Axions

14 Sep. 2016

@Invisibles16 Workshop

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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 θ is so small is the strong CP problem.

cf. More precisely, the physical strong CP phase is

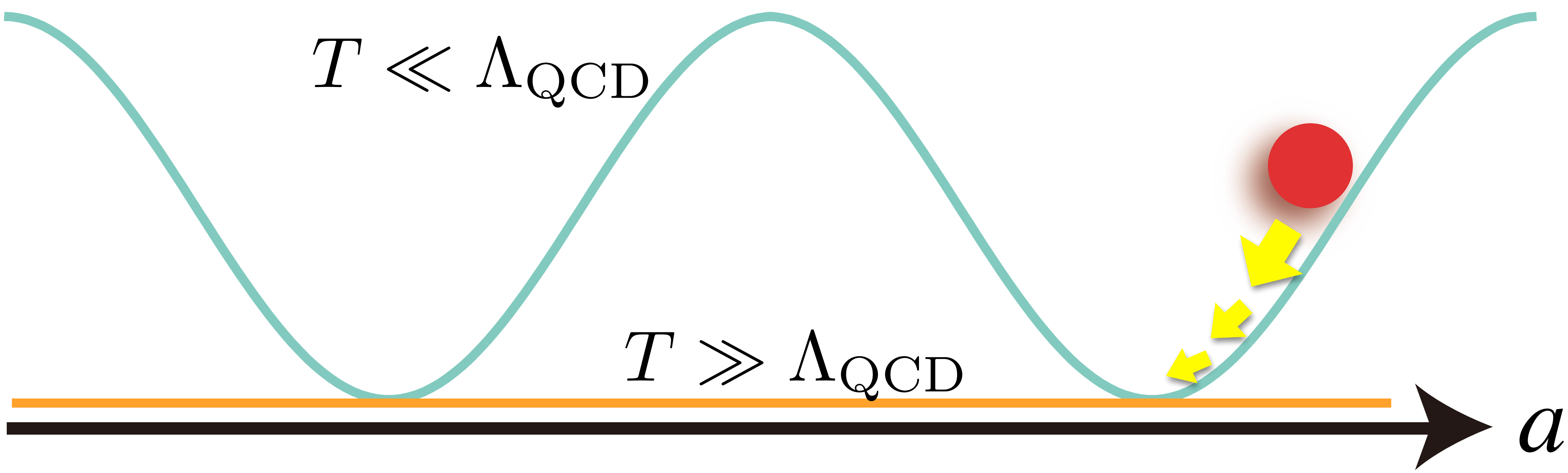
$$\bar{\theta} \equiv \theta - \arg\det\left(M_u M_d\right)$$

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

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



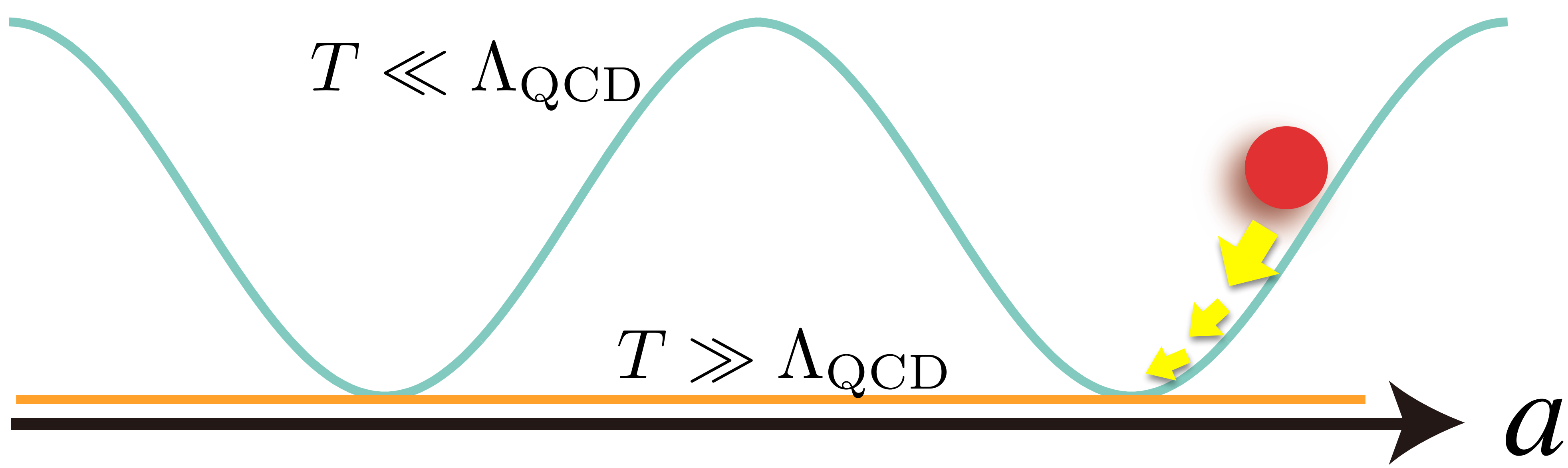
$$m_a \simeq 6 \times 10^{-6}\,{\rm eV} \left(\frac{f_a}{10^{12}\,{\rm GeV}}\right)^{-1}$$

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

Accordingly, the axion DM is produced as coherent oscillations [misalignment mechanism].

$$\Omega_a h^2 = 0.18\,\theta_i^2 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{1.19} \left(\frac{\Lambda_{\rm QCD}}{400\ \mathrm{MeV}}\right)$$ CDM

+ thermal production for small f_a HDM
+ non-thermal production from saxion decay DR



Axion as Nambu-Goldstone boson

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

Consider a simple case with a single PQ scalar.

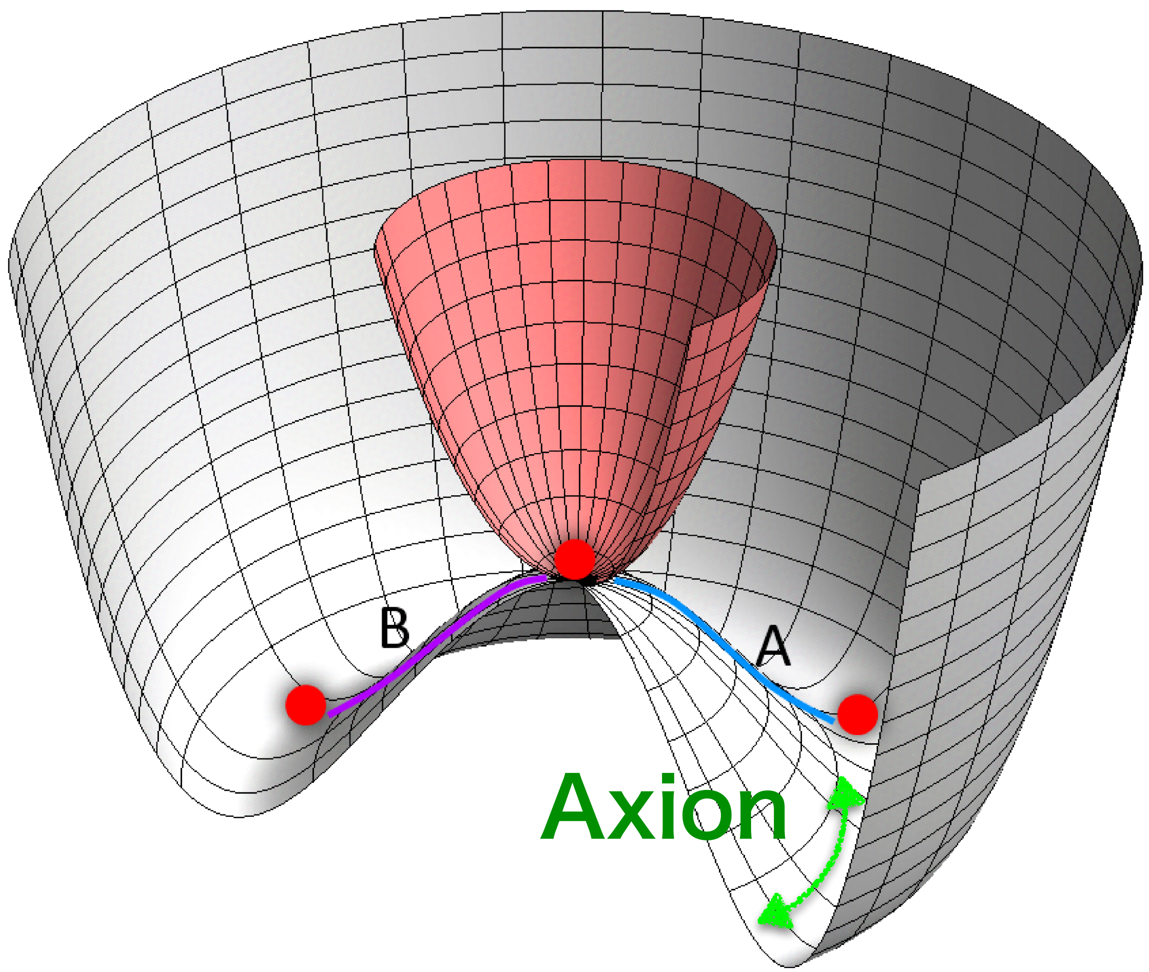
A global $U(1)_{PQ}$ symmetry:

$$\mathrm{U}(1)_{\mathrm{PQ}}: \;\; \Phi \to e^{i\alpha}\Phi$$

broken spontaneously by $\langle \Phi \rangle$.

$$\Phi = \frac{F_a + s}{\sqrt{2}} e^{ia/F_a}$$

s : saxion a : axion



Taken from M. Kawasaki's slide

The $U(1)_{PQ}$ symmetry is explicitly broken dominantly by its color anomaly.

$$\mathcal{L} = \Phi \bar{Q} Q \;\; \to \;\; \frac{\alpha_s}{8\pi}\frac{a}{F_a} G\tilde{G}$$

N.B. The PQ symmetry breaking scale can be different from F_a in general.

cf. Sikivie `86, Kim, Nilles Peloso `05, Higaki, Jeong, Kitajima, FT, 1512.05295,1603.02090

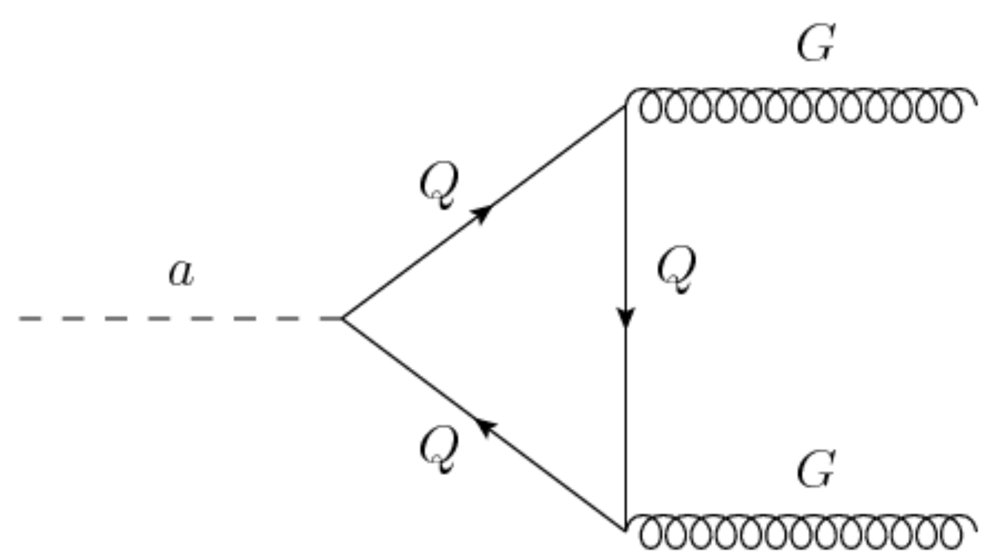
Axion interactions

- <u>Gluons</u>

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

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

$N_{\rm DW}$: domain wall number



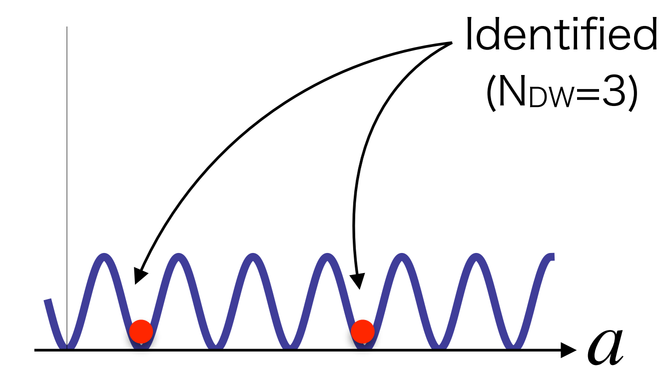


Figure taken from 1210.3196

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.

<u>N.B.</u> 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

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

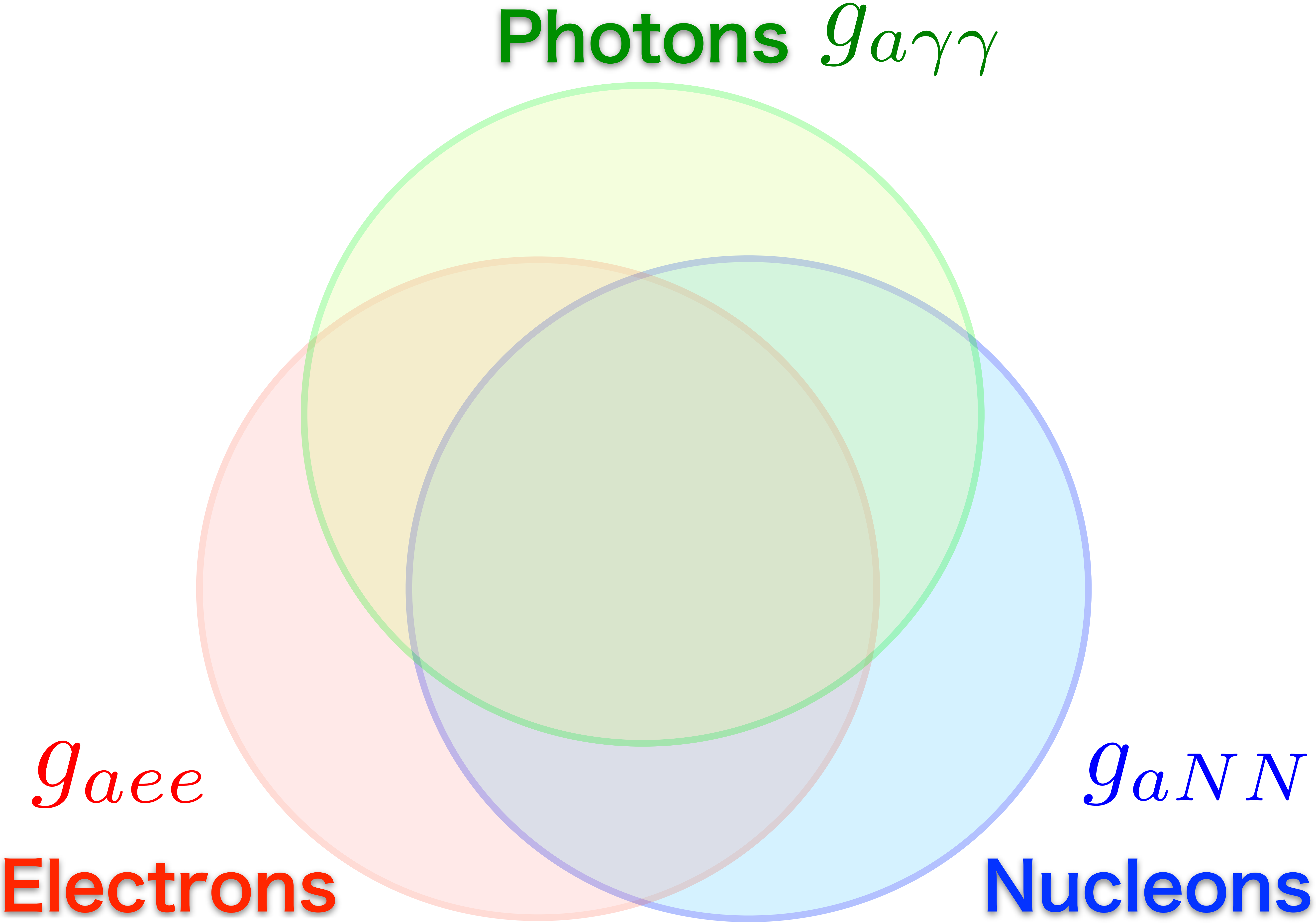
$$g_{aee} \equiv \frac{C_e m_e}{f_a}$$

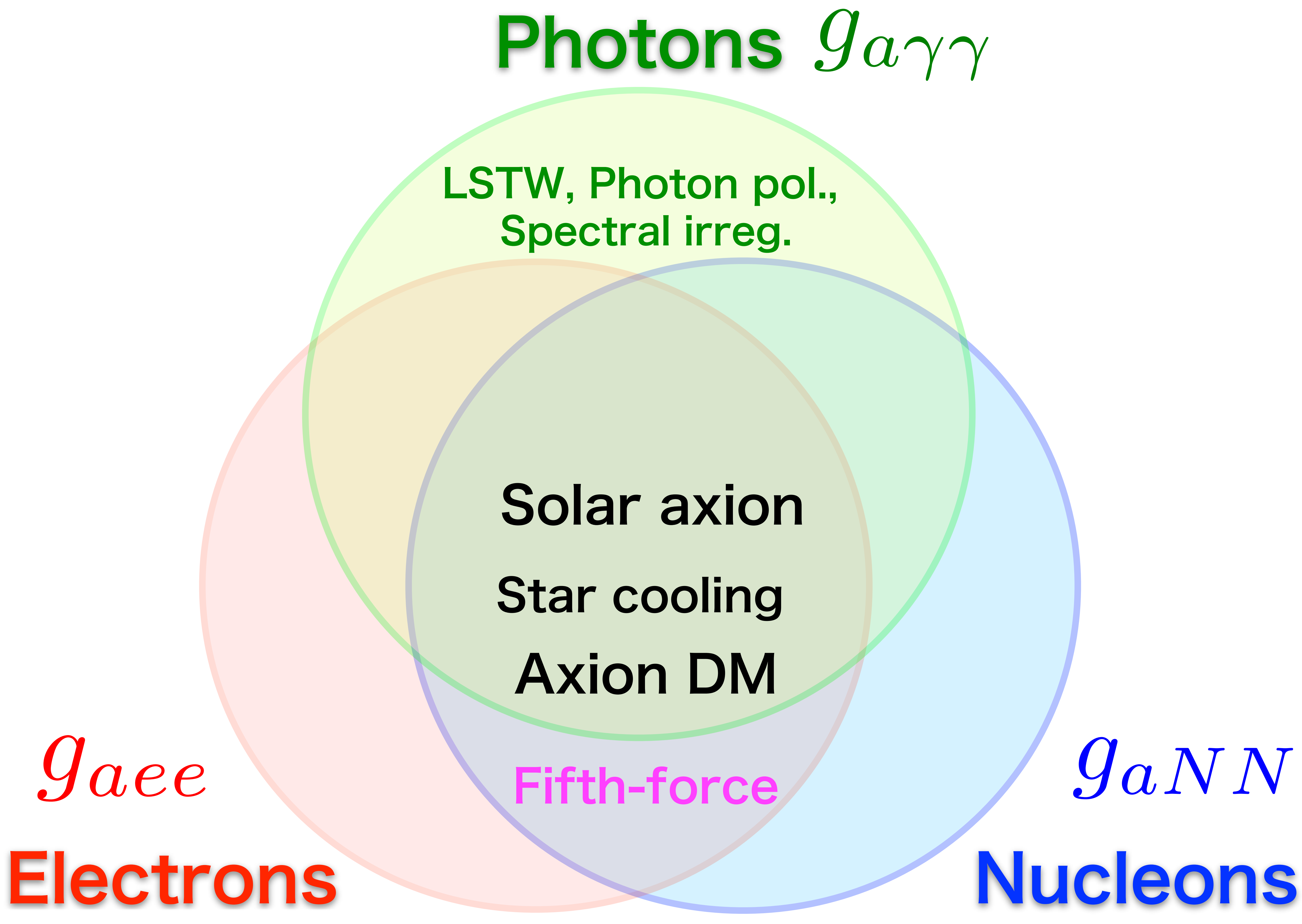
$C_e = \frac{\cos^2\beta}{3}$ for DFSZ axion.

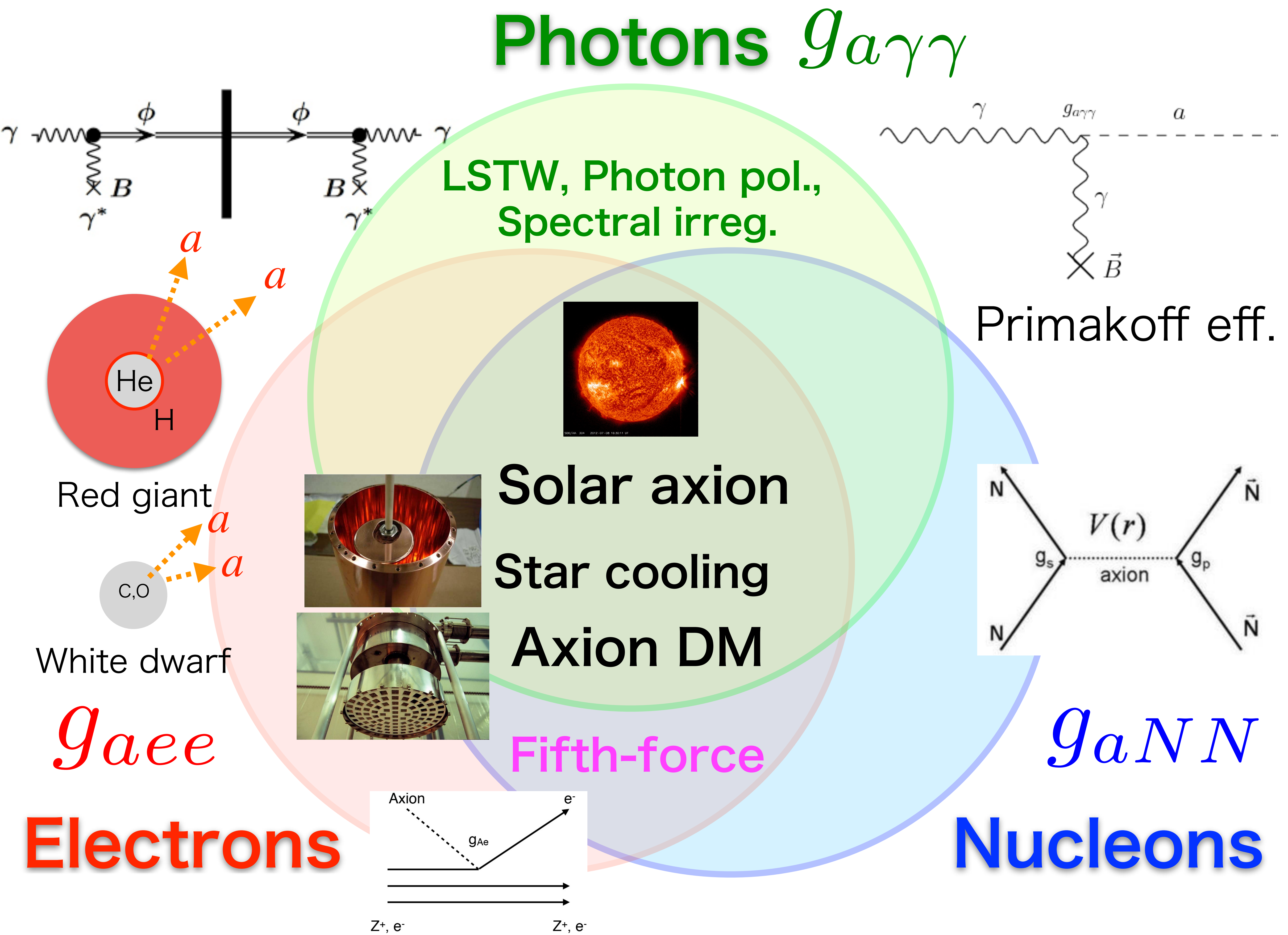
Model-dependent. Coupling to electrons appear only at loop-level in the hadronic axion.

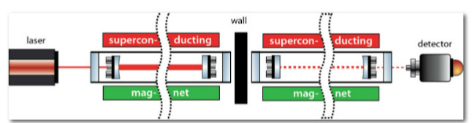
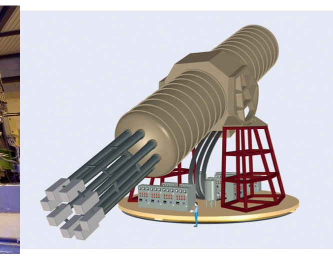
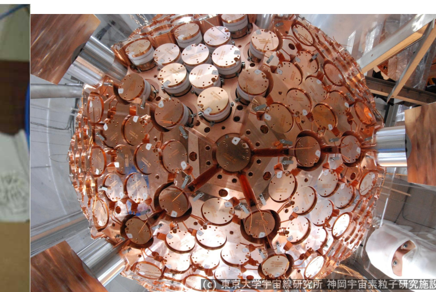
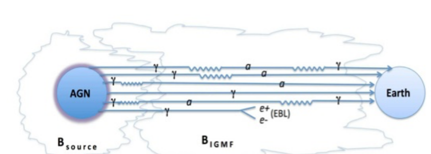
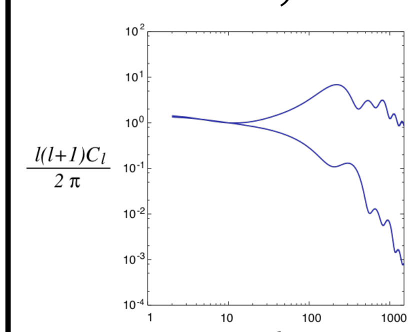
- Nucleons

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


Photons $g_{a\gamma\gamma}$
g_{aee}
Electrons
g_{aNN}
Nucleons


Photons $g_{a\gamma\gamma}$
LSTW, Photon pol.,
Spectral irreg.
Solar axion
Star cooling
Axion DM
g_{aee}
Electrons
Fifth-force
g_{aNN}
Nucleons


Photons $g_{a\gamma\gamma}$
γ ϕ B γ^* ϕ B γ^* γ
LSTW, Photon pol.,
Spectral irreg.
γ $g_{a\gamma\gamma}$ a γ $\vec{B}$
Primakoff eff.
a a
He
H
Red giant
a a
C,O
White dwarf
Solar axion
Star cooling
Axion DM
Fifth-force
N N $V(r)$ g_s axion g_p Ñ Ñ
g_{aee}
g_{aNN}
Electrons
Axion e- g_{Ae} Z+, e- Z+, e-
Nucleons

		Production		
		Terrestrial	**Celestial**	**Cosmological**
Detection	**Direct**	LSTW, Photon pol. Fifth force ALPS,OSQAR, PVLAS, ARIADNE 	Solar axion CAST, IAXO 	Axion DM ADMX, CAPP,ORPHEUS LC-circuits, CASPEr, XMASS, EDELWISE,XENON100. 
	Indirect		Excessive cooling of WD, RGB, HB, NS Spectral irreg. Transparency Fermi, IACT. 	Isocurvature, DR, spectral distortion, caustics, GW, etc. Planck, COrE+, PIXIE 

Constraints on axion-photon coupling

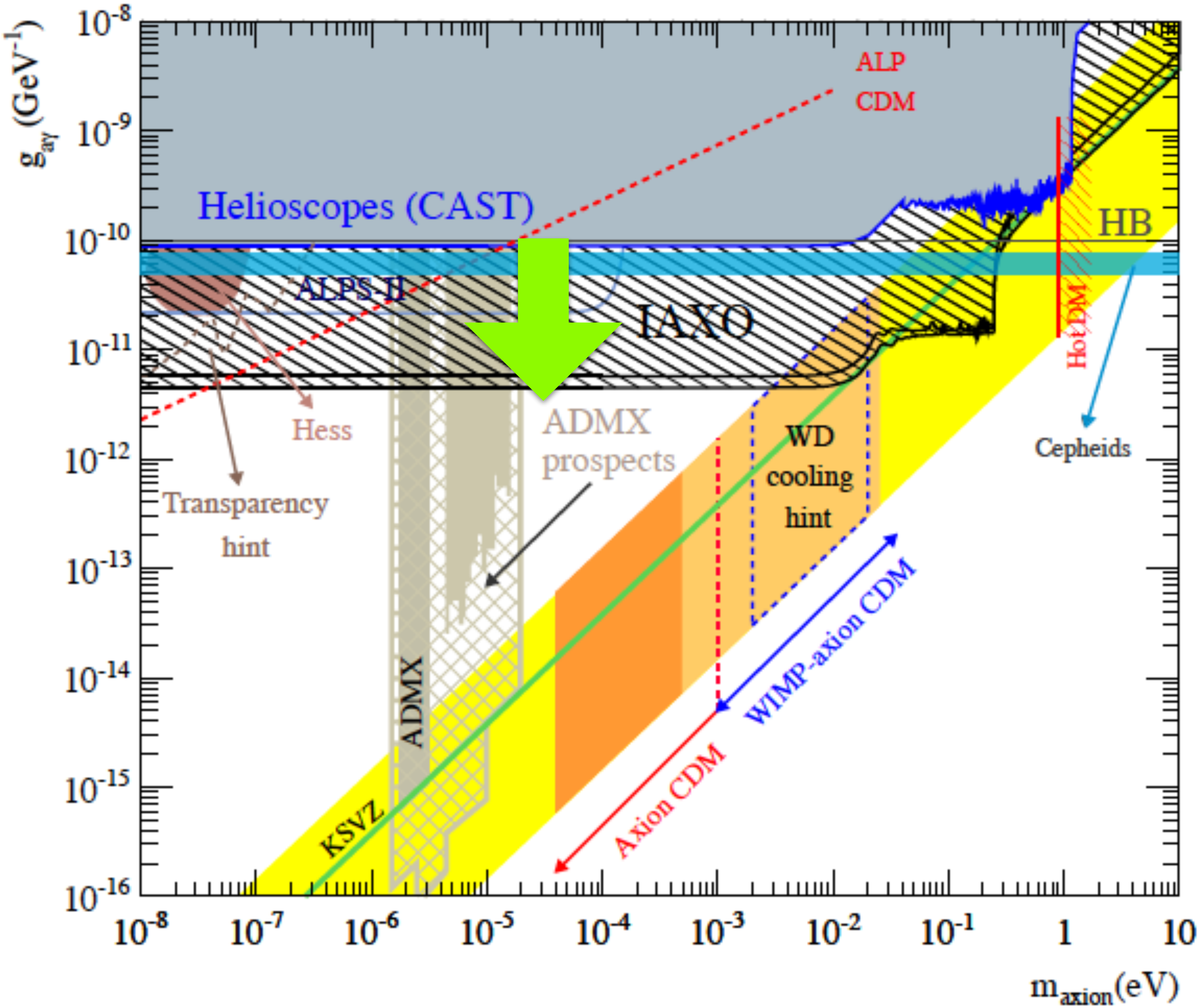
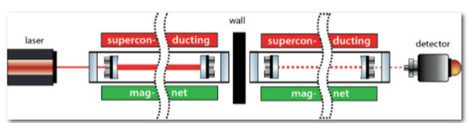
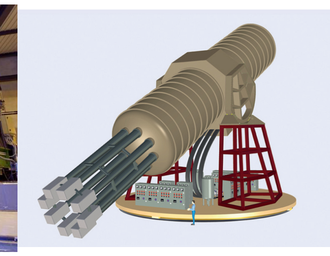
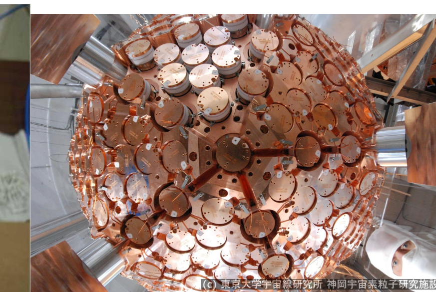
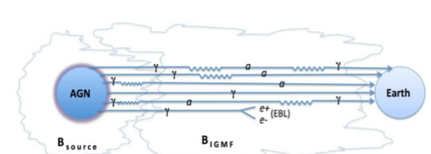
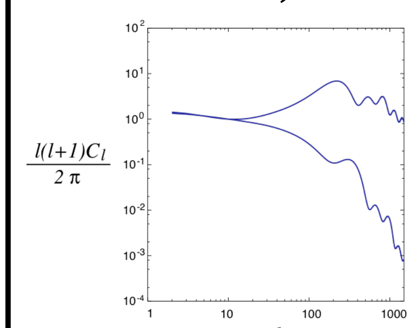
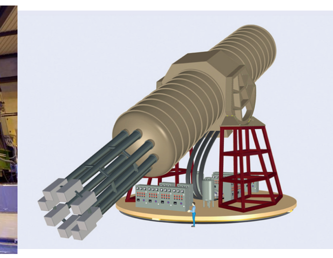
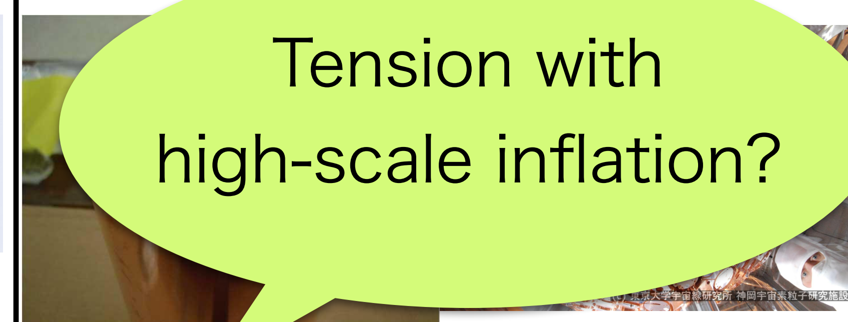
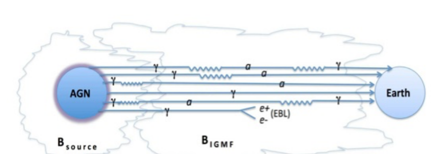
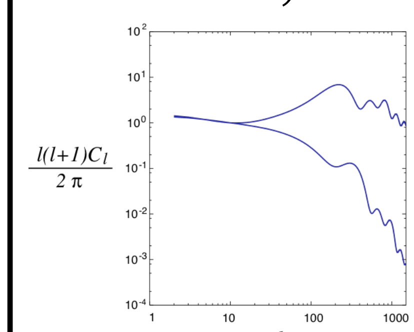


figure taken from Carosi et al, 1309.7035

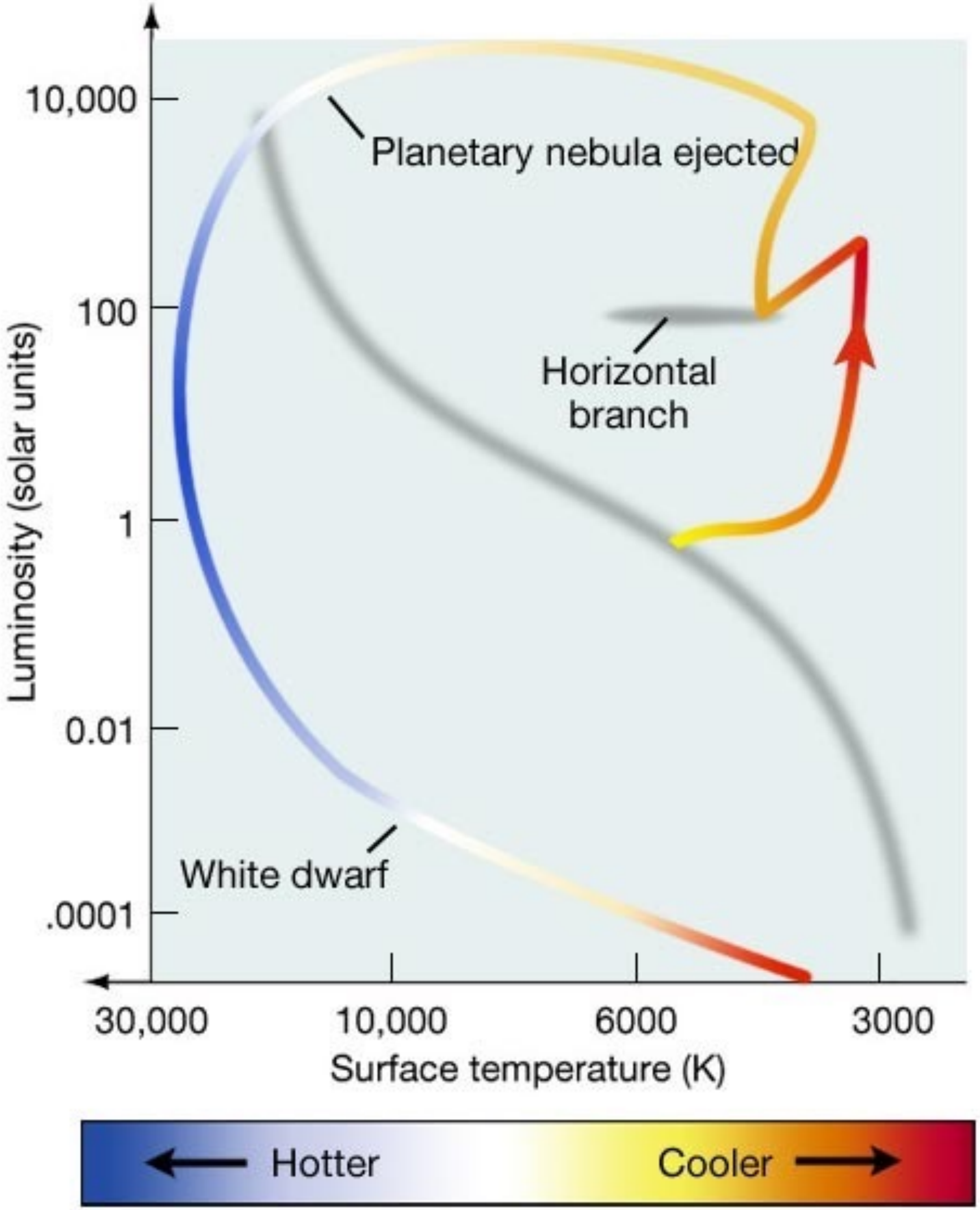
		Production		
		Terrestrial	**Celestial**	**Cosmological**
Detection	**Direct**	LSTW, Photon pol. Fifth force ALPS,OSQAR, PVLAS, ARIADNE 	Solar axion CAST, IAXO  	Axion DM ADMX, CAPP,ORPHEUS LC-circuits, CASPEr, XMASS, EDELWISE,XENON100.  
	Indirect		Excessive cooling of WD, RGB, HB, NS Spectral irreg. Transparency Fermi, IACT. 	Isocurvature, DR, spectral distortion, caustics, GW, etc. Planck, COrE+, PIXIE  

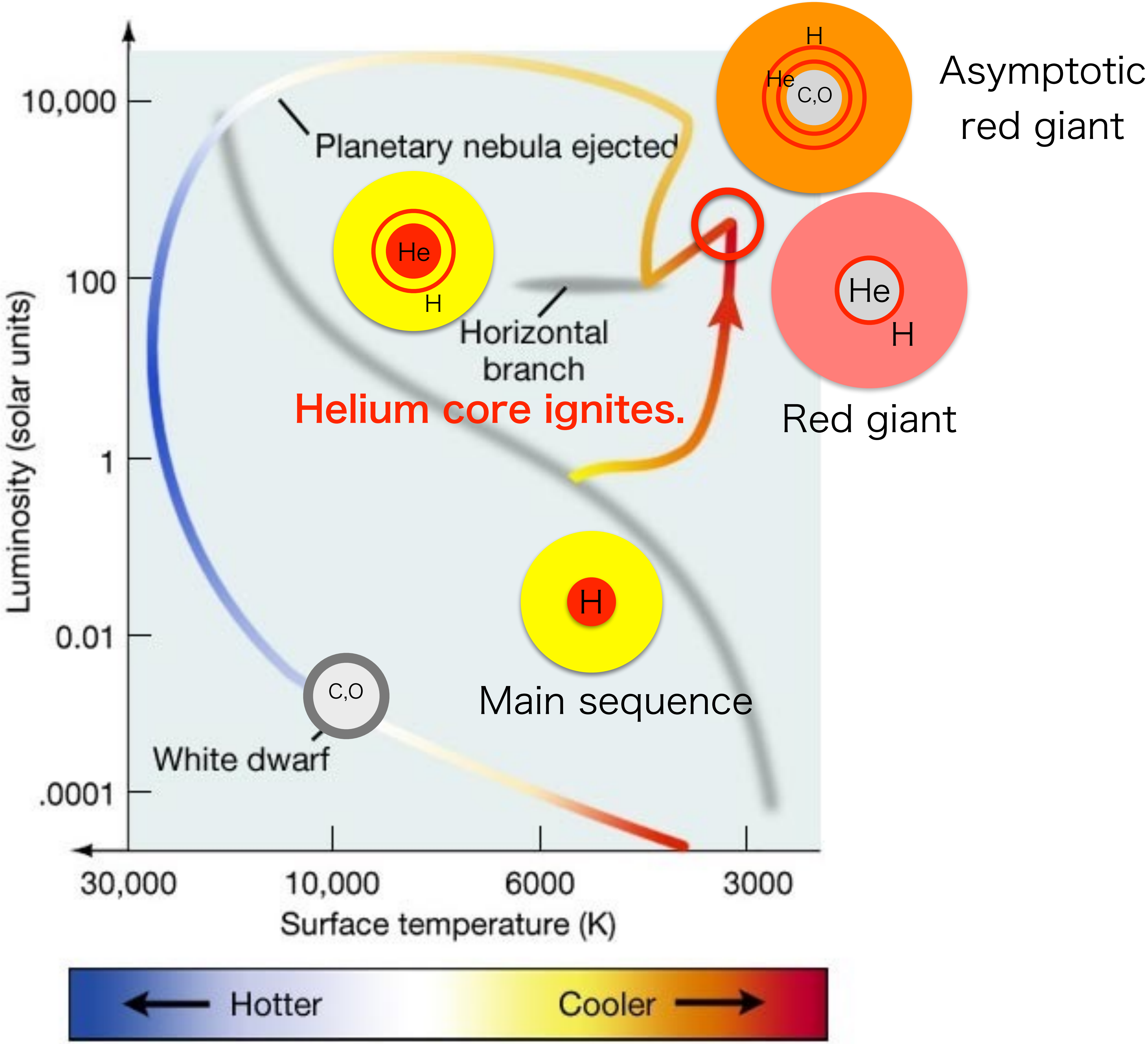
Production

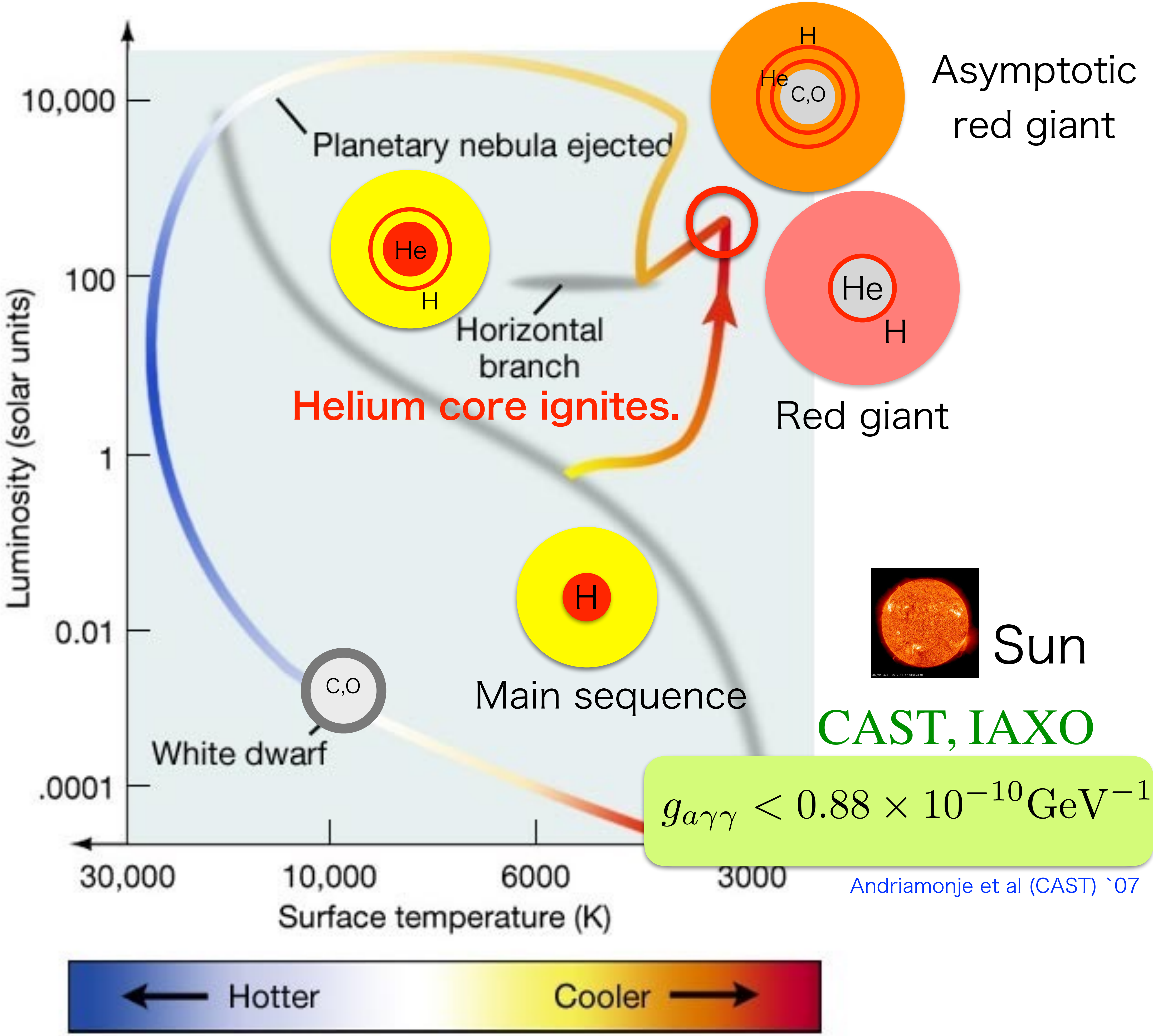
Detection		Terrestrial	Celestial	Cosmological
	Direct	LSTW, Photon pol. Fifth force ALPS,OSQAR, PVLAS, AD[illegible] 	Solar axion CAST, IAXO  	Axion DM ADMX, CAPP,ORPHEUS LC-circuits, CASPEr, XMASS, EDELWISE,XENON100. 
	Indirect		Excessive cooling of WD, RGB, HB, NS Spectral irreg. Transparency Fermi, IACT. 	Isocurvature, DR, spectral distortion, caustics, GW, etc. Planck, COrE+, PIXIE  

Hint for anomalous cooling?

Tension with high-scale inflation?

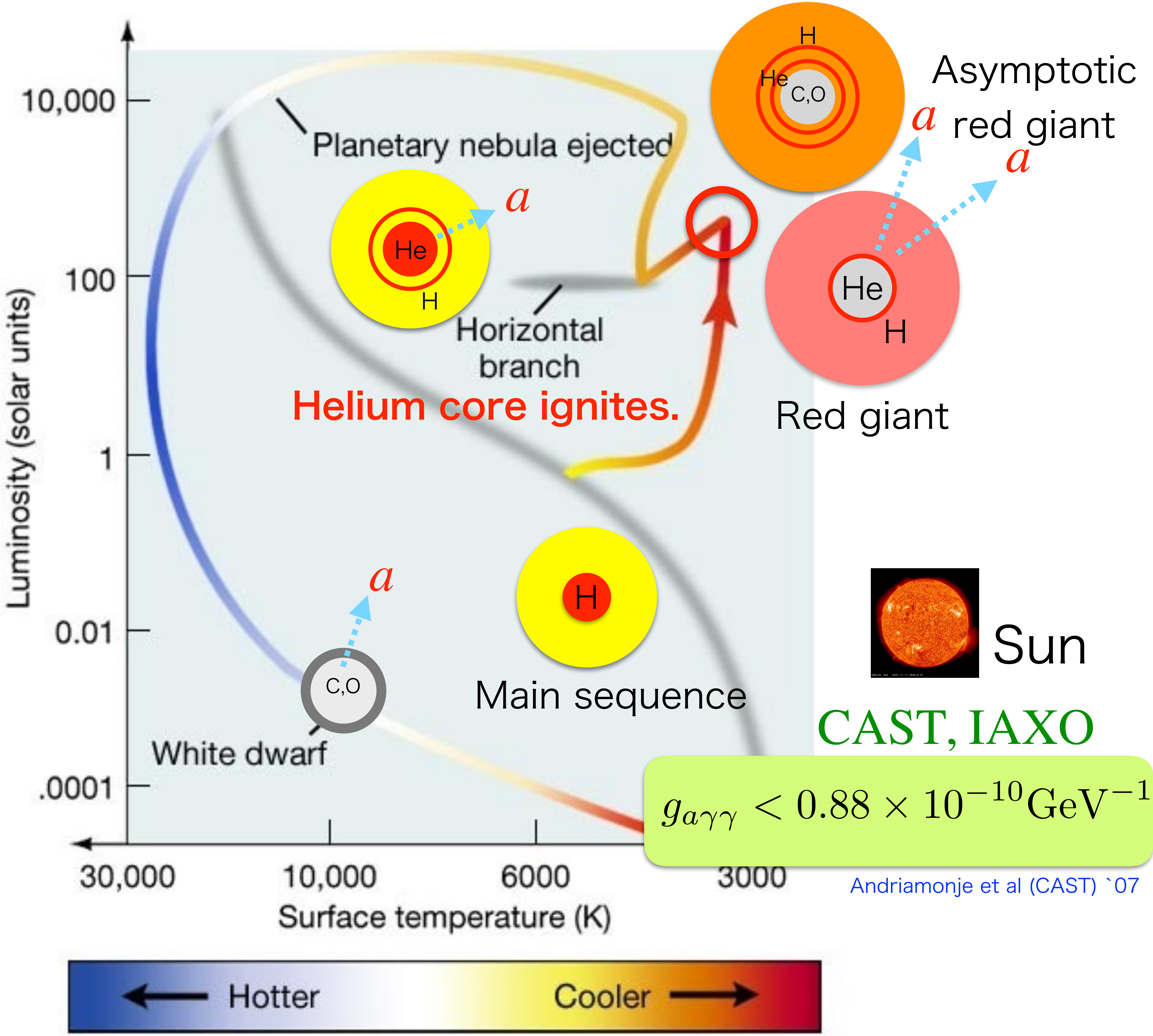

10,000
100
1
0.01
.0001
Luminosity (solar units)
Planetary nebula ejected
Horizontal branch
White dwarf
30,000
10,000
6000
3000
Surface temperature (K)
Hotter
Cooler

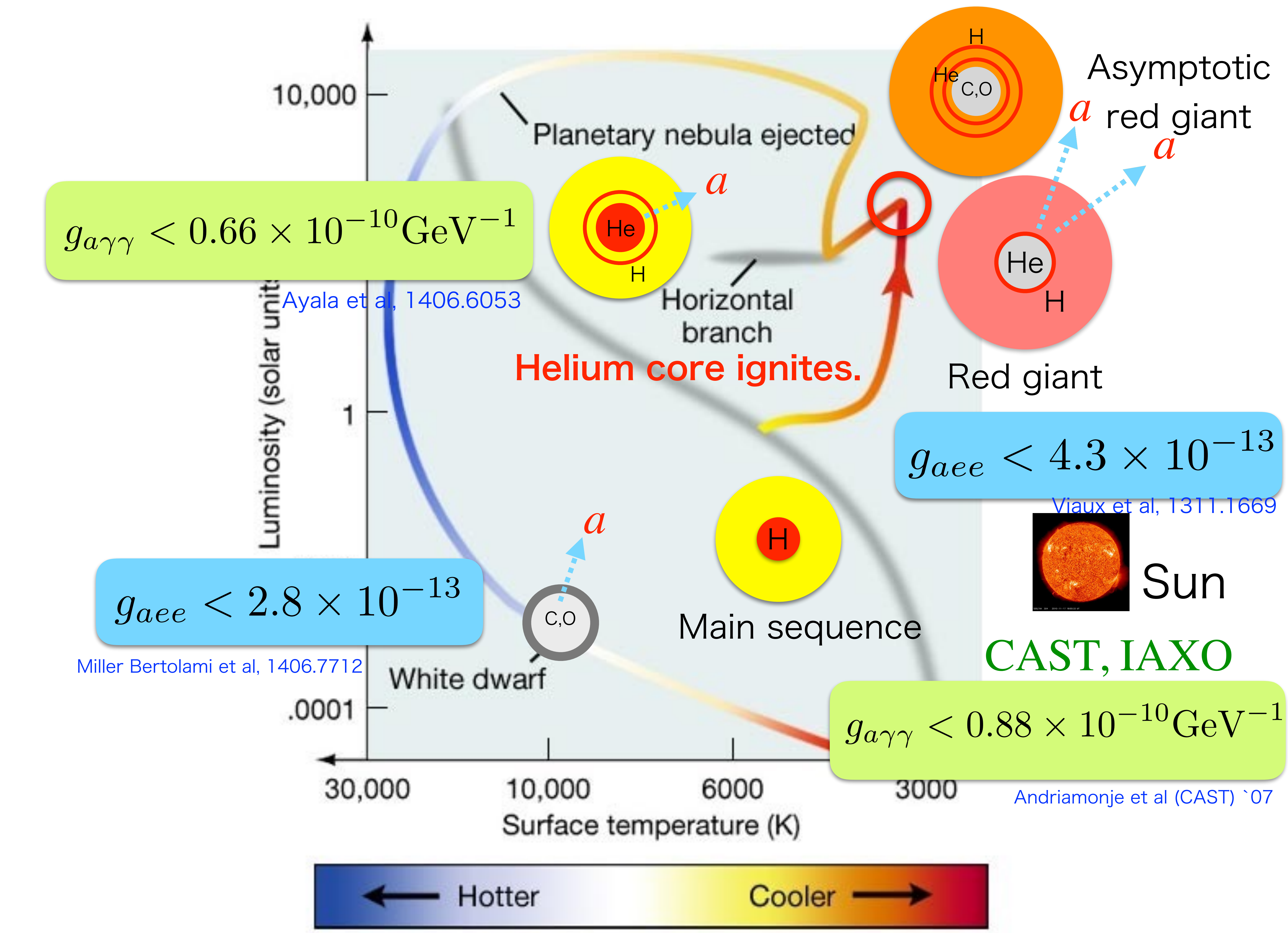

Asymptotic red giant
H
He
C,O
Planetary nebula ejected
He
H
Horizontal branch
Red giant
He
H
Helium core ignites.
H
Main sequence
C,O
White dwarf
10,000
100
1
0.01
.0001
Luminosity (solar units)
30,000
10,000
6000
3000
Surface temperature (K)
Hotter
Cooler



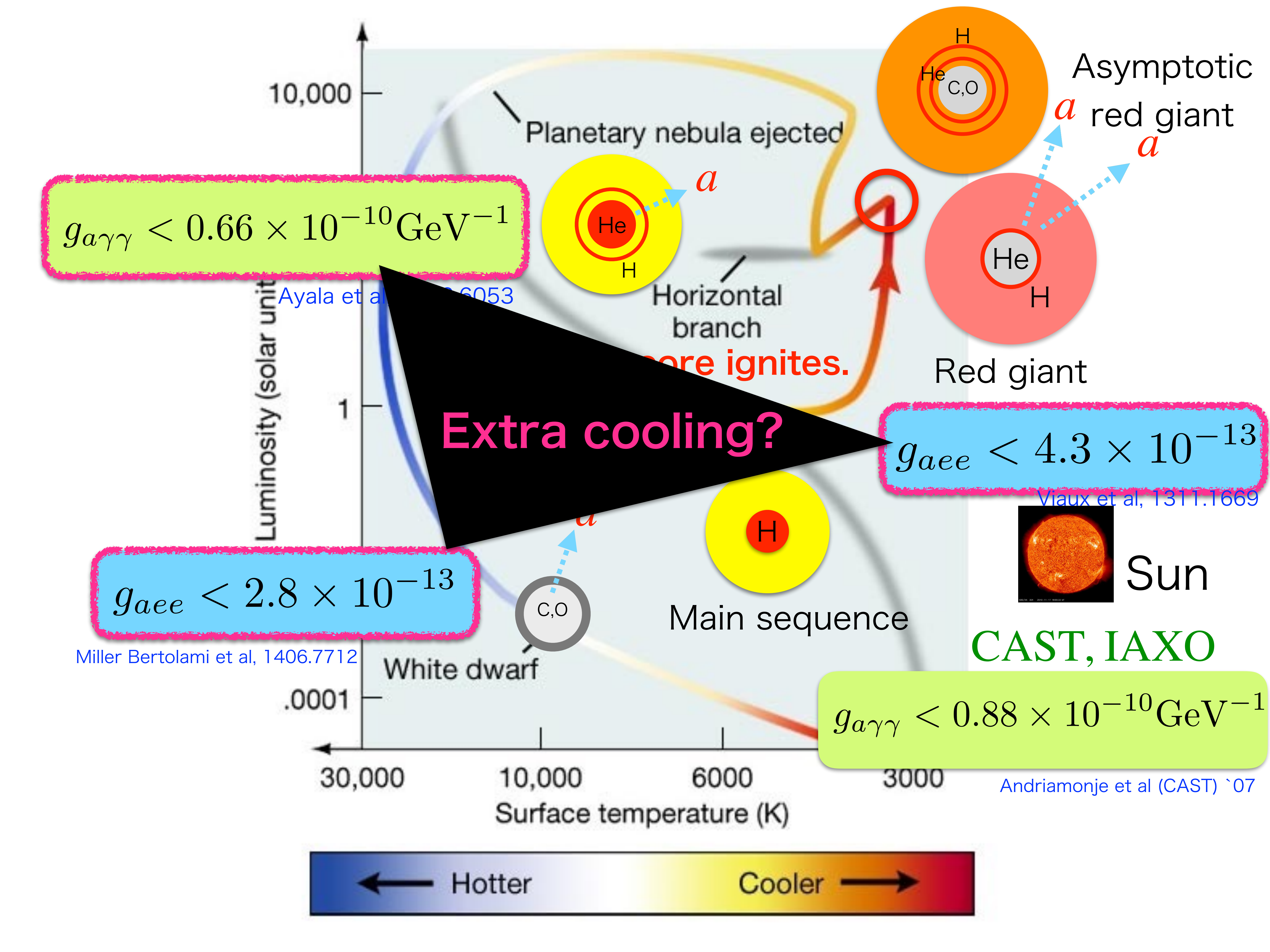
$$g_{a\gamma\gamma} < 0.88 \times 10^{-10}\mathrm{GeV}^{-1}$$

Andriamonje et al (CAST) `07


Asymptotic red giant
H
He
C,O
a
a
a
Planetary nebula ejected
He
H
Horizontal branch
Helium core ignites.
He
H
Red giant
Luminosity (solar units)
10,000
100
1
0.01
.0001
H
Main sequence
Sun
a
C,O
White dwarf
CAST, IAXO
$g_{a\gamma\gamma} < 0.88 \times 10^{-10}\mathrm{GeV}^{-1}$
Andriamonje et al (CAST) `07
30,000
10,000
6000
3000
Surface temperature (K)
Hotter
Cooler



Asymptotic red giant
H
He
C,O
a
a
Planetary nebula ejected
$g_{a\gamma\gamma} < 0.66 \times 10^{-10}\mathrm{GeV}^{-1}$
Ayala et al, 1406.6053
He
H
a
Horizontal branch
He
H
Red giant
Helium core ignites.
10,000
1
.0001
Luminosity (solar units)
$g_{aee} < 4.3 \times 10^{-13}$
Viaux et al, 1311.1669
a
H
Sun
$g_{aee} < 2.8 \times 10^{-13}$
Miller Bertolami et al, 1406.7712
C,O
White dwarf
Main sequence
CAST, IAXO
$g_{a\gamma\gamma} < 0.88 \times 10^{-10}\mathrm{GeV}^{-1}$
Andriamonje et al (CAST) `07
30,000
10,000
6000
3000
Surface temperature (K)
Hotter
Cooler



$g_{a\gamma\gamma} < 0.66 \times 10^{-10}\mathrm{GeV}^{-1}$
Ayala et al
Planetary nebula ejected
He
H
a
Horizontal
branch
Asymptotic
red giant
C,O
a
a
He
H
Red giant
Extra cooling?
$g_{aee} < 4.3 \times 10^{-13}$
Viaux et al, 1311.1669
H
Main sequence
Sun
CAST, IAXO
$g_{aee} < 2.8 \times 10^{-13}$
Miller Bertolami et al, 1406.7712
C,O
White dwarf
$g_{a\gamma\gamma} < 0.88 \times 10^{-10}\mathrm{GeV}^{-1}$
Andriamonje et al (CAST) `07
10,000
1
.0001
30,000
10,000
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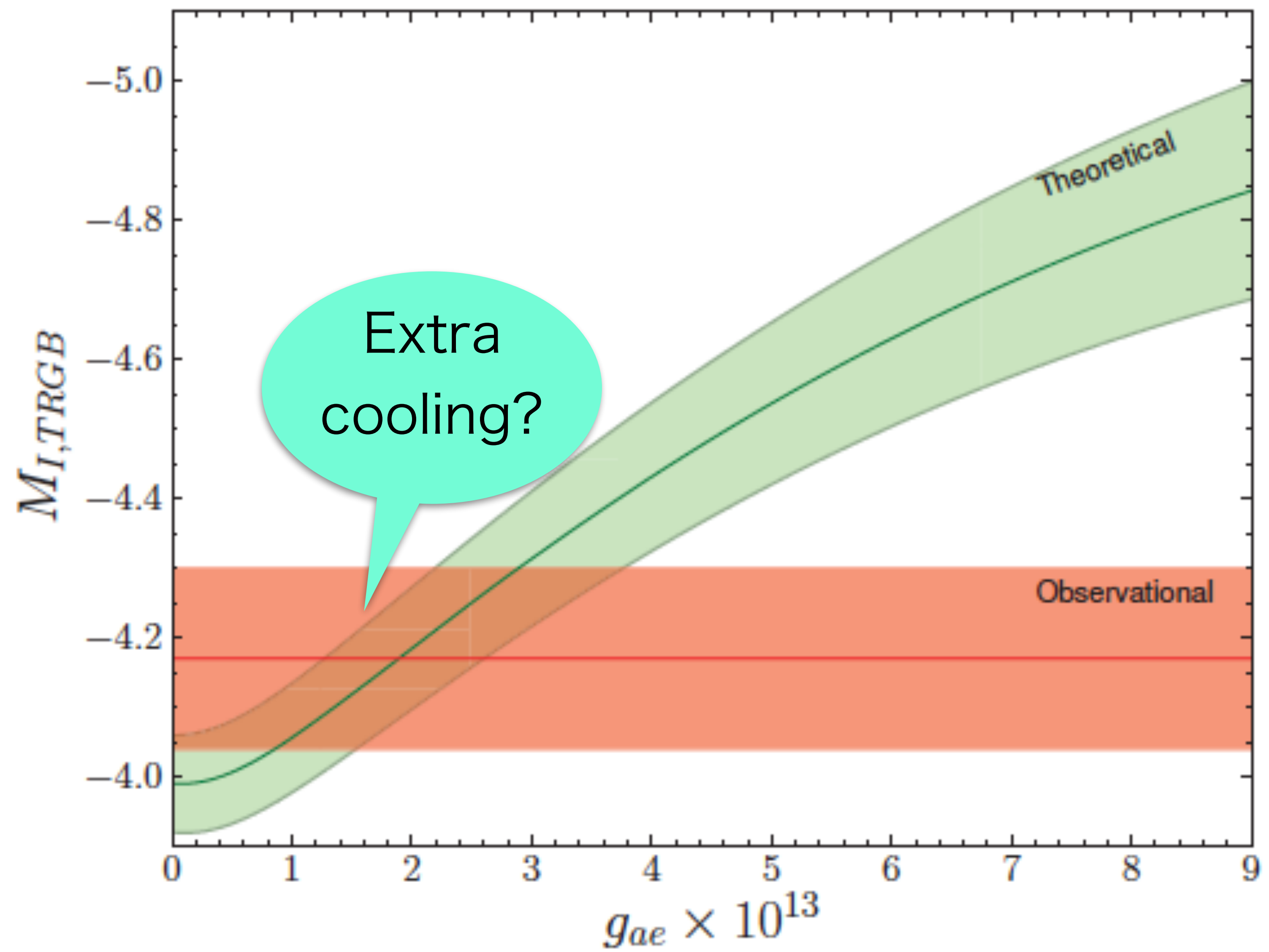
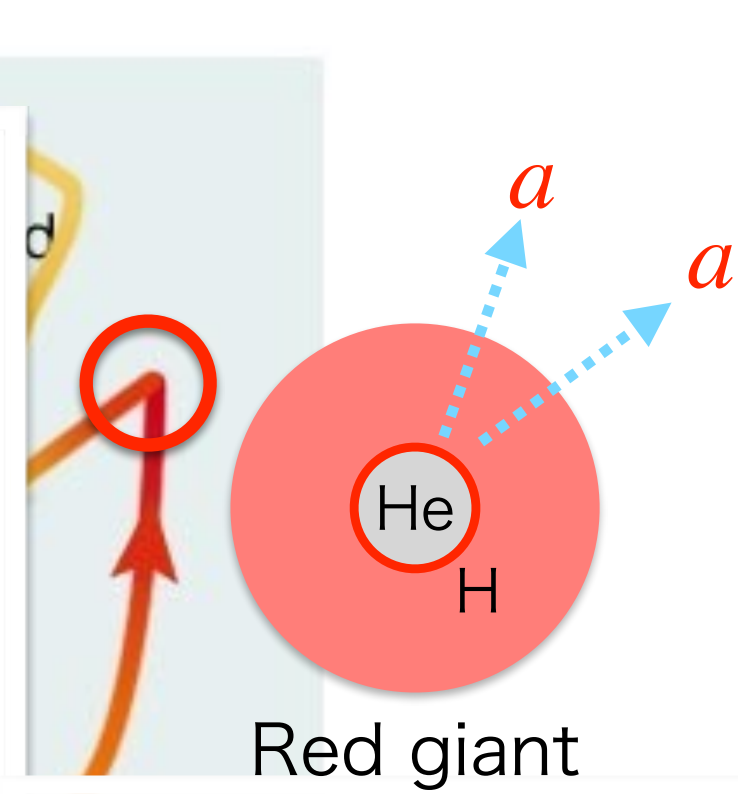
Surface temperature (K)
Hotter
Cooler

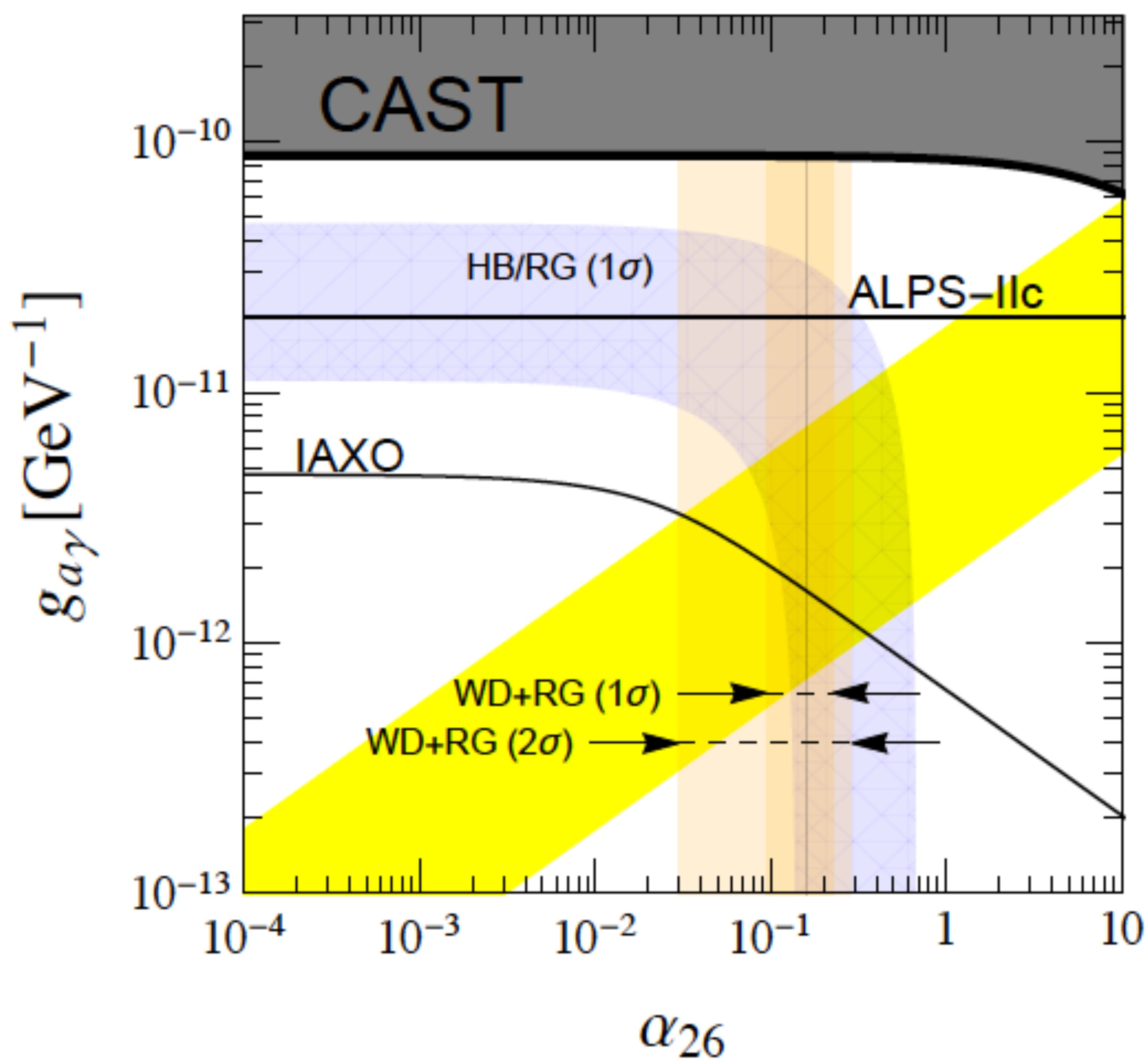


Viaux et al, 1311.1669

FIG. 2. Absolute *I*-band brightness of TRGB in cluster M5. *Red band:* Observations with 1σ error, dominated by distance. *Green band:* Theoretical prediction, depending on the axion-electron coupling, with 1σ systematic error, dominated by the bolometric correction.



Hints for extra cooling?



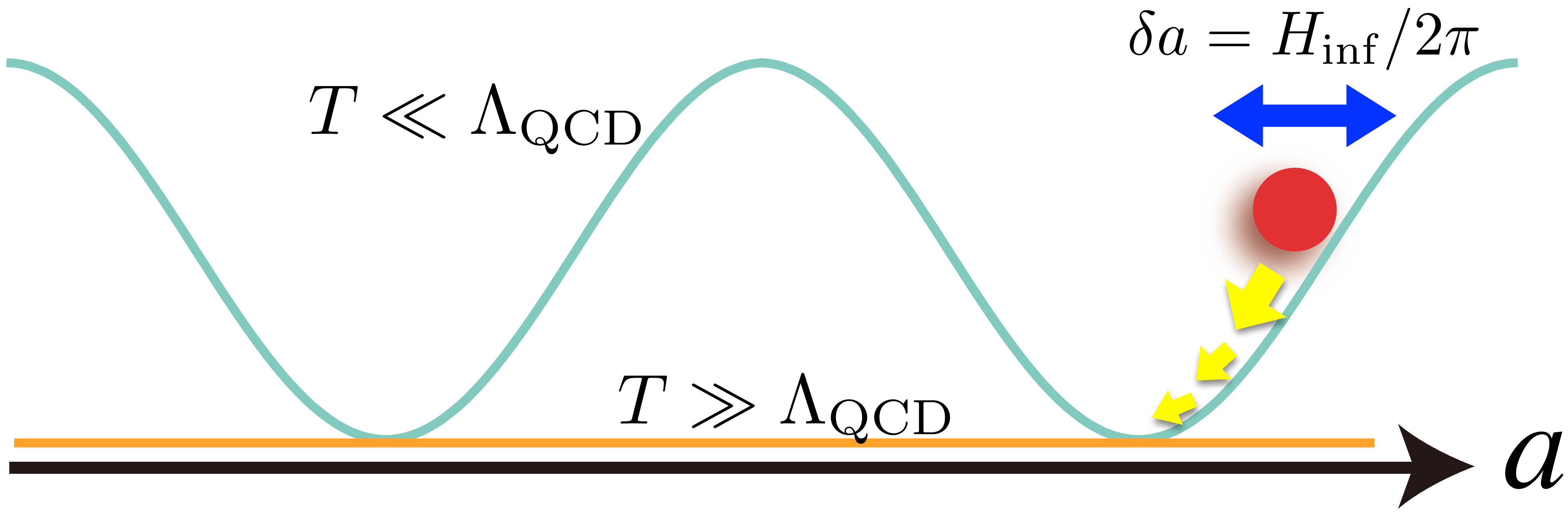
Giannotti et al, 1512.08108

Those hints for extra cooling can be explained by axion (ALP) with couplings within the reach of future experiments.

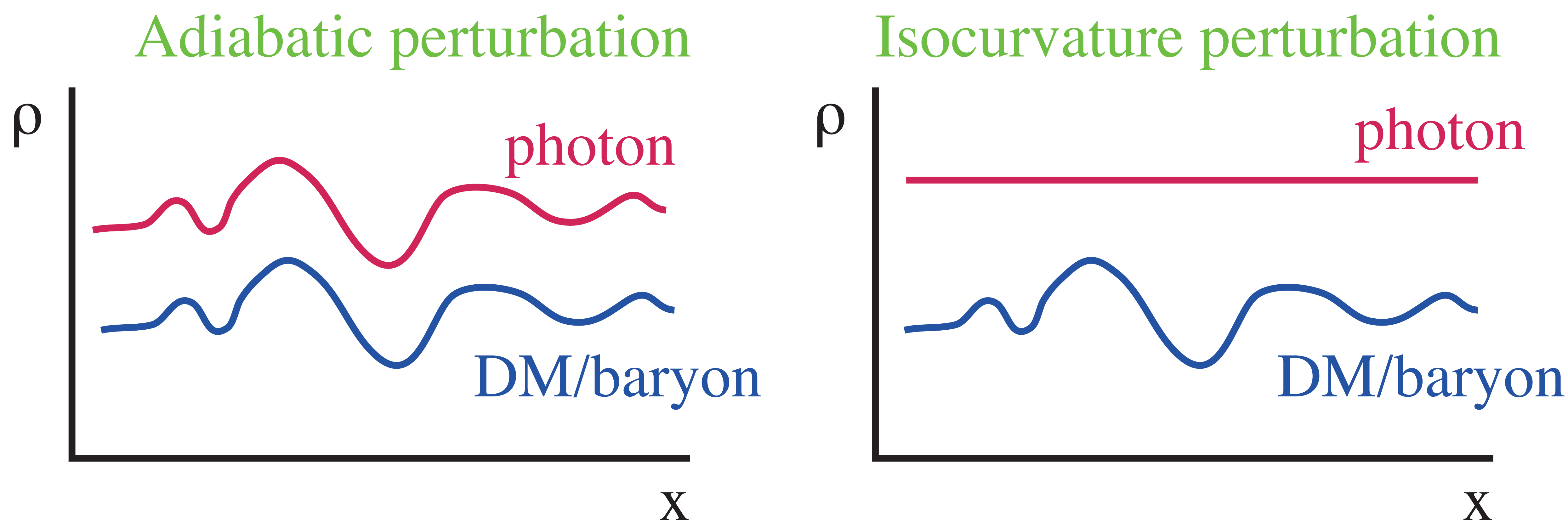
Axion isocurvature perturbations

If the axion exists during inflation, it acquires isocurvature fluctuations.

$$\frac{\delta\Omega_a}{\Omega_a} = 2\frac{\delta\theta_i}{\theta_i} \qquad \delta\theta_i = \frac{\delta a}{f_a}$$



Axion isocurvature perturbations

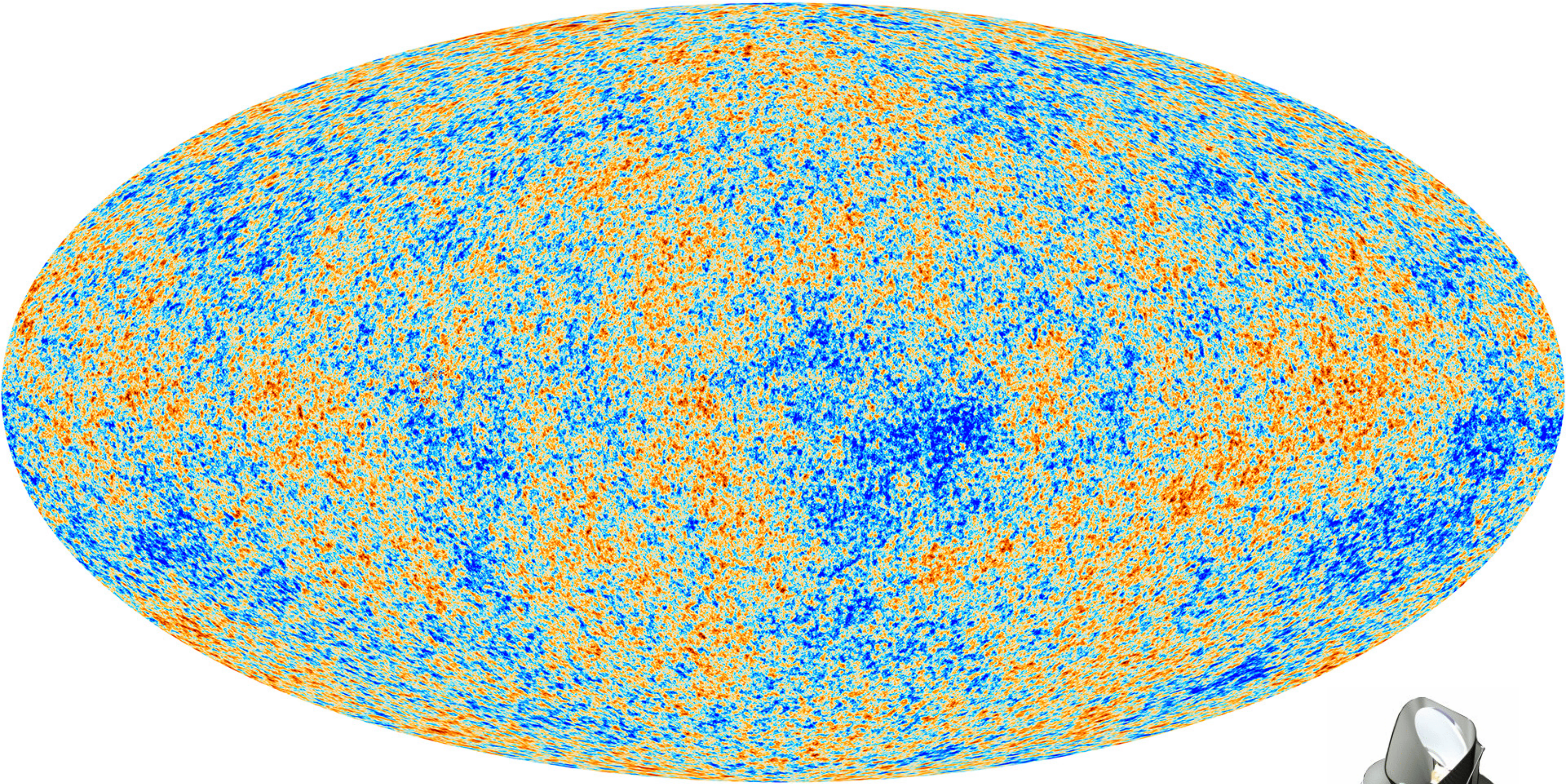


$$S = \frac{\Omega_a}{\Omega_{\rm CDM}} \frac{\delta\Omega_a}{\Omega_a} = \frac{\Omega_a}{\Omega_{\rm CDM}} \frac{2\delta\theta_i}{\theta_i} = \frac{\Omega_a}{\Omega_{\rm CDM}} \frac{H_{\rm inf}}{\pi\theta_i f_a}$$

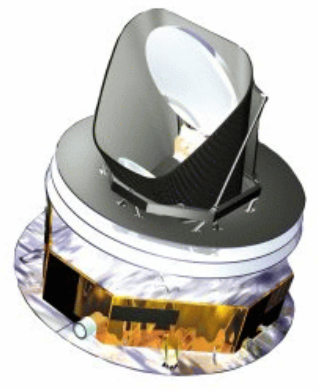
$$\beta_{\rm iso} = \frac{\mathcal{P}_S}{\mathcal{P}_{\mathcal{R}} + \mathcal{P}_S} < 0.038 \quad (95\%\,{\rm CL})$$

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

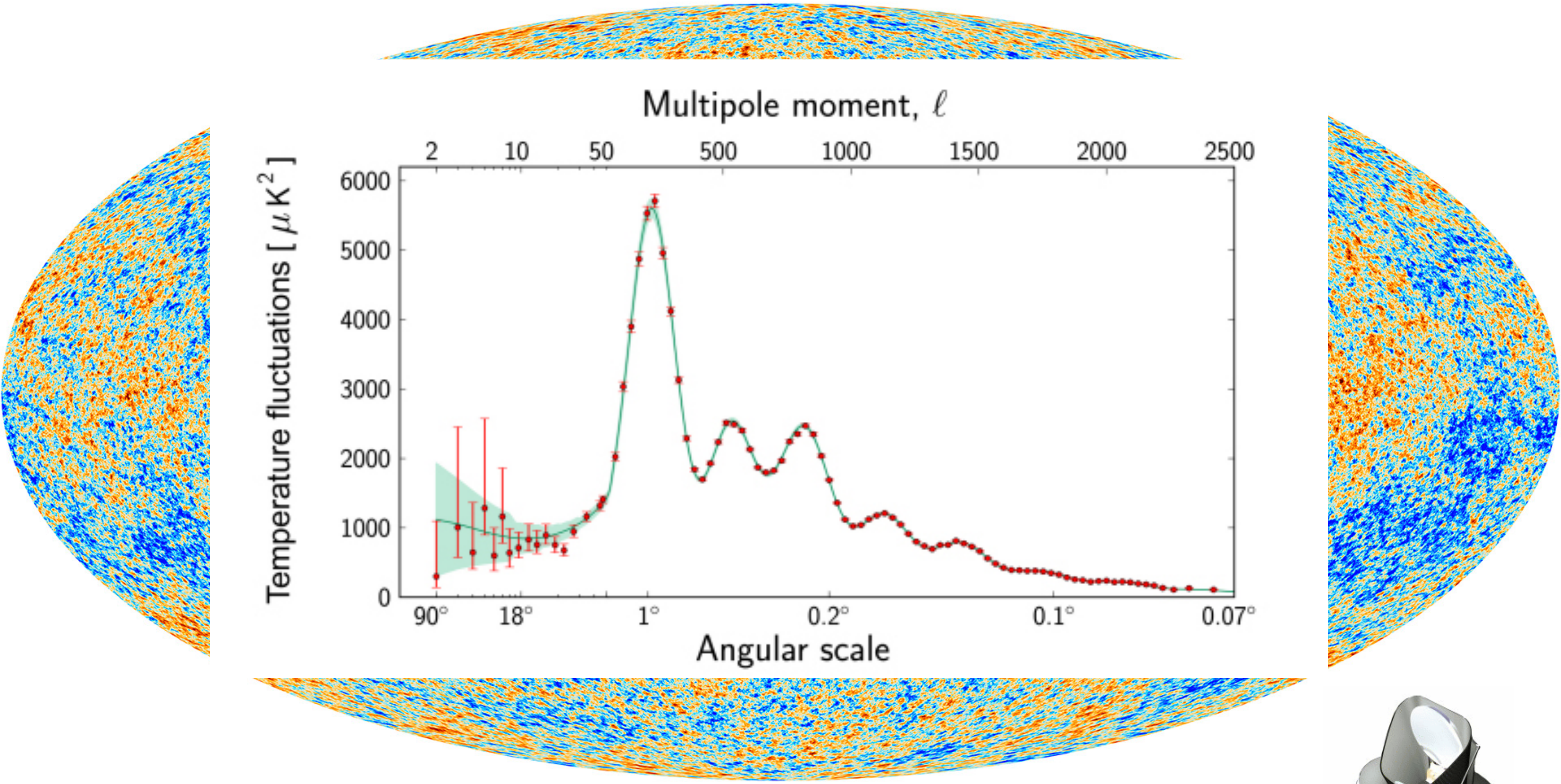
CMB angular power spectrum



Planck

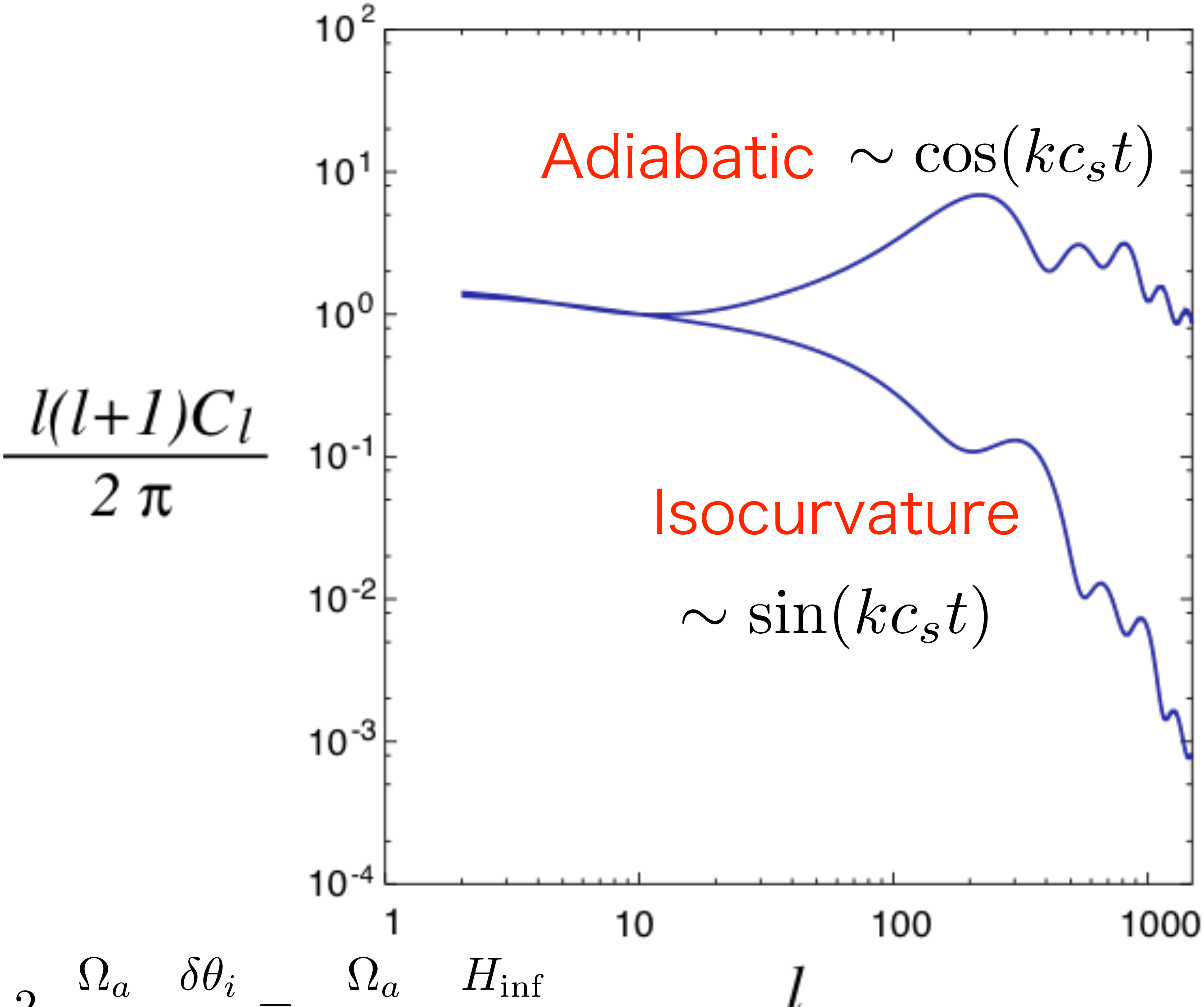


CMB angular power spectrum



Planck

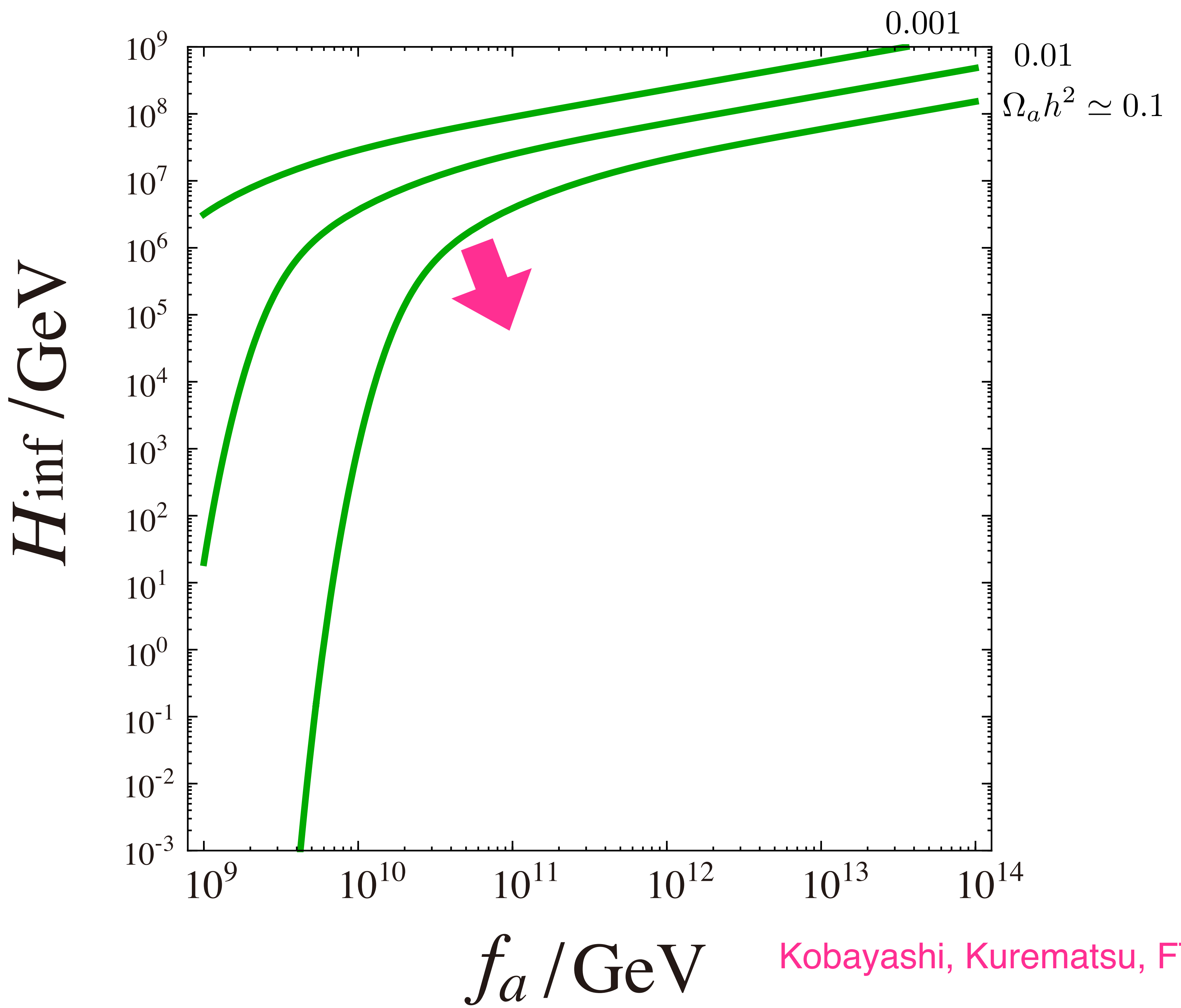
CMB angular power spectrum



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

(Taken from Kawasaki's slide)

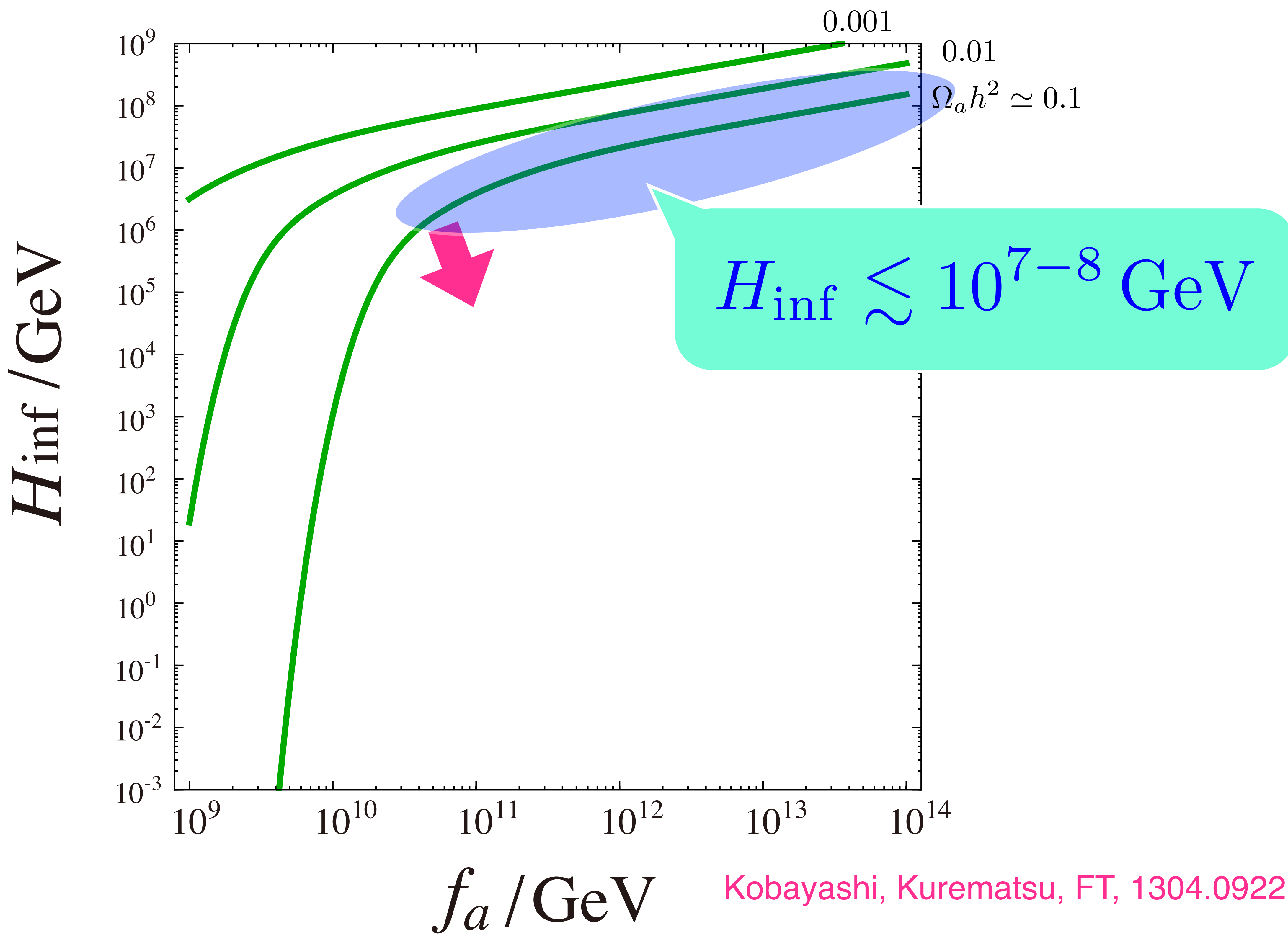
Isocurvature constraint on H_{inf}



Kobayashi, Kurematsu, FT, 1304.0922

Axion DM is in severe tension w/ many inflation models!

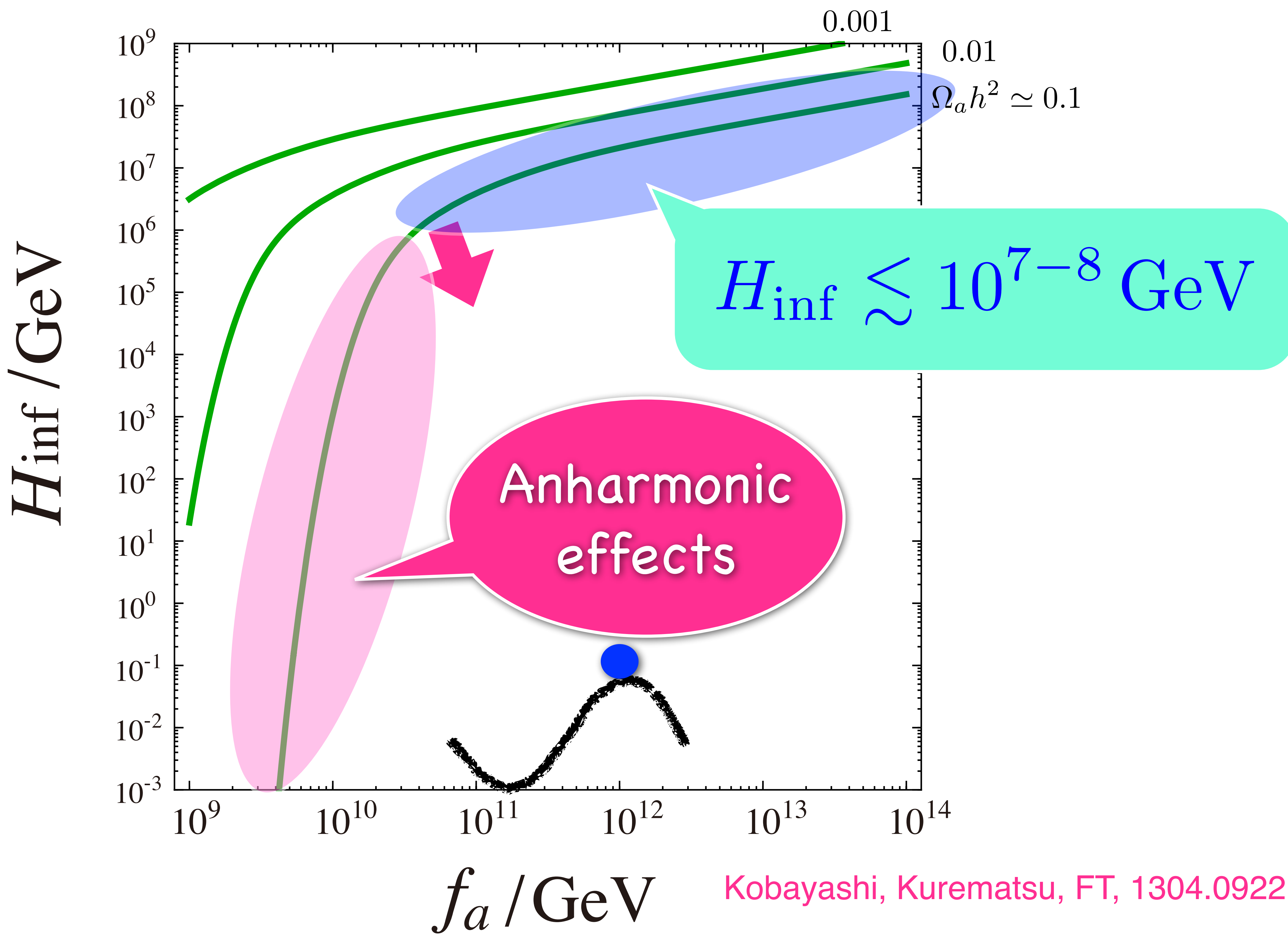
Isocurvature constraint on H_{inf}



Kobayashi, Kurematsu, FT, 1304.0922

Axion DM is in severe tension w/ many inflation models!

Isocurvature constraint on H_{inf}



Kobayashi, Kurematsu, FT, 1304.0922

Axion DM is in severe tension w/ many inflation models!

Solutions to isocuvature problem

1)Restoration of Peccei-Quinn symmetry during inflation.

Linde and Lyth `90 Lyth and Stewart `92

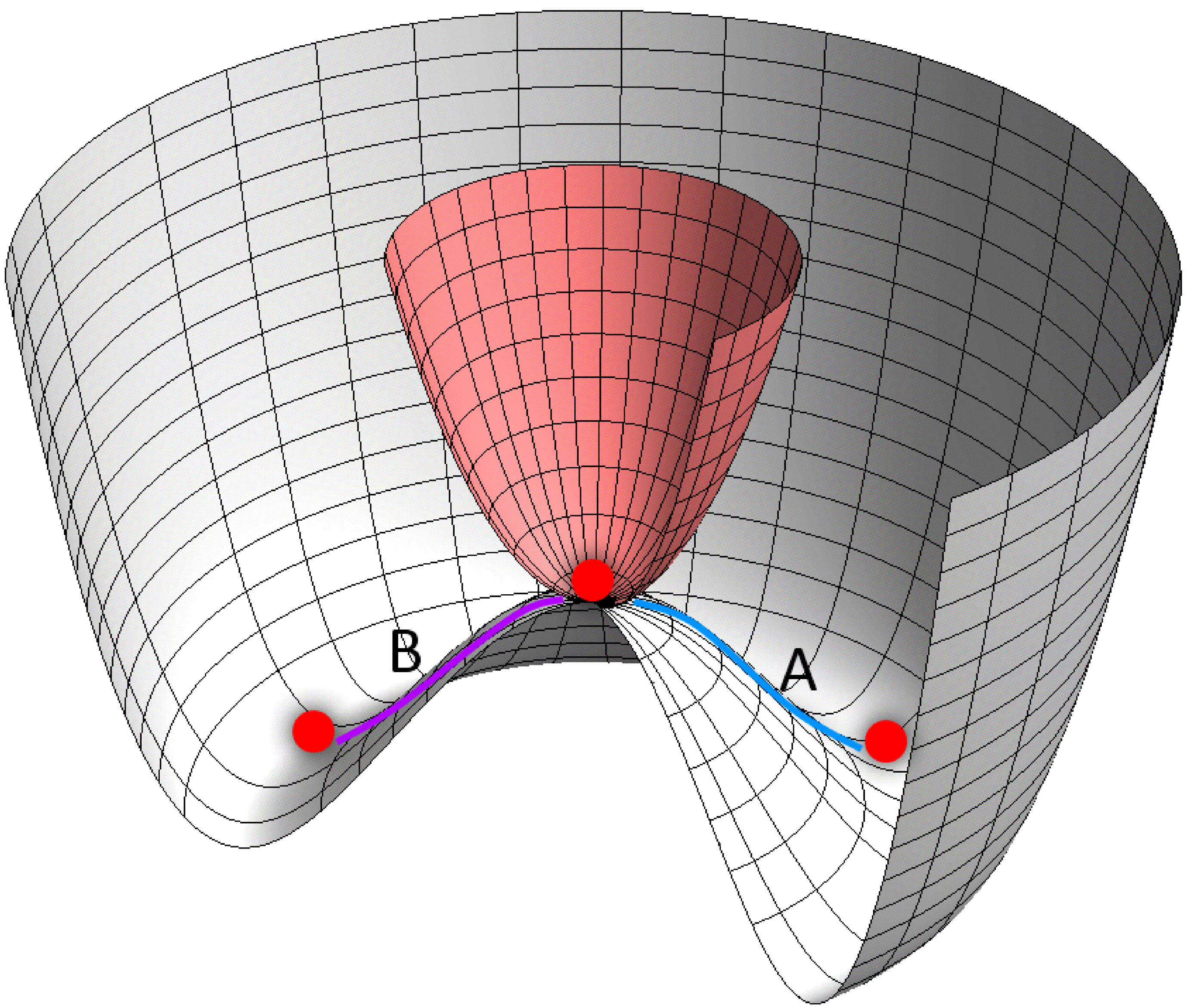


Figure taken from M. Kawasaki's slide

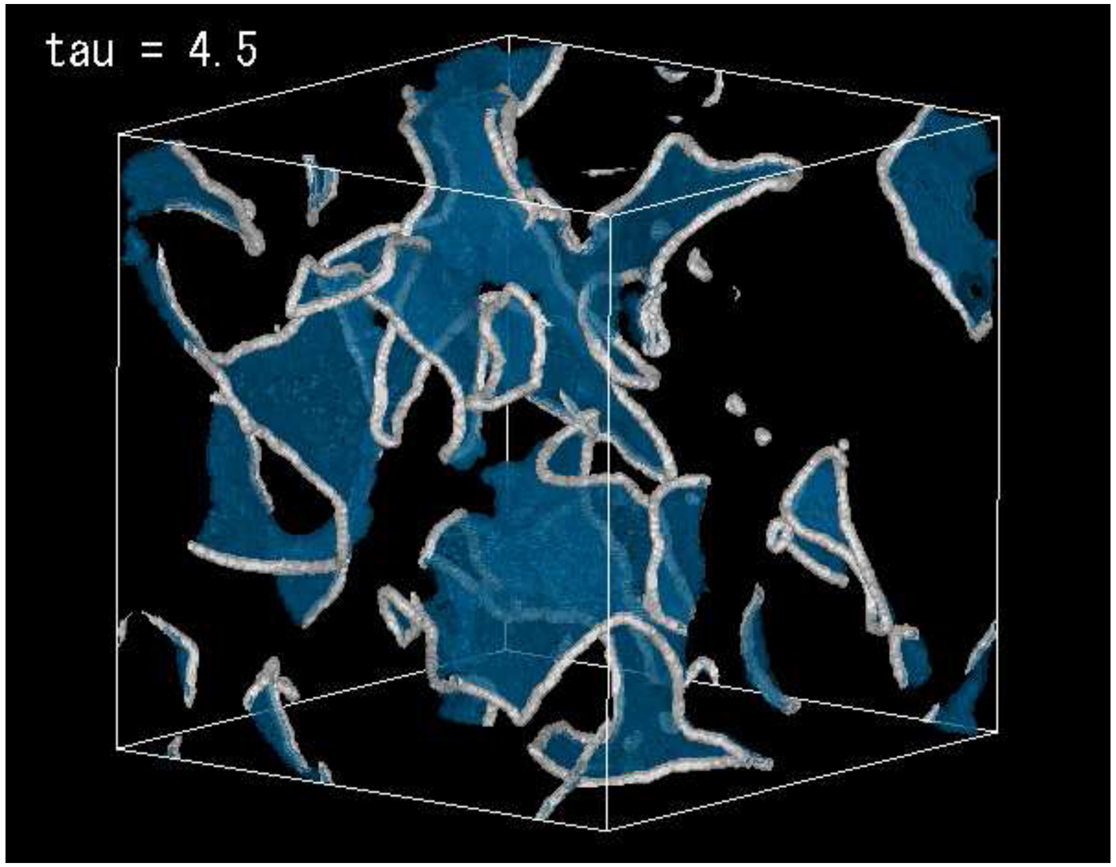
Solutions to isocuvature problem

1)Restoration of Peccei-Quinn symmetry during inflation.

Linde and Lyth `90 Lyth and Stewart `92

- Axions are produced from domain walls and axion DM is possible for $f_a = 10^{10}$GeV.

Hiramatsu, Kawasaki, Saikawa and Sekiguchi, 1202.5851,1207.3166



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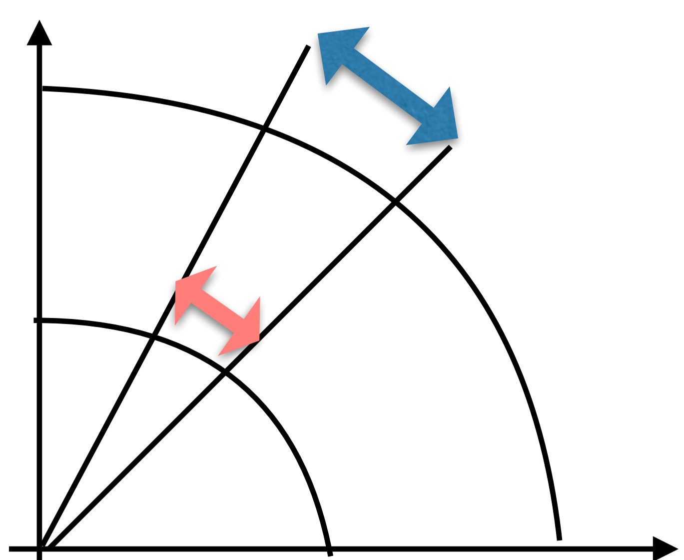
Hiramatsu, Kawasaki, Saikawa and Sekiguchi, 1202.5851,1207.3166

2)Dynamical axion decay constant

Linde and Lyth `90 Linde, `91



Axion: phase component

Saxion: radial component

$$S = \frac{f+\sigma}{\sqrt{2}} e^{ia/f}$$

$$\delta\theta = \text{const.} \quad \Rightarrow \quad \delta a = \delta a_{\rm inf} \left(\frac{f_0}{f_{\rm inf}} \right)$$

At small scales, however, axion fluctuations can be enhanced significantly!

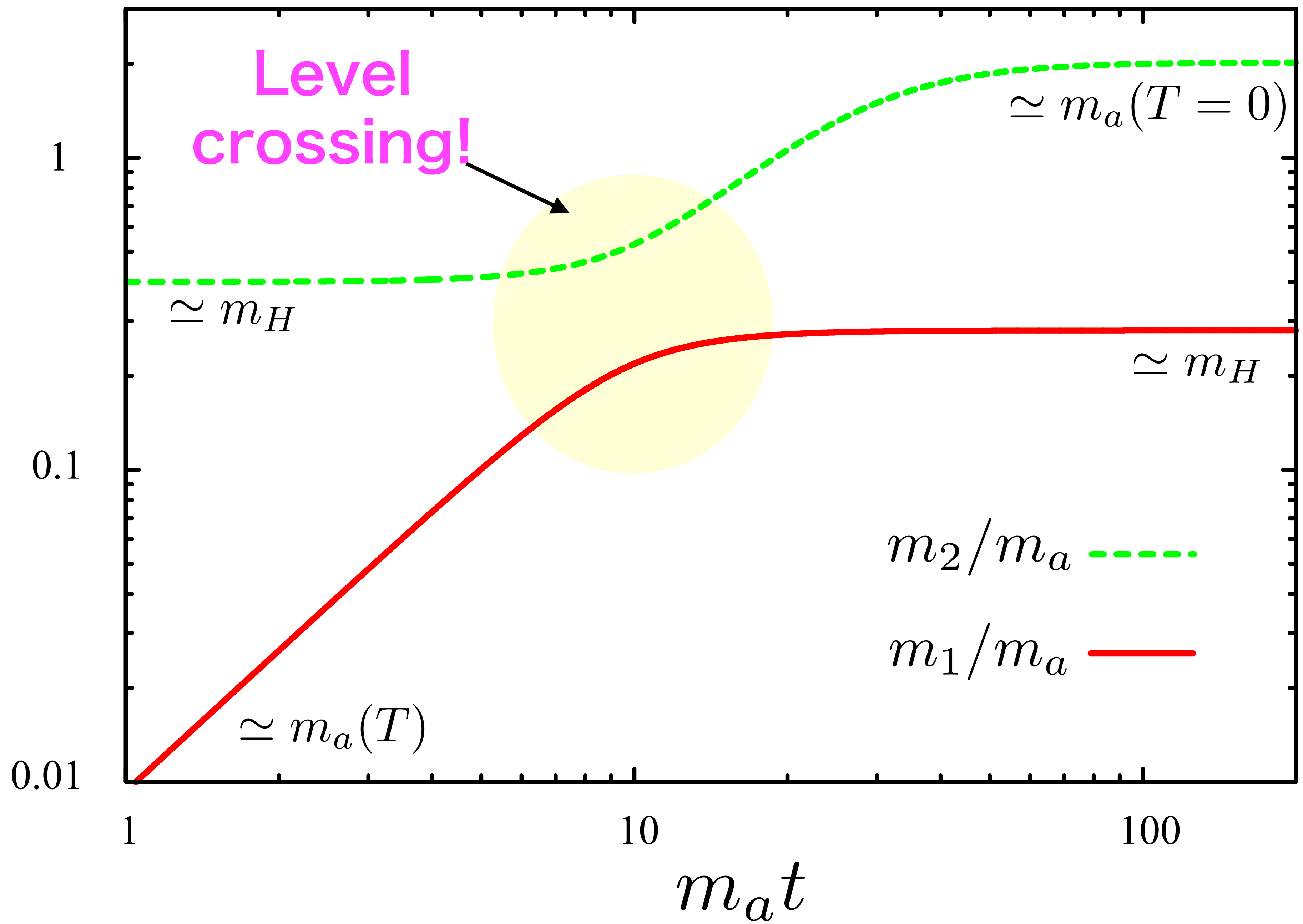
Takeshi Kobayashi, FT, 1607.04294

Solutions to isocuvature problem

3)MSW-like resonance btw. axion and ALP.

Hill, Ross `88, Kitajima, FT 1411.2011

The level crossing necessarily occurs if $m_H^2 < m_a^2(T=0)$.



Solutions to isocuvature problem

3)MSW-like resonance btw. axion and ALP.

Hill, Ross `88, Kitajima, FT 1411.2011

4)Heavy axions during inflation $m_a^2 \gtrsim H_{\rm inf}^2$

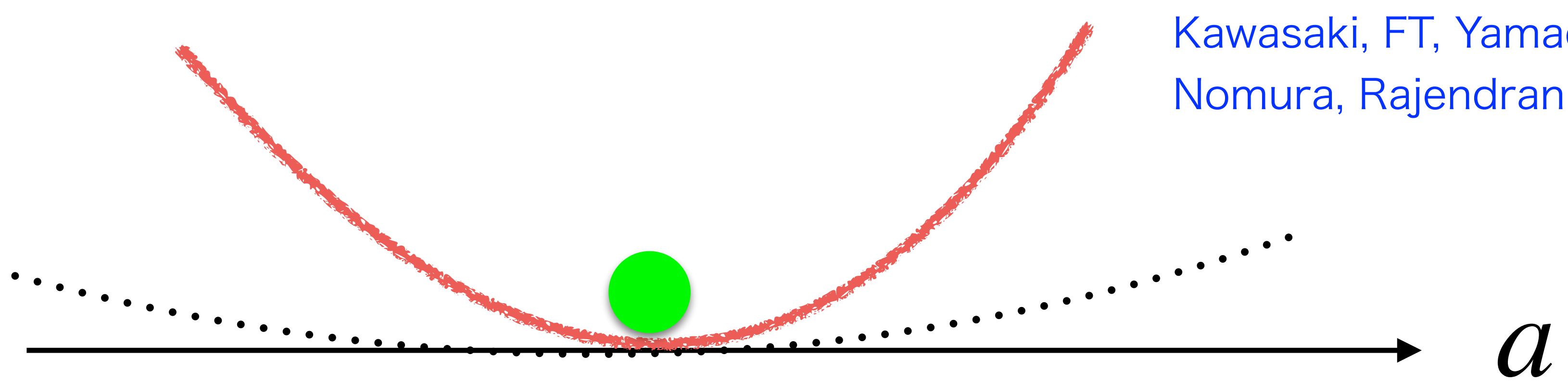
- Stronger QCD during inflation

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

- Extra explicit PQ breaking

e.g. Witten effect

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

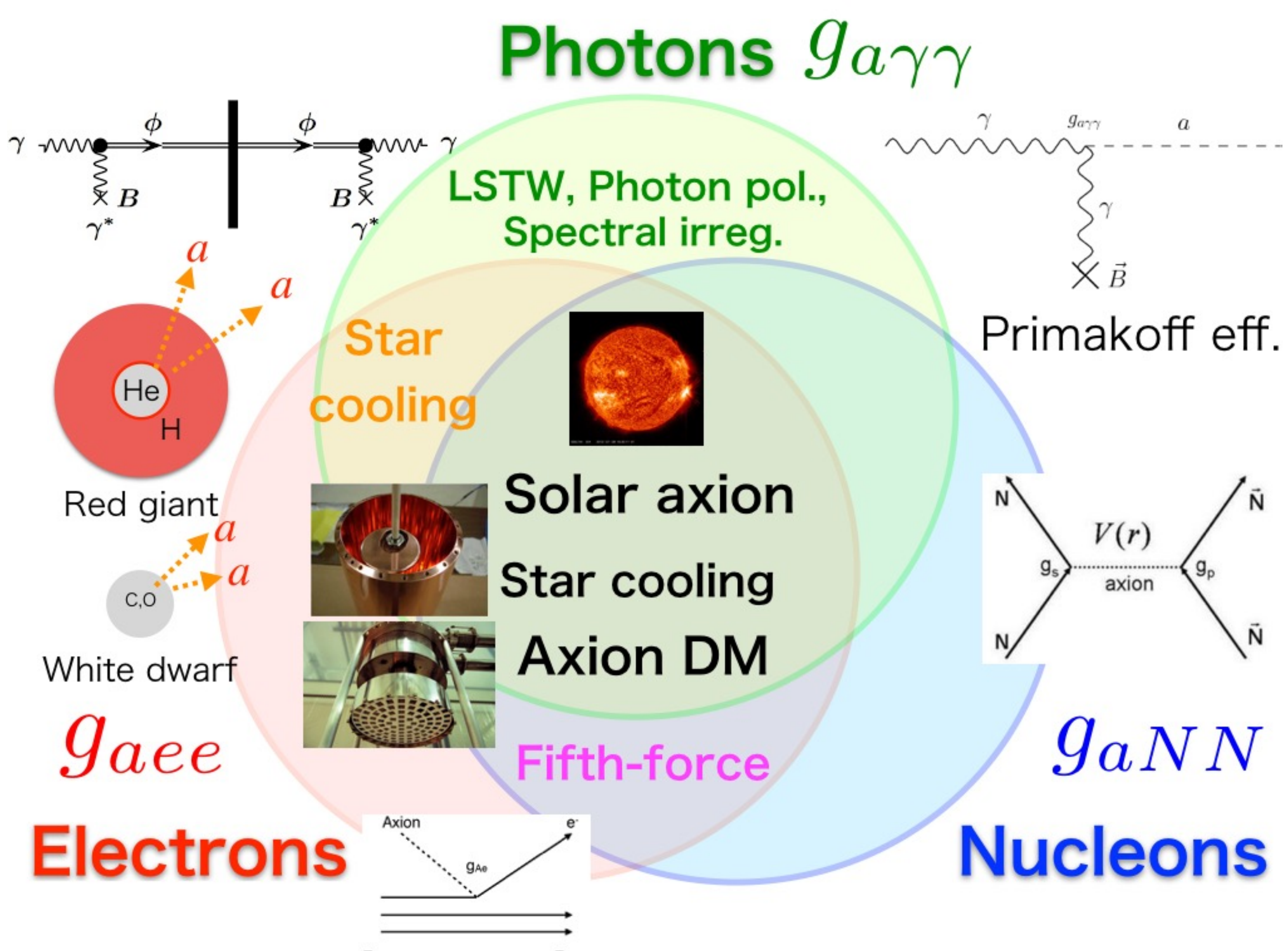


The extra PQ breaking term must be sufficiently suppressed at present.

Summary

✓ Axion and ALPs are motivated by PQ mechanism and BSM physics incl. string theory.

✓ Many on-going and planned axion search experiments, and powerful synergy among them is expected.



		Production		
		Terrestrial	Celestial	Cosmological
Detection	Direct	LSTW, Photon pol. Fifth force ALPS, OSQAR, PVLAS, ARIADNE	Solar axion CAST, IAXO	Axion DM ADMX, ORPHEUS LC-circuits, CASPEr, XMASS, EDELWISE, XENON100.
	Indirect		Excessive cooling of WD, RGB, HB, NS Spectral irreg. Transparency Fermi, IACT	Isocurvature, DR, spectral distortion, caustics, GW, etc. Planck, COrE+, PIXIE

Summary

- ✓ Axion and ALPs are motivated by PQ mechanism and BSM physics incl. string theory.

- ✓ Many on-going and planned axion search experiments, and powerful synergy among them is expected.

- ✓ Astrophysical hints for axions/ALPs from star cooling (and transparency) can be checked by future experiments.

- ✓ Axionic isocurvature tightly constrains the inflation scale, implying low-scale inflation, PQ symmetry restoration or other exotic possibilities.

The axion is a window to BSM and the early Universe!

Hidden Sector Physics and Cosmophysics

December 12 (Mon) - 15 (Thu), 2016

Panasonic Hall, YITP, Kyoto University, Kyoto, Japan

Invited Speakers

- Asimina Arvanitaki (Perimeter Inst)
- Carlos A. R. Herdeiro (U Aveiro)
- Ralph Blumenhagen (MPIfP)
- Joseph Conlon (Oxford U)
- Jens Chluba (U of Manchester)
- Yoshizumi Inoue (U Tokyo)
- Jonah Kanner (Caltech)
- David J. E. Marsh (King's College London)
- Natsumi Nagata (U Tokyo)
- Andreas Ringwald (DESY)
- Takahiro Tanaka (Kyoto U)

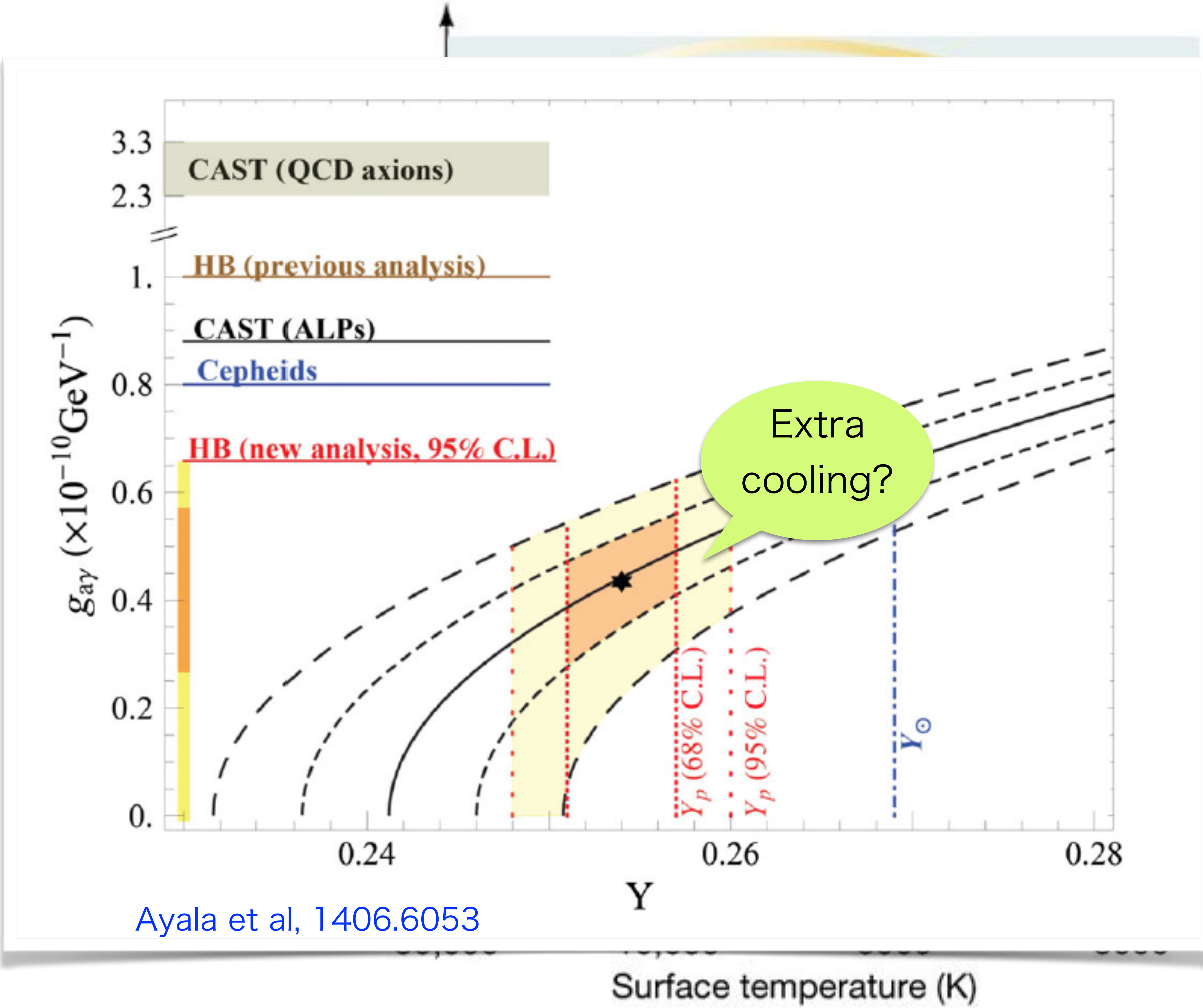
Important dates:

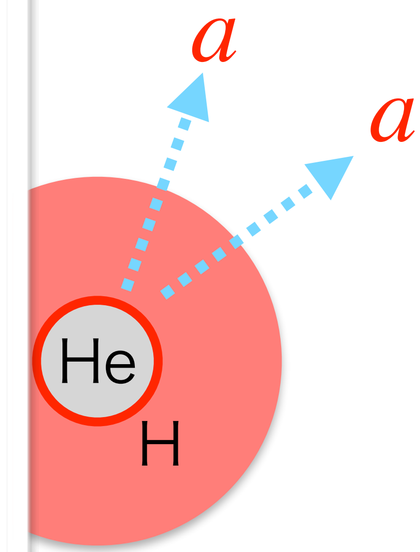
Abstract submission 10th Oct. 2016

Registration open until 10th Nov. 2016.

http://www2.yukawa.kyoto-u.ac.jp/~hideo.kodama/UTQuestWS5/

Back-up slides

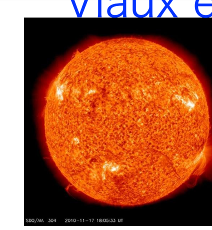




d giant

$< 4.3 \times 10^{-13}$

Viaux et al, 1311.1669

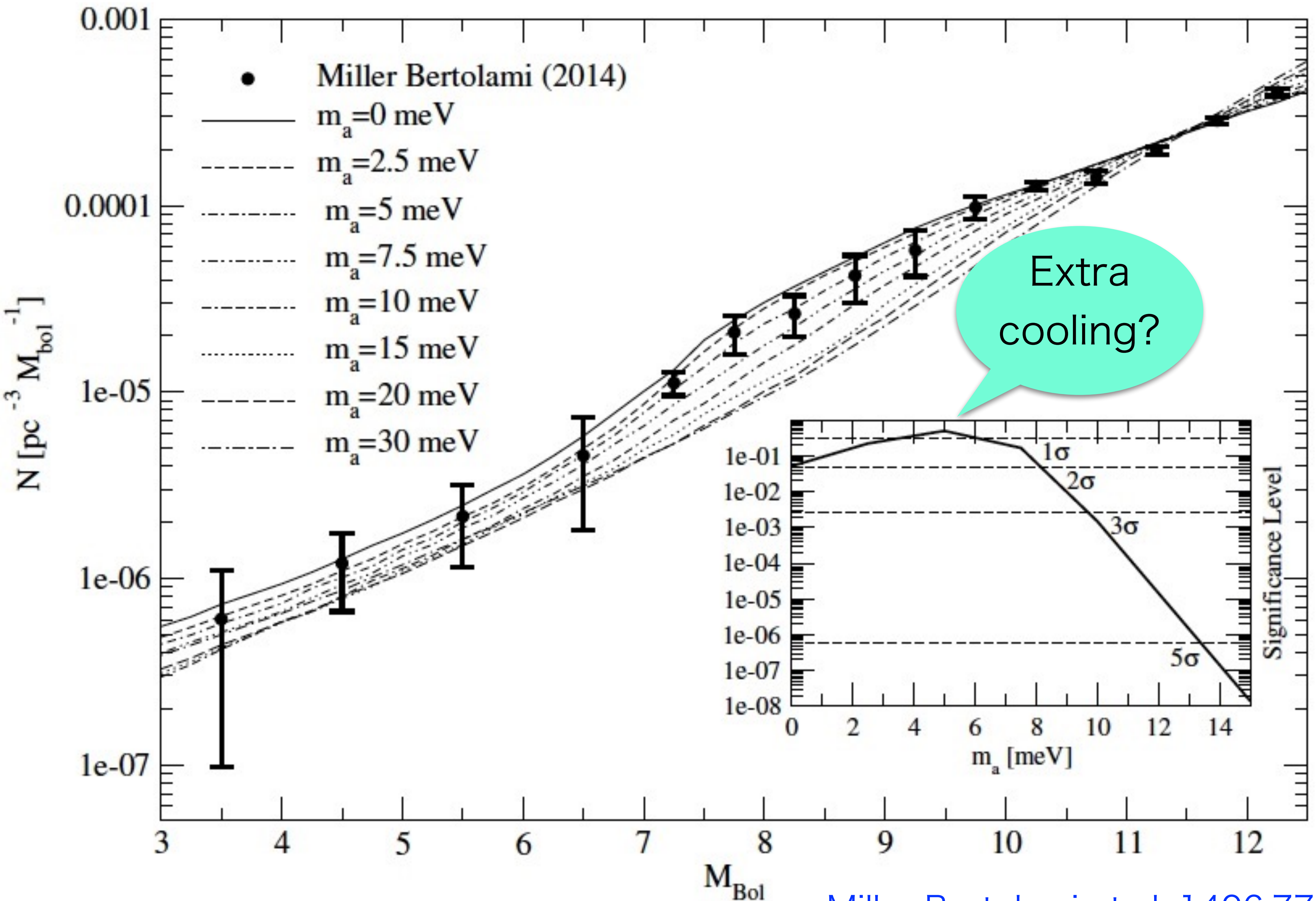


Sun

CAST, IAXO

$88 \times 10^{-10}\mathrm{GeV}^{-1}$

Andriamonje et al (CAST) `07



Miller Bertolami et al, 1406.7712

Figure 6. Comparison of the WDLF constructed by [48] with the theoretical WDLF for different axion masses. The continuous line in the inset shows the significance level at which different values of the axion mass are discarded by a χ^2-test. The significance levels associated with different σ-values are show for reference with short dashed lines.

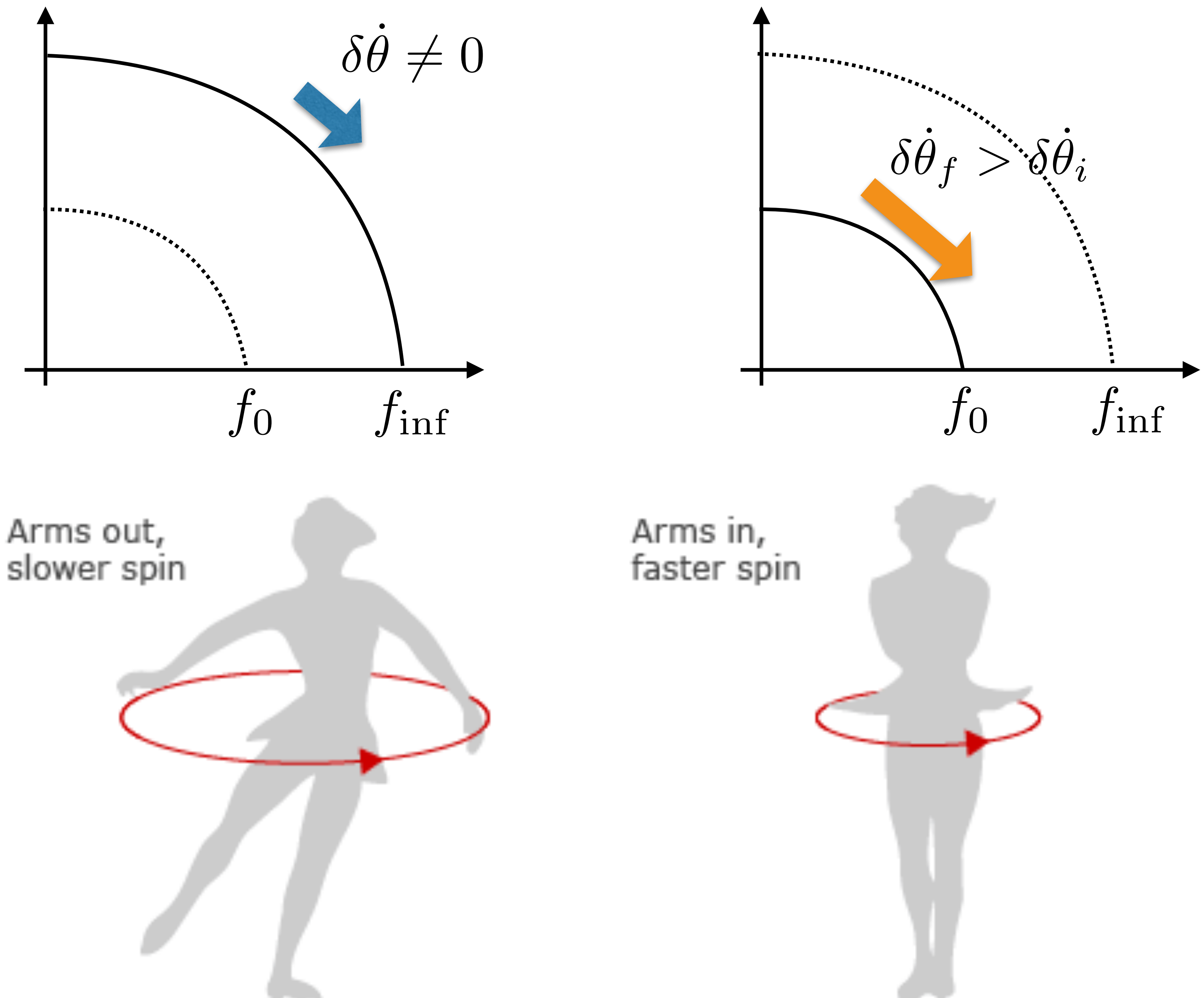
Asymptotic
ed giant
a

$\times 10^{-13}$
al, 1311.1669

Sun

AXO
$^{-10}\mathrm{GeV}^{-1}$
et al (CAST) `07

The enhancement of axion fluctuations at small scales can be understood by noting that “angular momentum” is conserved when the decay constant changes.



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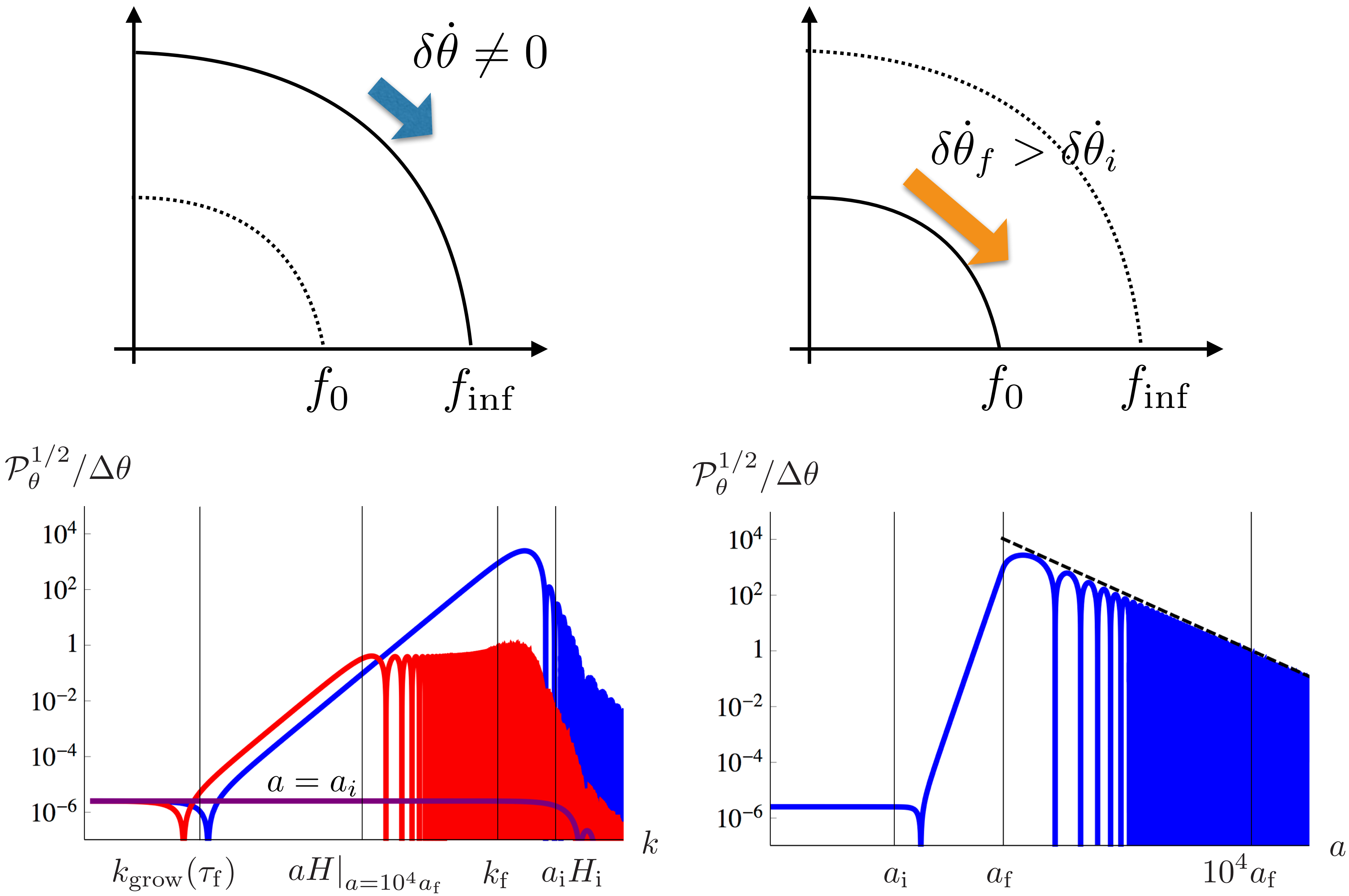
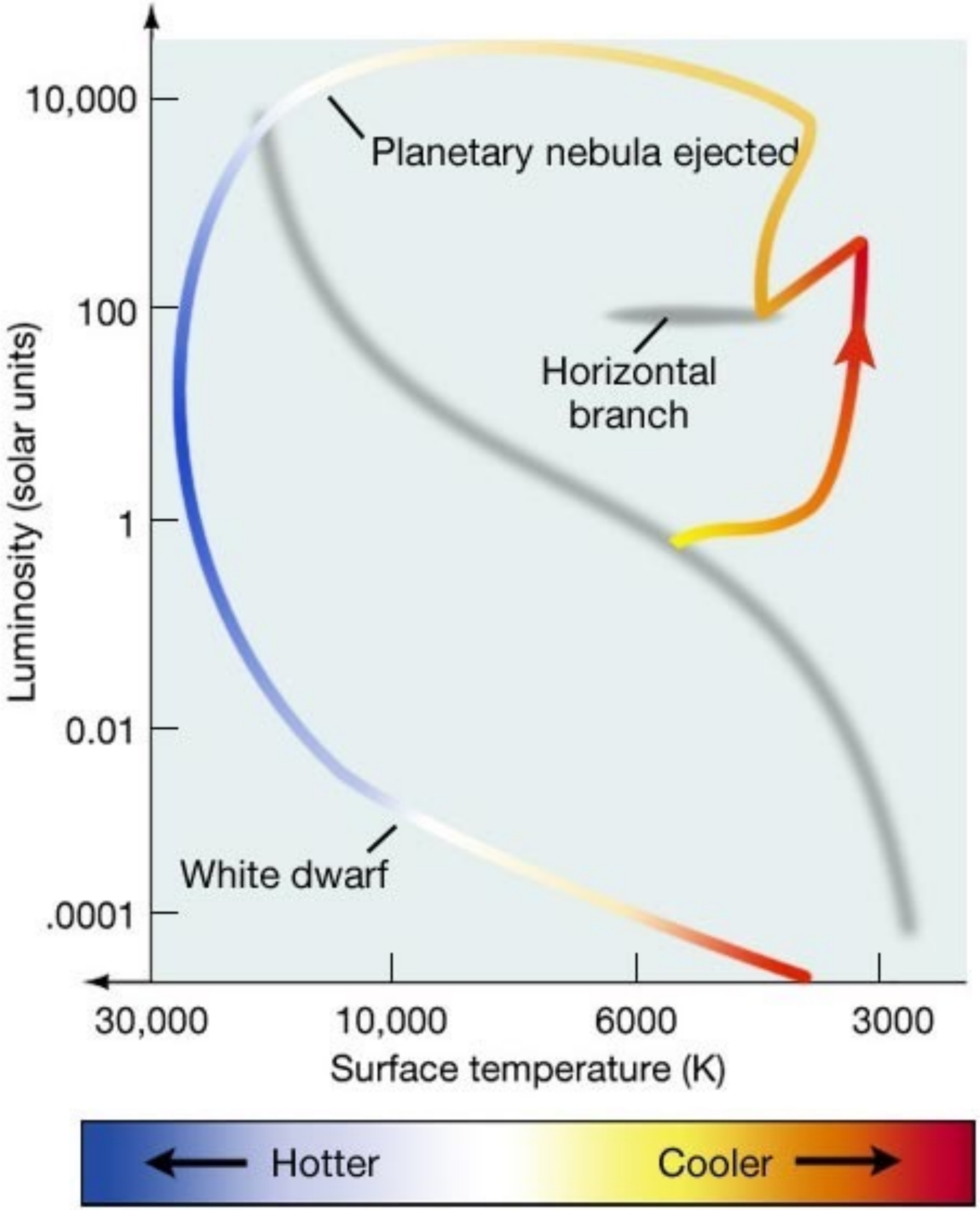
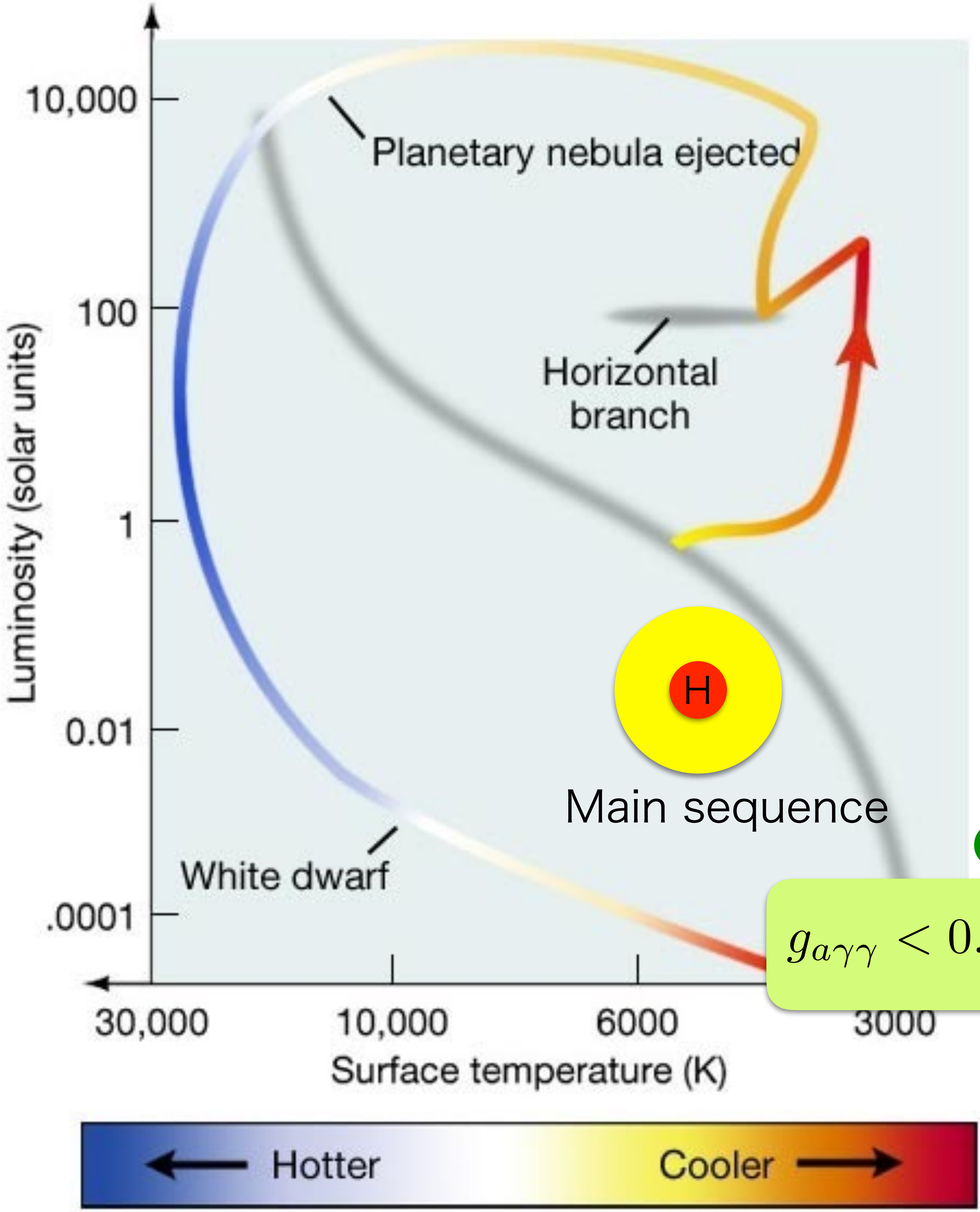
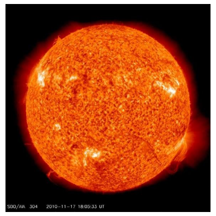


$H_{\rm inf} = 10^{14}\,{\rm GeV},\ f_0/N = 10^{11}\,{\rm GeV},\ f_{\rm inf}/N = 10^{18}\,{\rm GeV}$ Takeshi Kobayashi, FT, 1607.04294


10,000
100
1
0.01
.0001
Luminosity (solar units)
Planetary nebula ejected
Horizontal
branch
White dwarf
30,000
10,000
6000
3000
Surface temperature (K)
Hotter
Cooler



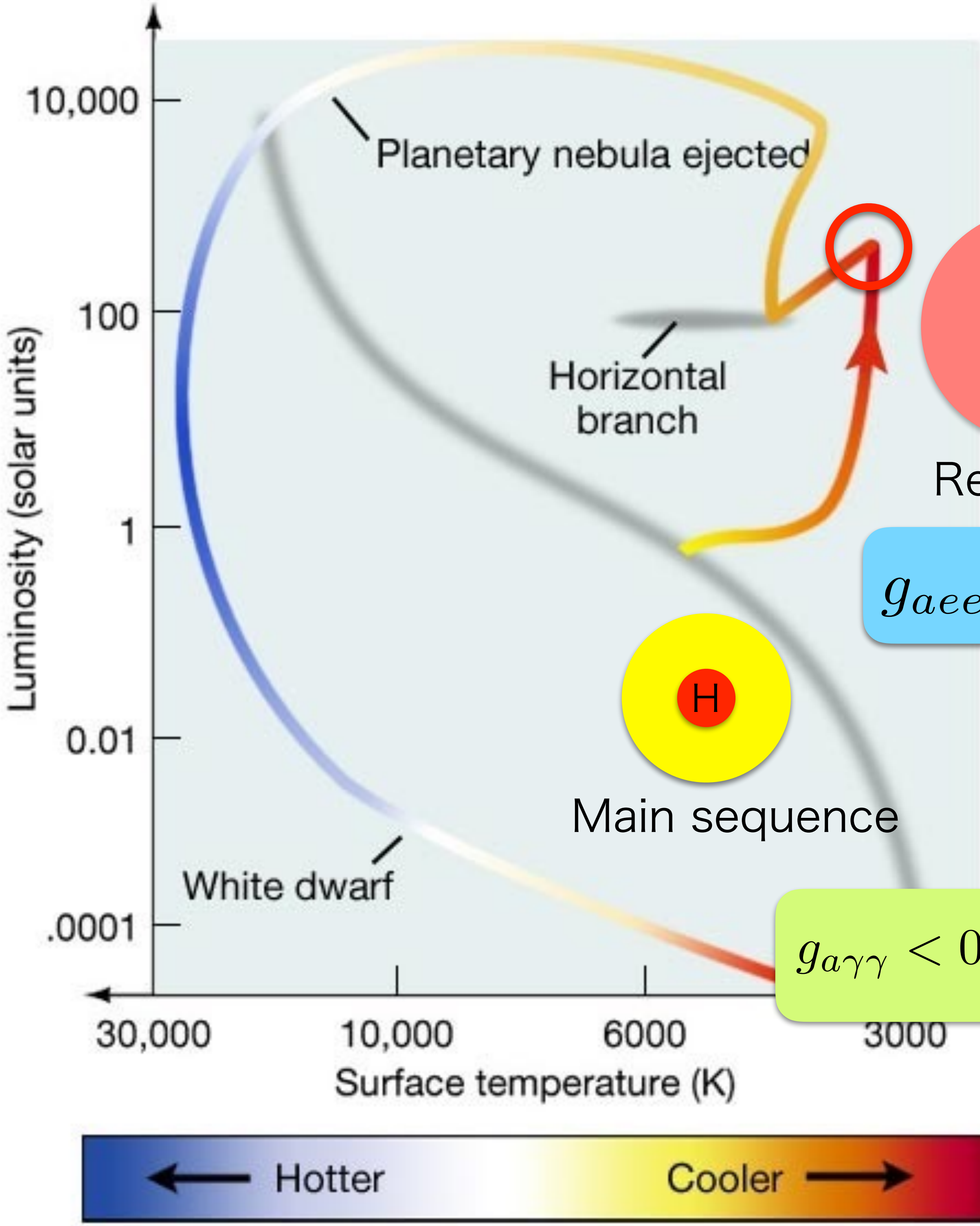


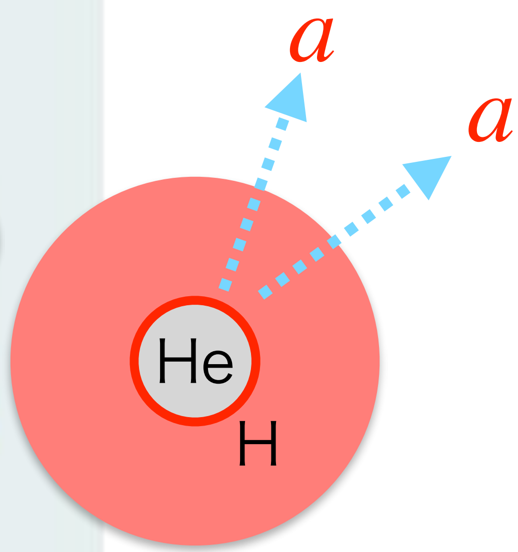
Sun

CAST, IAXO

$$g_{a\gamma\gamma} < 0.88 \times 10^{-10} \mathrm{GeV}^{-1}$$

Andriamonje et al (CAST) `07

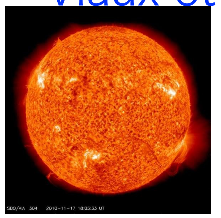




Red giant

$$g_{aee} < 4.3 \times 10^{-13}$$

Viaux et al, 1311.1669



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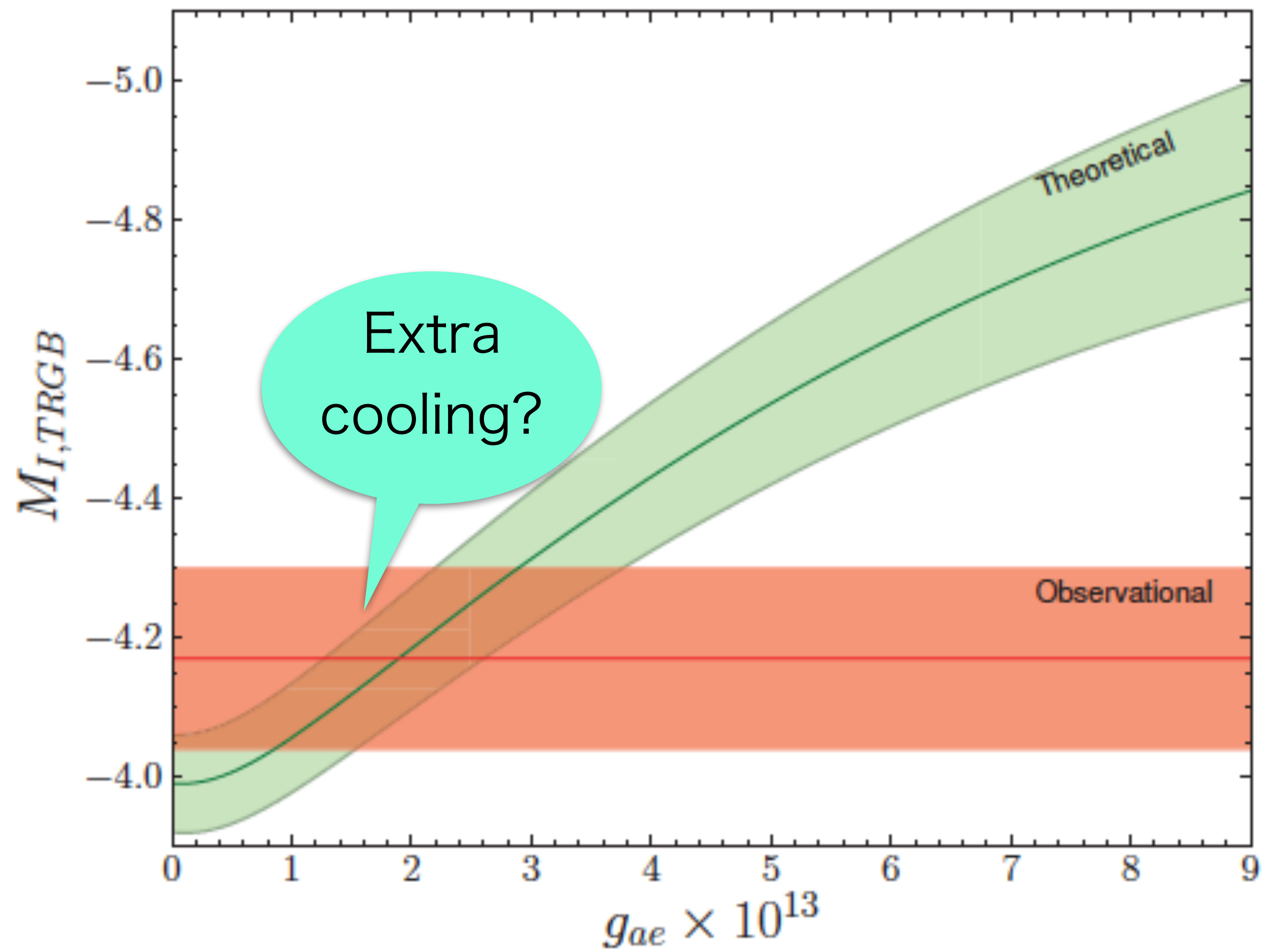
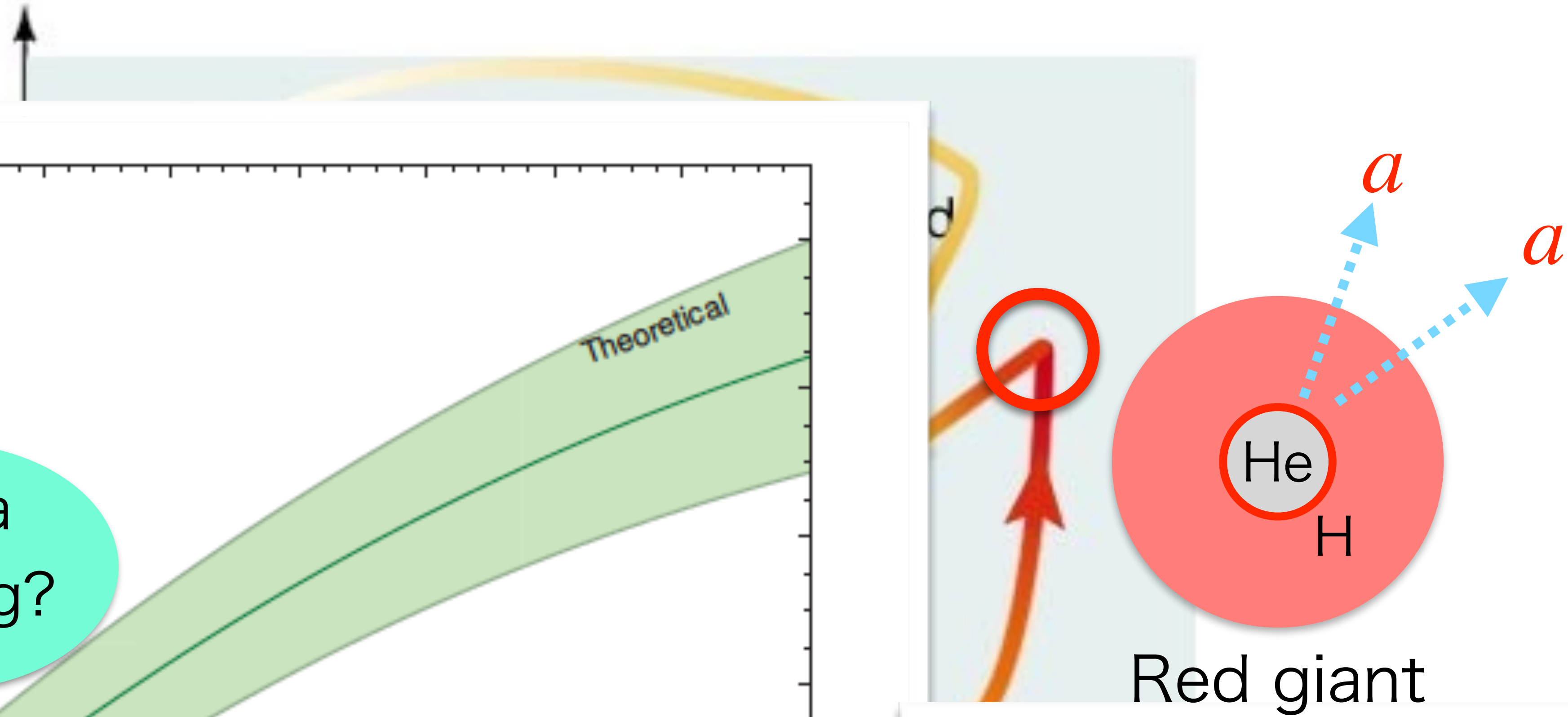


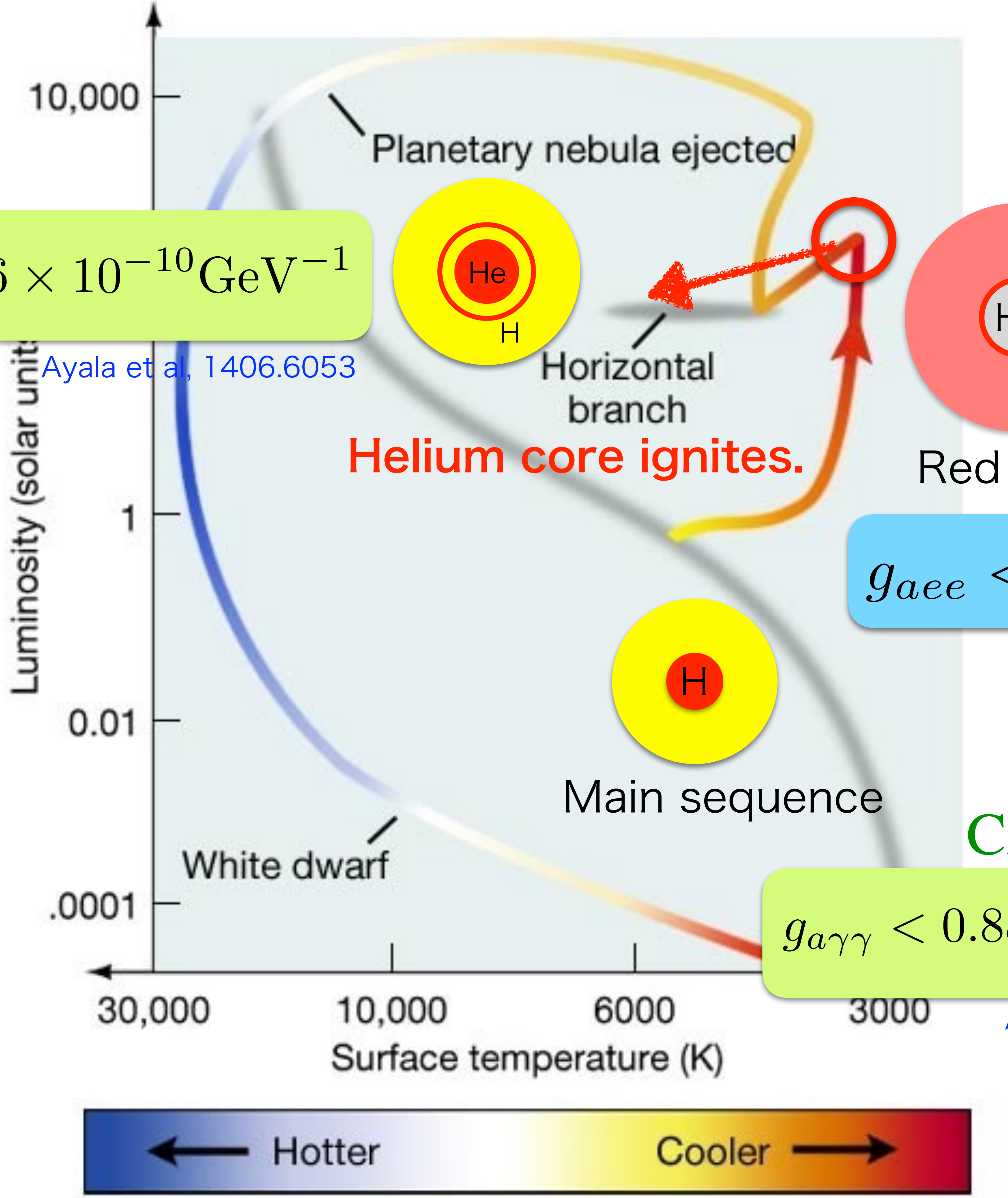


Viaux et al, 1311.1669

FIG. 2. Absolute I-band brightness of TRGB in cluster M5. *Red band:* Observations with 1σ error, dominated by distance. *Green band:* Theoretical prediction, depending on the axion-electron coupling, with 1σ systematic error, dominated by the bolometric correction.

$$g_{a\gamma\gamma} < 0.66 \times 10^{-10}\mathrm{GeV}^{-1}$$

Ayala et al, 1406.6053



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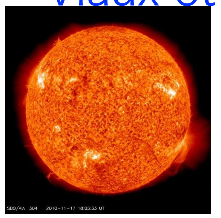
Viaux et al, 1311.1669



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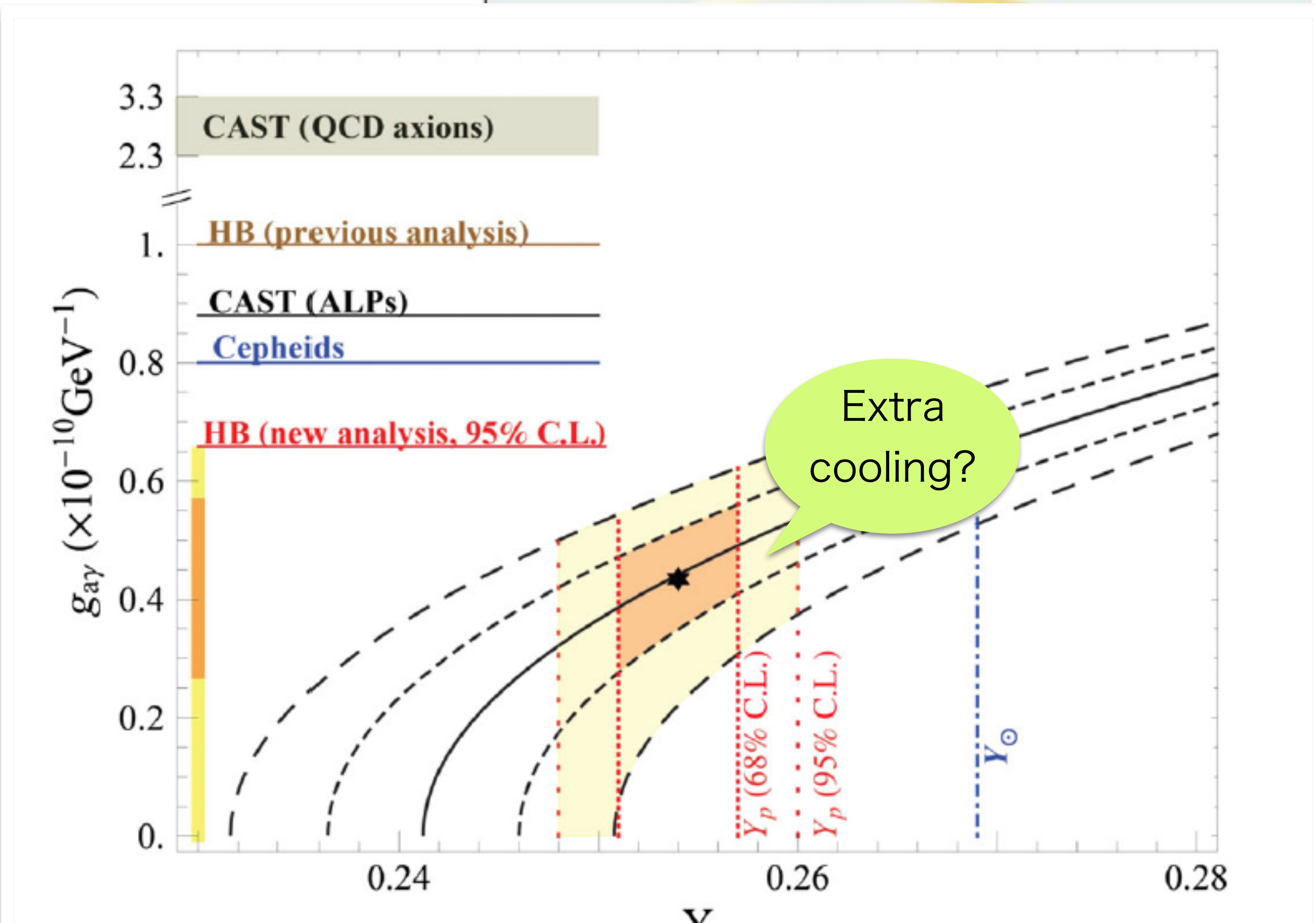

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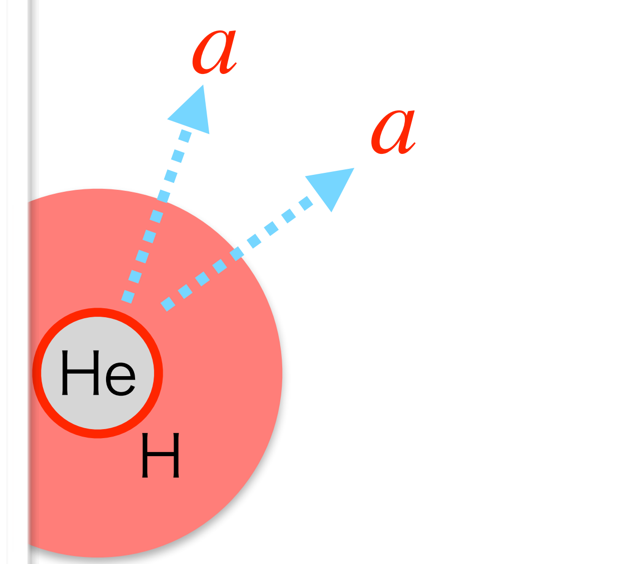

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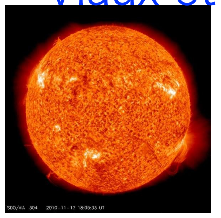

Sun

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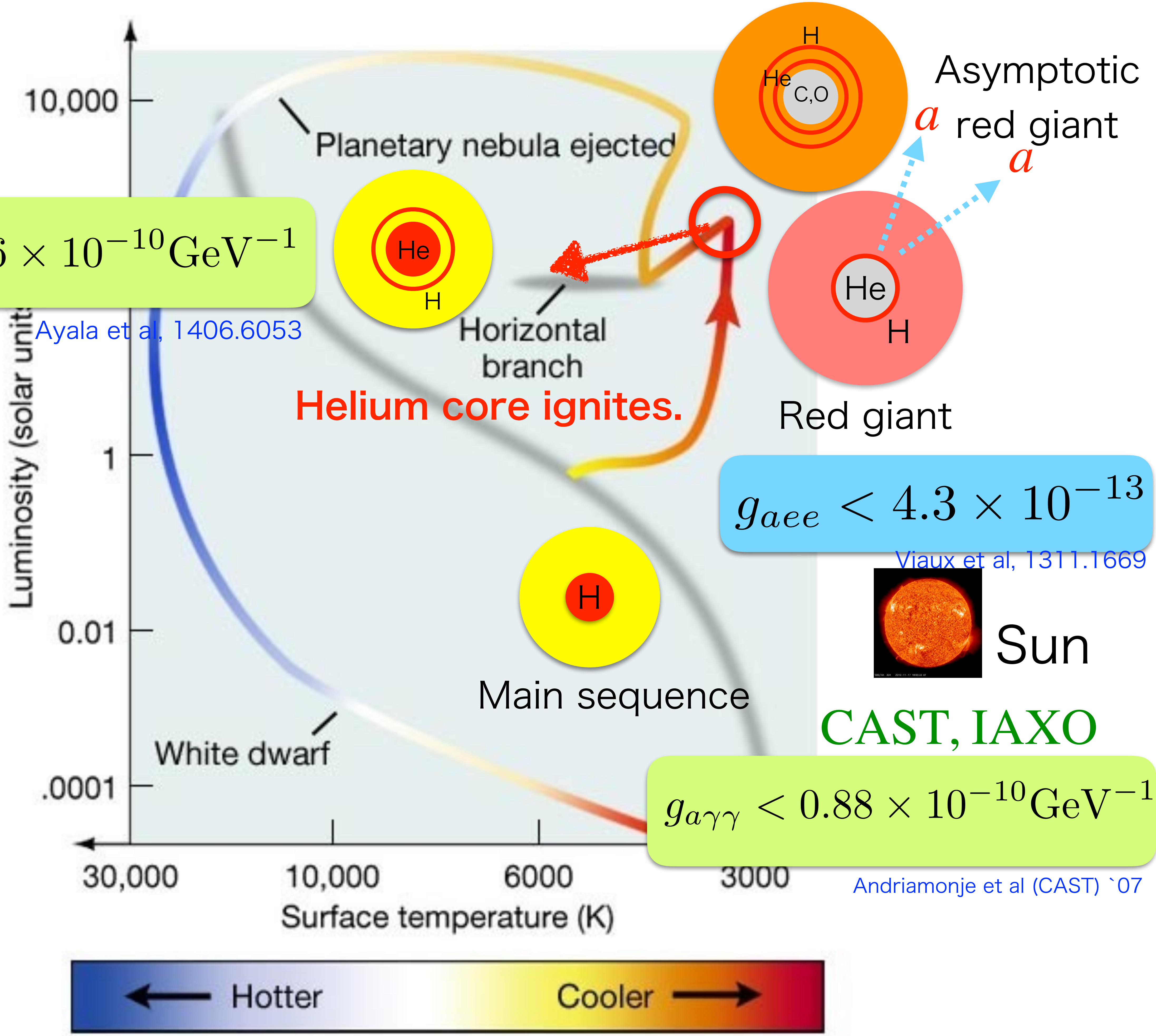
$88 \times 10^{-10}\mathrm{GeV}^{-1}$

Andriamonje et al (CAST) `07

Surface temperature (K)


Asymptotic red giant
H
He
C,O
a
a
$g_{a\gamma\gamma} < 0.66 \times 10^{-10} \mathrm{GeV}^{-1}$
Ayala et al, 1406.6053
He
H
Planetary nebula ejected
Horizontal branch
Helium core ignites.
He
H
Red giant
$g_{aee} < 4.3 \times 10^{-13}$
Viaux et al, 1311.1669
H
Main sequence
Sun
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Andriamonje et al (CAST) `07
White dwarf
10,000
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0.01
.0001
Luminosity (solar units)
30,000
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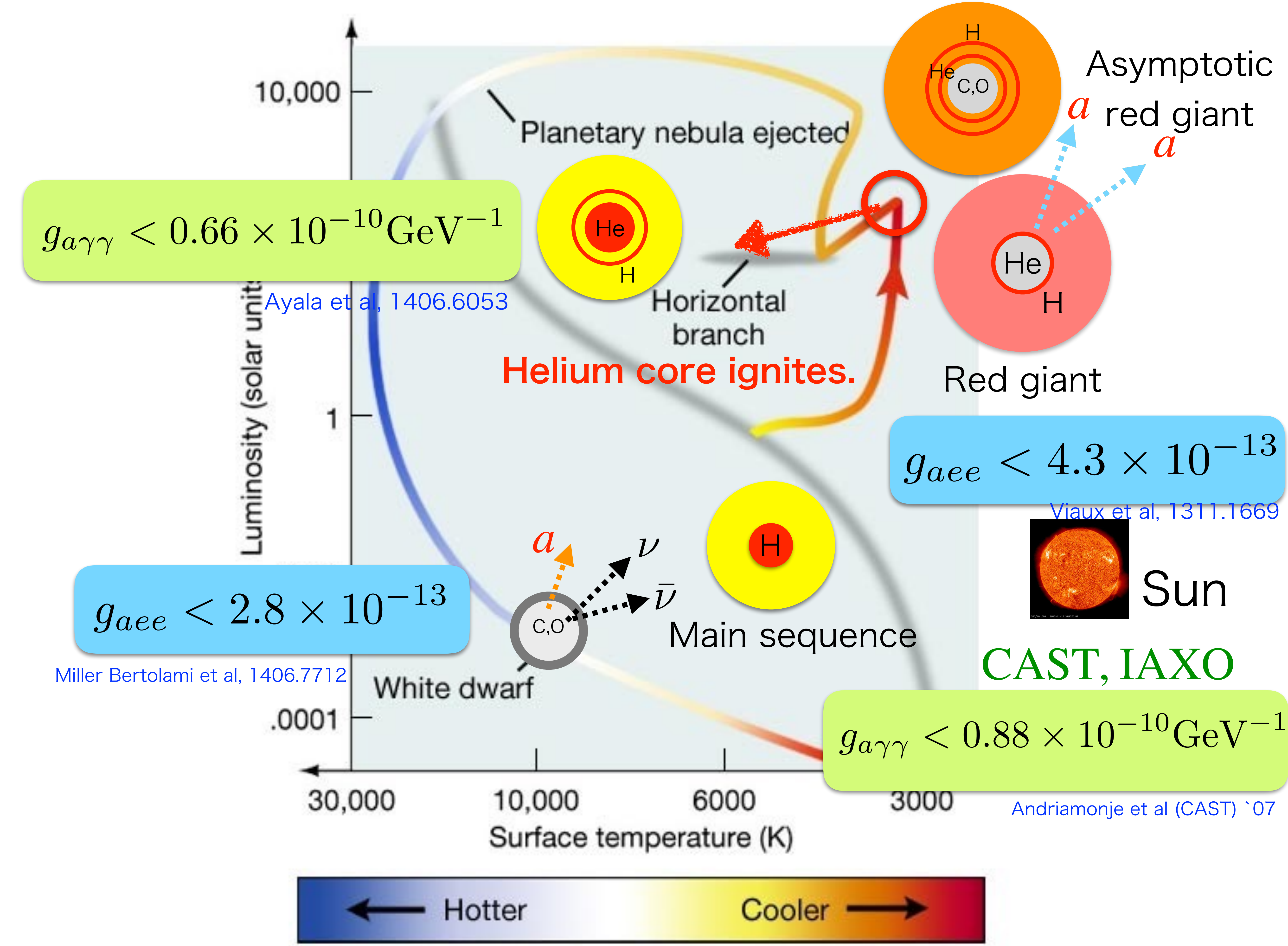
Hotter
Cooler



Asymptotic red giant
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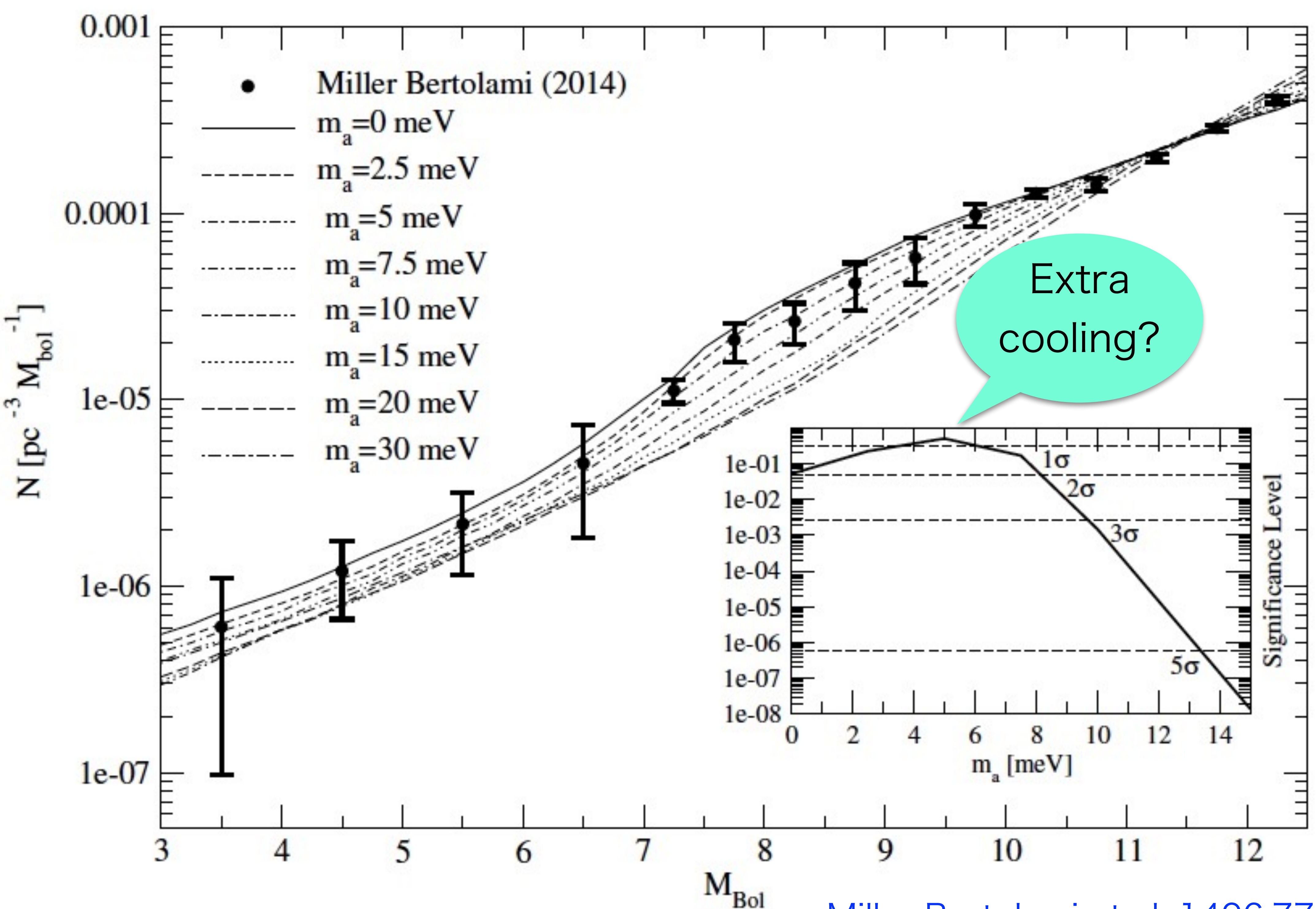

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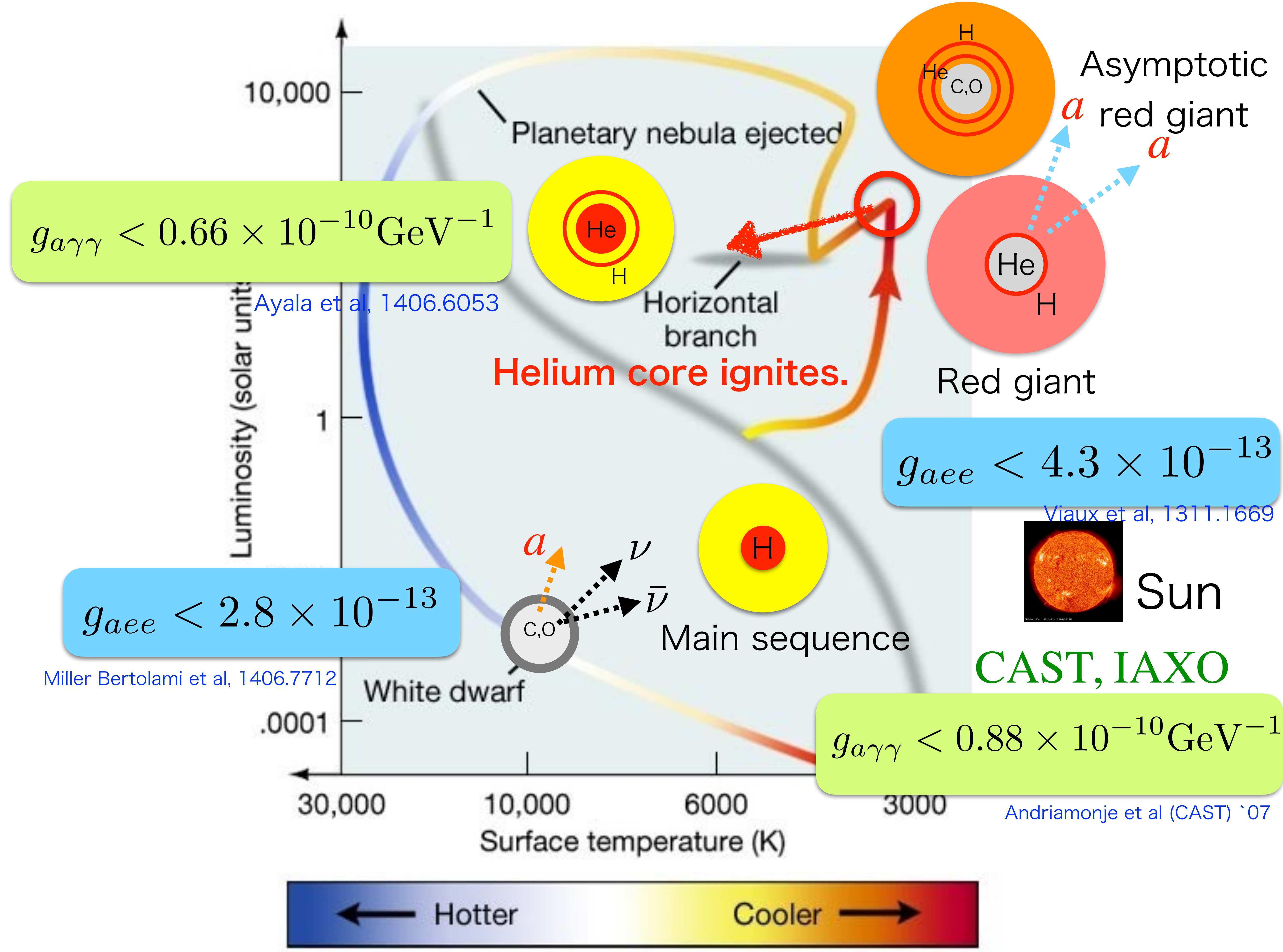

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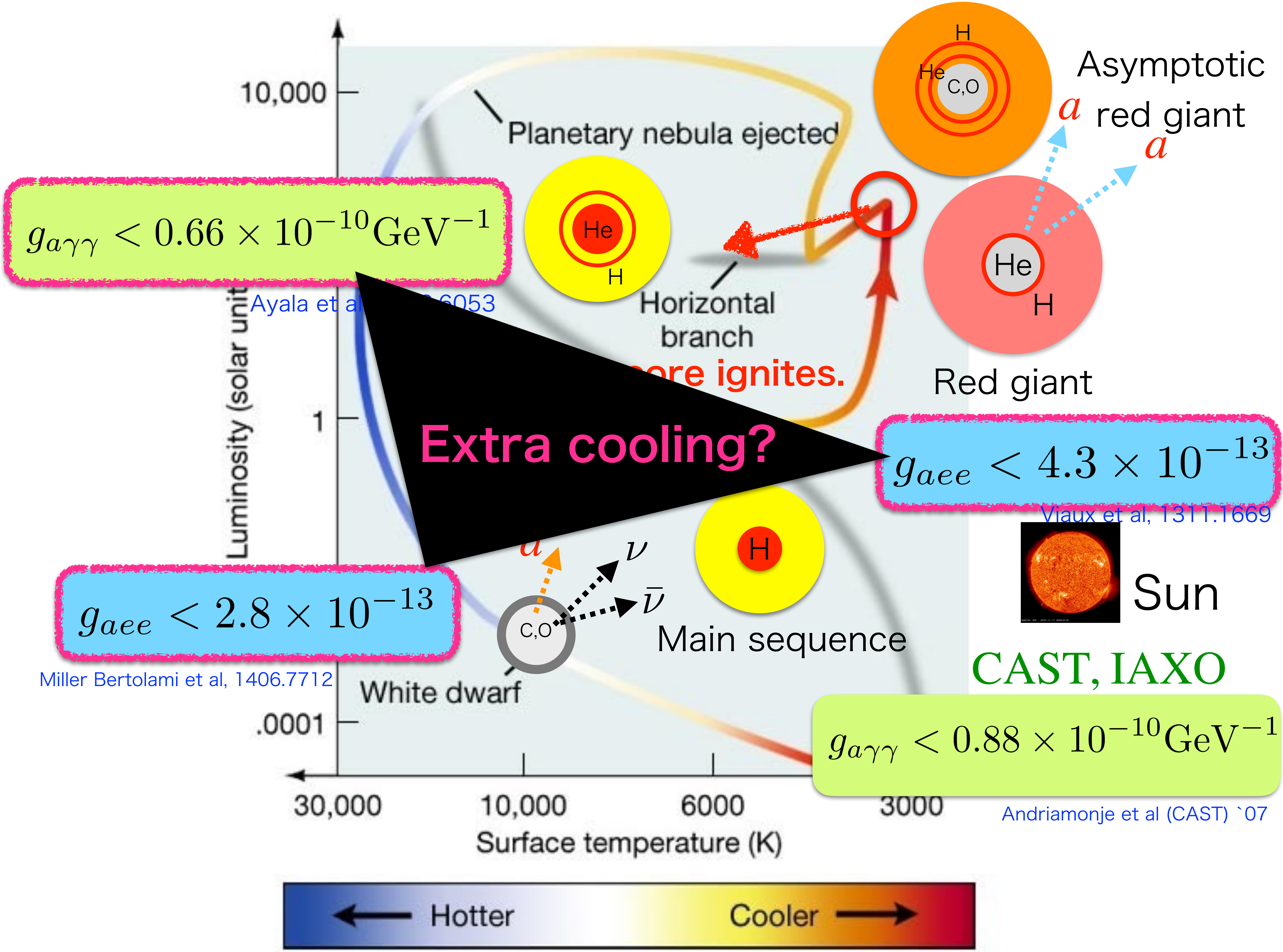

Asymptotic red giant
H
He
C,O
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a
Planetary nebula ejected
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He
H
Horizontal branch
He
H
Red giant
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10,000
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.0001
Extra cooling?
$g_{aee} < 4.3 \times 10^{-13}$
Viaux et al, 1311.1669
ν
$\bar{\nu}$
C,O
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CAST, IAXO
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