# Axions

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10th Anniversary Symposium

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(Tohoku)

# The Strong CP Problem

$$\mathcal{L}_\theta = \theta \frac{g_s^2}{32\pi^2} G^{a\mu\nu} \tilde{G}^a_{\mu\nu}$$

Experimental bound from neutron electric dipole moment reads

$$|\theta| < 10^{-10}$$

Why $\theta$ is so small is the strong CP problem.

cf. More precisely, the physical strong CP phase is

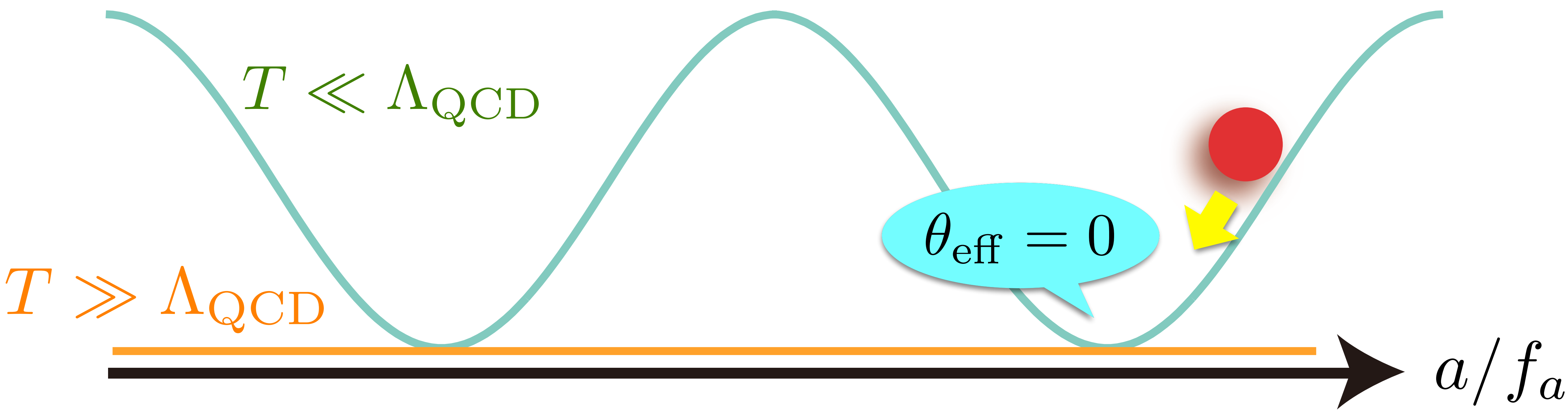
$$\bar{\theta} \equiv \theta - \arg\det\left(M_u M_d\right)$$

which makes the problem even more puzzling.

In the Peccei-Quinn solution, the strong CP phase is promoted to a dynamical variable:

Peccei, Quinn `77, Weinberg `78, Wilczek `78

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




Axion mass : $m_a \simeq 6 \times 10^{-6}\,{\rm eV} \left(\frac{f_a}{10^{12}\,{\rm GeV}}\right)^{-1}$

Axion-like particles (ALPS) do not satisfy the above relation.

# Axion Dark Matter

The axion dark matter (DM) is produced as coherent oscillations [misalignment mechanism].

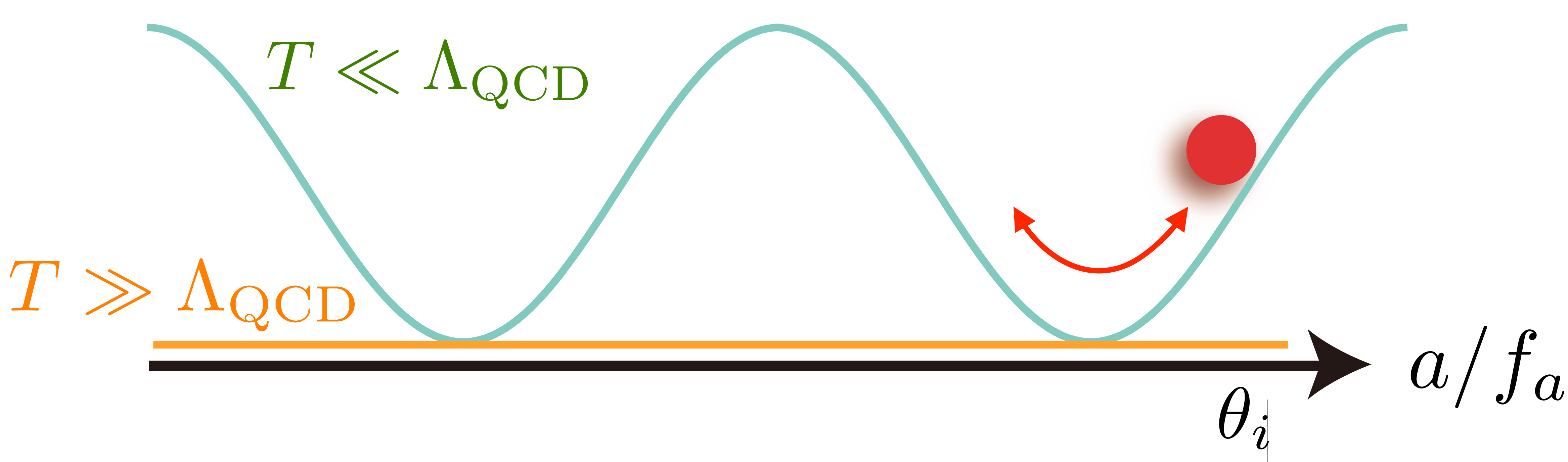
Preskill, Wise, Wilczek `83, Abbott, Sikivie, `83, Dine, Fischler, `83

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

CDM

Anharmonic effect

Bae, Huh, Kim `08, Visinelli and Gondolo `08



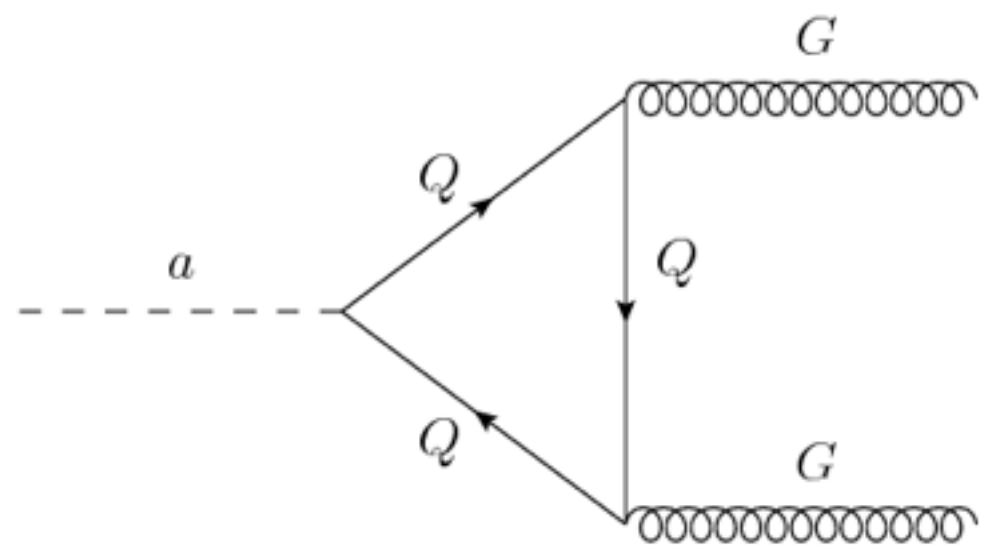
# Axion Interactions

- Gluons

$$\mathcal{L}_{aGG} = N_{\rm DW}\frac{a}{F_a}\frac{\alpha_s}{8\pi}G_{a\mu\nu}\tilde{G}^a_{\mu\nu} = \frac{a}{f_a}\frac{\alpha_s}{8\pi}G_{a\mu\nu}\tilde{G}^a_{\mu\nu}$$

defines the axion decay constant $f_a = \dfrac{F_a}{N_{\rm DW}}$.

$N_{DW}$: domain wall number



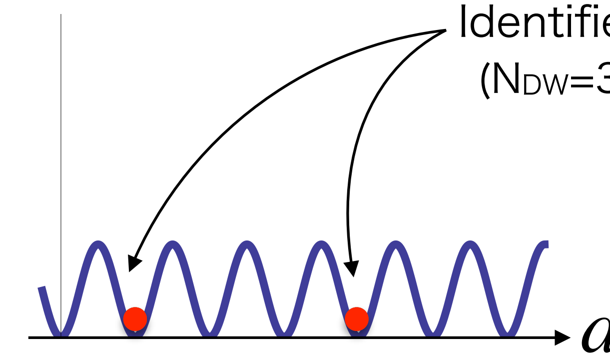




Figure taken from 1210.3196

**Hadronic/KSVZ axion**

Kim `79, Shifman, Vainshtein, and Zakharov `80

Yet unknown heavy quarks run in the loop.

**DFSZ axion**

Dine, Fischler, and Srednicki `81, Zhitnitsky `80

Ordinary SM quarks run in the loop. $N_{DW} = 3$ or $6$.

N.B. Both heavy and SM quarks, or only a part of SM quarks may run in the loop, which help to avoid the domain wall problem by $N_{DW} = 1$.

# Axion Interactions

- Photons

$$\mathcal{L}_{a\gamma\gamma} = \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}_{\mu\nu} = -g_{a\gamma\gamma}\, a\, \vec{E}\cdot\vec{B}$$

$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.9\right)$$

E and N are EM and color anomaly factors of the PQ current.

- Electrons

$$\mathcal{L}_{aee} = \frac{C_e}{2f_a}\partial_\mu a\,\left(\bar{\Psi}_e\gamma^\mu\gamma_5\Psi_e\right) = -ig_{aee}a\left(\bar{\Psi}_e\gamma_5\Psi_e\right) + \cdots$$

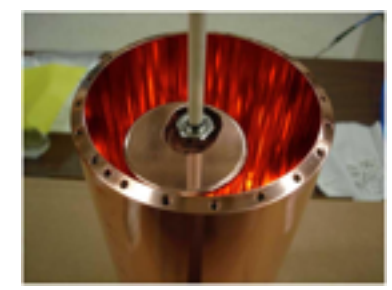
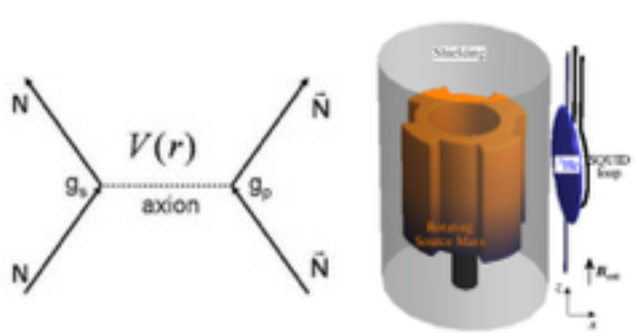
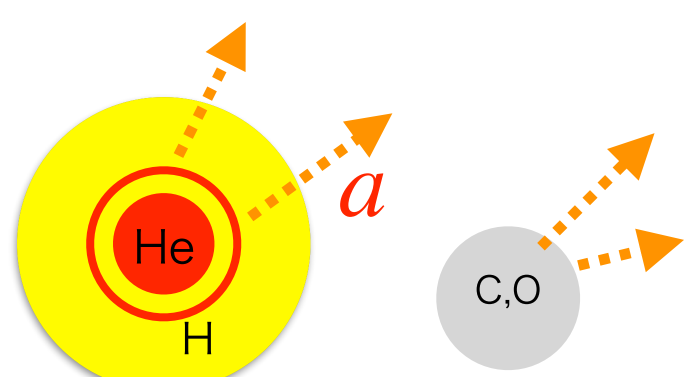
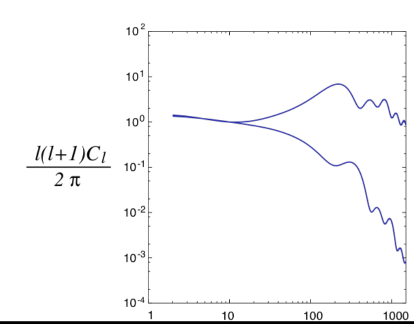
$$g_{aee} \equiv \frac{C_e m_e}{f_a}$$

$C_e = \frac{\cos^2\beta}{3}$ for DFSZ axion.

Model-dependent. Coupling to electrons appear only at loop-level in the hadronic axion.

- Nucleons

$$\mathcal{L}_{aNN} = \sum_{N=p,n}\frac{C_N}{2f_a}\partial_\mu a\,\left(\bar{\Psi}_N\gamma^\mu\gamma_5\Psi_N\right)$$


<table>
<tr><td></td><td></td><th colspan="3">Production</th></tr>
<tr><td></td><td></td><th>Terrestrial</th><th>Celestial</th><th>Cosmological</th></tr>
<tr><th rowspan="2">Detection</th><th>Direct</th>
<td>LSTW,<br>Photon pol.<br>ALPS, PVLAS, SAPPHIRES<br></td>
<td>Solar axion<br>CAST, IAXO, TASTE<br></td>
<td>Axion DM<br>ADMX, CAPP,ORPHEUS MADMAX, LC-circuits, CASPEr, LUX,XMASS, EDELWISE,XENON100<br></td></tr>
<tr><th>Indirect</th>
<td>Fifth force<br>ARIADNE<br><br></td>
<td>Excessive cooling of WD, RGB, HB, and NS<br><br></td>
<td>Isocurvature, DR, HDM, caustics, Spectral irreg. transparency<br>Fermi, Chandra, IACT<br>CMB, lensing, shear<br><br><br></td></tr>
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# Constraints on axion-photon coupling

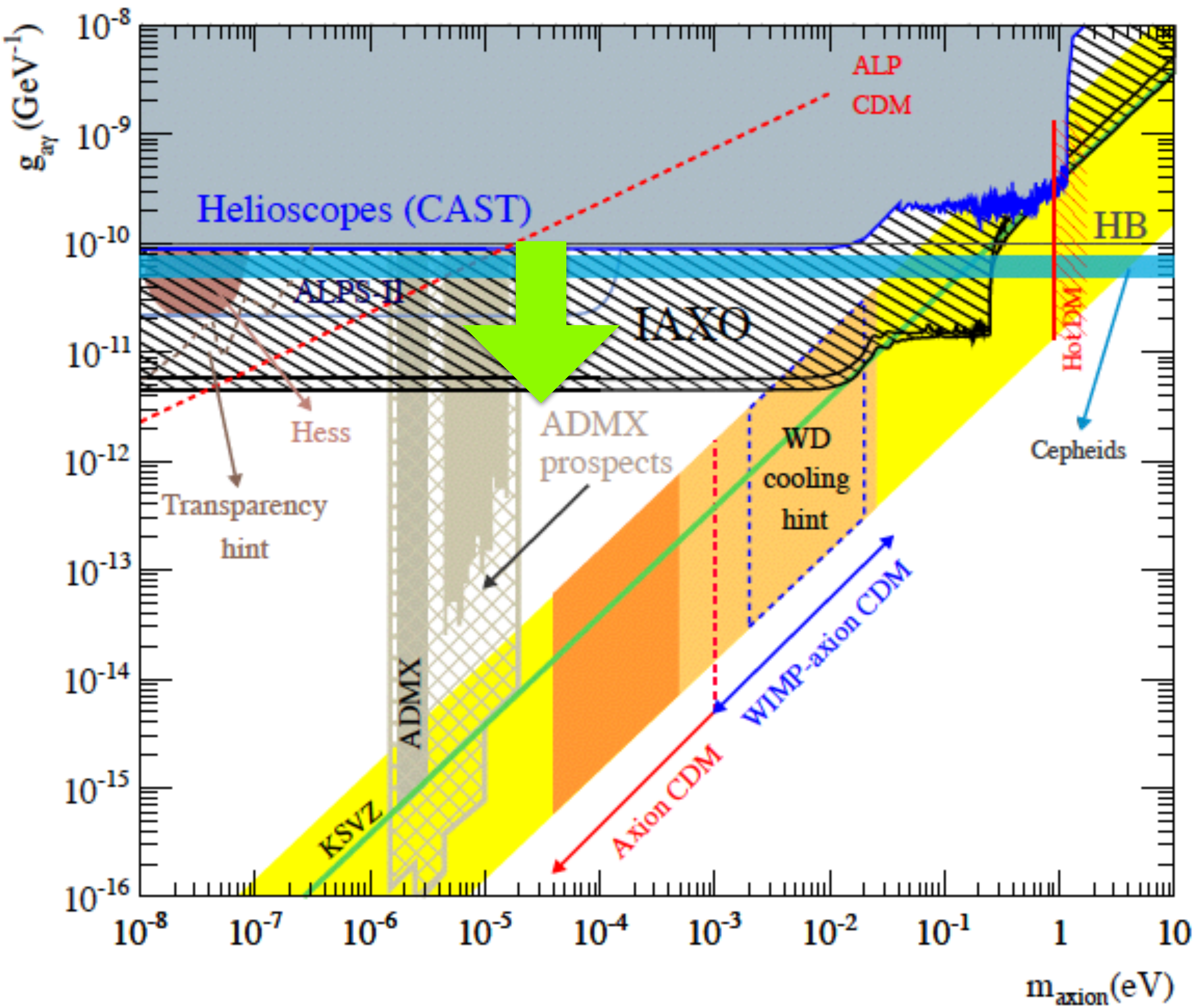


figure taken from Carosi et al, 1309.7035

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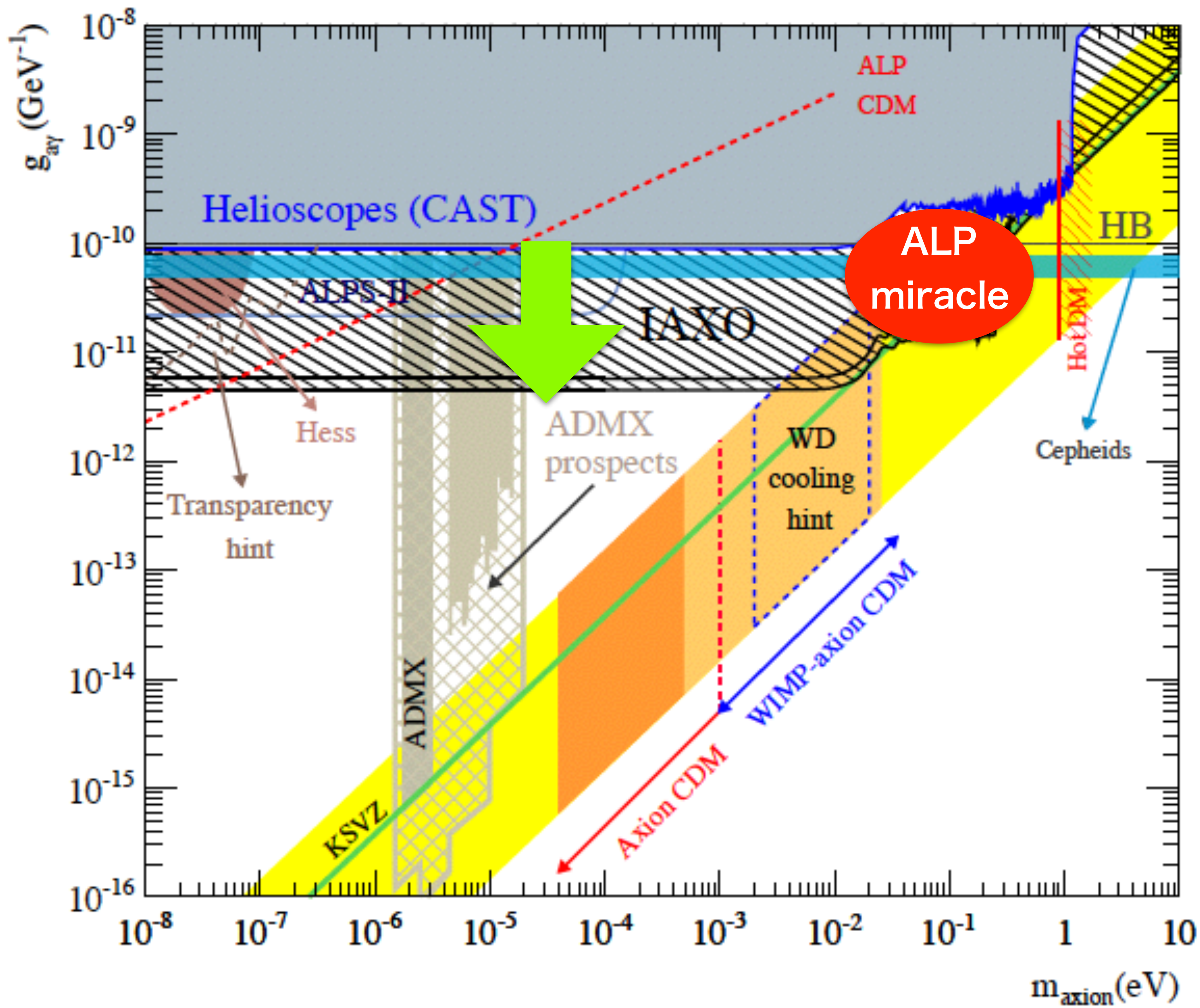


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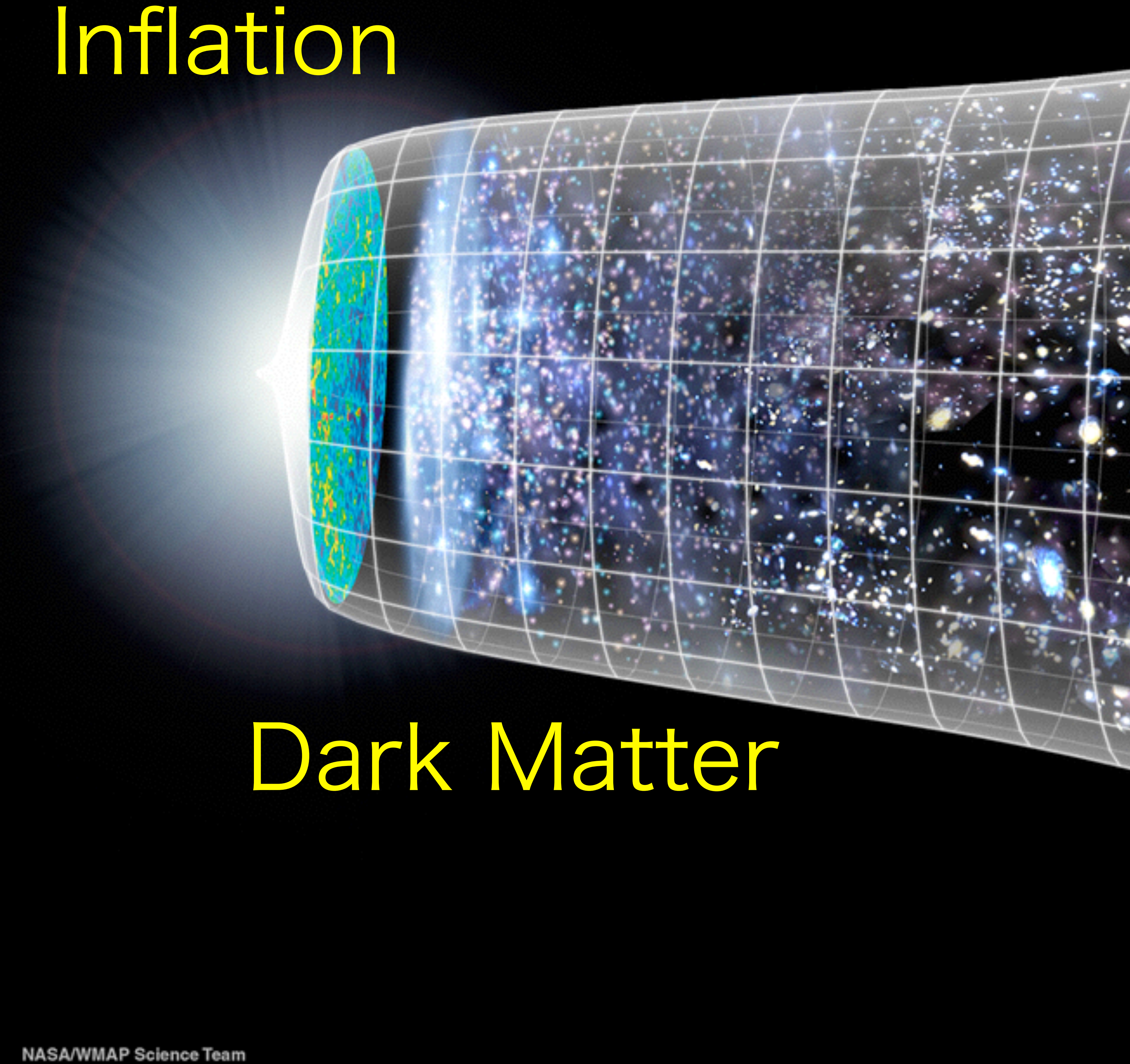
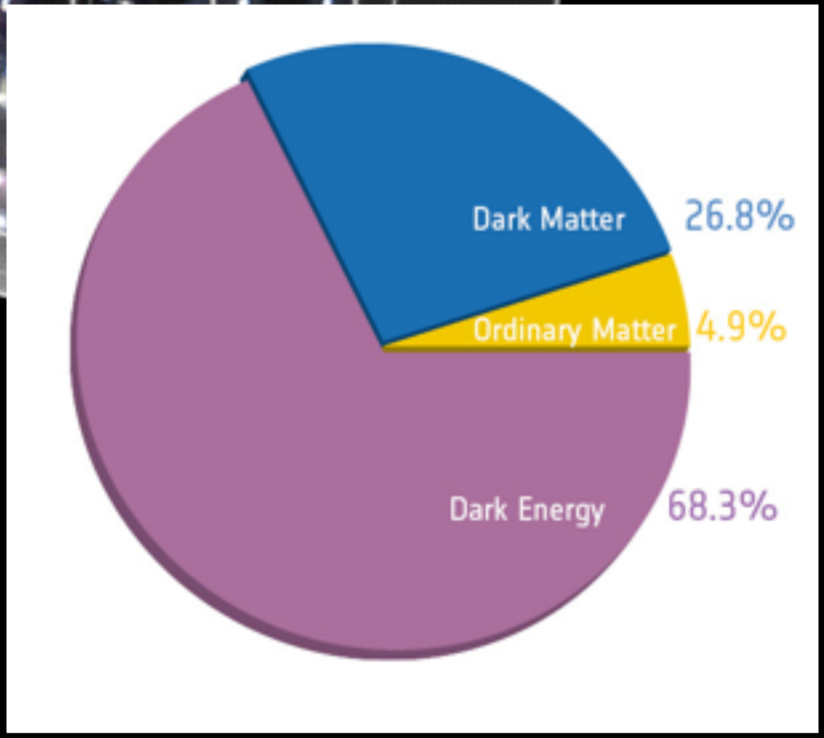
Inflation



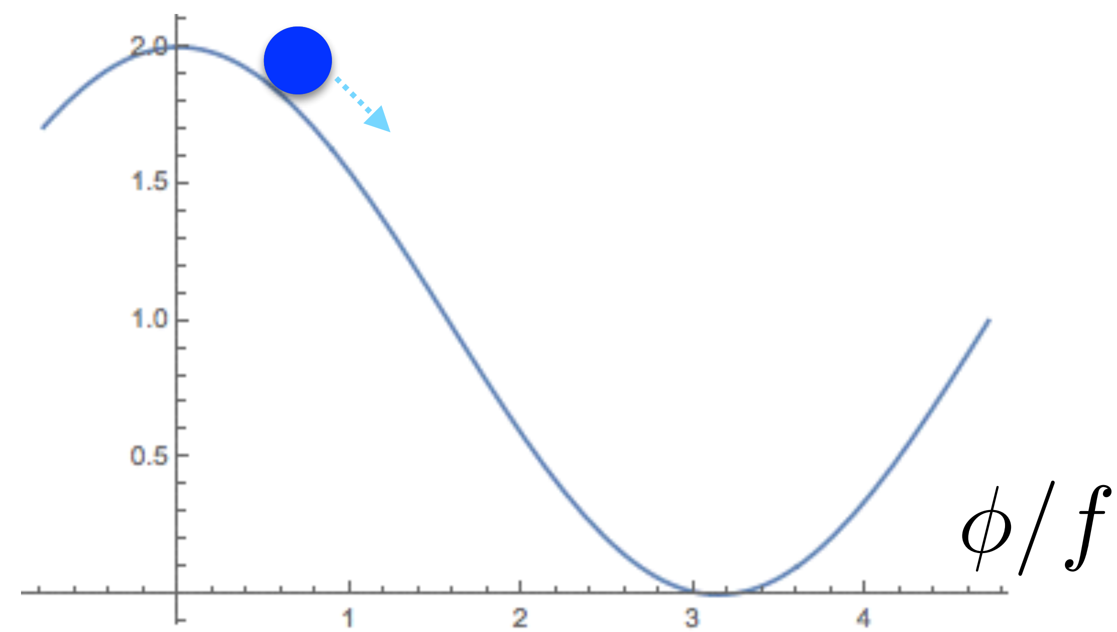

Dark Matter



#  • Natural inflation

Freese, Frieman, Olinto `90

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

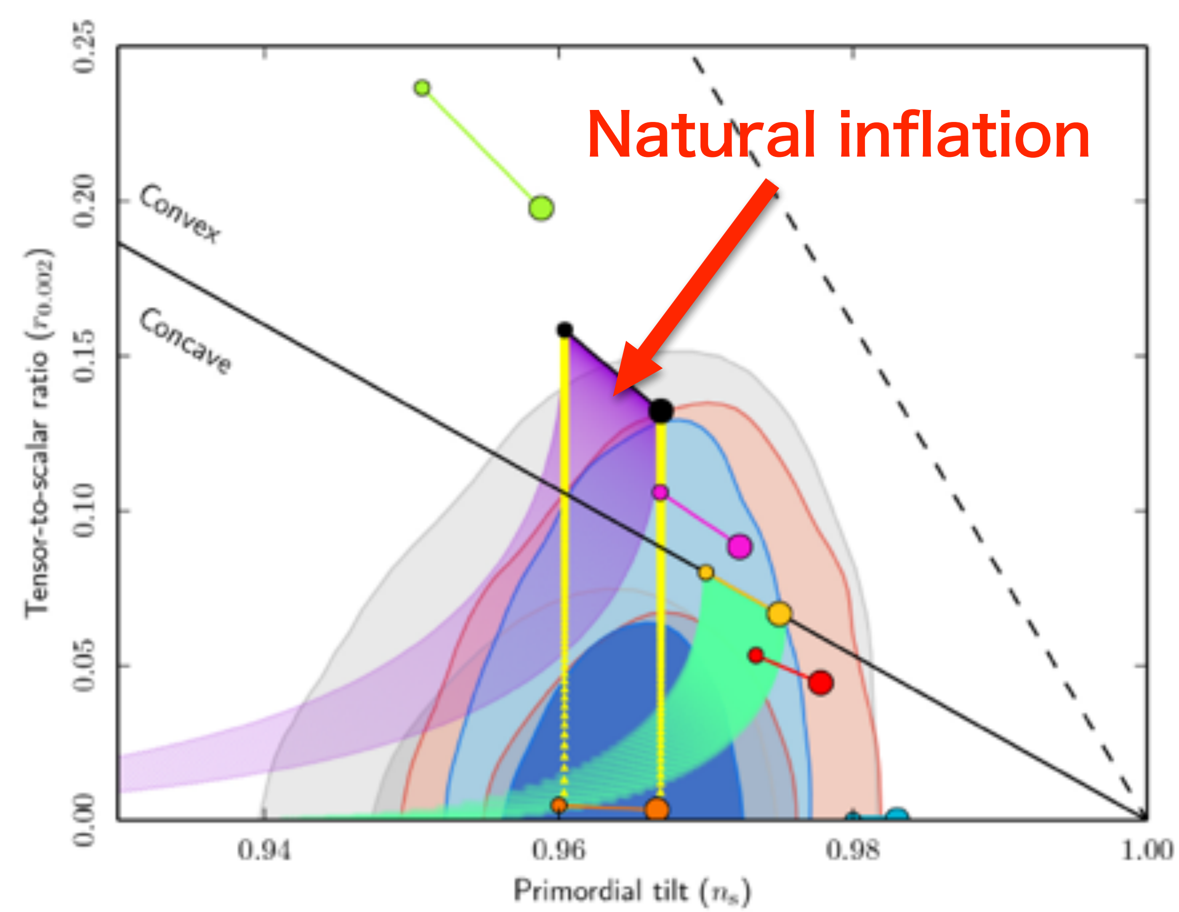



Only large-field inflation is possible with a single cosine term.

- Super-Planckian decay constant required:

$$f \gtrsim 5 M_P$$

- Predicted (ns,r) are not favored by CMB obs. ☹




Planck 2015

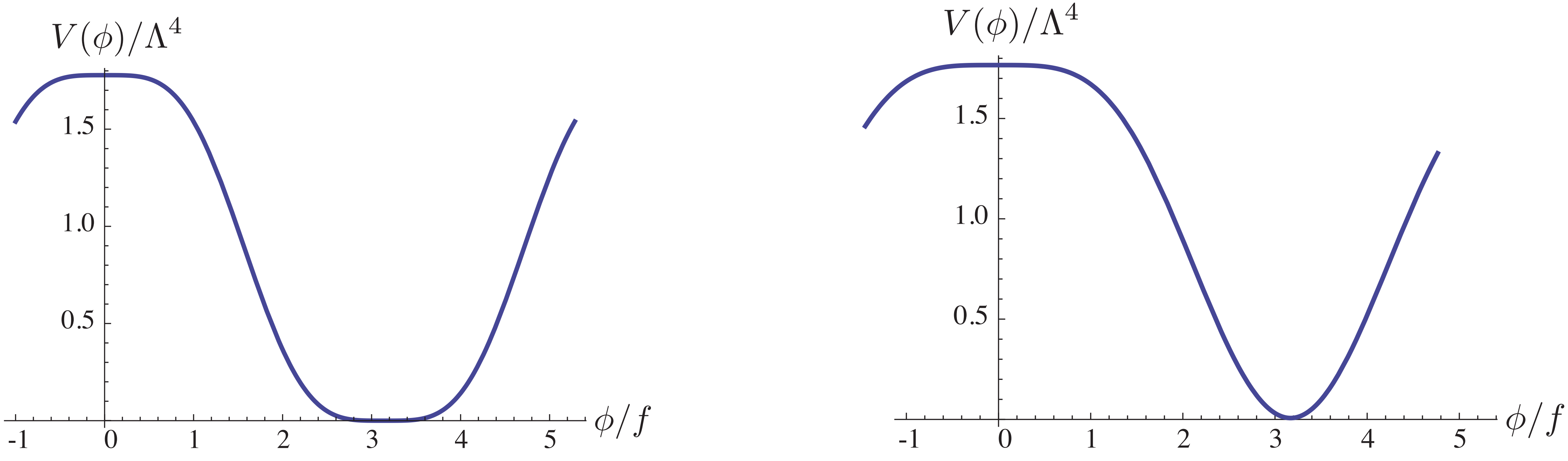
# • Axion hilltop inflation

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

Axion hilltop inflation can be realized with (at least) two cosine terms: "*Multi-natural inflation*"

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

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




Odd n

Even n

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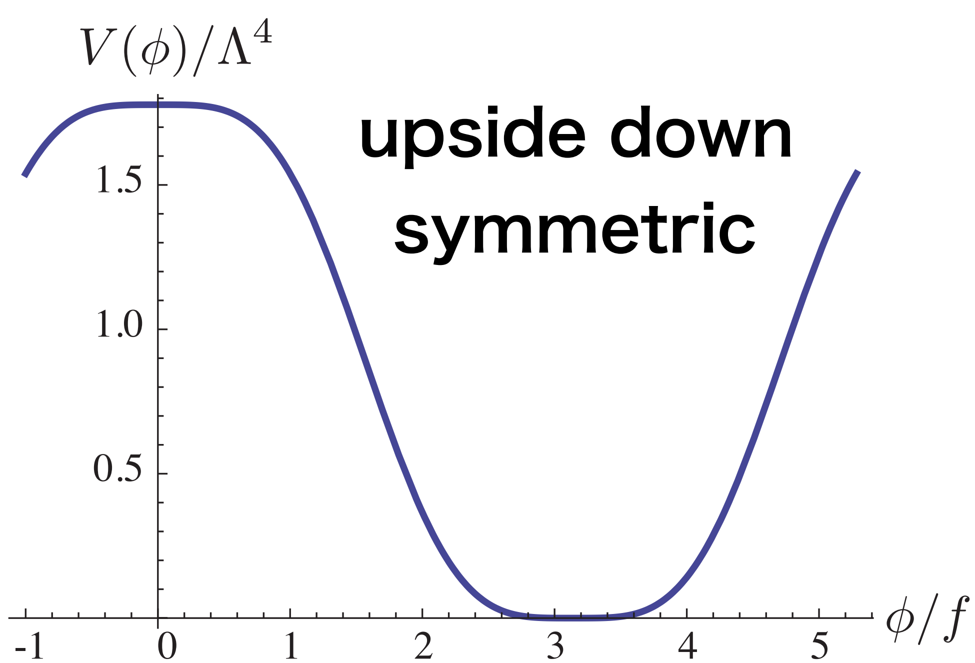


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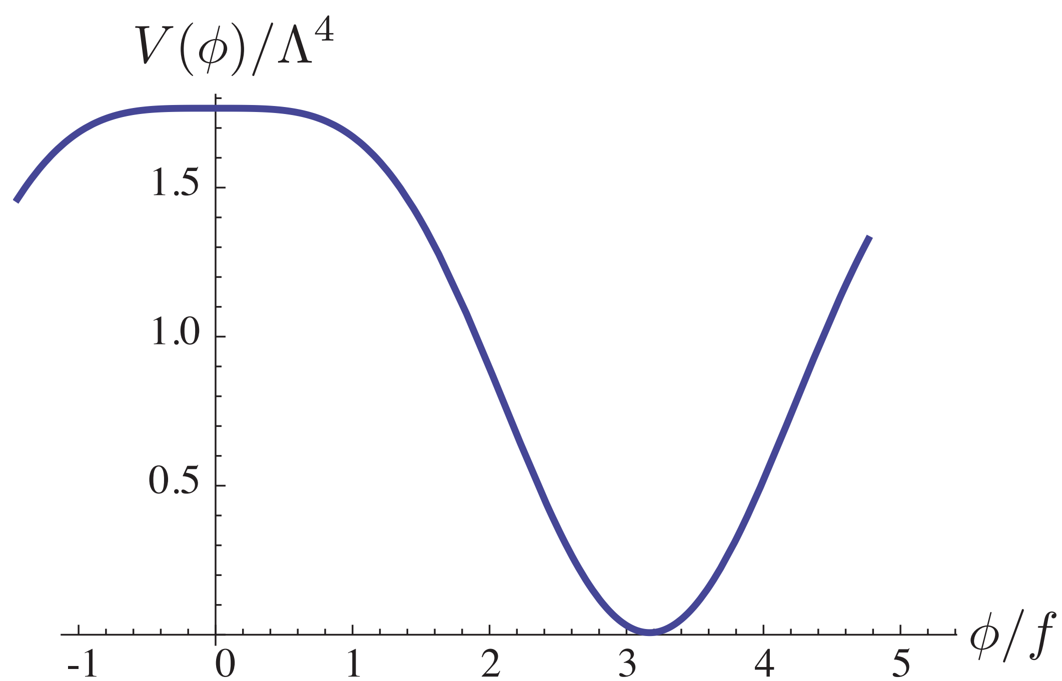


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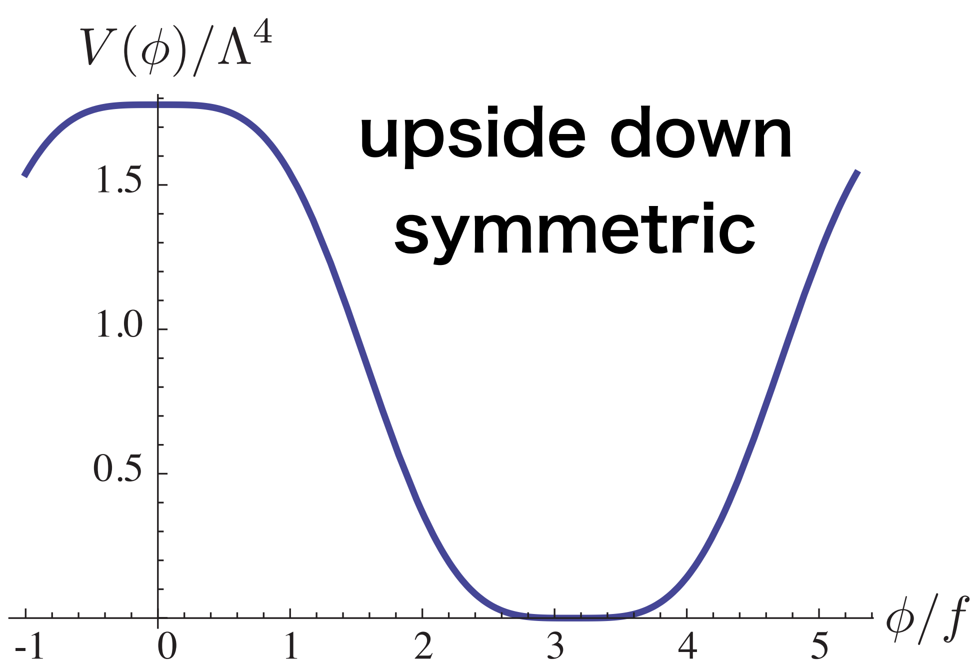



Odd n

- 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.

## • Relation between mass and decay constant

The CMB normalization of density perturbation and the spectral index fix the relation between $m_\phi$ and $f$ ,

$$\lambda \sim \left(\frac{\Lambda}{f}\right)^4 \sim 10^{-12}$$ : CMB normalization

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

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

$$\text{cf. } n_s \simeq 1 + 2\eta(\phi_*) = 1 + \frac{2}{3}\frac{V''(\phi_*)}{H_{\rm inf}^2} \simeq 0.968$$

$$f \sim 10^7\,\text{GeV}\sqrt{\frac{3}{n}}\left(\frac{m_\phi}{0.1\text{eV}}\right)^{\frac{1}{2}}$$

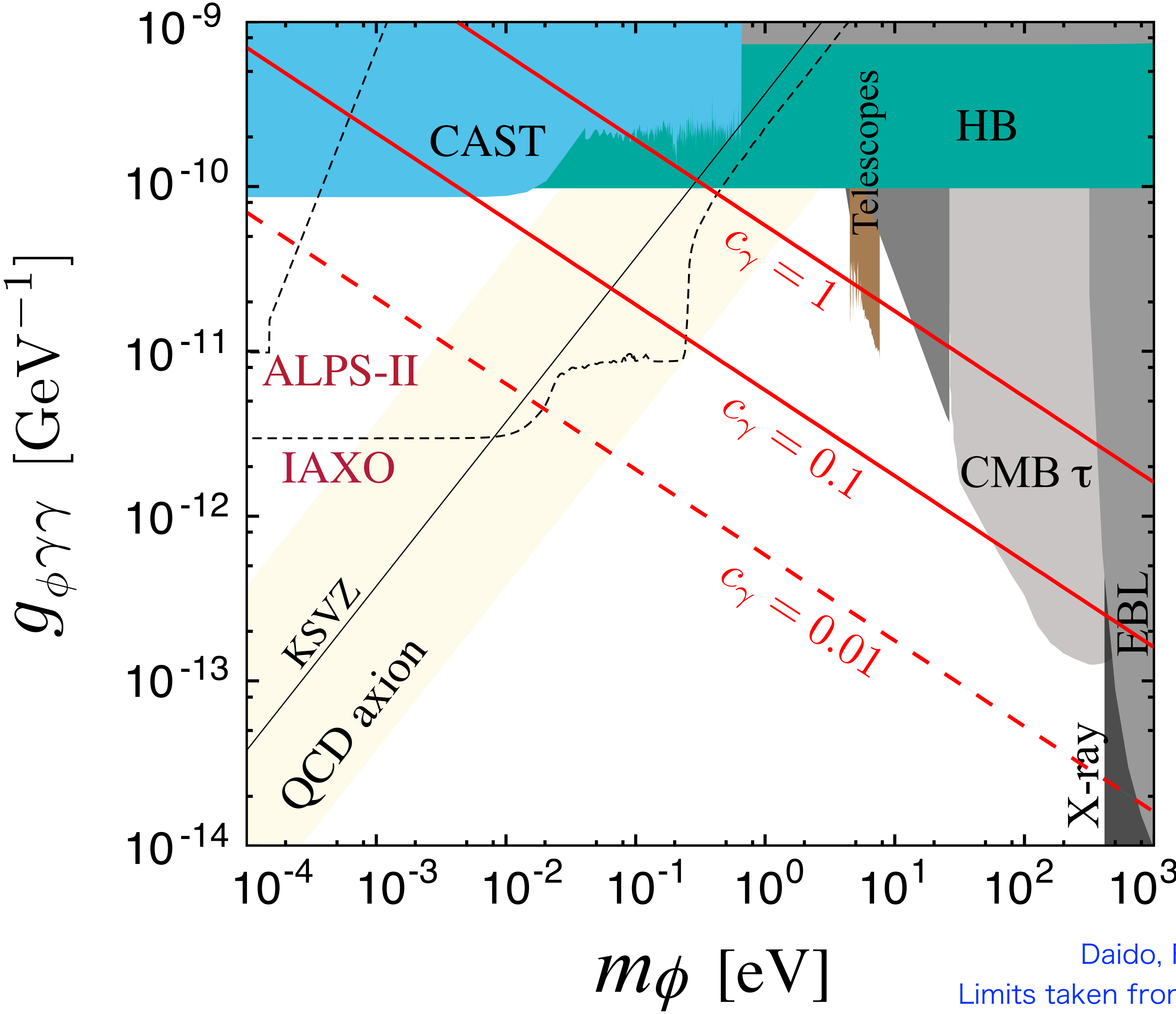
# • Inflaton (ALP) mass and coupling to photons

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

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

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

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




Daido, FT, and Yin 1702.03284

Limits taken from Essig et al 1311.0029

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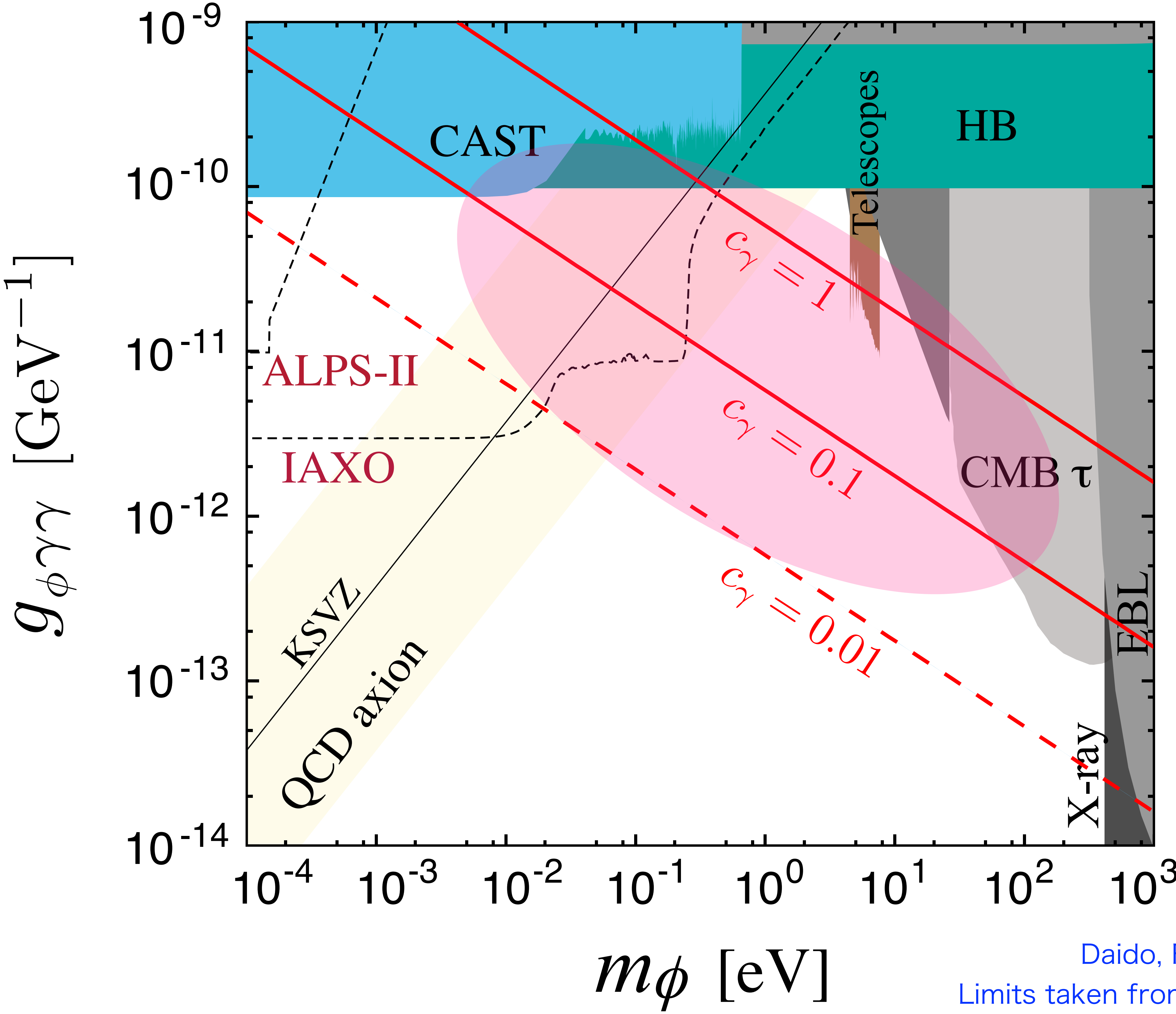
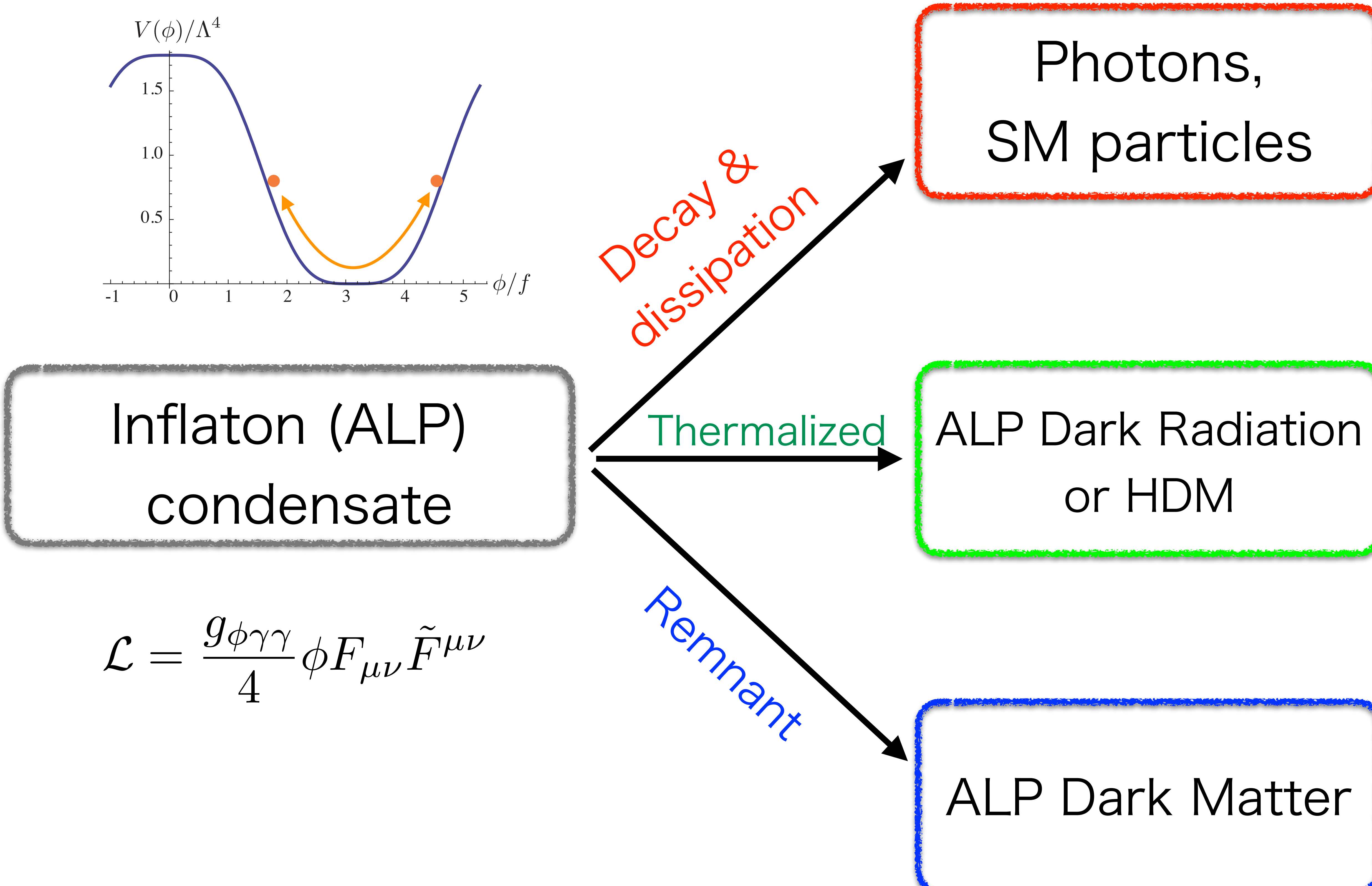



Successful inflation

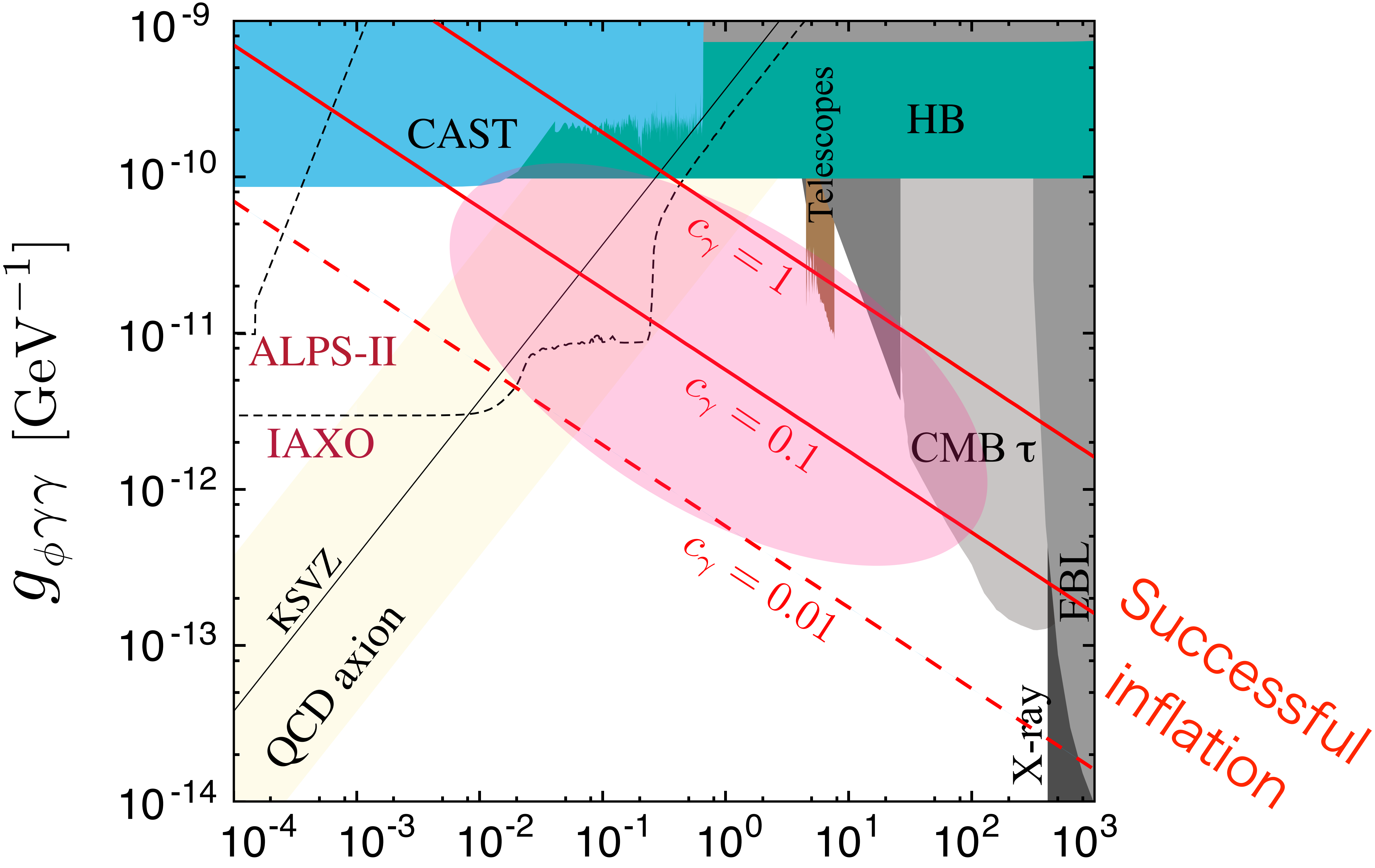
Daido, FT, and Yin 1702.03284

Limits taken from Essig et al 1311.0029

# Reheating and ALP DM

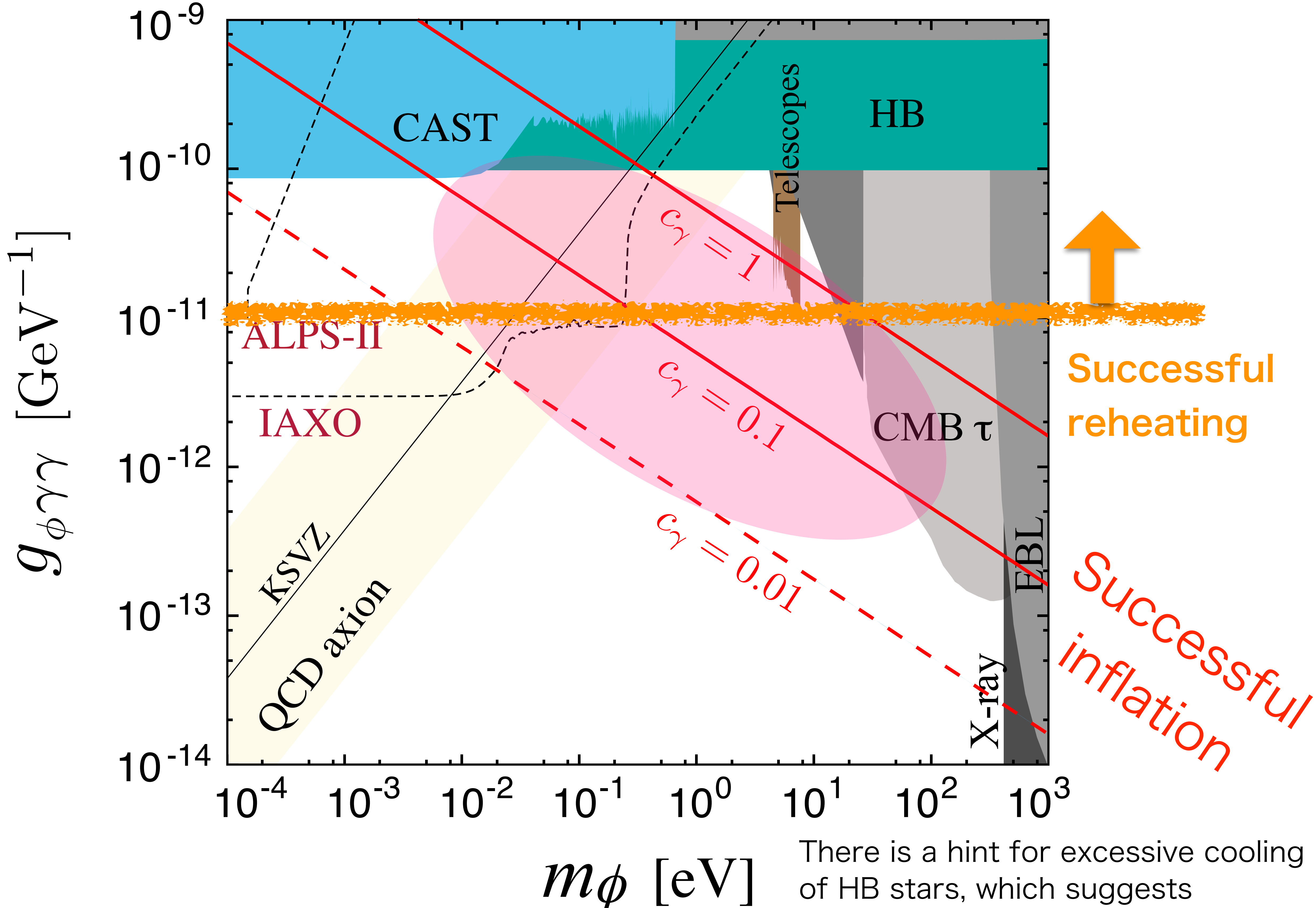



$$\mathcal{L} = \frac{g_{\phi\gamma\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$




There is a hint for excessive cooling of HB stars, which suggests

$$g_{\phi\gamma\gamma} = (0.29 \pm 0.18) \times 10^{-10}\,\mathrm{GeV}^{-1}$$

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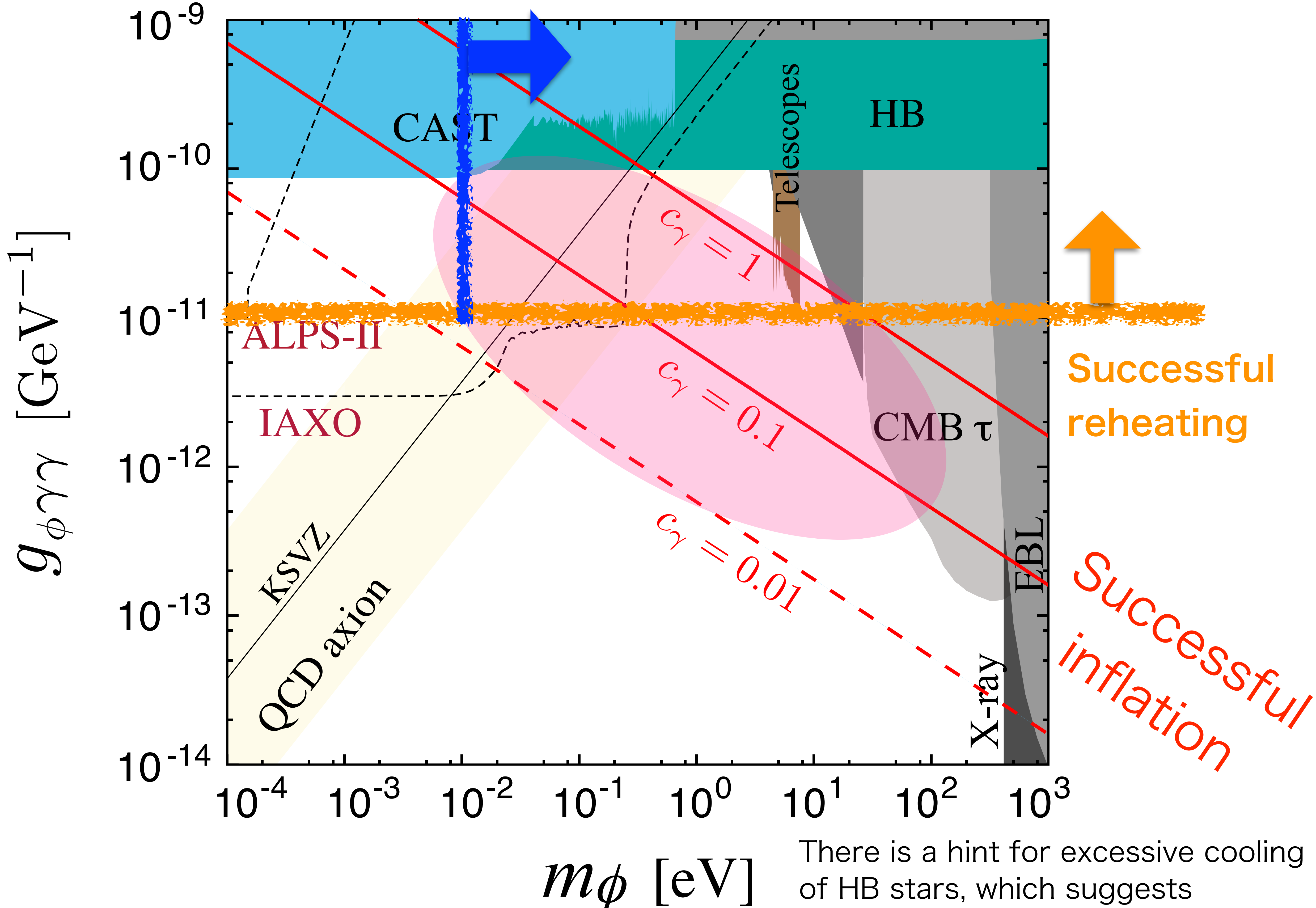
Small-scale structure constraint on ALP CDM

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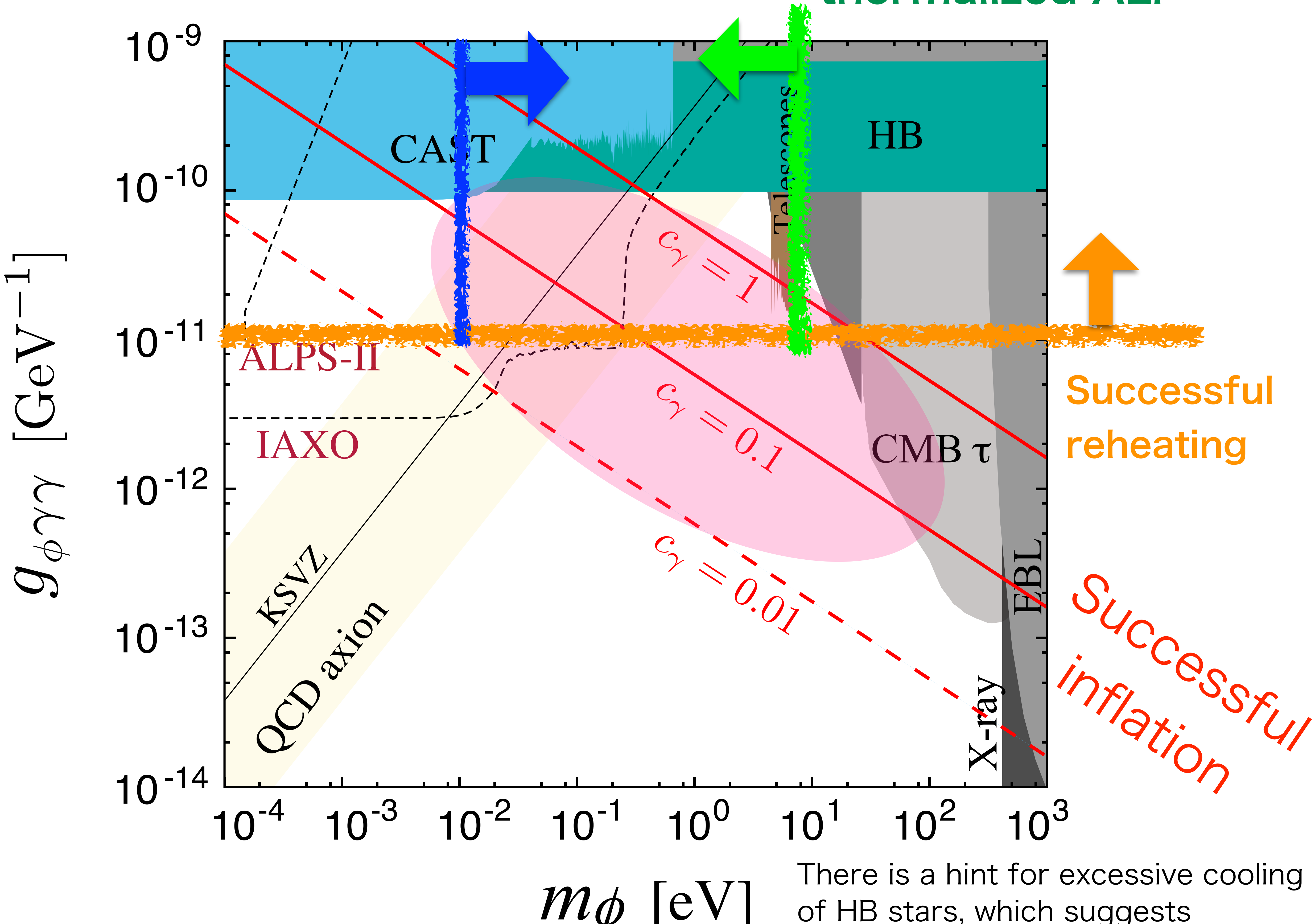
**Small-scale structure constraint on ALP CDM**

**HDM constraint on thermalized ALP**

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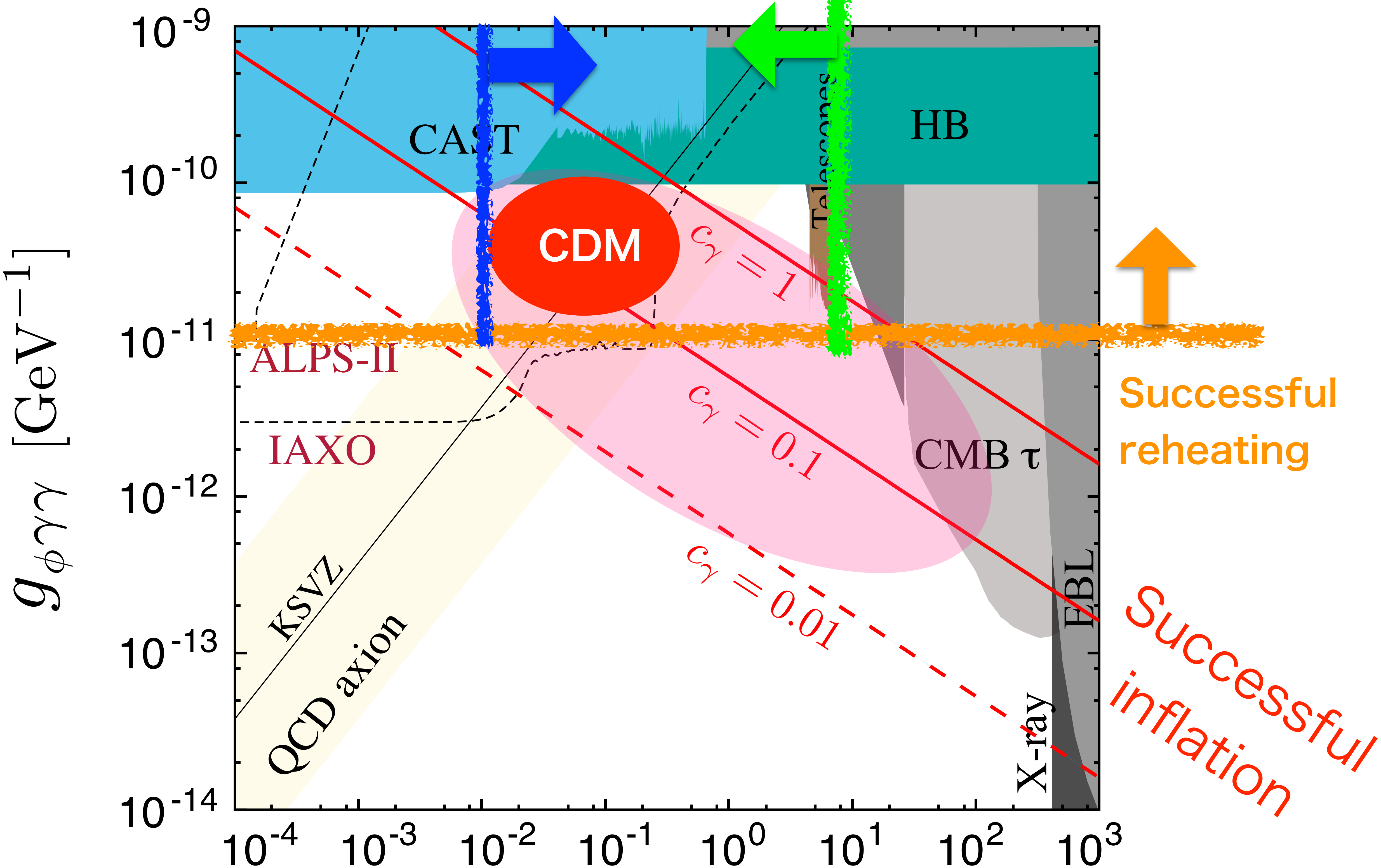


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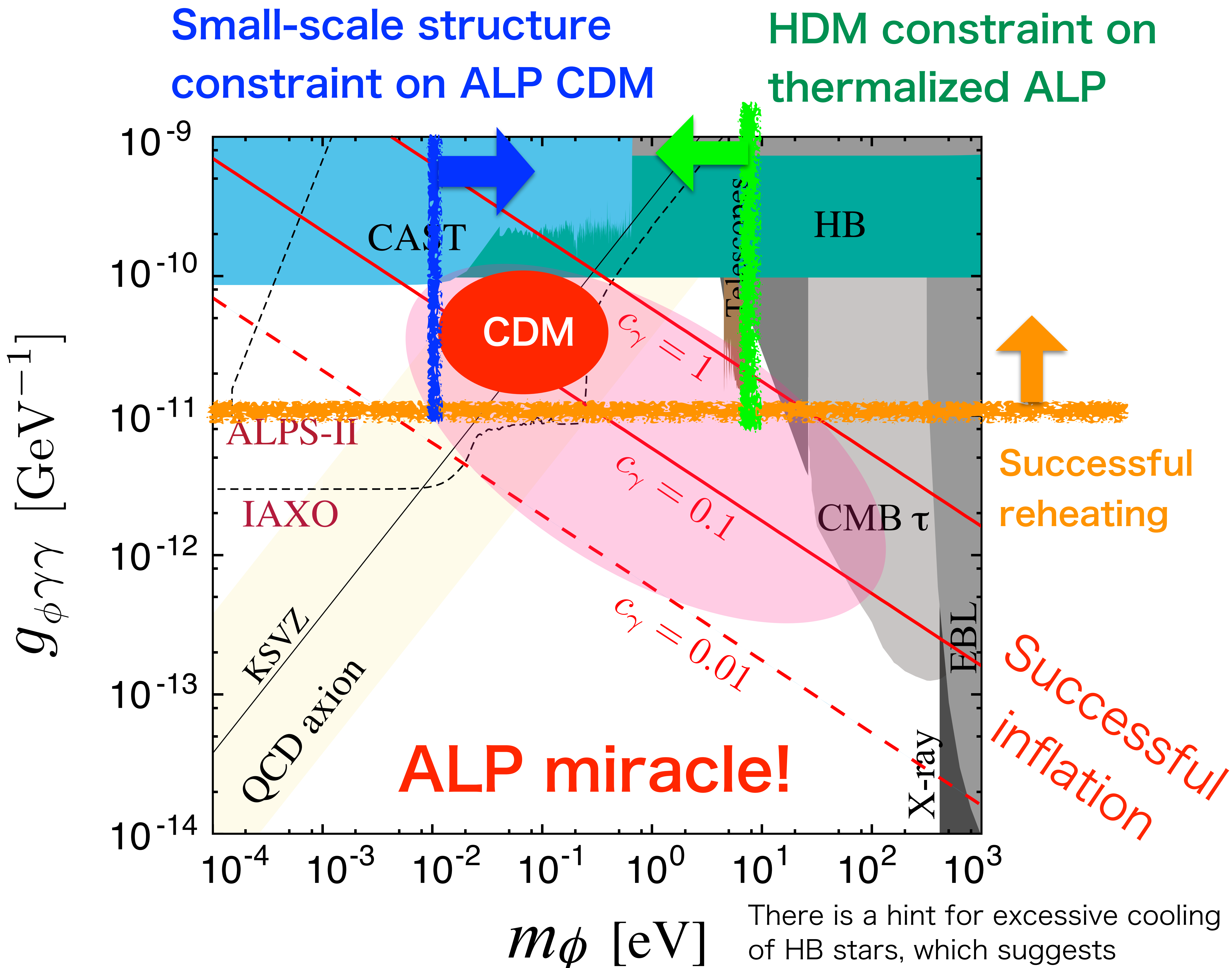


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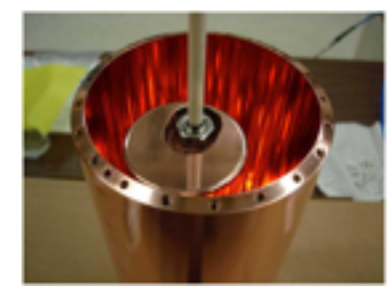
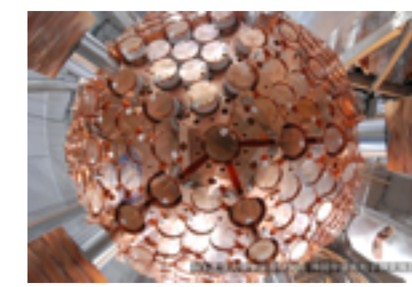
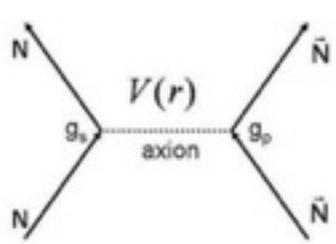
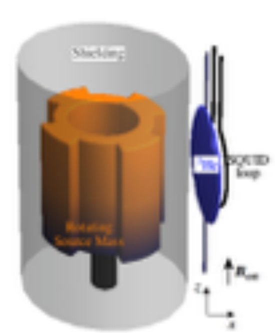
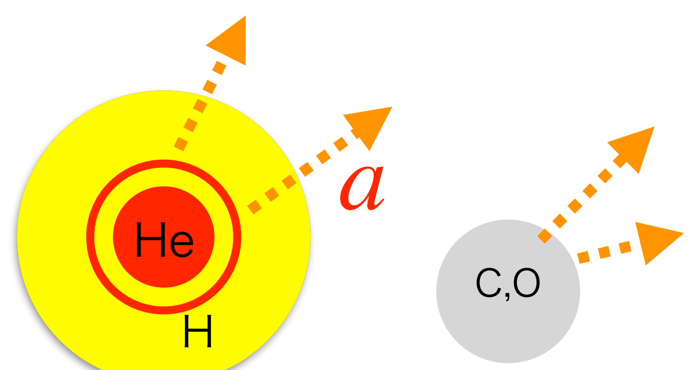
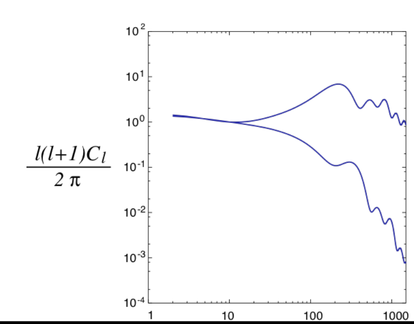
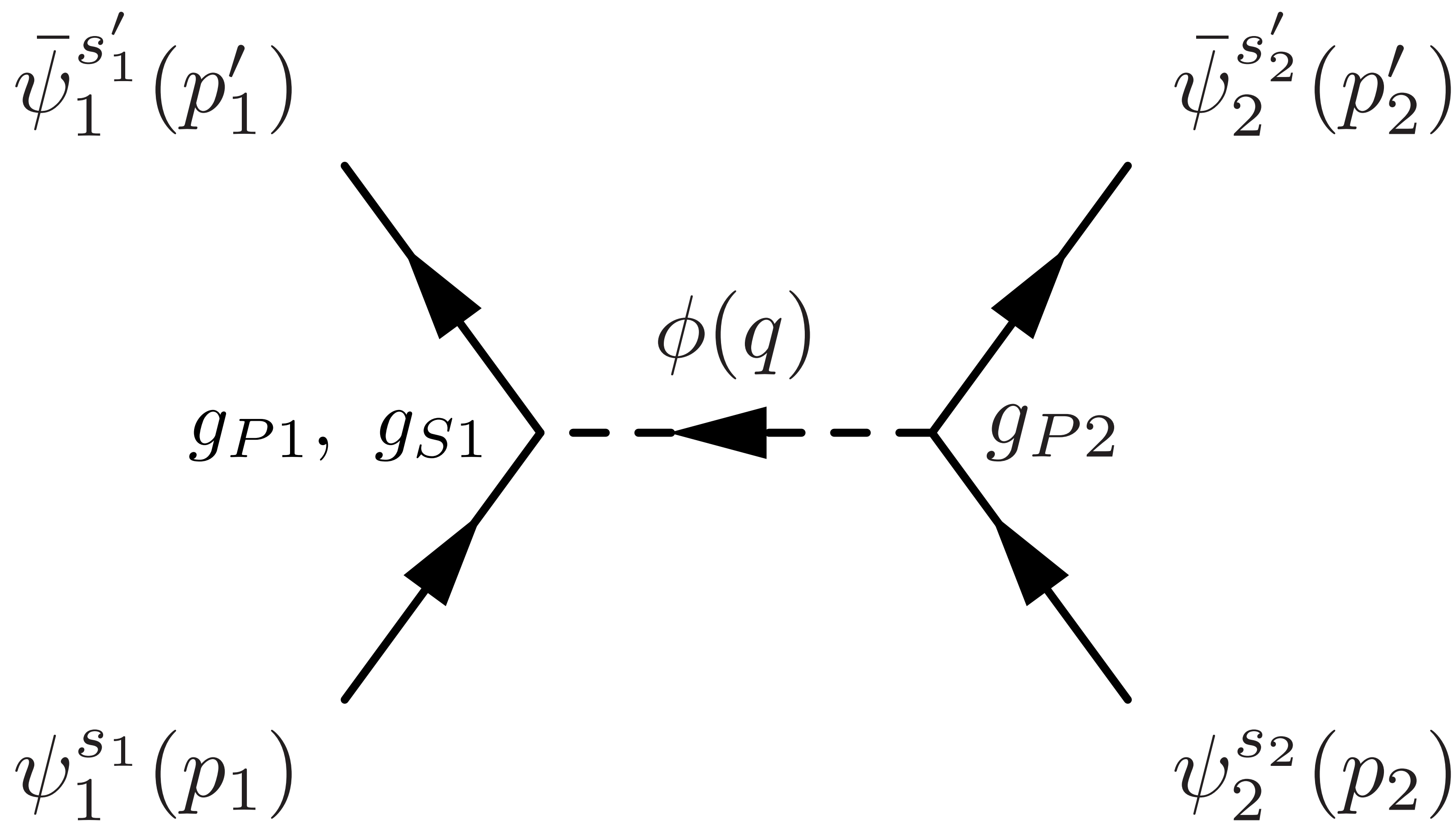
|---|---|---|---|---|
| | | **Terrestrial** | **Celestial** | **Cosmological** |
| **Detection** | **Direct** | LSTW, Photon pol. ALPS, PVLAS, SAPPHIRES  | Solar axion CAST, IAXO, TASTE   | Axion DM ADMX, CAPP,ORPHEUS MADMAX, LC-circuits, CASPEr, LUX,XMASS, EDELWISE,XENON100   |
| | **Indirect** | Fifth force ARIADNE    | Excessive cooling of WD, RGB, HB, and NS   | Isocurvature, DR, HDM, caustics, Spectral irreg. transparency Fermi, Chandra, IACT CMB, lensing, shear   |

# • Axion mediated force

Moody and Wilczek`84

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 + \sum_j \left(\bar{\psi}_j(i\gamma^\mu\partial_\mu - M_j)\psi_j - ig_{Pj}\phi\,\bar{\psi}_j\gamma_5\psi_j - g_{Sj}\phi\,\bar{\psi}_j\psi_j\right)$$



# • Axion mediated force

Moody and Wilczek`84

- Monopole-dipole potential

$$V(\vec{r}) = \frac{g_{S1} g_{P2}}{4\pi M_2} (\vec{\hat{S}}_2 \cdot \hat{r}) \left( \frac{m_\phi}{r} + \frac{1}{r^2} \right) e^{-m_\phi r},$$

- Dipole-dipole potential

$$V(\vec{r}) = \frac{g_{P1} g_{P2} \exp(-m_\phi r)}{4\pi M_1 M_2} \left[ (\vec{\hat{S}}_1 \cdot \vec{\hat{S}}_2) \left( \frac{m_\phi}{r^2} + \frac{1}{r^3} + \frac{4\pi}{3} \delta^3(r) \right) - (\vec{\hat{S}}_1 \cdot \hat{r})(\vec{\hat{S}}_2 \cdot \hat{r}) \left( \frac{m_\phi^2}{r} + \frac{3m_\phi}{r^2} + \frac{3}{r^3} \right) \right]$$

where $\hat{r} \equiv \vec{r}/r$ is the unit vector.

$$\rightarrow \quad \frac{g_{P1} g_{P2}}{4\pi M_1 M_2 r^3} \left[ \vec{\hat{S}}_1 \cdot \vec{\hat{S}}_2 - 3(\vec{\hat{S}}_1 \cdot \hat{r})(\vec{\hat{S}}_2 \cdot \hat{r}) \right], \qquad (m_\phi \rightarrow 0)$$

# Is the sign correct?

$$V(\vec{r}) \to \pm \frac{g_{P1} g_{P2}}{4\pi M_1 M_2 r^3} \left[ \vec{\hat{S}}_1 \cdot \vec{\hat{S}}_2 - 3(\vec{\hat{S}}_1 \cdot \hat{r})(\vec{\hat{S}}_2 \cdot \hat{r}) \right], \qquad (m_\phi \to 0)$$

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| + | - |
|---|---|
| (Theory)<br>• Moody and Wilczek, `84<br>• Arvanitaki and Geraci,`14<br>(Experiments)<br>• Vasilakis et al,0809.4700<br>• Ledbetter et al, 1203.6894<br>• Kotler et al, 1501.07891<br>• Terrano, Adelberger, Lee, Heckel, 1508.02463<br>• Ficek et al, 1608.05779<br>(Review)<br>• Adelberger et al, 2009<br>• Marsh,1510.07633<br>• Particle Data Group | (Theory)<br>• Dobrescu and Mocioiu, hep-ph/0605342 |

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| + | - |
|---|---|
| (Theory)<br>• Moody and Wilczek, `84<br>• Arvanitaki and Geraci,`14<br>(Experiments)<br>• Vasilakis et al,0809.4700<br>• Ledbetter et al, 1203.6894<br>• Kotler et al, 1501.07891<br>• Terrano, Adelberger, Lee, Heckel, 1508.02463<br>• Ficek et al, 1608.05779<br>(Review)<br>• Adelberger et al, 2009<br>• Marsh,1510.07633<br>• Particle Data Group | (Theory)<br>• Dobrescu and Mocioiu, hep-ph/0605342<br>• Daido and FT, 1704.00155<br>• Kahlhoefer et al, 1704.02149 |

# Is the sign correct?

$$V(\vec{r}) \to - \frac{g_{P1} g_{P2}}{4\pi M_1 M_2 r^3} \left[ \hat{\vec{S}}_1 \cdot \hat{\vec{S}}_2 - 3(\hat{\vec{S}}_1 \cdot \hat{r})(\hat{\vec{S}}_2 \cdot \hat{r}) \right], \qquad (m_\phi \to 0)$$

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Axion exchange: -

Photon exchange: +

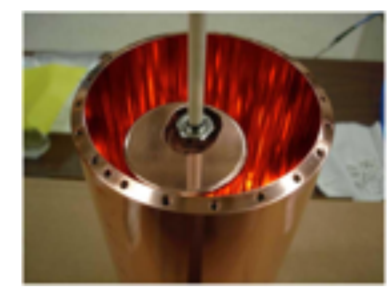
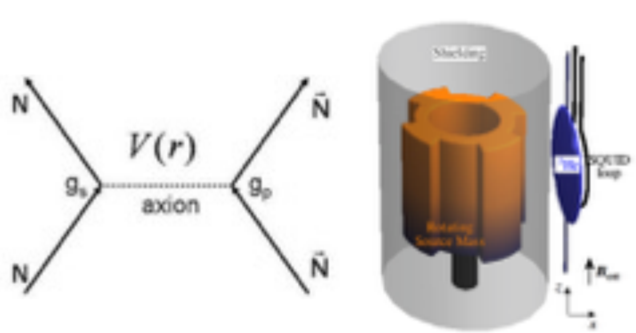
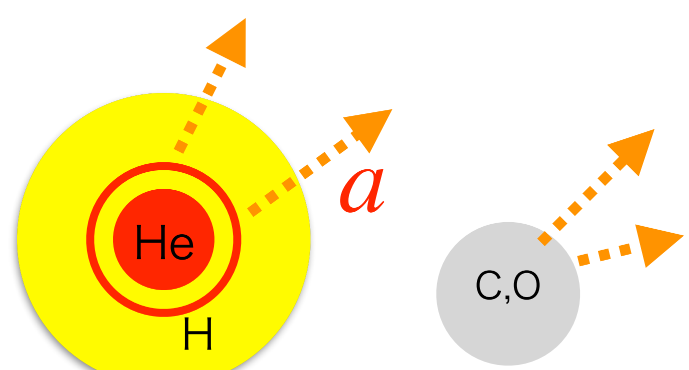
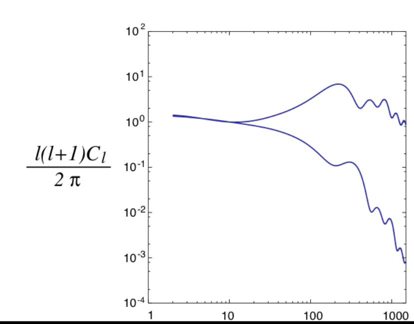
Graviton exchange: -

The sign of the dipole-dipole potential changes depending on spin of the mediating particle.

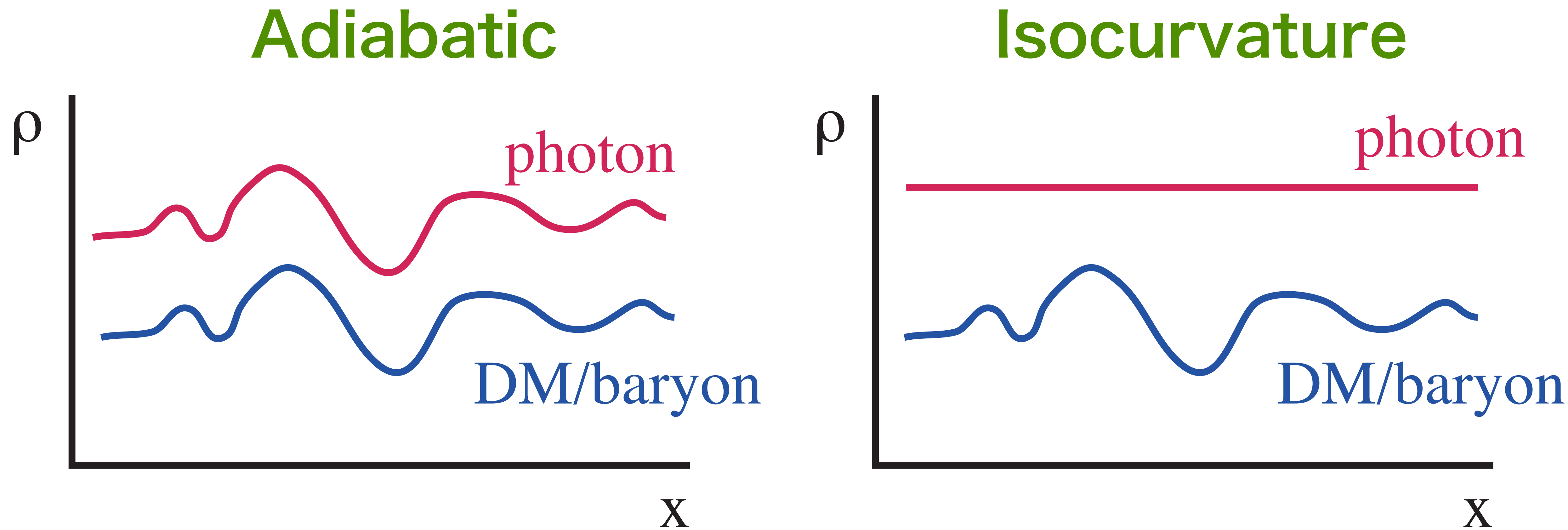
- Axion exchange

- Photon exchange

- Graviton exchange


| | | Production | | |
|---|---|---|---|---|
| | | **Terrestrial** | **Celestial** | **Cosmological** |
| **Detection** | **Direct** | LSTW, Photon pol.<br>ALPS, PVLAS, SAPPHIRES<br> | Solar axion<br>CAST, IAXO, TASTE<br> | Axion DM<br>ADMX, CAPP,ORPHEUS MADMAX, LC-circuits, CASPEr, LUX,XMASS, EDELWISE,XENON100<br> |
| | **Indirect** | Fifth force<br>ARIADNE<br> | Excessive cooling of WD, RGB, HB, and NS<br> | Isocurvature, DR, HDM, caustics, Spectral irreg. transparency<br>Fermi, Chandra, IACT<br>CMB, lensing, shear<br> |

# Axion isocurvature

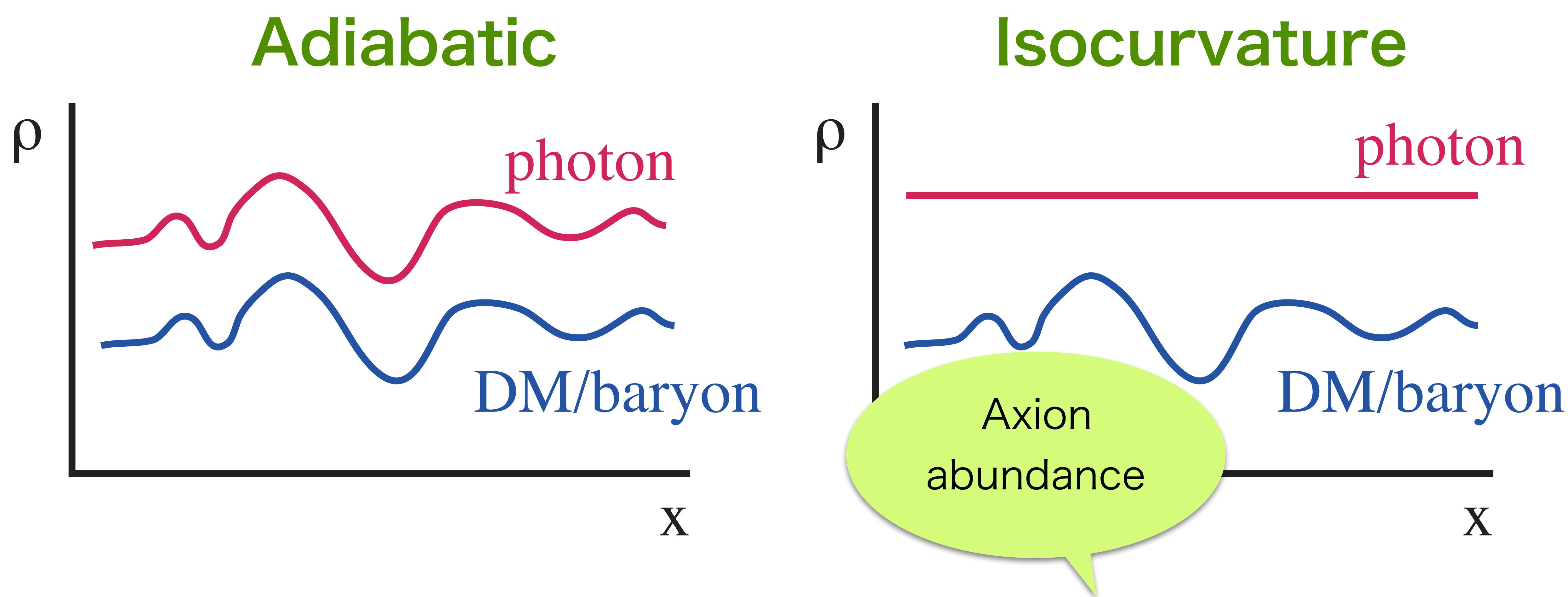



$$S = \frac{\Omega_a}{\Omega_{\rm CDM}} \frac{\delta\Omega_a}{\Omega_a} = \frac{\Omega_a}{\Omega_{\rm CDM}} \frac{2\delta\theta_i}{\theta_i} = \frac{\Omega_a}{\Omega_{\rm CDM}} \frac{H_{\rm inf}}{\pi\theta_i f_a}$$

$$\beta_{\rm iso} = \frac{\mathcal{P}_S}{\mathcal{P}_{\mathcal{R}} + \mathcal{P}_S} < 0.038 \quad (95\%\,{\rm CL})$$

Planck 2015
(Planck TT, TE, EE + lowP)

# Axion isocurvature

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Planck 2015
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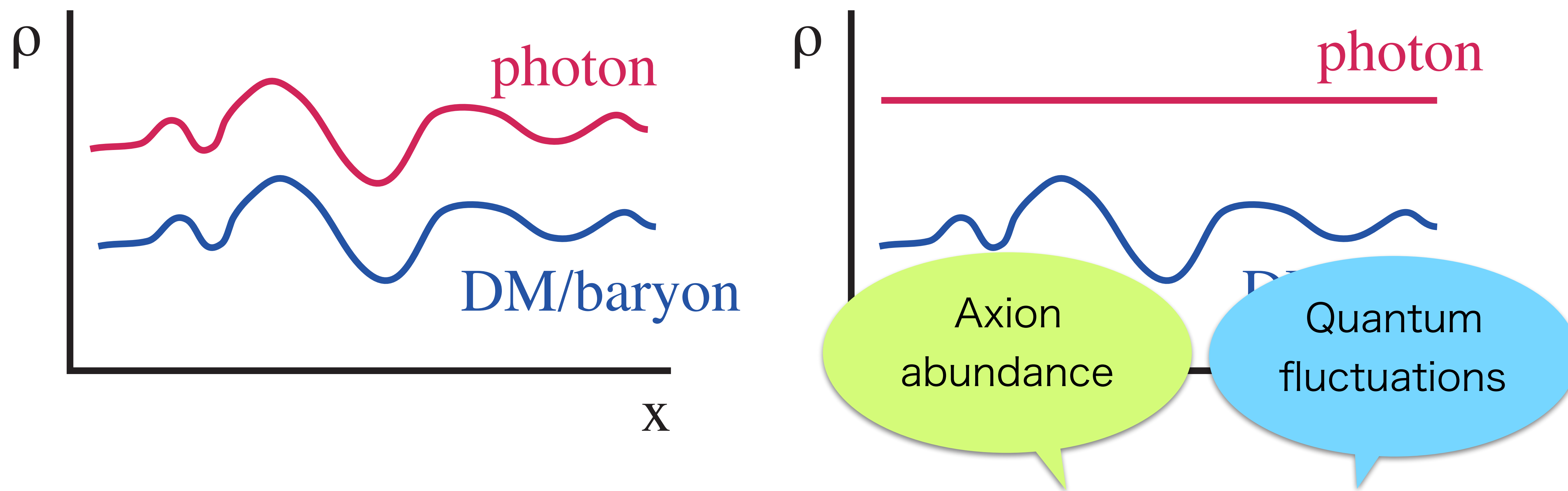
# Axion isocurvature

Adiabatic | Isocurvature

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Planck 2015
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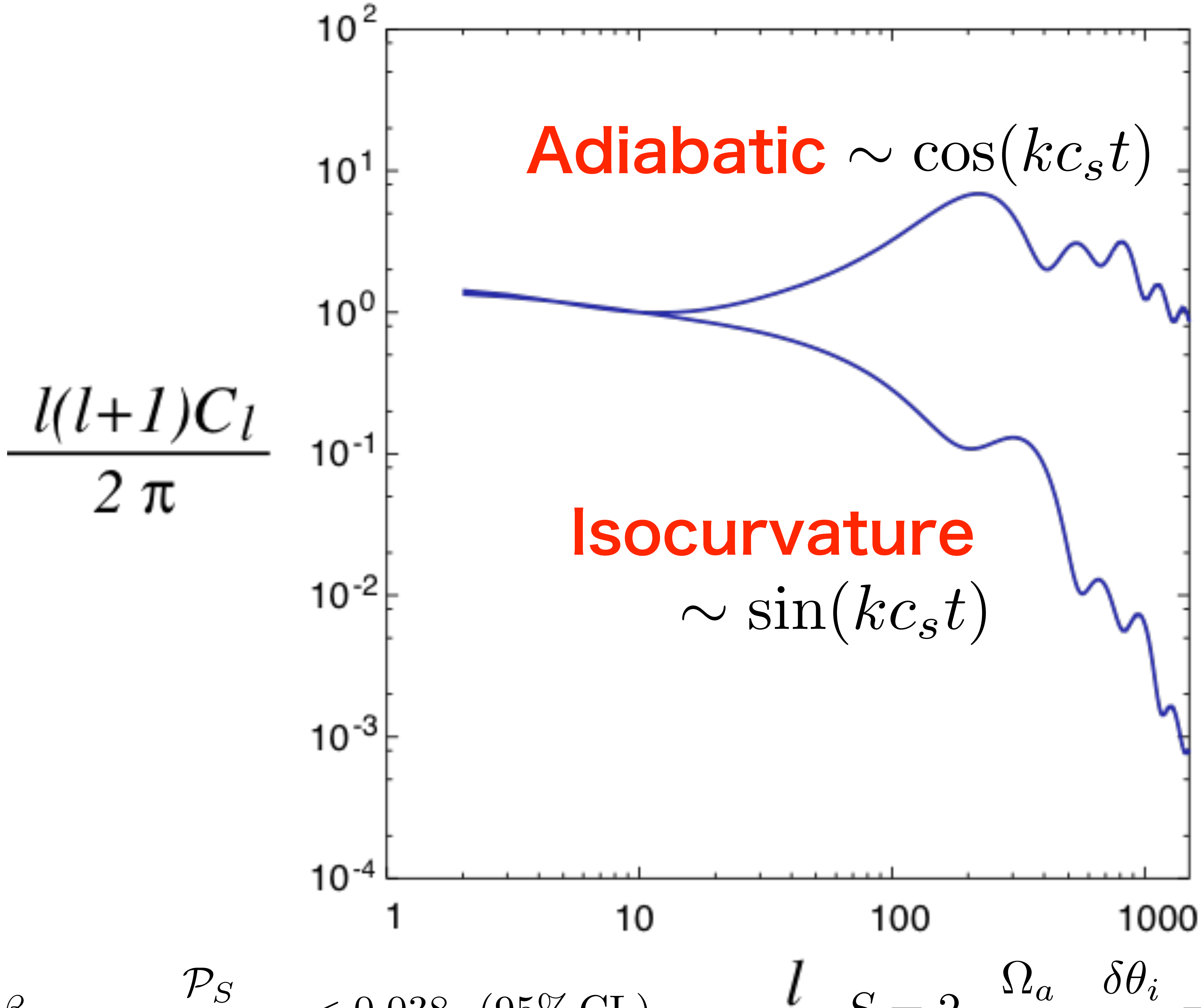
# CMB angular power spectrum

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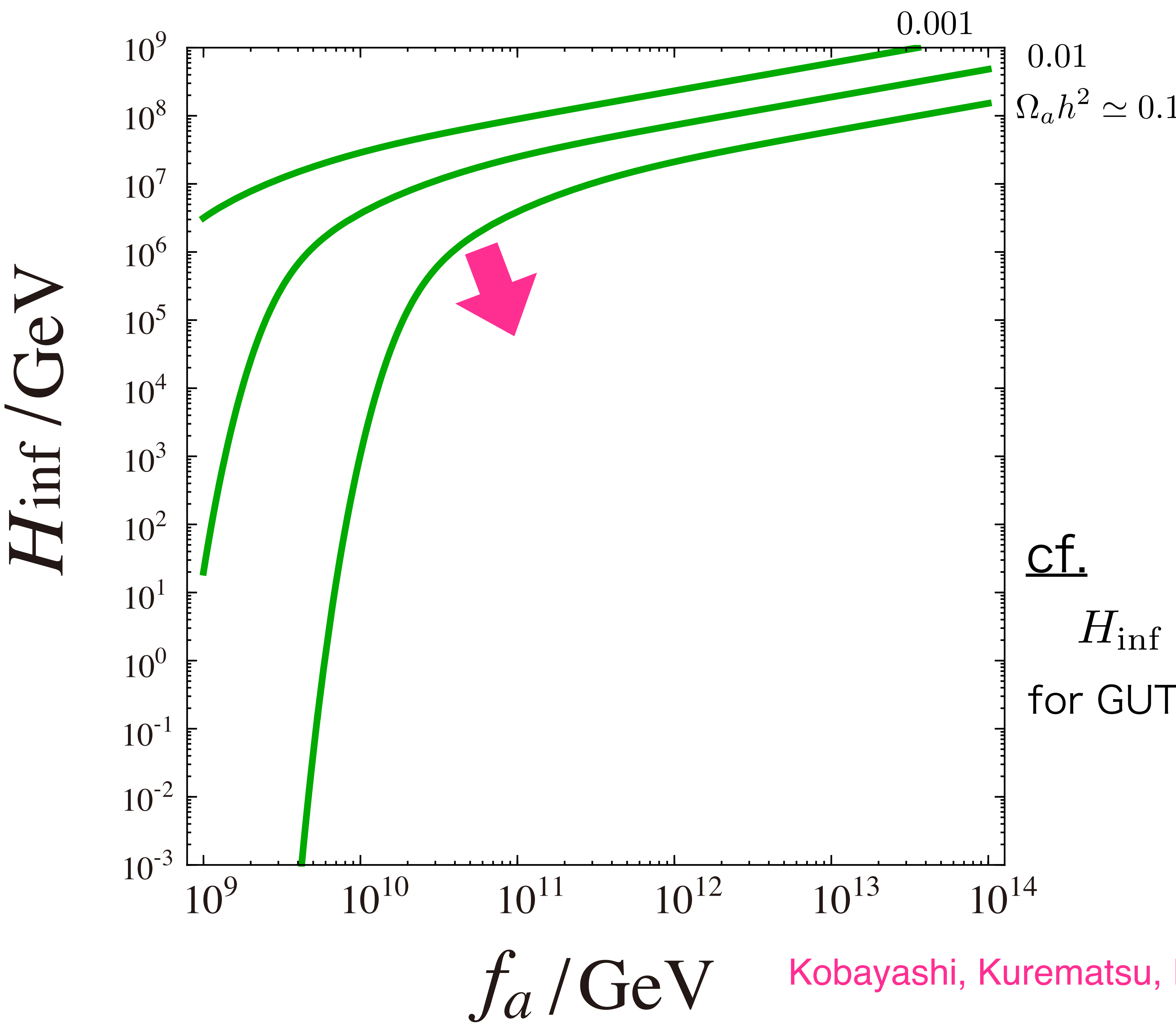
$$S = 2\frac{\Omega_a}{\Omega_{\rm CDM}}\frac{\delta\theta_i}{\theta_i} = \frac{\Omega_a}{\Omega_{\rm CDM}}\frac{H_{\rm inf}}{\pi\theta_i f_a}$$

# Isocurvature constraint on $H_{inf}$




<u>cf.</u>

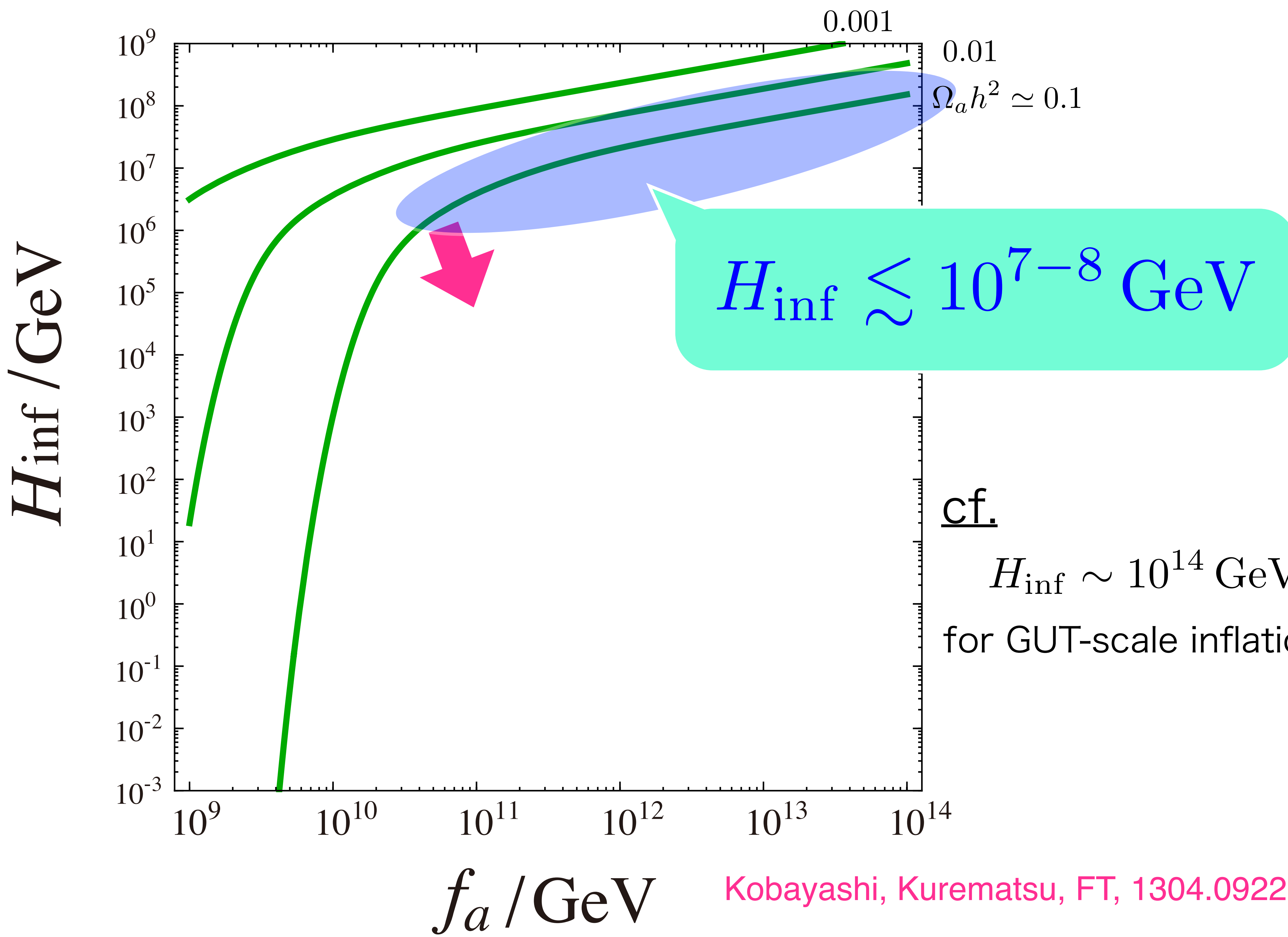
$$H_{\rm inf} \sim 10^{14}\ \mathrm{GeV}$$

for GUT-scale inflation.

Kobayashi, Kurematsu, FT, 1304.0922

**Axion DM is in conflict with high-scale inflation**

# Isocurvature constraint on $H_{inf}$

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**Axion DM is in conflict with high-scale inflation**

# Solutions to axion isocurvature

The simplest solution is to restore $U(1)_{PQ}$ symmetry.

Linde and Lyth `90 Lyth and Stewart `92

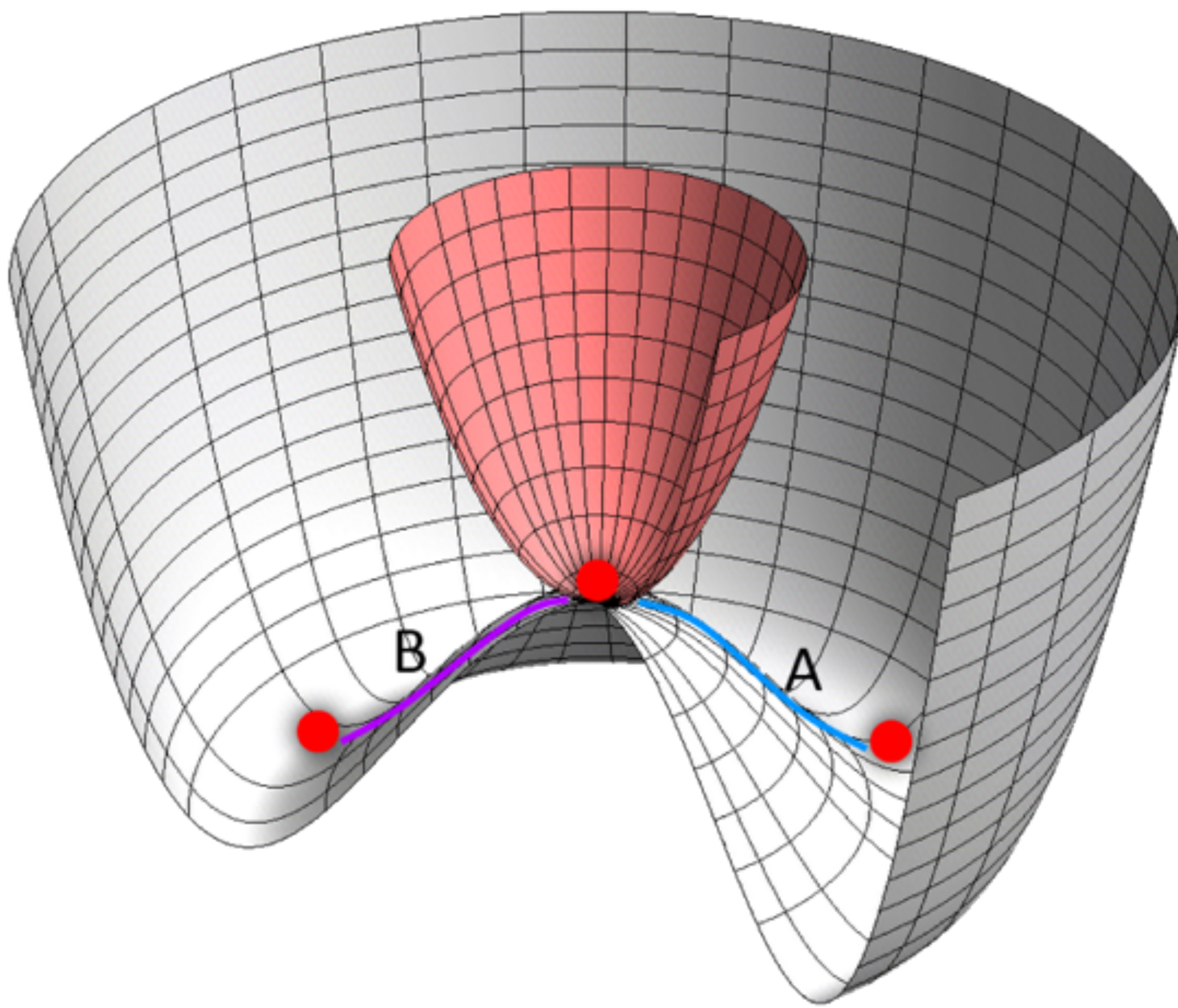


Figure taken from
M. Kawasaki's slide

**No axion during inflation!**

# Solutions to axion isocurvature

The simplest solution is to restore $U(1)_{PQ}$ symmetry.

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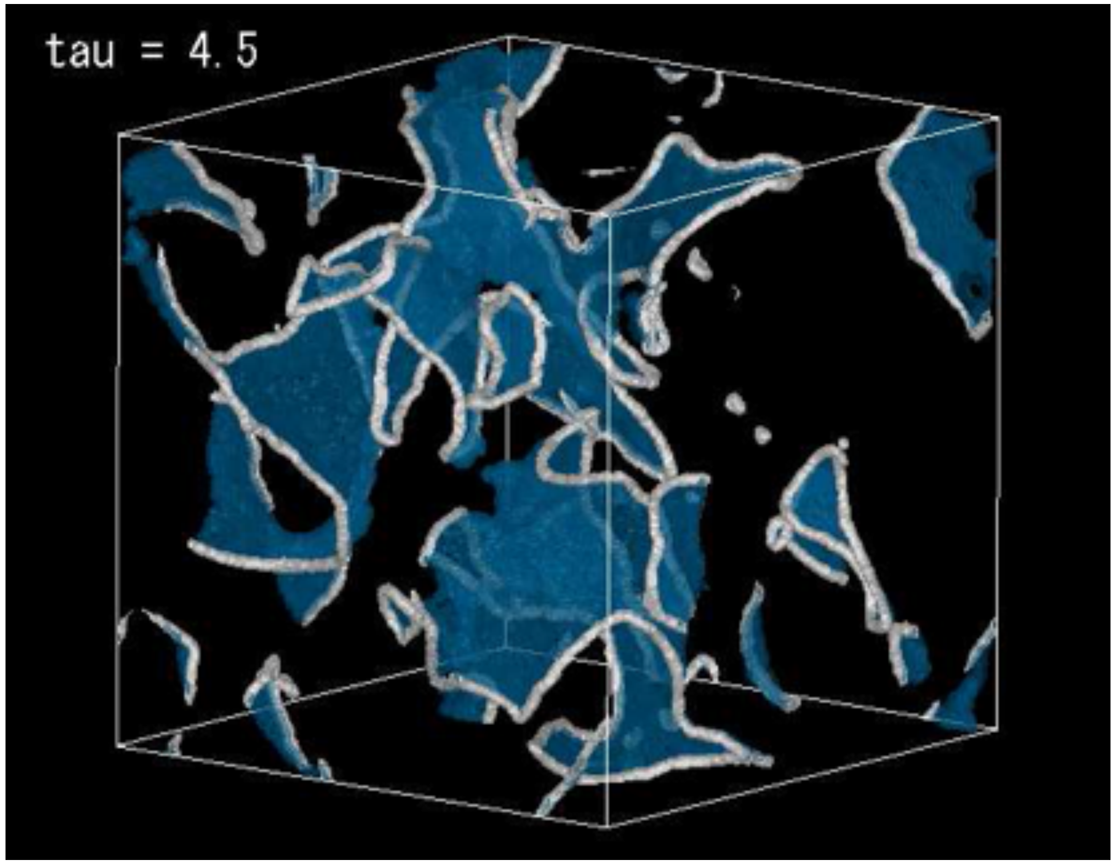
Axions are copiously produced by the topological defects, and only $f_a = O(10^{10})$ GeV is allowed.




Hiramatsu, Kawasaki, Saikawa and Sekiguchi, 1202.5851,1207.3166

# Solutions to axion isocurvature

Or explicitly break the PQ symmetry and make axion sufficiently heavy : $m_a^2 \gtrsim H_{\rm inf}^2$

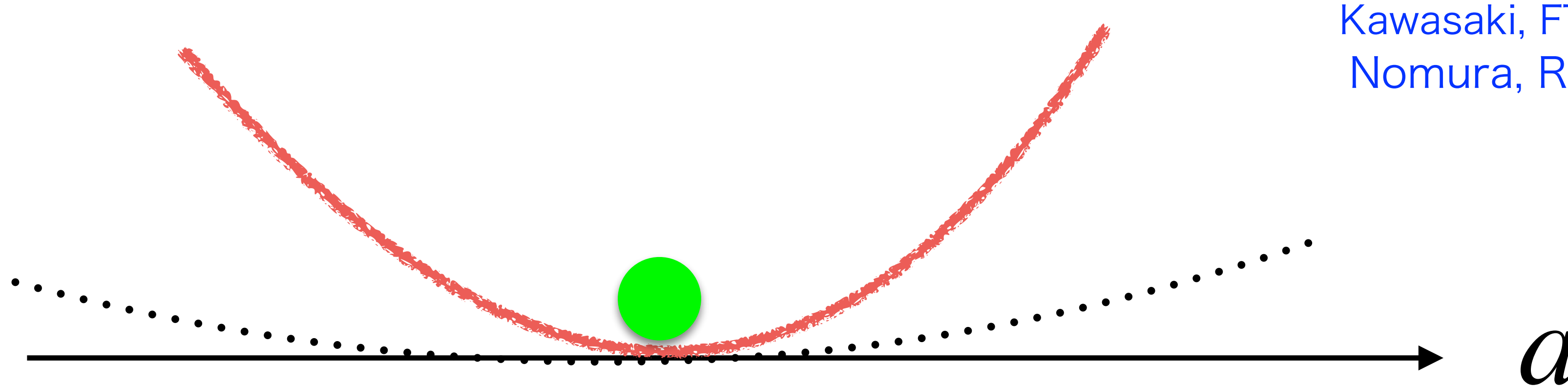
- Stronger QCD during inflation

cf. Dvali, `95, Jeong, FT 1304.8131
Choi et al, 1505.00306

- Extra explicit PQ breaking

e.g. the Witten effect of hidden monopoles

Dine, Anisimov hep-ph/0405256
Higaki, Jeong, FT, 1403.4186,
Barr and J.E.Kim, 1407.4311
FT and Yamada 1507.06387
Kawasaki, FT, Yamada, 1511.05030
Nomura, Rajendran, Sanches, 1511.06347




N.B. The explicit breaking should be sufficiently suppressed in the present Universe.

# Summary

- **Axion is a plausible candidate for BSM.**
  - The QCD axion or axion-like particle may constitute dark matter.
  - The ALP can even unify the inflaton and DM:

$$m_\phi = \mathcal{O}(0.01 - 0.1)\,\mathrm{eV} \quad g_{\phi\gamma\gamma} = \mathcal{O}(10^{-11})\,\mathrm{GeV}^{-1}$$

    within the reach of IAXO, TASTE, and laser exp.

  - The axion DM, if found, will have implications for the early Universe: e.g. high-scale inflation.
- There are many on-going and planned axion search experiments.