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Dark matter from initial conditions to structure formation in the Universe

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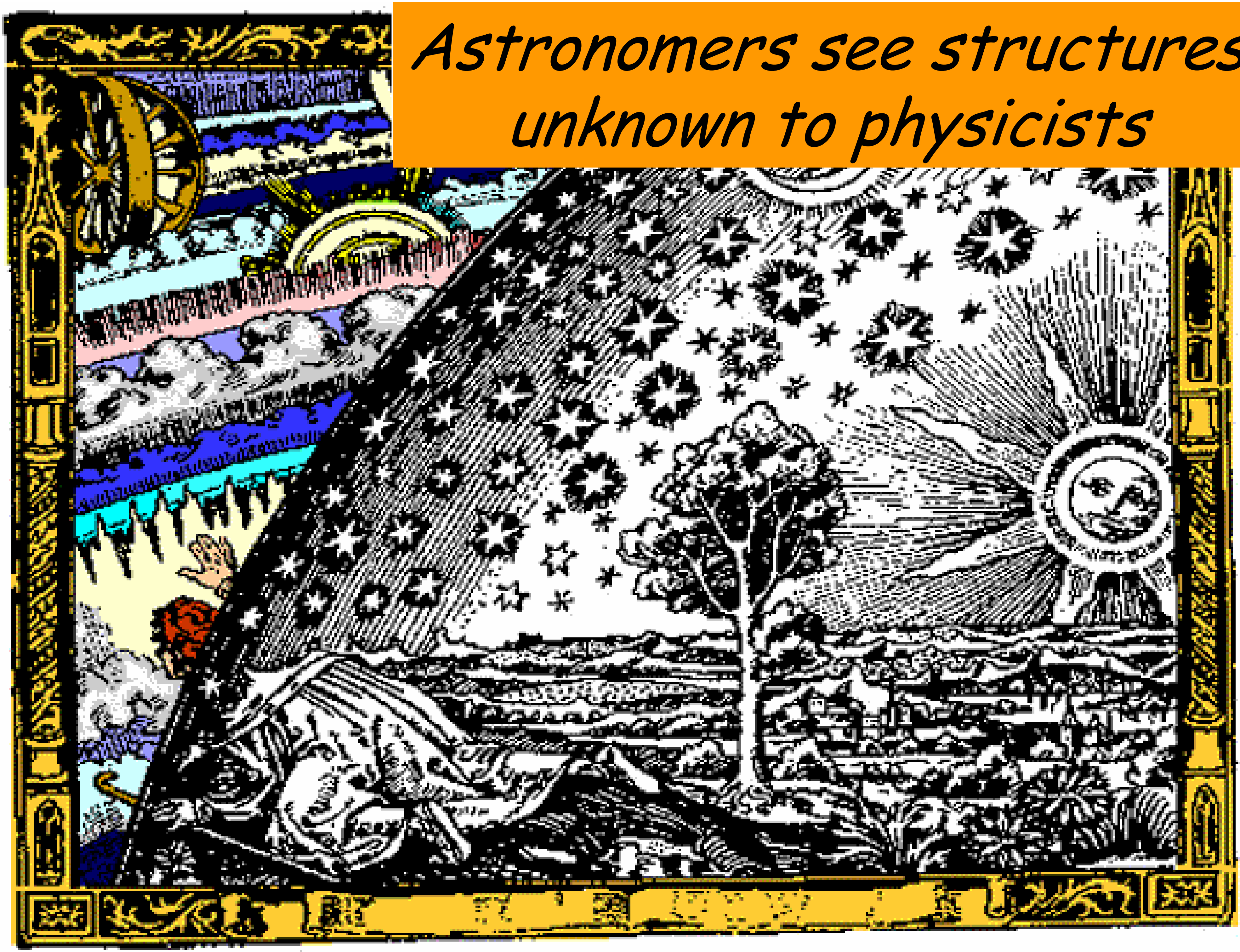
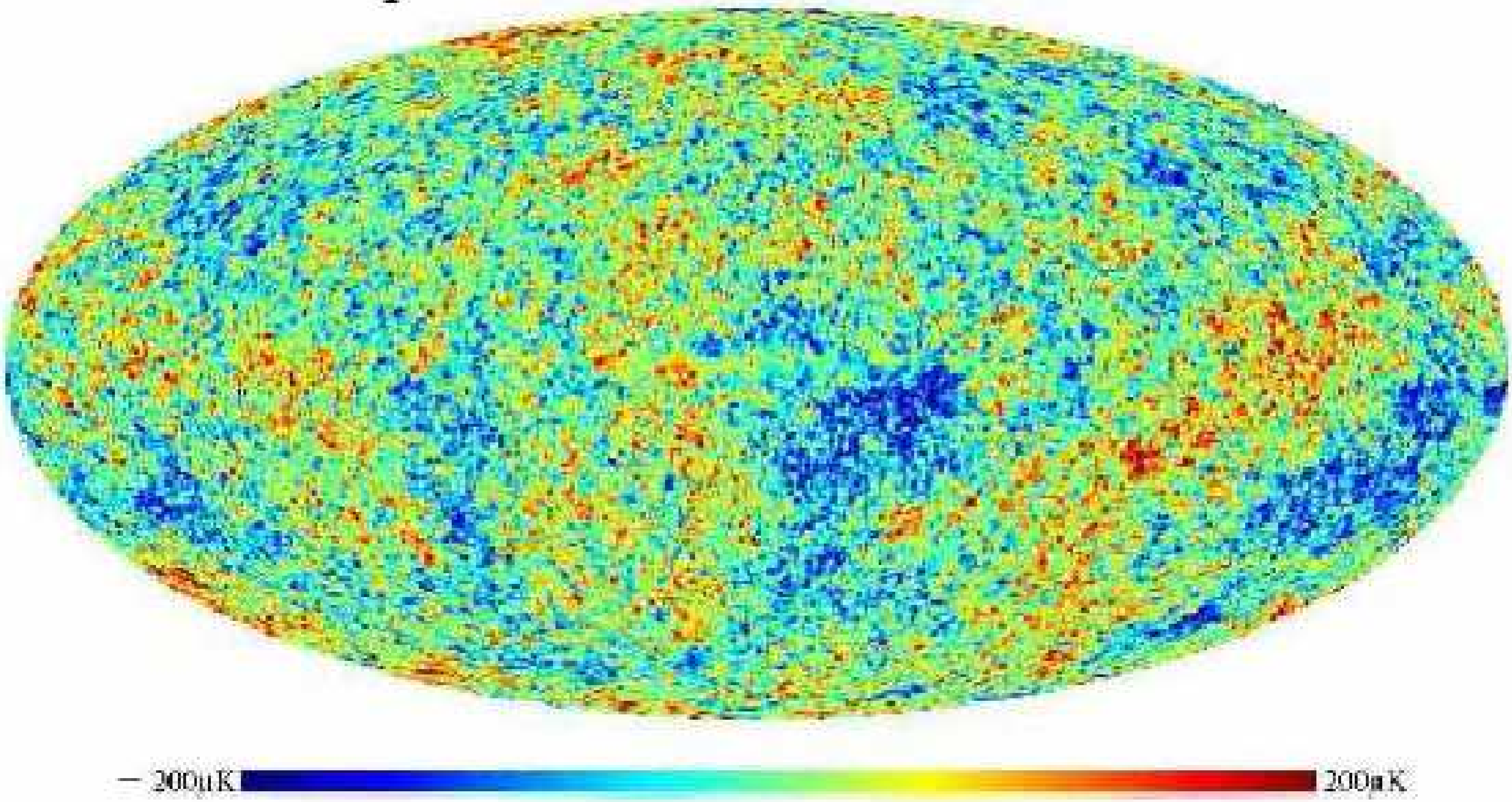
- Identification problem
- Early and late Universe
- Initial conditions for DM structures
- Dark side of matter: where to go ?
- On the eve of new physics

Astronomers see structures unknown to physicists




DM non interacted with radiation
however light is where DM

$$T = 2.725^\circ K, \;\; \frac{\delta T}{T} \sim 10^{-5}$$



WMAP

What we see is structure created from initial conditions + evolution

observational separation of the early and late Universe

no model
theory of origin of initial conditions

the model
no theory of origin of matter

Geometry of the Universe

- **zero order** **Hubble diagram** $a(t)$
- **first order**
  S-mode (density perturbations) $S(k)$
  T-mode (gravitational waves) $T(k)$
  V-mode (vortex perturbations) $V(k)$

Cosmological model in four functions

zero order: late Universe

- Hubble parameter $h = 0.65 \div 0.7$
- Relic CMBR $T = 2.725$ K
- Eucleadian space $\Omega = 1$
- Dark baryons $\Omega_b = 0.5$
- Cold dark matter $\Omega_c = 0.23$
- Dark energy $\Omega_\Lambda = 0.7$
- Theory of structure formation

no theory of
matter origin

first order: early Universe

- Small density perturbations
- Linear Gaussian field
- Scale-invariant spectrum (n_S=1)
- Gravitational waves (T/S < 0.2)
- Theory of initial conditions

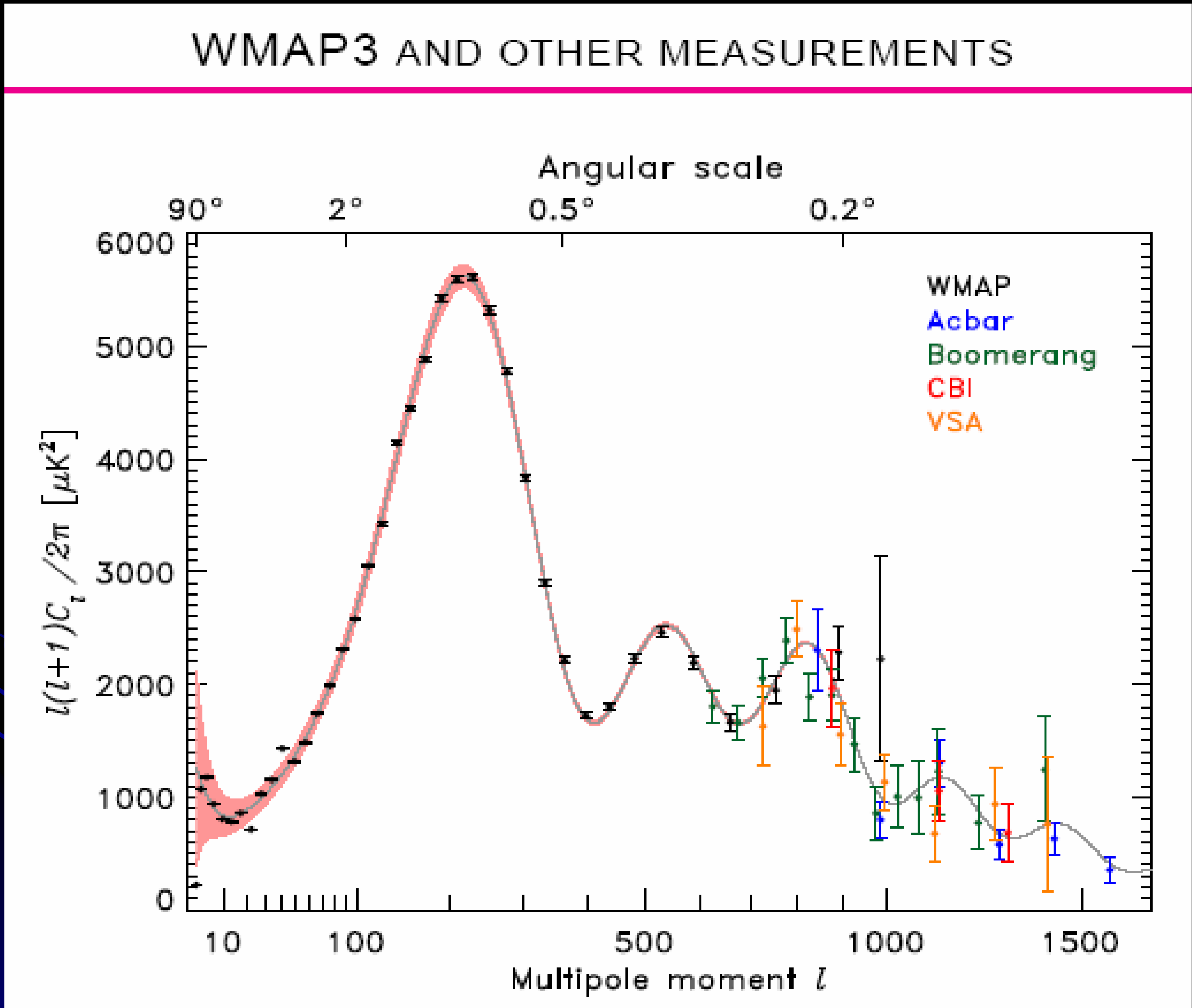
no model of early Universe (H & γ)

Initial conditions

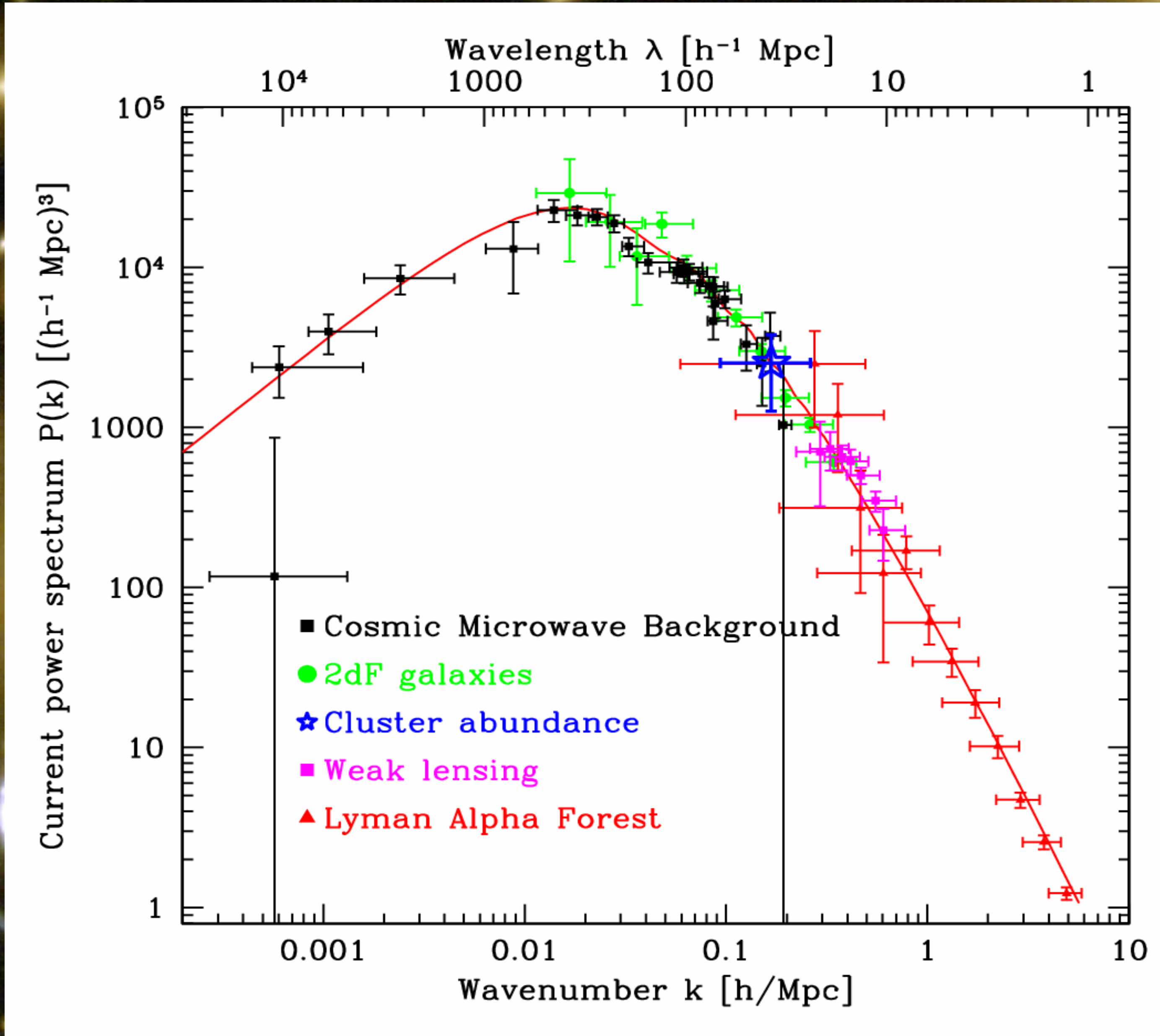
S → seeds for LSS structure (galaxies, clusters, voids..)

S+T+V → imprinted in CMB structure (anisotropy and polarization)

S+T+V


WMAP3 AND OTHER MEASUREMENTS
Angular scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l\ /2\pi\ [\mu K^2]$
WMAP
Acbar
Boomerang
CBI
VSA
10
100
500
1000
1500
Multipole moment l

only S



Tegmark, Zaldarriaga 2002

We live in the Universe with small **T&V**

All values $(\mathbf{T+V})/\mathbf{S} > 0.2$ *are excluded as in this case amplitude of S-mode is insufficient for the formation of the structure*

$\mathbf{T} + \mathbf{S+V} = (10^{-5})^2 \Rightarrow$ *fixed by CMB*

Theoretical physics

T is more fundamental than S !

T is not small, can be detected

T – a clue to the model of early Universe

V - non considered today (unknown seeds)

Origin of cosmological perturbations

quantum gravitational creation of massless fields under the action of non-stationary intensive gravity (parametric coupling), seeds – quantum fluctuations

- Creation of matter (particles, Grib, Starobinsky…1970s)
- Generation of T-mode (gravitational waves, Grishchuk 1974)
- Generation of S-mode (density perturbations, V N L 1980)

Generation of T and S modes in Friedmann cosmology is a quantum-mechanical problem of elementary oscillators $q_k(\eta)$ [λ= a/k, ω= βk] in the Minkowski space-time in the external parametric field $\alpha=\alpha(\eta)$, $\eta=\int dt/a$

$$S_k = \int L_k d\eta, \qquad L_k = \frac{\alpha^2}{2k^3}\left(q'^2 - \omega^2 q^2\right)$$

q_T **- transverse-traceless component of gravitational field**

$$\alpha_T^2 = a^2 / 8\pi G \quad , \qquad \beta = 1$$

q_S **- gauge-invariant superposition of longitudinal gravitational potential and the velocity potential of matter multiplied by the Hubble parameter**

$$\alpha_S^2 = a^2 \gamma / 4\pi G \beta^2 , \quad \beta = c_s / c$$

$$(\; \gamma = -\dot{H} / H^2 , \quad H = \dot{a} / a \;)$$

Evolution of elementary oscillators

$$\bar{q} = \frac{\alpha}{k} q = \beta^{-1/2} \hat{q} \qquad \hat{p} \equiv \frac{\partial L}{\partial \hat{q}'}, \qquad U = \frac{\alpha''}{\alpha}$$

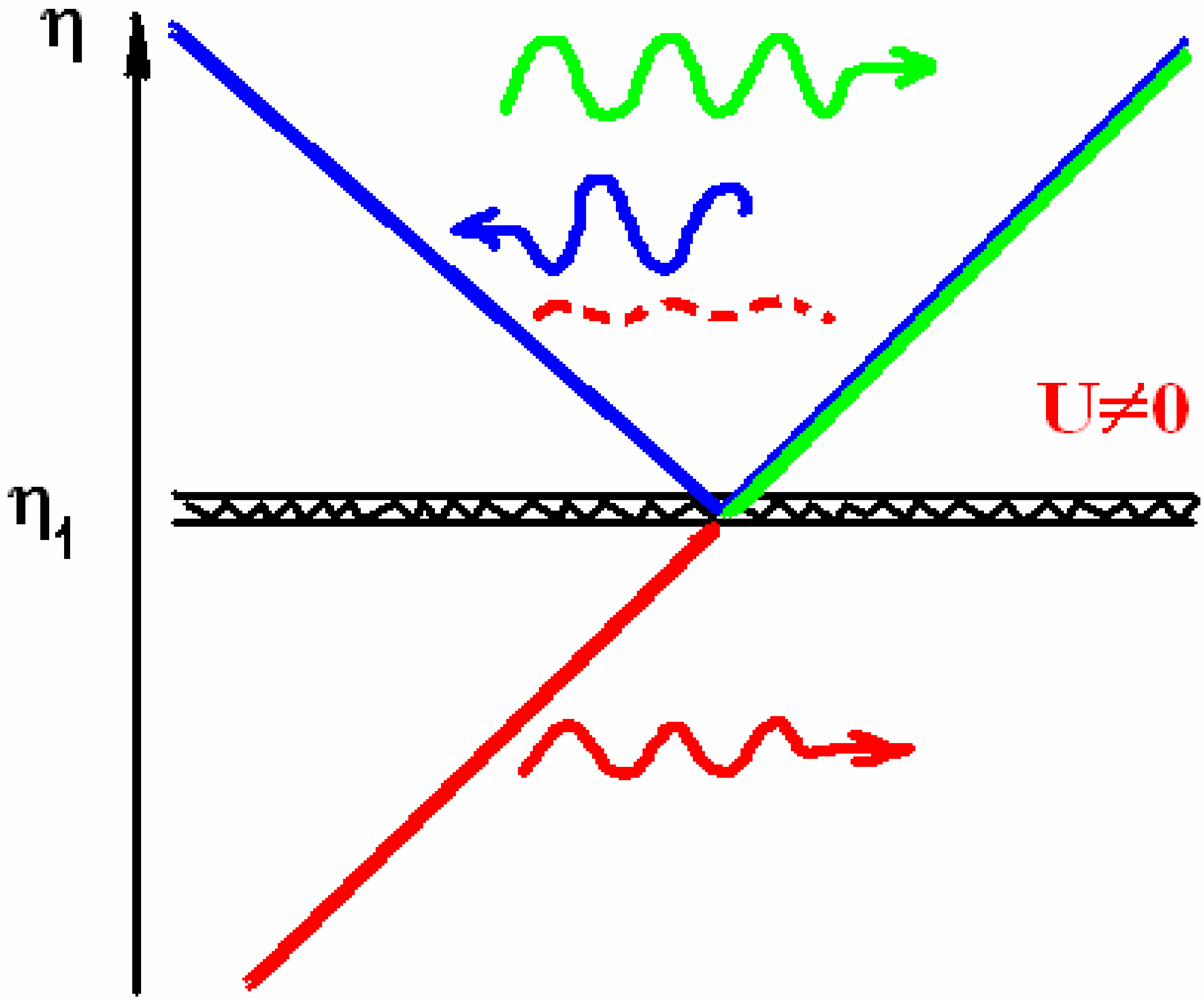
$$L = \frac{\alpha^2}{2k^3}(q'^2 - \omega^2 q^2) = \frac{\omega}{2}(\hat{p}^2 - \hat{q}^2)$$

$$\boxed{\bar{\mathbf{q}}'' + (\omega^2 - \mathbf{U})\bar{\mathbf{q}} = \mathbf{0}}$$

adiabatic zone $\quad \omega^2 > U : \quad |\hat{q}| \sim const$

parametric zone $\quad \omega^2 < U : \quad q \sim const$

creation moment $\quad \omega^2 = U \approx (2-\gamma)(aH)^2$



η
η1
U≠0

Phase information: only growing mode of perturbations is created

$$U = 0: \qquad q = C_1 \underbrace{\frac{\sin\kappa}{\kappa}}_{\text{growing mode}} + \cancel{C_2 \underbrace{\frac{\cos\kappa}{\kappa}}_{\text{decaying mode}}}$$

$(a \sim \eta)$

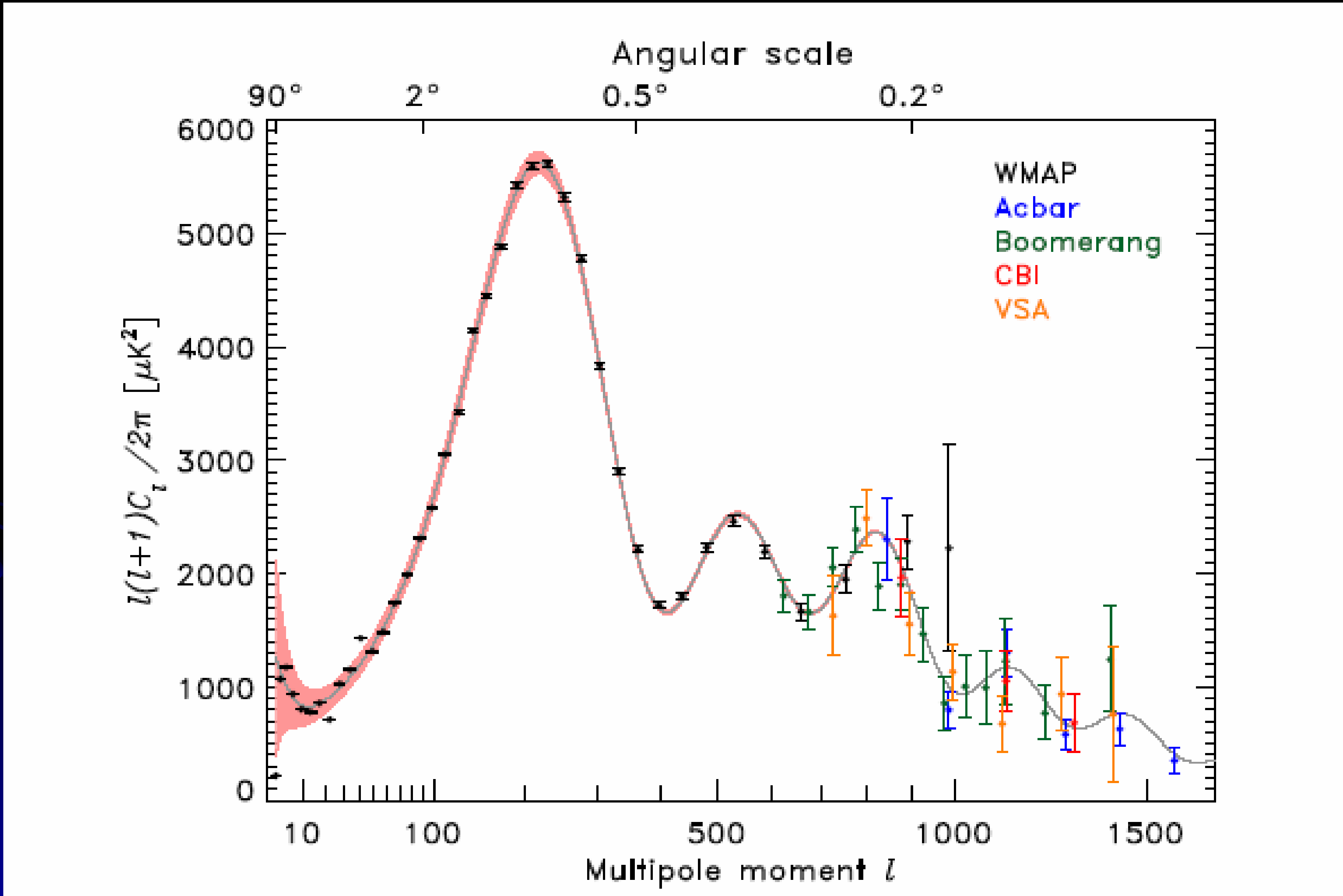
$$\kappa = \omega\eta$$

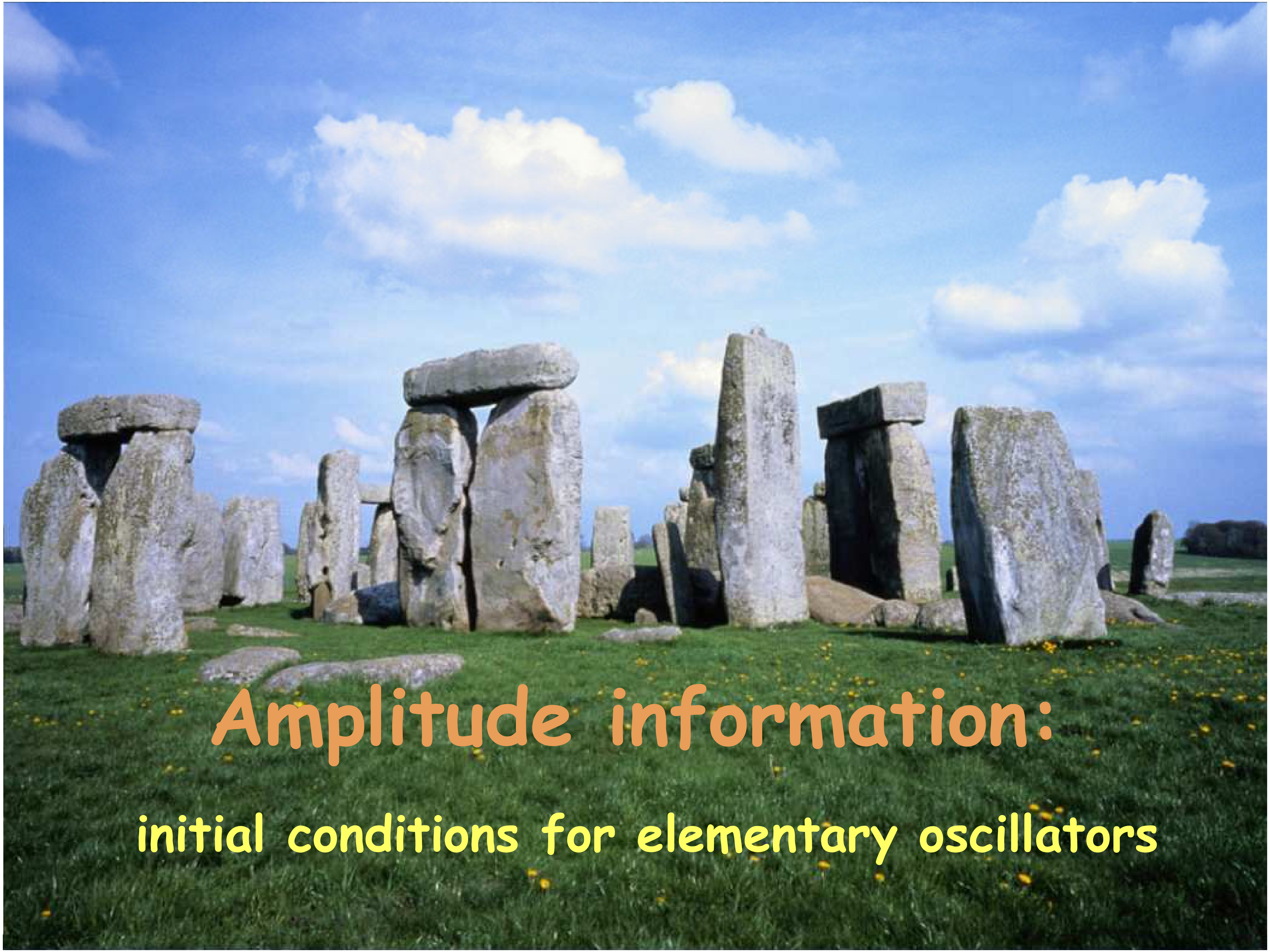
vacuum: $|C_1| = |C_2|$, after creation: $|C_1| >> |C_2|$

first peak: $\kappa = \pi$

$$\ell_p = \pi\eta_0 \cong \frac{\pi\sqrt{3}\eta_0}{\eta_{rec}} \cong 200$$

we see the sound !




Amplitude information:
initial conditions for elementary oscillators

$$T \equiv 2\langle q_T \rangle^2, \qquad S \equiv \langle q_S \rangle^2$$

two polarizations of gravitational wave

$\langle \ \rangle$ **initial vacuum state,**

the minimal level of excitations of an elementary oscillator in adiabatic zone

$$\boxed{\langle \hat{\mathbf{p}}^2 \rangle = \langle \hat{\mathbf{q}}^2 \rangle = \frac{\hbar}{\mathbf{2}}}$$

Uniqueness of the ground state in the Friedmann geometry (VNL 2006)

General scenario of early Universe

Vacuum is determined in adiabatic zone, $\eta<\eta_0$

$$\boxed{\left\langle \hat{p}^2 \right\rangle = \left\langle \hat{q}^2 \right\rangle = \frac{\hbar}{2}}$$

Parametric zone, $\eta>\eta_0$

$$\left\langle q^2 \right\rangle_{\eta\geq\eta_0} \approx \frac{k^2}{\alpha^2\beta}\left\langle \hat{q}^2 \right\rangle_{\eta\leq\eta_0} = \frac{\hbar k^2}{2\alpha^2\beta}$$

$$\frac{T}{S} \equiv 2\left.\frac{\left\langle q_T \right\rangle^2}{\left\langle q_S \right\rangle^2}\right|_{\eta>\eta_0} = 2\beta\left(\frac{\alpha_S}{\alpha_T}\right)^2 = 4\frac{\gamma}{\beta}\left(\frac{a_S}{a_T}\right)^2$$

Universal result

$$T = 4\pi(2-\gamma)\left(\frac{H}{M_P}\right)^2 \quad , \quad \frac{T}{S} = 4\gamma$$

expected:

$$\mathbf{H < 10^{13}\,Gev \quad , \quad \gamma < 0.05}$$

Two ways to realize $U=(2-\gamma)(aH)^2>0$

$*\quad \gamma \le 2:$ scattering problem ($\gamma=2 \rightarrow$ RD)

($T \sim k^2$ - **blue spectra**, Kompaneets, V.N.L. 1981)

$$n_T \equiv \frac{d\ \ln(T)}{d\ \ln(k)} = 2 = 0.25\ \frac{T}{S} > 1$$

$*\quad (aH)^{\bullet} = \ddot{a} > 0 \quad (\gamma < 1):$ inflation

($T \sim H^2$ - **red spectra**, Starobinski 1979)

$$-n_T = 2\gamma = 0.5\frac{T}{S} < 1$$ - **Inflation test!**

T is not negligible !

Power-law inflation on massive field:

the amplitude of T-mode is five times as less than the amplitude of S-mode

Dark side of matter
where to go ?

- ✓ Origin of matter
- ✓ DM properties
- ✓ DM particles ?


Origin of matter
Only hypotheses, no theory

Message from the early Universe

DM mystery is related
to baryonic asymmetry


We live in matter world
Prompt: $\varepsilon_b \cong \varepsilon_{DM}$ now and early

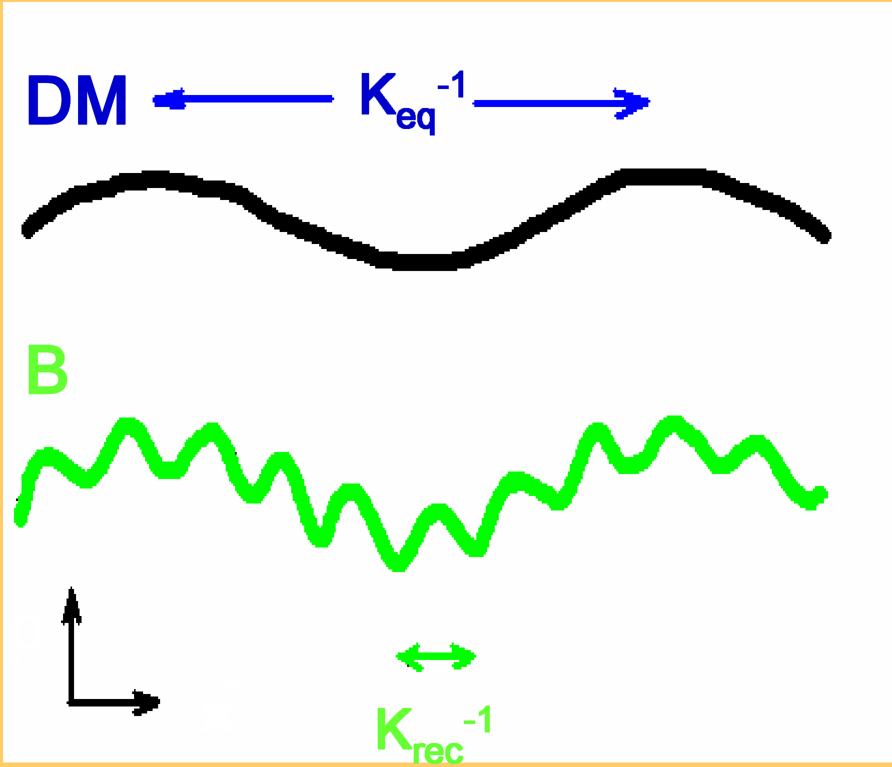
Other prompt:
coincidence of LSS and CMB scales

$$\left(\frac{\eta_B}{\eta_{DM}}\right)^2 = \frac{z_{eq}}{z_{rec}} \cong \frac{3200}{1100} \cong \boxed{3}$$

LSS: $$k_{DM} = \frac{1}{\eta_{eq}}$$

CMB: $$k_B = \frac{1}{c_S \eta_{rec}} \cong \frac{\boxed{\sqrt{3}}}{\eta_{rec}}$$

$$\frac{k_{DM}}{k_B} = \frac{\eta_{rec}}{\sqrt{3}\eta_{eq}} = 1$$



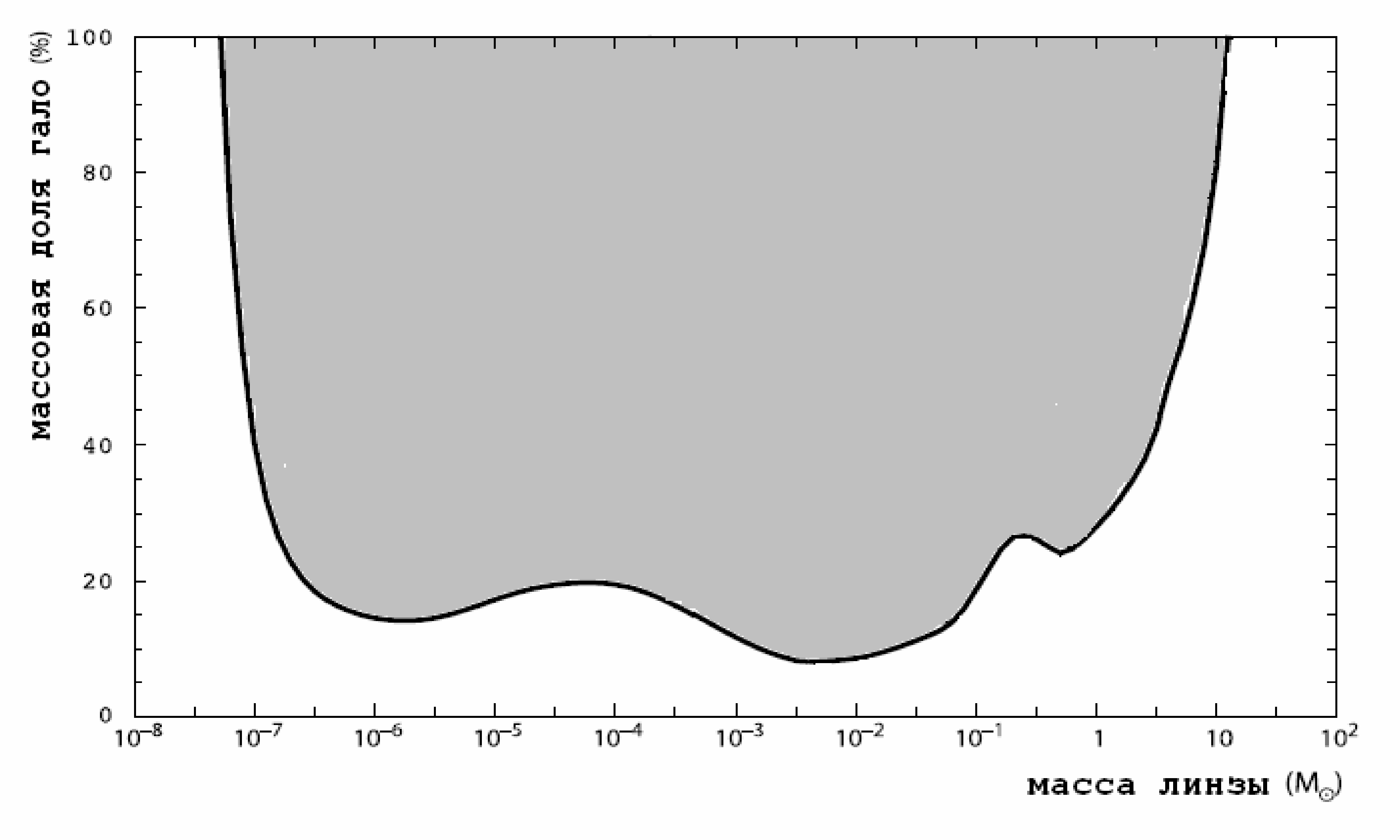
Where is DM matter ?

Visible: * stars and gas in galaxies
* gas in clusters (T~ keV)

Dark baryons:
* intergalactic gas (T~ 0.1 keV)
* MACHO (BH, NS, WD, BD, jupiters, asteroids)

in galactic halo - no more than 20% of MACHO

the rest 80% - nonbaryonic DM



Upper bound on galaxy MACHO objects (EROS)

Where else is non-baryonic DM ?

* large velocity dispersion in clusters (1930)
* flat rotation curves in spiral galaxies (1970)
* galaxy clusters' masses determined (1980)

→ X-ray gas (T~ keV)
→ gravitational lenses

answer: nonbaryonic DM is in gravitational bounded systems

weakly interacting particles
do not dissipate as baryons

Baryons cool down radiationally and reside to centers of dark matter halos getting rotational equilibrium

Dark matter remains assembling around visible matter at scale ~ 200 кpc
(the mass of Local Group ~ $2 \div 4 \cdot 10^{12}\ M_{\odot}$
about half in Milky Way and Andromeda)

Hypotheses of non-baryonic DM

"Go there don't know where. Bring me that don't knw what"

candidats	mass
Gravitons	10^{-21} eV
Axions	10^{-5} eV
Sterile neutrinos	10 keV
Mirror particles	1 GeV
Massive particles	100 GeV
Supermassive particles	10^{13} GeV
Monopoles, defects	10^{19} GeV
Primordial black holes	10^{-16}-10^{-7} $M_{\odot}$

Basic DM version
(to be verified in LHC, 2008)

- unknown particles (WIMPs)
- mass ~ 100 ГэВ, one particle in a glass
- stable, neutral, weakly interacting (neutralino)

New physics!

Independent verification: WIMP minihalos

Probability for Earth to be in minihalo ~ 10%

Excess of DM particles in minihalo ~ 10

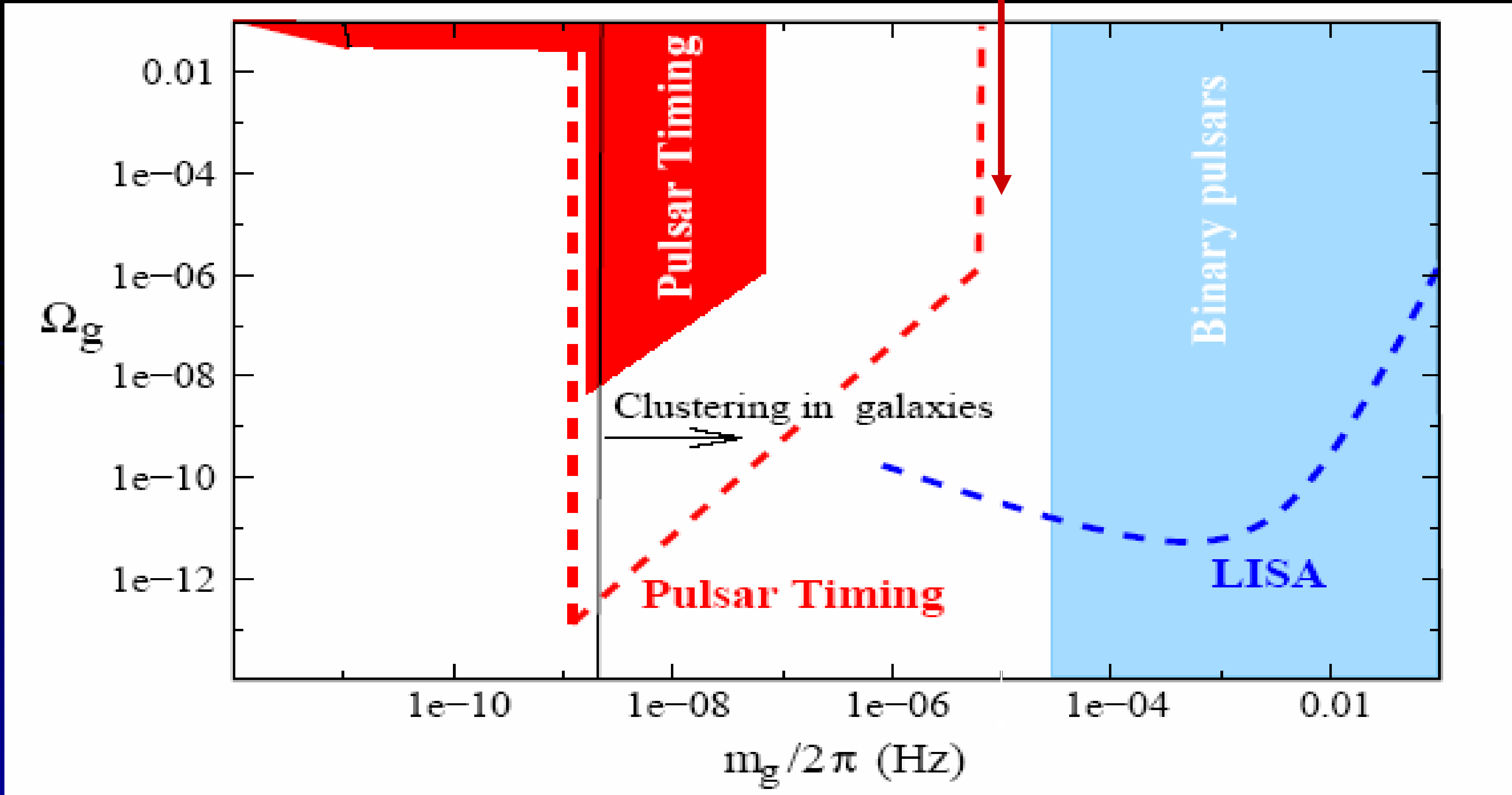
Gain in the annihilation signal > 10

Cusp problem – a key to DM physics

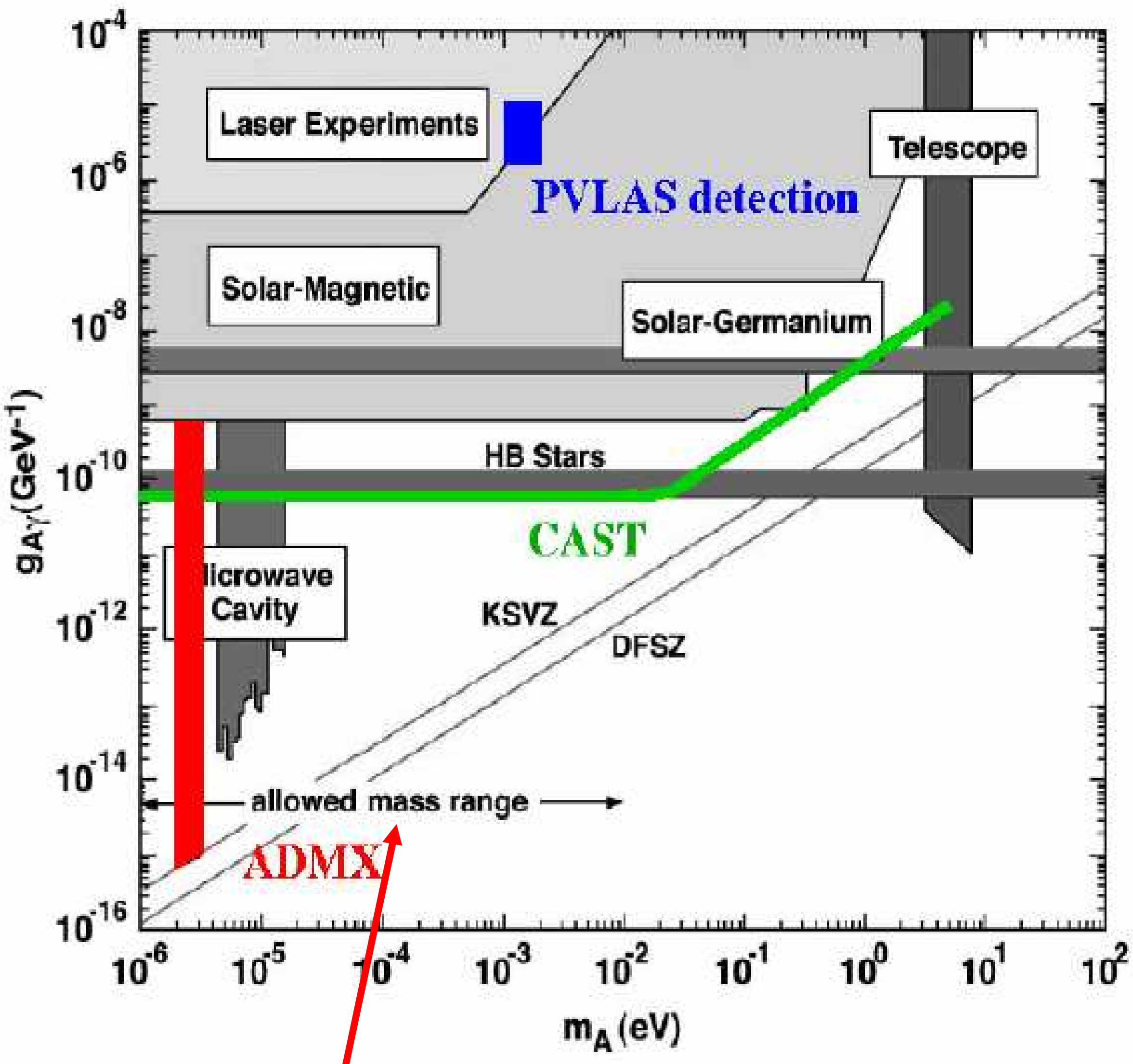
* predicted in simulations ...
* unobserved in dwarf galaxies ..
* possible connection with massive BHs

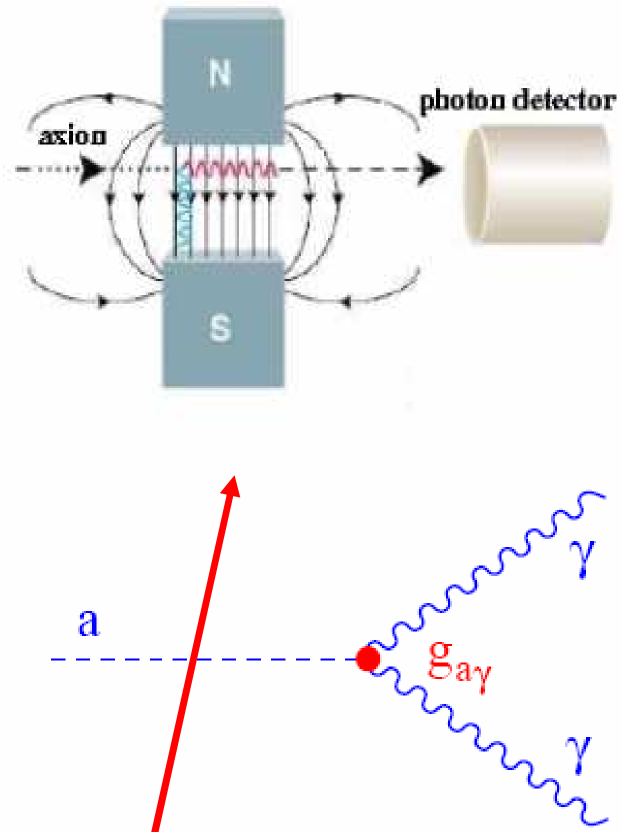
DM alternative- modification of gravity

example: massive gravitons (gravitational creation in early Universe, <u>monochromatic signal for LISA</u>)



Constraints on parameters of axion

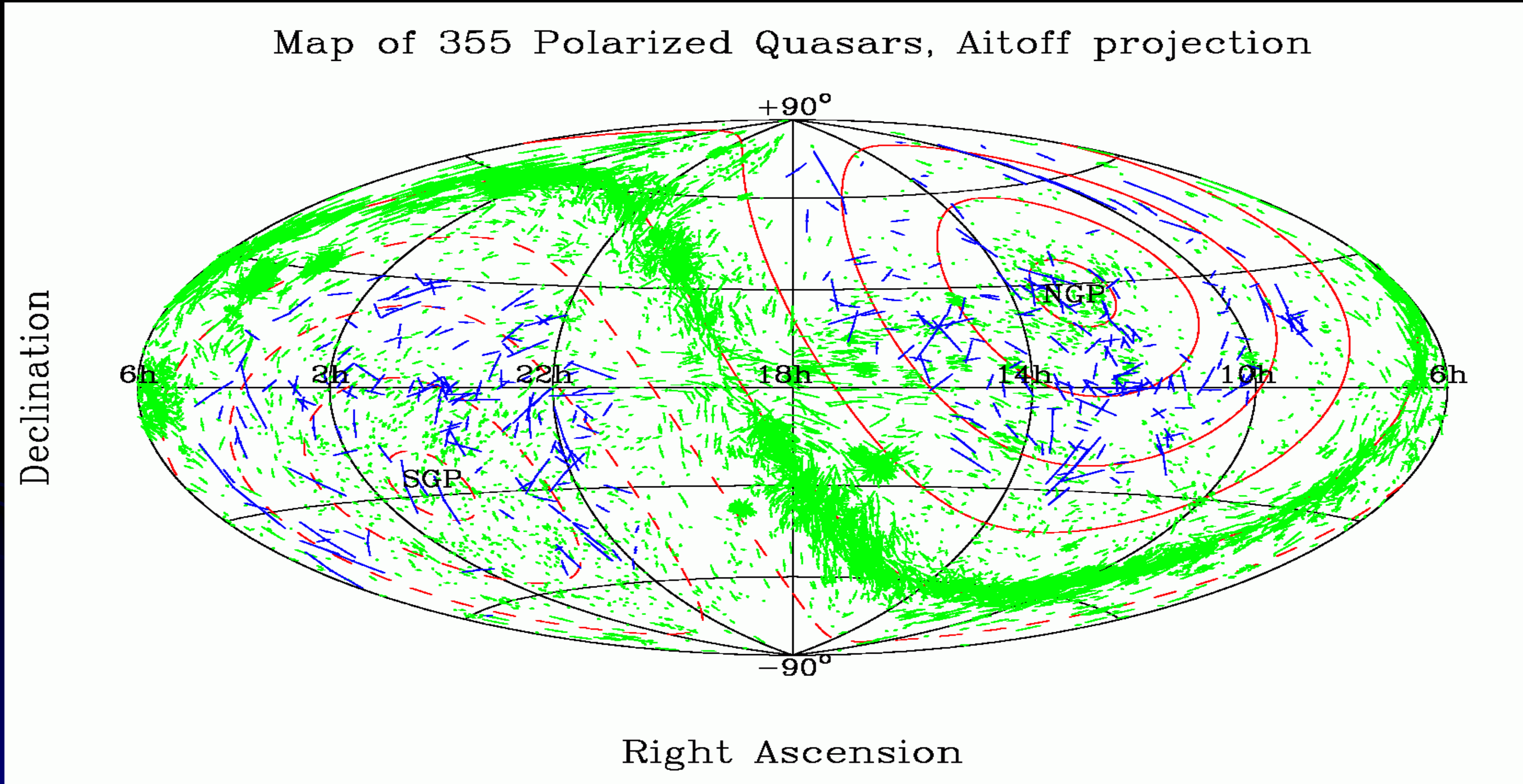




allowed masses

conversion axion-photon -axion in magnetic field

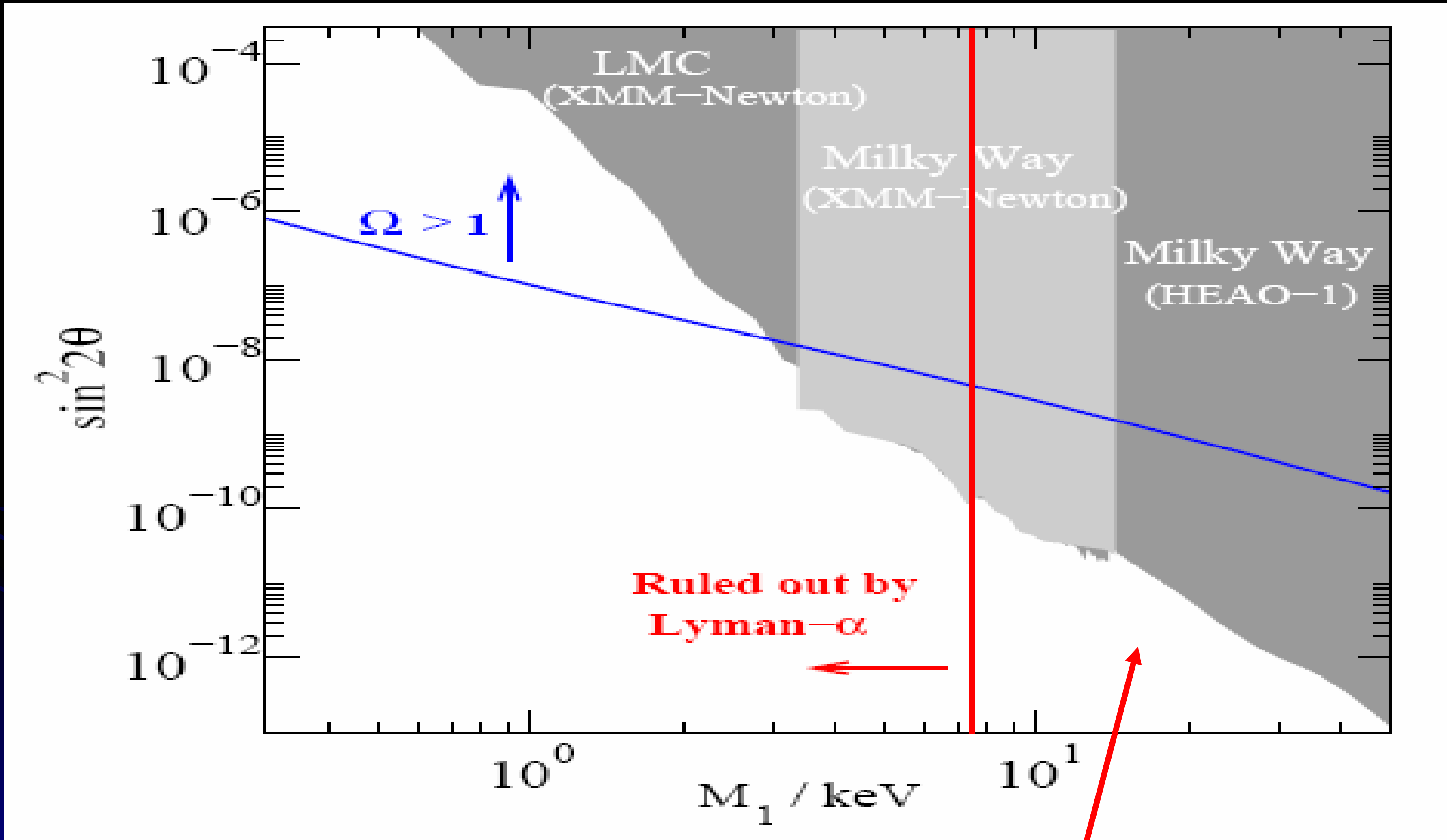
Large scale correlation of the QSO polarization position angle



may arise in extragalactic magnetic field due to conversion of photons to axions

Constraints on sterile neutrino

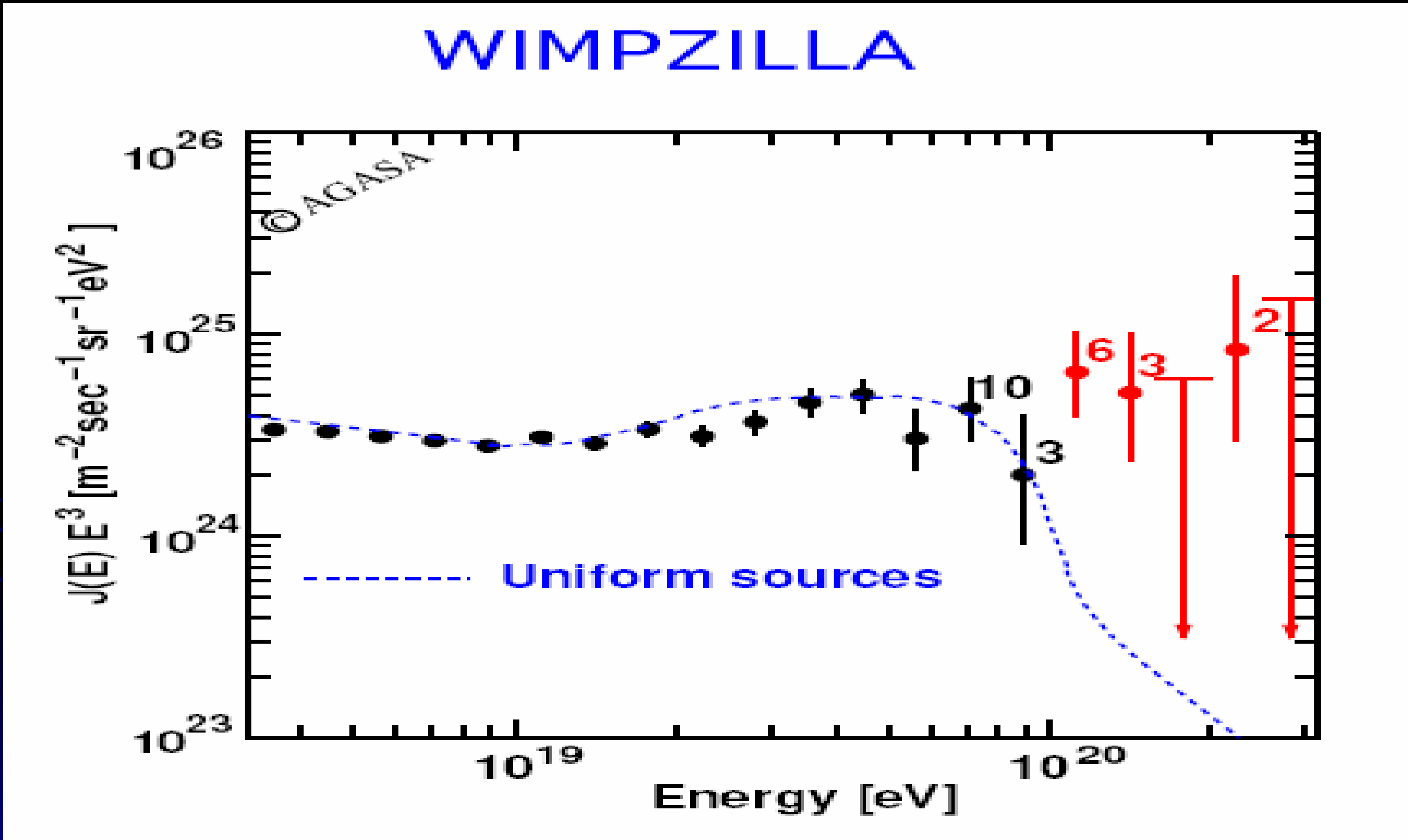
(DM is not dark because of massive neutrino decay)



remaining region for 10 keV neutrinos

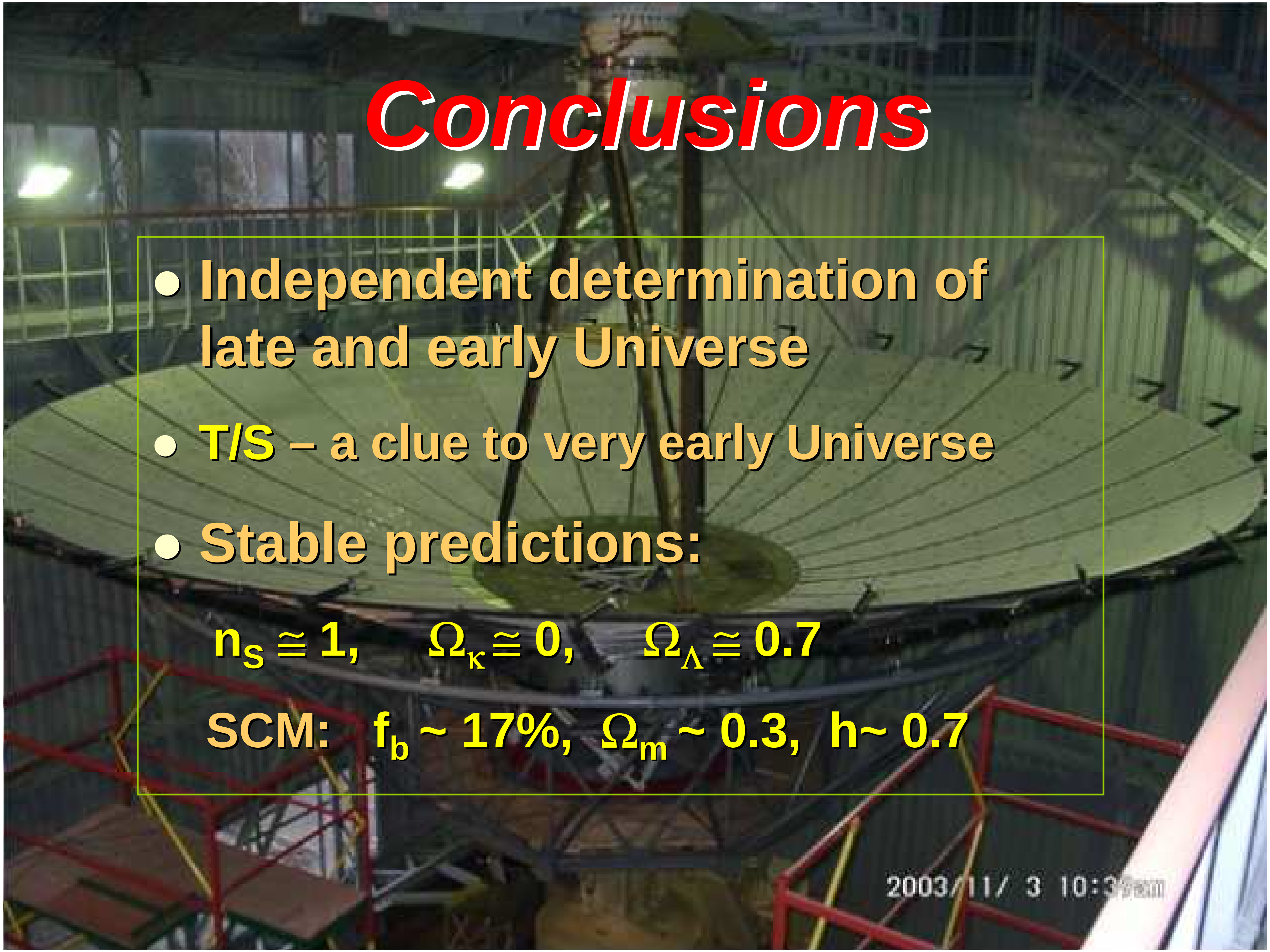
Supermassive particles ~ 10^{13} GeV

(gravitational creation in the early universe)



Prediction: anisotropy in UHECR distribution

Conclusions



- **Independent determination of late and early Universe**
- **T/S – a clue to very early Universe**
- **Stable predictions:**

$n_S \cong 1$, $\Omega_\kappa \cong 0$, $\Omega_\Lambda \cong 0.7$

SCM: $f_b \sim 17\%$, $\Omega_m \sim 0.3$, $h \sim 0.7$

Theory is exhausted

presenting a list where/how
to search for DM particles

Experiment's turn

The situation reminds great historical moments: quarks, W-Z-bosons, neutrino oscillations, CMB anisotropy, polarization

Why Nature is generous to us and discloses its secrets ?