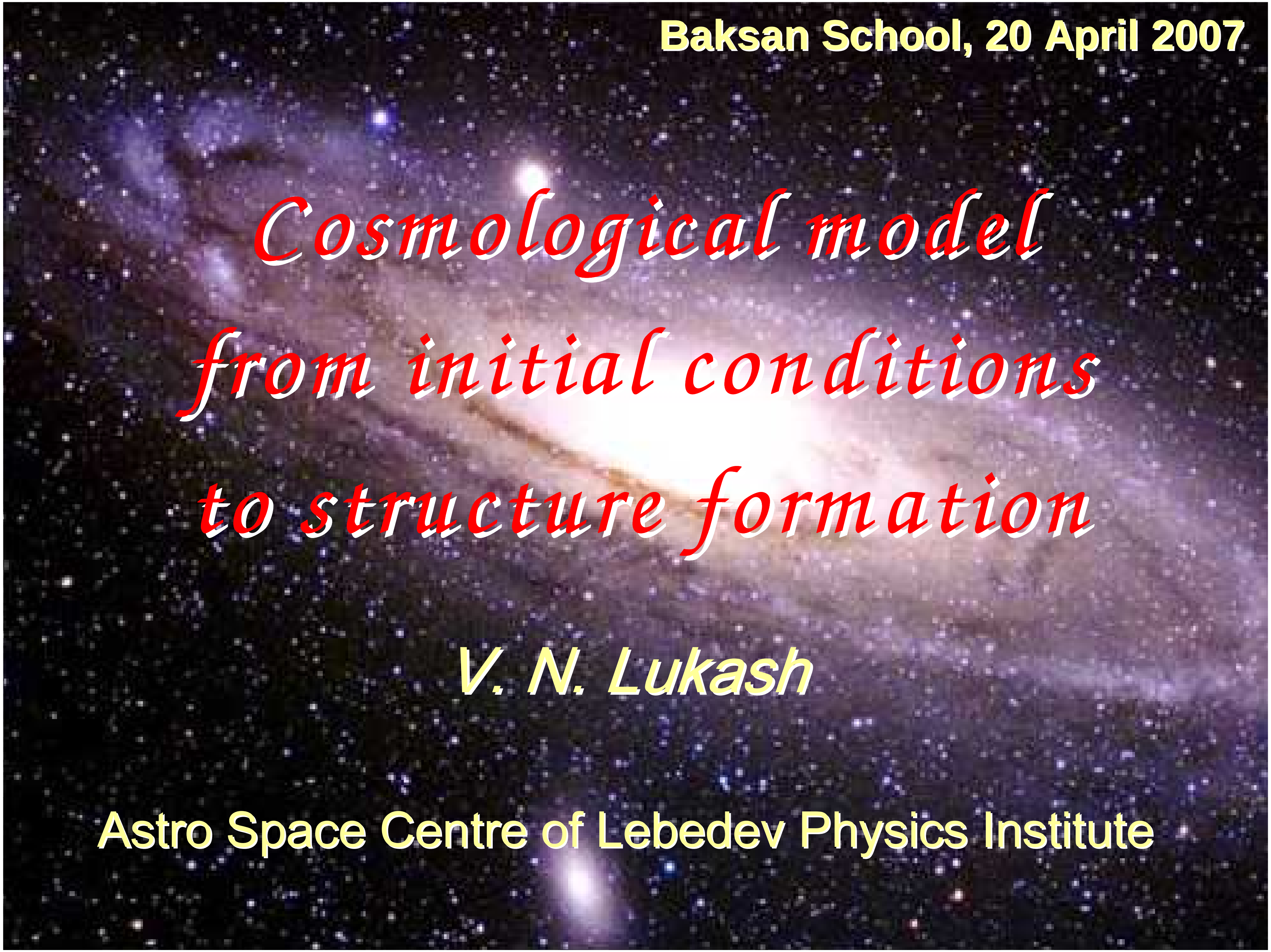


Baksan School, 20 April 2007

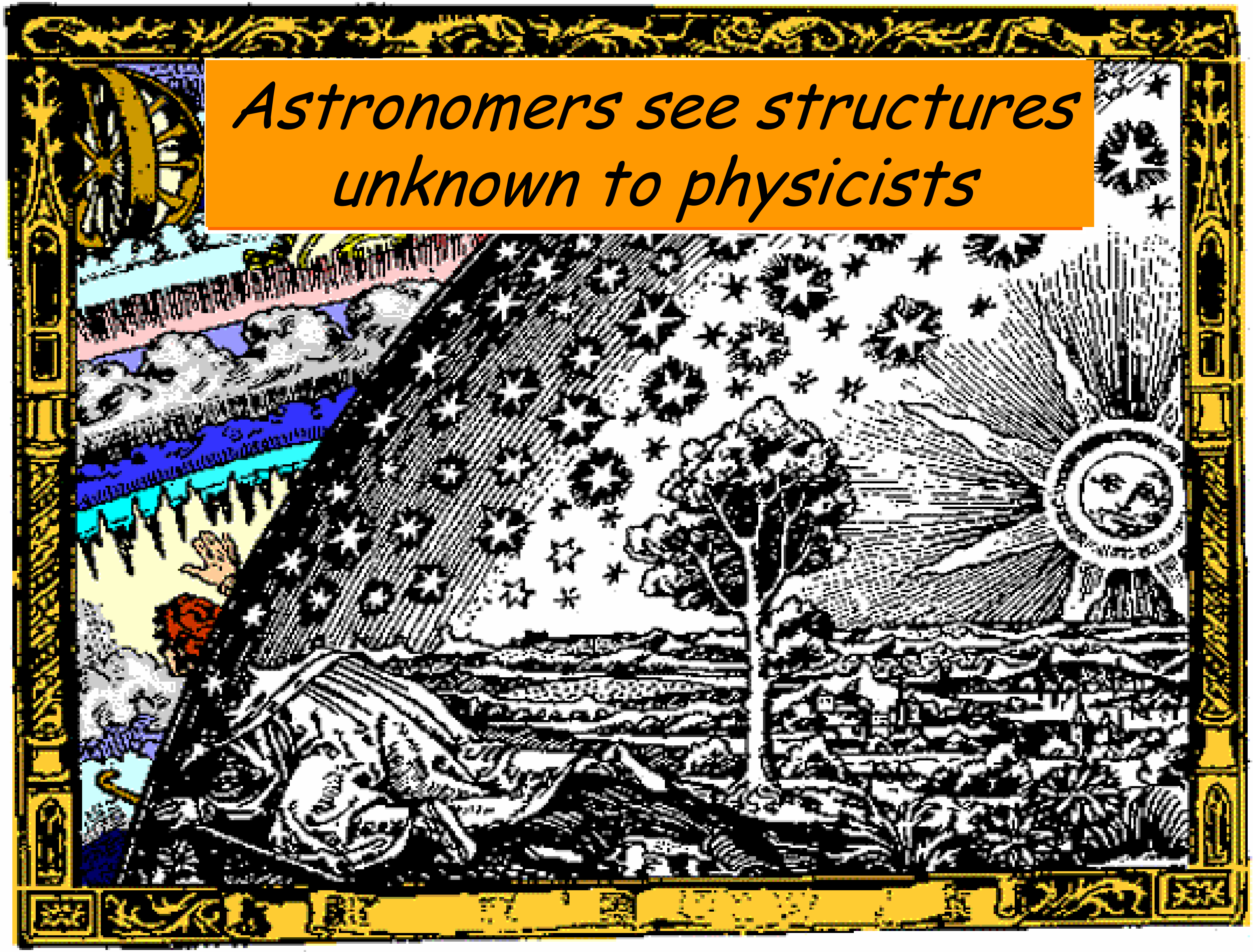
Cosmological model from initial conditions to structure formation

V. N. Lukash

Astro Space Centre of Lebedev Physics Institute

- Identification problem
- Origin of initial conditions
- Dark side of the Universe
- On the eve of new physics

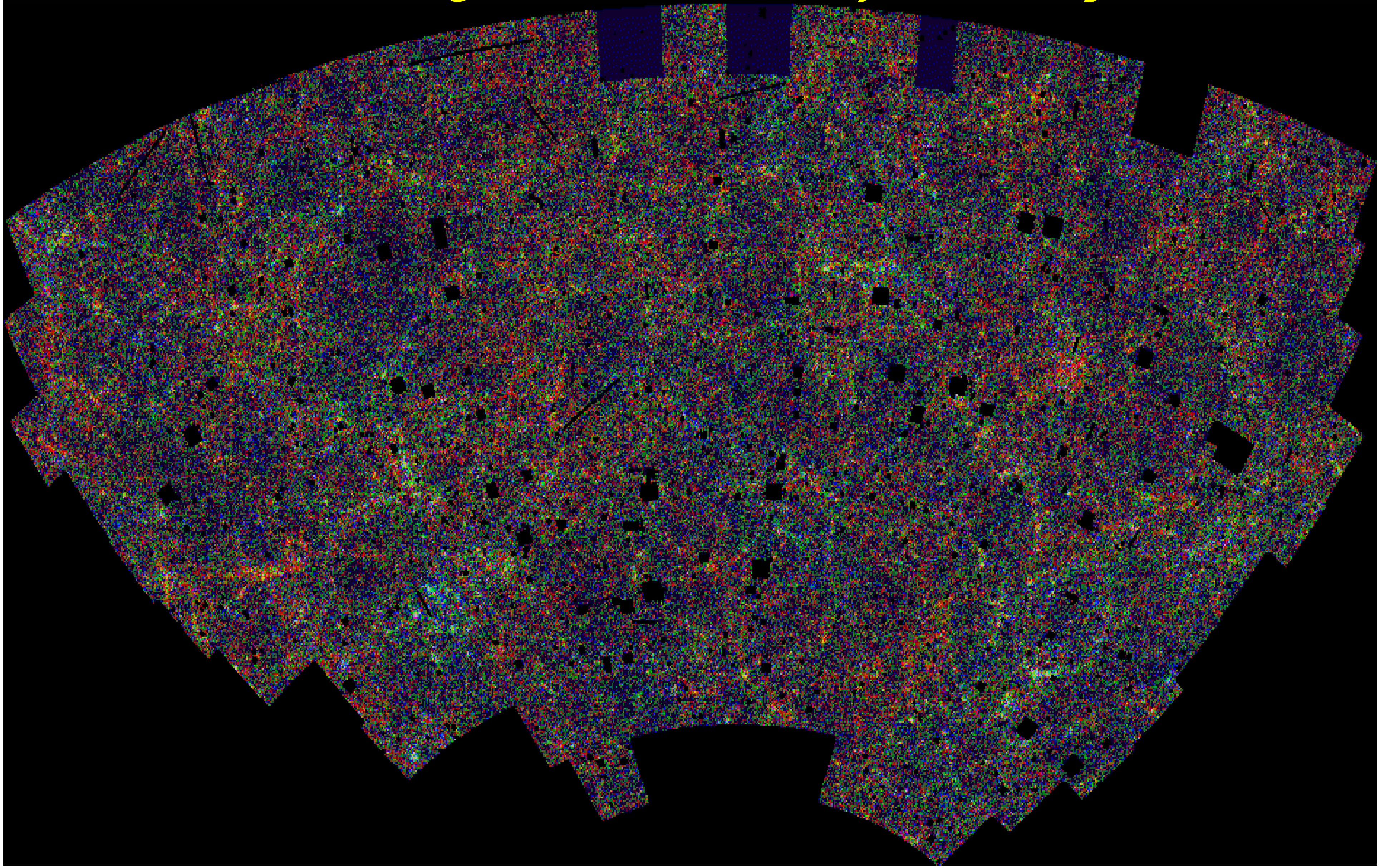
Astronomers see structures unknown to physicists

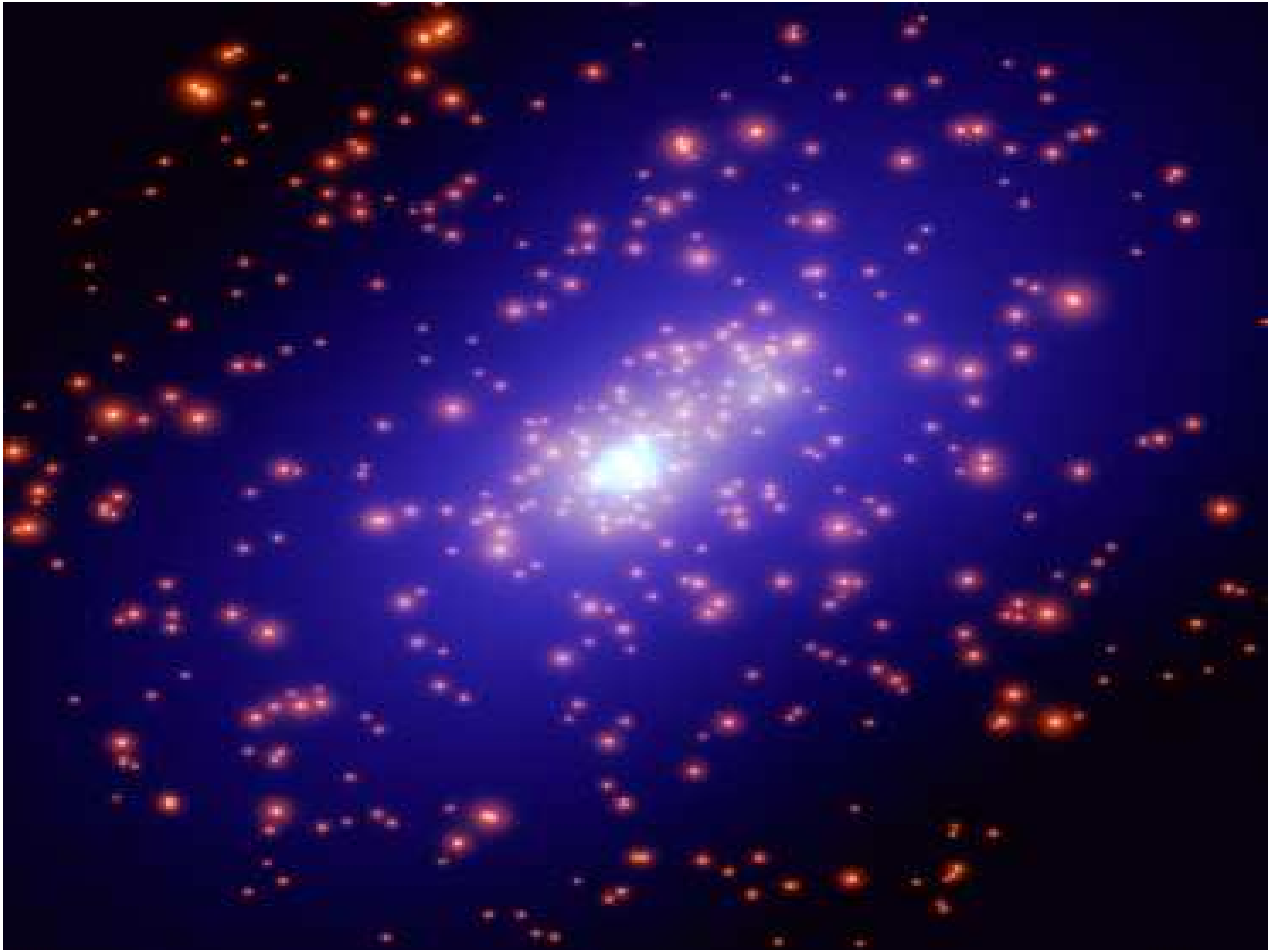


DM non interacted with radiation
however light is where DM

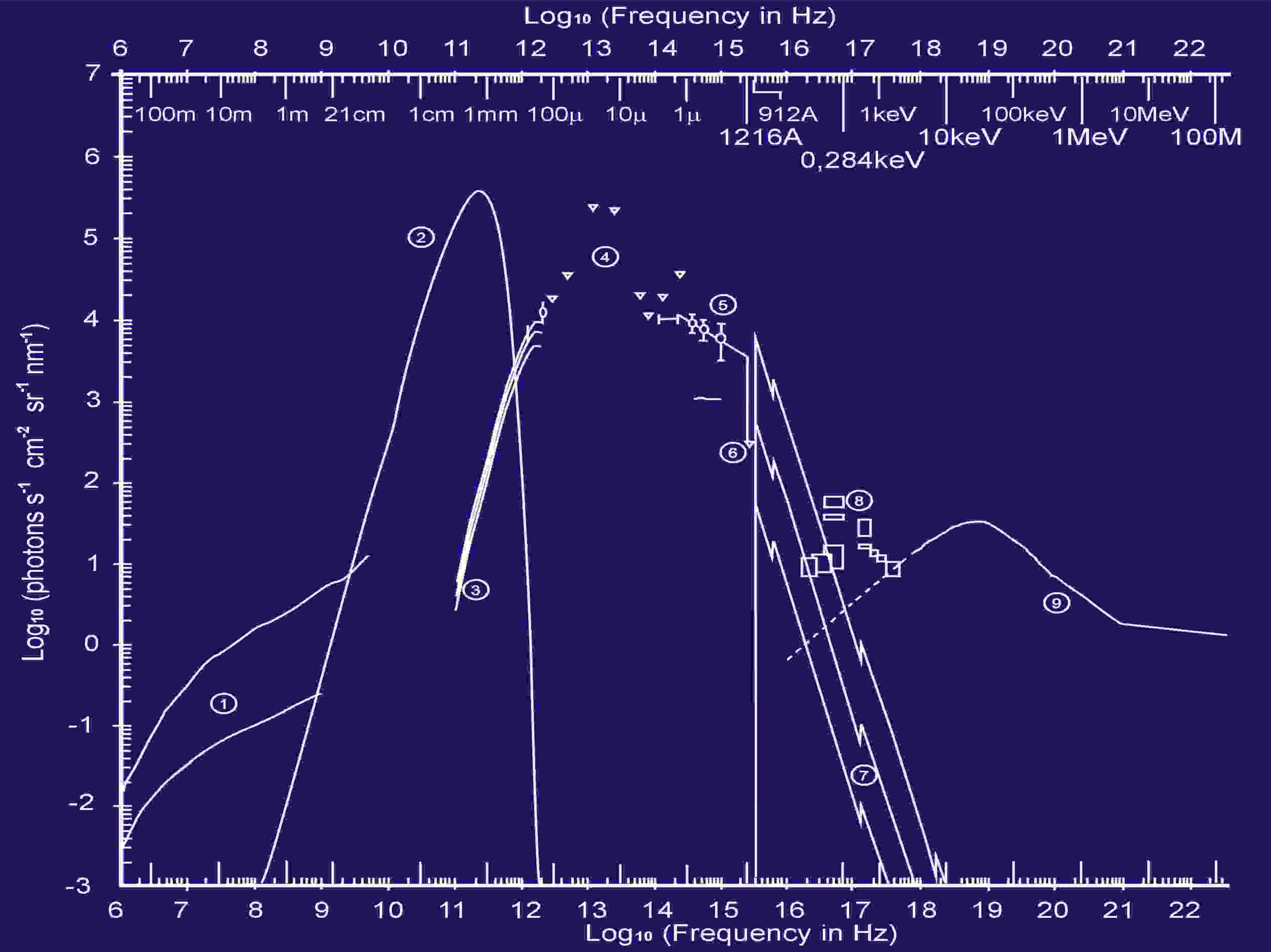
APM galaxy catalog

(2 million galaxies, 1/10 of the Sky)



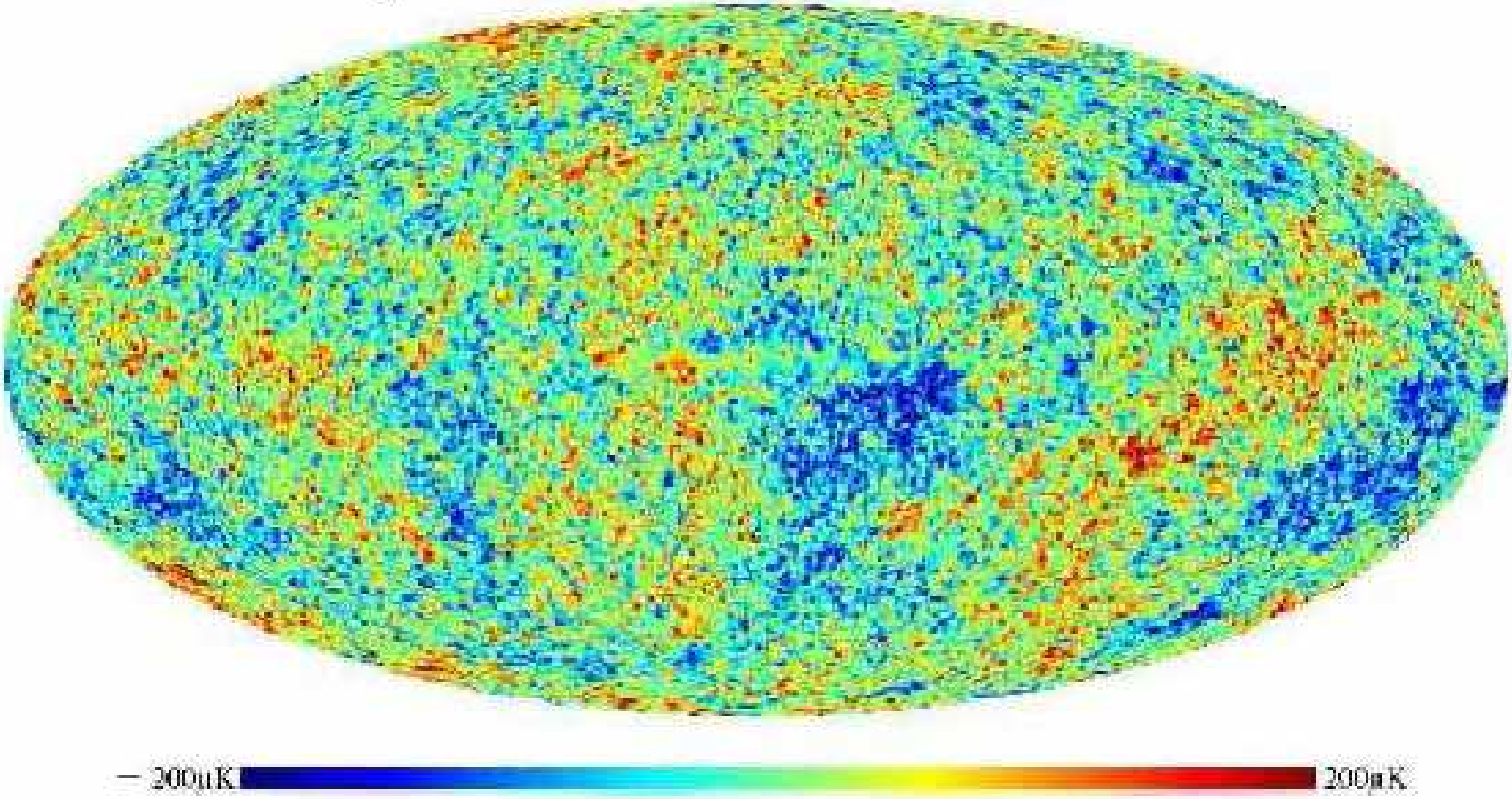


...rare exception



Log₁₀ (Frequency in Hz)
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
100m
10m
1m
21cm
1cm
1mm
100µ
10µ
1µ
912A
1216A
0,284keV
1keV
10keV
100keV
1MeV
10MeV
100M
7
6
5
4
3
2
1
0
-1
-2
-3
Log₁₀ (photons s⁻¹ cm⁻² sr⁻¹ nm⁻¹)
①
②
③
④
⑤
⑥
⑦
⑧
⑨
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
Log₁₀ (Frequency in Hz)

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



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 our 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÷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

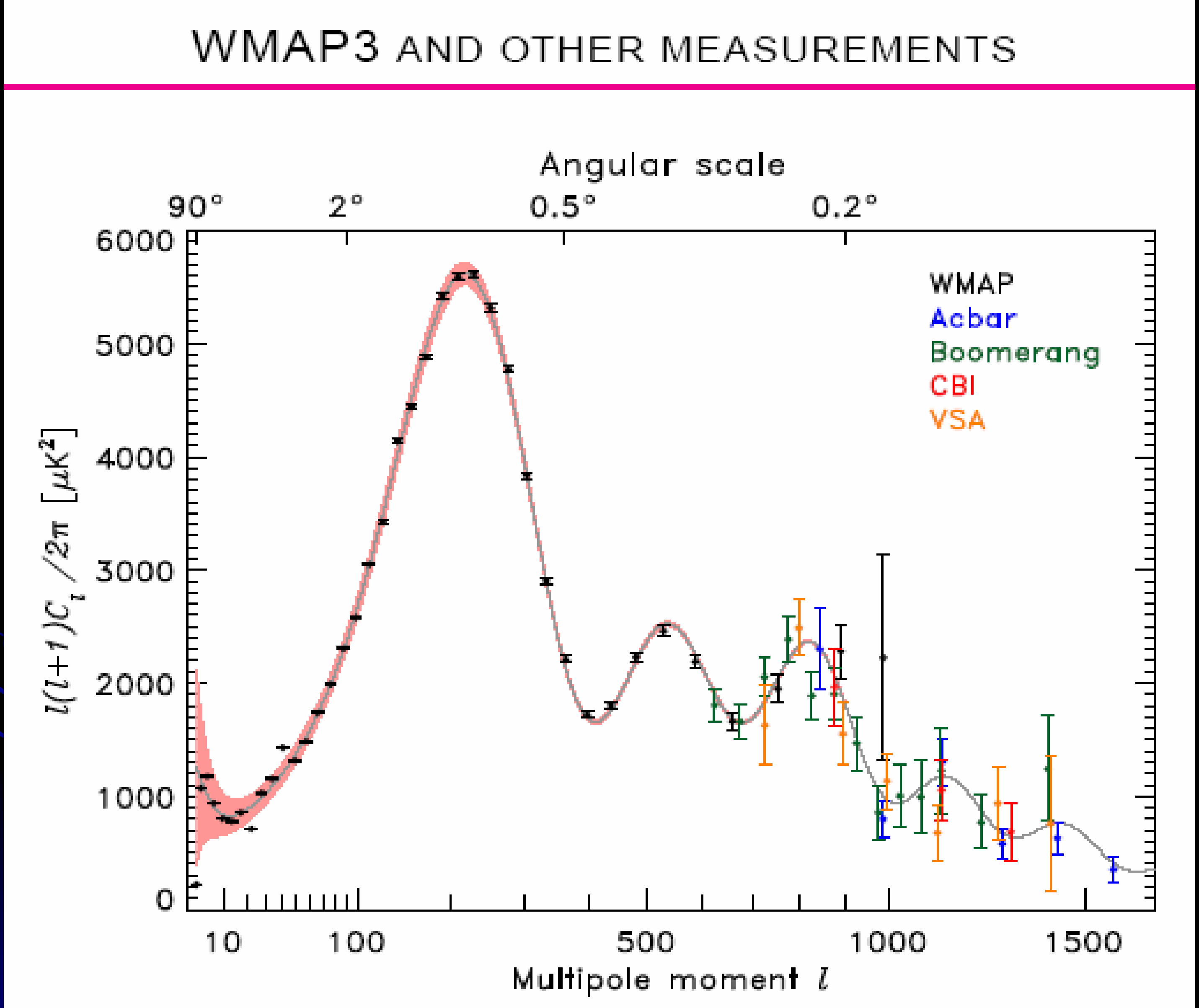
no model of early
Universe (H & γ)

Initial conditions

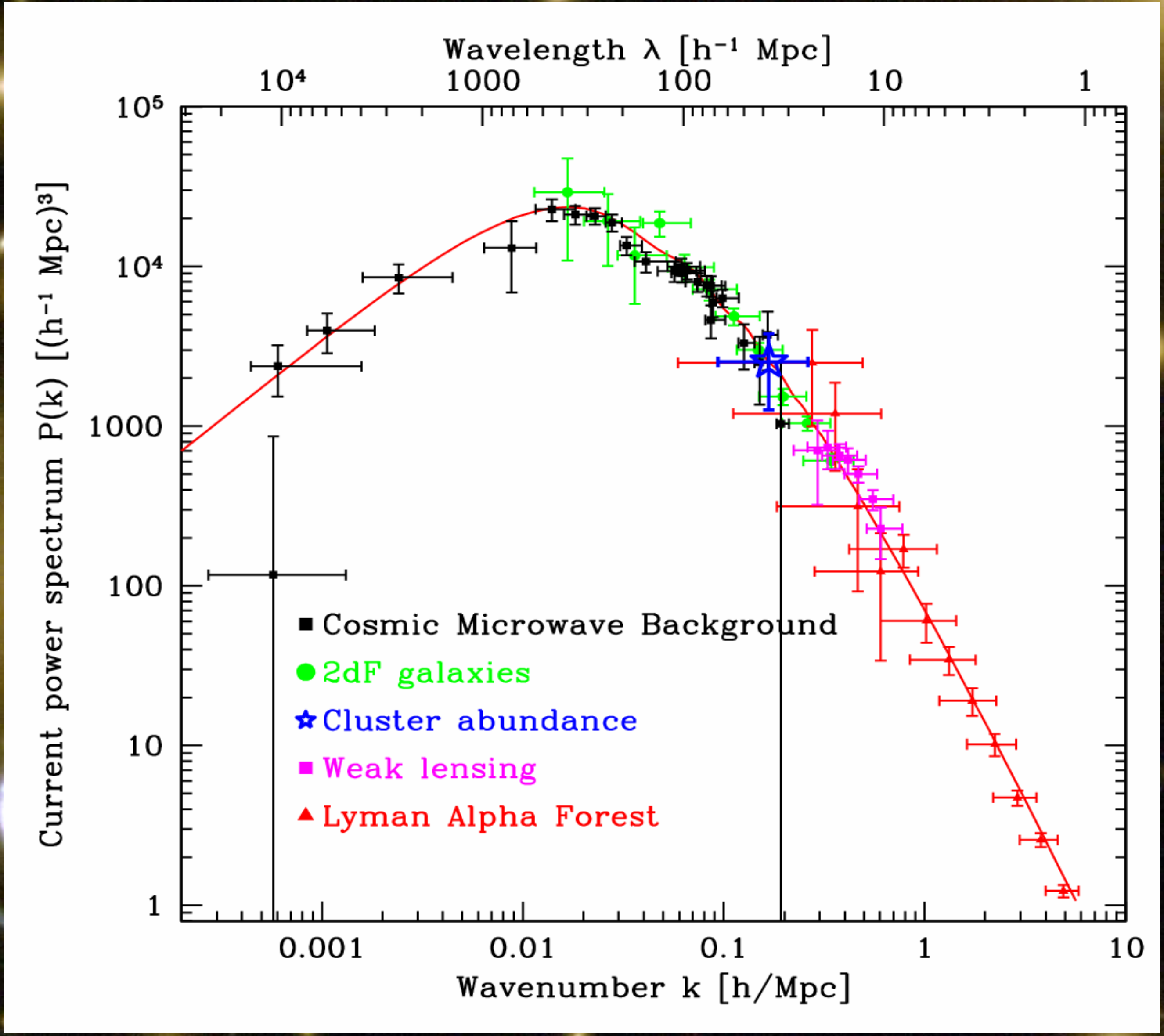
S → seeds for LSS structure
(galaxies, clusters, voids..)

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

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 - 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 a non-stationary gravitational potential (external coupling)

- 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 (ƛ= a/k, ω= βk) in external parametric field α=α(η)

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

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**

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

$$\boxed{g_{\mu\nu} \rightarrow g_{\mu\nu} + h_{\mu\nu}, \quad T_{\mu\nu} \rightarrow T_{\mu\nu} + \delta T_{\mu\nu}}$$

$$h_{\mu\nu} = \begin{pmatrix} 2D & C_{,i} \\ C_{,i} & 2a^2(A\delta_{ij} + B_{,ij} + G_{ij}) \end{pmatrix}$$

$$\delta T_0^0 = \delta\varepsilon \;, \quad \delta T_i^0 = (\varepsilon + p)v_{,i}$$

$$\delta T_i^j = -\delta p\,\delta_{ij} + E_{,ij}$$

$$\boxed{\mathrm{q} = \mathrm{A} + \mathrm{H}\mathrm{v}}$$

$$\boxed{\mathrm{G}_i^j = \mathrm{G}_i^j{}_{,j} = 0}$$

S and V modes need additional constraints (matter properties)

Concept of ideal matter

$$T_\alpha^\beta = (\varepsilon + p) u_\alpha u^\beta - p \delta_\alpha^\beta$$

equation of state in perturbation sector

$$\delta_c X = \delta X - \dot{X} v$$

$$E = 0, \quad \delta_c p = \beta^2 \delta_c \varepsilon$$

↑

Sufficient conditions to resolve S-mode

Rotationless ideal fluid = field theory

Potential motions of ideal fluid

$$\boxed{u^{\mu} = w\frac{dx^{\mu}}{d\varphi}, \quad u_{\mu} = \frac{\varphi_{,\mu}}{w}}$$

Scalar field φ is just potential of the 4-velocity of the matter

Evolution of elementary oscillators

$$\bar{\mathbf{q}} = \frac{\alpha}{\mathbf{k}}\mathbf{q}$$

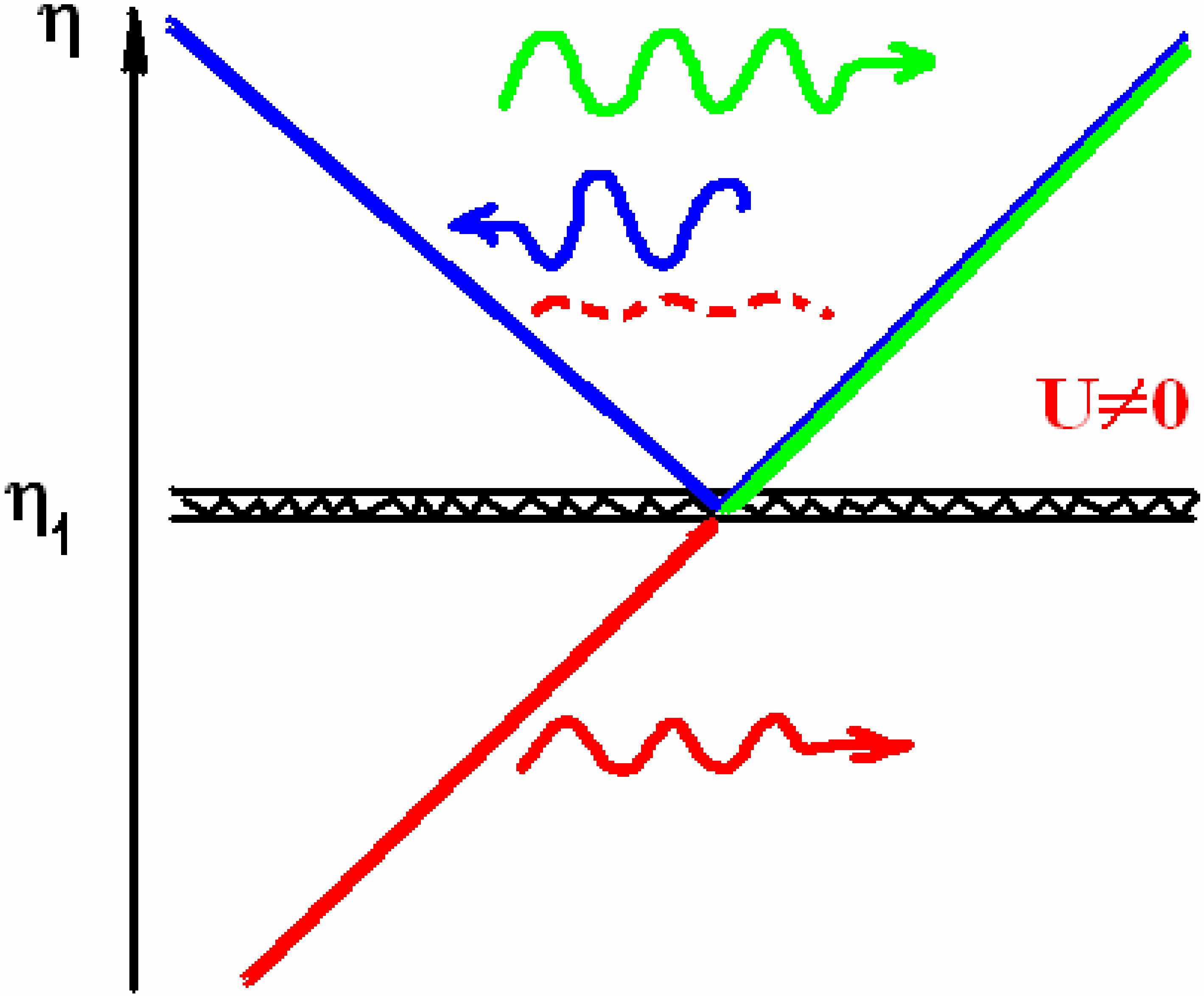
$$\mathbf{U} \equiv \frac{\alpha''}{\alpha}\,, \quad \omega = \beta\,\mathbf{k}$$

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

evolution:

$$\omega^2 > U\ : \quad |q| \sim (\,\alpha\sqrt{\beta}\,)^{-1}$$

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


η
η₁
U≠0

Phase information: only growing mode of perturbation is created

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

$$(a \sim \eta)$$

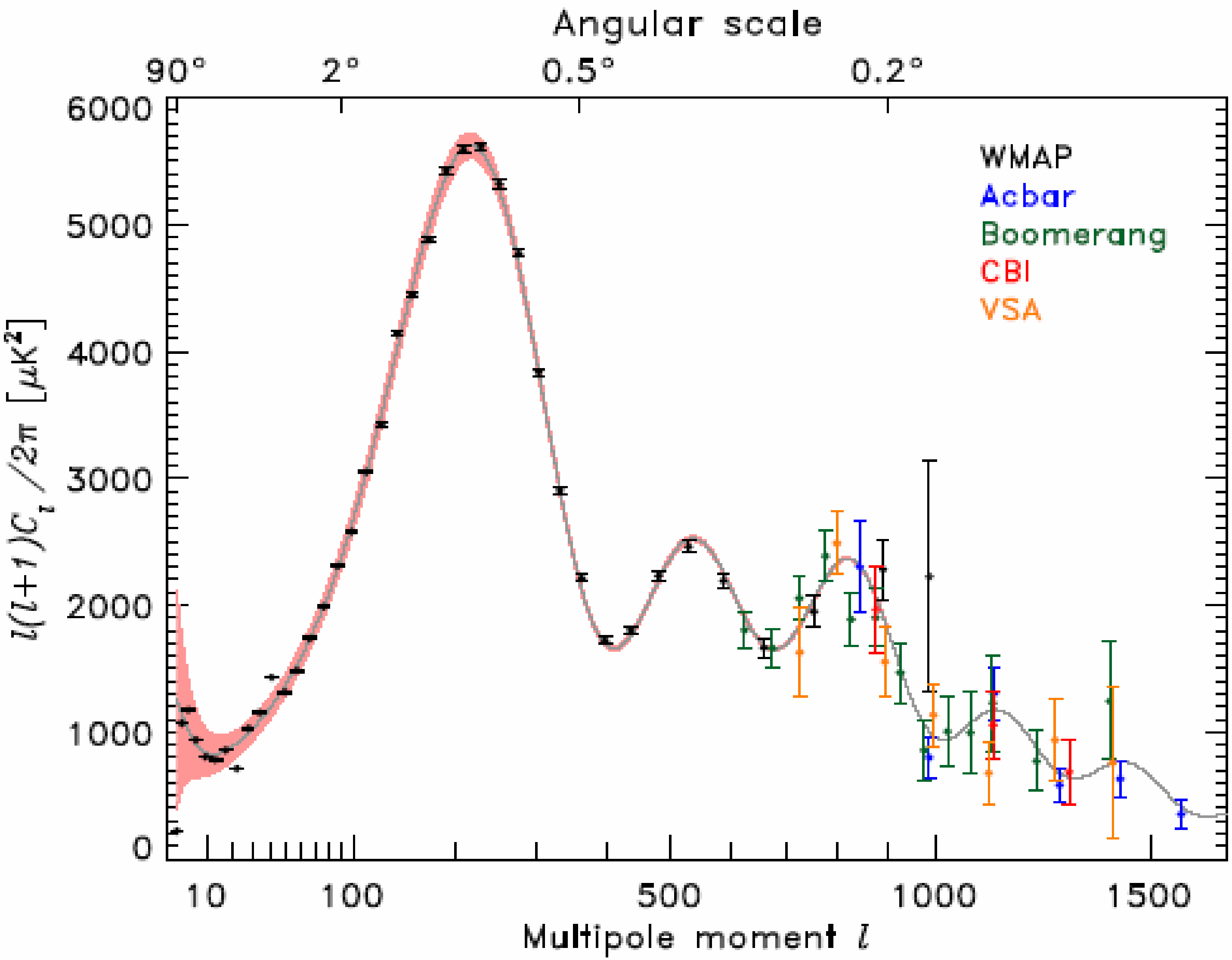
$$\kappa = \omega\eta$$

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 condition problem
for elementary oscillators

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

two polarizations of gravitational waves

$|0\rangle$ **- initial vacuum state**

Canonical form

$$\widehat{q} = \sqrt{\beta}\,\overline{q} = \frac{\alpha\sqrt{\beta}}{k}q \quad , \qquad \widehat{p} \equiv \frac{\partial L_k}{\partial \widehat{q}'}$$

$$L_k = \frac{\alpha^2}{2k^3}\left(q'^2 - \omega^2 q^2\right) = \frac{\omega}{2}\left(\widehat{p}^2 - \widehat{q}^2\right)$$

adiabatic zone $\omega^2 > U :$ $\quad \left|\widehat{q}\right| \sim \mathrm{const}$

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

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

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

Uniqueness of ground state in Friedmann geometry (V.N.L.2006)

General scenario of early Universe

Vacuum is determined in adiabatic zone, η<η0

$$\left\langle \widehat{\mathrm{p}}^2 \right\rangle = \left\langle \widehat{\mathrm{q}}^2 \right\rangle = \frac{\hbar}{2}$$

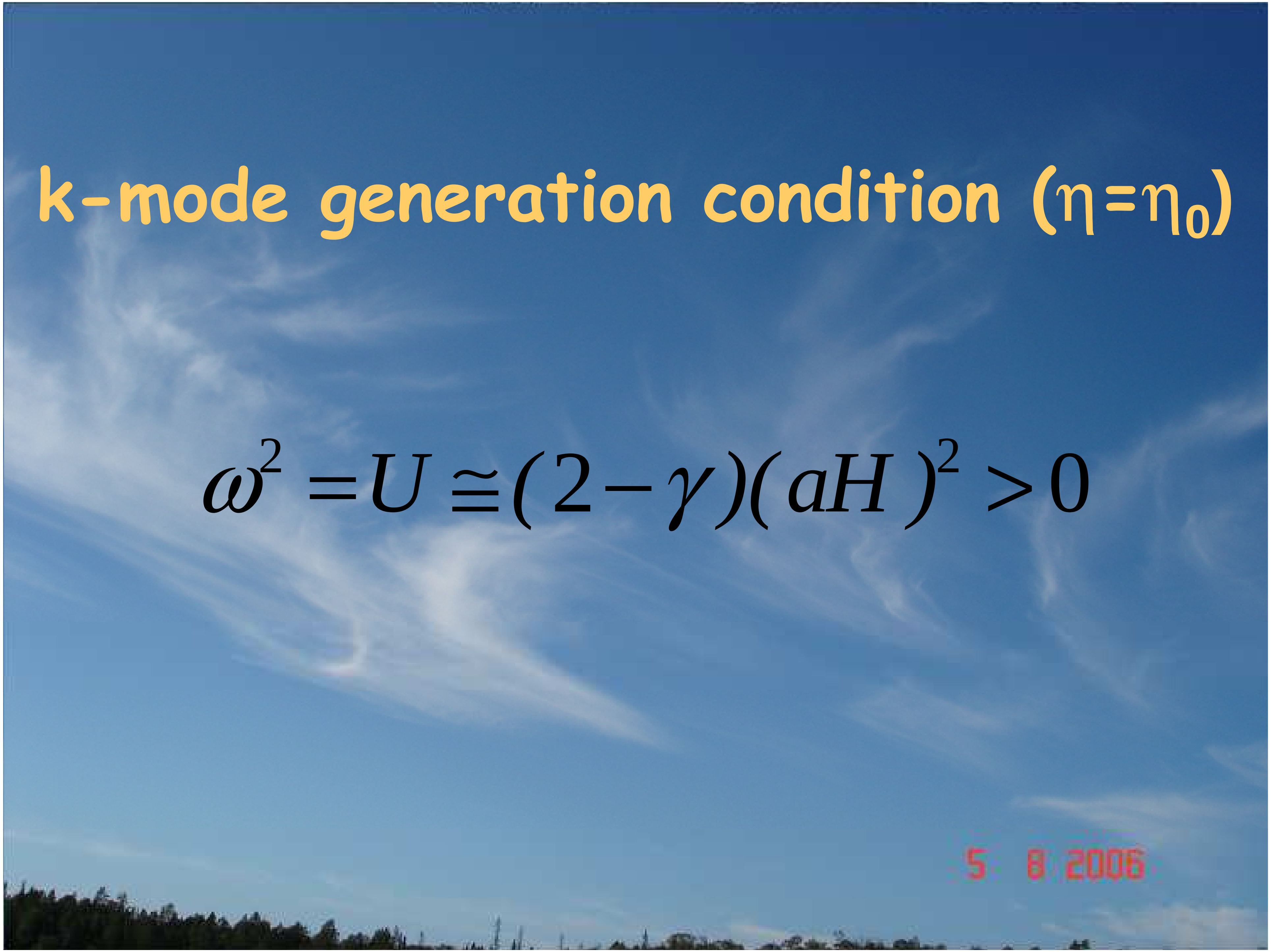
Parametric zone, η>η0

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

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

k-mode generation condition ($\eta=\eta_0$)

$$\omega^2 = U \cong (2-\gamma)(aH)^2 > 0$$



Universal result

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

expected:

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

Two ways to realize condition U>0:

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

(T~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~H^2 - **red spectra**, Starobinski 1979)

$$-n_T = 2\gamma = 0.5\frac{T}{S} < 1$$

- **Inflation test!**

Model of the early Universe: H and γ

$$T \cong \frac{H^2}{M_P^2}, \qquad \frac{T}{S} = 4\gamma$$

$H \equiv \frac{\dot{a}}{a} = \frac{k}{a}$ - Hubble parameter at the moment of creation of perturbation with λ = a/k

→ the energy scale of BB $= \sqrt{M_P H}$

$\gamma \equiv -\frac{\dot{H}}{H^2} = \frac{d\ln(H^{-1})}{d\ln(a)} \approx \left(10^5 \frac{H}{M_P}\right)^2$ - dynamics of H

→ the physical model of BB

Conclusions (initial conditions)

- T/S – a clue to very early Universe
- T/S < 0.2
- Power-law inflation:
  only massive field ($m^2\varphi^2$) remains
- n_S>1 - Λ-inflation
  n_S<1 - «chaotic» or «new» or …

The dark side of the Universe

✓ Origin of matter
✓ First objects
✓ Cusp problem in halos

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

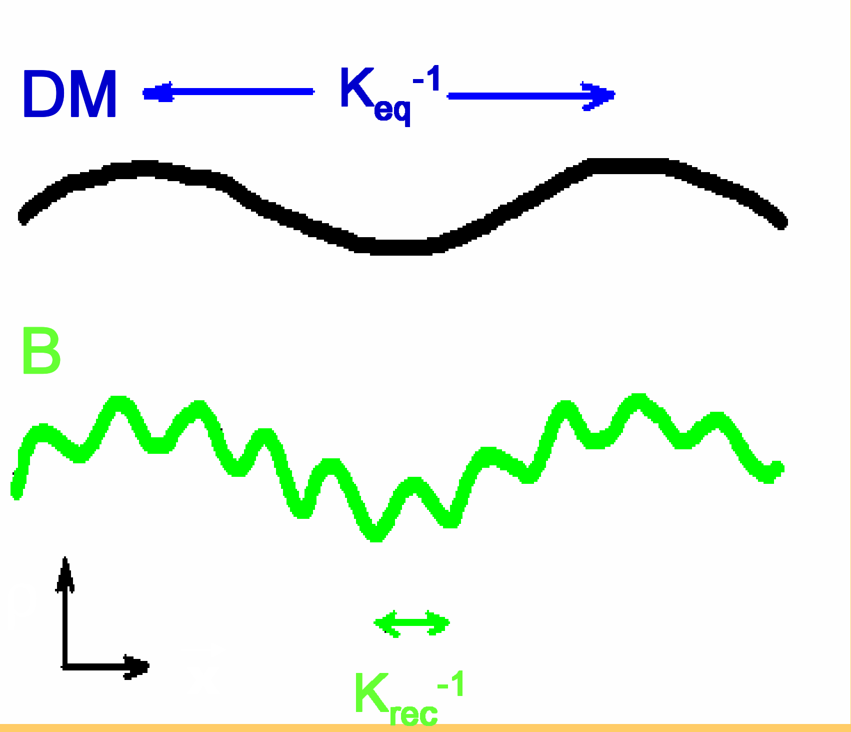
Other prompt:
coincidence of LSS and CMB scales

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

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

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

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

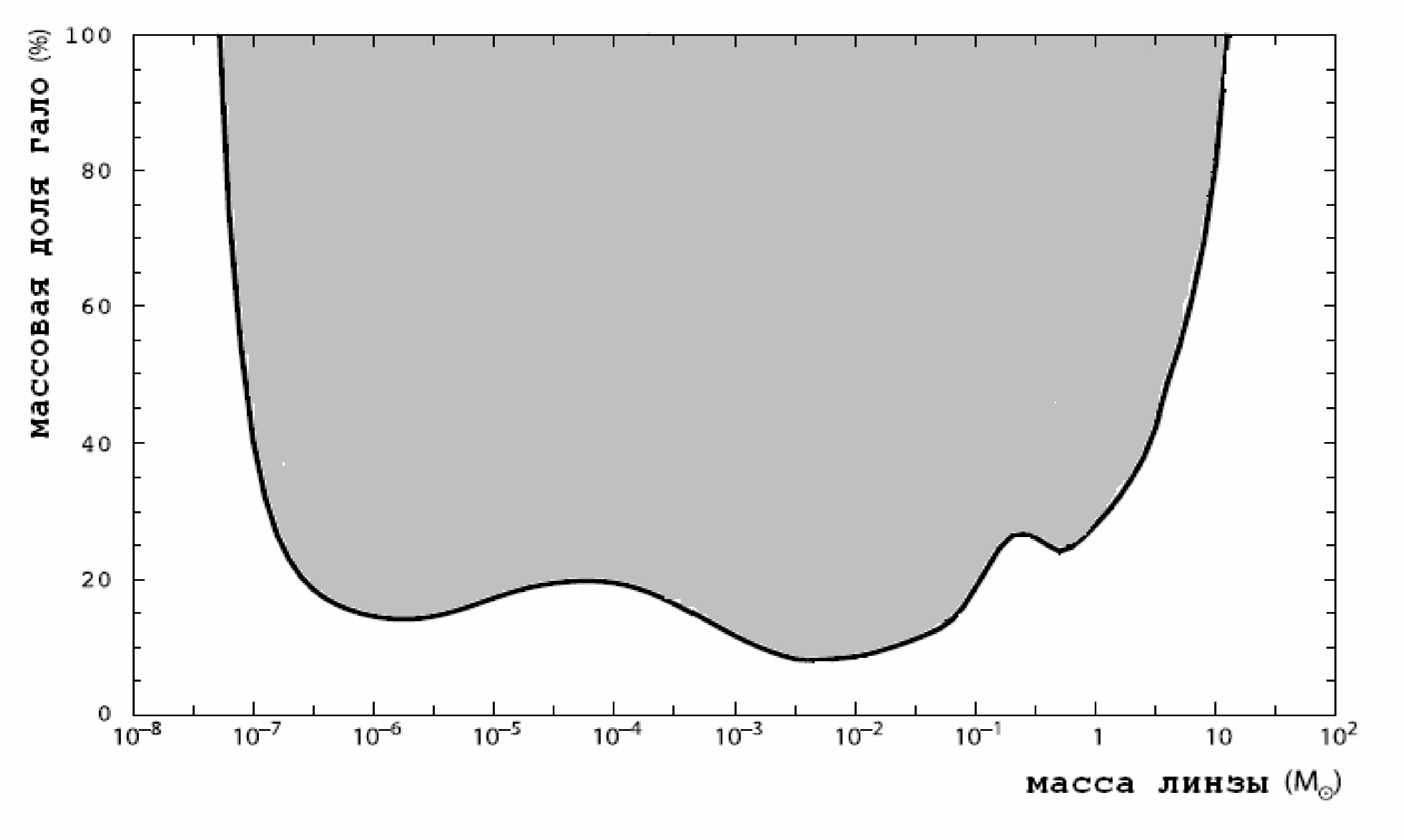


Where the matter is ?

Visible: * stars in galaxies
* gas in clusters (T~1 кэВ)

Dark baryons:
* intergalactic gas (T~0.01 кэВ)
* 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 mass fraction in MACHO objects

next question:

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~1 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 κpc
(the mass of Local Group ~ $2 \div 4 \cdot 10^{12}$ $M_{\odot}$
about half in Milky Way and Andromeda)

Hypotheses of nonbaryonic DM

(weakly interacting particles, defects, primordial BHs)

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} $M_{\odot}$

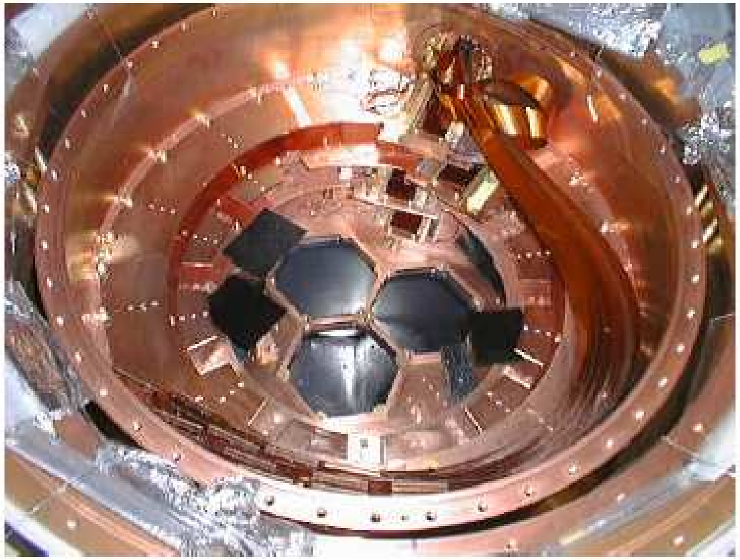
Basic DM version

(to be checked at LHC in 2008)

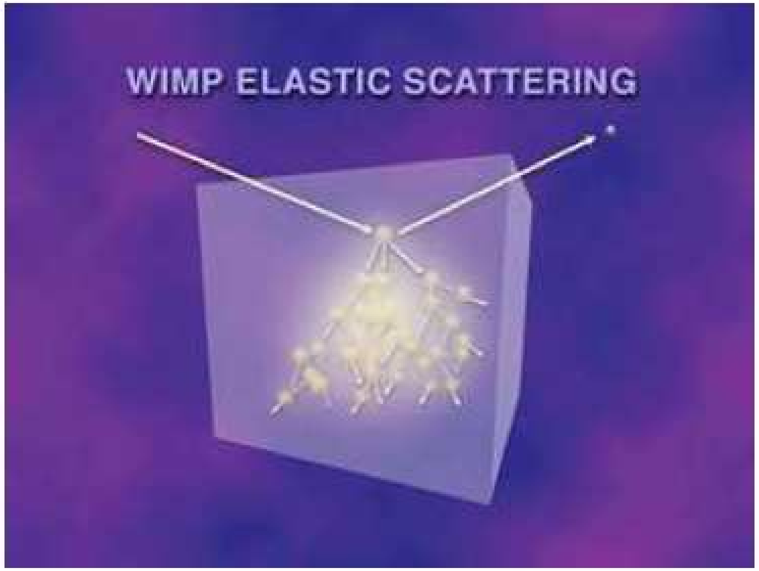
- unknown particles (WIMPs)
- mass ~ 100 ГэВ, one particle in a glass
- stable, neutral, weakly interacting (neutralino)

New physics!

Direct detection



Ожидается 1 событие в день на 10 кг вещества детектора



Все на глубине 1 км

Non-direct detection

(annihilation signal from DM cusps)

Cusp problem – a key to DM physics

* predicted in simulations ...

* unobserved in dwarf galaxies ..

* possible connection with massive BHs

Theory (talk of E.Mikheeva here):

- Initial small scale perturbations prevent cusp formation in DM halos

$10^6 M_\odot < M < 10^{12} M_\odot$

- N-body : underestimation of initial conditions, results depend on program (Moore, NFW, Klypin)

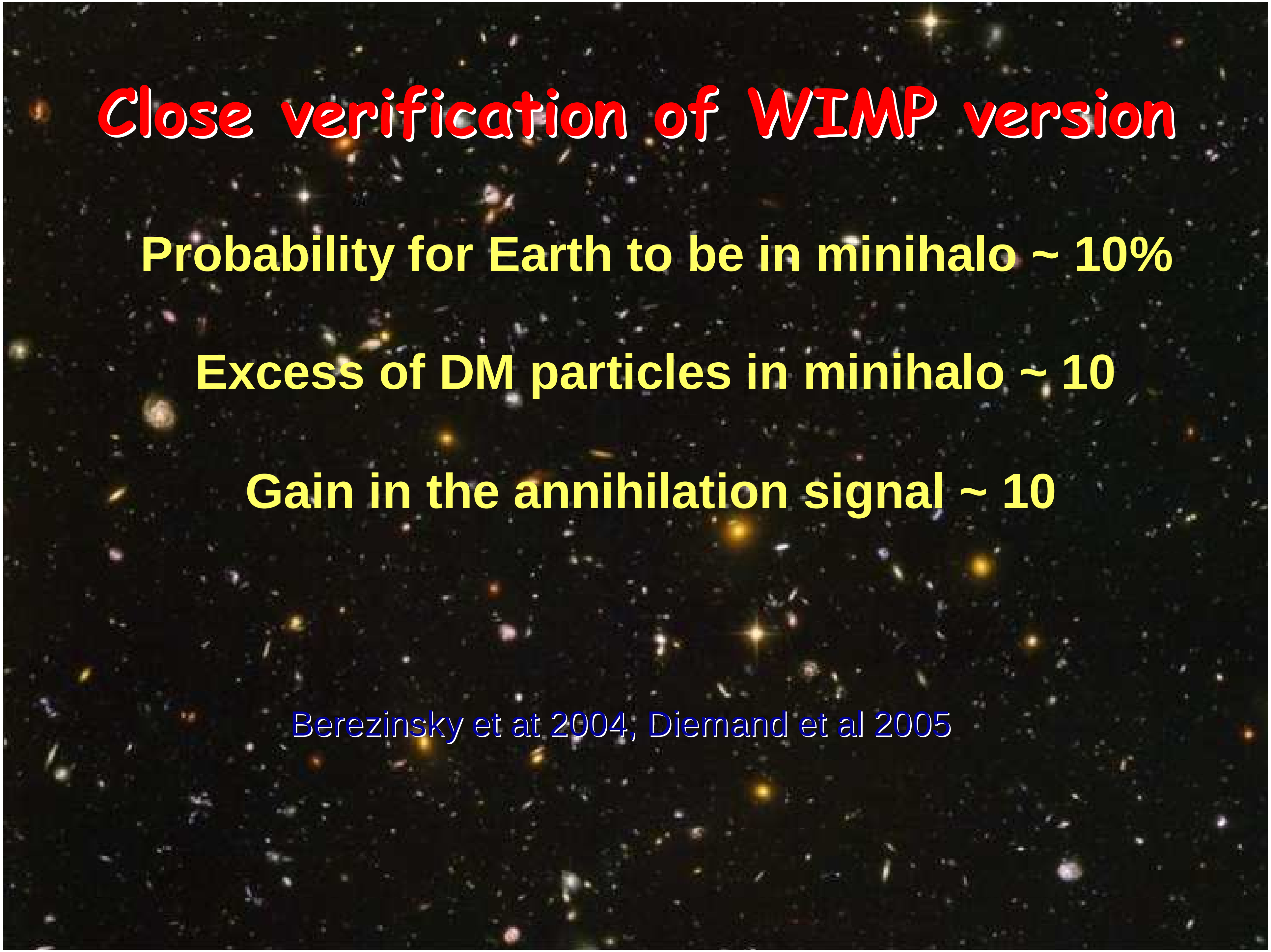
Prediction of neutralino DM model

WIMP minihalos

Size of the Solar system

Mass of the Earth

Minihalos are partially disrupted in collisions with starts, the remnants used to travel through the Earth



Close verification of WIMP version

Probability for Earth to be in minihalo ~ 10%

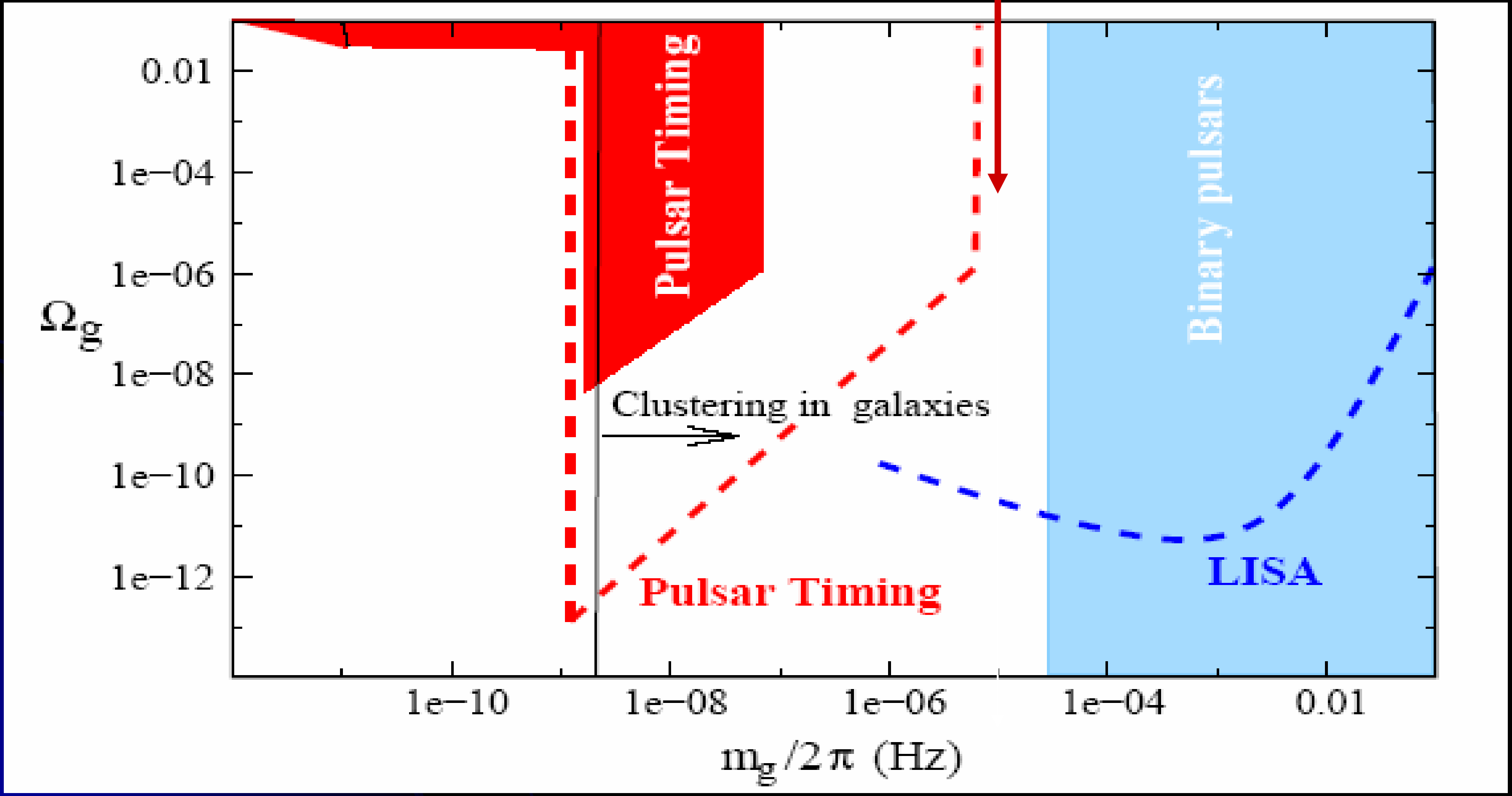
Excess of DM particles in minihalo ~ 10

Gain in the annihilation signal ~ 10

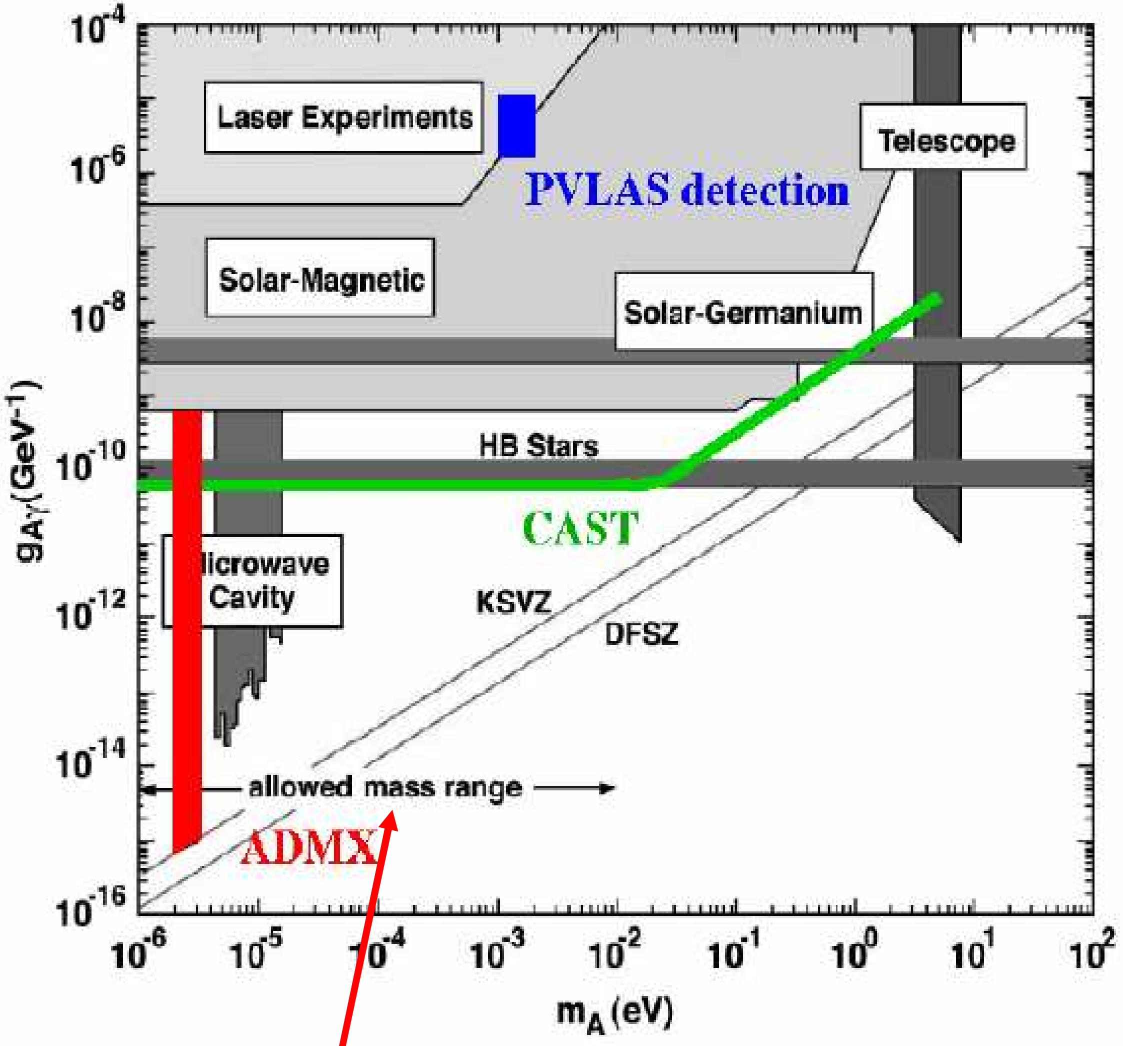
Berezinsky et at 2004, Diemand et al 2005

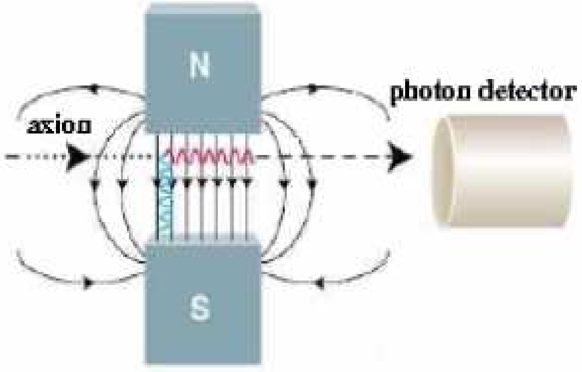
DM alternative- modification of gravity

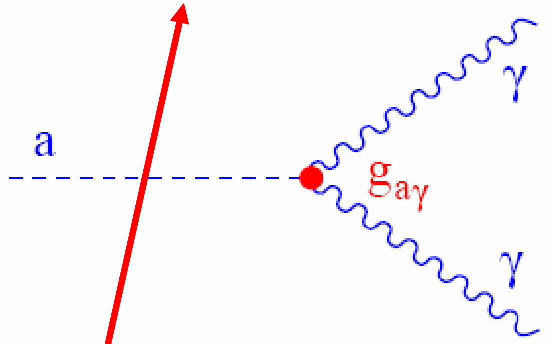
example: **massive gravitons** (gravitational creation in early Universe, **monochromatic signal for LISA**)



Constraints on parameters of axion



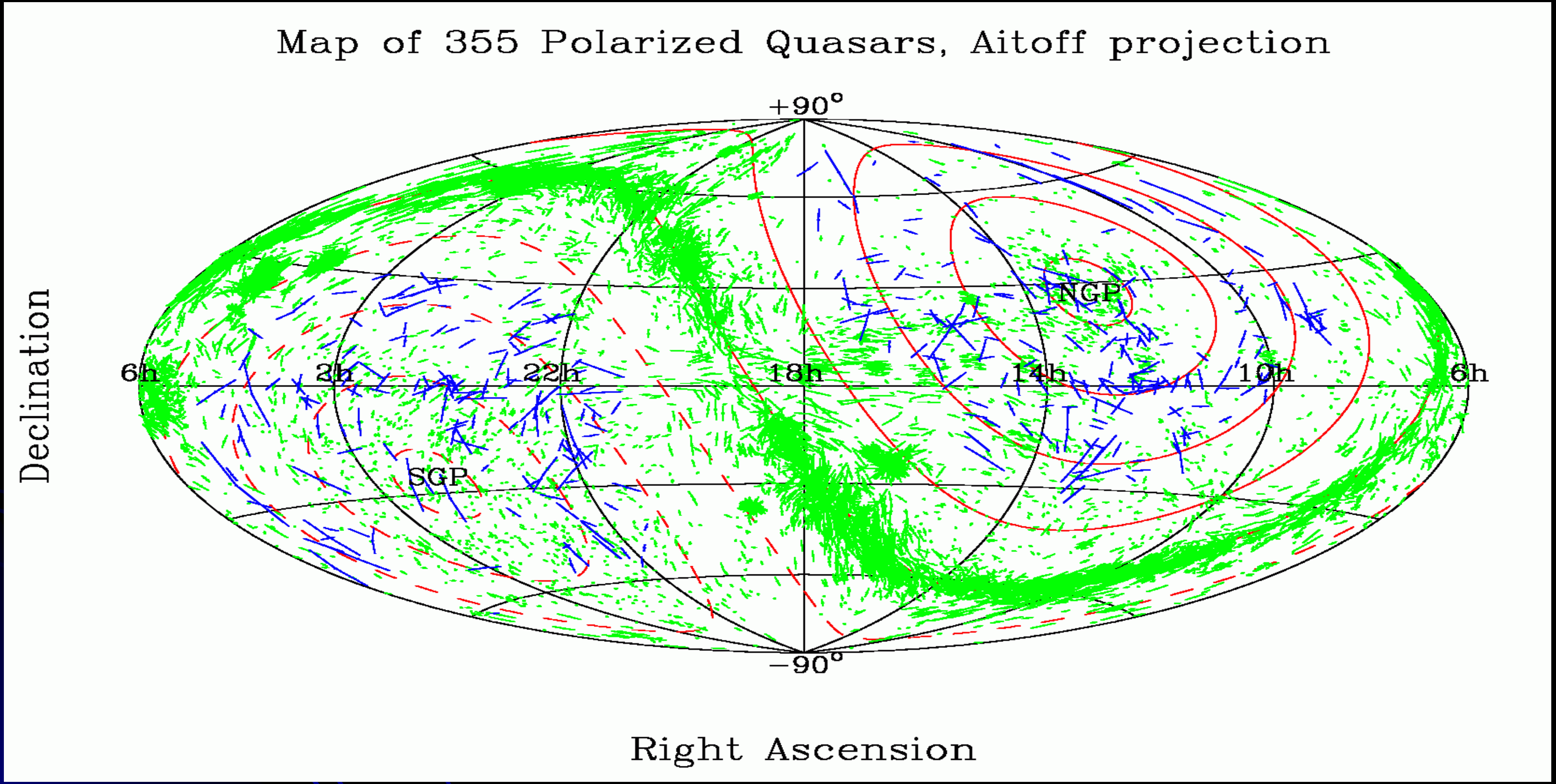




allowed masses

conversion axion-photon
-axion in magnetic field

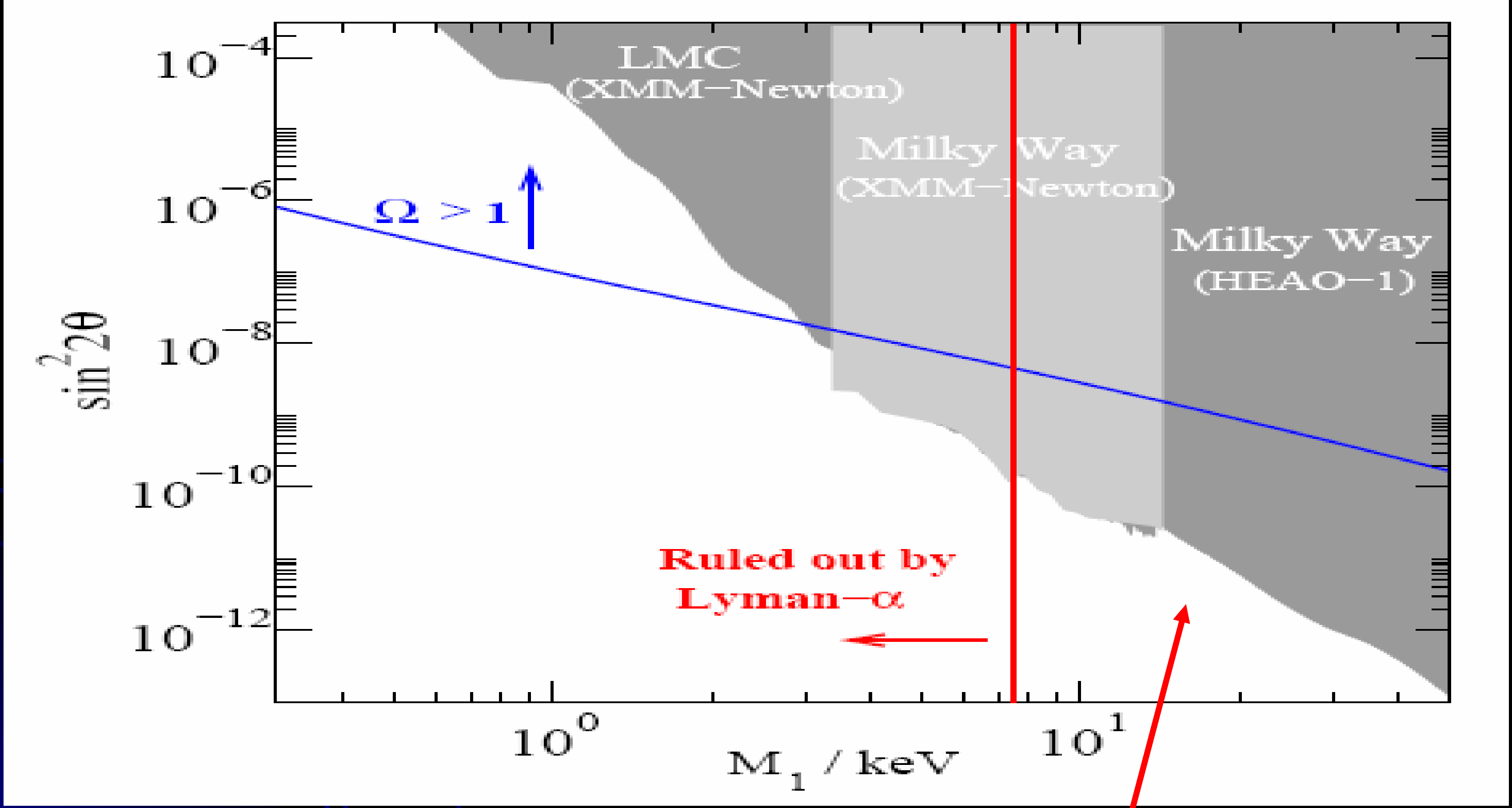
Large scale correlation of the QSO polarization position angle



..arises in extragalactic magnetic field due to conversion of photons to axions

Constraints on sterile neutrino

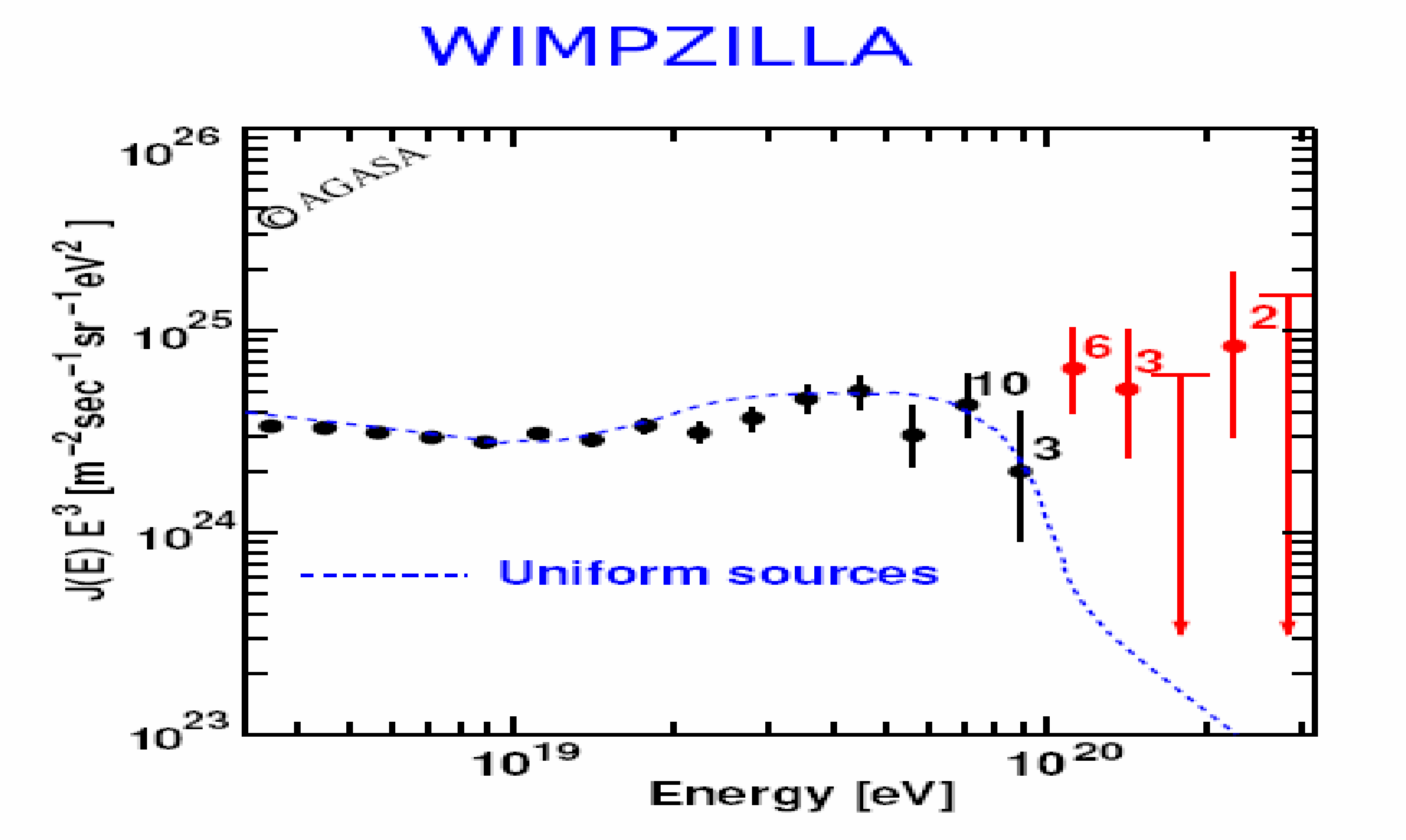
DM is not dark because of oscillations to ordinary neutrino and matter interaction



remaining region for 10-keV neutrinos

Supermassive particles ~ 10^{13} GeV

(gravitational creation in the early universe)



Prediction: anisotropy of UHECR distribution

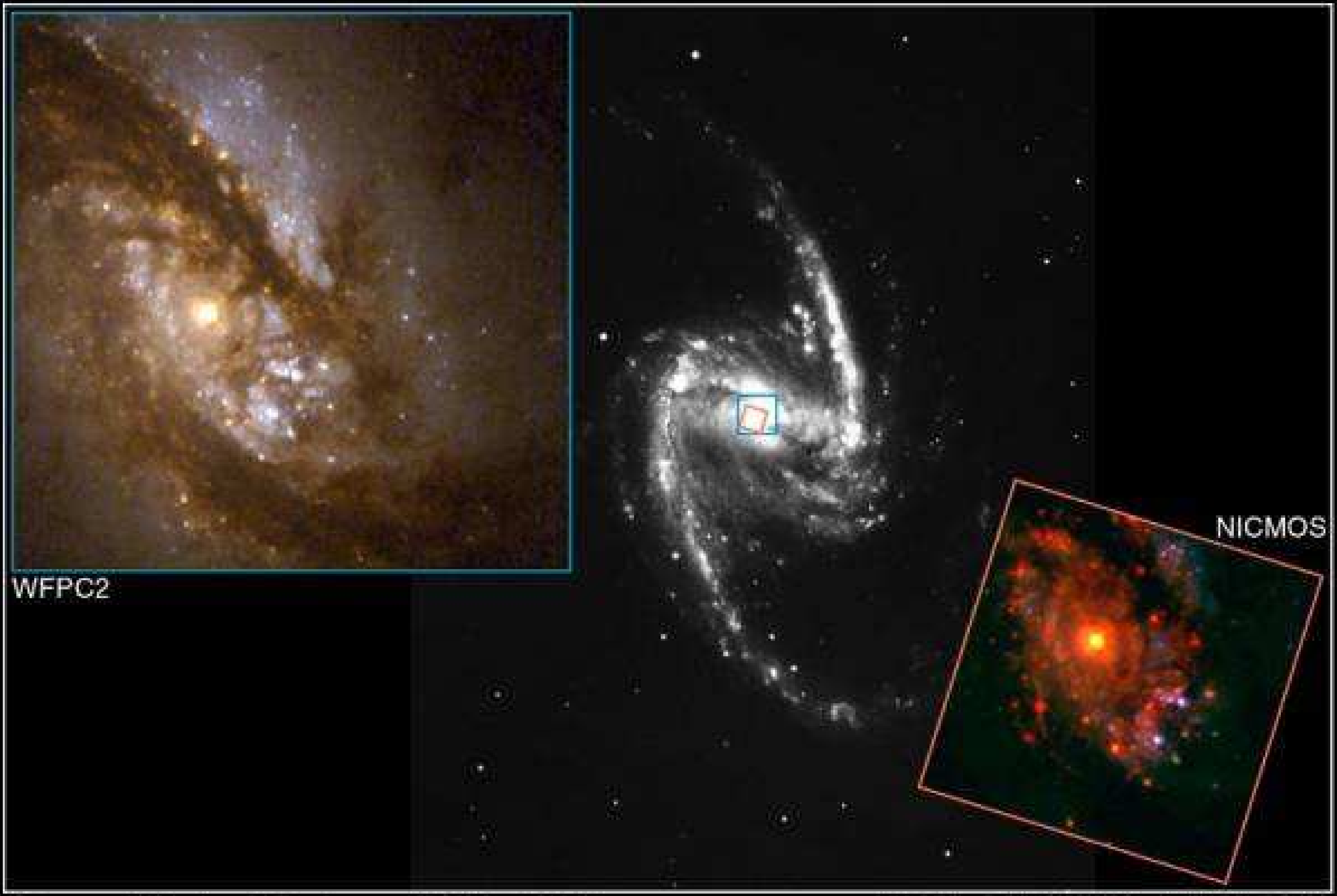
First galaxies

- The collapse of $M=10^6 M_\odot$ at $z \sim 20$

- Cooling on H_2, $M_J \sim 10^3\ M_\odot$, starburst formation at $z \sim 10$ ($Z_{cr} \sim 5 \cdot 10^{-4}\ Z_\odot$)

first stars create black holes

- GRBs from MBHs ($z>10$) → SWIFT (50% GRB at $z>5$)

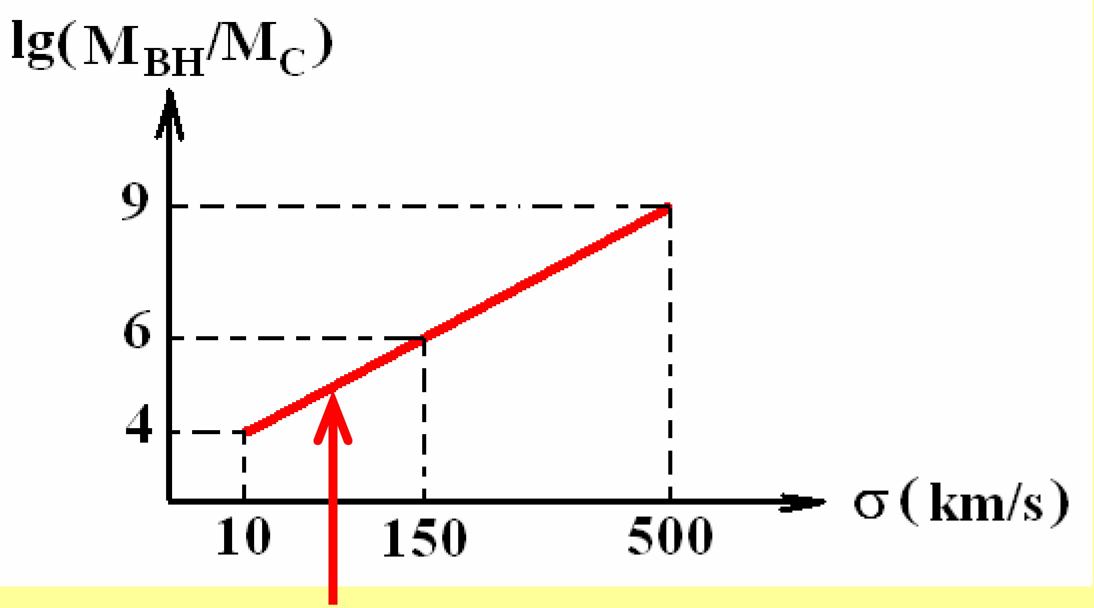

WFPC2
NICMOS

QSO in galactic centers:

+ 8 QSO at z>6 (expected ~ 50)

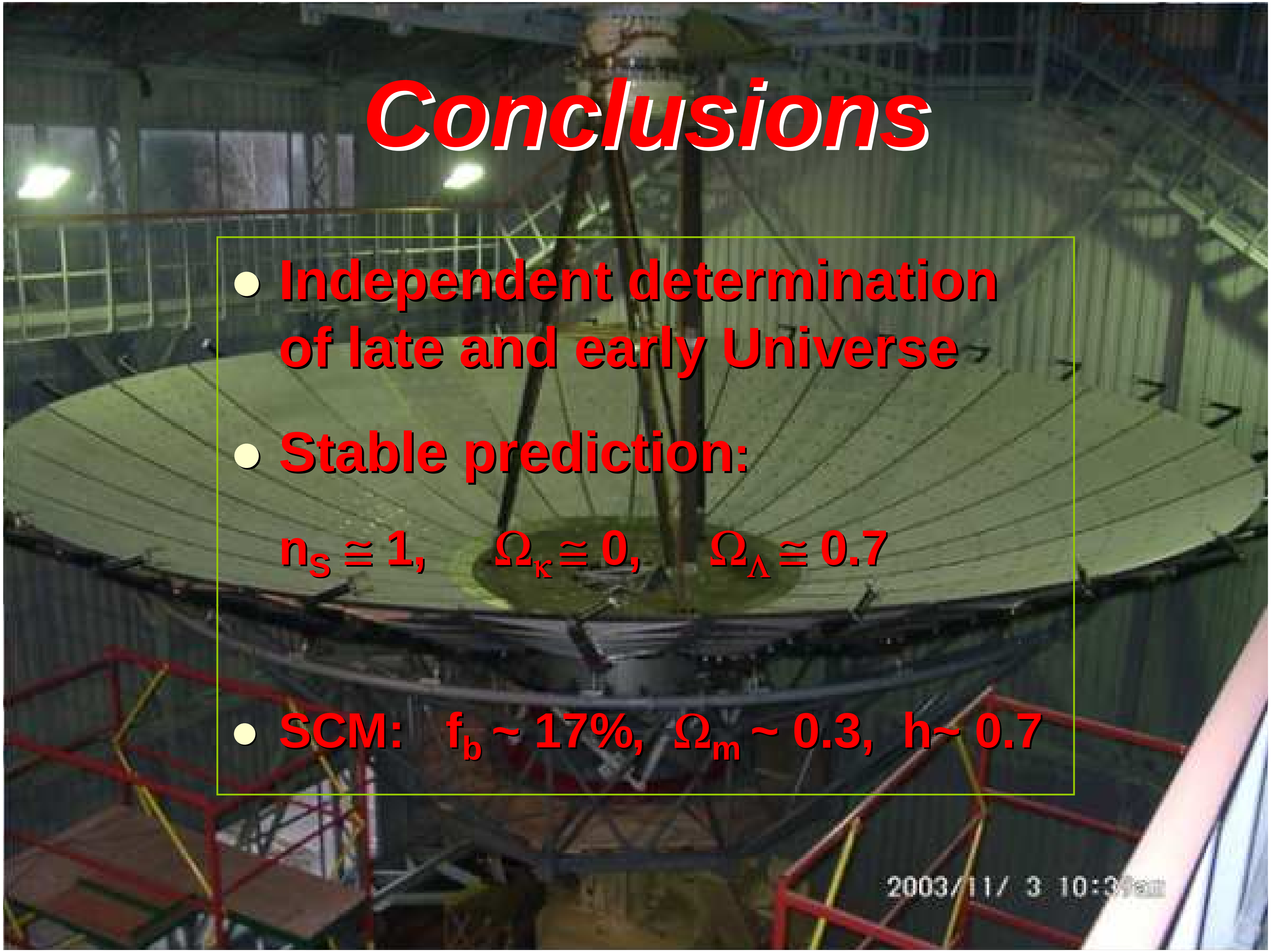
+ smm: star formation rate ~ 1000 $M_\odot$/год

+ MBHs form before galaxies



week AGN from SDSS

Conclusions



- Independent determination of late and early Universe

- Stable prediction:

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

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

Theory is exhausted

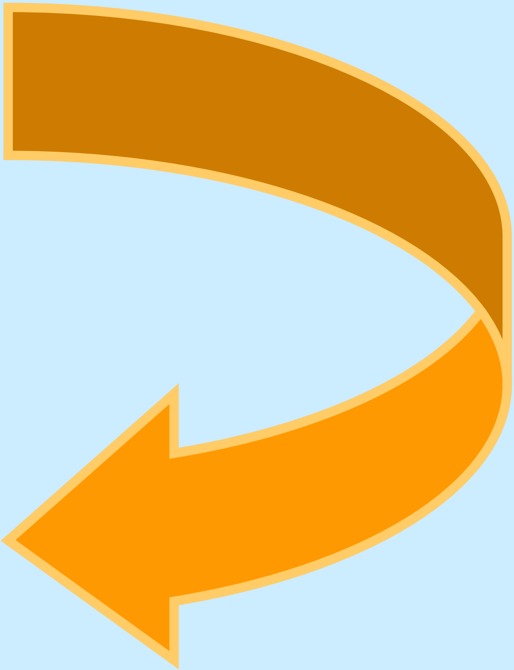
presenting a list where/how
to search for DM particles

Experiment in search
for new DM physics

The situation reminds the previous discoveries: **quarks, W-bosons, neutrino oscillations, CMB anisotropy & polarization**

Why nature is kind to us
to disclose its secrets ?

Observational constraints on inflationary models



Observational constraints on φ-field potential energy

$$H^2 = \frac{8\pi V(\varphi)}{3M_P^2} \quad , \quad \sqrt{\pi\gamma} = \frac{M_P V'}{4V}$$

Which kind of inflation could to be realized in the Universe?

Predicted T/S is not small (while $\gamma<1$)

example - **power law inflation** - all p>1 forbidden !

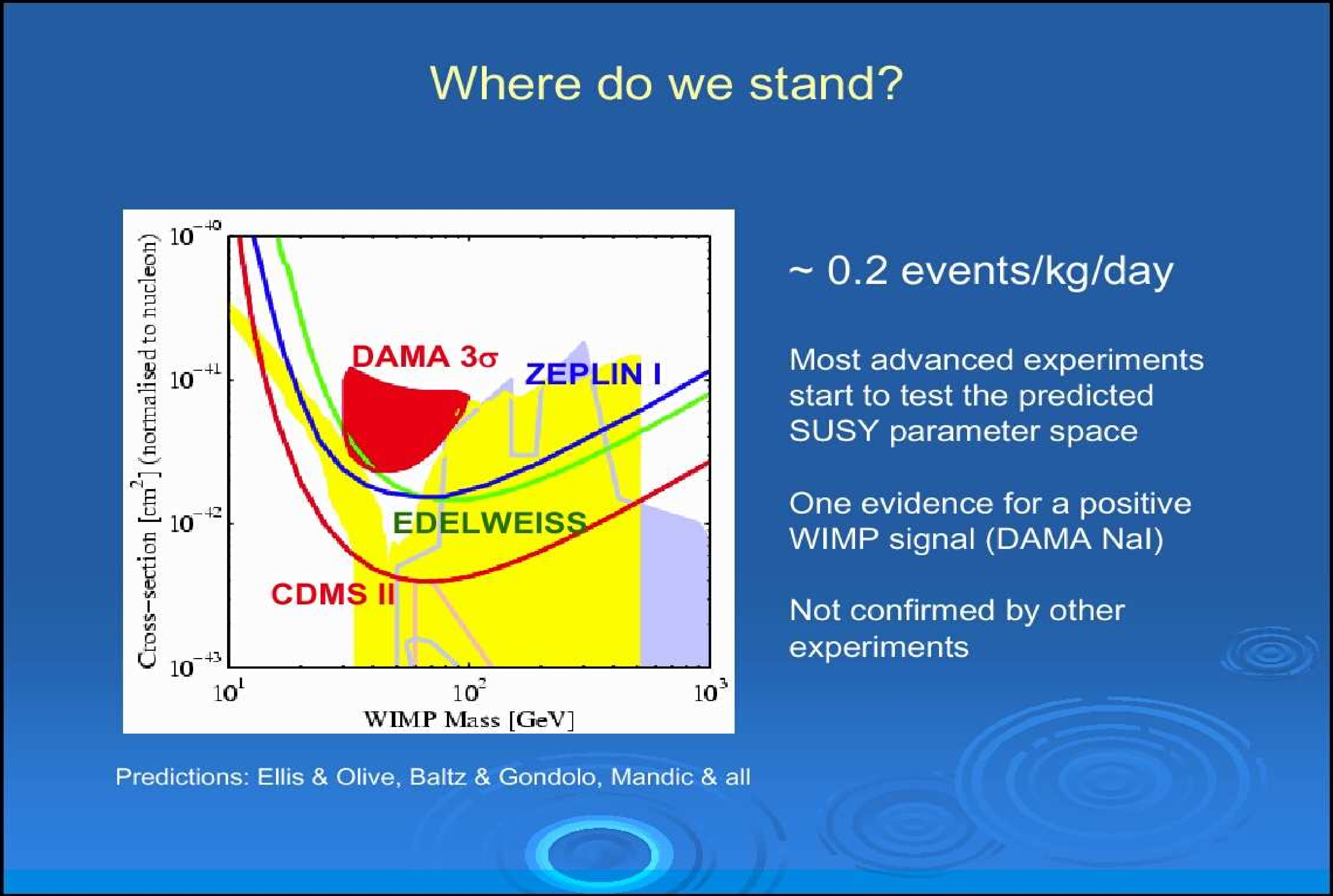
$V \approx \varphi^{2p}, \quad p-$ integer number

$$\frac{T}{S} = \frac{2p}{N} = (1-n_S)\frac{2p}{1+p} \cong 0.04p$$

$$N = 2\pi G\varphi^2 / p = ln\left(\frac{1000\,Мпк}{3\,мм}\right) \cong 50$$

For $p=1$ (massive field) the amplitude of T-mode is just 5 times as much less than the amplitude of S-mode ($0.04^{1/2} = 0.2$)

... unconfirmed results



Where do we stand?

~ 0.2 events/kg/day

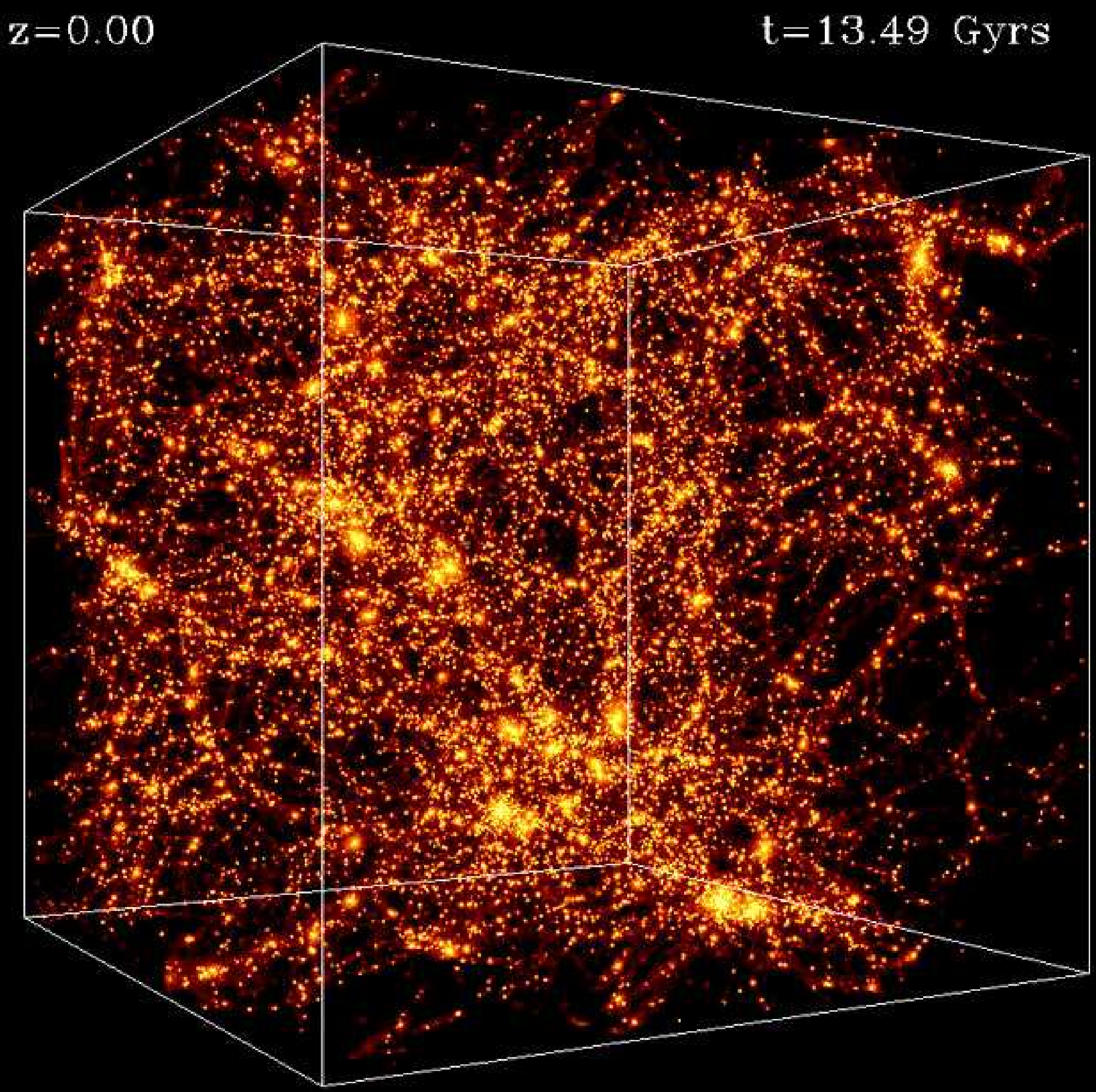
Most advanced experiments start to test the predicted SUSY parameter space

One evidence for a positive WIMP signal (DAMA NaI)

Not confirmed by other experiments

Predictions: Ellis & Olive, Baltz & Gondolo, Mandic & all

60 Mpc/h

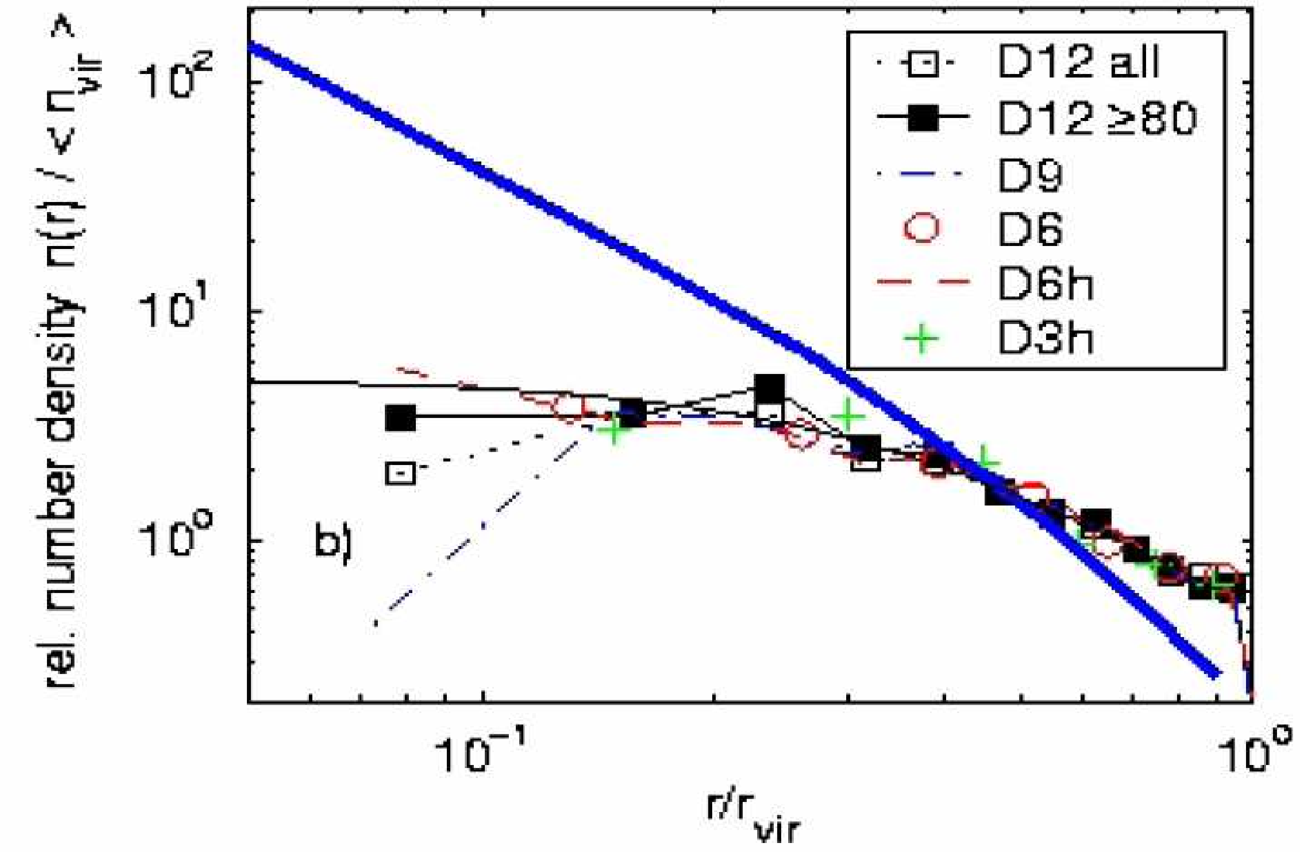


Cusps in DM halos

(simulations)

$\rho \sim r^{-\gamma}$

$\gamma \in$ **(1, 3/2)**



Diemand et al. 2004