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Time dependent dark energy

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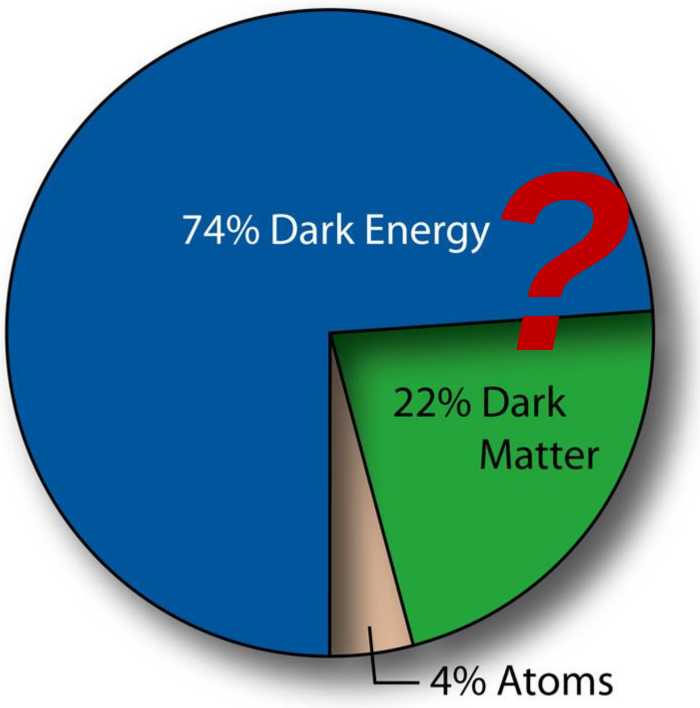
IAP, Paris, 23 October 2018

Outlines

- **What can make dark energy time varying?**
- **Gauge model of family symmetry breaking and horizontal unification.**
- **Unstable dark matter and time varying unclustered energy density**
- **Phenomenology of Λ(H) model. Acceleration with positive pressure.**
- **Λ(H) from backreaction of evaporating BEC codensate**

Composition of the Modern Unverse



$$\Omega \equiv \frac{\rho}{\rho_{cr}}$$

$$\Omega_{\mathrm{b}} \approx 0.044 \qquad \Omega_{\mathrm{CMB}} \approx 0.5 \cdot 10^{-4}$$

$$\Omega_{\mathrm{DM}} \approx 0.20$$

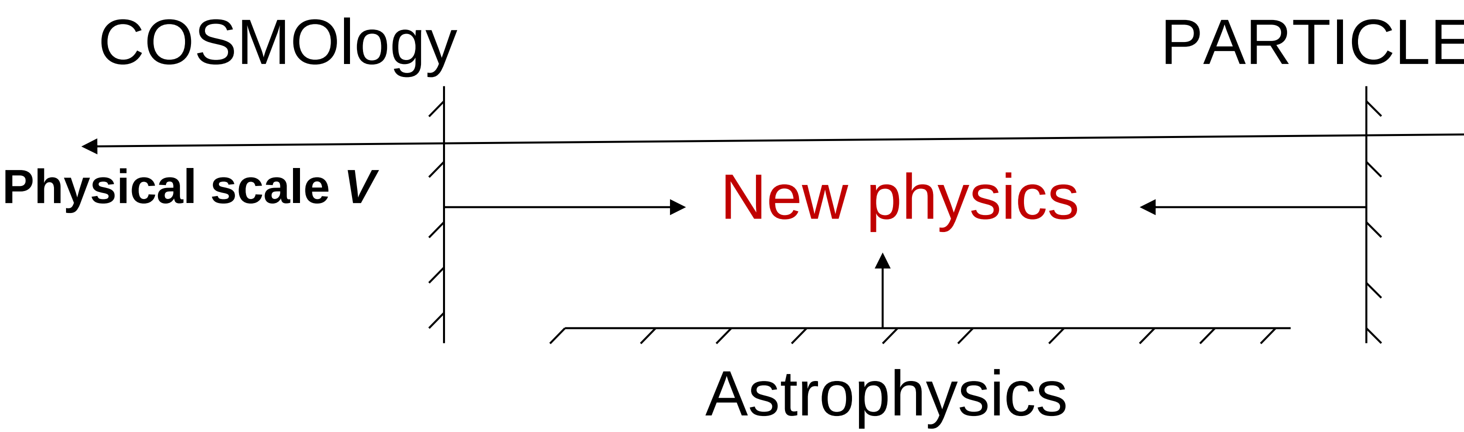
$$\Omega_{\Lambda} \approx 0.7$$

$$\boxed{\Omega_{\mathrm{tot}} \approx 1.0}$$

In the modern Universe dominate dark energy and dark matter – their nature is related to the new physics – physics beyond the Standard model, on which the bedrocks of modern cosmology are based

Cosmoparticle physics probes for new physics

- **Physics beyond the Standard model can be studied in combination of indirect physical, astrophysical and cosmological effects**
- **New symmetries imply new conserved charges. Strictly conserved charge implies stability of the lightest particle, possessing it.**
- **New stable particles should be present in the Universe. Breaking of new symmetries implies cosmological phase transitions. Cosmological and astrophysical constraints are supplementary to direct experimental search and probe the fundamental structure of particle theory**
- **Combination of physical, cosmological and astrophysical effects provide an over-determined system of equations for parameters of particle theory**



Extremes of physical knowledge converge in the mystical Uhrohboros wrong circle of problems, which can be resolved by methods of Cosmoparticle physics

The bedrocks of modern cosmology

Our current understanding of structure and evolution of the Universe implies three necessary elements of Big Bang cosmology that can not find physical grounds in the standard model of electroweak and strong interactions. They are:

- Inflation
- Baryosynthesis
- Dark matter/energy

The latter (Dark energy) is the topic of our discussion today

What can make DE time varying?

- Dark energy (DE) drives acceleration of expansion and thus should have vacuum energy equation of state.
- Cosmological constant is the simplest solution, but in the general context of cosmoparticle physics may be accomplished by nontrivial features that lead to time variation of Λ.
- I’ll draw attention today to two possibilities:

  Λ+UDM and Λ(H)

UDM AND HORIZONTAL UNIFICATION

Problem of quark-lepton families

- There are free families of quarks and leptons with apparent symmetry of their interactions and apparent hierarchy of their mass states.

$$\begin{pmatrix} \nu_e \\ e \\ u \\ d \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \\ c \\ s \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \\ t \\ b \end{pmatrix}$$

Masses of fermions are determined by EW scale.

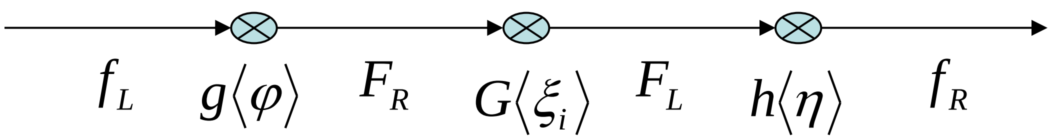
Masses of H-gauge bosons must be much heavier than this scale, due to the absence of flavor changing neutral currents (FCNC)

Gauge model of broken family symmetry

- To avoid symmetric mass terms L- and R-handed states of fermions should belong to different representations. It excludes orthogonal and vector-like groups of family symmetry and reduces the choice to SU(3) for 3 generations [8 H gauge bosons].
- Heavy partners F of ordinary fermions f acquire mass by Yukawa coupling with Higgs fields [3 multiplets $\langle \xi_i \rangle$ and singlet $h\langle \eta \rangle = \mu$]. Mixing of F and f induces SU(3) symmetry breaking pattern in mass pattern of quarks and leptons.
- To compensate anomalies heavy partners N of neutrinos are necessary. It provides the mechanism of neutrino mass.
- Natural choice of Higgs potential leads to additional global U(1) symmetry. It links physics of axion to physics of broken family symmetry.

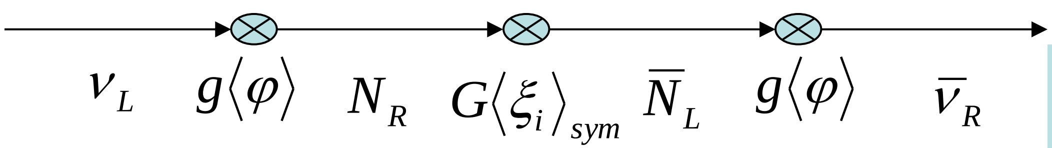
Fermion masses

- Dirac see-saw mechanism of mass generation for quarks and charged leptons



$$m_f = \frac{h\langle\eta\rangle}{G\langle\xi_i\rangle} g_f \langle\varphi\rangle$$

- Maiorana see-saw mechanism for neutrino mass.



$$m_\nu = \frac{g_f\langle\varphi\rangle}{G\langle\xi_i\rangle} g_f\langle\varphi\rangle = m_f \frac{g_f\langle\varphi\rangle}{h\langle\eta\rangle}$$

- Pattern of symmetry breaking

$$SU(3)\otimes U(1) \xrightarrow[\langle\xi_0\rangle]{} SU(2)\otimes U'(1) \xrightarrow[\langle\xi_1\rangle]{} U''(1) \xrightarrow[\langle\xi_2\rangle \equiv V]{} I$$

- Results in mass pattern $m_i \propto \langle\xi_i\rangle^2$

Reduction of number of parameters

Hierarchy of masses is not given by hands, but follows from pattern of family symmetry breaking

	e	μ	τ
e	m_e	s_{12}	s_{13}
μ	s_{12}	m_μ	s_{23}
τ	s_{13}	s_{23}	m_τ

	e	μ	τ
e	0	p	0
μ	p	0	q
τ	0	q	r

3 parameters instead of 9

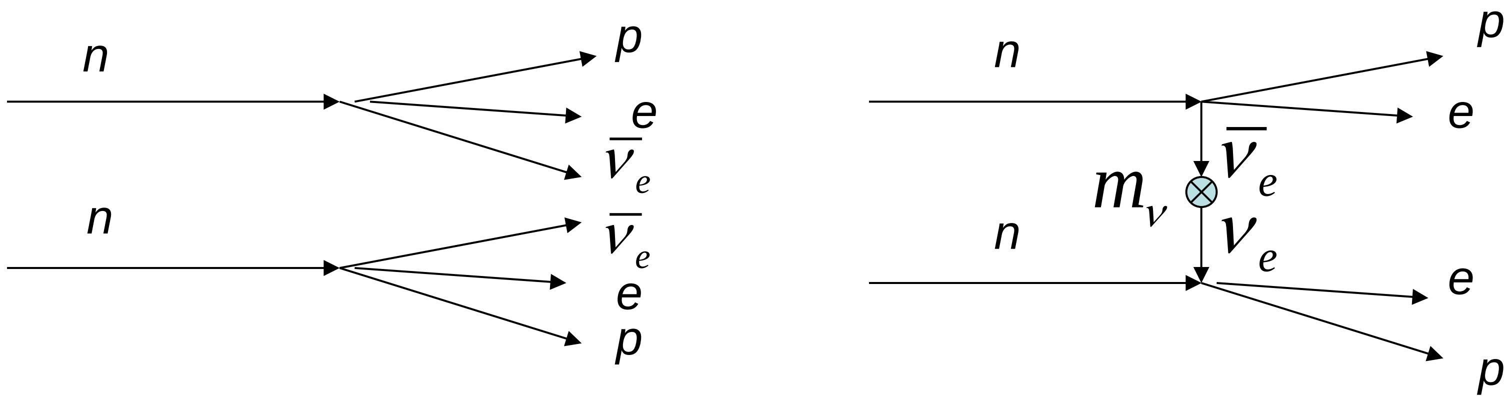
Archion

- The assumption that Higgs potential contains only terms, which can be generated by radiative effects of gauge and Yukawa couplings excludes the term $\propto p\xi_i \xi_j \xi_k$.
- It leads to additional global U(1) symmetry. Breaking of this symmetry results in the existence of Goldstone boson α .
- This boson shares the properties of Majoron, familon and axion and was called archion.
- Archion couplings are proportional to 1/*V* and its mass is given by

$$m_\alpha = C \frac{f_\pi}{V} m_\pi$$

Physical consequences

- FCNC, due to H-bosons $K \to \mu e; \bar{D}^0 \leftrightarrow D^0; \ldots$
- Mass of neutrino $m_\nu \propto V^{-1}$, neutrino oscillations, double neutrinoless beta-decay due to Majorana mass



- Archion decays $K \to \pi\alpha; \mu \to e\alpha; \ldots$
- Archion decays of massive neutrinos

$$\nu_H \to \nu_L \alpha \qquad \tau = \frac{V^2}{a_{HL}^2 m_H^3} \propto V^5$$

Astrophysical consequences

- Archion emission speeds up stellar evolution

$$t_s = \frac{Q}{L + L_\alpha} < t_s = \frac{Q}{L} \qquad L_\alpha \propto 1/V^2$$

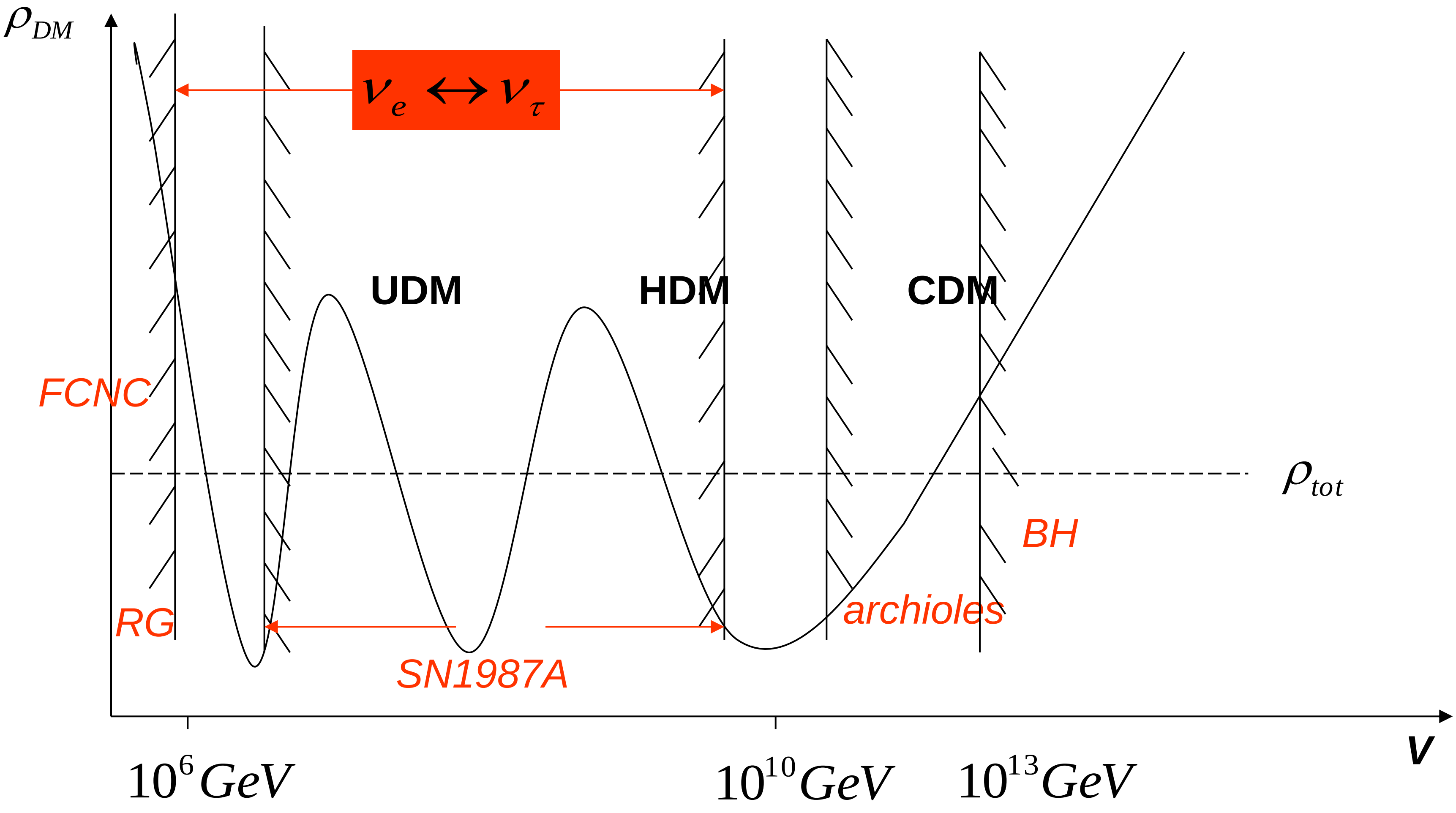
It puts lower limit $V > 10^6 GeV$ from observation of red giants.

- Neutrino radiation from collapsing stars is suppressed due to energy loss by archion emission
- Detection of neutrino from SN1987A constrains $10^{10} GeV > V \geq 3 \cdot 10^6 GeV$ (at low *V* archion energy losses decrease due to opacity of stellar matter)

Dark matter candidates

- Massive neutrinos $n_\nu = \frac{3}{11} n_\gamma$, $\rho_\nu = m_\nu n_\nu \propto V^{-1}$
- Unstable massive neutrinos. Due to strong dependence $\tau(\nu_H \to \nu_L \alpha) \propto V^5$ at lower *V* neutrino lifetime can become $\tau < t_U$
- Primordial archion field oscillations $\rho_\alpha \propto V$
- Density of all the candidates is determined by the same scale of family symmetry breaking *V* and they can be treated within the unique framework.

Unified model of dark matter



Unstable dark matter (UDM)

A. G. Doroshkevich and M. Yu. Khlopov

Mon. Not. R. astr. Soc. (1984) **211,** 277–282

Formation of structure in a universe with unstable neutrinos

A. G. Doroshkevich, A. A. Klypin and M. U. Khlopov

Mon. Not. R. astr. Soc. (1989) **239,** 923–938

Large-scale structure of the Universe in unstable dark matter models

UDM+Lambda

$$\Omega_{\rm d} + \Omega_{\rm R} + \Omega_{\rm hot} + \Omega_{\rm cold} + \Omega_{\Lambda} = 1$$

$$(\text{at } t \ll \tau\, \Omega_{\rm d} = 1 - \Omega_{\rm st} \text{ and } \Omega_{\rm cold} = \Omega_{\rm st}).$$

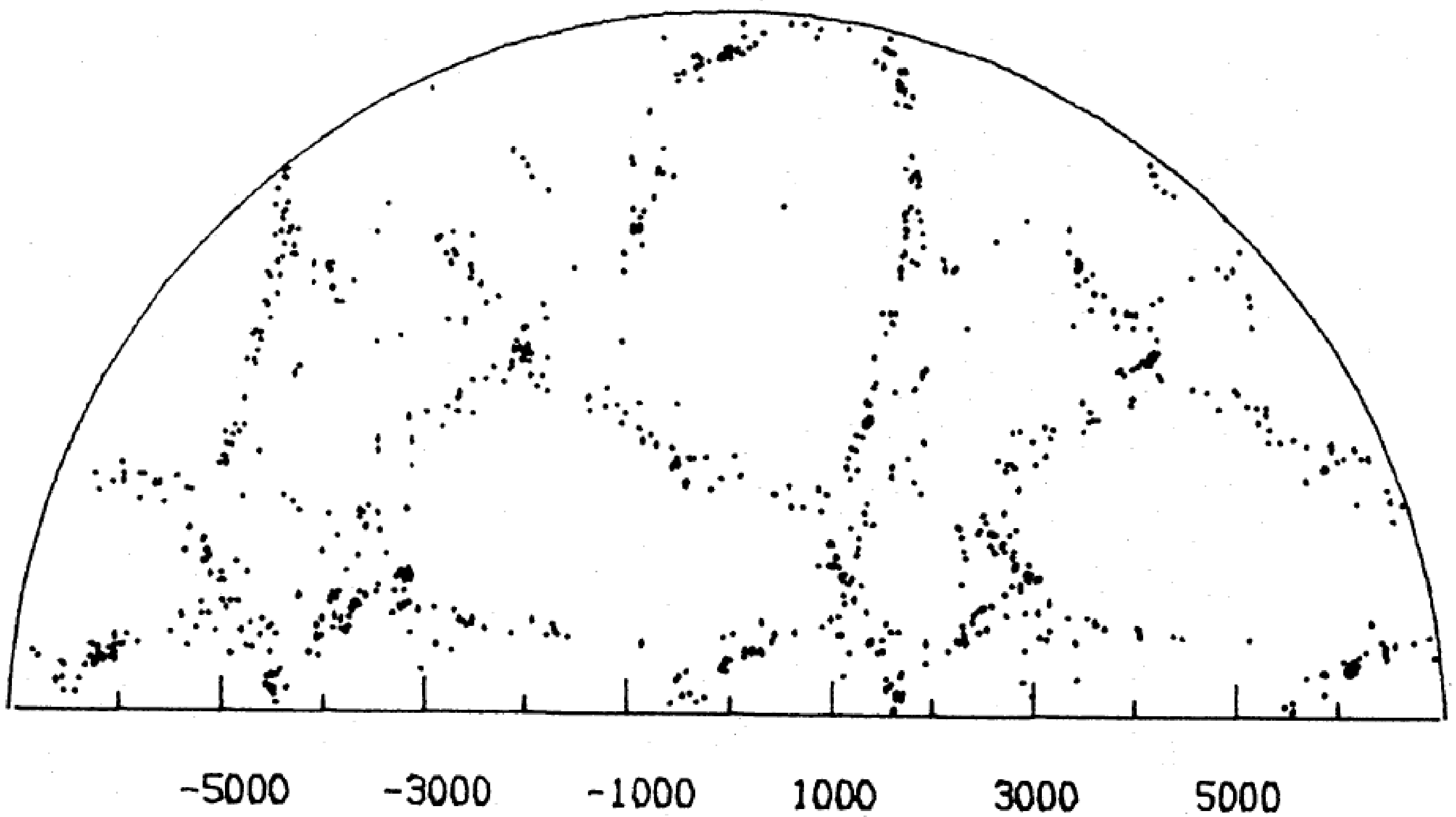
$$1 + z_{\max} = (3\Omega_{\Lambda}/\Omega_{R})^{0.25}, \qquad \Omega_{\max}^{-1} - 1 = 4(\Omega_{\Lambda}/\Omega_{\rm cold})\,(\Omega_{\rm R}/3\Omega_{\Lambda})^{0.75}$$

$$\Omega_{\Lambda\max} = 0.25(1 - \Omega_{\max}), \qquad \Omega_{\rm R} = 1 - \Omega_{\rm cold} - \Omega_{\Lambda}.$$

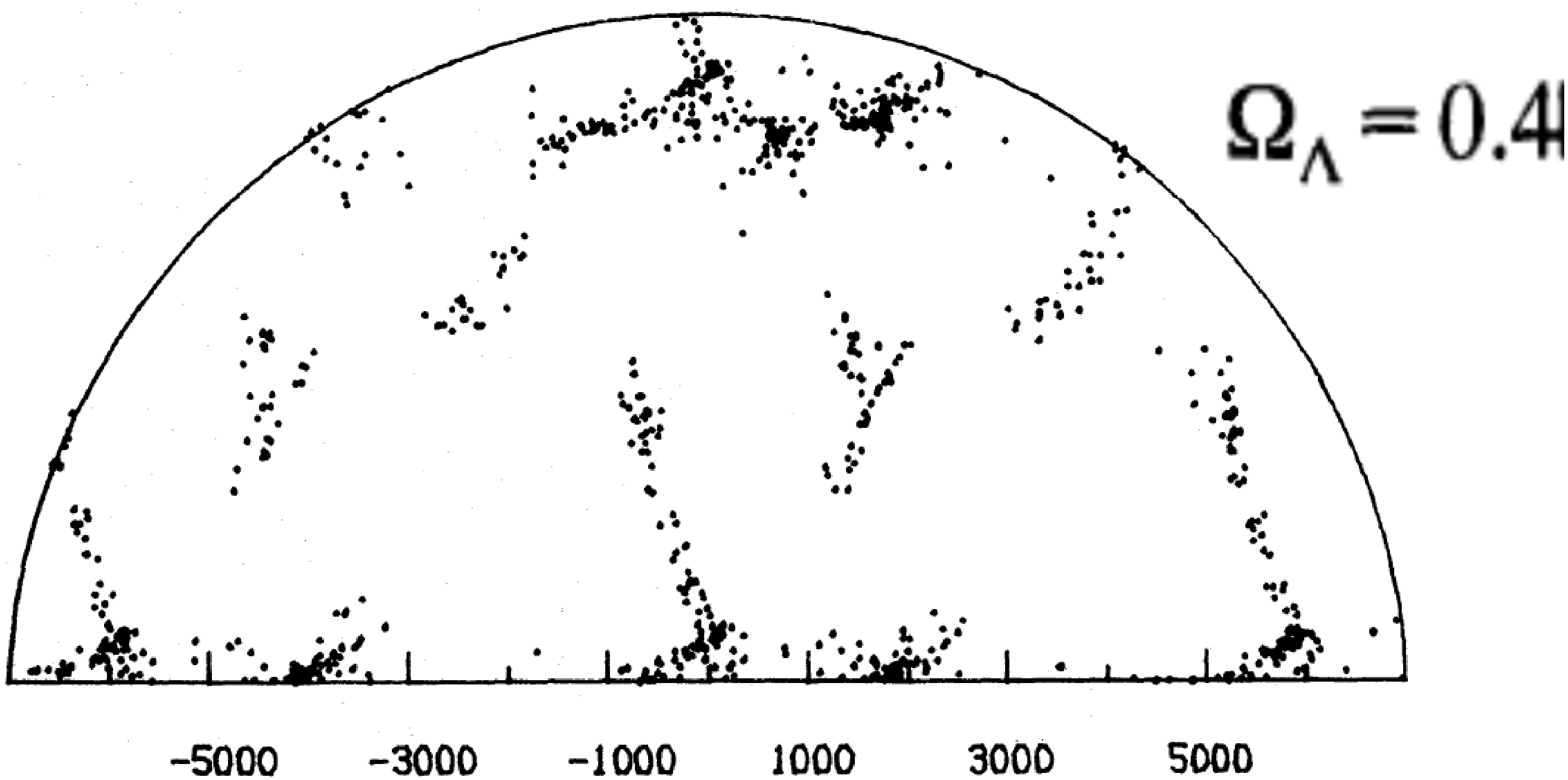
Numerical models

Model	1	2	3	4	5	6	7
Spectrum	HZ	SS	SS	HZ	HZ	HZ	HZ
m_H eV	70	70	85	65	85	68	78
$\tau/10^9$ yr	1.3	1.3	1.0	0.3	0.3	1.1	0.16
z_τ	2.1	2.1	2.9	7.3	7.3	2.7	11.8
$T_U\ 10^{-9}$ yr	10.5	10.5	10.4	12.7	12.7	10.7	12.0
Ω_{cold}	0.16	0.16	0.19	0.30	0.15	0.32	0.38
Ω_R	0.84	0.84	0.81	0.30	0.35	0.68	0.10
Ω_Λ	0.00	0.00	0.00	0.40	0.47	0.00	0.00
Ω_{st}	0.05	0.05	0.05	0.10	0.05	0.10	0.10
σ_{LT}	1.6	1.6	1.8	2.0	1.8	1.8	2.1
r_c Mpc	7.3	4.1	3.8	9.1	7.1	8.4	7.3
r_c^* Mpc	8.5	6.0	5.1	11.8	9.7	12.0	8.5
$Q/10^{-5}$	2.40	0.02	0.02	2.50	2.00	2.40	2.10
$\Delta/10^{-5}$	1.2	0.4	0.4	1.2	1.2	1.2	1.2
$\mathscr{D}/10^{-5}$	0.7	0.6	0.8	0.8	0.8	0.6	0.7

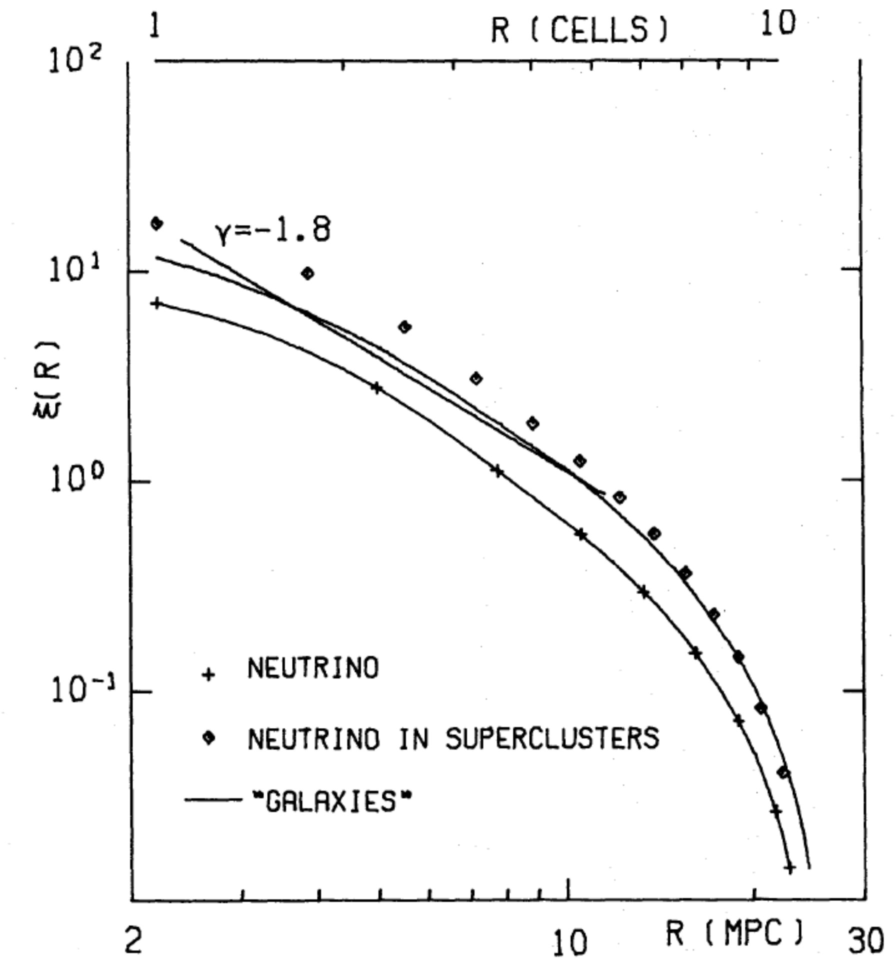
Wedge diagram for matter inside pancakes without Lambda



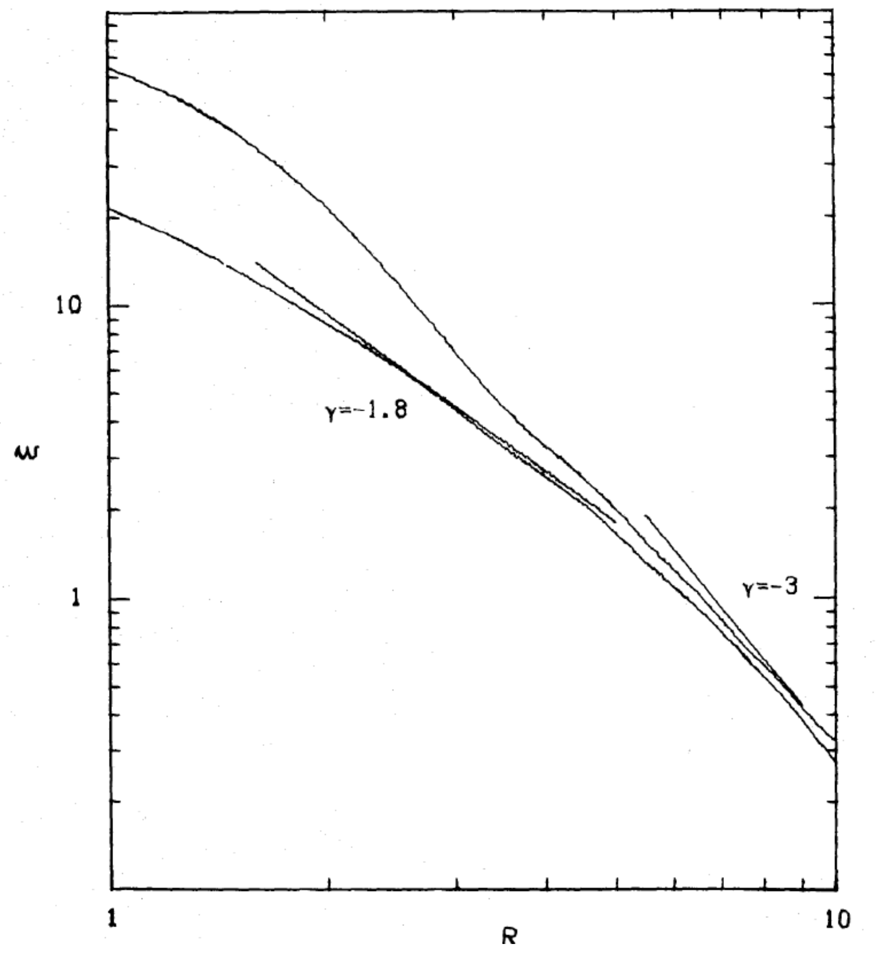
Wedge diagram for matter inside pancakes with Lambda



Correlation function inside superclusters without Lambda



Correlation function inside superclusters with Lambda



$$\Omega_\Lambda = 0.4$$

Hierarchical neutrino decay scenario (excluded by neutrino oscillations)

- **Formation of Large Scale Structure (LSS) in succession of stages of dominance of massive neutrinos and their decay products.**
- **Dominance of** ν_τ **with mass *m*=1 keV at** $10^8 s < t < 10^{11} s$ **provides growth of fluctuations on galactic scales.**
- **Dominance of** ν_μ **with mass *m*=100 eV at** $10^{12} s < t < 10^{16} s$ **provides growth of fluctuations on scales of LSS. The structure is formed by equal fractions of primordial** ν_μ **having after** ν_τ **dominance spectrum, typical for particles with mass 1 keV, and of non-equilibrium** ν_μ **from** $\nu_\tau \rightarrow \nu_\mu + \alpha$ **decays, which have spectrum of fluctuations typical for hot particles with mass ~1eV**
- **Products of decay of** ν_μ **form homogeneously distributed dark matter, which can be alternative to dark energy.**

UDM versus LCDM

- **UDM:**
- H<50, age of Universe does not need Lamda
- LSS evolution slows down **absolutely** due to decrease of density in it
- Homogeneously distributed dark matter – products of decay of unstable dark matter
- SN data are interpreted in terms of non-accelerated expansion

- **LCDM:**
- H>50, age of Universe needs Lamda
- LSS evolution slows down **relative** to accelerated expansion
- Homogeneous dark energy is provided by Lambda-term, quintessence…
- SN data are interpreted in terms of accelerated expansion

UDM+Lambda

- In the light of the current data UDM cannot be alternative for LambdaCDM
- Neutrino oscillations exclude the masses for UDM scenario for known neutrinos.
- However, for sterile neutrinos such a scenario is possible.
- Effect of UDM leads to time variation of the equation state for unclustered energy density and deserves interest for our analysis of the observational data.

Λ(H) PHENOMENOLOGY AND MECHANISM

- **Phenomenology of Λ-CDM Model: A Possibility of Accelerating Universe with Positive Pressure**

Saibal Ray · Maxim Khlopov · Partha Pratim Ghosh ·Utpal Mukhopadhyay

Int J Theor Phys (2011) 50: 939–951

The model

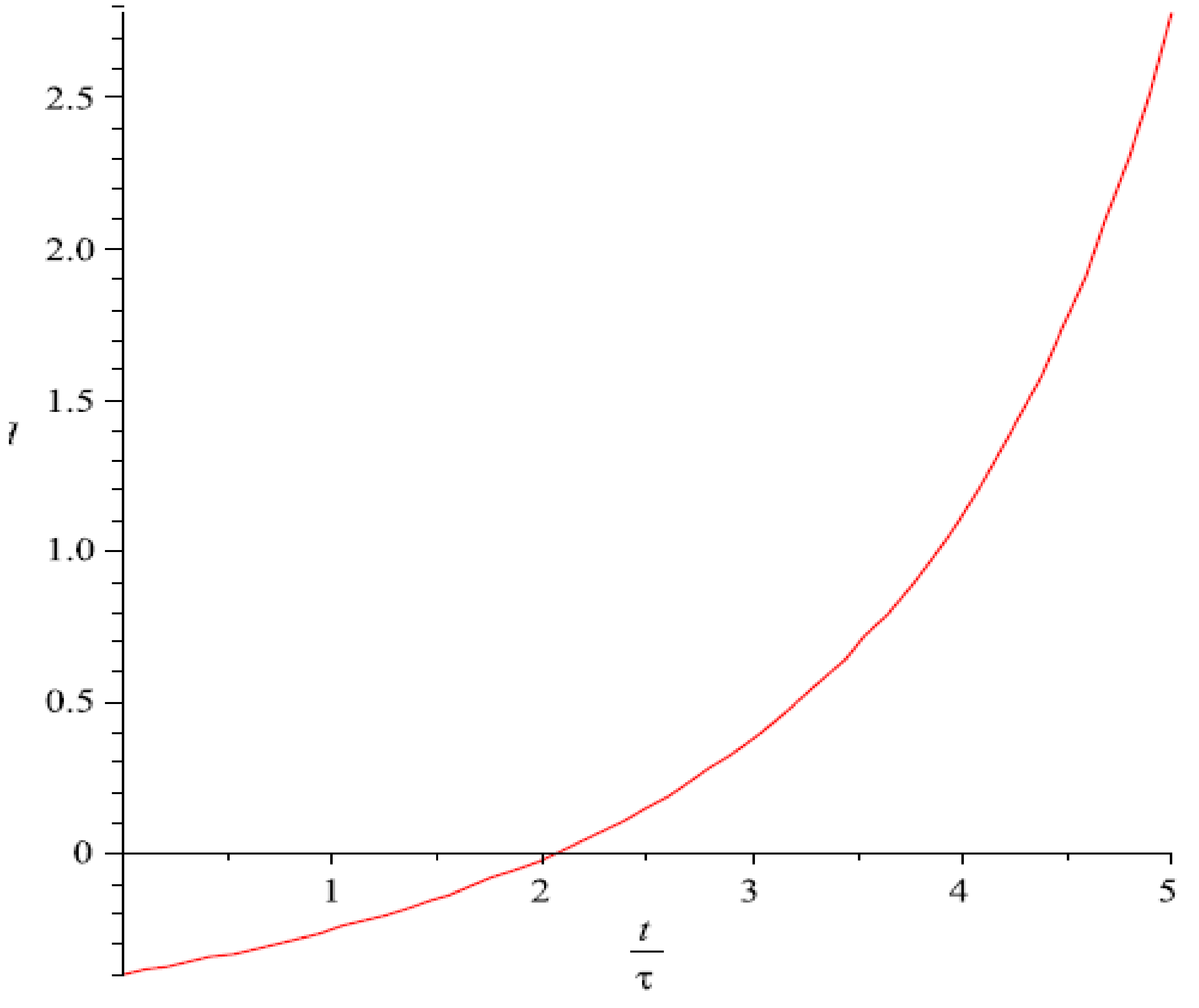
The model assumed both time varying Lambda and barotropic equation of state

$$3H^2 + \frac{3k}{a^2} = 8\pi G\rho + \Lambda,$$

$$3H^2 + 3\dot{H} = -4\pi G(\rho + 3p) + \Lambda$$

It lead to nontrivial solution of accelerated expansion at positive pressure but negative energy density.

Variation of deceleration parameter *q*



I. Dymnikova, M. Khlopov

Decay of cosmological constant in self-consistent inflation

Eur. Phys. J. C 20, 139–146 (2001)

The mechanism for Λ(H) phenomenology

- The idea of chaotic inflation is that slow rolling scalar field provides accelerating expansion. Usually it takes place for $m<H$.
- However it turns out to be possible also if $m>H$, if backreaction of evaporating BEC is taken into account.
- Decay of cosmological constant as Bose condensate evaporation

Backreaction at BEC evaporation

- At $m>H$ scalar field starts oscillations around it minimum.
- Products of decay of condensate destroy coherence of oscillations so that these oscillations are damped and slowed down
- Studies of BEC in atomic physics prove this effect
- The timescale of slowing down depends on the cross section of decay products with condensate

Conclusions

- We live in the world governed by new physics. Its effects can shed new light on the nature of the dark energy.

- Gauge model of broken family symmetry extends standard model to explain the observed mass hierarchy and mixing between families. It naturally leads to neutrino mass hierarchy and massive neutrino decays. Neutrino oscillations, excluding such a possibility for active neutrinos, do not prevent such a scenario for sterile neutrinos

- Λ+UDM scenario leads to time dependent dark energy.

- Phenomenology of $\Lambda(H)$ model leads to nontrivial cosmological solutions.

- Time dependent dark energy can find its nature in BEC decay.

Physics of vacuum is:

a) pumps and vacuum chambers

b) all the other physics

I.Ya.Pomeranchuk