Research status of A02 and the ALP miracle

Mar. 8 2017 @KEK
新学術領域「加速宇宙」

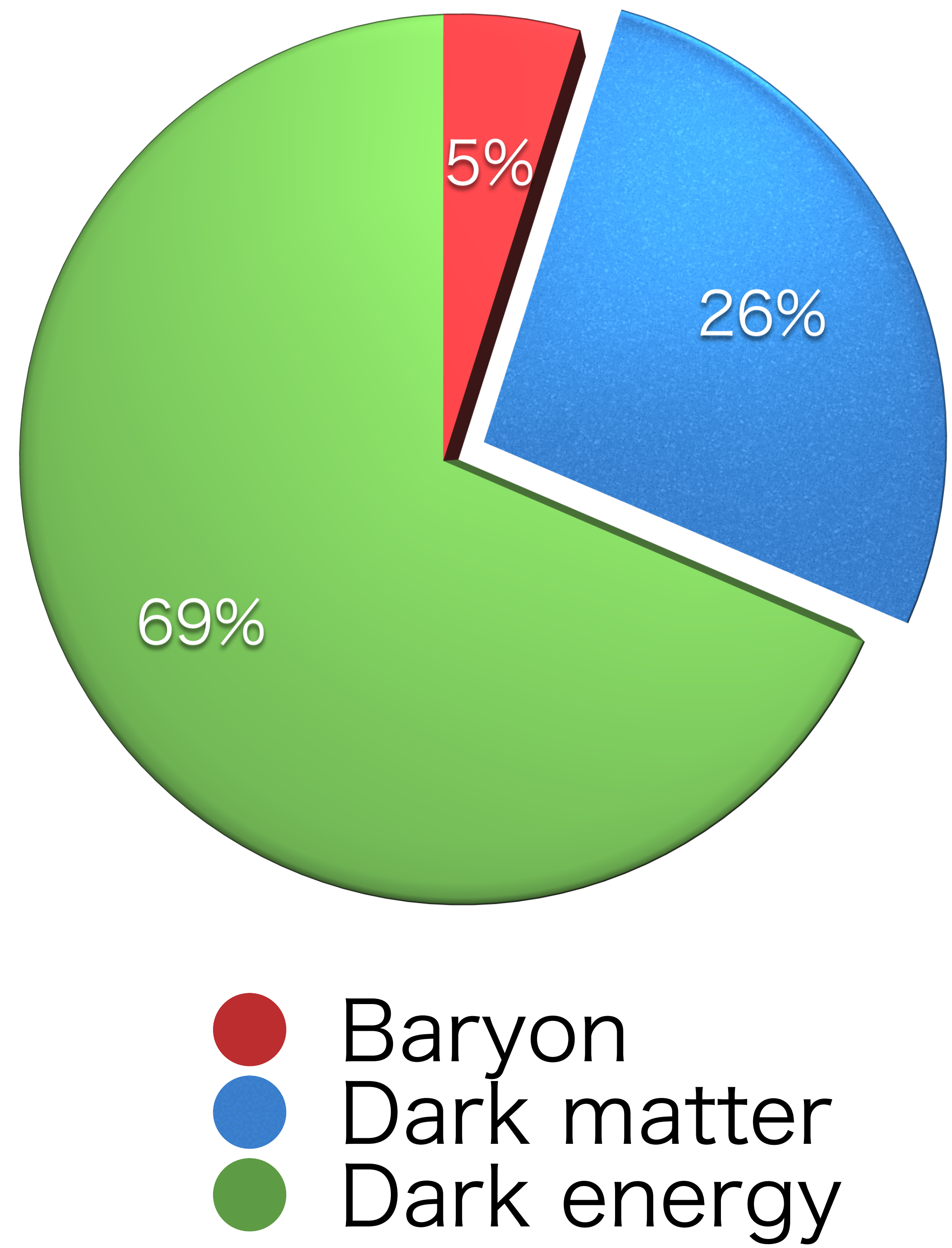
Fuminobu Takahashi
(Tohoku)

Dark Matter

The presence of DM has been firmly established.

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

However, we do not know what DM is made of.



✓ **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**

✓ **DM distribution** in dSphs, galaxies, and clusters.

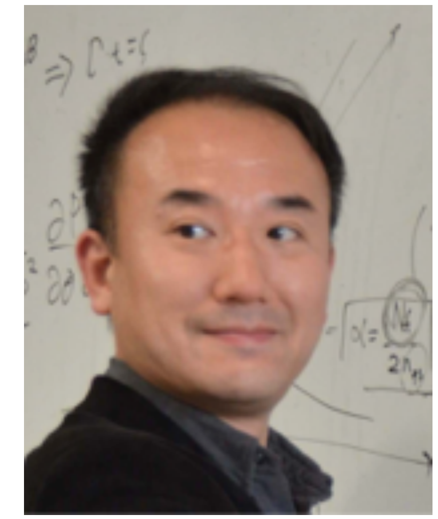
- Any tension with LCDM and N-body simulations?

✓ **Any relation with inflation and/or DE?**

✓ **Any predictions for observations?**

Members

- Masahiro Kawasaki (ICRR)
- Kazunori Kohri (KEK)
- Atsushi Taruya (Kyoto)
- Fuminobu Takahashi (Tohoku)
- Masashi Chiba (Tohoku)
- Masahiro Ibe (ICRR)
- Norimi Yokozaki (Tohoku)




Publications

61 papers from A02 group (as of Mar.1)

Highlights

- PBH formation (Kawasaki) **See talk by Kawasaki**
- Limits on CHAMP (Kohri)
- Perturbation theory kernels (Taruya)
- Axion-like particle miracle (FT)
- Discovery of new ultra faint satellites and dusty dwarf galaxy (Chiba) **See talk by Chiba**
- Dark matter models (Ibe)
- Mini-charged particles and GUT (Yokozaki)

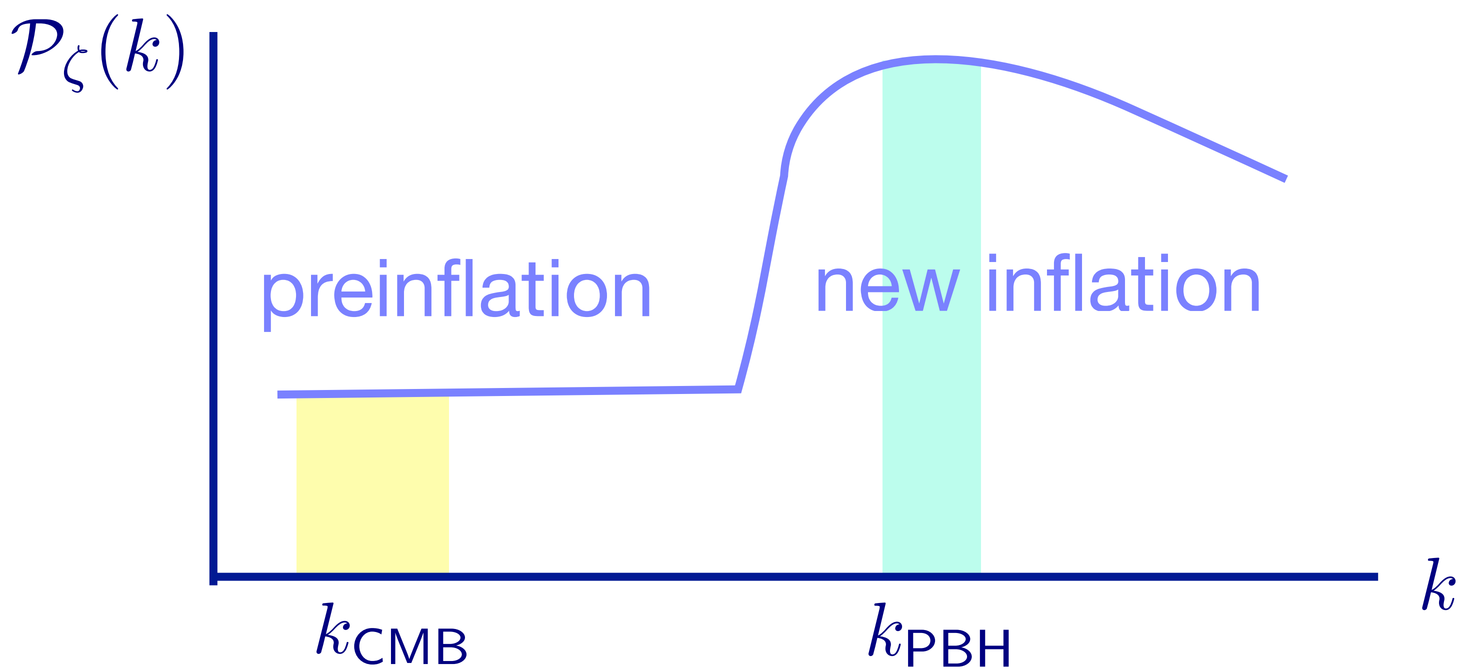
See talk by Yokozaki

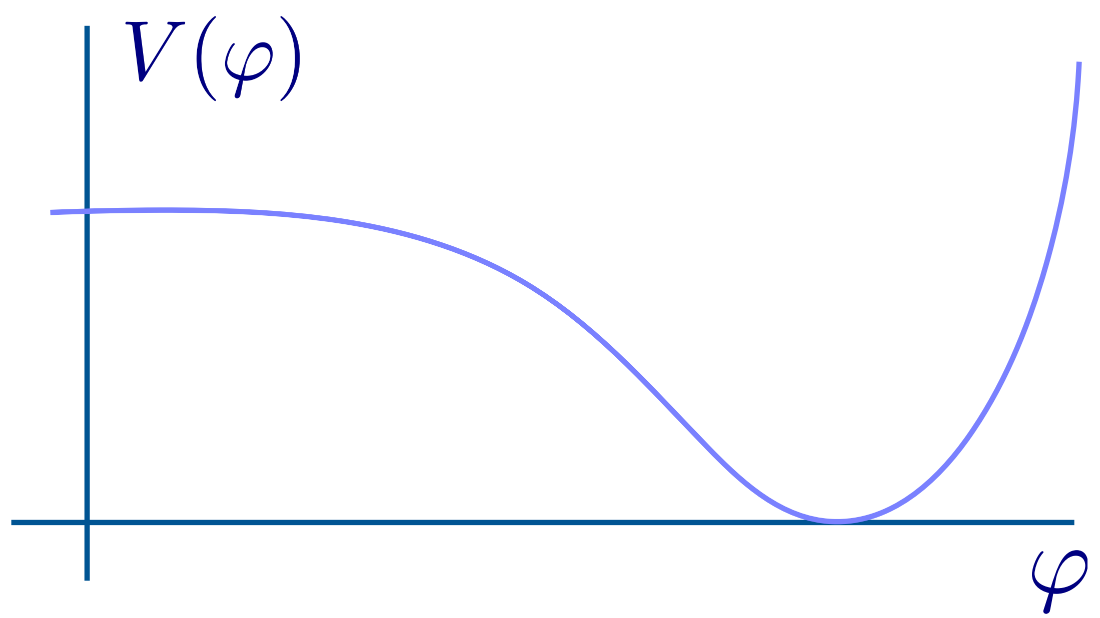
PBH formation in double inflation

MK Kusenko Mukaida Tada Yanagida (2016)
Inomata MK Mukaida Tada Yanagida (2016, 2017)

- PBHs can be formed by gravitational collapse of over-density region in the early universe
- Large density fluctuations δ with O(0.1) are required for PBH formation but δ ~ O(10^{-5}) on CMB scale
- We consider double inflation (preinflation+new inflation)
- New inflation model (no specific model is required for pre-inf.)

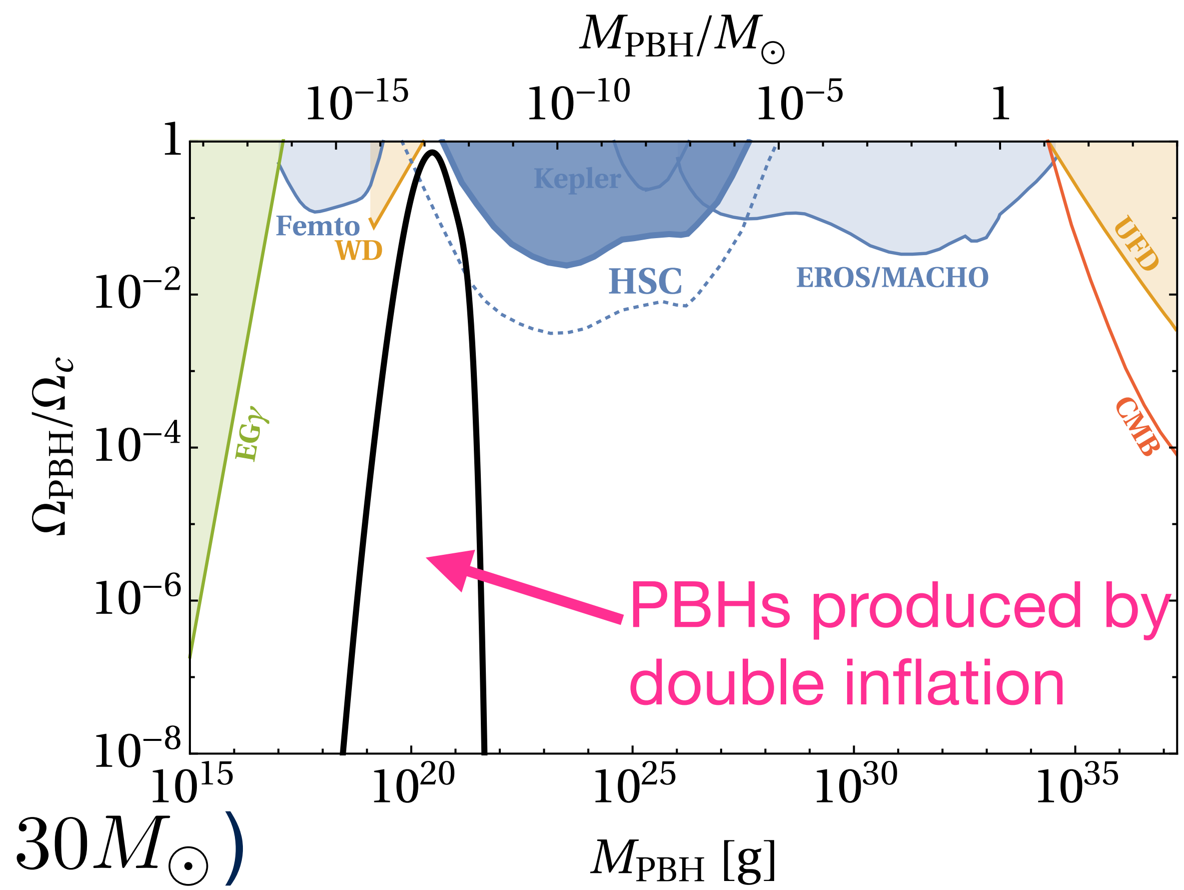
$$V(\varphi) = (v^2 - g\varphi^n)^2 - \varepsilon v^4 \varphi - \frac{1}{2}\kappa v^4 \varphi^2 \quad n = 3, 4, \cdots \quad M_p = 1$$

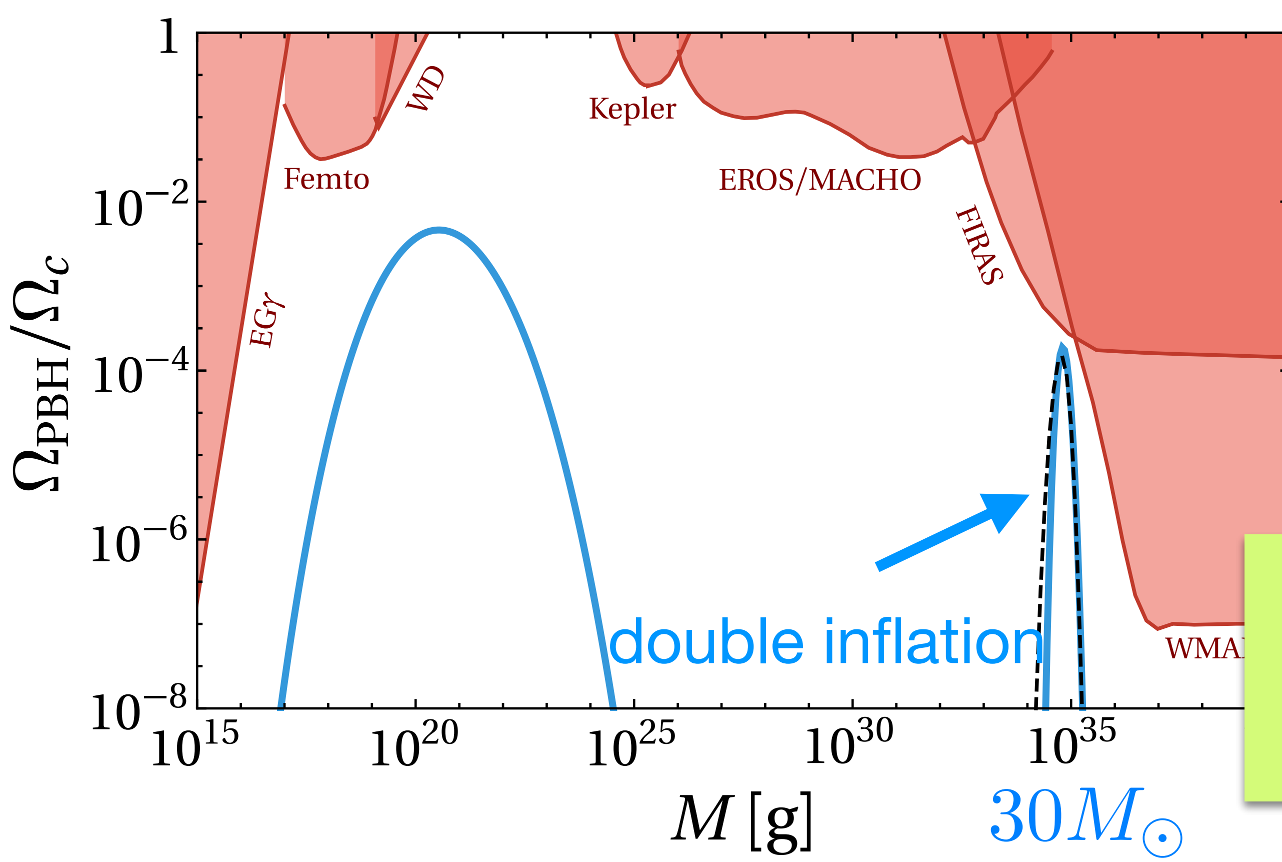


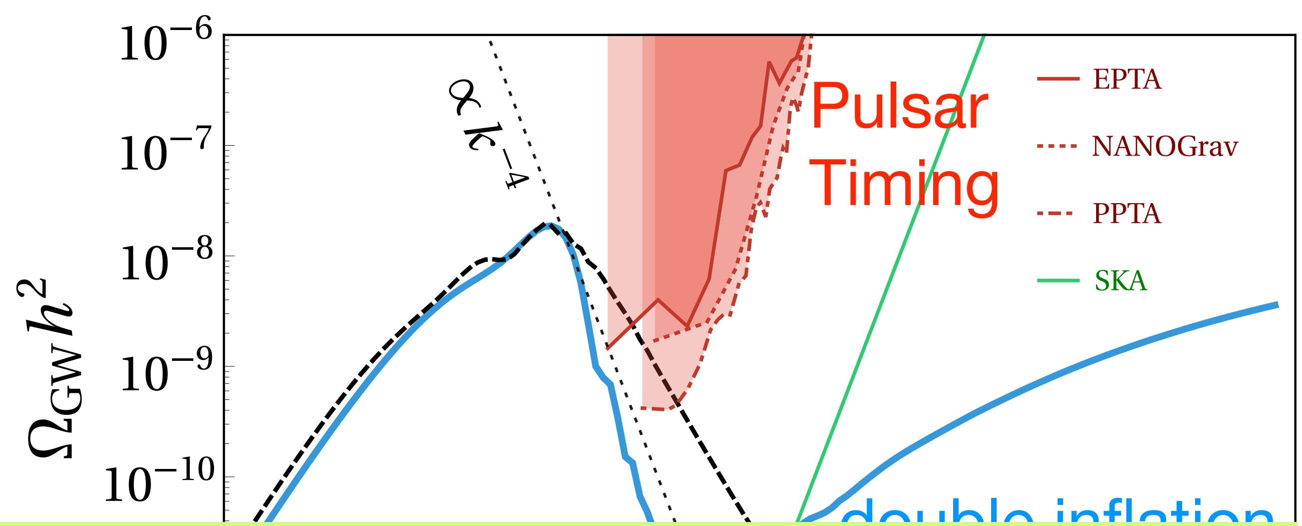


PBH formation in double inflation

- PBHs produced by double inflation can account for dark matter
  - Stringent observational constraints
  - PBHs with mass~ 10^{20}g can be DM
- Double inflation can produce PBHs which account for LIGO event ($M_{PBH} \sim 30 M_\odot$)
  - 2nd order curvature perturbations induce tensor modes
  - Constraint from pulsar timing exp. → marginally consistent







See talk by M. Kawasaki

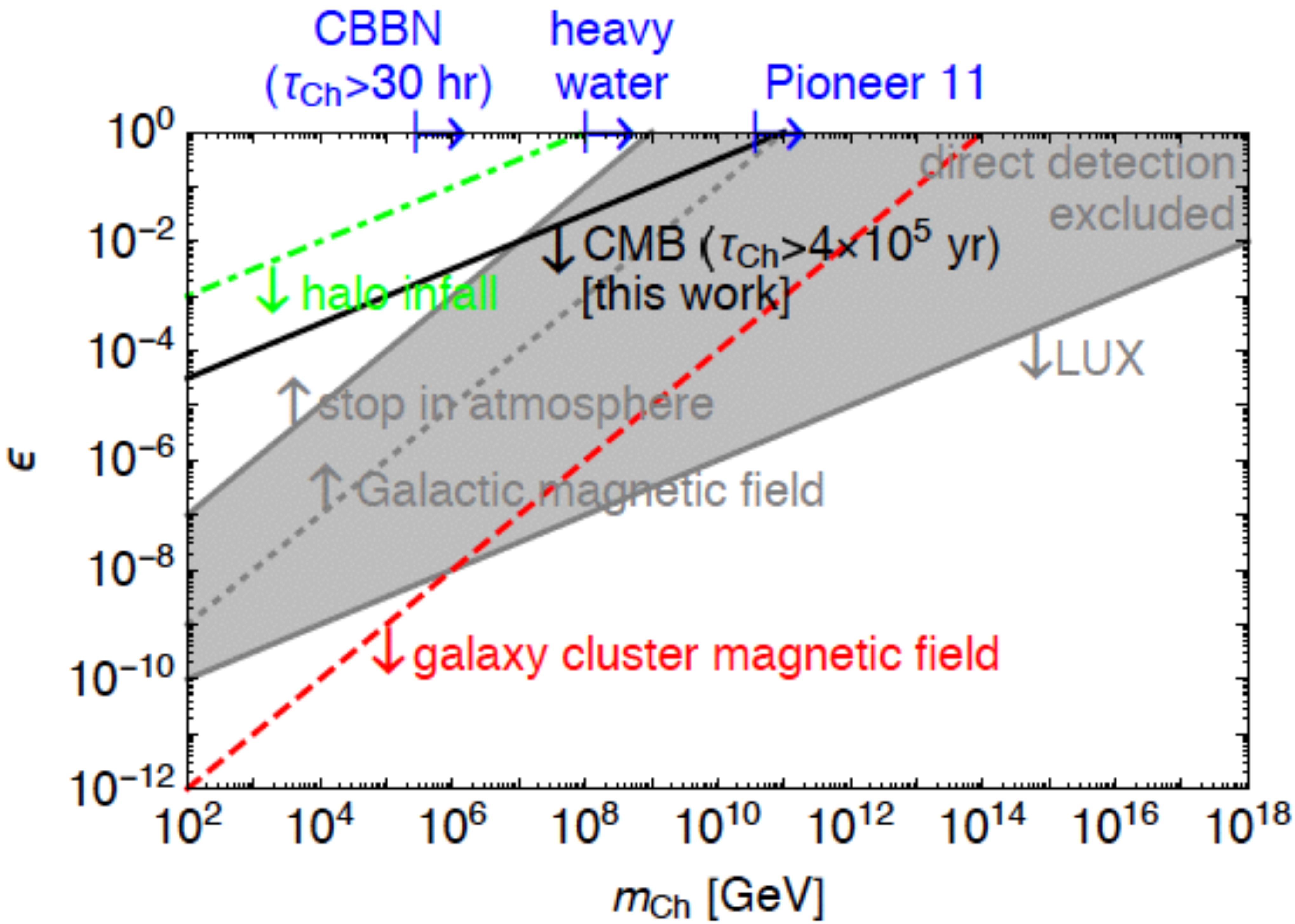
Cosmological constraints on CHArged Massive Particles (CHAMPs)

A.Kamada, Kohri, T.Takahashi, and N.Yoshida,   arXiv:1604.07926 [astro-ph.CO]

A.Kamada, K.T.Inoue, Kohri, and T.Takahashi , arXiv:1703.XXXXX [astro-ph.CO]

- Matter density perturbations are suppressed through the acoustic damping due to the electromagnetic charges of CHAMPs.
- Cosmological observations by Cosmic Microwave Background (CMB), and/or Large Scale Structures (LSSs) of galaxies are very sensitive to lifetime, the fraction to CDM, and the masses of CHAMPs.

1) Constraints on charges vs. masses of CHAMPs by CMB and BBN



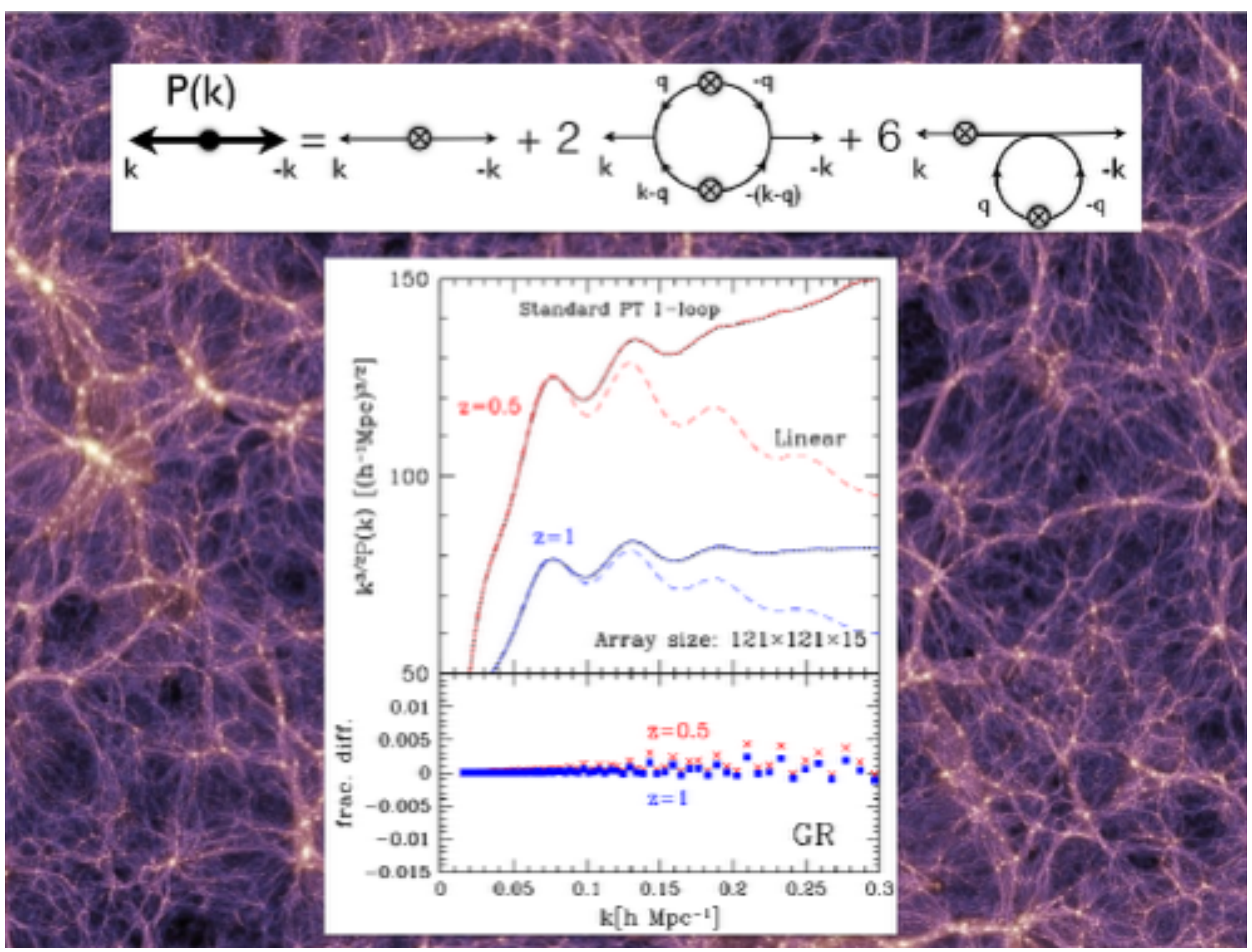
A.Kamada, Kohri, T.Takahashi, and N.Yoshida, arXiv:1604.07926 [astro-ph.CO]

Constructing perturbation theory kernels for large-scale structure in generalized cosmologies

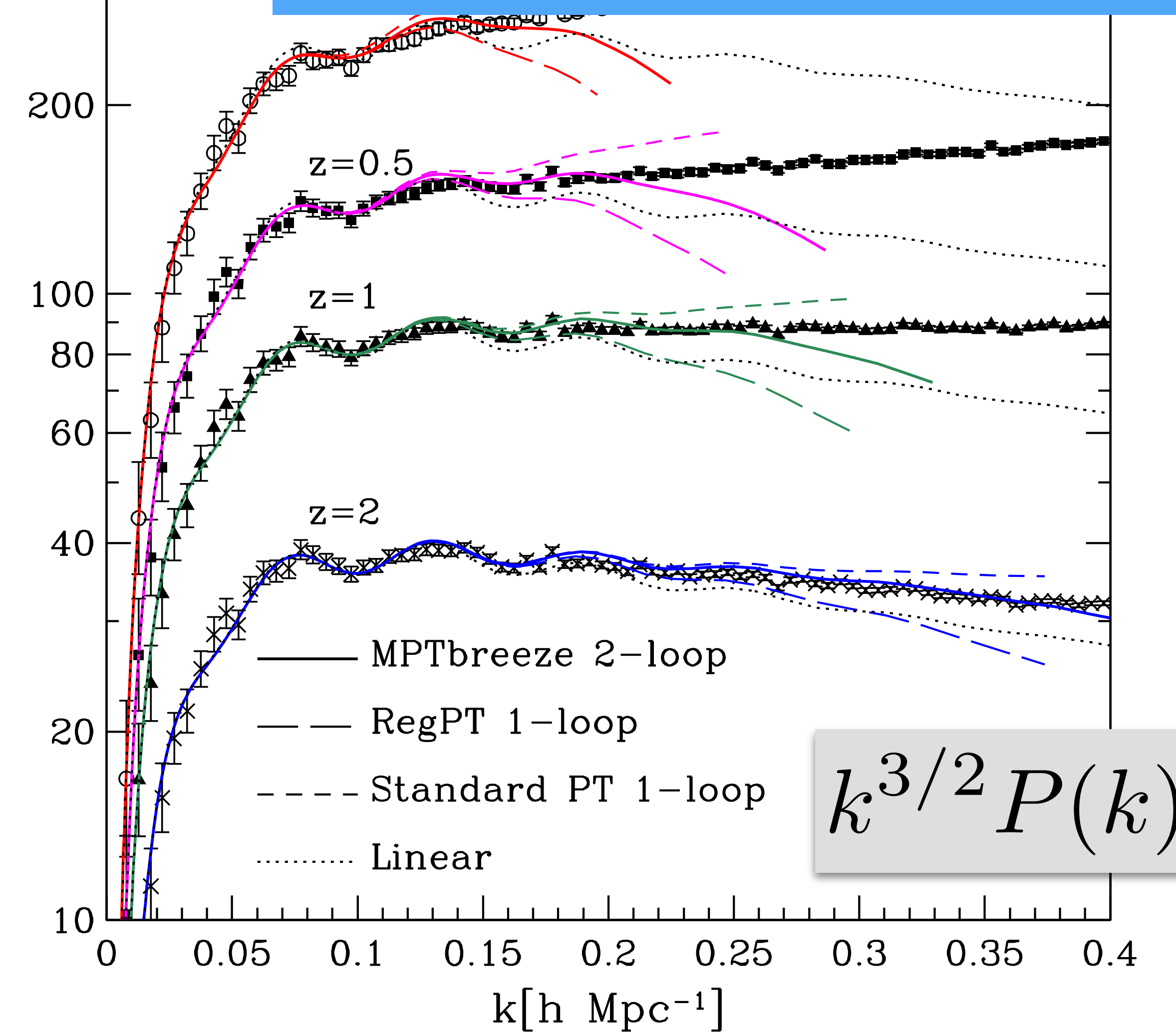
A. Taruya

A numerical scheme to construct perturbation theory kernels, as building blocks of statistical calculations of large scale structures

→ applicable to generalized structure formation including modified gravity



Performance in f(R) gravity

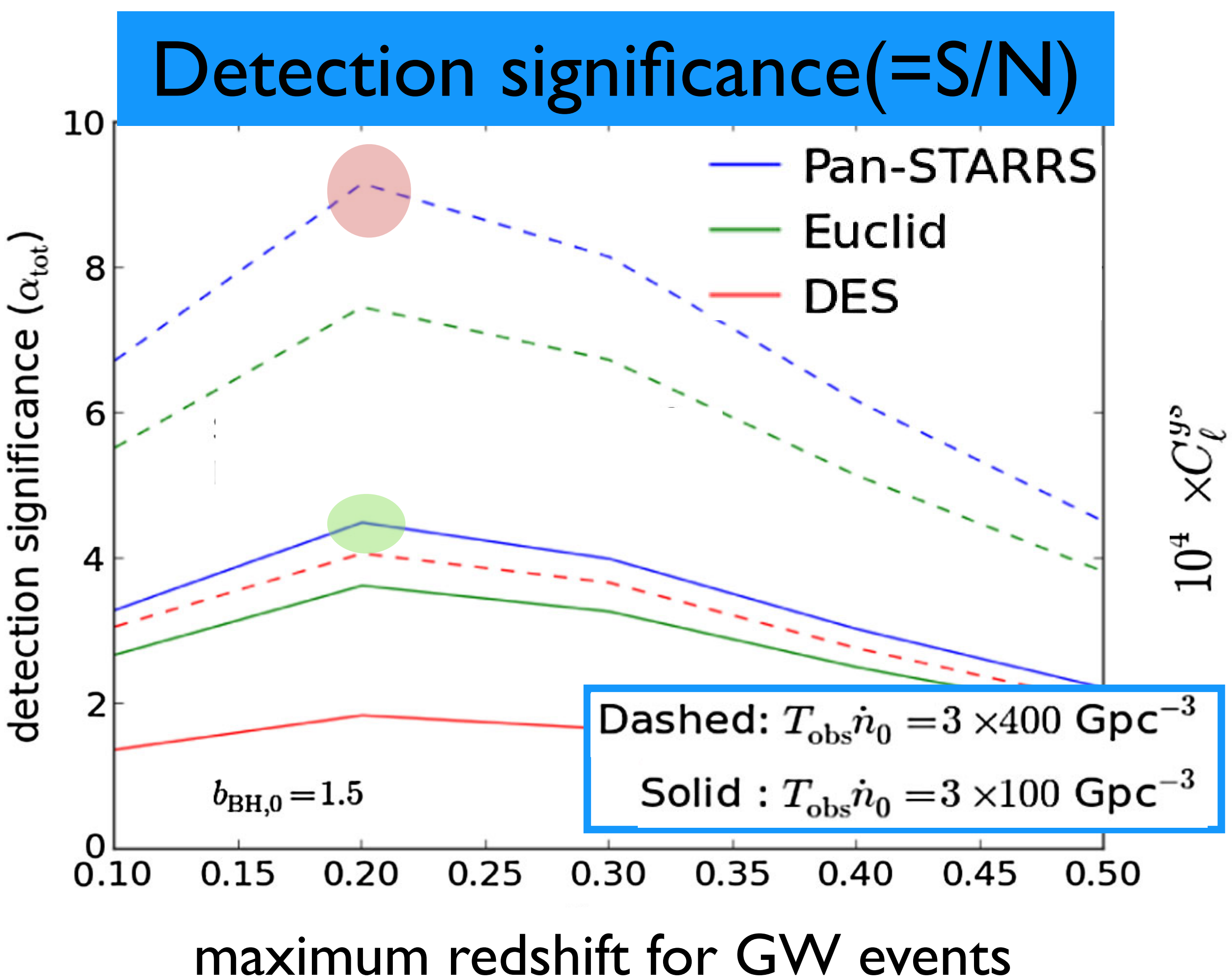


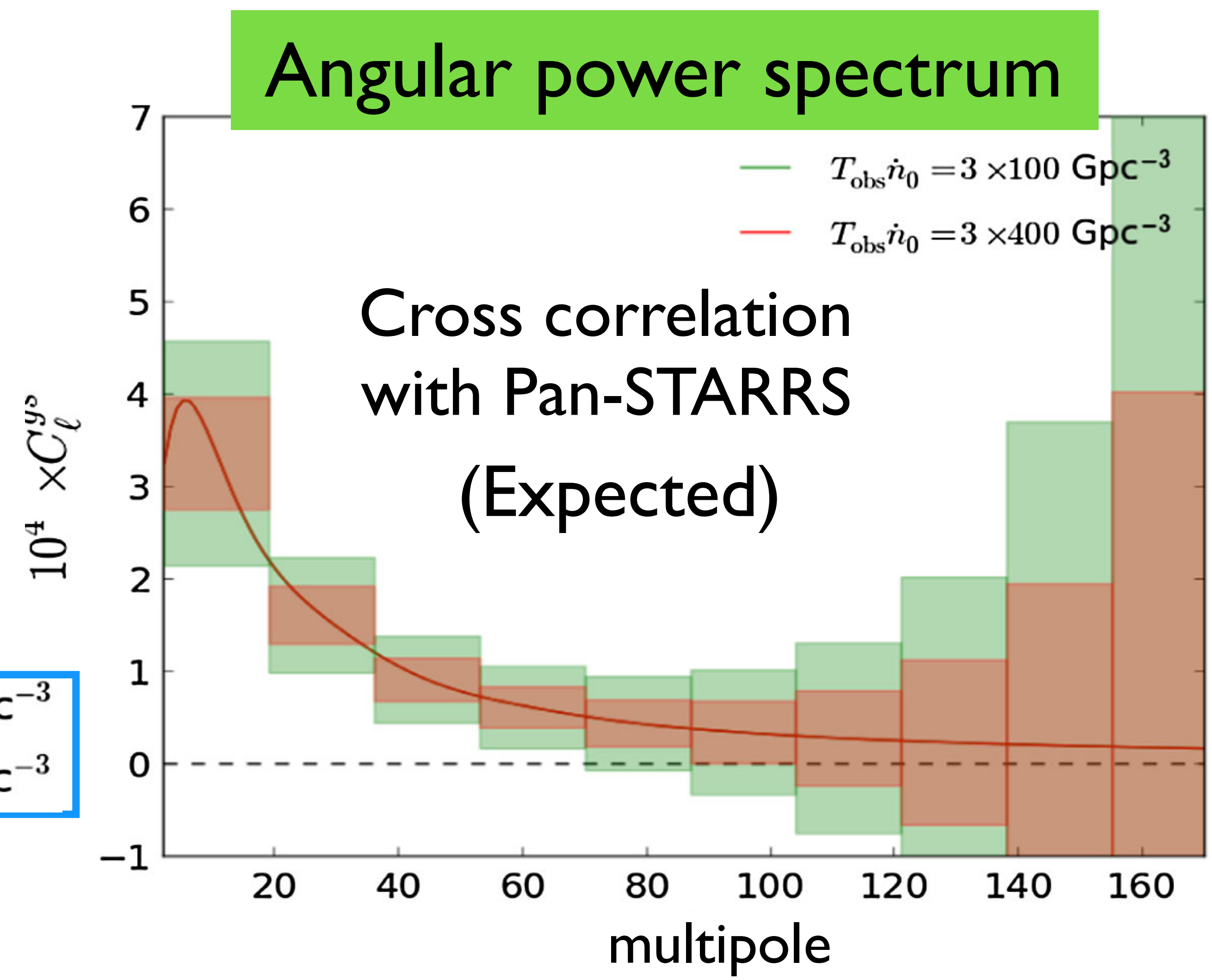
Detecting black-hole binary clustering via the second-generation gravitational-wave detectors

T. Namikawa, A. Nishizawa, A. Taruya

Implications of gravitational wave (GW) events like GW150914, which will be detected by 2nd-G laser interferometers

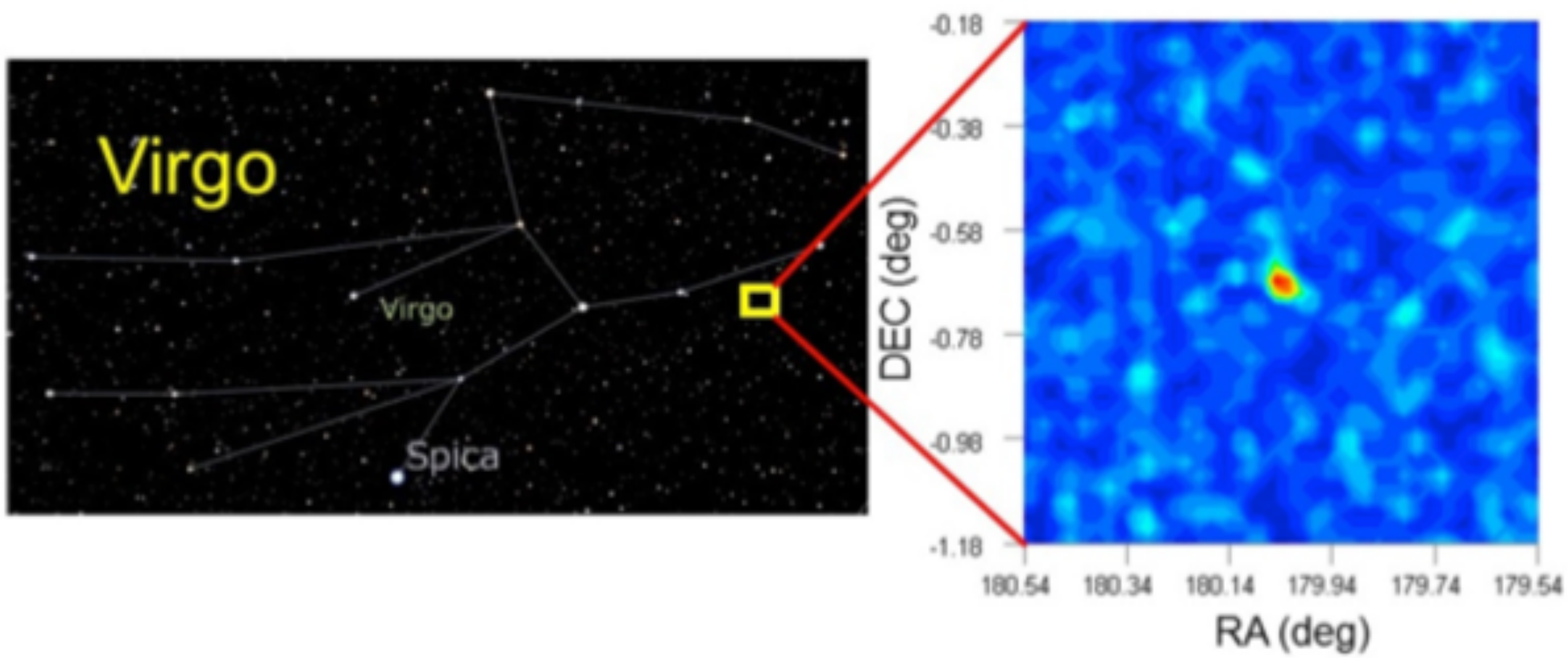
Cross-correlation signal of GW events with galaxies is shown to be detectable → A clue to origin/formation of black-hole binaries

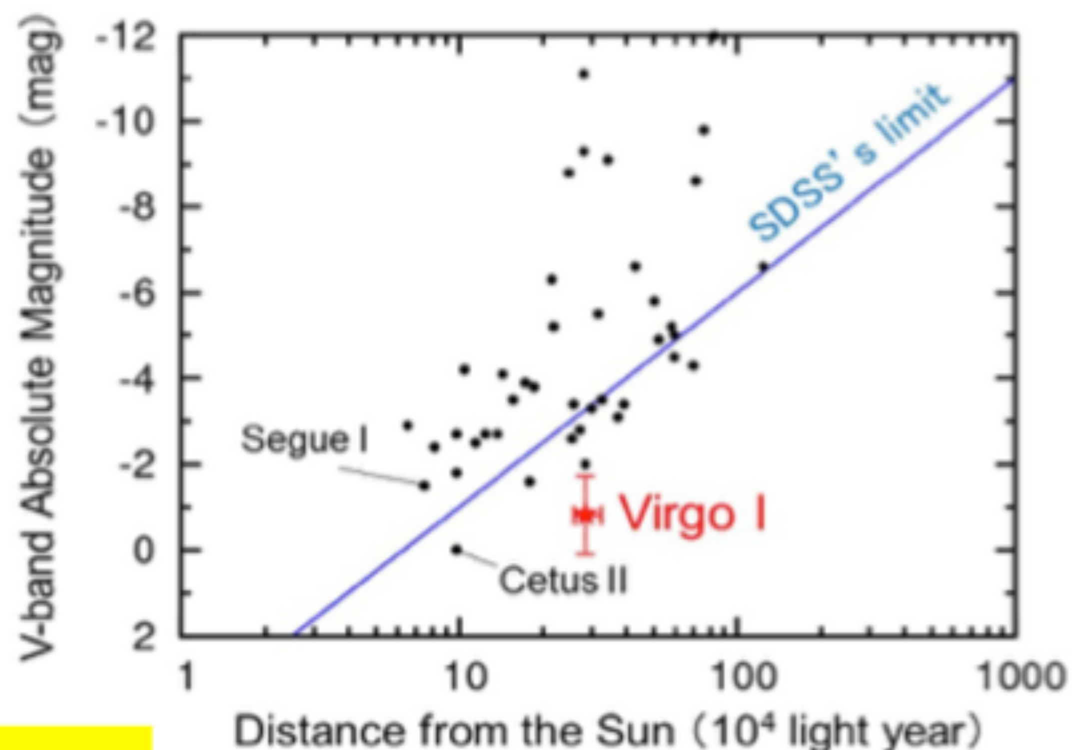




1. Discovery of new ultra-faint satellites in the Milky Way from Subaru/HSC survey data

- A record-braking faint satellite, Virgo I, is found beyond the reach of SDSS.
- This discovery gives new insights into the missing satellites problem.

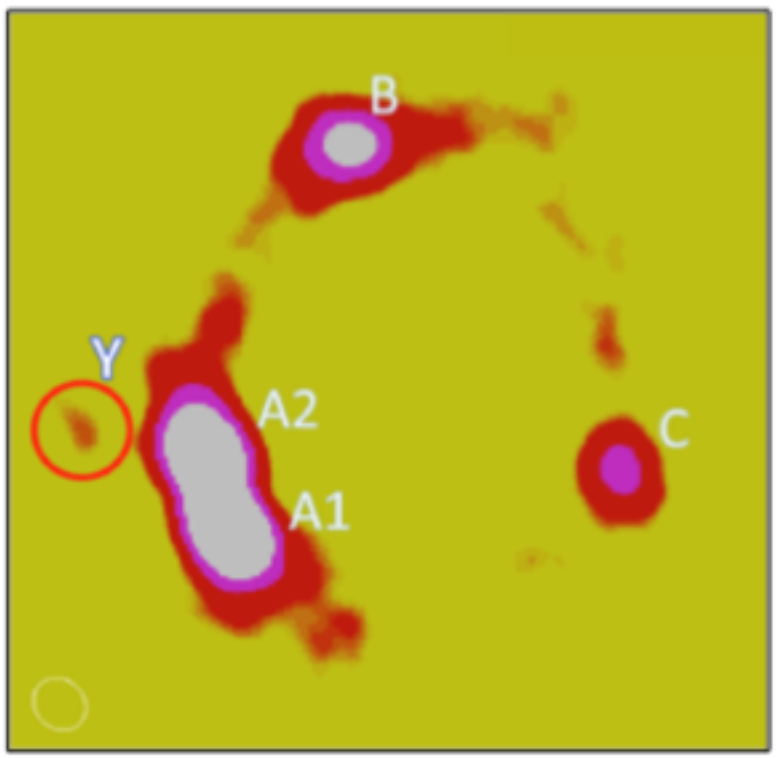


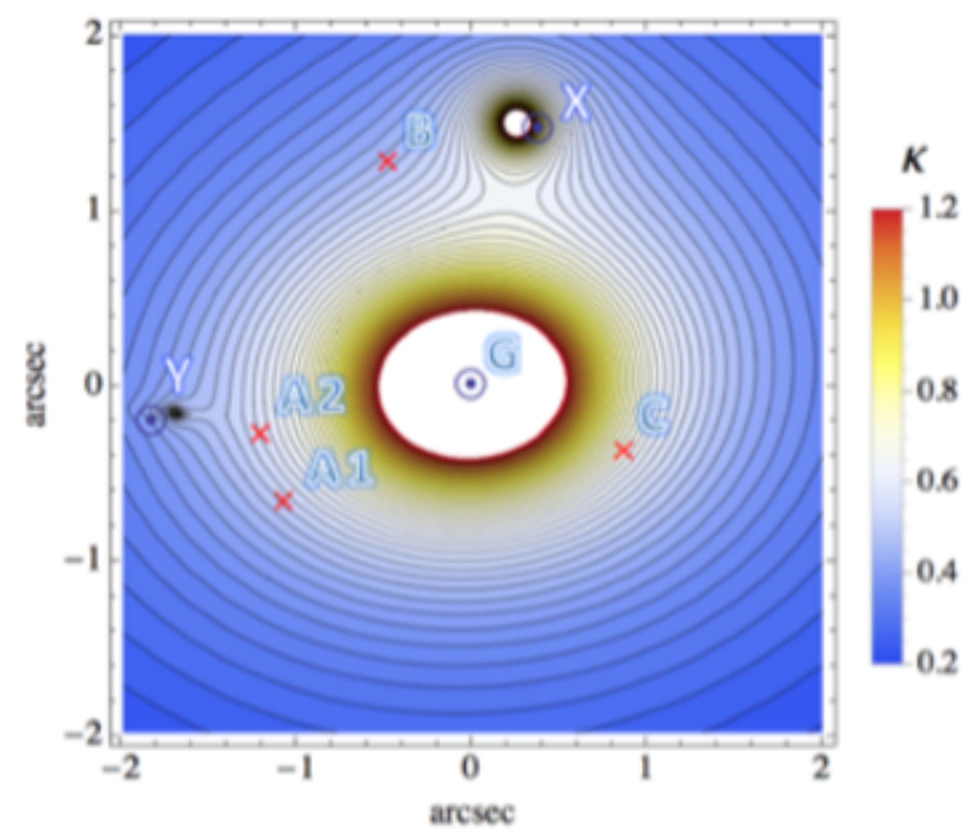


Homma, D., Chiba, M. et al. 2016, ApJ, 832, 21

2. Discovery of a dusty dark dwarf galaxy in the quadruple lens MG0414+0534 with ALMA

- This dwarf is found to explain the anomalous flux ratio between A1 and A2 images.
- This discovery gives new insights into the missing satellites problem.

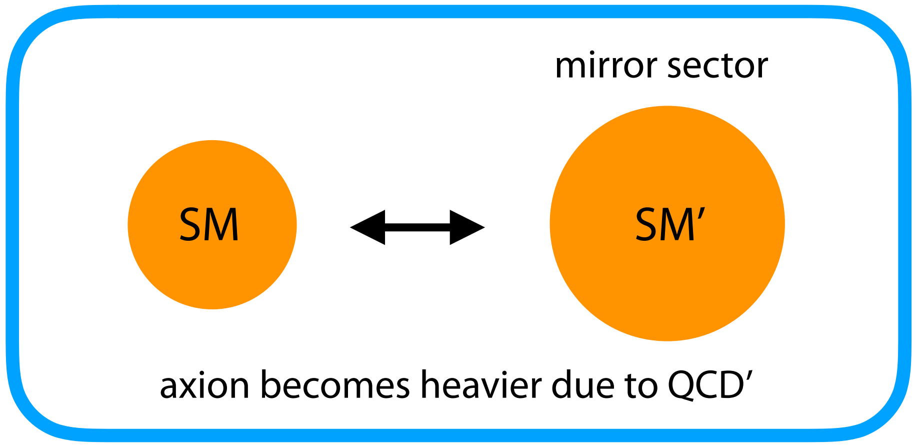




Inoue, K. T., S. Matsushita, T. Minezaki, Chiba, M. 2017, ApJ, 835, L23

(1) Dark Matter Candidates in a Visible Heavy QCD Axion Model

arXiv:1702.00227 : Hajime Fukuda, Masahiro Ibe, Tsutomu T. Yanagida.



e' , π' , N' , ν' can explain the observed DM abundance.

In the case of N' DM, its decay,

$n' \rightarrow \nu' + a$

gives contribution to the extra-galactic background gamma-rays.

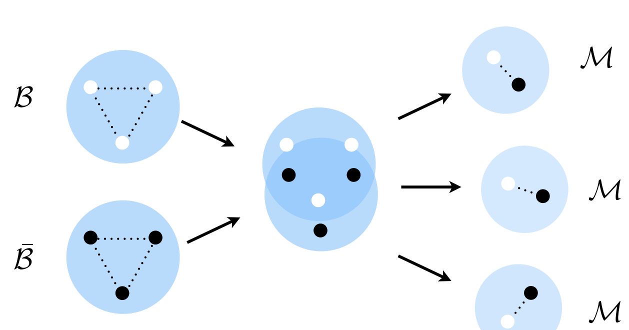
(2) Revisiting gravitino dark matter in thermal leptogenesis

arXiv:1609.06834 : Masahiro Ibe, Motoo Suzuki, Tsutomu T. Yanagida

The gravitinos are well-motivated DM candidate, especially if the R-parity is broken. When combined with thermal leptogeneis, most of the parameter region is already excluded by the LHC data so far, and all the region will be covered by future LHC run.

(3) Thermal Relic Dark Matter Beyond the Unitarity Limit

arXiv:1606.00159 : Keisuke Harigaya, Masahiro Ibe, Kunio Kaneta, Wakutaka Nakano, Motoo Suzuki



R >> de Broglie length

The annihilation cross section of composite DM (hidden baryon) with its radius greater than the de Broglie radius is given by the geometrical cross section, and they annihilate into mesons.

Due to its large annihilation cross section, its mass can be heavier than the usual unitarity bound derived for a more compact or elementary particle DM.

The ALP miracle

ALP = axion-like particle

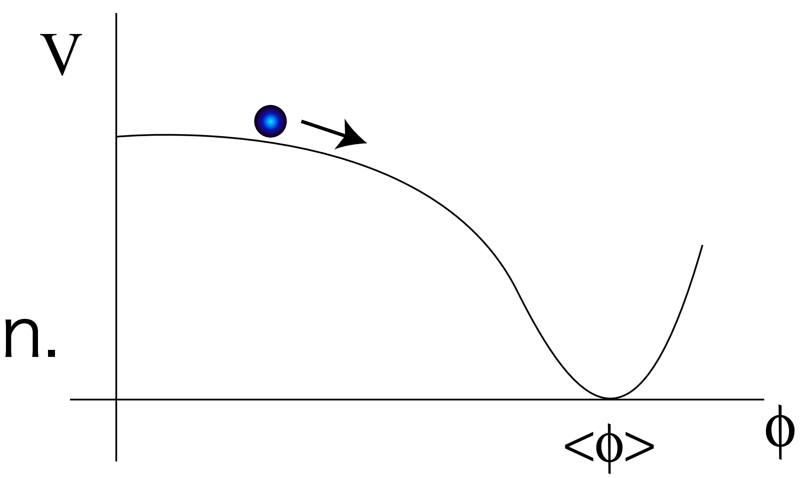
R. Daido, FT, and W. Yin 1702.03284

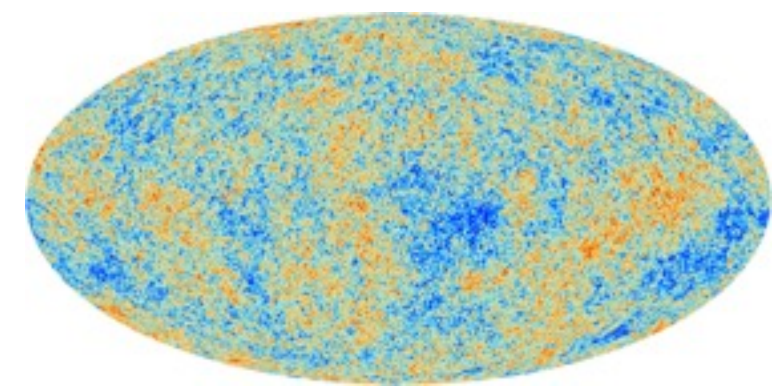
1. Introduction

Success of the ΛCDM model relies on the two unknown degrees of freedom (except for the origin of Λ)

- Inflaton

Very flat potential
for slow-roll inflation.



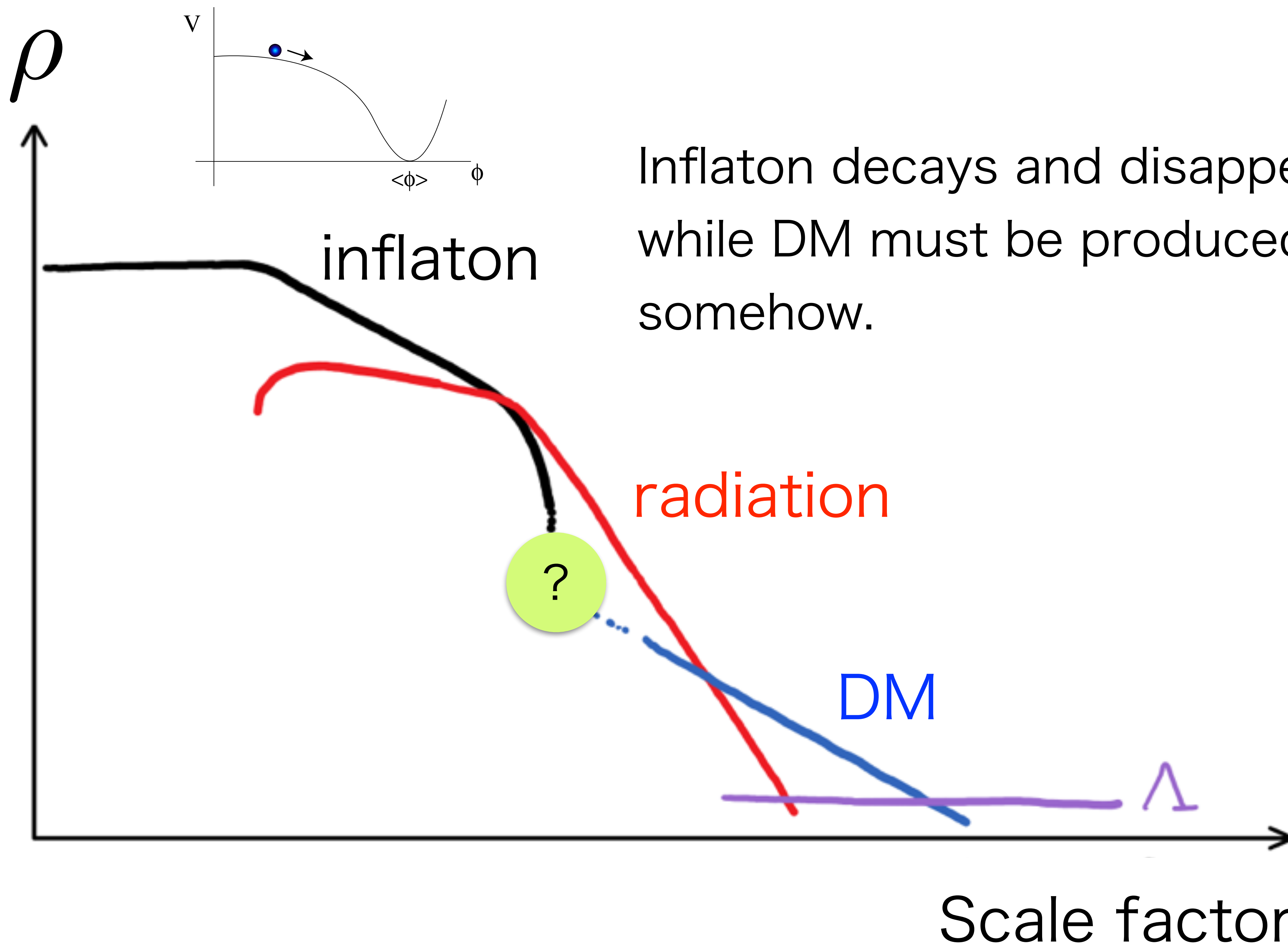


- Dark matter

Cold, neutral,
and long-lived.

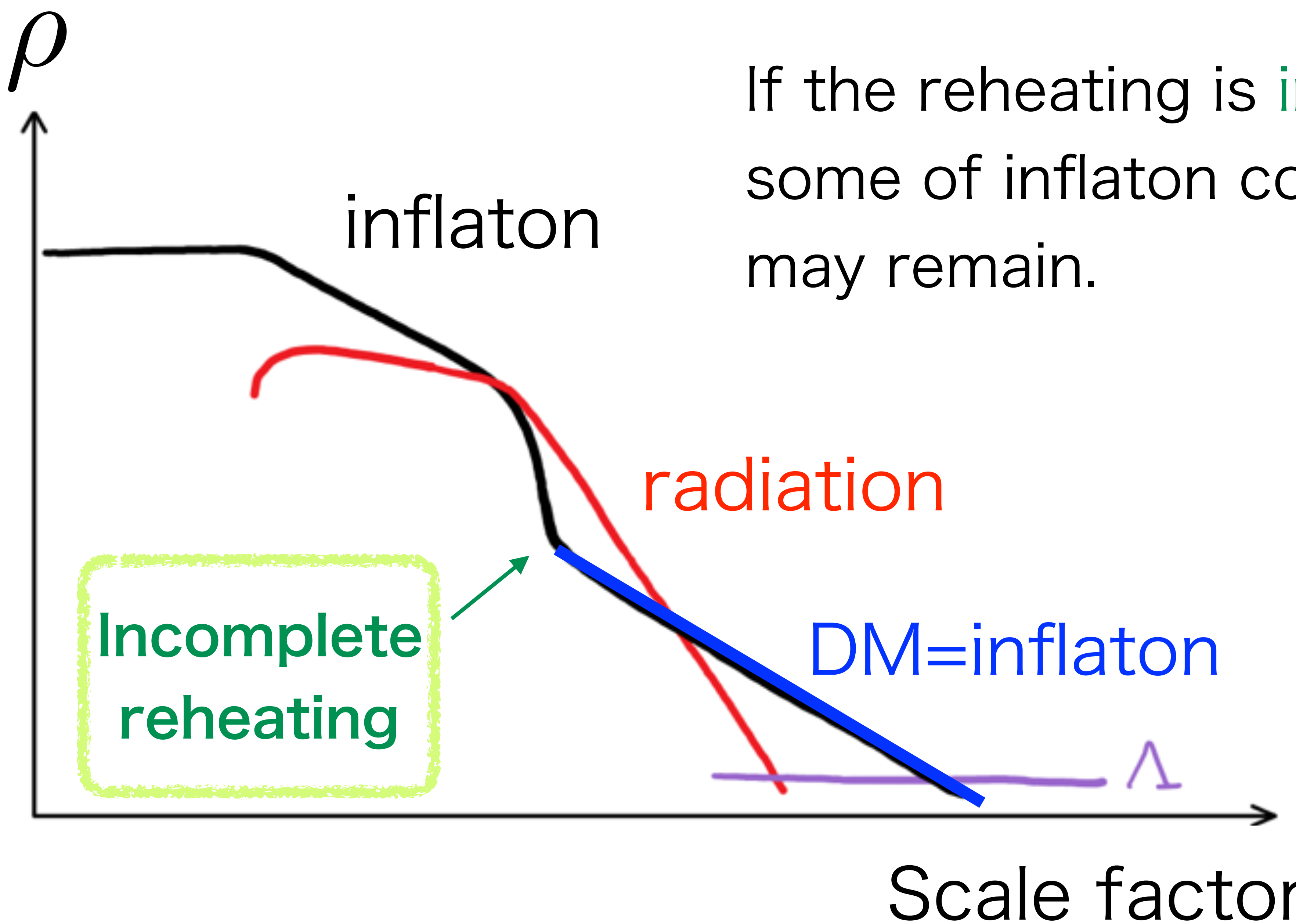
Both are neutral and occupied a significant fraction of the energy density of the Universe.

Thermal history



Inflaton decays and disappears, while DM must be produced somehow.

Inflaton = DM ?



If the reheating is incomplete, some of inflaton condensate may remain.

The remnant inflaton condensate due to incomplete reheating can be dark matter.

cf. Kofman, Linde, Starobinsky `94, Mukaida, Nakayama 1404.1880, Bastero-Gil, Cerezo, Rosa,1501.05539
see also Lerner, McDonald 0909.0520, Okada, Shafi 1007.1672, Khoze 1308.6338 for inflaton WIMP.

What we did

R. Daido, FT, and W. Yin 1702.03284

- **Inflaton = DM = Axion-like particle (ALP)**

- The observed CMB and LSS data fix the relation between the ALP mass m_ϕ and decay constant f .

- Successful reheating and DM abundance point to

$$m_\phi = \mathcal{O}(0.01)\,\mathrm{eV}\,,\ g_{\phi\gamma\gamma} = \mathcal{O}(10^{-11})\,\mathrm{GeV}^{-1}$$

  within the reach of IAXO.

- Thermalized ALPs play a role of HDM with $\Delta N_{\rm eff} \simeq 0.03$

- Matter power spectrum suppressed at small scales.

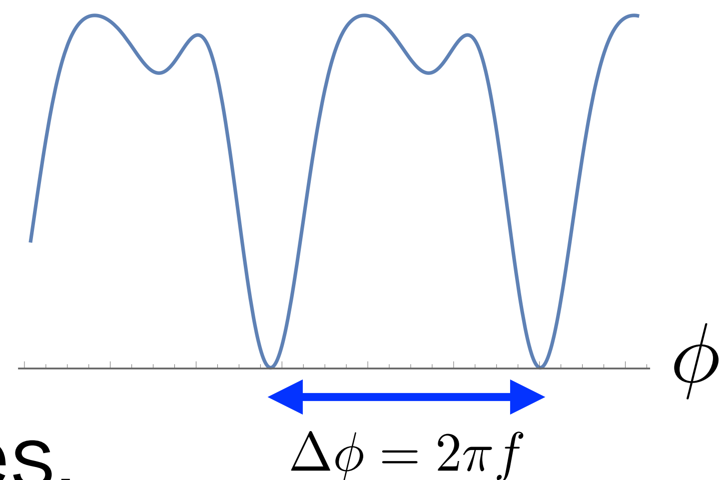
2. Axion Hilltop Inflation

Let us suppose that the inflaton is an axion which enjoys a (discrete) shift symmetry,

$$\phi \to \phi + 2\pi n f \qquad n \in \mathbf{Z}$$

Dangerous radiative corrections are suppressed.
The inflaton potential is periodic, i.e.,

$$V(\phi) = V(\phi + 2\pi f)$$



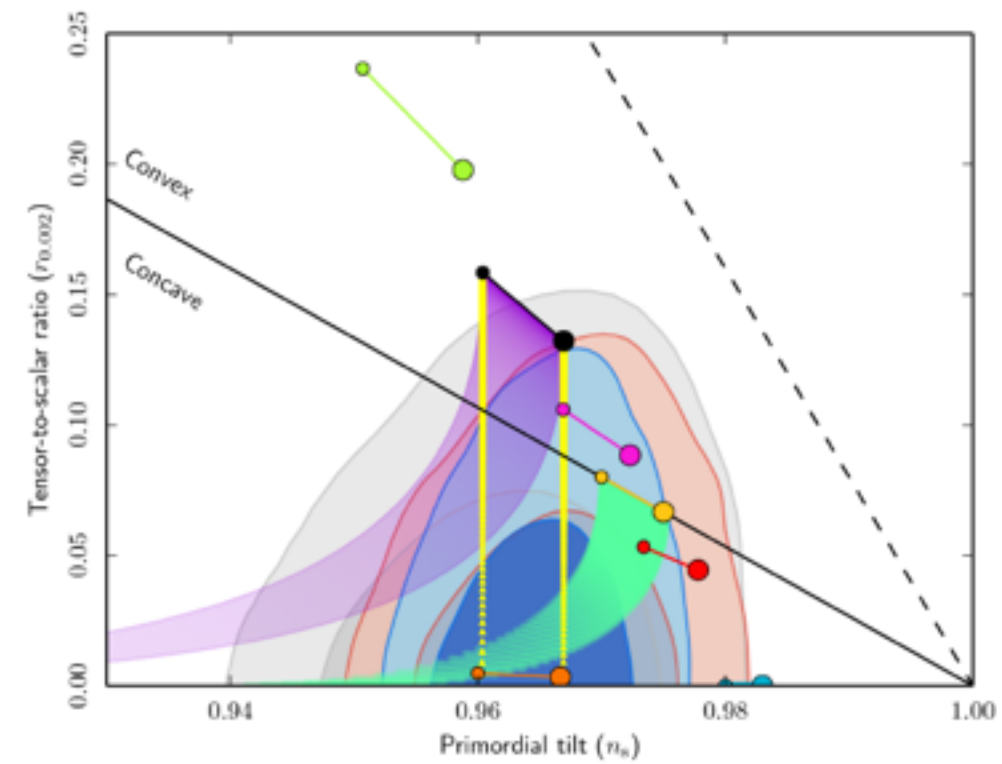
and can be expressed as Fourier series,

$$V(\phi) = \sum_{n\in\mathbf{Z}} c_n e^{in\frac{\phi}{f}}$$

• Natural inflation

Freese, Frieman, Olinto `90

$$V = \Lambda^4 \left(1 - \cos\left(\frac{\phi}{f}\right)\right)$$

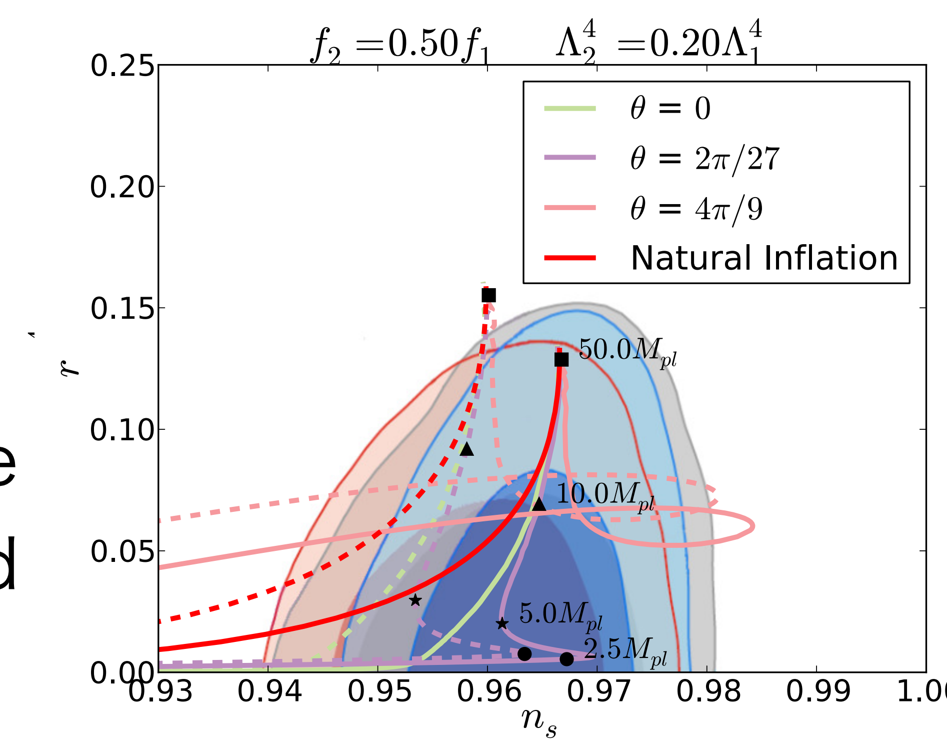


Only large-field inflation is possible, and f is bounded below: $f \gtrsim 5M_P$

• Multi-Natural inflation

Czerny, FT 1401.5212,
Czerny, Higaki, FT 1403.0410, 1403.5883

$$V = \sum_{i=1}^{N_{\rm source}} \Lambda_i^4 \cos\left(\frac{\phi}{f_i} + \theta_i\right) + \text{const.}$$



For $N_{\rm source} = 2$, various values of (n_s, r) are possible, and in particular, no lower bound on the decay constants.

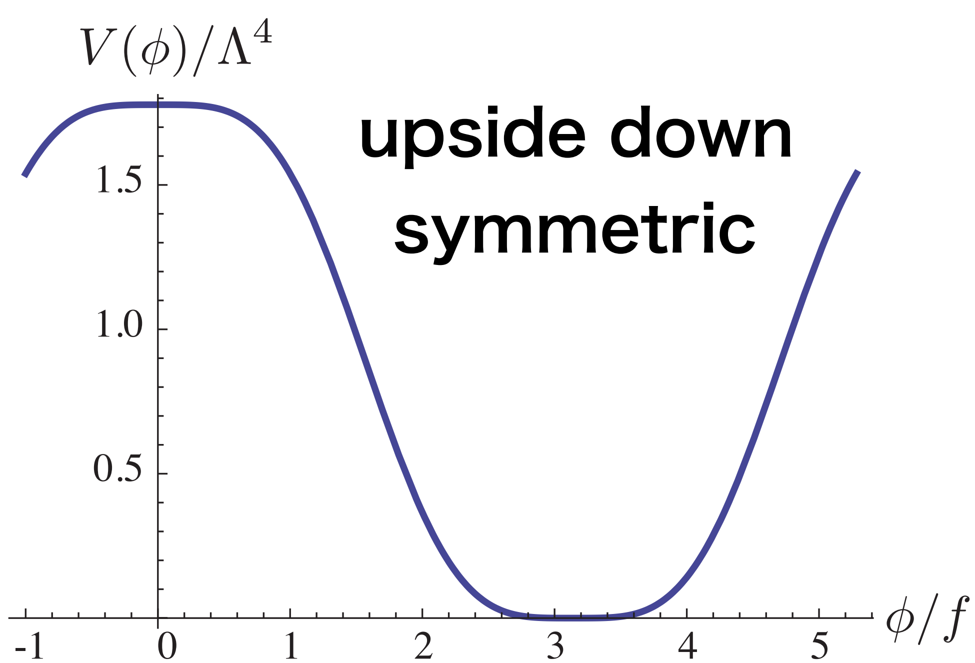
• Axion hilltop inflation

Czerny, FT 1401.5212, Czerny, Higaki, FT 1403.0410, 1403.5883
Croon and Sanz, 1411.7809

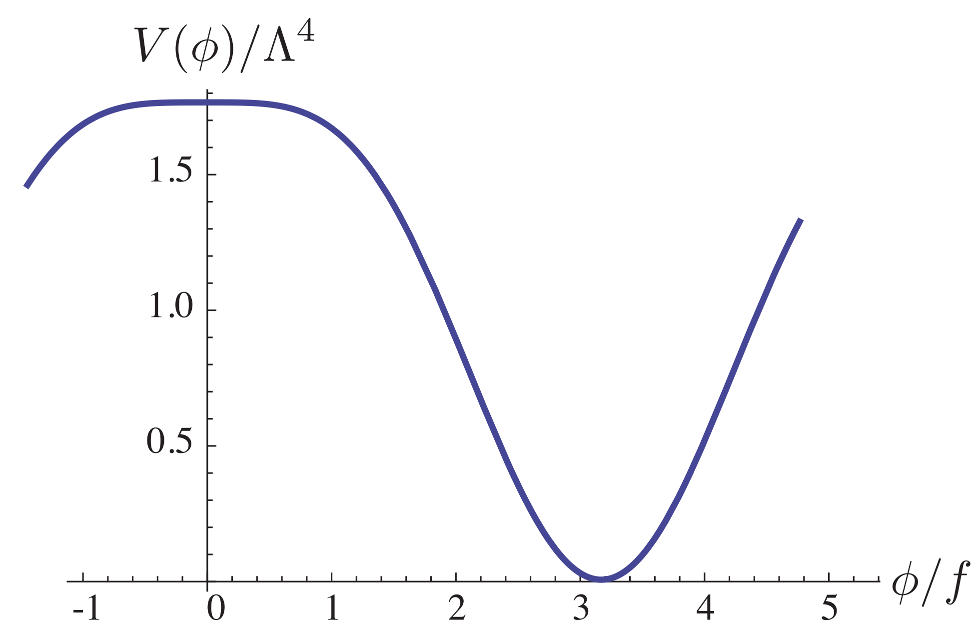
Axion hilltop inflation (~ hilltop quartic inflation) can be realized as a small-field limit of multi-natural inflation with N = 2.

$$V_{\rm inf}(\phi) = \Lambda^4 \left(\cos\left(\frac{\phi}{f} + \theta\right) - \frac{c_n}{n^2} \cos\left(\frac{n\phi}{f}\right)\right) + \text{ const.}$$

$$= V_0 - \lambda\phi^4 - \Lambda^4\theta\frac{\phi}{f} - (1-c_n)\frac{\Lambda^4}{2f^2}\phi^2 + \cdots$$



Odd n



Even n

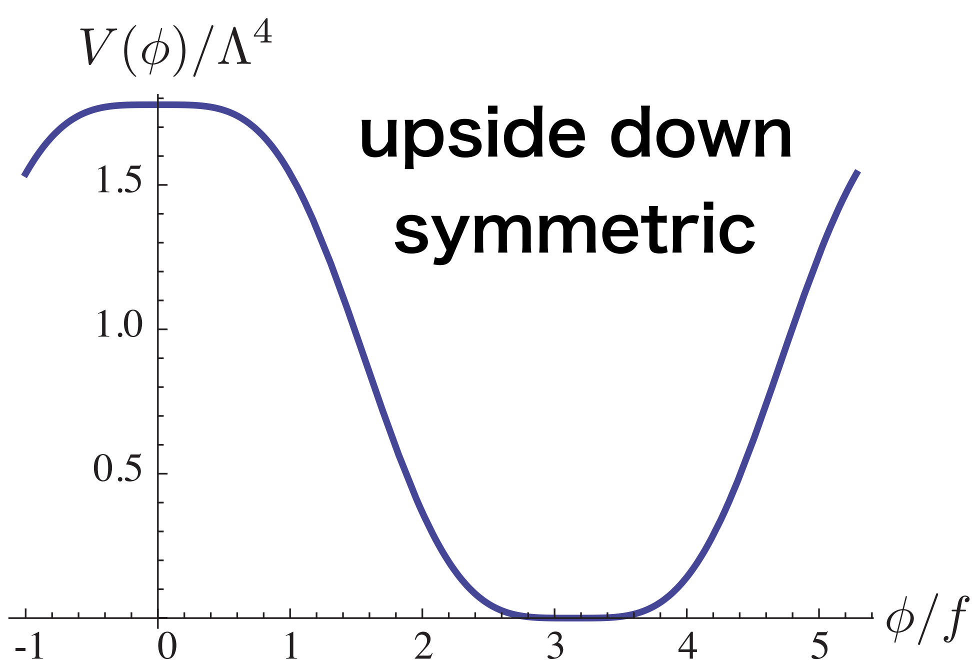
• Axion hilltop inflation

Czerny, FT 1401.5212, Czerny, Higaki, FT 1403.0410, 1403.5883

Axion hilltop inflation (~ hilltop quartic inflation) can be realized as a small-field limit of multi-natural inflation with N = 2.

$$V_{\rm inf}(\phi) = \Lambda^4 \left(\cos\left(\frac{\phi}{f} + \theta\right) - \frac{c_n}{n^2} \cos\left(\frac{n\phi}{f}\right)\right) + \text{ const.}$$

$$= V_0 - \lambda\phi^4 - \Lambda^4 \theta \frac{\phi}{f} - (1 - c_n)\frac{\Lambda^4}{2f^2}\phi^2 + \cdots$$



Odd n

- Inflaton potential is upside-down sym.
- In particular, inflaton is light both during inflation and in the true min.

$$m_\phi^2 = V''(\phi_{\rm min}) = -V''(\phi_{\rm max})$$

Flatness implies longevity.

• Axion hilltop inflation

Czerny, FT 1401.5212, Czerny, Higaki, FT 1403.0410, 1403.5883

Axion hilltop inflation (~ hilltop quartic inflation) can be realized as a small-field limit of multi-natural inflation with N = 2.

$$V_{\rm inf}(\phi) = \Lambda^4 \left(\cos\left(\frac{\phi}{f} + \theta\right) - \frac{c_n}{n^2} \cos\left(\frac{n\phi}{f}\right)\right) + \text{ const.}$$

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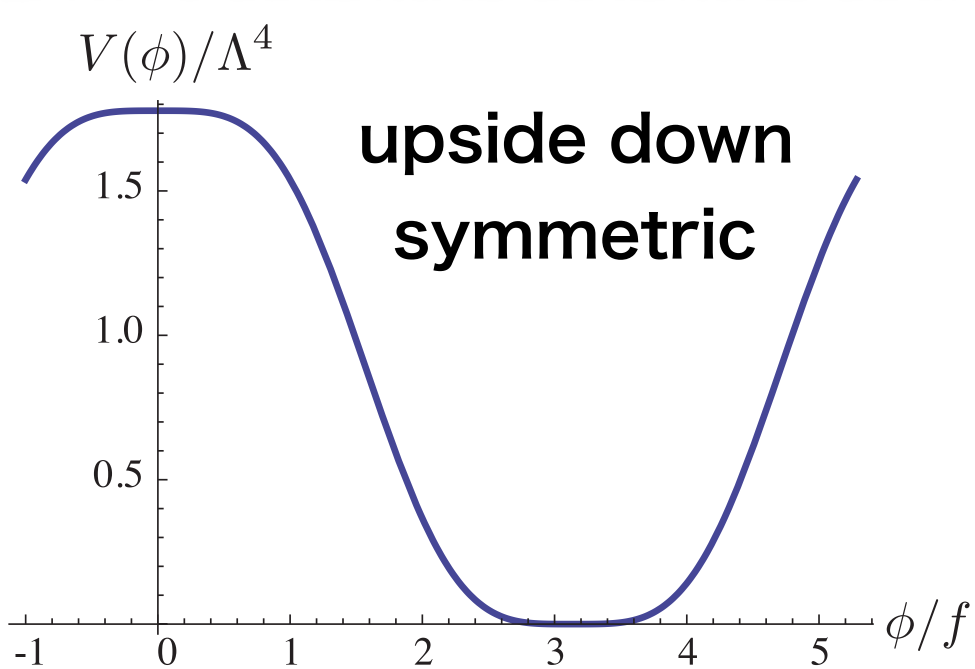


✓ Planck normalization:

$$\lambda \simeq 7.5 \times 10^{-14} \left(\frac{N_*}{50}\right)^{-3}.$$

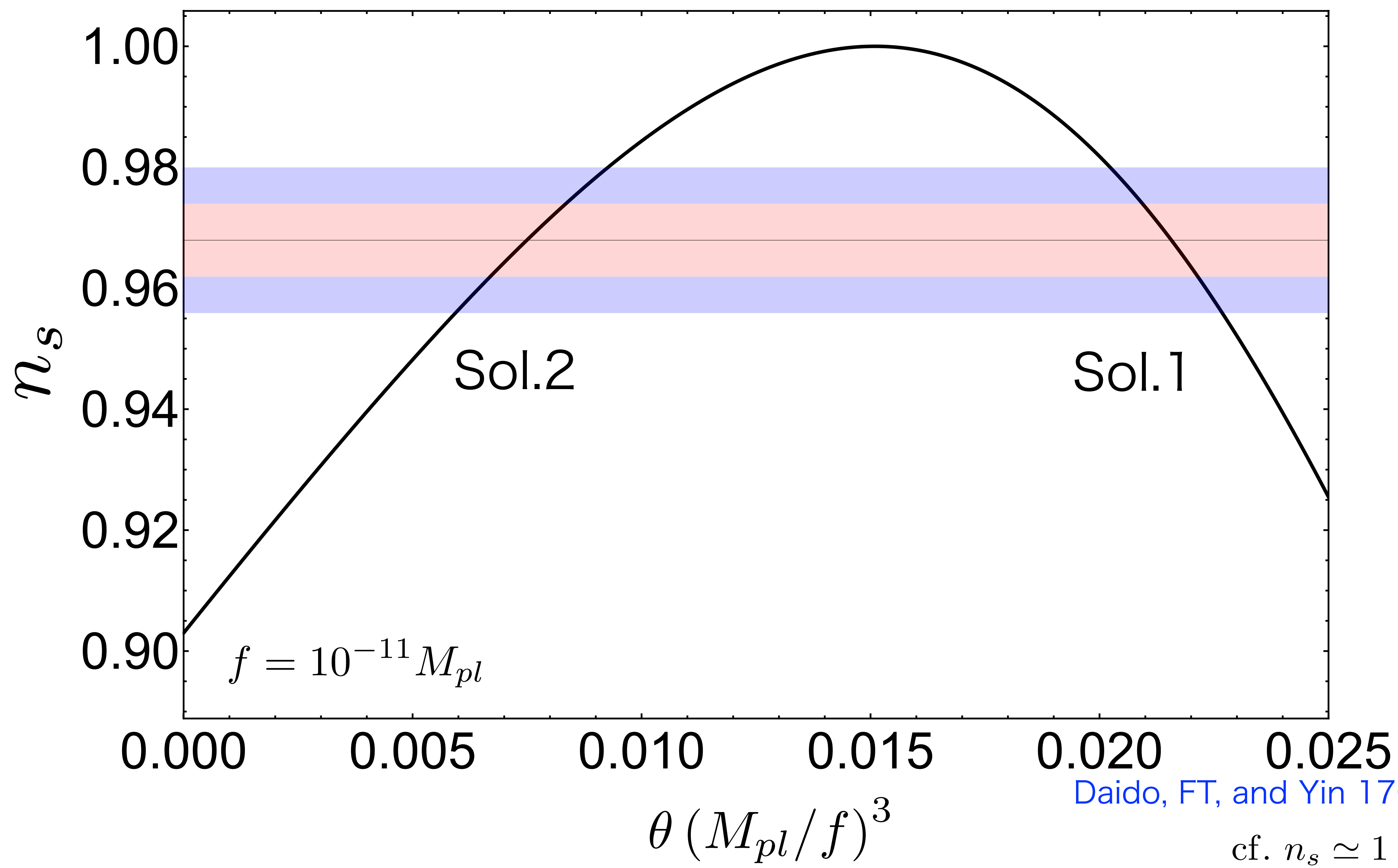
$$N_* \simeq 61 + \ln\left(\frac{H_*}{H_{\rm inf}}\right)^{\frac{1}{2}} + \ln\left(\frac{H_{\rm inf}}{10^{14}\text{GeV}}\right)^{\frac{1}{2}}$$

✓ Spectral index $(\theta = 0,\ c_n = 1)$

$$n_s \simeq 1 + 2\eta(\phi_*) \simeq 1 - \frac{3}{N_*}$$

• Spectral index as a function of relative phase

$$n_s = 0.968 \pm 0.006$$ Planck `15



Daido, FT, and Yin 1702.03284

cf. $n_s \simeq 1 + 2\eta(\phi_*)$

The inflaton mass is induced: $m_\phi \sim \theta^{\frac{1}{3}} \dfrac{\Lambda^2}{f} = \mathcal{O}(0.1) H_{\rm inf}$

• Relation between mass and decay constant

The Planck normalization of density perturbation and the spectral index fix the relation between m_ϕ and f ,

$$\lambda \sim \left(\frac{\Lambda}{f}\right)^4 \sim 10^{-13}$$: Planck normalization

$$\Lambda^4 \sim H_{\rm inf}^2 M_{pl}^2$$: Friedman eq.

$$m_\phi \sim 0.1 H_{\rm inf}$$: Scalar spectral index

cf. $n_s \simeq 1 + 2\eta(\phi_*)$

$$f \sim 4 \times 10^7\,{\rm GeV} \sqrt{\frac{3}{n}} \left(\frac{m_\phi}{1\,{\rm eV}}\right)^{\frac{1}{2}}$$

(for the solution 1)

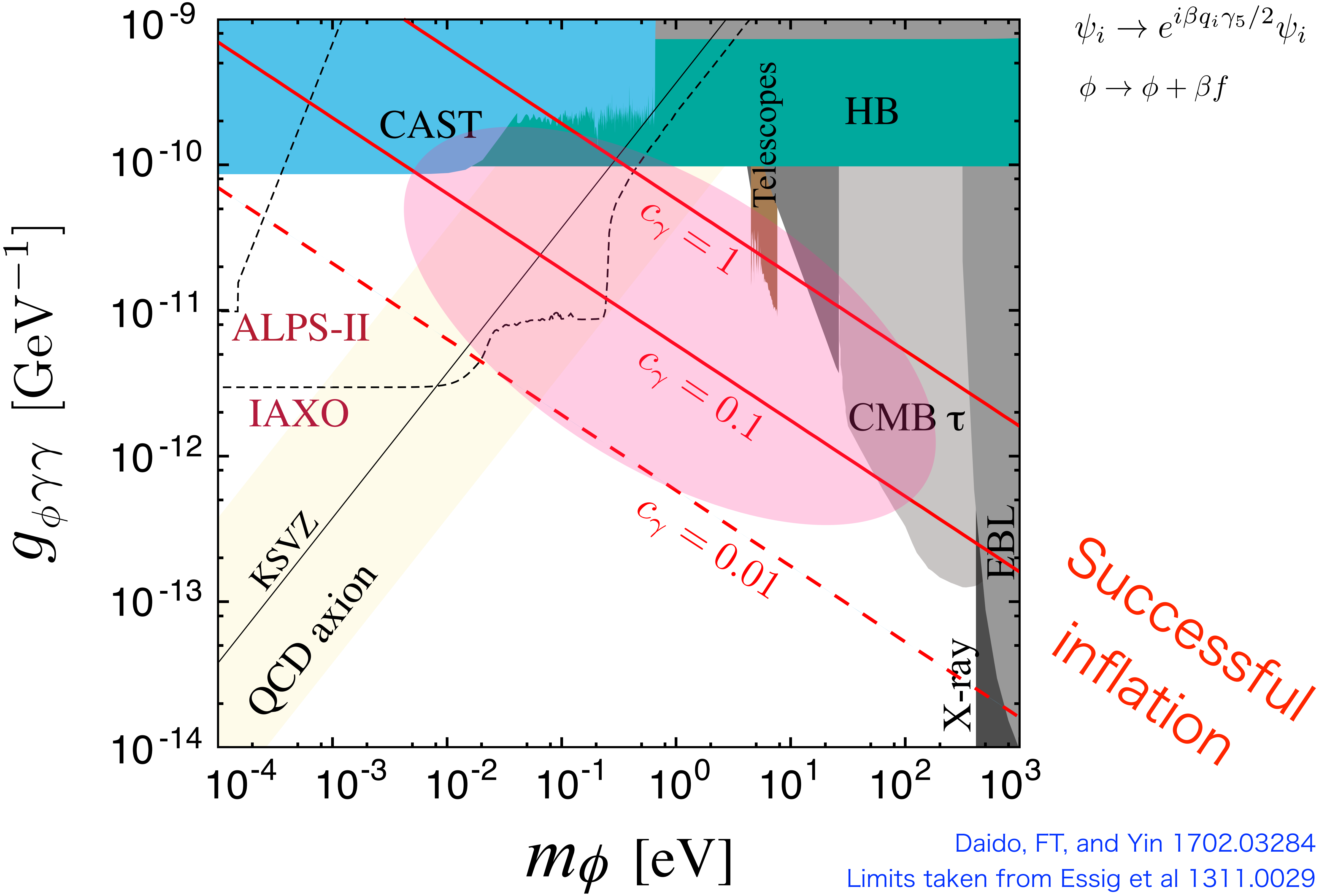
• Inflaton mass and coupling to photons

$$\mathcal{L} = \frac{g_{\phi\gamma\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} \quad g_{\phi\gamma\gamma} = \frac{c_\gamma \alpha}{\pi f}$$

$$c_\gamma = \sum_i q_i Q_i^2$$

$$\psi_i \to e^{i\beta q_i \gamma_5/2}\psi_i$$

$$\phi \to \phi + \beta f$$



Daido, FT, and Yin 1702.03284

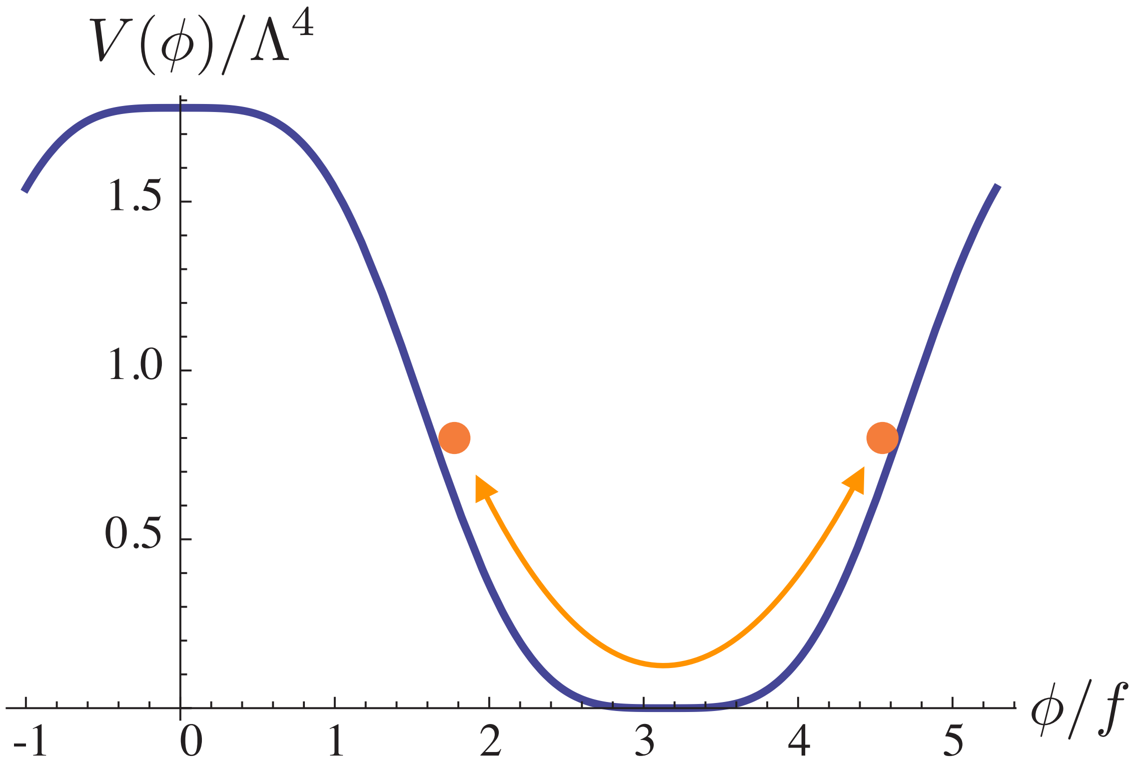
Limits taken from Essig et al 1311.0029

3. Reheating and ALP DM

The inflaton oscillates about $\phi_{\rm min} = \pi f$ in a quartic potential.

The effective mass, $m_{\rm eff}^2(t) = V''(\phi_{\rm amp}) = 12\lambda\phi_{\rm amp}^2$

decreases with time.



✓The decay rate into two photons :

$$\Gamma_{\rm dec}(\phi \to \gamma\gamma) = \frac{c_\gamma^2 \alpha^2}{64\pi^3} \frac{m_{\rm eff}^3}{f^2} \sqrt{1 - \left(\frac{2m_\gamma^{(th)}}{m_{\rm eff}}\right)^2}$$

✓The dissipation rate is roughly given by

$$\Gamma_{{\rm dis},\gamma} = C \frac{c_\gamma^2 \alpha^2 T^3}{8\pi^2 f^2} \frac{m_{\rm eff}^2}{e^4 T^2}$$

Moroi, Mukaida, Nakayama and Takimoto,1407.7465
cf. Salvio, Strumia, Xue, 1310.6982

Here C represents an uncertainty of the order-of-magnitude estimate as well as spatial inhomogeneities due to tachyonic preheating.

Due to the decay and dissipation,

$$\xi \equiv \left. \frac{\rho_\phi}{\rho_\phi + \rho_R} \right|_{\text{after reheating}} = \mathcal{O}(0.01)$$

for $\quad g_{\phi\gamma\gamma} = \ (\text{several}) \times 10^{-11}\,\text{GeV}^{-1}$

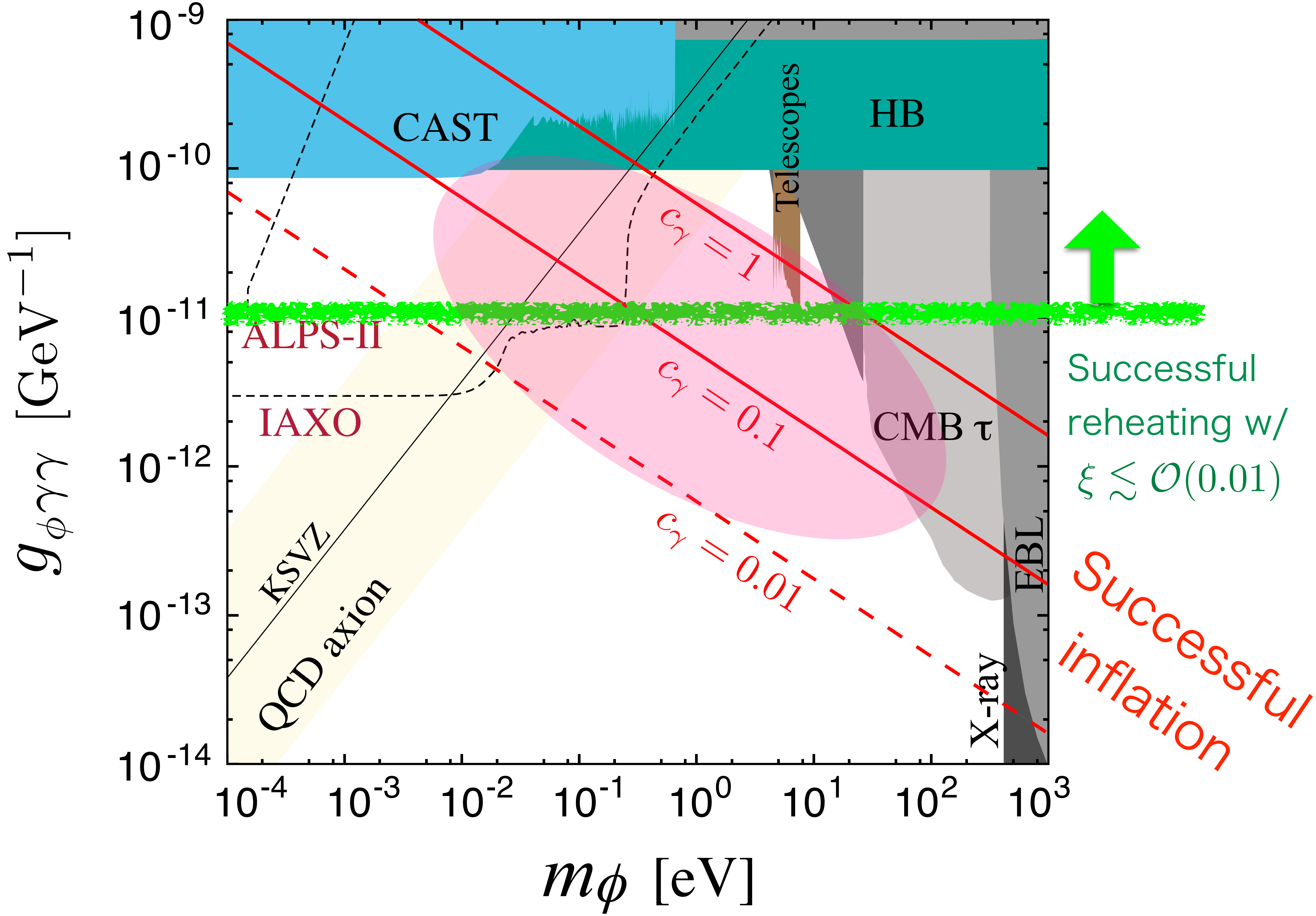
$c_2, c_Y, C, C', C'' = \mathcal{O}(1)$

The reheating temperature is $T_R \sim \mathcal{O}(10)\,\text{TeV} \left(\frac{m_\phi}{1\,\text{eV}} \right)^{\frac{1}{2}}$

For successful reheating with $\xi \lesssim \mathcal{O}(0.01)$, one needs

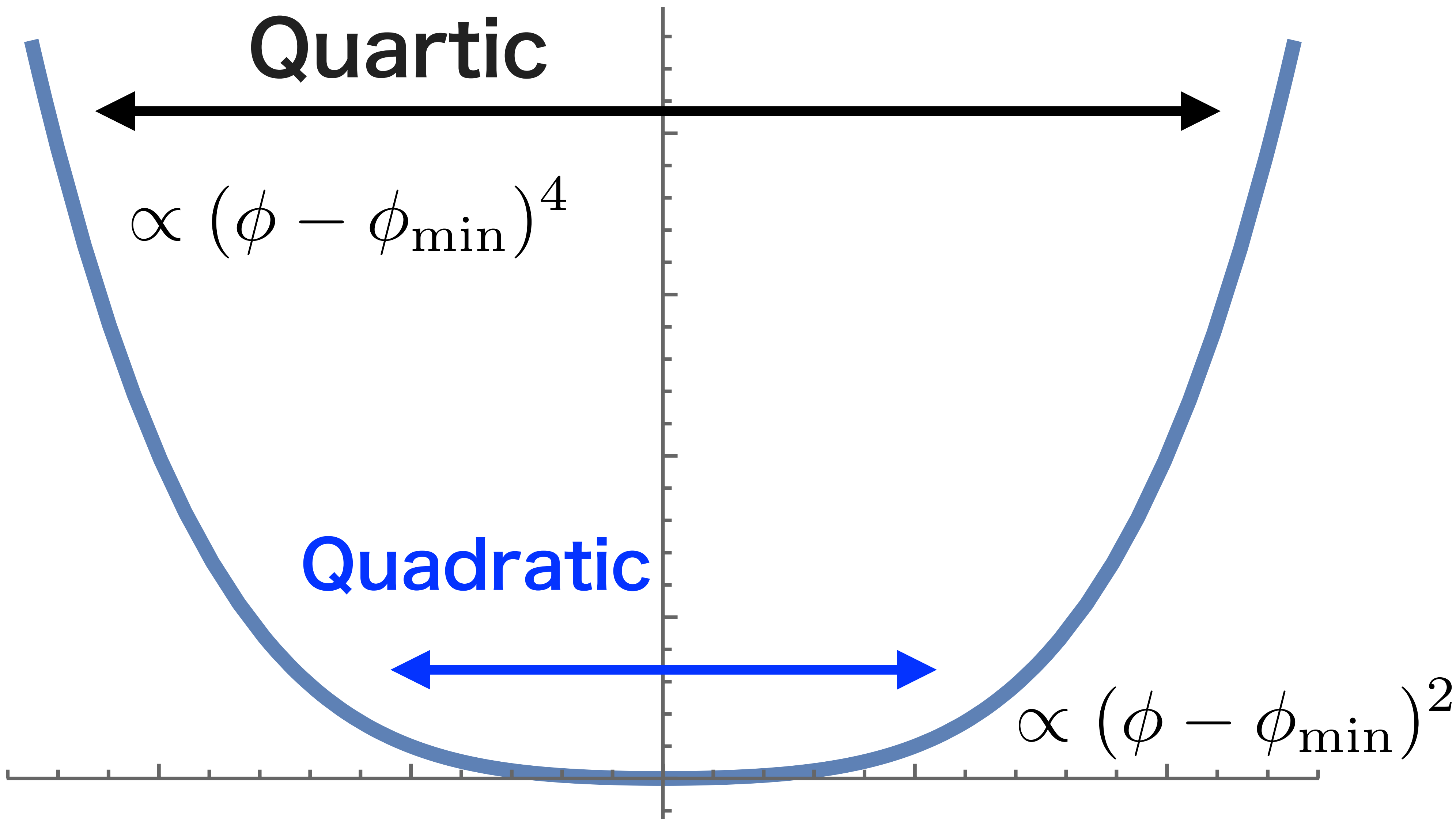
$$g_{\phi\gamma\gamma} \gtrsim 10^{-11}\,\text{GeV}^{-1}$$

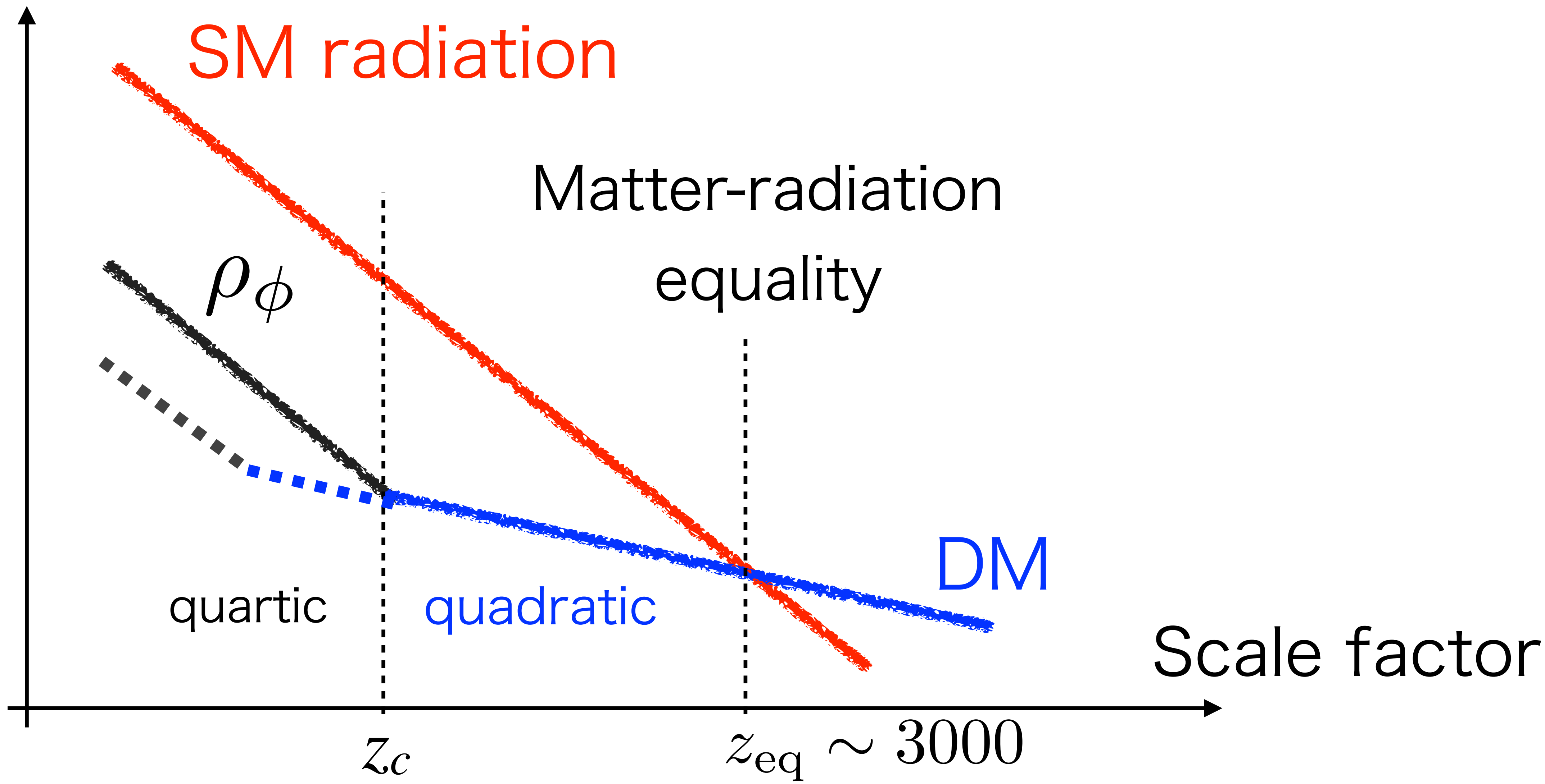
Note that the inflaton mass is then bounded above.



$g_{\phi\gamma\gamma}$ [GeV^{-1}]
m_ϕ [eV]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
CAST
HB
Telescopes
ALPS-II
IAXO
CMB τ
EBL
X-ray
KSVZ
QCD axion
$c_\gamma = 1$
$c_\gamma = 0.1$
$c_\gamma = 0.01$
Successful reheating w/ $\xi \lesssim \mathcal{O}(0.01)$
Successful inflation

ρ_ϕ decreases like radiation until the potential becomes quadratic.





DM should be formed before $z_c \gtrsim \mathcal{O}(10^5)$ by SDSS and Ly-alpha

Sarkar, Das, Sethi, 1410.7129

$$\xi \lesssim 0.02 \left(\frac{g_{*s}(T_R)}{106.75}\right)^{\frac{1}{3}} \left(\frac{3.909}{g_{*s}(T_c)}\right)^{\frac{1}{3}} \left(\frac{\Omega_\phi h^2}{0.12}\right) \left(\frac{5\times 10^5}{1+z_c}\right).$$

Efficient reheating is required by matter power spectrum.

$$\xi \equiv \left.\frac{\rho_\phi}{\rho_\phi + \rho_R}\right|_{\text{after reheating}}$$

The abundance of the remnant inflaton condensate can be expressed as

$$\frac{\rho_\phi}{s} \simeq \frac{3}{4}\xi^{\frac{3}{4}} \frac{m_\phi T_R}{\sqrt{2\lambda} f x}$$

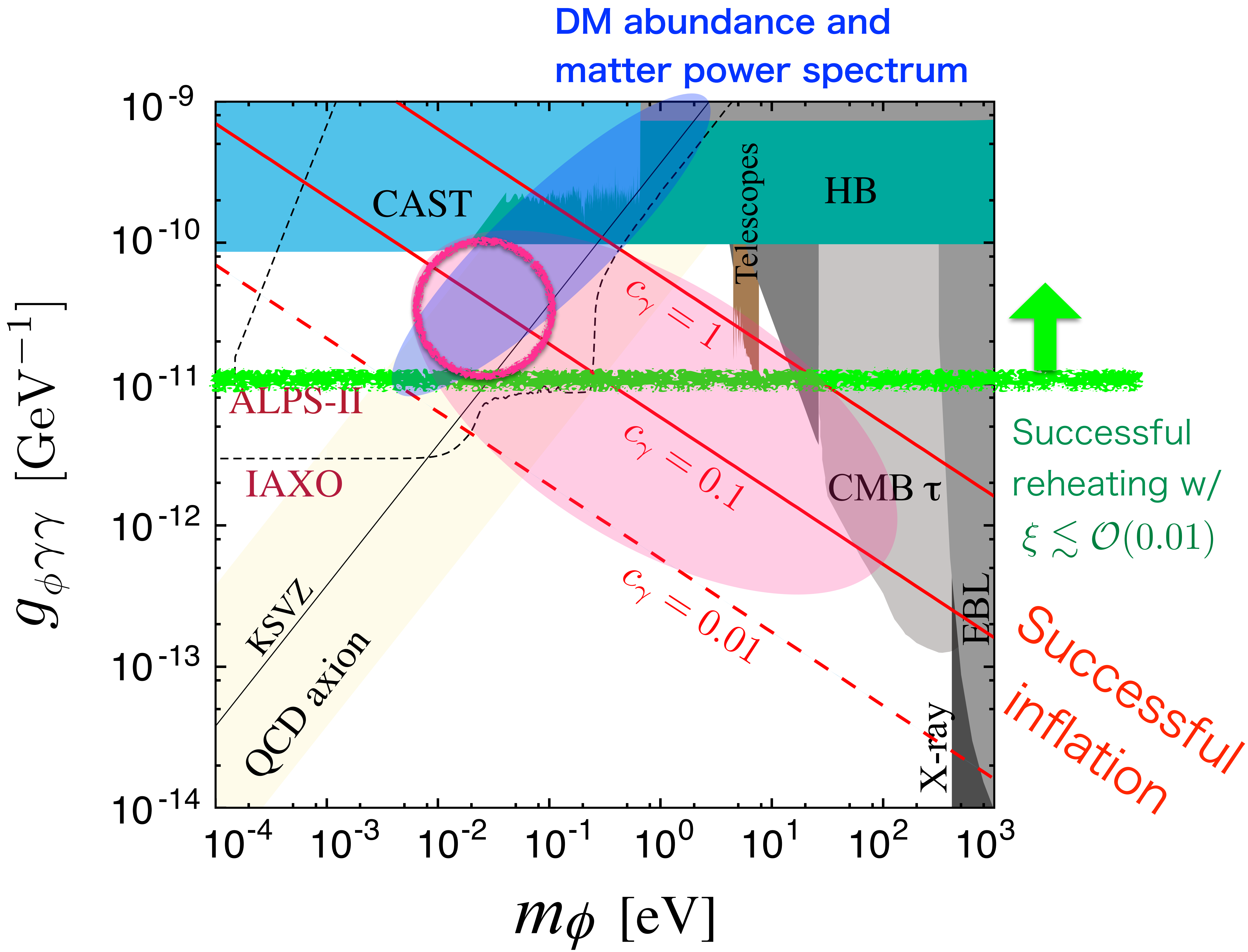
$$\phi_{\rm amp} = x\,\xi^{\frac{1}{4}} f$$
$$x = \mathcal{O}(1)$$

$$\begin{aligned} m_\phi &\simeq 0.07\, x^{-1} \left(\frac{\xi}{0.01}\right)^{-\frac{3}{4}} \left(\frac{\Omega_\phi h^2}{0.12}\right) {\rm eV}, \\ &\gtrsim 0.04\, x^{-1} \left(\frac{106.75}{g_{*s}(T_R)}\right)^{\frac{1}{4}} \left(\frac{g_{*s}(T_c)}{3.909}\right)^{\frac{1}{4}} \left(\frac{\Omega_\phi h^2}{0.12}\right)^{\frac{1}{4}} \left(\frac{1+z_c}{5\times 10^5}\right)^{\frac{3}{4}} {\rm eV}, \end{aligned}$$

Here the limit on ξ due to SDSS and Ly-alpha was used.

For more efficient reheating, the inflaton mass needs to be heavier to account for the DM abundance. But this may be in a tension with the upper bound on the mass.

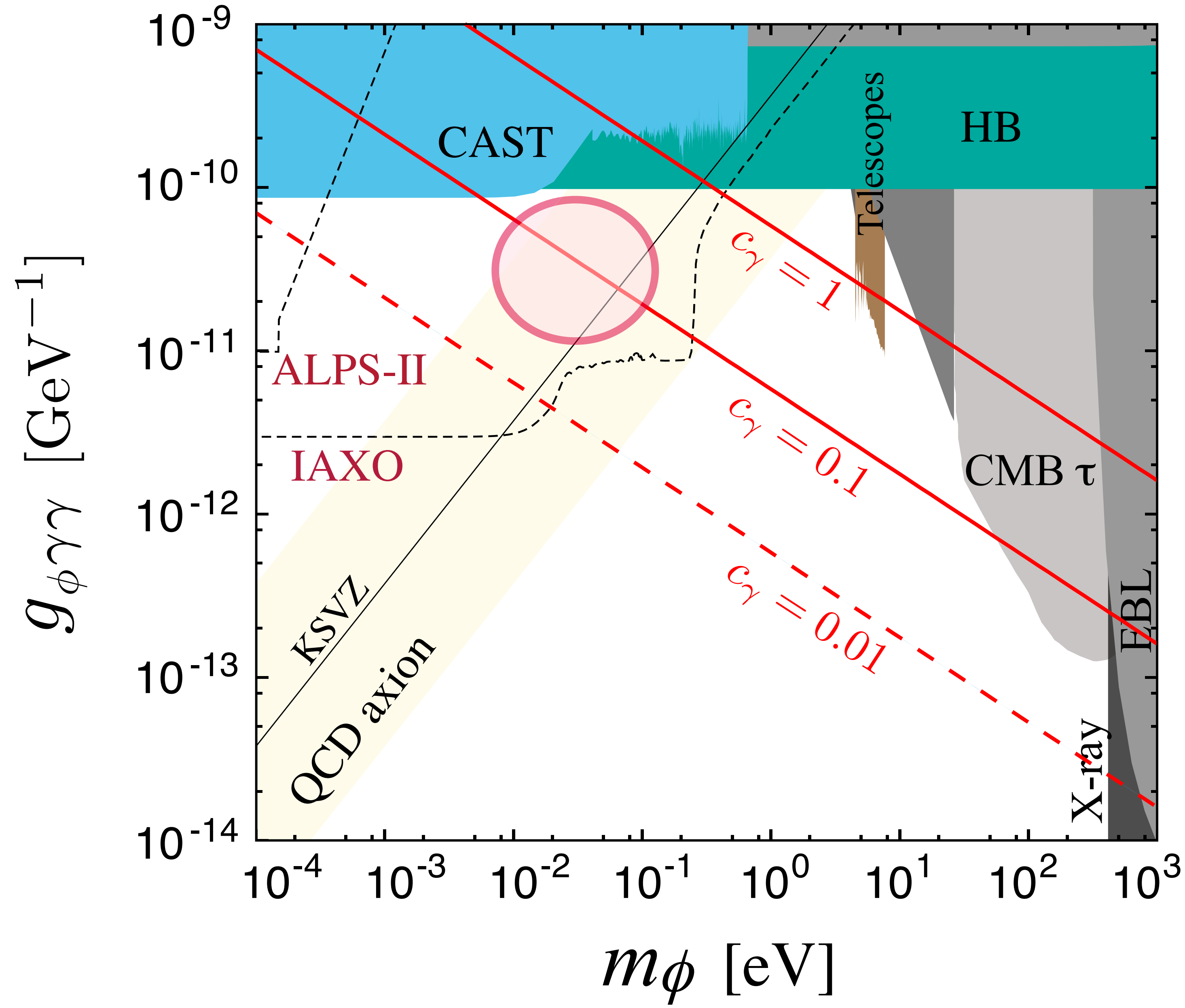
Recall $g_{\phi\gamma\gamma} \propto \frac{1}{f} \propto \frac{1}{\sqrt{m_\phi}}$


DM abundance and
matter power spectrum
CAST
HB
Telescopes
ALPS-II
IAXO
CMB τ
EBL
X-ray
KSVZ
QCD axion
$c_\gamma = 1$
$c_\gamma = 0.1$
$c_\gamma = 0.01$
Successful
reheating w/
$\xi \lesssim \mathcal{O}(0.01)$
Successful
inflation
$g_{\phi\gamma\gamma}$ [GeV^{-1}]
m_ϕ [eV]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}

Inflaton = DM = ALP

$$m_\phi = \mathcal{O}(0.01)\,\mathrm{eV}$$
$$g_{\phi\gamma\gamma} = \mathcal{O}(10^{-11})\,\mathrm{GeV}^{-1}$$

within the reach of future axion helioscope, IAXO.



We call the coincidence as “The ALP miracle”.

- **Other implications:**

  ✓ Thermalized ALPs contribute to HDM with $\Delta N_{\rm eff} \simeq 0.03$.

  ✓ Matter power spectrum suppressed at small scales.

  ✓ Reheating temperature is in the range of TeV - 10TeV.
    - EW baryogenesis possible.

  ✓ Inflaton mass and the inflation scale can be determined by the ultralight ALP search experiments.

Summary

- All the members are actively working on dark matter physics from various aspects.
- More interactions among different members and different groups (both theory & obs) needed.
- The ALP miracle connects inflation with DM and provides several predictions like
  - ✓ A light ALP within the reach of IAXO.
  - ✓ A small amount of HDM.
  - ✓ Suppression of matter power spectrum at small scales
  - ✓ Depending on the mass, light ALP can be decaying DM into photons.