Searching for triangles in the Universe

Gustavo Niz

XII Taller – Div. GFM - SMF

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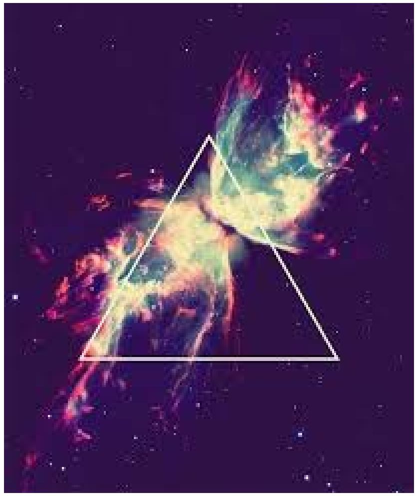
Content

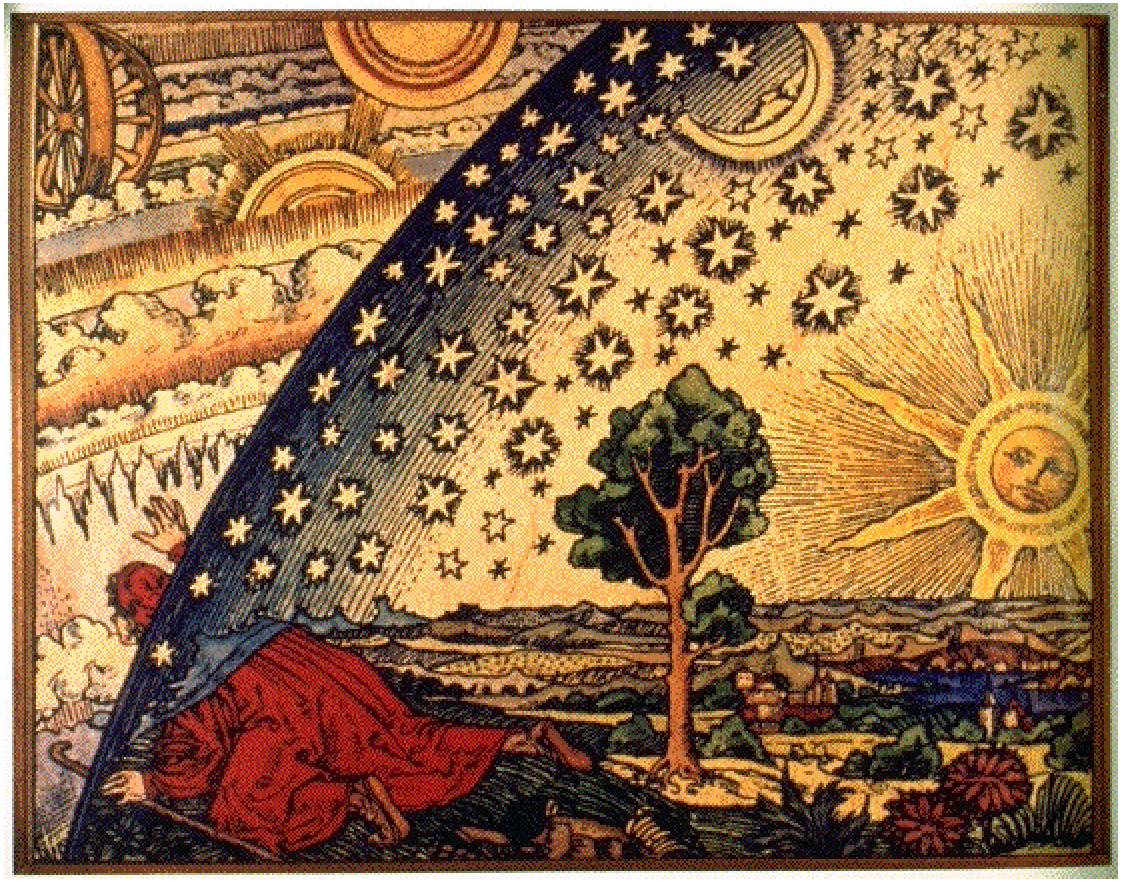


Our Universe
- What we know...
- What we don't know...

Physics of the “cosmic collider”
- Early Universe
- Cosmic Microwave Background (CMB)
- Large Scale Structure (LSS)
- Triangles!

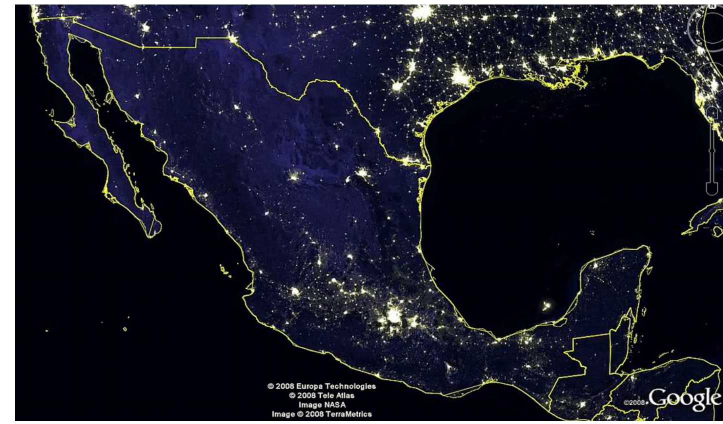
Dark Energy Spectroscopic Instrument

What do we know about the Universe?



Flammarion, 1888

What do we know about the Universe?



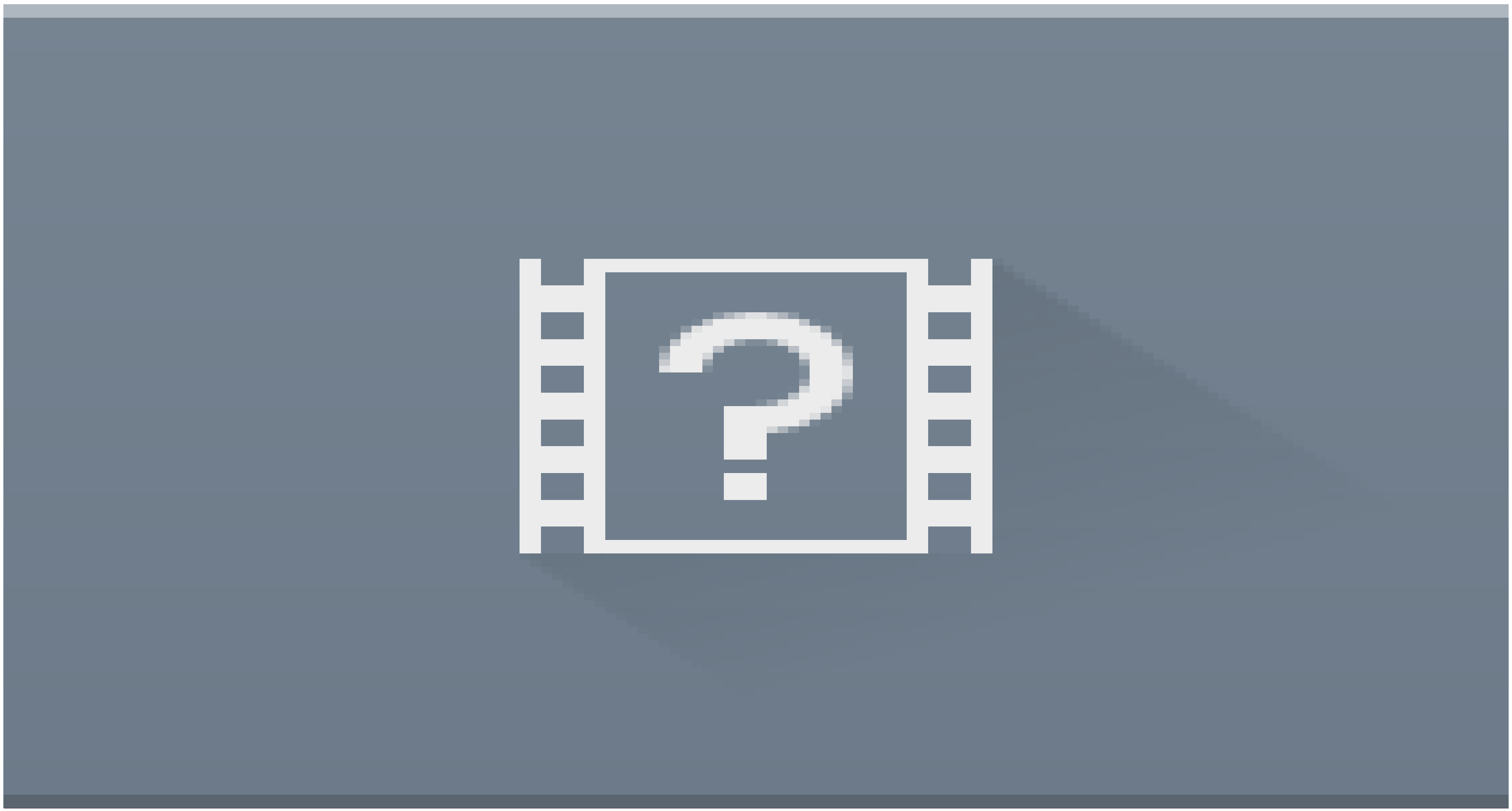
We observe the Universe by

1) Mostly  (photons)

2) but also by: neutrinos, alpha particles, gravitational waves (Nobel 2017!), ...

Note: We observe the past and only on the "light-cone"

What we know...



Sloan Digital Sky Survey

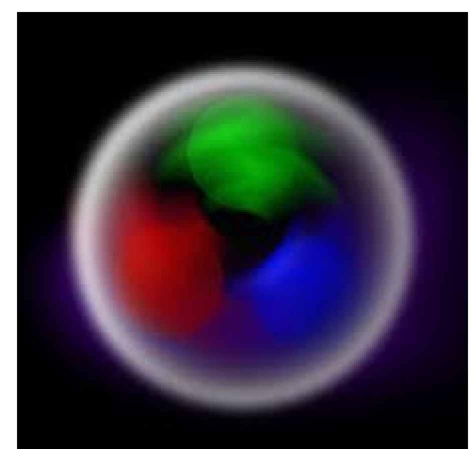
What we know...

Our visible Universe is BIG

93 billion light years = 10^{26} m

Universe

Sun 10^{8} m



Guadalajara 10^{3} m

Proton 10^{-15} m

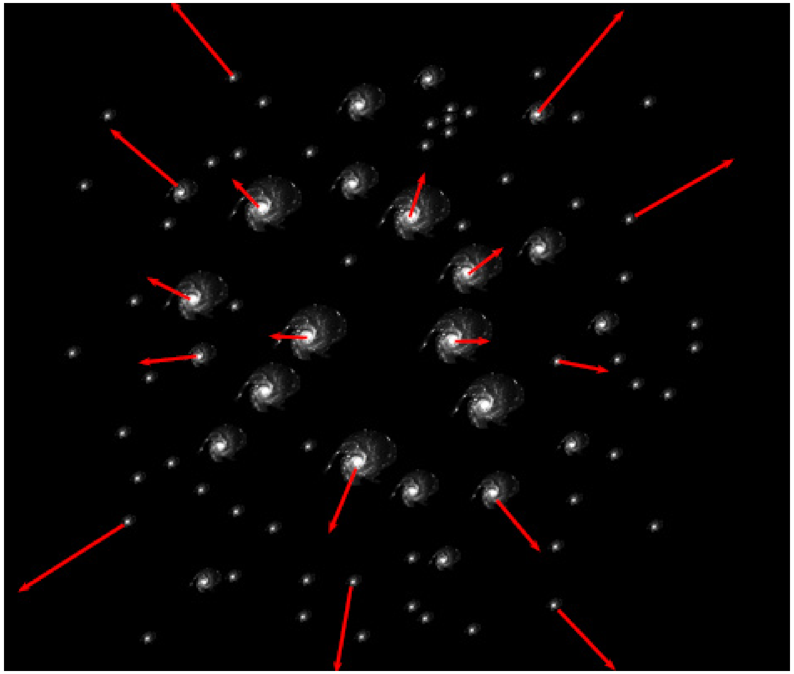
What we know...

13.7 billion years

Oldest stars ~ 13.6 billion years

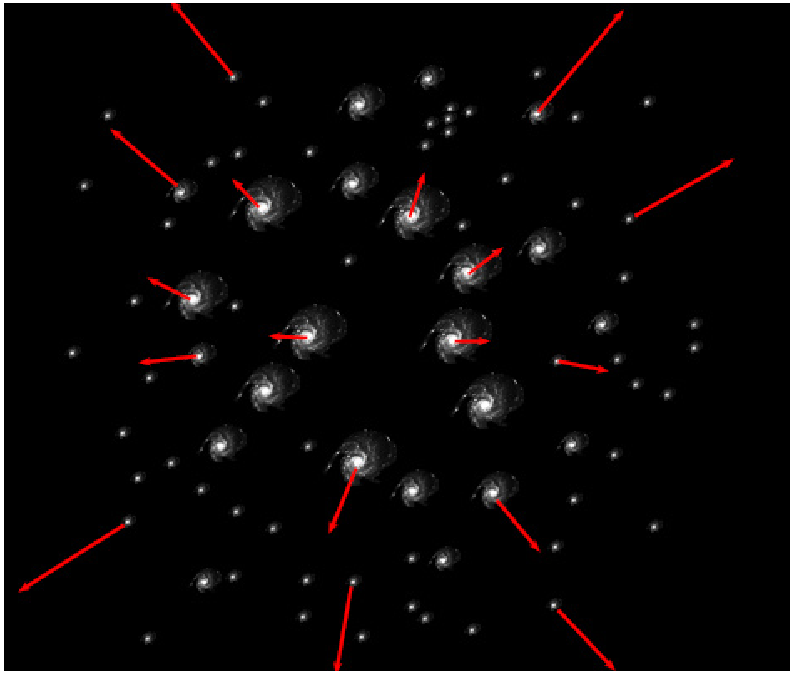
What we know...

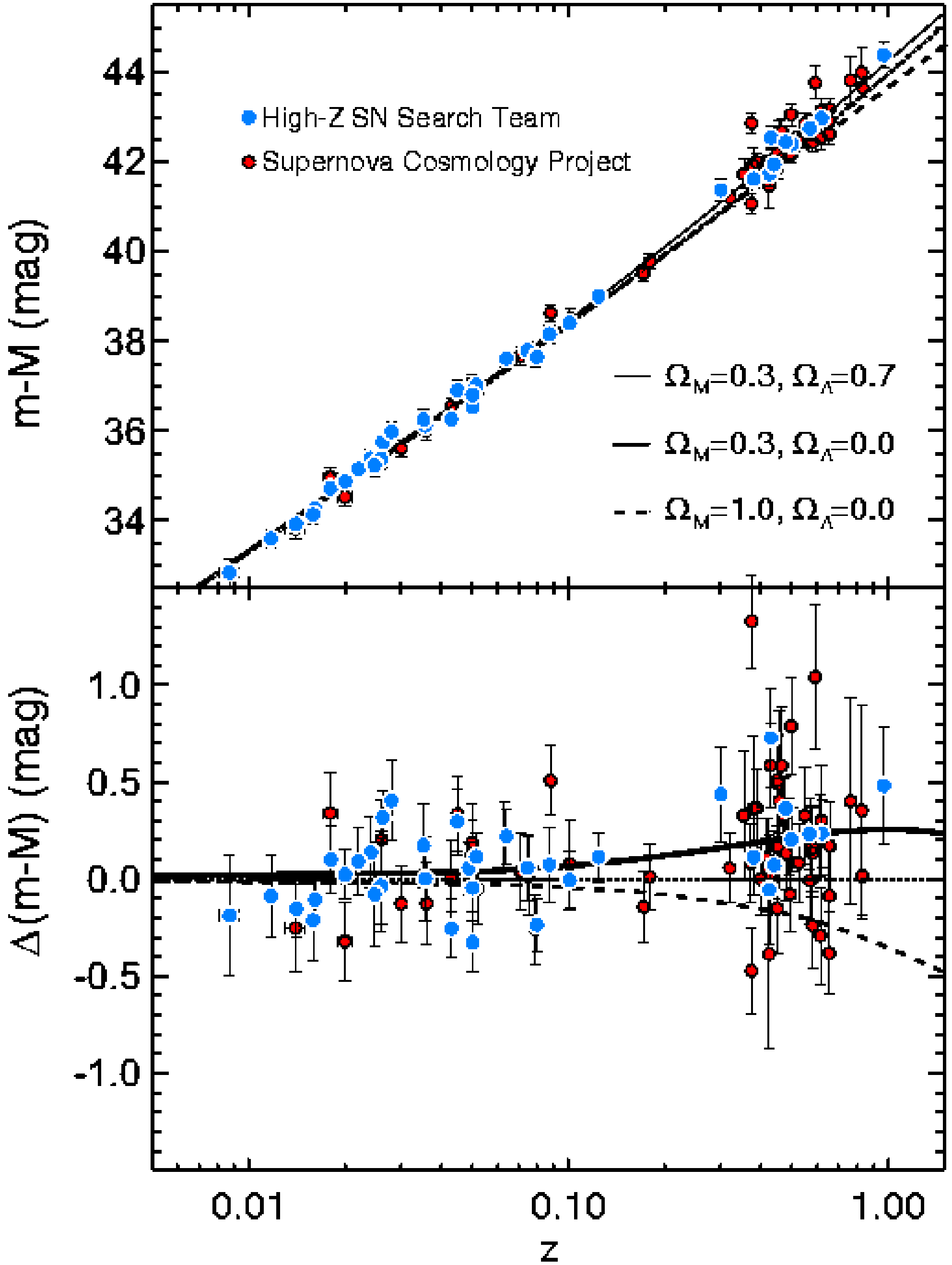
The Universe expands



What we know...

The Universe expands





What we know...

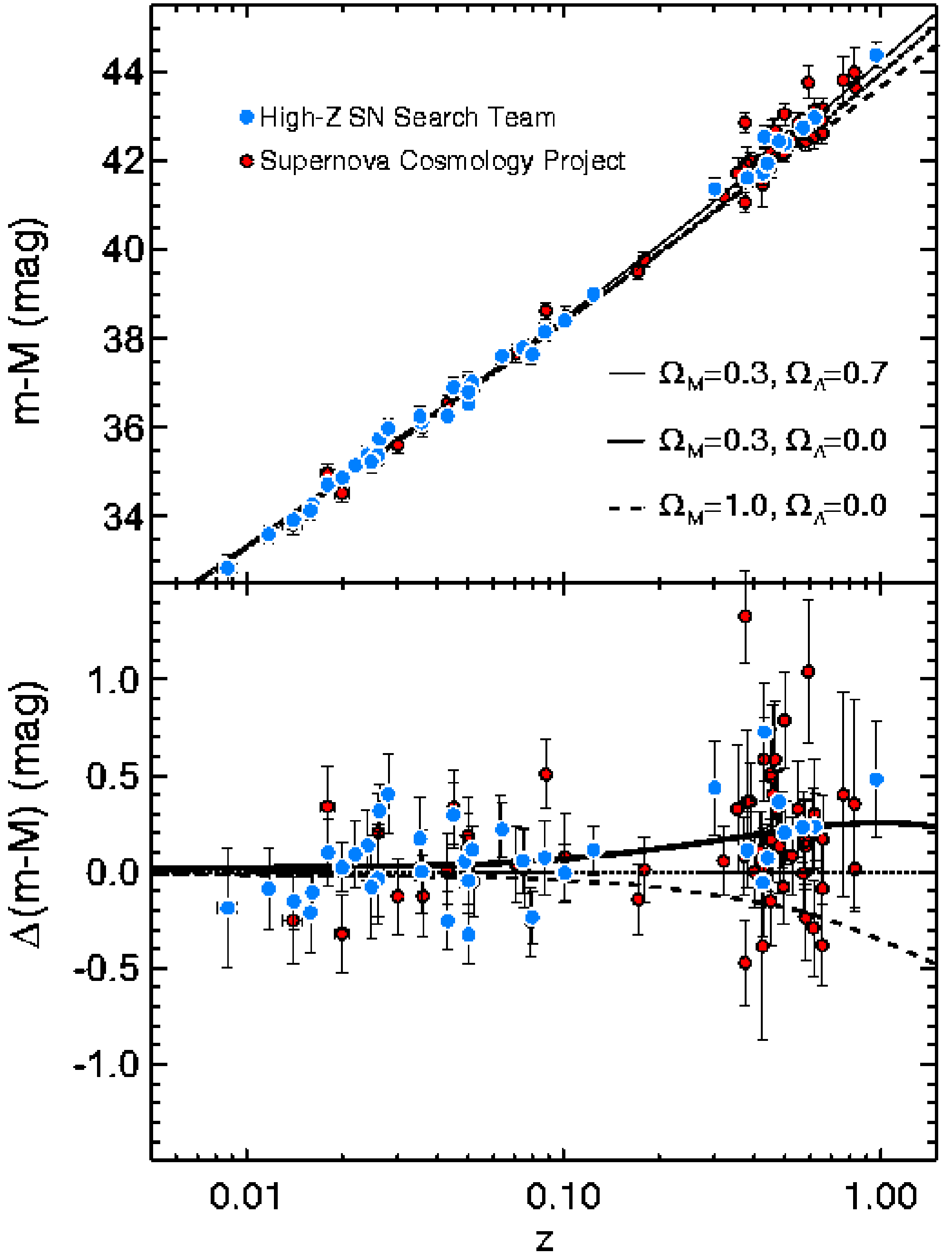
The Universe expands

Actually, it accelerates!

(Nobel 2011 to Perlmutter, Riess & Schmidt).

Cause:

DARK ENERGY!



What we know...

Expansion

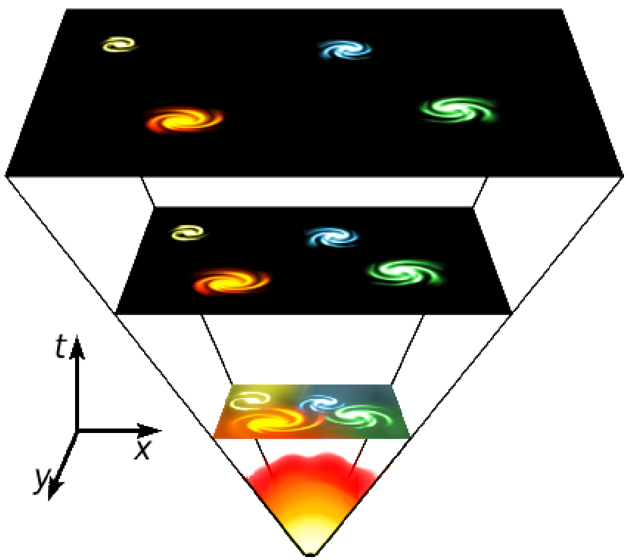
gave rise to the BIG BANG THEORY

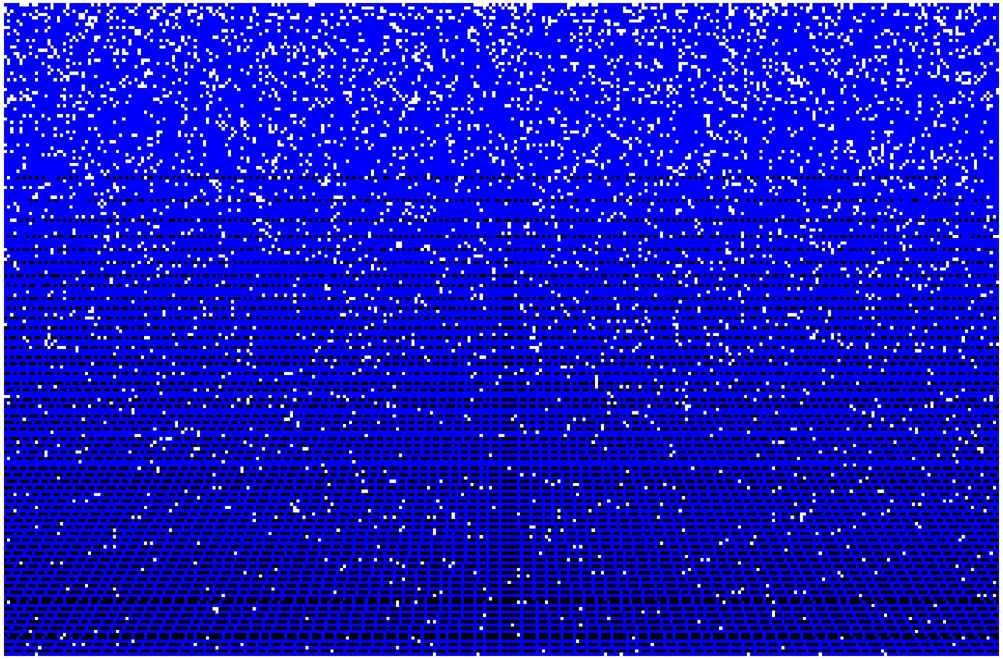
What we know...

Expansion

gave rise to the BIG BANG THEORY

What we know...



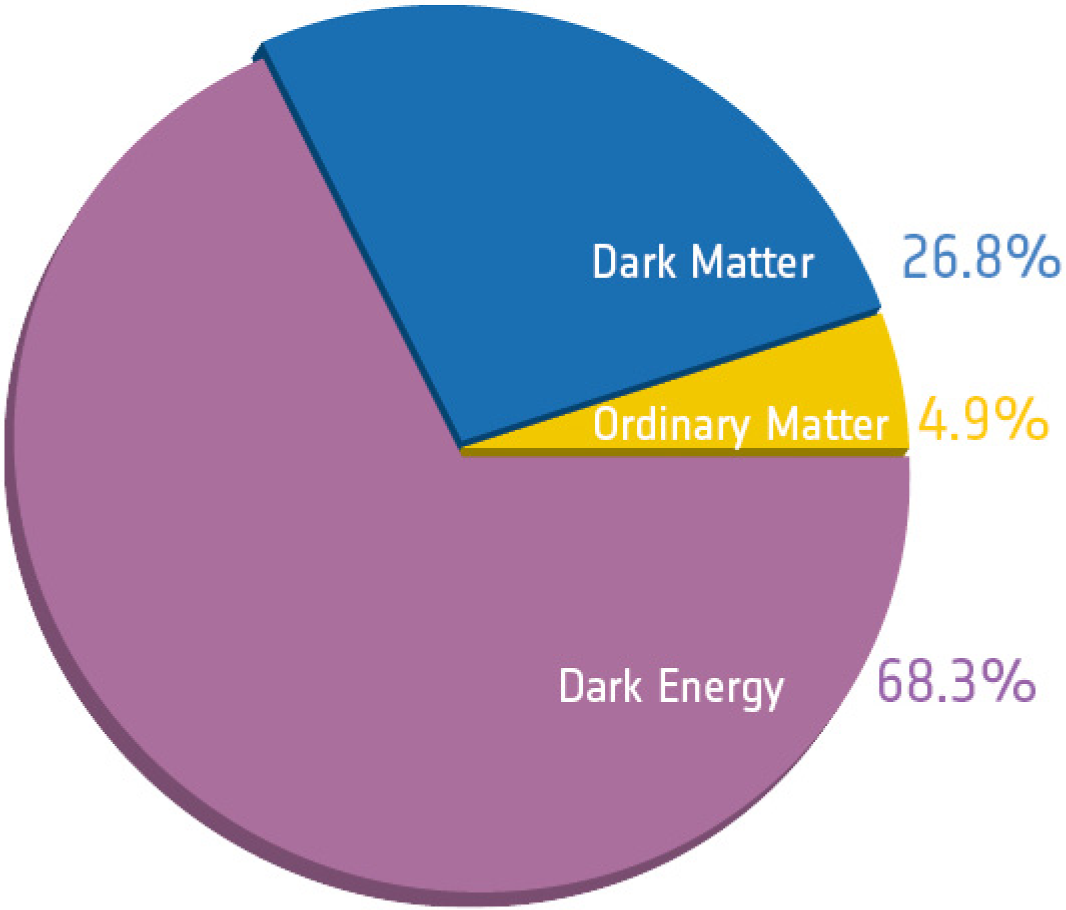


Observations

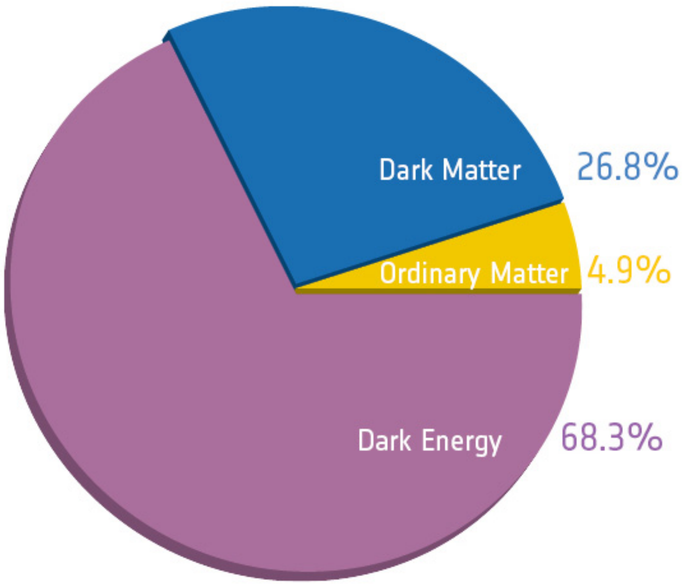
- There was no explosion
- No expansion into something else
- Expansion may be faster than speed of light

What we know...

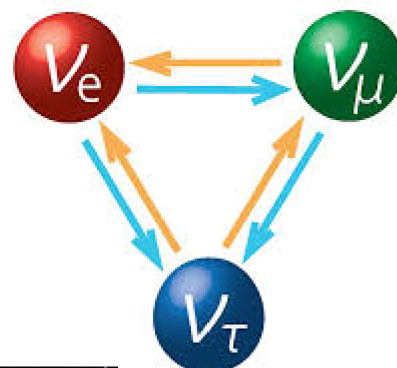
Composed today by



What we know...



Heavy elements ~ 0.03%

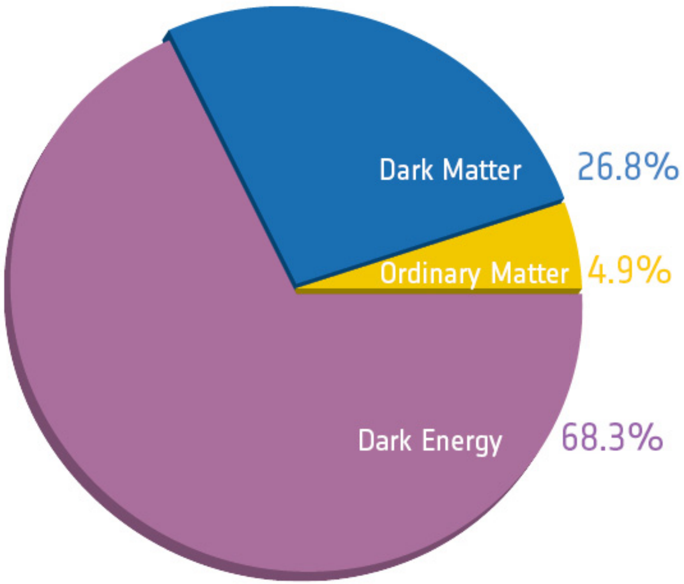


Neutrinos ~ 0.3%

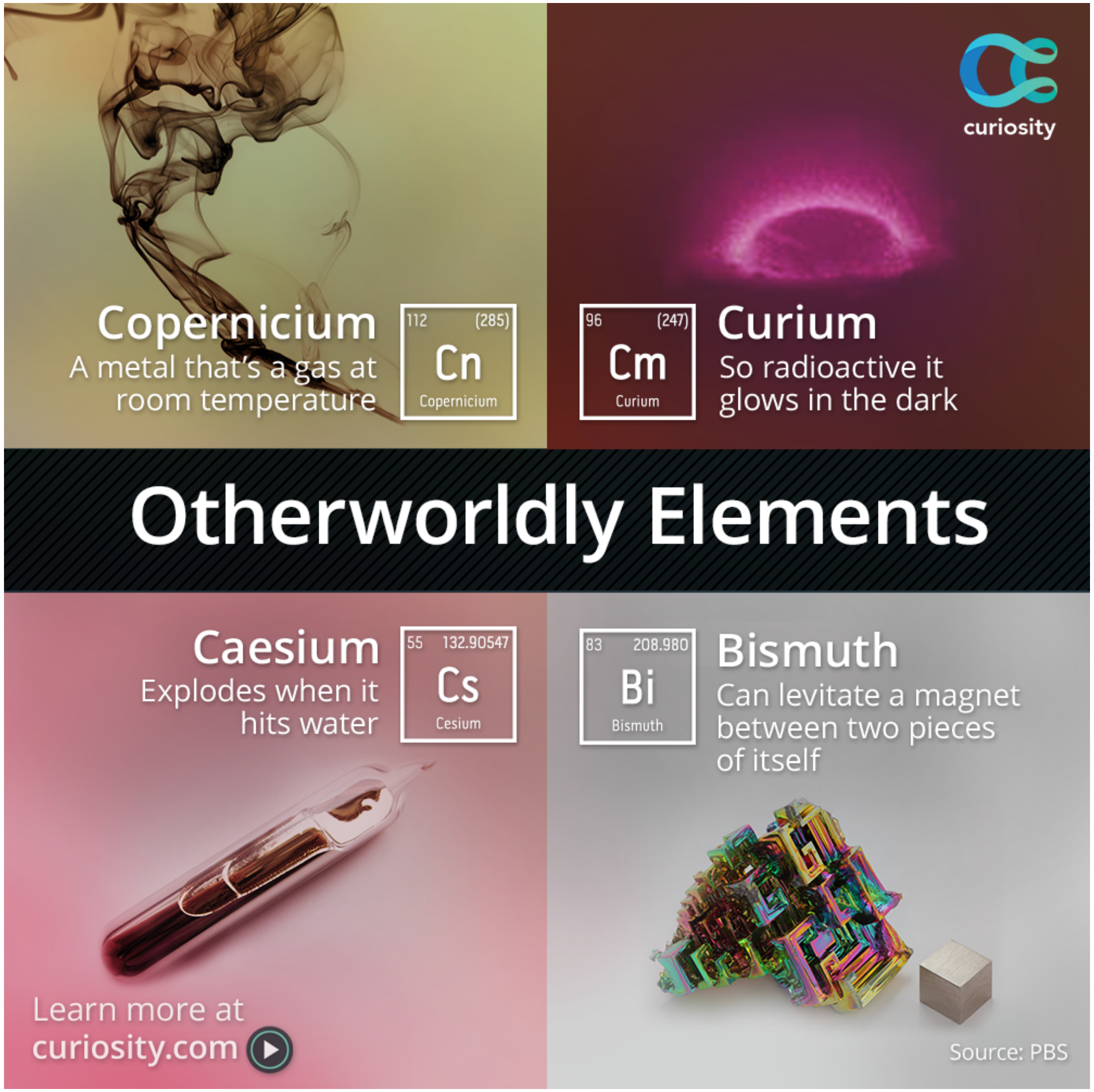
Free hydrogen & Helium ~ 0.4%

Stars ~ 0.5%

What we know...

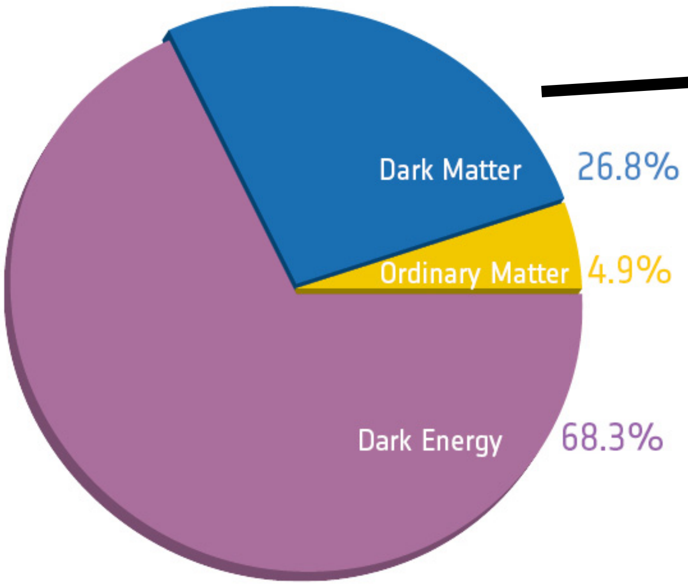


Dark Matter
26.8%
Ordinary Matter
4.9%
Dark Energy
68.3%

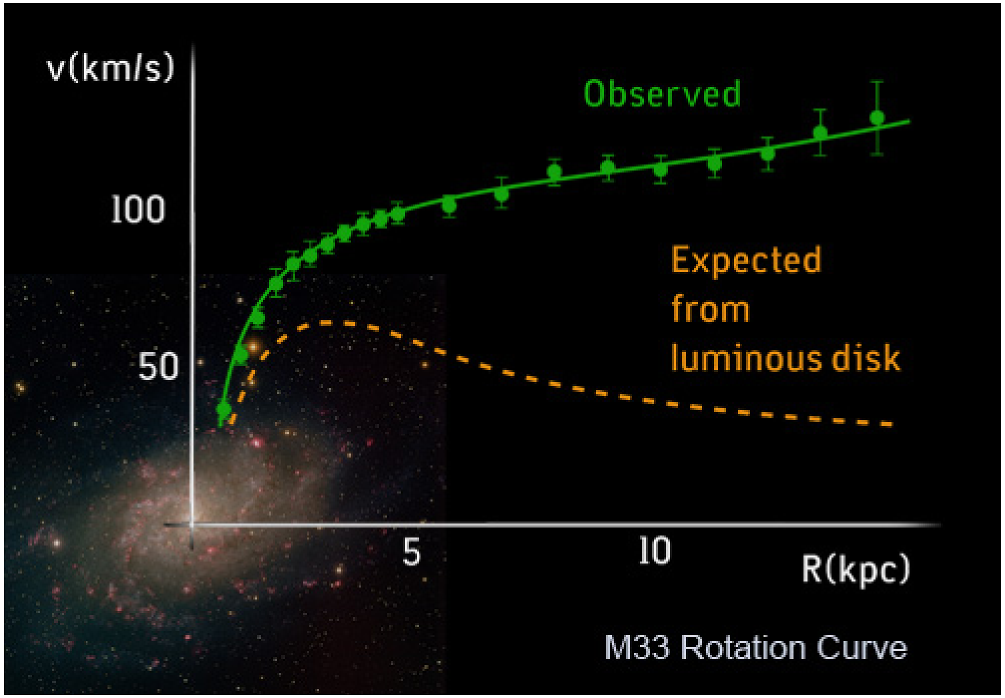


curiosity
Copernicium
A metal that's a gas at room temperature
112 (285) Cn Copernicium
96 (247) Cm Curium
Curium
So radioactive it glows in the dark
Otherworldly Elements
Caesium
Explodes when it hits water
55 132.90547 Cs Cesium
83 208.980 Bi Bismuth
Bismuth
Can levitate a magnet between two pieces of itself
Learn more at curiosity.com
Source: PBS

What we do not know...



Dark Matter

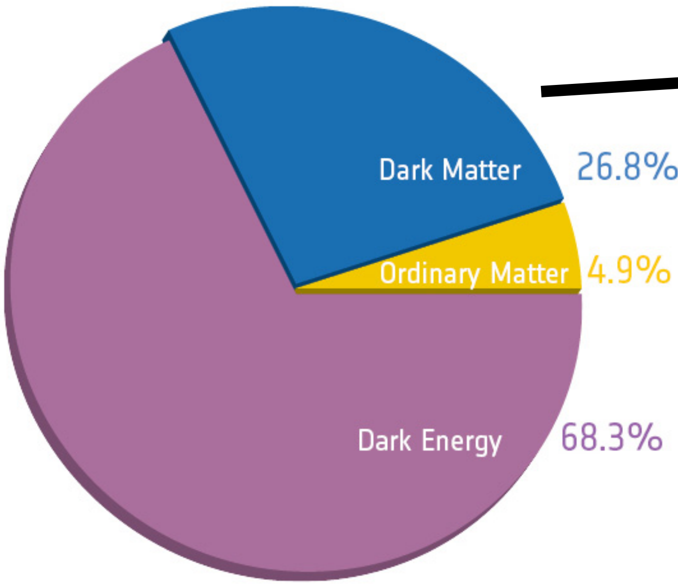


Best candidate:

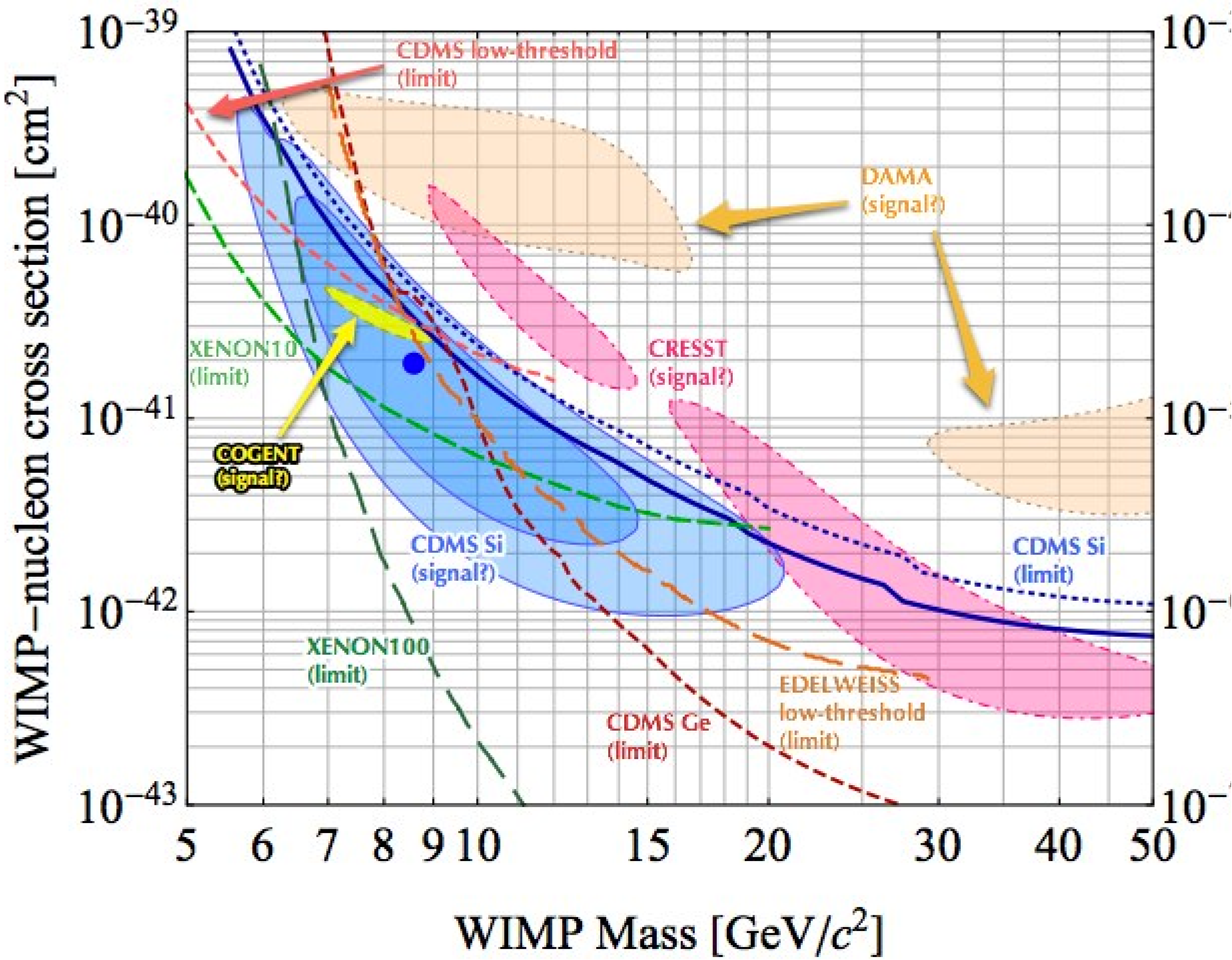
Massive particle with:

Null or weak interactions with the visible matter

What we do not know...



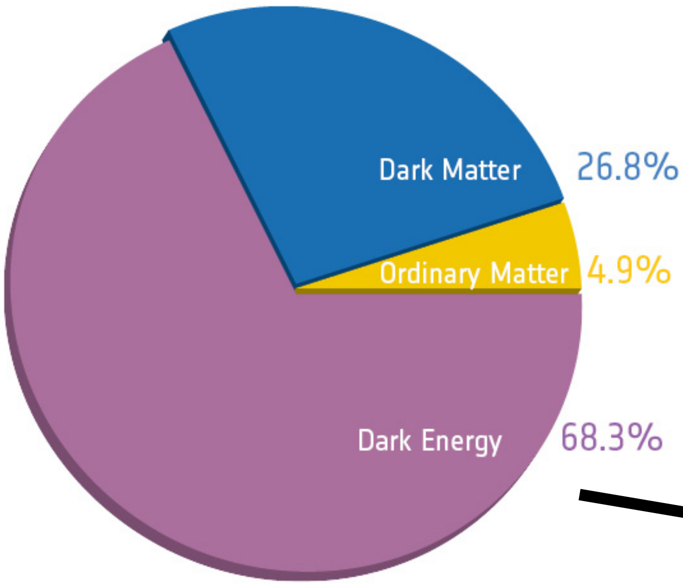
Dark Matter



Tens of experiments

...searching...

What we do not know...



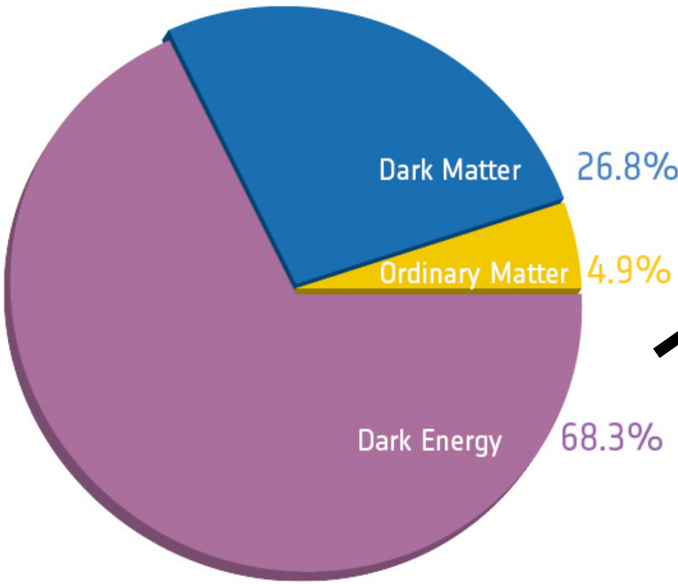
Dark Energy

Best candidate:

Cosmological Constant

$$\Lambda$$

What we do not know...



Dark Energy

Theoretical problem

Cosmological Constant value

$$\Lambda_{vac} = 10^{120}\Lambda_{obs}$$

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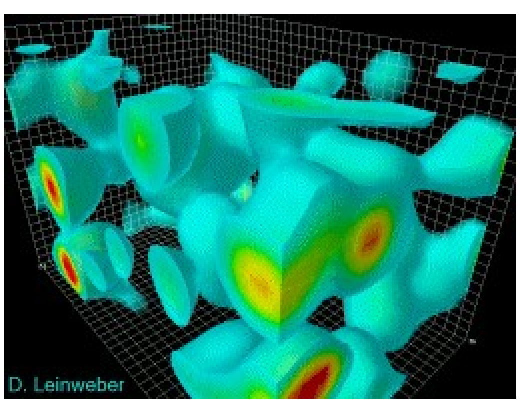
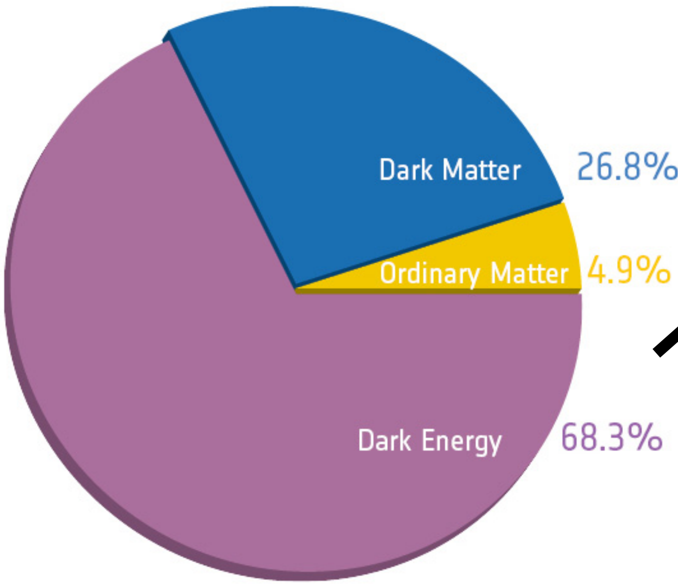
00000000000000000000000000000000



Empty space perturbations

What we do not know...



Dark Energy

Vacuum energy

Modified gravity

New particle

EFT

Alberto and PhD students

$$S = \int d^4x\sqrt{-g}\left[\frac{RM_*^2}{2} - cg^{00} - \Lambda + \frac{M_2^4}{2}(\delta g^{00})^2 + \frac{M_3^4}{3!}(\delta g^{00})^3 + \ldots - \frac{\bar{m}_1^3}{2}\delta g^{00}\delta K - \frac{\bar{M}_2^2}{2}\delta K^2 + \ldots\right] + S_m\left[f^{-1}(t)g_{\mu\nu}, \psi_i\right] \,,$$

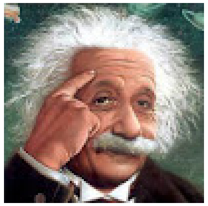
Physics in the “cosmic collider”

The Perturbed Universe

From Quantum Fluctuations to Human Beings...

Simple model

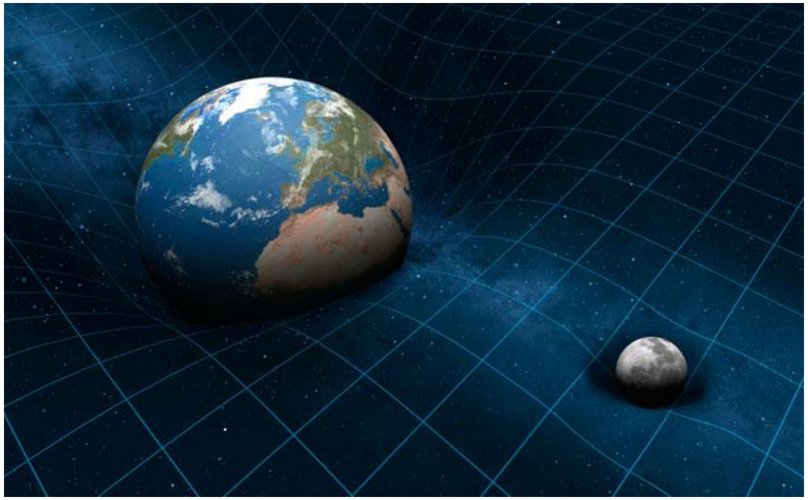
Einstein (1915)



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

Space-time

Geometry

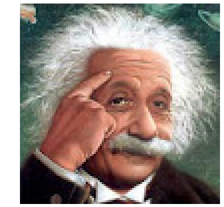


Matter/energy

Non-linear theory - describes interactions!

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

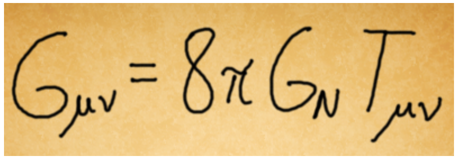
Simple model



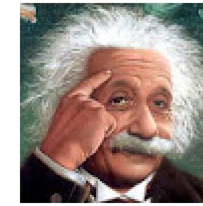
$$\mu = \nu = 3$$

$$\begin{aligned}
&\frac{1}{4}\,\mathrm{g00}^{-1}\,\mathrm{g11}^{-1}\,\mathrm{g22}^{-1}\,\frac{\partial\,\mathrm{g00}}{\partial y}\,\frac{\partial\,\mathrm{g11}}{\partial y} + \frac{1}{4}\,\mathrm{g00}^{-1}\,\mathrm{g11}^{-1}\,\mathrm{g33}^{-1}\,\frac{\partial\,\mathrm{g11}}{\partial t}\,\frac{\partial\,\mathrm{g33}}{\partial t} + \frac{1}{4}\,\mathrm{g00}^{-1}\,\mathrm{g11}^{-1}\,\mathrm{g33}^{-1}\,\frac{\partial\,\mathrm{g00}}{\partial x}\,\frac{\partial\,\mathrm{g33}}{\partial x} + \\
&\frac{1}{4}\,\mathrm{g00}^{-1}\,\mathrm{g11}^{-1}\,\mathrm{g33}^{-1}\,\frac{\partial\,\mathrm{g00}}{\partial z}\,\frac{\partial\,\mathrm{g11}}{\partial z} + \frac{1}{2}\,\mathrm{g00}^{-1}\,\mathrm{g11}^{-1}\,\frac{\partial^2\,\mathrm{g11}}{\partial t^2} - \frac{1}{4}\,(\mathrm{g00}^{-1})^2\,\mathrm{g11}^{-1}\,\frac{\partial\,\mathrm{g00}}{\partial t}\,\frac{\partial\,\mathrm{g11}}{\partial t} - \\
&\frac{1}{4}\,\mathrm{g00}^{-1}\,(\mathrm{g11}^{-1})^2\left(\frac{\partial\,\mathrm{g11}}{\partial t}\right)^2 + \frac{1}{2}\,\mathrm{g00}^{-1}\,\mathrm{g11}^{-1}\,\frac{\partial^2\,\mathrm{g00}}{\partial x^2} - \frac{1}{4}\,(\mathrm{g00}^{-1})^2\,\mathrm{g11}^{-1}\left(\frac{\partial\,\mathrm{g00}}{\partial x}\right)^2 - \\
&\frac{1}{4}\,\mathrm{g00}^{-1}\,(\mathrm{g11}^{-1})^2\,\frac{\partial\,\mathrm{g00}}{\partial x}\,\frac{\partial\,\mathrm{g11}}{\partial x} + \frac{1}{4}\,\mathrm{g00}^{-1}\,\mathrm{g22}^{-1}\,\mathrm{g33}^{-1}\,\frac{\partial\,\mathrm{g00}}{\partial y}\,\frac{\partial\,\mathrm{g33}}{\partial y} + \frac{1}{2}\,\mathrm{g00}^{-1}\,\mathrm{g33}^{-1}\,\frac{\partial^2\,\mathrm{g33}}{\partial t^2} - \\
&\frac{1}{4}\,(\mathrm{g00}^{-1})^2\,\mathrm{g33}^{-1}\,\frac{\partial\,\mathrm{g00}}{\partial t}\,\frac{\partial\,\mathrm{g33}}{\partial t} - \frac{1}{4}\,\mathrm{g00}^{-1}\,(\mathrm{g33}^{-1})^2\left(\frac{\partial\,\mathrm{g33}}{\partial t}\right)^2 + \frac{1}{2}\,\mathrm{g00}^{-1}\,\mathrm{g33}^{-1}\,\frac{\partial^2\,\mathrm{g00}}{\partial z^2} - \\
&\frac{1}{4}\,(\mathrm{g00}^{-1})^2\,\mathrm{g33}^{-1}\left(\frac{\partial\,\mathrm{g00}}{\partial z}\right)^2 - \frac{1}{4}\,\mathrm{g00}^{-1}\,(\mathrm{g33}^{-1})^2\,\frac{\partial\,\mathrm{g00}}{\partial z}\,\frac{\partial\,\mathrm{g33}}{\partial z} + \frac{1}{4}\,\mathrm{g11}^{-1}\,\mathrm{g22}^{-1}\,\mathrm{g33}^{-1}\,\frac{\partial\,\mathrm{g11}}{\partial y}\,\frac{\partial\,\mathrm{g33}}{\partial y} + \\
&\frac{1}{2}\,\mathrm{g11}^{-1}\,\mathrm{g33}^{-1}\,\frac{\partial^2\,\mathrm{g33}}{\partial x^2} - \frac{1}{4}\,\mathrm{g11}^{-1}\,(\mathrm{g33}^{-1})^2\left(\frac{\partial\,\mathrm{g33}}{\partial x}\right)^2 - \frac{1}{4}\,(\mathrm{g11}^{-1})^2\,\mathrm{g33}^{-1}\,\frac{\partial\,\mathrm{g11}}{\partial x}\,\frac{\partial\,\mathrm{g33}}{\partial x} + \\
&\frac{1}{2}\,\mathrm{g11}^{-1}\,\mathrm{g33}^{-1}\,\frac{\partial^2\,\mathrm{g11}}{\partial z^2} - \frac{1}{4}\,\mathrm{g11}^{-1}\,(\mathrm{g33}^{-1})^2\,\frac{\partial\,\mathrm{g11}}{\partial z}\,\frac{\partial\,\mathrm{g33}}{\partial z} - \frac{1}{4}\,(\mathrm{g11}^{-1})^2\,\mathrm{g33}^{-1}\left(\frac{\partial\,\mathrm{g11}}{\partial z}\right)^2
\end{aligned}$$

Non-linear theory

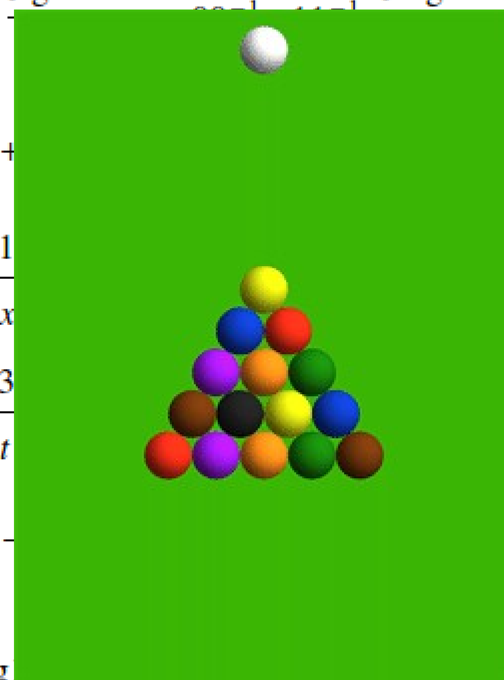


Simple model



$\mu = \nu = 3$

$$
\begin{aligned}
&\frac{1}{4}\, g00^{-1}\, g11^{-1}\, g22^{-1}\, \frac{\partial\, g00}{\partial\, y}\, \frac{\partial\, g11}{\partial\, y} + \frac{1}{4}\, g00^{-1}\, g11^{-1}\, g33^{-1}\, \frac{\partial\, g11}{\partial\, t}\, \frac{\partial\, g33}{\partial\, t} + \frac{1}{4}\, g00^{-1}\, g11^{-1}\, g33^{-1}\, \frac{\partial\, g00}{\partial\, x}\, \frac{\partial\, g33}{\partial\, x} + \\
&\frac{1}{4}\, g00^{-1}\, g11^{-1}\, g33^{-1}\, \frac{\partial\, g00}{\partial\, z}\, \frac{\partial\, g11}{\cdots} \cdots \frac{1}{\cdots} \cdots \frac{\partial^2\, g11}{\cdots} \cdots \frac{1}{4}\, (g00^{-1})^2\, g11^{-1}\, \frac{\partial\, g00}{\partial\, t}\, \frac{\partial\, g11}{\partial\, t} - \\
&\frac{1}{4}\, g00^{-1}\, (g11^{-1})^2 \left(\frac{\partial\, g11}{\partial\, t}\right)^2 + \cdots (g00^{-1})^2\, g11^{-1} \left(\frac{\partial\, g00}{\partial\, x}\right)^2 - \\
&\frac{1}{4}\, g00^{-1}\, (g11^{-1})^2\, \frac{\partial\, g00}{\partial\, x}\, \frac{\partial\, g1\cdots}{\partial\, x} \cdots \frac{\partial\, g33}{\partial\, y} + \frac{1}{2}\, g00^{-1}\, g33^{-1}\, \frac{\partial^2\, g33}{\partial\, t^2} - \\
&\frac{1}{4}\, (g00^{-1})^2\, g33^{-1}\, \frac{\partial\, g00}{\partial\, t}\, \frac{\partial\, g3\cdots}{\partial\, t} \cdots + \frac{1}{2}\, g00^{-1}\, g33^{-1}\, \frac{\partial^2\, g00}{\partial\, z^2} - \\
&\frac{1}{4}\, (g00^{-1})^2\, g33^{-1} \left(\frac{\partial\, g00}{\partial\, z}\right)^2 - \cdots + \frac{1}{4}\, g11^{-1}\, g22^{-1}\, g33^{-1}\, \frac{\partial\, g11}{\partial\, y}\, \frac{\partial\, g33}{\partial\, y} + \\
&\frac{1}{2}\, g11^{-1}\, g33^{-1}\, \frac{\partial^2\, g33}{\partial\, x^2} - \frac{1}{4}\, g \cdots \left(\frac{\cdots}{\partial\, x}\right) \cdots \frac{\cdots}{4} \cdots 1^{-1})^2\, g33^{-1}\, \frac{\partial\, g11}{\partial\, x}\, \frac{\partial\, g33}{\partial\, x} + \\
&\frac{1}{2}\, g11^{-1}\, g33^{-1}\, \frac{\partial^2\, g11}{\partial\, z^2} - \frac{1}{4}\, g11^{-1}\, (g33^{-1})^2\, \frac{\partial\, g11}{\partial\, z}\, \frac{\partial\, g33}{\partial\, z} - \frac{1}{4}\, (g11^{-1})^2\, g33^{-1} \left(\frac{\partial\, g11}{\partial\, z}\right)^2
\end{aligned}
$$

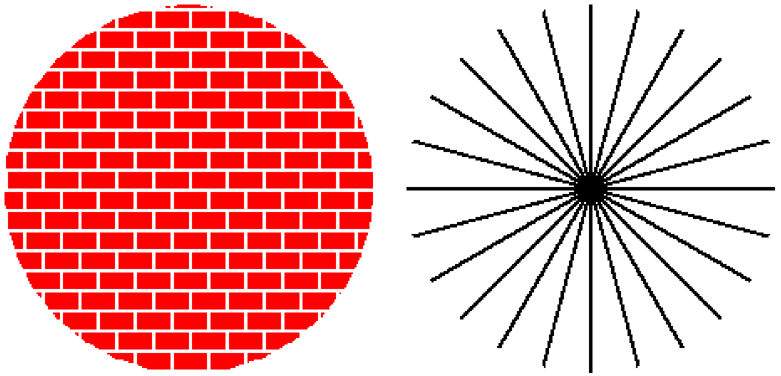


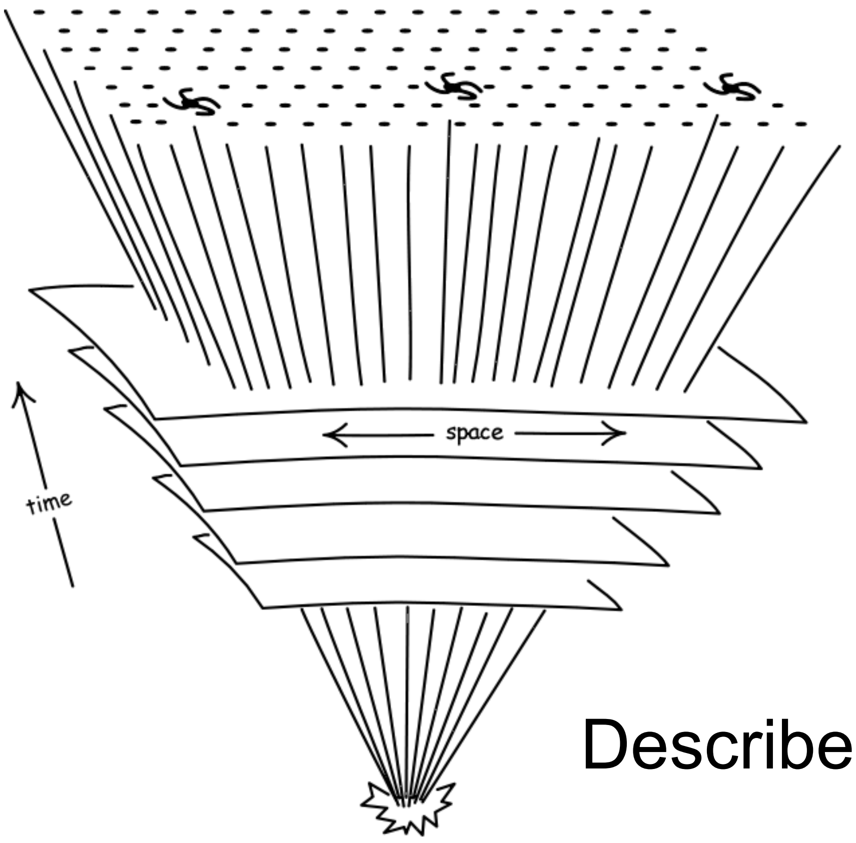
Describes interactions!

Simple model

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

Cosmological principle:
Isotropy and homogeneity

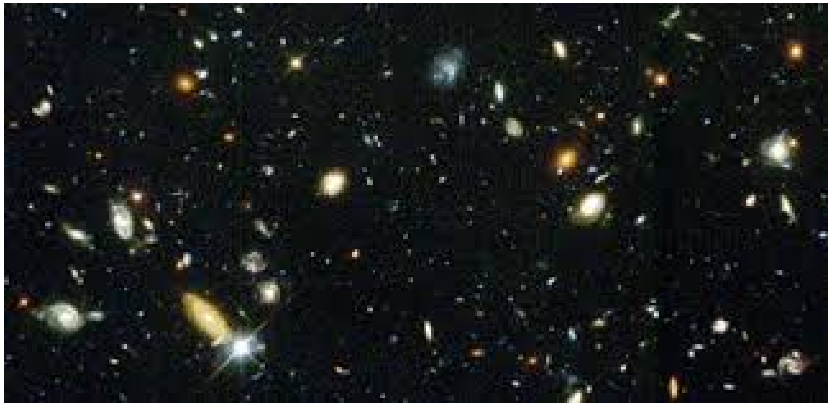




FRWL

Describes well the AVERAGED Universe

Beyond average



Universe is not fully homogeneous and isotropic

Trick: Use perturbation theory

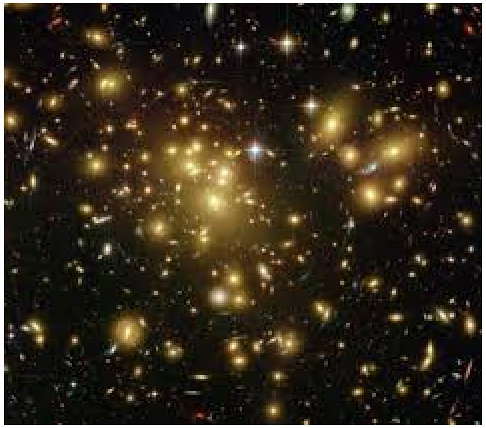
$$\rho = \bar{\rho}(1 + \delta) \qquad \delta \ll 1$$

Beyond average

$$\rho = \bar{\rho}(1+\delta)$$

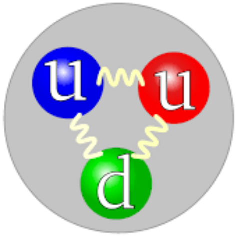
$$\bar{\rho} \sim 10^{-26}\mathrm{Kg/m^3}$$

Note that



$$\delta \sim 100$$

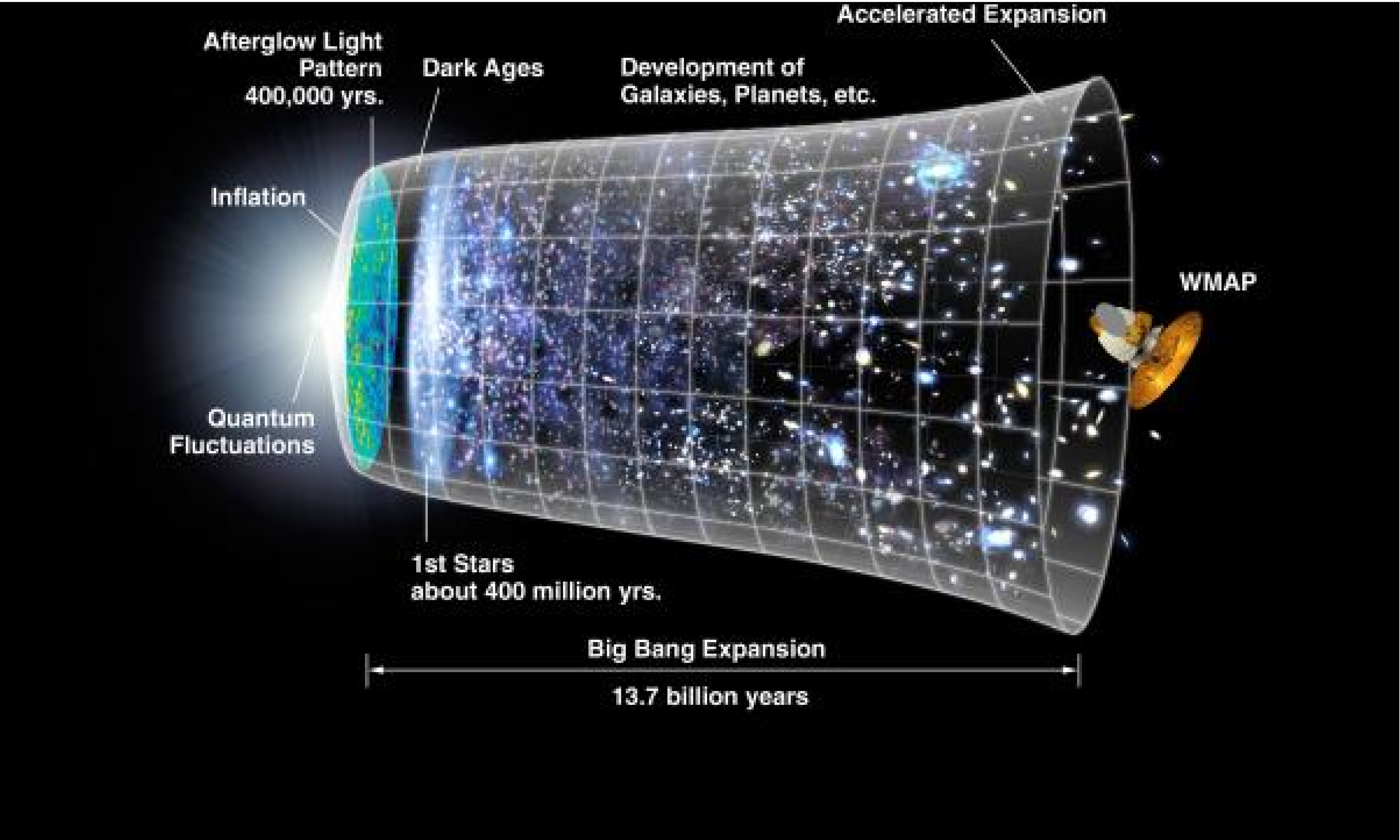
$$\delta \sim 10^{29}$$



$$\delta \sim 10^{43}$$

Could it really describe our Universe?

Basic idea


Accelerated Expansion
Afterglow Light Pattern 400,000 yrs.
Dark Ages
Development of Galaxies, Planets, etc.
Inflation
WMAP
Quantum Fluctuations
1st Stars about 400 million yrs.
Big Bang Expansion
13.7 billion years

The story of "pertuby"

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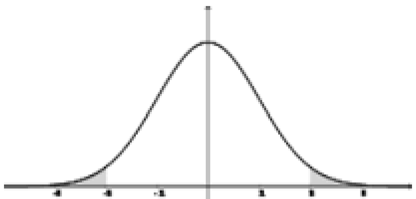
QUANTUM

RADIATION

MATTER

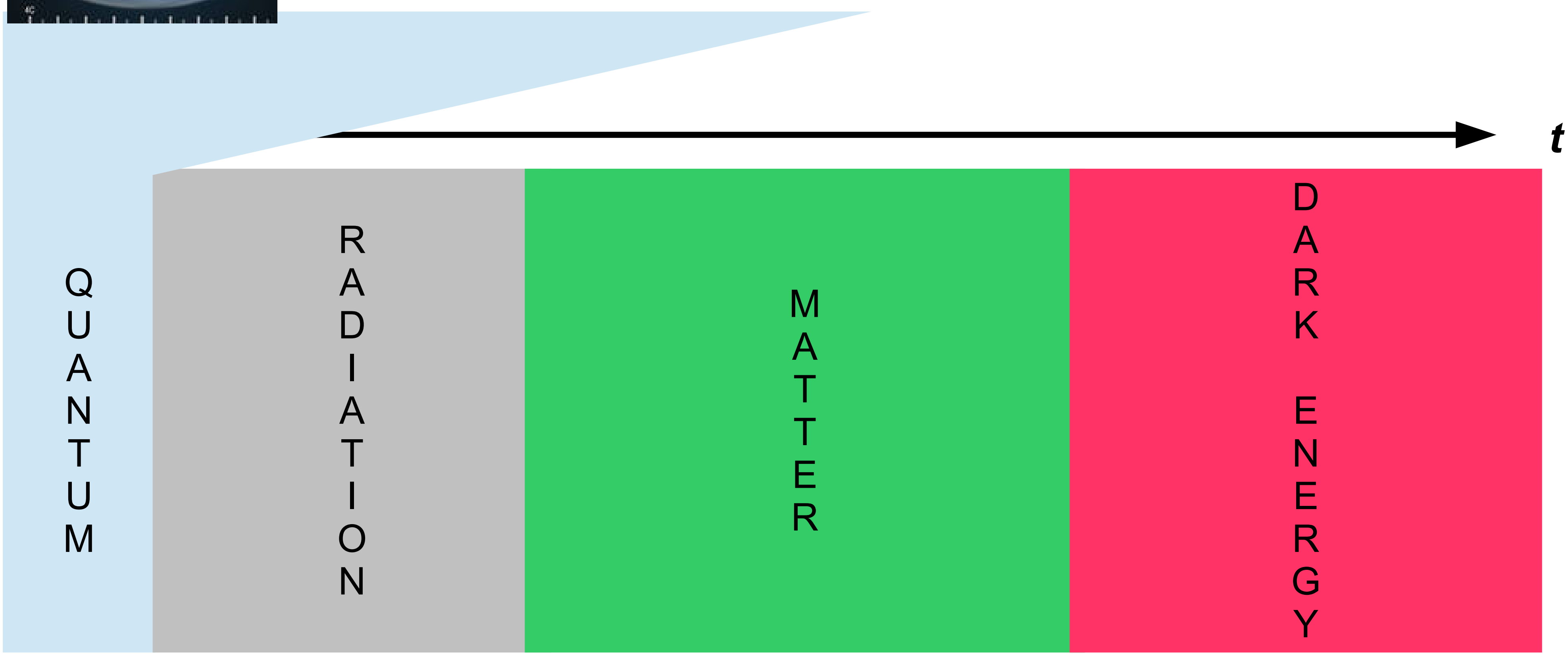
DARK ENERGY

The story of “pertuby”



“Classical” pert.

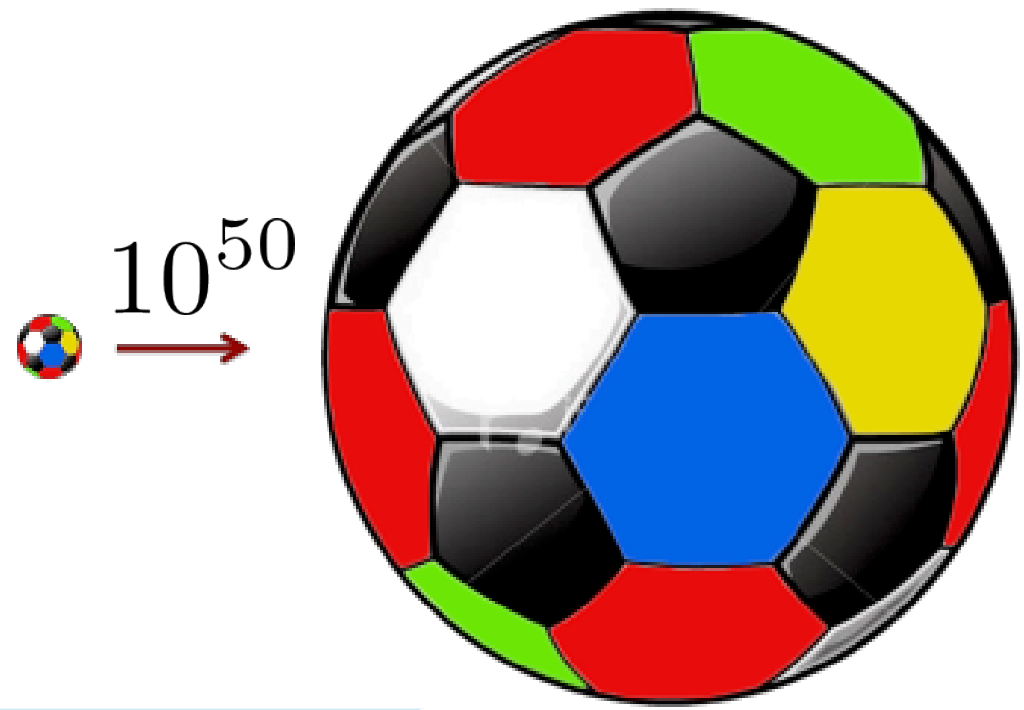
Interactions!

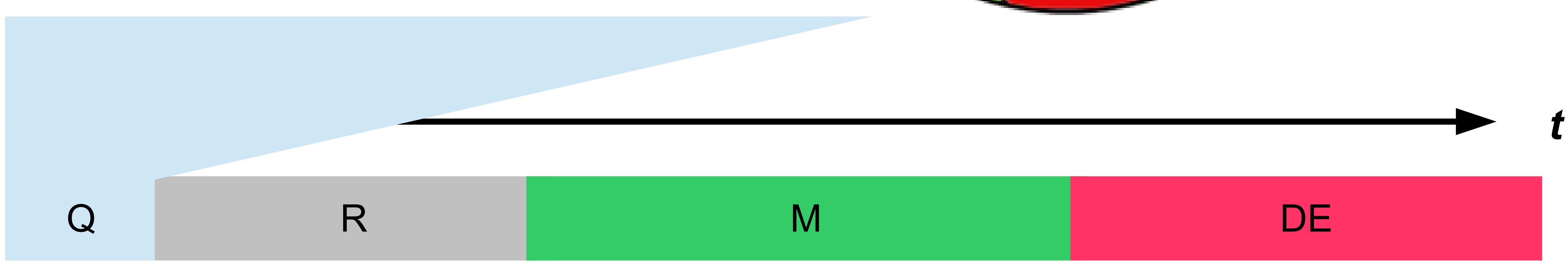


The story of “pertuby”

Formally (the inflationary mechanism)

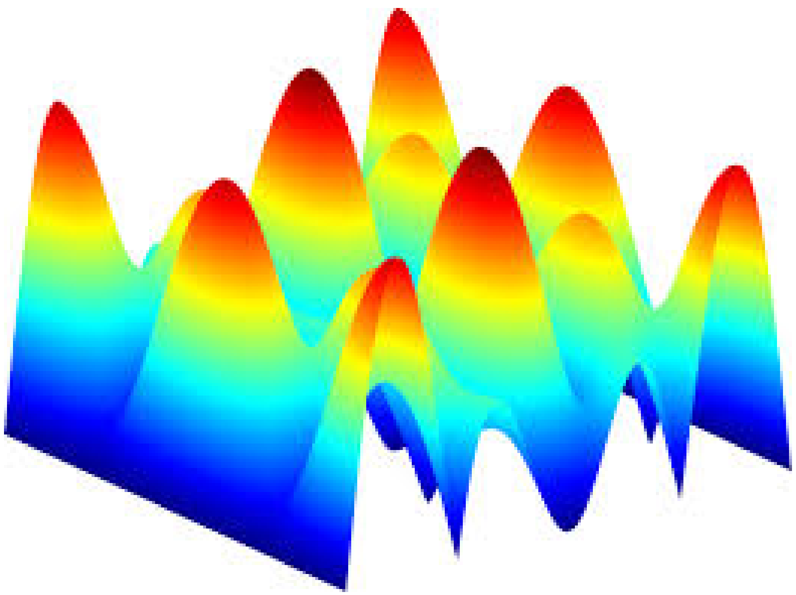
$$t \sim 10^{-32}$$



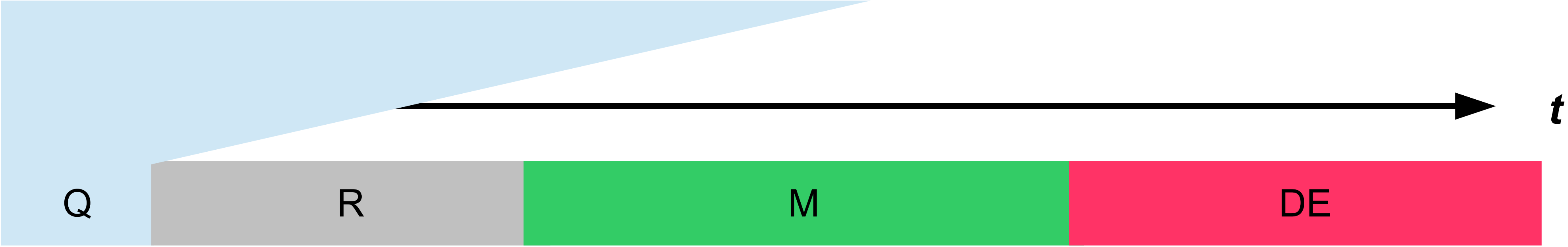


The story of “pertuby”

By the end of inflation we're left with a ***distribution*** of fluctuations

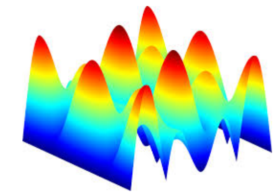


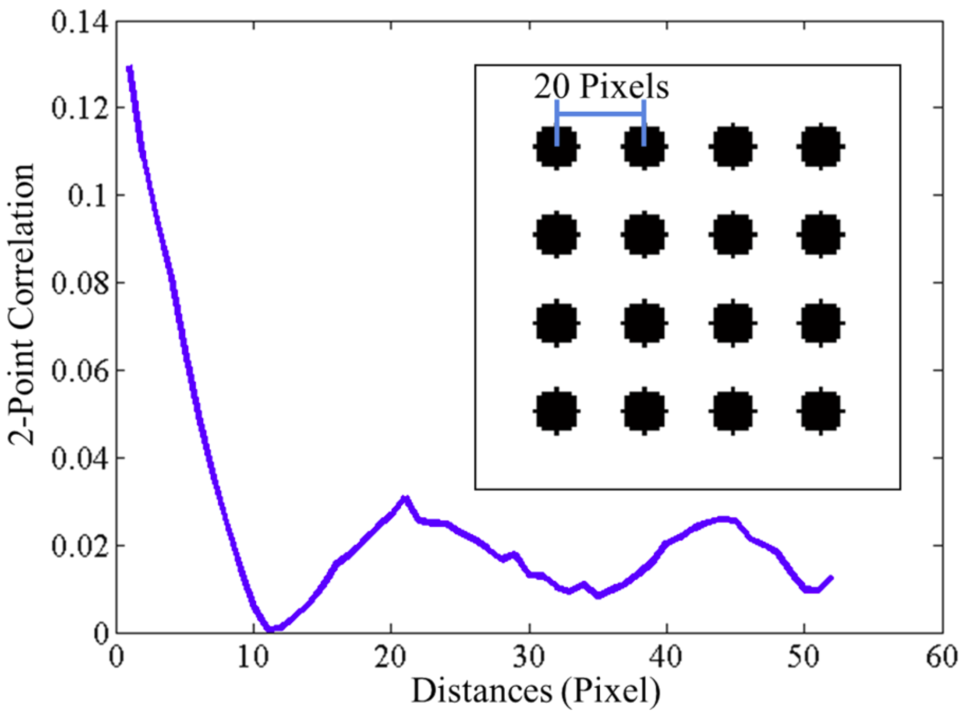
don’t know initial conditions of each perturbation



The story of “pertuby”

How do we describe a distribution?

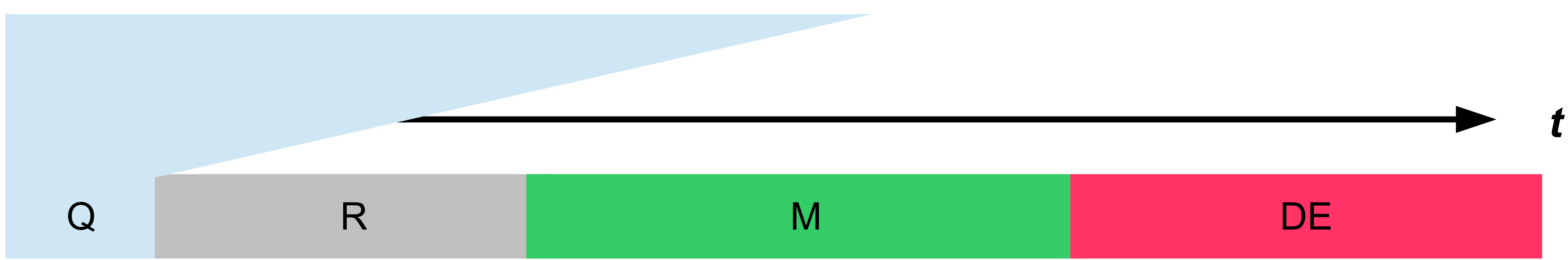




$\xi \sim \langle$  $\rangle$

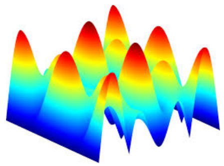
Fourier

$$P(k)\delta(k-k') \sim < \hat{\delta}(k)\hat{\delta}(k') >$$



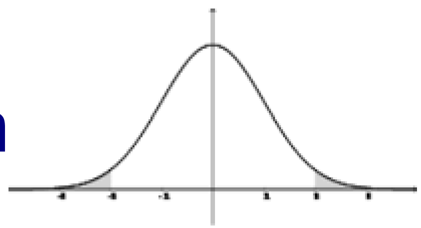
The story of "pertuby"

Power spectrum $P(k)$ by the end of inflation



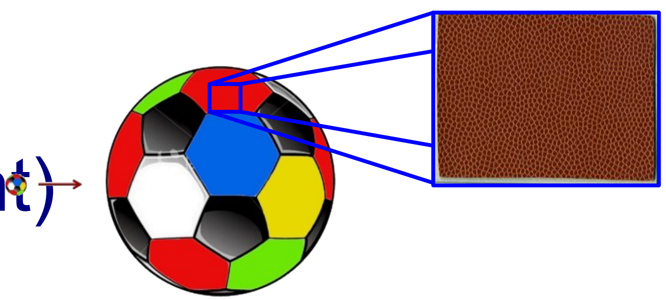
*Almost scale invariant

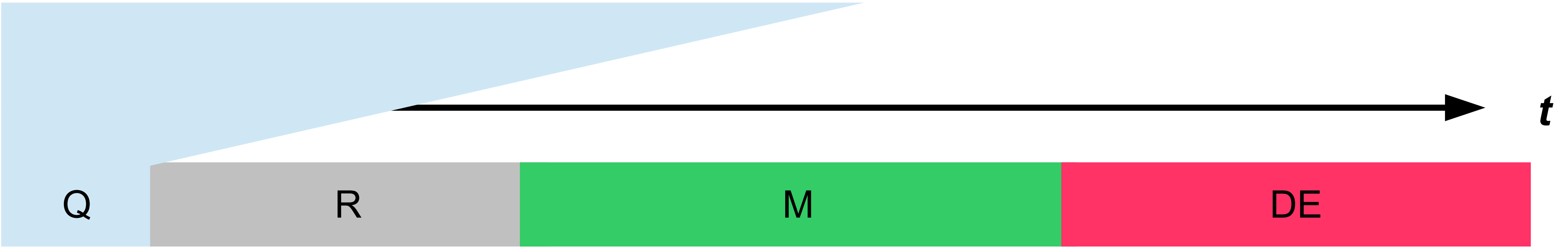
*Very Gaussian (pair correlations are enough
NO TRIANGLES)



*Input amplitude of (0.00001).

*Gravitational waves (model dependent)



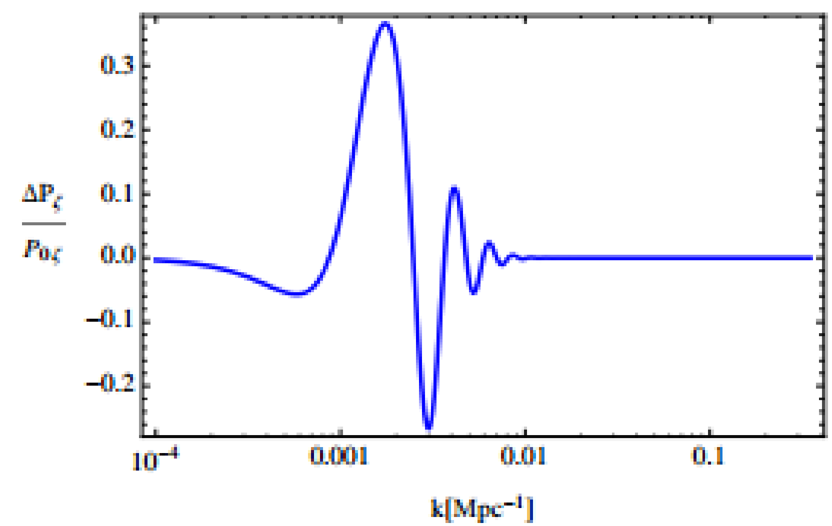


The story of "pertuby"

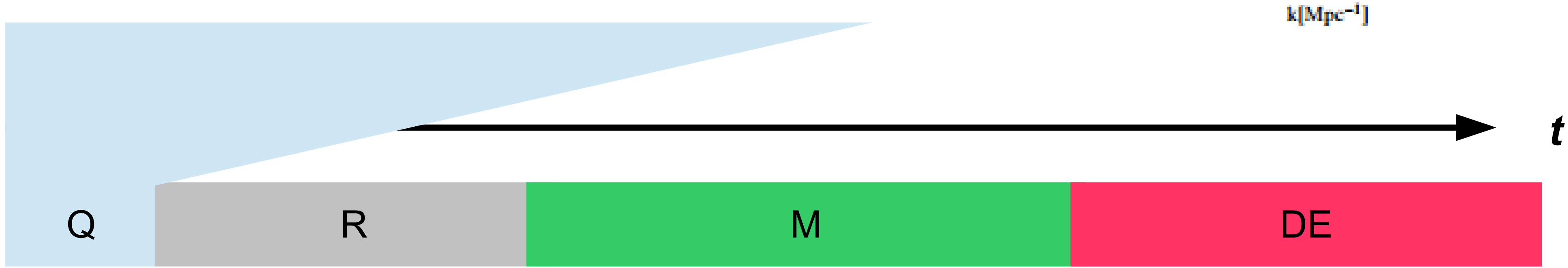
Beyond the vanilla model

-Sharp features (temporary break of de Sitter phase)

- bumps in potential
- sound speed variations
- bending trajectories (more dof's)
- Injections of new physics

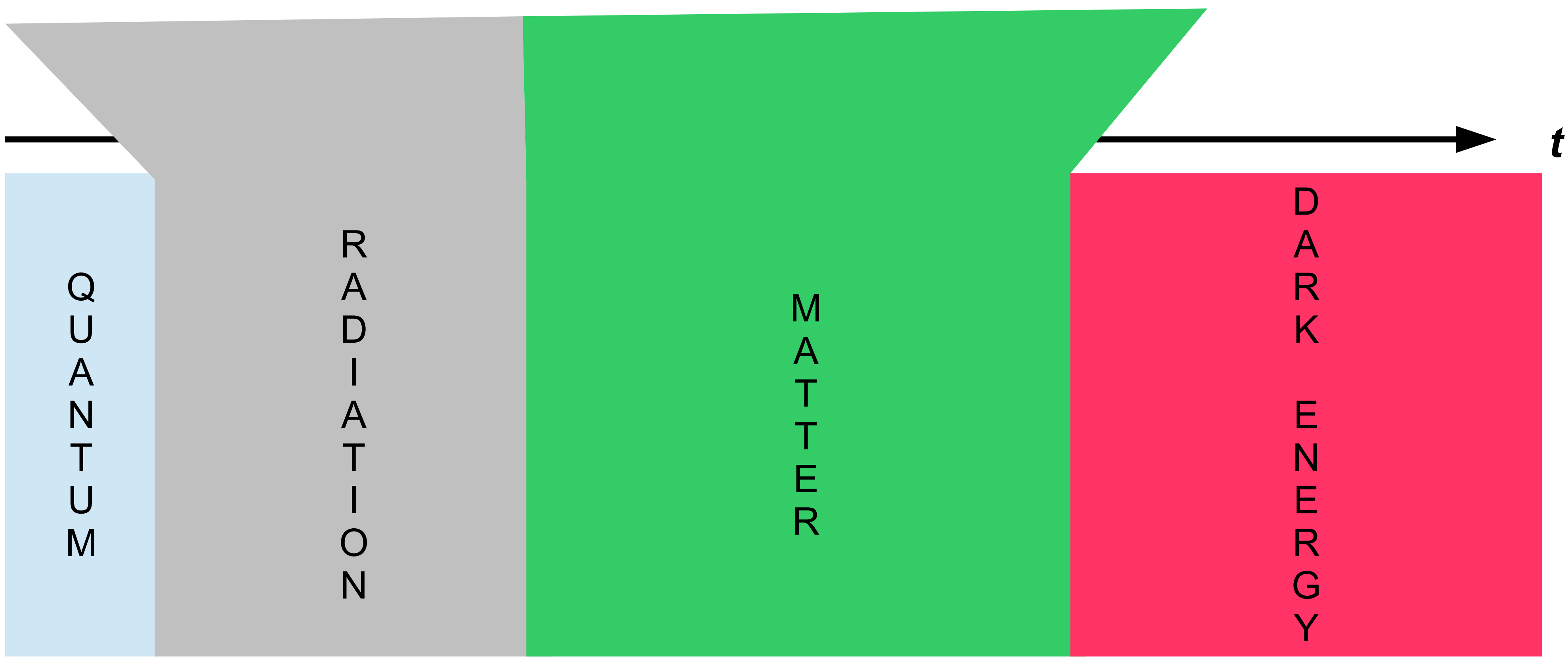


-Periodic features (stringy models)
-O(1) non-Gaussianities
-etc.

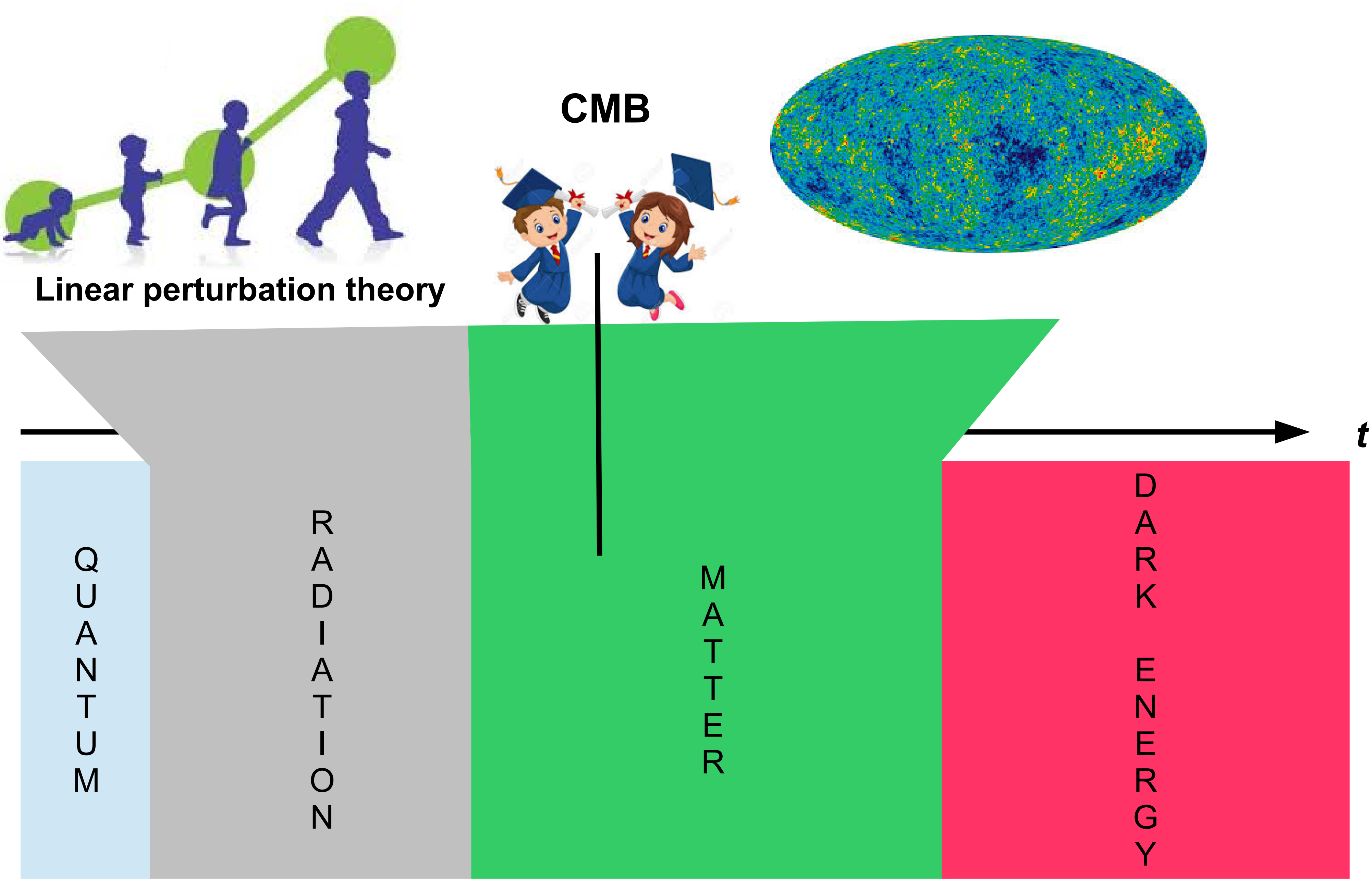


The story of "pertuby"

Linear perturbation theory

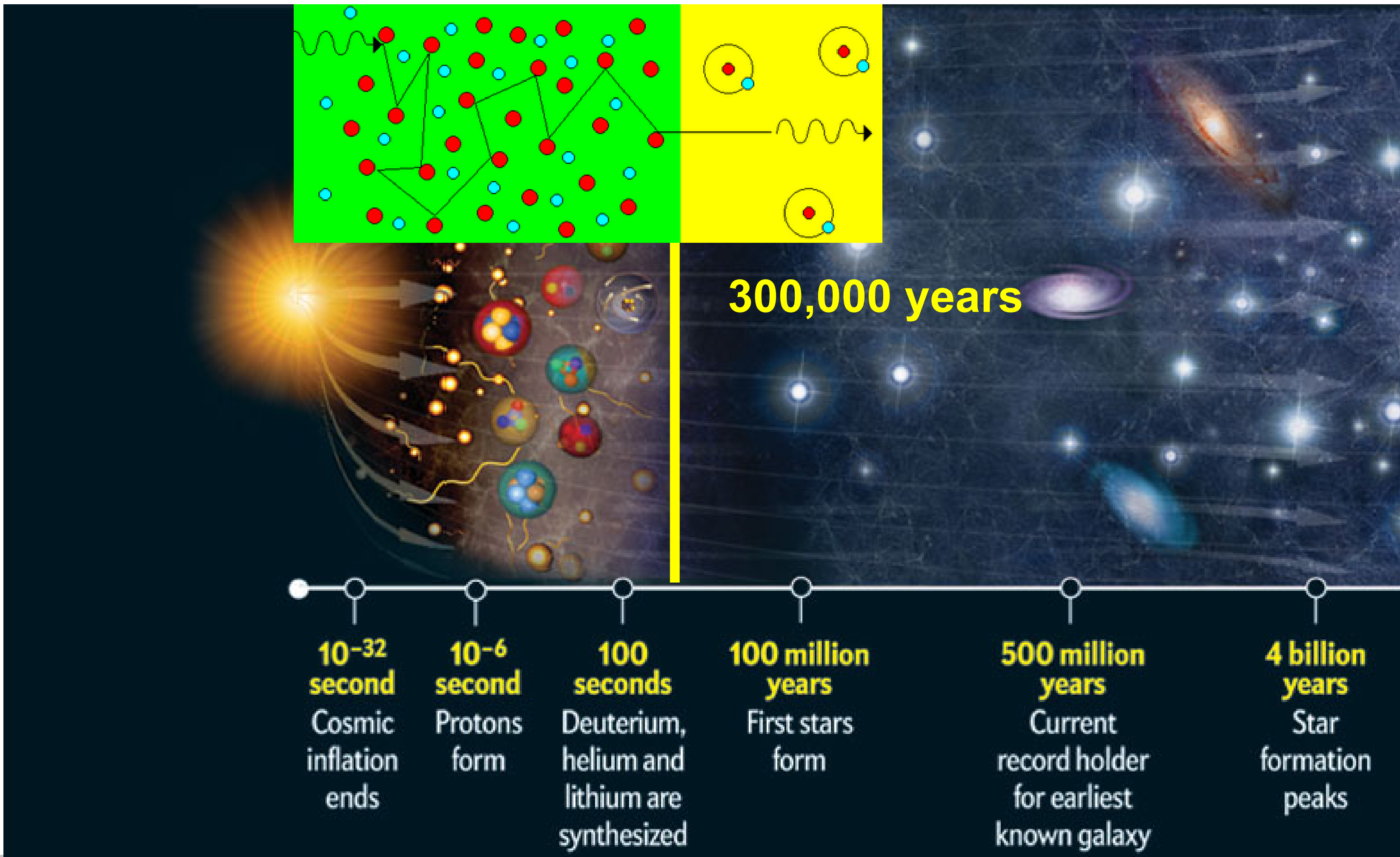


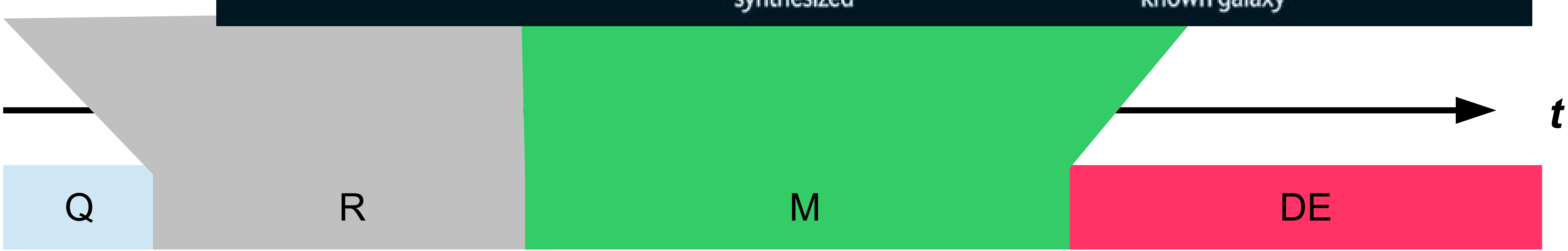
The story of “pertuby”



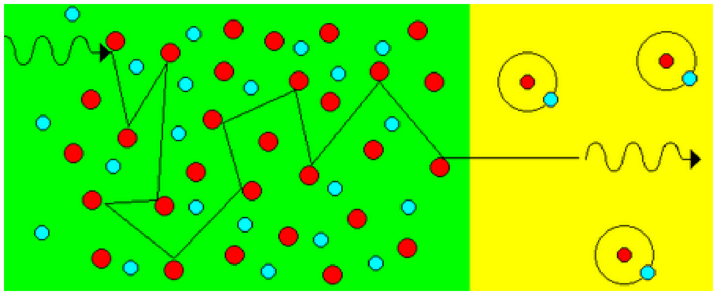
The story of “pertuby”

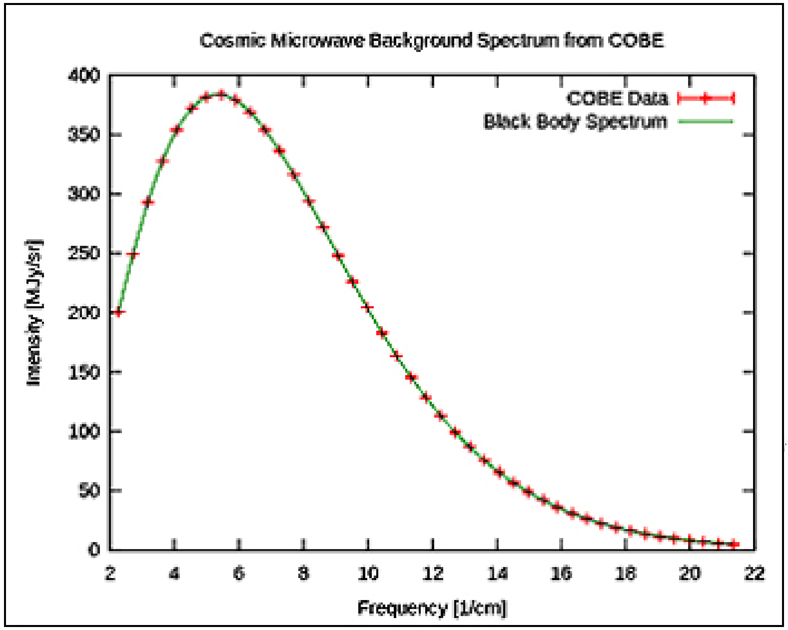
CMB

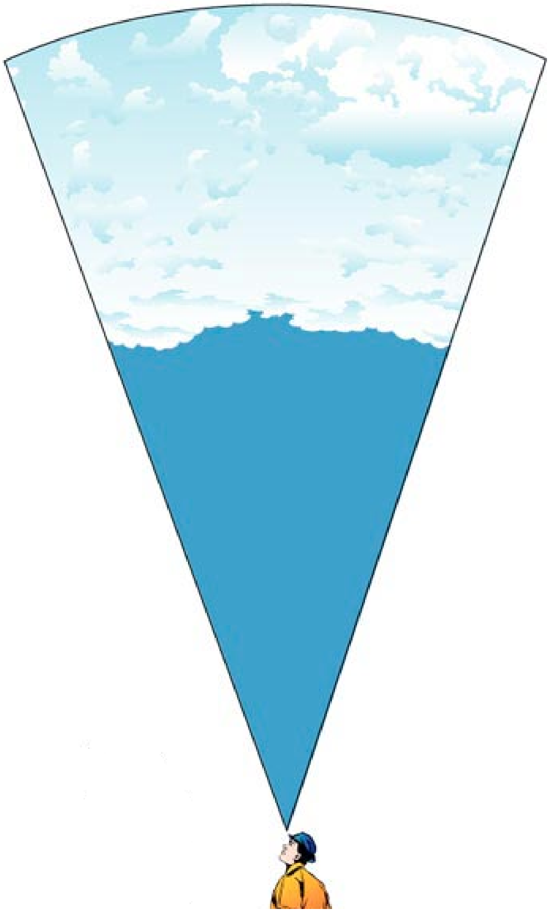




The story of “pertuby”







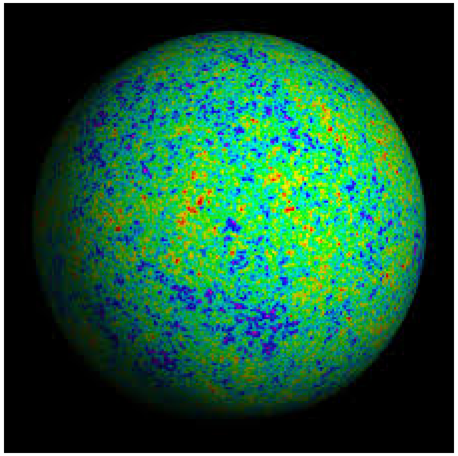
CMB
(First observable)

The story of “pertuby”

CMB Anisotropies

Natural to use spherical harmonics

$$\frac{\Delta T}{\bar{T}} = \sum_{lm} T_{lm} Y_{lm}$$

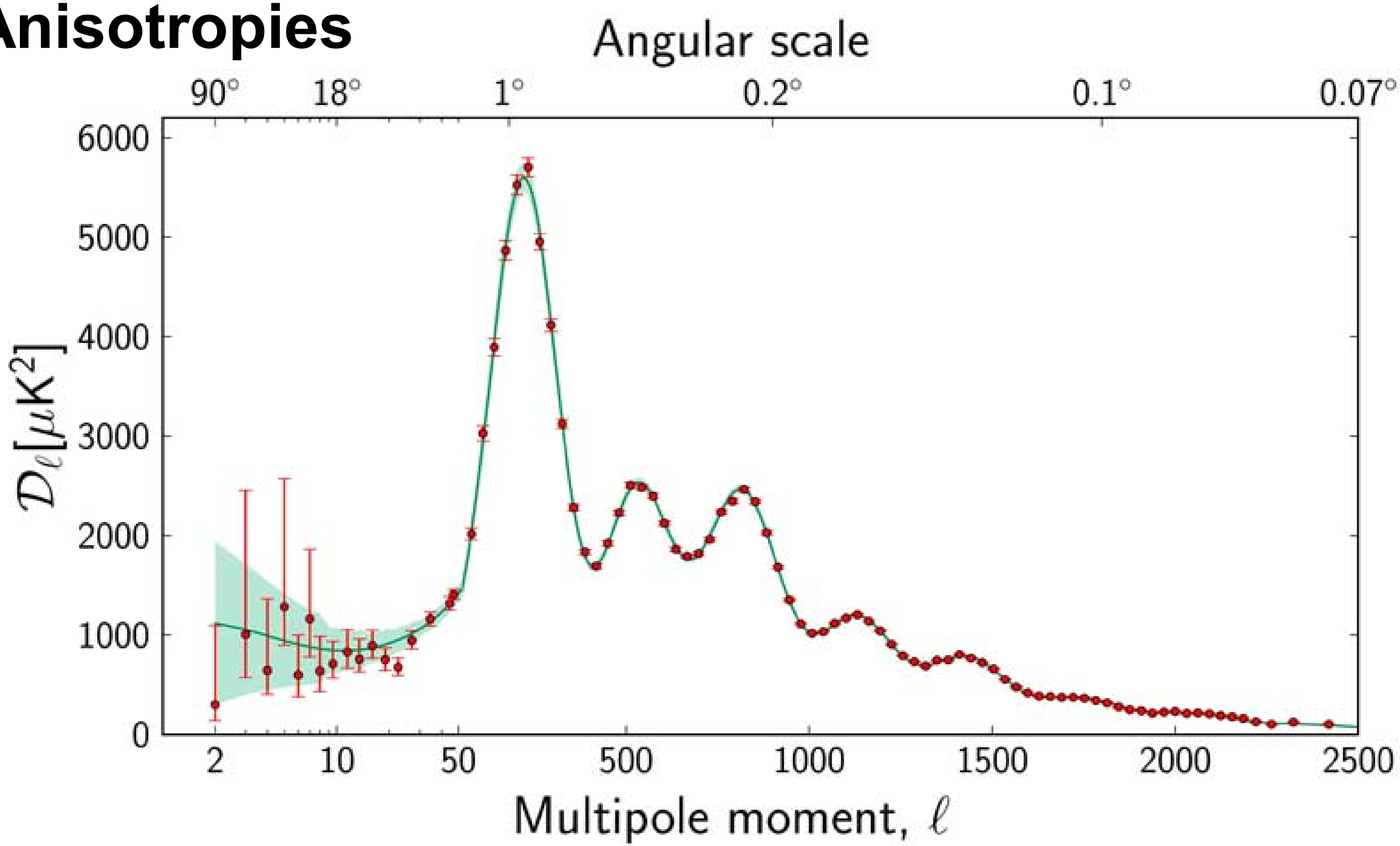


Power spectrum

$$< T_{lm} T_{l'm'} > = 2\pi \mathcal{D}_l \ \delta_{ll'} \delta_{mm'}$$

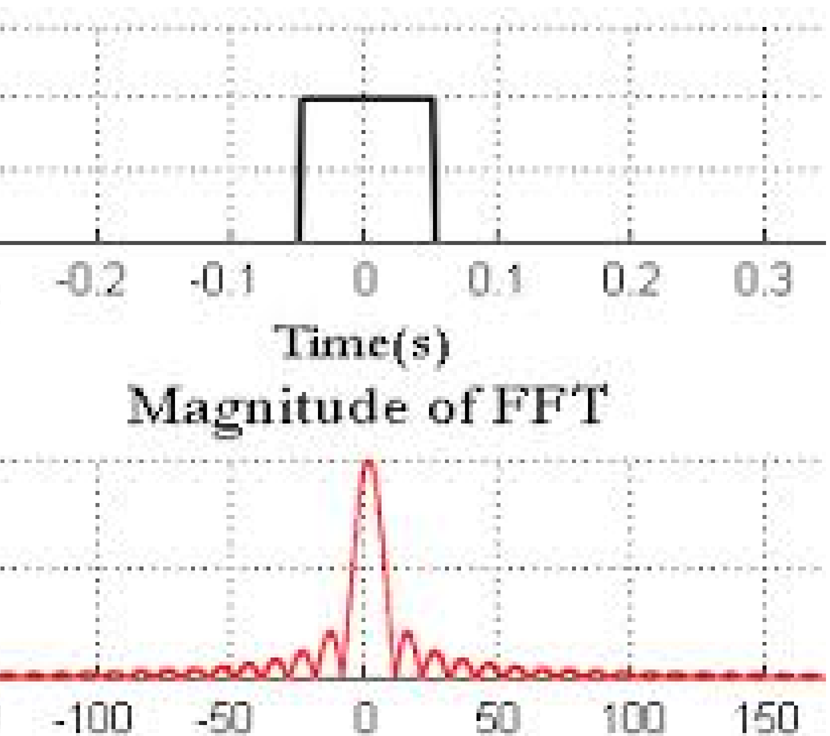
The story of "pertuby"

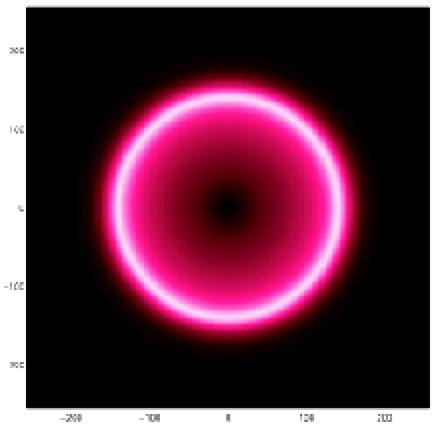
CMB Anisotropies



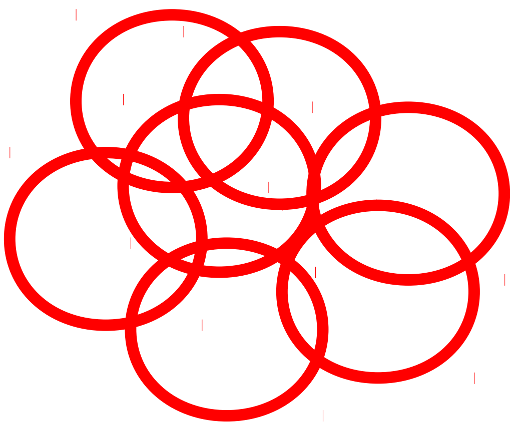
The story of "pertuby"

CMB Oscilations

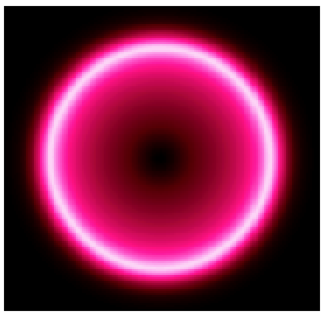


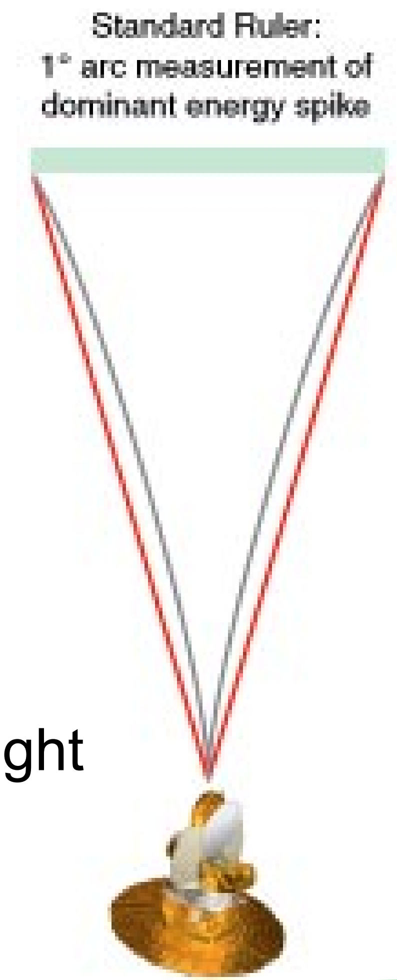


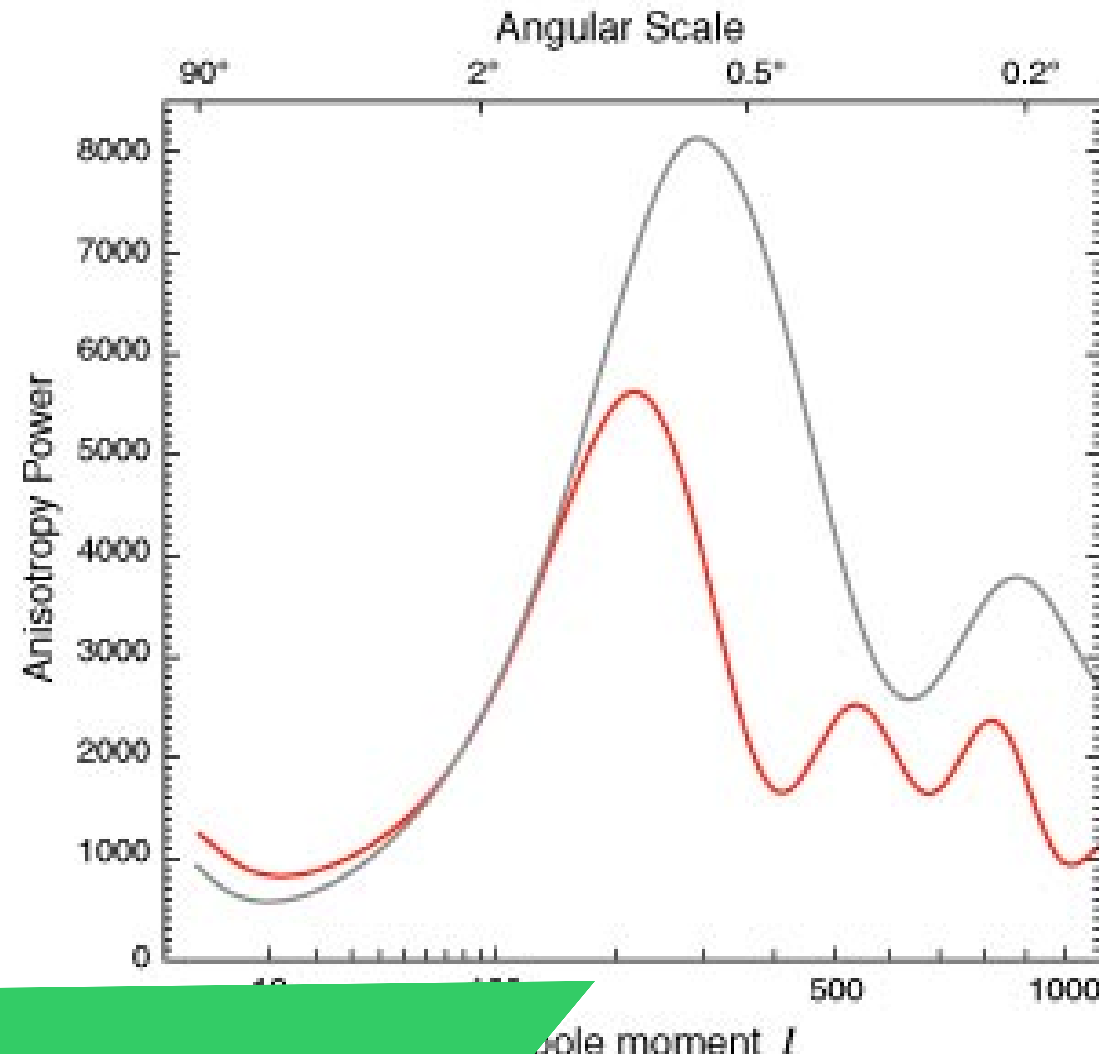
Remnant of photon's pressure



The story of “pertuby”

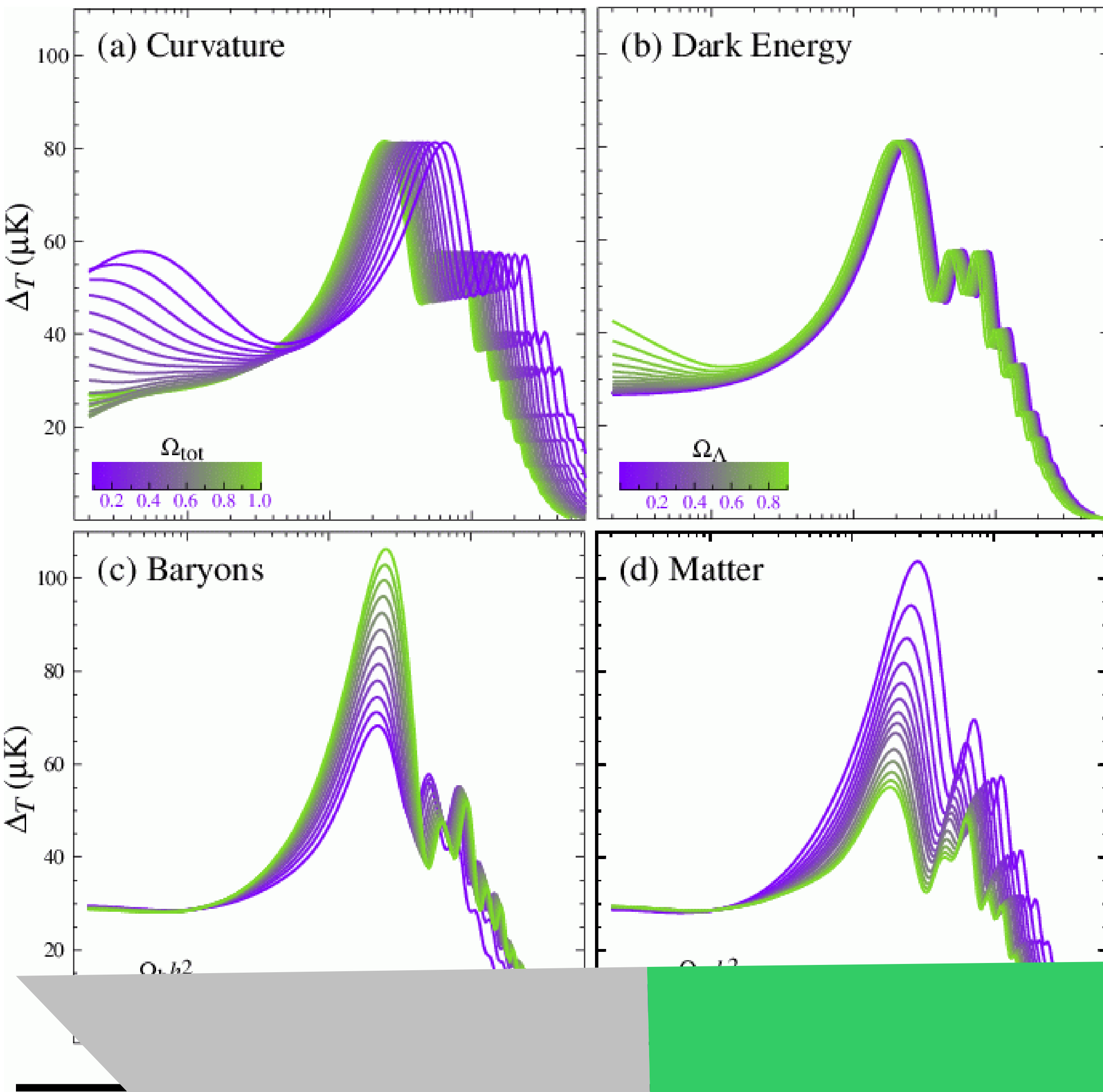






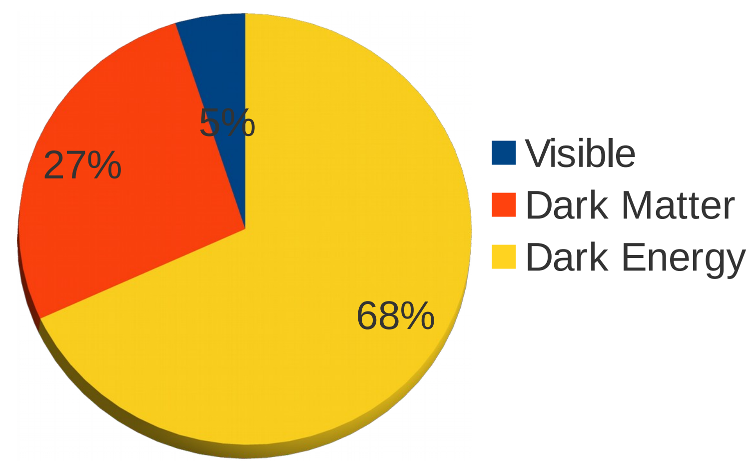
Planck
To 0.1% the flat
Universe model is right

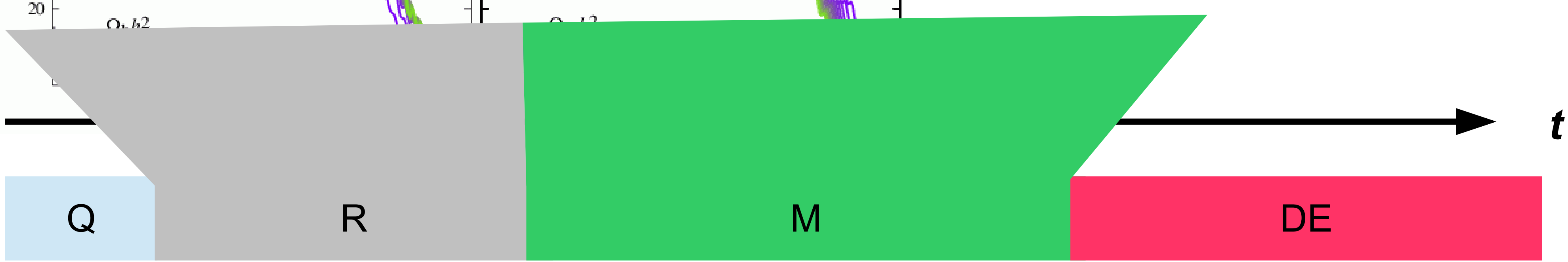
The story of “pertuby”



Planck satellite

Flat Universe to 1%





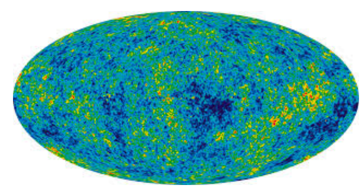
The story of “pertuby”

CMB

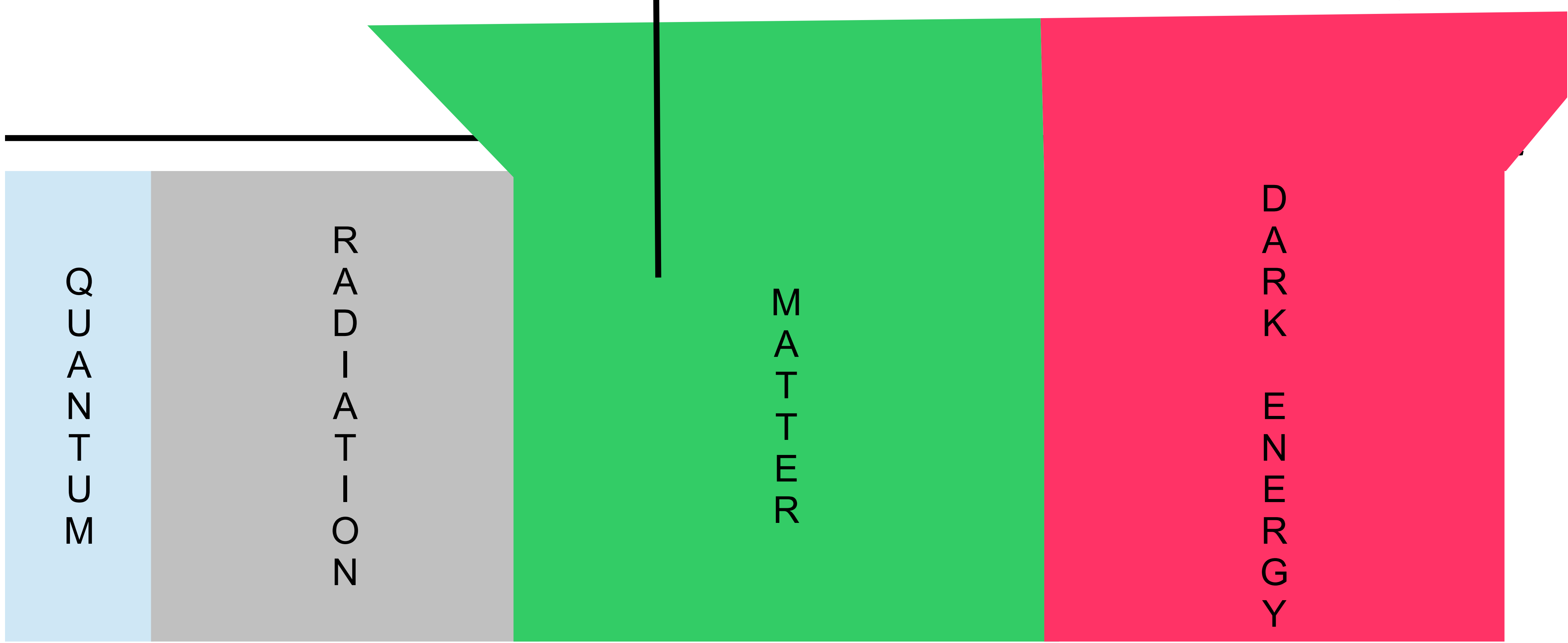
- Consistent with inflation (Gaussian & almost scale invariant distribution)
- Nothing about interactions… No Triangles!
- No further features/physics
- No tensors (B-modes) yet!
- Cannot gain more mode statistics to achieve better accuracy than with Planck

Future: explore the LSS

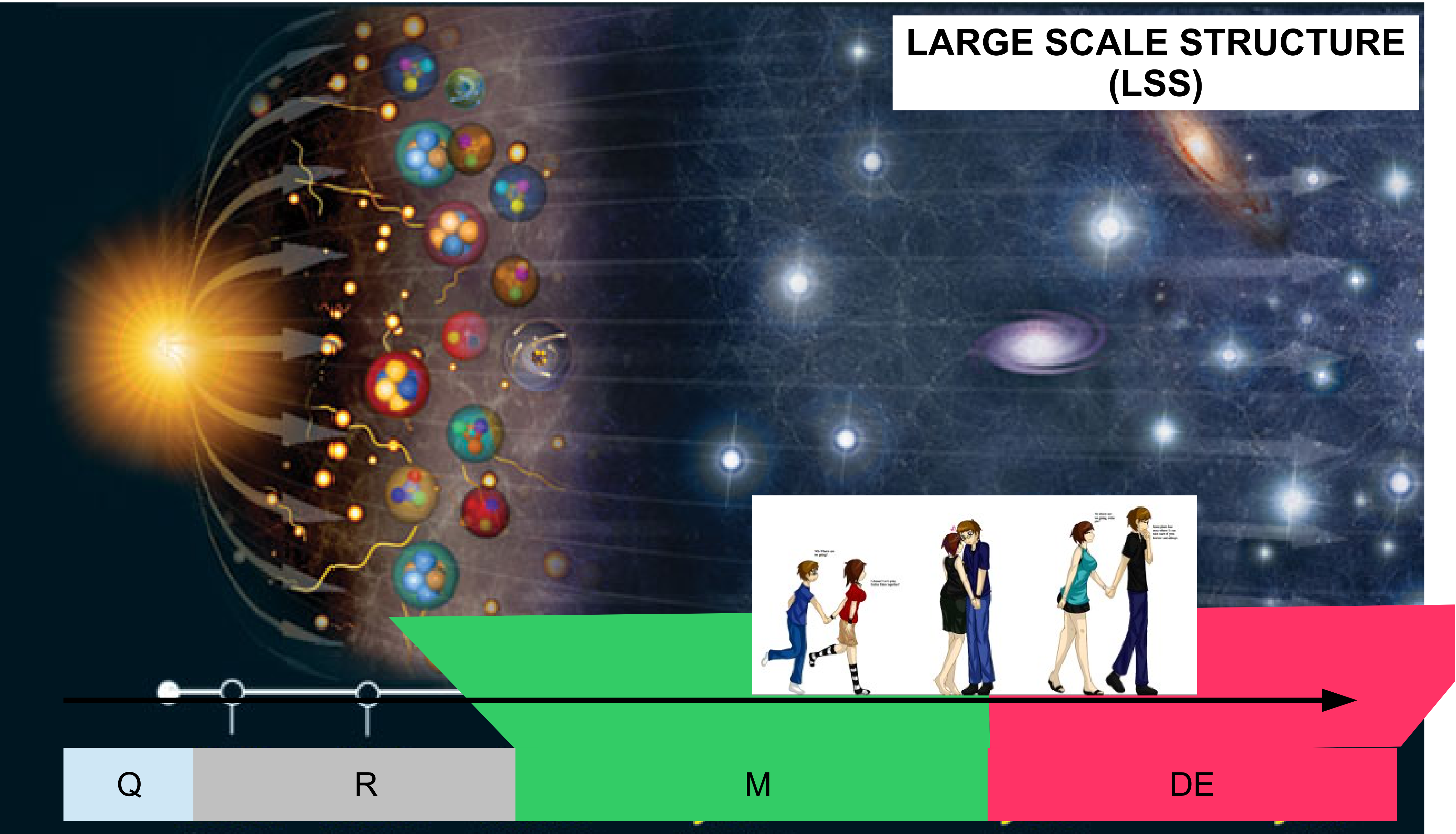
The story of "pertuby"



Non-linear perturbation theory

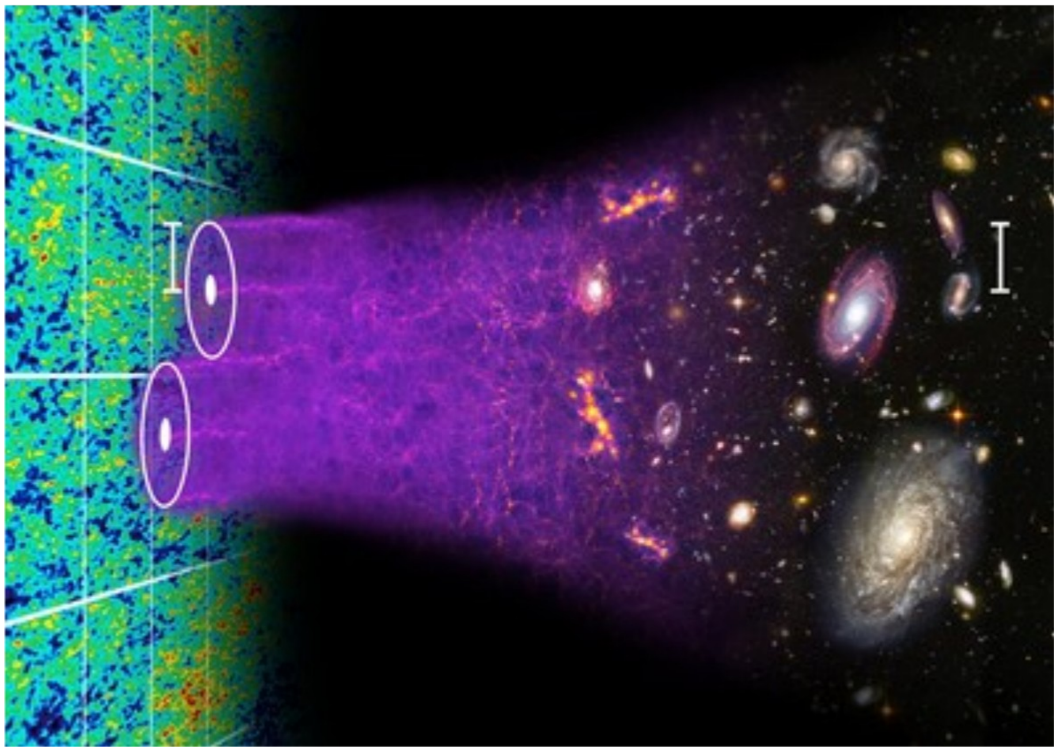


The story of “pertuby”

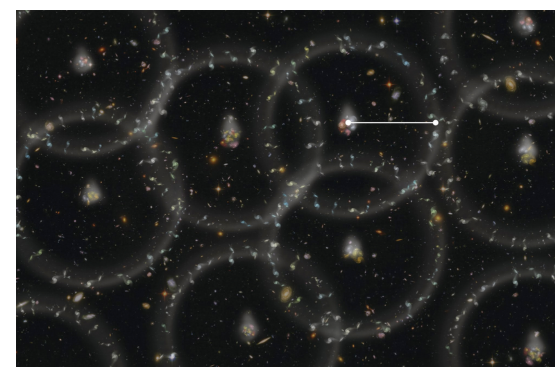


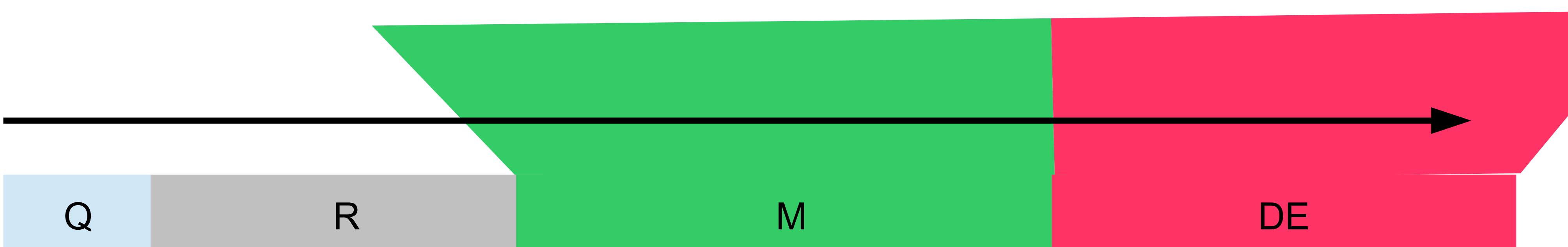
The story of “pertuby”

CMB seeds the structure at large scales

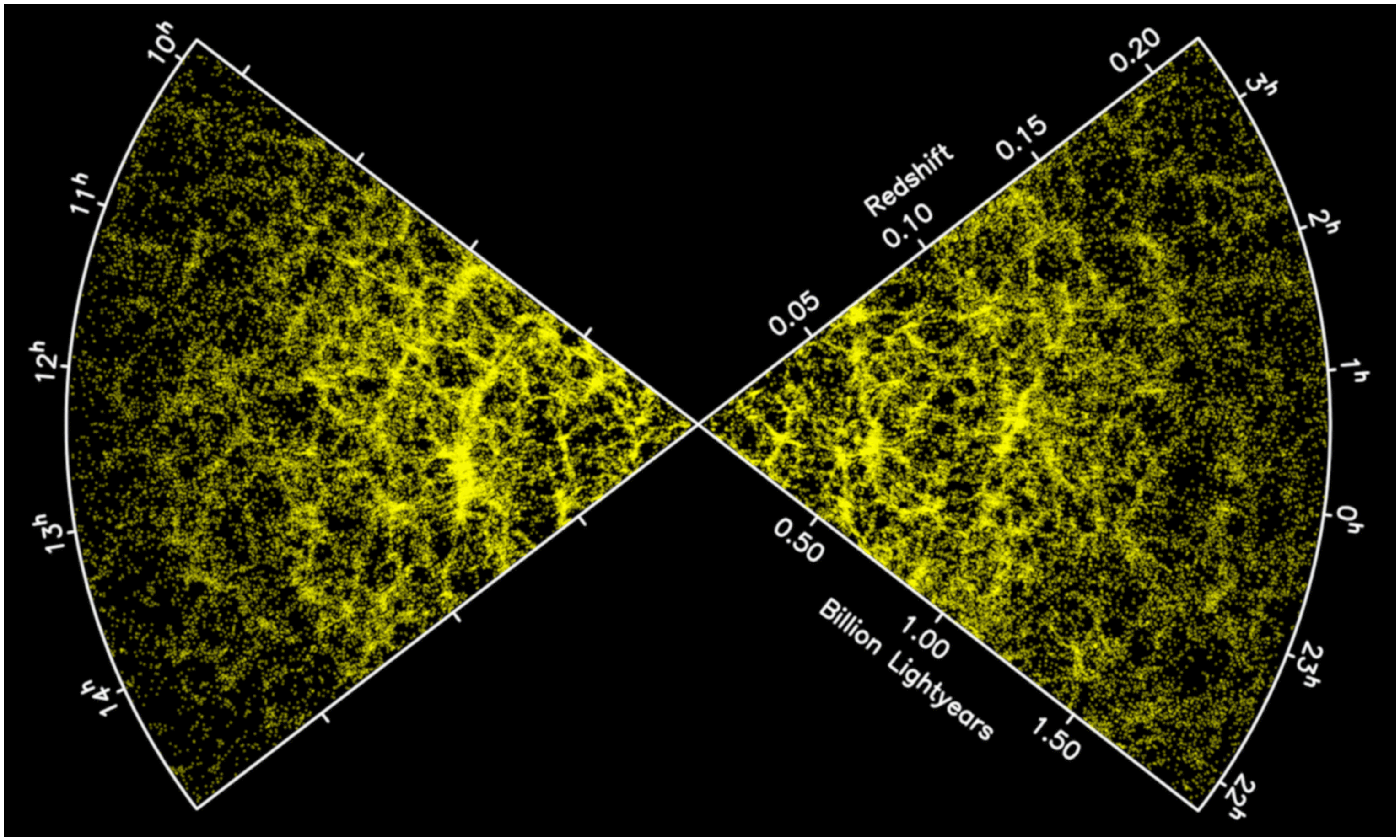


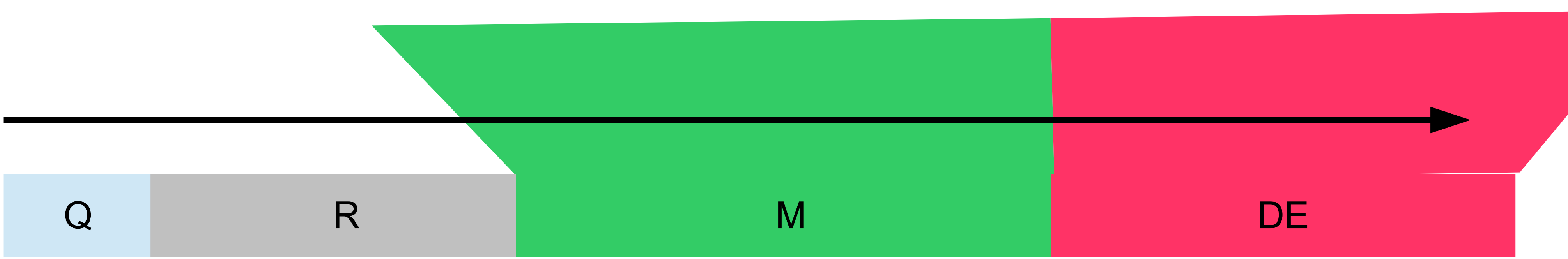
Baryonic
Acoustic
Oscillations





The story of “pertuby”



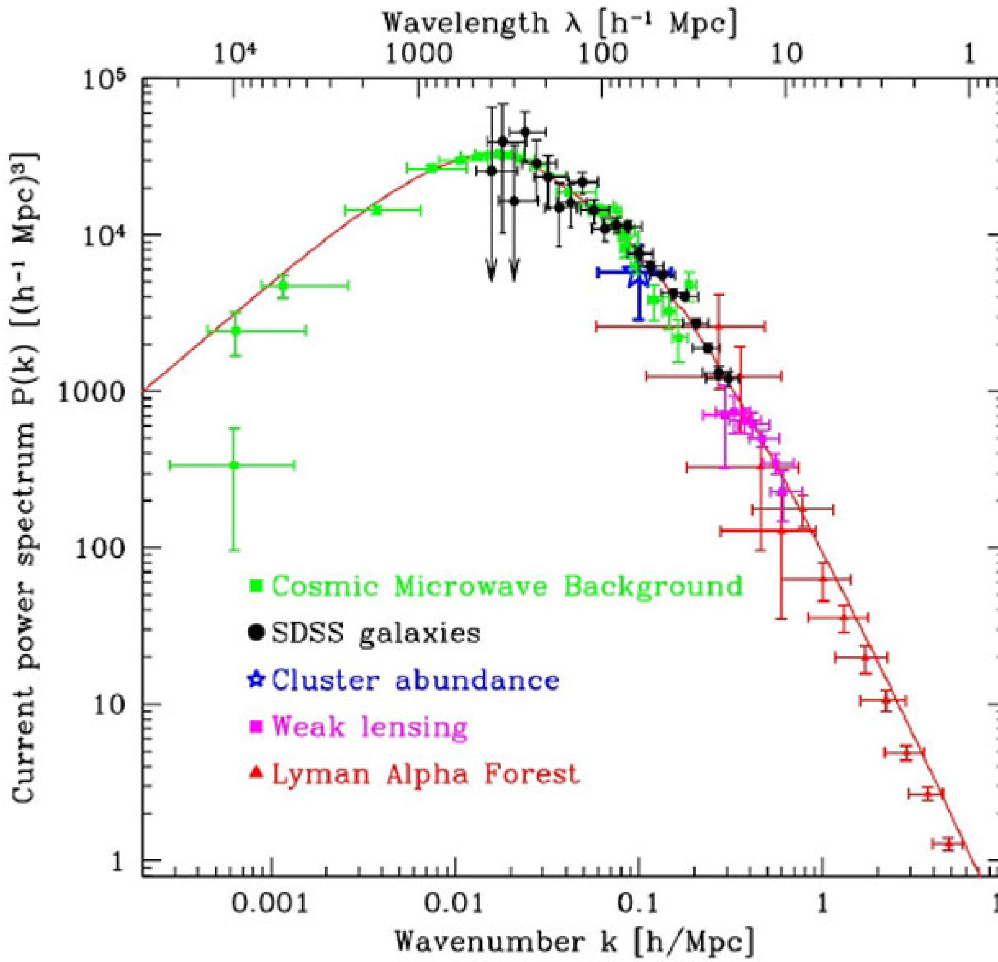


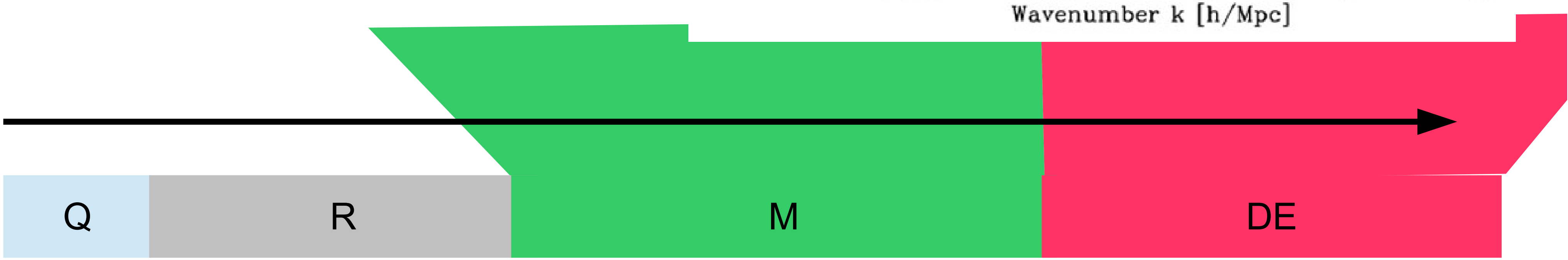
The story of “pertuby”

Benefits

1) Volume Vs area (CMB)
   *More Resolution!!!

2) Non-linear physics
   *More difficult
   *Richness





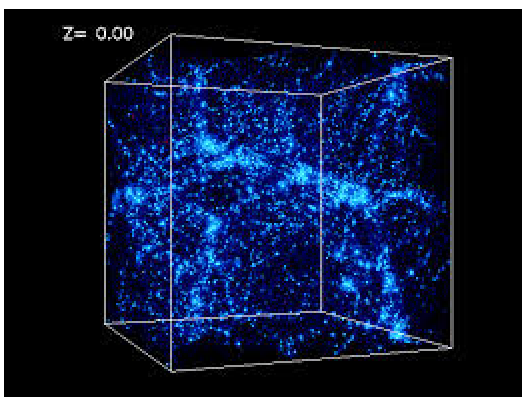
The story of “pertuby”

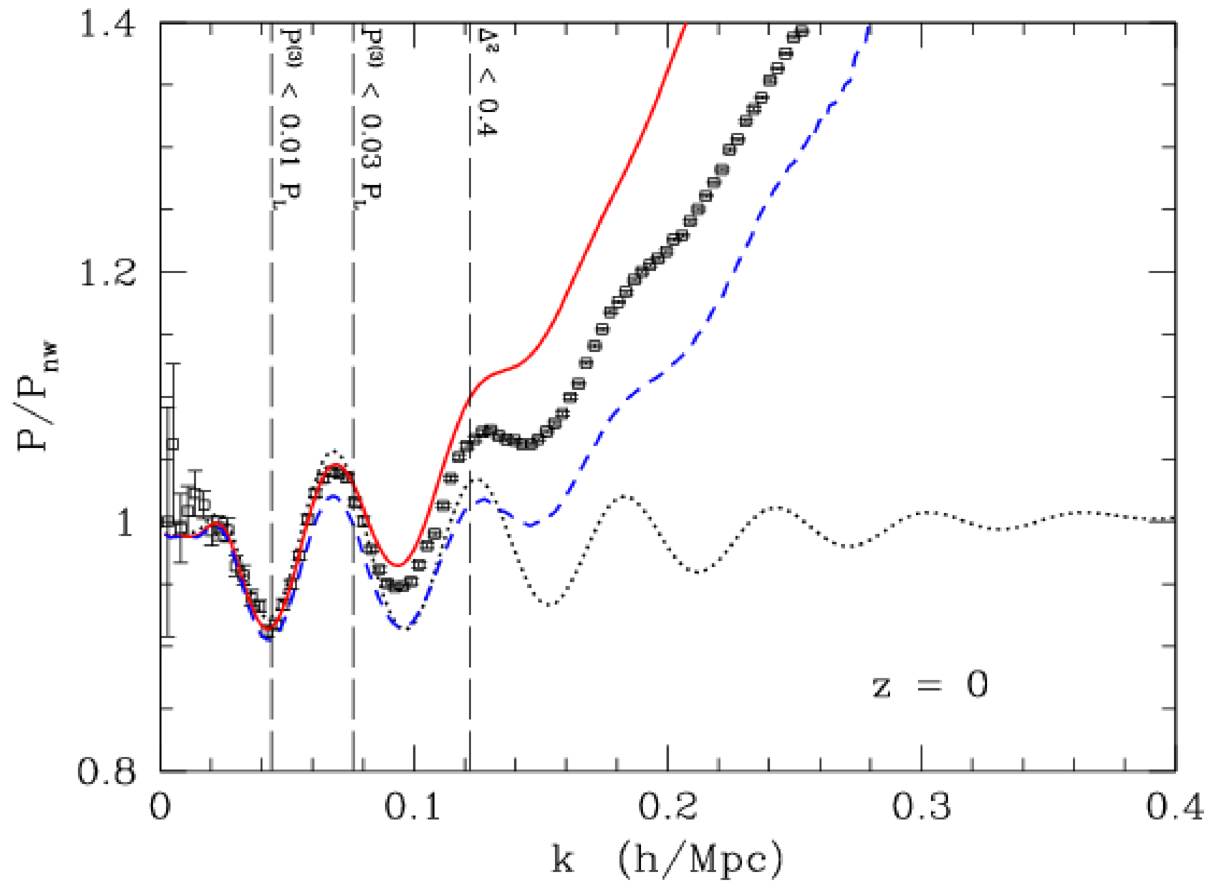
Perturbation theory

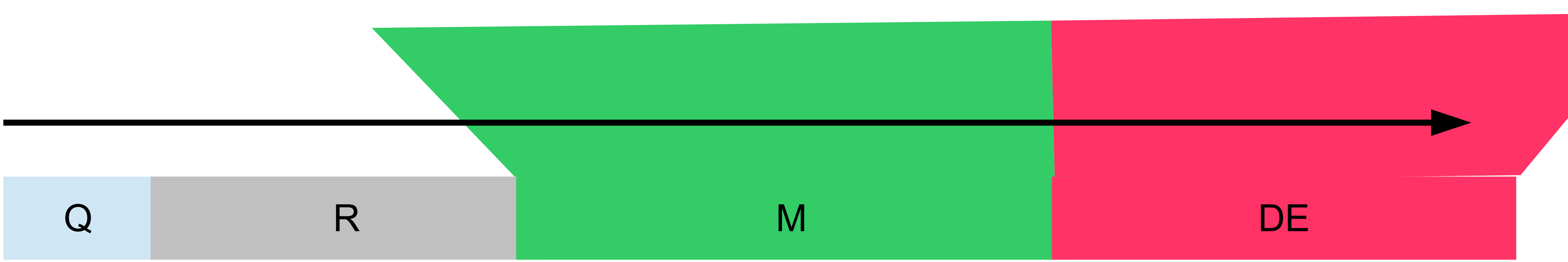
1) Series does not converge

2) Active area of research

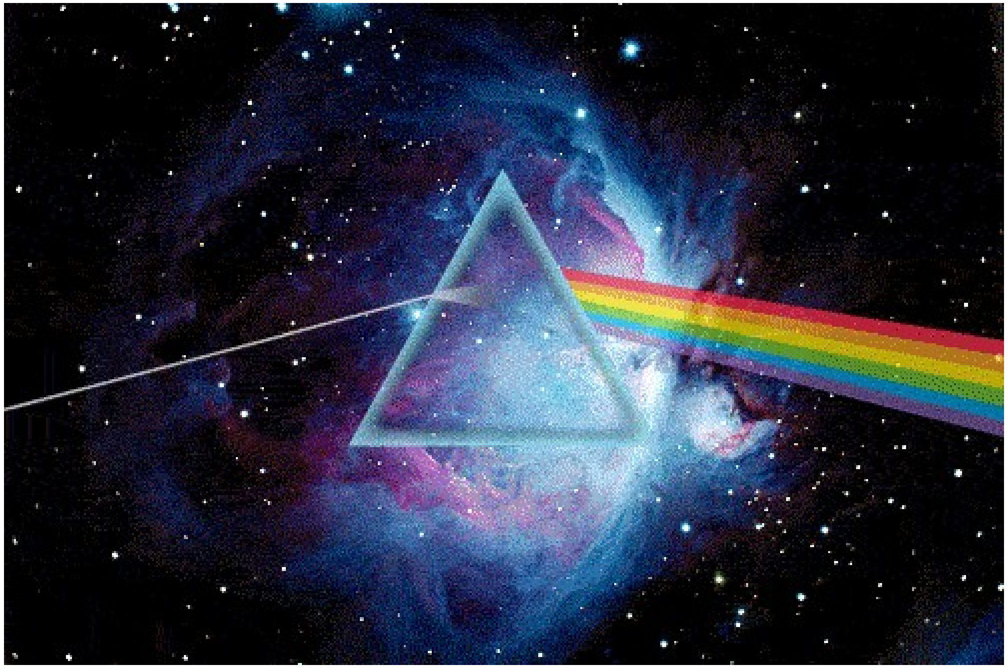
3) Tool

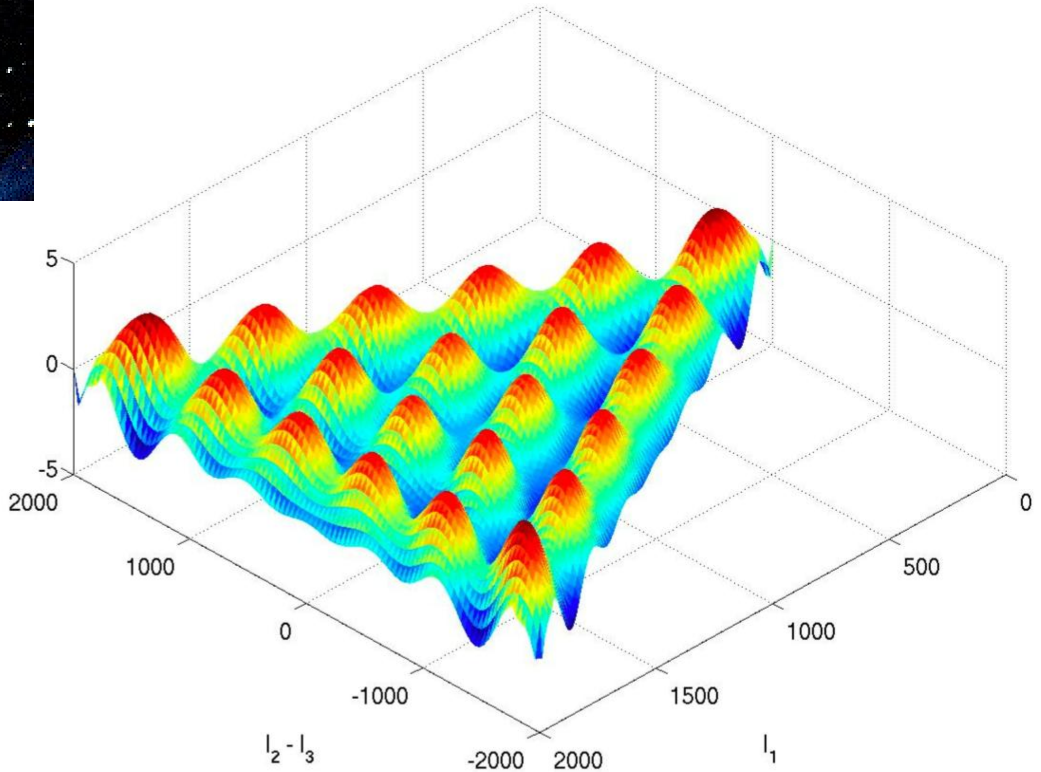




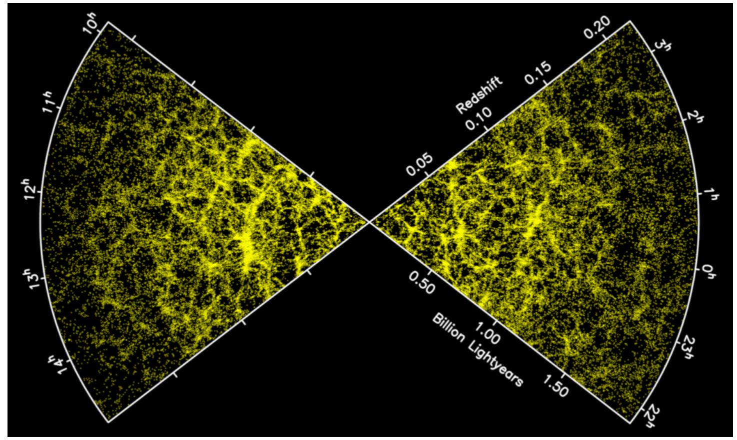


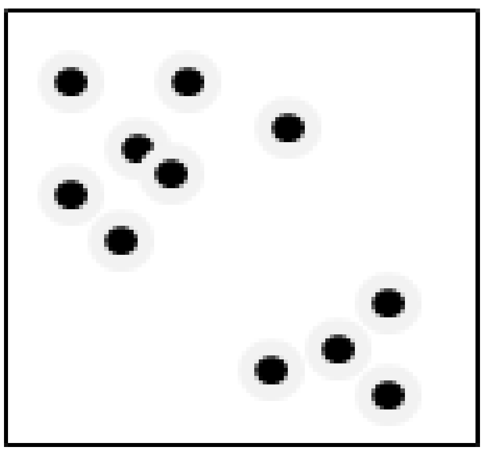
Triangles in the LSS



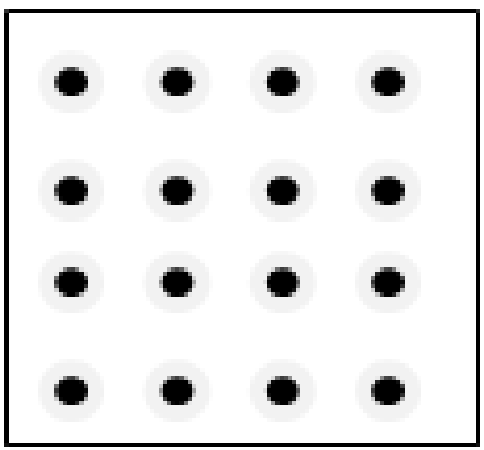


LSS

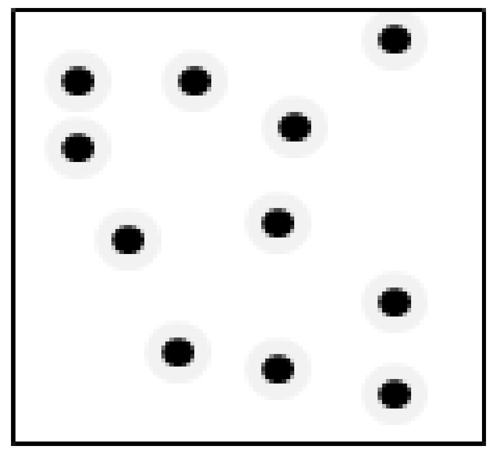




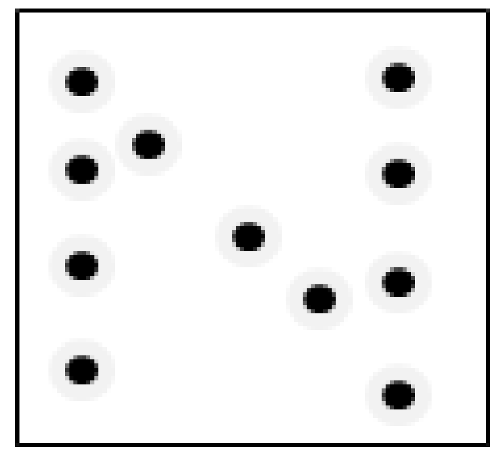
Clusters



Ordered



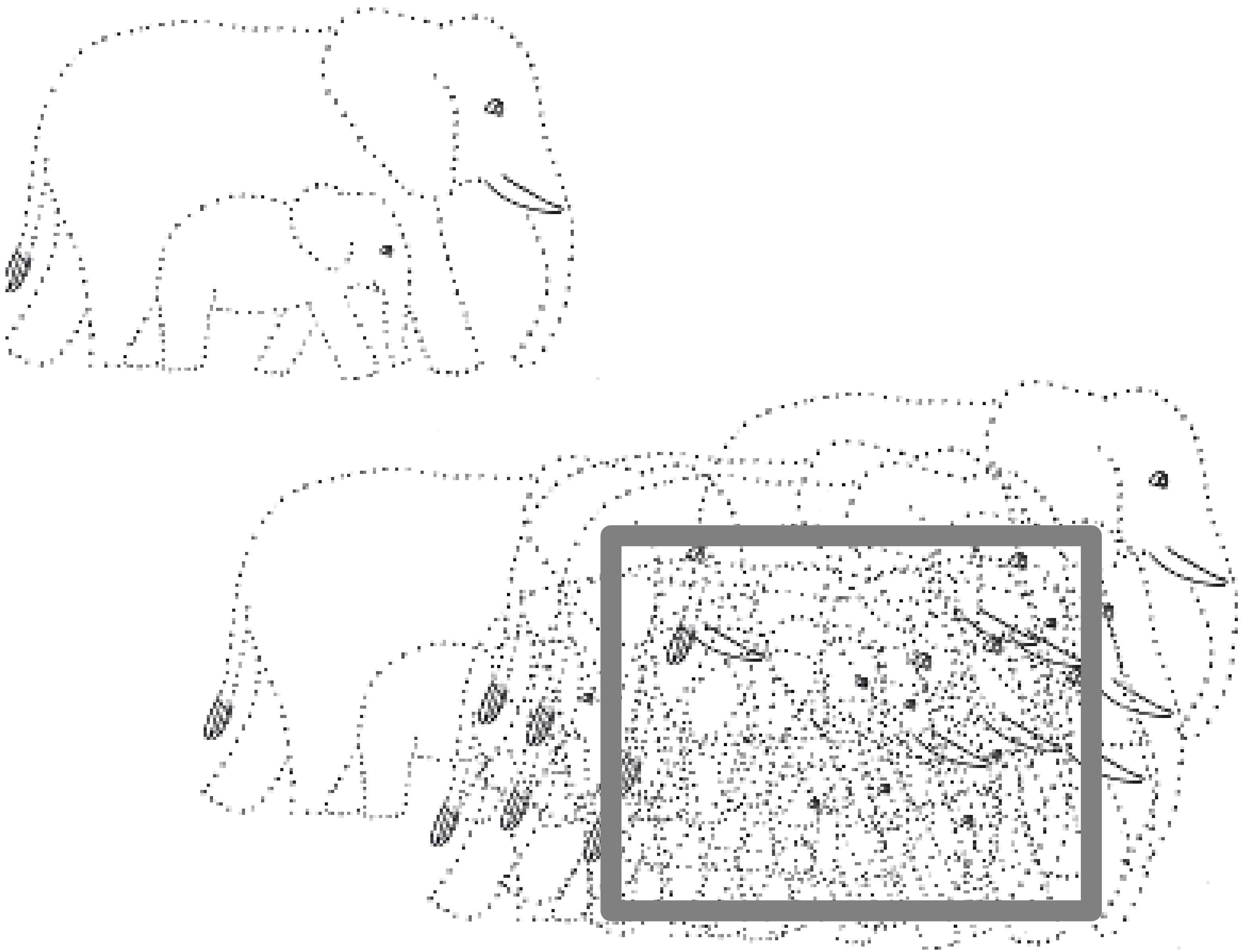
Random



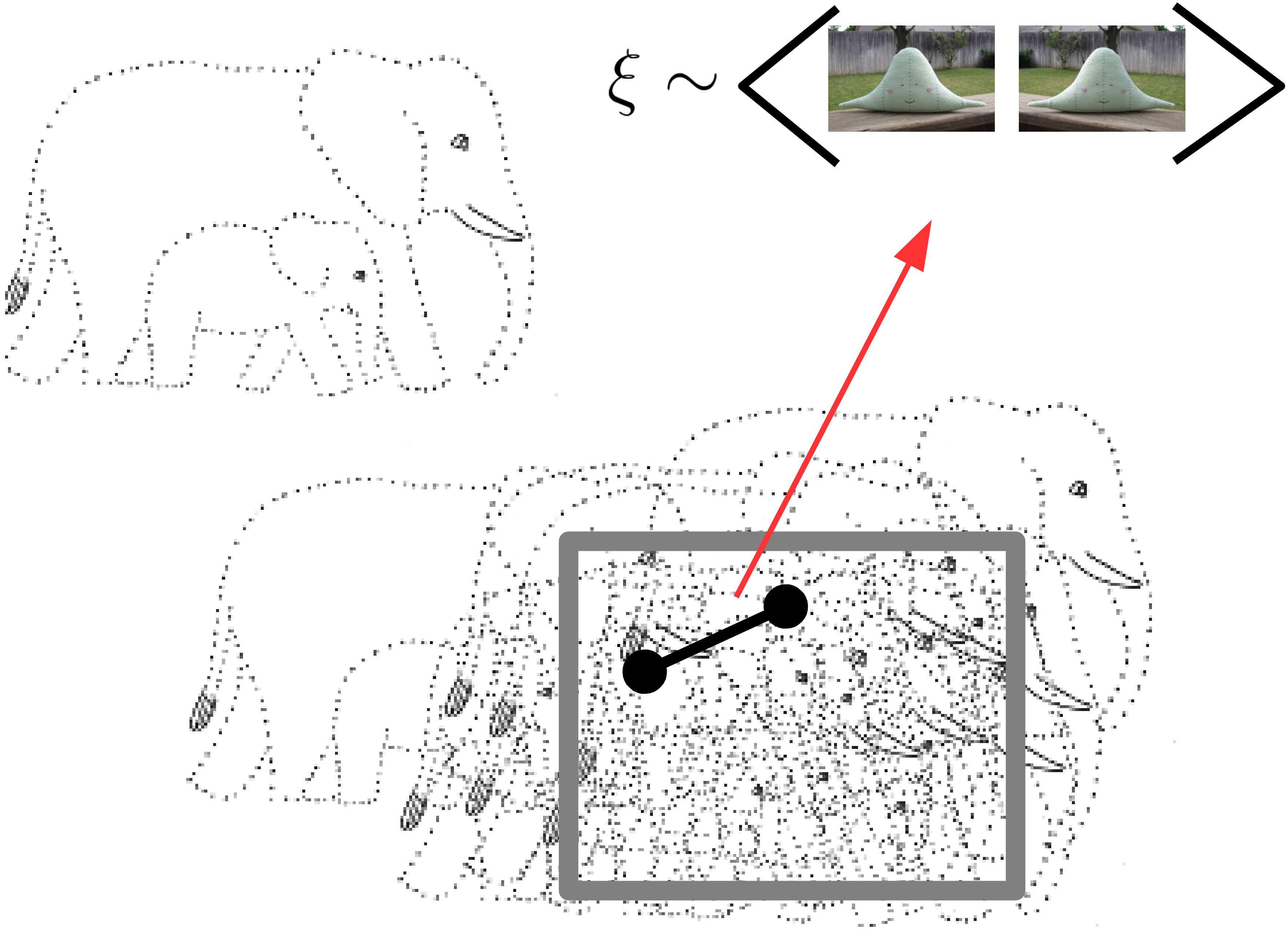
Patterns

Does the distribution of galaxies in the LSS contains info like this?

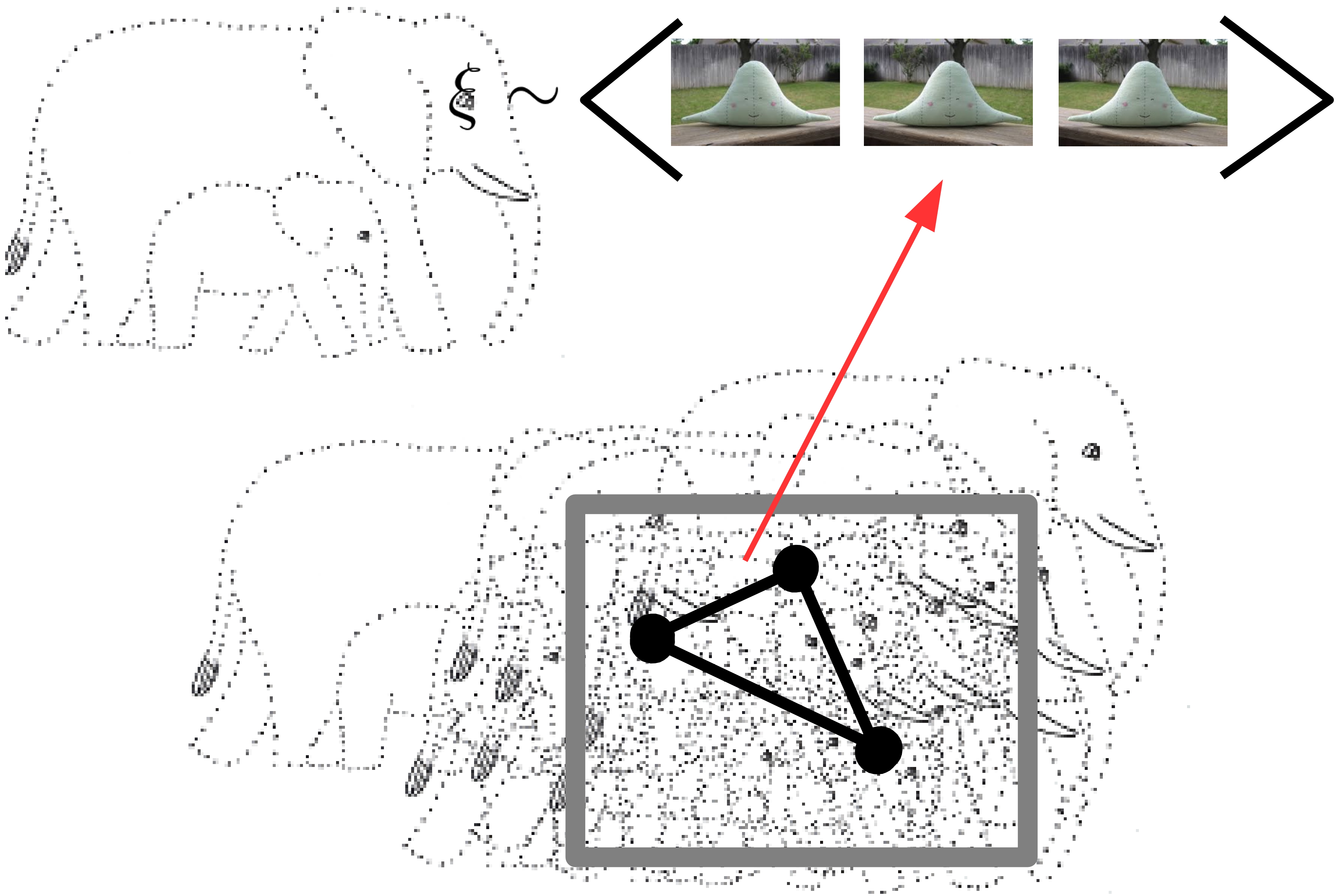
LSS



LSS

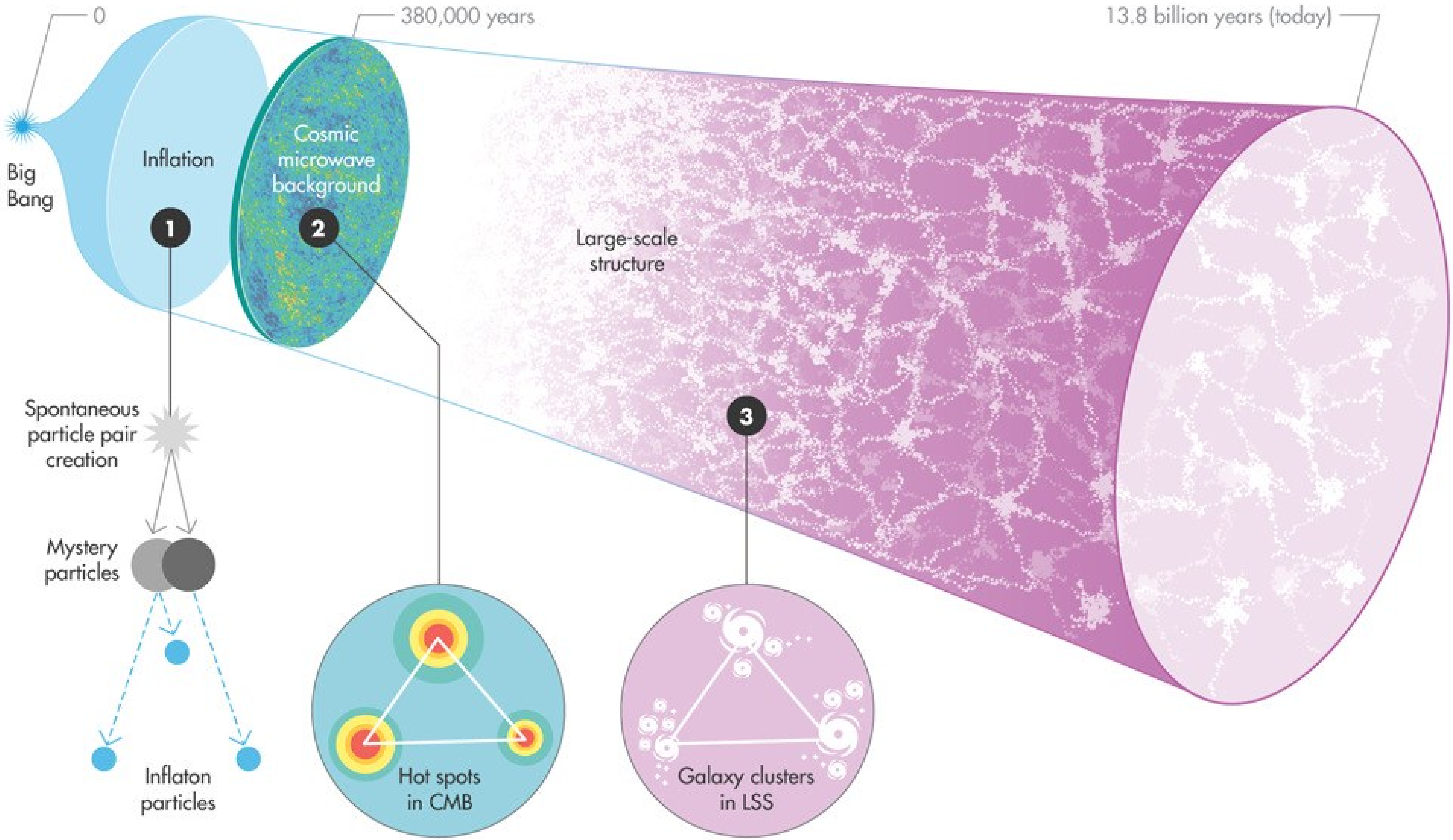


LSS



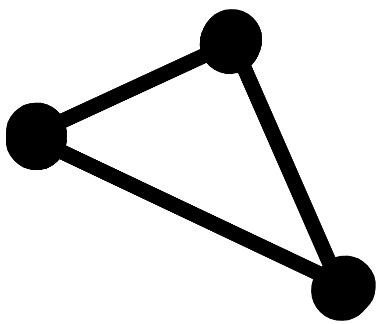
TRIANGLES IN THE SKY

According to the theory of cosmic inflation, pairs of particles spontaneously surfaced throughout the primordial universe. Some pairs decayed into three "inflaton" particles, producing triangular configurations that expanded into arrangements of cosmological structures that are visible today. Triangles may appear as correlations between three hot spots in the 2-D cosmic microwave background (CMB), or between three galaxy clusters in the 3-D large-scale structure (LSS). These triangles and other shapes reveal the types and relationships of particles that existed during inflation.

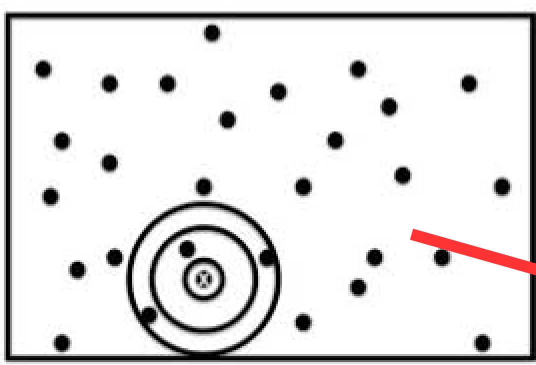


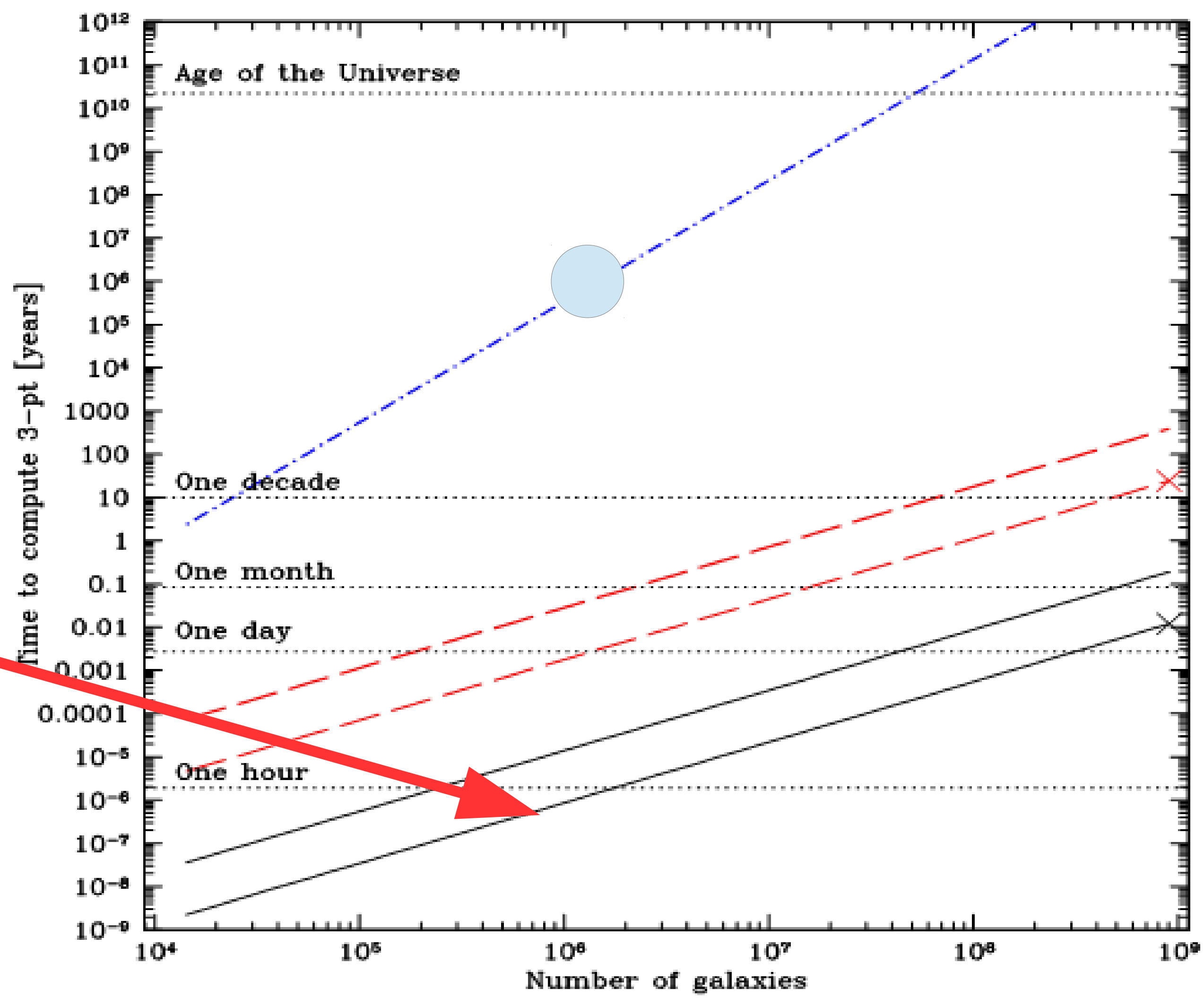
Heavy numerics

- Naive algorithm scales as N^3



Slepian & Eisenstein

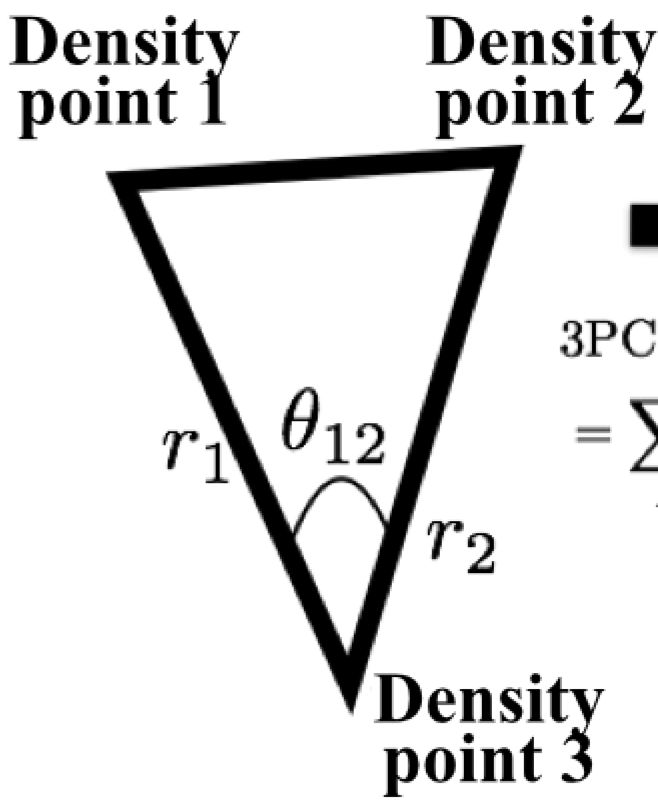




Slepian & Eisenstein

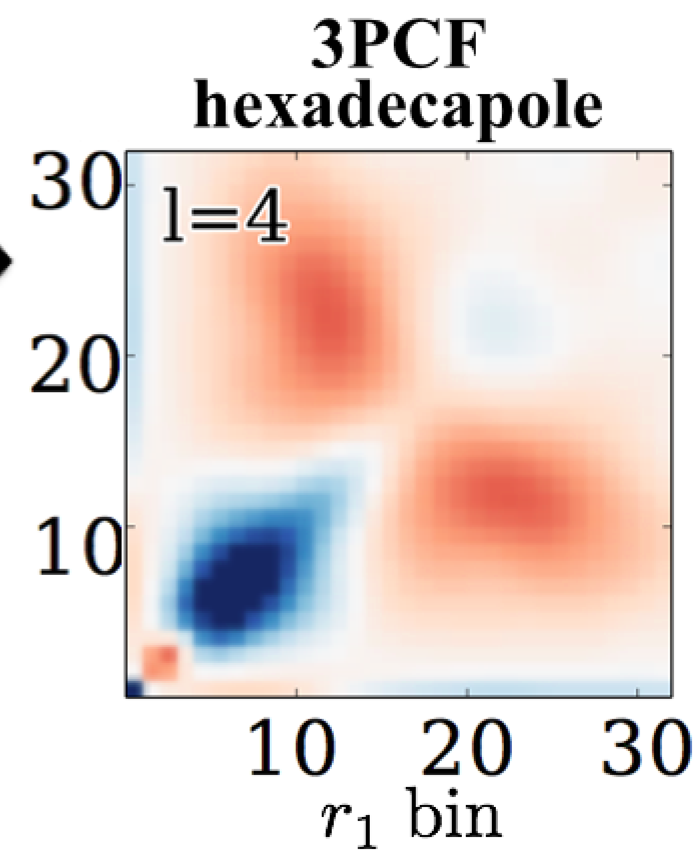
O(N^2) algorithm

- Use a Legendre Basis for the angle



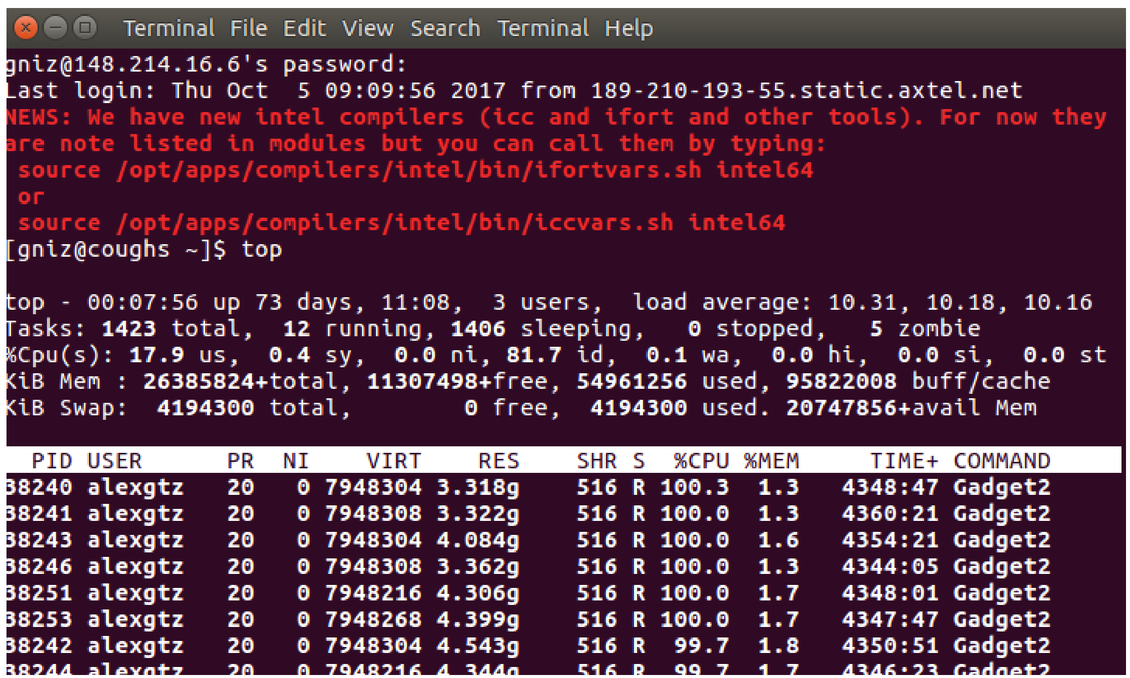
$$3\text{PCF} = \zeta(r_1, r_2; \cos\theta_{12})$$
$$= \sum_\ell \zeta_\ell(r_1, r_2) P_l(\cos\theta_{12})$$

red = excess
blue = deficit

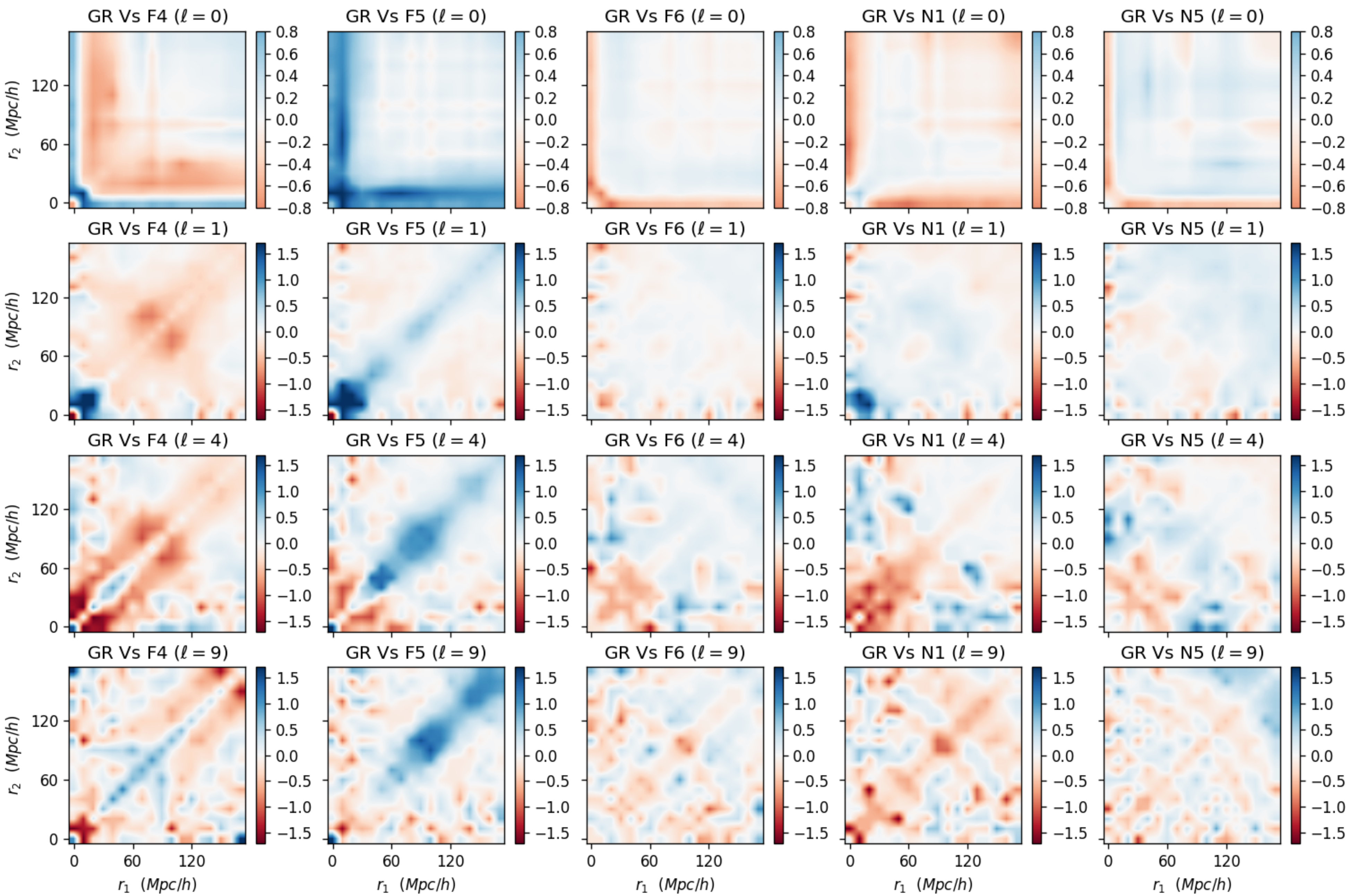


C O U G H S

Cosmology UG Hacking System



Test gravity



Bright Future

- DESI
- LSST
- DES
- HETDEX
- WFIRST
- EUCLID
- Others.....

Bright Future

- DESI
- LSST
- DES
- HETDEX
- WFIRST
- EUCLID
- Others.....

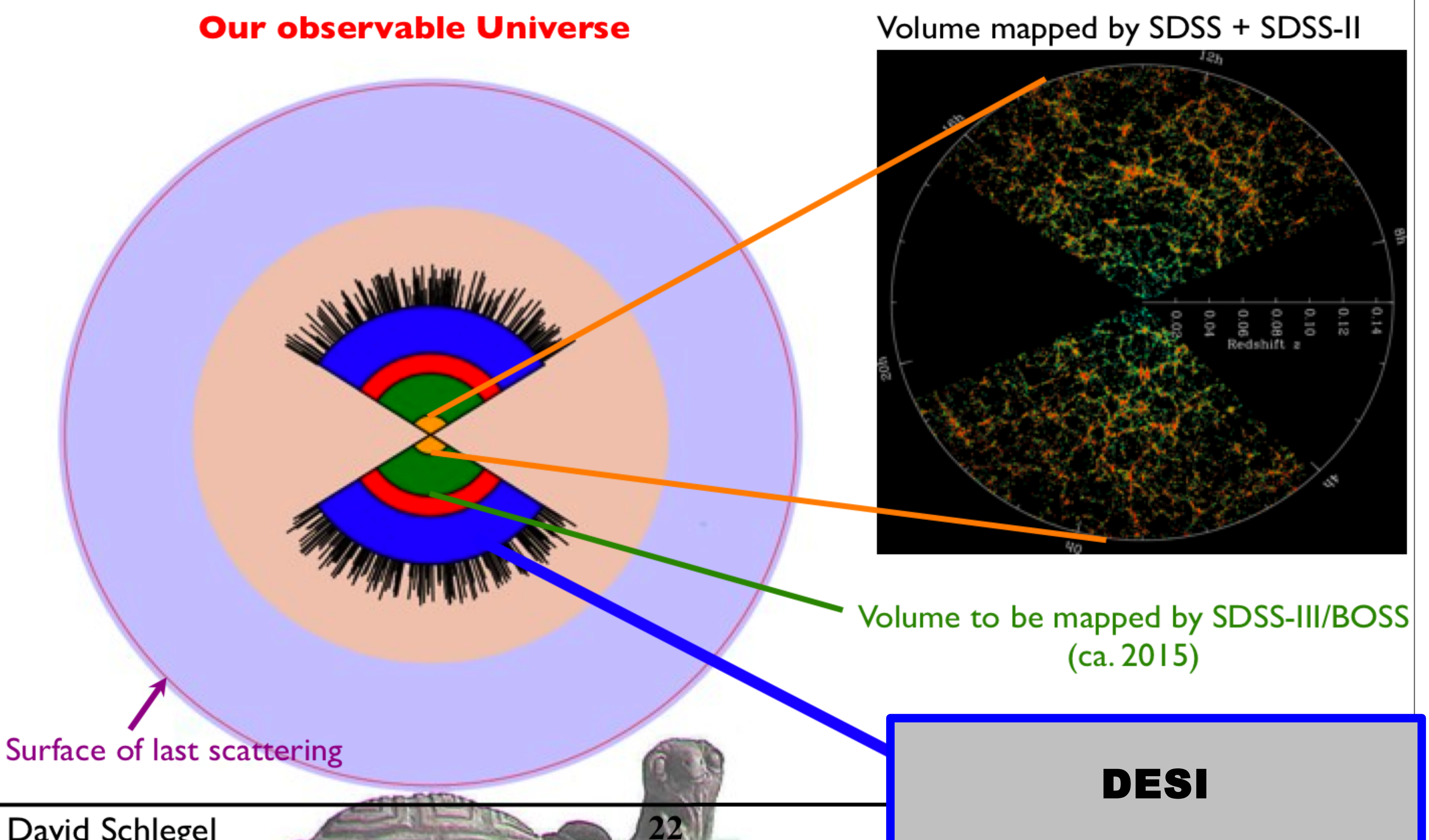
DESI MEXICO

- 12 researchers + students
  - 6 UNAM (A. de la Macorra, M. Vargas, O. Valenzuela, M. Alcubierre, S. Fromentau, C. Ningombam)
  - 3 DCI-UG: Gustavo Niz, L. Ureña, A. González
  - 1 Cinvestav (T. Matos)
  - 2 ININ (J. Cervantes, A. Avilés)
- “Proyecto fronteras de la ciencia” CONACYT

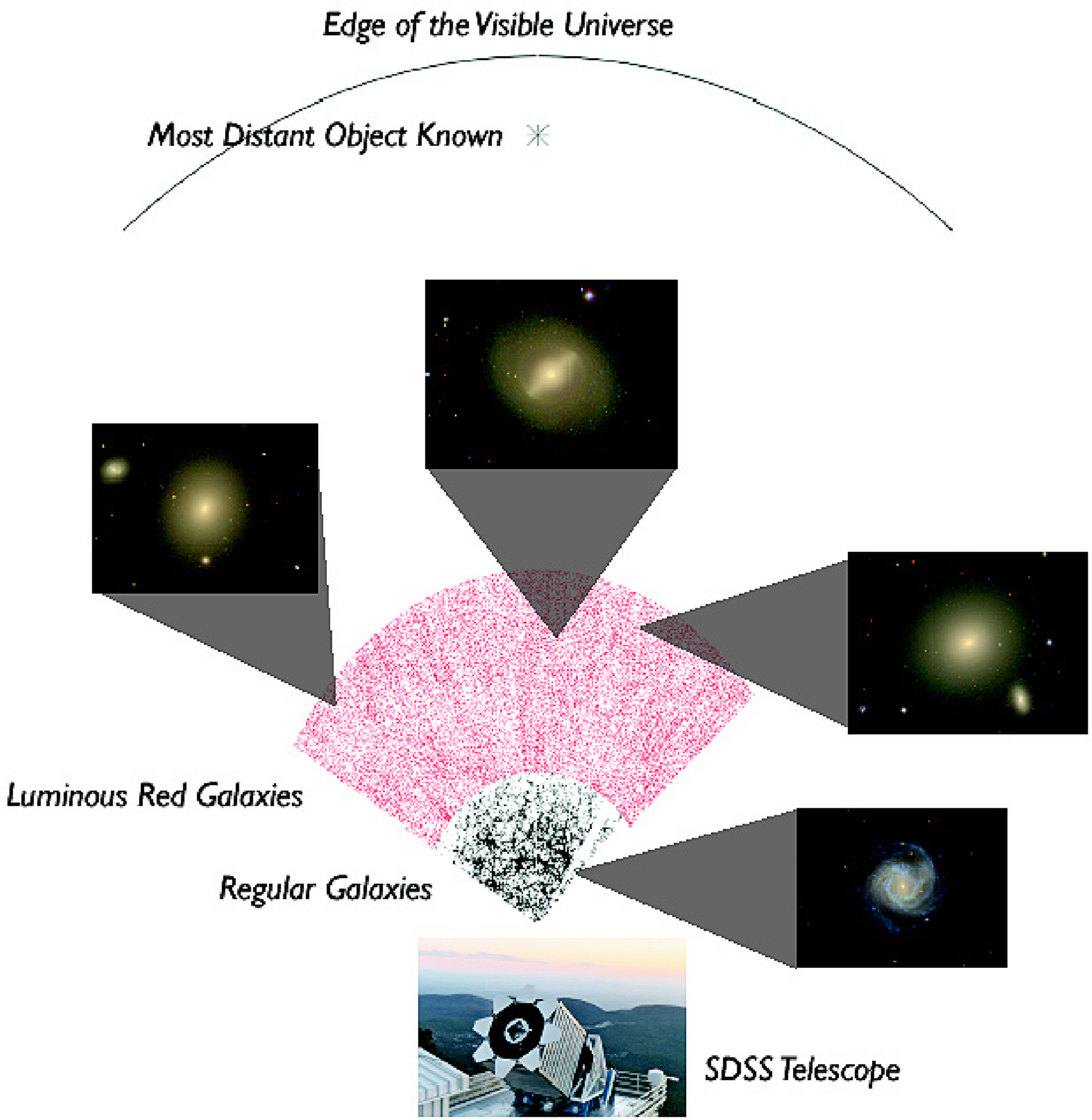
- Cosmological simulations
- Data analysis
- Alternative LCDM models

Dark Energy Spectroscopic Instrument

Sensitivity to new physics scales as volume surveys -- # of modes

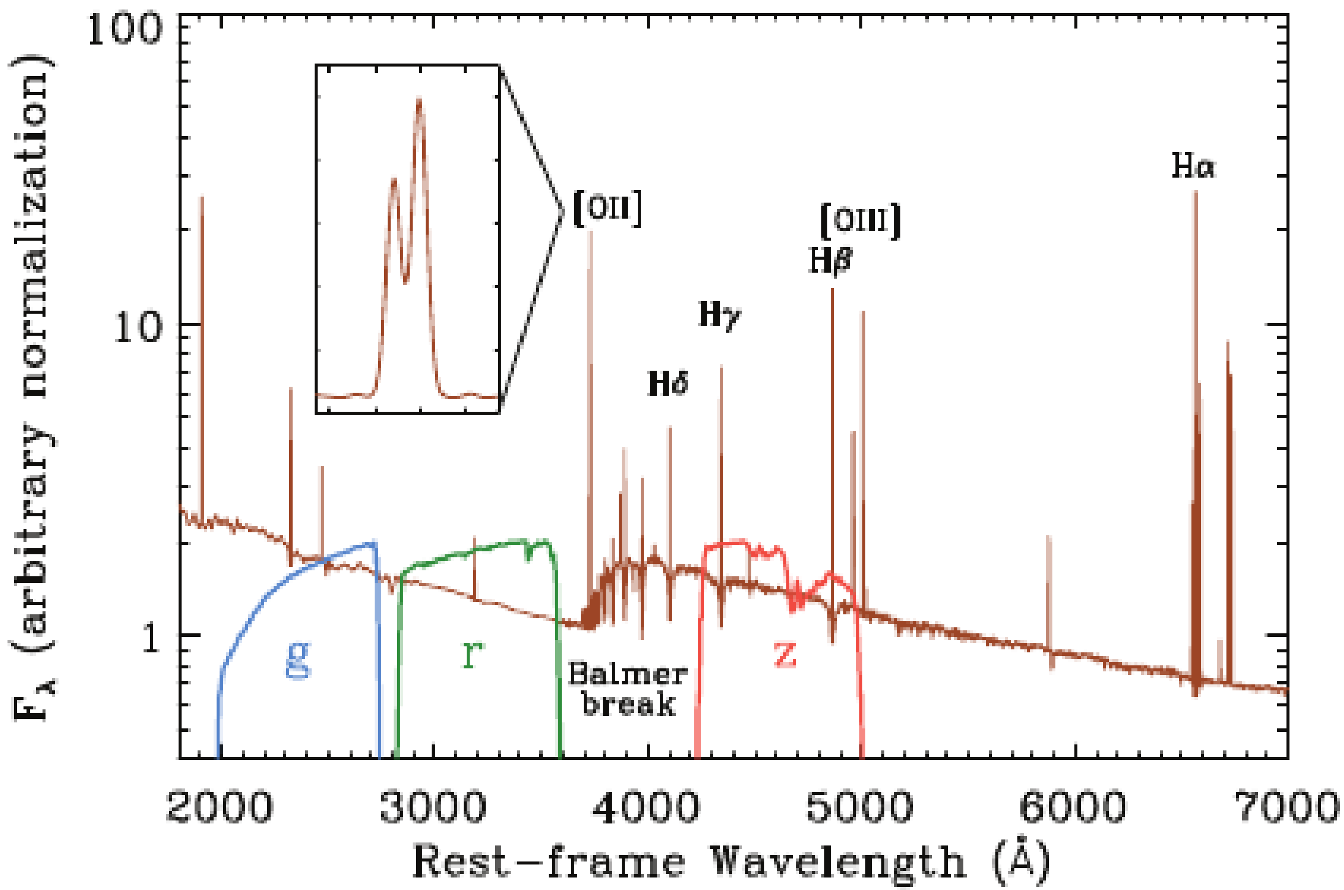


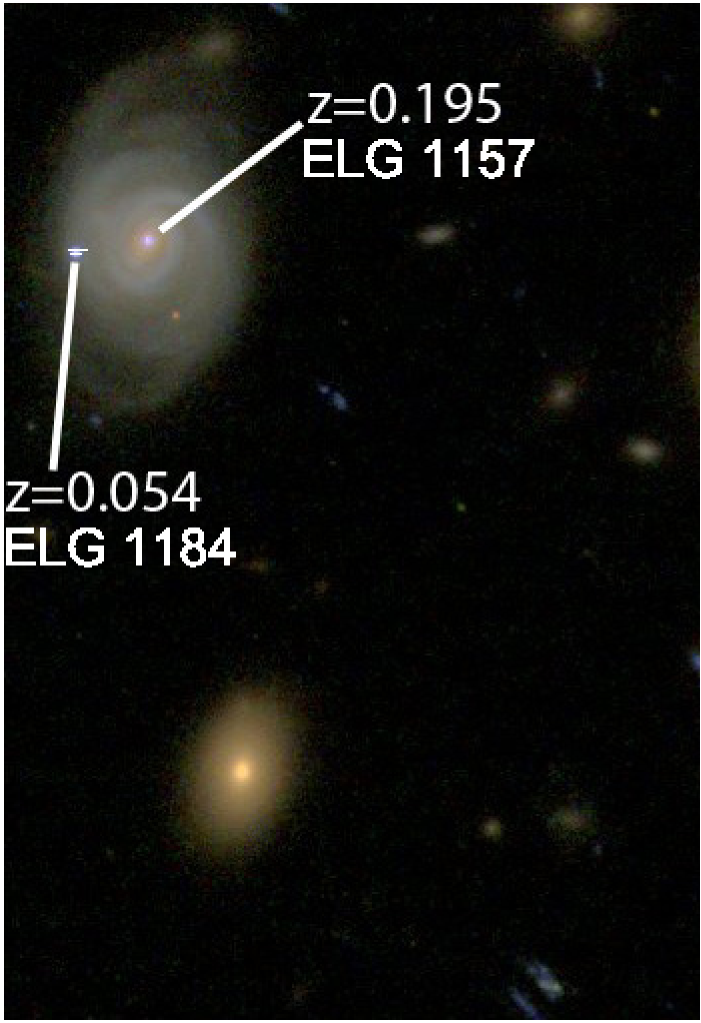
Luminous Red Galaxies (LRG)



DESI

Emission Line Galaxies (ELG)

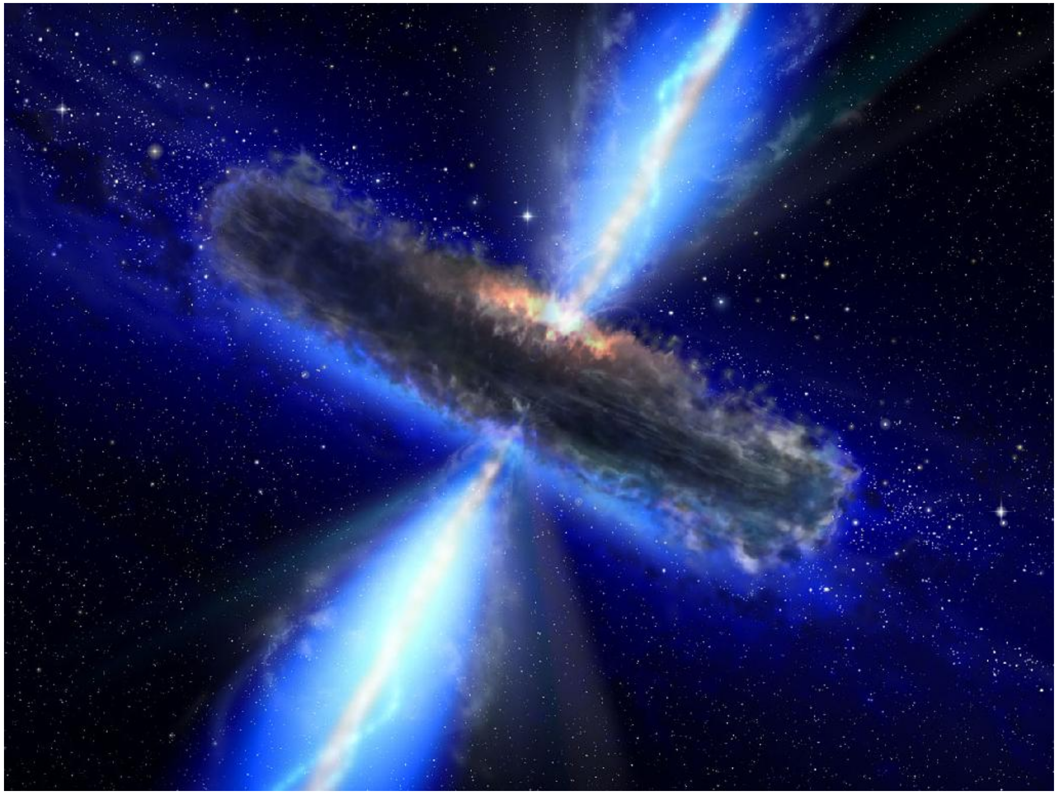




DESI

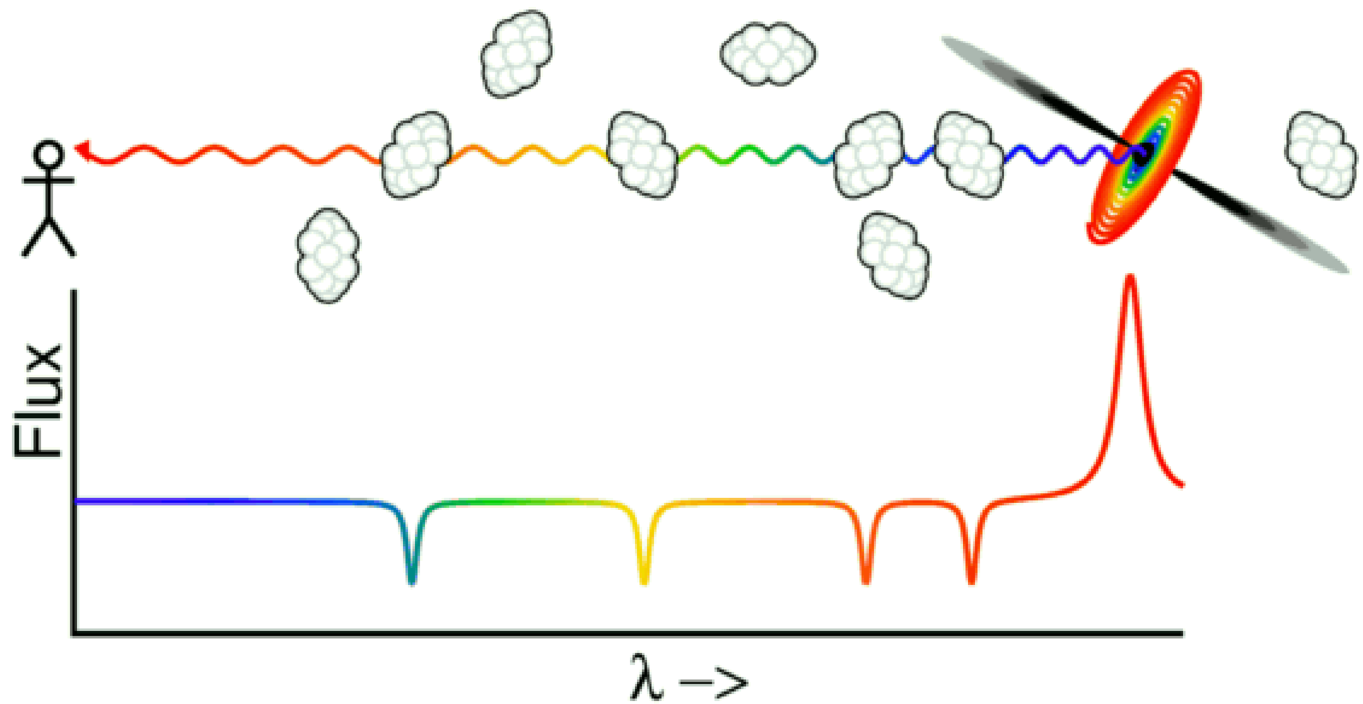
Quasars

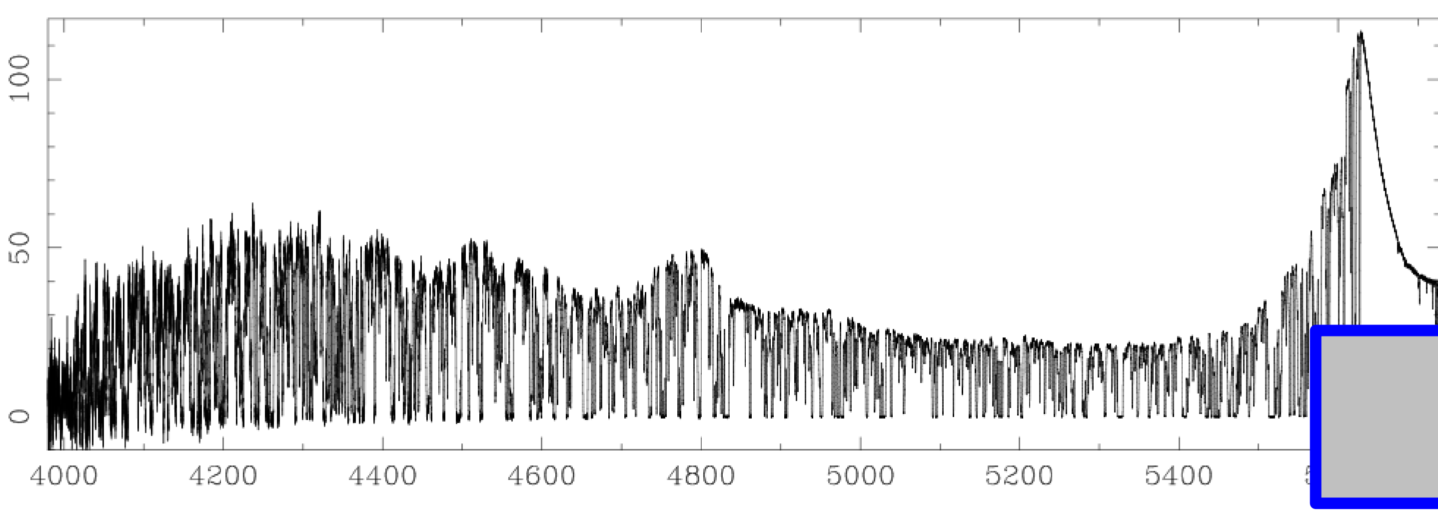
ULAS J1120+0641
(z~7)



DESI

Lyman-alfa forest





DESI

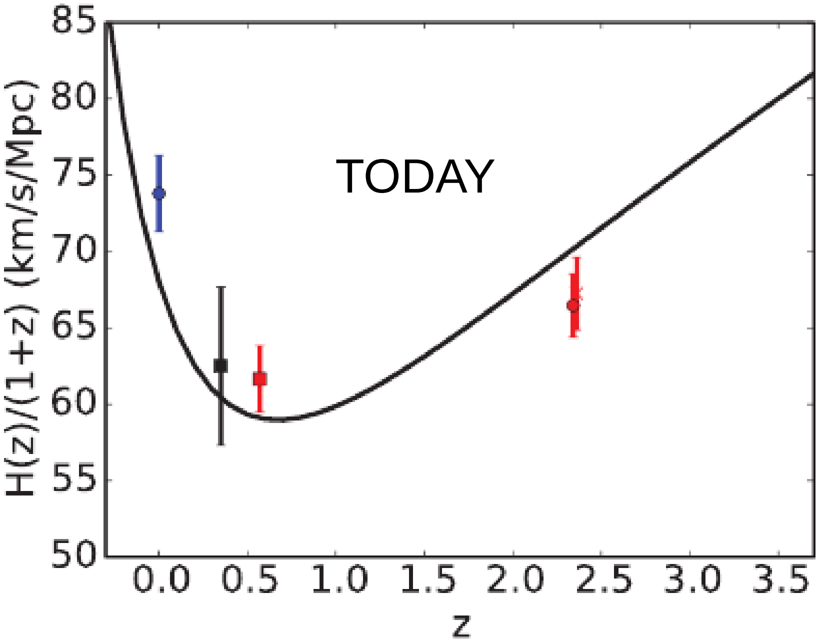
Goal: to map

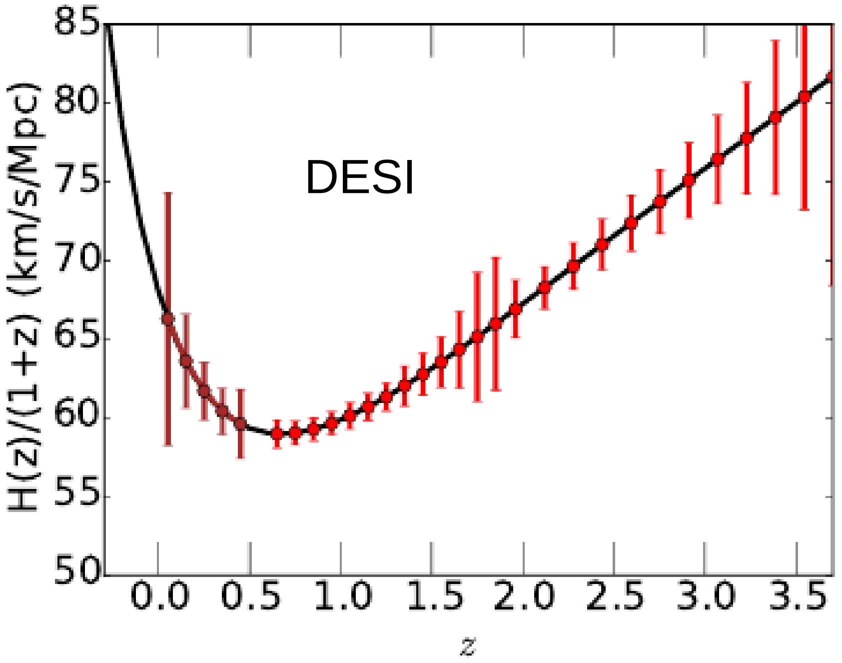
- > 18 millions of ELG
- > 4 millions of LRG
- > 2.5 millions of quasars
- > 0.5 millions of Ly-alfa forest

Precision < 1%

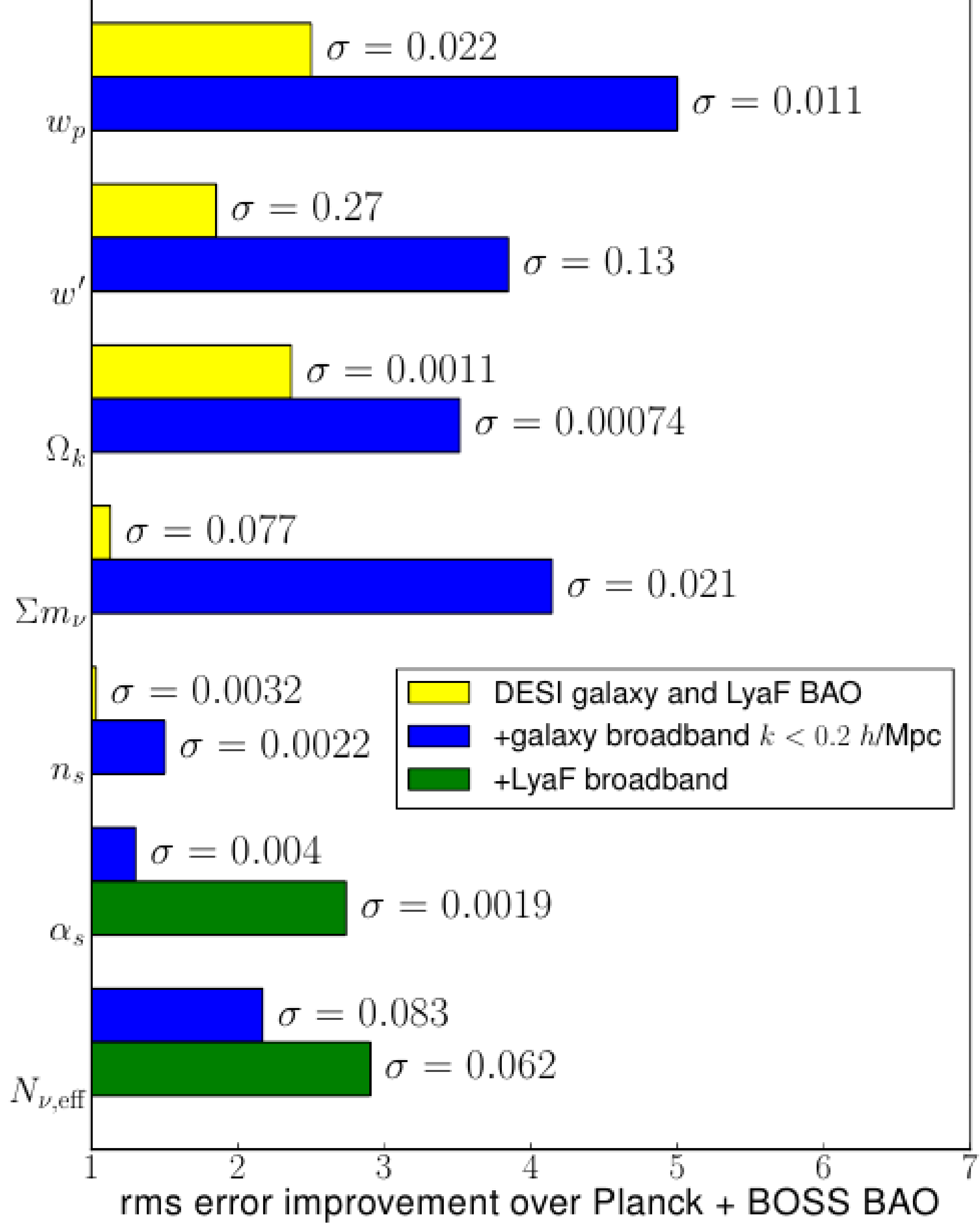
DESI

Esperamos....

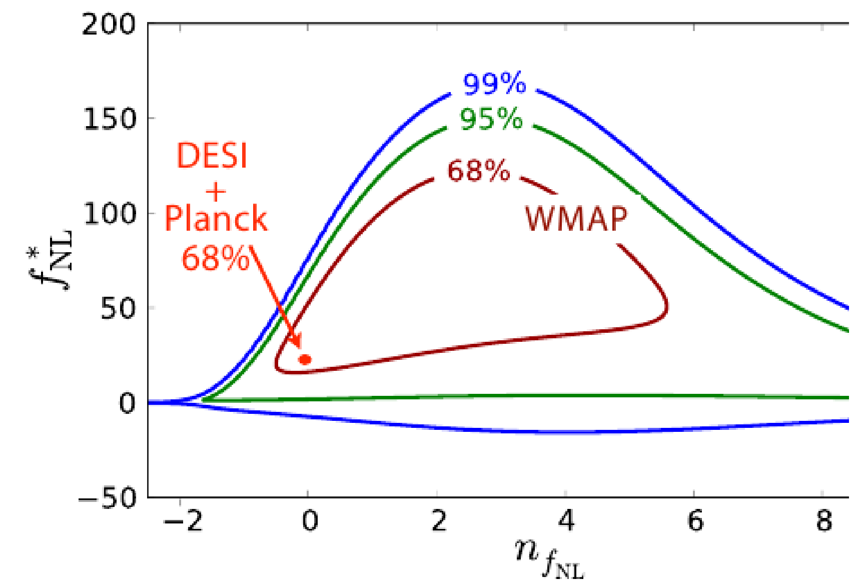




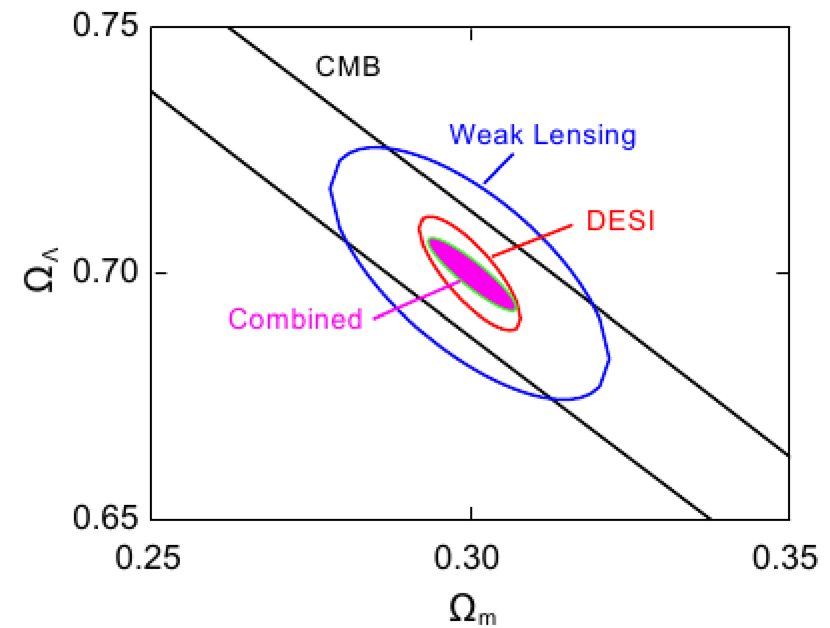
DESI



$\sigma = 0.022$
$\sigma = 0.011$
w_p
$\sigma = 0.27$
$\sigma = 0.13$
w'
$\sigma = 0.0011$
$\sigma = 0.00074$
Ω_k
$\sigma = 0.077$
$\sigma = 0.021$
Σm_ν
$\sigma = 0.0032$
$\sigma = 0.0022$
n_s
$\sigma = 0.004$
$\sigma = 0.0019$
α_s
$\sigma = 0.083$
$\sigma = 0.062$
$N_{\nu,\mathrm{eff}}$
DESI galaxy and LyaF BAO
+galaxy broadband $k < 0.2\ h$/Mpc
+LyaF broadband
1 2 3 4 5 6 7
rms error improvement over Planck + BOSS BAO



99%
95%
68%
DESI + Planck 68%
WMAP
f^*_{NL}
$n_{f_{\mathrm{NL}}}$
200 150 100 50 0 −50
−2 0 2 4 6 8

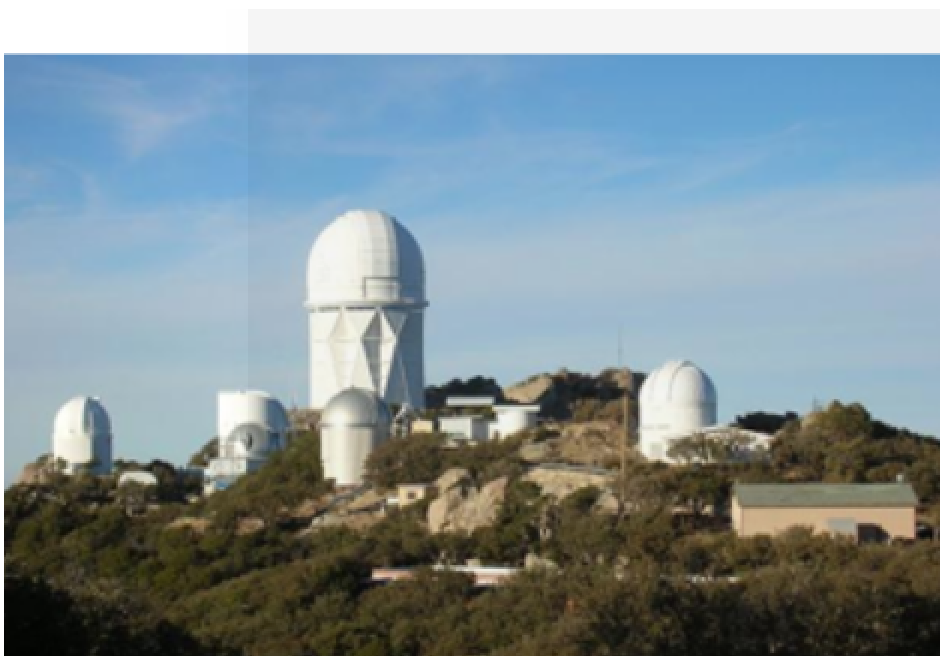


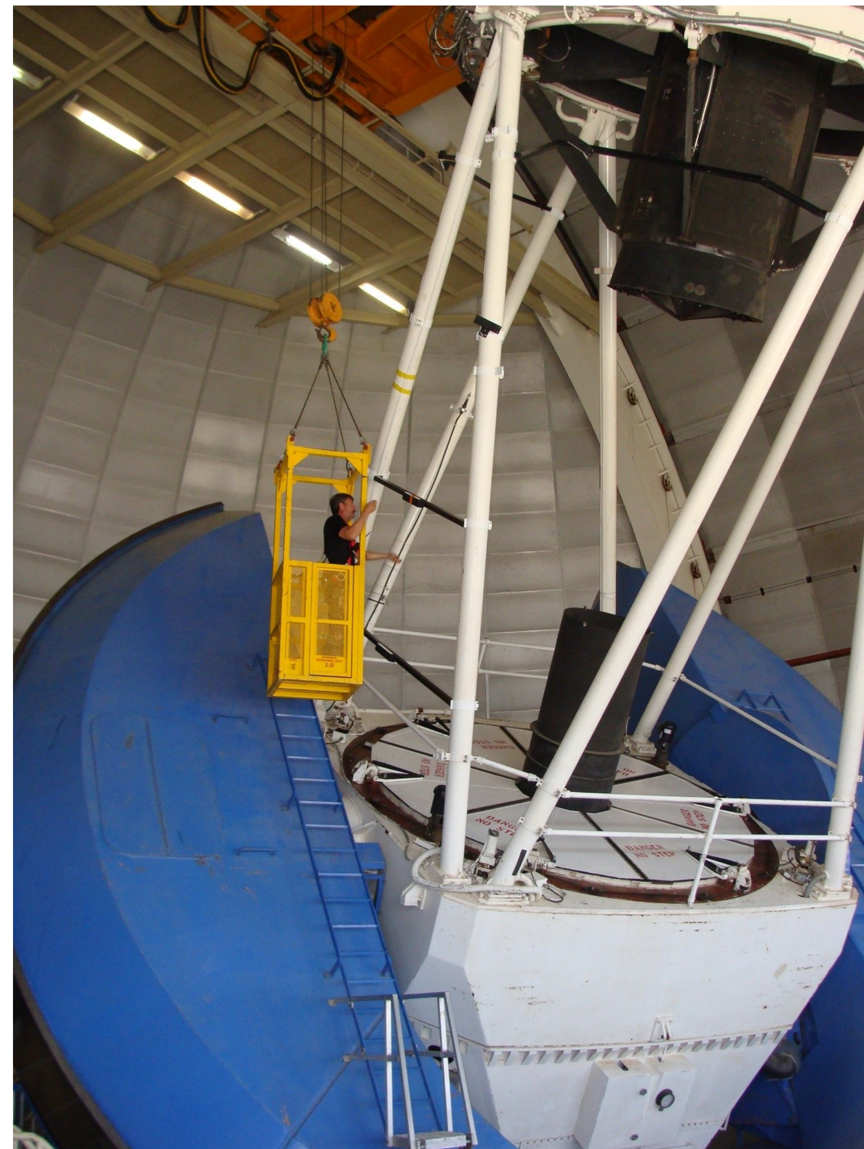
CMB
Weak Lensing
DESI
Combined
Ω_Λ
Ω_m
0.75 0.70 0.65
0.25 0.30 0.35

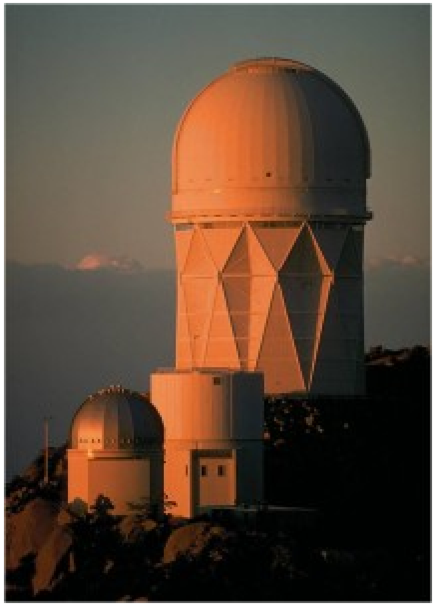
DESI

Dark Energy Spectroscopic Instrument

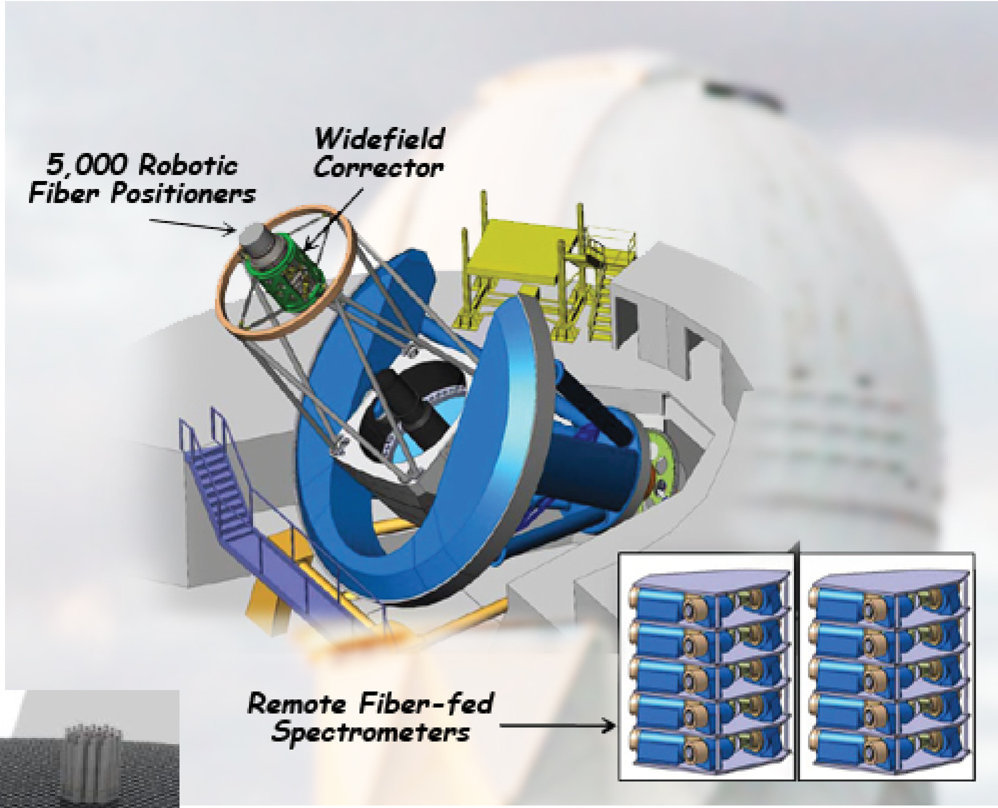
- Mayall telescope
- Kitt peak, Arizona

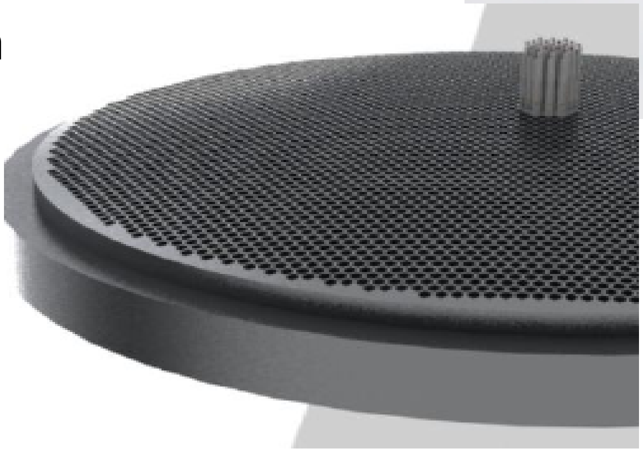






Kitt Peak Mayall 4m

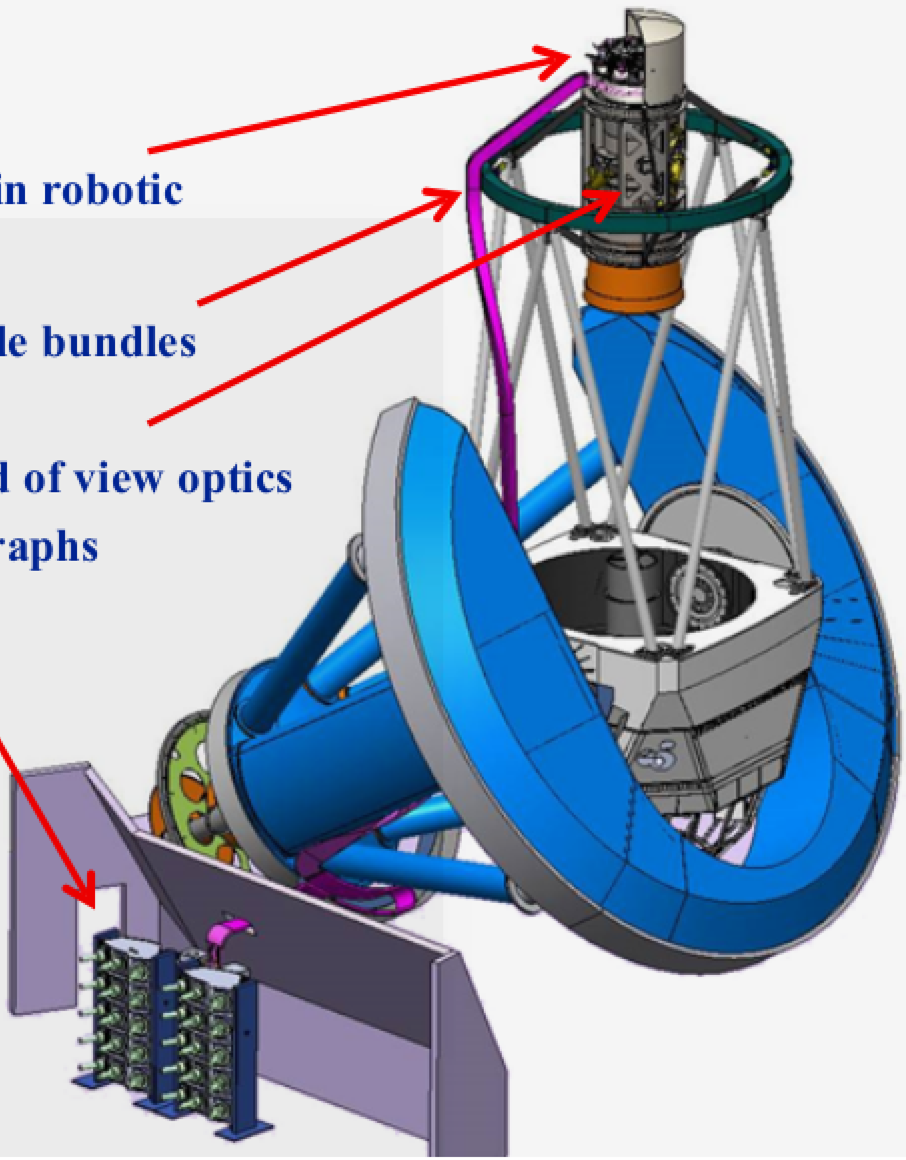




DESI

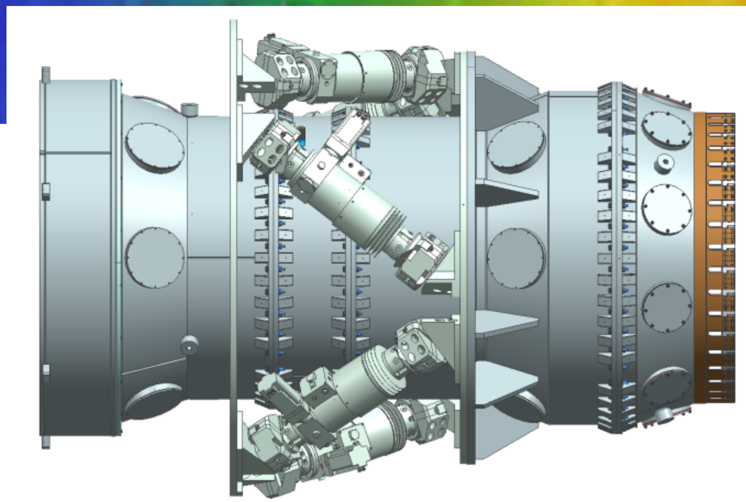
DESI

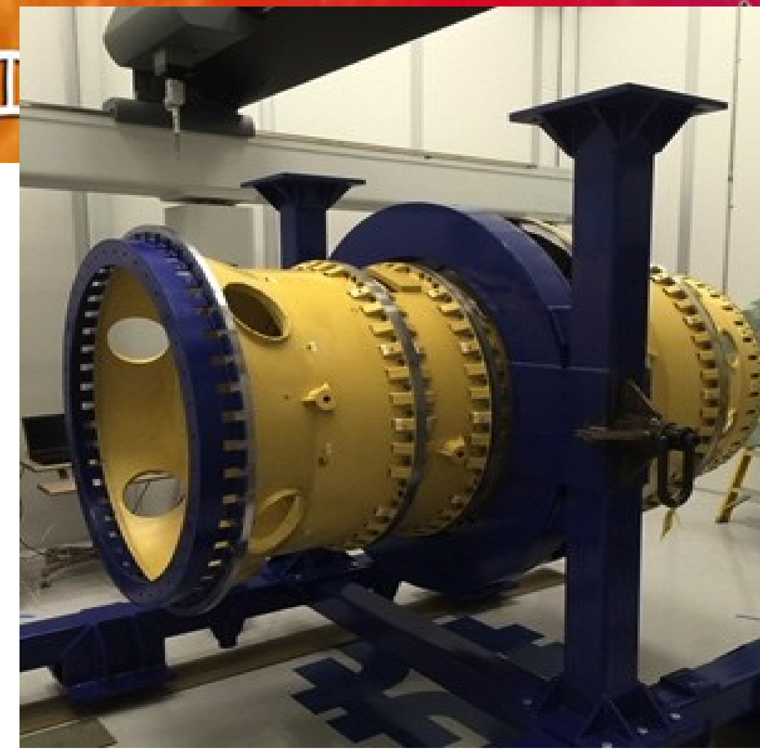
- 5000 fibers in robotic actuators
- 10 fiber cable bundles
- 3.2 deg. field of view optics
- 10 spectrographs

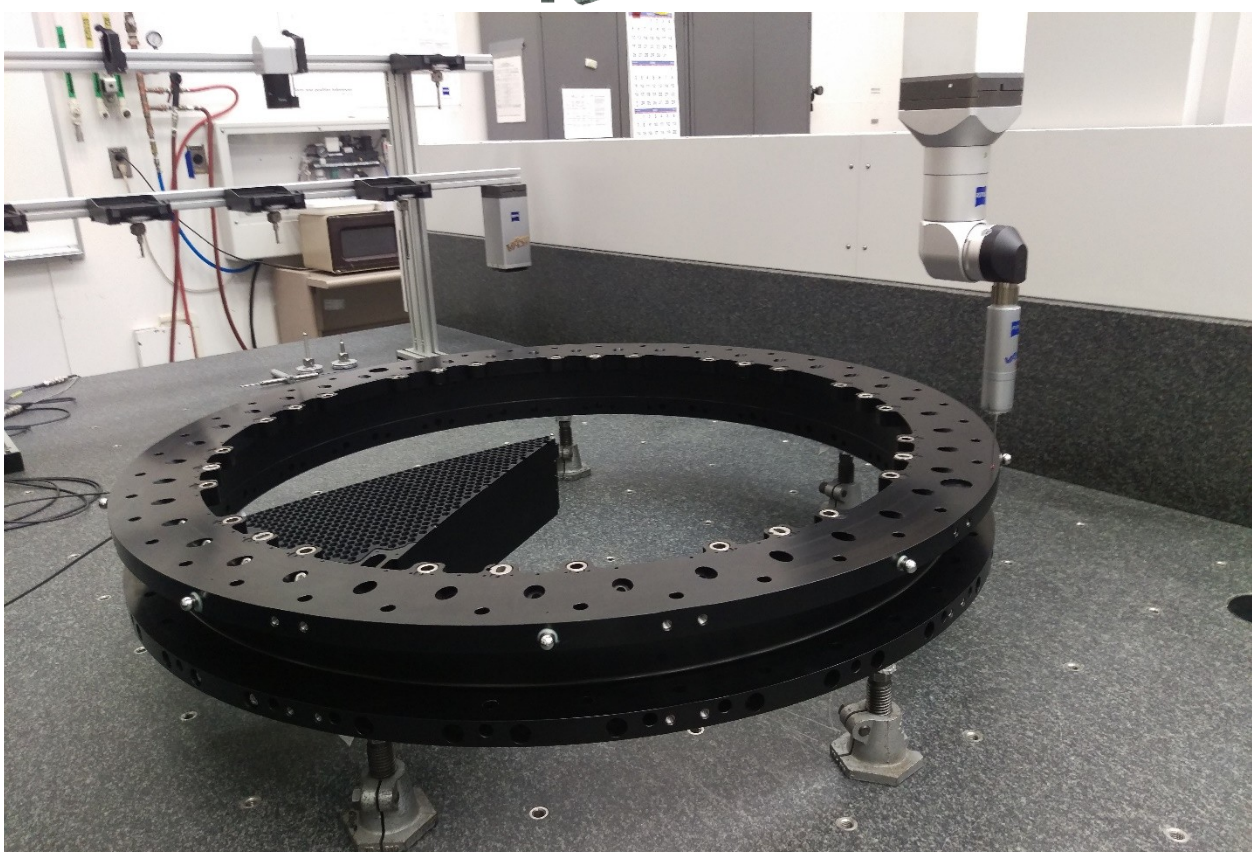


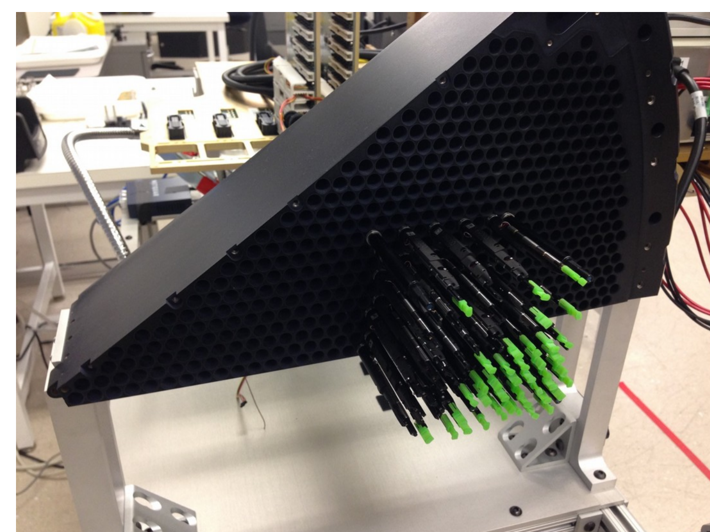
Mayall 4m
Telescope
Kitt Peak
Tucson, AZ

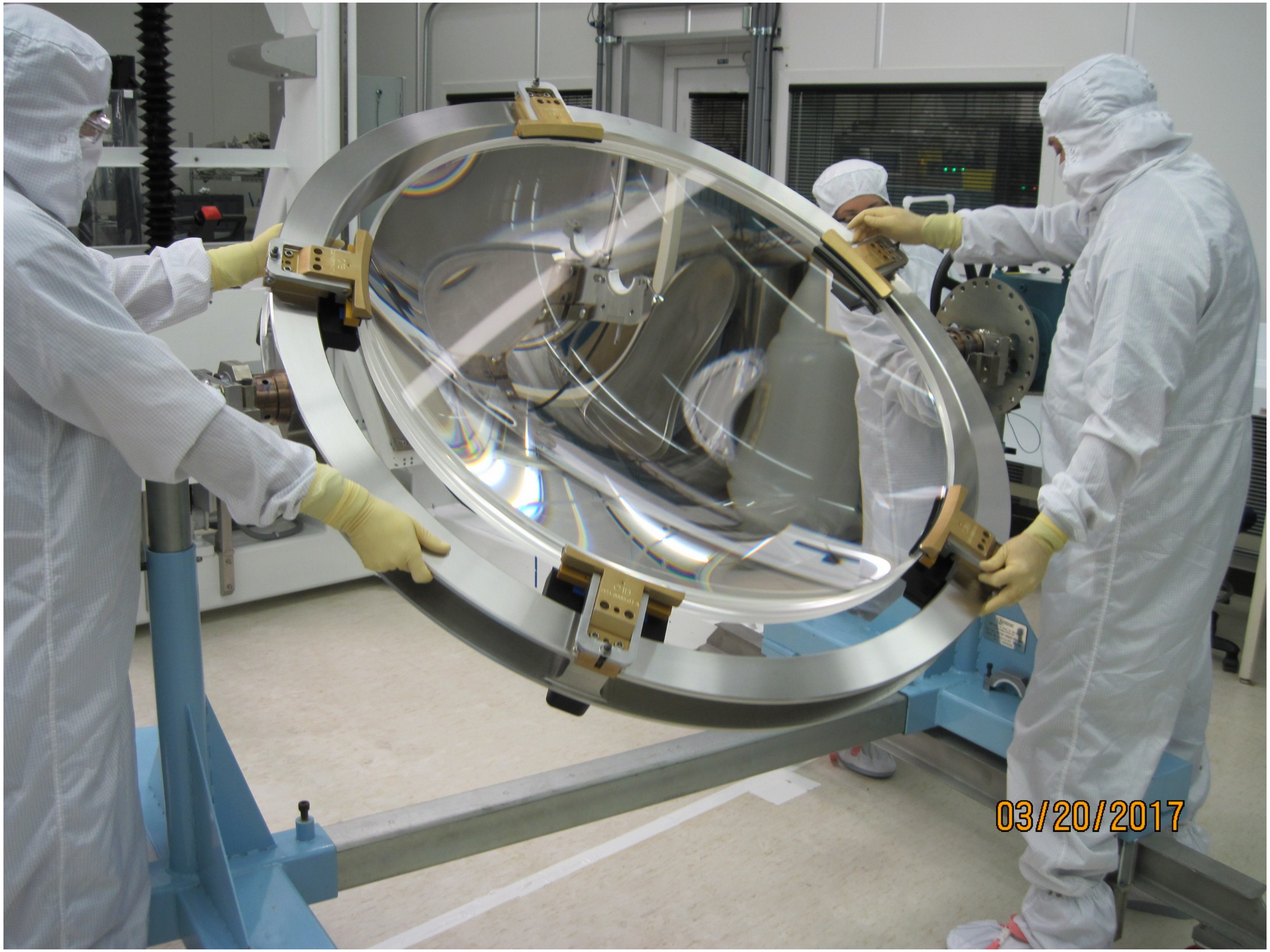
Readout
& Control

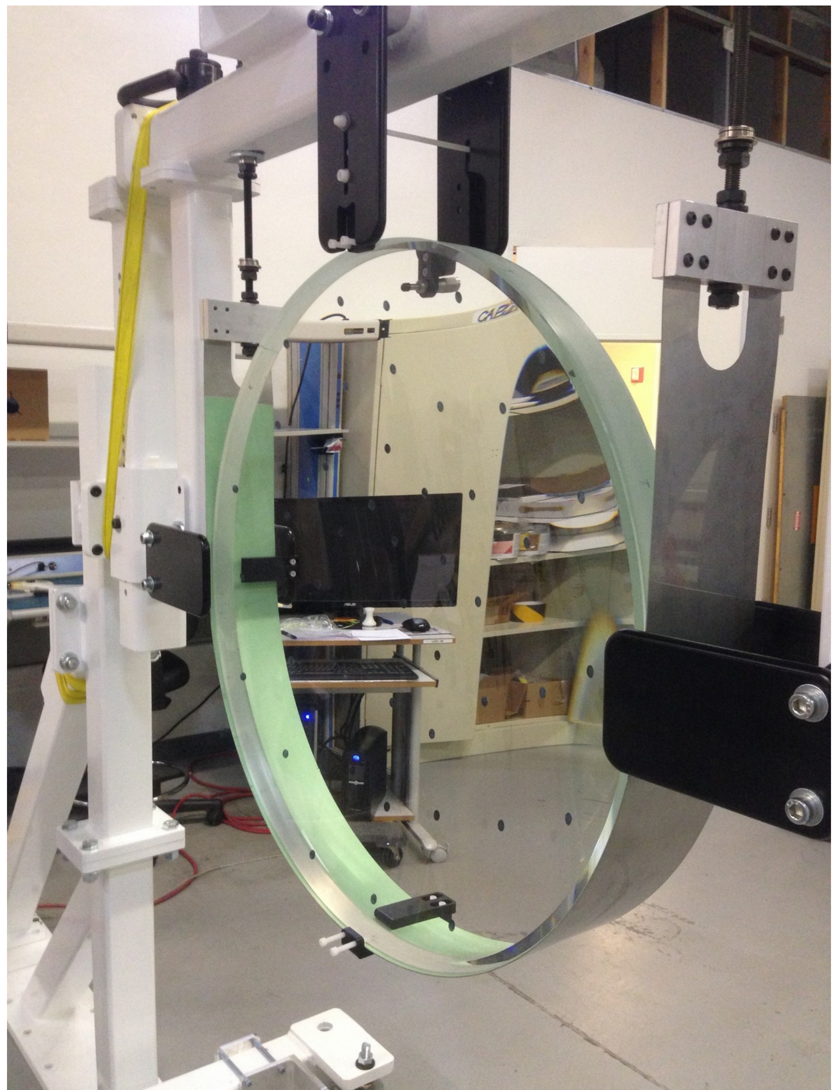


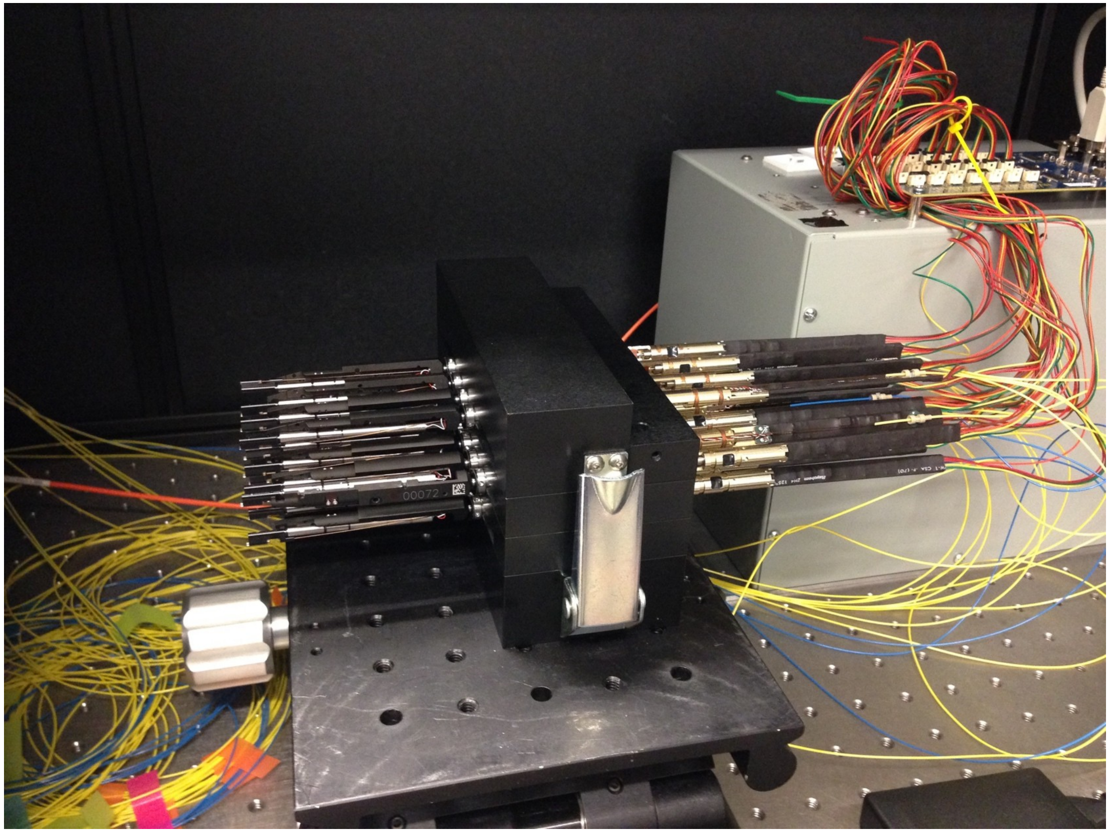







03/20/2017

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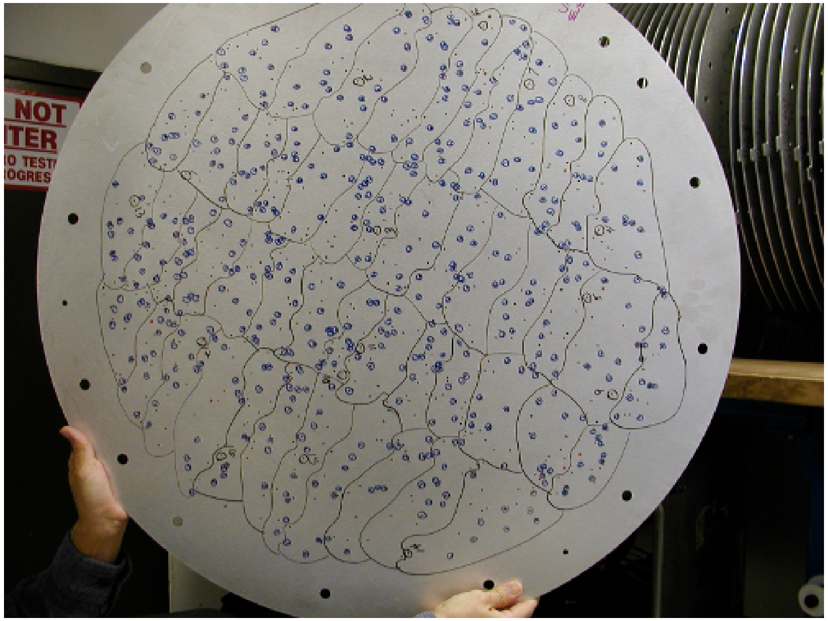

NOT

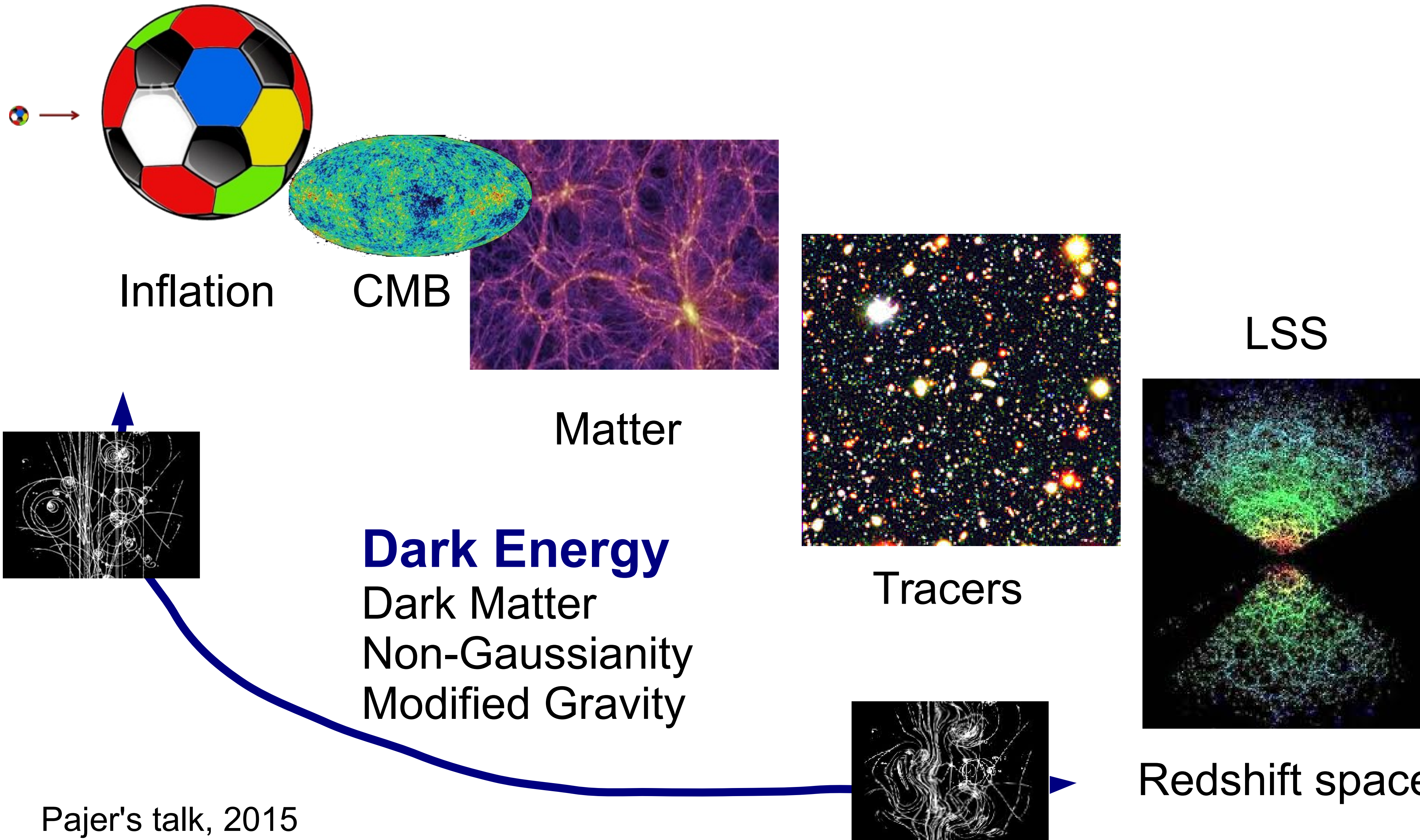
Dark Energy Spectroscopic Instrument

NERSC

Conclusions

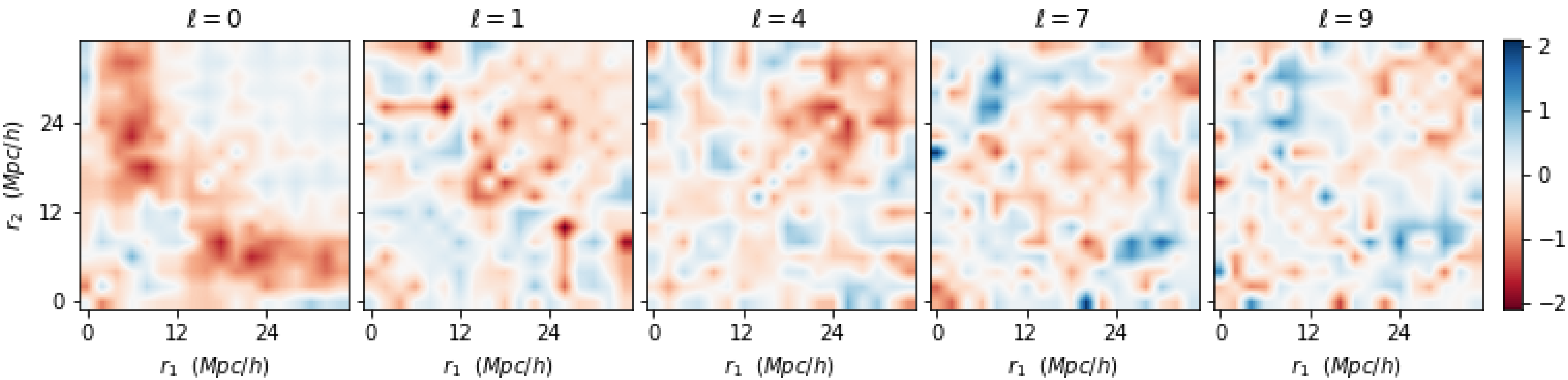
- Observables in the Universe (CMB & LSS) are a door to the Early Universe physics and the dark sector (dark matter & **dark energy**)
- High precision cosmology, such as **DESI**, needs same accuracy in theory (**Perturbation theory**) and simulations
- These ideas unify particle physics and gravity

Cosmic collider

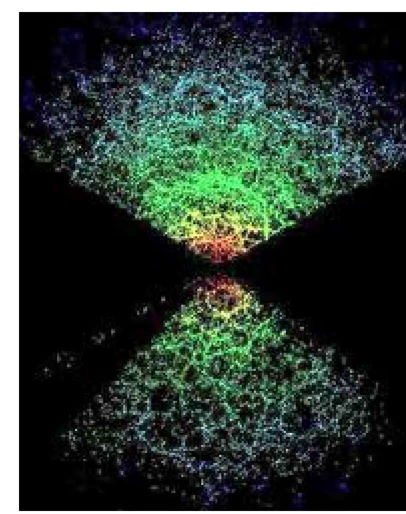


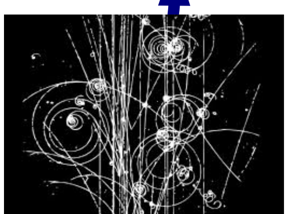
Pajer's talk, 2015

Cosmic collider

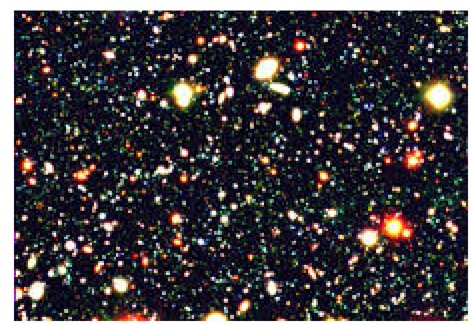


LSS



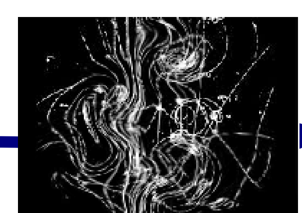


Matter



Tracers

Dark Energy
Dark Matter
Non-Gaussianity
Modified Gravity



Redshift space

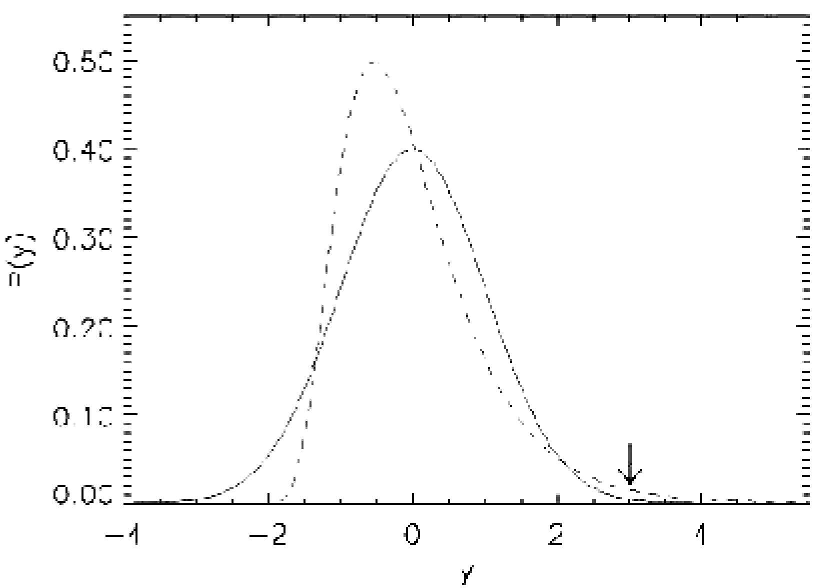
Pajer's talk, 2015

LSS is not Gaussian!

- Assume primordial non-Gaussianity is zero

$$\langle \delta_k^{(2)} \delta_k^{(2)} \rangle \sim \int d^3k' \, \langle \delta^{(1)}_{k-k'} \delta^{(1)}_{k-k'} \rangle \, \langle \delta^{(1)}_{k'} \delta^{(1)}_{k'} \rangle$$

Gaussian spectra



Effect should be small!

N-point correlation functions

(N>2)

- Non-trivial for non-Gaussian distributions
- New observables to describe galaxy distributions
  - Break degeneracies (DM-matter bias, MG, DE, neutrinos, etc.).
  - Measurements in BOSS arXiv:1607.06097 ,...
- Computationally expensive
  - Fast estimators? (e.g. arXiv:1411.6595)
- Shapes (higher dim. space). New physics?

Consistency conditions

$$\langle \Phi_{\vec{q}}(\eta)\delta_{\vec{k}_1}(\eta_1)\cdots\delta_{\vec{k}_n}(\eta_n)\rangle'_{q\to 0} = P_\Phi(q)\sum_a \mathcal{O}_a\langle\delta_{\vec{k}_1}(\eta_1)\cdots\delta_{\vec{k}_n}(\eta_n)\rangle' \;,$$

$$\boxed{< n+1 > \sim \mathcal{O} < n >}$$

- Inherited from inflation
- Robust to baryons physics, non-perturbative effects, etc.
- Test gravity:

  Equivalence principle violation when Gaussian initial conditions are assumed (arXiv:1312.6074, arXiv:1504.04366)

The story of “pertuby”

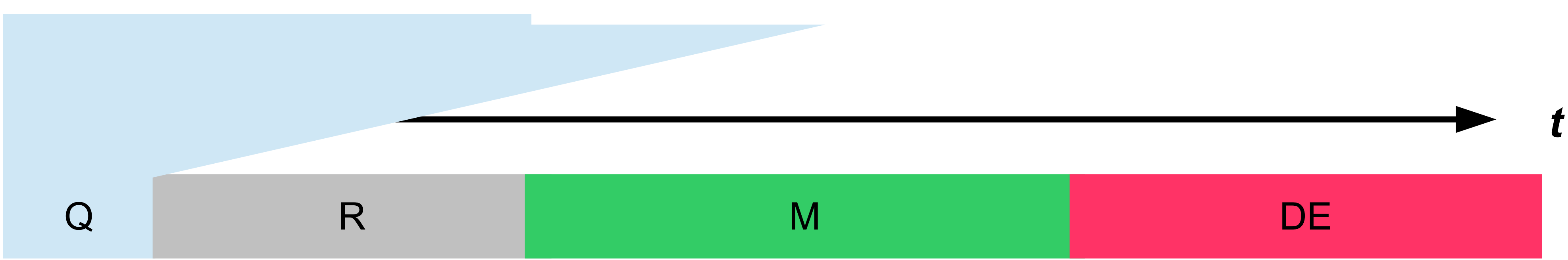
Formally (EFT perspective)

A single “clock” stopping de Sitter (accelerated) phase that spontaneously breaks time symmetry

$$\pi \sim \delta t \sim \frac{\delta\phi}{\dot{\phi}}$$

Goldstone mode related to metric perturbations

$$\zeta \sim \frac{\delta a}{a} \sim H\pi$$



The story of "pertuby"

Most general Lagrangian which breaks time symmetry

$$S = \int d^4x\, \sqrt{-g} \quad \Big[\frac{1}{2} M_{\rm Pl}^2 R - M_{\rm Pl}^2 \left(3H^2(t+\pi) + \dot{H}(t+\pi)\right) +$$

$$+ M_{\rm Pl}^2 \dot{H}(t+\pi)\left((1+\dot\pi)^2 g^{00} + 2(1+\dot\pi)\partial_i\pi g^{0i} + g^{ij}\partial_i\pi\partial_j\pi\right) +$$

$$\frac{M_2(t+\pi)^4}{2!}\left((1+\dot\pi)^2 g^{00} + 2(1+\dot\pi)\partial_i\pi g^{0i} + g^{ij}\partial_i\pi\partial_j\pi + 1\right)^2 +$$

Oscar, PhD students

$$\frac{M_3(t+\pi)^4}{3!}\left((1+\dot\pi)^2 g^{00} + 2(1+\dot\pi)\partial_i\pi g^{0i} + g^{ij}\partial_i\pi\partial_j\pi + 1\right)^3 + \ldots\Big]$$

Tensors & Higher der.

*Unifies most single field models
*Avoids questions about inflation