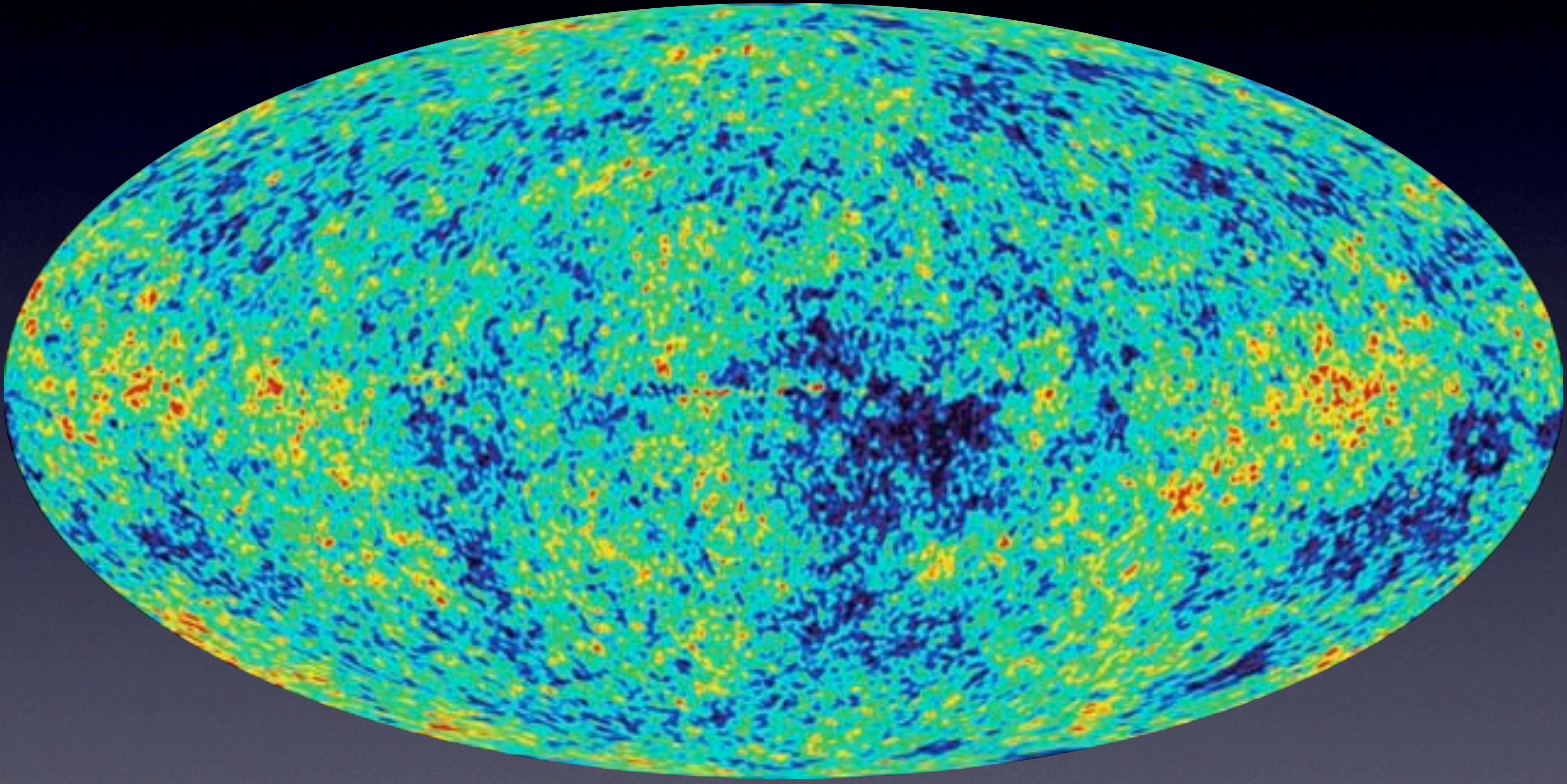
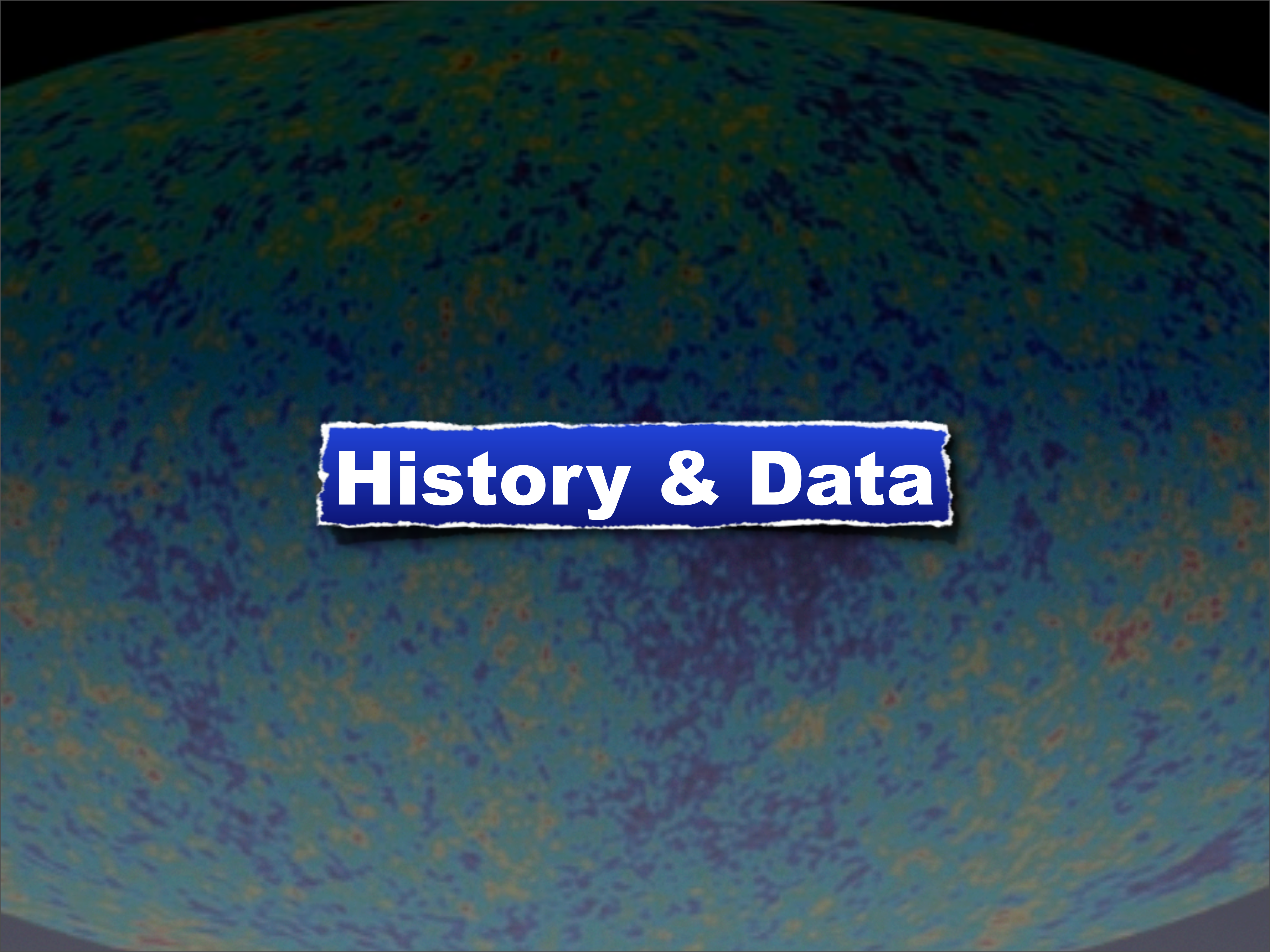
The Cosmic Microwave Background: Listening to the Symphony of the Big Bang

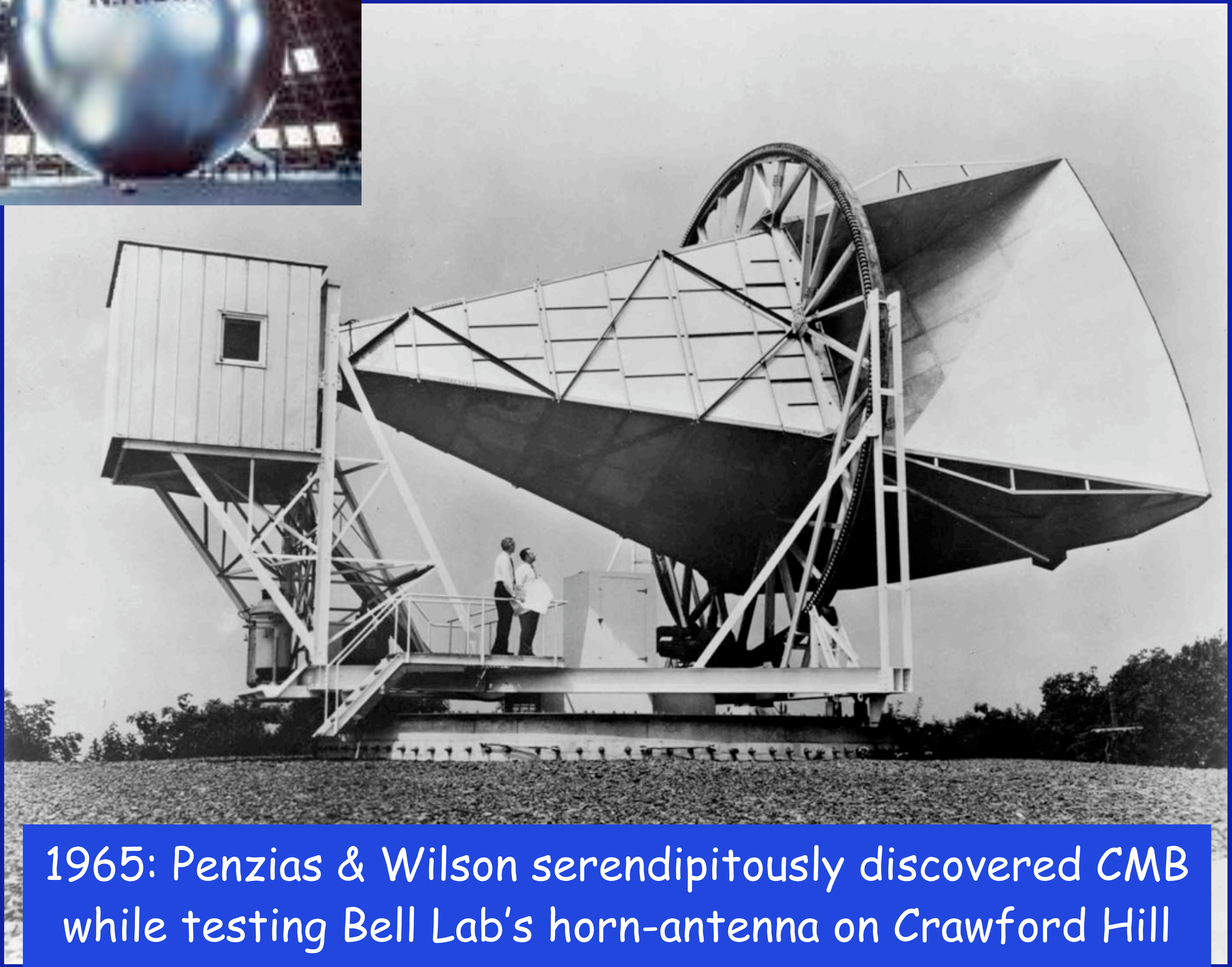


PROF. FRANK VAN DEN BOSCH
DEPT. OF PHYSICS & ASTRONOMY

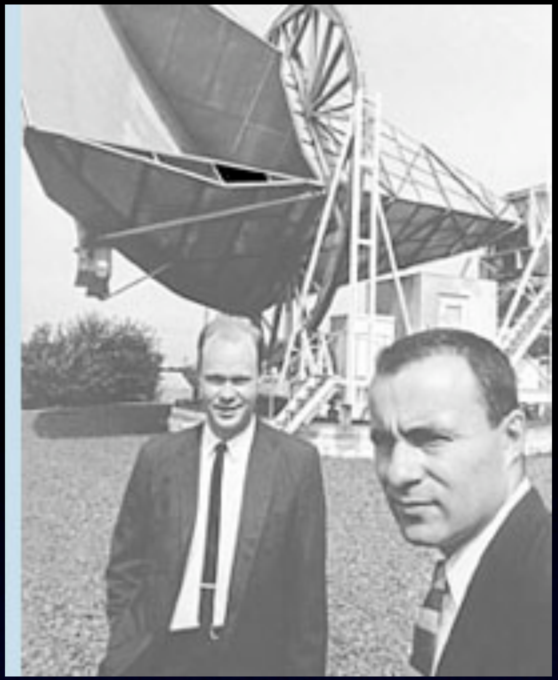


History & Data

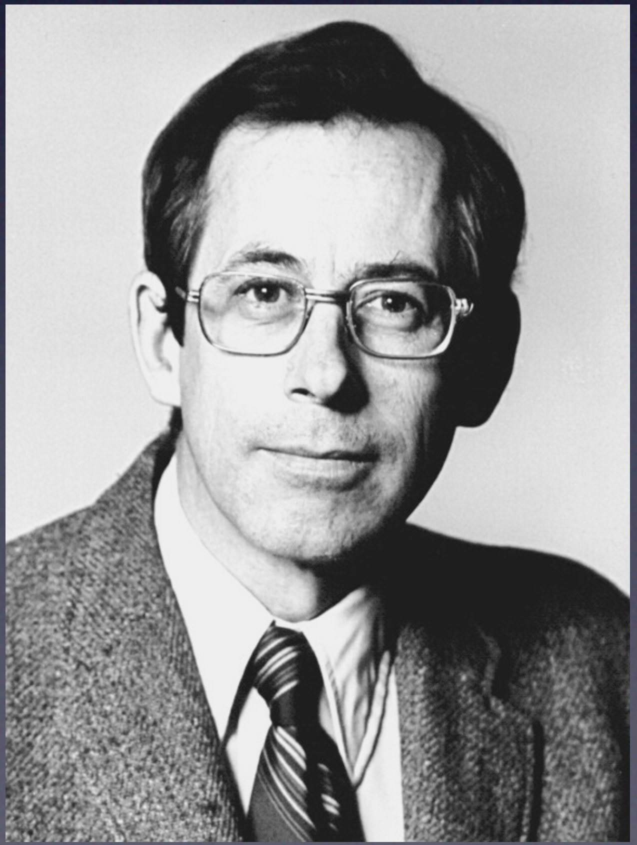
The Story of Discovery



1965: Penzias & Wilson serendipitously discovered CMB while testing Bell Lab's horn-antenna on Crawford Hill at Holmdell, New Jersey.
Were awarded 1978 Nobel Prize in Physics



Arno Penzias &
Robert Wilson



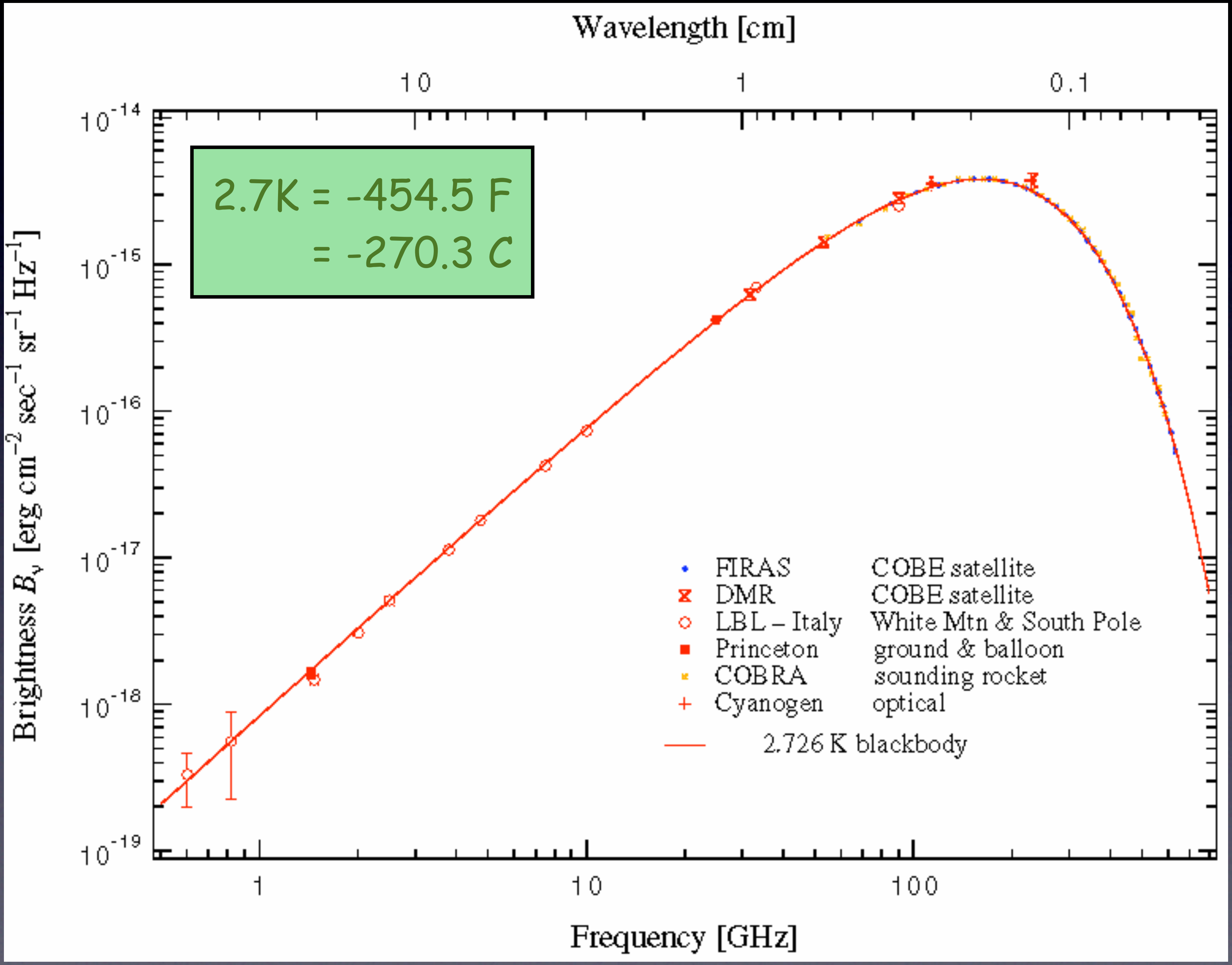
Jim Peebles (Princeton)

Observing the CMB: do it yourself...

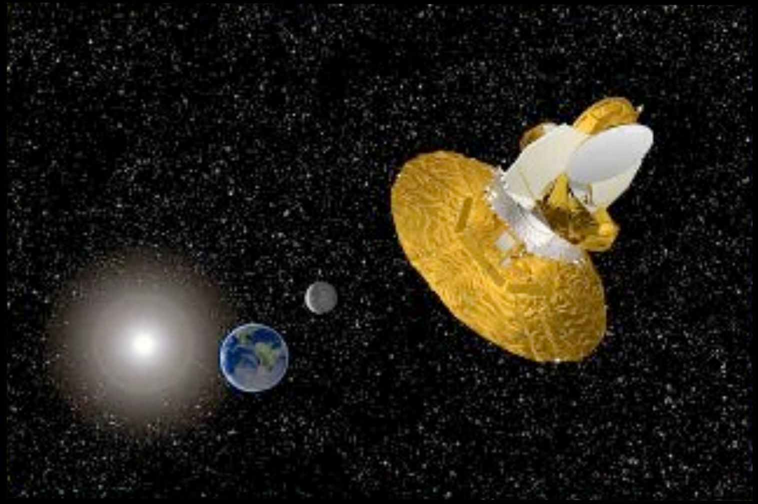
Roughly 1 percent of the static on your TV is CMB!!!

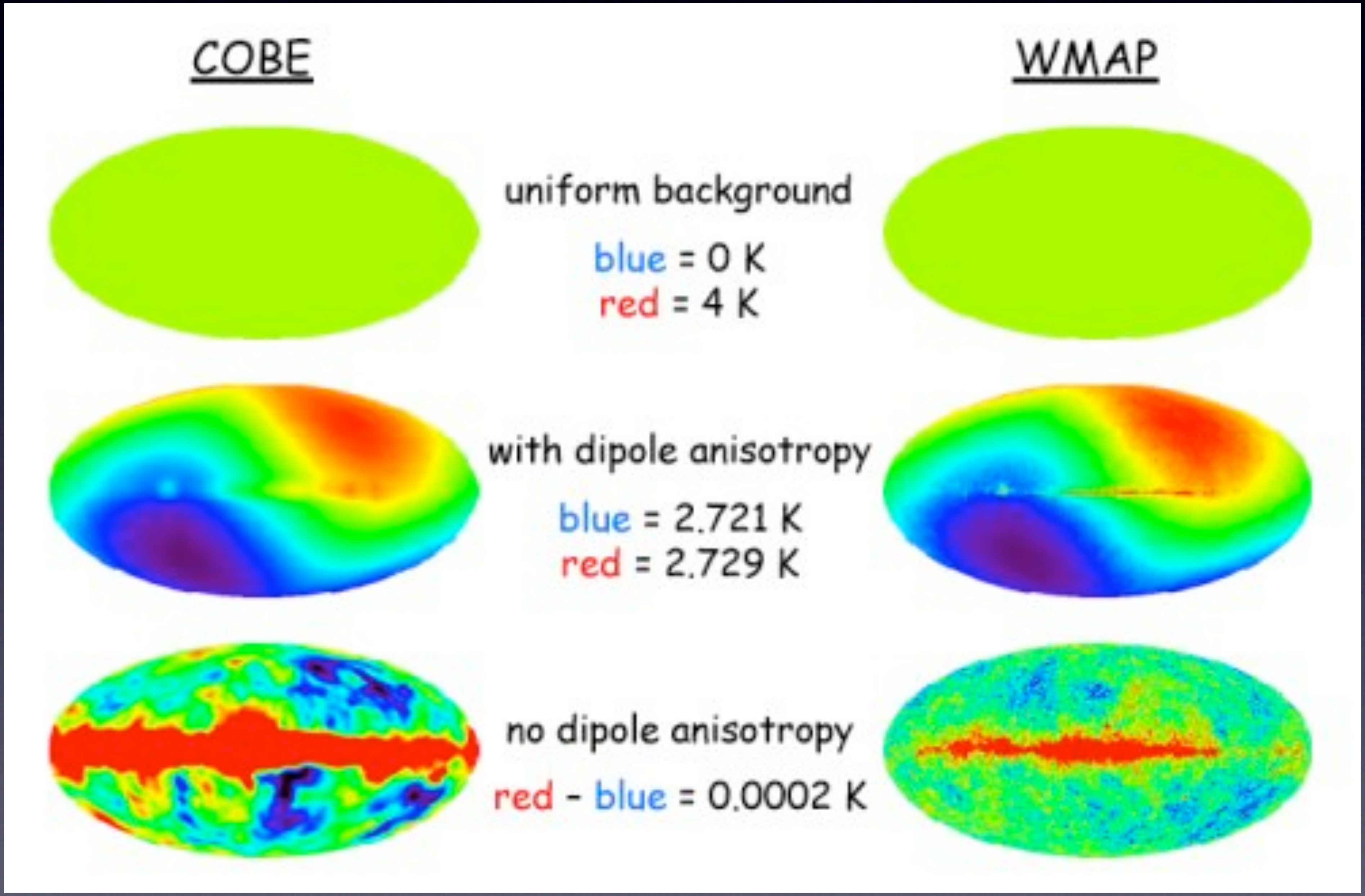
http://www.youtube.com/watch?v=PH54cp2ggFk&feature=related

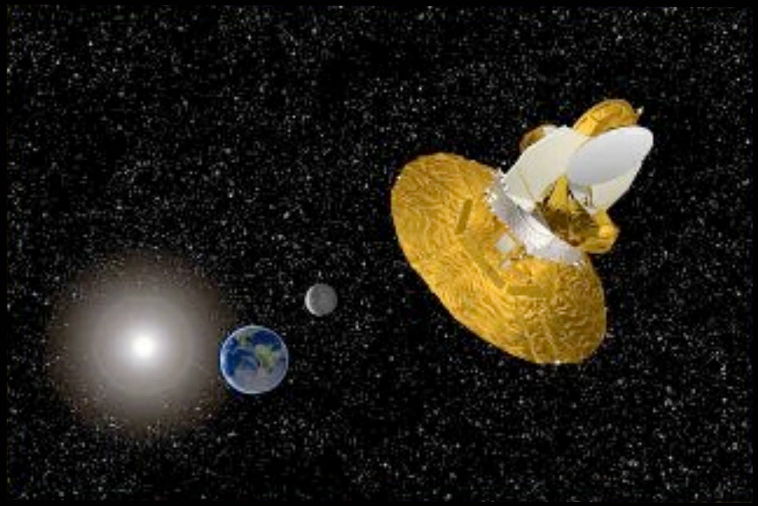
Most Accurate Planck Curve ever measured

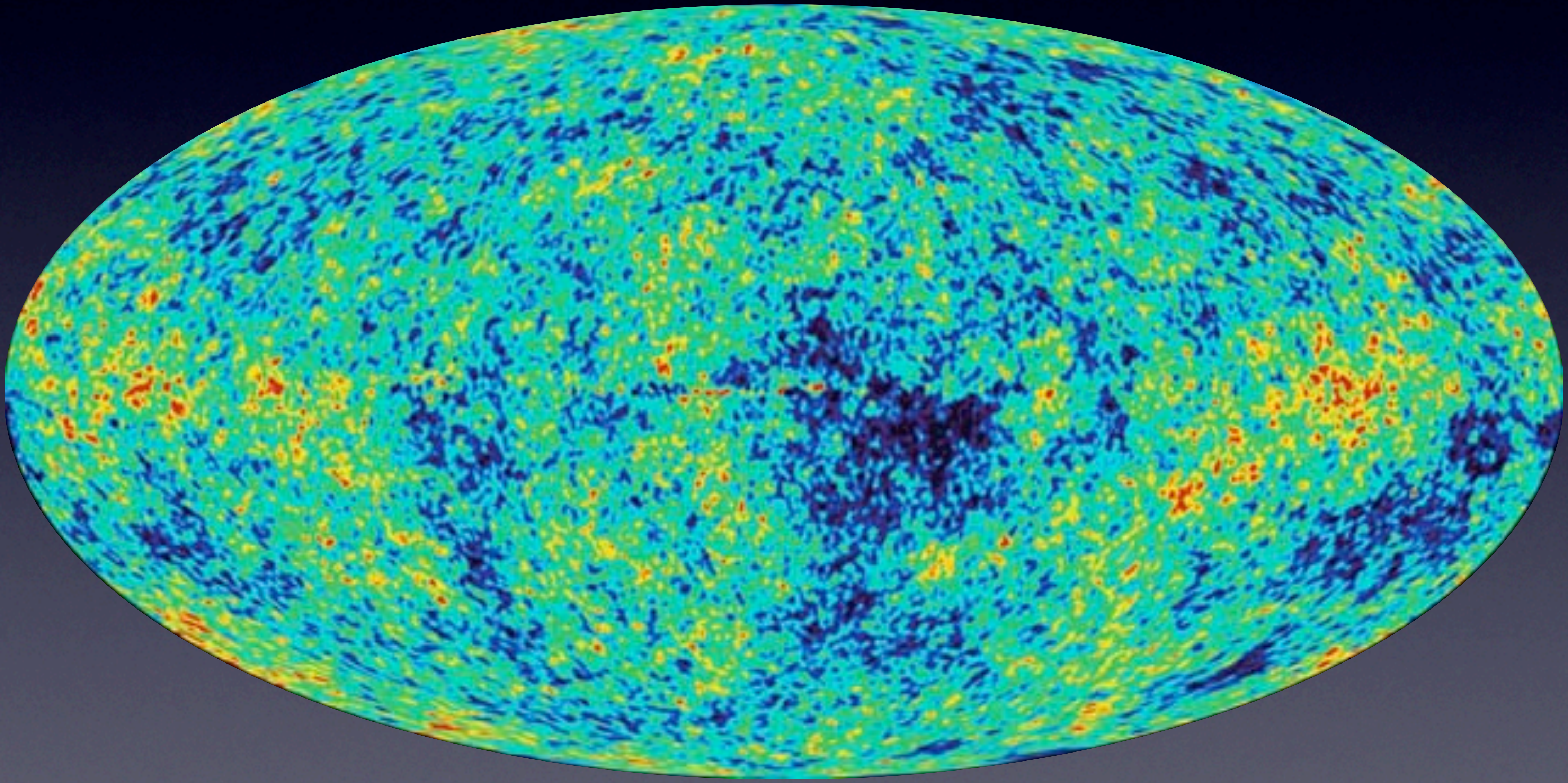


2.7K = -454.5 F
= -270.3 C



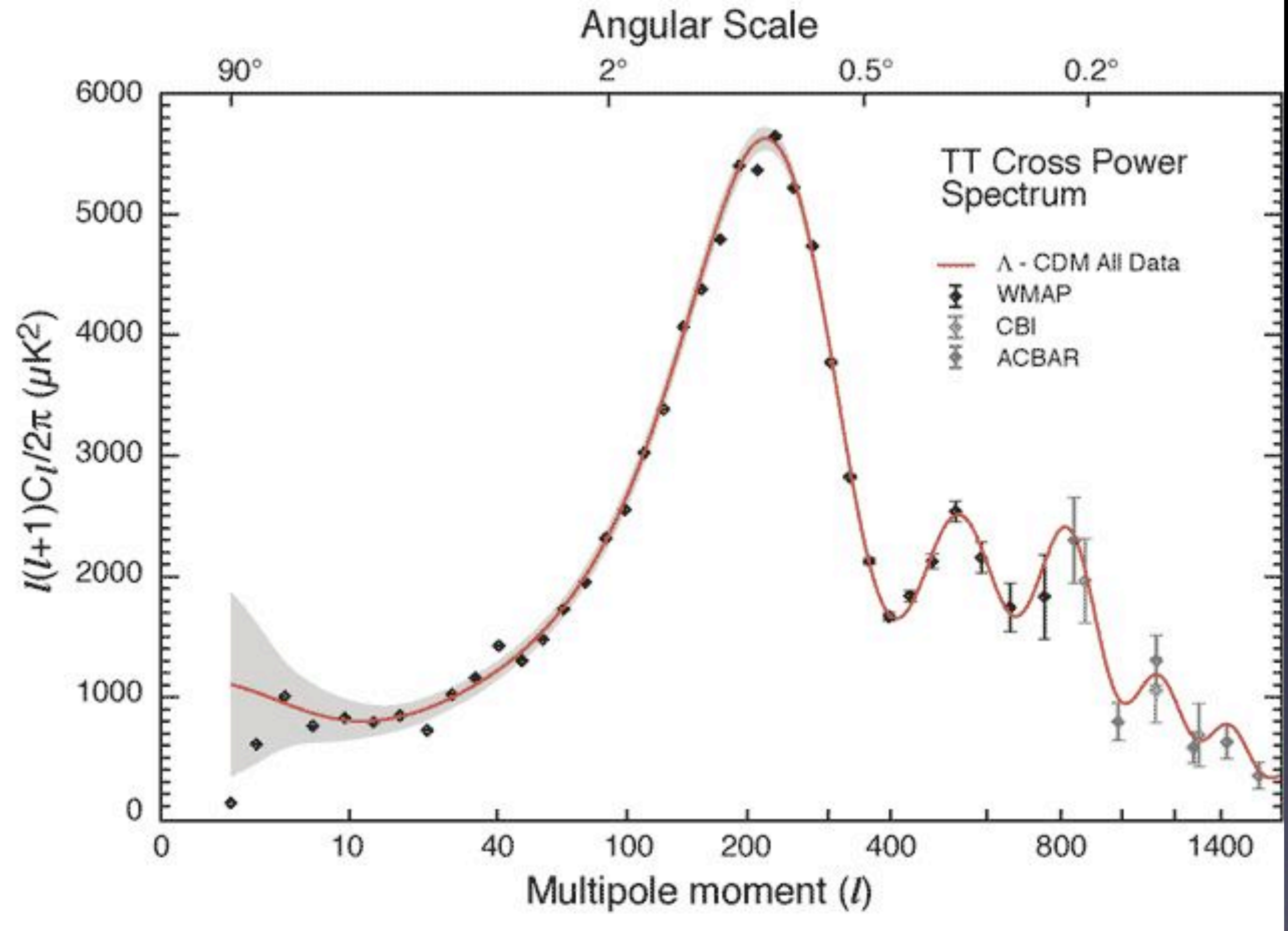

COBE
WMAP
uniform background
blue = 0 K
red = 4 K
with dipole anisotropy
blue = 2.721 K
red = 2.729 K
no dipole anisotropy
red - blue = 0.0002 K





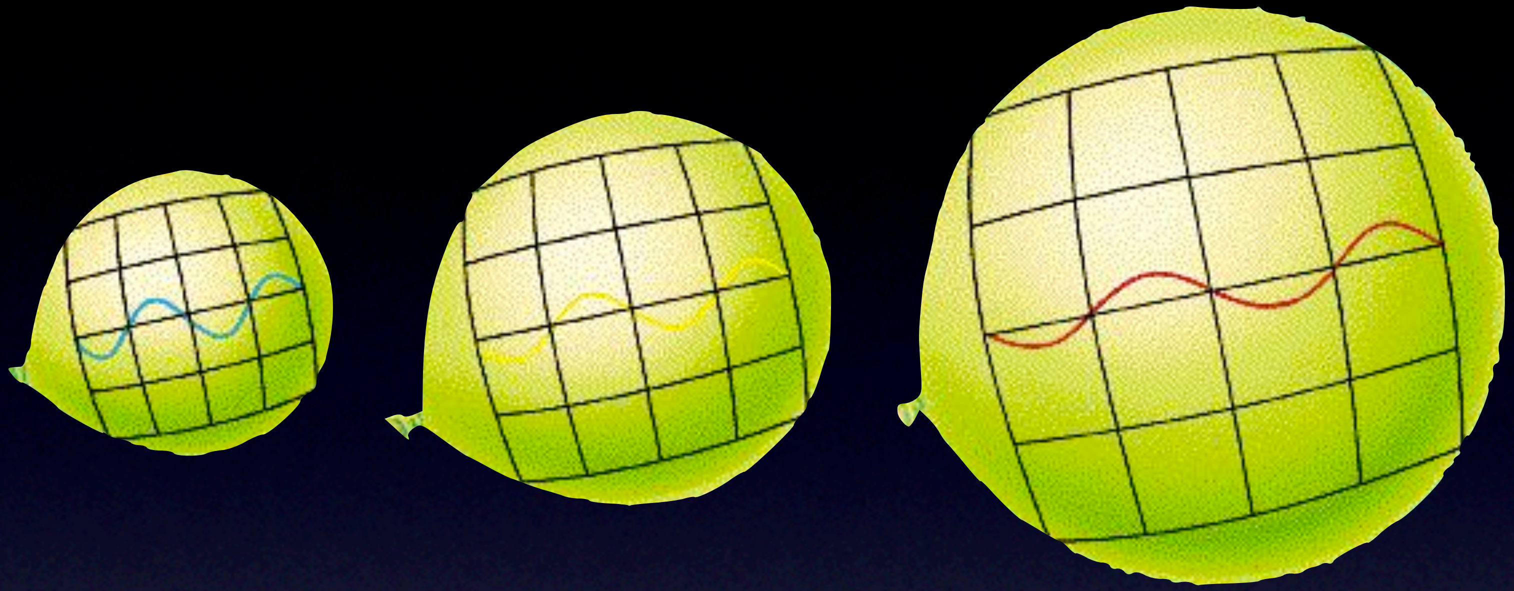
After removal of contribution of Milky Way

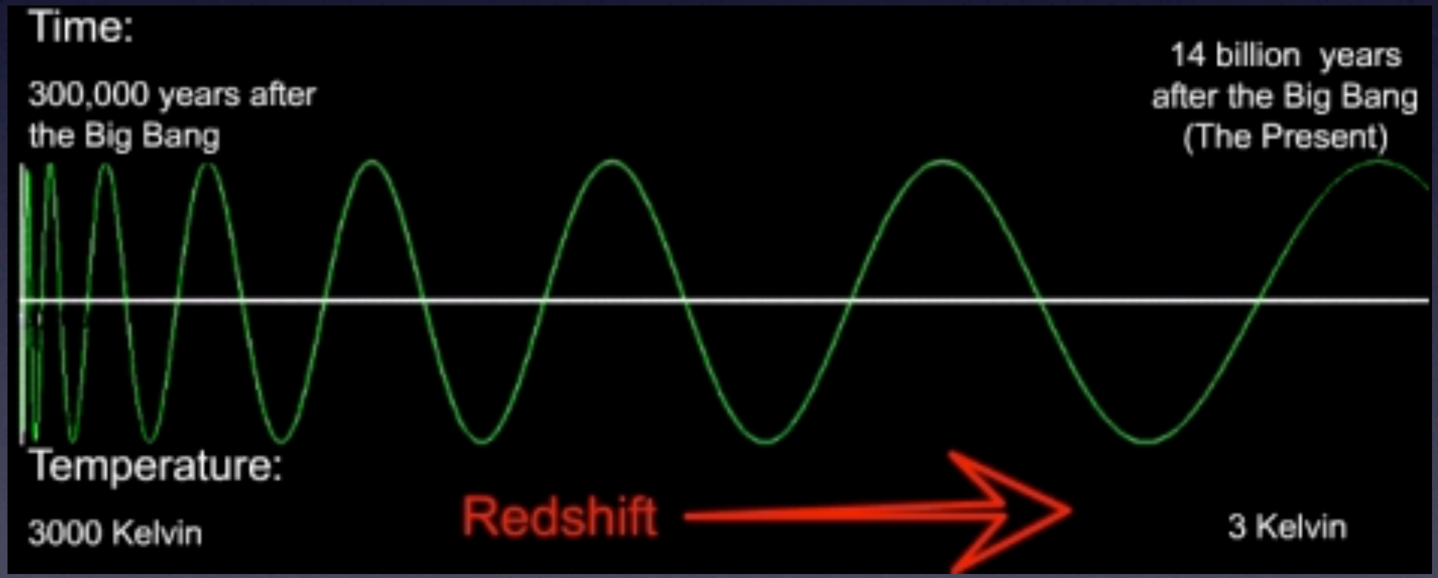
The CMB Power Spectrum



Observations in an Expanding Universe

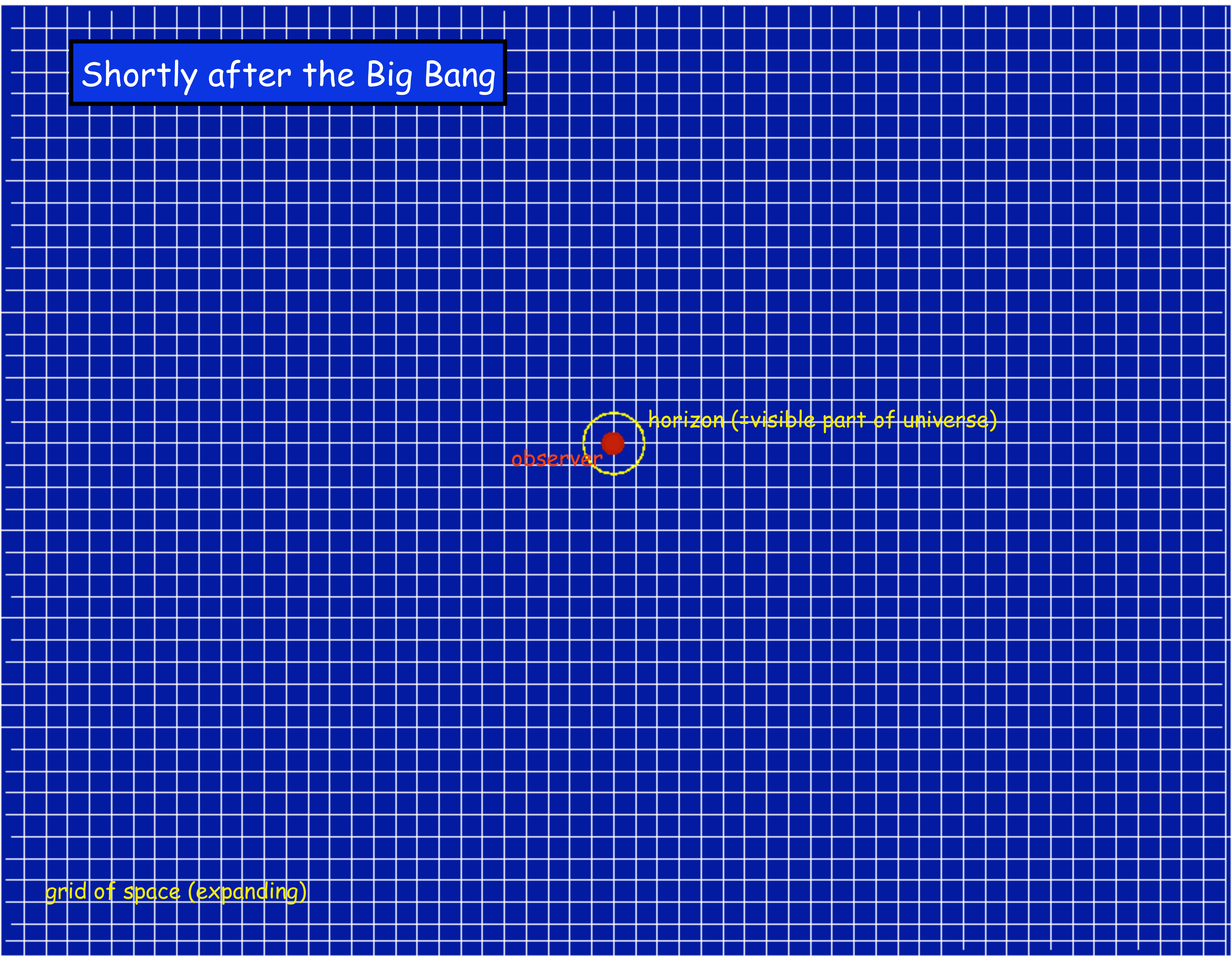
Cosmological Redshift

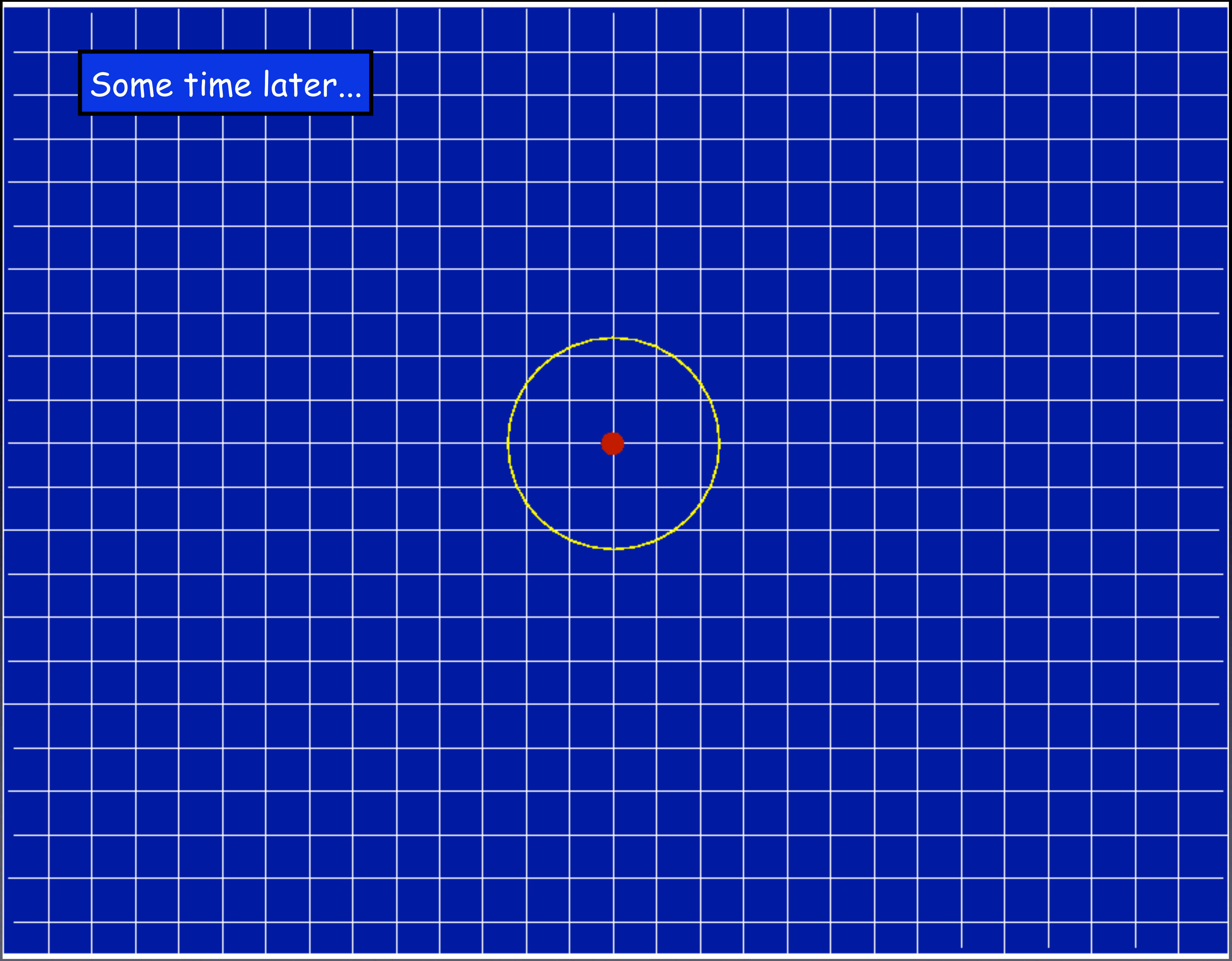


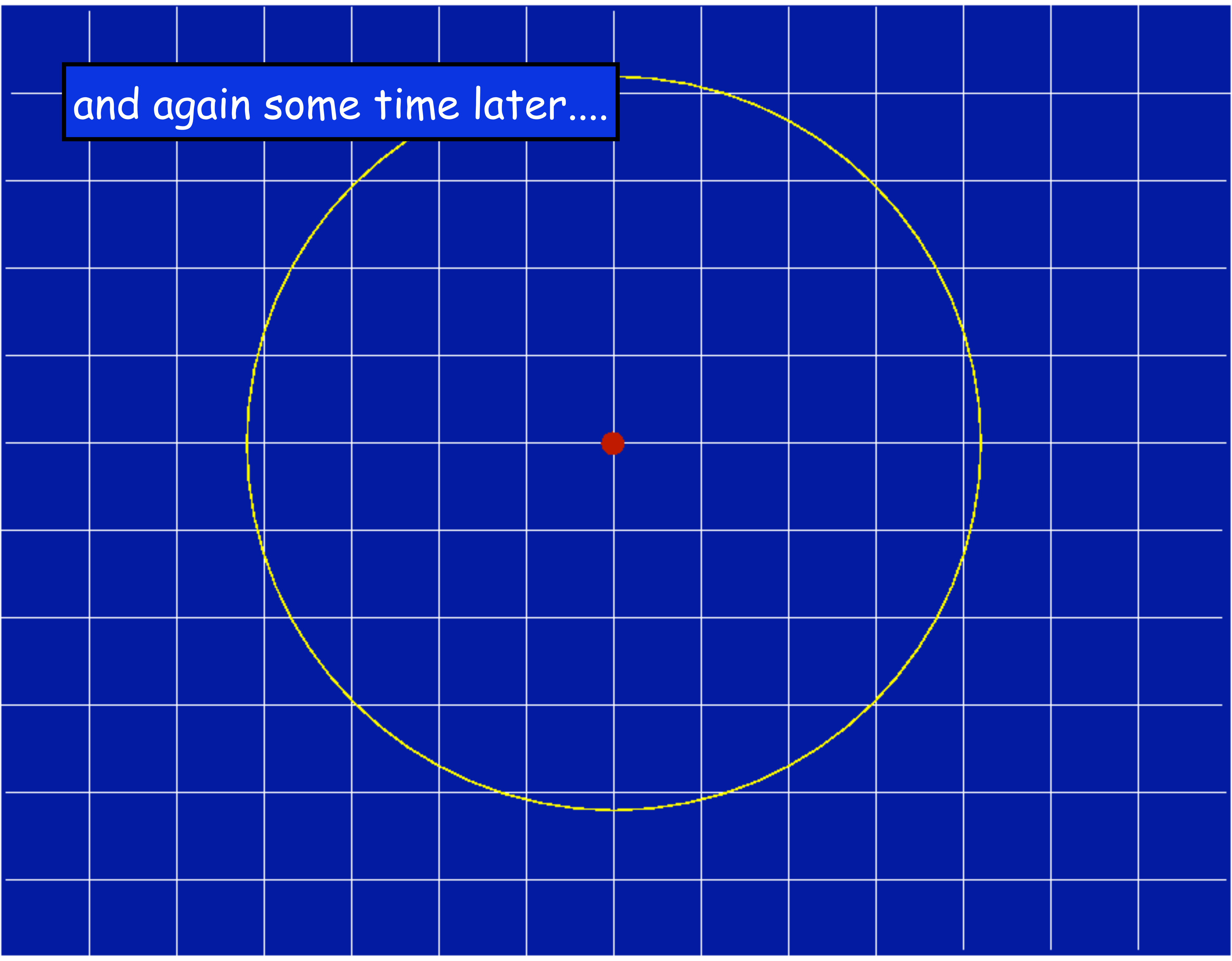


- Light and other radiation reaches us in form of photons.
- Photons are characterized by a wavelength, which reflects their energy.
- Due to expansion of Universe, photons get redshifted (become less energetic).

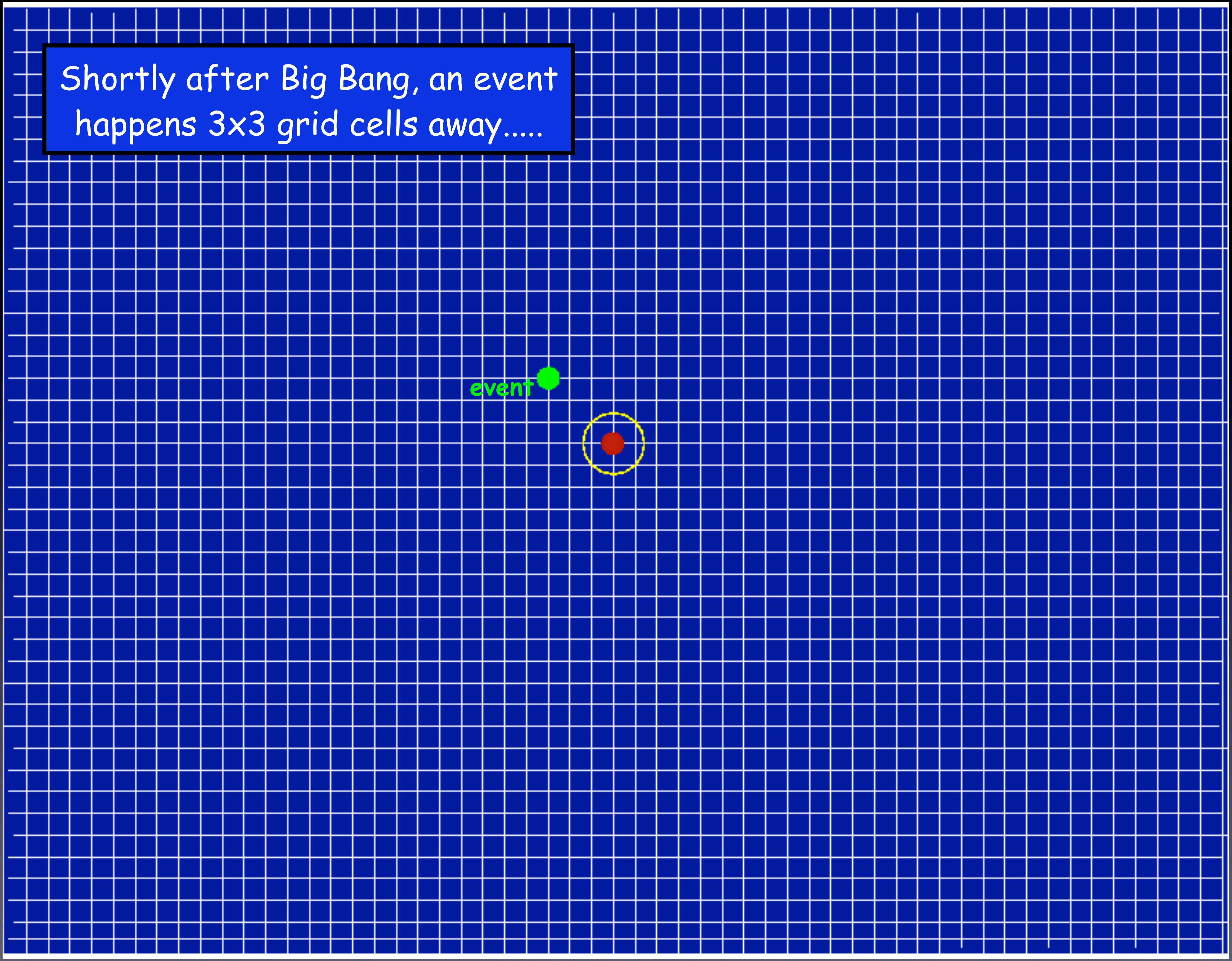
Shortly after the Big Bang

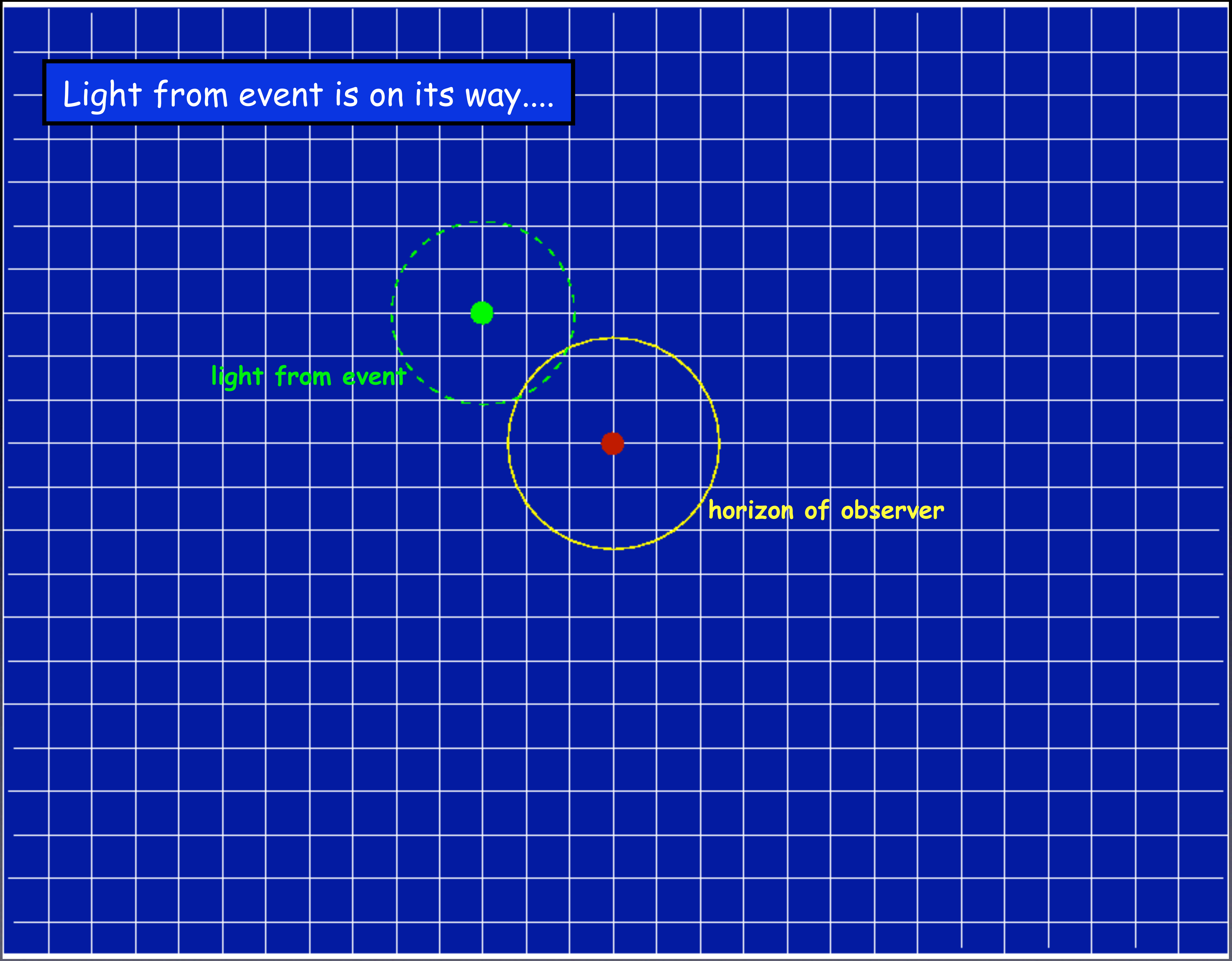



Some time later...

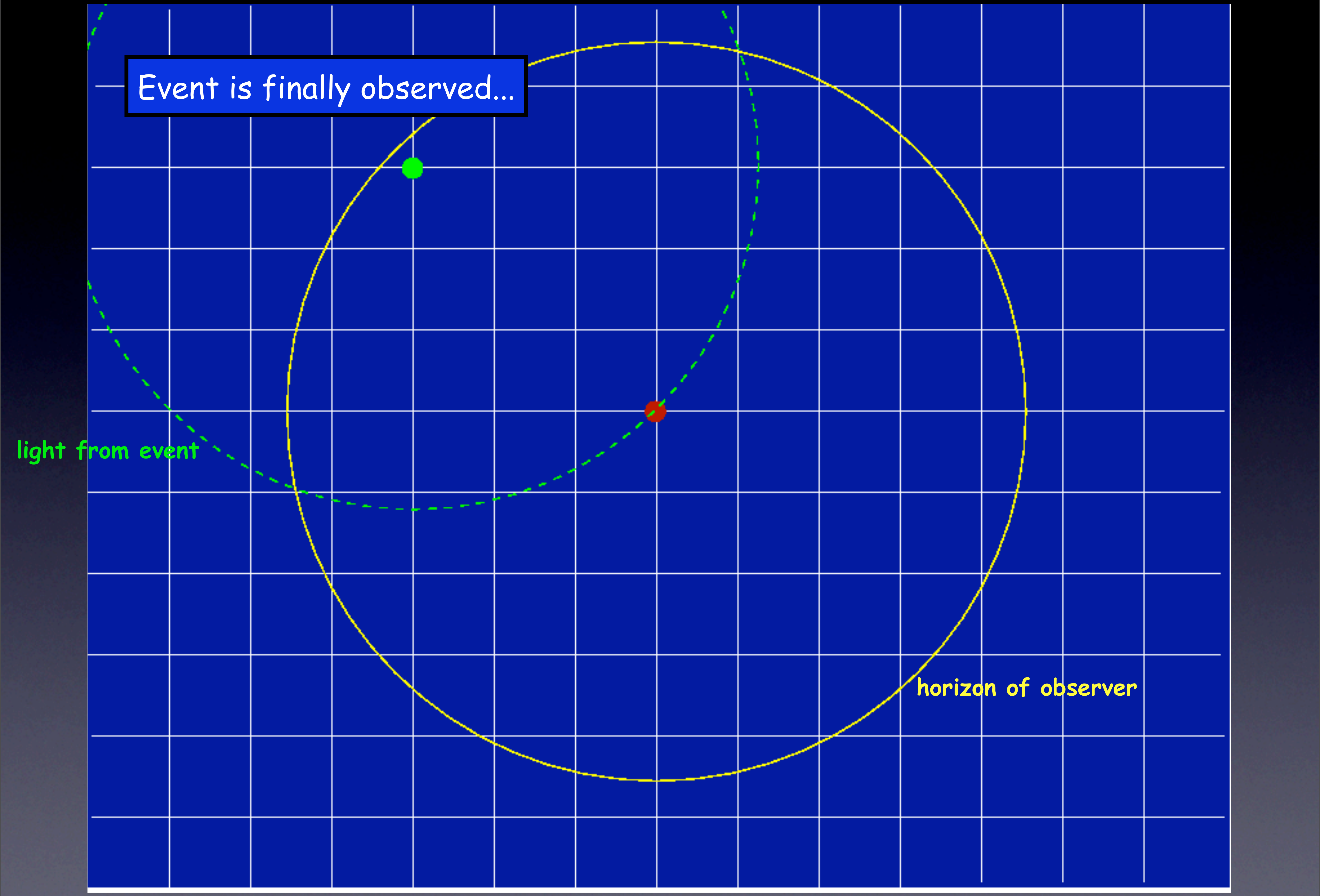


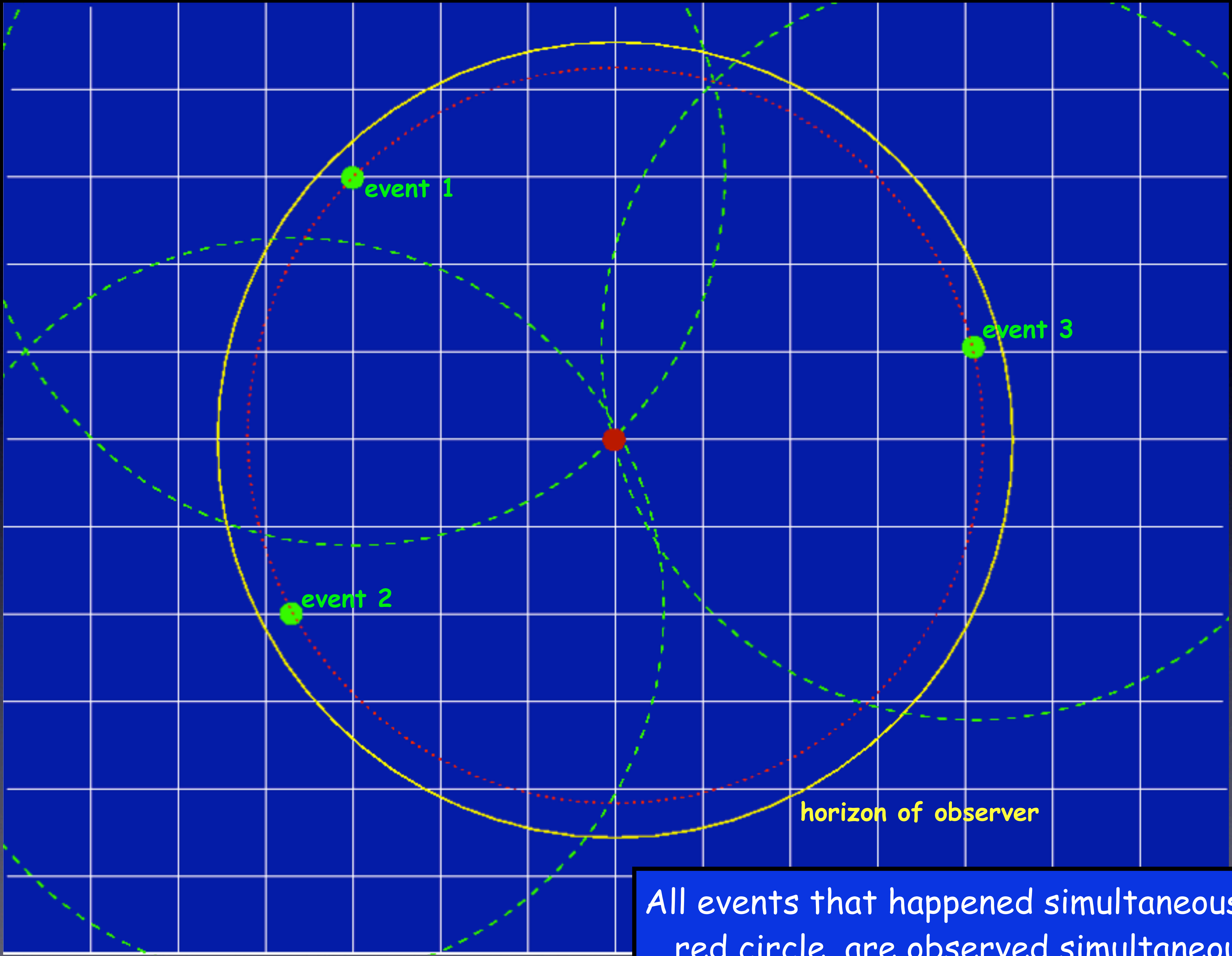
and again some time later....


Shortly after Big Bang, an event happens 3x3 grid cells away.....

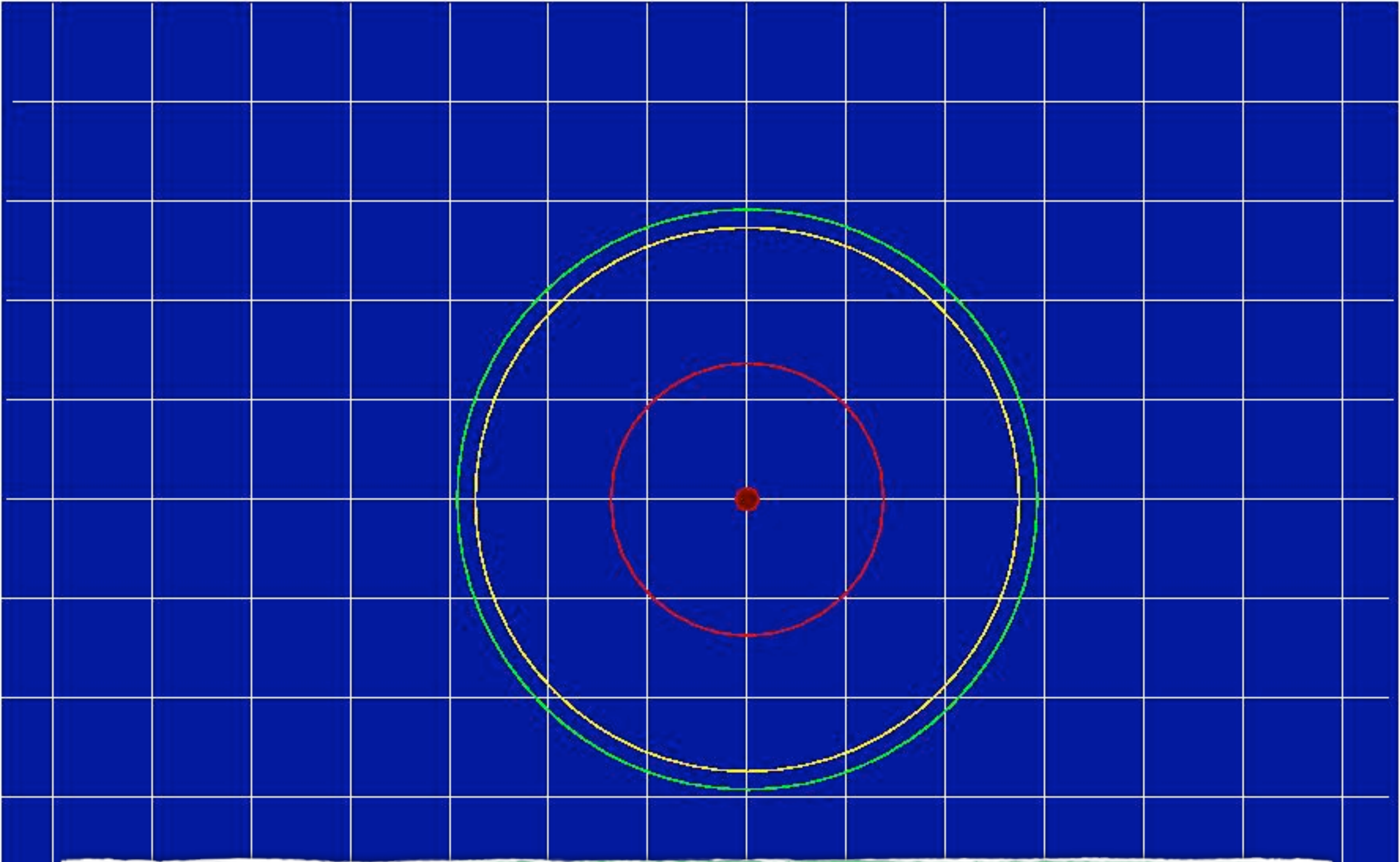


Light from event is on its way....


Event is finally observed...
light from event
horizon of observer



All events that happened simultaneous on red circle, are observed simultaneous



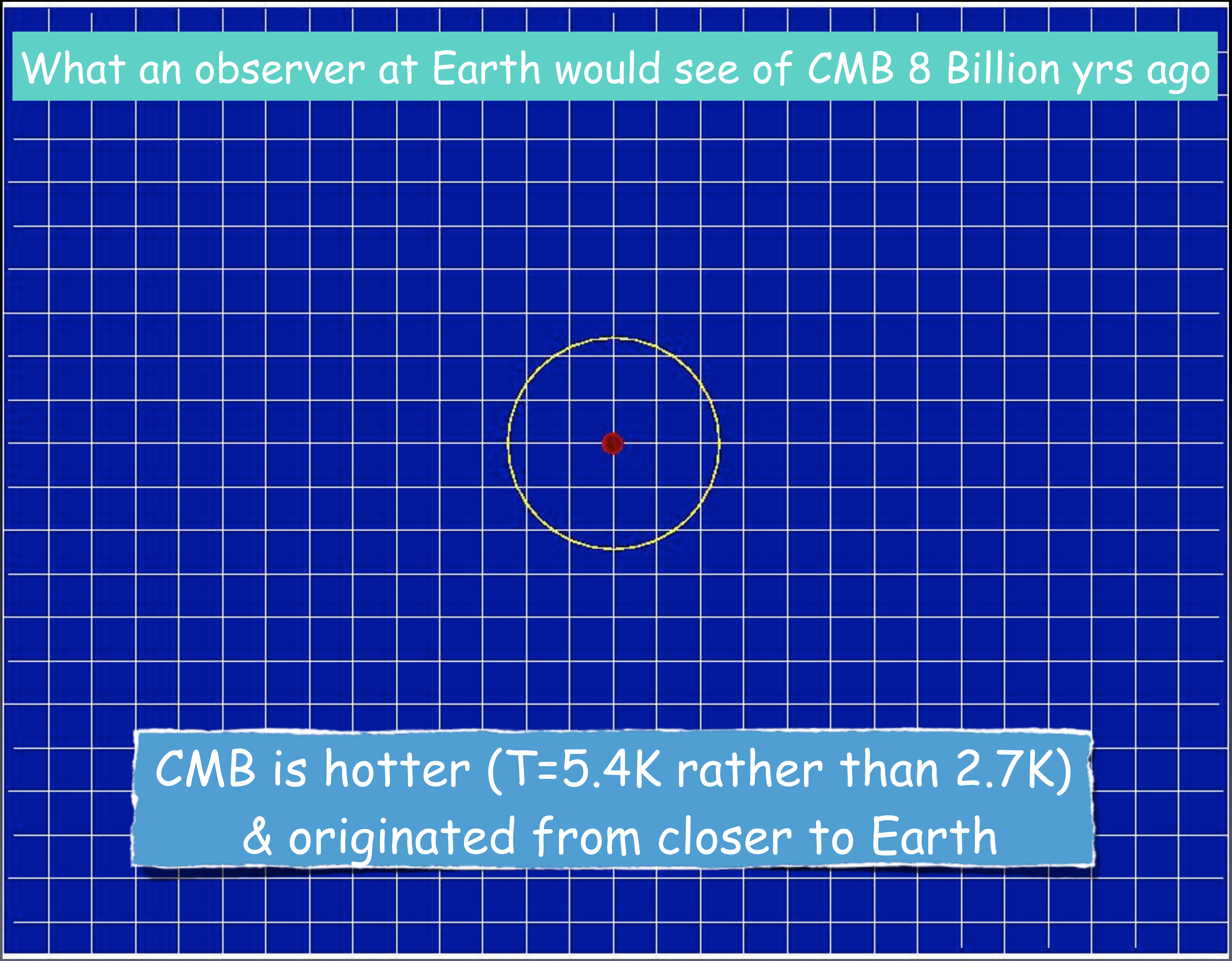
What we observe today of what happened 8 Billion yrs after Big Bang (z=1)

What we observe today of what happened 380.000 yrs after Big Bang (z=1100)

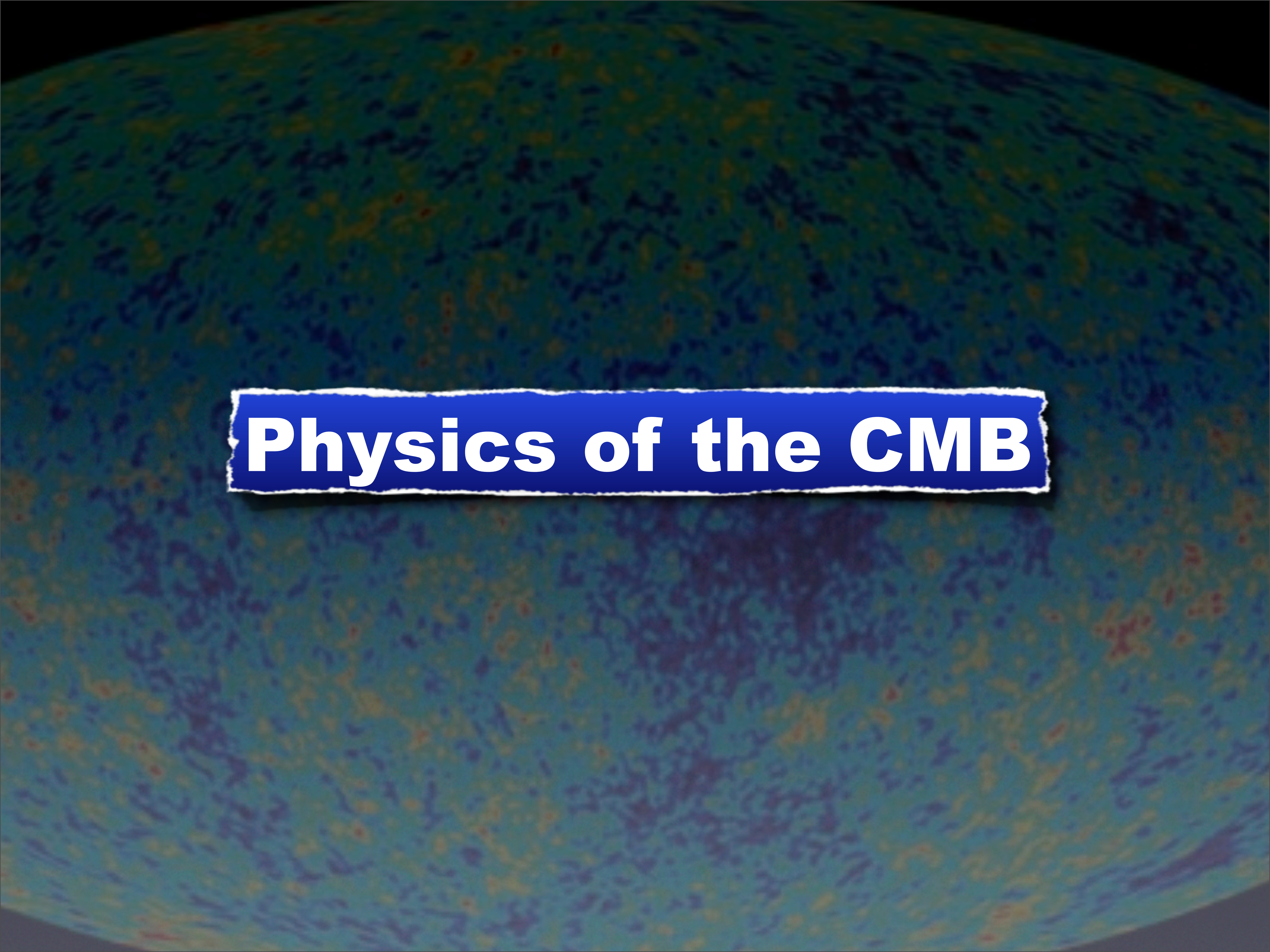
What we observe today of what happened at the Big Bang (z=infinity)

What an observer at Earth would see of CMB 8 Billion yrs ago

What an observer at Earth would see of CMB 8 Billion yrs ago



CMB is hotter (T=5.4K rather than 2.7K)
& originated from closer to Earth

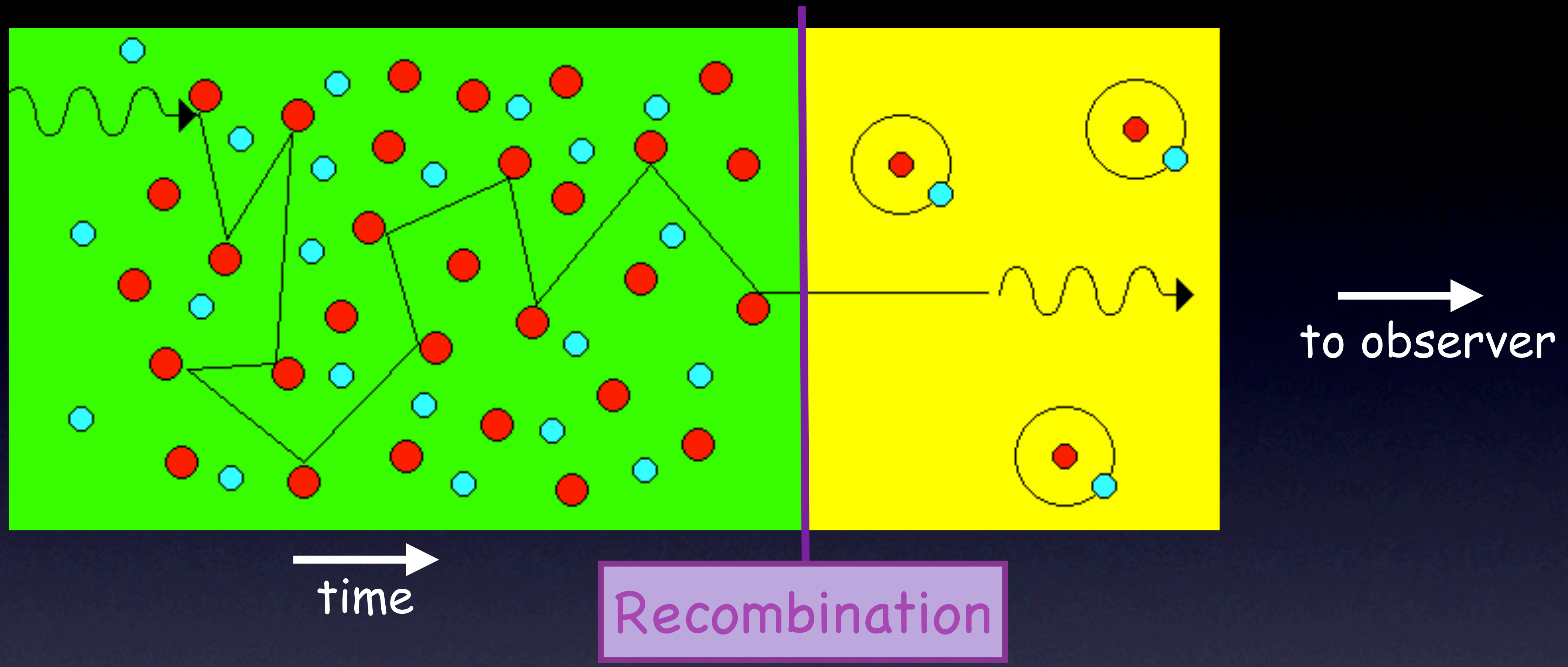


Physics of the CMB

Turning Back the Clock...

- In present day Universe, mean free path of photons exceeds horizon; average photon traverses visible Universe without interaction (which is why we can see galaxies etc.)
- Going back in time, the Universe becomes denser & hotter.
- There comes a time, when photons are so energetic that they destroy hydrogen atoms: H --> p + e
- At earlier times, photons interact strongly with free electrons (Thomson scattering), while electrons have Coulomb interactions with free protons: photon-baryon fluid.
- In photon-baryon fluid, mean free path of photons is tiny; photons are trapped, and can't get `out of box'

Recombination; the Origin of CMB Radiation



Shortly after Big Bang, Universe consists of dark matter and a photon-baryon fluid; photons are trapped.

About 380.000 yrs after Big Bang, Universe has cooled to the point where electrons & protons combined to form Hydrogen atoms: sudden increase in mean free path of photons --> CMB

The Last Scattering Surface

The CMB are photons from the last scattering surface at a redshift of z~1100, when the Universe recombined.

At recombination T ~ 3000K. Because of expansion of Universe, photons have been redshifted to T ~ 3 K.

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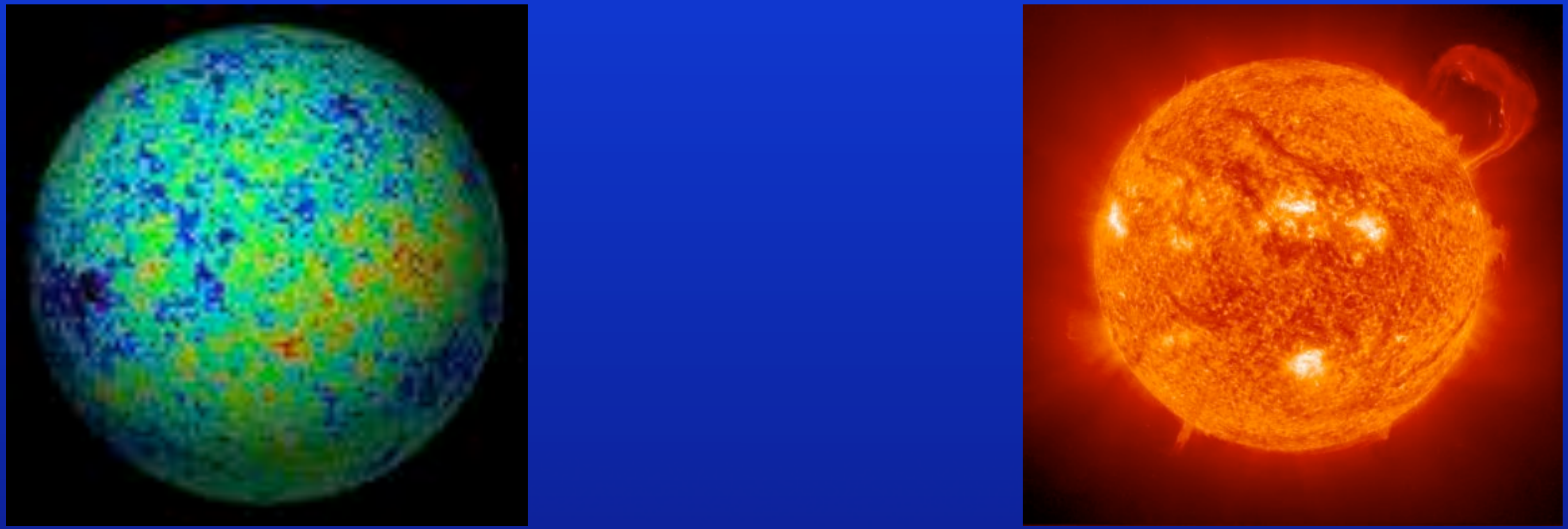
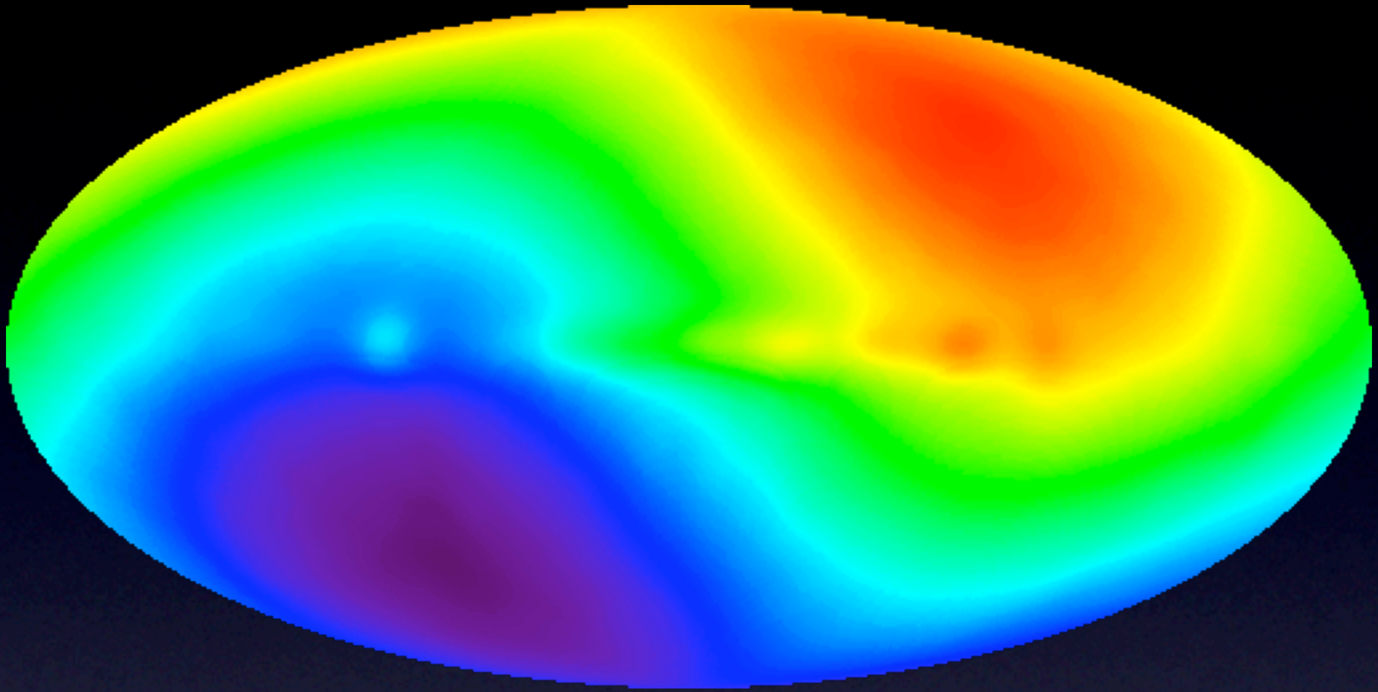
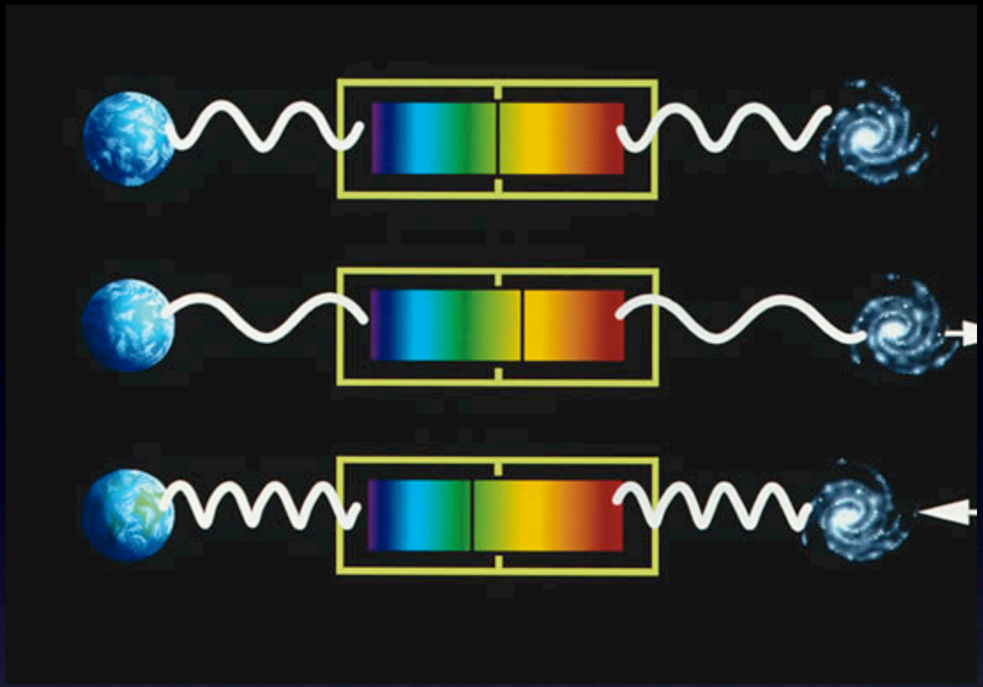


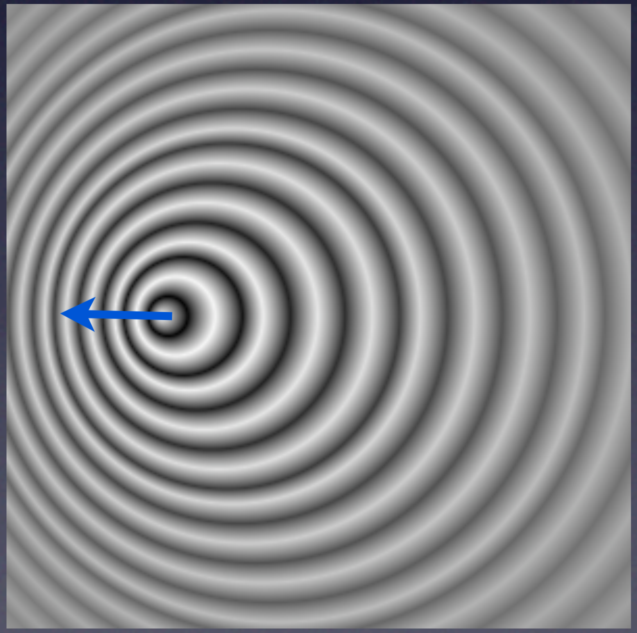
Last Scattering Surface is like photosphere of Sun; no information from before recombination can reach us (except for neutrinos & gravitational waves)

Origin of the Dipole

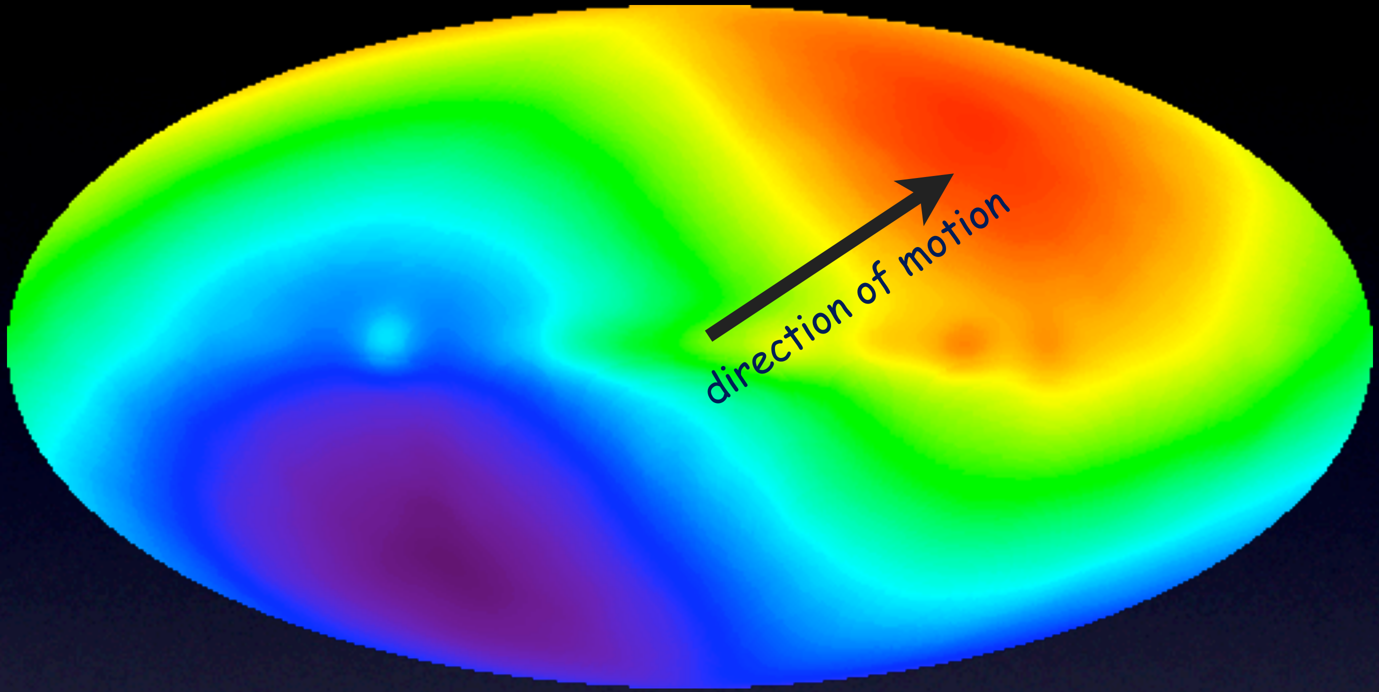


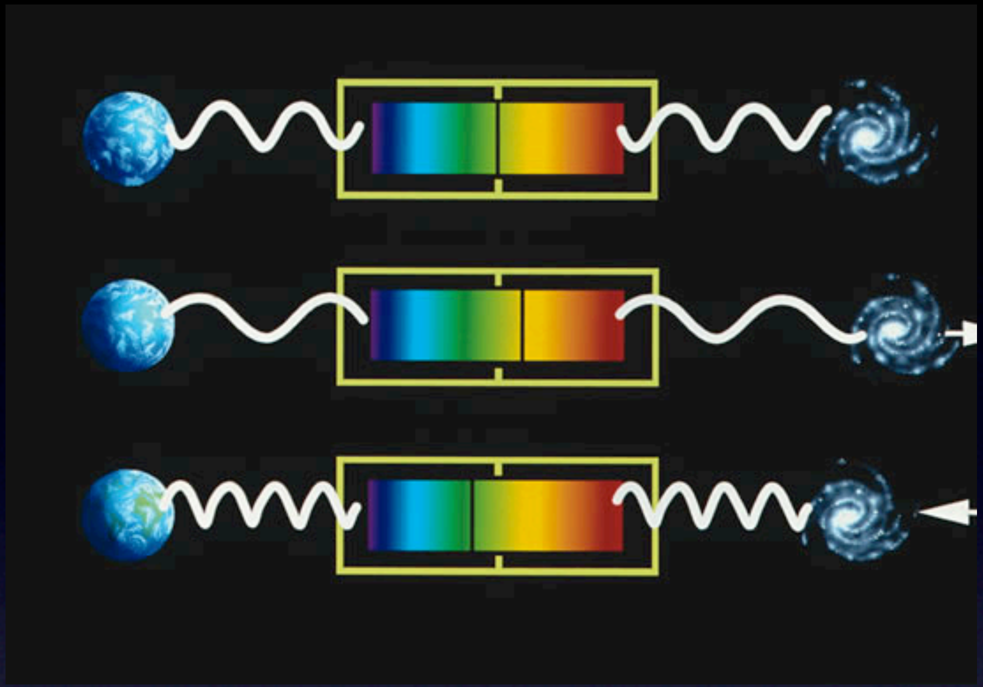


The origin of the dipole in the CMB is the
the Doppler effect due to our peculiar motion

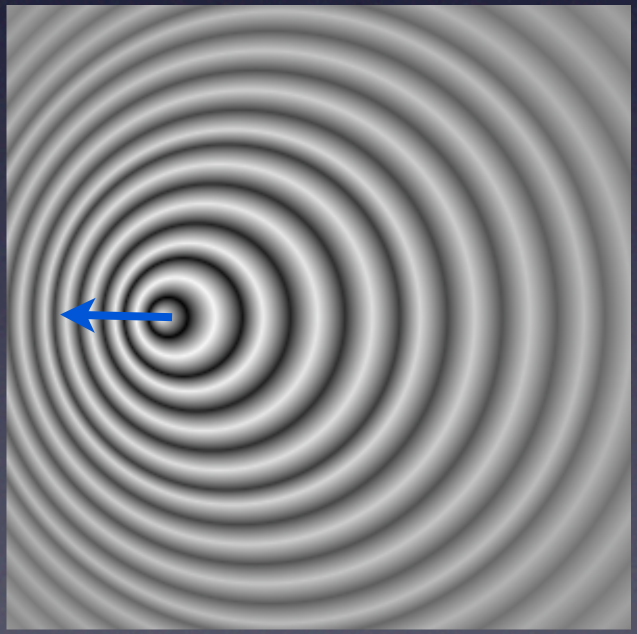


Origin of the Dipole

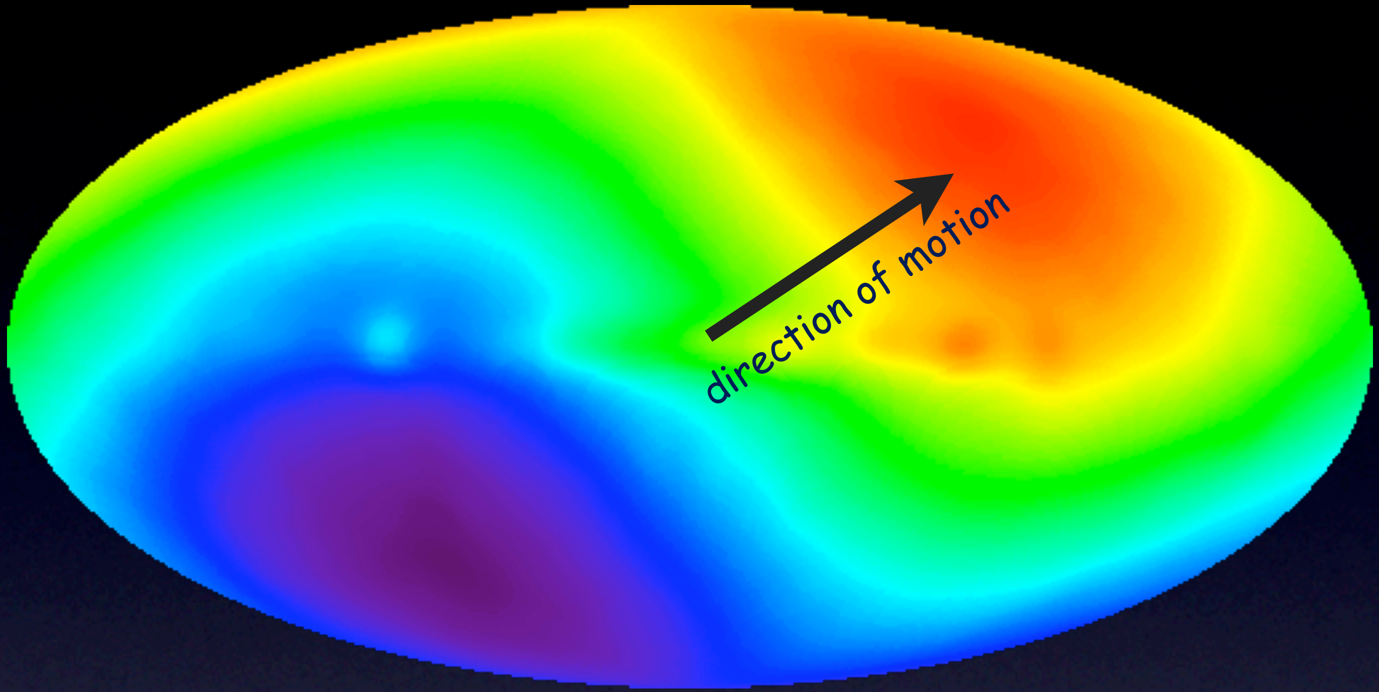


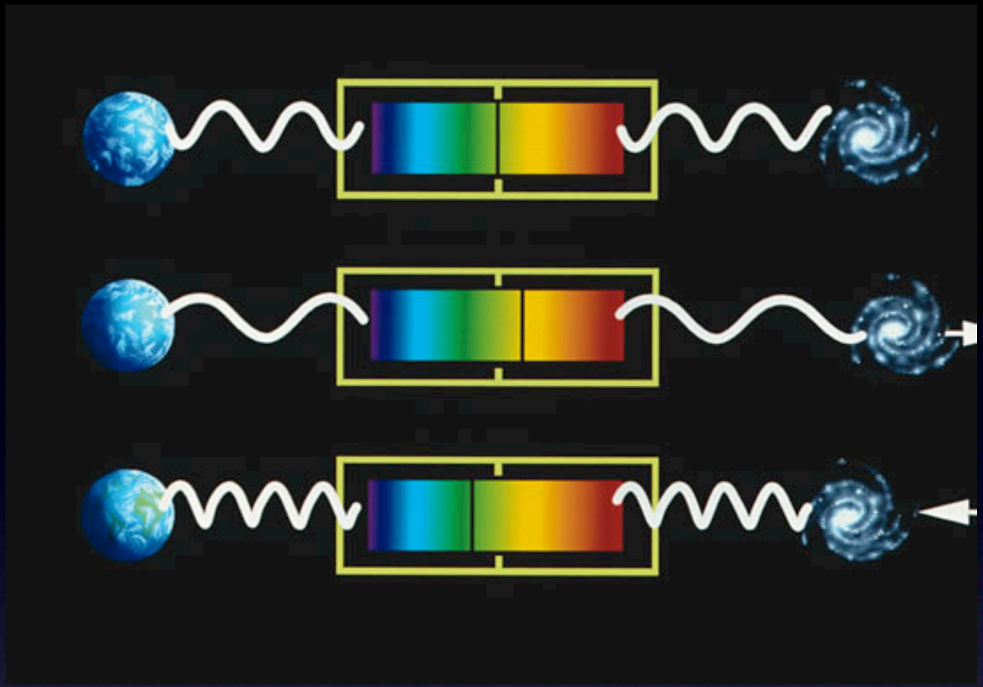


The origin of the dipole in the CMB is the the Doppler effect due to our peculiar motion



Origin of the Dipole





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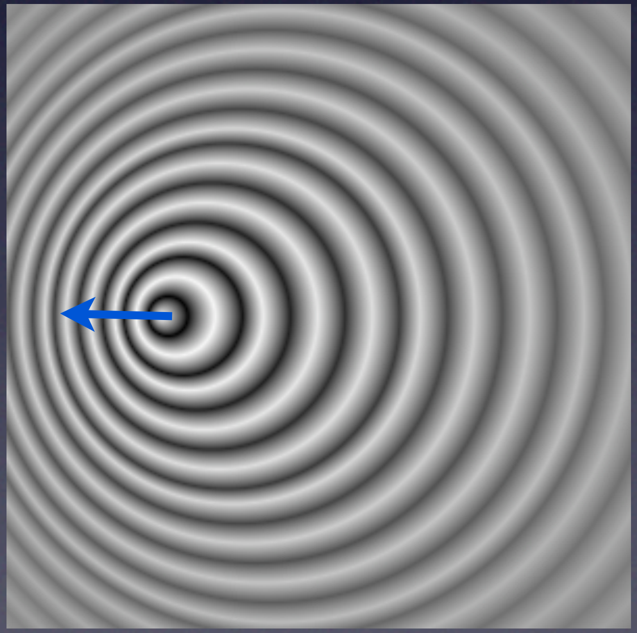
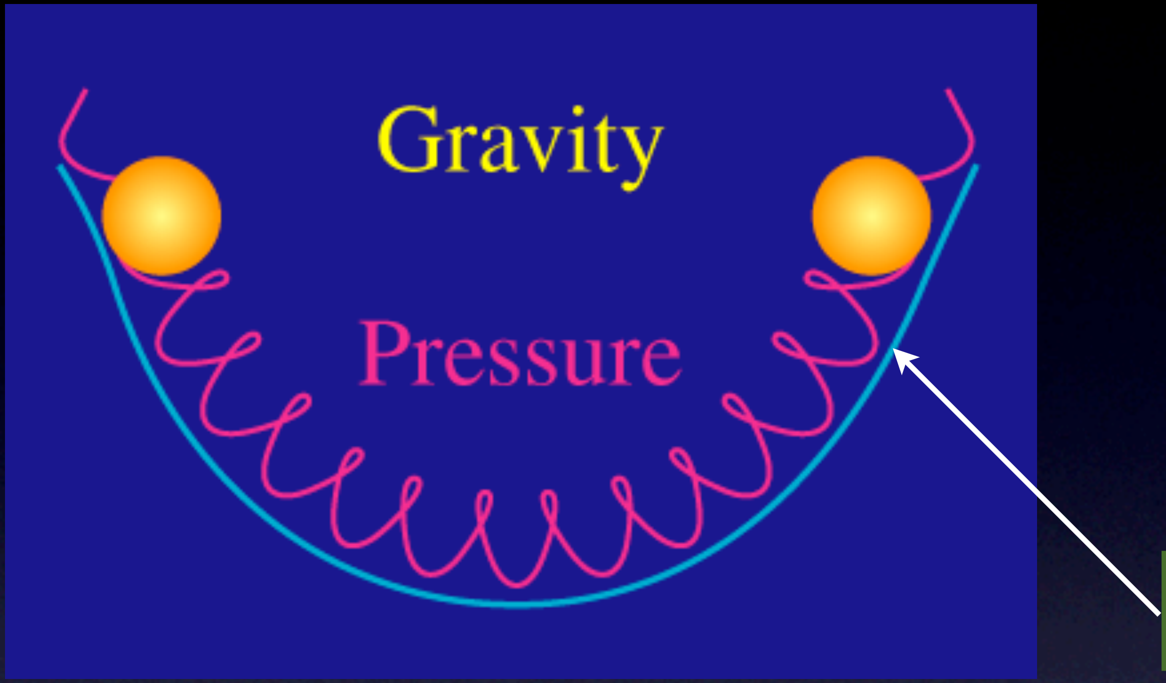


Peculiar motion made up of:

- Motion of Earth around Sun (~30 km/s)
- Motion of Sun around MW center (~220 km/s)
- Motion of MW towards Virgo cluster (~300 km/s)

Total vector sum of 369 km/s

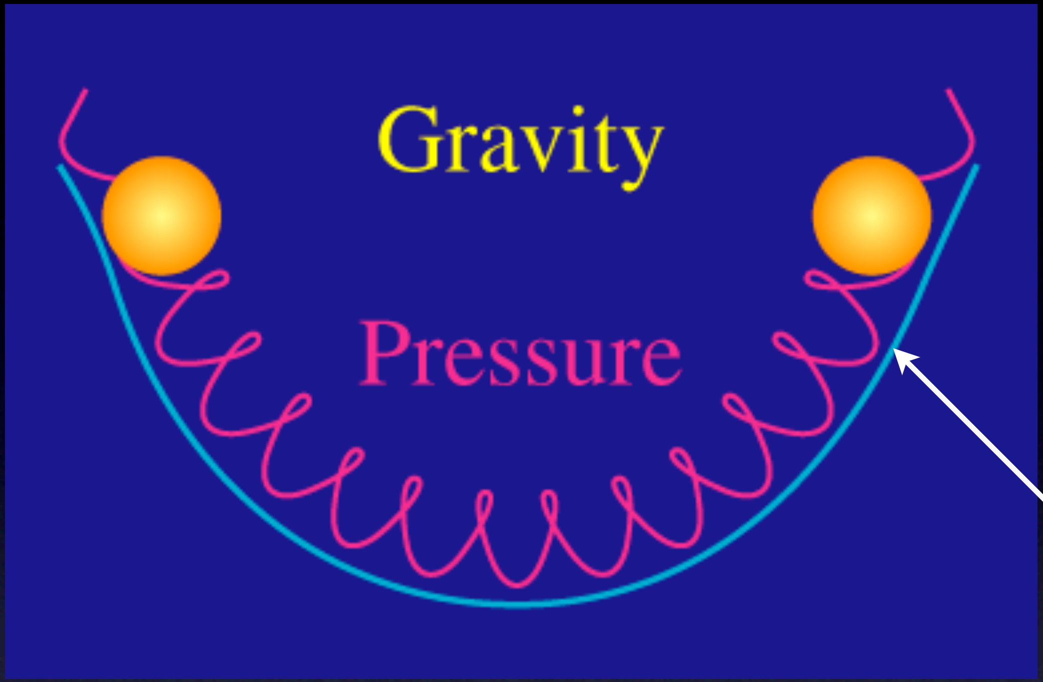
Origin of Acoustic Peaks



Dark Matter Perturbation --> Potential well

Pressure of photon-baryon fluid resists gravity, giving rise to oscillations --> sound waves

Origin of Acoustic Peaks

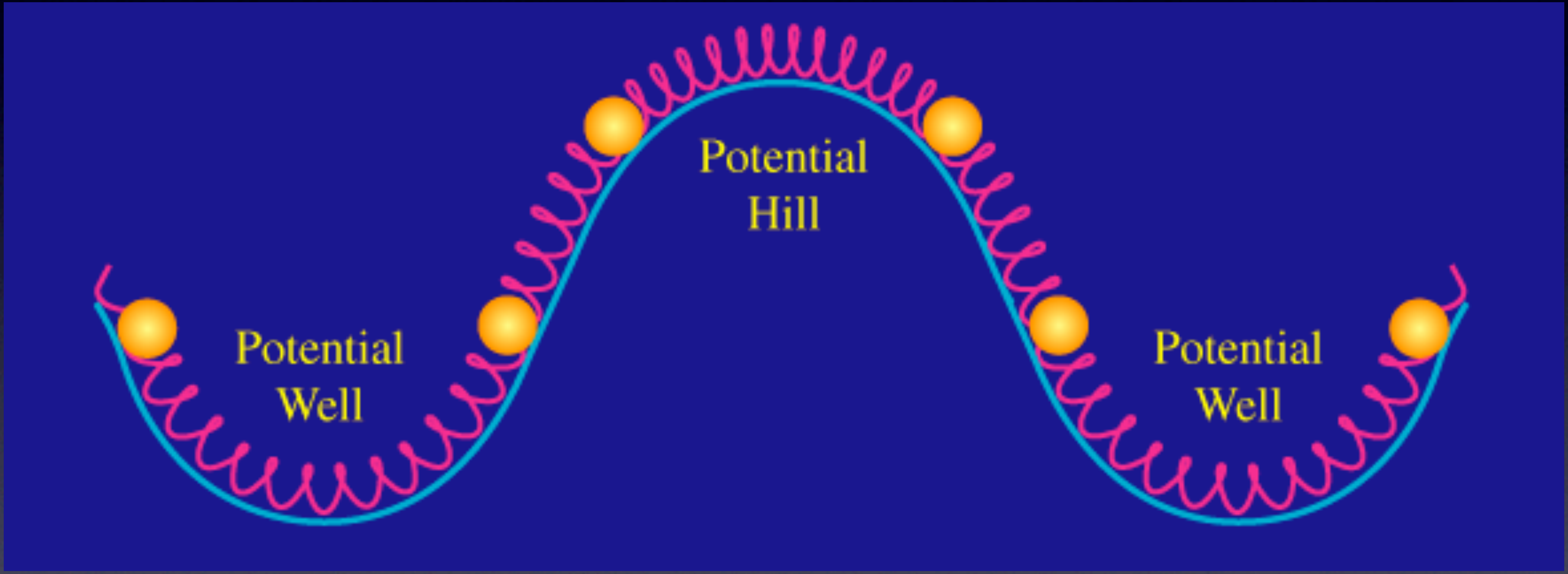


Dark Matter Perturbation --> Potential well

Pressure of photon-baryon fluid resists gravity, giving rise to oscillations --> sound waves

Compressing a gas heats it up, expanding a gas cools it down --> Temperature fluctuations

Origin of Acoustic Peaks

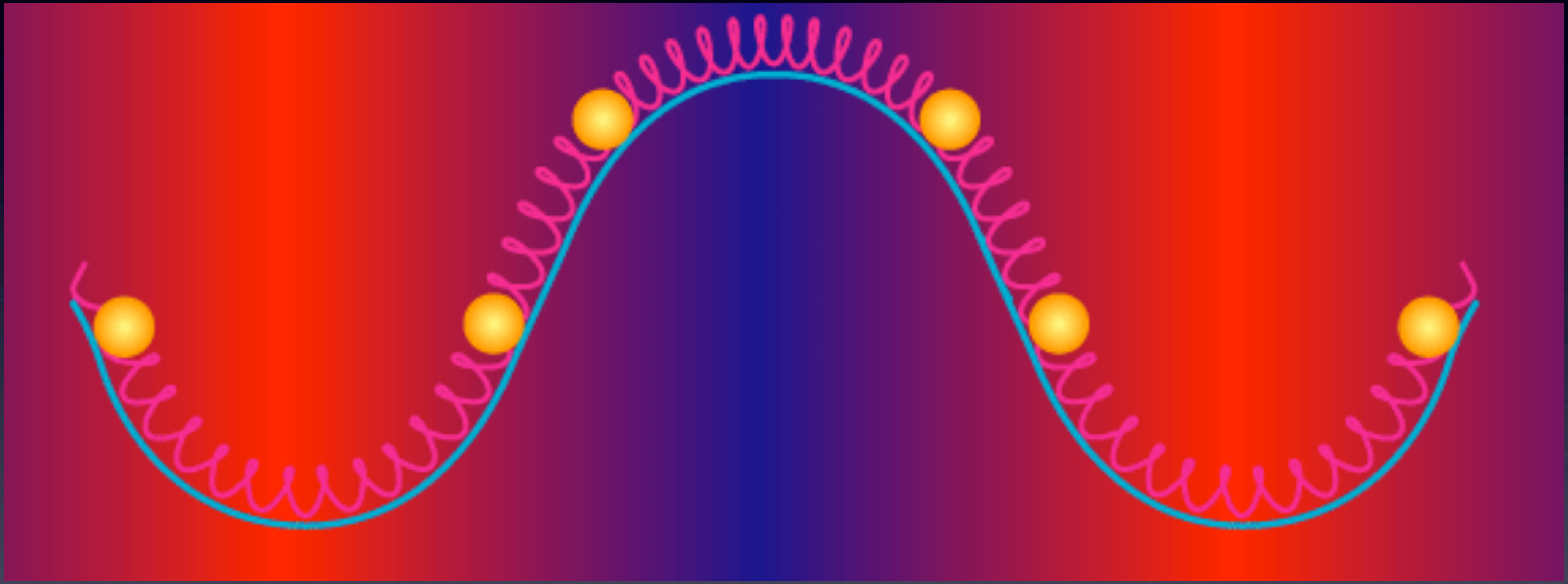


Origin of Acoustic Peaks

Red is Cold

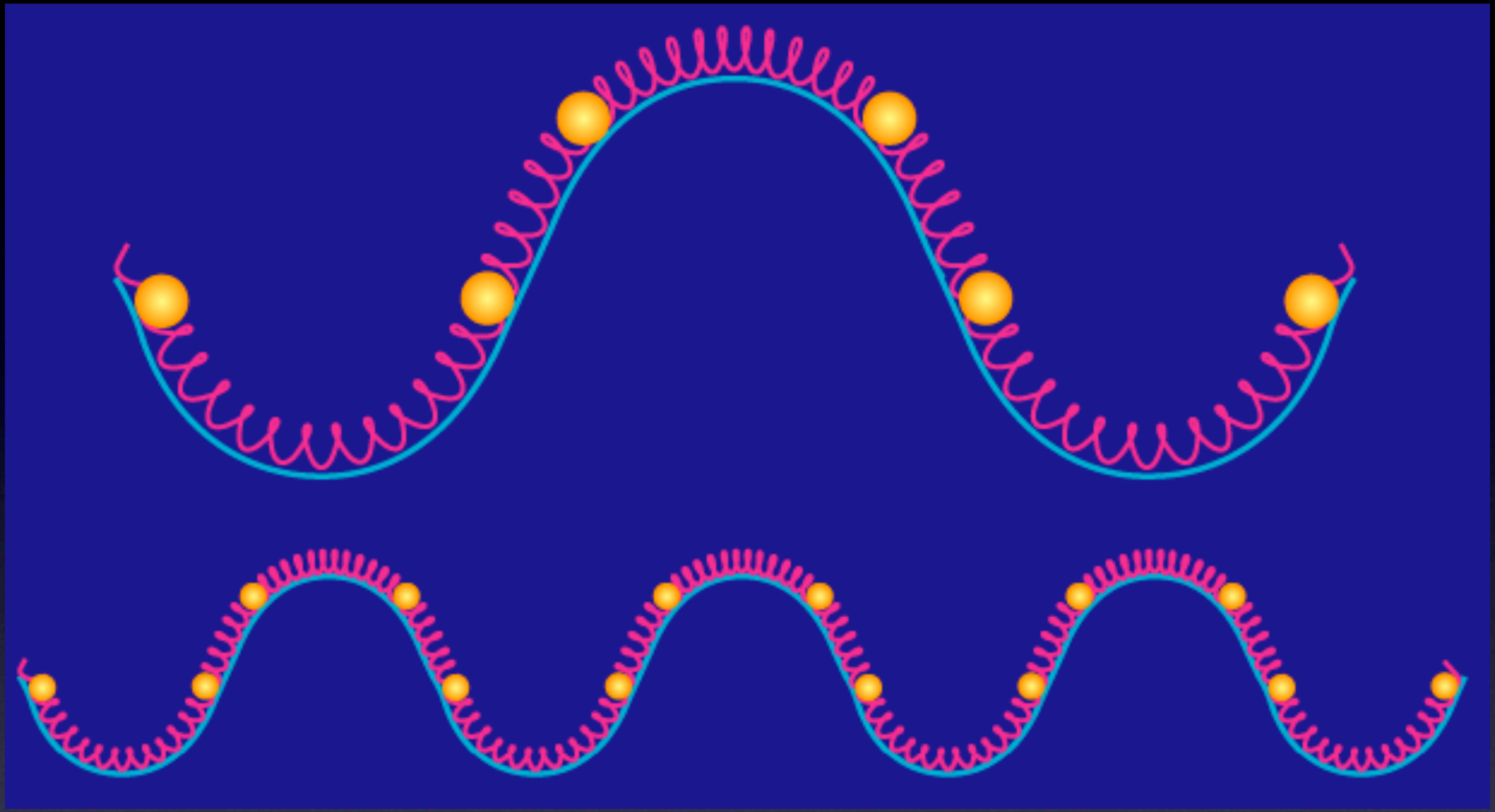
Blue is Hot

Compression results in higher temperature
Rarefaction results in lower temperature



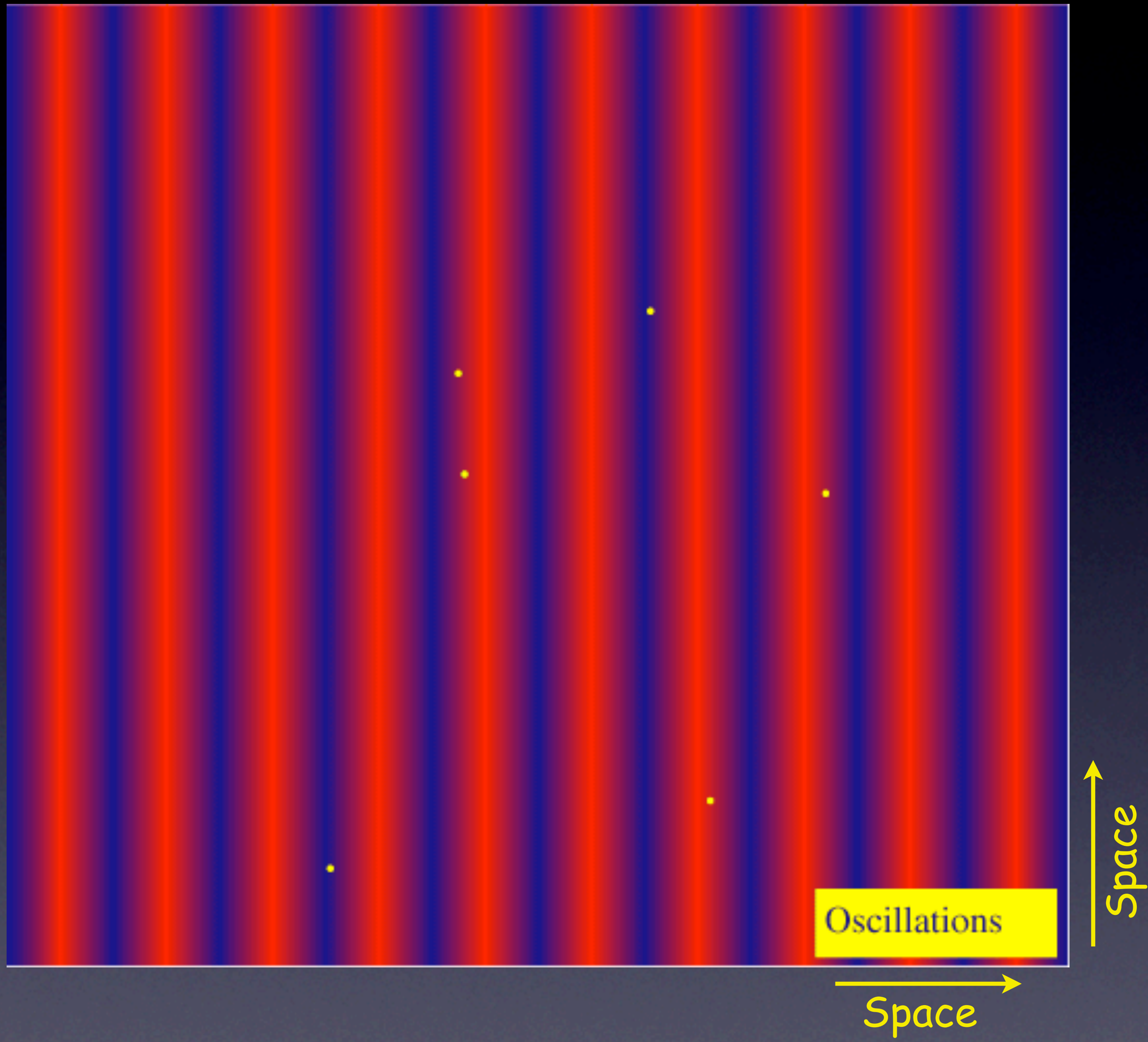
Compression in valley & rarefaction at hill
followed by
compression at hill & rarefaction in valley

Origin of Acoustic Peaks



- Density perturbation field is a combination of perturbations with different wavelengths (different `modes')
- Modes with smaller wavelengths oscillate faster.
- Modes stop oscillating at recombination (phases are `frozen')

Origin of Acoustic Peaks



Shown is a single mode, and the locations of six `photon-boxes'.

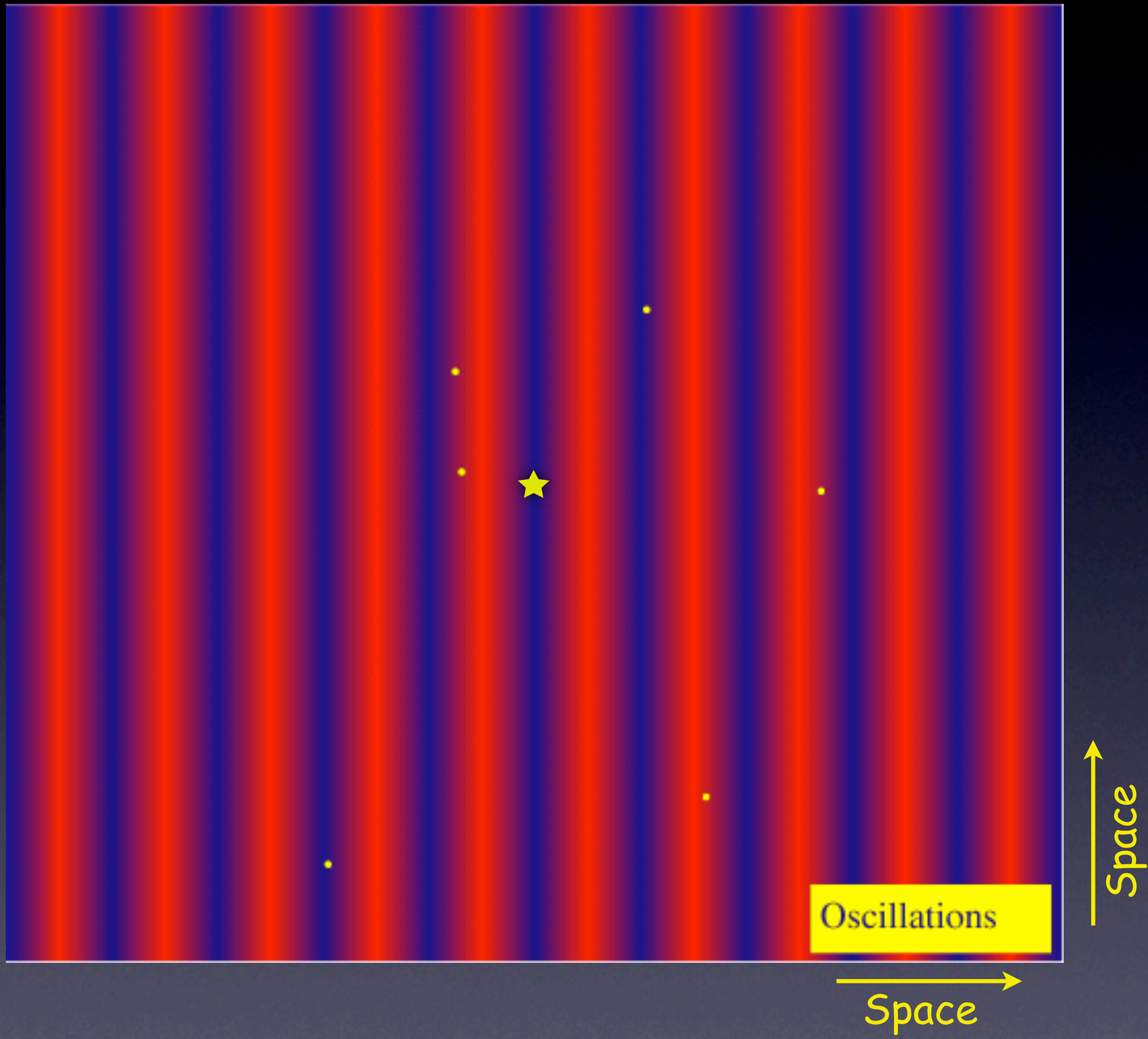
Origin of Acoustic Peaks

★=observer

At recombination, photons decouple & start to free-stream; angular scale of fluctuations proportional to wavelength of mode.

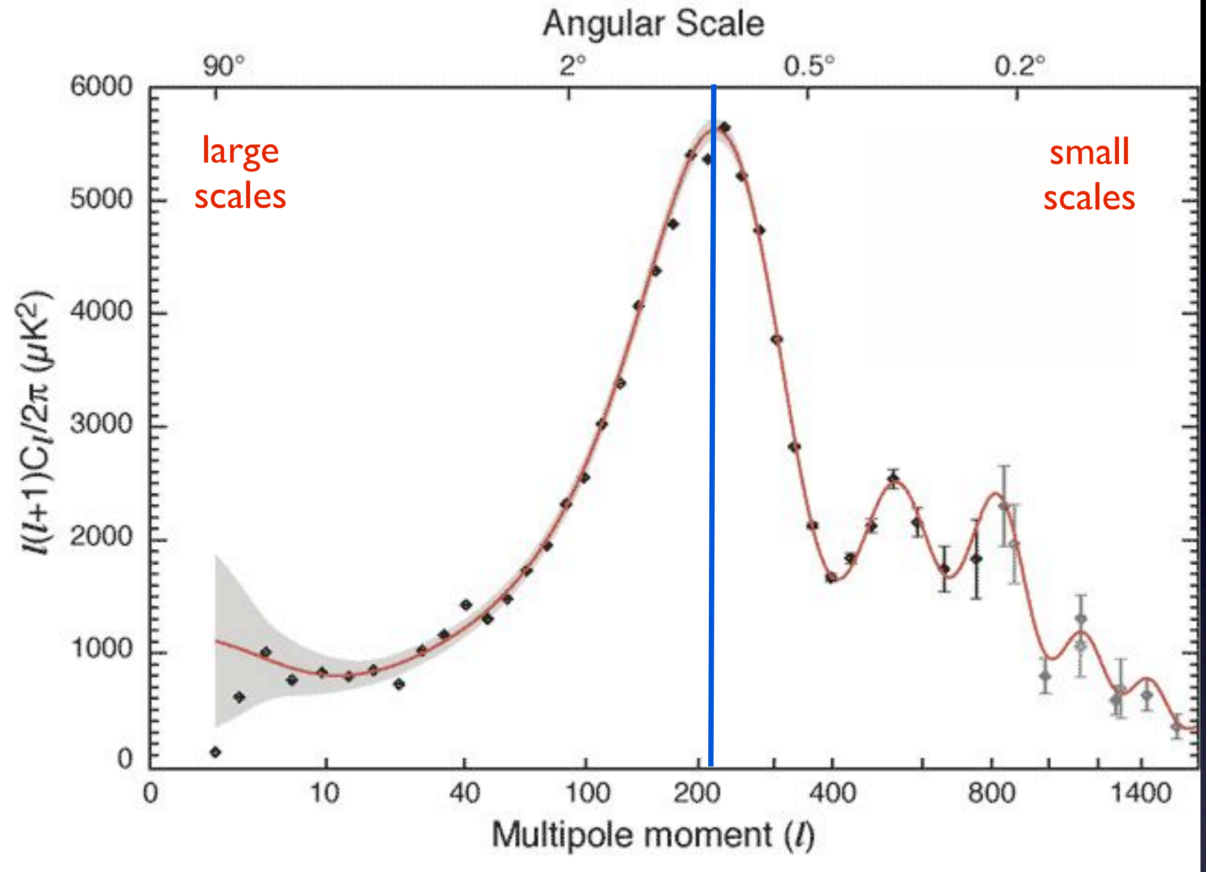
Origin of Acoustic Peaks

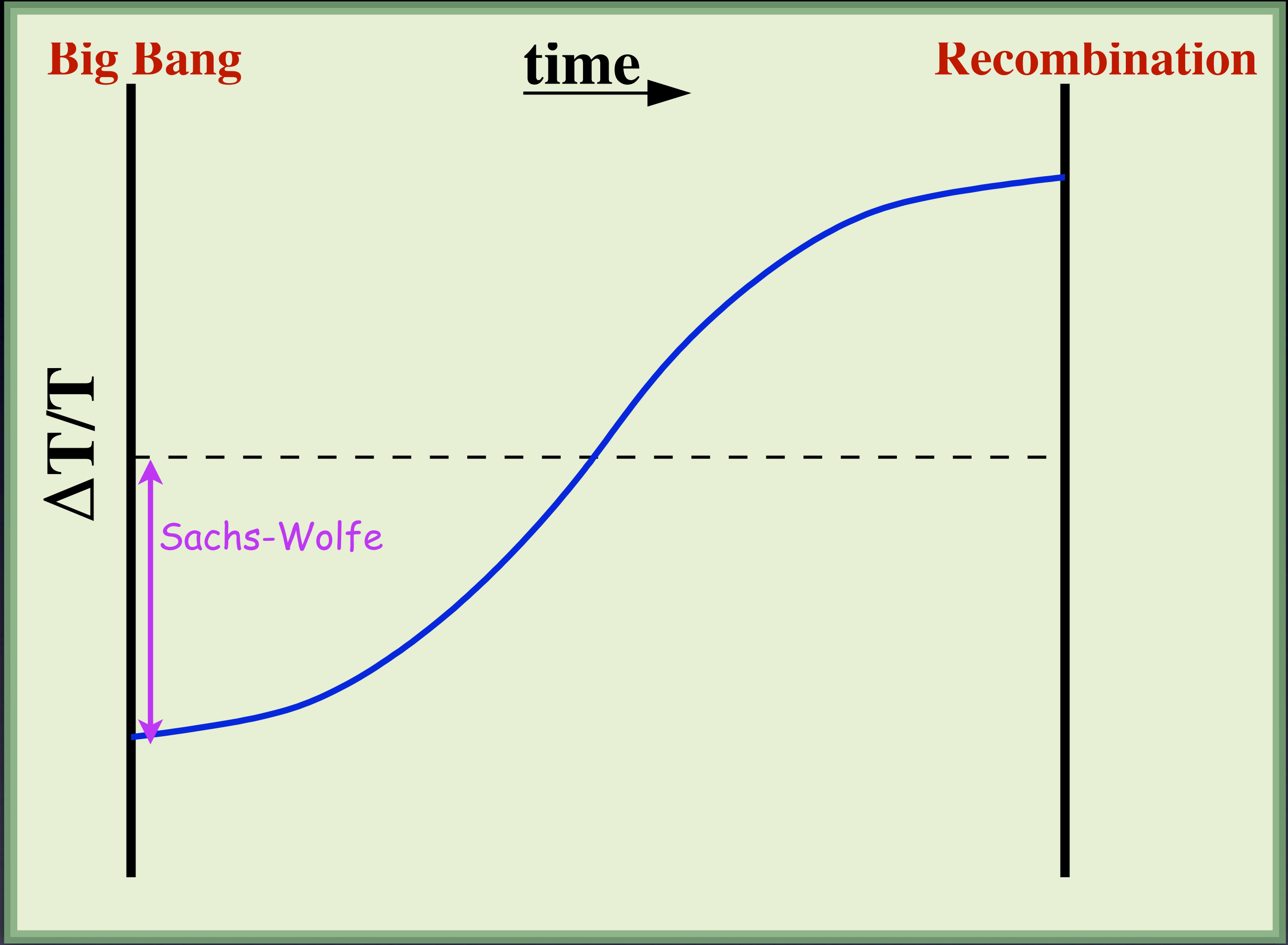
★=observer

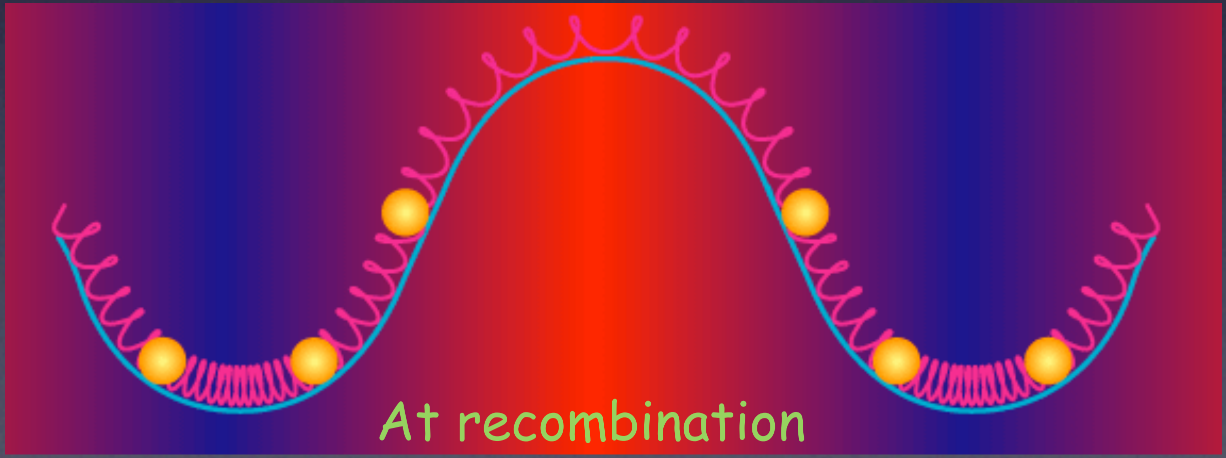


At recombination, photons decouple & start to free-stream; angular scale of fluctuations proportional to wavelength of mode.

Origin of First Acoustic Peak

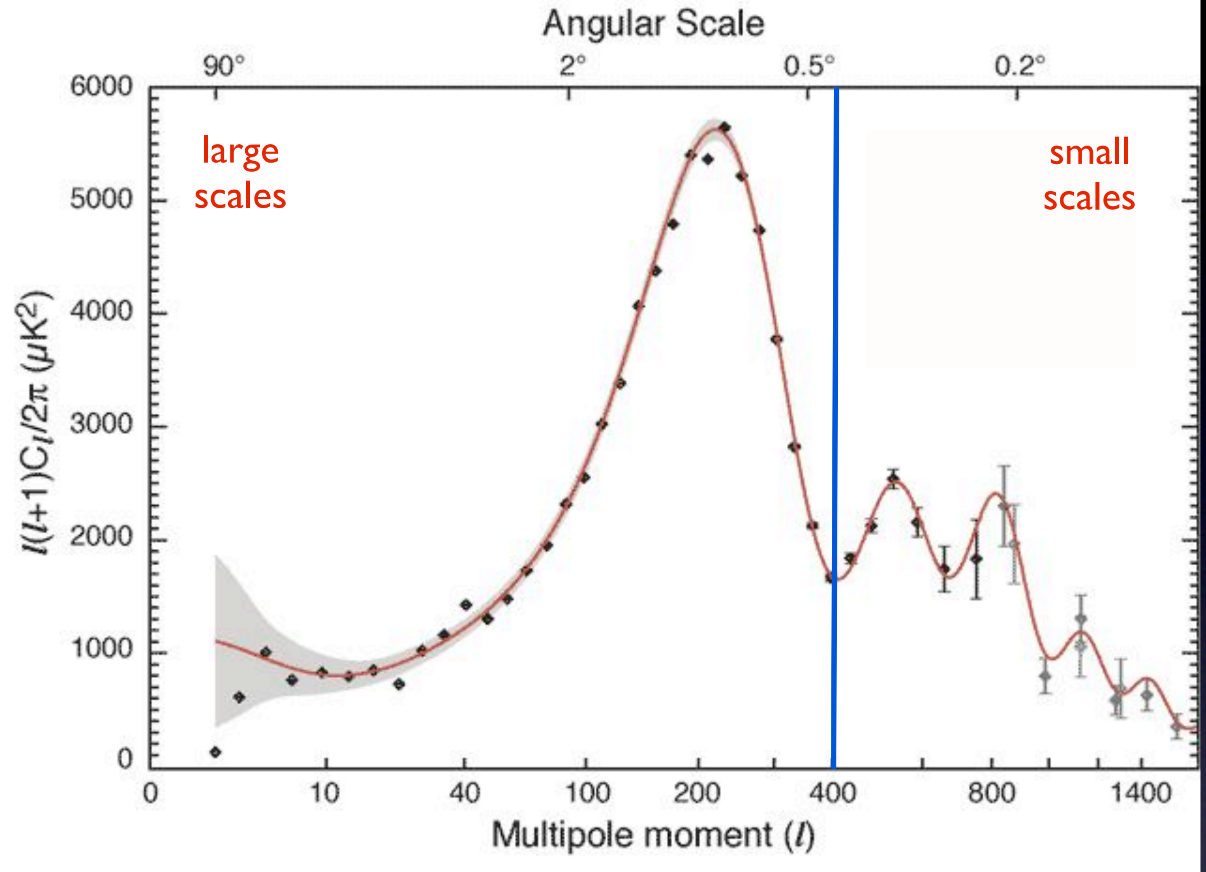


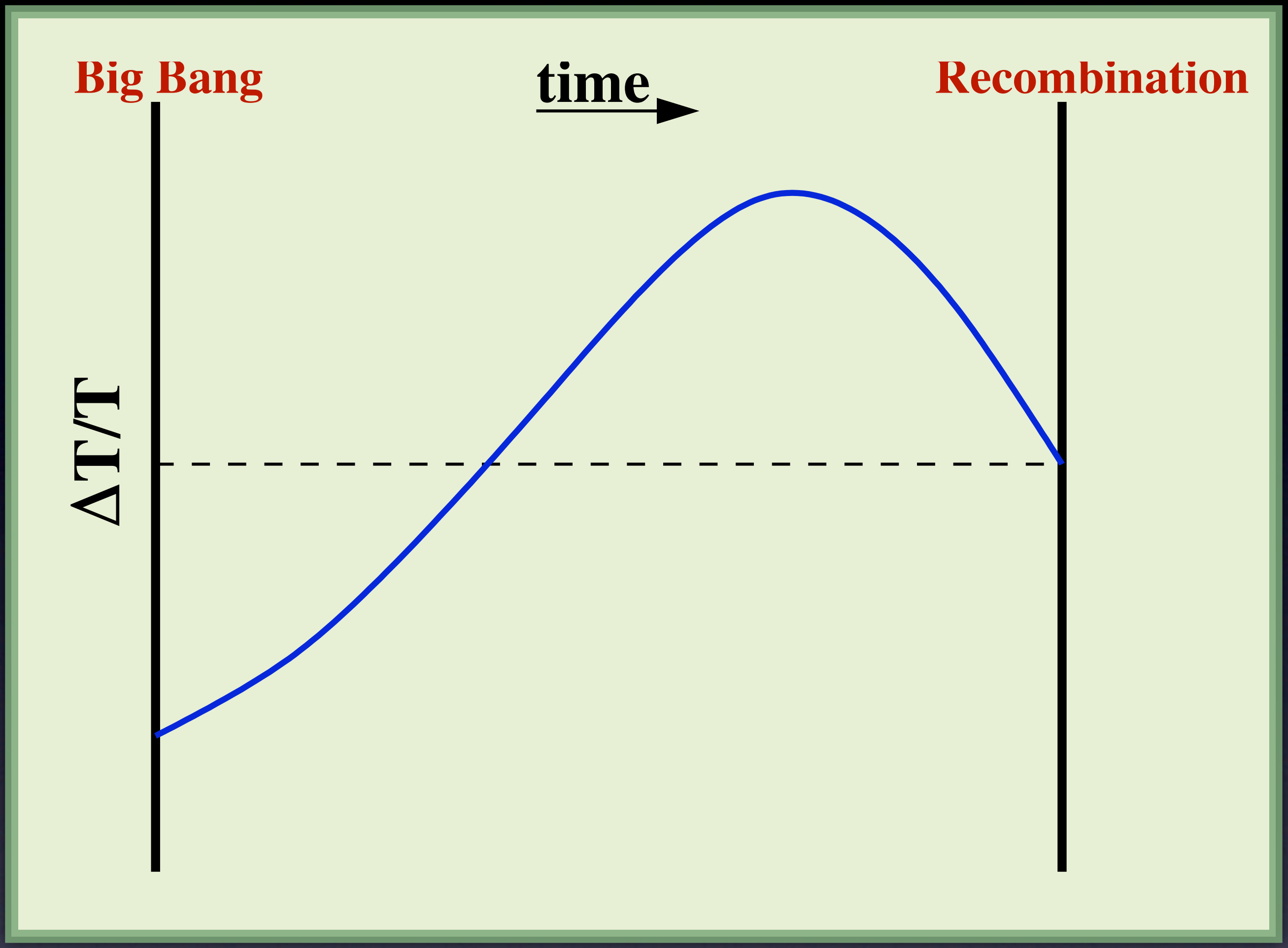


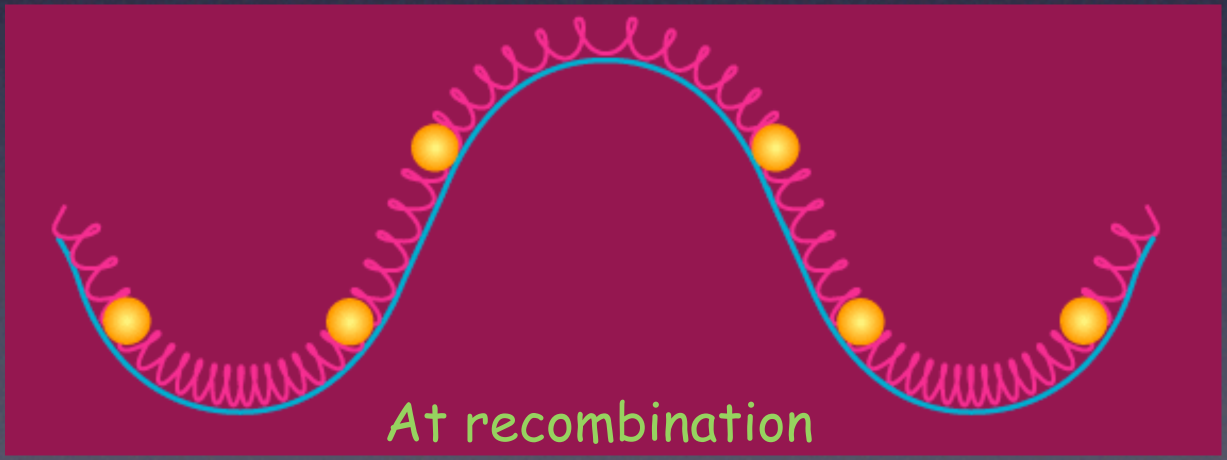


First peak due to mode that just reaches maximal compression in valley/rarefaction on hill top for first time

Origin of First Acoustic Trough

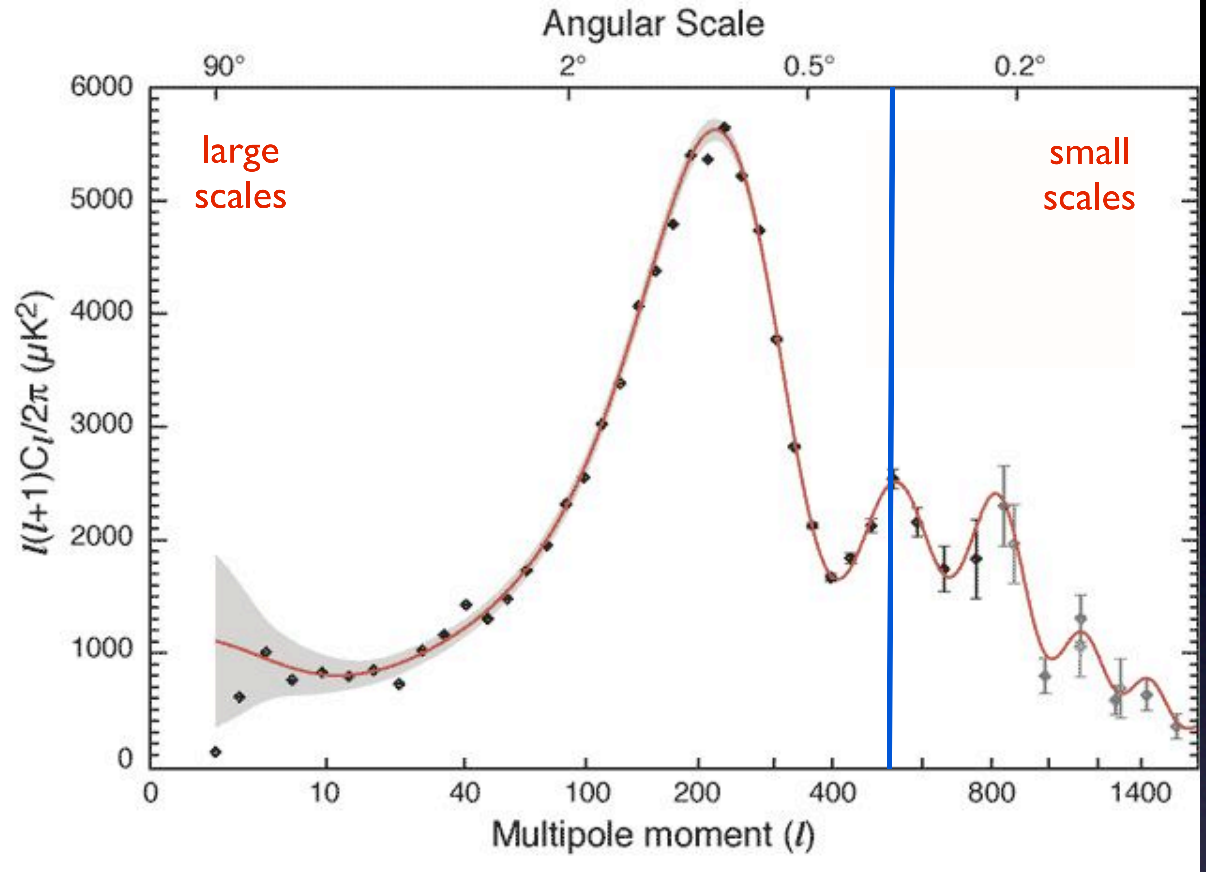


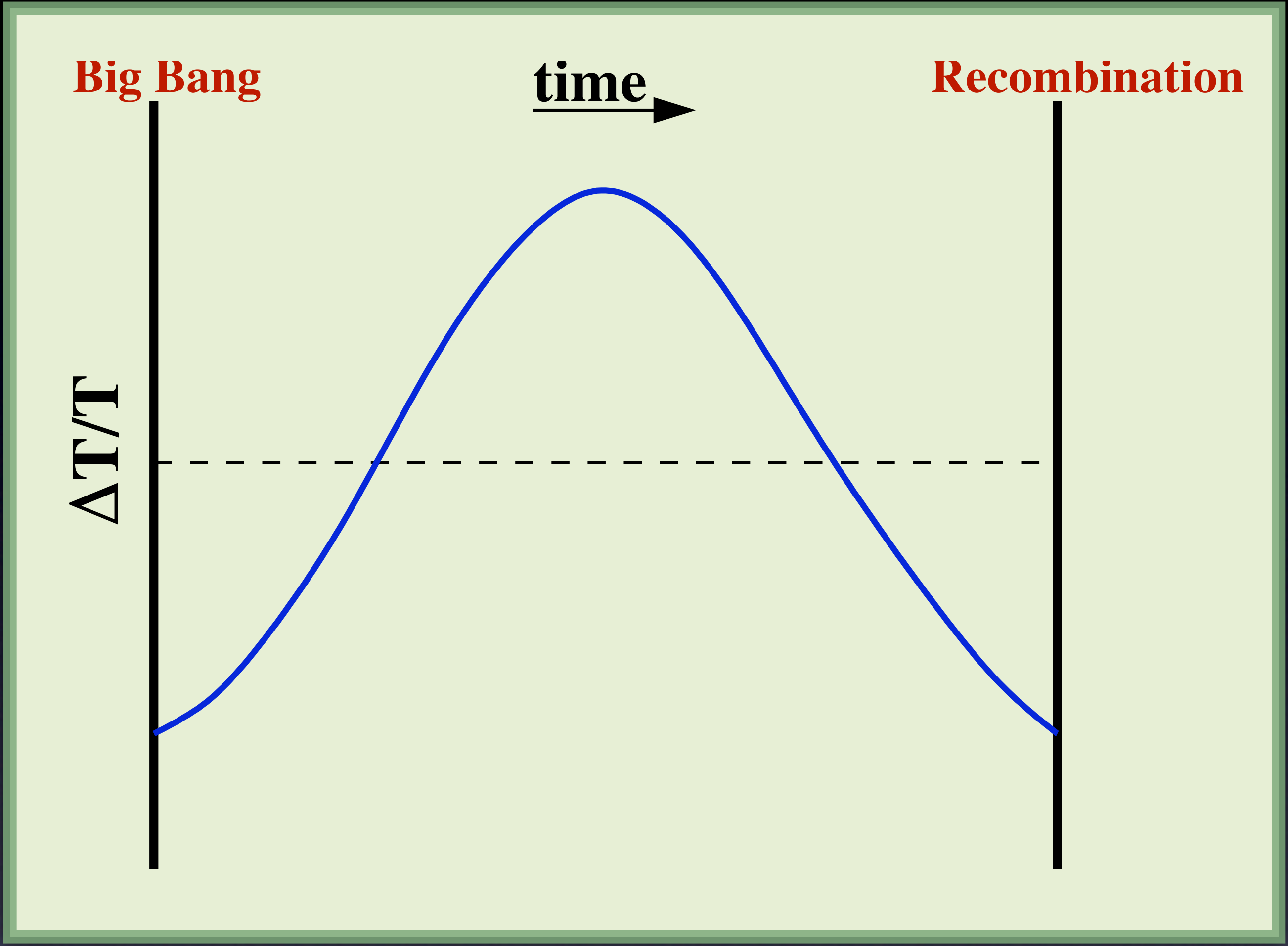


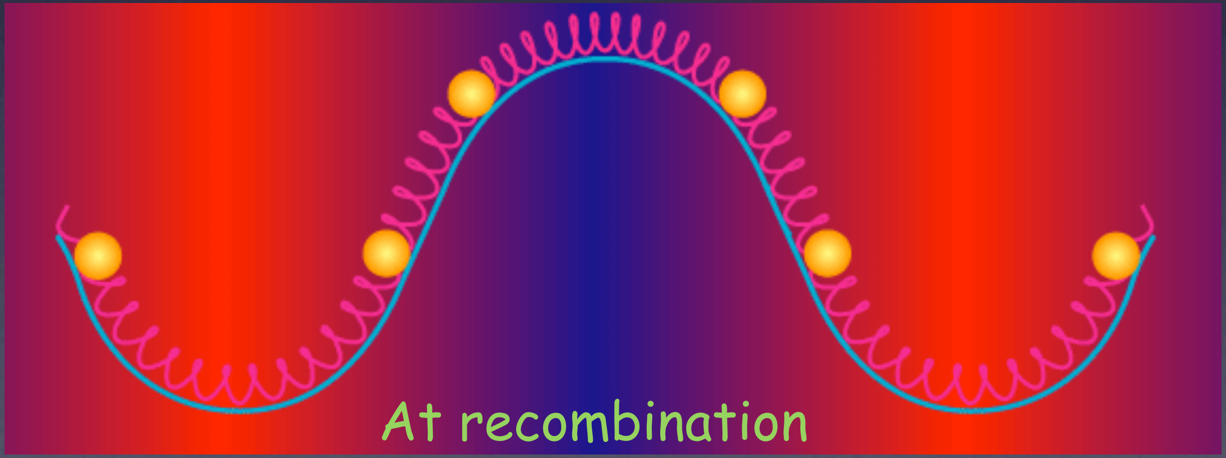


At troughs, temperature fluctuations are not zero due to motions of photon-baryon fluid --> Doppler effect.

Origin of Second Acoustic Peak

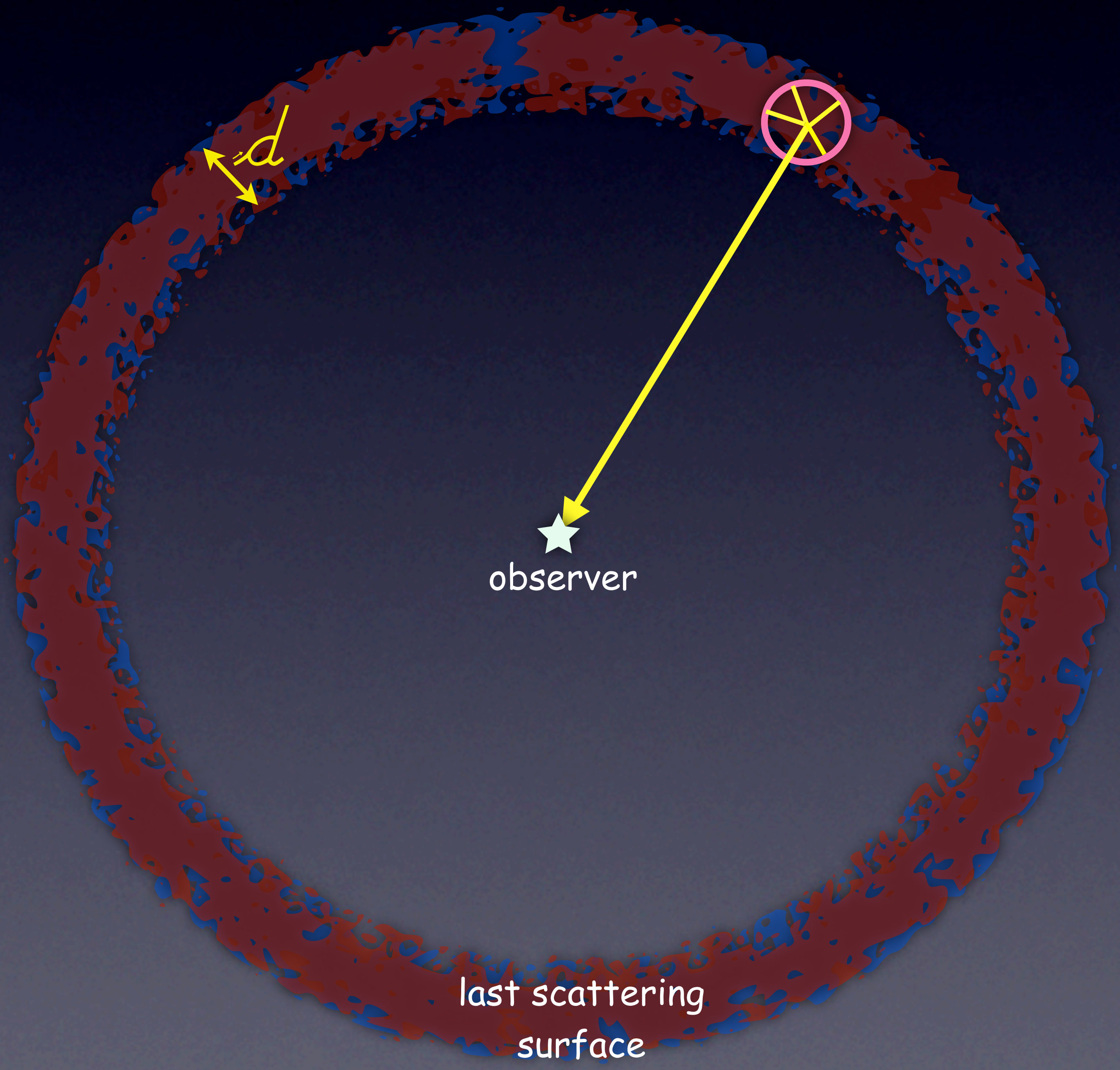


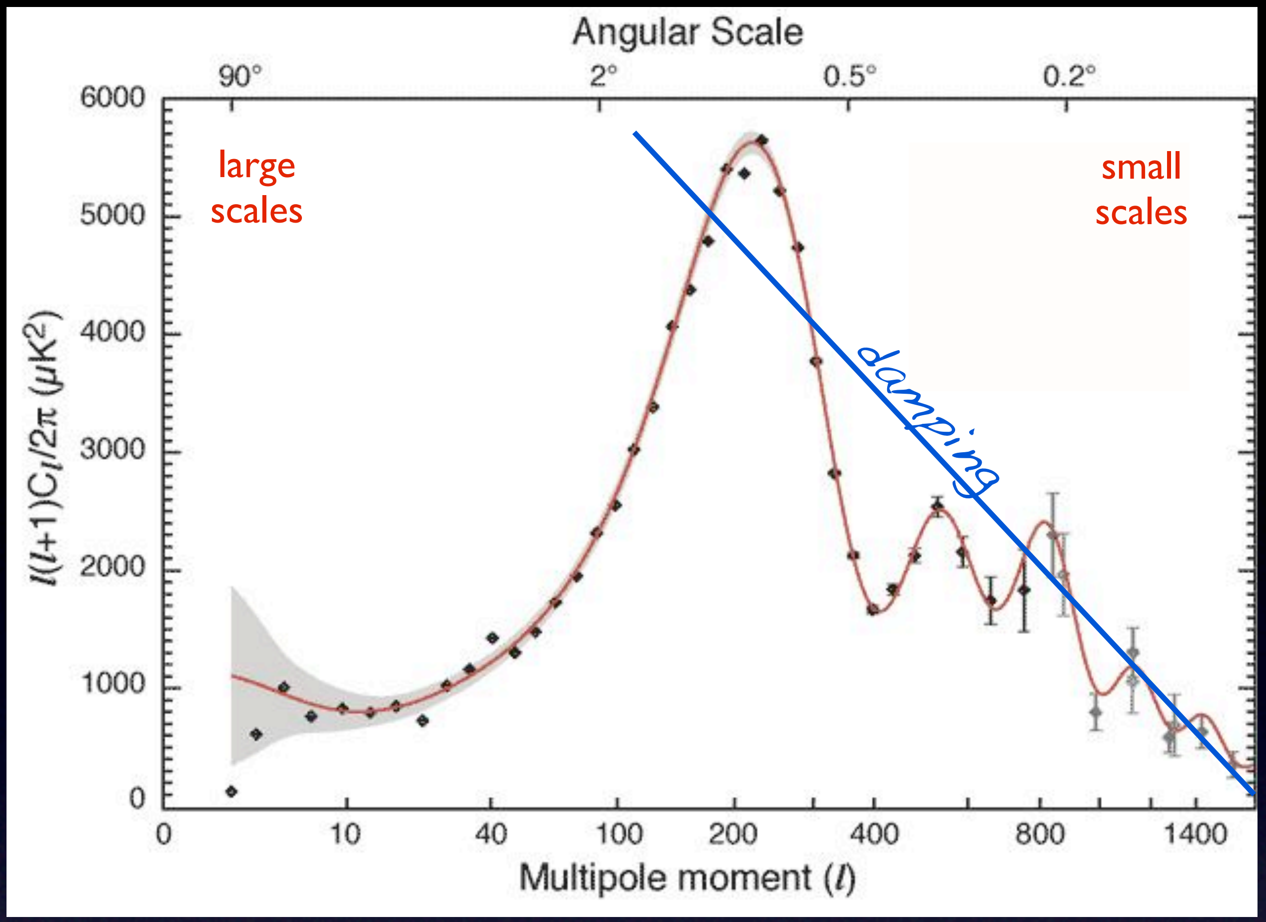




Second peak due to mode that just reaches maximal rarefaction in valley/compression on hill top for first time

Diffusion Damping



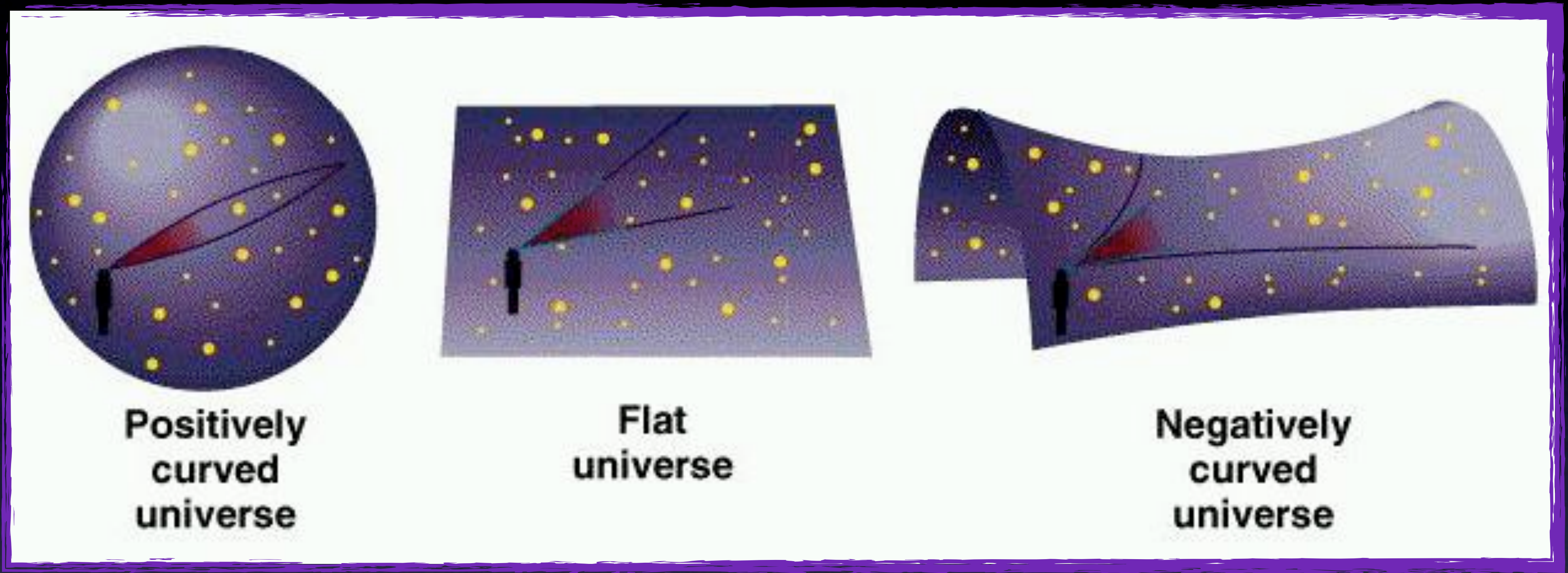


Recombination is not instantaneous; rather the last scattering surface has finite thickness d

Consequently, fluctuations on scales smaller than d are washed out causing damping on small angular scales.

Lessons Learned

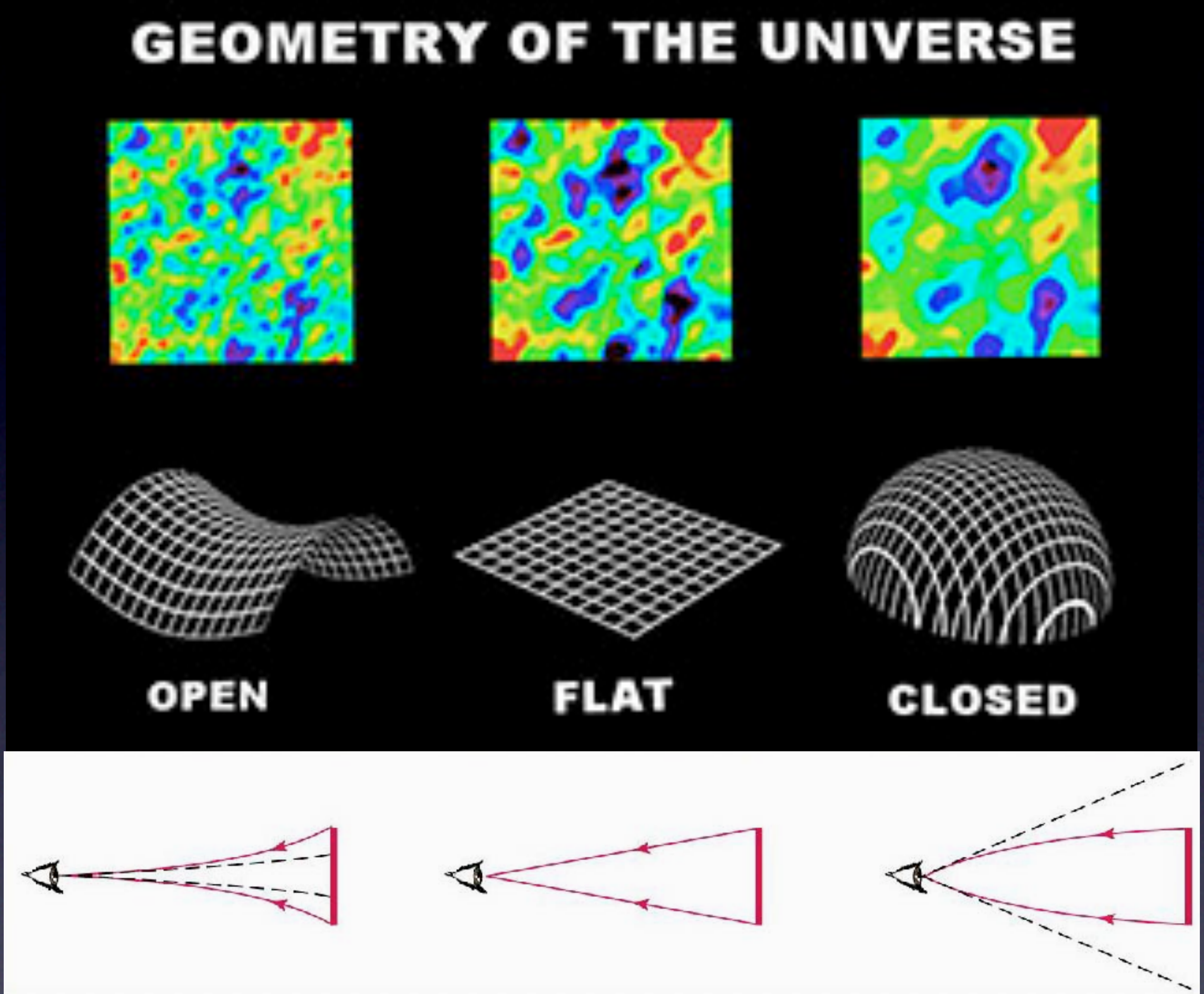
The Curvature of the Universe



Curvature of Universe can be probed using large-scale triangles

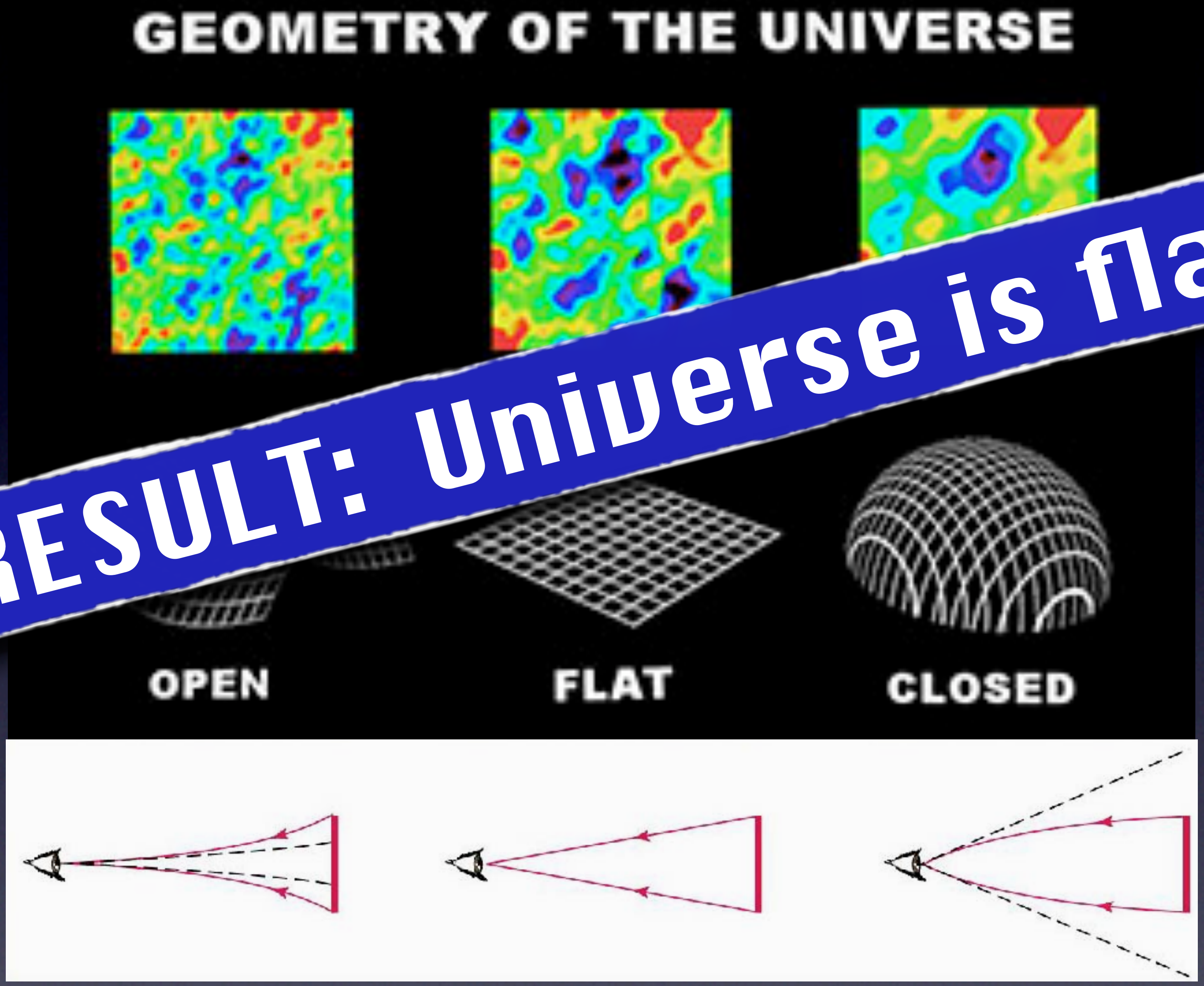
The Curvature of the Universe

The Curvature of the Universe



One such triangle comes from angular scale of first acoustic peak: $\Delta\Theta \sim v_{\rm sound} t_{\rm rec}$

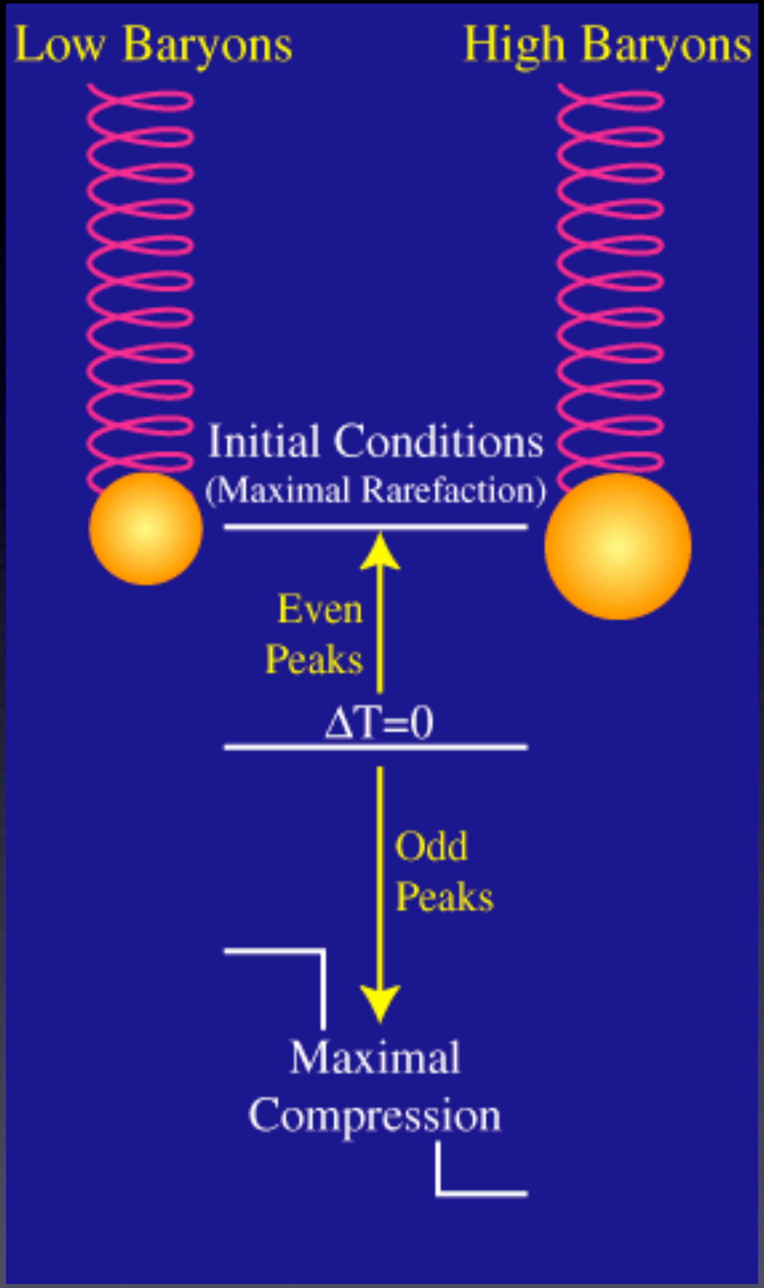
The Curvature of the Universe



RESULT: Universe is flat

One such triangle comes from angular scale of first acoustic peak: $\Delta\Theta \sim v_{\rm sound} t_{\rm rec}$

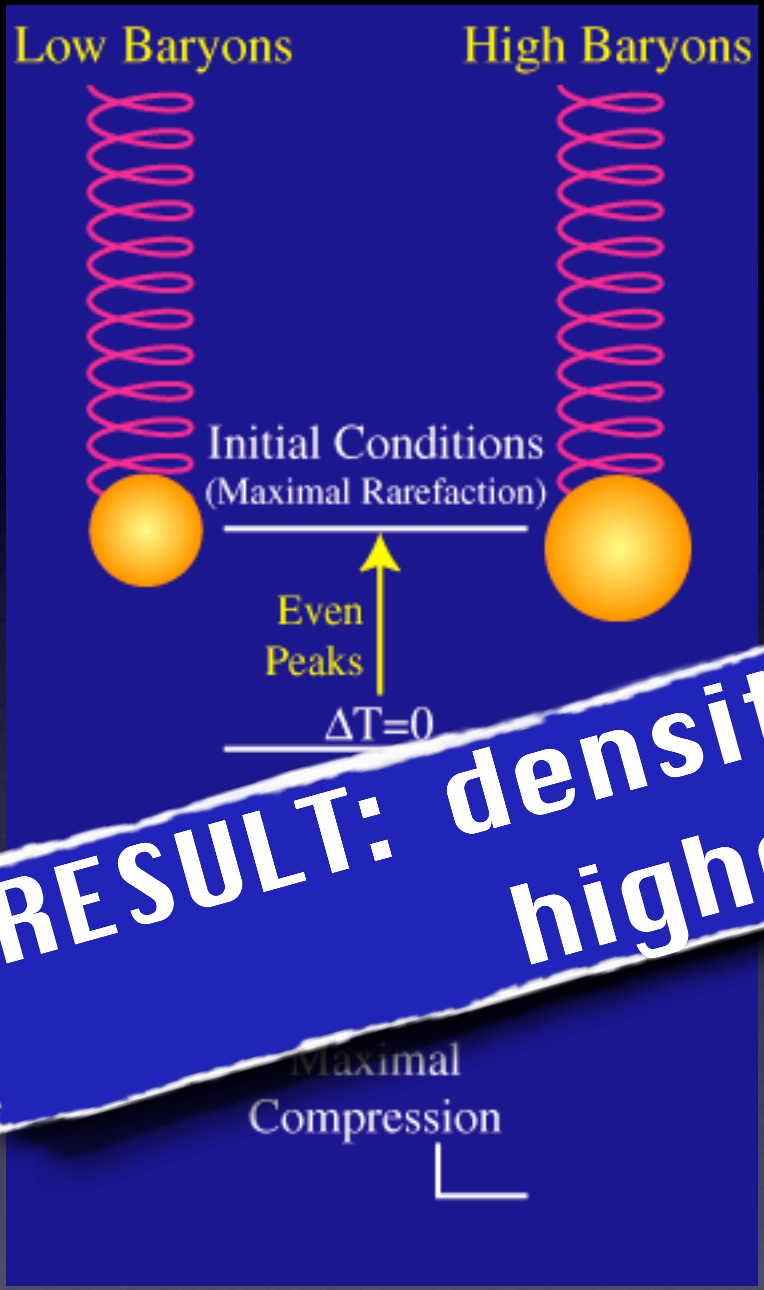
The Baryon-to-Dark Matter Ratio



Increasing density of baryons causes stronger compression in valleys (due to self-gravity of baryons), and less compression on hill tops.

Ratio of odd to even acoustic peaks holds information regarding ratio of baryons to dark matter

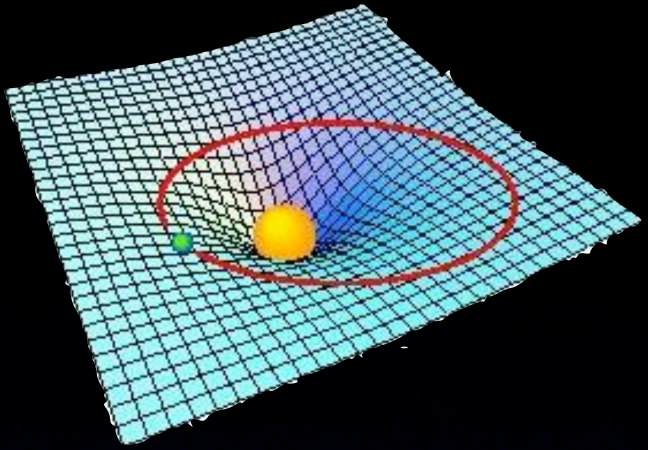
The Baryon-to-Dark Matter Ratio



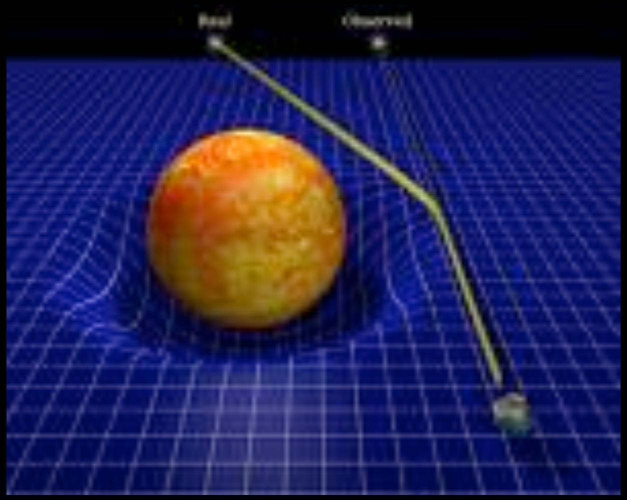
Increasing density of baryons causes stronger compression in valleys (d
self-gravity of baryo
compressio

atio of odd to even acoustic peaks holds information regarding ratio of baryons to dark matter

RESULT: density in dark matter about 6 times higher than that in baryons

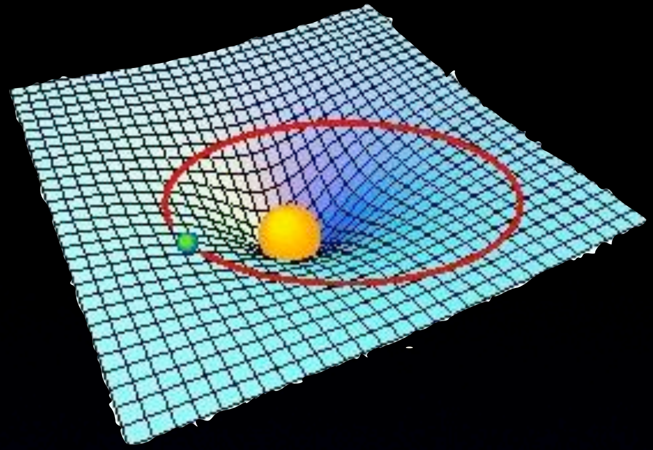


$$G_{\mu\nu}=8\pi T_{\mu\nu}$$

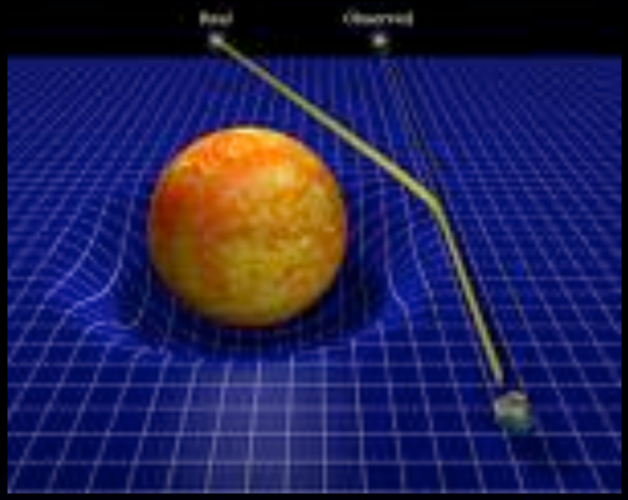


"Geometry" ⟷ "Energy Density"

Flat geometry implies that Universe has critical density



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



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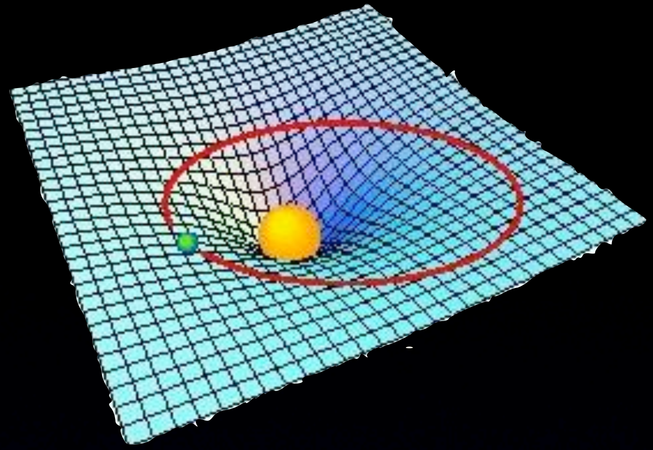
Flat geometry implies that Universe has critical density

Summing densities due to dark matter and baryonic matter only accounts for ~27% of “critical density”

→

Dark Energy makes up ~73% of Universe



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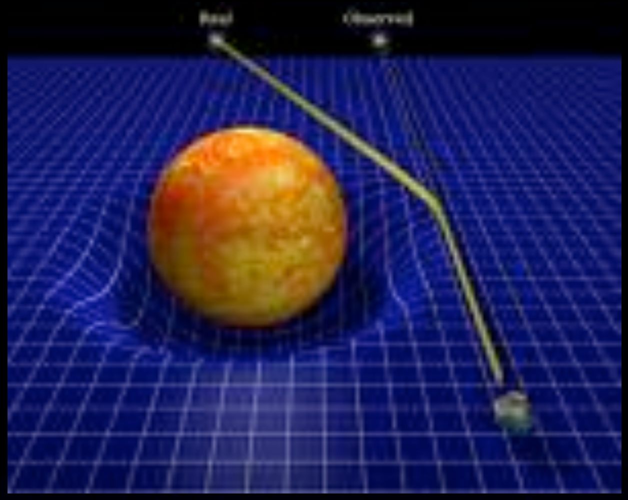

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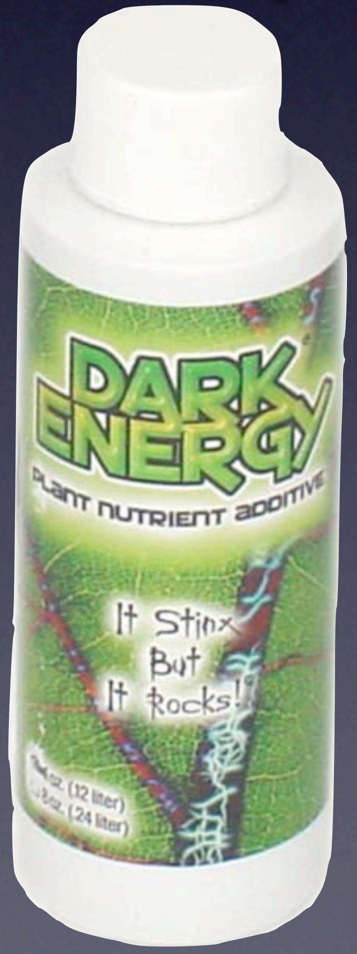
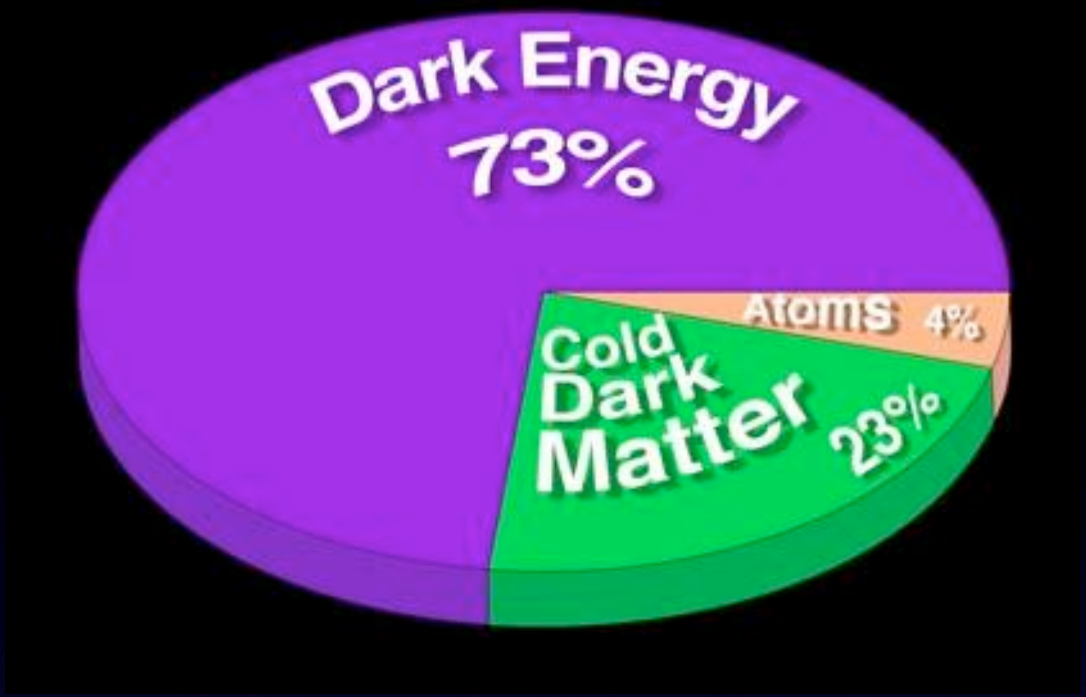
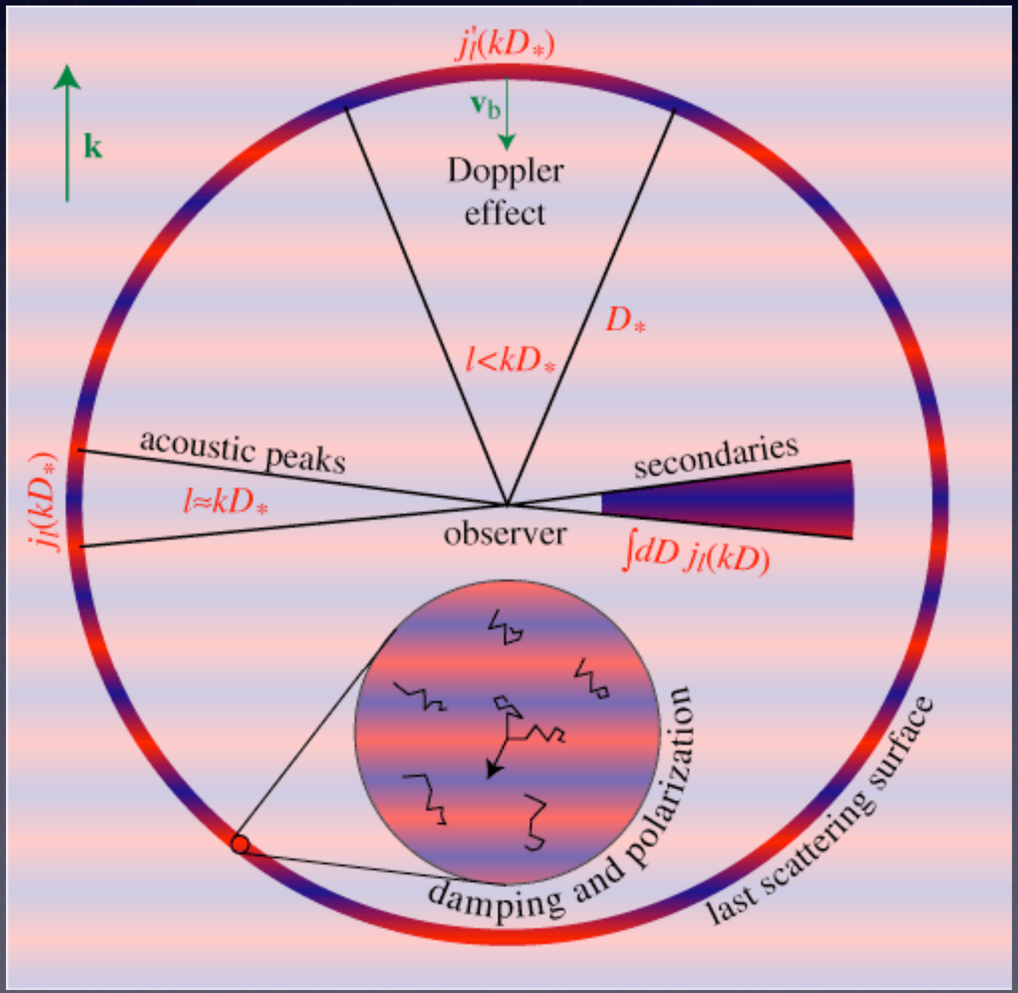
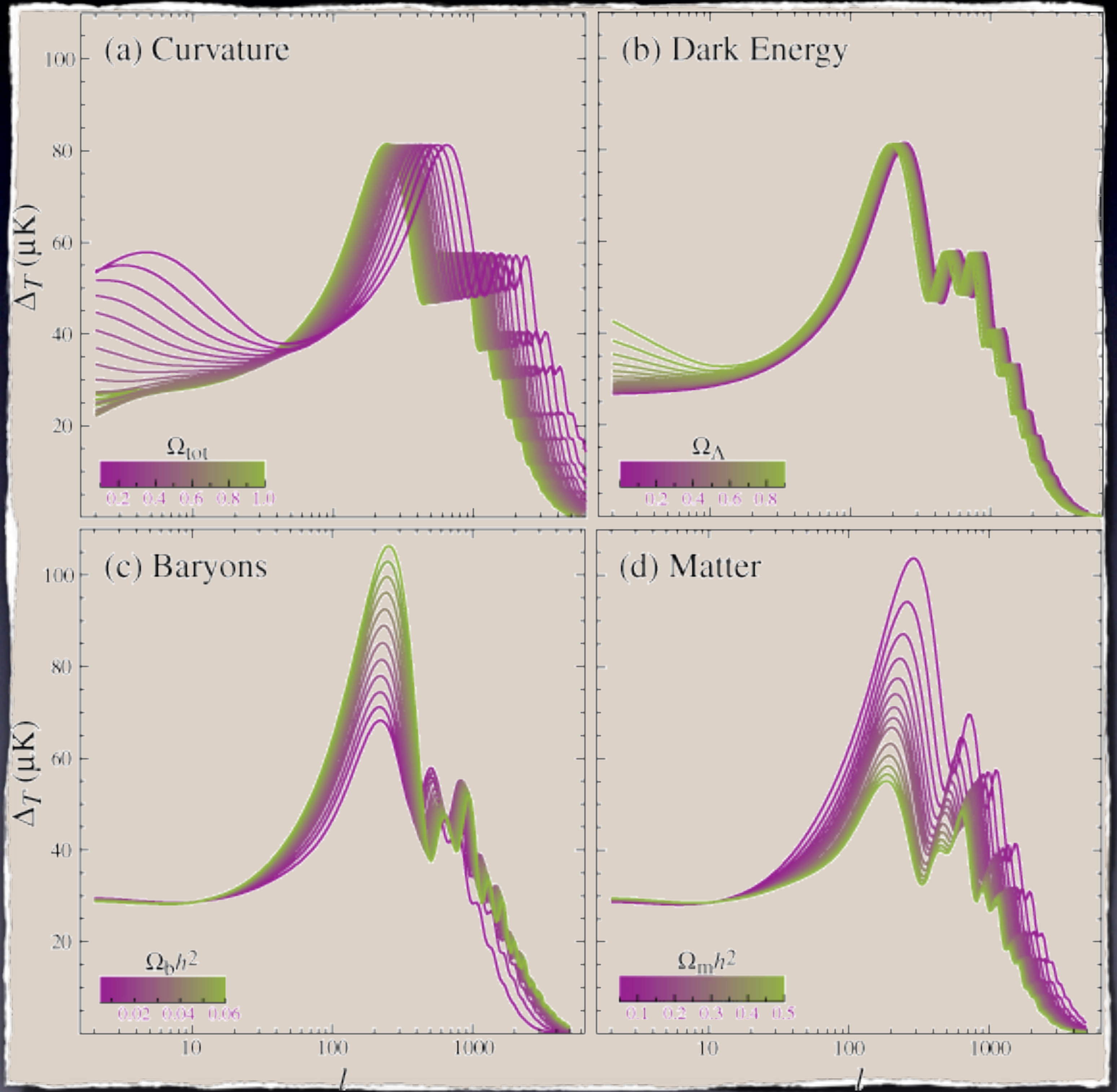



Dark Energy
73%
Atoms 4%
Cold Dark Matter
23%

SUMMARY


$j_l'(kD_*)$
k
v_b
Doppler effect
D_*
$l<kD_*$
acoustic peaks
$l \approx kD_*$
$j_l(kD_*)$
secondaries
observer
$\int dD\, j_l(kD)$
damping and polarization
last scattering surface


(a) Curvature
(b) Dark Energy
(c) Baryons
(d) Matter
Δ_T (μK)
20
40
60
80
100
l
10
100
1000
Ω_{tot}
0.2 0.4 0.6 0.8 1.0
Ω_Λ
0.2 0.4 0.6 0.8
$\Omega_b h^2$
0.02 0.04 0.06
$\Omega_m h^2$
0.1 0.2 0.3 0.4 0.5

CREDITS: Many of the illustrations and movies have been taken from the excellent website created by Prof. Wayne Hu http://background.uchicago.edu/