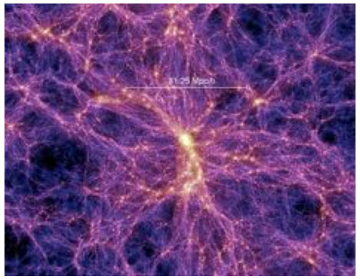
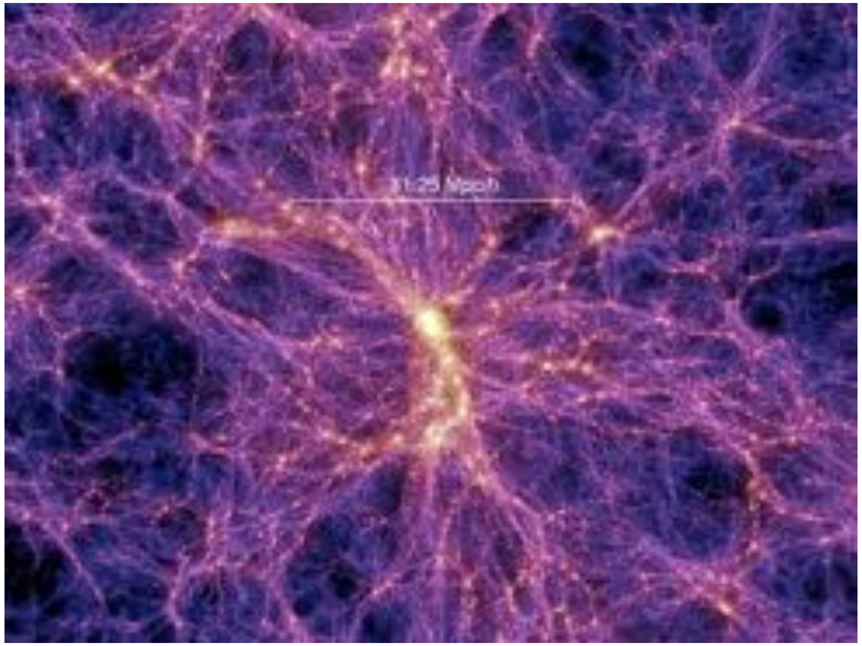
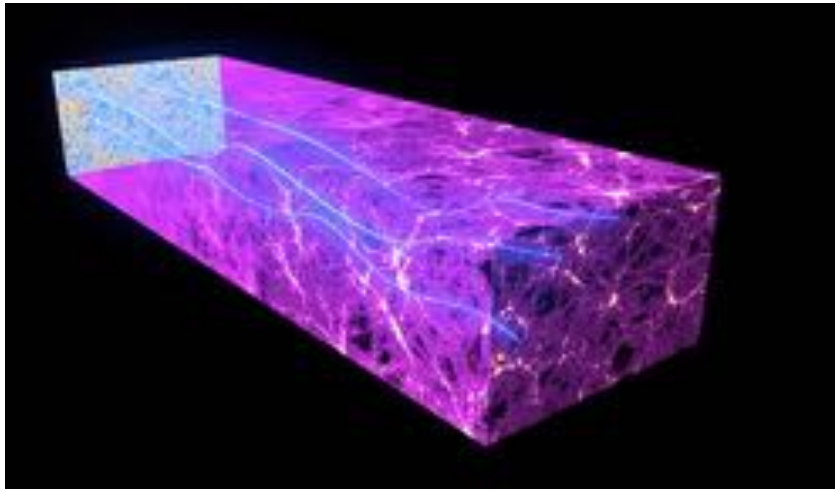
O Universo em grande escala:

das flutuações primordiais à formação das estruturas





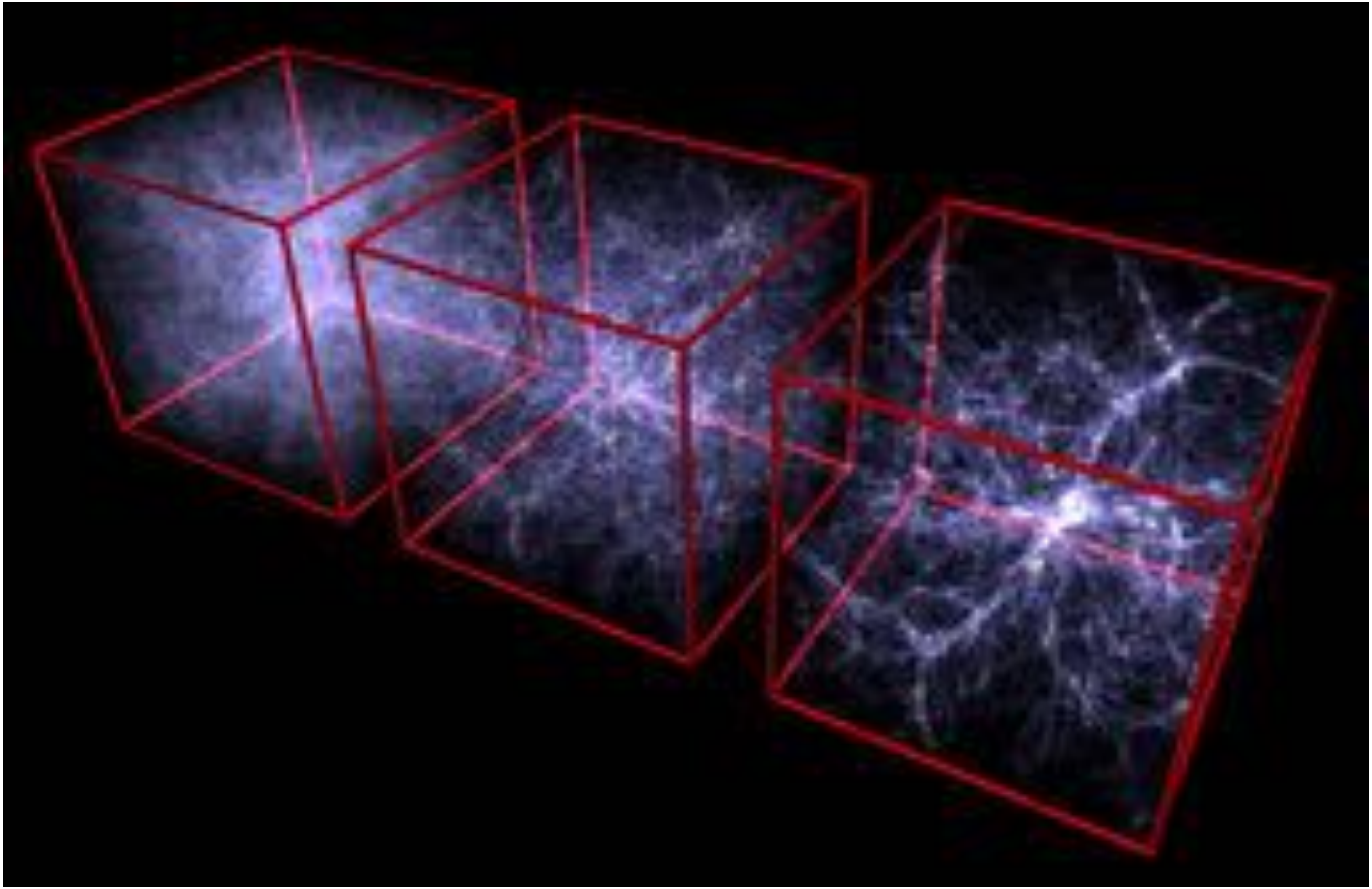
Armando Bernui



What
Why
How

LESSON 3

The observed Universe: modern cosmological probes



How to measure matter clustering?

2-point correlation function

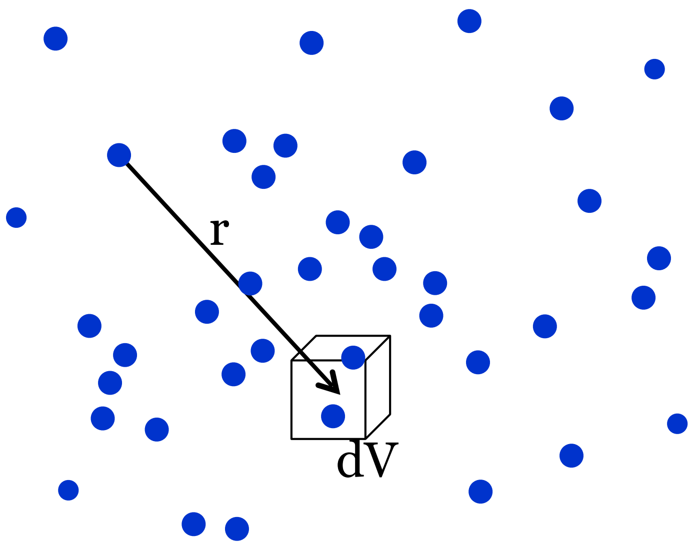
The 2-point statistics $(P(k), \xi(r))$ provide a complete statistical description of the density field under Gaussian initial conditions and linear growth of fluctuations

2-p correlation function (2PCF): $\xi(r)$

If you are sitting on a galaxy, the probability dP that you will find another galaxy in a volume dV a distance r away from you is given by

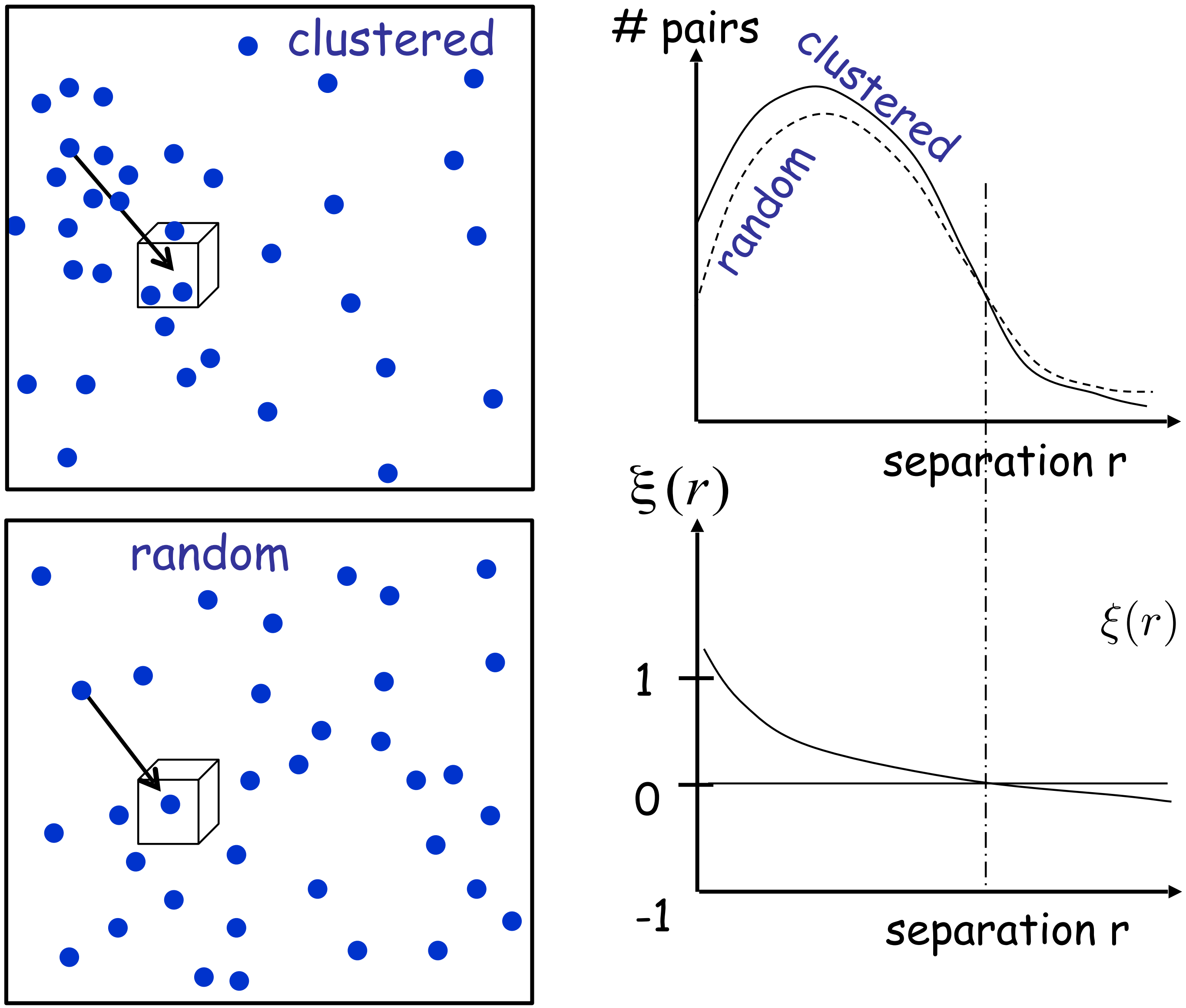
$$dP = n\, dV\, [1 + \xi(r)]$$

where n is the average number density of galaxies.



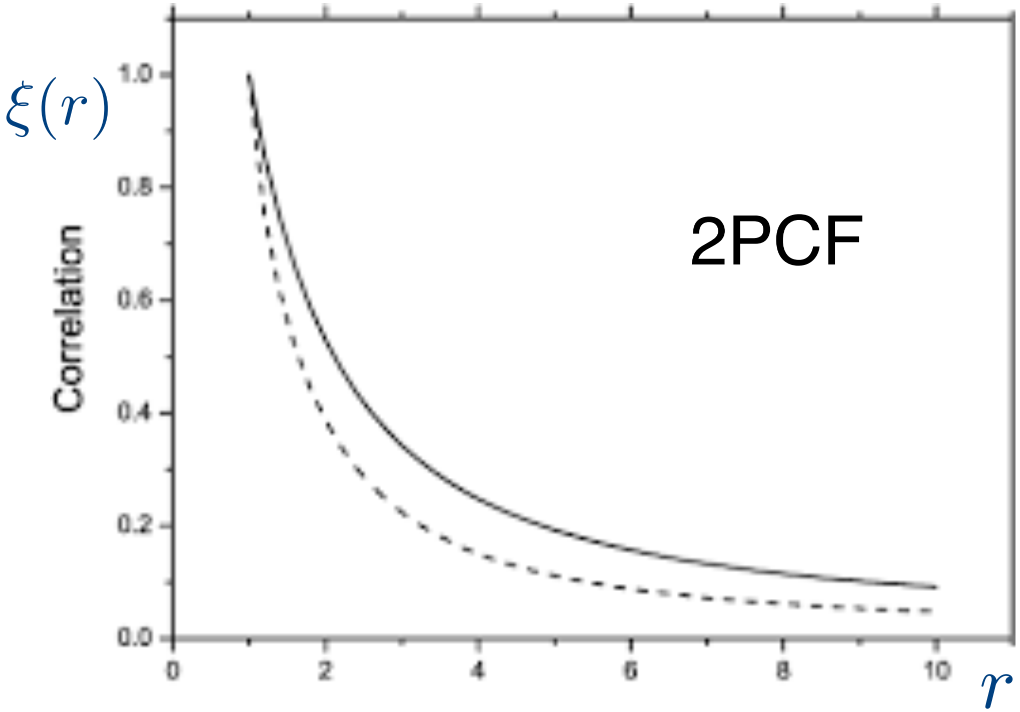
dP is the number of galaxies you expect to find in a volume dV.

What does the 2PCF measures?



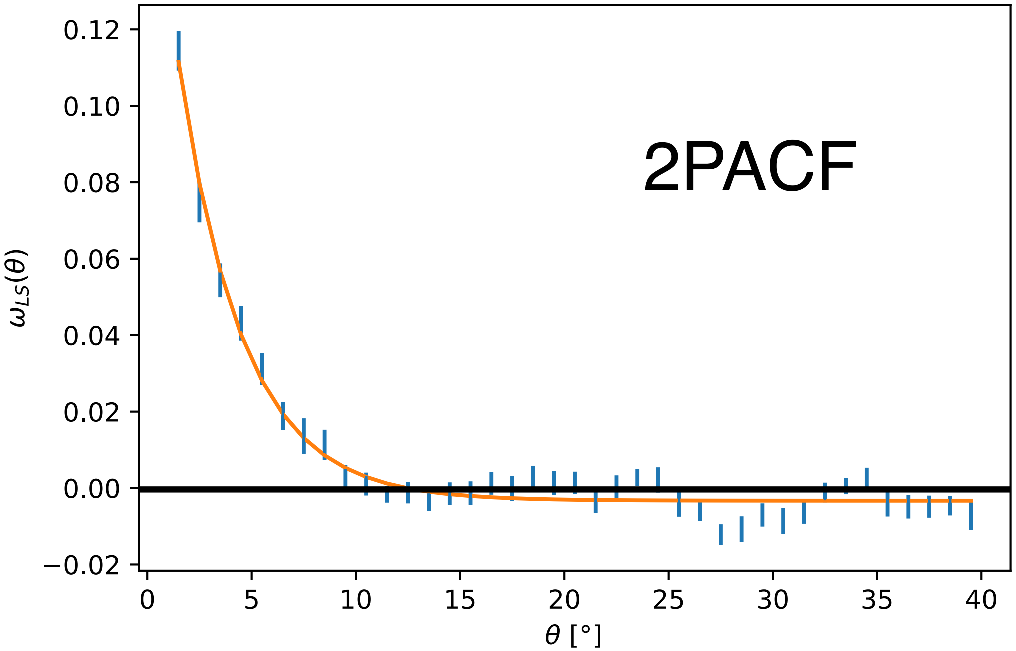
$$\xi(r) = \frac{DD(r)}{RR(r)} - 1$$

2-point correlation function



$$\xi(r) \propto r^{-\alpha}$$

$$\xi(r) = \left(\frac{r_0}{r}\right)^{\alpha}$$



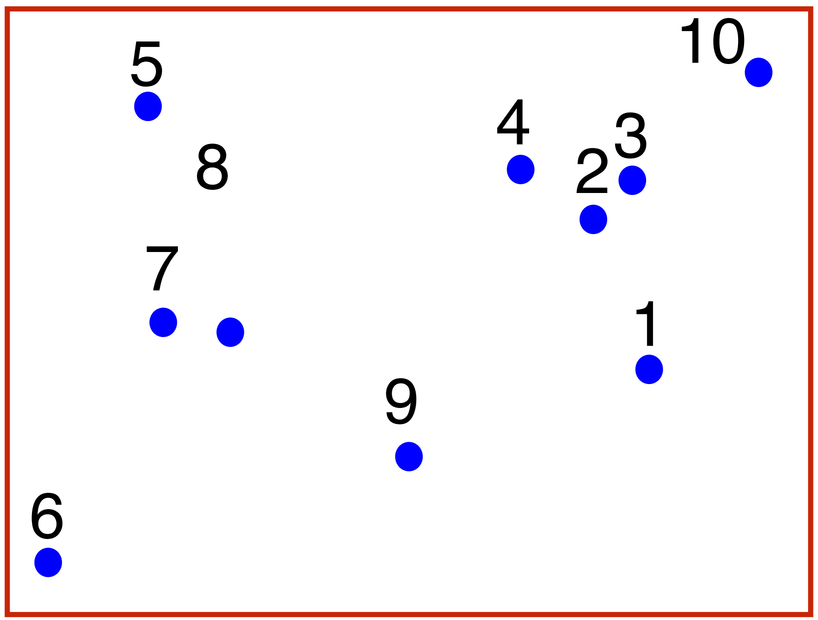
$$\omega(\theta) \propto \theta^{-\beta}$$

$$\omega(\theta) = \left(\frac{\theta_0}{\theta}\right)^{\beta}$$

How to count pairs in a data catalogue?

pairs distances
D_{12}
D_{13}
$\cdots$
$D_{1,10}$
D_{21}? X
D_{23}
$\cdots$
$D_{2,10}$
D_{34}
$\cdots$
$\cdots$
$D_{9,10}$

D



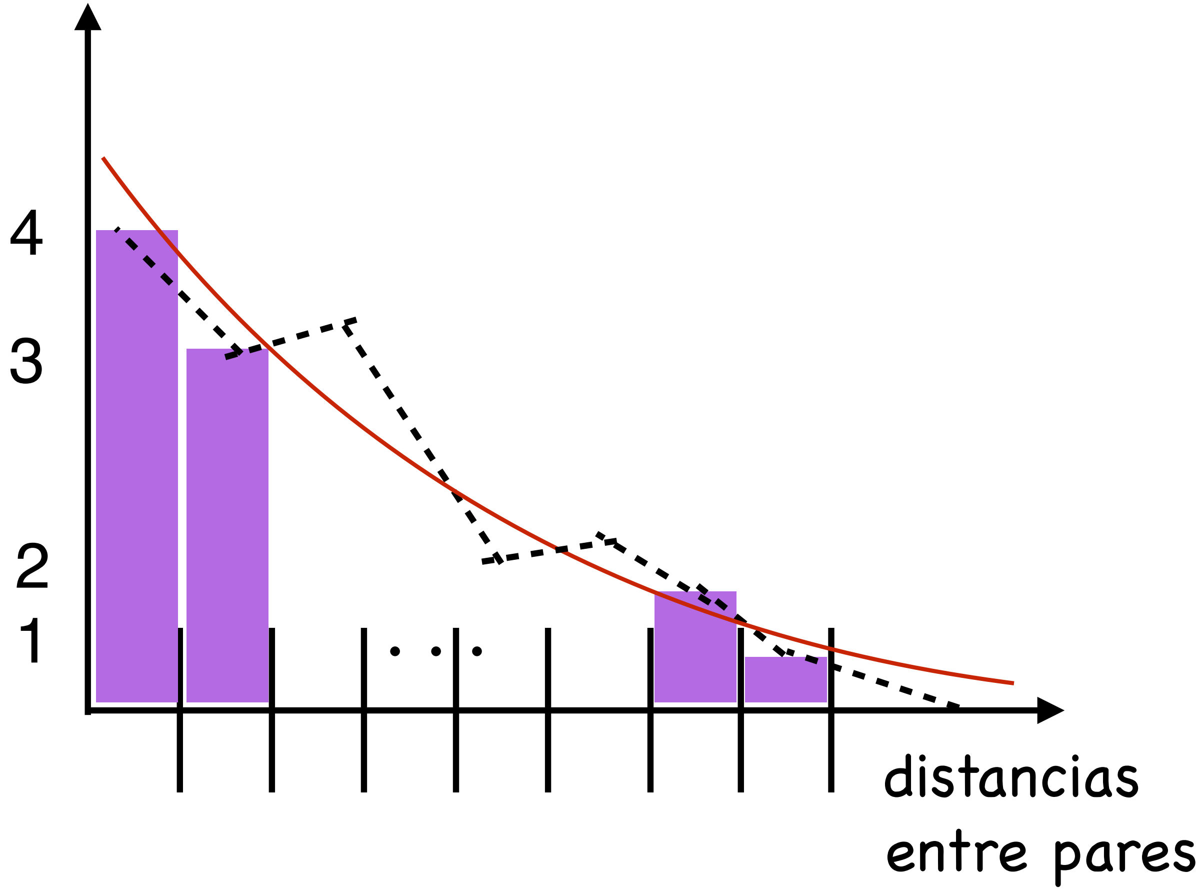
$$\{D_{23}, D_{24}, D_{34}, D_{58}\} \in \mathrm{bin}_1$$

$$\{D_{12}, D_{39}, D_{78}\} \in \mathrm{bin}_2$$

$$\{D_{26}, D_{36}\} \in \mathrm{bin}_{n-1} \cdots \{D_{6,10}\} \in \mathrm{bin}_n$$

How many data pairs did we get?

pairs distances
D_{12} D_{13} $\cdots$ $D_{1,10}$
D_{21}? X D_{23} $\cdots$ $D_{2,10}$
D_{34} $\cdots$ $\cdots$ $D_{9,10}$



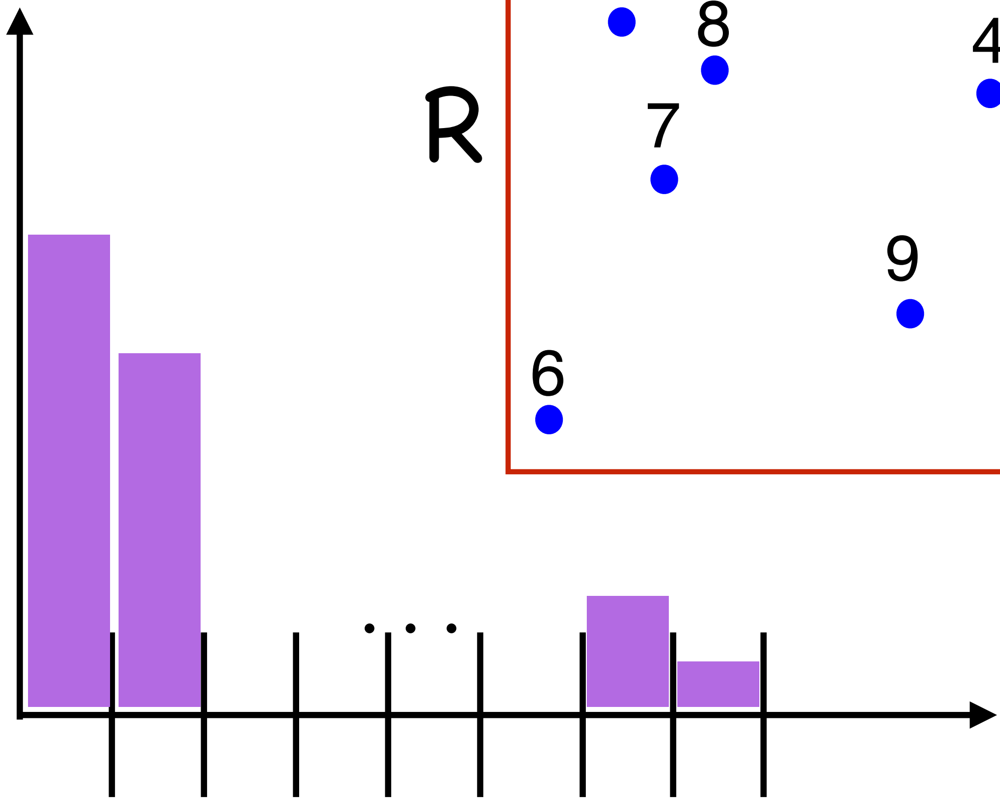
Histograma de contagem de distancias entre pares D

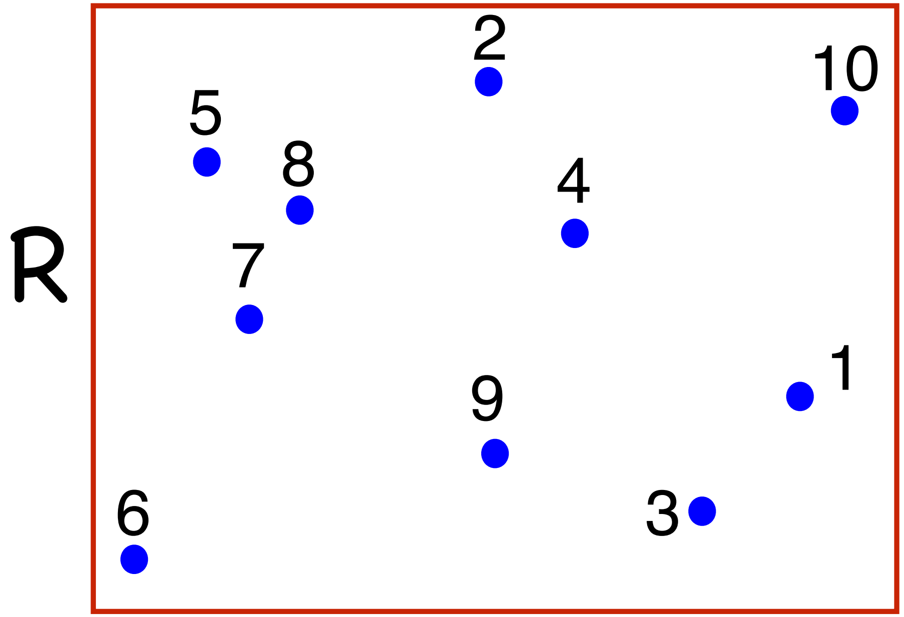
$= DD(r)$

$\neq \xi(r)$

Now, we generate a random catalogue in the same region of the data sample

pairs distances	
R_{12}	
R_{13}	
$\cdots$	
$R_{1,10}$	
R_{21}?	X
R_{23}	
$\cdots$	
$R_{2,10}$	
R_{34}	
$\cdots$	
$\cdots$	
$R_{9,10}$	





Histograma de contagem de distancias entre pares R $= RR(r)$

2-point correlation function

Landy-Szalay

$$\xi(r) = \frac{DD(r) - 2DR(r) + RR(r)}{RR(r)}$$

Peebles-Hauser

$$\boxed{\xi(r) = \frac{DD(r)}{RR(r)} - 1}$$

$$\xi(r) = \frac{1}{N} \sum_{i=1}^{N} \frac{DD(r) - RR_i(r)}{RR_i(r)}$$

Homework

2-point angular correlation function

Landy-Szalay
$$\omega(\gamma) = \frac{DD(\gamma) - 2DR(\gamma) + RR(\gamma)}{RR(\gamma)}$$

Peebles-Hauser
$$\omega(\gamma) = \frac{DD(\gamma) - RR(\gamma)}{RR(\gamma)}$$

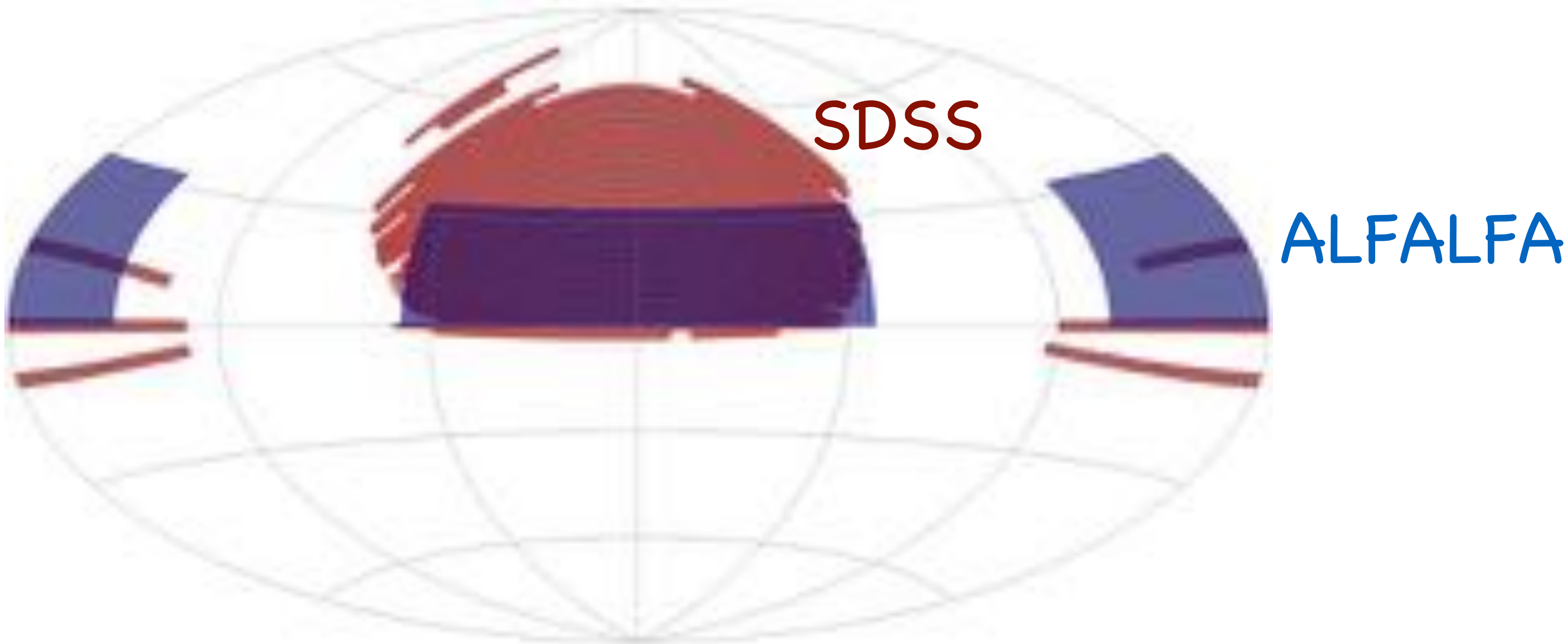
$$\boxed{\omega(\gamma) = \frac{1}{N}\sum_{i=1}^{N}\frac{DD(\gamma) - RR_i(\gamma)}{RR_i(\gamma)}}$$

Compute $\omega(\gamma)$ for a sample of HI sources from ALFALFA survey

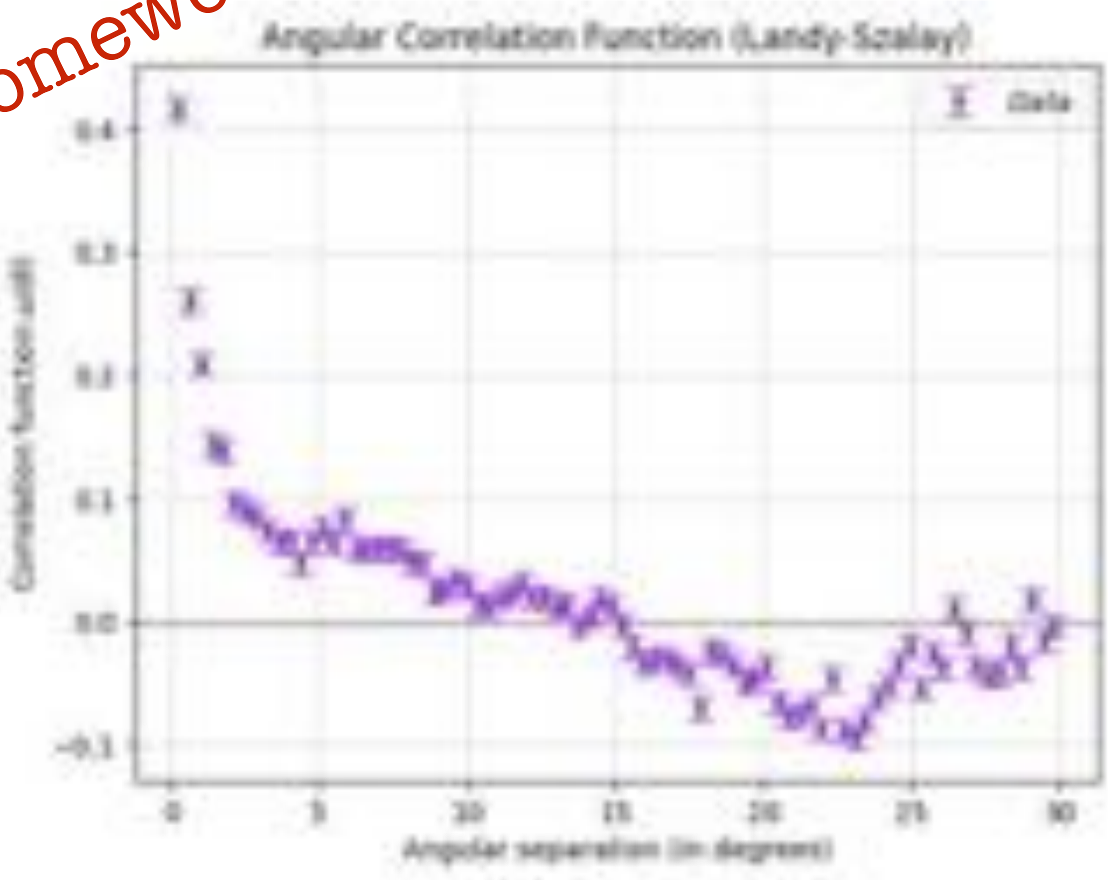
- 2D with data on a sphere with: $\theta \in [\theta_1, \theta_2]$, $\phi \in [\phi_1, \phi_2]$

$$\gamma = \cos^{-1}[\cos(\theta_1)\cos(\theta_2) + \sin(\theta_1)\sin(\theta_2)\cos(\phi_1 - \phi_2)$$

Survey ALFALFA



Homework

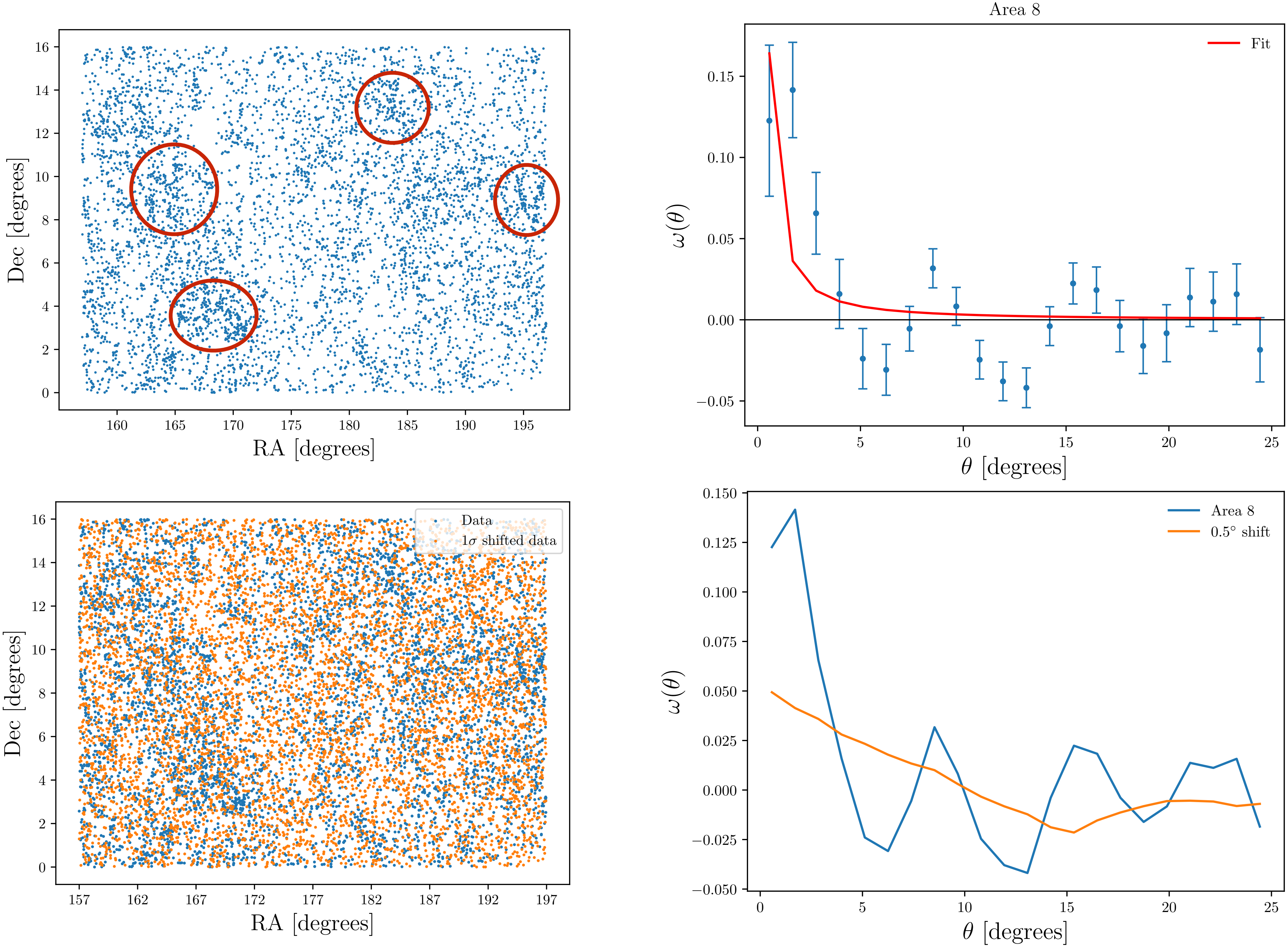


GitHub: 2PACF

https://github.com/mavipoppi/wsON_correlationfunction

Gentileza de: **Maria Vitoria Lazarin**

Gentileza de: **Camila Franco**



The cosmological model of the Universe

stands on:

- Metric theory, e.g., General Relativity
- Cosmological principle
- Observational probes

Traditional Observational Probes:

① $\boxed{\text{Expansion of the Universe}}$ ✓ 1929-1931

✓ 1945-1960

② Nucleosynthesis of primordial nuclei

✓ 1964- …

③ Cosmic Microwave Background Radiation

① "Grande debate de 1920":

universo de estrelas x *universo de galáxias*

Harlow Shapley	Heber D. Curtis
Via Láctea muito grande Sol a 15 kpc do centro Nebulosas fazem parte da galáxia	Via Láctea pequena Sol está no centro Nebulosas são "universos ilhas"

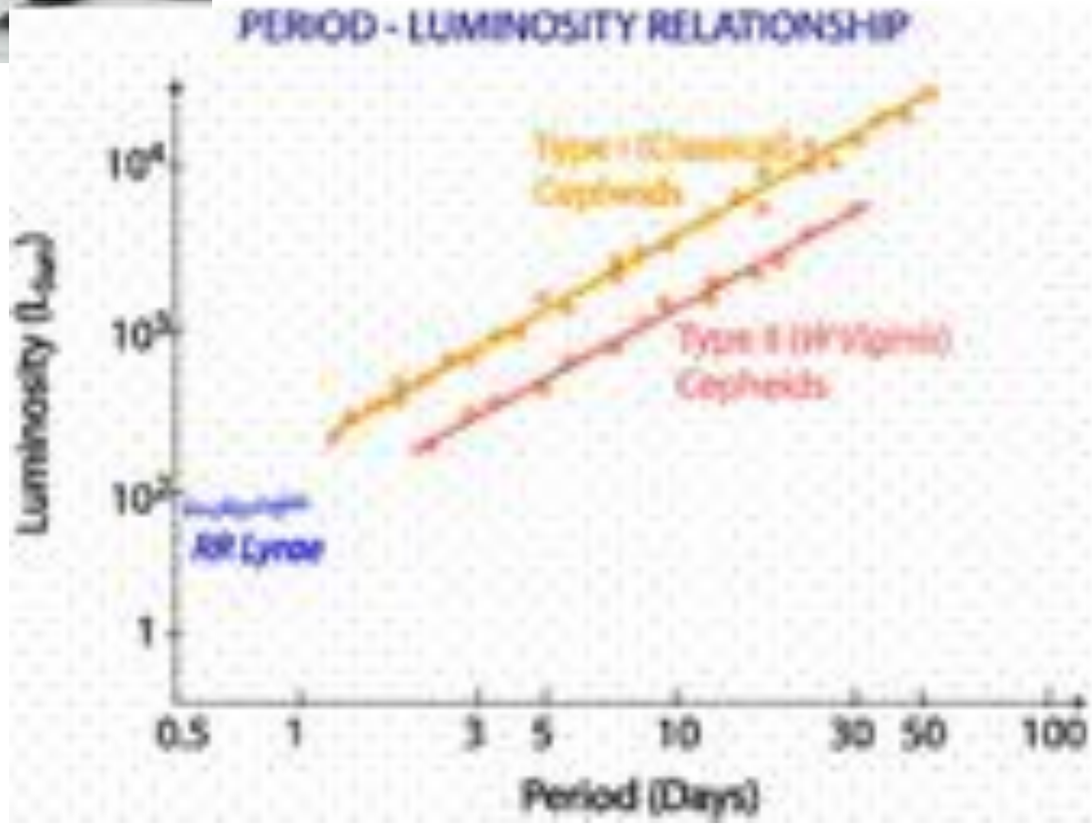
modelo de Kapteyn (1901)

- O grande problema era a determinação de distâncias das nebulosas.

①

Henrietta Leavitt
1867-1921

She studied variable stars and discovered the period-luminosity relationship



distância Via Láctea-Andrômeda:

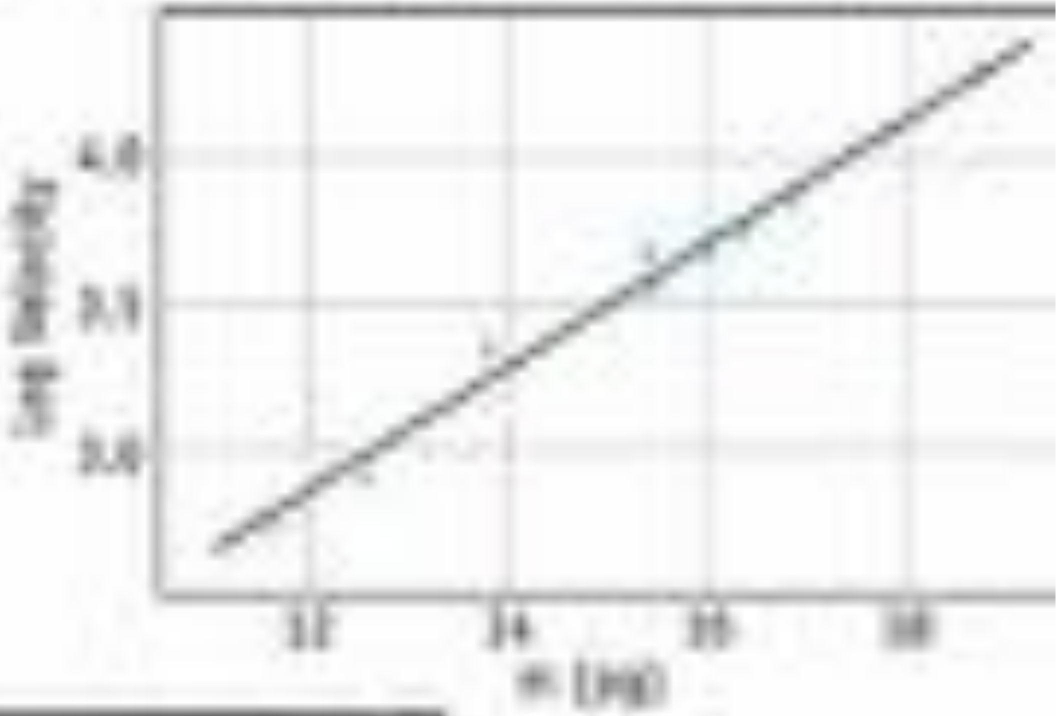
$$d_L(\mathrm{M31}) = 760 \pm 50\,\mathrm{kpc}$$

diâmetro da VL: 32Kpc

①

DISCOVERY OF EXPANDING UNIVERSE

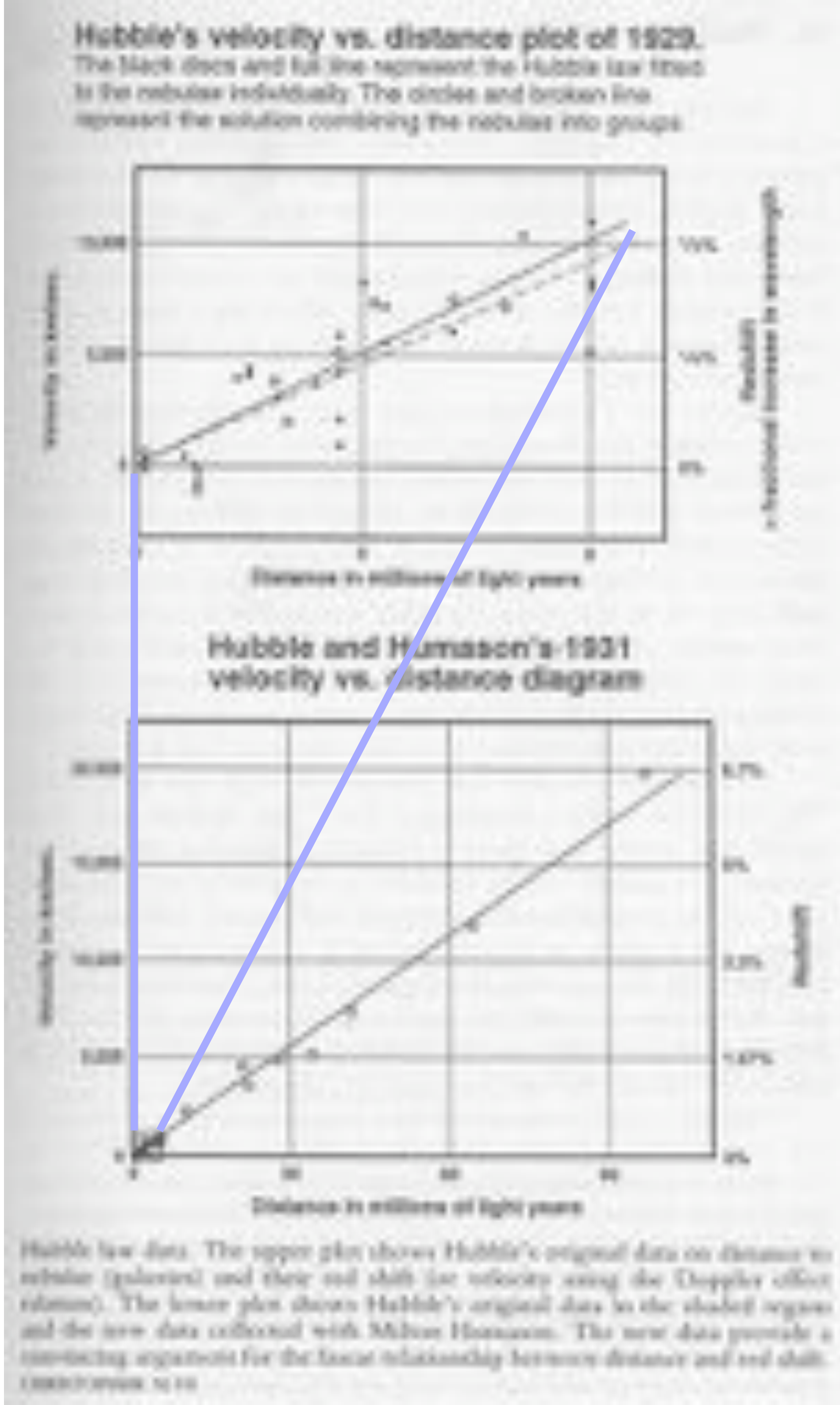
Edwin Hubble



Mt. Wilson 100 Inch Telescope

Hubble, **1929**

Hubble & Humason, **1931**



Traditional Observational Probes:

① Expansion of the Universe ✓ 1929-1931

✓ 1945-1960

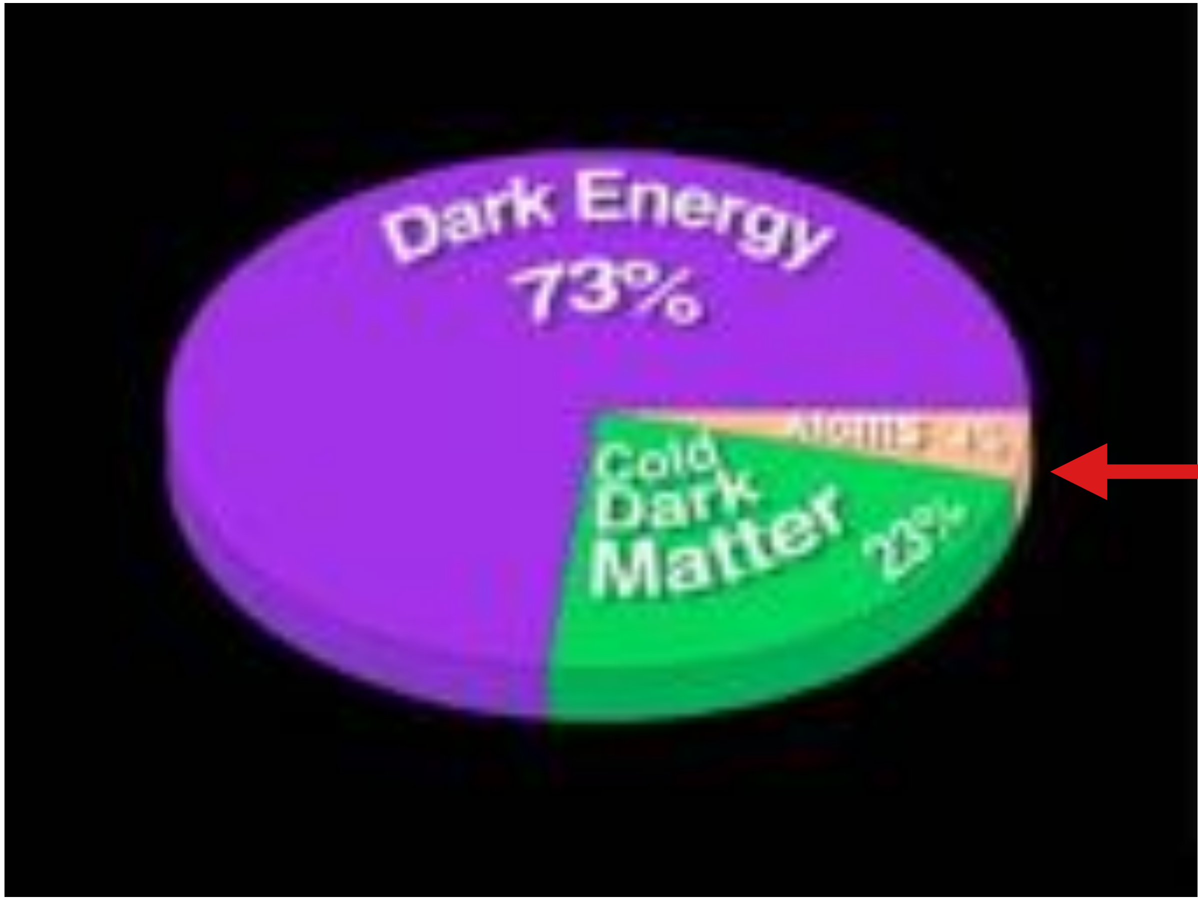
② Nucleosynthesis of primordial nuclei

✓ 1964- …

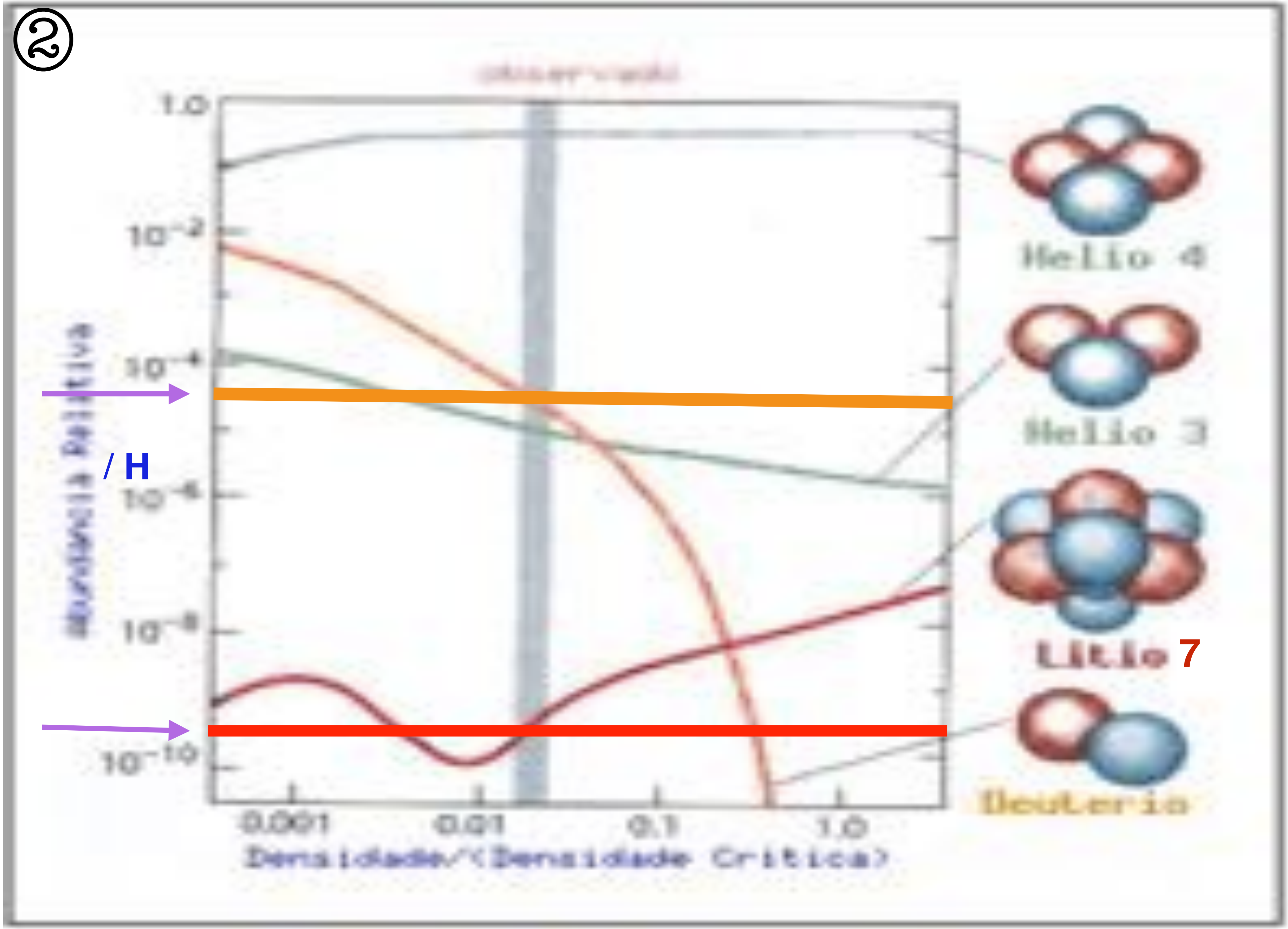
③ Cosmic Microwave Background Radiation

2

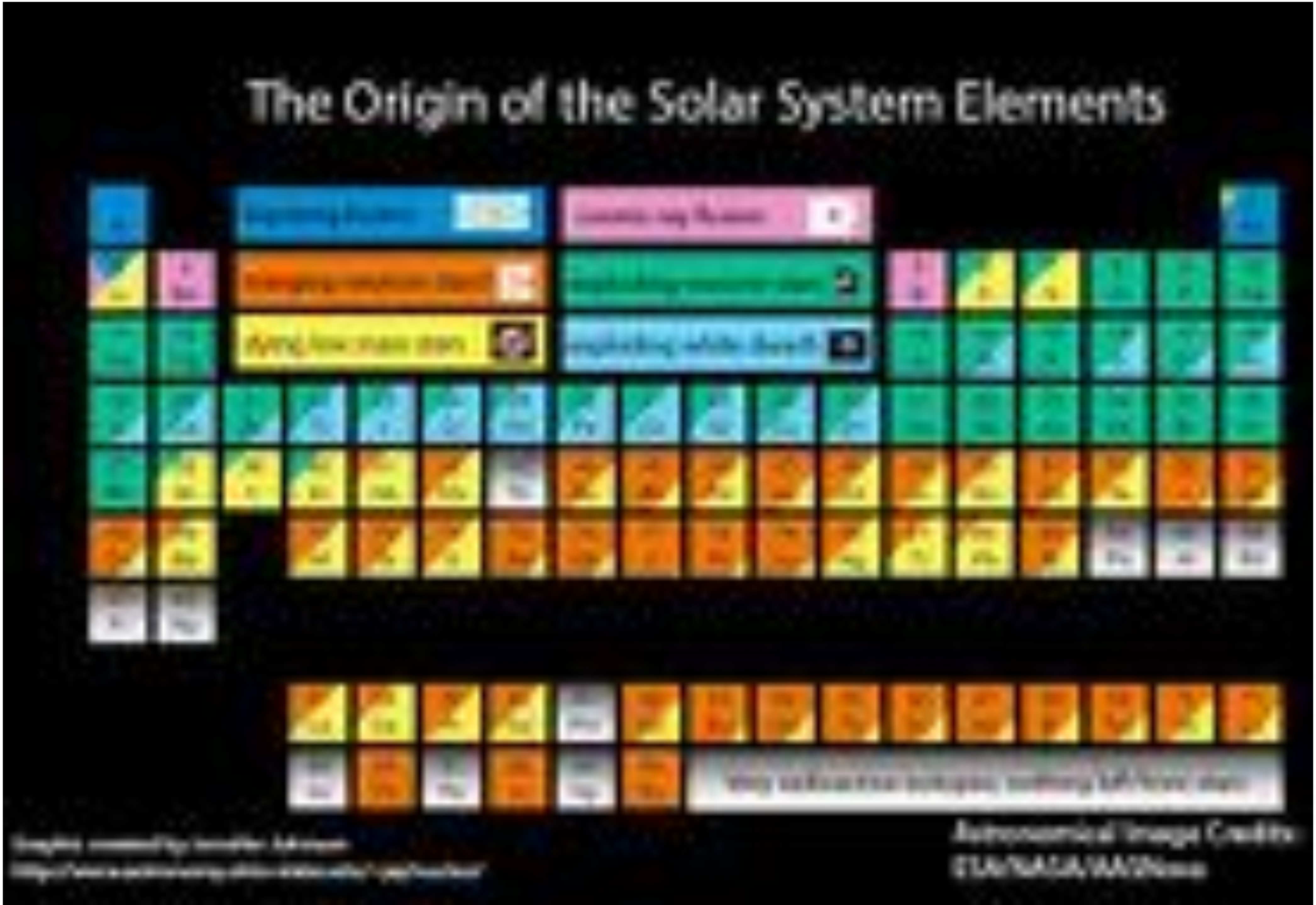
What is the universe made of?



Matéria Bariônica


②
observado
1.0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
Abundancia Relativa
/ H
Helio 4
Helio 3
Litio 7
Deuterio
0.001
0.01
0.1
1.0
Densidade/(Densidade Critica)

Matéria Bariônica



Traditional Observational Probes:

① Expansion of the Universe ✓ 1929-1931

✓ 1945-1960

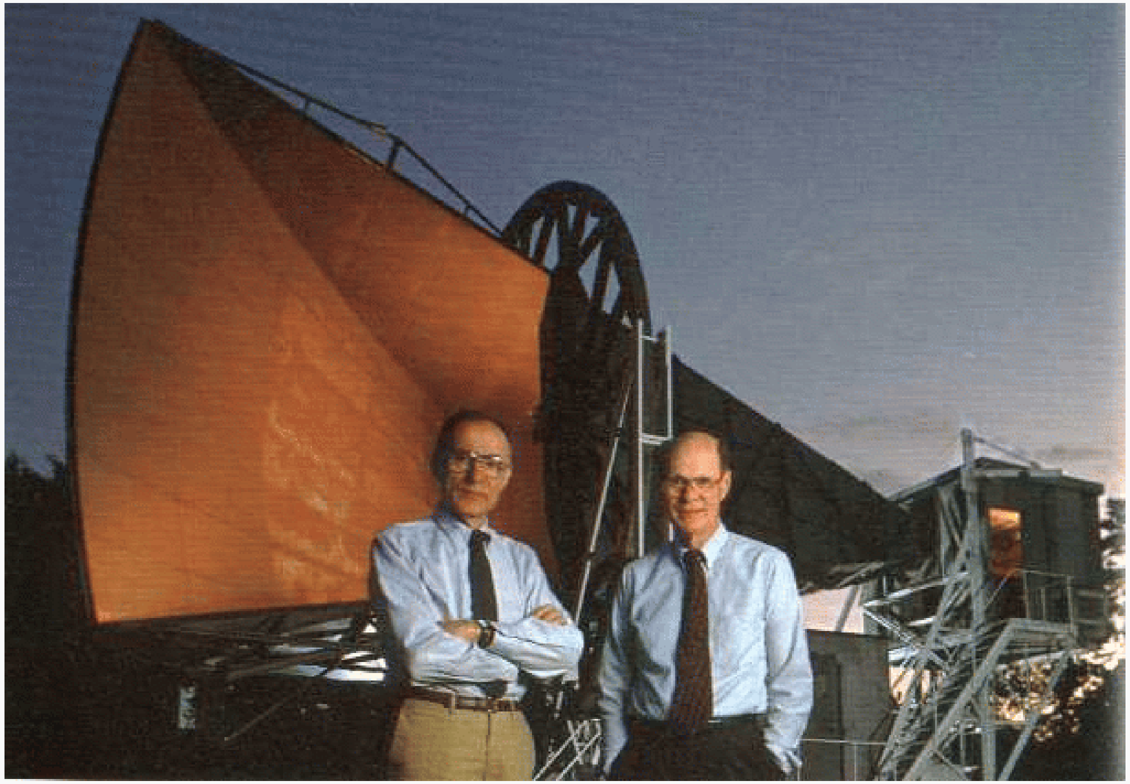
② Nucleosynthesis of primordial nuclei

✓ 1964- …

③ Cosmic Microwave Background Radiation

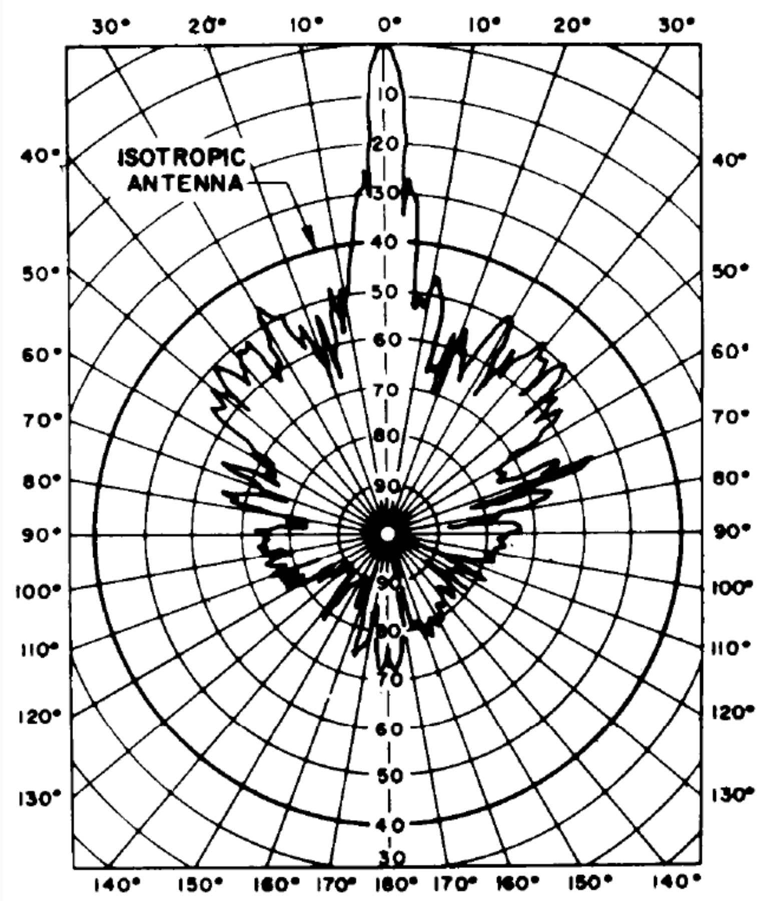
③

A descoberta da RCF (1964)

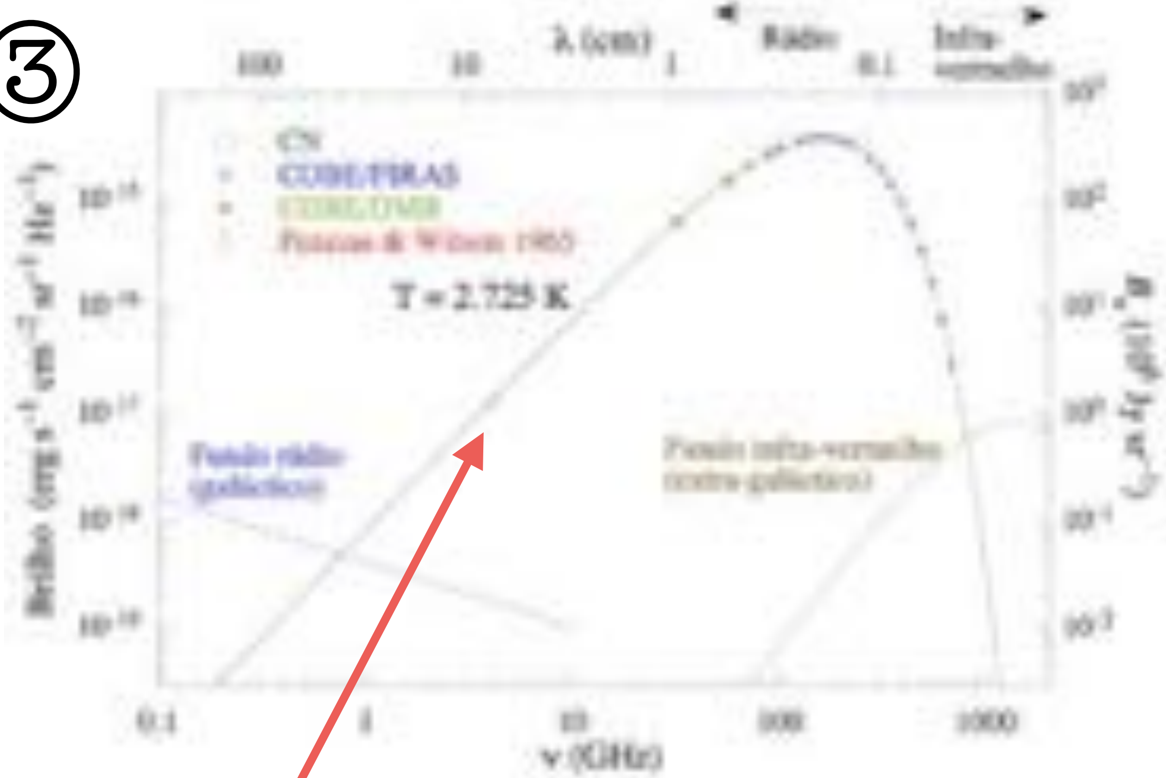


- Antena projetada em 1960 para testes de comunicação de baixo ruído com o satélite echo.

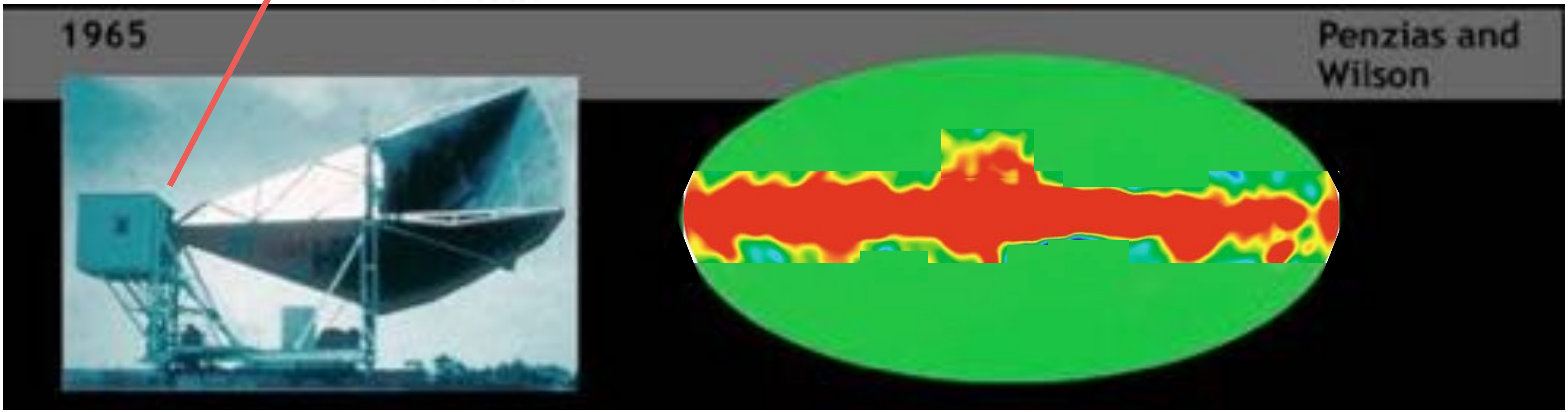
- Sistema direcional de baixo ruído (< 0.05 K) operando em λ = 7.35 cm.



③

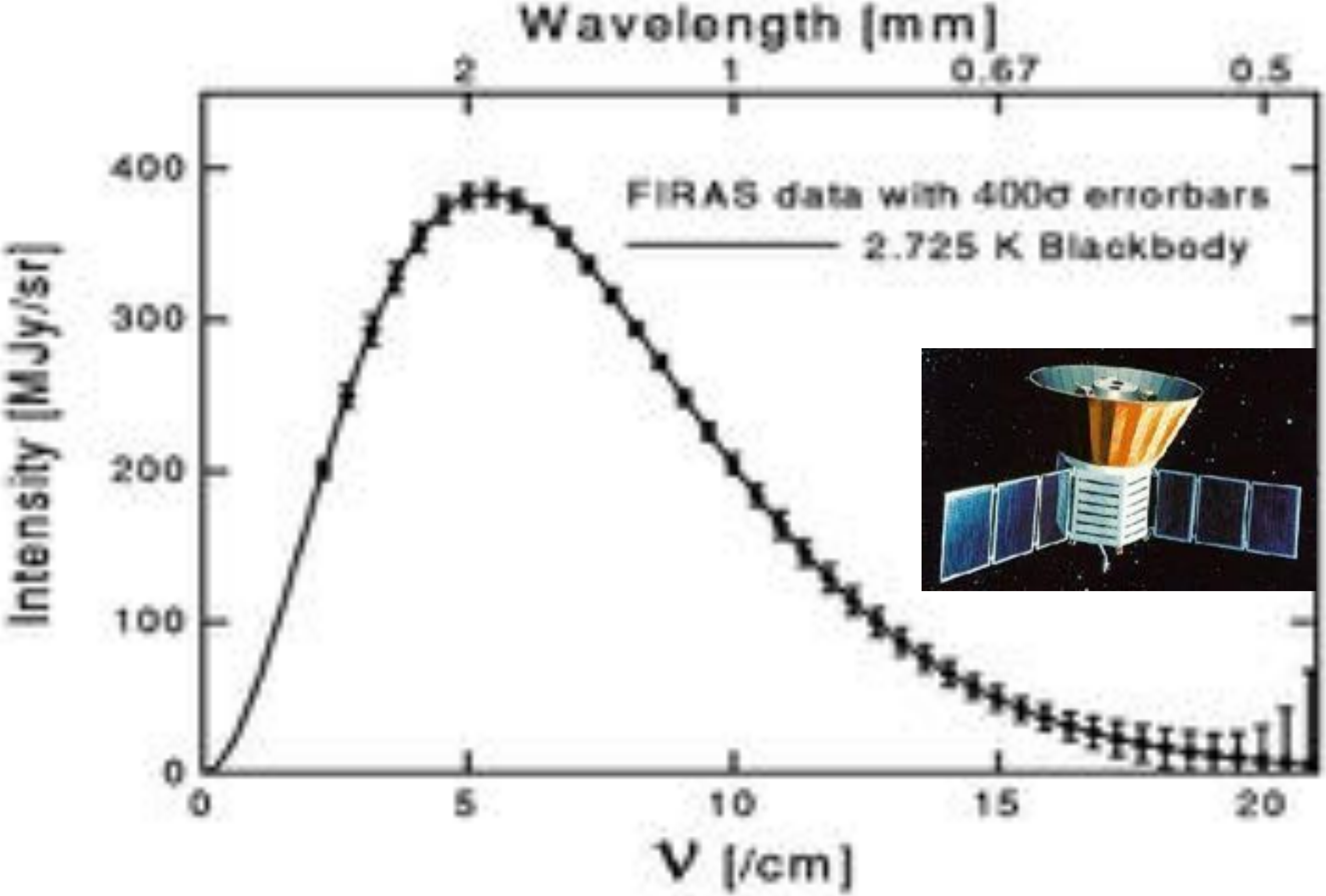


cosmic noise?



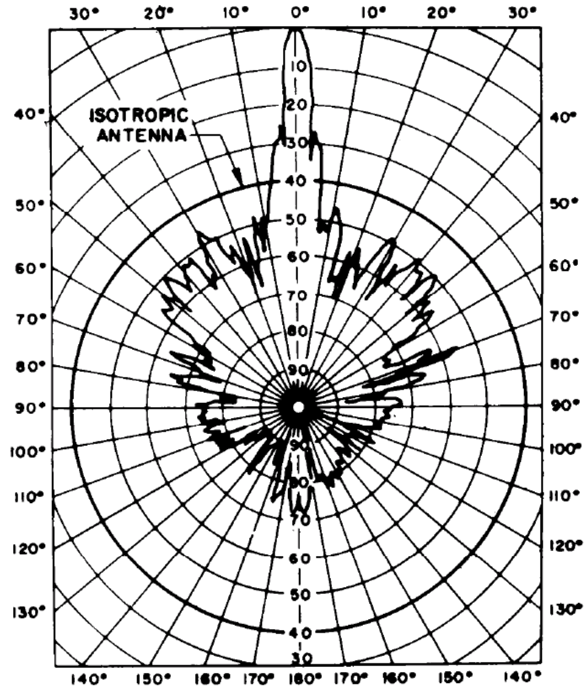
③

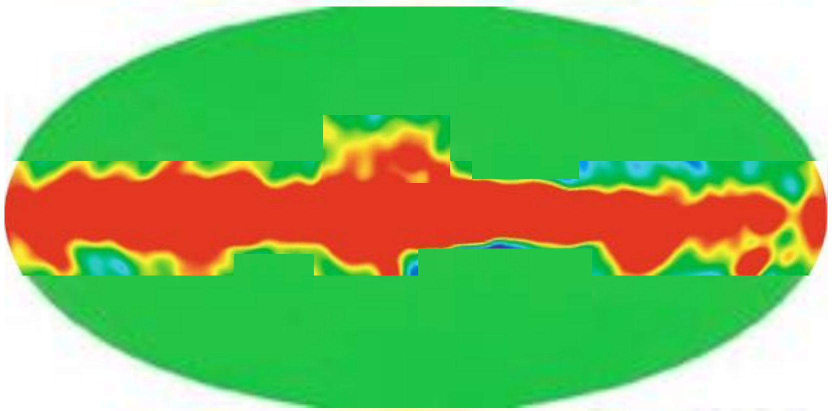
Black-body radiation



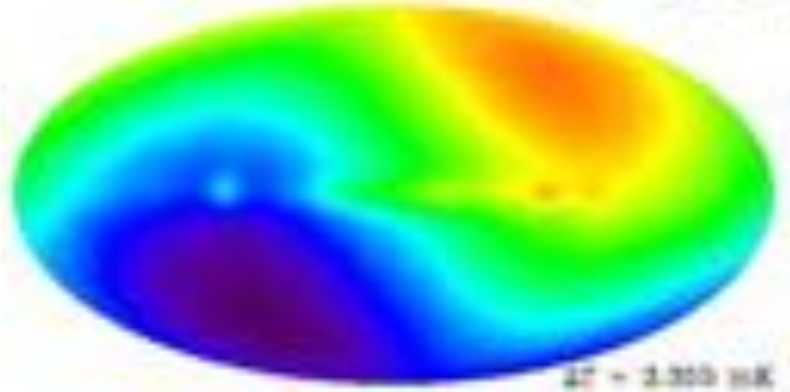
③

COBE's maps

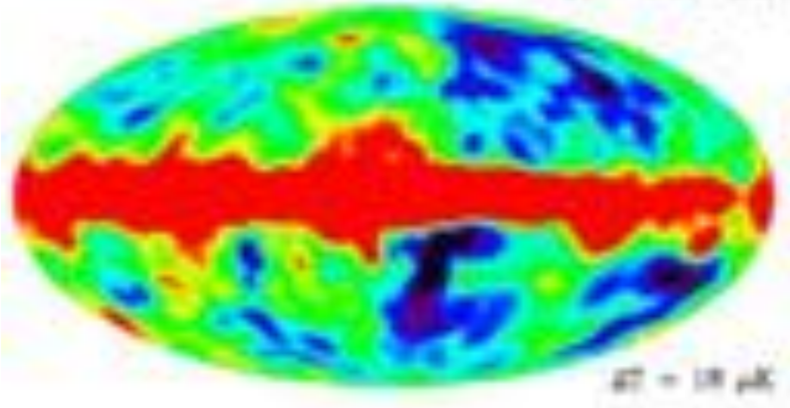




Monopole



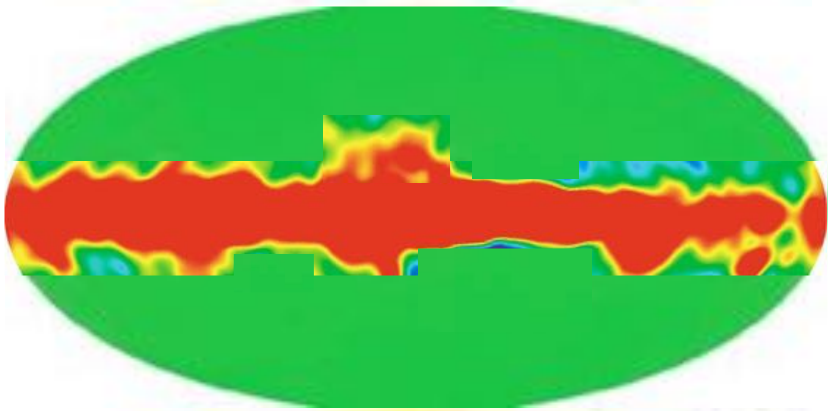
Dipole



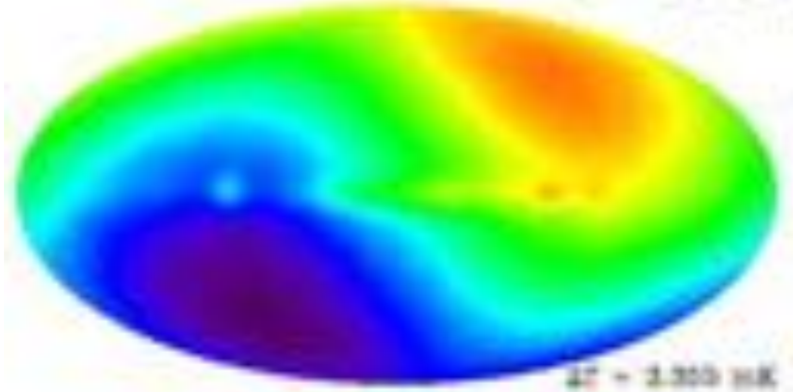
? ?

③

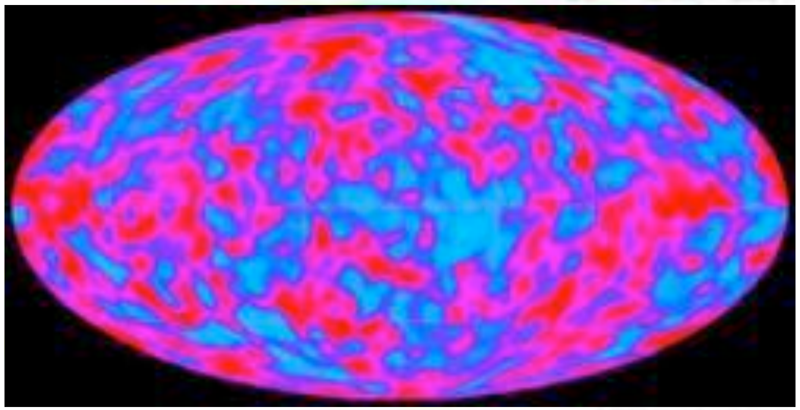
COBE's maps



Monopole



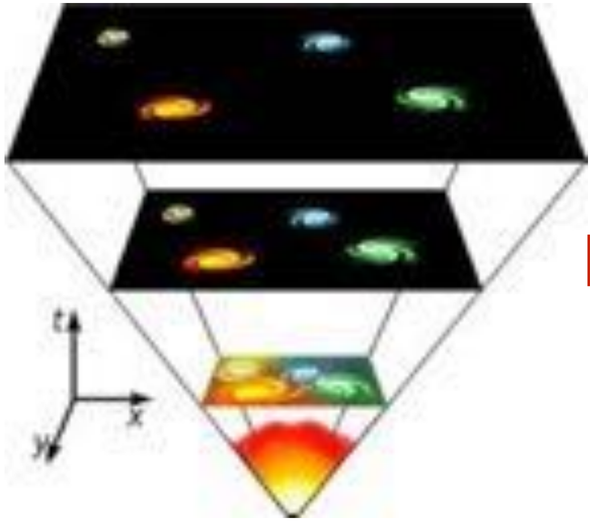
Dipole



- se houve um passado denso e quente, então matéria e radiação acoplaram-se —em equilíbrio termodinâmico— até o Universo esfriar o suficiente; depois desacoplaram e os fótons formam uma radiação relíquia que viaja (quase) livre

- em aproximação zero (= background), mostra-se que o Universo que expande esfria (isto pressupõe condições adiabáticas e a 1ra. lei da termodinâmica)

Hubble, 1929



Expansion of the Universe implies a dense and hot past!

A hot gas of photons in thermodynamic equilibrium in an expanding Universe implies (dQ=0 + 1st. law):

$$T(t) = \frac{a_0 T_0}{a(t)}$$

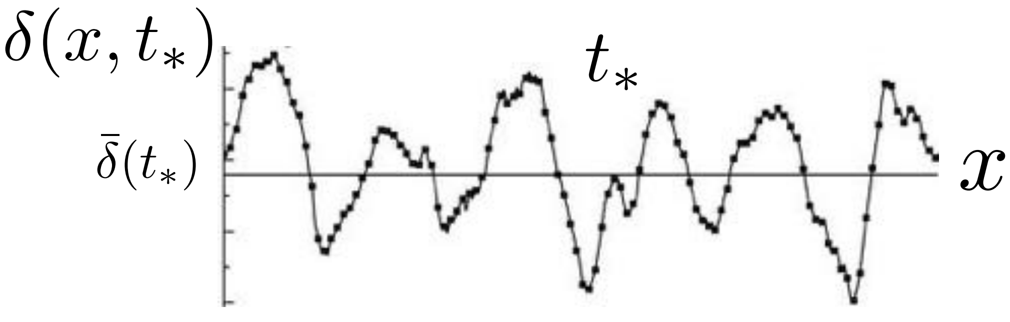
Thermal history of the Universe

Corollary: A cosmic time t exists and is well defined

- se houve um passado denso e quente, então matéria e radiação acoplaram-se —em equilíbrio termodinâmico— até o Universo esfriar o suficiente; depois desacoplaram e os fótons formam uma radiação relíquia que viaja (quase) livre

- em aproximação zero (= background), mostra-se que o Universo que expande esfria (isto pressupõe condições adiabáticas e a 1ra. lei da termodinâmica)

- a ordem zero não explica a formação de estruturas: precisamos perturbações do campo de densidade de matéria (equivalentemente, do potencial gravitacional)



$$\delta(x, t_*) \equiv \frac{\rho(x, t_*) - \bar{\rho}(t_*)}{\bar{\rho}(t_*)}$$

- se houve um passado denso e quente, então matéria e radiação acoplaram-se —em equilíbrio termodinâmico— até o Universo esfriar o suficiente; depois desacoplaram e os fótons formam uma radiação relíquia que viaja (quase) livre

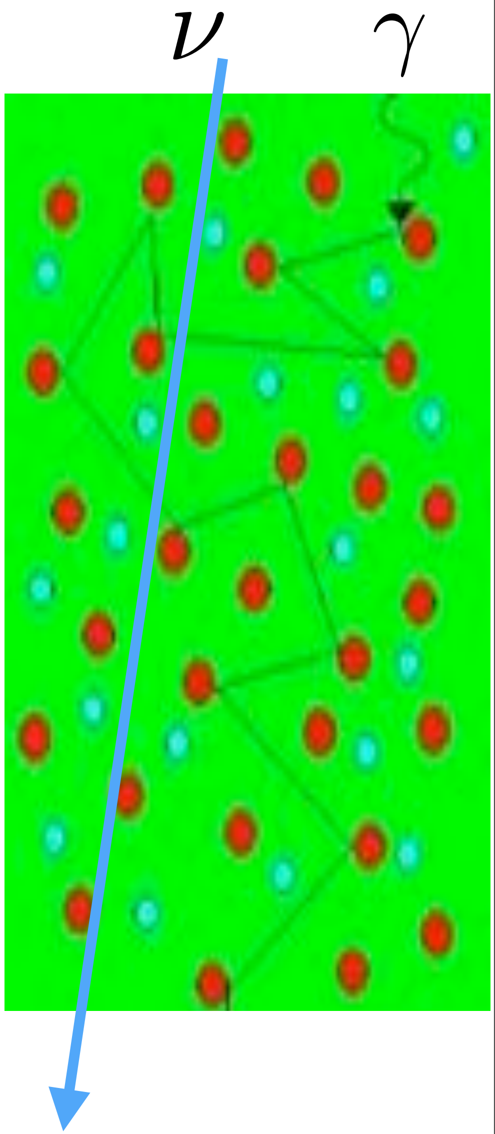
- em aproximação zero (= background), mostra-se que o Universo que expande esfria (isto pressupõe condições adiabáticas e a 1ra. lei da termodinâmica)

- a ordem zero não explica a formação de estruturas: precisamos perturbações do campo de densidade de matéria (equivalentemente, do potencial gravitacional)

- perturbações na matéria geram flutuações no campo da radiação (devido ao acoplamento fótons-bárions)

a história do Universo: passado denso e quente

- Houve uma fase onde o fluido matéria–radiação (composto por bárions e fótons interagindo via espalhamento Thomson) estava em equilibrio termodinámico, e agia como se fosse um fluido só (photon-baryon fluid); $\eta \equiv \frac{n_\gamma}{n_b} \simeq 10^9$.



$$1K = 8.6 \times 10^{-5}\,\mathrm{eV}$$

$$T = \frac{T_0}{a(z)} = 3K(1+z)$$

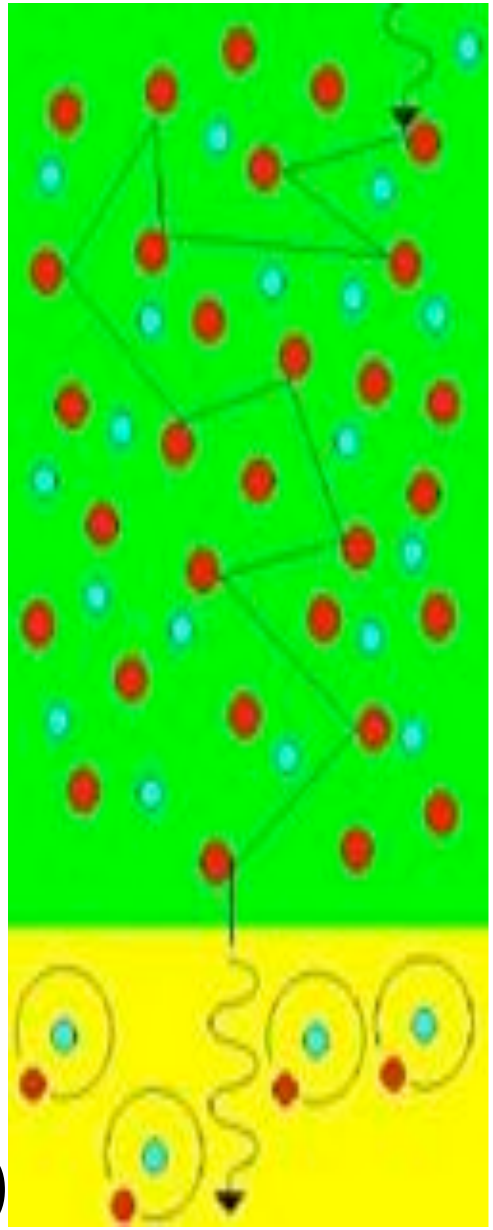
$$z_{LSS} \simeq 1100 \;\rightarrow\; T_{LSS} \simeq 3000K$$

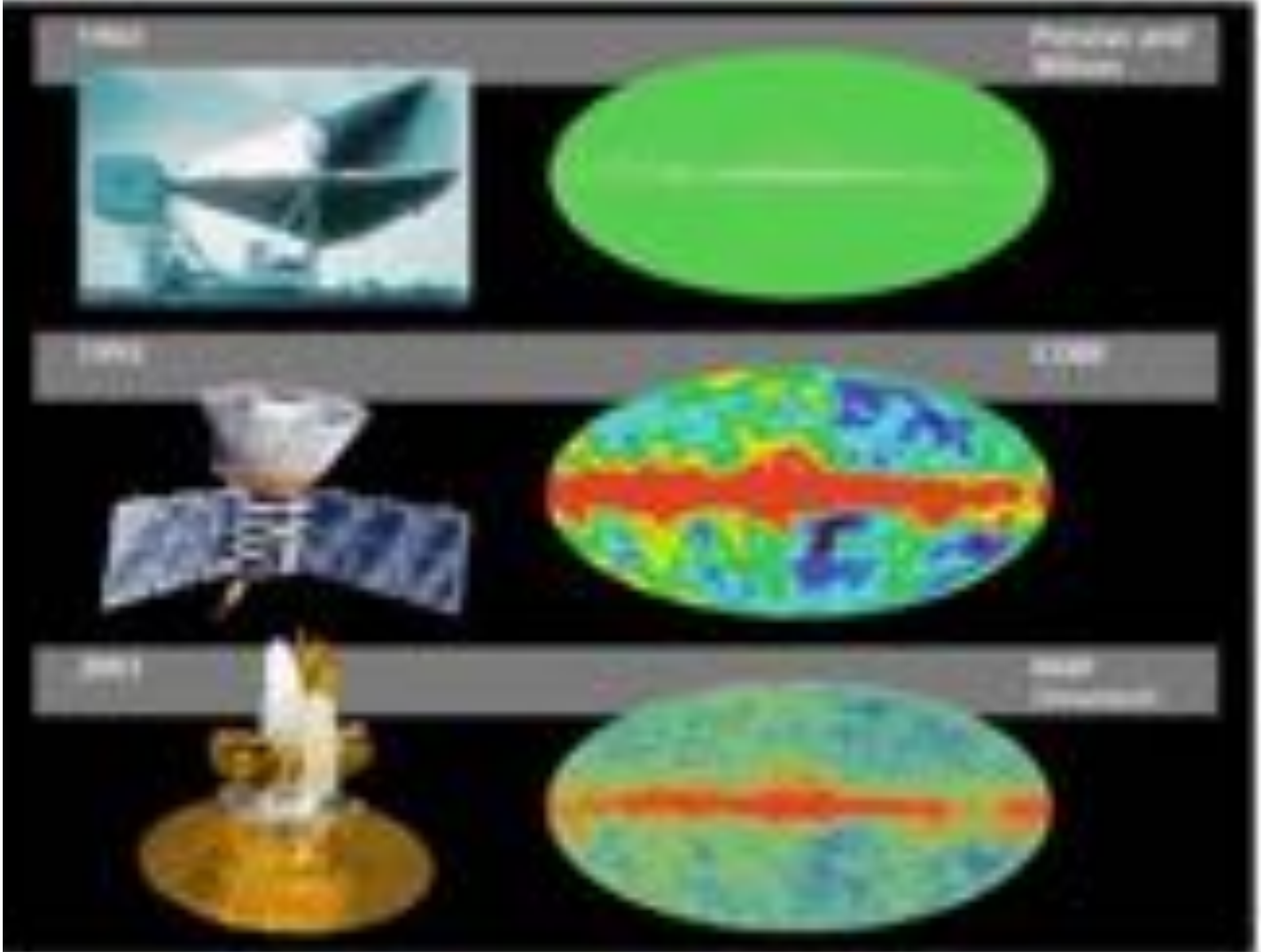
a história do Universo: passado denso e quente

- Houve uma fase onde o fluido matéria–radiação (composto por bárions e fótons interagindo via espalhamento Thomson) estava em equilibrio termodinámico, e agia como se fosse um fluido só (photon-baryon fluid); $\eta \equiv \frac{n_\gamma}{n_b} \simeq 10^9$.

- Ao expandirse o Universo resfria e o fluido alcanza uma temperatura crítica que produz o desacoplamento matéria−radiação: $T \simeq 3000$ K $\simeq 0.3\, eV$.

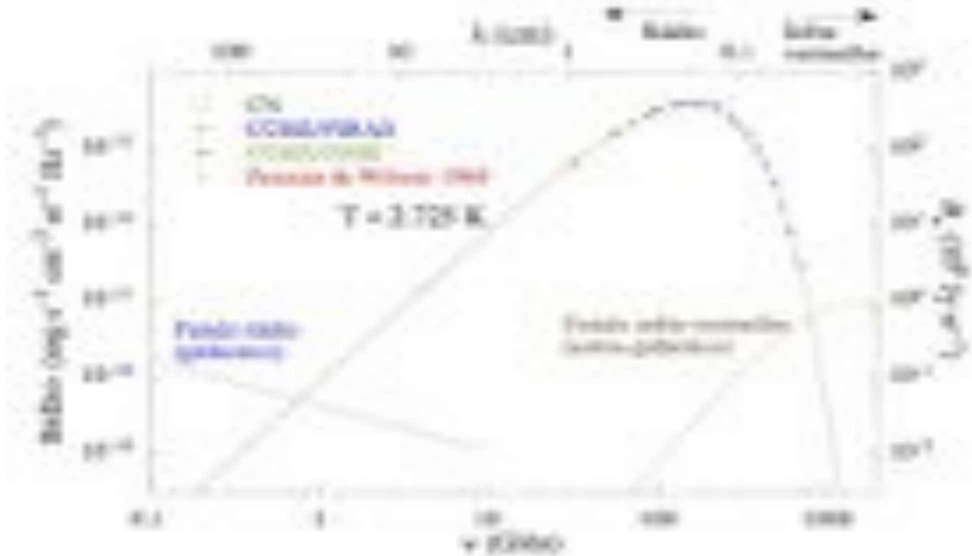
- Esses fótons livres (de ser espalhados pelos elétrons) constituem uma radiação relíquia do Universo primordial, chamada Radiação Cósmica de Fundo (RCF)





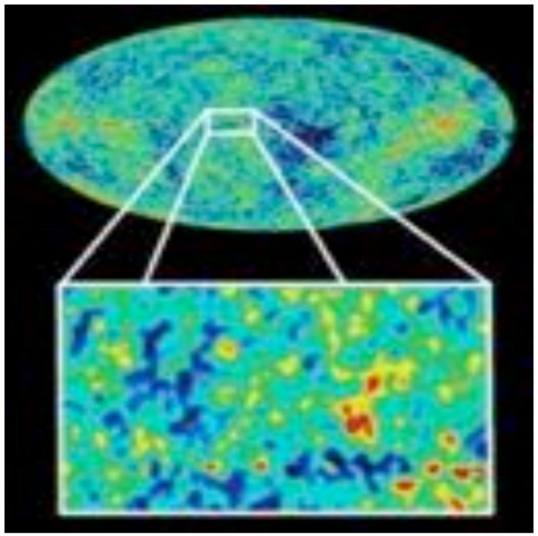
RCF: espectro de corpo negro à temperatura $T_{\rm Planck} = (2.725 \pm 0.001)$K

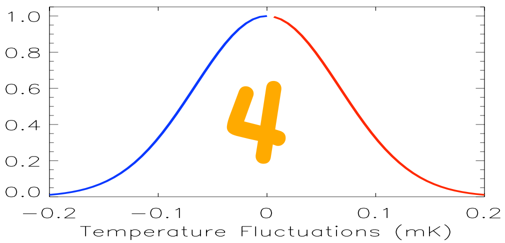
1



1965 – 1992

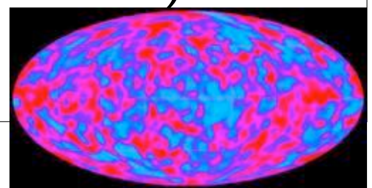
3 Em 1992 verificou-se que ao redor da $T_{\rm Planck}$ $\exists$ pequenas flutuações positivas $\Delta T > 0$ e negativas $\Delta T < 0$, da ordem $\frac{\Delta T}{T_{\rm Planck}} \sim 10^{-5}$





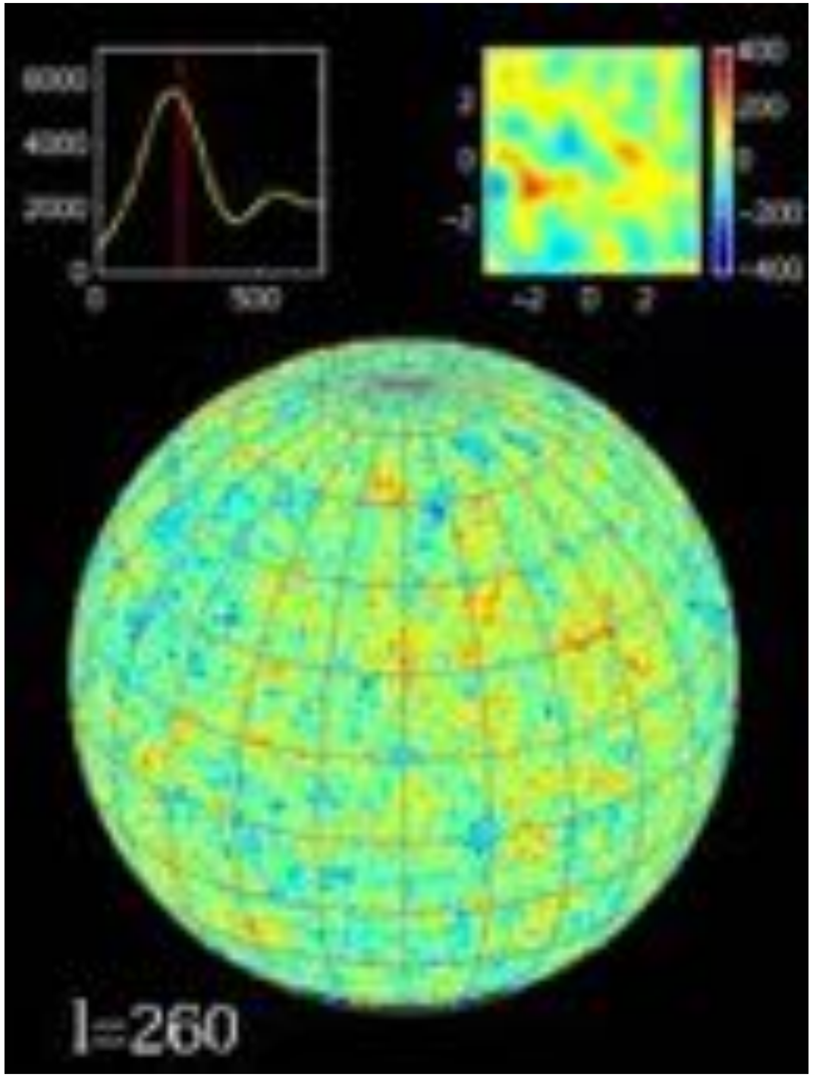
$\rightarrow \Delta T \sim (-200\mu\mathrm{K}, 200\mu\mathrm{K})$

Estas flutuações de temp. ΔT ficam visiveis neste mapa depois de retirar da RCF as componentes monopolo (2.725K) e dipolo (3.346mK) 5

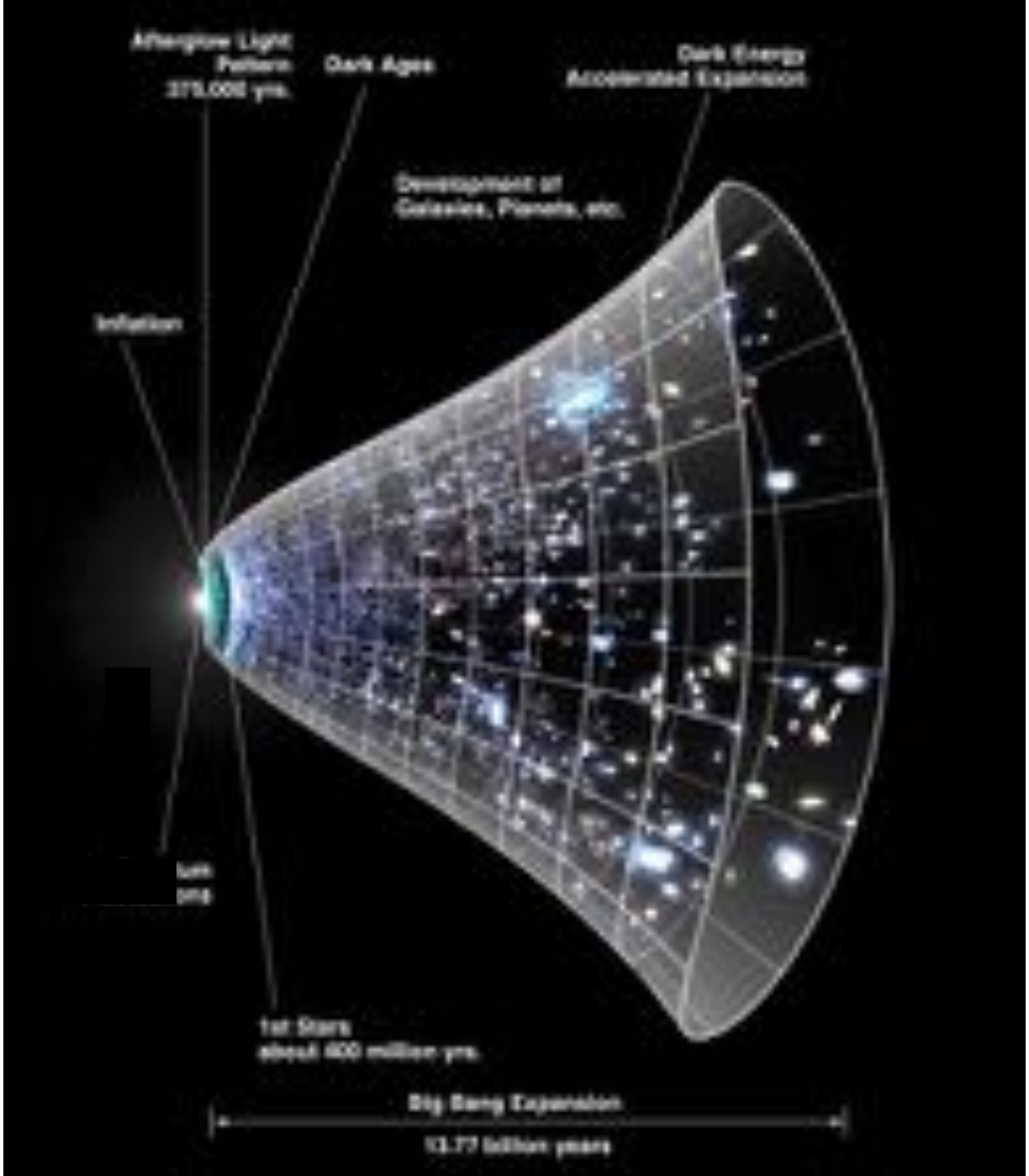


Harmonic Multipoles and the CMB sky: http://spud.spa.umn.edu/~pryke/logbook/20000922/

http://spud.spa.umn.edu/~pryke/logbook/20000922/cumulative_cmb.html



Large Scale Structure



Modern Observational Probes:

- Acceleration of the Universe 1998
- BAO: baryon acoustic oscillations 2005
- Growth of cosmic structures 2005-today
- Probes of stat. homogeneity & isotropy 2000-today
- CMB lensing, evidences of DM, etc.
  2010-today 2000-today

Modern Observational Probes:

- Acceleration of the Universe ✓ 1998
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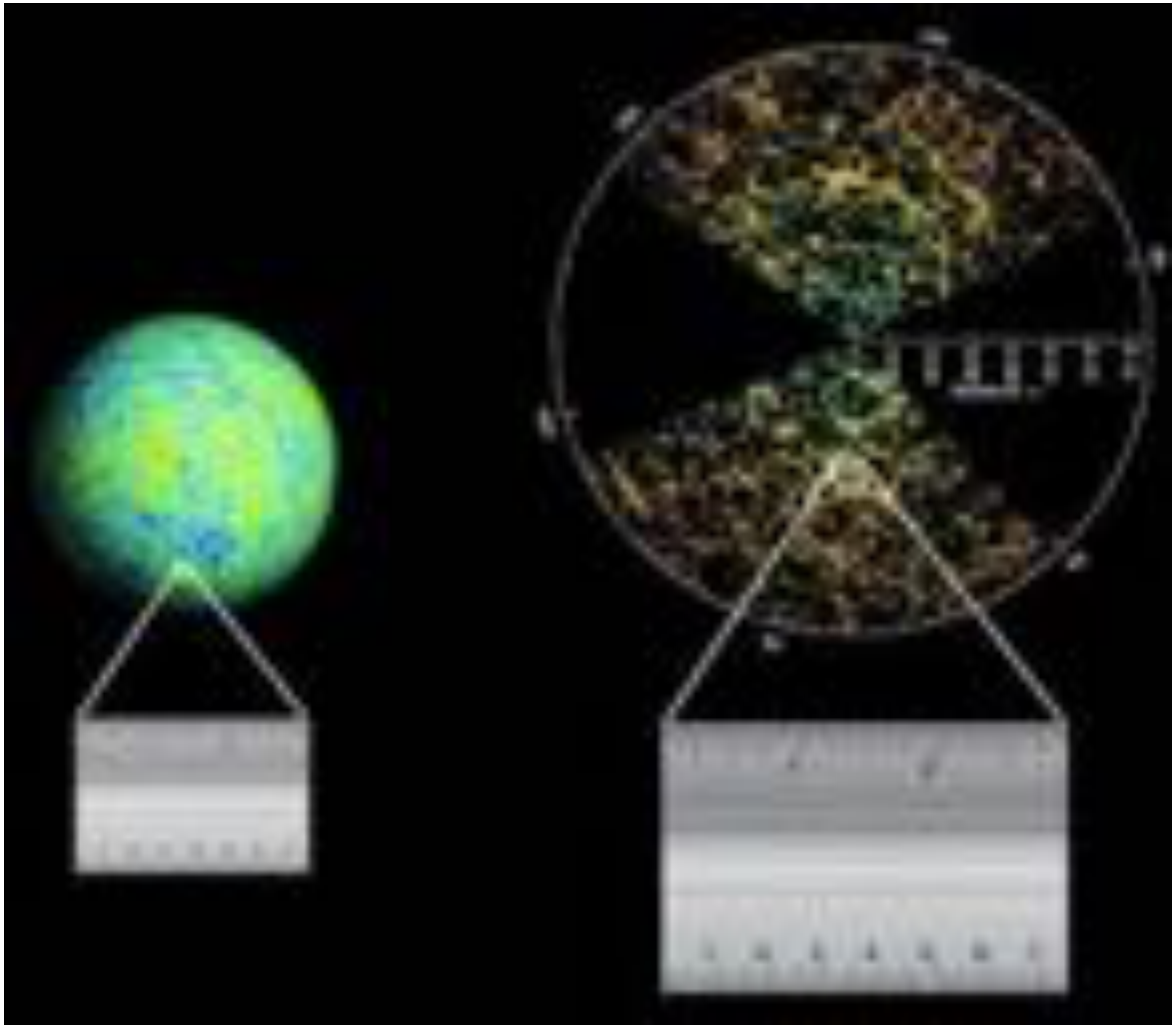
- CMB lensing, evidences of DM, etc. ✓ 2010-today ✓ 2000-today

BAO: a standard ruler



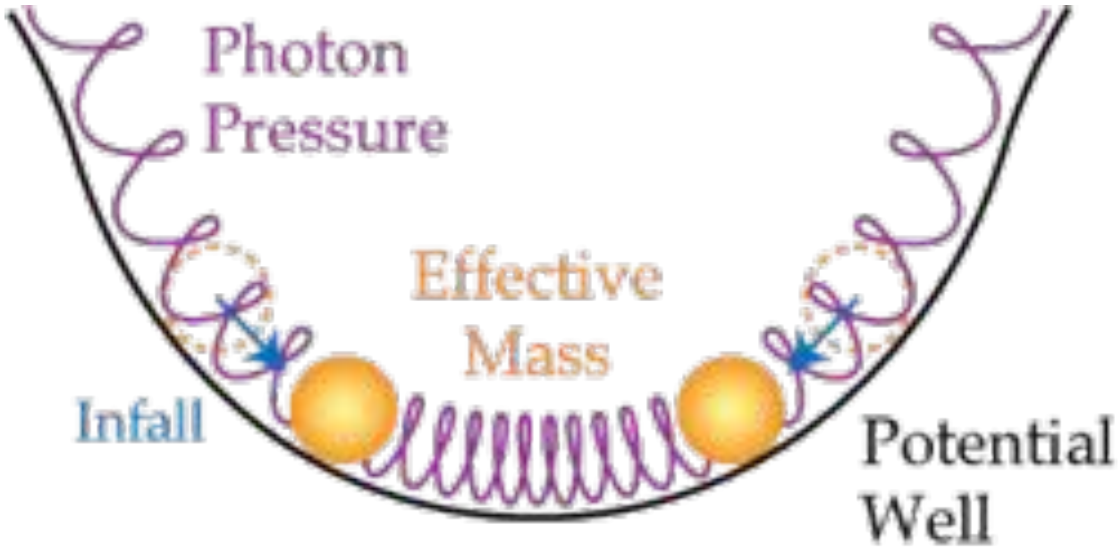
Perturbations in the primordial plasma produced:

3D Sound Waves

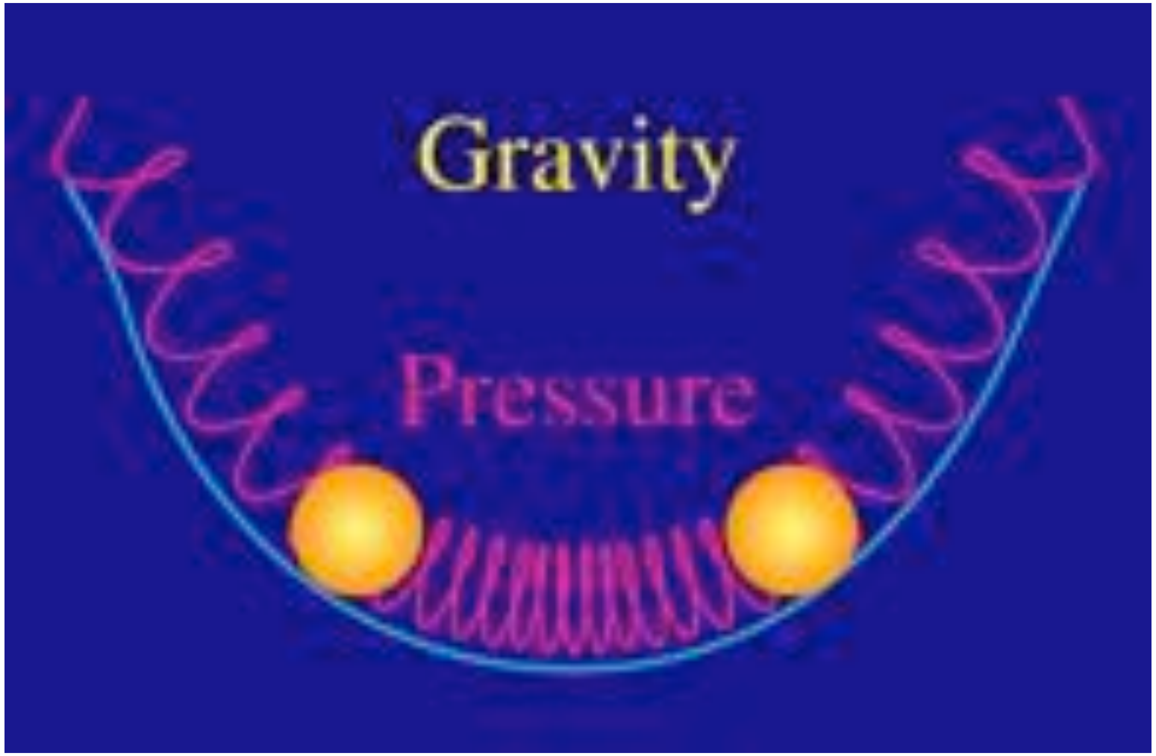
https://www.youtube.com/watch?v=jpXuYc-wzk4

Nature of [CMB+Baryons] temperature fluctuations

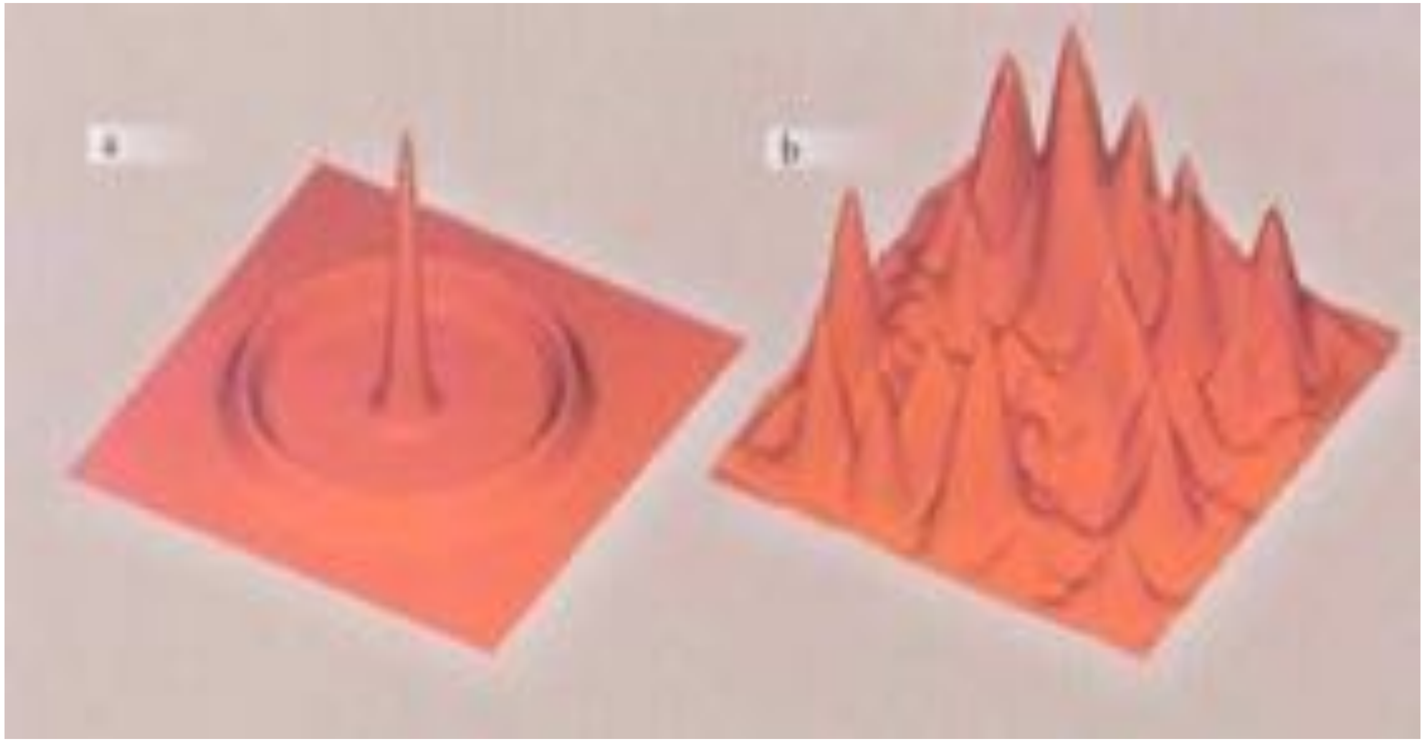
BAO originate because a tightly coupled matter-radiation fluid interacts with dark matter potential wells

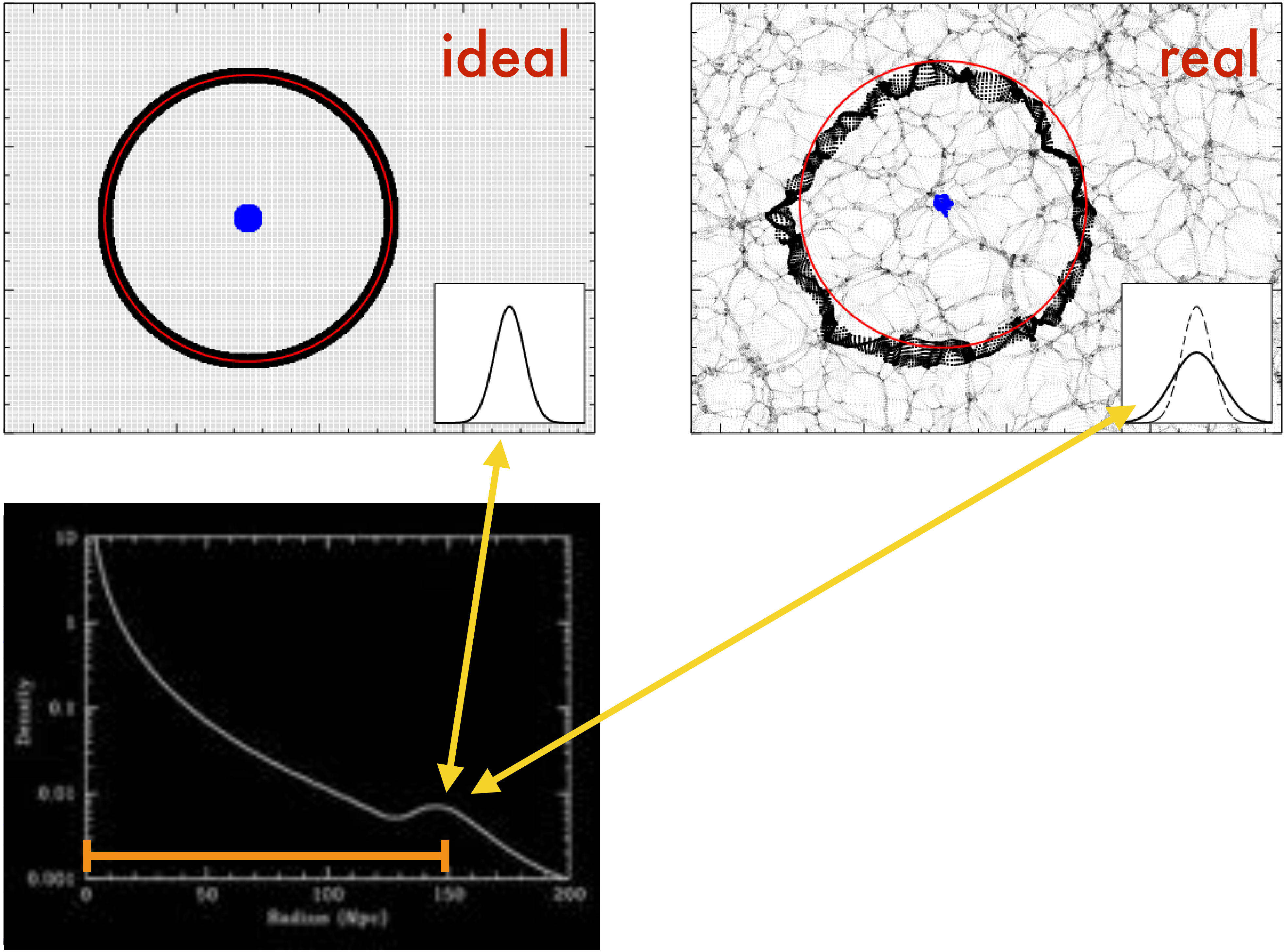


Denser is hotter: $\delta\rho_{\gamma b}(t,\mathbf{r}) \sim \delta T(t,\mathbf{r})$


Gravity
Pressure

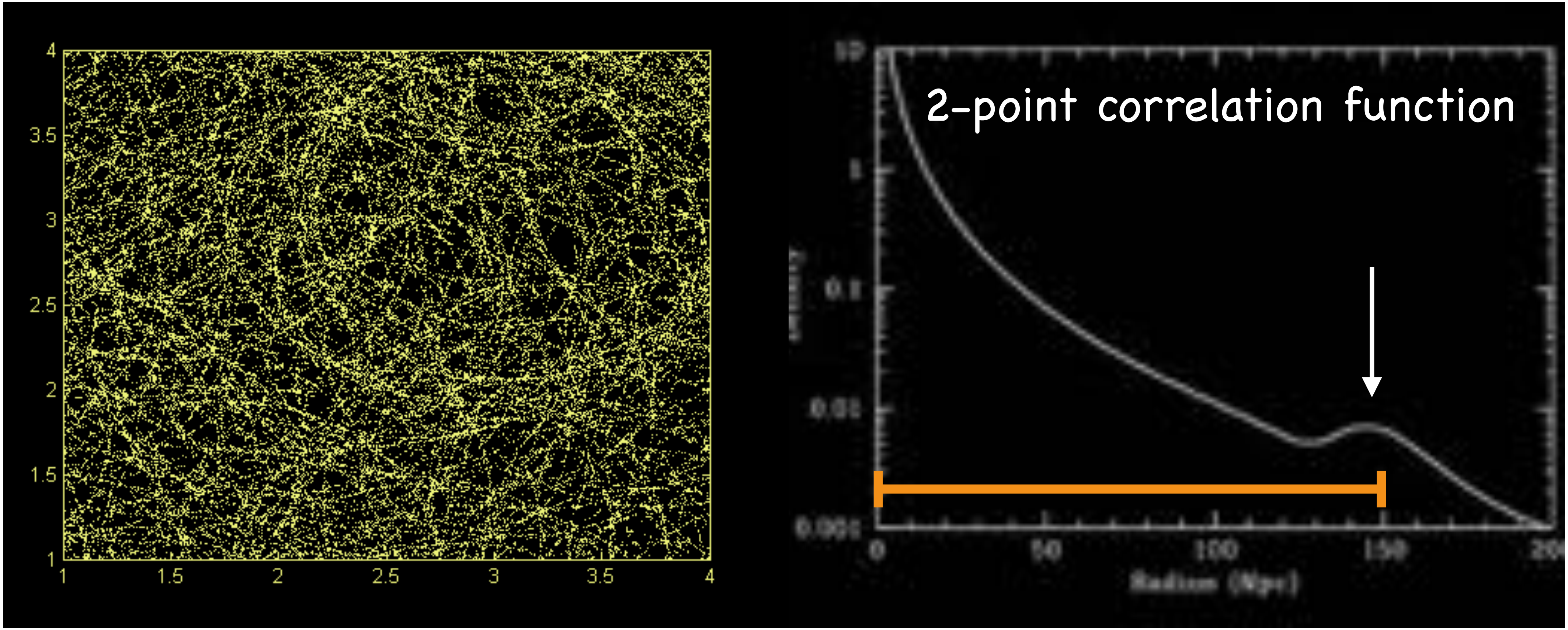
BAO: baryon acoustic oscillations



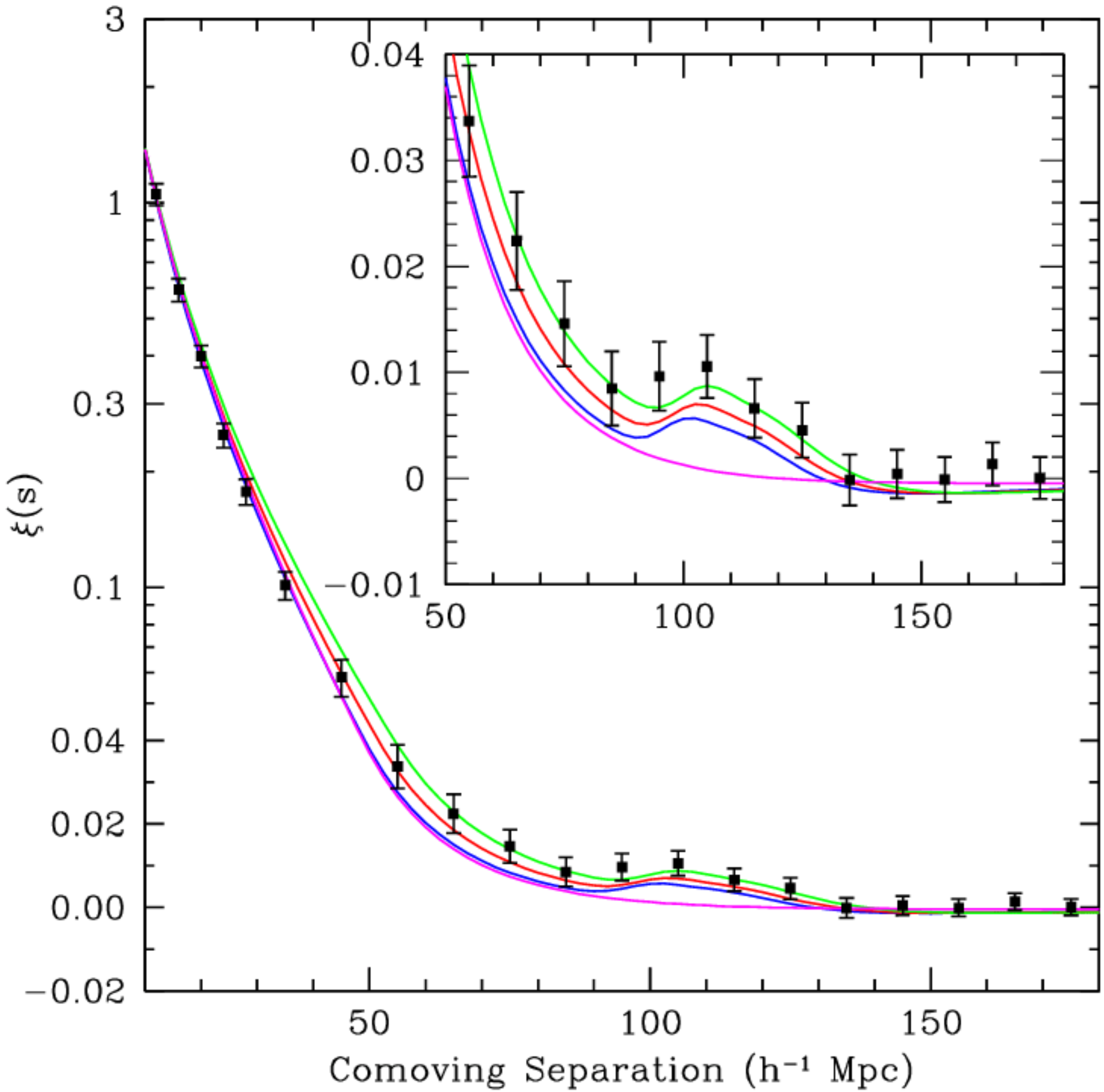

ideal
real
10
1
0.1
0.01
0.001
Density
0
50
100
150
200
Radius (Mpc)

BAO: standard cosmological ruler

– Small but detectable signal



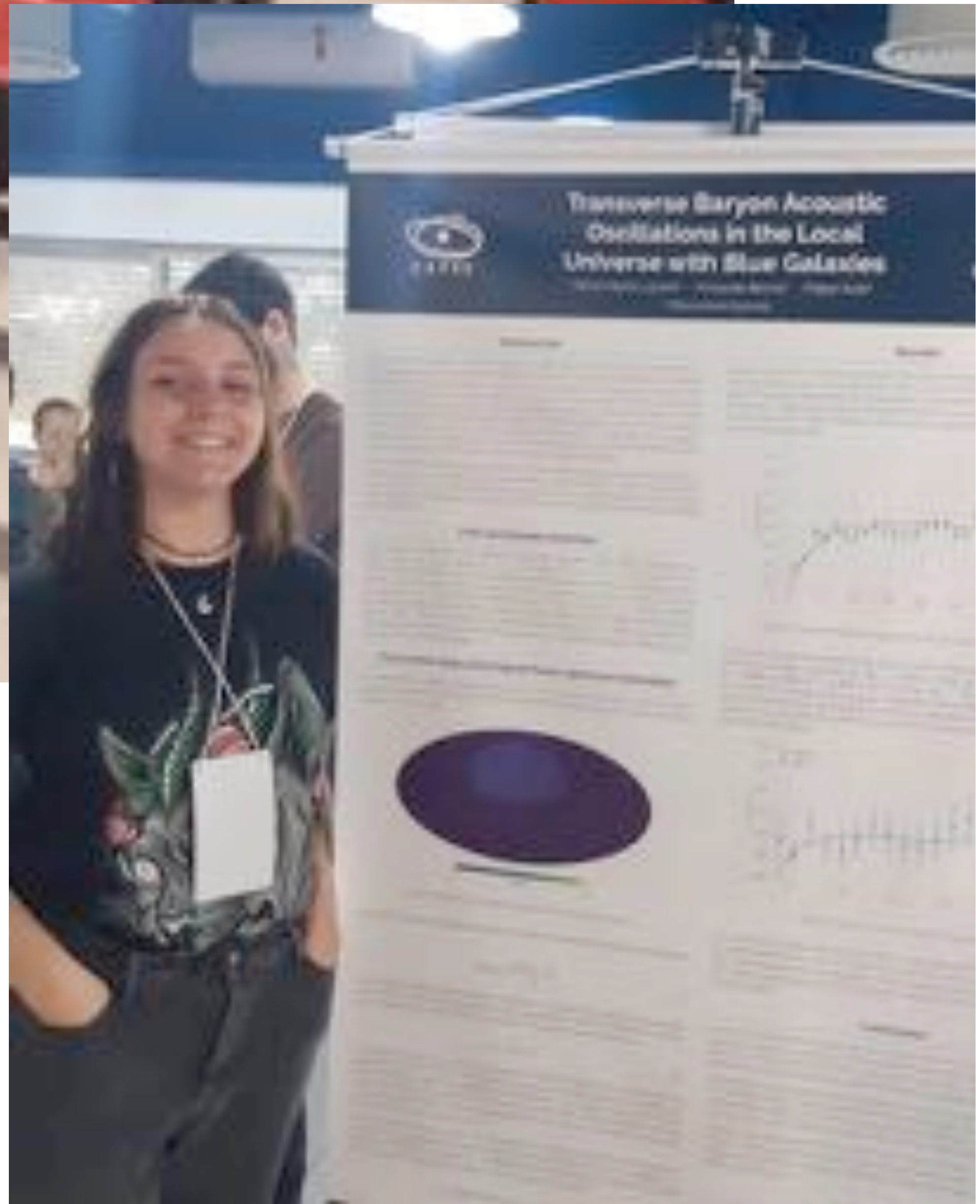
https://www.youtube.com/watch?v=jpXuYc-wzk4

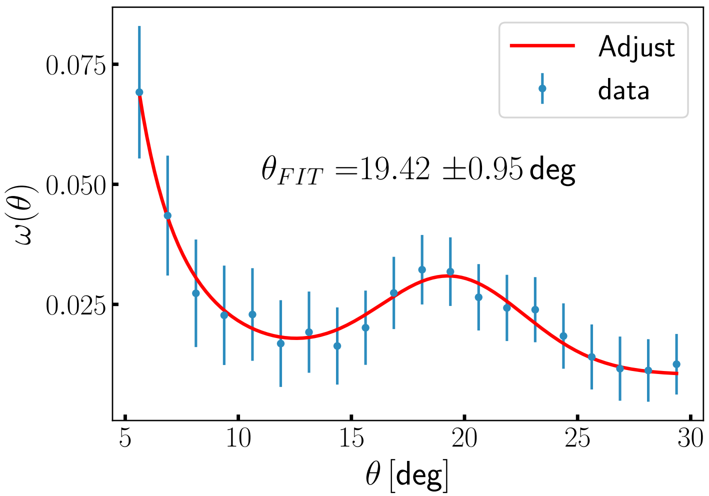


2-point correlation function

BAO 3D

Eisenstein et al. (SDSS), 2005





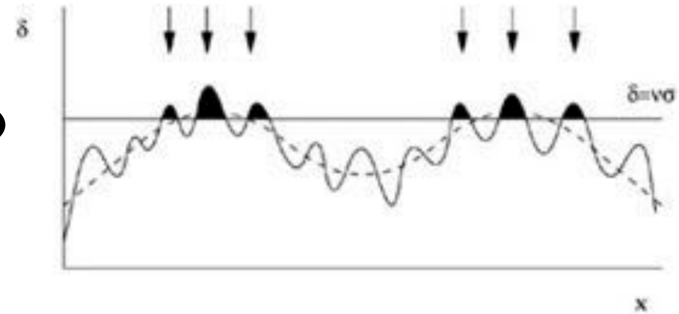
2PACF
w/blue
galaxies

Modern Observational Probes:

- Acceleration of the Universe ✓ 1998
- BAO: baryon acoustic oscillations ✓ 2005
- **Growth of cosmic structures** ✓ 2005-today
- Probes of stat. homogeneity & isotropy ✓ 2000-today
- CMB lensing, evidences of DM, etc.
  ✓ 2010-today ✓ 2000-today

Spacetime density fluctuations:

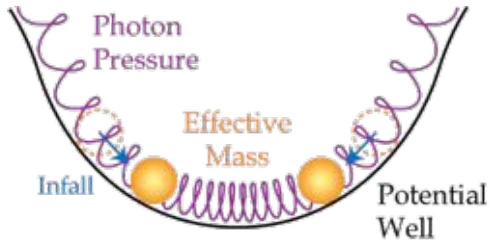
$$\delta\Phi \Longrightarrow \delta T_{\mu\nu} \Longrightarrow \delta g_{\mu\nu} \Longrightarrow \delta\Phi$$

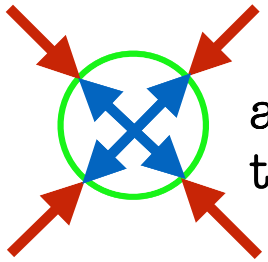


⇨ Perturbed Einstein eqs.: Continuity, Euler, Laplace

Structures formation: evolution of the perturbations (gravitational instability)

$$\ddot{\delta}_k + 2\frac{\dot{a}}{a}\dot{\delta}_k + \left(\underbrace{\frac{c_s^2 k^2}{a^2}}_{\text{pressure repulsion}} - \underbrace{4\pi G\bar{\rho}}_{\text{gravitational attraction}}\right)\delta_k = 0$$

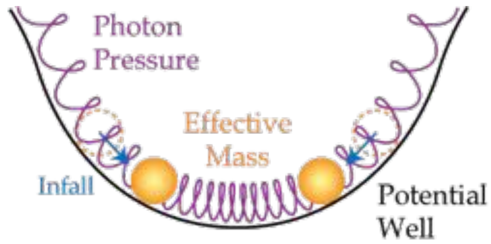




action of
two effects

Structures formation: evolution of the perturbations (gravitational instability)

$$\ddot{\delta}_k + 2\frac{\dot{a}}{a}\dot{\delta}_k + \Big(\underbrace{\frac{c_s^2 k^2}{a^2}}_{\text{pressure repulsion}} - \underbrace{4\pi G\bar{\rho}}_{\text{gravitational attraction}}\Big)\,\delta_k = 0$$



MD: After matter-radiation decoupling, z < 1100, this eq. converts into

$$\ddot{\delta}_k + 2\frac{\dot{a}}{a}\dot{\delta}_k - 4\pi G\bar{\rho}\,\delta_k = 0$$

it has two solutions: δ^+, δ^-, the second one decreases!

$$\delta^+(t) = \delta_0\, t^{2/3} \propto a(t)$$

this solution form gravitational potential wells that are the seeds to form structures (by gravitational instability)!

$\delta_c,\ \delta_b,\ \delta_\gamma$

large scales

small scales

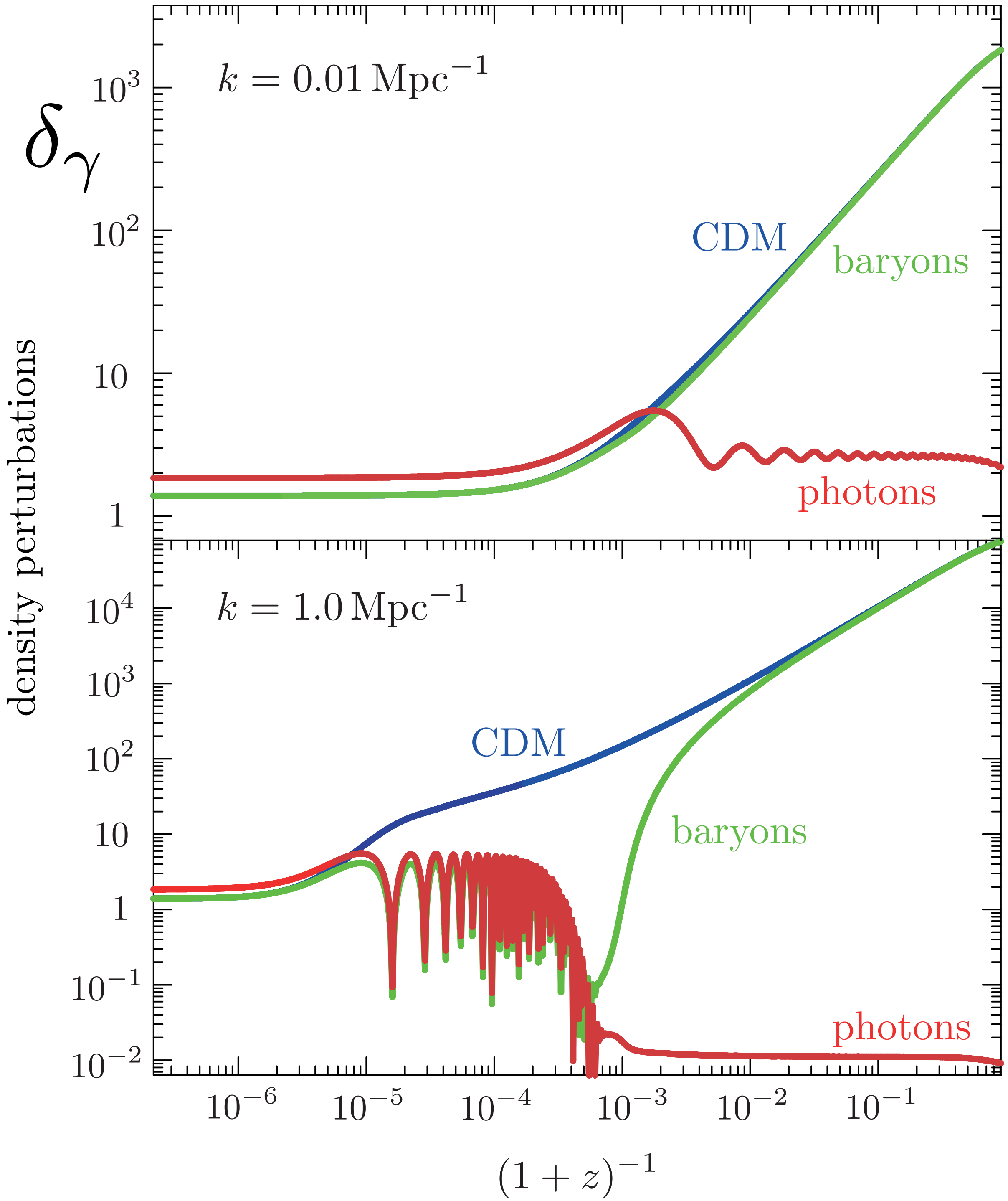
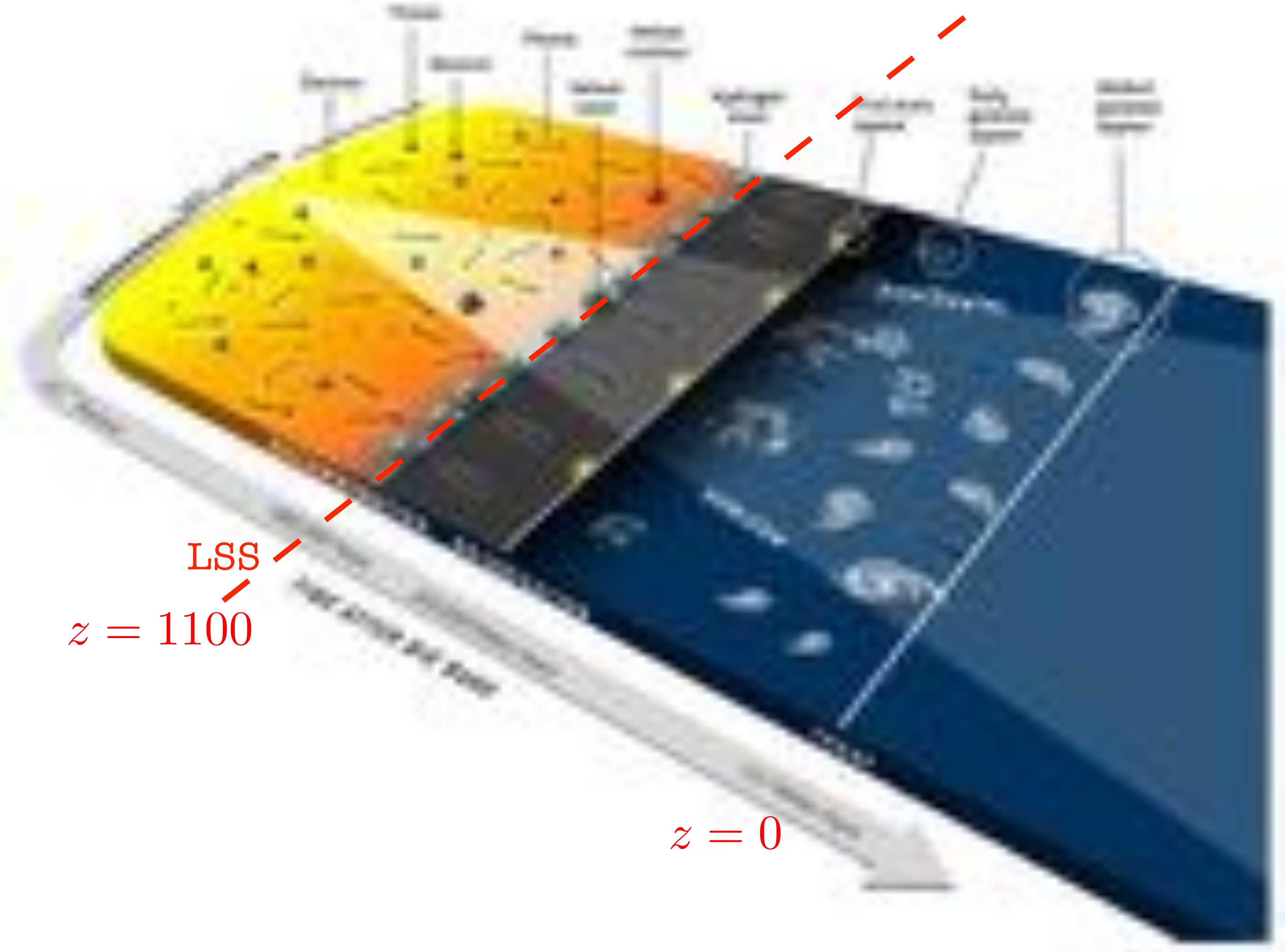


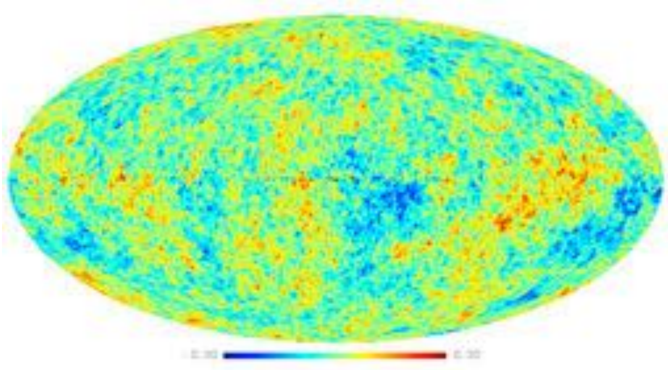
Figure 5.5: *Evolution of photons, baryons and dark matter.*


LSS
$z = 1100$
$z = 0$

density contrast:

$$\delta_{LSS} = ? \quad \rightarrow \quad \delta_{b/LSS} = ? \qquad \delta_{cdm/LSS} = ?$$

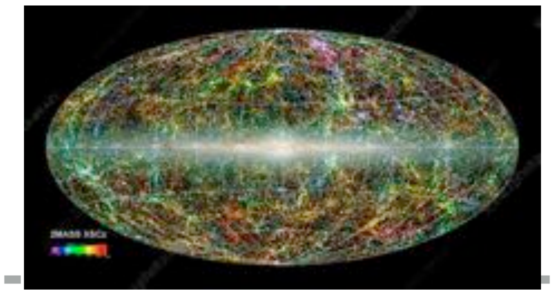
$$\boxed{\delta_{cdm/LSS} \sim a(z) = \frac{1}{1+z}}$$



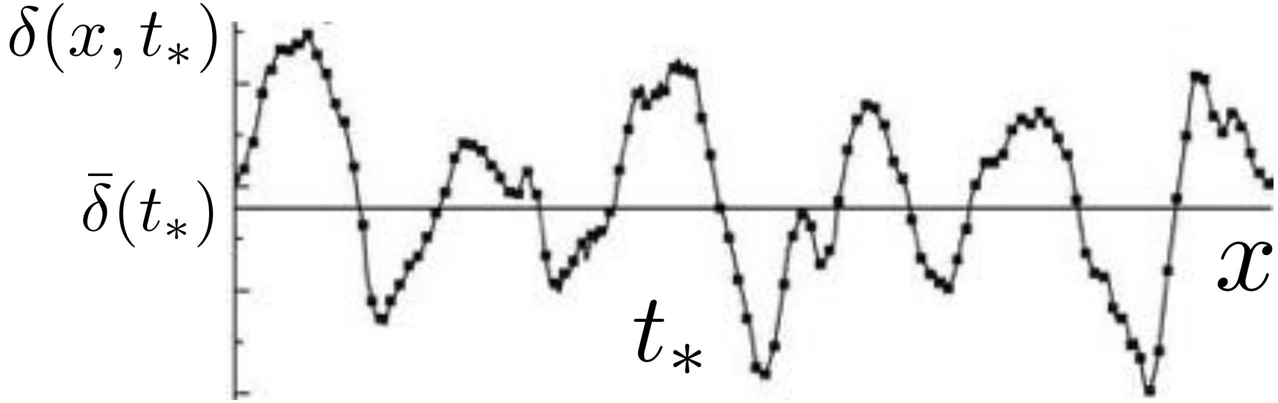
$$\delta_{b/LSS} \equiv \frac{\delta\rho_b}{\bar{\rho}_b} \sim \frac{\Delta T}{T_0} \sim 10^{-5}$$

$z = 1100$	$z = 0$
$a(z=1100) \simeq 10^{-3}$ $\delta_{b/LSS} \simeq 10^{-5}$ $\delta_{cdm/LSS} \simeq 10^{-2} - 10^{-3}$	$a(z=0) = 1$ $\delta_{b+cdm/today} \simeq 1$

$$\Rightarrow$$

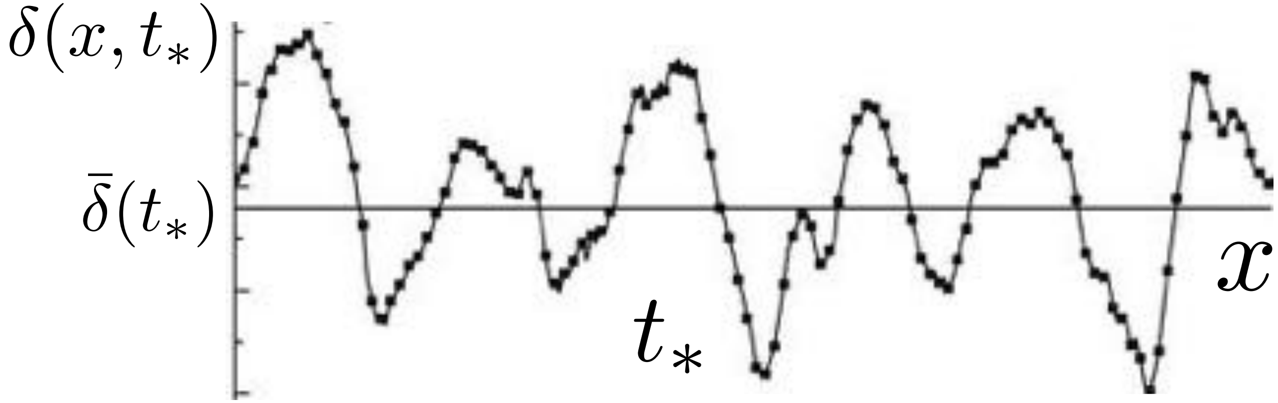


density contrast $\delta(x,t_*) \equiv \dfrac{\rho(x,t_*) - \bar{\rho}(t_*)}{\bar{\rho}(t_*)}$



$$\delta(x,t_0) = \sum_i c_i \lambda_i(x,t_0)$$

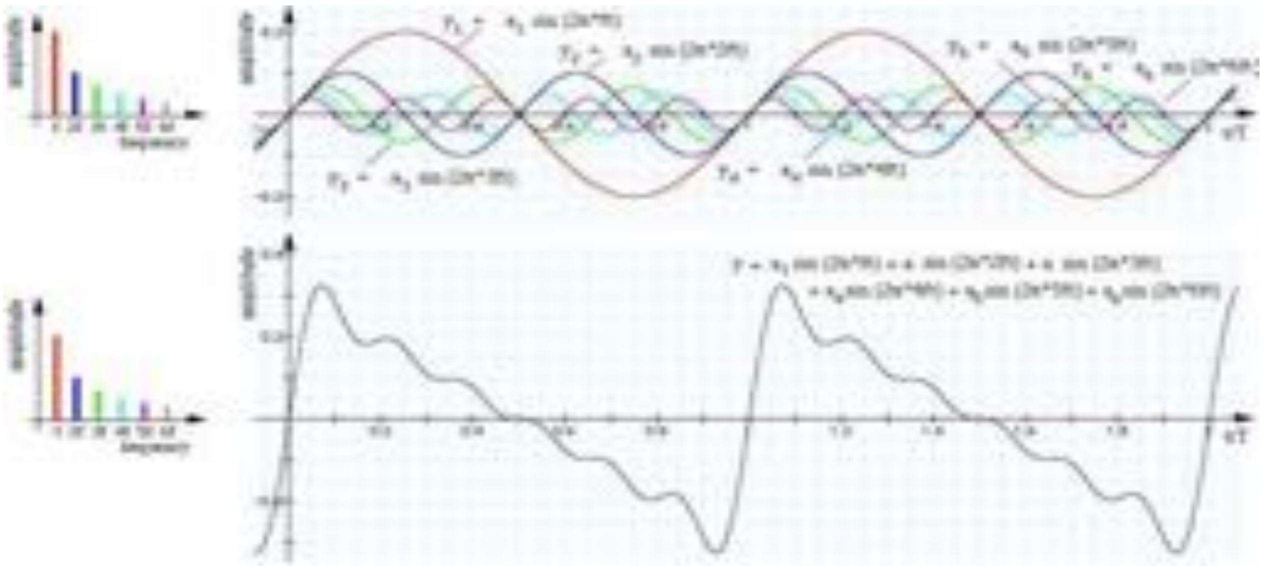
density contrast $\delta(x, t_*) \equiv \dfrac{\rho(x, t_*) - \bar{\rho}(t_*)}{\bar{\rho}(t_*)}$



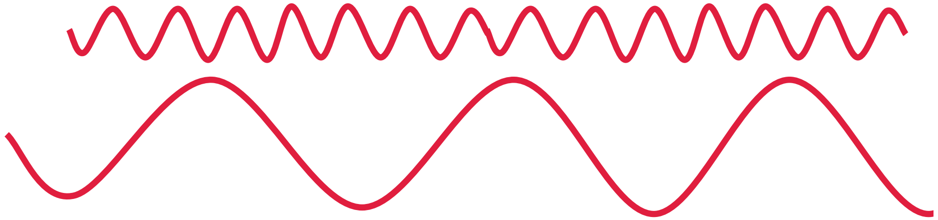
$$\delta(x, t_0) = \sum_i c_i \lambda_i(x, t_0)$$

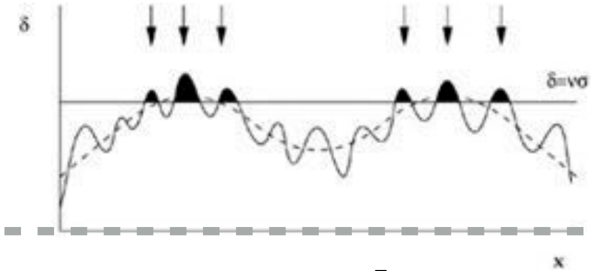
Harmonic analyses in 1-d

A vibrating string with fixed boundaries: it can vibrate in fundamental harmonics (FH): 1$^{\rm st}$harm., 2$^{\rm nd}$harm.,etc. Then, an arbitrary perturbation of the string can be represented as a superposition of the **FH**:



the amplitude for each frequency = spectrum of the perturbation



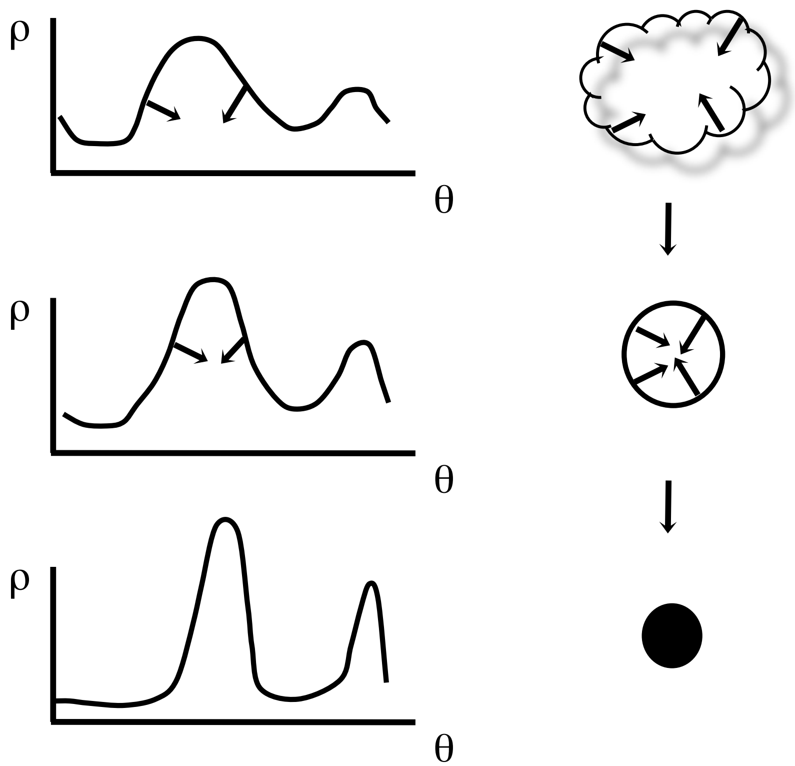


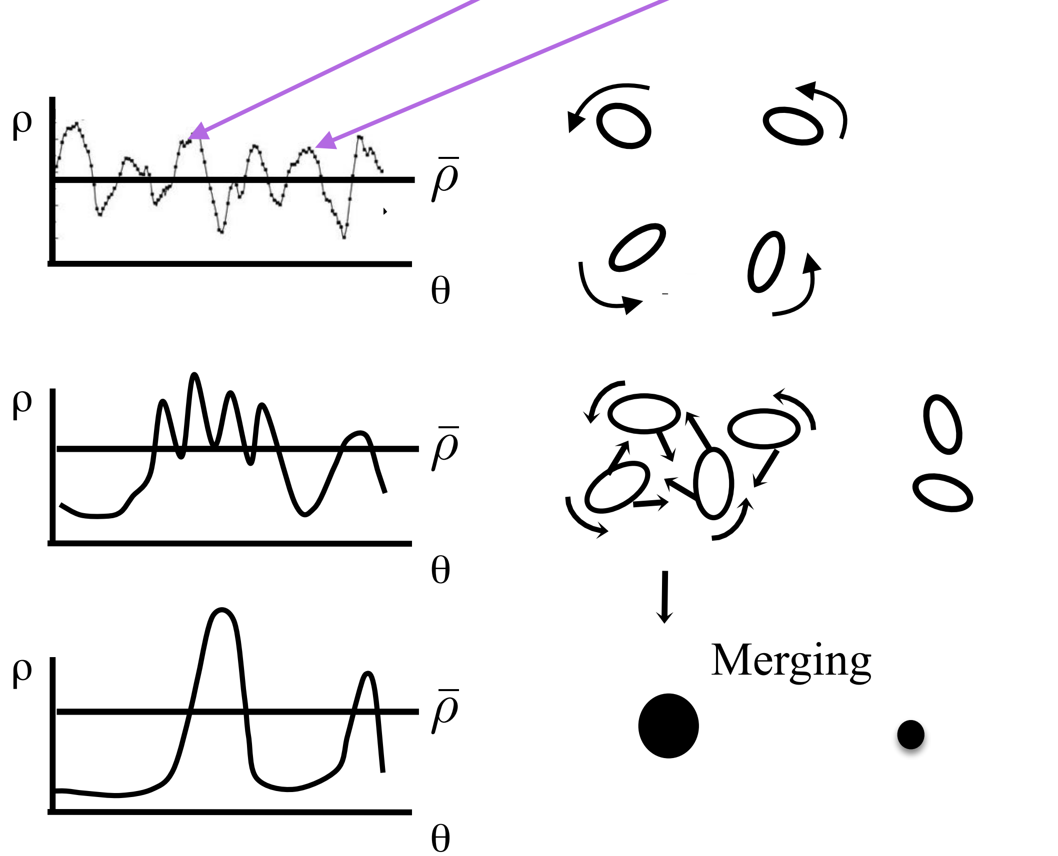
Two collapse scenarios:

Initial collapse (top down)

Hierarchical merging (bottom up)

gravitacional wells

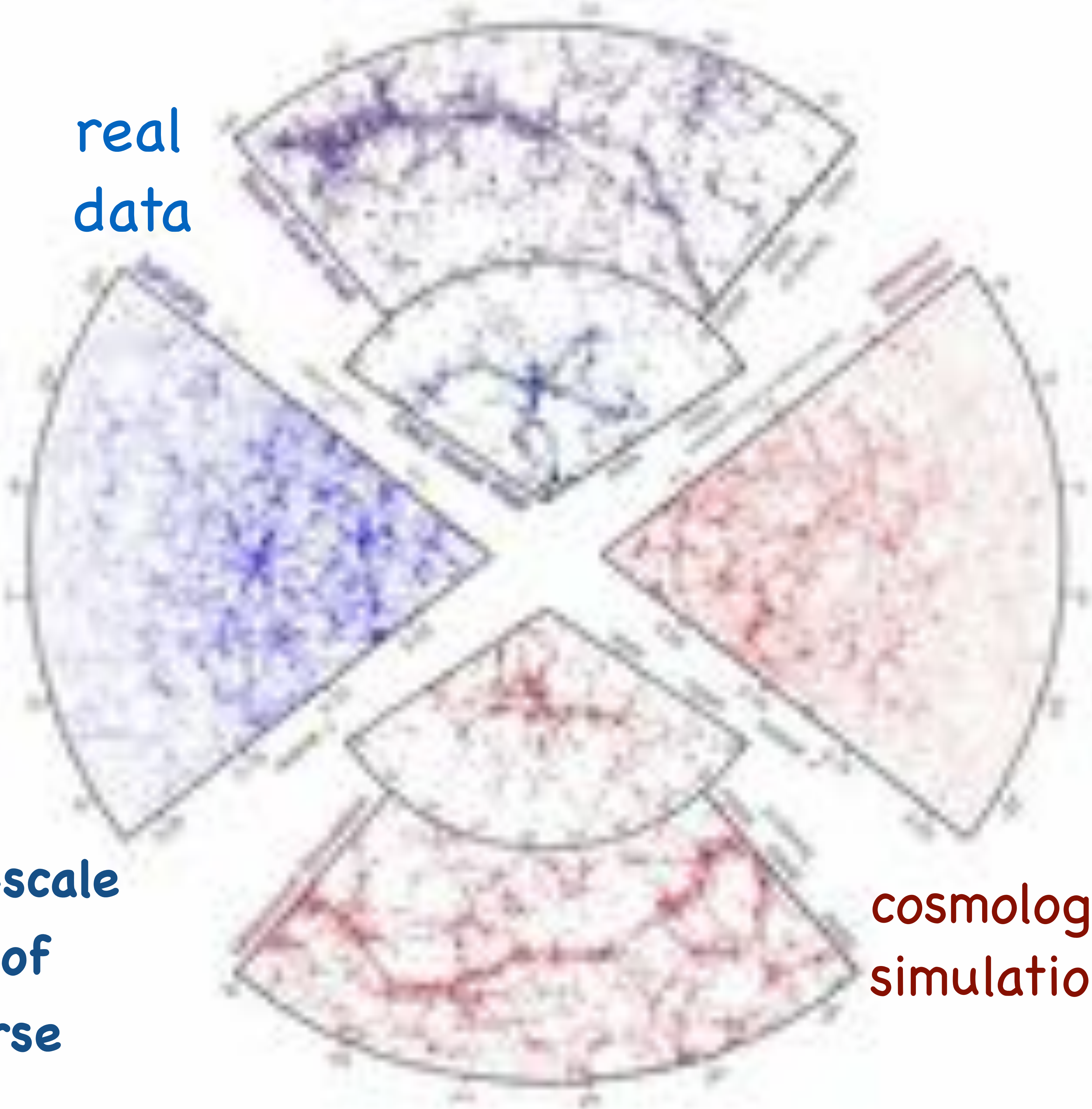




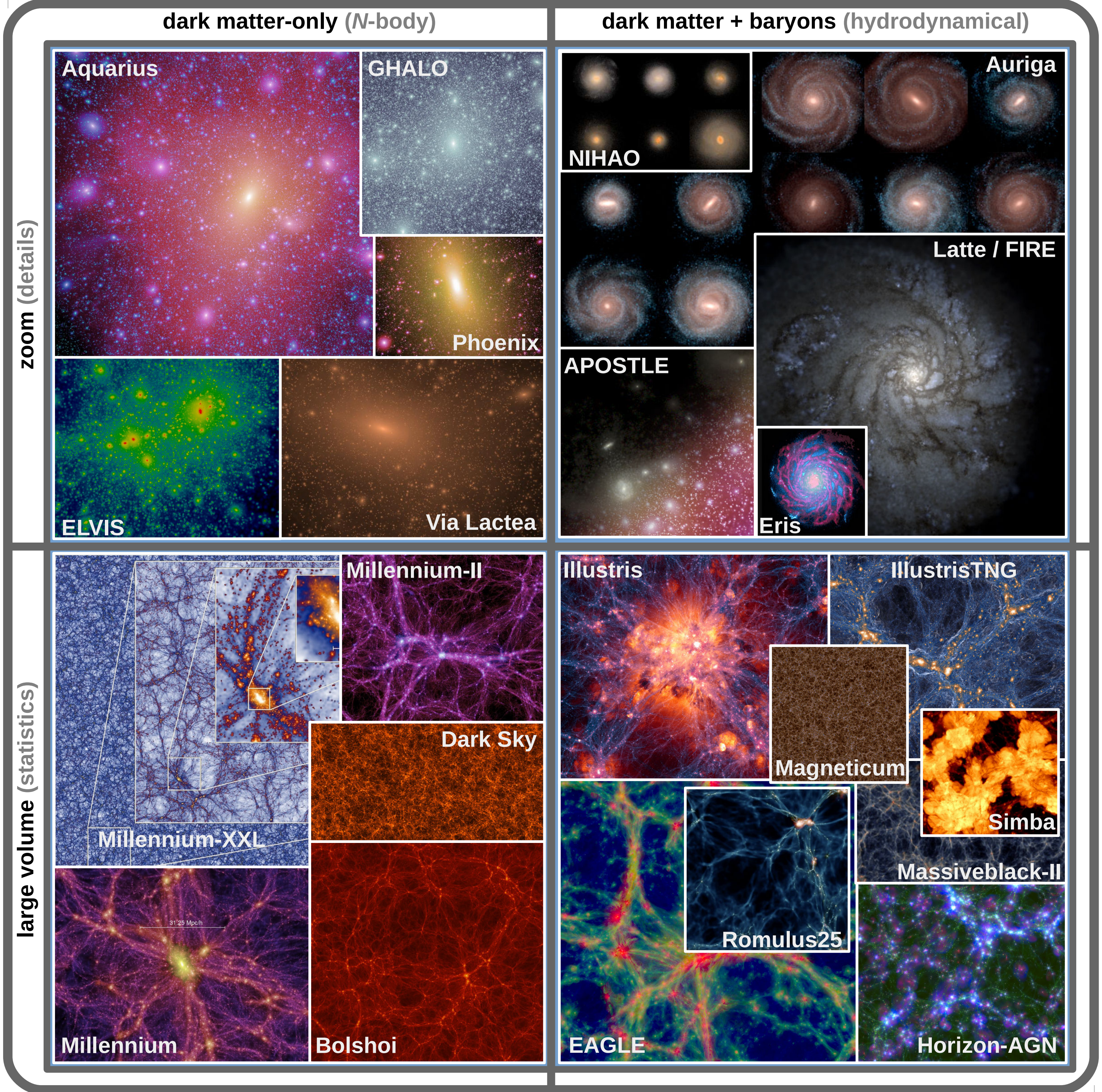
The Future: cosmological simulations

Simulating the large-scale structure of the Universe

real data



cosmological simulation

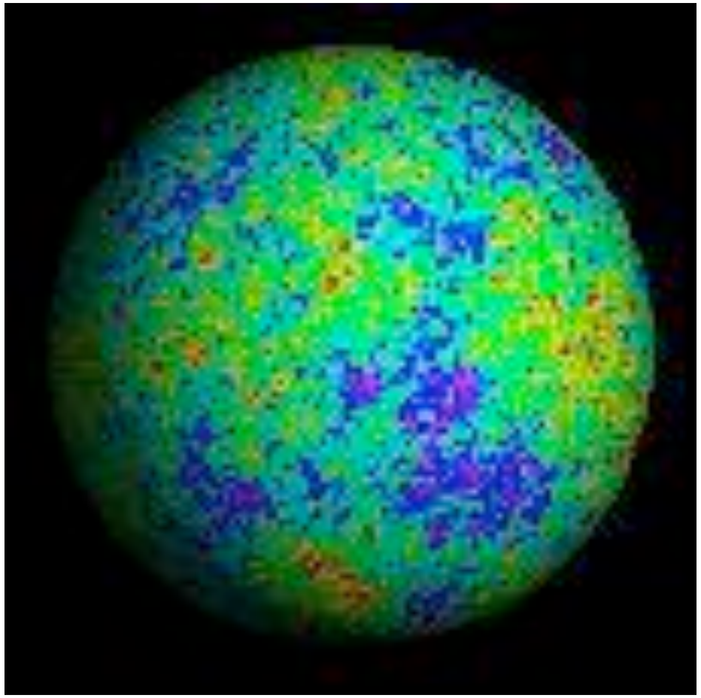

dark matter-only (N-body)
dark matter + baryons (hydrodynamical)
zoom (details)
large volume (statistics)
Aquarius
GHALO
Phoenix
ELVIS
Via Lactea
NIHAO
Auriga
Latte / FIRE
APOSTLE
Eris
Millennium-II
Dark Sky
Millennium-XXL
Millennium
Bolshoi
Illustris
IllustrisTNG
Magneticum
Simba
Massiveblack-II
Romulus25
EAGLE
Horizon-AGN

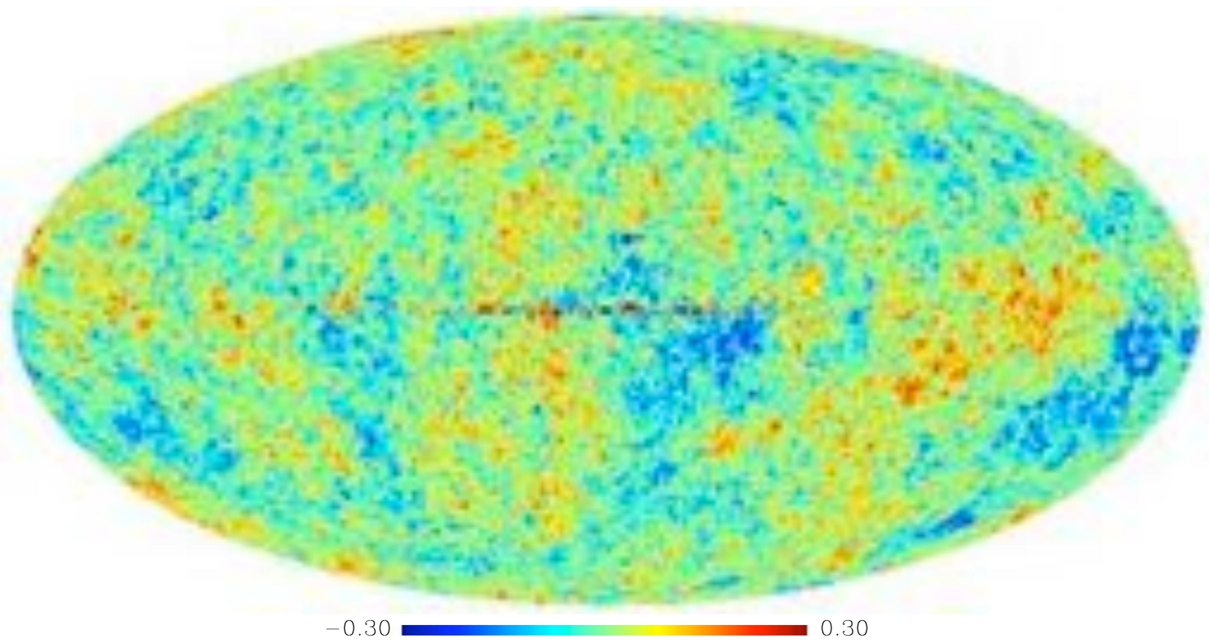
Modern Observational Probes:

- **CMB temperature fluctuations:**
  what is the shape of the Universe?

Do we live in an isotropic Universe?

CMB sphere?



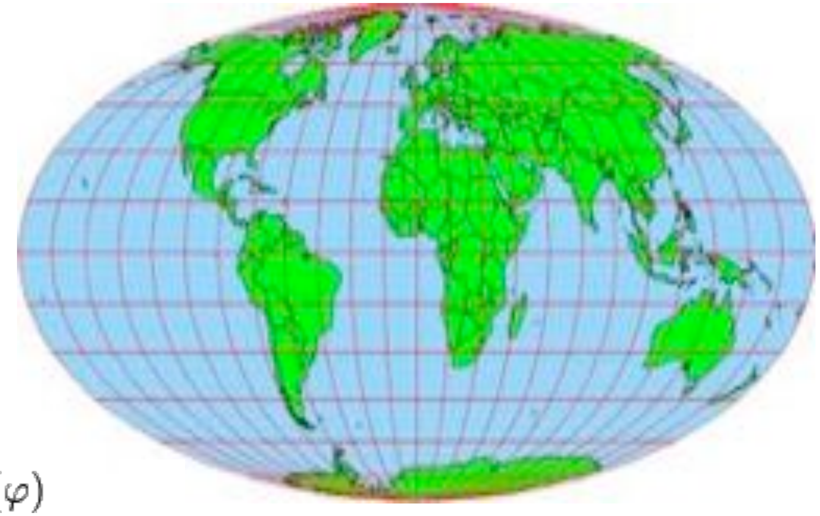


Esfera S^2 **Projeção Mollweide sobre um plano**

$$x = \frac{2\sqrt{2}}{\pi}\lambda \cos(\theta),$$

$$y = \sqrt{2}\sin(\theta),$$

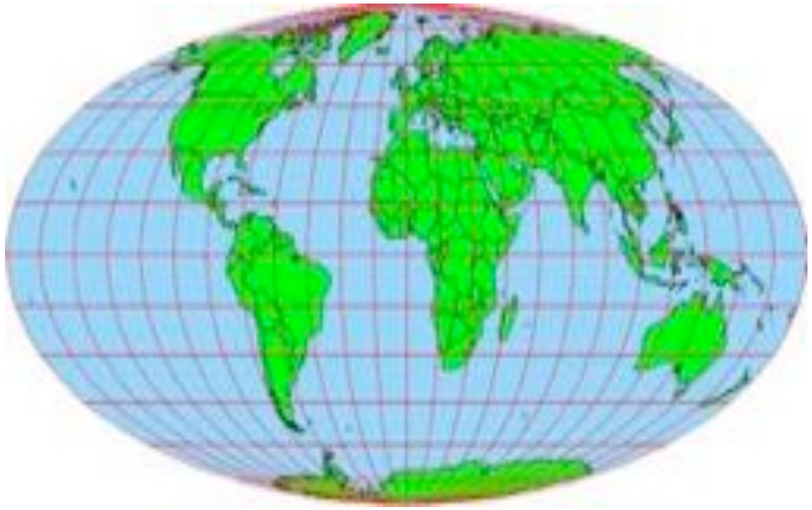
$$2\theta + \sin(2\theta) = \pi \sin(\varphi)$$

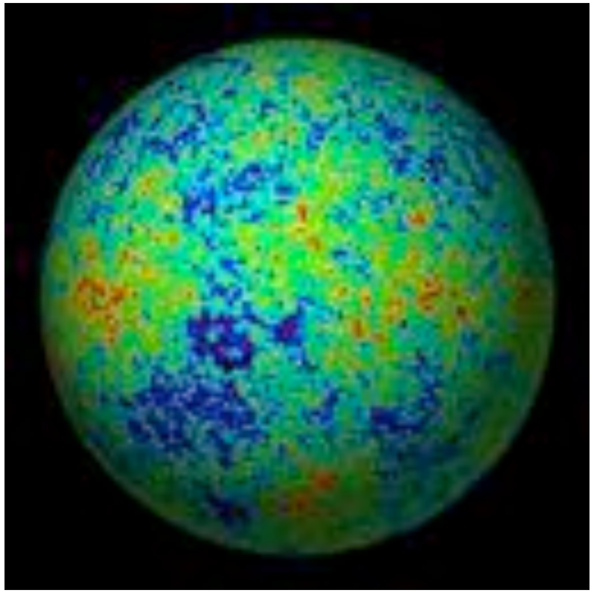


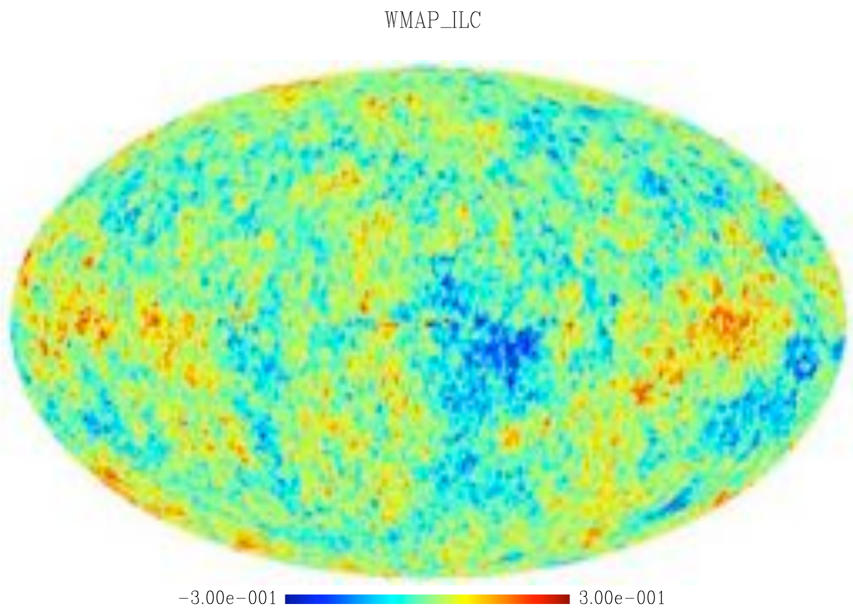
K. Mollweide (1774-1825)

Matemático

Esfera S^2 | Projeção Mollweide sobre um plano

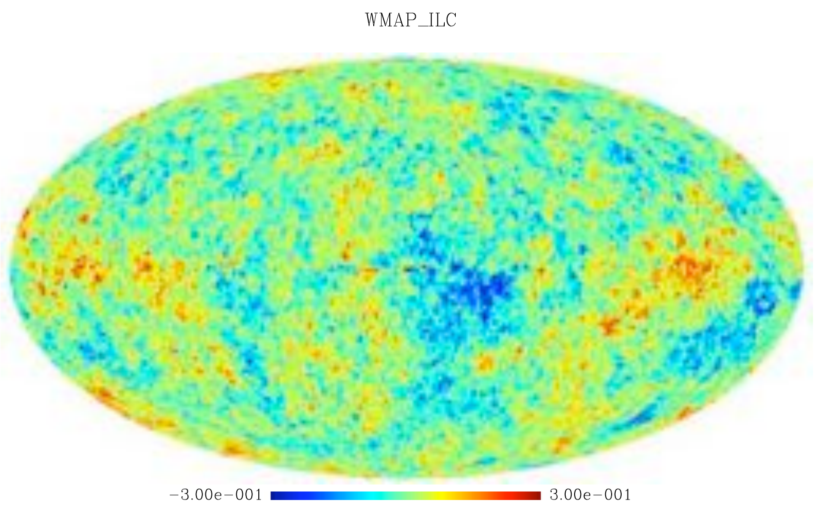


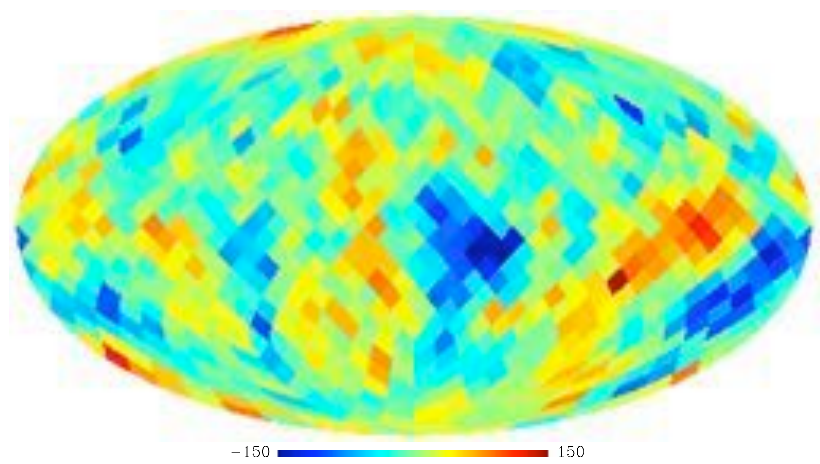




Mapas da Radiação Cósmica de Fundo

- a esfera celeste é dividida em N pixels da mesma área
- as flut. de temp. da RCF ΔT representam-se usando uma escala linear de cores: azul (= mín.), verde ($\simeq 0$), e vermelho (=máx.). Representamos: $\frac{\Delta T(\theta,\phi)}{T_{Planck}} = \Sigma_{\ell,\, m}\, a_{\ell\, m} Y_{\ell\, m}(\theta, \phi)$.
- os pixels são tão pequenos que os mapas parecem um contínuo de manchas coloridas, mas ... basta degradar o mapa para observar eles:

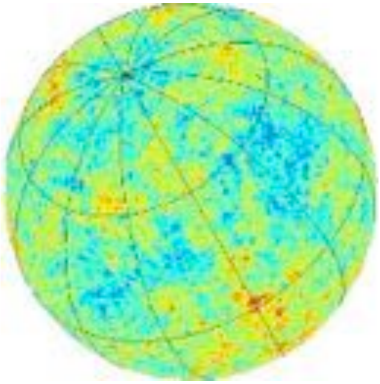




- a esfera celeste é dividida em N pixels, todos de igual área, seguindo o esquema de pixelização (HEALPIX)

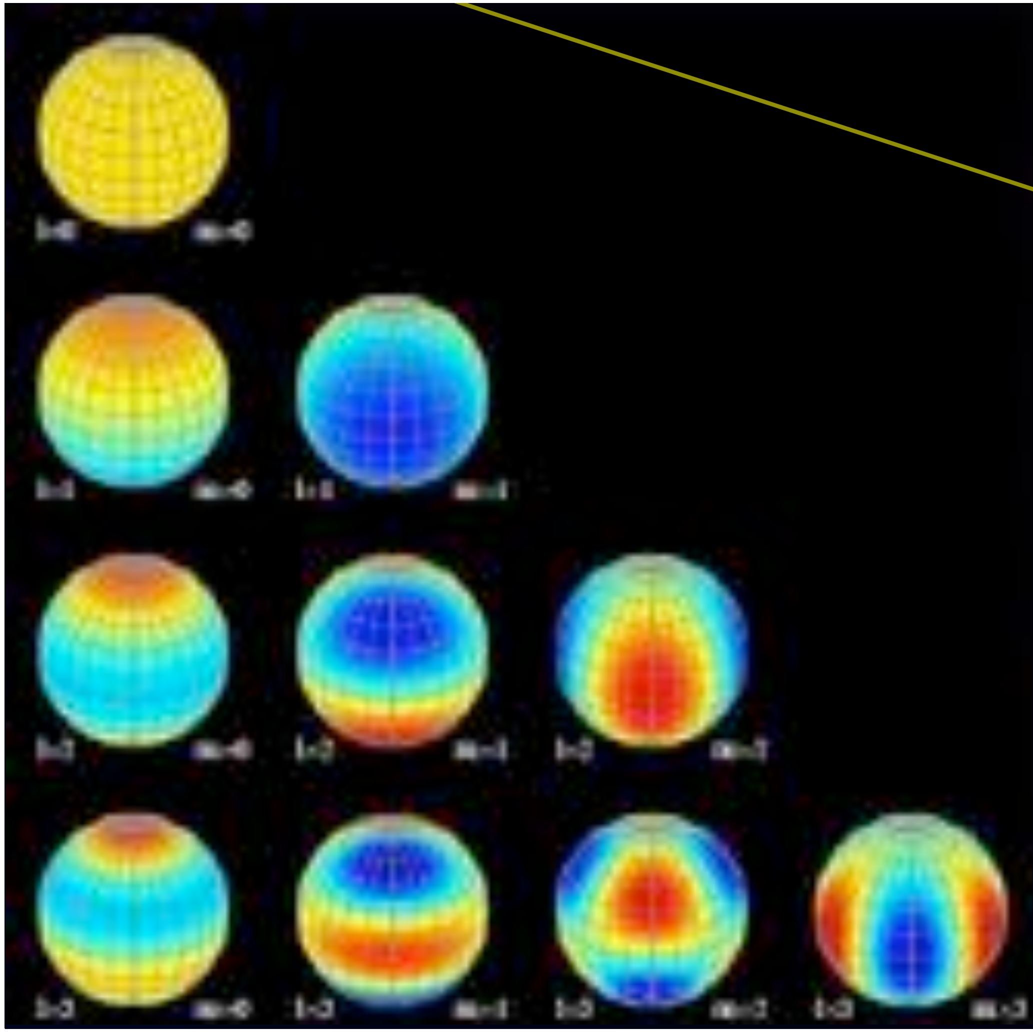
Harmonic analyses in 2-d

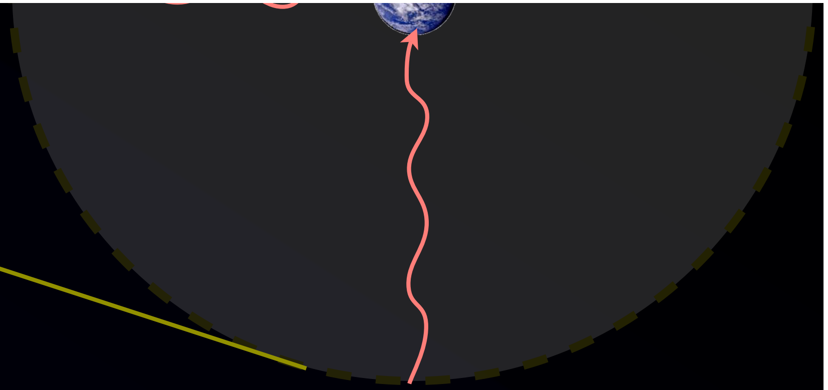
Analogously, on the spherical surface S^2 any function $\Delta T = \Delta T(\theta, \varphi)$ can be represented as a combination of the spherical harmonics $Y_{\ell\, m}$



$$= \frac{\Delta T(\theta, \phi)}{T_o} = \Sigma_{\ell,\, m}\, a_{\ell\, m} Y_{\ell\, m}(\theta, \phi)$$

where the coefficients $a_{\ell\, m}$ have the complete information about the spectrum perturbation ΔT, where the variable ℓ (also called multipole order) is associated to the angular scale θ ($\sim \pi/\ell$) and the variable m is associated to the angular scale φ.

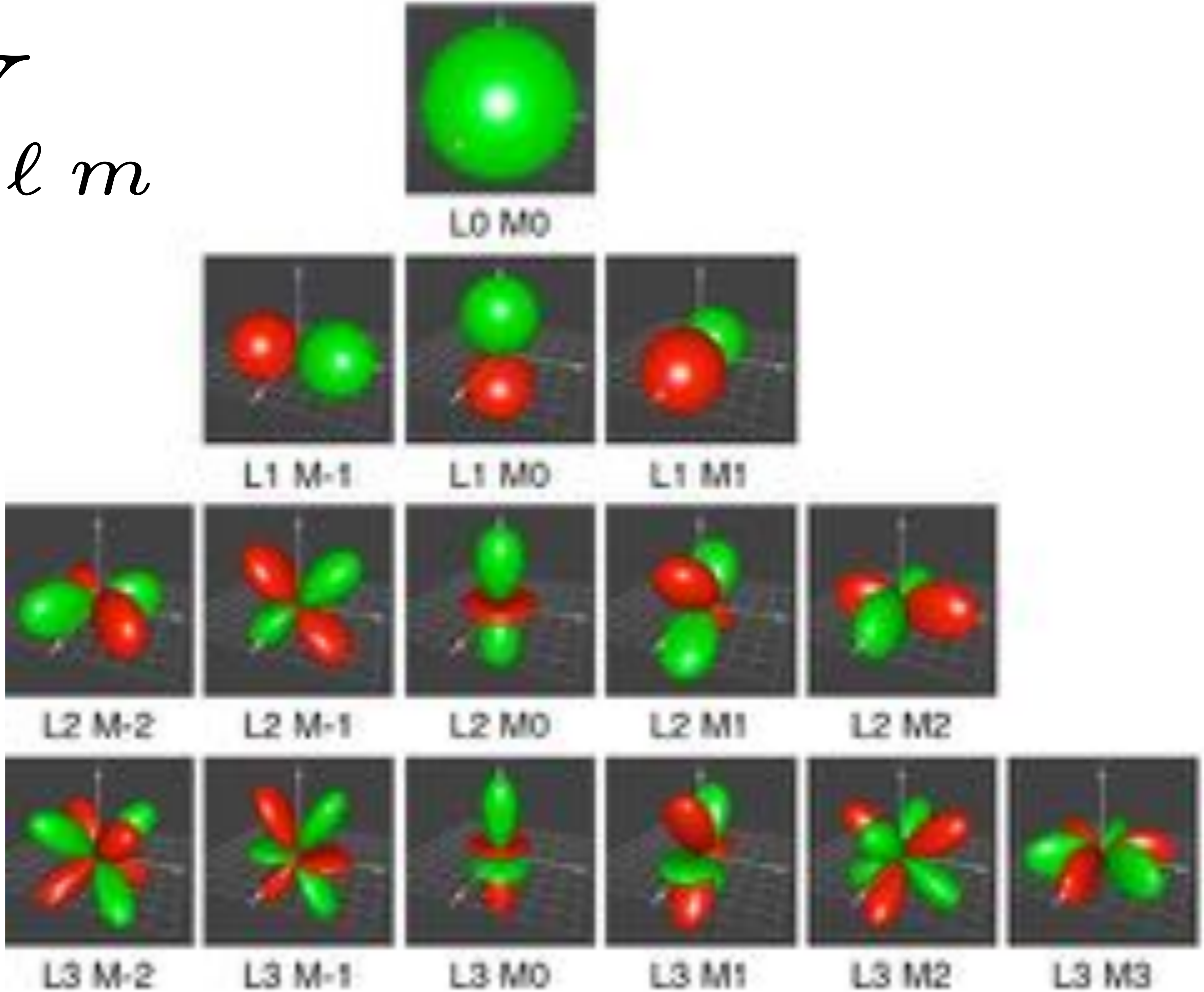




$$\delta T(\theta,\varphi) = \sum_{\ell,m} a_{\ell m} Y_\ell^m(\theta,\varphi)$$

$$C_\ell = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell} \left|a_{\ell m}\right|^2$$

$$Y_{\ell\, m}$$

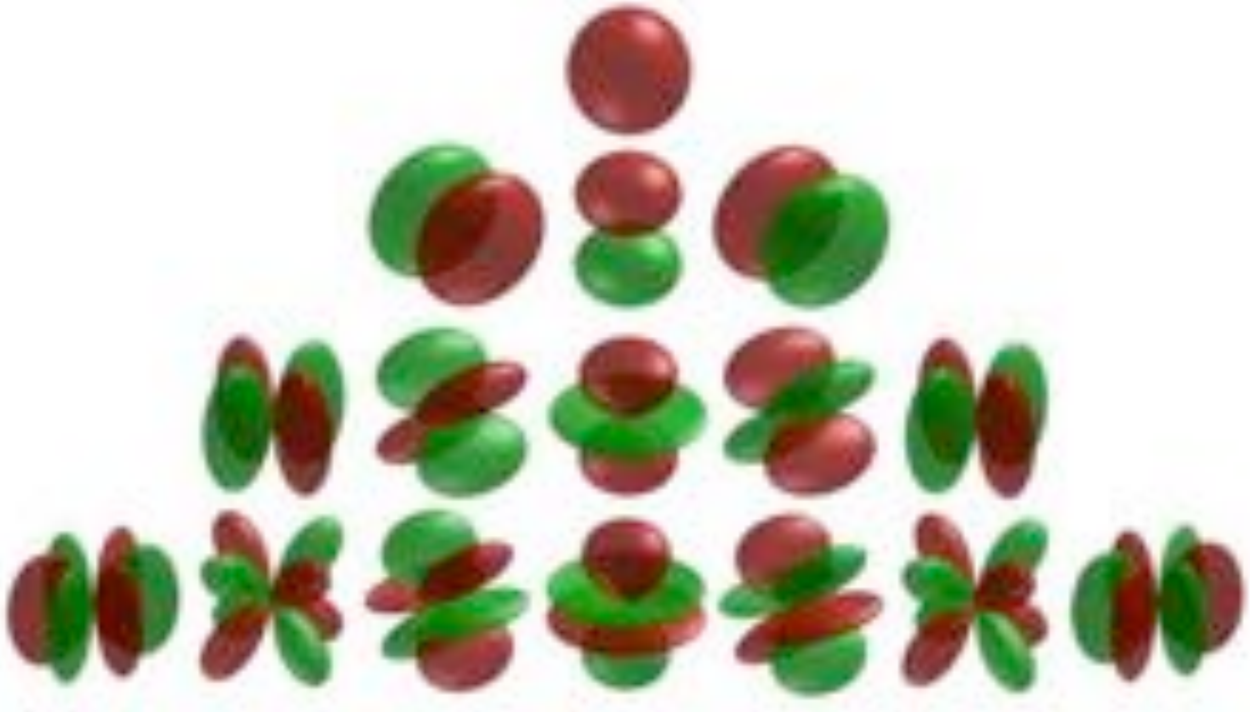


L0 M0
L1 M-1
L1 M0
L1 M1
L2 M-2
L2 M-1
L2 M0
L2 M1
L2 M2
L3 M-2
L3 M-1
L3 M0
L3 M1
L3 M2
L3 M3

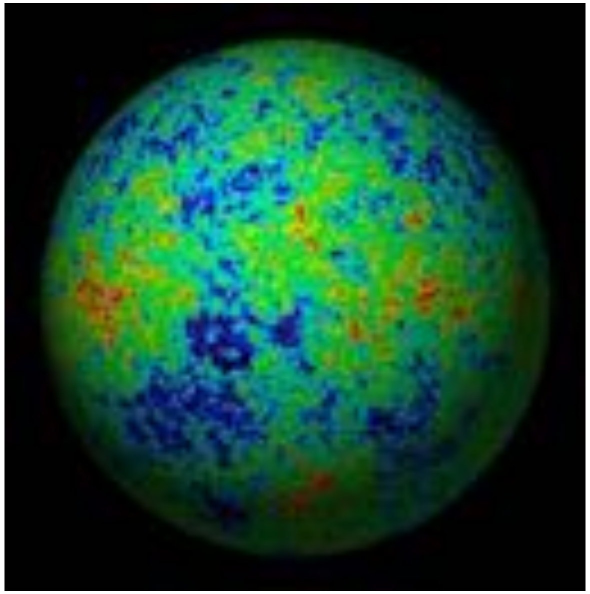
P.-S. Laplace

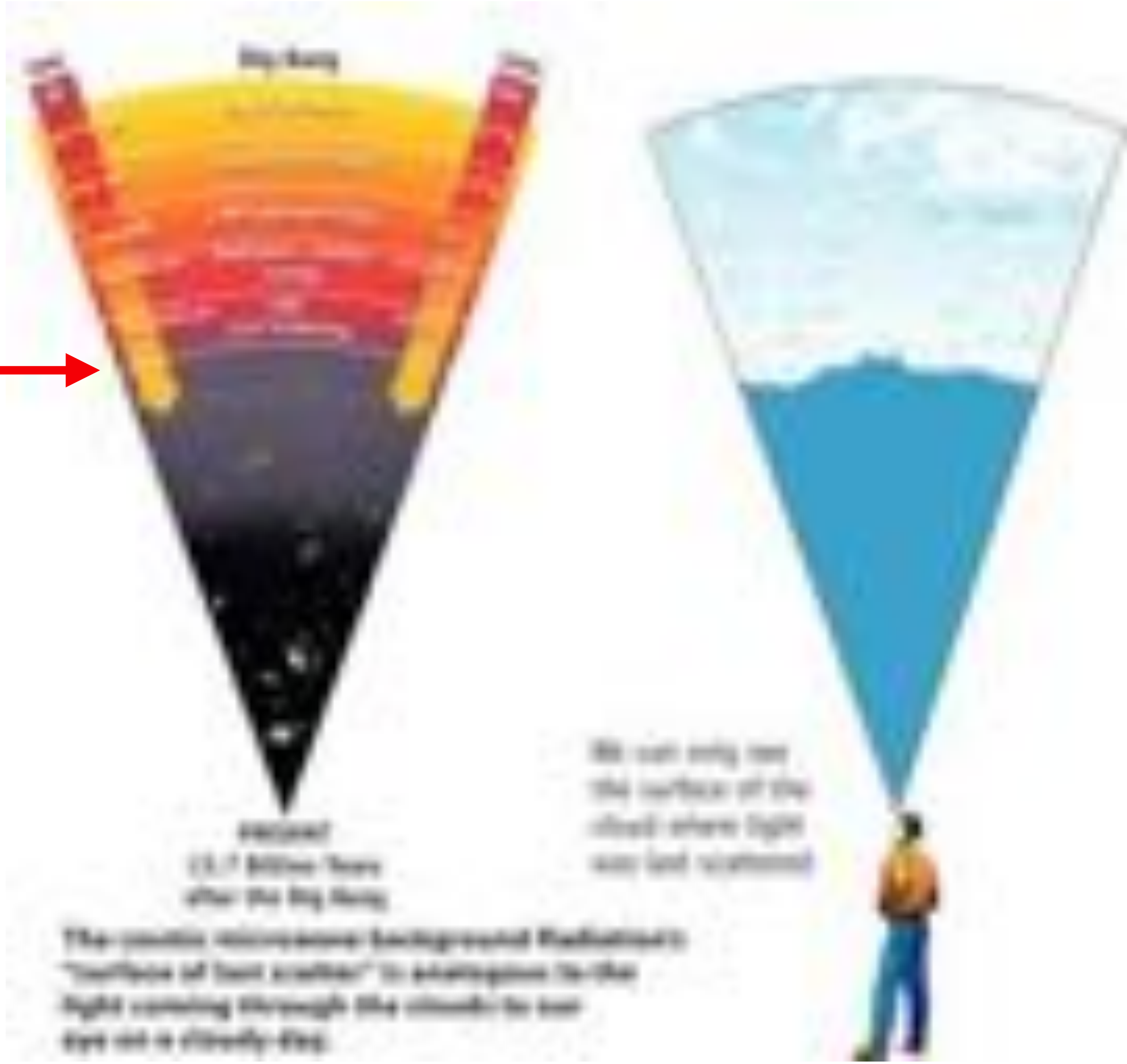
$$\nabla^2 V = \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} = 0.$$

$$\nabla^2 f = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \frac{\partial f}{\partial r}\right) + \frac{1}{r^2 \sin\theta}\frac{\partial}{\partial \theta}\left(\sin\theta \frac{\partial f}{\partial \theta}\right) + \frac{1}{r^2 \sin^2\theta}\frac{\partial^2 f}{\partial \varphi^2} = 0.$$

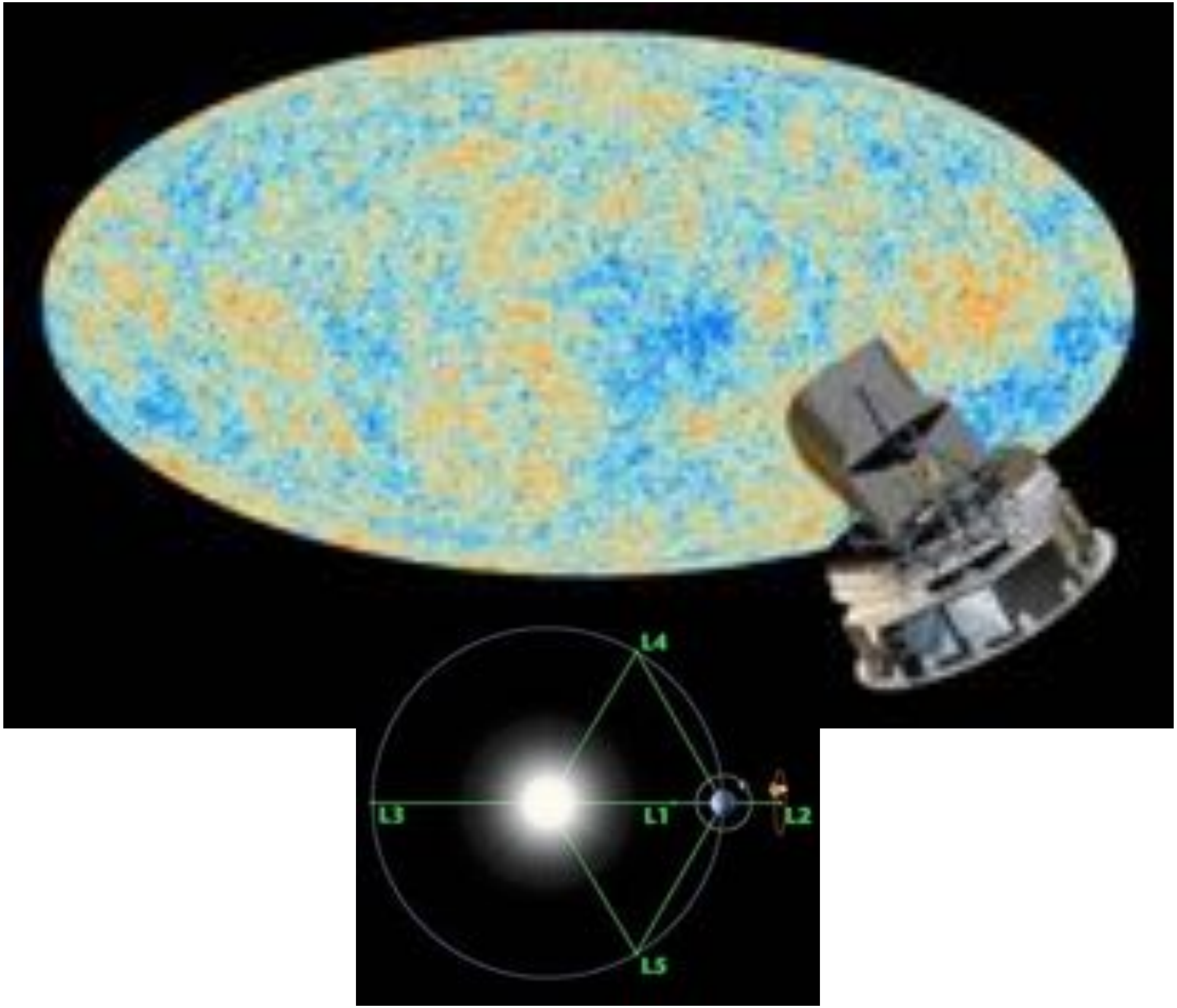


$$Y_\ell^m(\theta, \varphi) = N\, e^{im\varphi}\, P_\ell^m(\cos\theta)$$

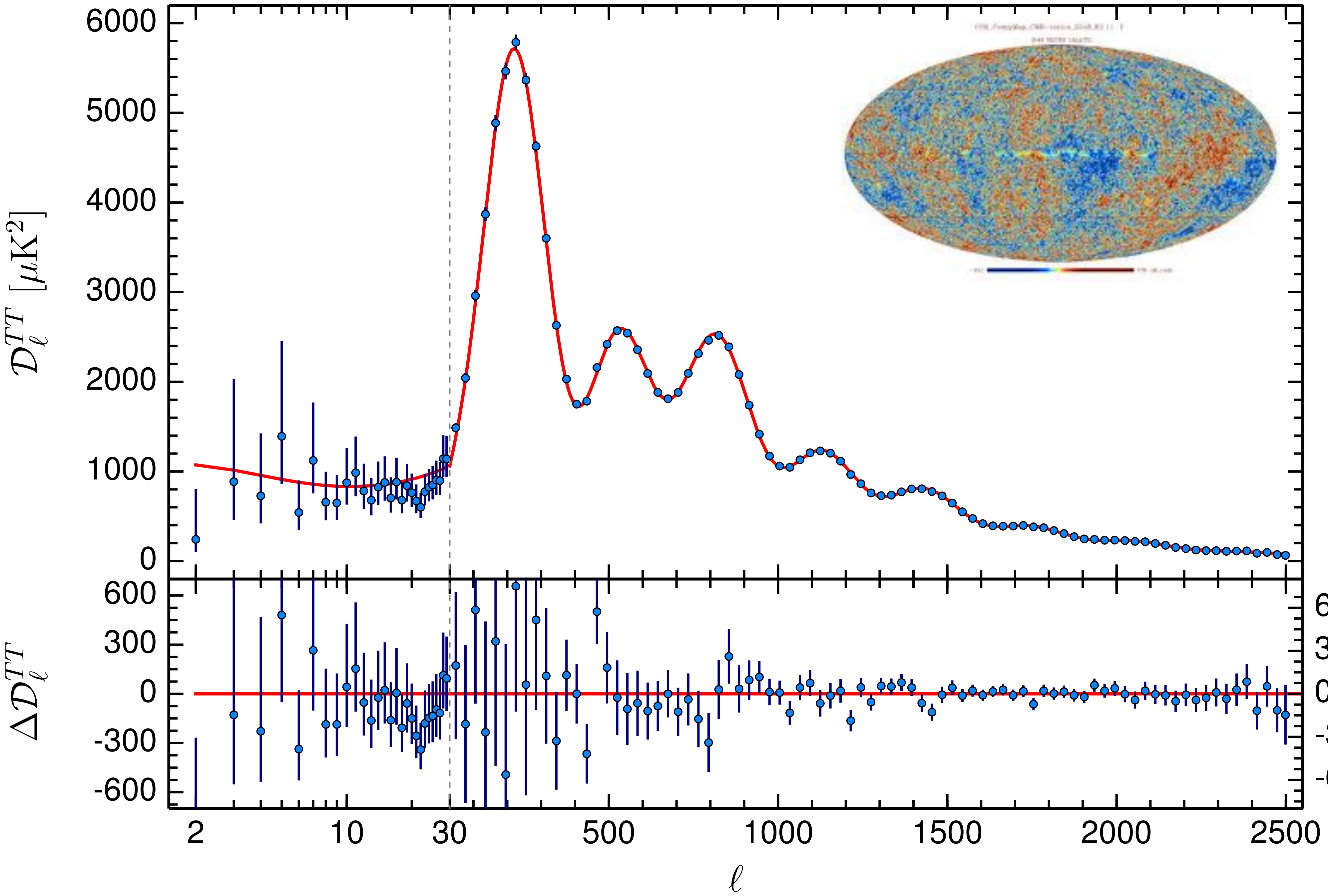




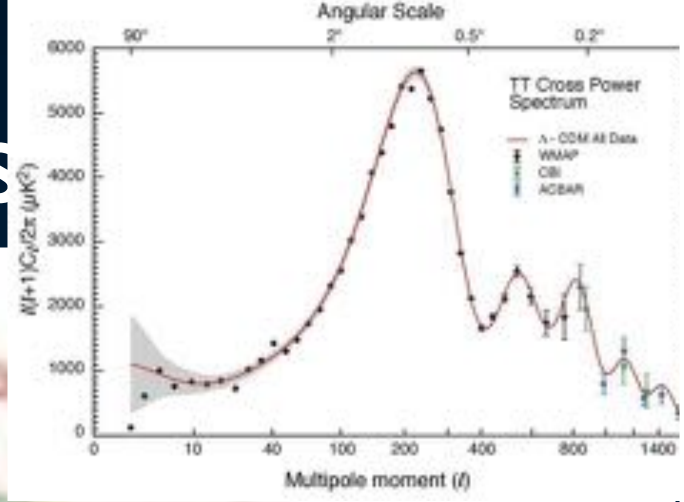
2018 Planck CMB data

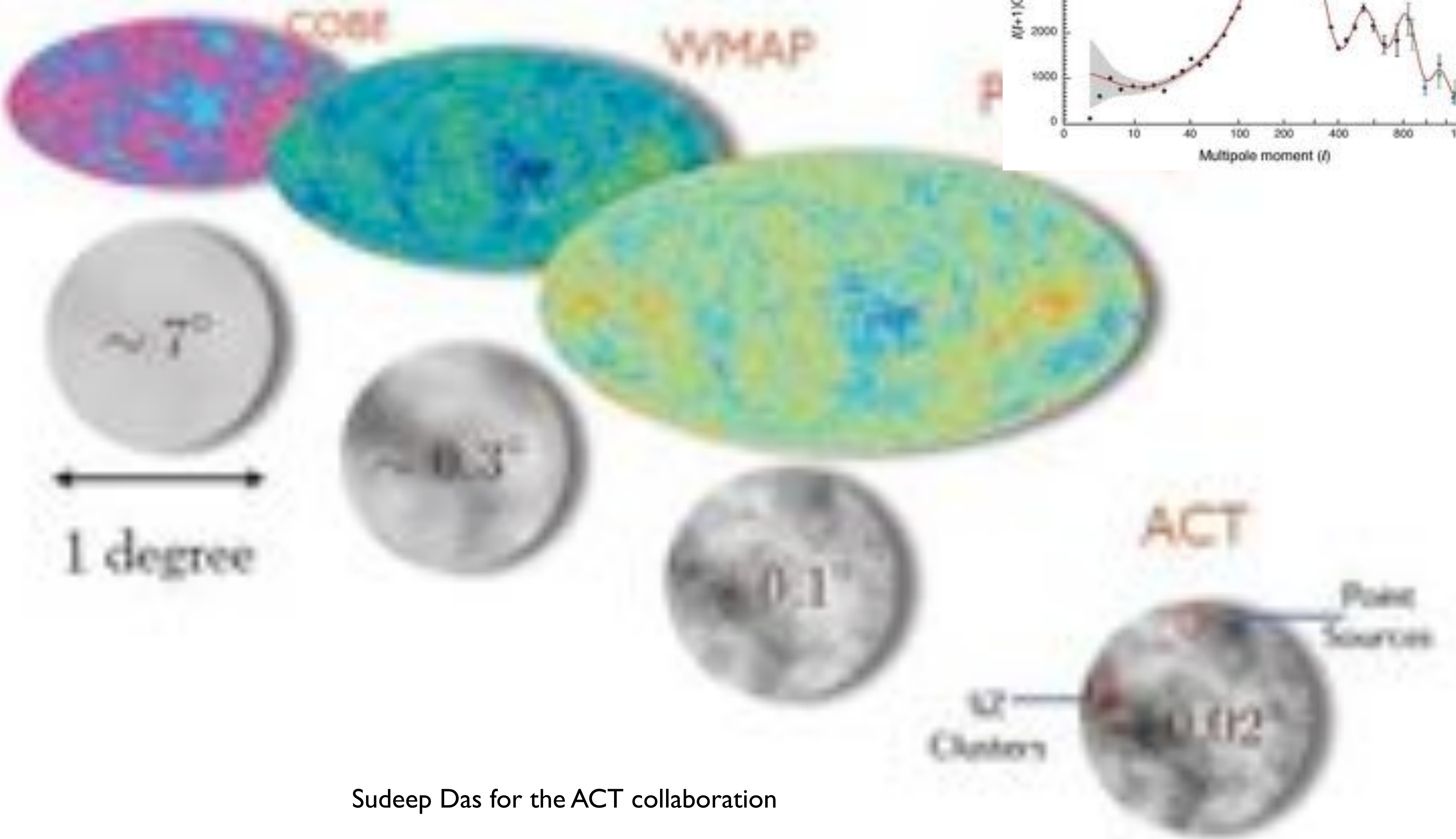


CMB temperature fluctuations: Angular Power Spectrum

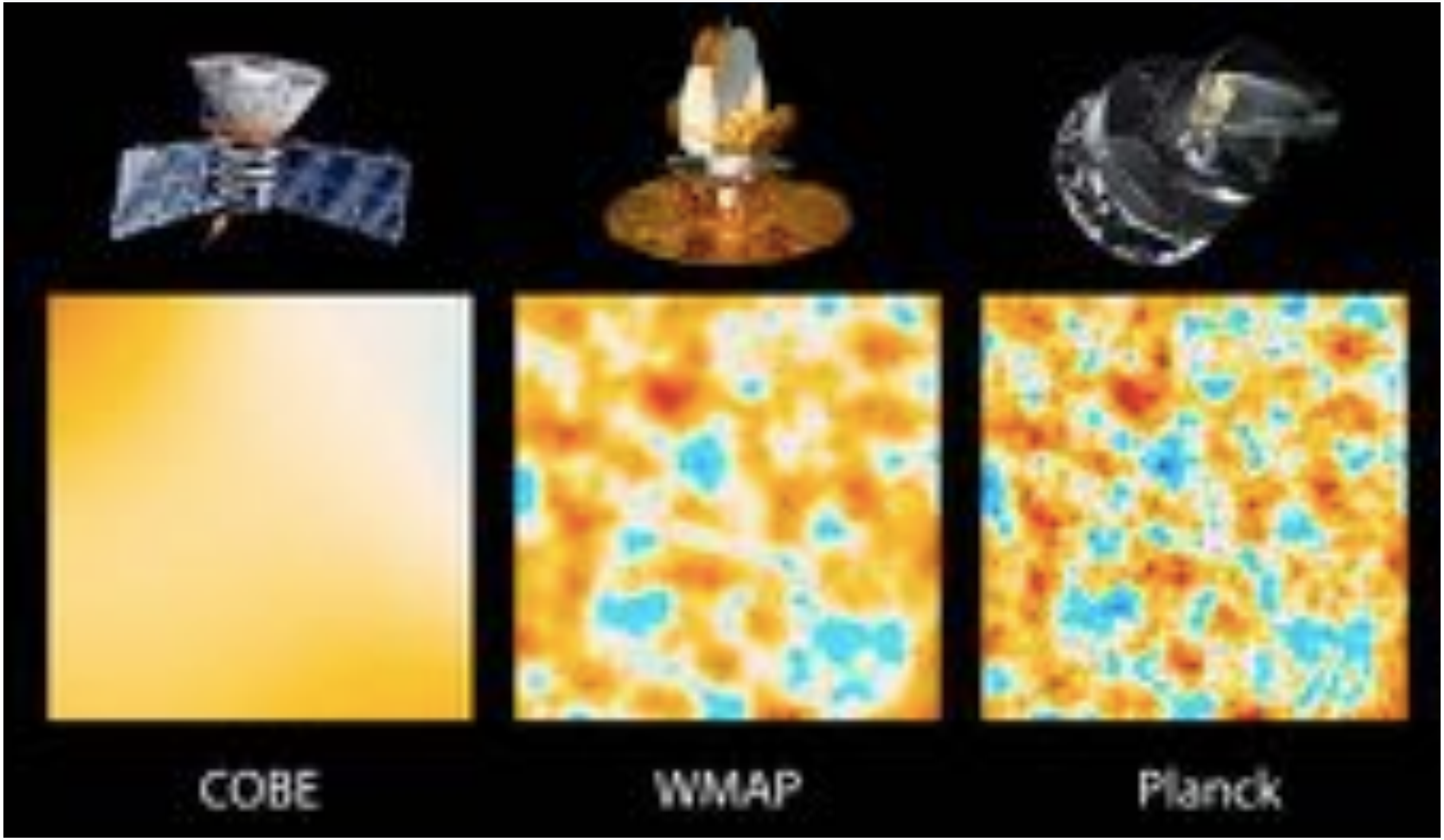


Going to small scales





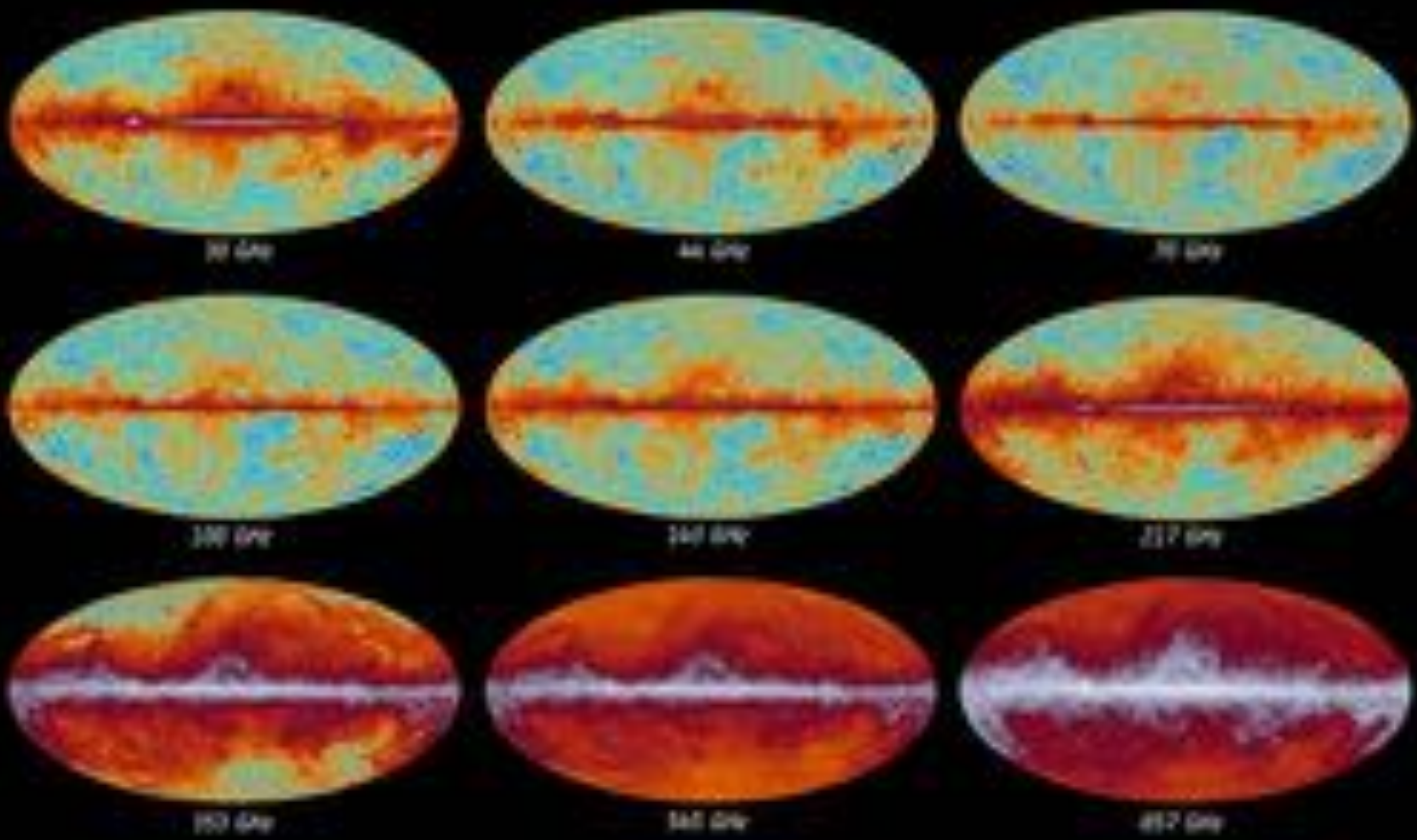
Sudeep Das for the ACT collaboration


COBE
WMAP
Planck

planck

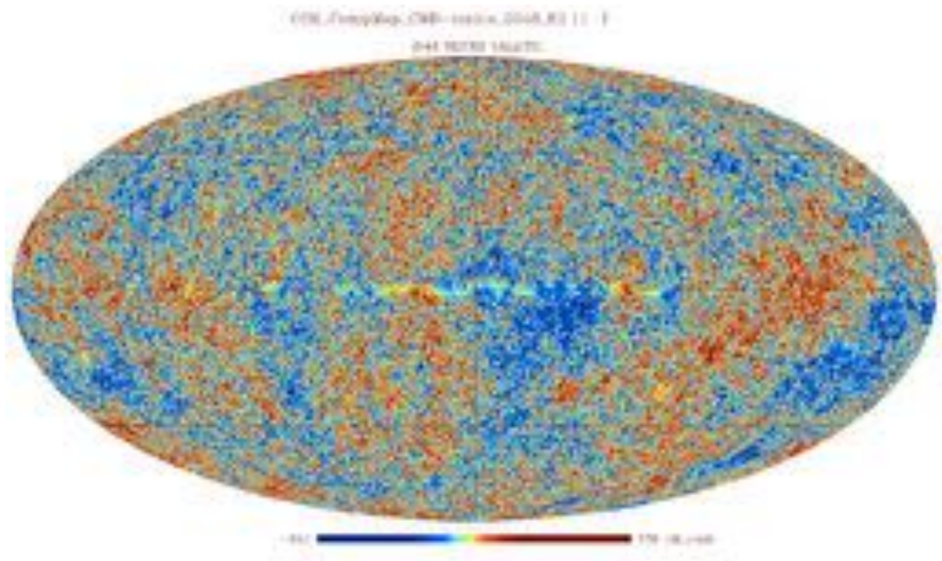
The sky as seen by Planck

esa

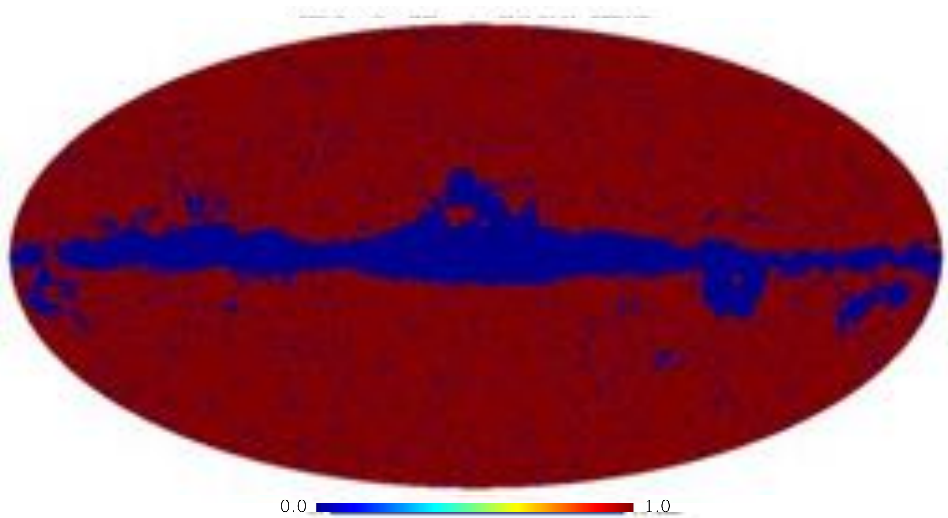


2018 Planck CMB data

SMICA



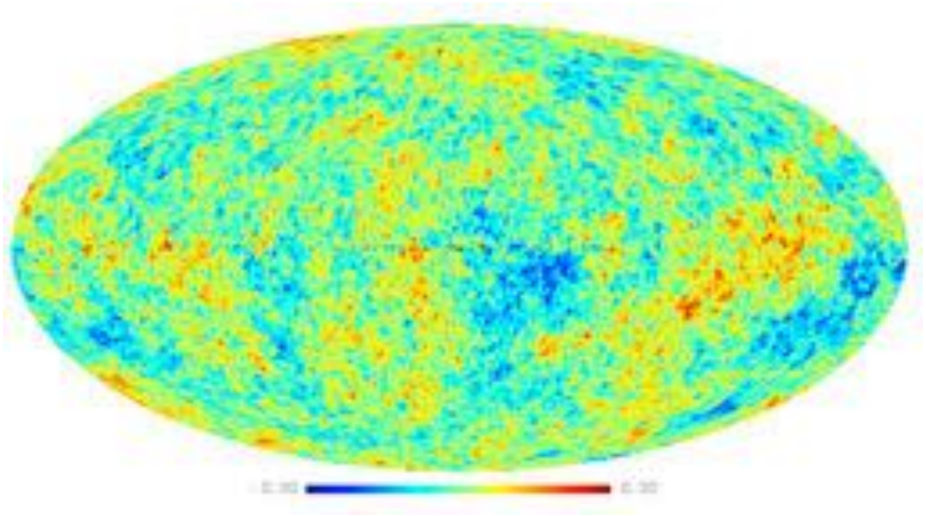
M82



Is the CMB field isotropic?

- Null hypothesis: "the observed universe is isotropic". Does current observational data show evidence against this hypothesis?

Em um universo estatísticamente isotrópico



$$\langle a_{\ell\, m} a^*_{\ell'\, m'} \rangle \; = \; C_\ell \, \delta_{mm'} \, \delta_{\ell\ell'} \quad \longrightarrow \quad C_\ell \equiv \frac{1}{2\ell+1} \Sigma_m \, |a_{\ell\, m}|^2$$

Em um universo estatísticamente anisotrópico

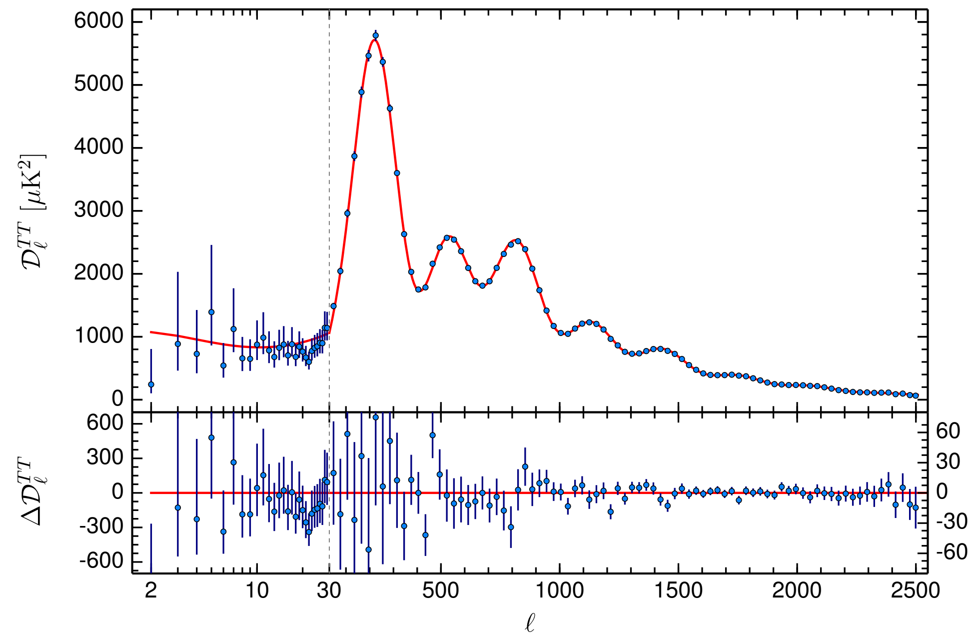
$$\langle a_{\ell\, m} a^*_{\ell'\, m'} \rangle \; = \; C_{\ell\, m}^{\ell'\, m'} \quad \not\longrightarrow \quad C_\ell \equiv \frac{1}{2\ell+1} \Sigma_m \, |a_{\ell\, m}|^2$$

Como analizar dados sem assumir IE?

Is the CMB field isotropic?

- Null hypothesis: "the observed universe is isotropic". Does current observational data show evidence against this hypothesis?

Em um universo estatísticamente isotrópico



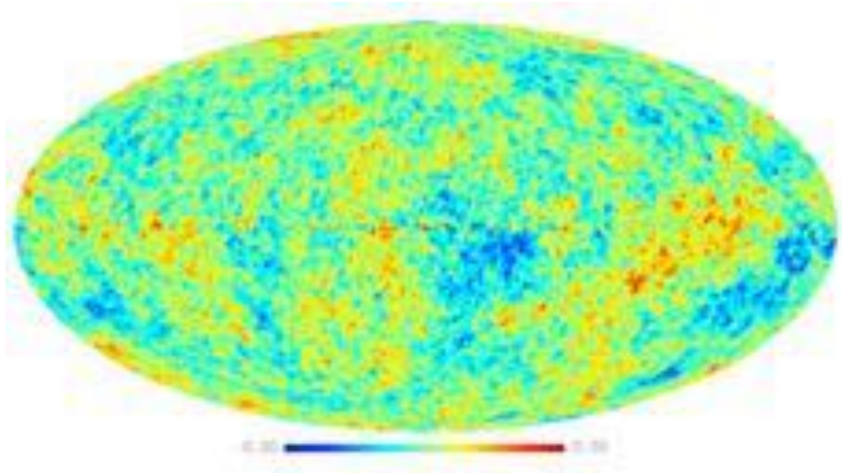
$$\langle a_{\ell\, m} a^*_{\ell'\, m'} \rangle \; = \; C_\ell\, \delta_{mm'}\, \delta_{\ell\ell'} \quad \longrightarrow \quad C_\ell \equiv \frac{1}{2\ell+1} \Sigma_m \, |a_{\ell\, m}|^2$$

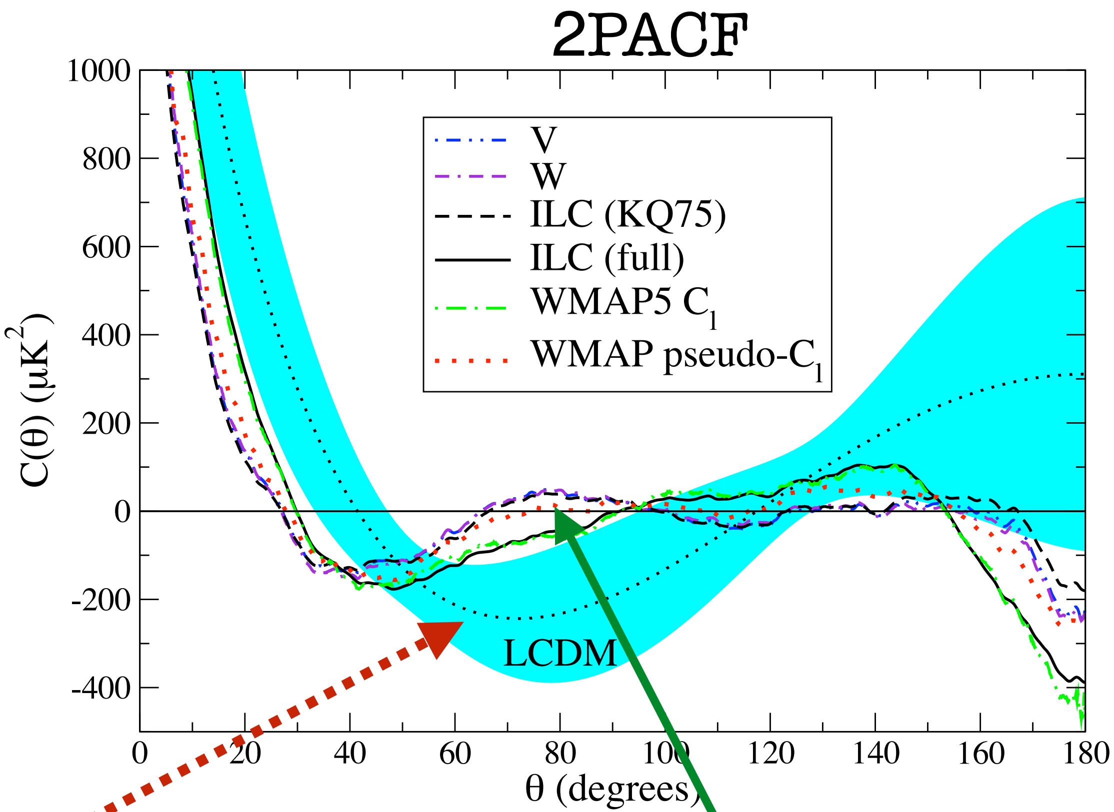
Em um universo estatísticamente anisotrópico

$$\langle a_{\ell\, m} a^*_{\ell'\, m'} \rangle \; = \; C_{\ell\, m}^{\ell' m'} \quad \not\longrightarrow \quad C_\ell \equiv \frac{1}{2\ell+1} \Sigma_m \, |a_{\ell\, m}|^2$$

Como analizar dados sem assumir IE?

Is the CMB field isotropic?





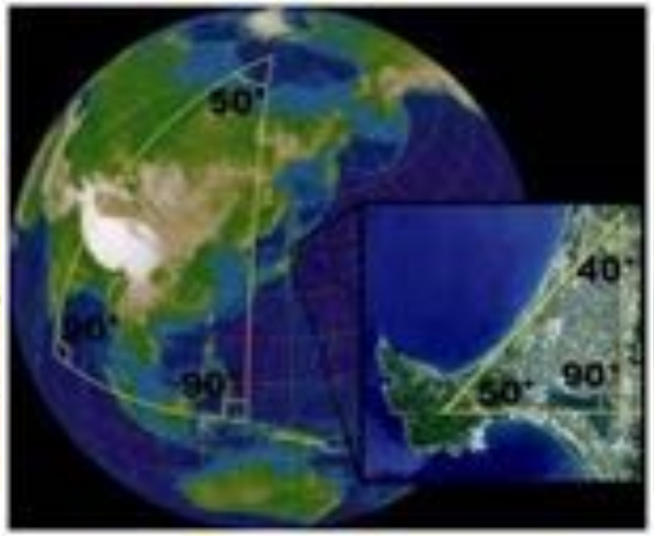
$$C_{exp}(\theta) = \sum_{\ell} \frac{2\ell+1}{4\pi} C_\ell P_\ell(\cos\theta)$$

esta expressão assume isotropia estatística

$$C_{obs}(\theta) \equiv \langle \frac{\Delta T}{T_0}(\varphi) \frac{\Delta T}{T_0}(\varphi+\theta) \rangle$$

esta expressão não assume isotropia estatística

The form of the Universe



the geometry of the Universe?

<u>local properties</u>: angles, distances, areas, parallelism,...

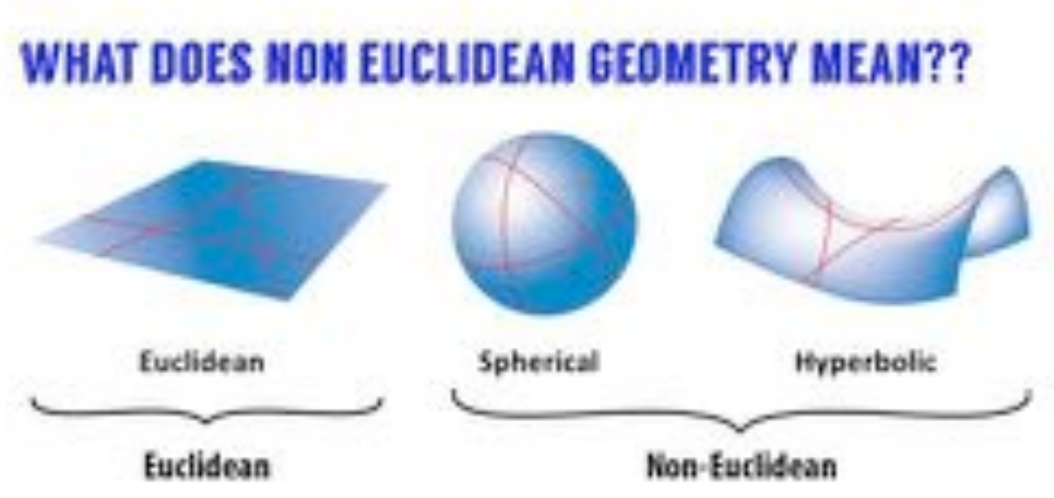
the topology of the Universe?

<u>global properties</u>:
without boundary, size, isometries, simple vs. multi-connectedness,...

UNI-VERSO

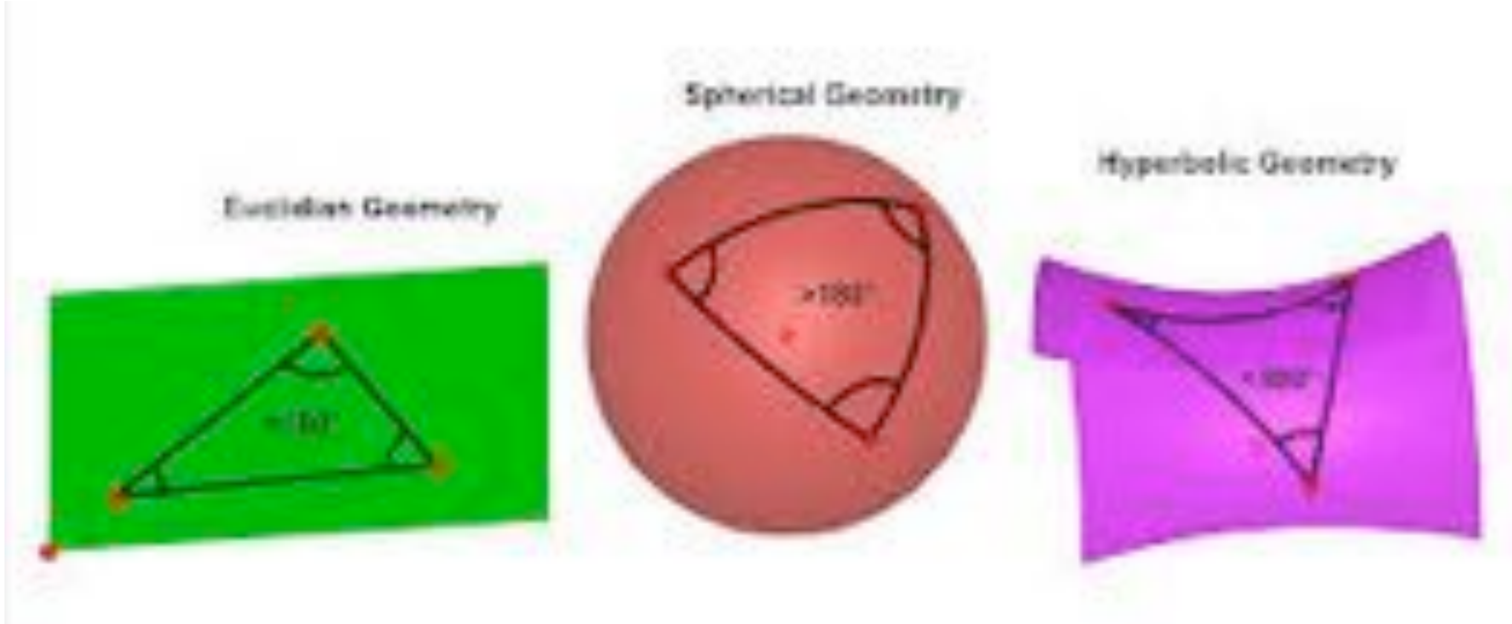
3D geometry

What is the relation between Euclides, Riemann, and Lobachevsky geometries?



⇨ Euclidian Postulate #5

Attention: these are 2D exms.!



simple vs. multiple-connectedness

the cylinder: 1D compact 2D space $\mathbb{R} \times \mathbb{S}^1$

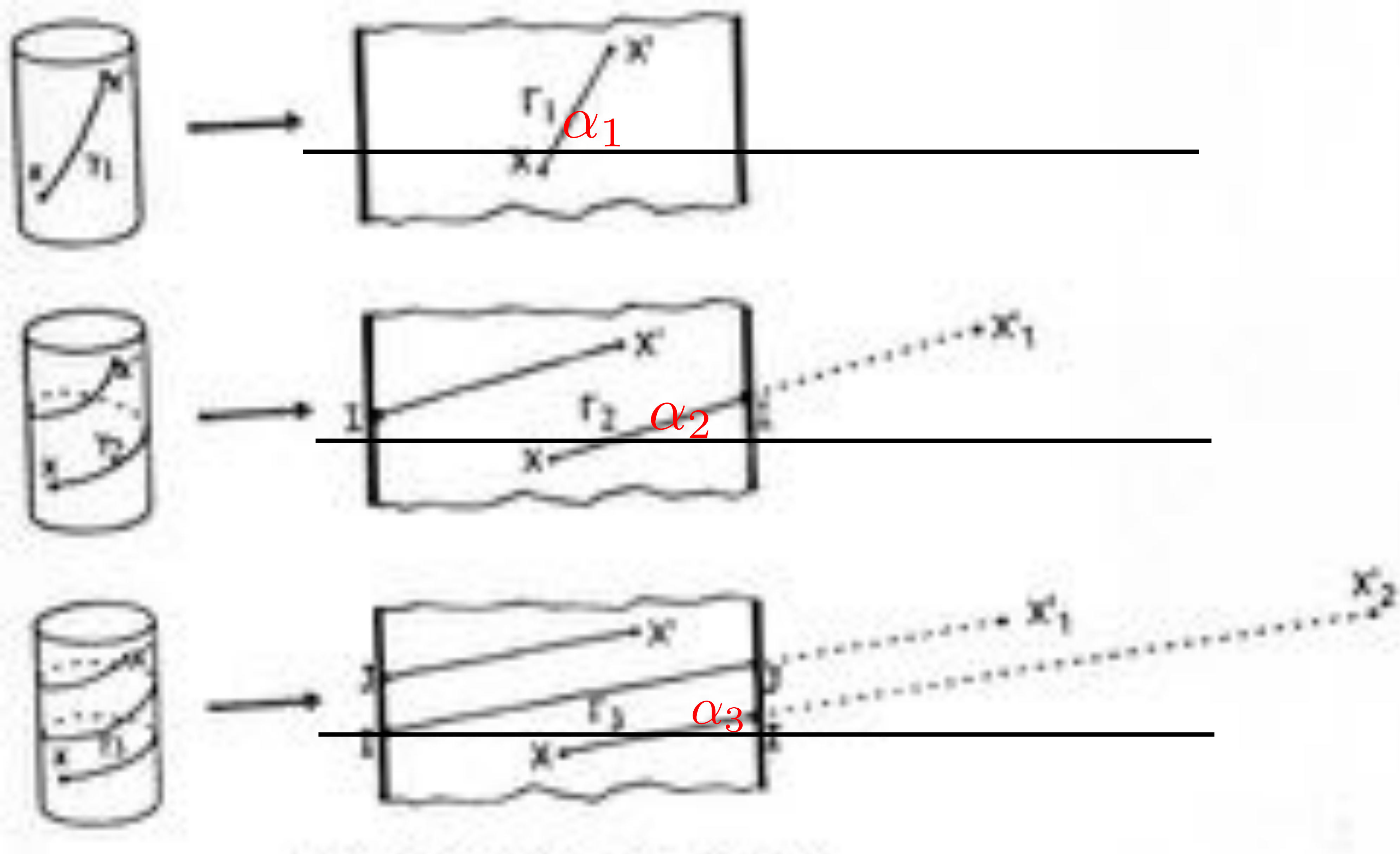


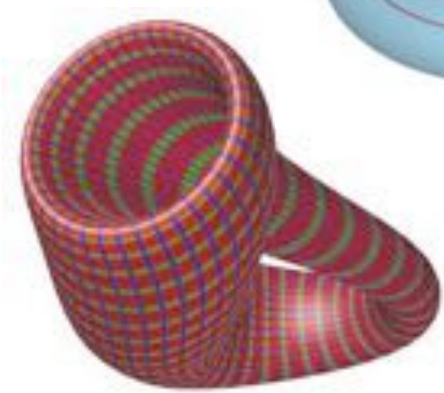
Fig. 3. Las geodésicas del cilindro

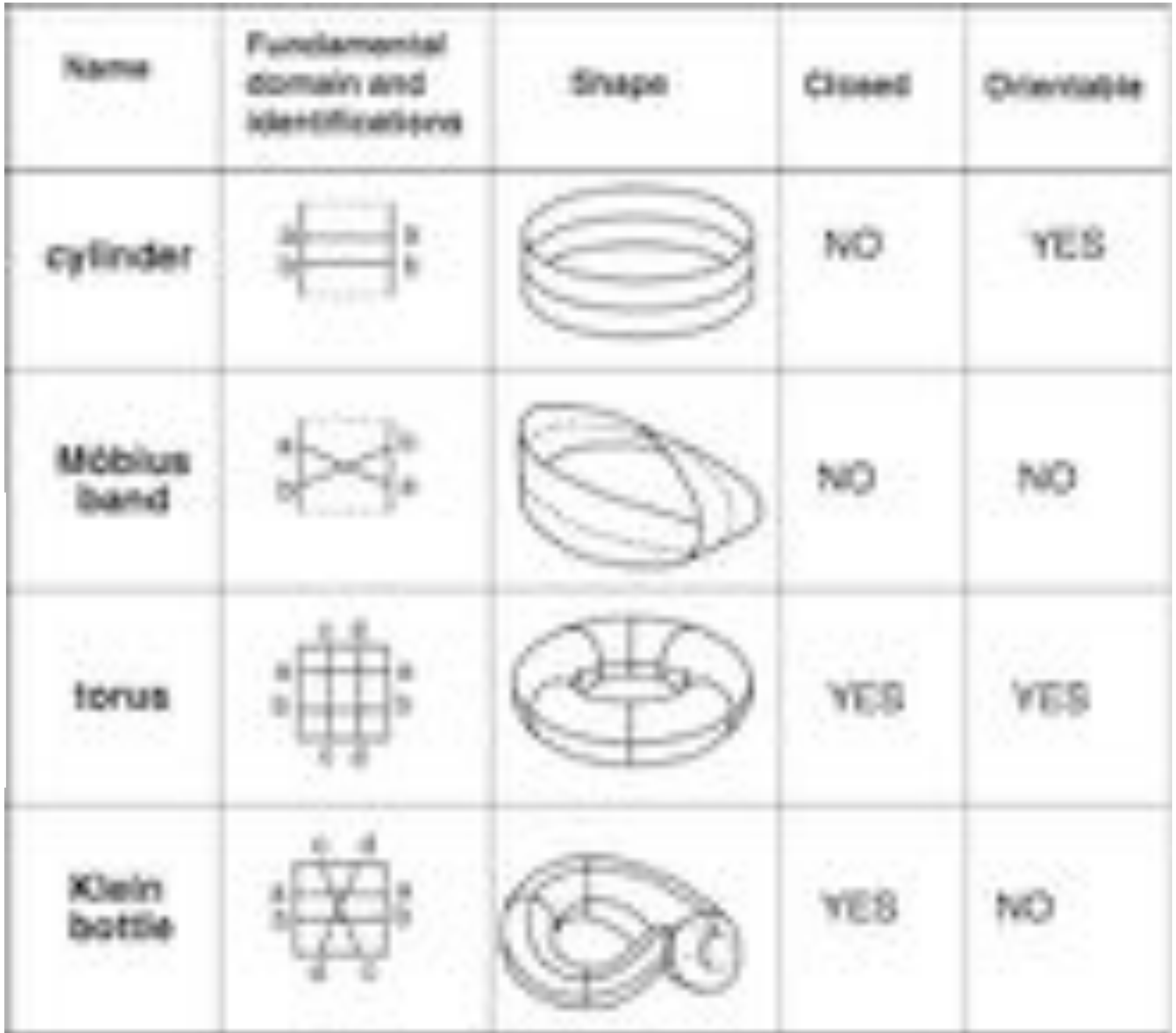
$\mathbb{R}^2$

3D topology

simple vs. multiple-connectedness

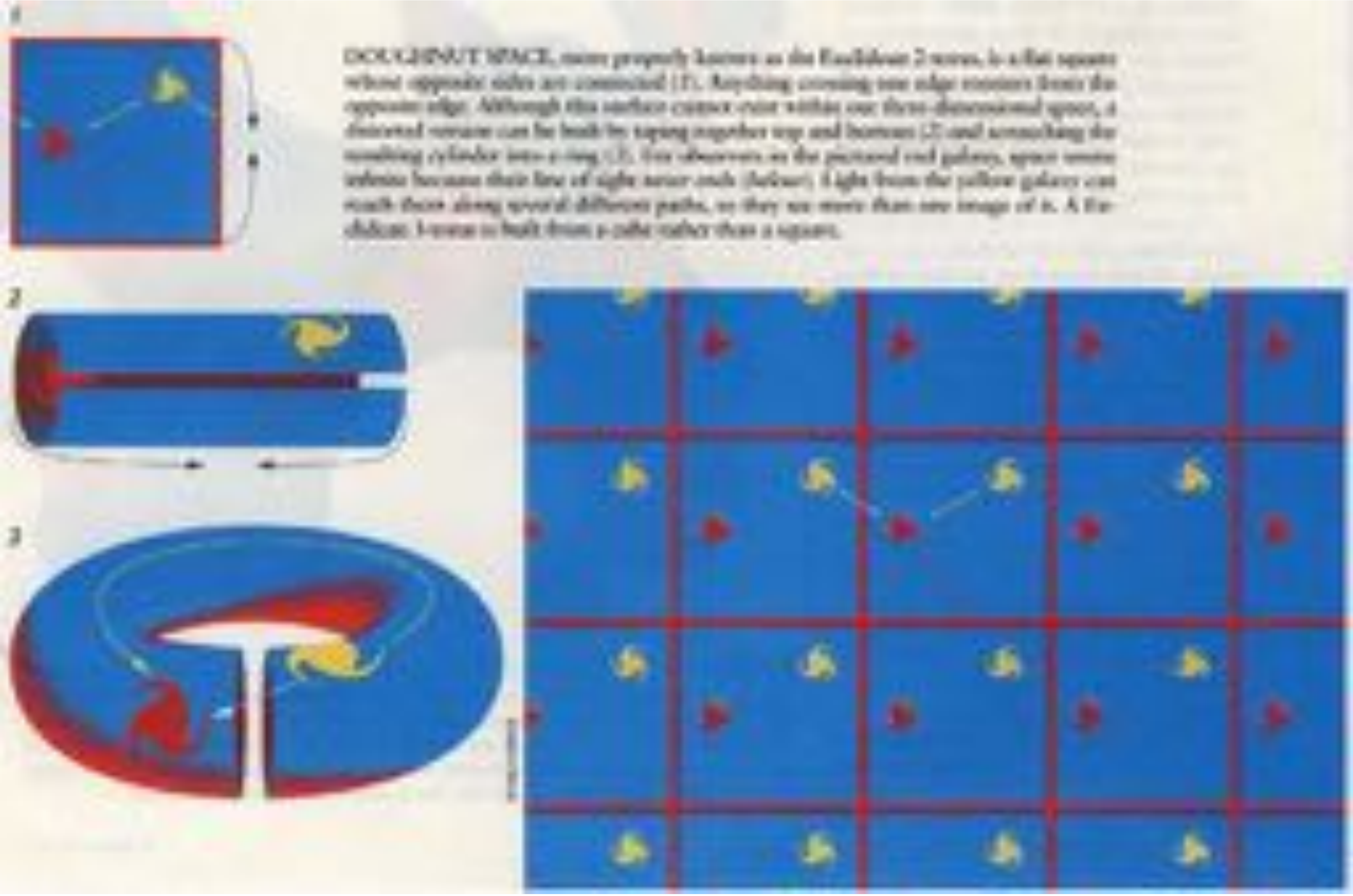
$\mathbb{R} \times \mathbb{S}^1$



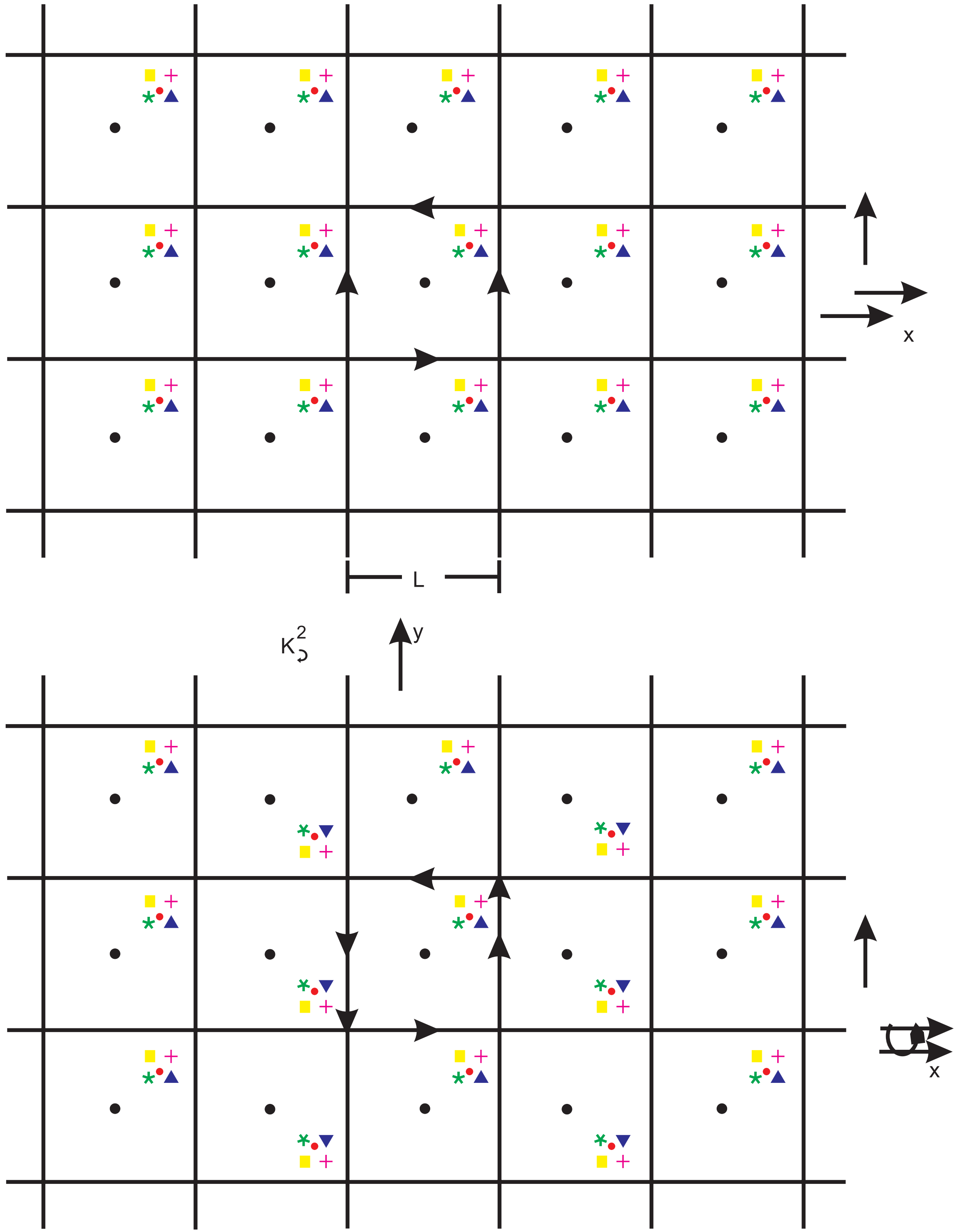


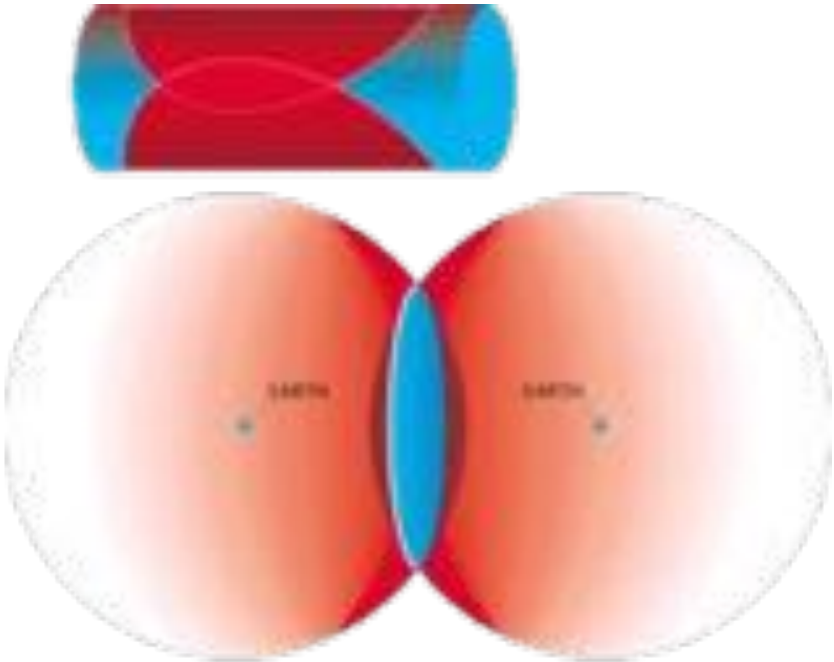
Name	Fundamental domain and identifications	Shape	Closed	Orientable
cylinder	[illegible]	[illegible]	NO	YES
Möbius band	[illegible]	[illegible]	NO	NO
torus	[illegible]	[illegible]	YES	YES
Klein bottle	[illegible]	[illegible]	YES	NO

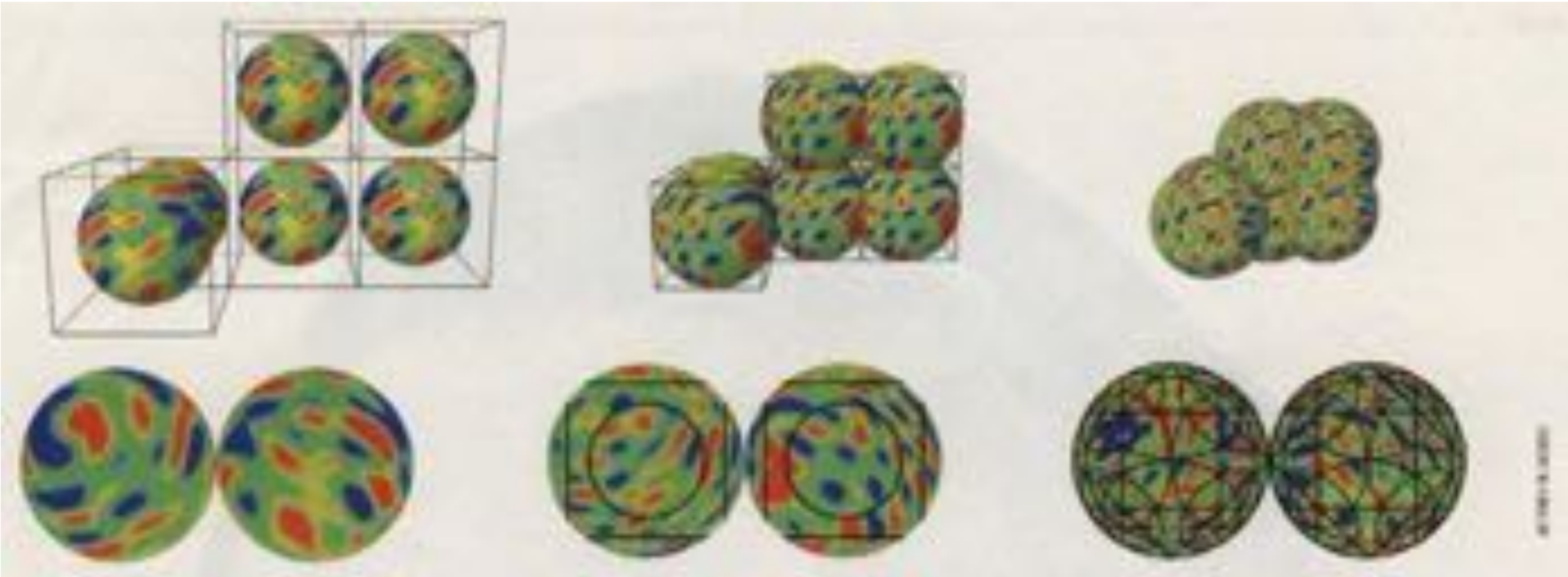
simple vs. multiple-connectedness?



ISOMETRIES




EARTH
EARTH



Large angular scale CMB anomalies

- Few reports on breakdown of statistical isotropy of CMB at large angu (consistent for WMAP and Planck data):
  - Lack of correlation at large scales
  - Hemispherical asymmetry
  - Quadrupole-octopole alignment
  - Power spectrum asymmetry
  - Power spectrum deficit for large scales ($l < 50$)
  - Low variance
  - Point-parity asymmetry
  - The cold spot
  - …

Pavel Bielewicz, 2016

"extraordinary claims require extraordinary evidence" C. Sagan

Anomalies $\Leftrightarrow$ $> 3\,\sigma$

CMB anomalies $\Rightarrow$ anisotropic Universe?

Cosmic Topology

Is the CMB sphere anomalous?

- Quadrupole-Octopole alignment

- Lack of large-angle correlations

- Hemispherical asymmetry

- Low quadrupole: $C_2 << 1150\ muK^2$ (LCDM)

$C_2 \in [1150/8, 1150/5]$

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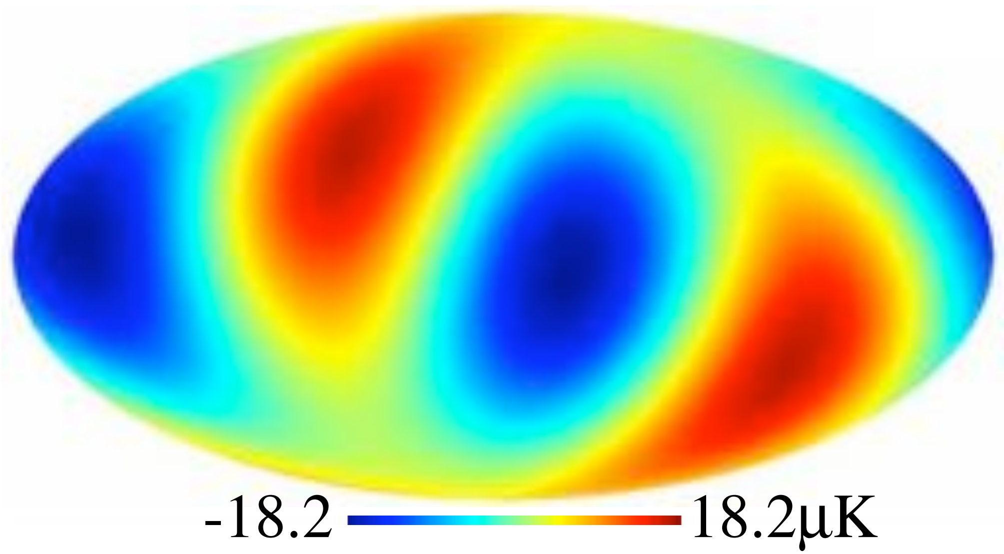
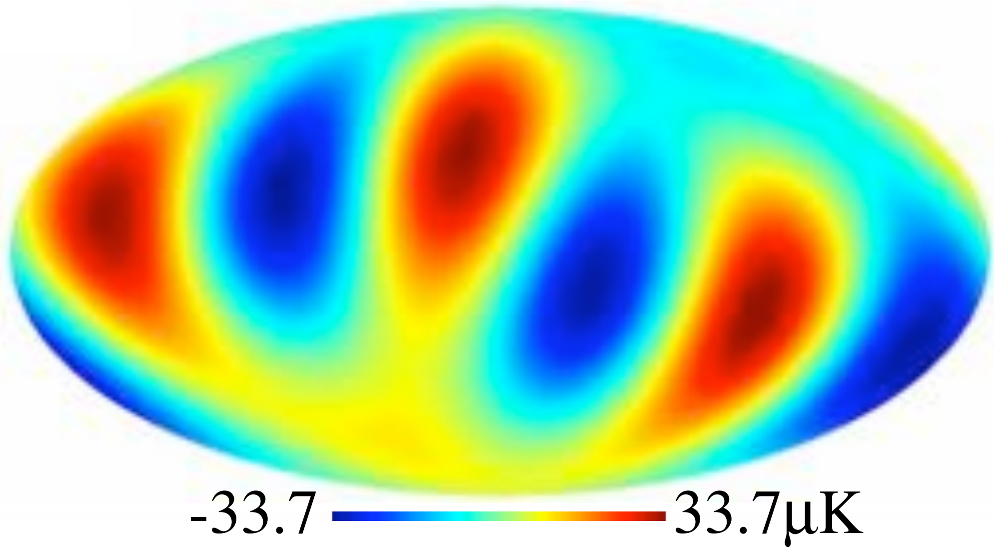
Quadrupole-Octopole alignment



quadrupole



octopole

... planar and aligned

Why is this a CMB anomaly?

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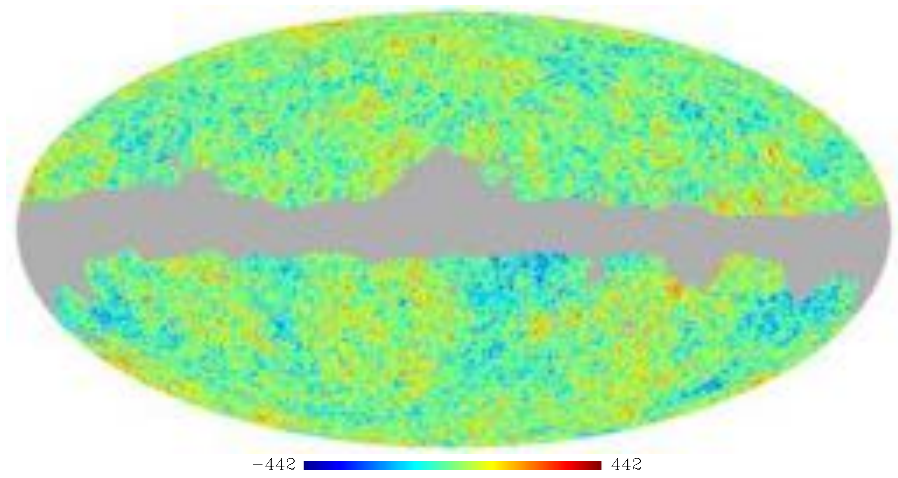
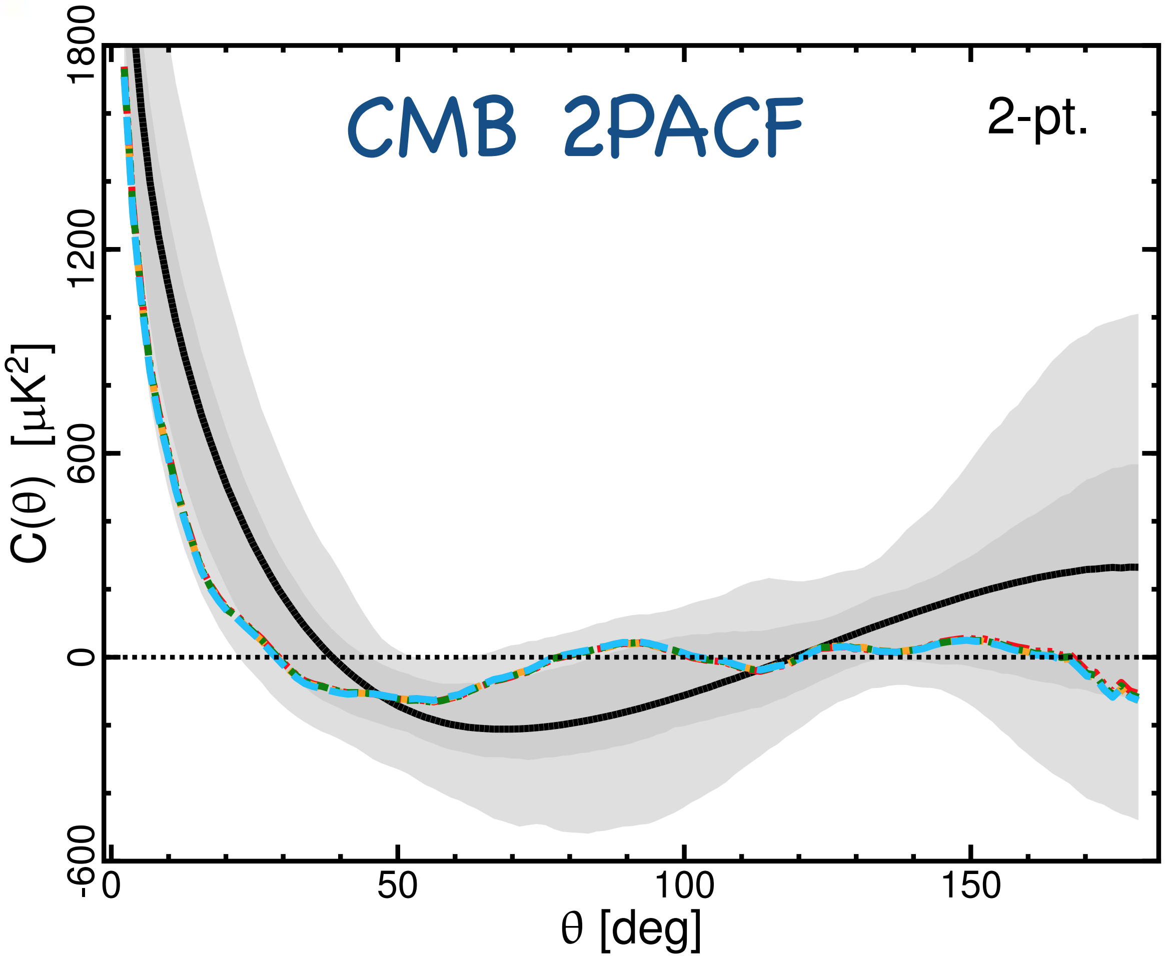
$C_2 \in [1150/8,\ 1150/5]$

Lack of correlation at large scales



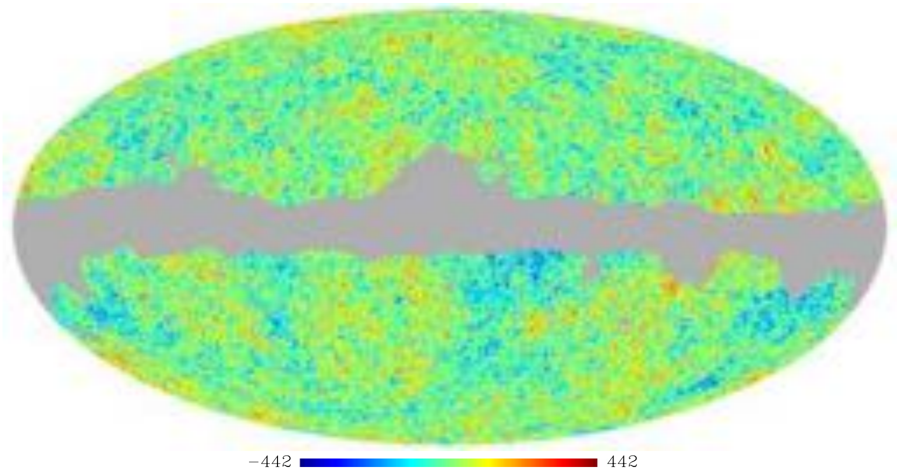
$$\hat{n} \cdot \hat{n}' = \cos(\theta)$$

$$\mathbf{C}(\theta) \equiv \langle \Delta T(\hat{n}) \Delta T(\hat{n}') \rangle$$



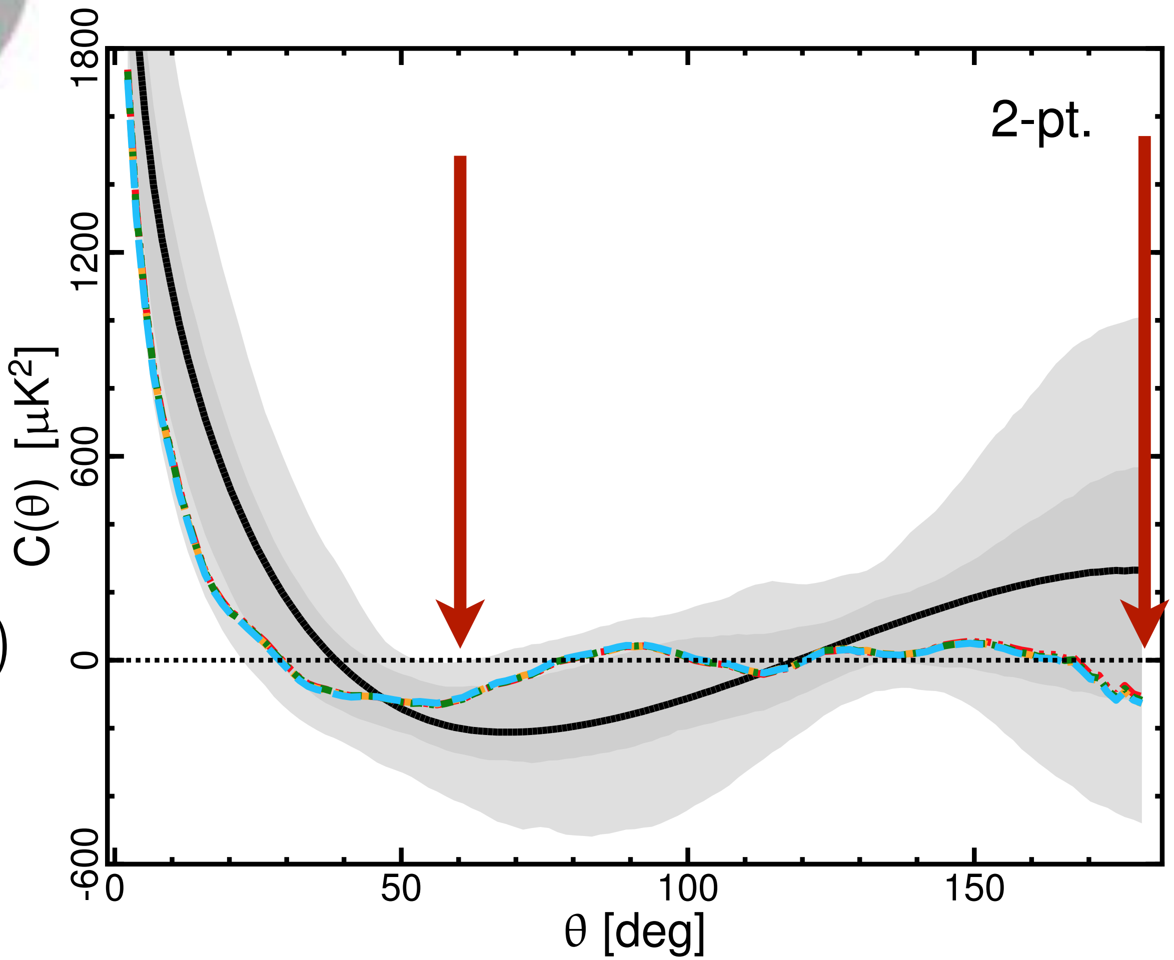
Planck XVI, 2015

Why is this a CMB anomaly?



2PACF

$$\mathbf{C}(\theta) \equiv \langle \Delta T(\hat{n}) \Delta T(\hat{n}') \rangle$$



$$S_{1/2} \equiv \int_{-1}^{1/2} \mathbf{C}(\theta)^2 \, d(\cos\theta)$$

p-value: 0.3% - 1%

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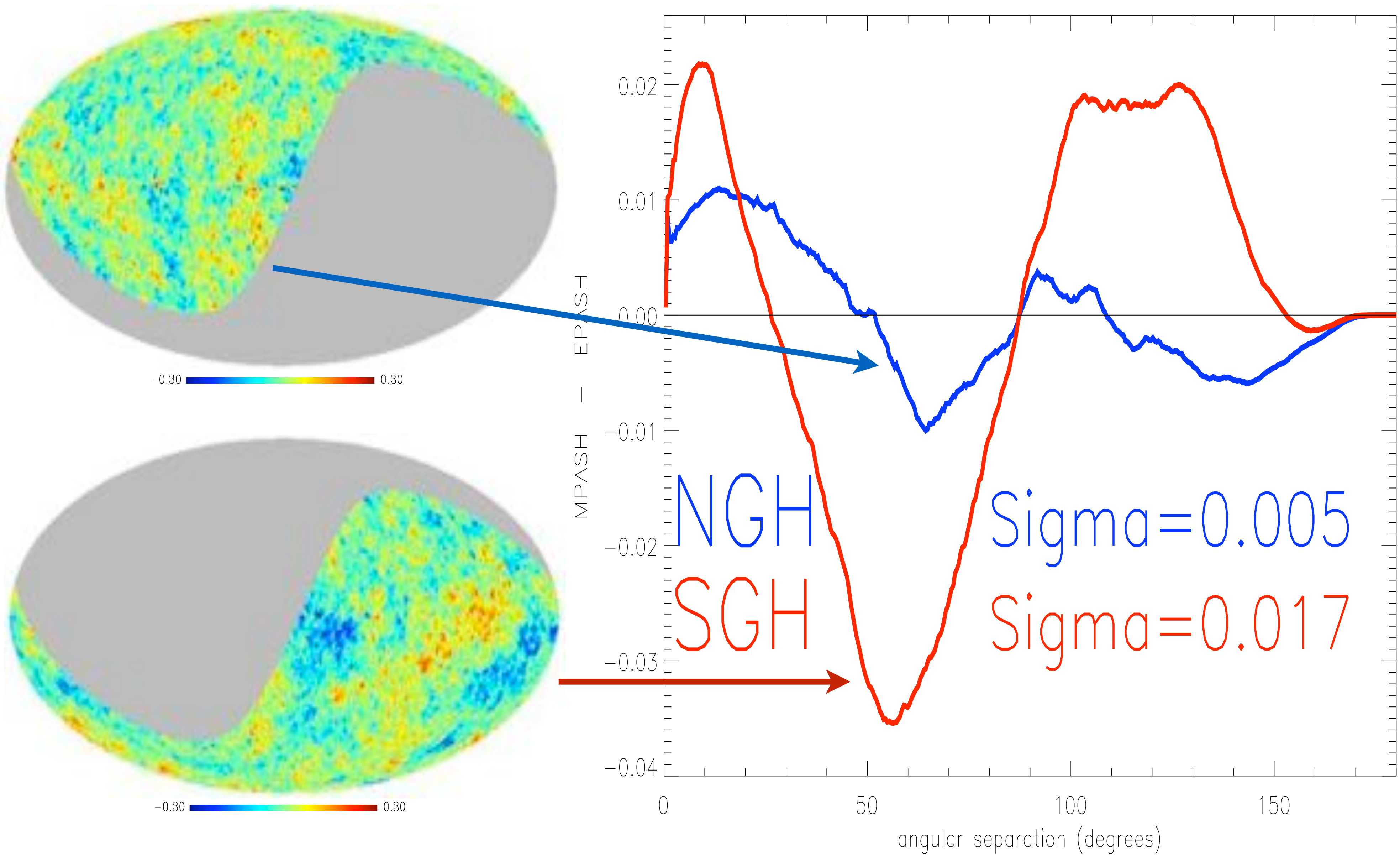
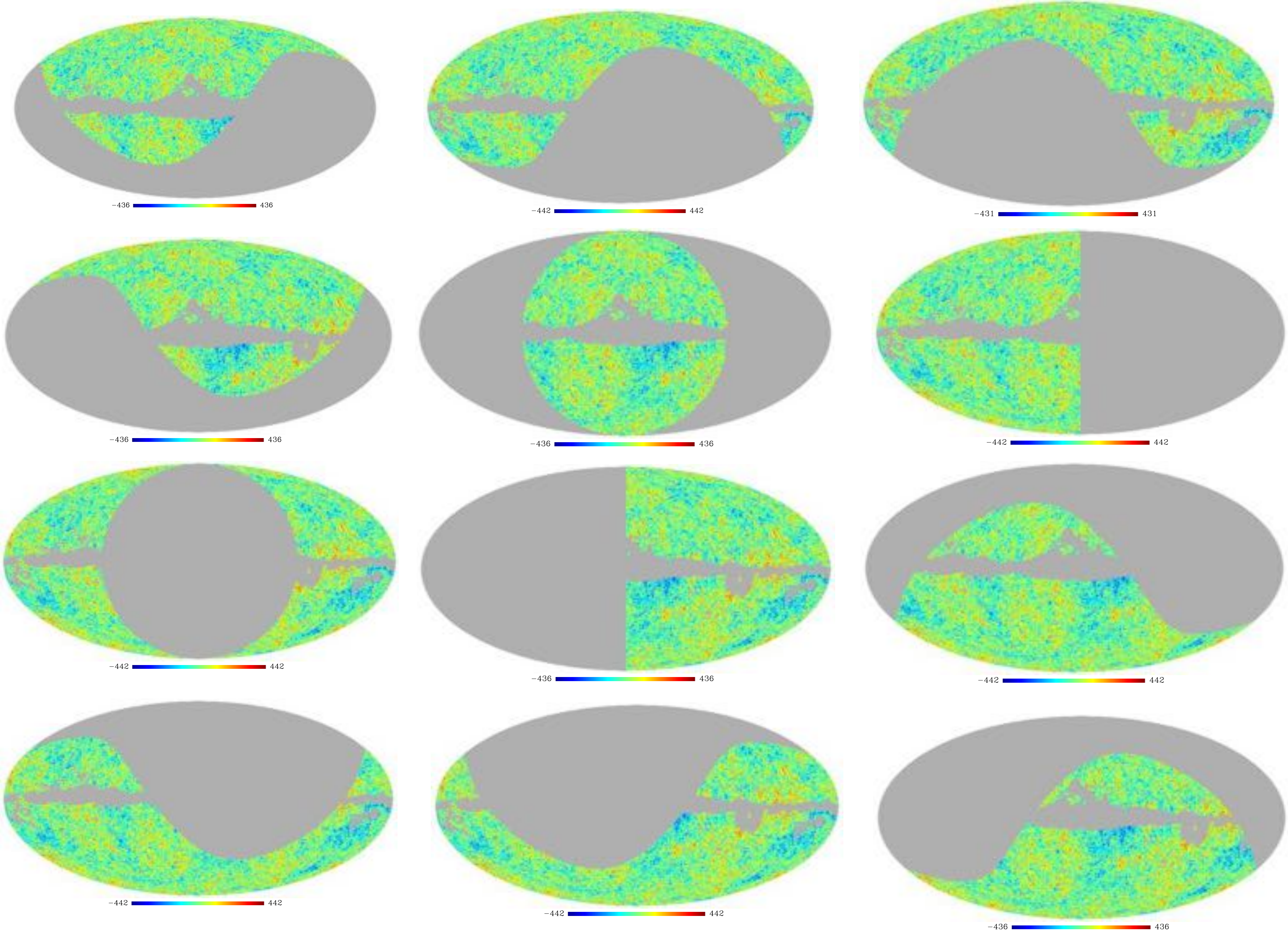
$C_2 \in [1150/8, 1150/5]$

Hemispherical asymmetry



WMAP3, 2006


−436 436
−442 442
−431 431
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−442 442
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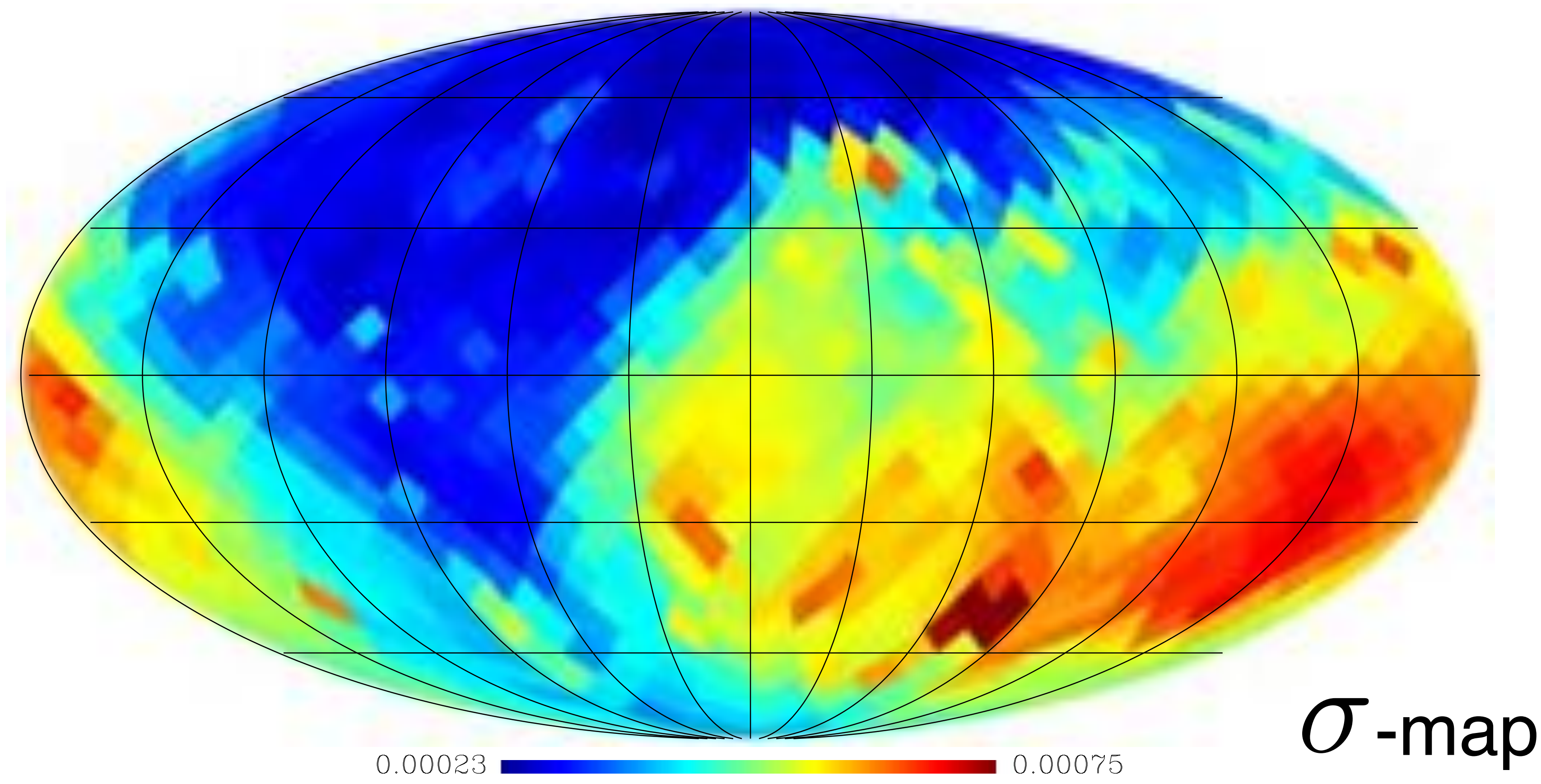
−442 442
−436 436

Hemispherical asymmetry



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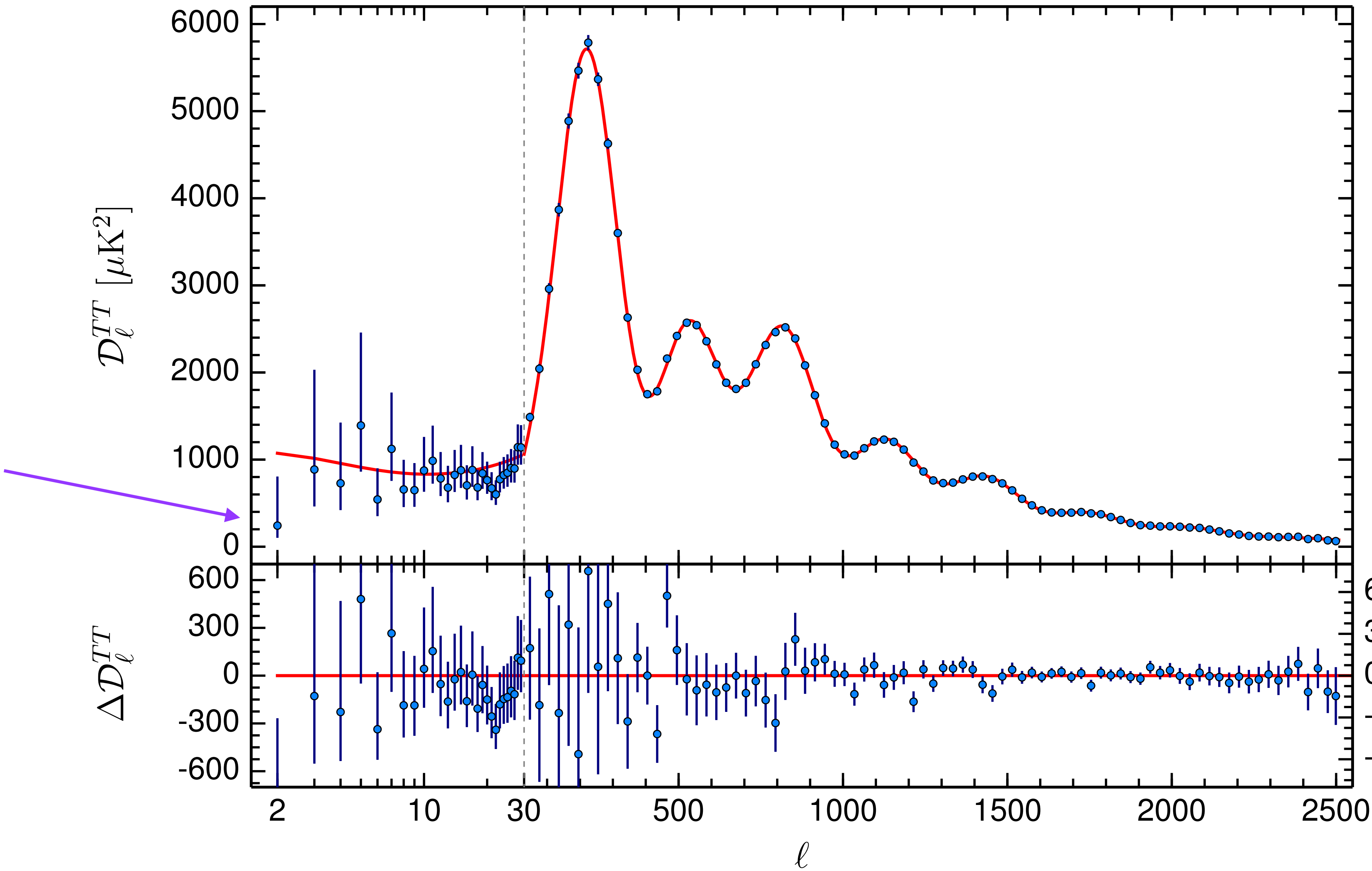

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-600
$\Delta\mathcal{D}_\ell^{TT}$
60
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-60
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500
1000
1500
2000
2500
ℓ

In the last $\sim$23 years of CMB-anomalies literature:

- dozens of models (hypotheses, explanations,..)
- hundreds of papers (data analyses &/ models)
- thousands of citations

What we conclude:

(1) the correct model/solution should explain all the CMB anomalies!

(2) the model should provide one global preferred axis!

Suitability: cosmic topology provides manifolds with one global preferred axis, but...which one?

Motivation: B. Mota et al. astro-ph/0309371

"If the universe underwent an inflationary phase st:
$|\Omega_0 - 1| = |\Omega_K| \ll 1$, then

$\mathbb{R}^2 \times \mathbb{S}^1$

"a generic detectable non-flat manifold is locally indistinguishable from either a cylindrical (R2×S1) or toroidal (R×T2) manifold, irrespective of its global shape, with the former being more likely"

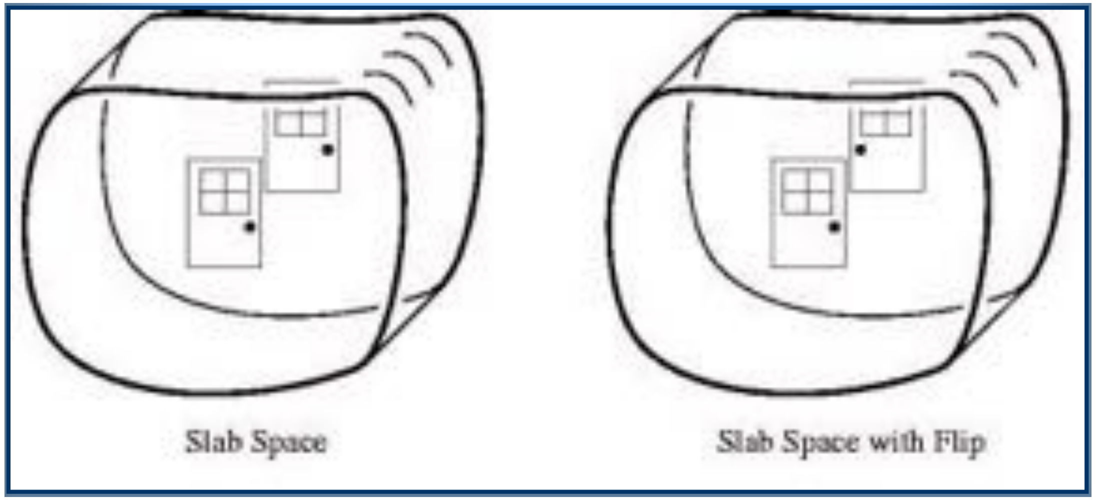
$\mathbb{R} \times \mathbb{T}^2$

Current limit: $|\Omega_K| < 0.005$ Planck XIII, arXiv:1502.01589

Why not study features there ...

the slab-space (3d):

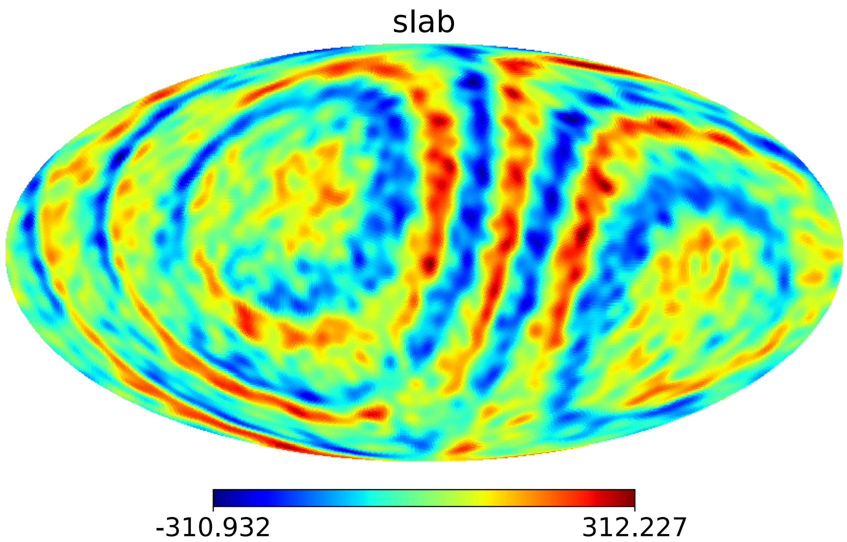
$$\mathcal{M}_3 = \mathbb{R}^2 \times \mathbb{S}^1$$



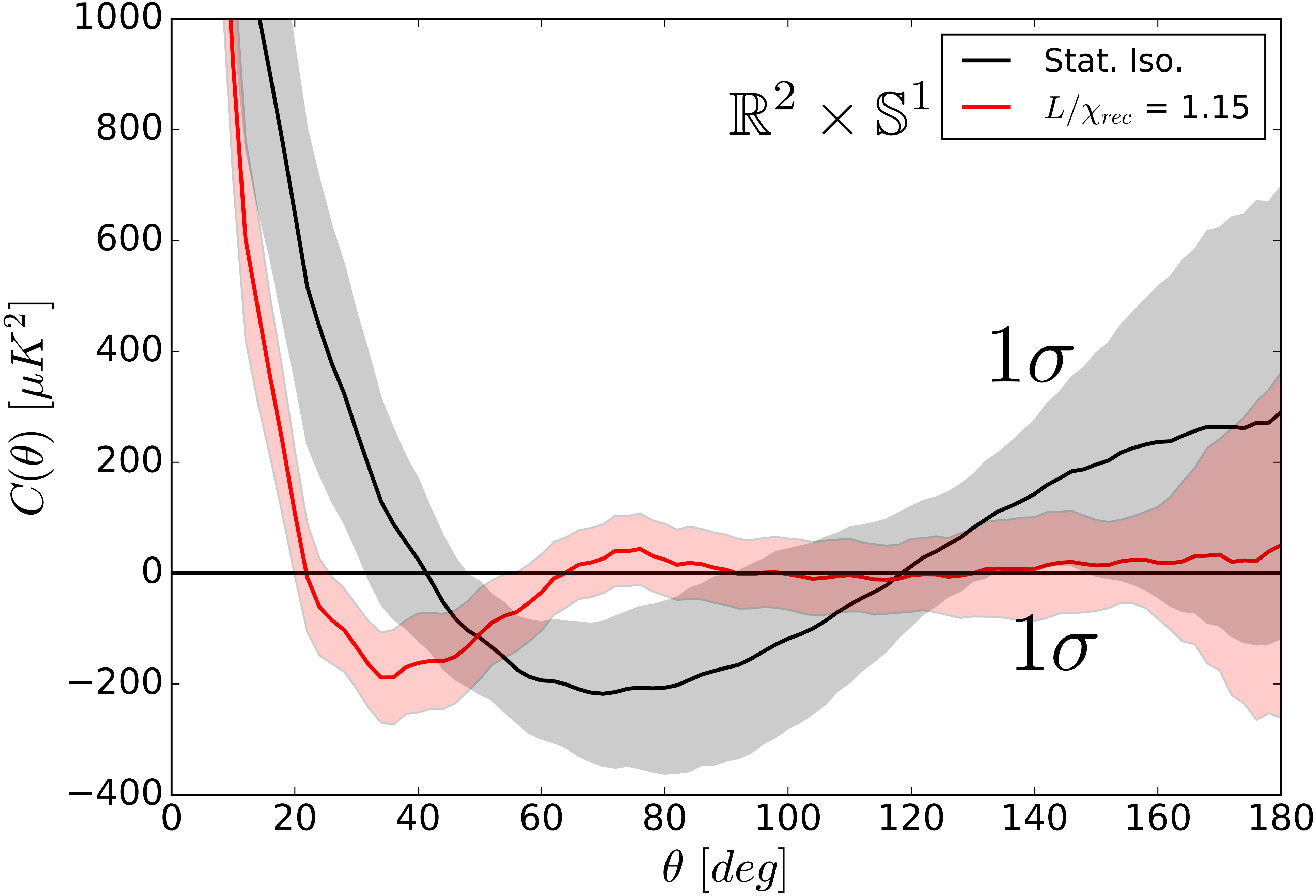
with the current limit: $\mathrm{L}/\chi_{rec} > 1.12$

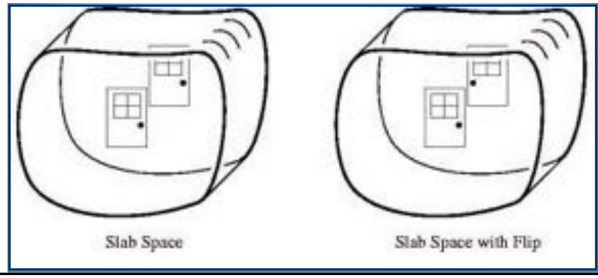
toy-slab:

$$\mathrm{L}/\chi_{rec} = 0.5$$

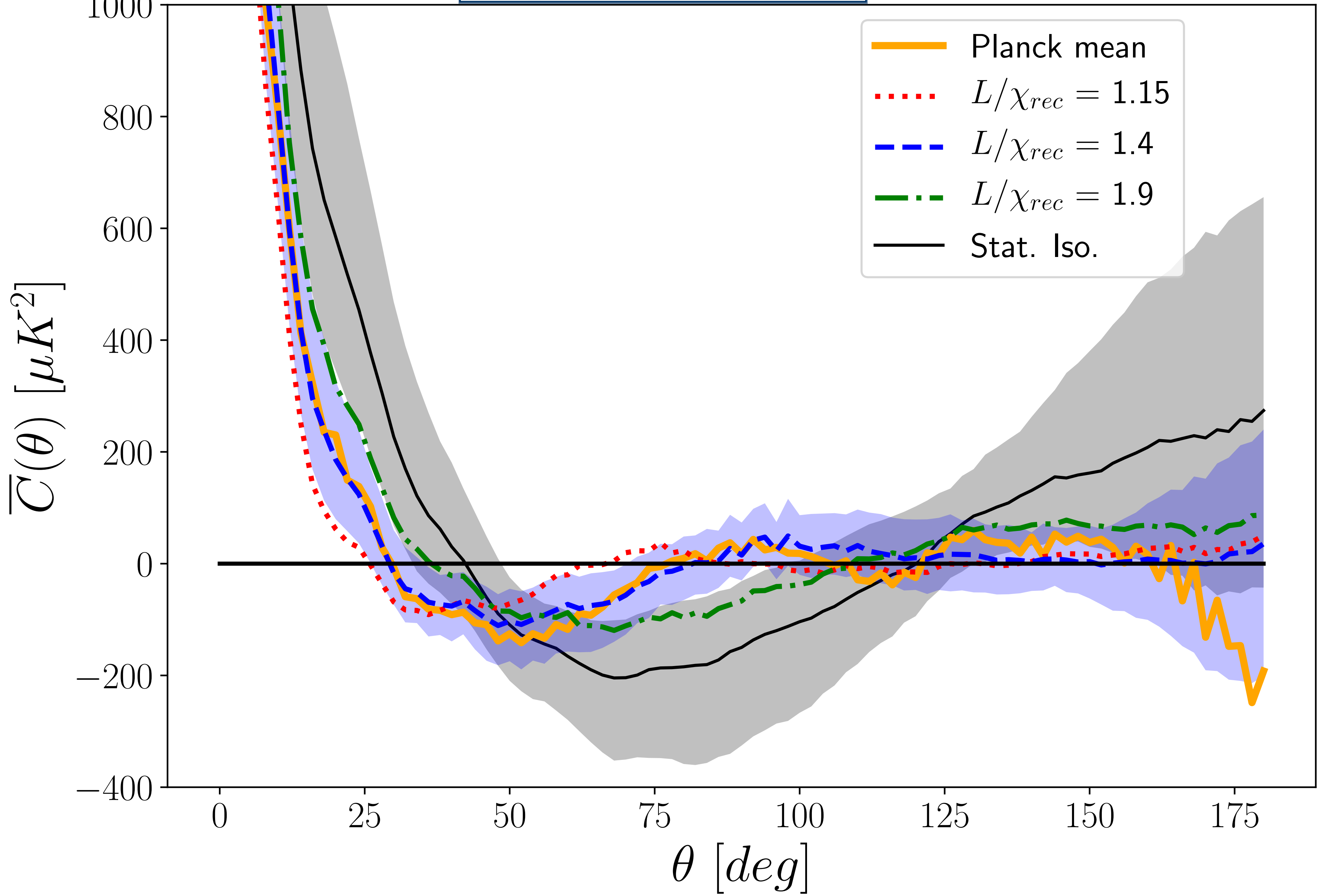


Proposal of solution: slab-space





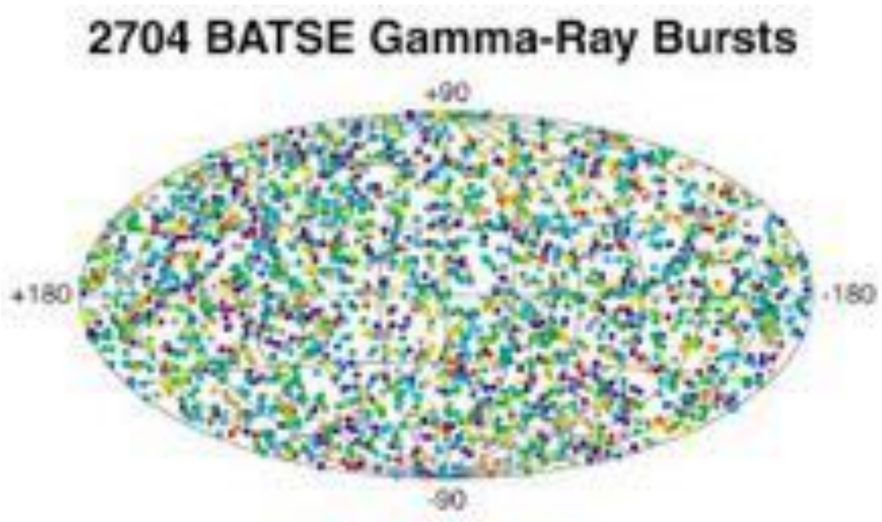
$\mathbb{R}^2 \times \mathbb{S}^1$



Para encerrar .....

Nossa profissão vive de ideias científicas!

Isotropia estatística de GRBs



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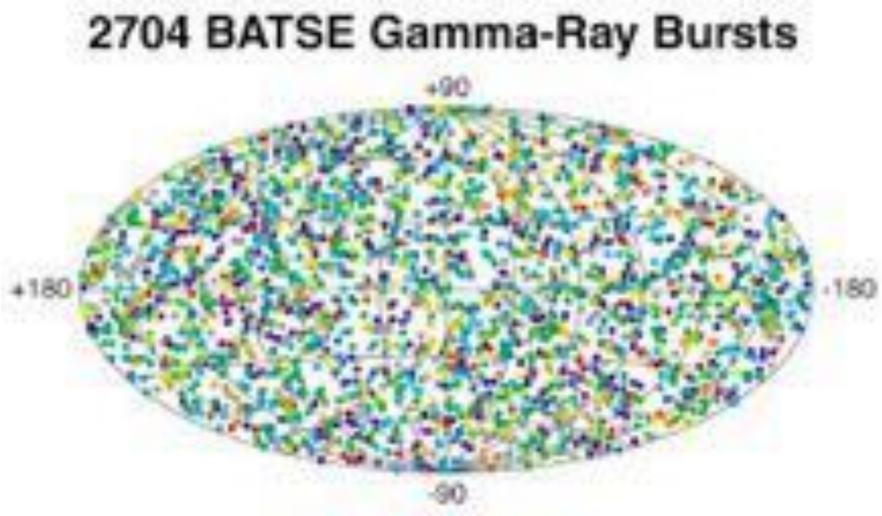


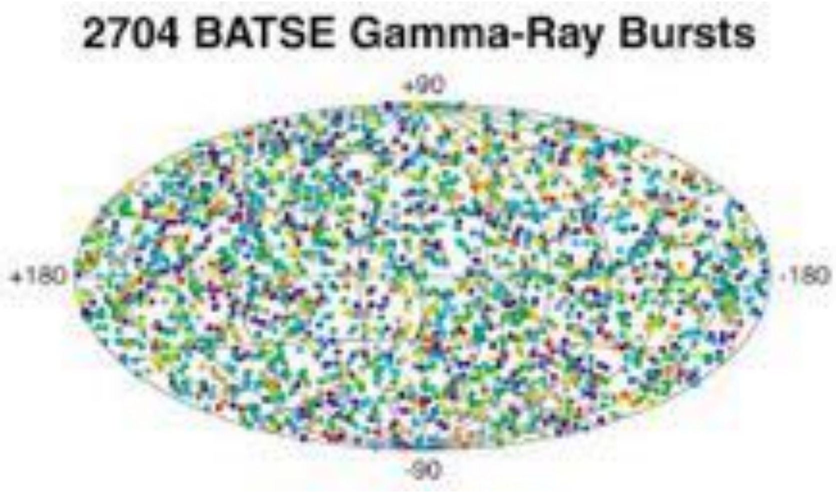
The Astrophysical Journal, 673:968–971, 2008 February 1

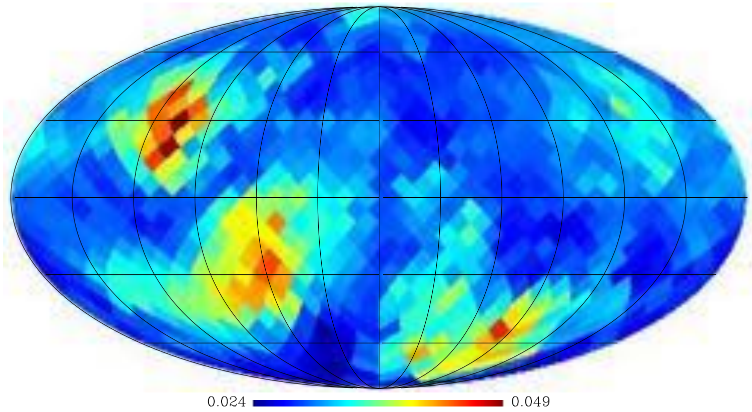
ON THE LARGE-SCALE ANGULAR DISTRIBUTION OF SHORT GAMMA-RAY BURSTS

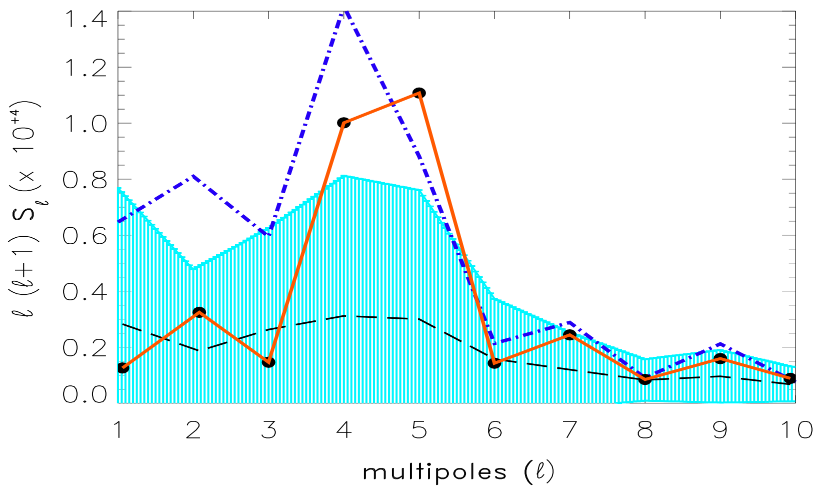
A. Bernui, I. S. Ferreira, and C. A. Wuensche
Instituto Nacional de Pesquisas Espaciais, Divisão de Astrofísica, Avenida dos Astronautas 1758, CEP 12227-010 São José dos Campos, SP, Brazil; bernui@das.inpe.br; ivan@das.inpe.br; alex@das.inpe.br
Received 2007 April 12; accepted 2007 October 8

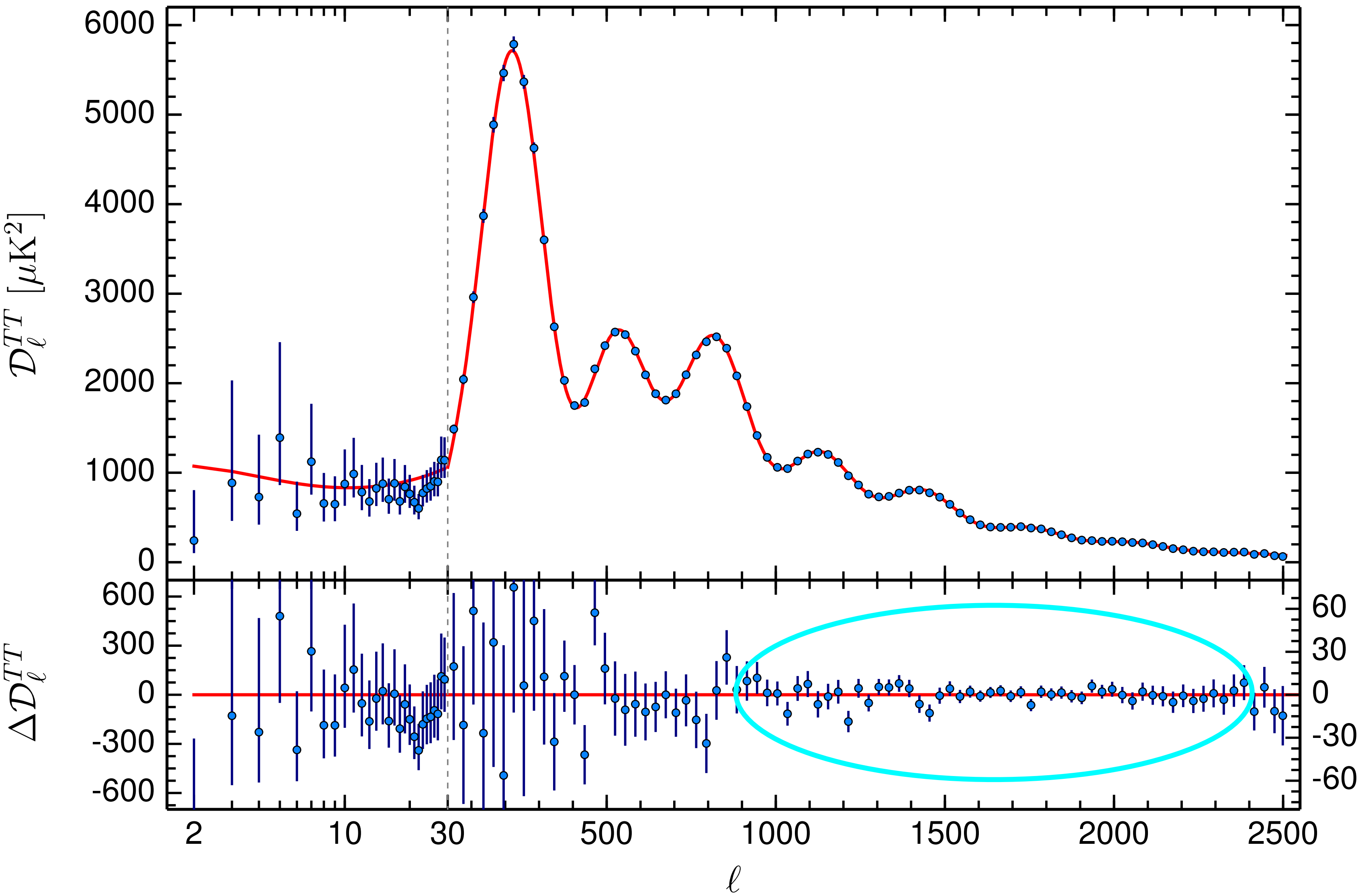
Problema científico

Isotropia estatística de GRBs









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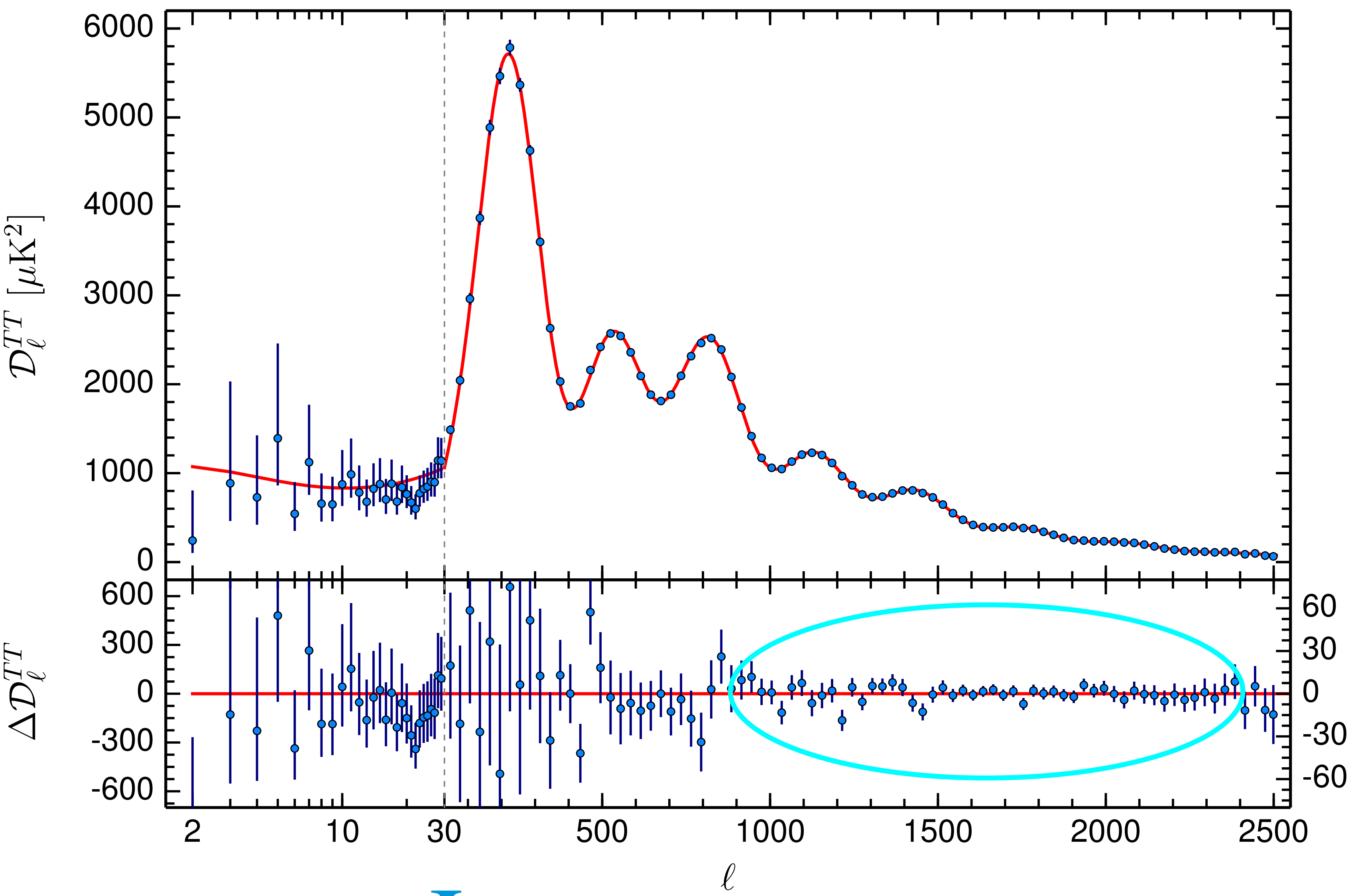
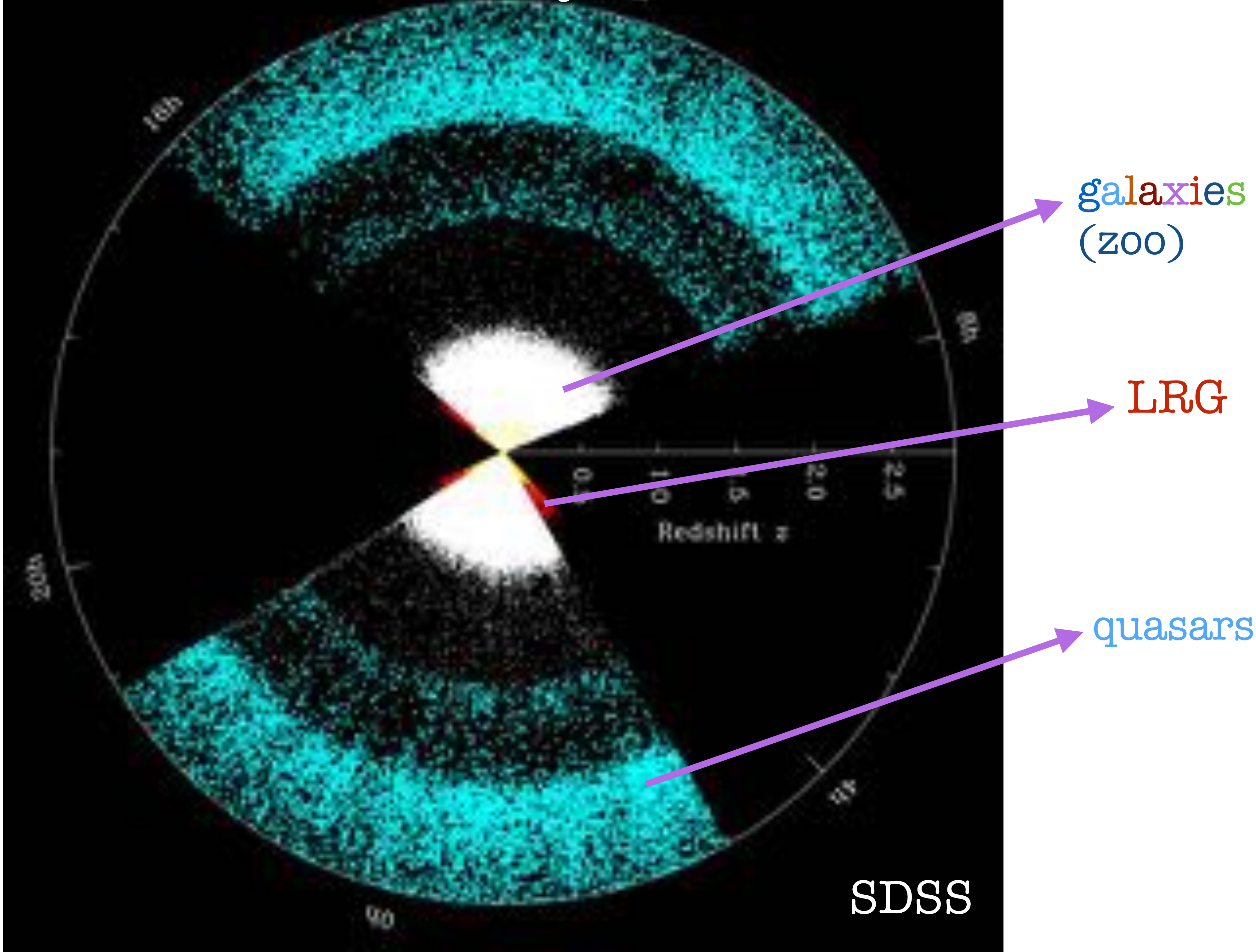


Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Excess of lensing amplitude in the Planck CMB power spectrum

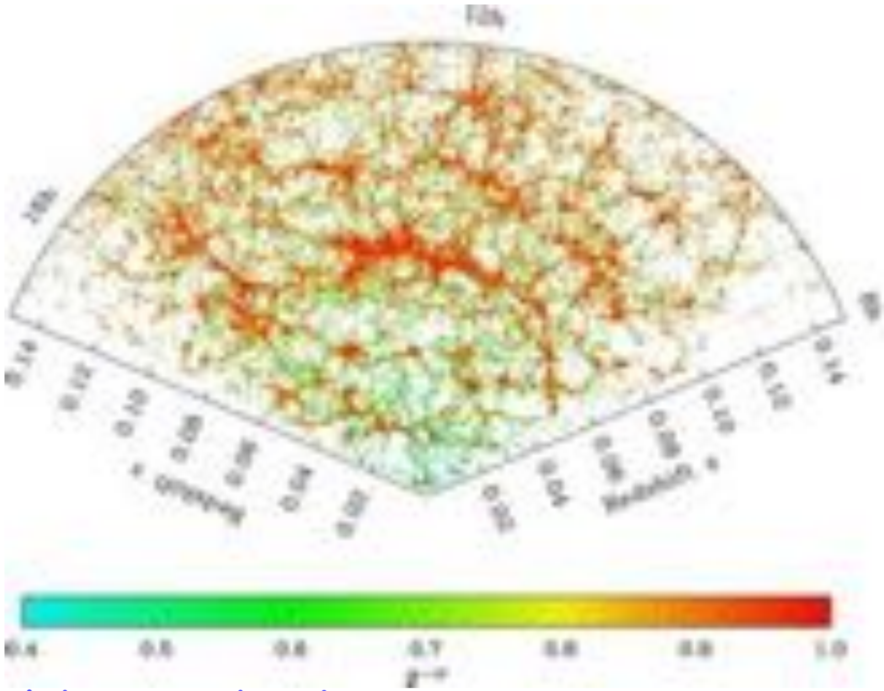
Rahima Mokeddem,[a,*] Wiliam S. Hipólito-Ricaldi[b]
and Armando Bernui[c]

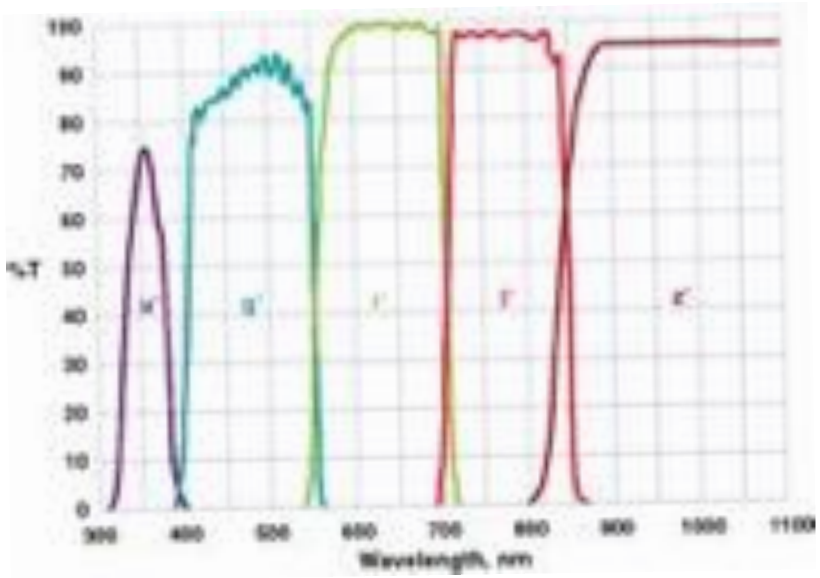
Cosmic Tracers: to study the Universe LSS



Cosmic Tracers: to study the large-scale structure

SDSS Main Galaxy Sample (MGS)





blue galaxies:

Local Universe

ugriz

Cosmologia observacional: estudamos o Universo em largas escalas...

Aprendemos de outras áreas da astrofísica quando utilizamos diversos traçadores cósmicos:

HI (ALFALFA), blue galaxies (SDSS+SPLUS), LRG (SDSS), quasares (SDSS+SPLUS), GRB (Batse+Fermi), CMB (Planck) LPM (Planck), galaxy clusters (Planck), SNe (Pantheon+),...

3 artigos

5 artigos

5 artigos

7 artigos

1 artigo

1+1 artigos

2+1 artigos

1 artigo

1+1 artigos