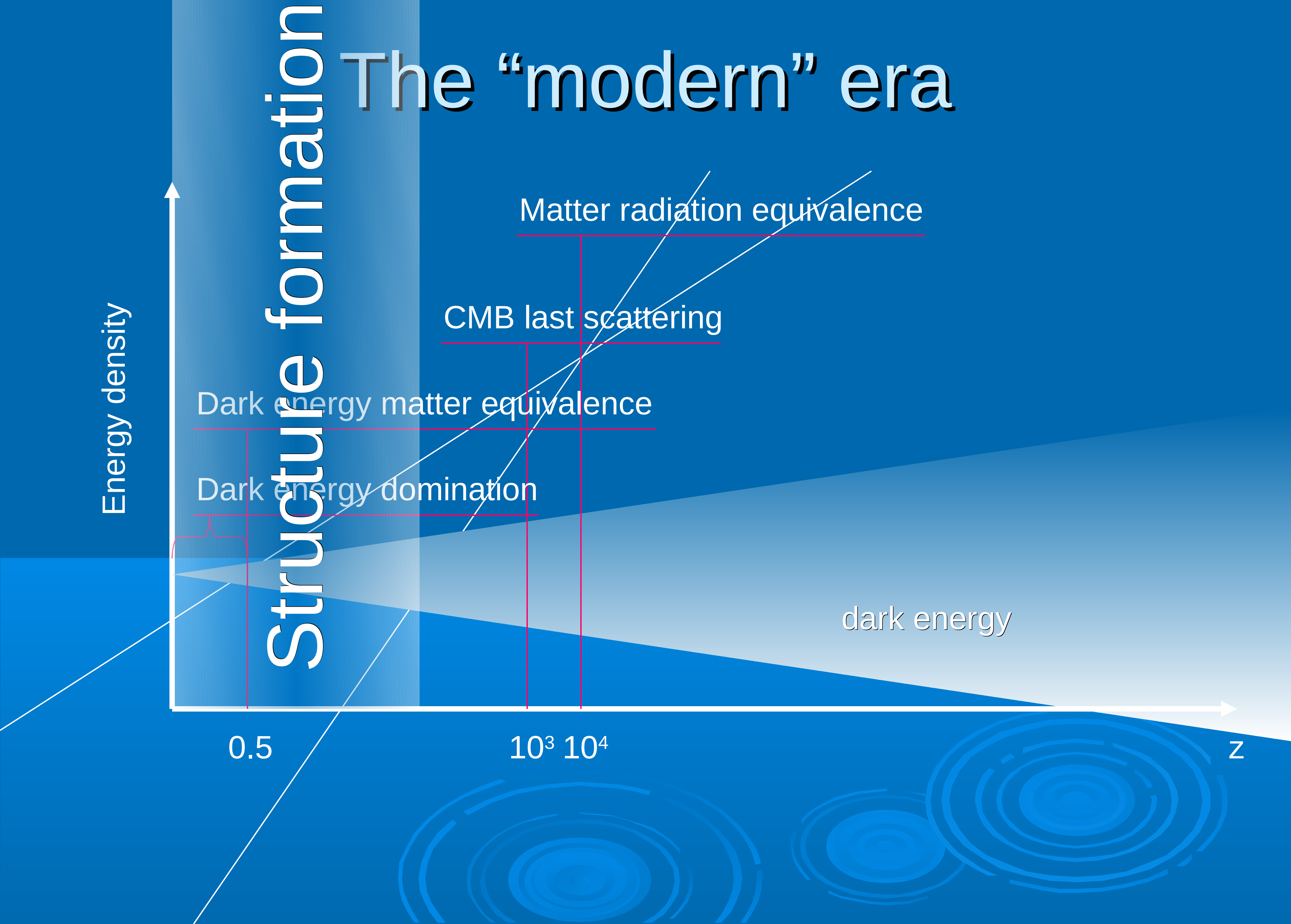

The "modern" era: study the signatures of structure formation on the CMB

- Beat cosmic variance by predicting the ISW effect from local and observed structures (de Bernardis et al., Xia et al. 2011 and references therein)
- Study lensed CMB

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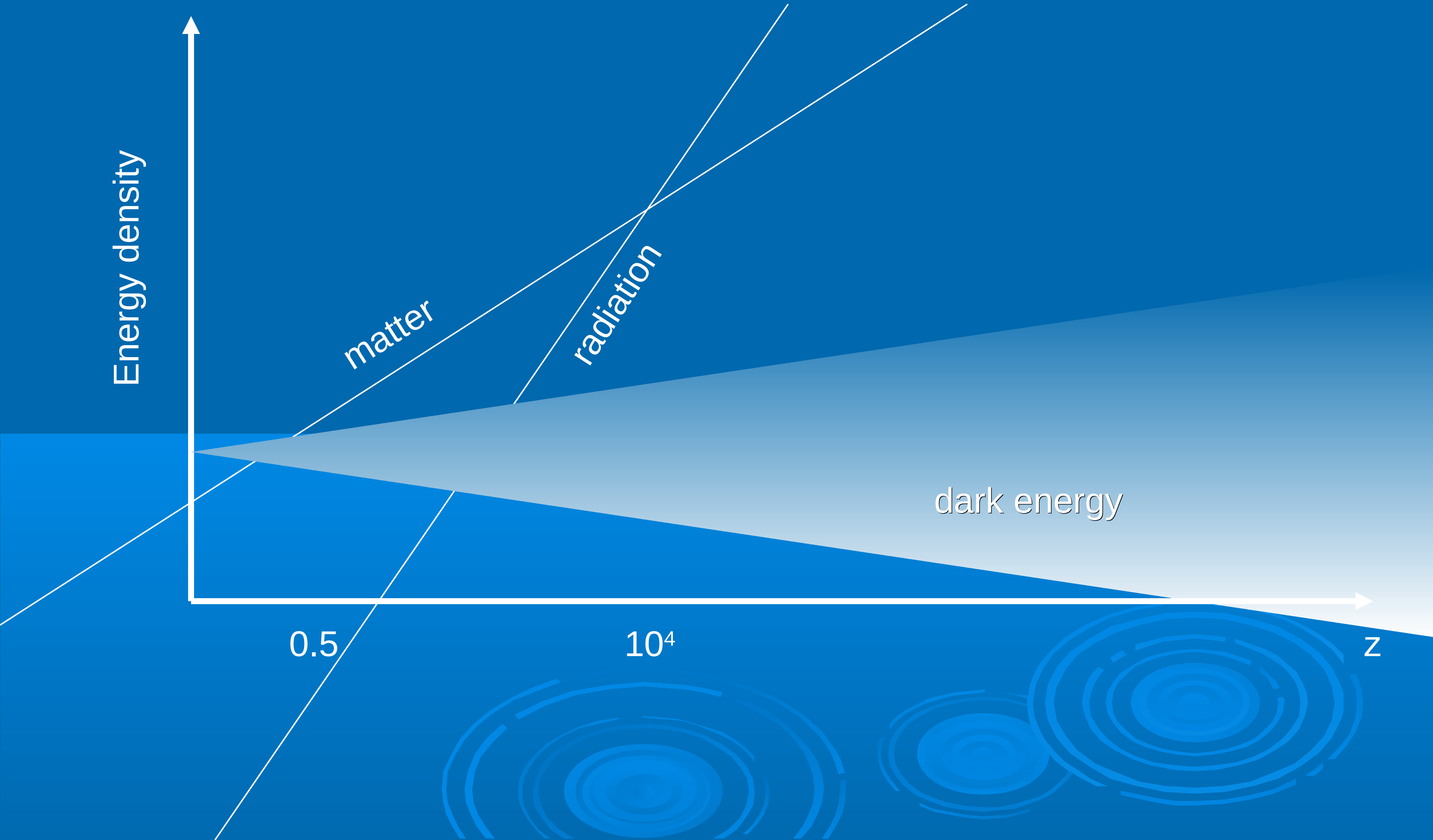
The promise of lensing



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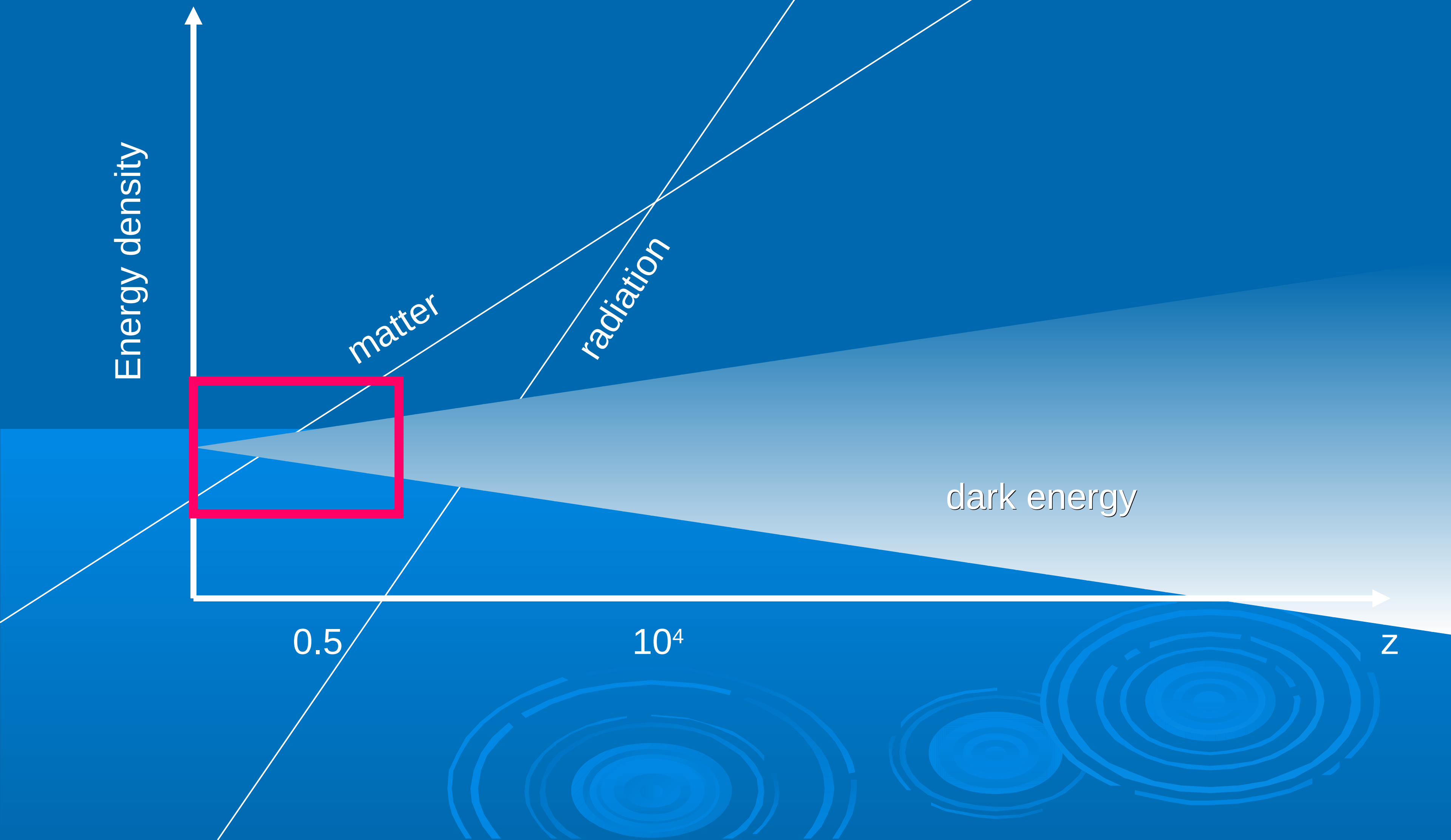

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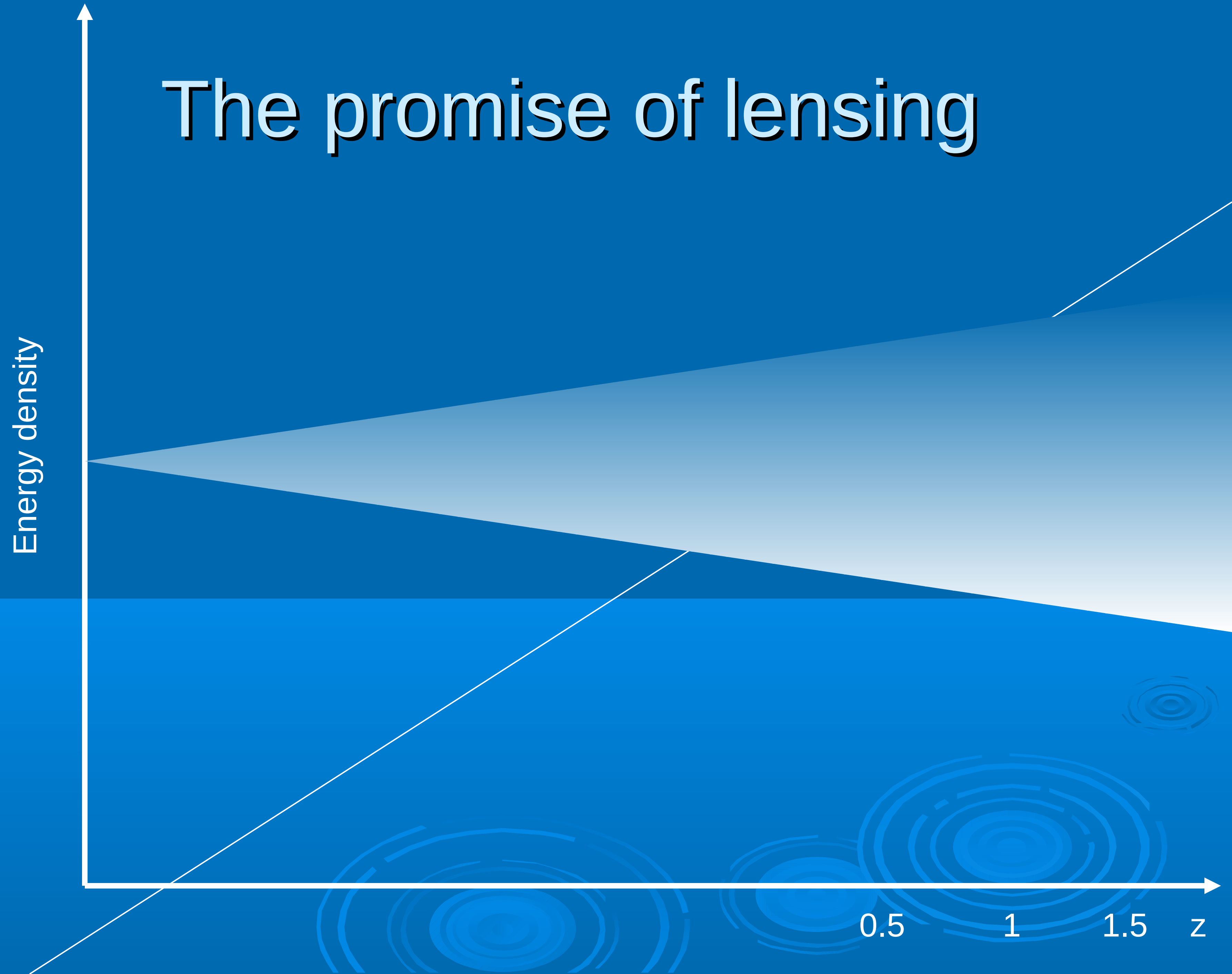

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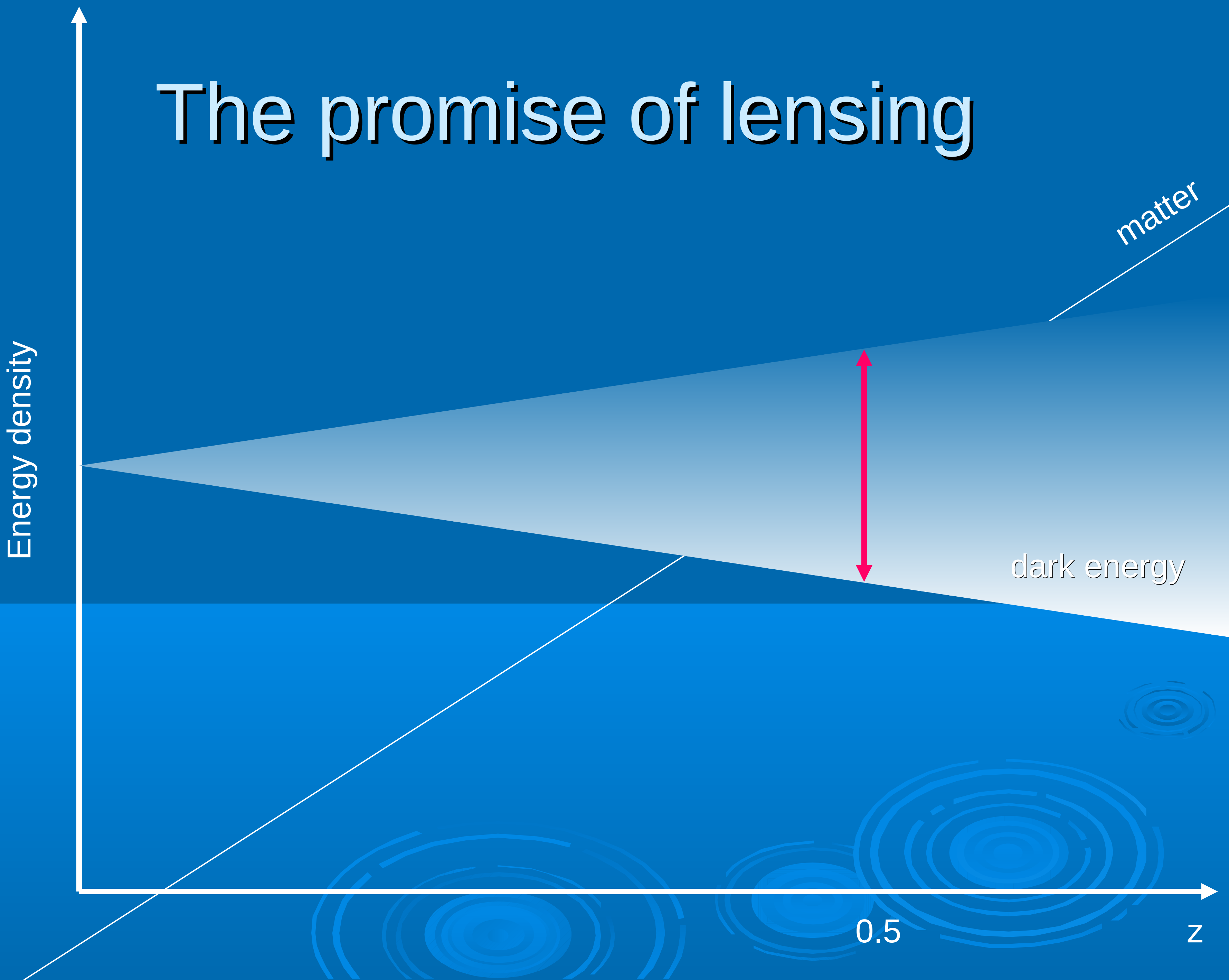
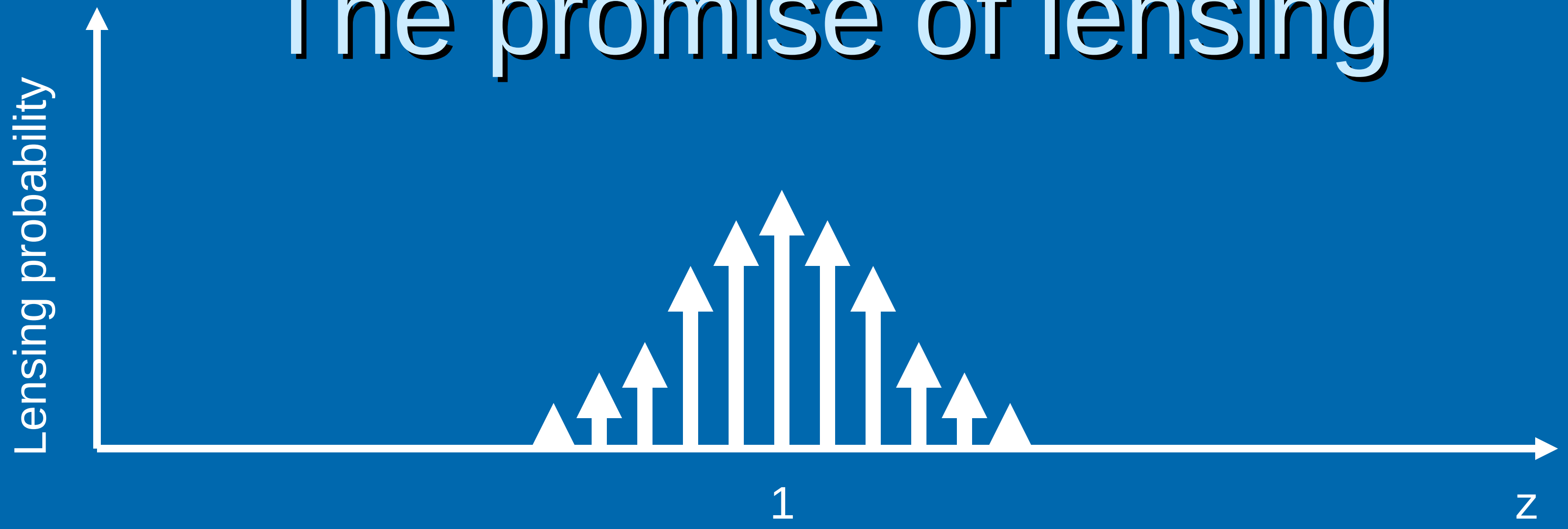
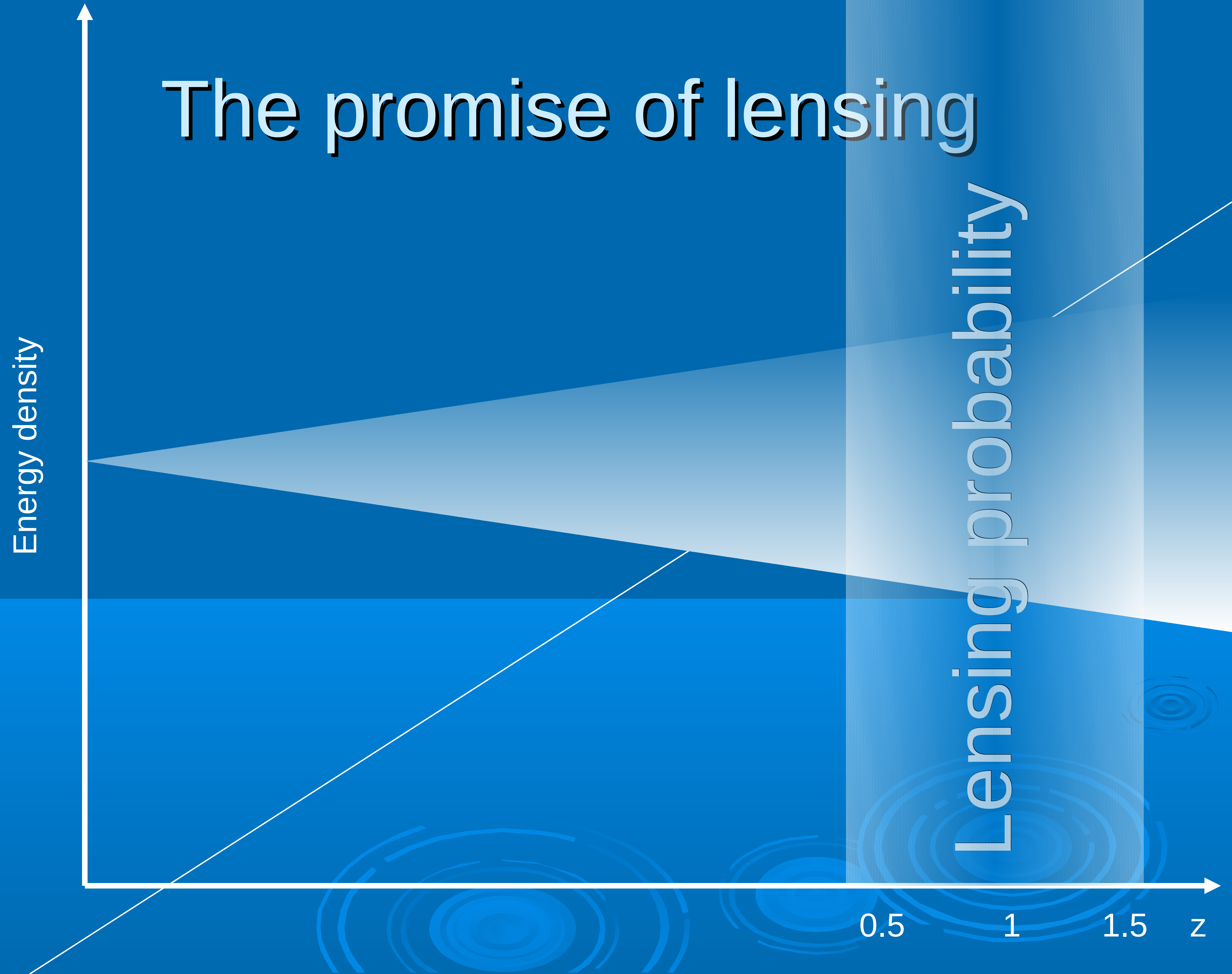


The promise of lensing



- 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 lensing power 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 smears 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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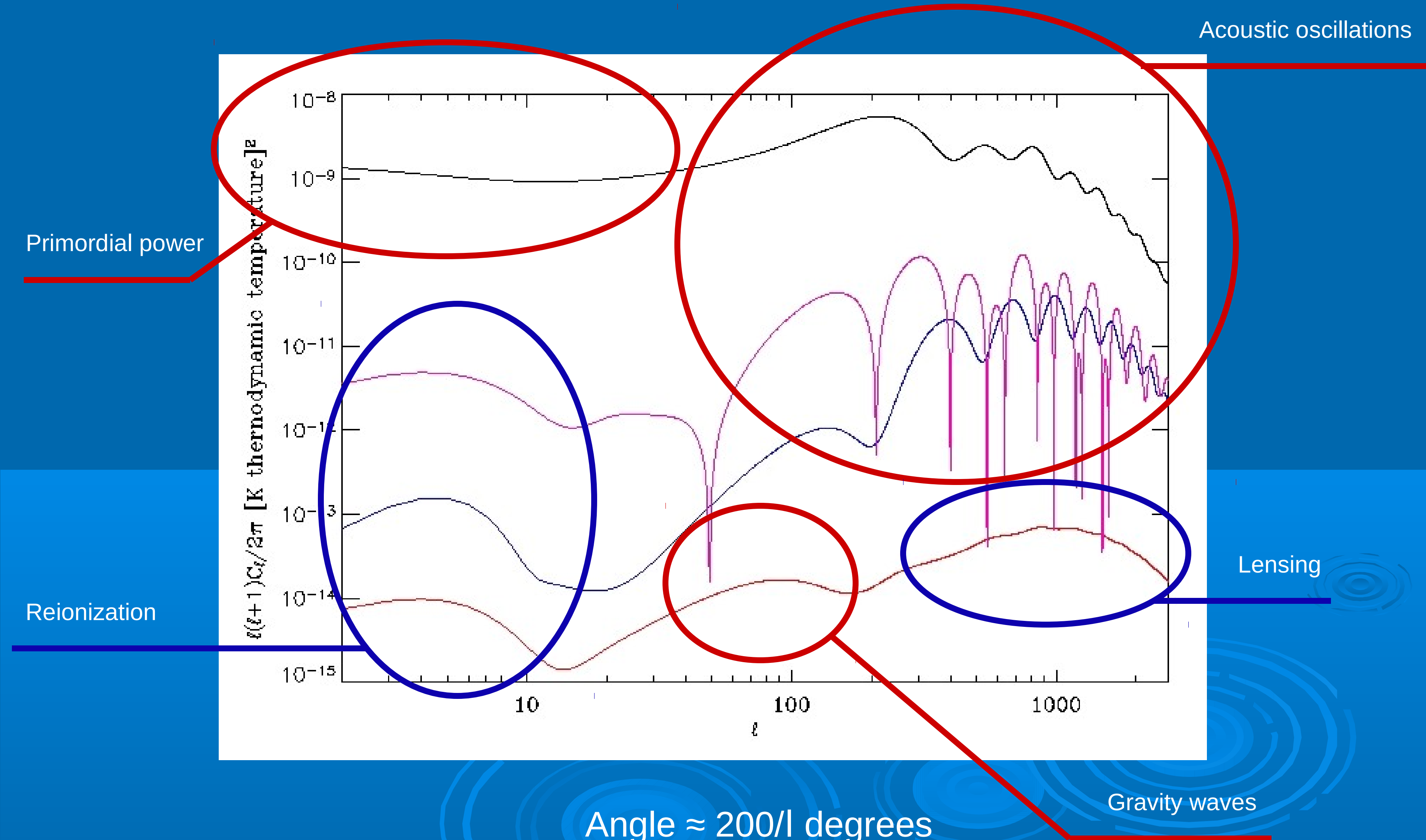
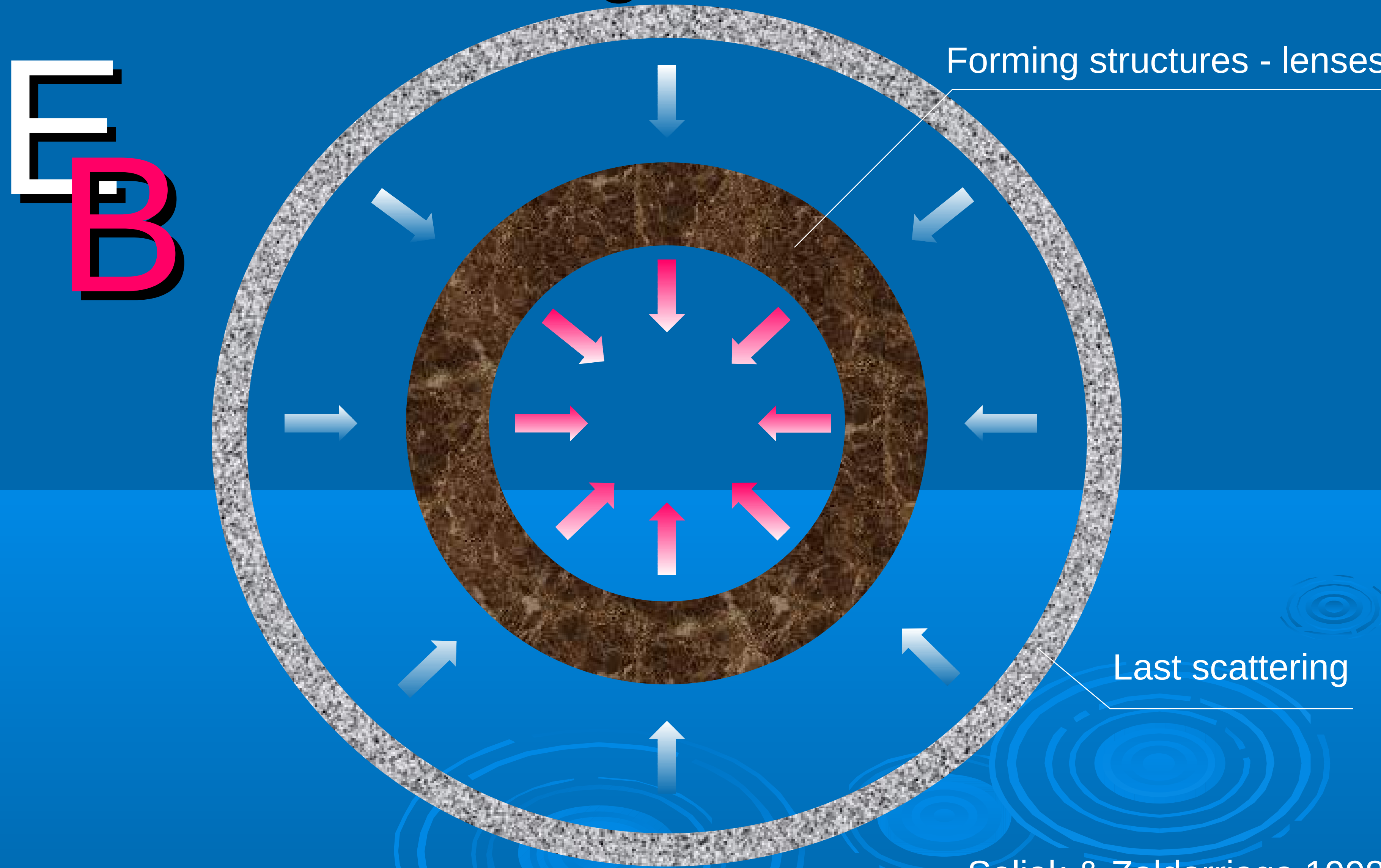
Seljak & Zaldarriaga 1997, Spergel & Goldberg 1999, Hu 2000, Giovi et al. 2005

CMB angular power spectrum



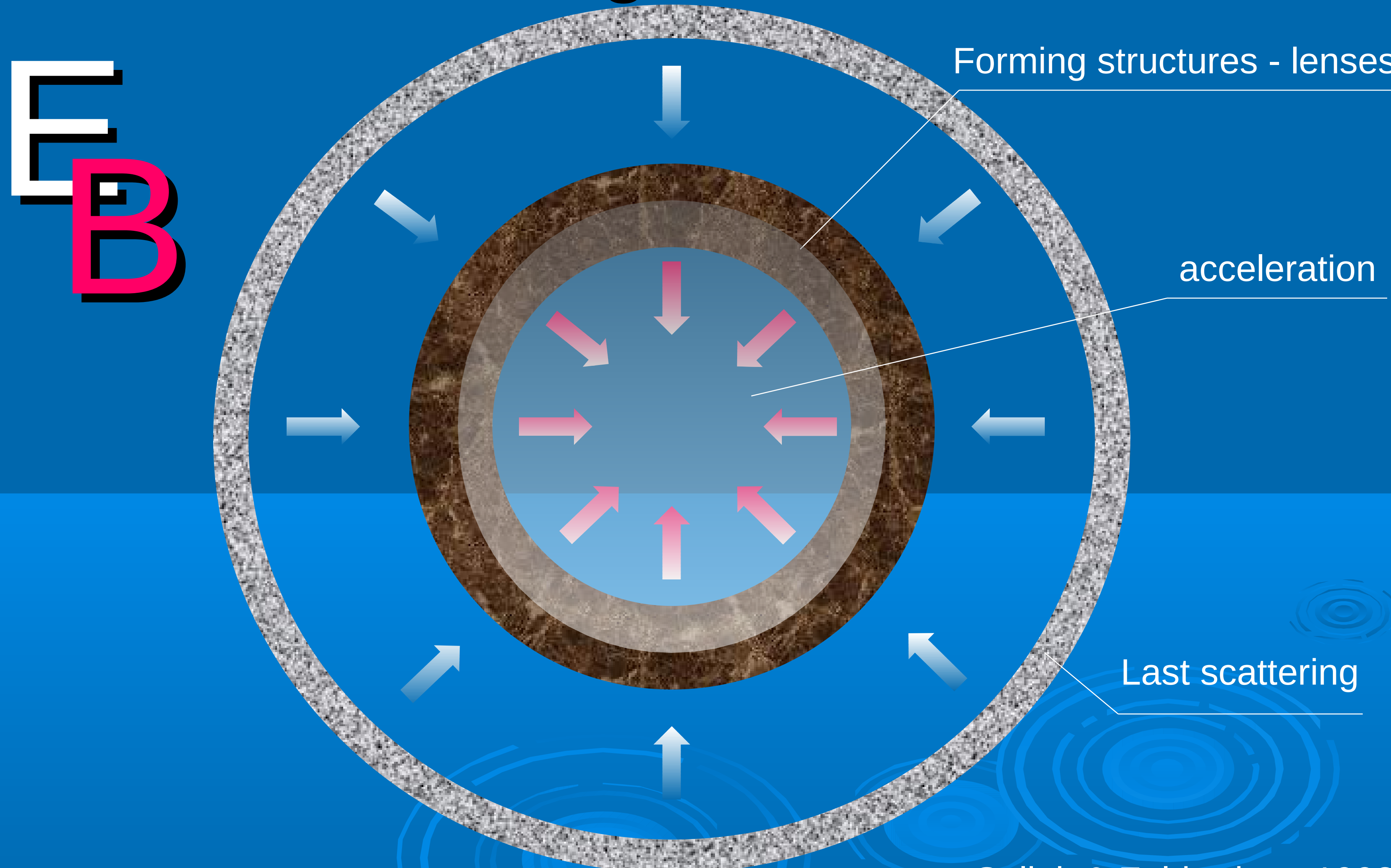
Angle ≈ 200/l degrees

Lensing B modes



Seljak & Zaldarriaga 1998

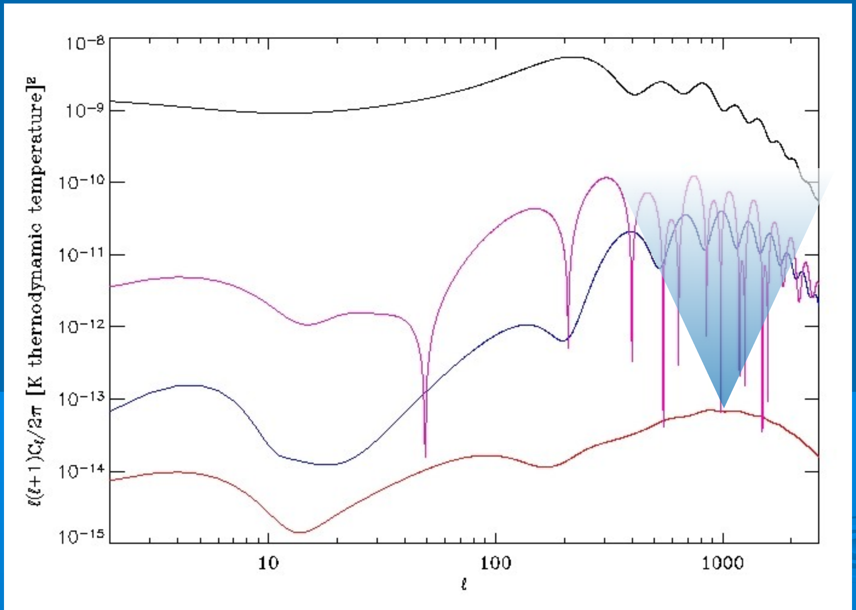
Lensing B modes



Seljak & Zaldarriaga 1998

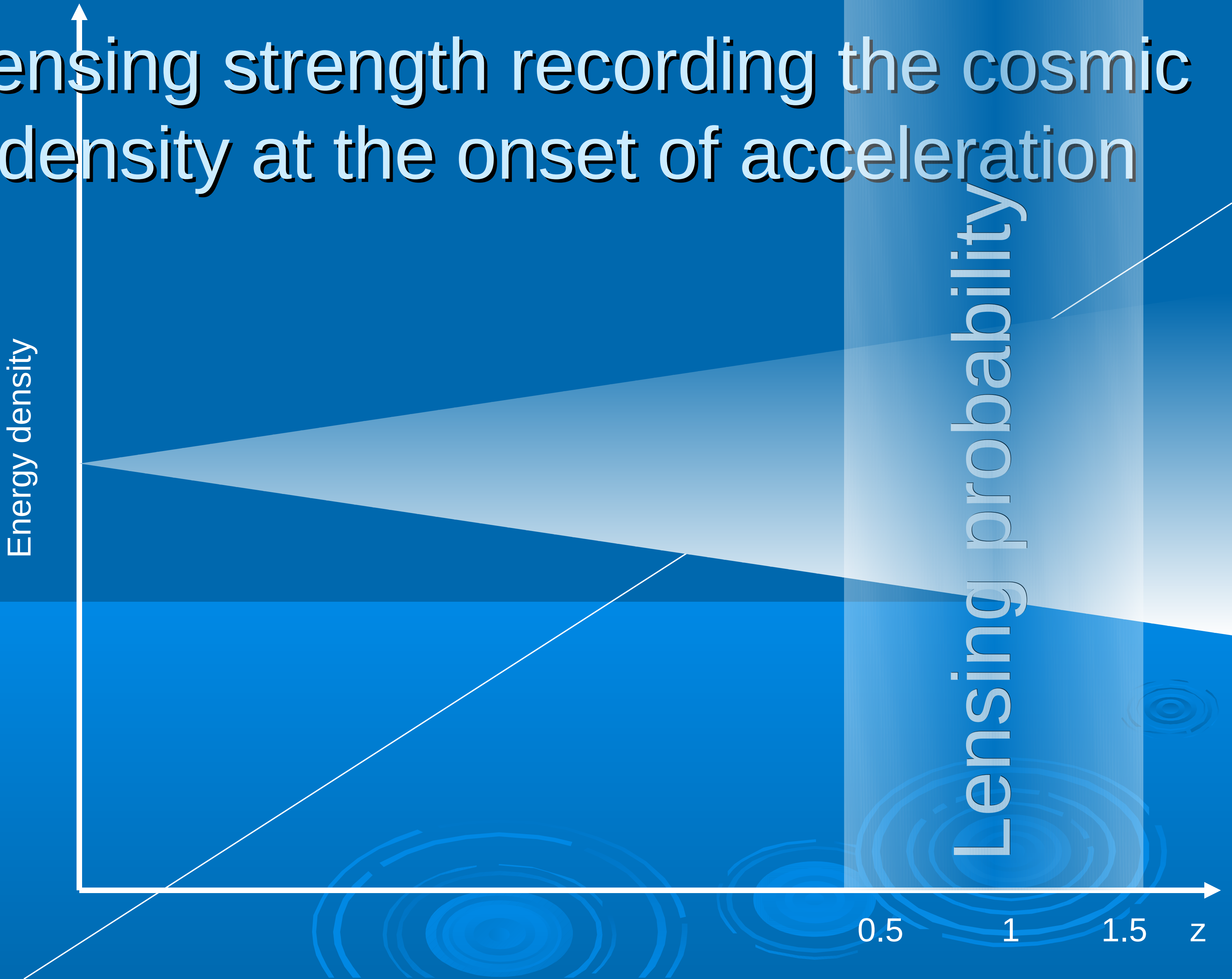
CMB lensing: a science per se

- Lensing is a second order cosmological effect
- Lensing correlates scales
- The lensing pattern is non-Gaussian
- Statistics characterization in progress, preliminary investigations indicate an increase by a factor 3 of the uncertainty from cosmic variance



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

Lensing strength recording the cosmic density at the onset of acceleration



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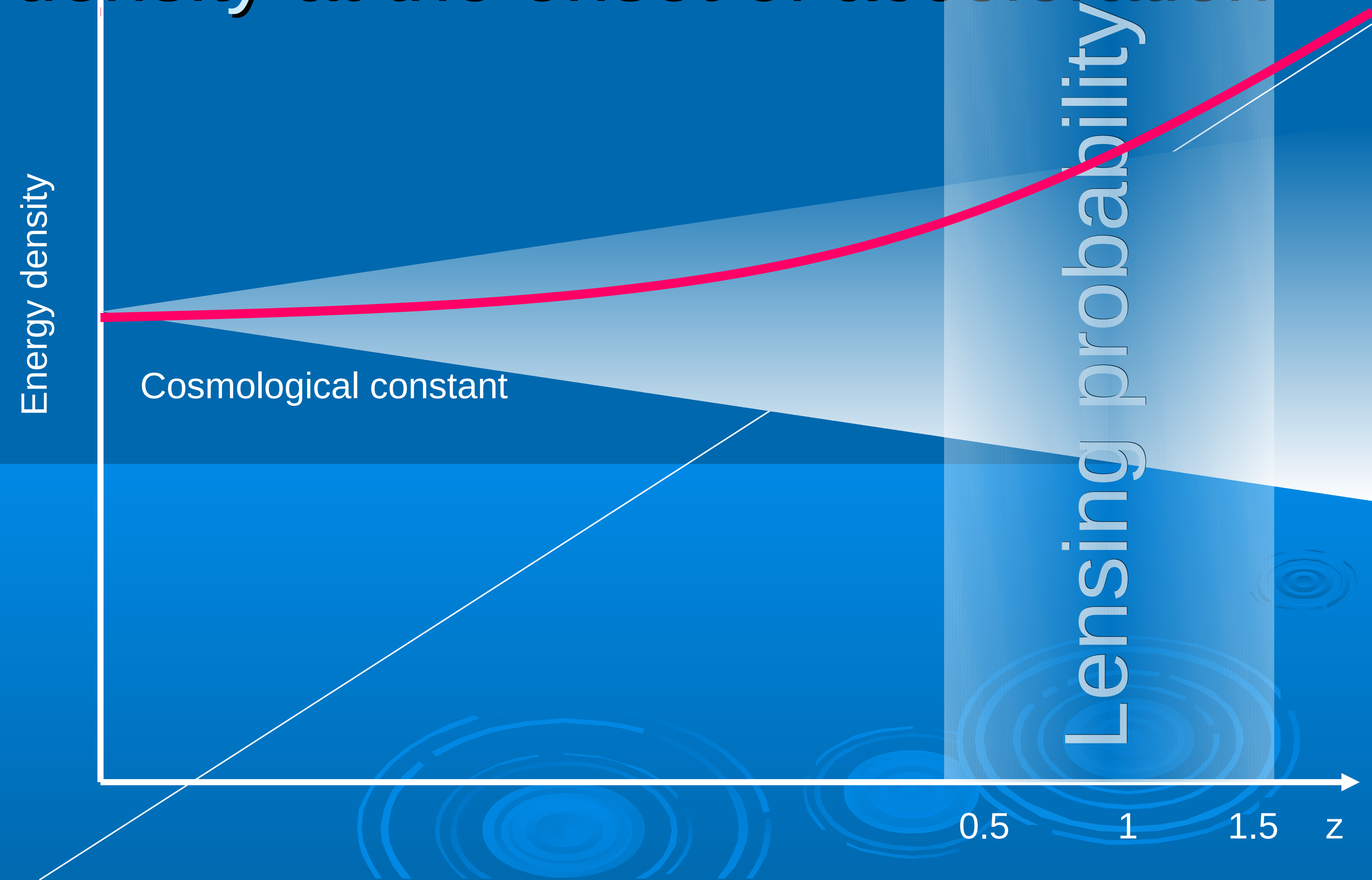

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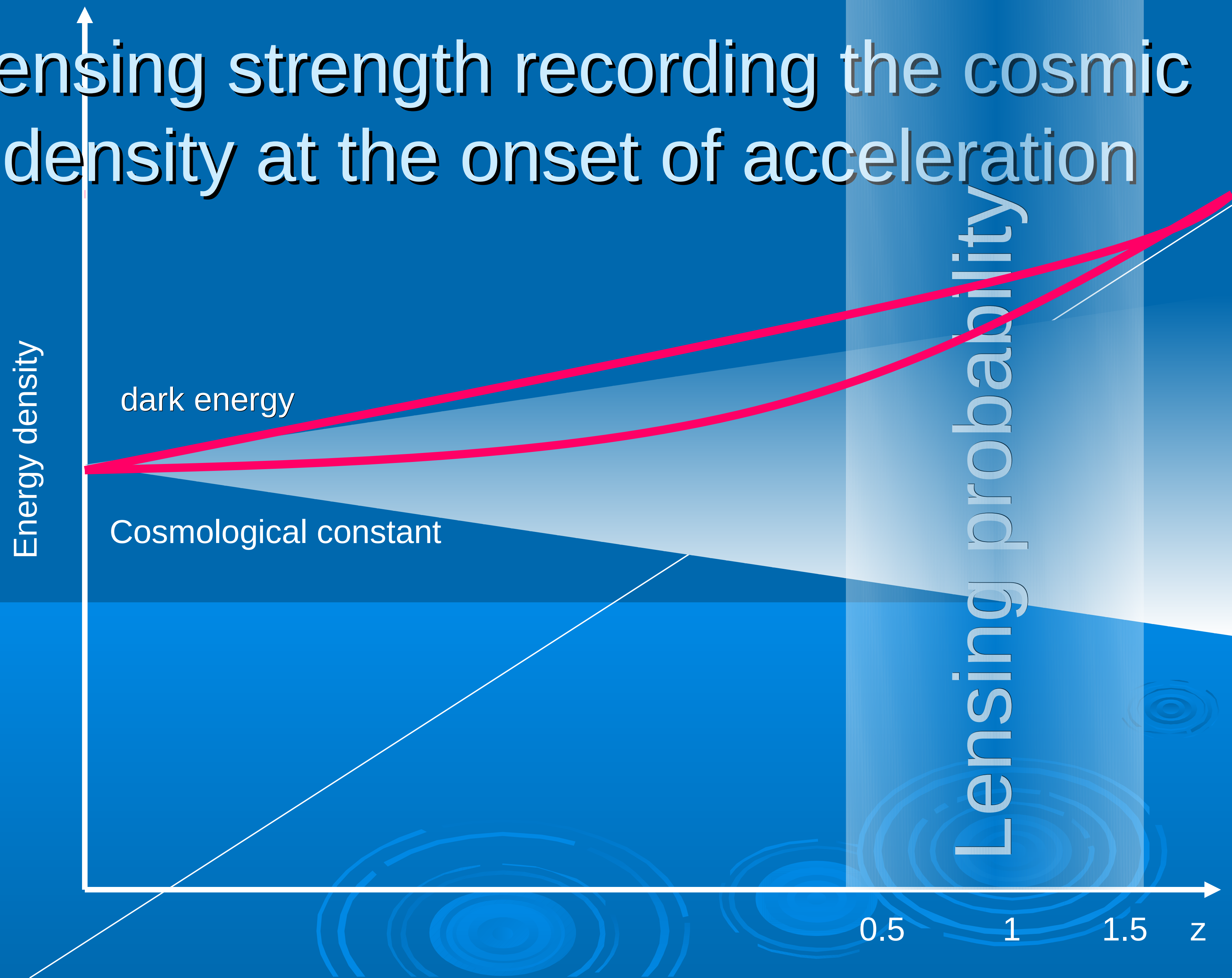
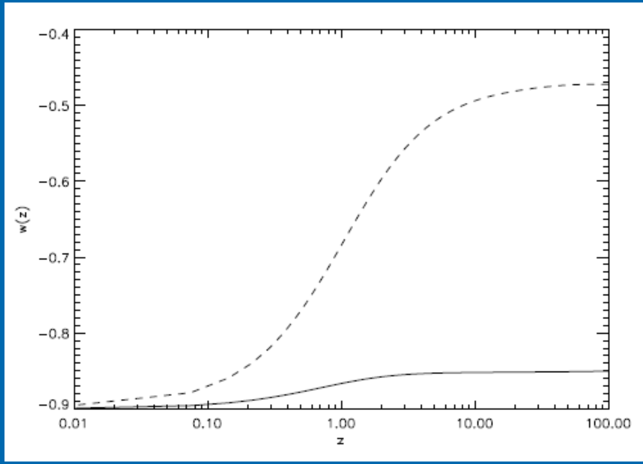


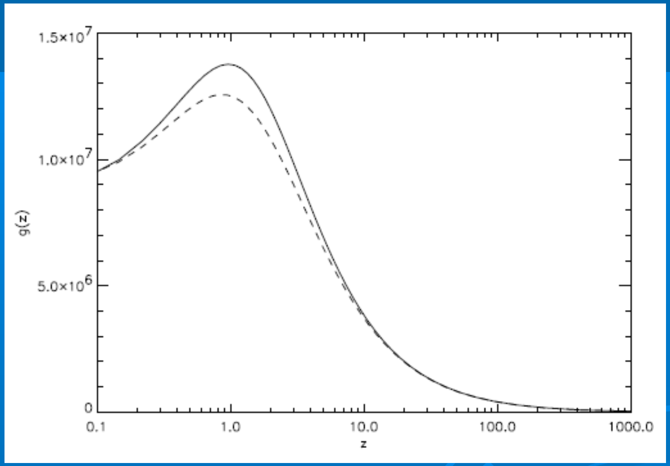
So let's play…

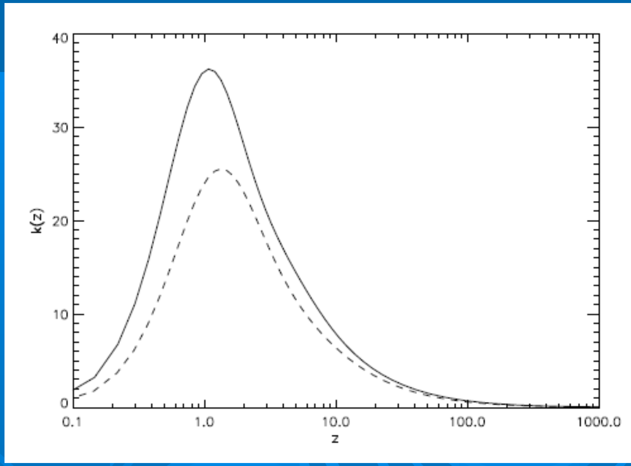
- Upgrade a Boltzmann code for lensing computation in dark energy cosmologies (Acquaviva et al. 2004 experienced doing that with cmbfast, lensing.f had to be substantially changed…)
- Get lensed CMB angular power spectra for different dark energy dynamics
- Look at the amplitude of lensing B modes

Play…

- 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



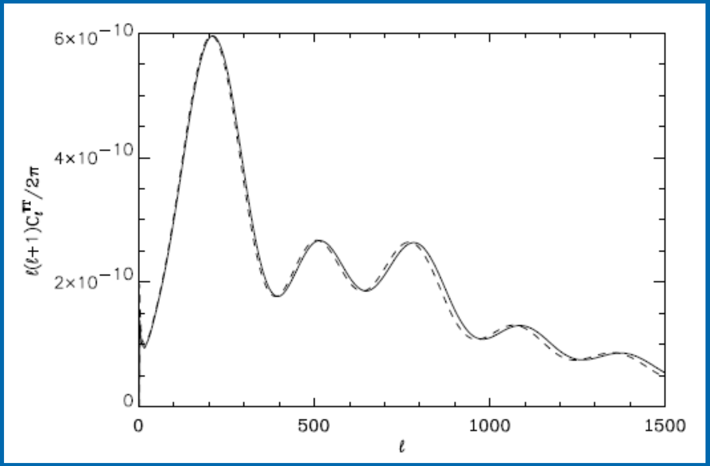


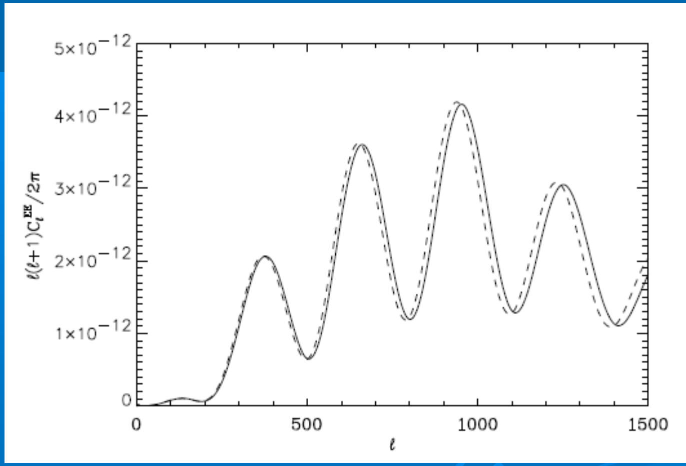


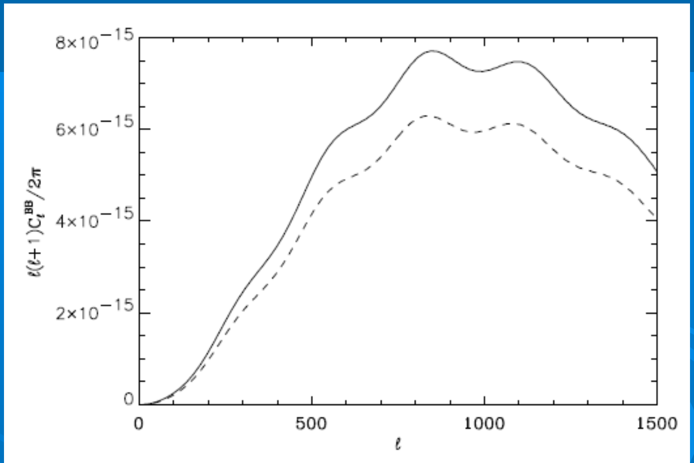
Acquaviva & Baccigalupi 2006

Play…

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

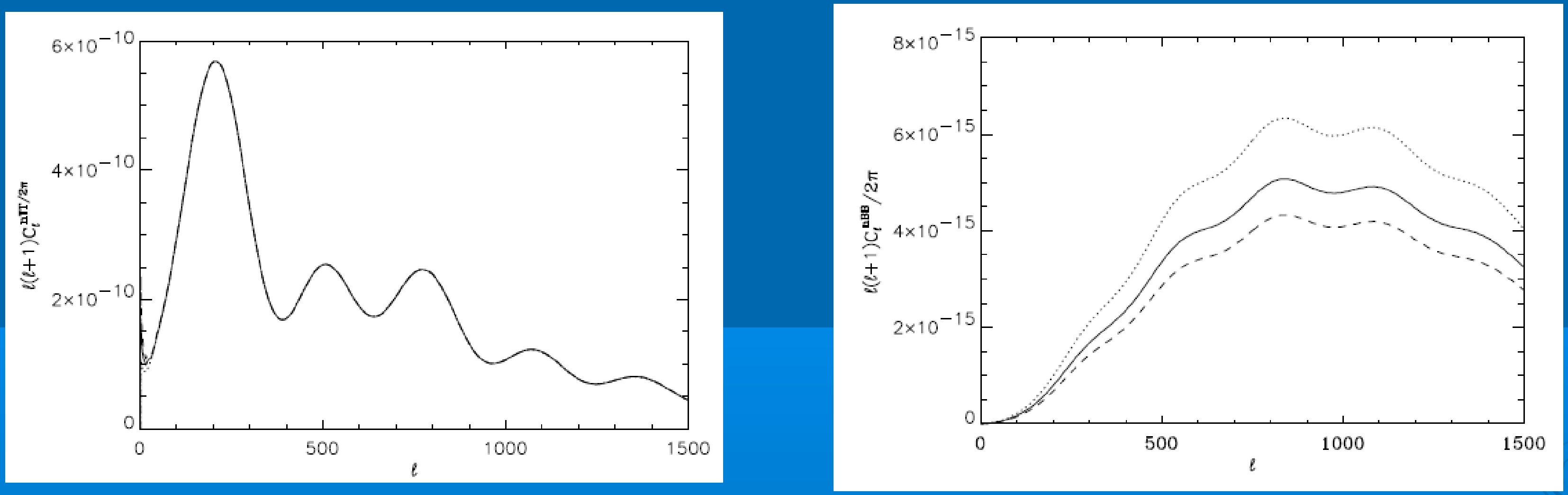






Acquaviva & Baccigalupi 2006

Breaking projection degeneracy



Acquaviva & Baccigalupi 2006

Get serious…

- A Fisher matrix analysis indicates that a 1%-10% measuremtent on both w_0 and w_a is achievable by having lensing B modes measured on a large sky area, few arcminute resolution, micro-K noise
- New relevance for searching B modes in CMB polarization?
- To be investigated in the context of future CMB data from Planck and sub-orbital experiments, Large Scale Structure surveys such as Euclid

Acquaviva & Baccigalupi 2006

Conclusions

- The Dark energy affects the CMB through structure formation, ISW and lensing
- The ISW provides an integrated information, while CMB lensing sensitivity is at high redshifts
- The CMB is a differential dark energy probe: present investigations indicate that it can reasonably put two error bars on the dark energy abundance at z=0 and 1
- Forthcoming CMB data, and simulations in light of the proposed large scale structure survey by Euclid, represent huge areas of work for confirming or rejecting these expectations in the incoming years

Suggested reading

- ''Modern Cosmology'' textbook from Scott Dodelson
- Cosmological inflation and large scale structure, textbook from Andrew R. Liddle and David H. Lyth
- Linear Cosmological perturbations: Kodama & Sasaki, Progr.Theor.Phys. 78, 1, 1984
- CMB physics: Hu and White, Phys. Rev .D 56, 596,1997
- Papers quoted in these lectures
- These lectures are available in pdf format at people.sissa.it/~bacci/work/lectures/