A02

Dark Matter and Large-Scale Structure

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@Kavli IPMU

Fuminobu Takahashi
(Tohoku U)

Members

Masahiro Kawasaki (ICRR)

CDM/baryon isocurv. 21cm, CMB

Kazunori Kohri (KEK)

Decaying DM, CHAMP, MaVaN

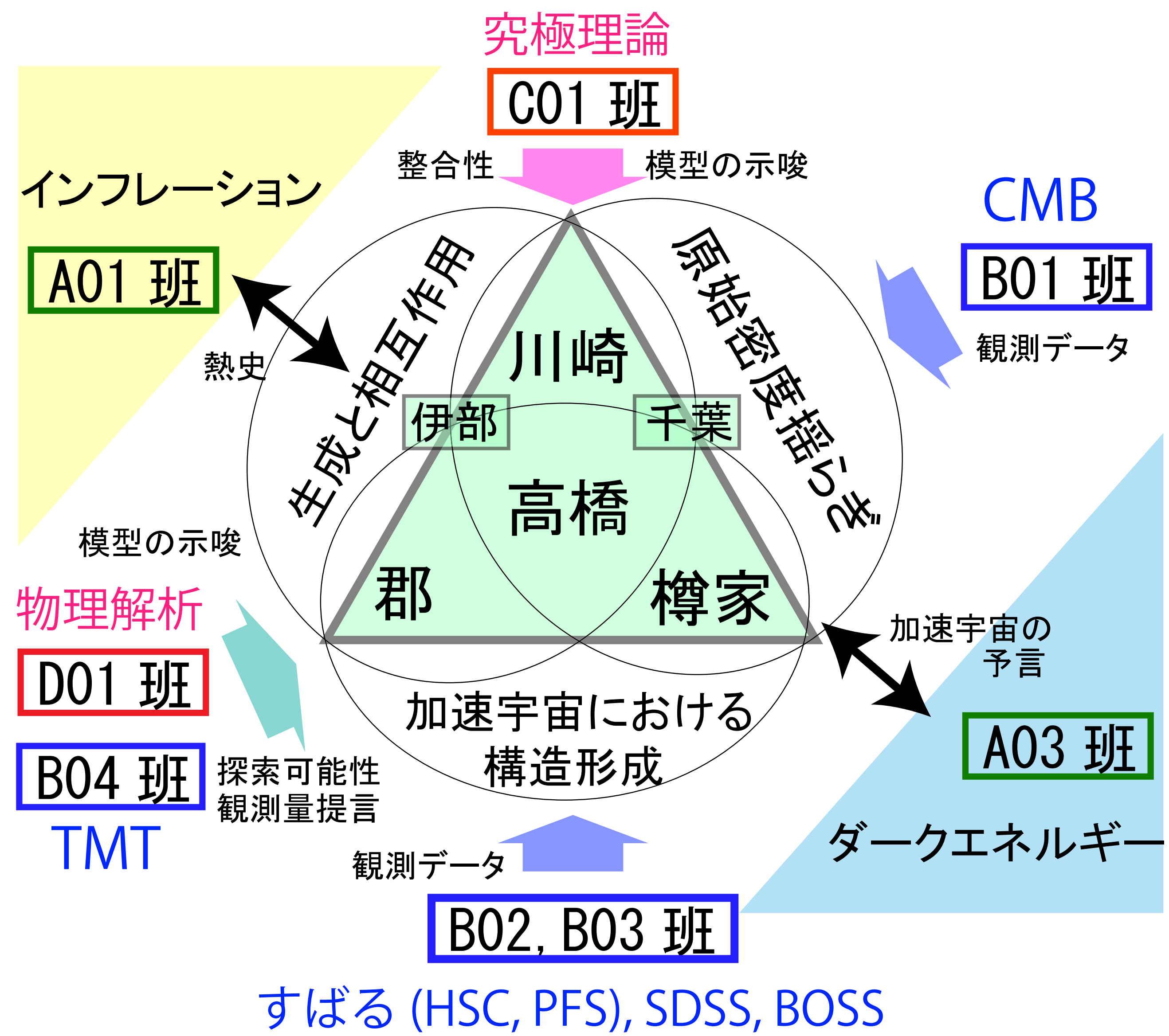
Atsushi Taruya (Kyoto)

Structure formation history

Non-linear gravitational evolution

Fuminobu Takahashi (Tohoku)

Axion, sterile nu, dark photons

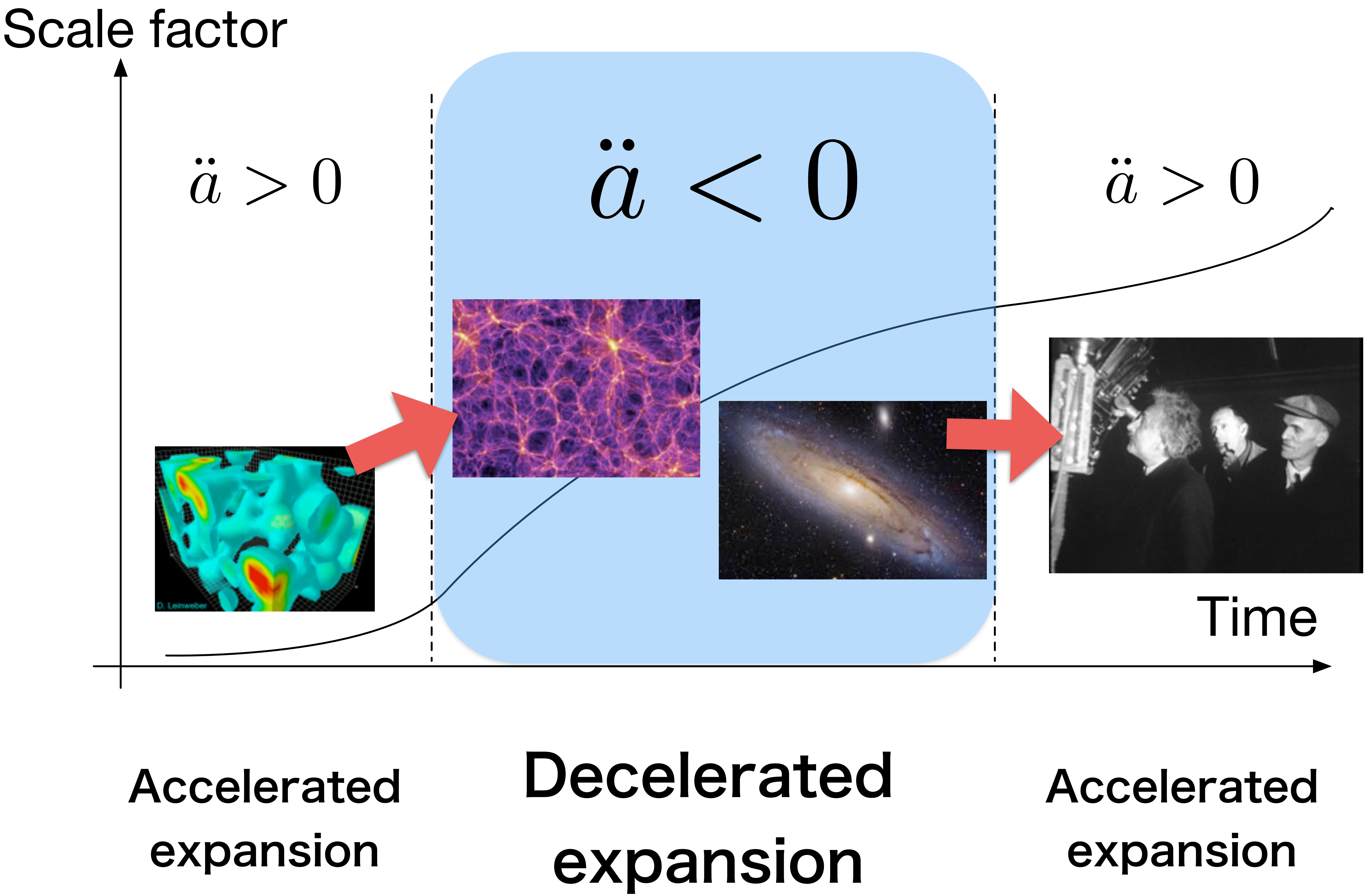


<u>連携研究者</u>：

Masashi Chiba (Tohoku)

DM distribution

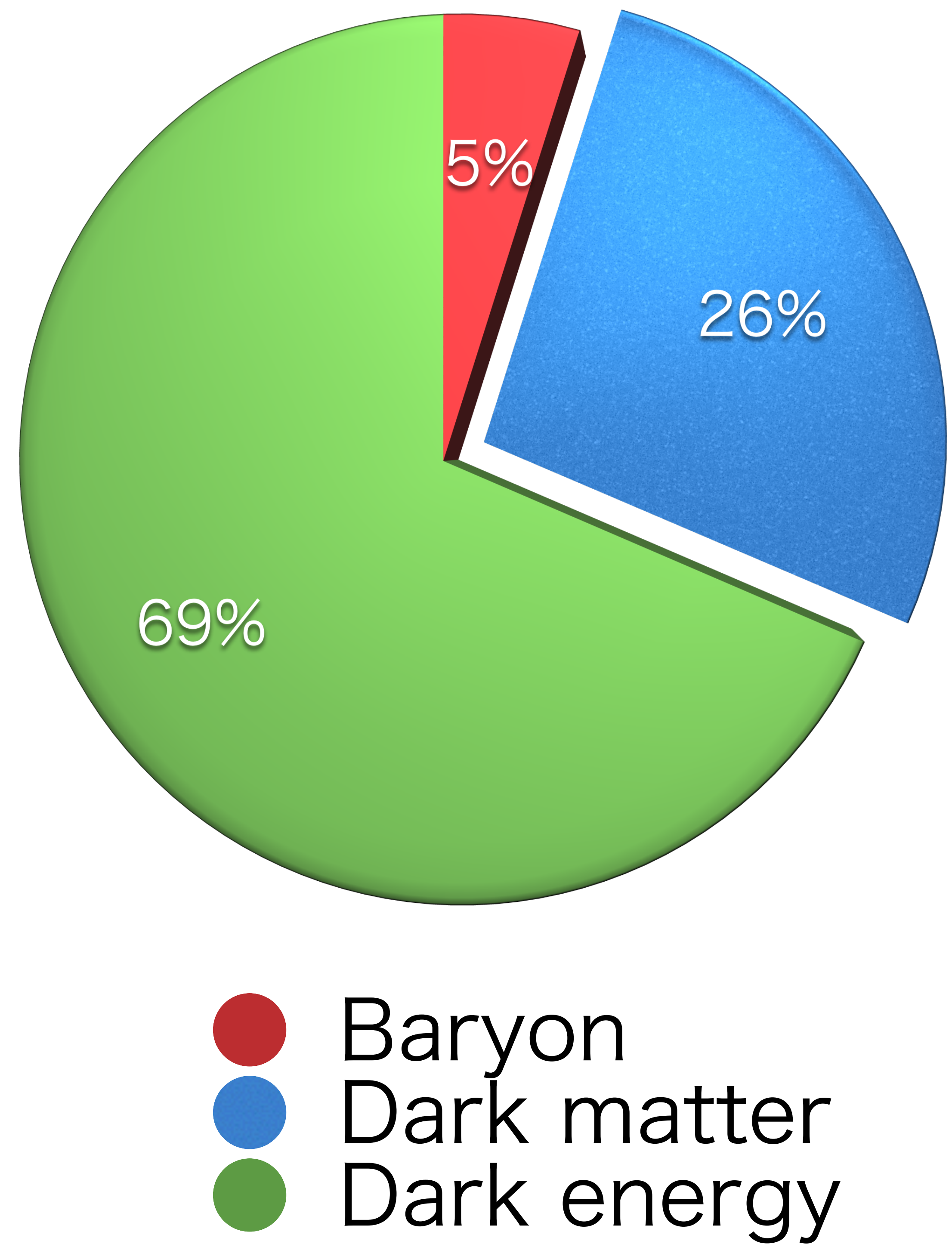
Masahiro Ibe (ICRR) DM model building


Scale factor
$\ddot{a} > 0$
$\ddot{a} < 0$
$\ddot{a} > 0$
D. Leinweber
Time
Accelerated expansion
Decelerated expansion
Accelerated expansion

Dark Matter

The presence of DM has been firmly established.

$$\Omega_{\mathrm{DM}} \simeq 0.26$$



DM may be made of an as-yet-undiscovered particle.

What we know

- ✓ DM gravitates.
- ✓ DM is electrically neutral.
- ✓ DM has only (very) weak interactions with the SM particles.
- ✓ DM is non-relativistic.
- ✓ DM is long-lived.
- ✓ DM played a crucial role for LSS formation.

What we want to know

✓ **What is DM?**
- Why long-lived?
- How produced? Abundance?
- Cold or warm?
- Non-gravitational couplings?

✓ **DM density perturbations**
- Isocurvature mode/non-Gaussianity?

✓ **Non-linear gravitational evolution**

See talk by Taruya

✓ **DM distribution** in dSphs, galaxies, and clusters.
- Any tension with LCDM and N-body simulations?

See talk by Chiba

Research Themes

(1) Dark matter density perturbations

Kawasaki

Isocurvature perturbations, non-Gaussianity

Takahashi

(2) Production and properties of dark matter

Ibe

Non-thermal production, self-interacting/decaying DM

Taruya

(3) Structure formation and DM distribution

Chiba

Non-linear gravitational evolution, halo bias

Matter power spectrum modified by WDM or CHAMP

Kohri

(4) Unification of dark matter and dark energy

Mass-Varying Neutrinos, Ultra-light axions

Kohri

(5) Anything about DM!

Why long-lived?

1) Symmetry

- e.g. R-parity, KK parity: LSP, LKP.

2) Light mass

- e.g. modulus lifetime: $\tau \simeq \frac{M_p^2}{m_{\rm DM}^3}$

3) Very weak interactions

- e.g. Hidden sector, gravity sector

The light mass and/or weak int. may be due to symmetry (e.g. chiral, shift sym, SUSY), extra dim or compositeness.

These are not exclusive: e.g. axion [2&3], gravitino [1,2,3]

How produced?

1) From the standard model thermal plasma

- DM was in thermal equilibrium

Neutralino LSP

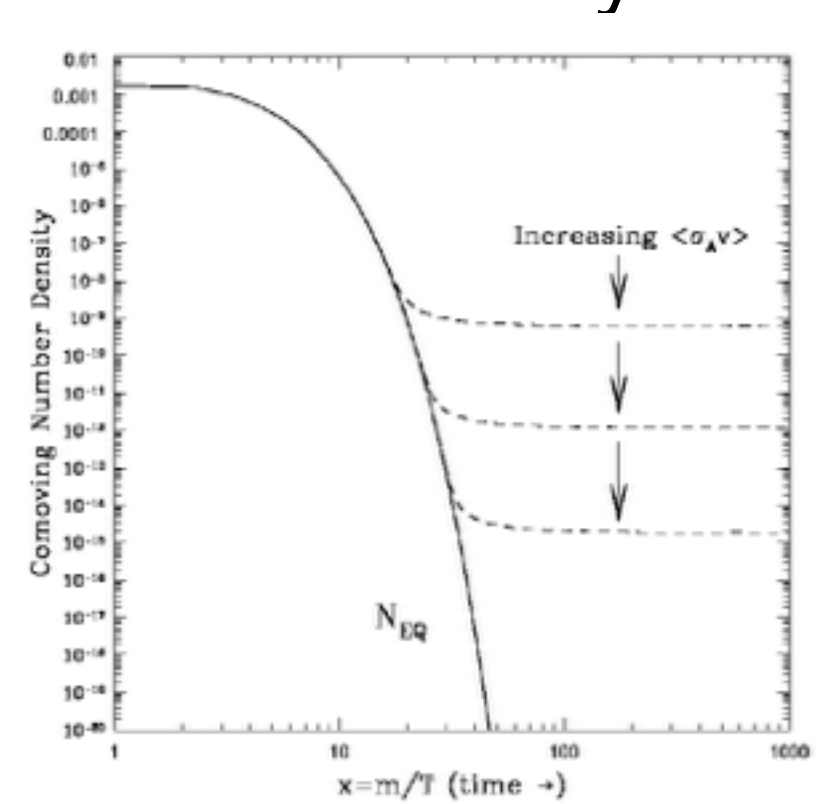
"WIMP miracle"

- Thermal relic abundance of WIMPs of mass O(100)GeV is close to the observed DM density.

$$\Omega_{\rm WIMP} \simeq \frac{0.3}{\langle \sigma v \rangle / \mathrm{pb}}$$

$$\langle \sigma v \rangle \simeq 3 \times 10^{-26} \mathrm{cm}^3 / \mathrm{sec}$$

Sounds reasonable if there is new physics around TeV scale.



How produced?

1) From the standard model thermal plasma

- DM was in thermal equilibrium   Neutralino

- Non-thermal process; decay, oscillations, scattering.
  SuperWIMP, sterile nu, gravitino,etc.

2) From other sources

- decay of inflaton or some other heavy particle
  Gravitino
- scalar condensate   QCD axion, moduli
- hidden plasma (thermal or non-thermal)
- gravitational production
- etc.

Cold or Warm

Free streaming length (sterile neutrino)

$$\lambda_{\rm FS} \simeq 1\,{\rm Mpc}\left(\frac{m_{\rm DM}}{\rm keV}\right)^{-1}\left(\frac{\langle p_{\rm DM}/T\rangle}{3.15}\right)$$

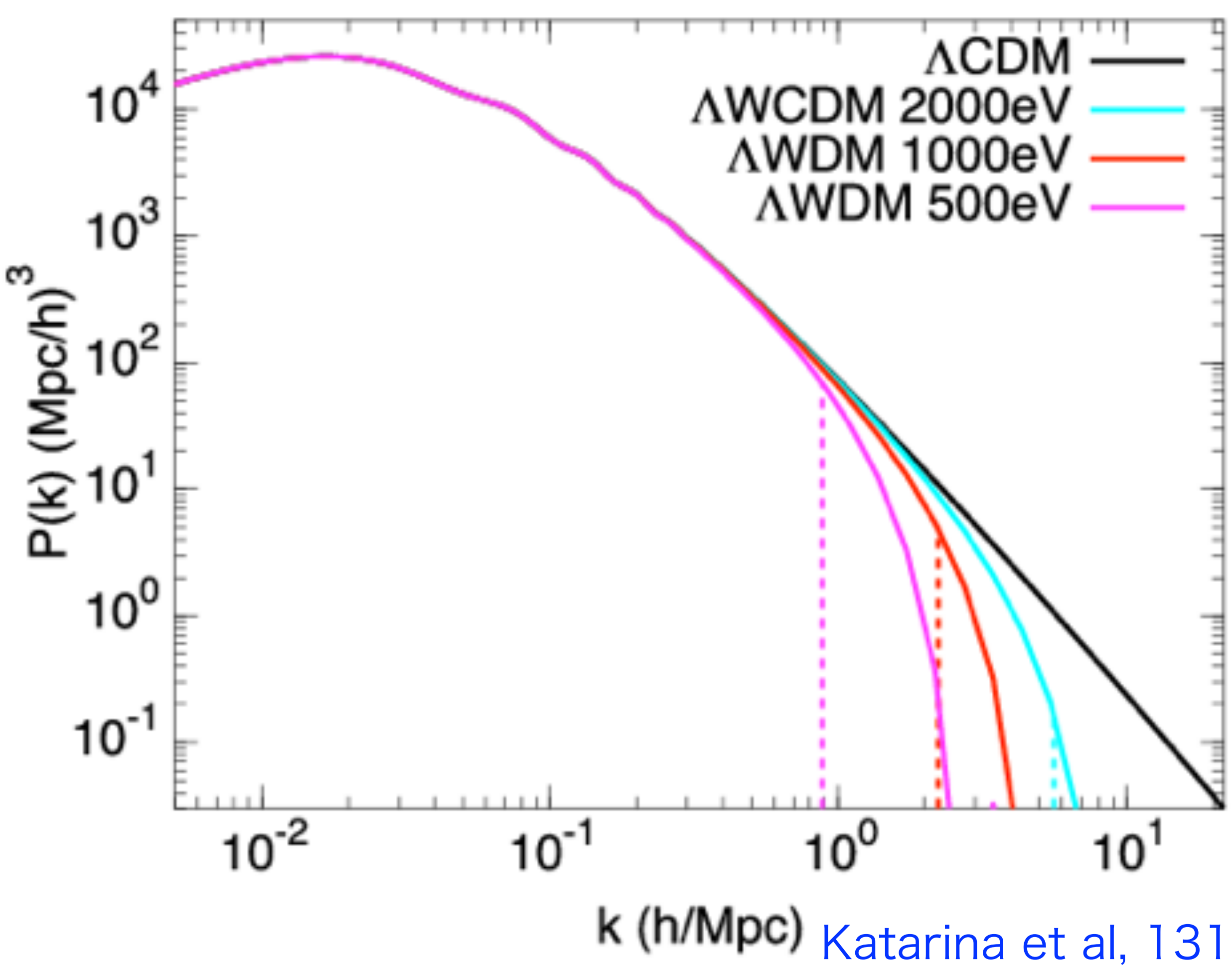
$$M_{\rm FS} \simeq 3\times 10^7 M_\odot \left(\frac{m_{\rm DM}}{\rm keV}\right)^{-3}\left(\frac{\langle p_{\rm DM}/T\rangle}{3.15}\right)^3$$

DM mass　　Production process

WDM suppresses power on small scales.

Similar suppression is possible with long-lived CHAMP.

cf. Kohri & T.Takahashi, 0909.4610



Katarina et al, 1311.5223

Sterile neutrino DM

Let us consider SM + 3 RH neutrinos.

$$-\mathcal{L} = \frac{1}{2}\kappa_I M \bar{N}_I^c N_I + \lambda_{I\alpha}\bar{N}_I L_\alpha H + \mathrm{h.c.},$$

$\alpha = e, \mu, \tau$

$\kappa_3 > \kappa_2 > \kappa_1$ $M_I = \kappa_I M$ M : B-L breaking scale

The seesaw formula for the light neutrino mass:

Minkowski `77, Yanagida `79, Ramond `79, Glashow `80

$$(m_\nu)_{\alpha\beta} = \lambda_{\alpha I}\lambda_{I\beta}\frac{v^2}{M_I}, \quad v = \langle H^0 \rangle \simeq 174\,\mathrm{GeV}$$

$$\Delta m^2_{\mathrm{atm}} \simeq 2.3 \times 10^{-3}\mathrm{eV}^2 \quad \Delta m^2_\odot \simeq 8 \times 10^{-5}\,\mathrm{eV}^2$$

The B-L breaking is $M \sim 10^{15}\,\mathrm{GeV}$ for $\lambda_{I\alpha} \sim \kappa_I \sim 1$

Sterile neutrino DM

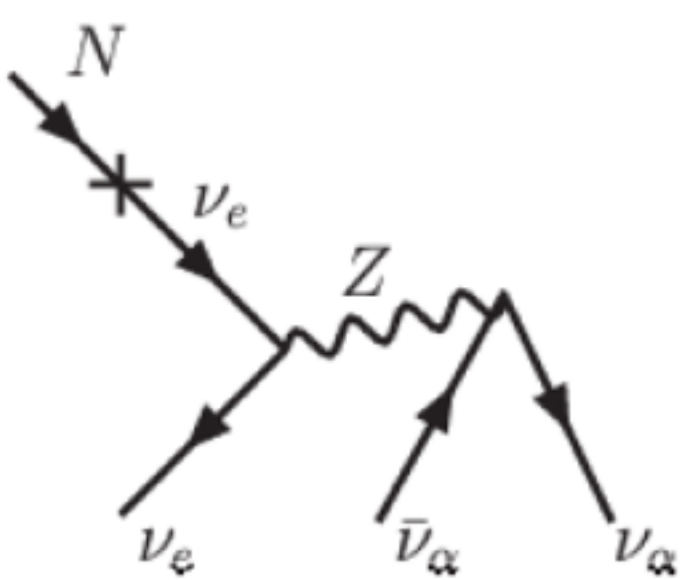
Suppose that the lightest one is very light.

$$-\mathcal{L} = \frac{1}{2}\kappa_I M \bar{N}_I^c N_I + \lambda_{I\alpha}\bar{N}_I L_\alpha H + \text{h.c.},$$

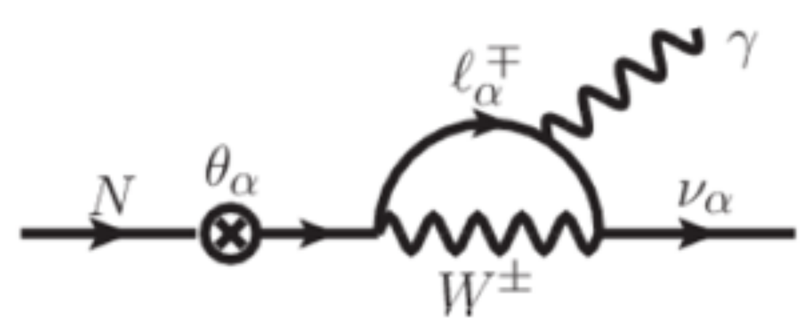
$\alpha = e, \mu, \tau$

$\kappa_3 > \kappa_2 \gg \kappa_1$ $\quad M_I = \kappa_I M \quad M$: B-L breaking scale

Sterile neutrino decays thru mixings with active nu.



$N \to \nu\nu\bar{\nu}$



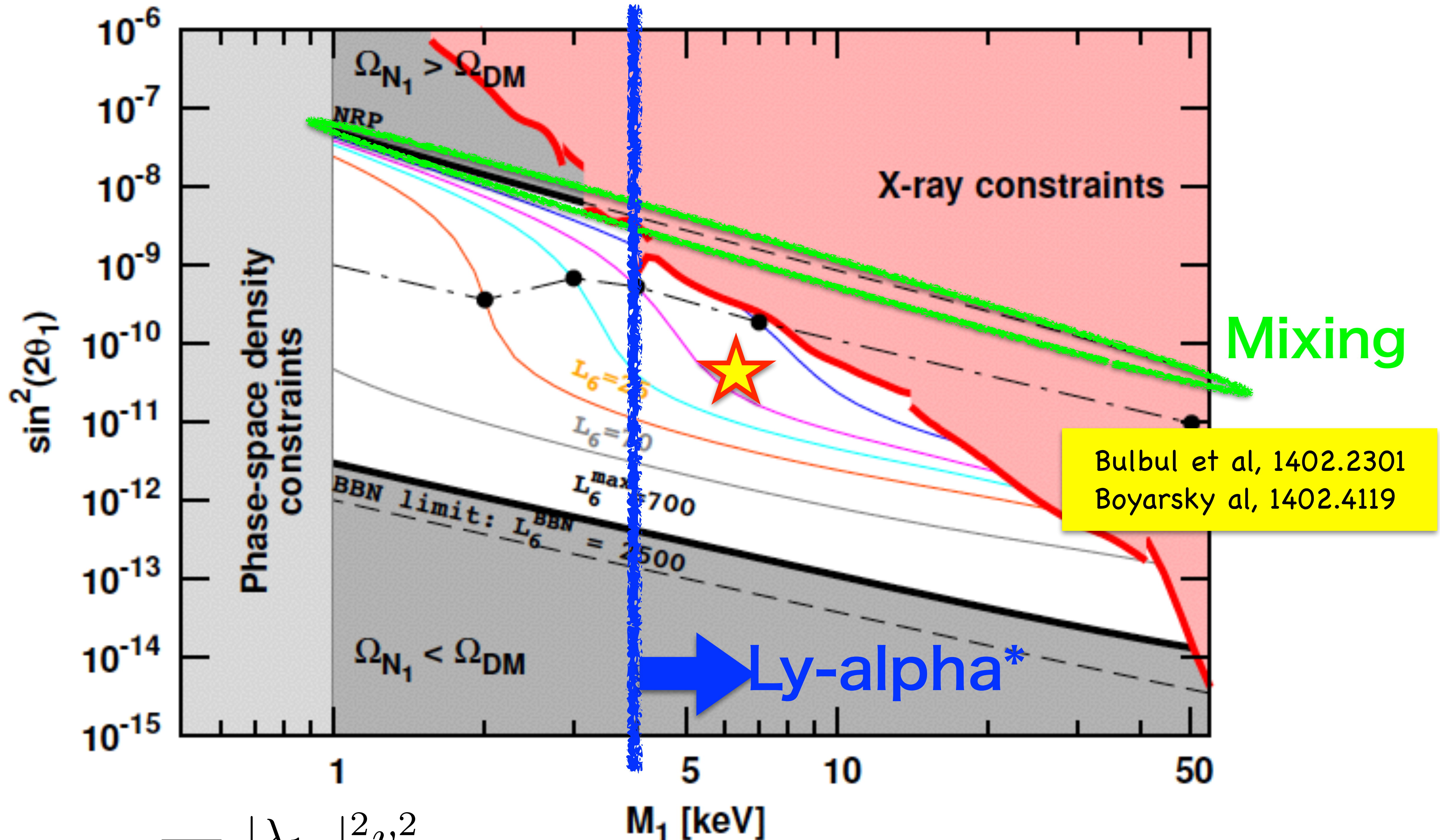
$N \to \nu\gamma$

$$\theta^2 \equiv \sum_\alpha \frac{|\lambda_{1\alpha}|^2 v^2}{M_1^2}$$

From Boyarsky et al, 1306.4954

Cosmological bounds

$\Gamma^{-1} > 200\,\mathrm{Gyr}$



$$\theta^2 \equiv \sum_\alpha \frac{|\lambda_{1\alpha}|^2 v^2}{M_1^2}$$

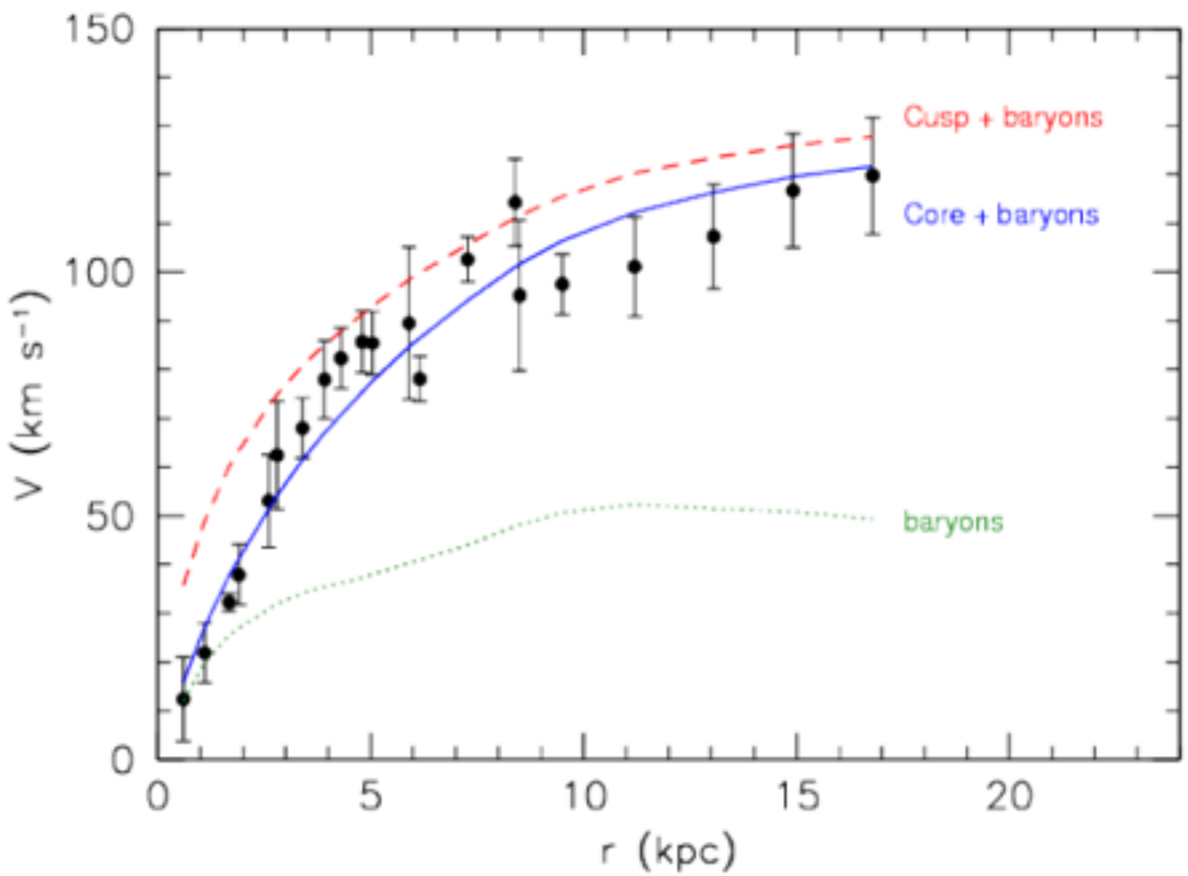
From ``Light Sterile Neutrinos: A White Paper "
1204.5379

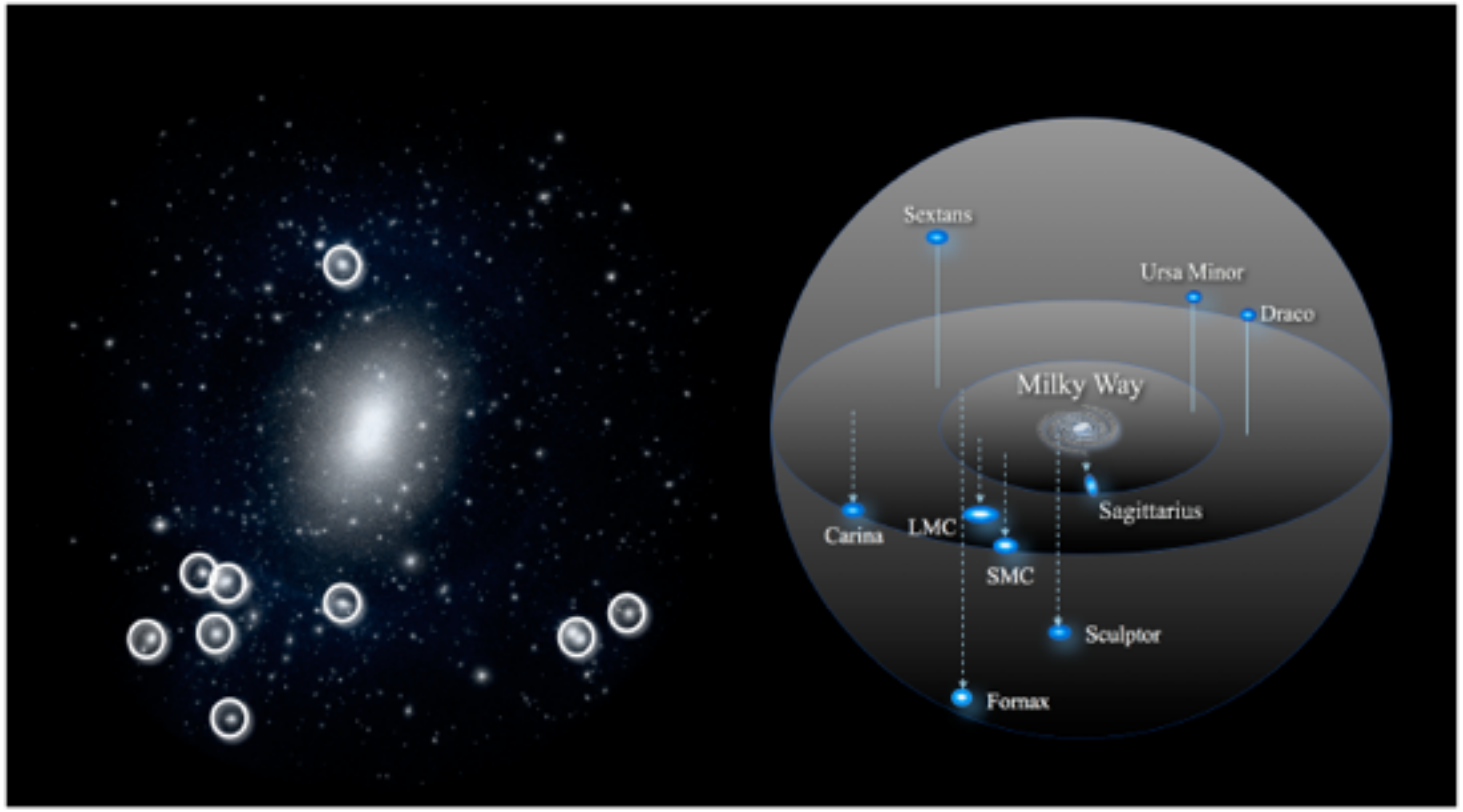
*Viel et al, 0709.0131

Crisis of LCDM?

See talk by Chiba

- Core-cusp problem
- Too-big-to-fail problem
- Missing satellite problem





Taken from H. Weniberg et al, 1309.0913

N-body simulation with collisionless CDM predicts more DM in the central regions of typical galaxies.

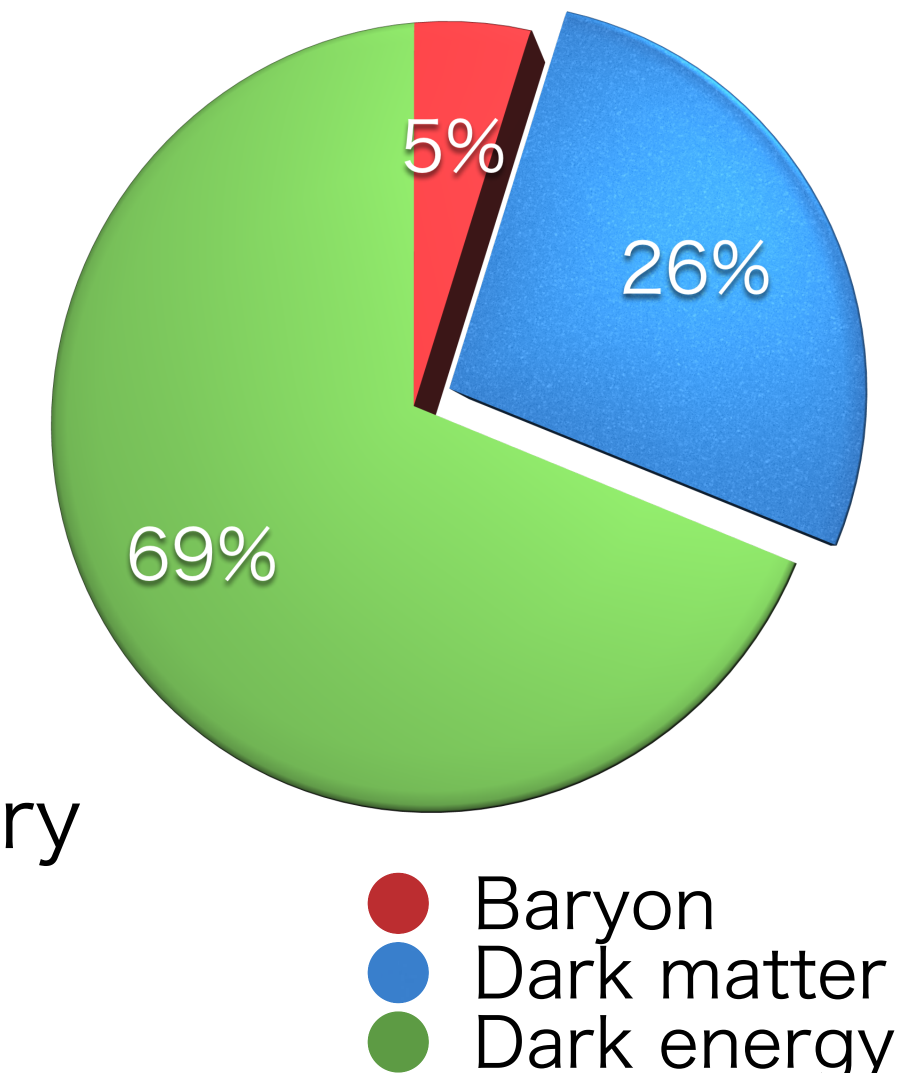
Complex baryon physics or DM properties (WDM, self-coupling?)

Abundance

The baryon-DM coincidence problem:

Why $\Omega_{\rm DM} \sim 5\Omega_B$?

$$\Omega_{\rm DM} \simeq 0.26 \qquad \Omega_B \simeq 0.05$$



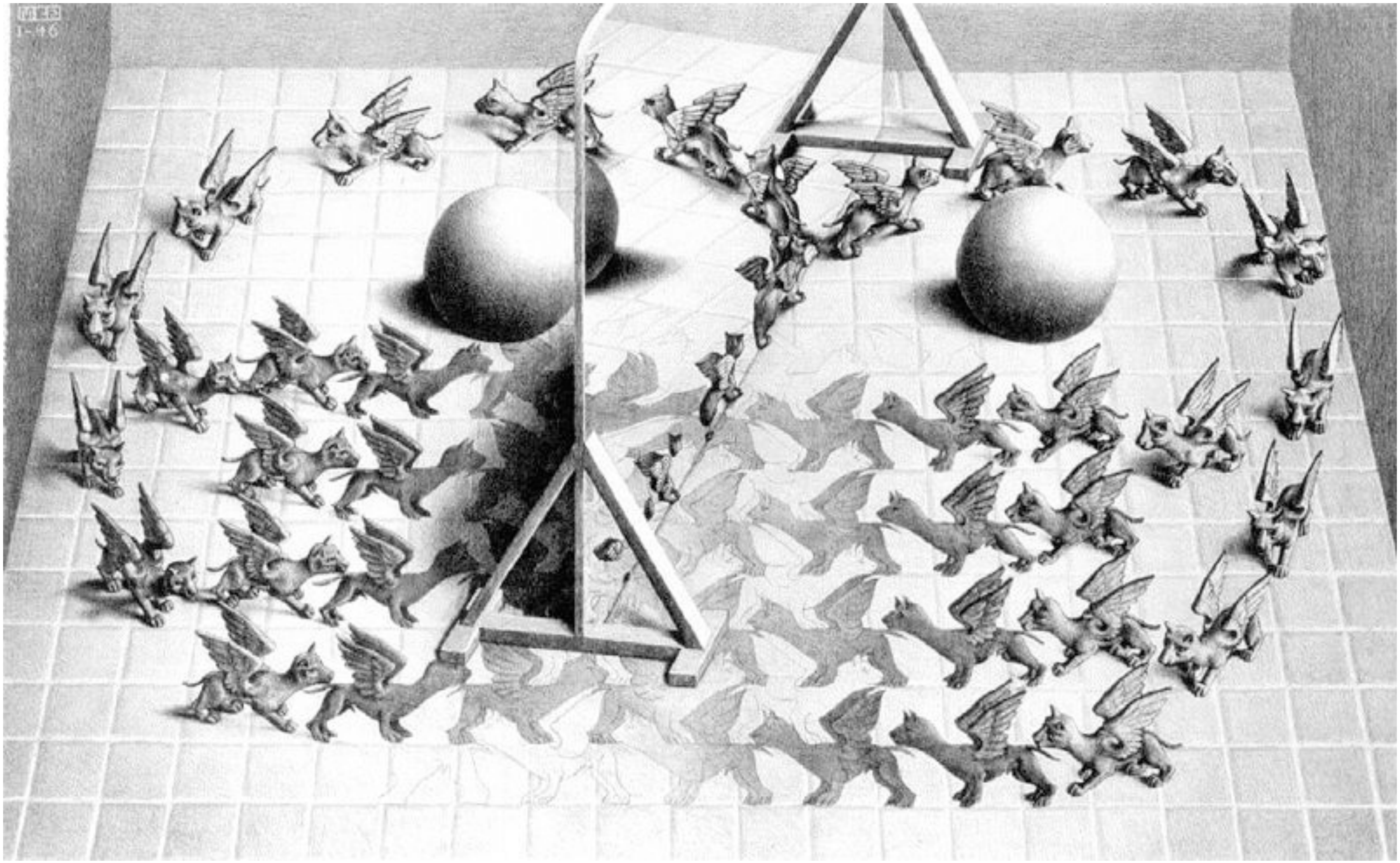
It is a puzzle if DM and baryon asymmetry have a different origin.

Many works on this puzzle. e.g. asymmetric DM

(Kaplan, Luty, Zurek 0901.4117 and many others.)

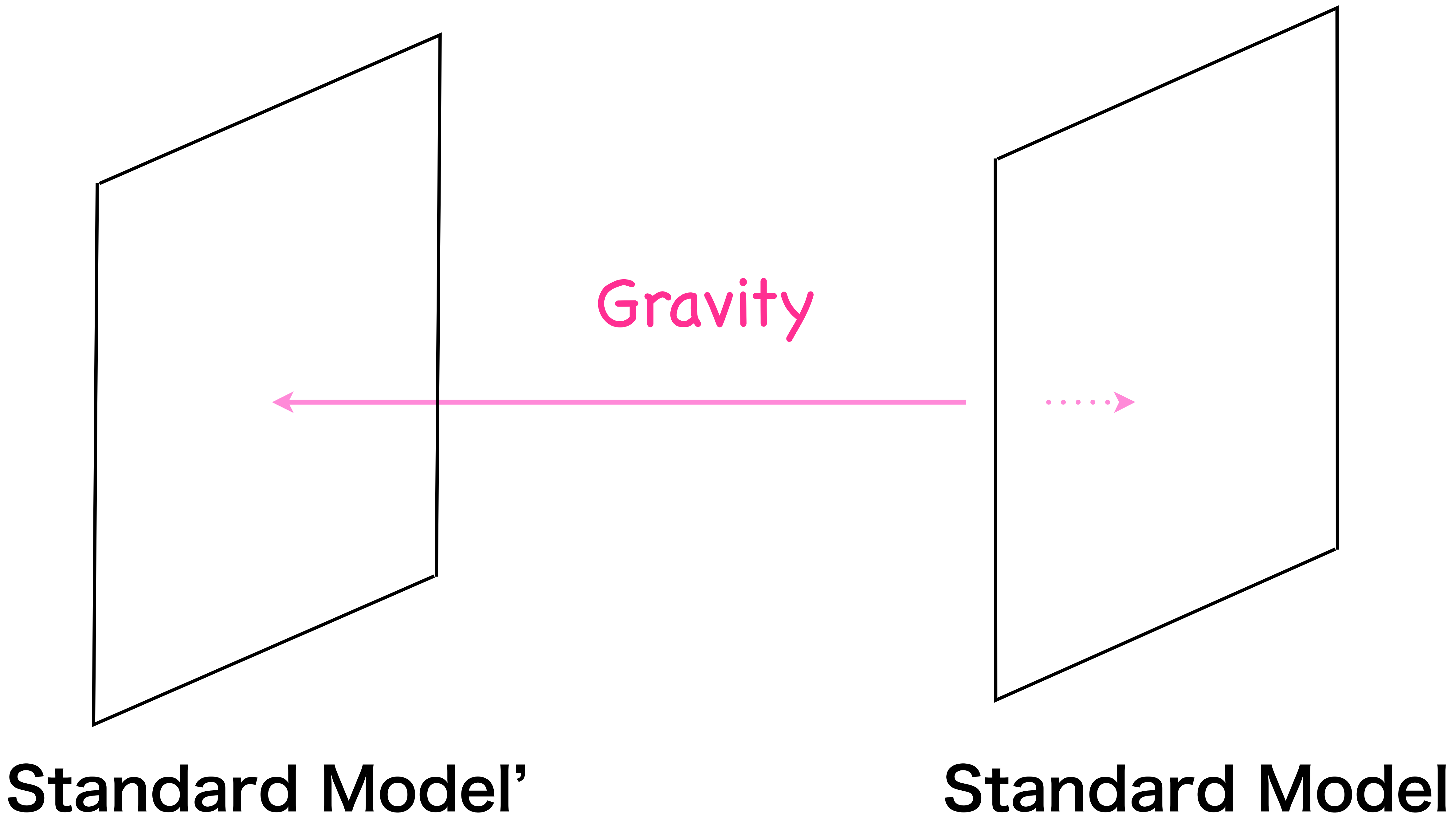
In order to solve the coincidence problem, however, the DM must know somehow the proton mass.

Parallel World



“Magic mirror” by Escher

Parallel World



Parallel World

- Has the same gauge structure SU(3)xSU(2)xU(1) and the particle content of the SM.

e.g. the counterpart of photon = γ' , para-photon, or simply p-photon.

- The parameters in the Lagrangian can be different by a O(1) factor.

cf. The so-called "mirror world" assumes an exact Z_2 parity.

(Lee & Yang `56, Blinnikov &Khlopov `82 and many others)

- Interacts with the SM (almost) thru gravity.

*There are many variations: Higgs portal, U(1) kinetic mixing, neutrino portal, etc.

Parallel World

- Dark matter = p-baryon (p-neutron)

Self-interacting DM

- Dark radiation = p-photon and p-neutrino(s)

Dark radiation

- Sterile neutrino = massive p-neutrino(s)

HDM

The amount of DR and sterile neutrinos satisfy a certain relation: $N_s^{\frac{4}{3}} = \kappa \Delta N_{\rm eff}$

Higaki, Jeong and FT, 1302.2516

κ depends on the neutrino mass hierarchy

N_s : effective # of sterile neutrinos

Self-Interacting Dark Matter

Spergel and Steinhardt `00.

- DM self-coupling is constrained by the halo shape of galaxy clusters:

$$\frac{\sigma_{\rm DM}}{m_{\rm DM}} \lesssim \mathcal{O}(0.1)\,{\rm cm}^2/{\rm g}$$

Rocha et al, 1208.3025
Peter et al, 1208.3026

cf. σ /m = 0.6 cm²/g can solve the central density problem of dwarf spheroidals.

Zavala et al, 1211.6426

For comparison, the neutron-neutron cross section is

$$\frac{\sigma_{nn}}{m_n} \sim 30\,{\rm cm}^2/{\rm g}$$

The above bound is satisfied if the QCD' scale is several times higher than the QCD scale.

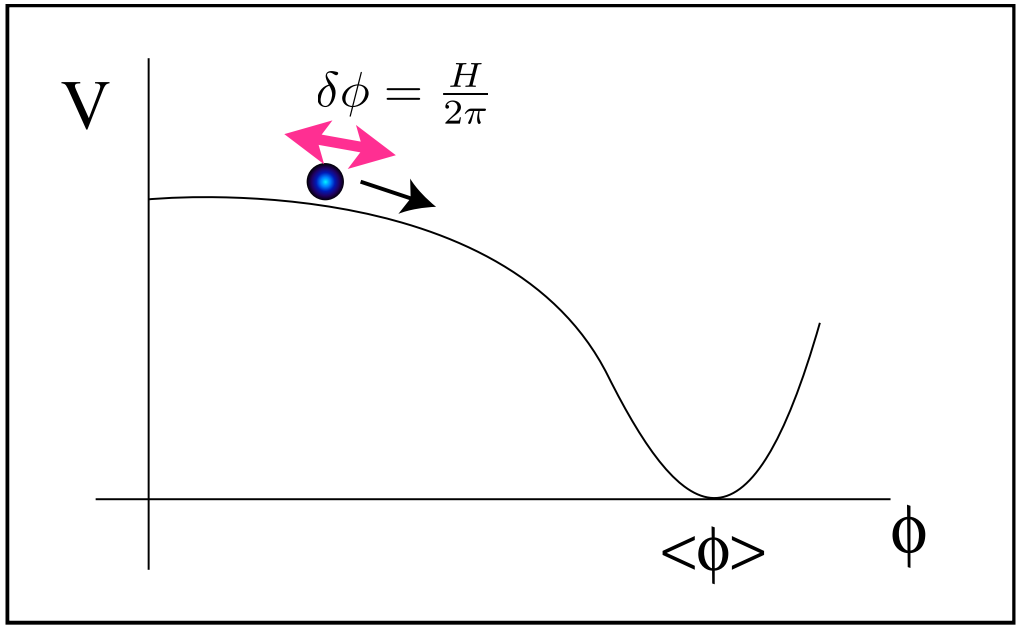
Dark matter density perturbations

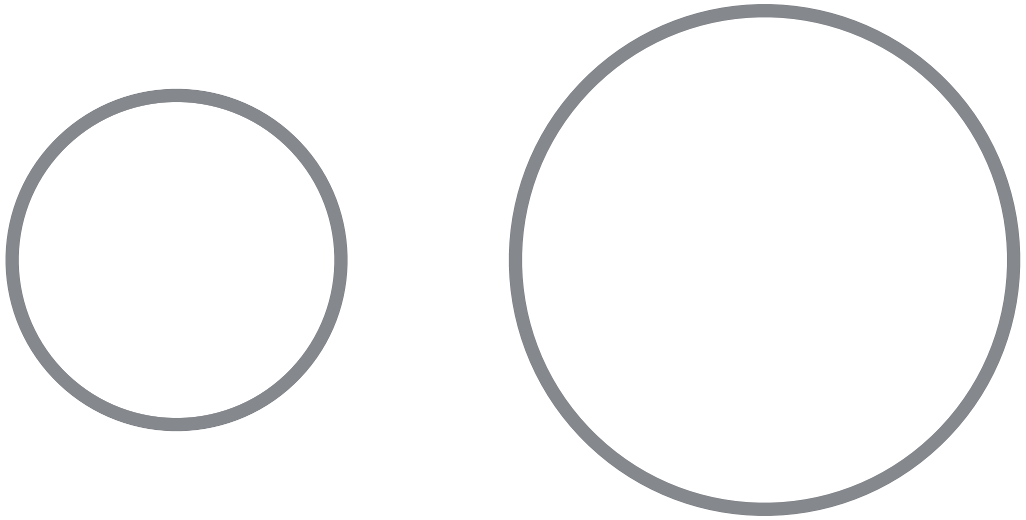
Adiabatic perturbations :

(usually) produced by quantum fluctuations of the inflaton. Fluctuation of time and volume.

Gravitational potential **Curvature perturbatinos**

$$ds^2 = -(1+2\Phi)dt^2 + a(t)^2(1+2\Psi)d\mathbf{x}^2$$





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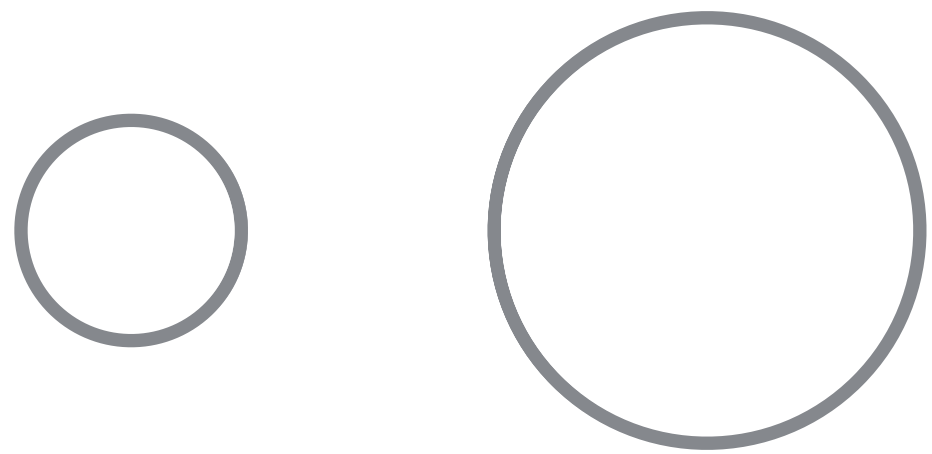
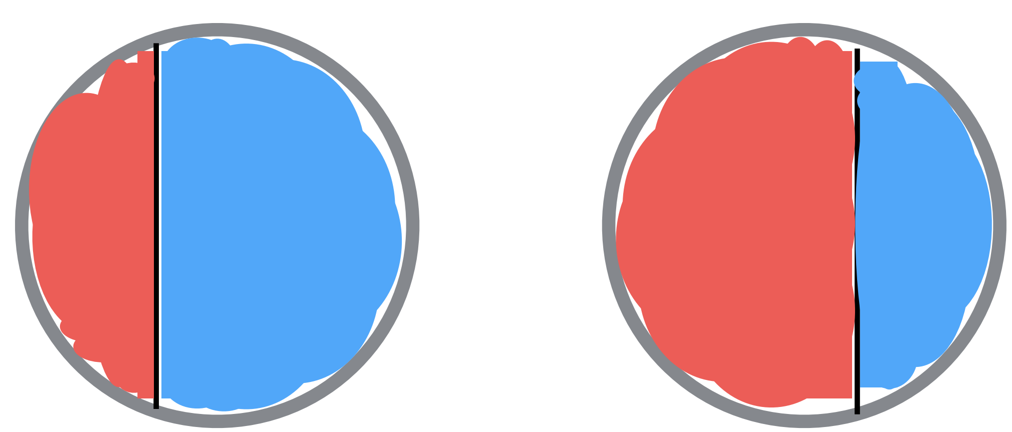
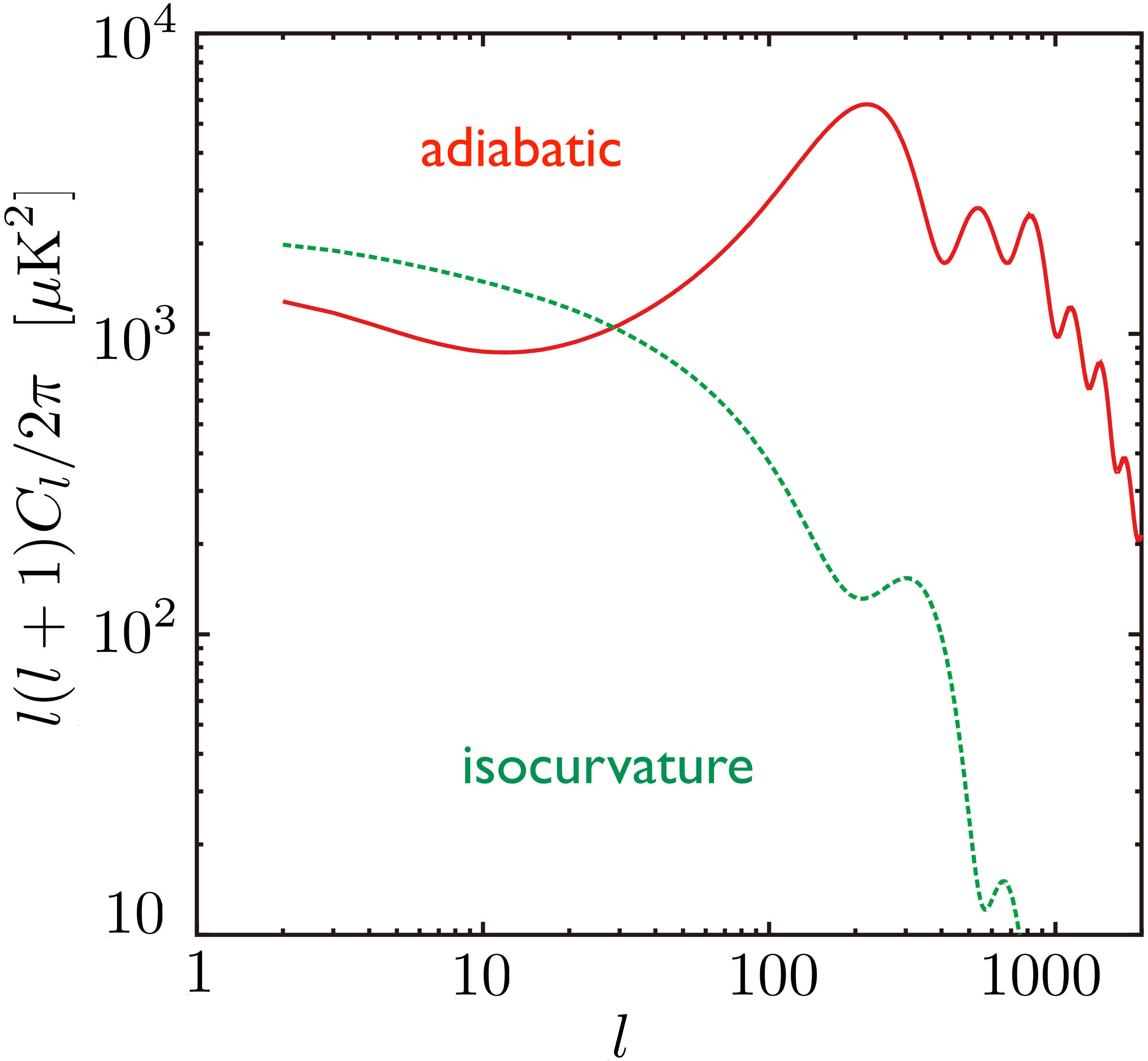


Isocurvature perturbations:

Fluctuations between components



Adiabatic/isocurvature perturbations



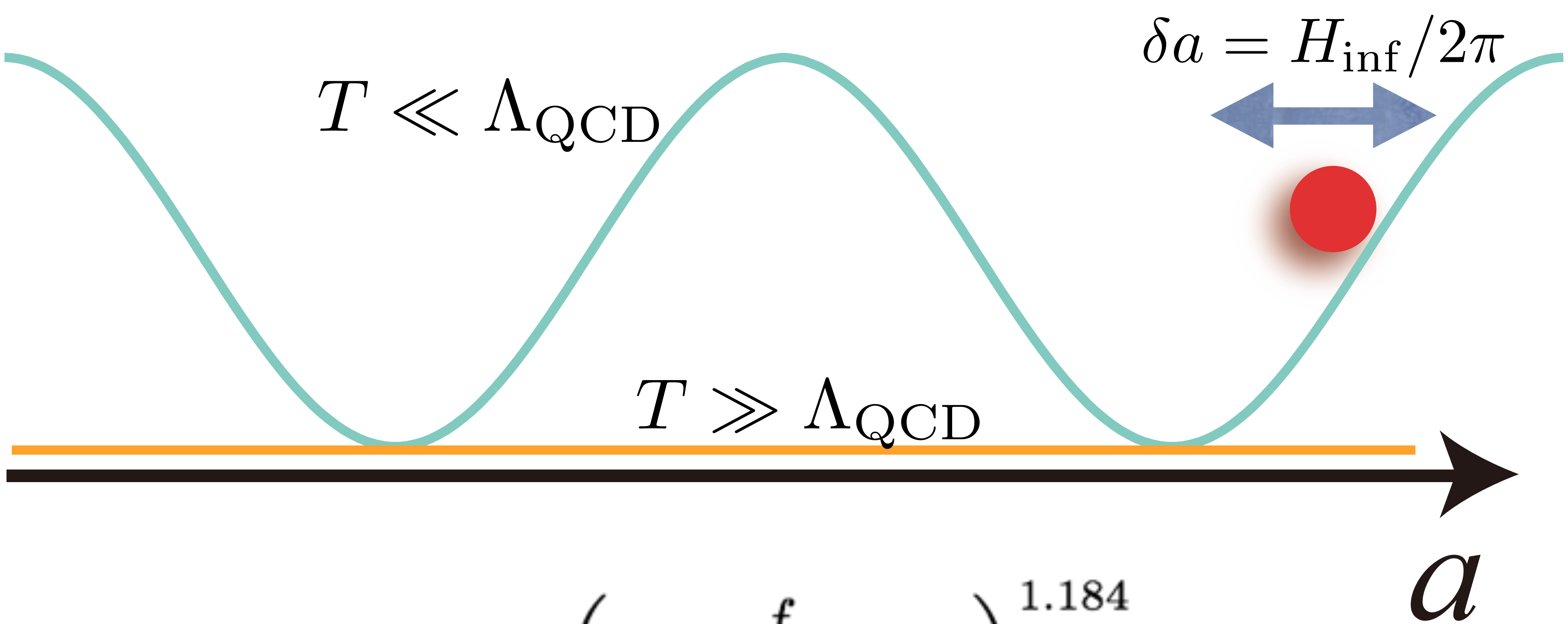
$$\beta_{\rm iso}(k) = \frac{\mathcal{P}_{\mathcal{II}}(k)}{\mathcal{P}_{\mathcal{RR}}(k) + \mathcal{P}_{\mathcal{II}}(k)} < 0.038 \ (95\% \ \mathrm{CL})$$

(uncorrelated)

@ $k = 0.05\,\mathrm{Mpc}^{-1}$

QCD Axion

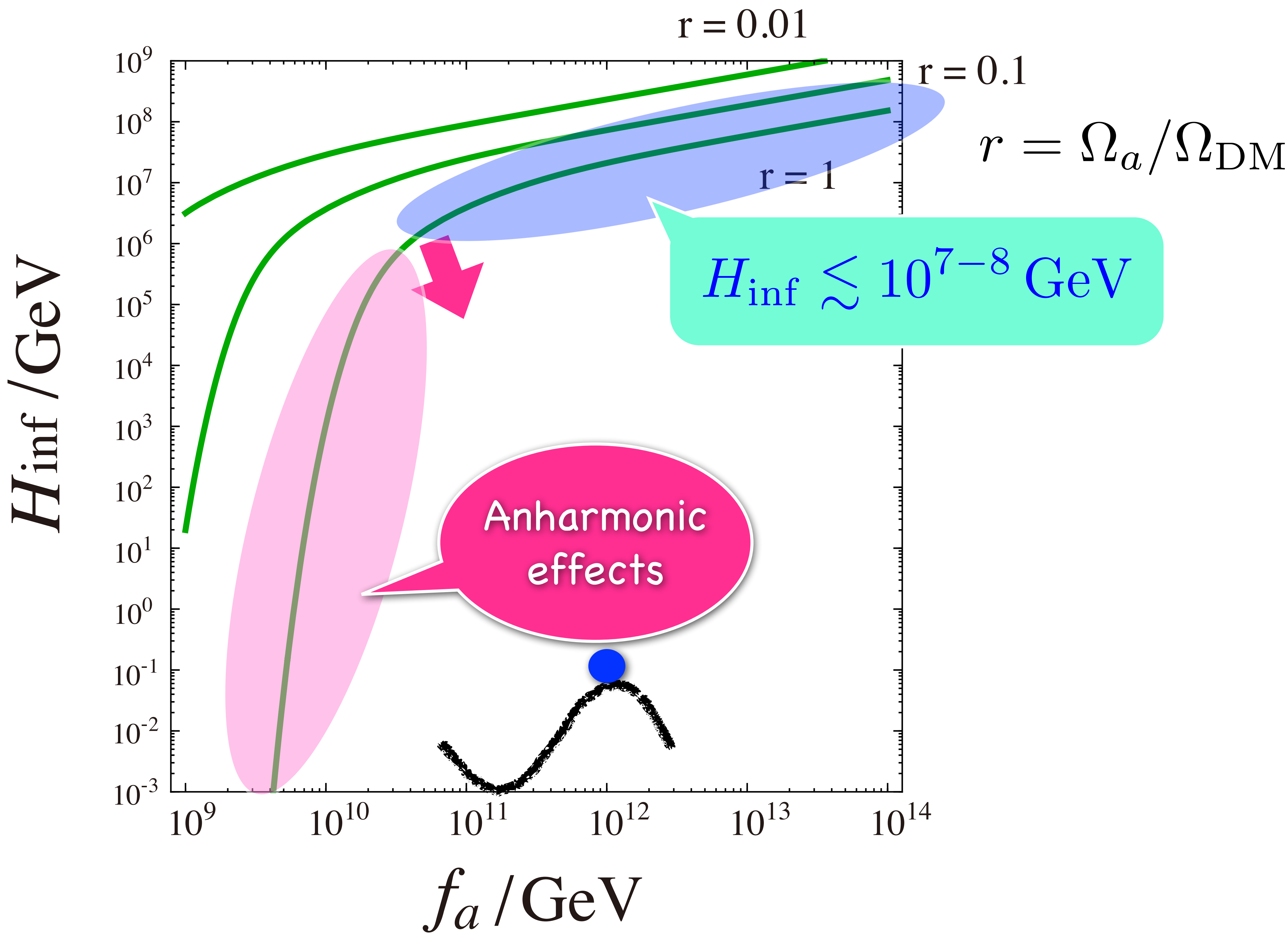
$$\mathcal{L} = \left(\theta + \frac{a}{f_a}\right) \frac{g_s^2}{32\pi^2} G^{\mu\nu}\tilde{G}_{\mu\nu}$$



$$\Omega_a h^2 \simeq 0.11 \left(\frac{f_a}{5\times 10^{11}\,\mathrm{GeV}}\right)^{1.184} F(\theta_*)\theta_*^2$$

$$S \simeq \left(\frac{\Omega_a}{\Omega_{\rm DM}}\right)\left[2\frac{\delta a}{a_*} + \left(\frac{\delta a}{a_*}\right)^2\right]$$

Isocurvature constraint on H_{inf}



Kobayashi, Kurematsu, FT, 1304.0922

Isocurvature constraint on H_{inf}

The tension with high-scale inflation can be avoided if

1. PQ symmetry restored during/after inflation

   Linde and Lyth `90

2. Larger effective decay constant during inflation.

   Linde `91

3. Temporarily enhanced PQ symmetry breaking.

   Dine, Anisimov `05,
   Jeong, FT `13, FT, Yamada `15.

Summary

The decelerated expansion itself may be reasonable as the gravitational force is attractive, but there are many puzzles about DM:

- ✓ **What is DM?**
  - Why long-lived? How produced? Abundance? Cold or warm? Non-gravitational couplings?
- ✓ **DM density perturbations**
  - Isocurvature mode/non-Gaussianity?
- ✓ **Non-linear gravitational evolution** See talk by Taruya
- ✓ **DM distribution** in dSphs, galaxies, and clusters.
  - Any tension with LCDM and N-body simulations? See talk by Chiba
- ✓ **Unified picture of DM and DE?**
  - Ultralight axion DE and saxion DM, Mass-varying neutrinos, etc.