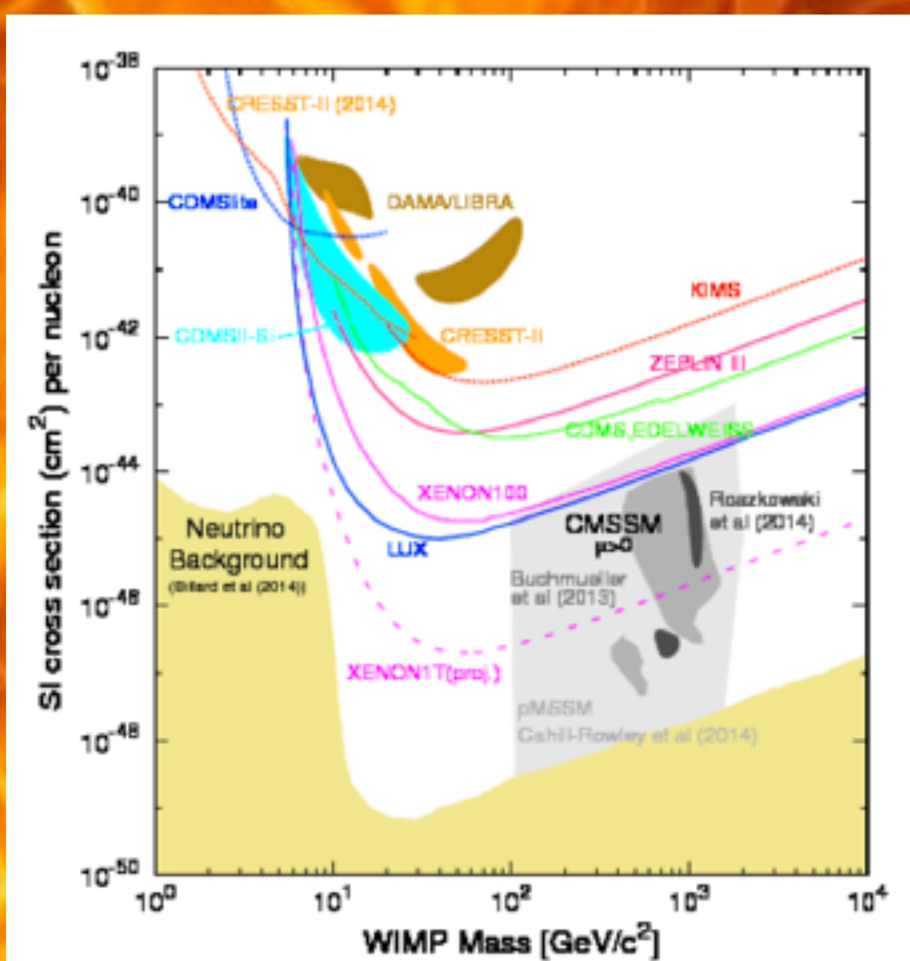
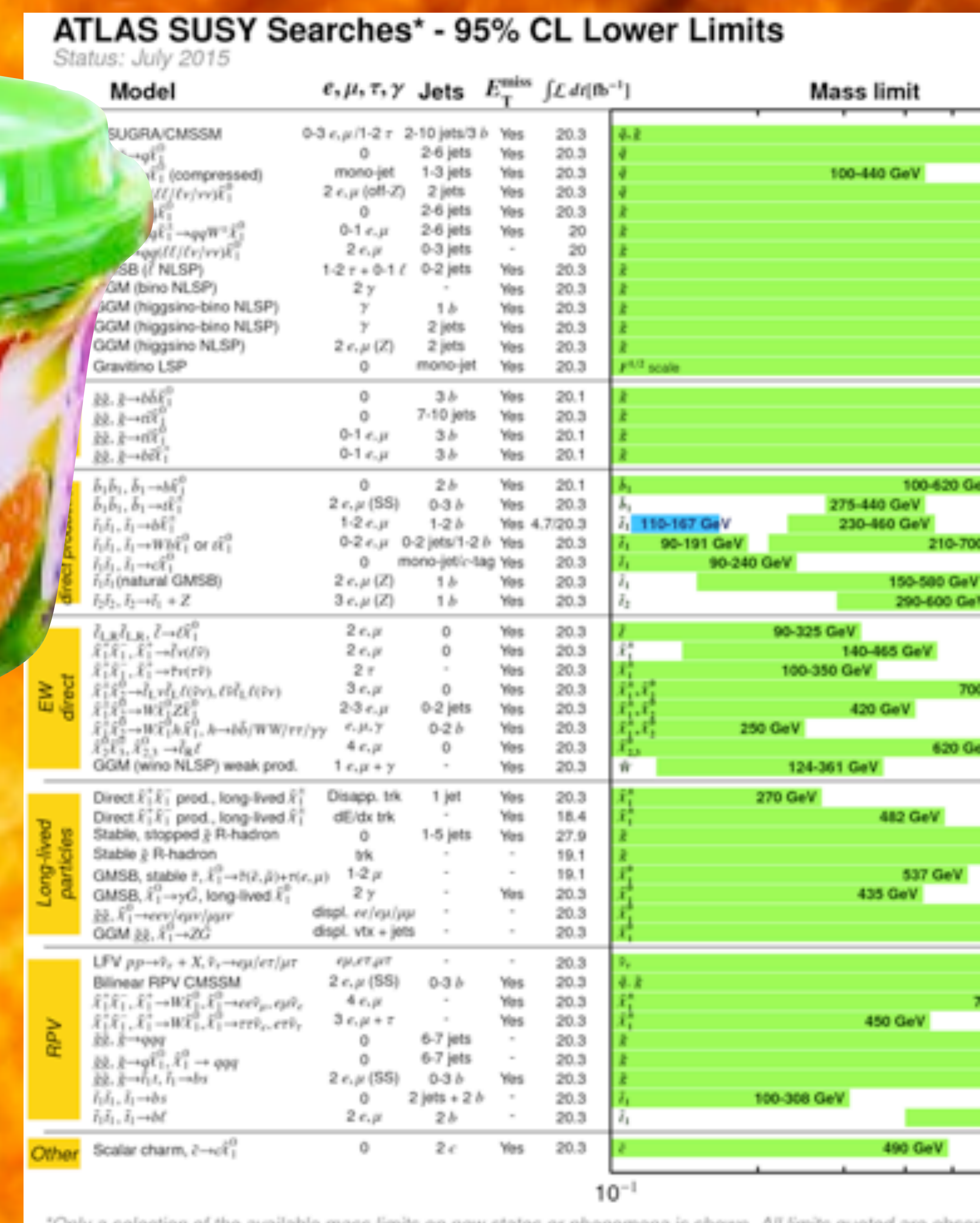
Axions are on fire!





Axions are on fire!

Theory

Experiments

Cosmology

Astrophysics

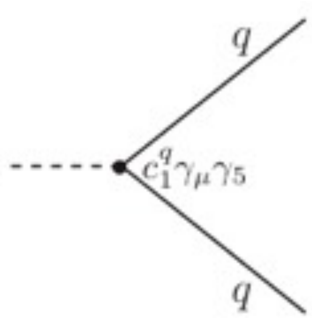
Theory

- Peccei-Quinn mechanism, solution of strong CP problem -> QCD axion

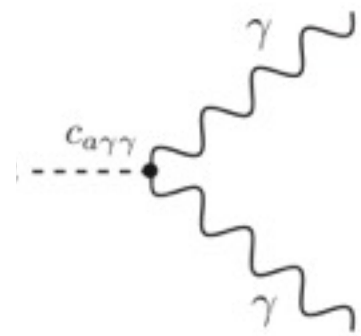
$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi} G_{\mu\nu a}\widetilde{G}_a^{\mu\nu}\left(\frac{a}{f_a} + \theta\right) + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) \qquad V_{\rm QCD}(\theta + a/f_a = 0) = \min.$$

- axion = Goldstone boson (similar to pion)

coupling to hadrons



coupling to photons

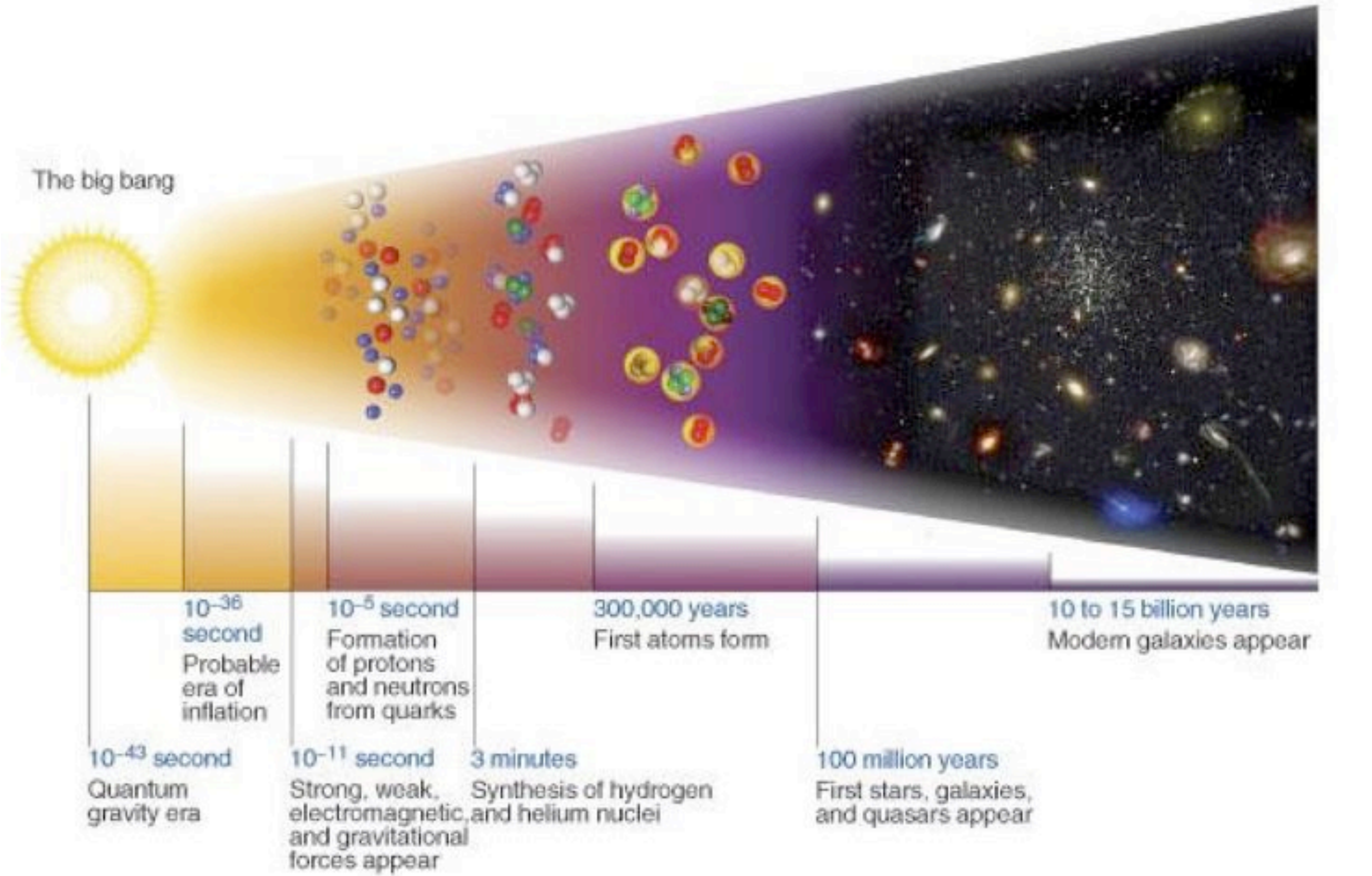


... $m_a^2 \sim \frac{\chi_{\rm QCD}}{f_a^2}$

- New energy scale f_a (axion decay constant)

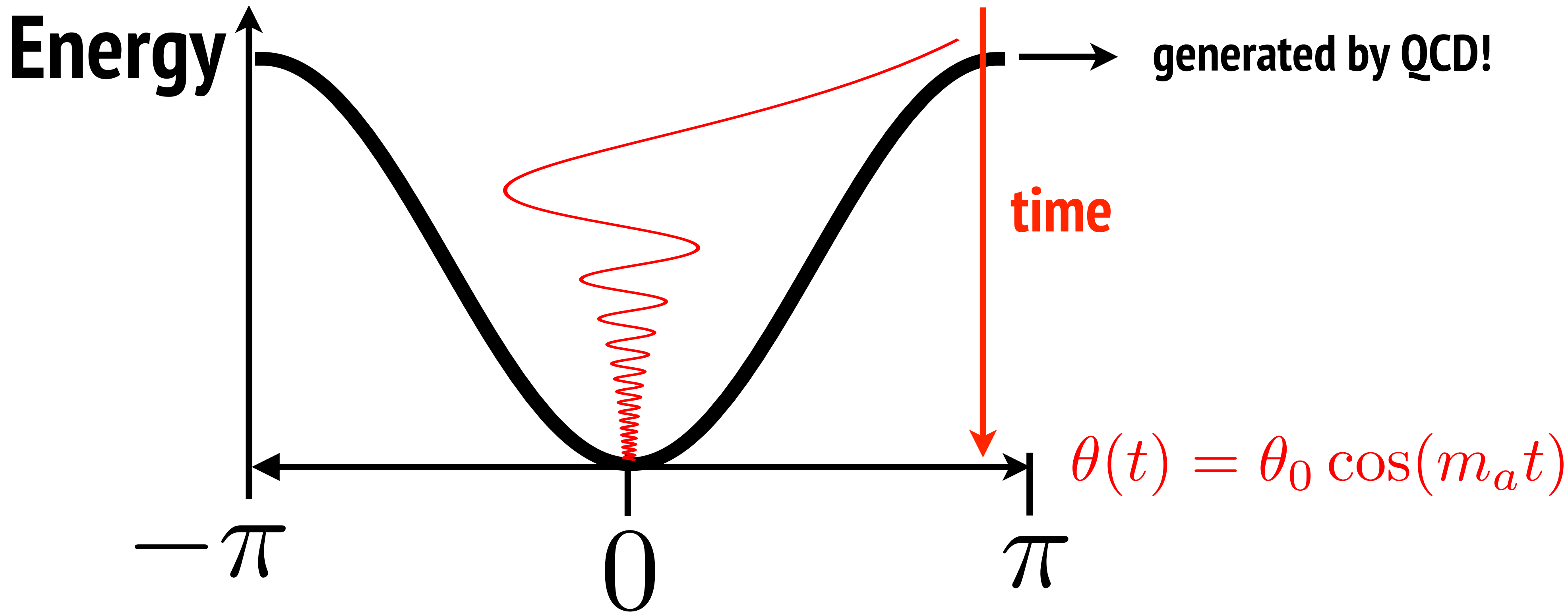
- Axions appear BSM,
- compatible with GUT, SUSY, String theory
- String theory predicts many <u>axion-like particles</u> = axiverse
- SMASH model
- relation with neutrino mass

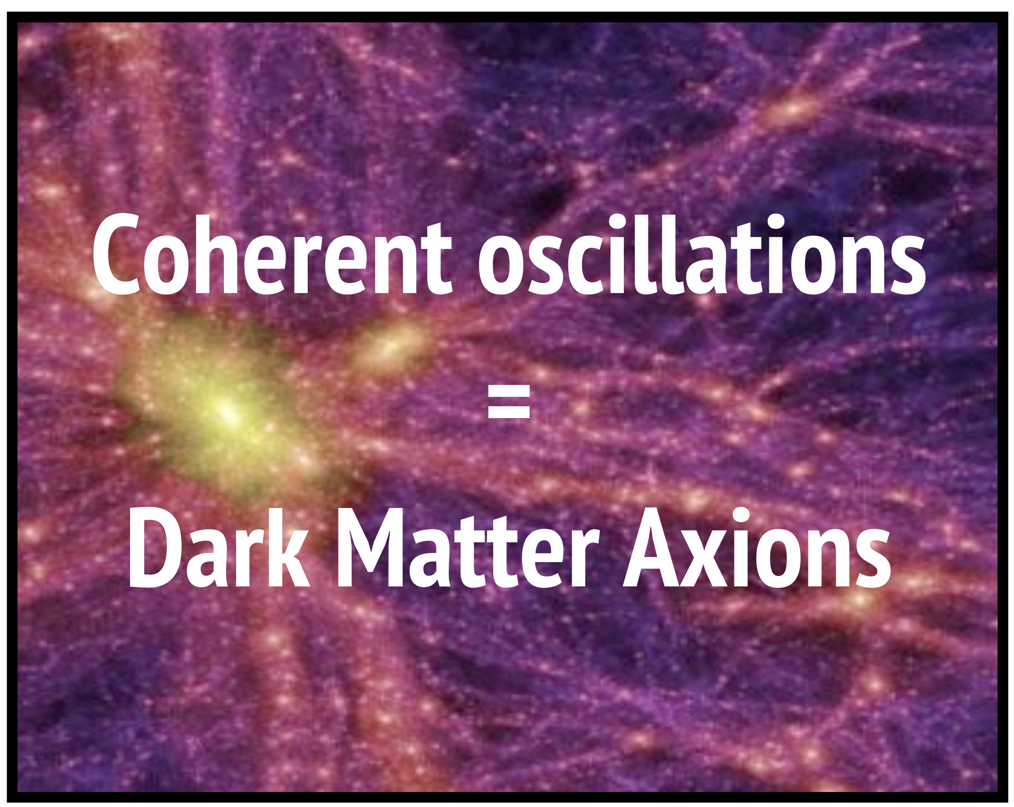
Cosmology


The big bang
10^{-43} second
Quantum gravity era
10^{-36} second
Probable era of inflation
10^{-11} second
Strong, weak, electromagnetic, and gravitational forces appear
10^{-5} second
Formation of protons and neutrons from quarks
3 minutes
Synthesis of hydrogen and helium nuclei
300,000 years
First atoms form
100 million years
First stars, galaxies, and quasars appear
10 to 15 billion years
Modern galaxies appear

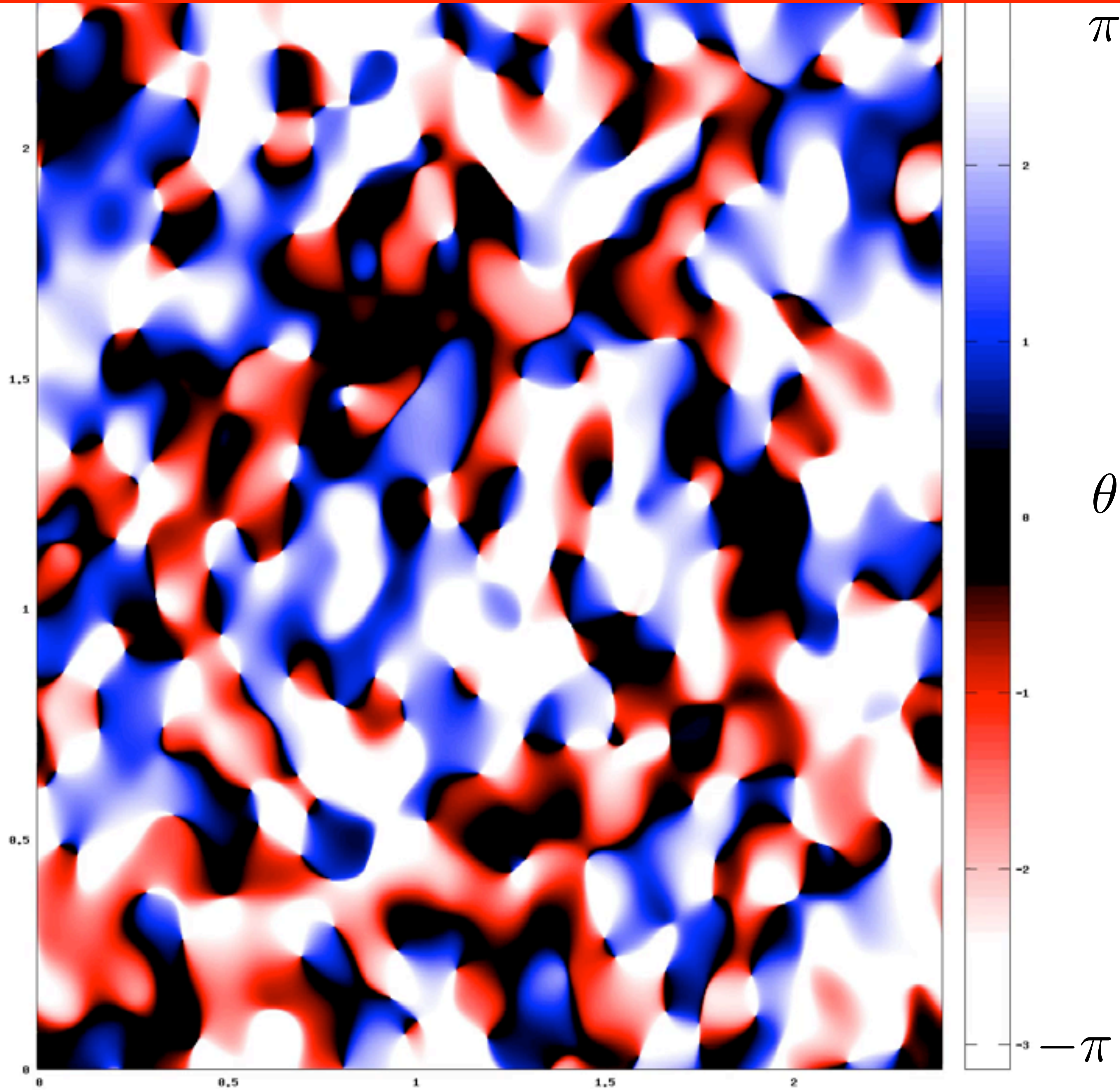
Dark matter

- $\theta(t, \mathrm{x})$ **relaxes to its minimum, overshoots and oscillates**

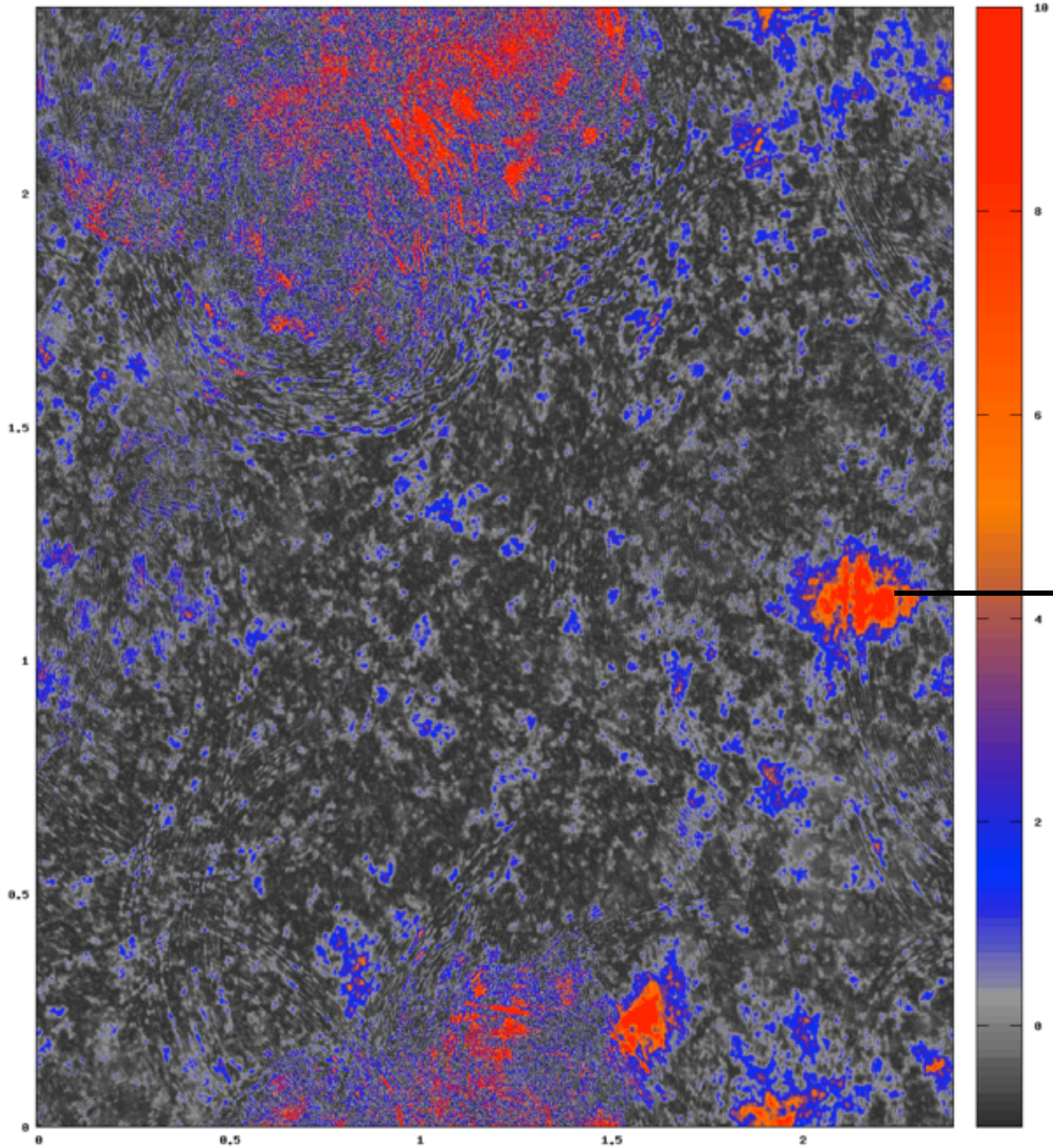




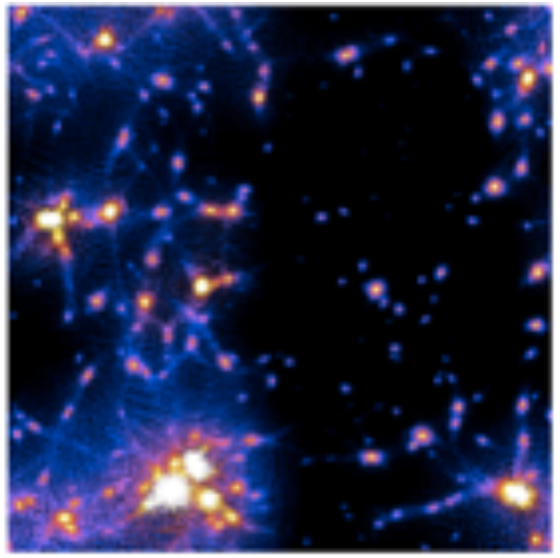
Theta evolution, Averaged SCENARIO I



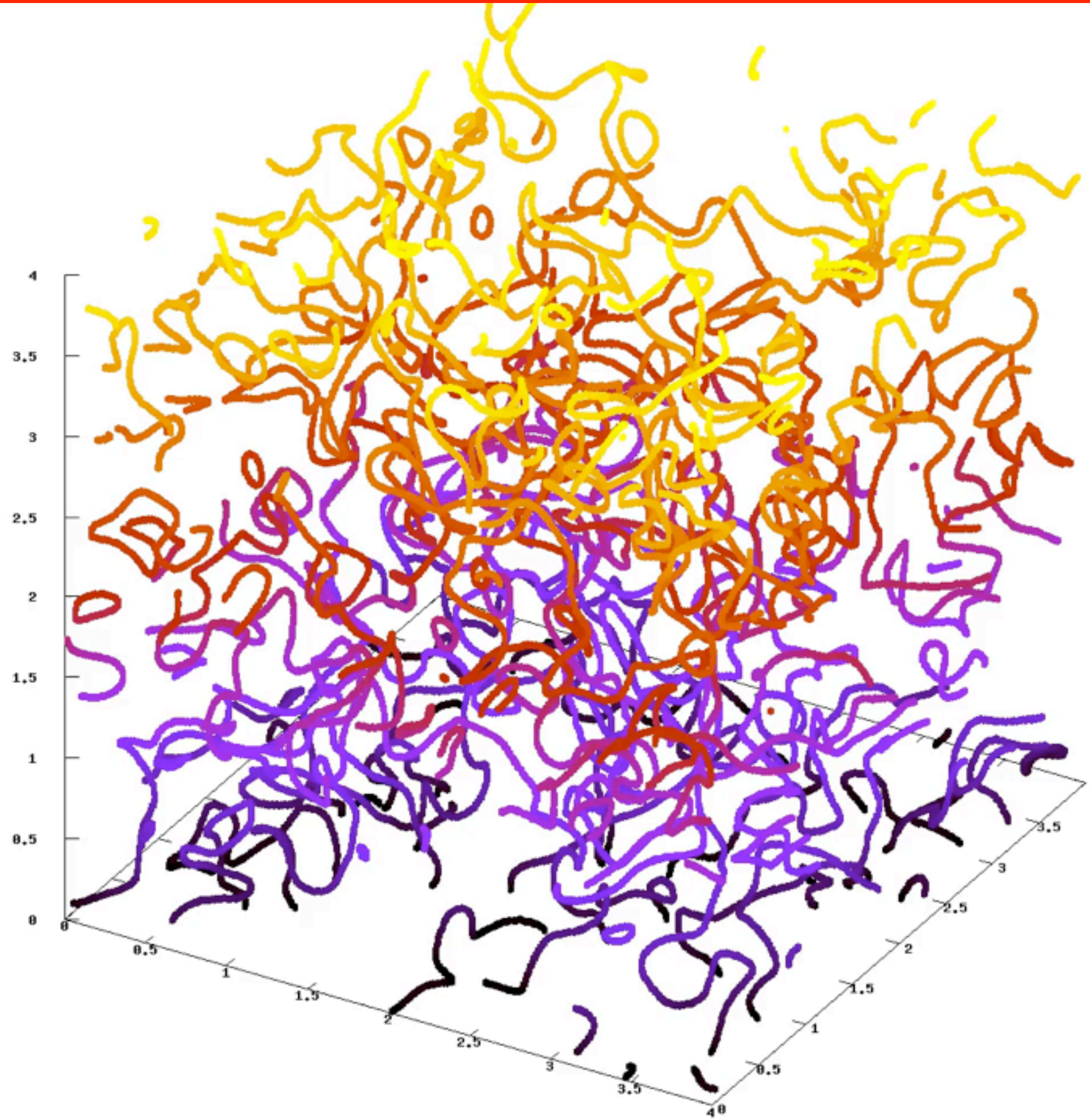
Dark matter density, inhomogeneous at comoving mpc scales



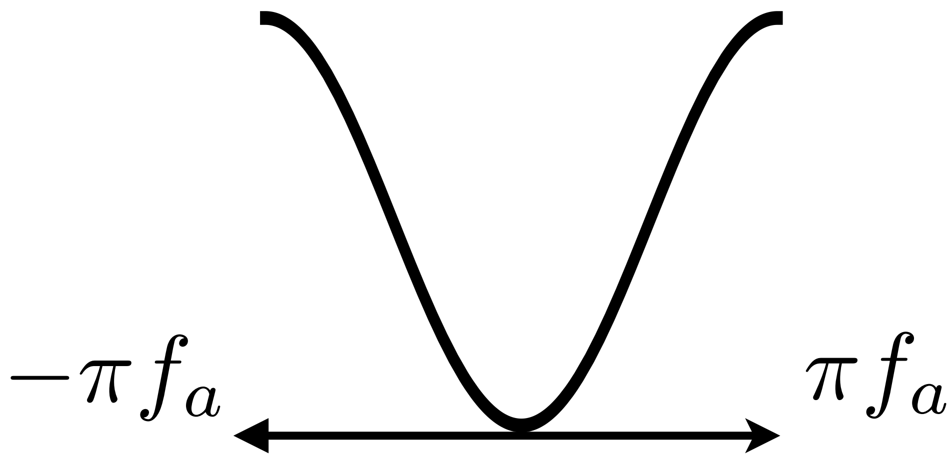
minicluster seed!



Strings

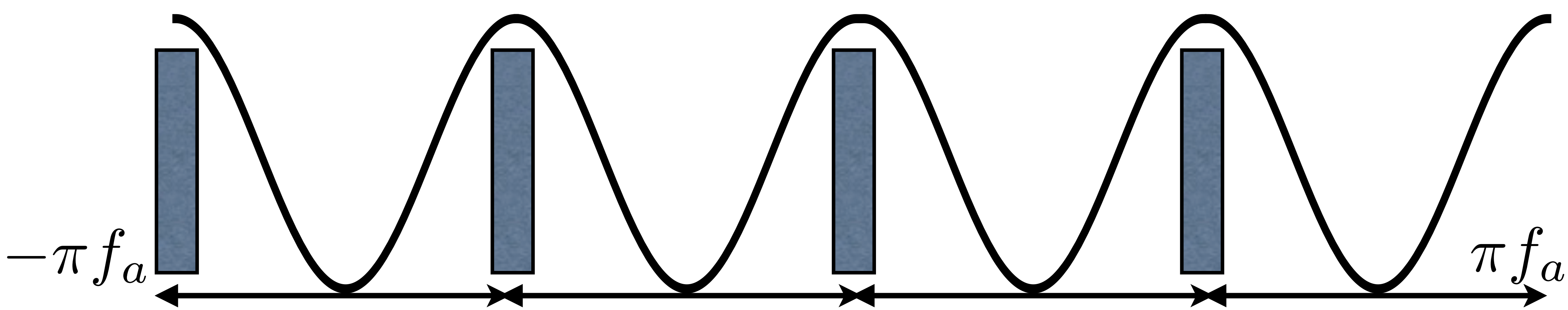


SCENARIO I, N=1

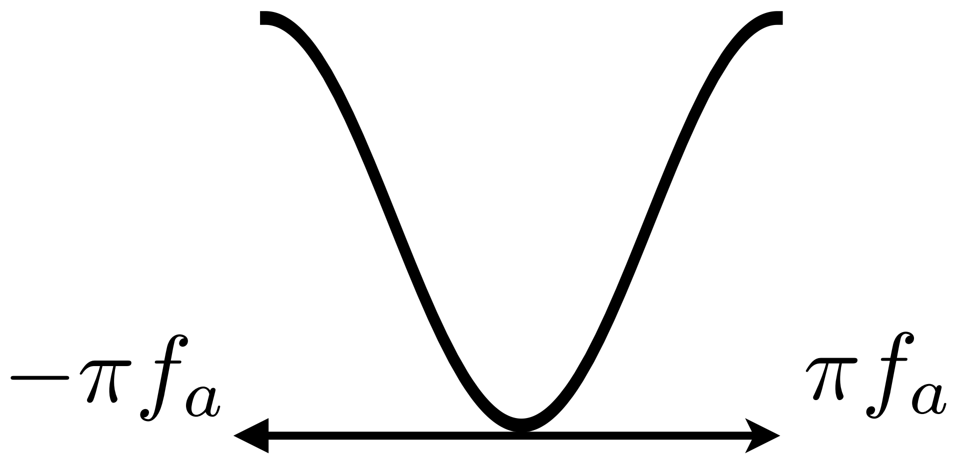


$$\frac{a}{f_a} = N\theta$$

SCENARIO I, N>1, Domain Walls stable-> cosmological disaster

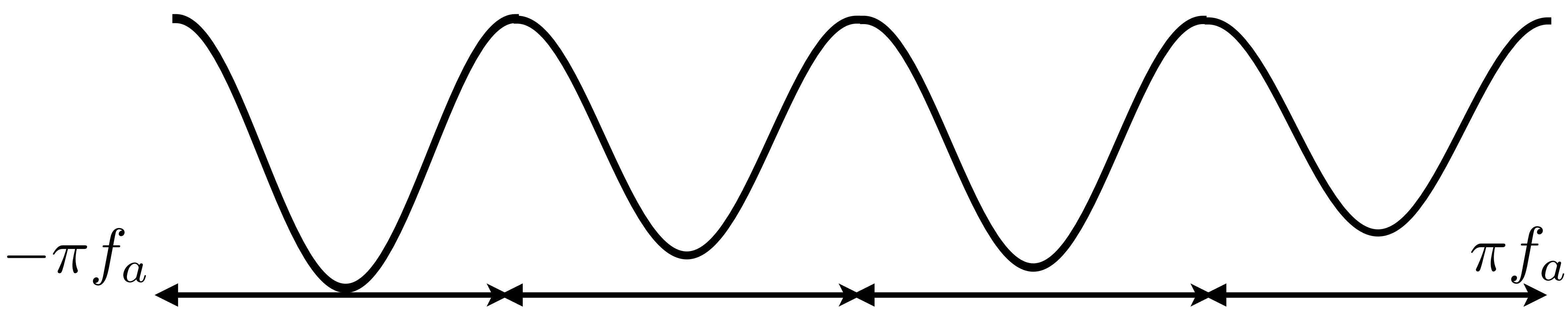


SCENARIO I, N=1

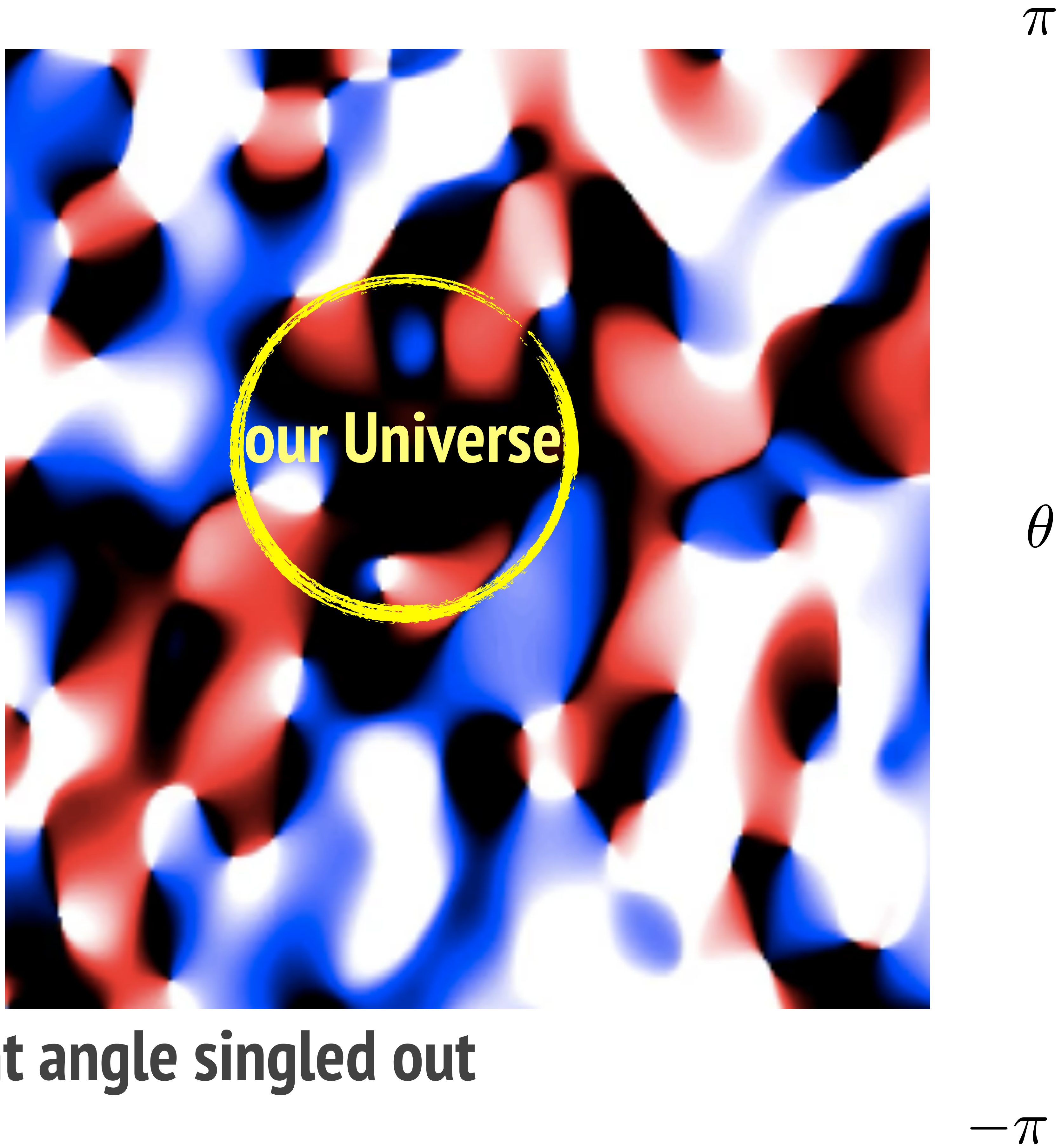


$$\frac{a}{f_a} = N\theta$$

SCENARIO I, N>1, break slightly degeneracy (quantum gravity?)

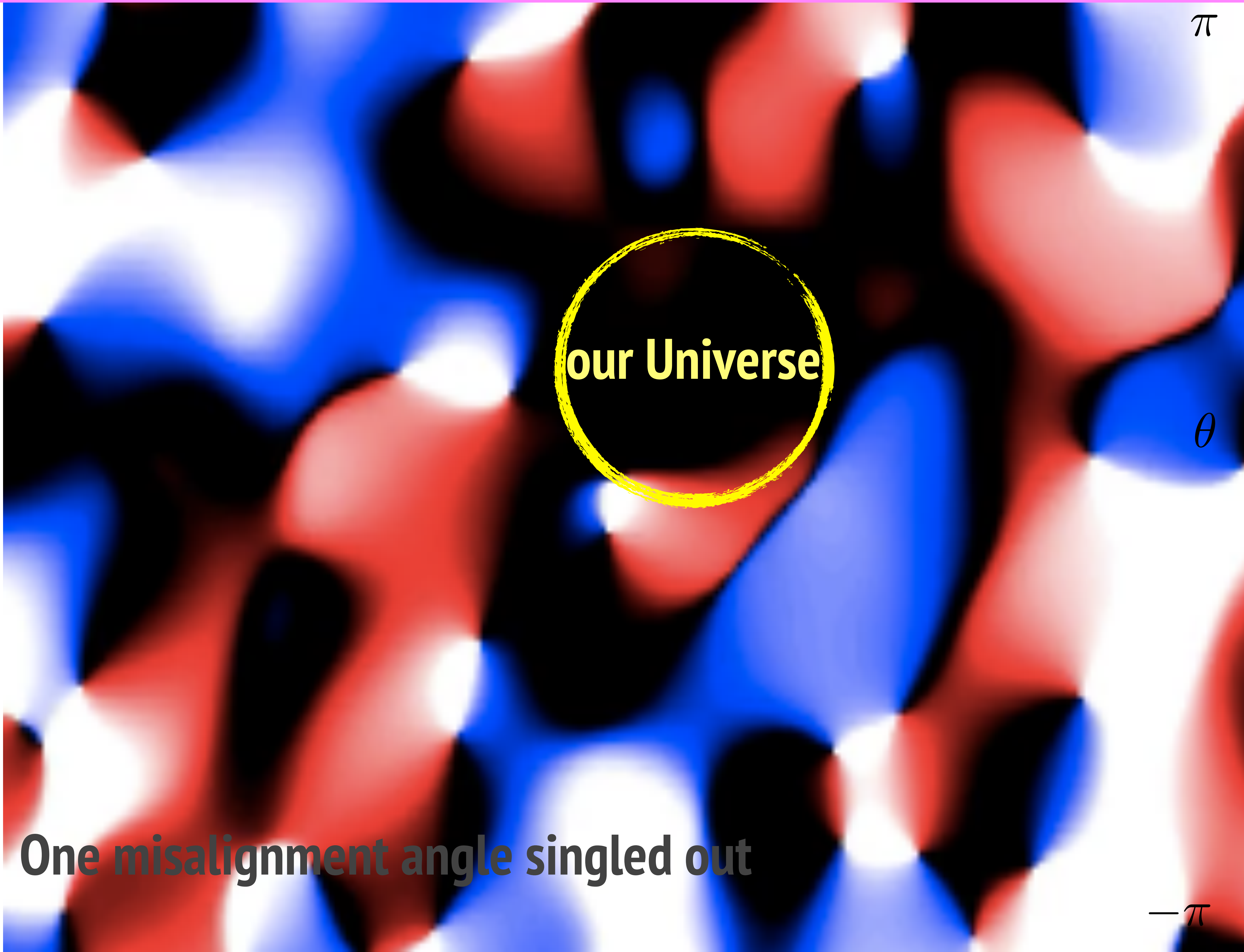


Theta evolution, inflated SCENARIO I



One misalignment angle singled out

Theta evolution, inflated SCENARIO I



Axion DM, isocurvature issue and BICEP2

SCENARIO-II

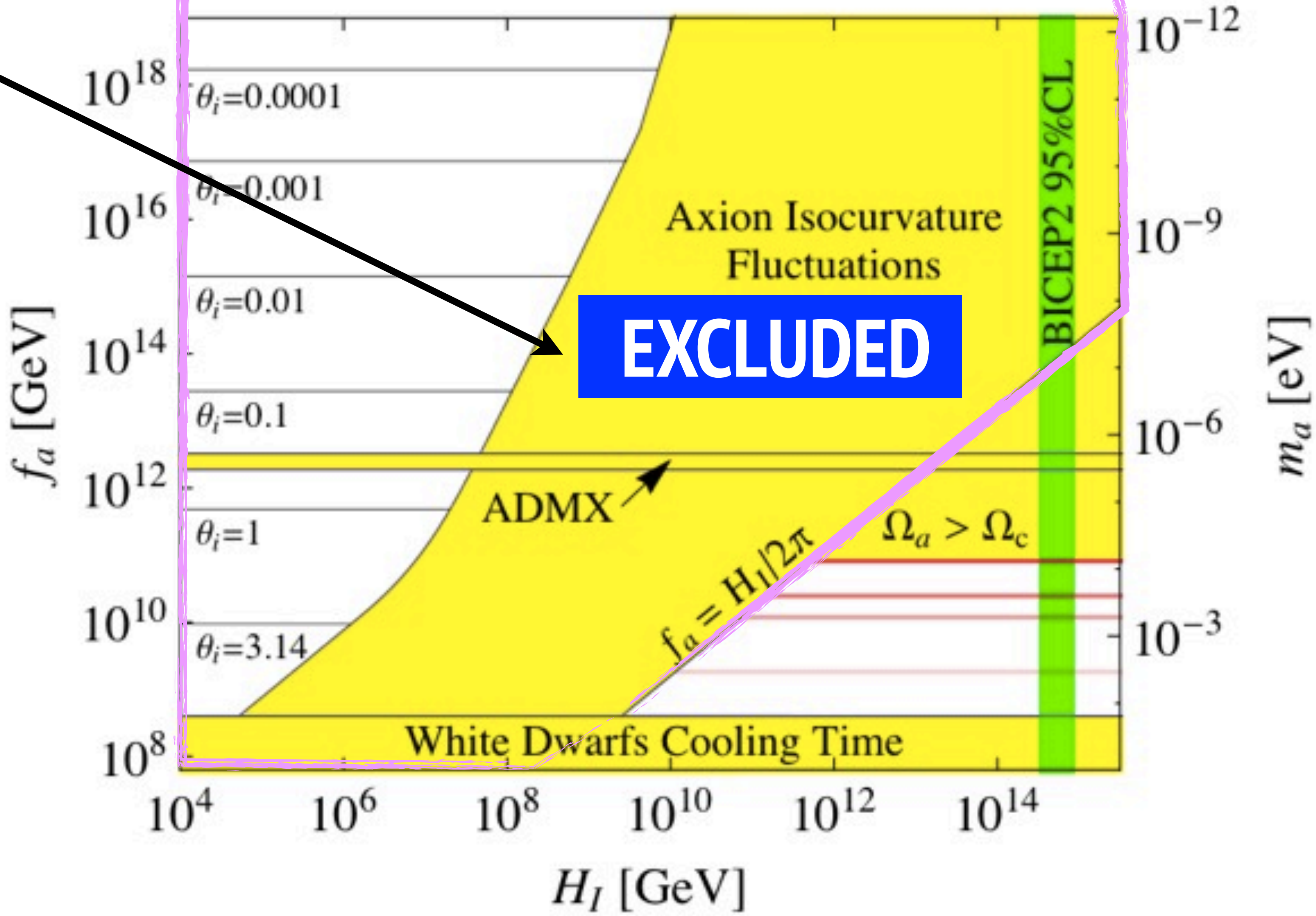
- **Axion fluctuates during inflation (entropy perturbations)**

$$P_{\rm iso} = \frac{d\langle n_a\rangle}{n_a} \sim \frac{d\langle a^2\rangle}{a_I^2} = \frac{H_I^2}{\pi^2 a_I^2} = \frac{H_I^2}{\pi^2 f_a^2 \theta_I^2}$$

insisting on axion DM $\theta_I = \theta_I(f_a)$

Constraint $f_a(H_I)$,

$f_a \gg H_I$



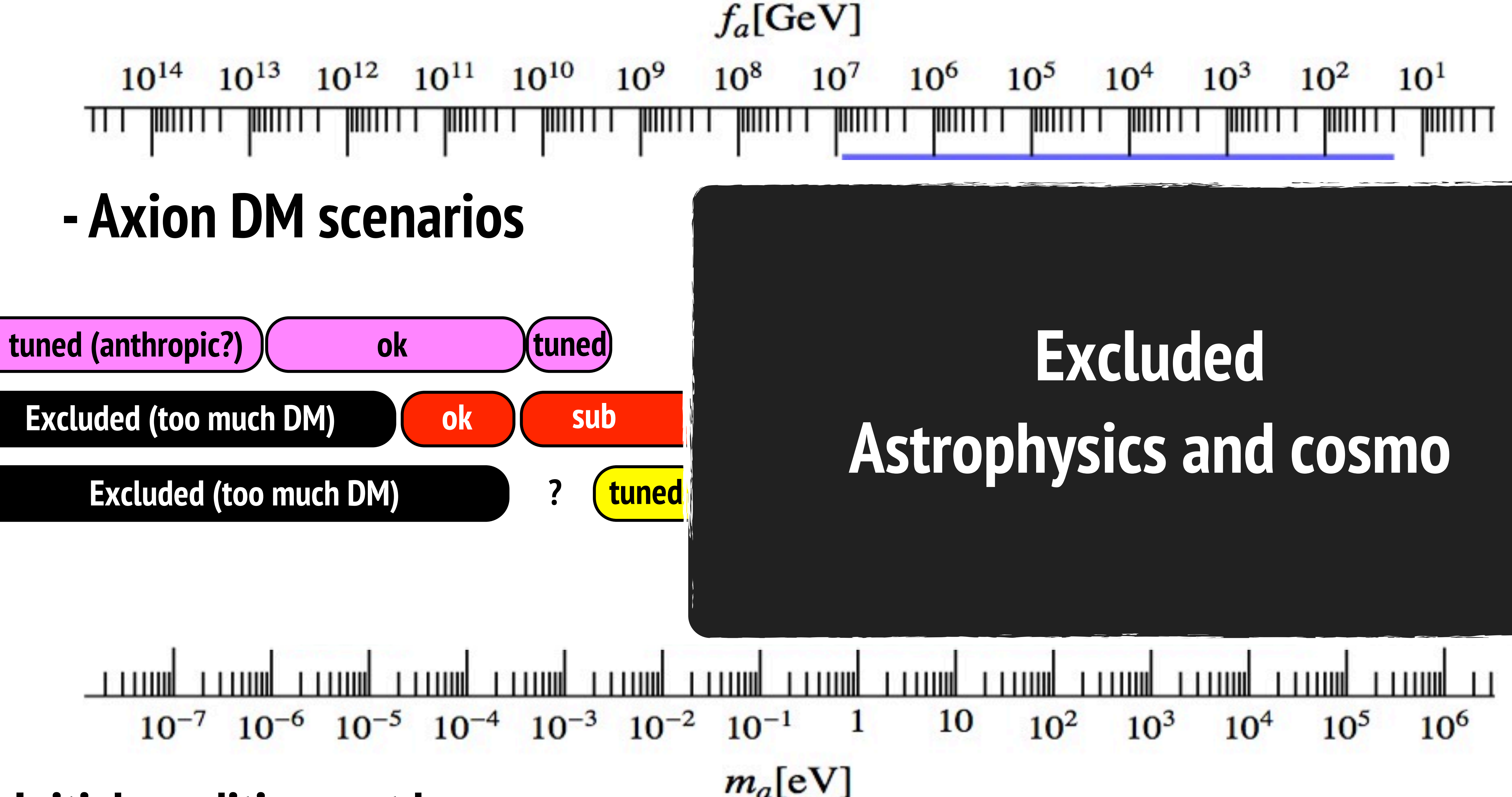
BICEP2 had excluded SC-II in the simplest models...

plenty of ways out ...

1 - BICEP2 wrong
2- ...

Axion dark matter scenarios

- Axion DM scenarios



Initial conditions set by :

Inflation smooth

$$\Omega_{\rm aDM} h^2 \simeq \theta_I^2 \left(\frac{80\,\mu\text{eV}}{m_a}\right)^{1.19}$$

Phase transition (N=1)

strings+unstable DW's

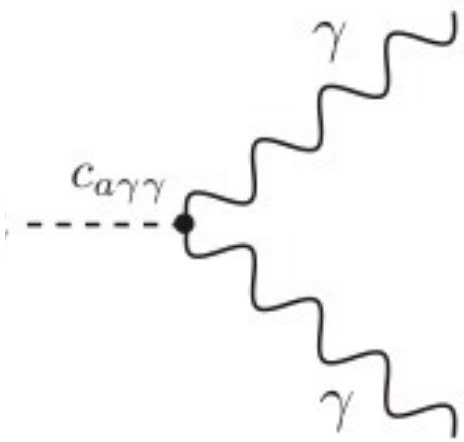
Phase transition (N>1)

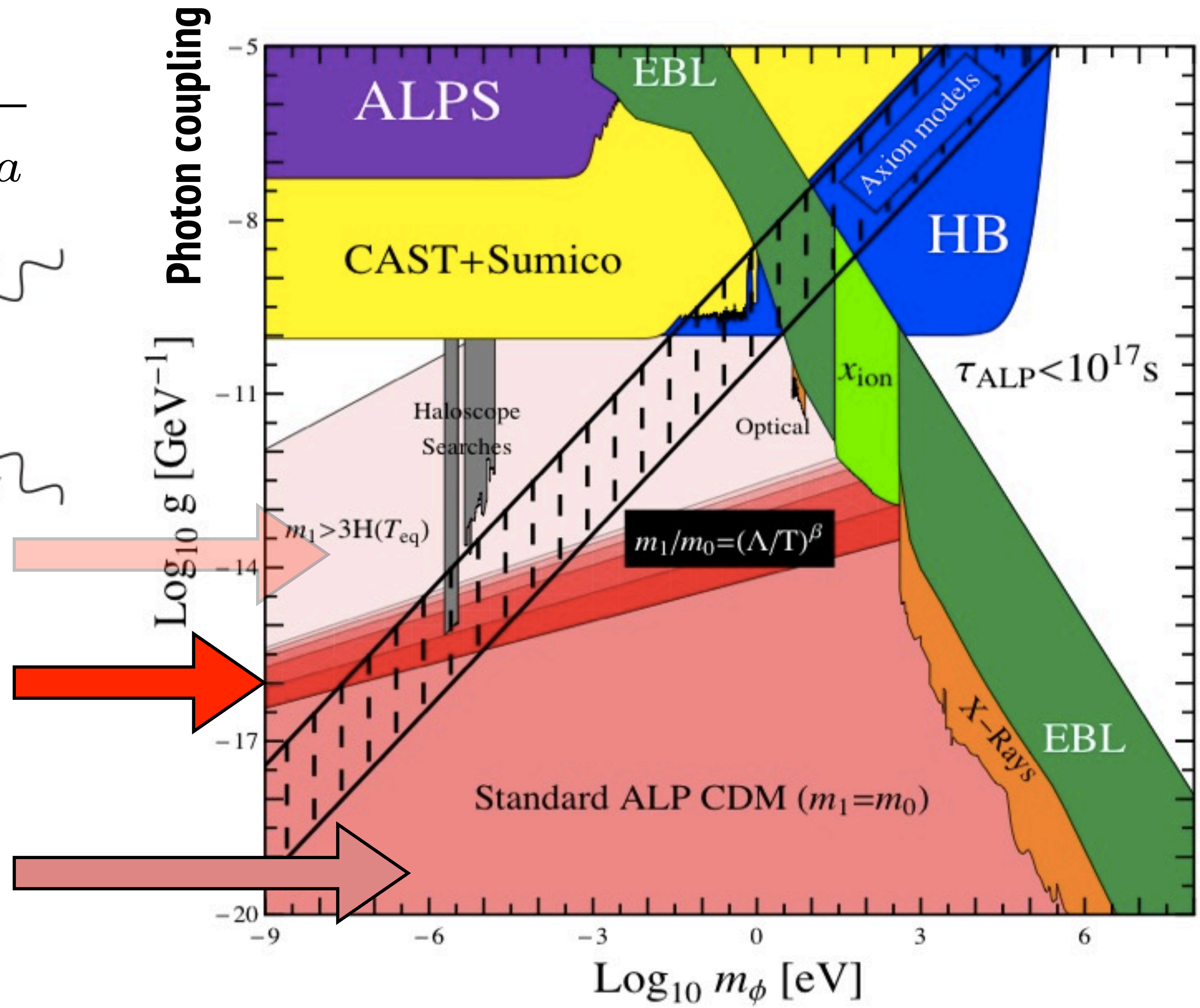
strings+long-lived DWs

Generalisation for ALPs coupled to photons

Arias et al 2012

$$g_{a\gamma} \sim \frac{\alpha}{2\pi f_a}$$

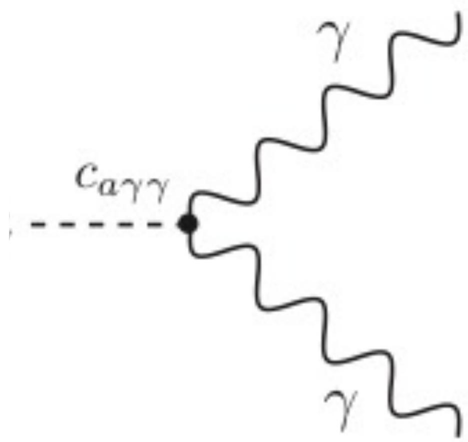


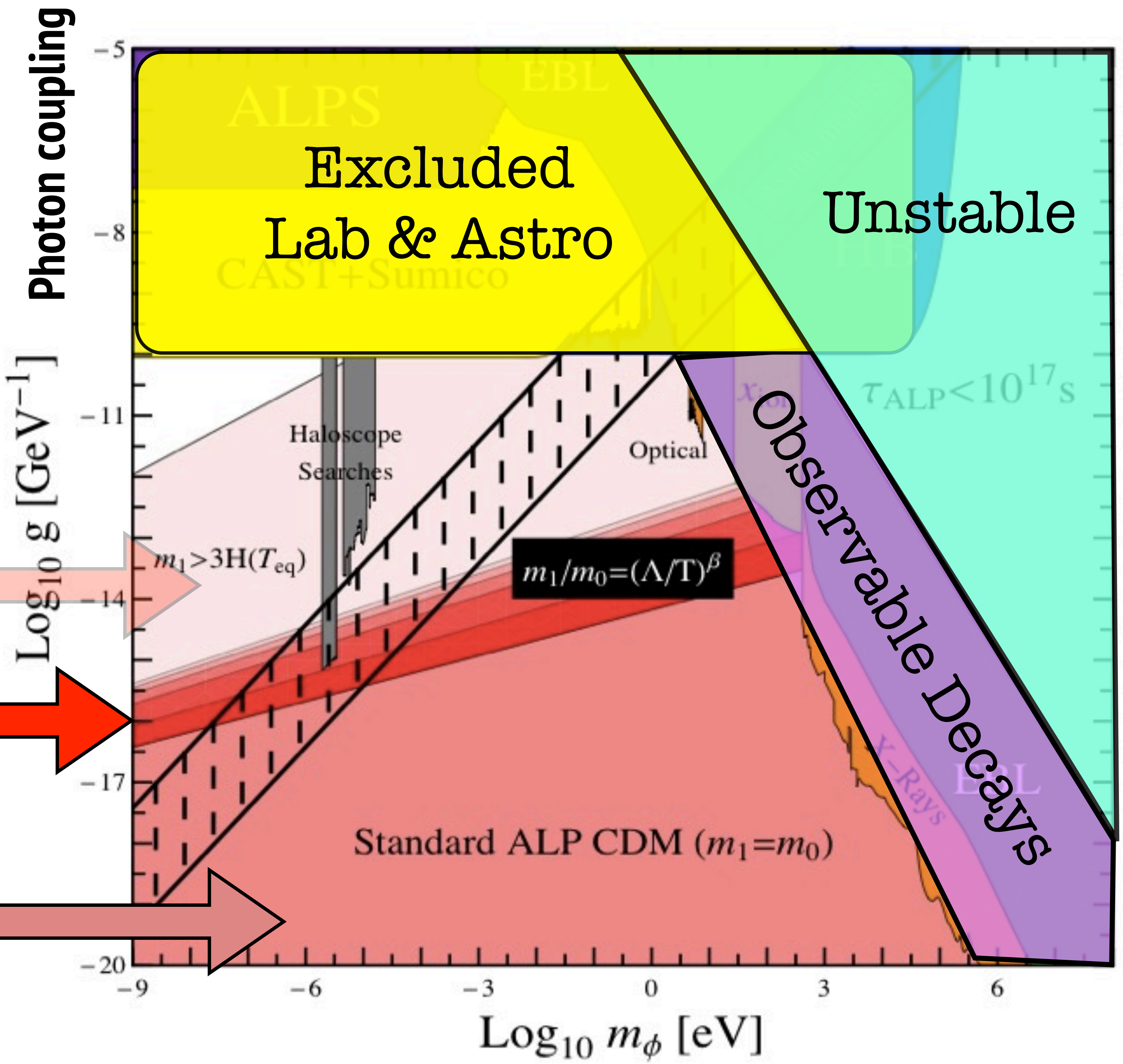


Generalisation for ALPs coupled to photons

Arias et al 2012

$$g_{a\gamma} \sim \frac{\alpha}{2\pi f_a}$$





N>1 equiv.

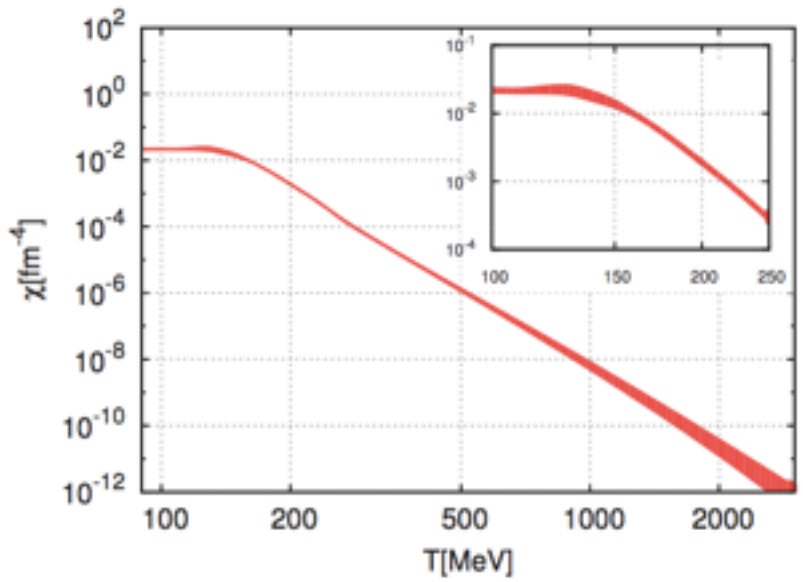
N=1 equiv.

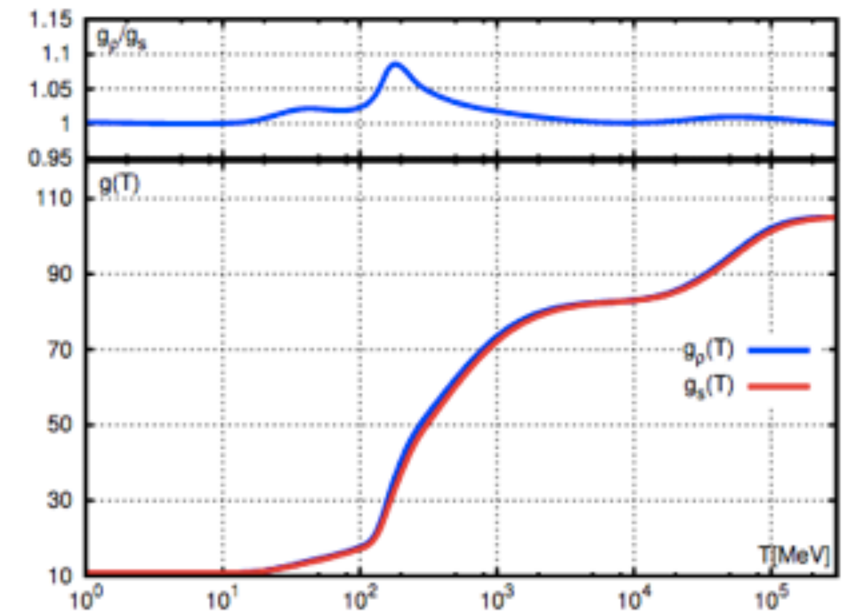
Scenario II

More on Cosmology

- race to improve $\chi(T)$

arXiv:1606.07494





- cosmic string contribution still uncertain (WIP)

- hot dark matter / dark radiation (Neff)
- Ultralight axions affect large scale structure formation
- Axion-like inflation

More on Cosmology

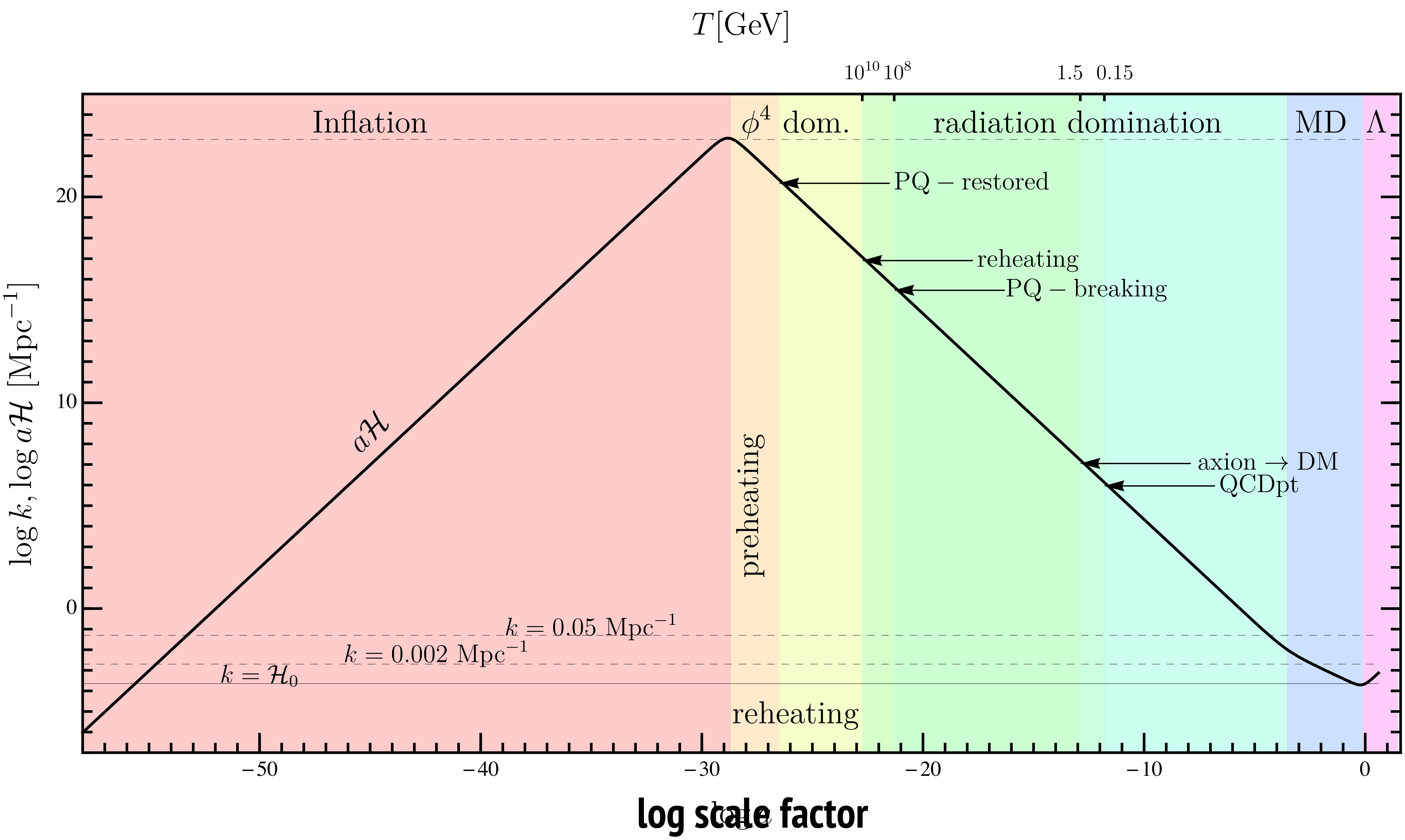
- race to improve $\chi(T)$ arXiv:1606.07494

- cosmic string contribution still uncertain (WIP)

- hot dark matter / dark radiation (Neff)
- Ultralight axions affect large scale structure formation
- Axion-like inflation

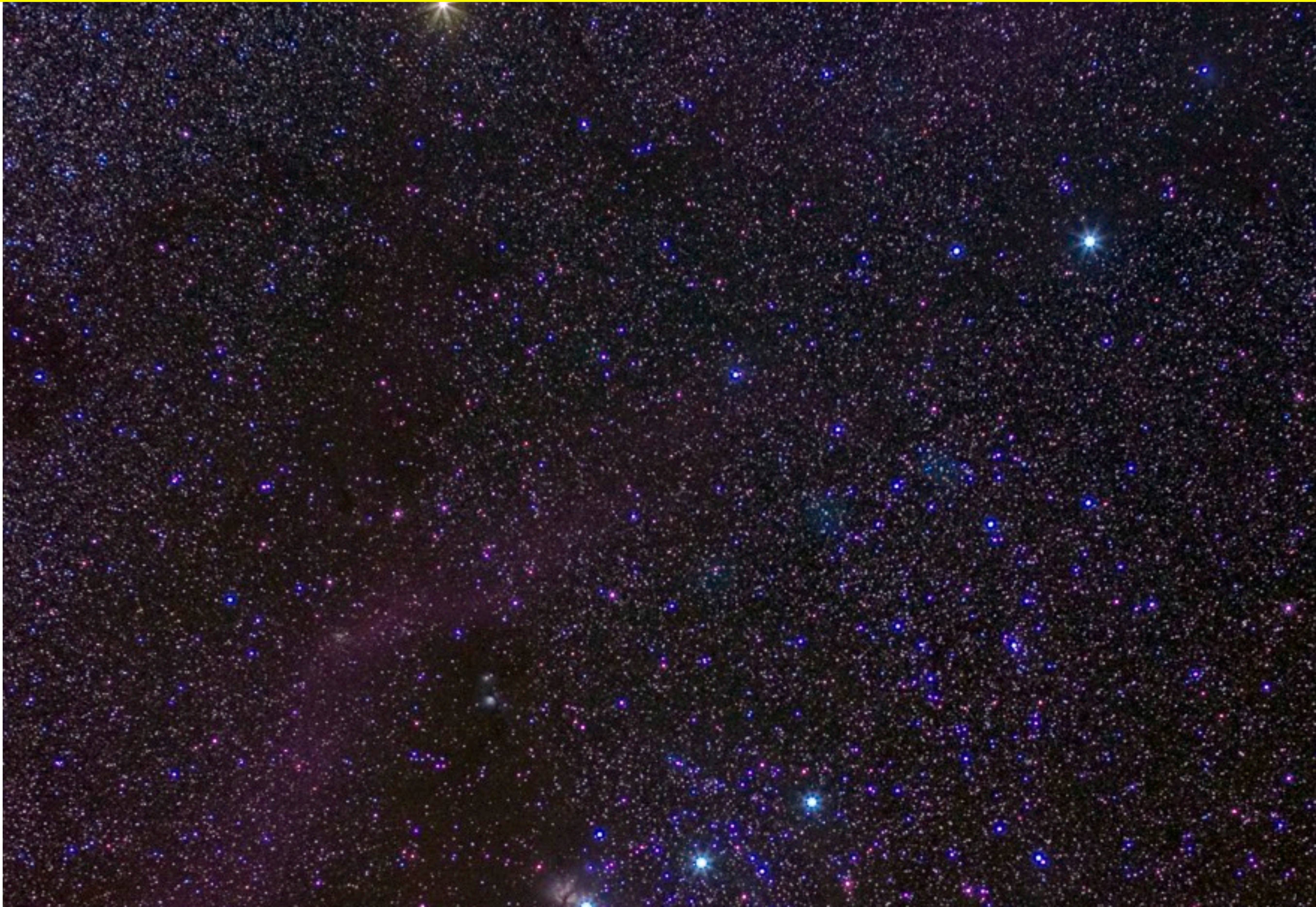
SMASH

model of particle physics and cosmology based on axions



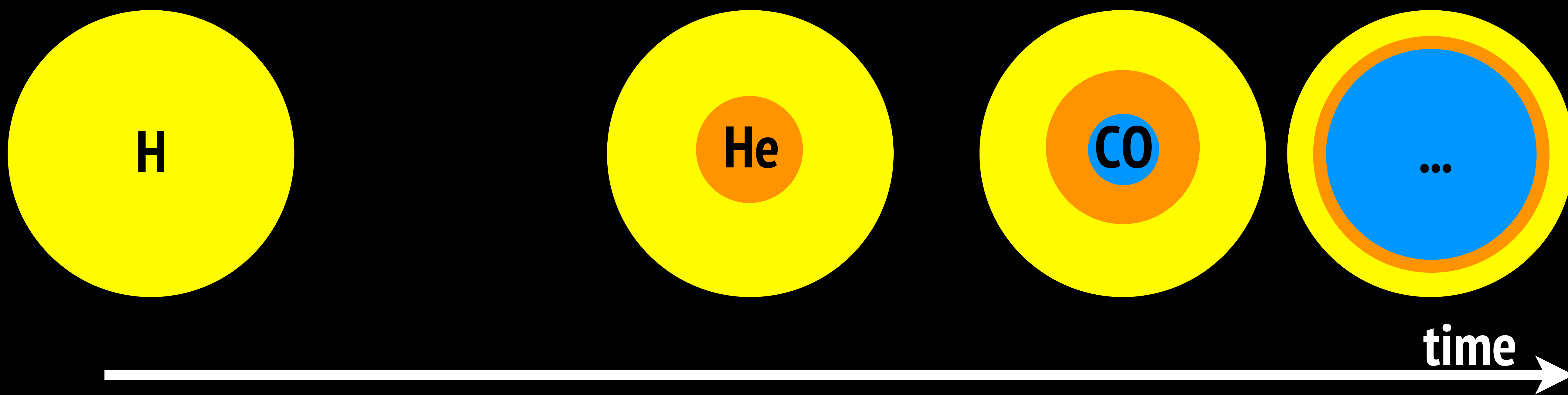
log scale factor

Bounds and hints from astrophysics

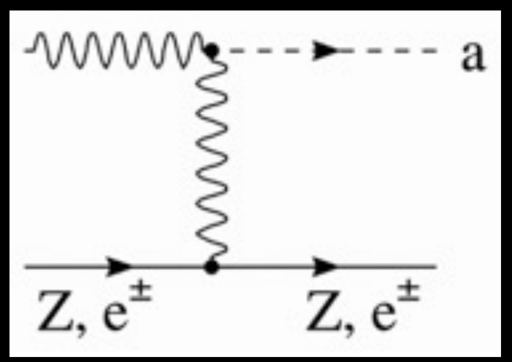


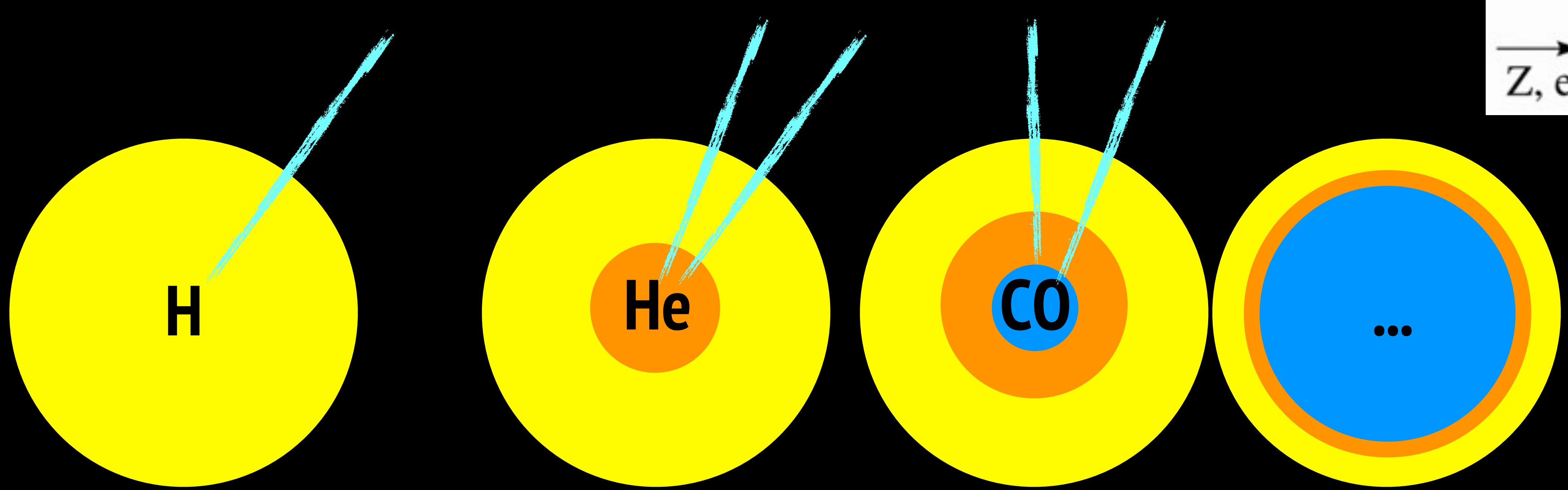
Stellar evolution and axions

- Stellar evolution (speed limited by energy loss)



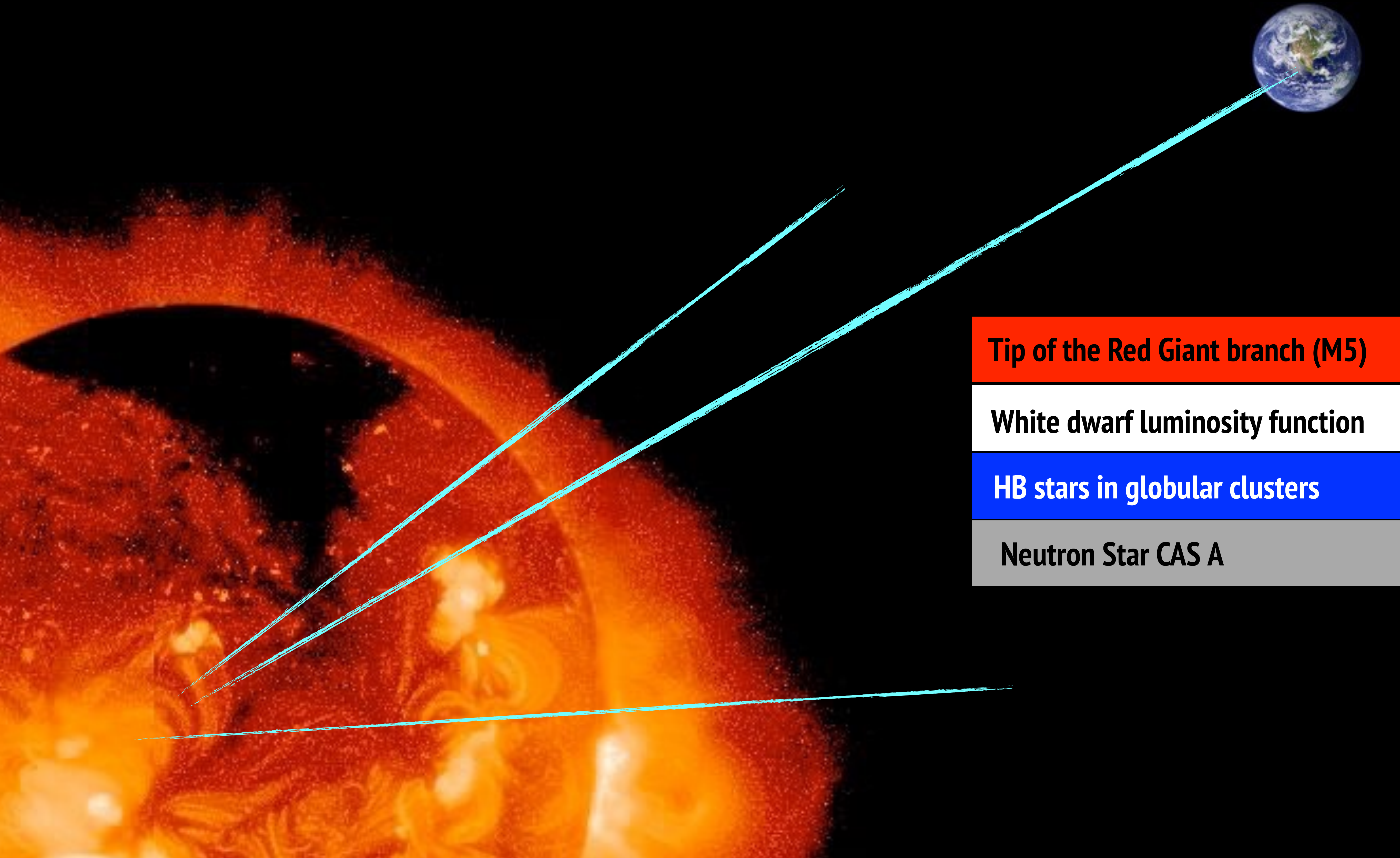
- Axions emitted from stars accelerate stellar evolution



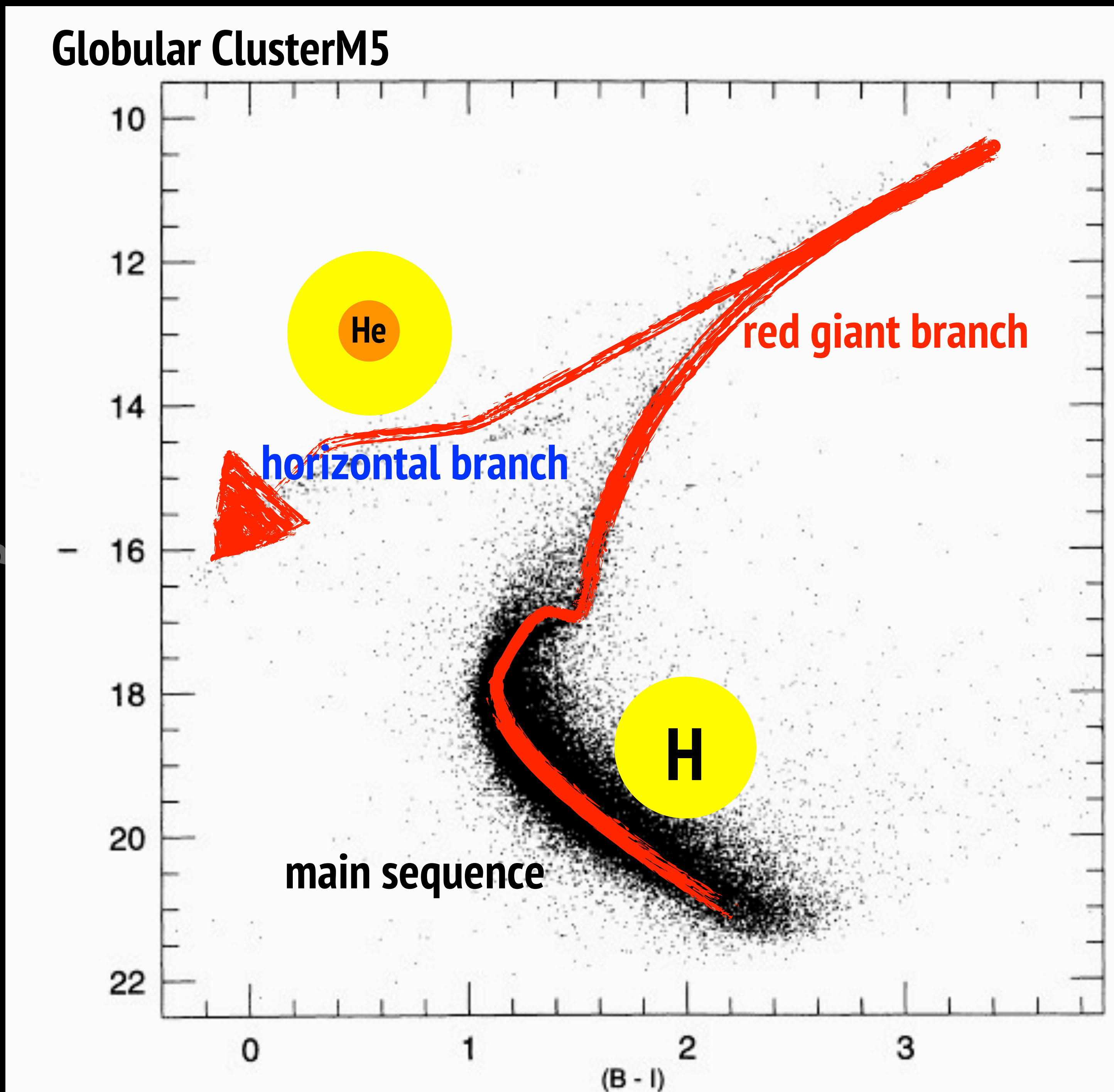


hints from stellar evolution

- Some systems improve with additional axion cooling!



Globular clusters



Brigthness

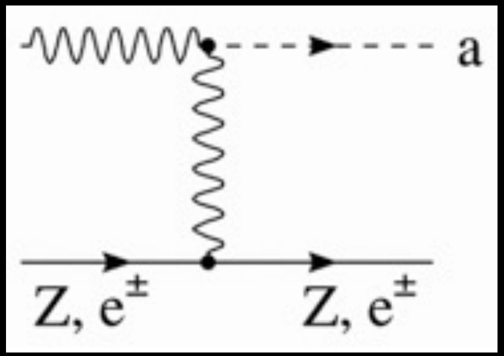
COLOR

-Different phases affected differently

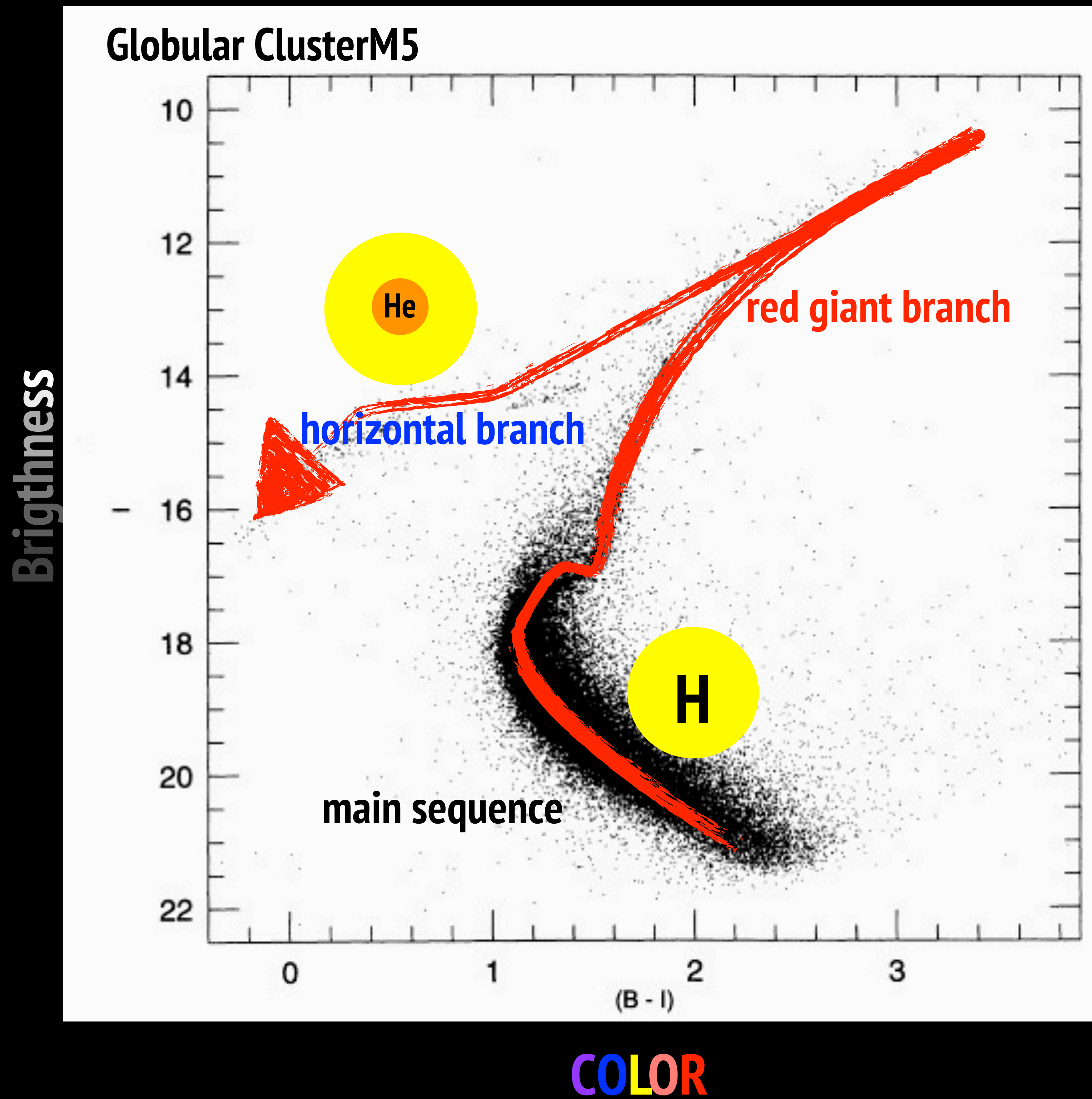
$$\frac{\#\ \text{horizontal branch}}{\#\ \text{red giant branch}} \downarrow$$

-Recent study of 39 GCs (Ayala '14)

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



Globular clusters

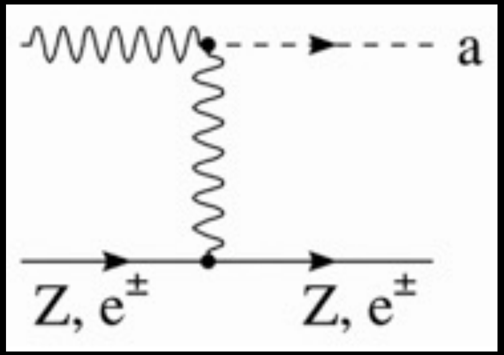


-Different phases affected differently

$$\frac{\text{\# horizontal branch}}{\text{\# red giant branch}} \downarrow$$

-Recent study of 39 GCs (Ayala '14)

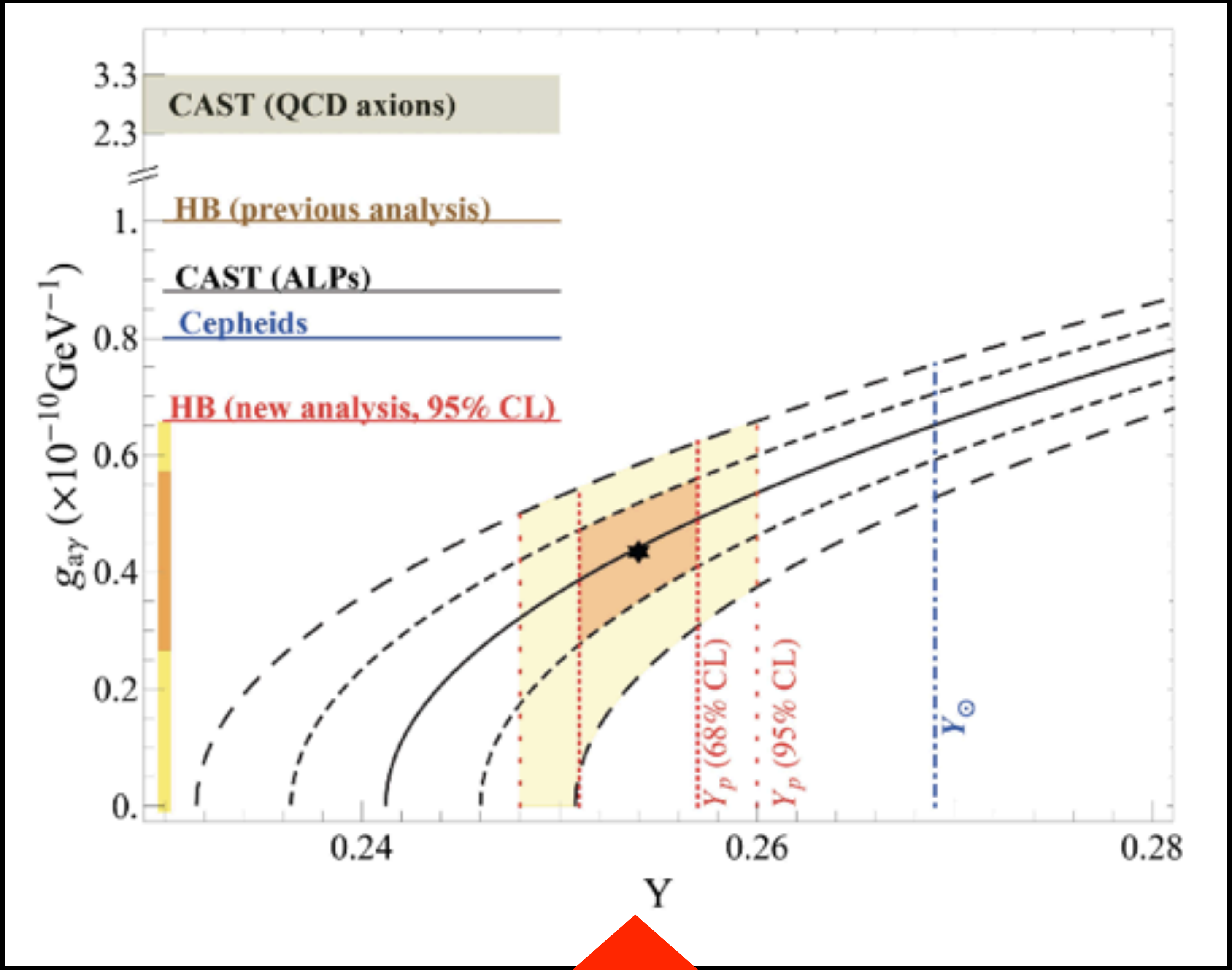
$$g_{a\gamma} < 0.66 \times 10^{-10}\mathrm{GeV}^{-1}$$



$\boxed{\text{-But a mild preference (~2 sigma)} \quad g_{a\gamma} = 0.45^{+0.12}_{-0.16} \times 10^{-10}\mathrm{GeV}^{-1}}$

Globular clusters : Ayala et al

-Degeneracy between initial Helium abundance (Y) and axion energy loss



Primordial value

Globular clusters : Ayala et al (new analysis)

-New: Sinthetic CM diagrams, nuclear rates

$$g_{a\gamma} = (0.29 \pm 0.18) \times 10^{-10}\mathrm{GeV}$$
$$g_{a\gamma} < 0.65 \times 10^{-10}\mathrm{GeV}(95\%\, C.L.)$$

Model prescriptions and error budget

Measured parameters

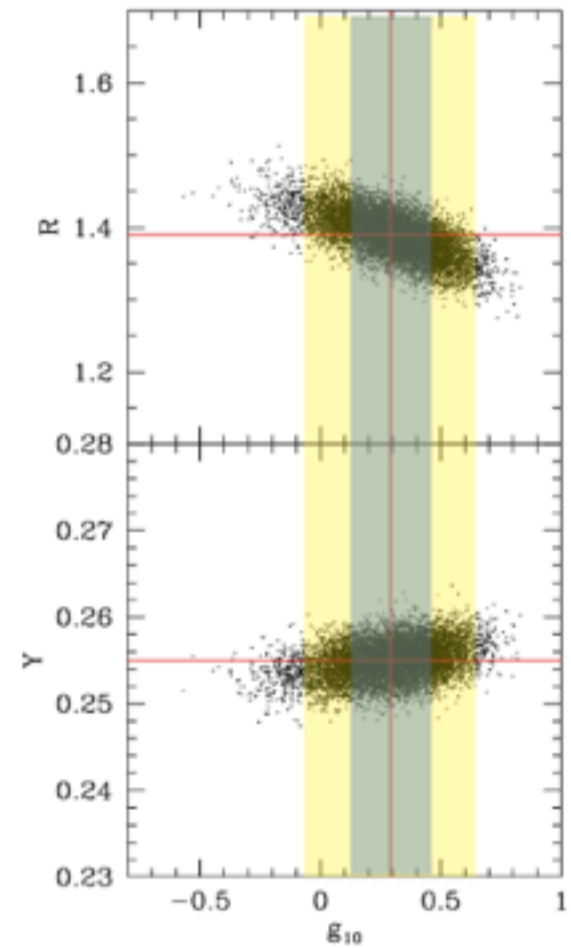
Parameter	uncertainty	Reference
R	1.39±0.03	Ayala et al. 2014
Y	0.255±0.002	Izotov et al. 2015, Aver et al. 2014

Model Parameters: Nuclear reaction rates

Reaction	uncertainty	Reference
^{4}N(p,γ)^{15}O	7%	SF II , Adelberger et al. 2011 (LUNA 2005)
^{4}He(2α,γ)^{12}C	10%	Angulo et al. 1999 (NACRE), Fymbo 2005
^{12}C(α,γ)^{16}O	20%	Kunz et al. 2001 , Shurman et al. 2013

Treatment of convection (HB):

Induced overshoot (He -> C,O) + Semiconvection
(see Straniero et al 2003, ApJ 583, 878)



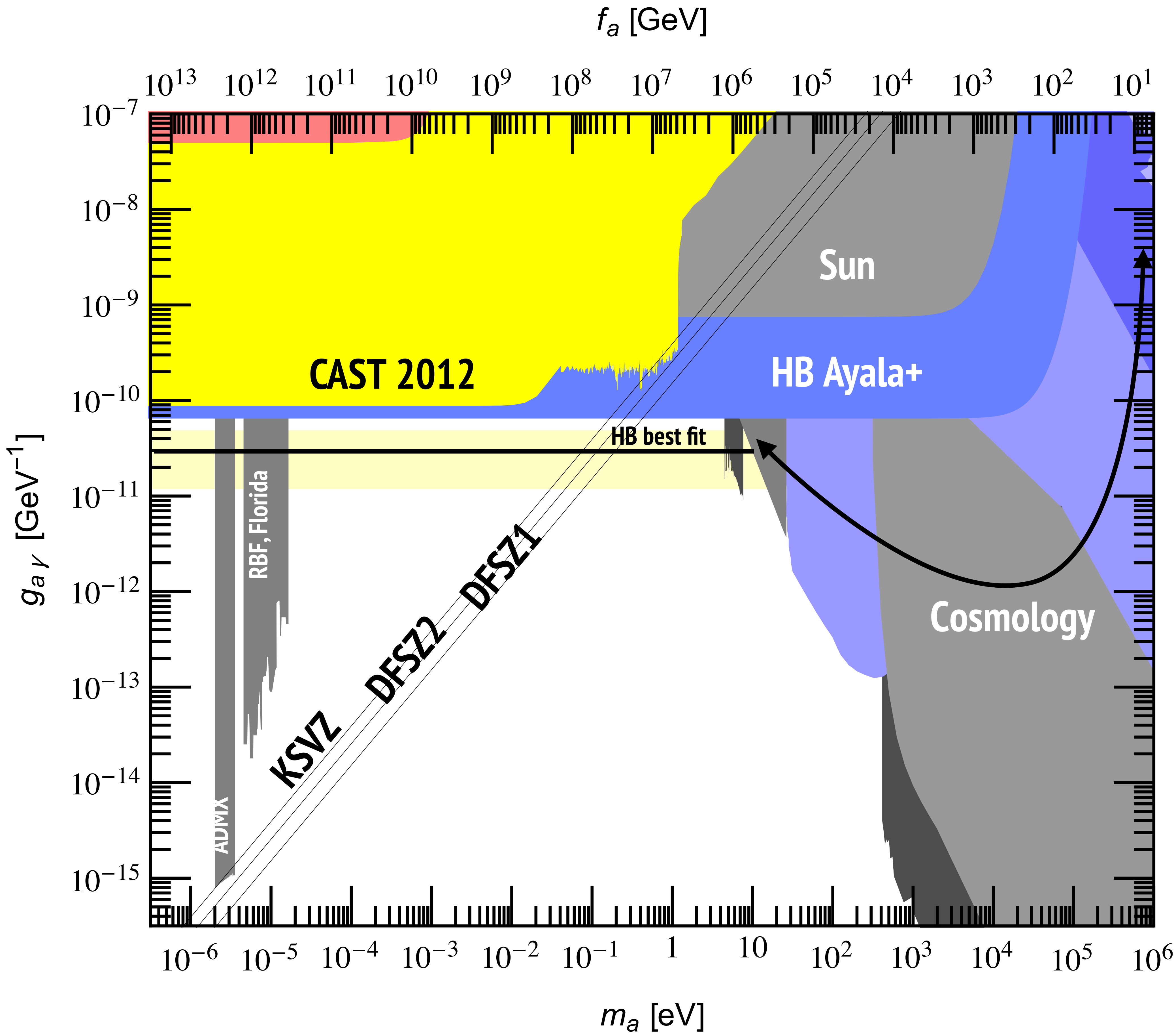
Plasma neutrinos (RGB):

Esposito et al. 2003, Nucl. Phys. B 658, 217
Haft et al. 1994 ApJ. 425, 222
Itoh et al. 1996, ApJ 470, 1015 .

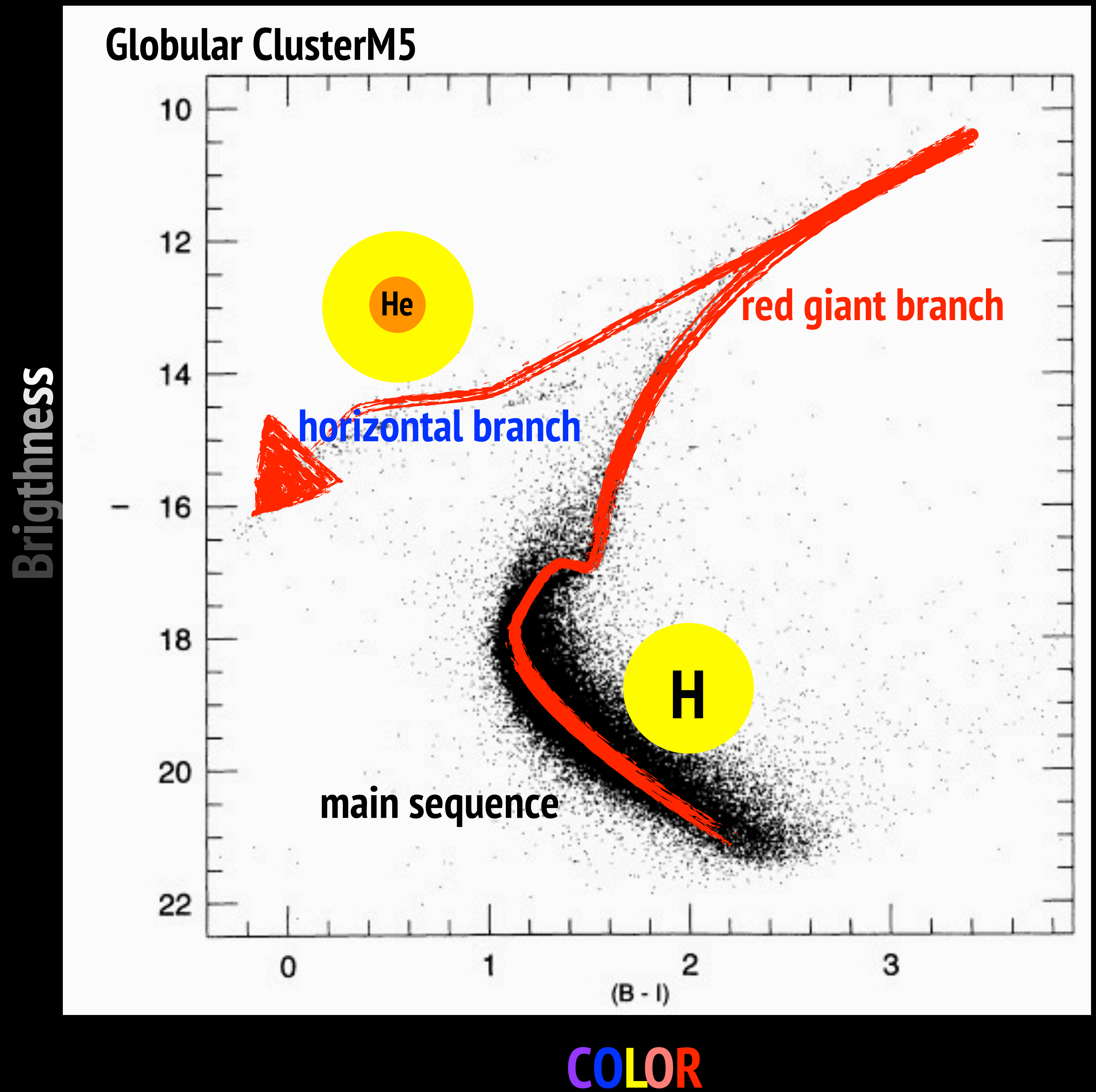
$\boxed{\textit{5 PARAMETERS}} \rightarrow$

$$g_{a\gamma} = a\vartheta^2 + b\vartheta$$
$$\vartheta = R_{g=0} - R = cY + f(r1, r2, r3) + d - R$$
$$a = 5.2706 \qquad b = 4.675$$
$$c = 7.3306 \qquad d = -0.409$$

Globular clusters : Ayala et al (new analysis)



Globular clusters with axion-electron

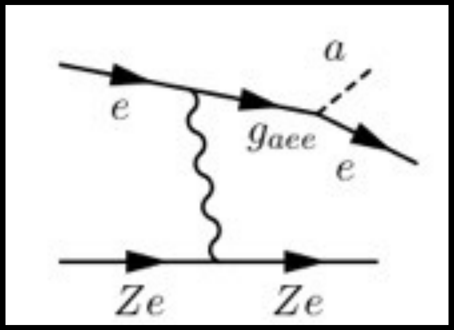


-Different phases affected differently

$$\frac{\text{horizontal branch}}{\text{red giant branch}} \downarrow$$

-Can be due to axion-electron coupling

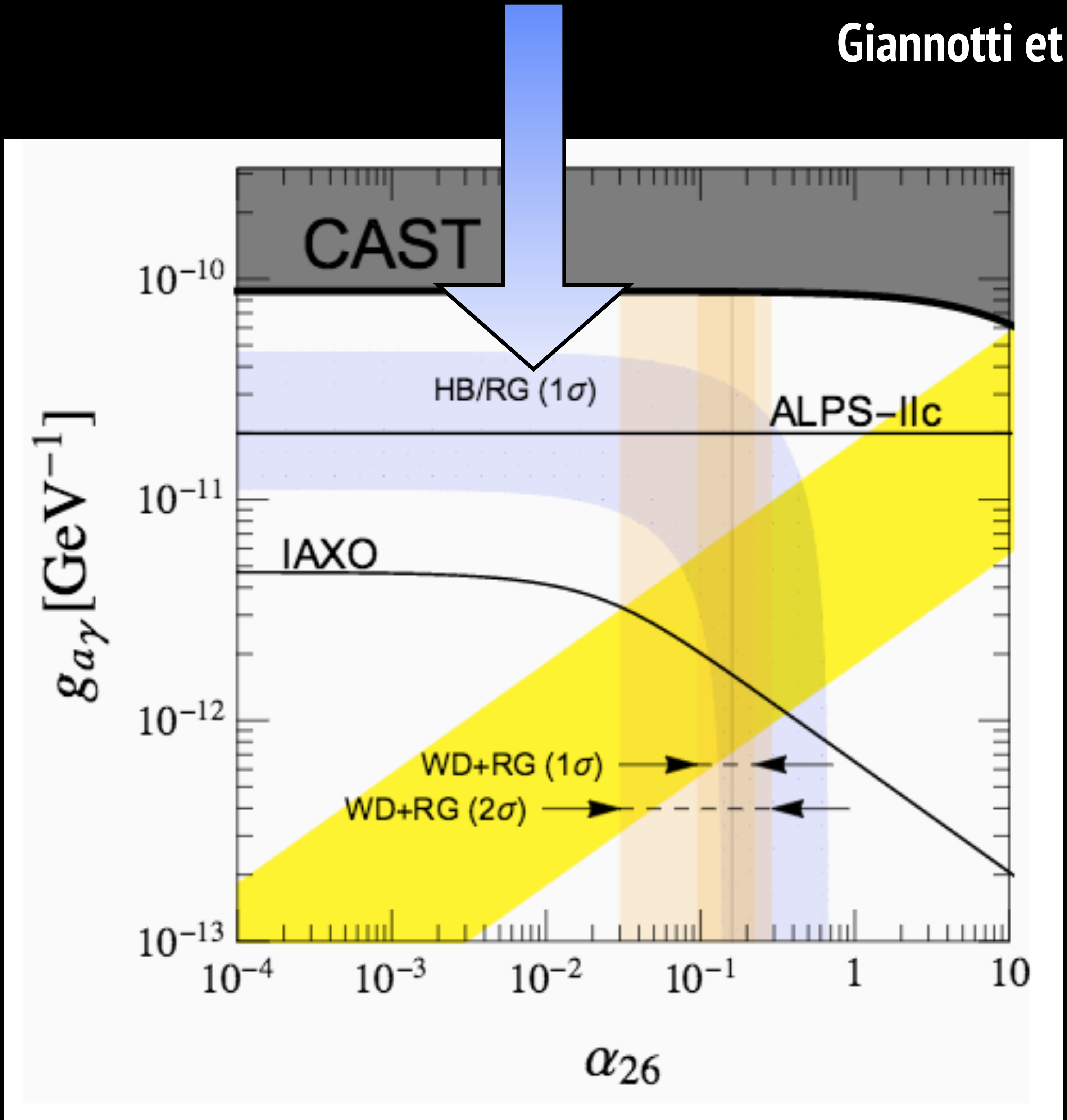
$$g_{ae} \sim 2.2^{+0.7}_{-1.1} \times 10^{-13}$$



Giannotti et al (arXiv:1512.08108)

Globular clusters with axion-photon+axion-electron

Giannotti et al (arXiv:1512.08108)

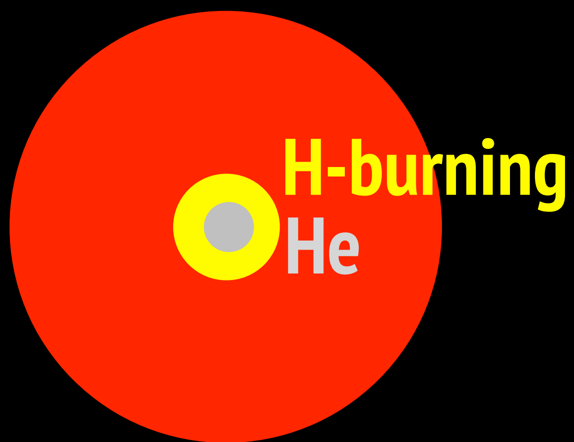


Axion-photon

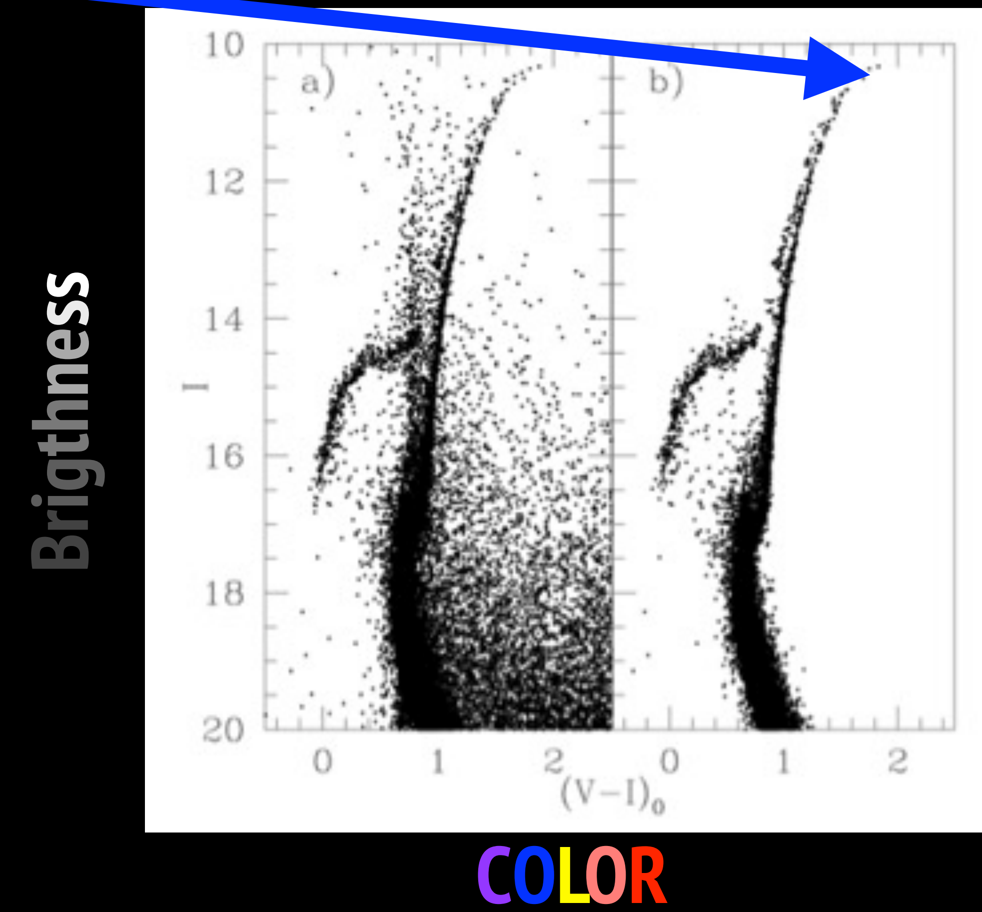
Axion-electron

Tip of the Red Giant branch (M5)

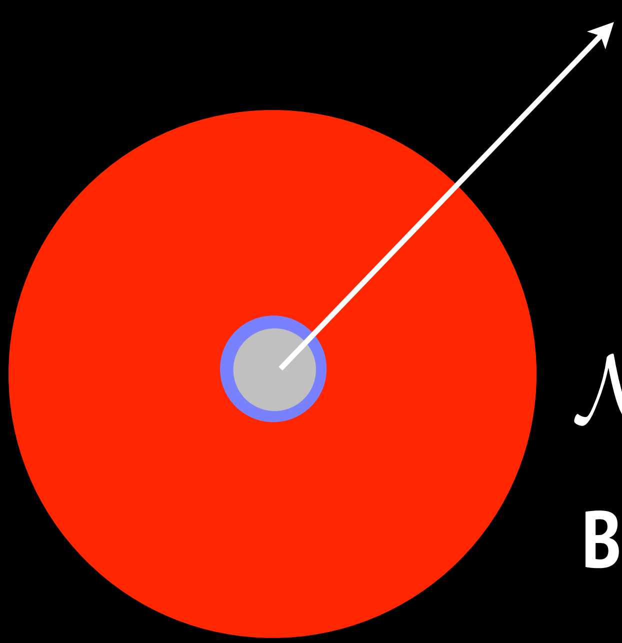
Increase He core until 3alpha ignition (T~8.6 KeV)

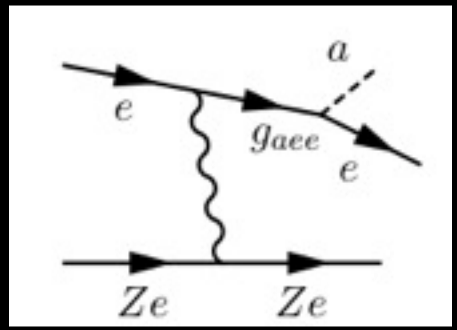


Globular ClusterM5



Axion emission cools down core, delays ignition





$$\mathcal{M}_{\rm core}\uparrow, T_{\rm H}\uparrow, \mathcal{L}\uparrow$$

Brighter Helium flash!

Tip of the Red Giant error budget (M5)

Theory

Table 4. Error budget in theoretically predicted $M^{\rm the}_{I,\rm TRGB}$

Input quantity	Adopted Range	$\Delta M_{I,\rm TRGB}$ [0.01 mag]
Mass ($M_\odot$)	0.820 ± 0.025	± 0.2
Y	0.245 ± 0.015	± 1.0
Z	0.00136 ± 0.00035	$+0.7/-0$
$[\alpha/\rm Fe]$	0.3 ± 0.1	∓ 0.4
$\alpha_{\rm MLT}$	$\alpha^{\rm calibrated}_{\rm MLT} \pm 0.2$	± 5.6
Atomic diffusion	See text	$+0/-0.6$
Boundary conditions	$(1 \pm 0.05)\, T(\tau)$	∓ 0.7
$\kappa_{\rm rad}$	$\pm 10\%$	∓ 0.02
$\kappa_{\rm c}$	$\pm 10\%$	± 1.6
Nuclear Rates	See Table 3	± 1.9
Nuclear Screening	$\pm 20\%$	± 1.1
Neutrino emission	$\pm 5\%$	∓ 1.3
EOS	8 cases	$+2.4/-0.5$
Mass loss ($M_\odot$)	0.12–0.28	$+2.2/+3.5$

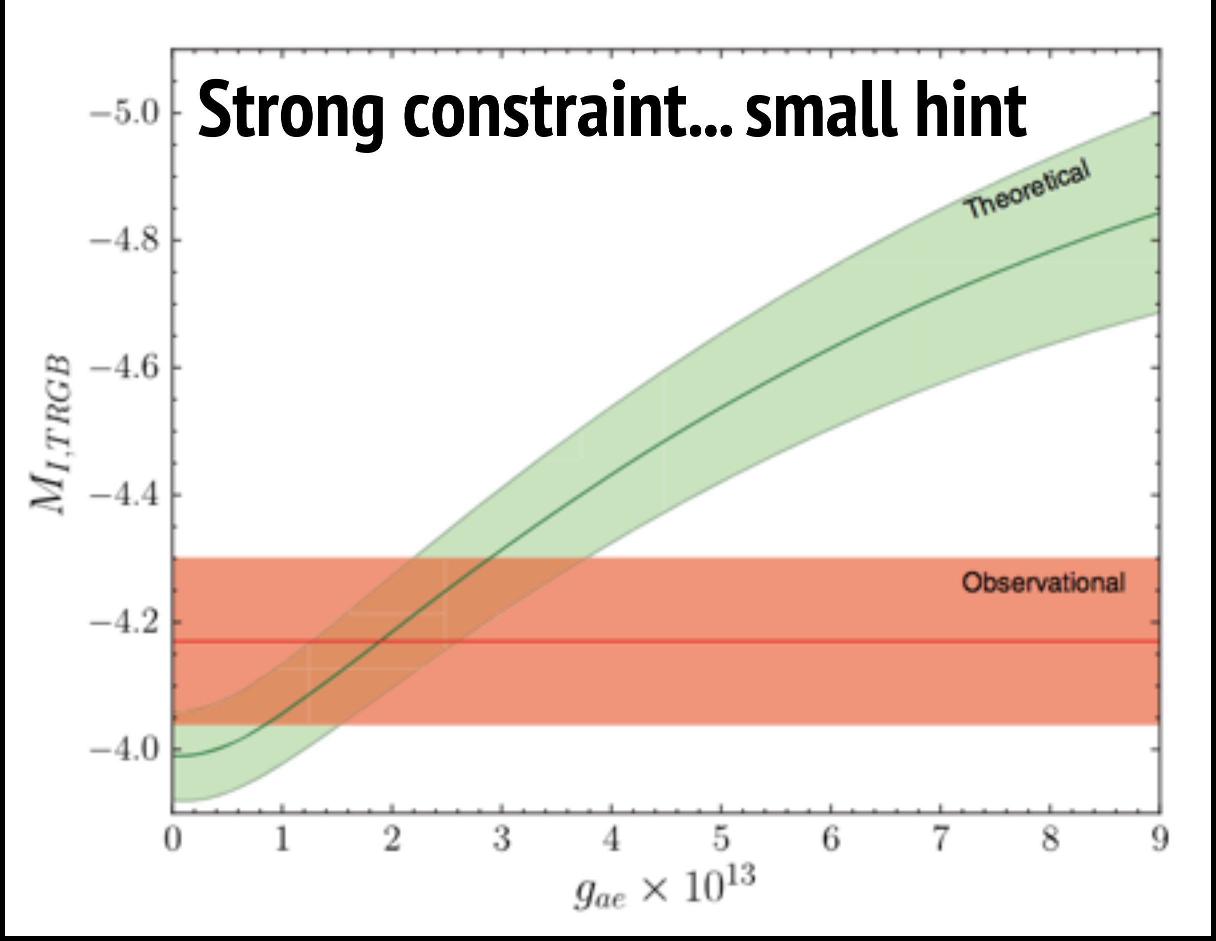
Bol-correction $\sigma_{\rm BC} = (0.08 + 0.013\,\mu_{12})$ mag

Observation

$$M^{\rm obs}_{I,\rm TRGB} = -4.17 \pm 0.13 \text{ mag}\,,$$

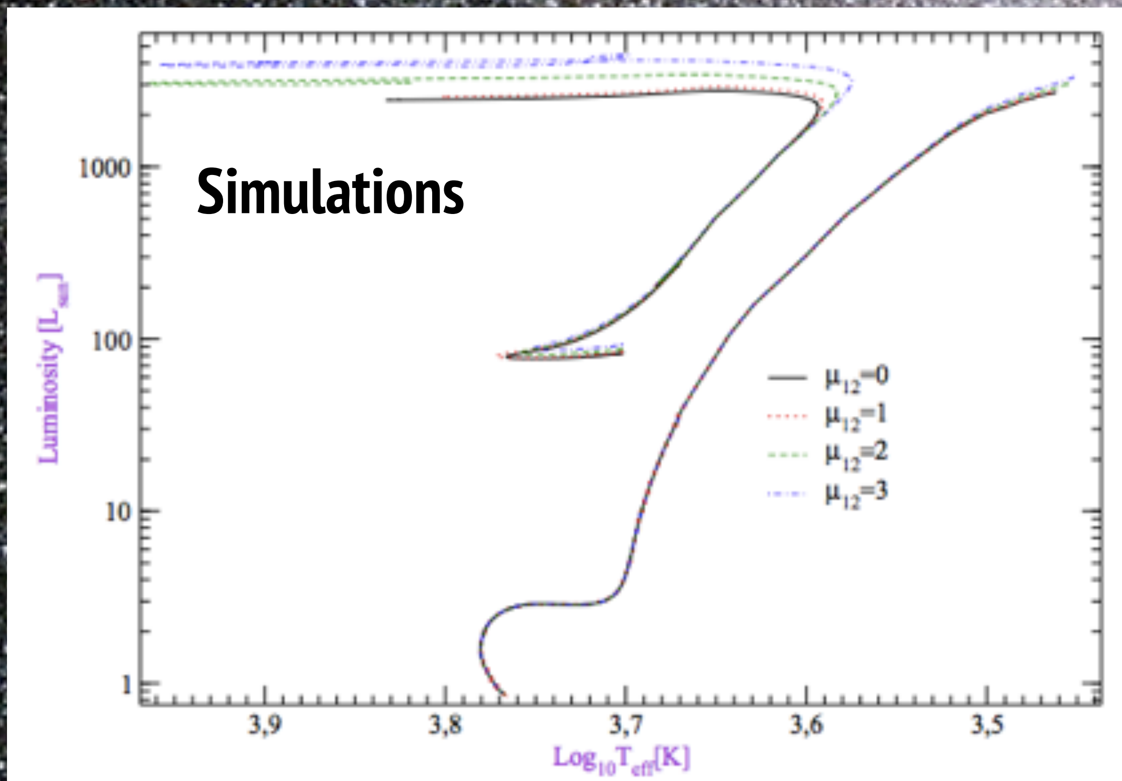
Distance $\sigma_{m-M} = 0.11$

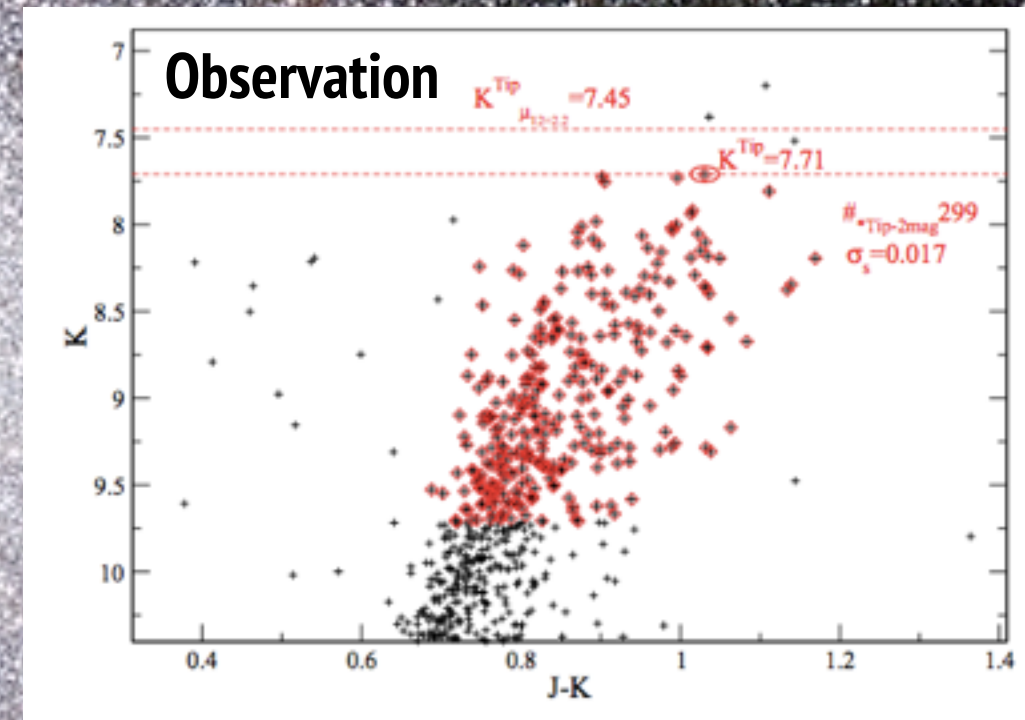
Tip-brightest $\sigma_{\Delta_{\rm tip}} = 0.058.$

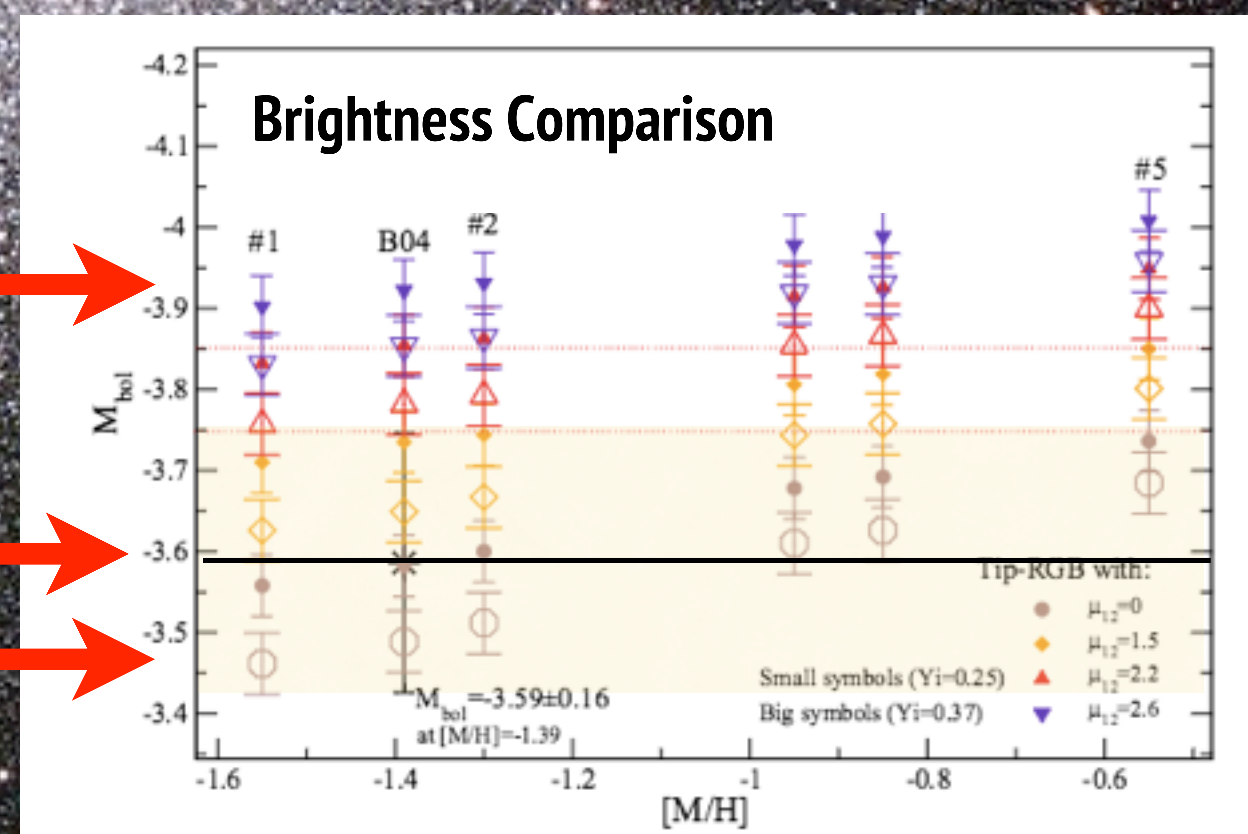


Omega-Centauri (neutrino moment)

AP 2016, S. Arceo-Díaz, K.-P. Schröder, K. Zuber, D. Jack







too much (2-s)

but maybe a bit ...

No extra energy loss

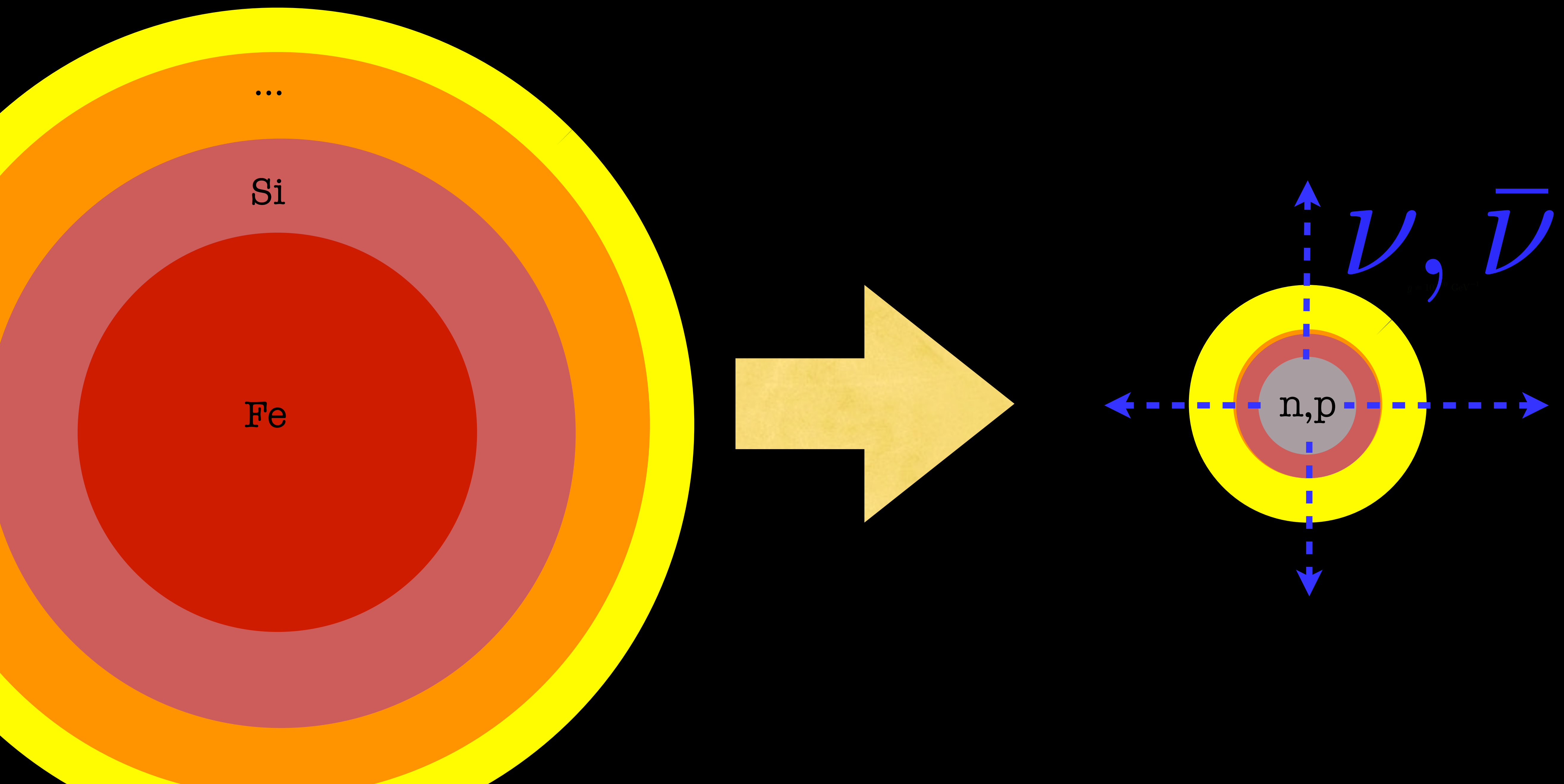
Core collapse SN

Iron Core collapse when electron degeneracy pressure cannot support its grav. pull

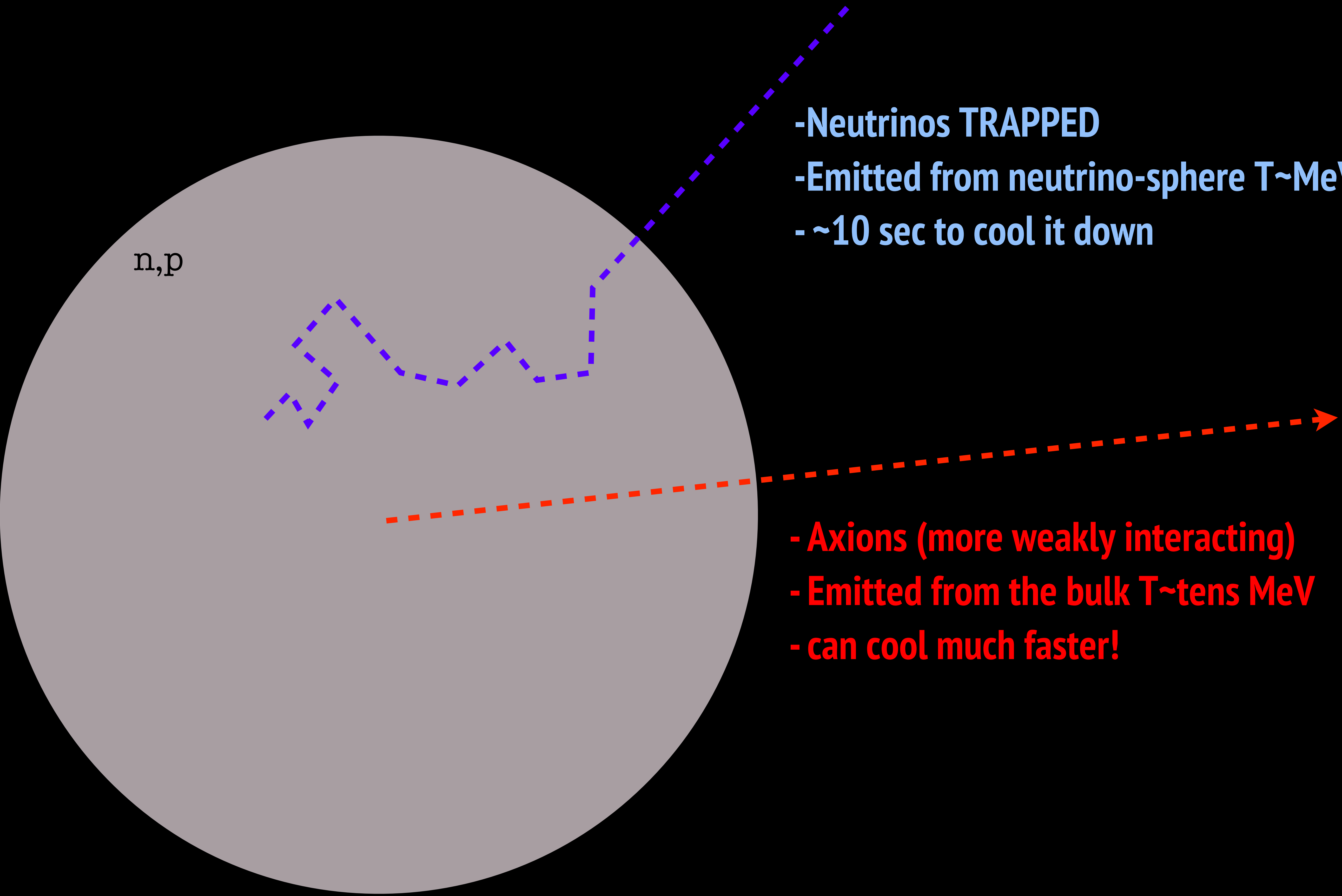
$$\mathcal{M}_{\rm core} \sim 1.4 \mathcal{M}_\odot$$

The gravitational energy of the core is mainly to be radiated away in neutrinos

$$E = 3 \times 10^{53} \text{ erg}$$



Neutrino burst



-Neutrinos TRAPPED

-Emitted from neutrino-sphere T~MeV

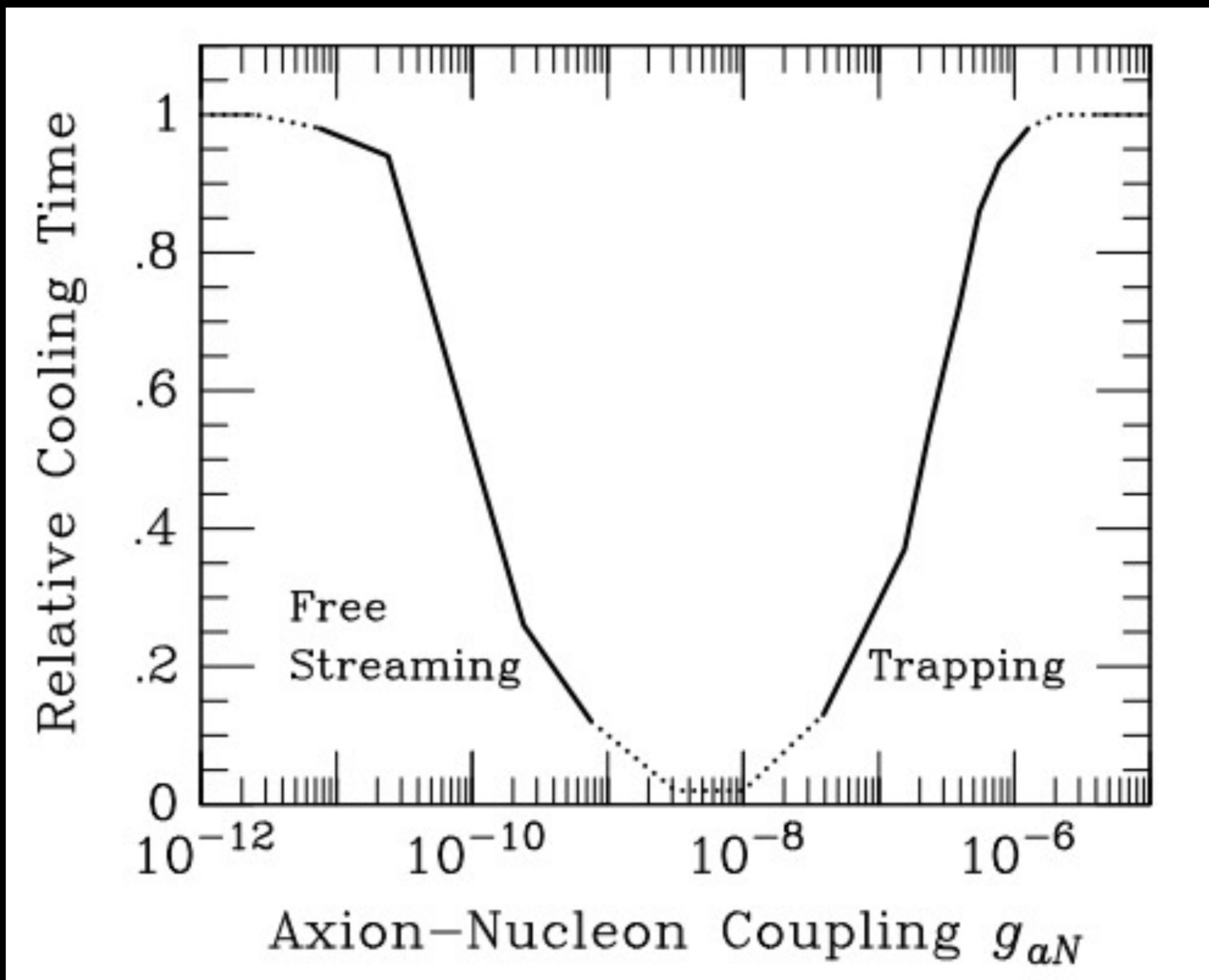
- ~10 sec to cool it down

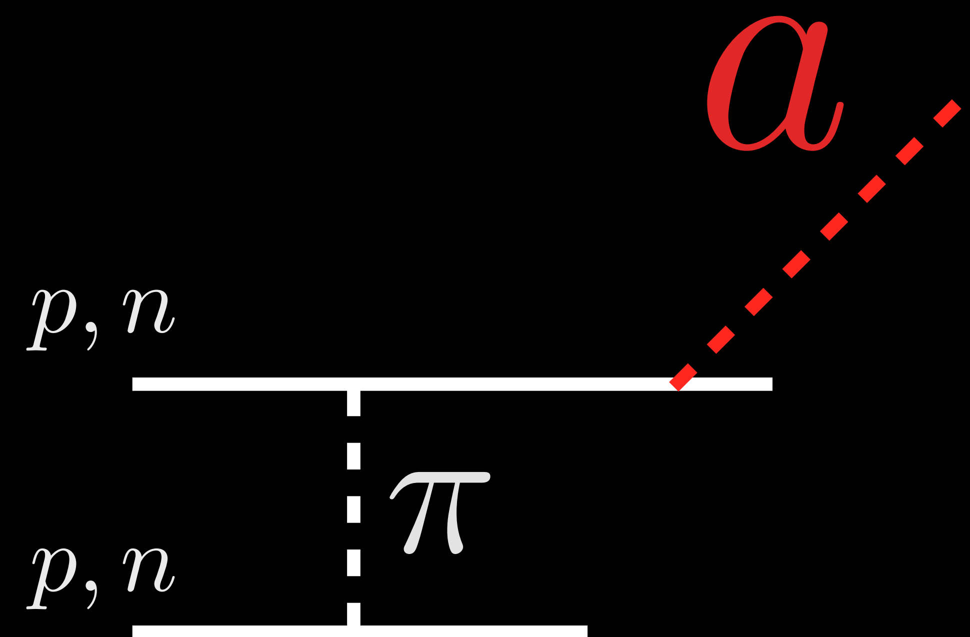
- Axions (more weakly interacting)

- Emitted from the bulk T~tens MeV

- can cool much faster!

Reduction of nu burst $N + N \to N + N + a$





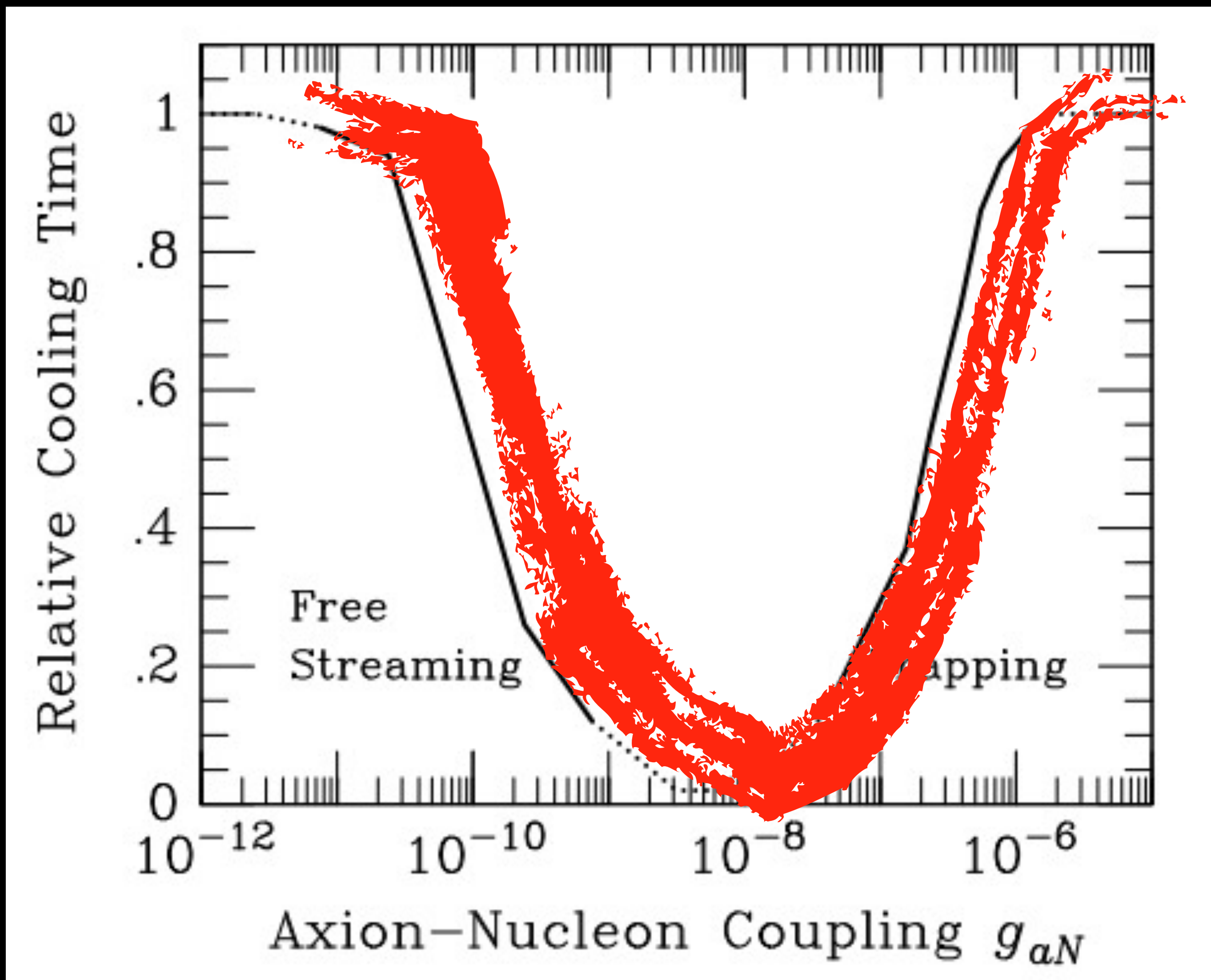
first approx. (pi pole too hard...)

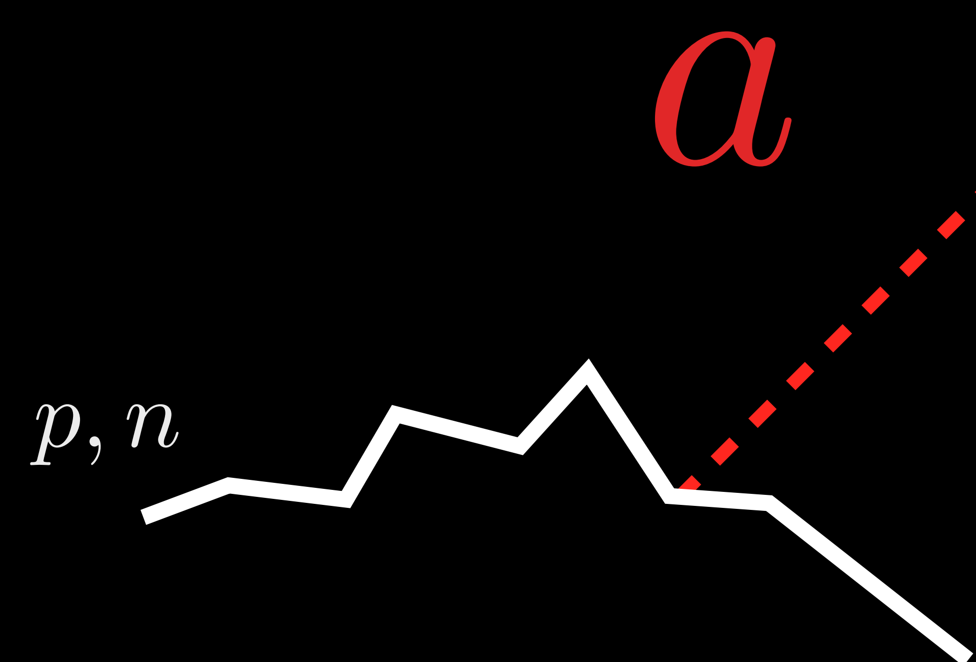
axion production not significant

Cool the PNS eficiently reduce the neutrino burst!

axions are reabsorbed inside the SN

Reduction of nu burst $N + N \rightarrow N + N + a$





axion emission is suppressed due to high density effects !

SN1987A

- Cooling ~ 10 s
- Exotics, Eloss/mass and time

$$\epsilon \lesssim 10^{19} \mathrm{erg/gs}$$

- Axion emission ...

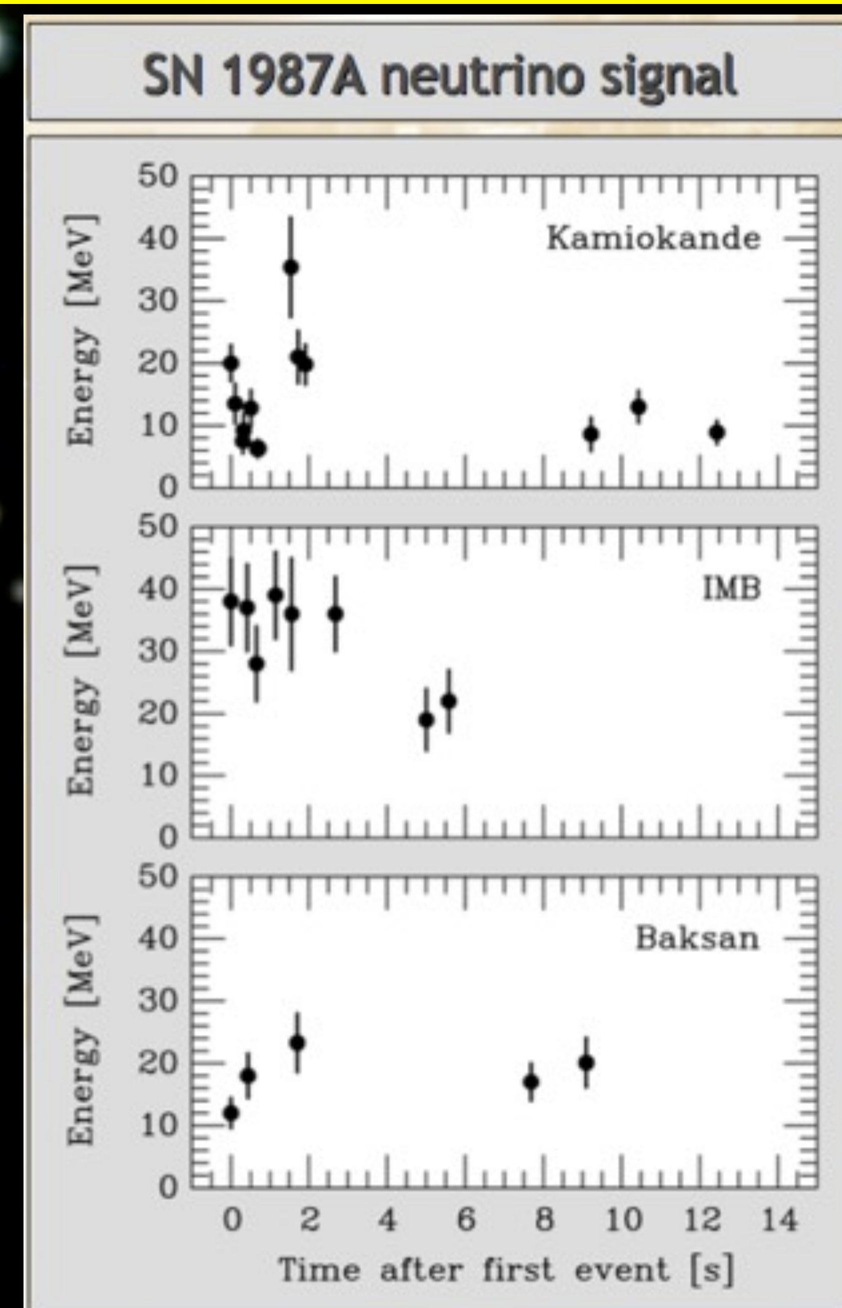
$$\epsilon_a \sim g_{ap}^2 1.6 \times 10^{37} \mathrm{erg/gs} \left(\frac{T}{30\mathrm{MeV}} \right)^4$$

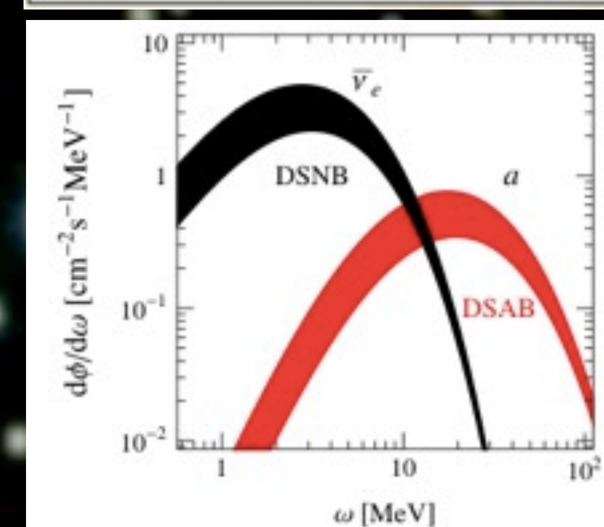
- Constraint ...

$$g_{ap} \lesssim 0.8 \times 10^{-9}$$

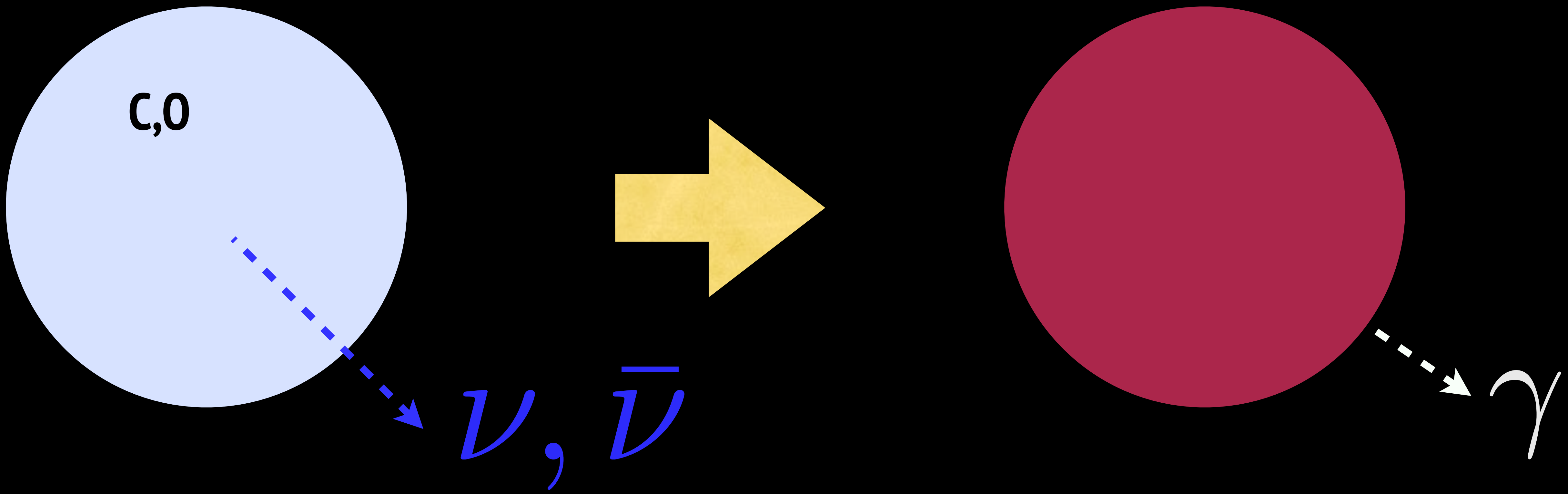
- Axions saturating the bound take ~50% Ecore

Diffuse Supernova Axion Background





White dwarf luminosity function

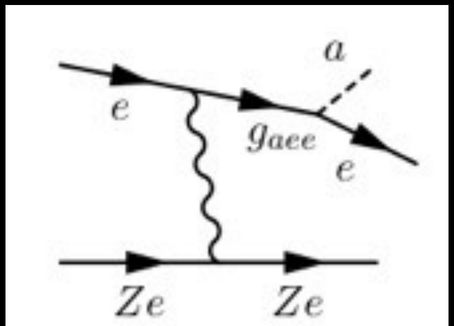


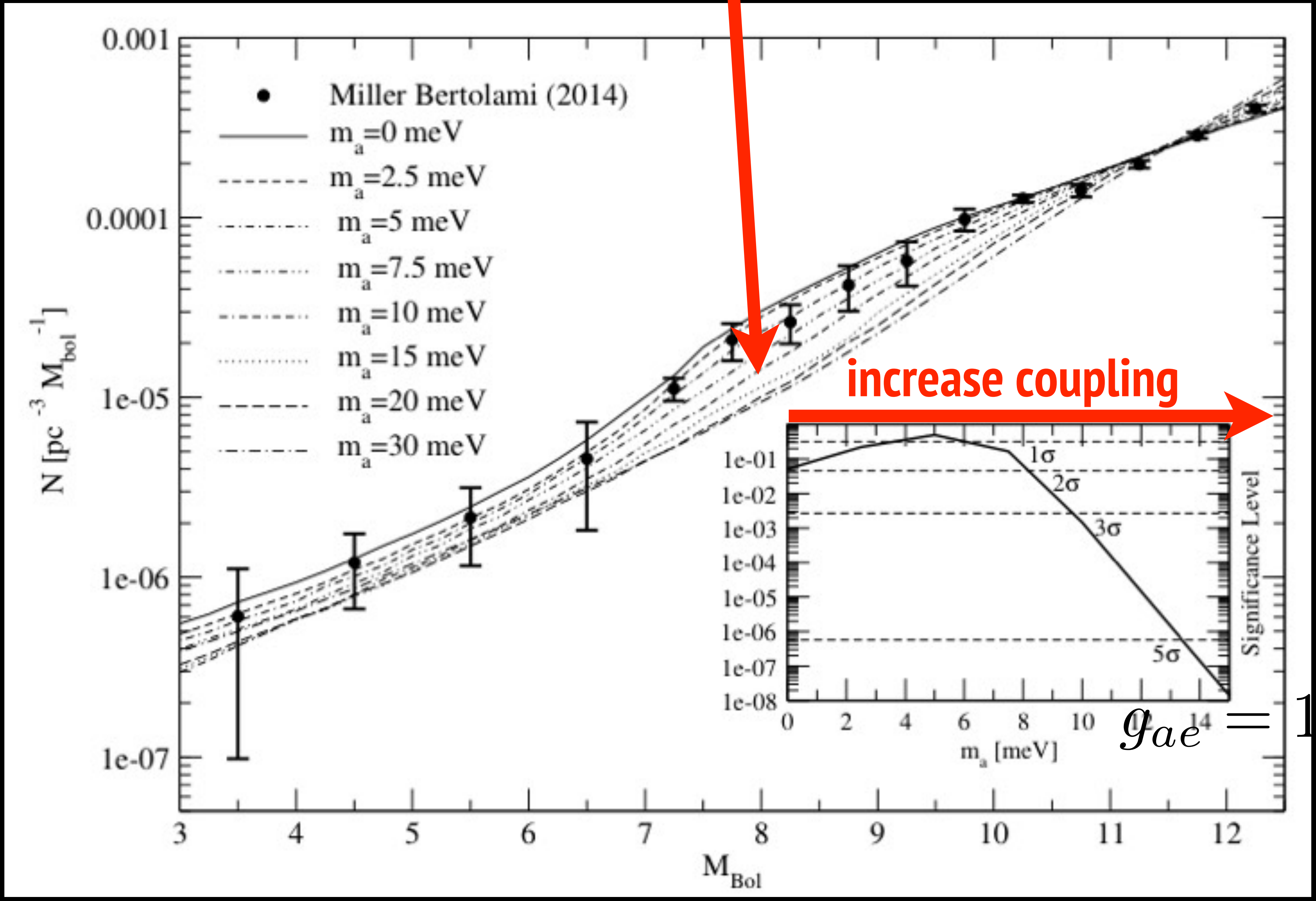
- White dwarfs are death stars (sustain no fusion)
- final phase of intermediate mass stars which cannot fuse C and O (Sun...)
- Cool by 1) neutrino emission and 2) by photon surface emission

White dwarf luminosity function

$$\frac{d\,N_{\mathrm{WD}}}{\mathrm{Vol}\,d\mathcal{L}} = \frac{k}{d\mathcal{L}/dt + d\mathcal{L}_a/dt}$$

with axion-electron bremsstrahlung

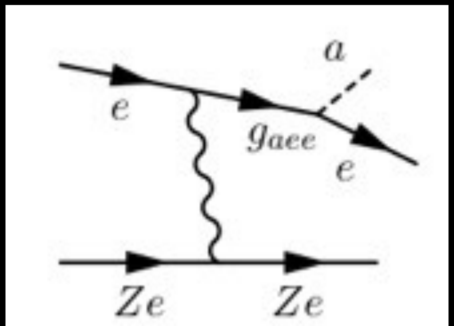


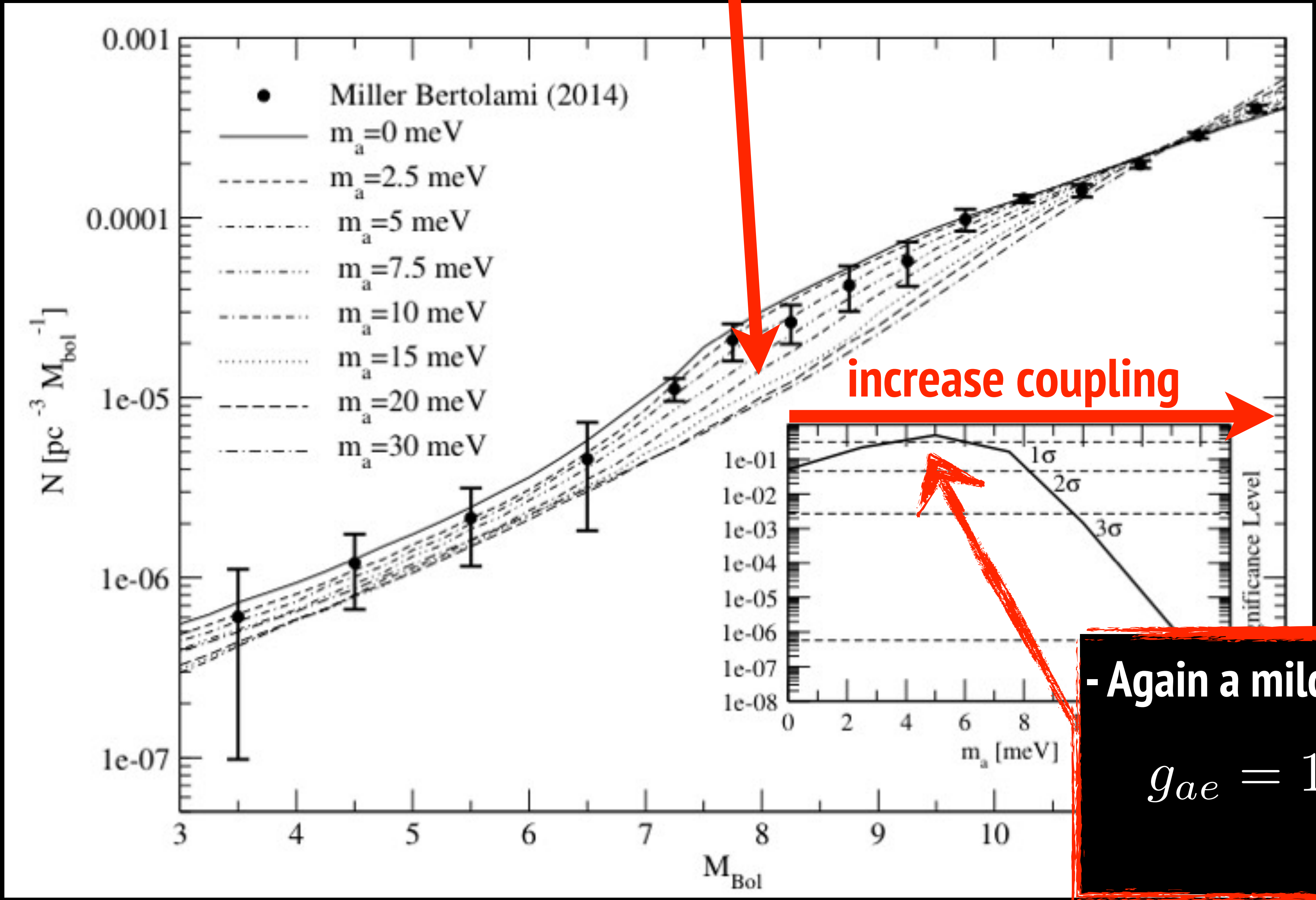


White dwarf luminosity function

$$\frac{d\,N_{\mathrm{WD}}}{\mathrm{Vol}\,d\mathcal{L}} = \frac{k}{d\mathcal{L}/dt + d\mathcal{L}_a/dt}$$

with axion-electron bremsstrahlung





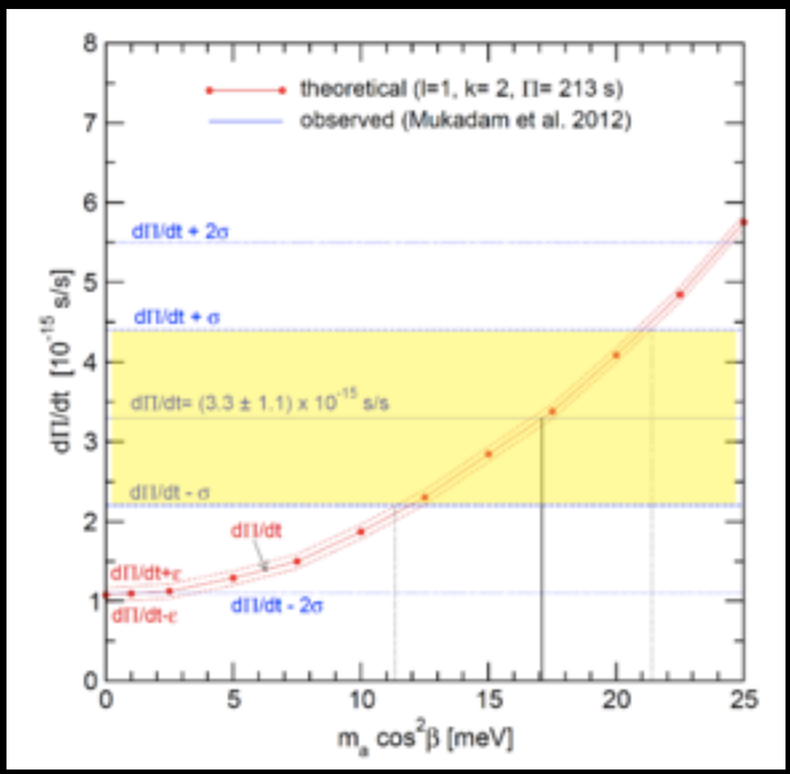
- Again a mild preference (Isern'14)

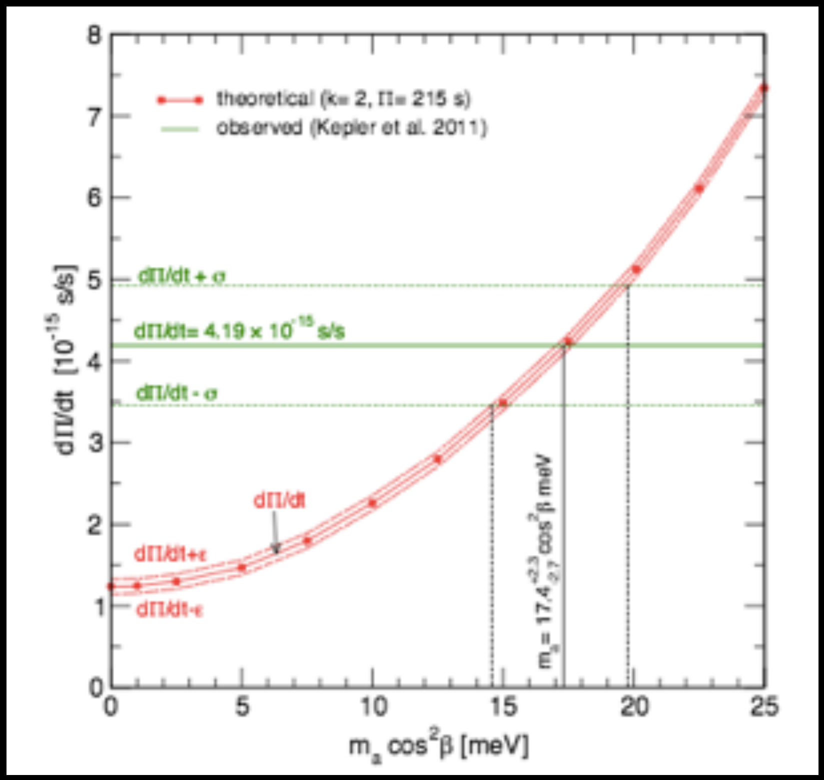
$$g_{ae} = 1.4^{+0.3}_{-0.3} \times 10^{-13}$$

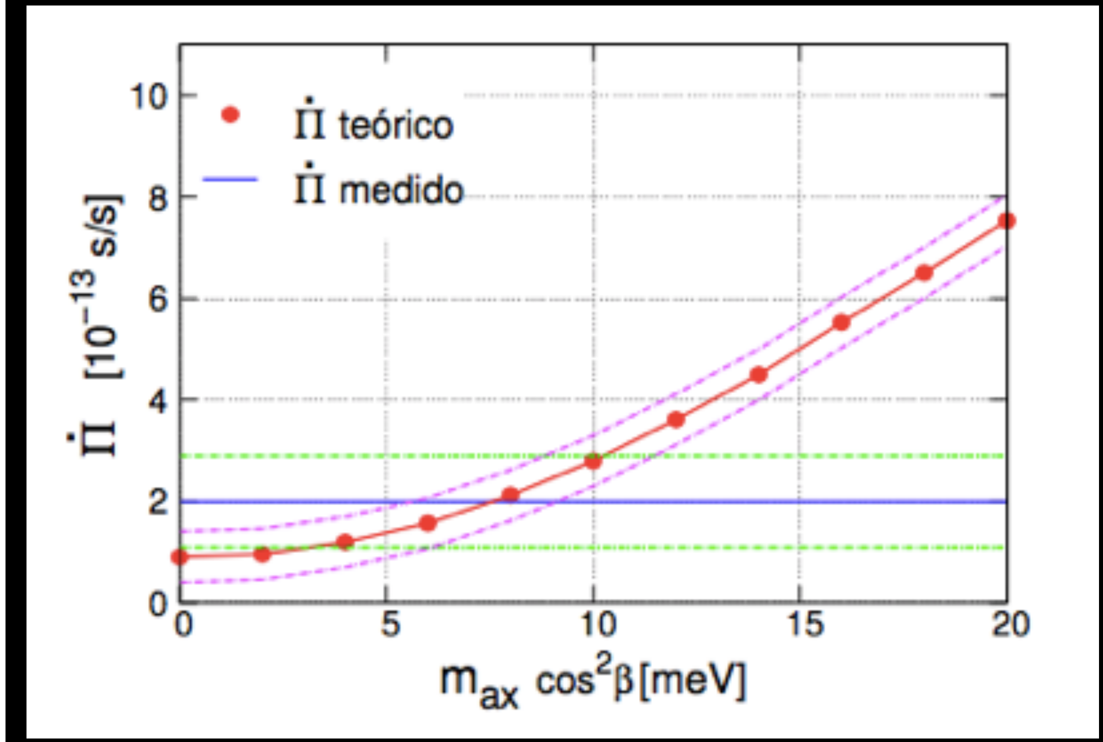
Pulsating WDs

- DAV, DBVs period decrease (traces energy loss) faster than theory models

R548 | **G117-B15A** | **PG 1351+489**







arXiv:1211.3389 | arxiv:1205.6180 | Battich, priv. com.

$$g_{ae} = 0.28 \times 10^{-13} m_a[\mathrm{meV}] \cos^2\beta$$

- Values of axion-couplings suggested by DAV's LARGER then WDLF and DBV
- Is the pulsating mode well identified?

arXiv:1406.7712

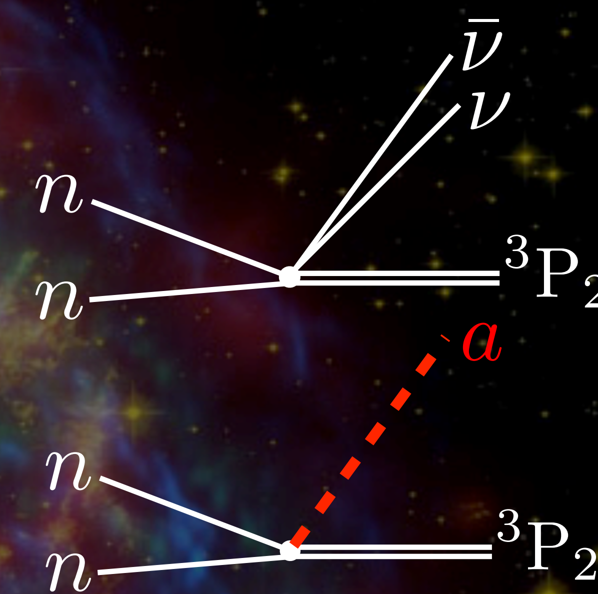
disfavoured by the study of the WDLF. It is worth noting that the high mass of the axion derived in those works is a direct consequence of the identification of the 215 s (213 s) mode of G117-B15A (R548) as a mode trapped in the envelope. Consequently, our result can also be viewed as a strong argument that those modes are not trapped modes. This is true

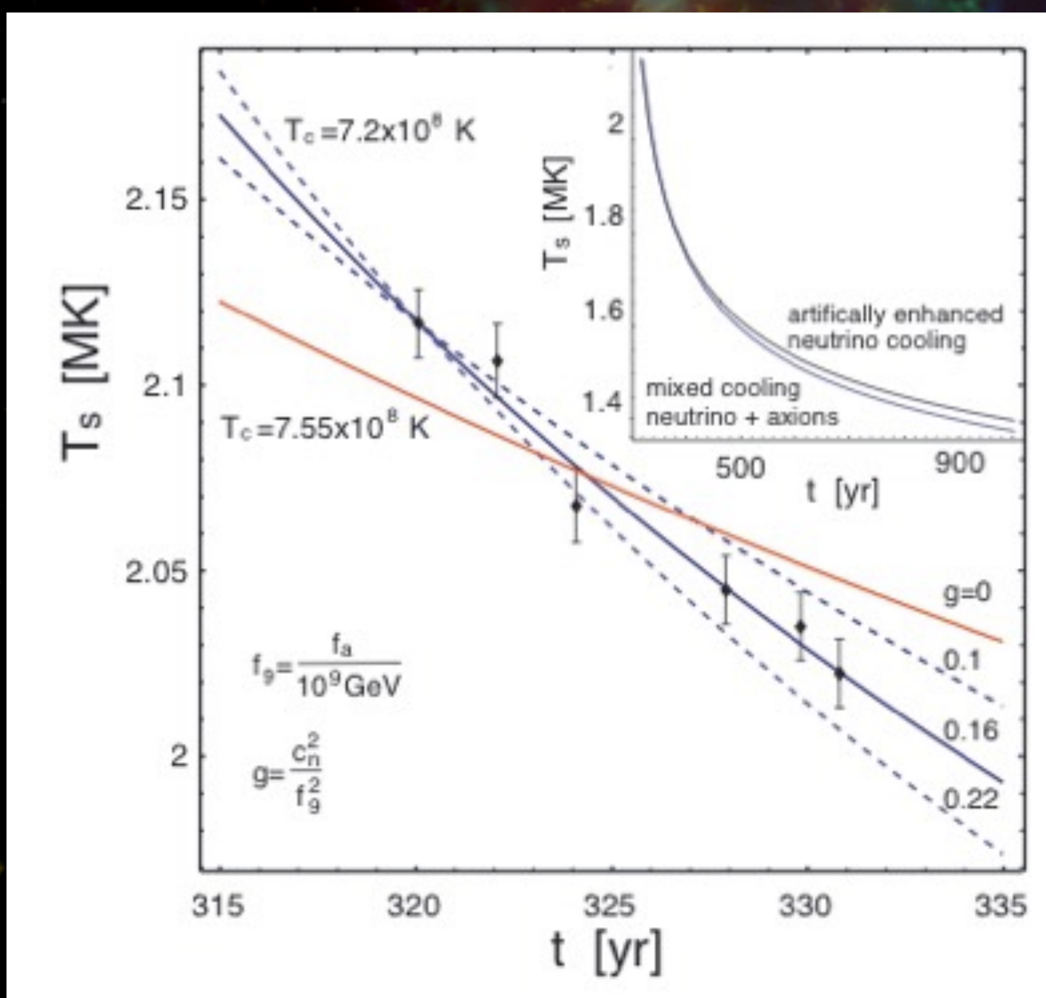
Cassiopeia A: neutron star cooling

- Cooling measured by Chandra, ~4% in ten years!

- Evidence of $\bar{\nu}\nu$ emission in n Cooper pair formation $^3P_2$

- Factor of ~2 extra cooling required, axions?





Hints, constraints and models ... any preference?

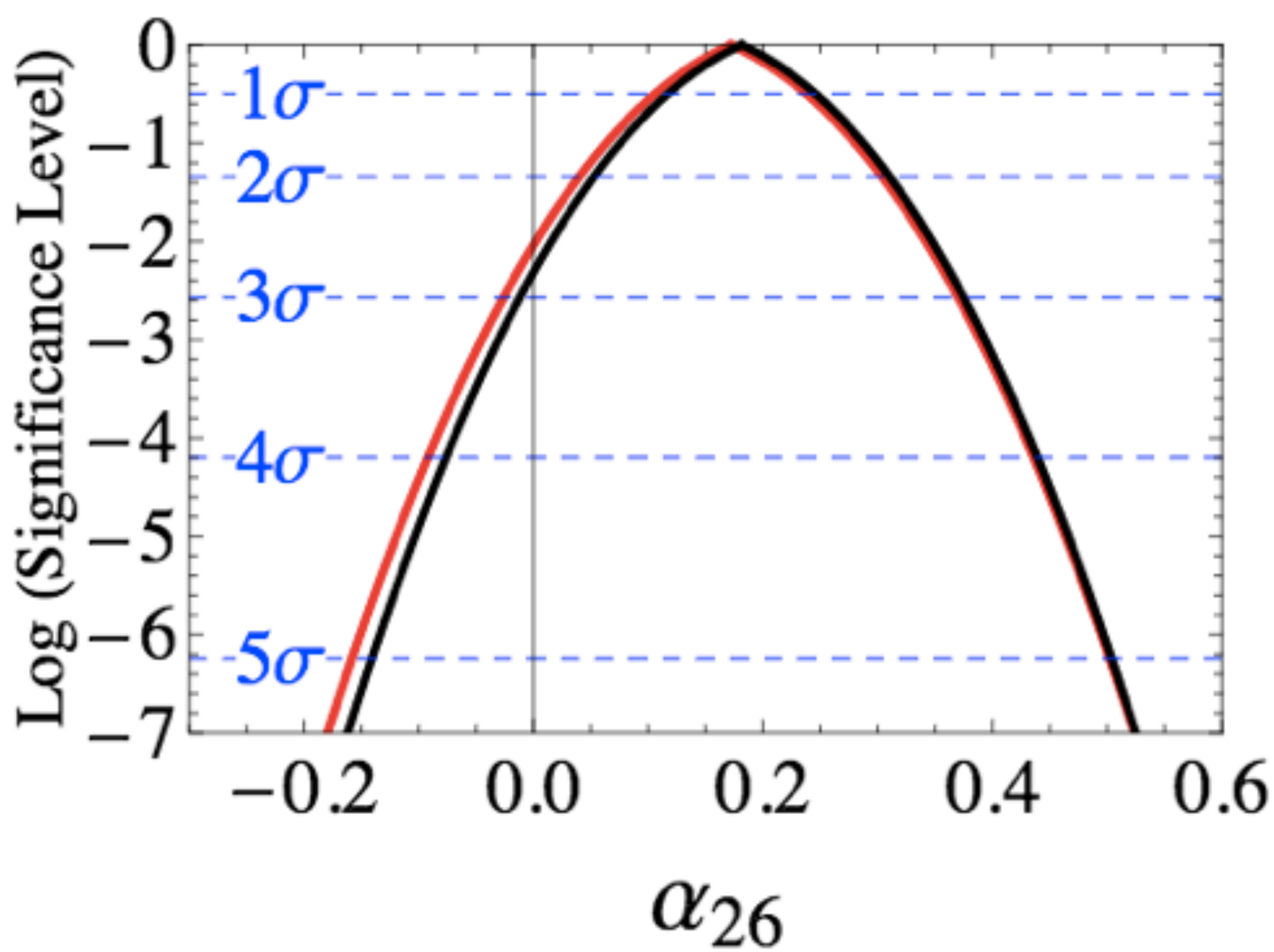
Hb/RG Globular clusters

Tip of the Red Giant branch (M5)

White dwarf luminosity function

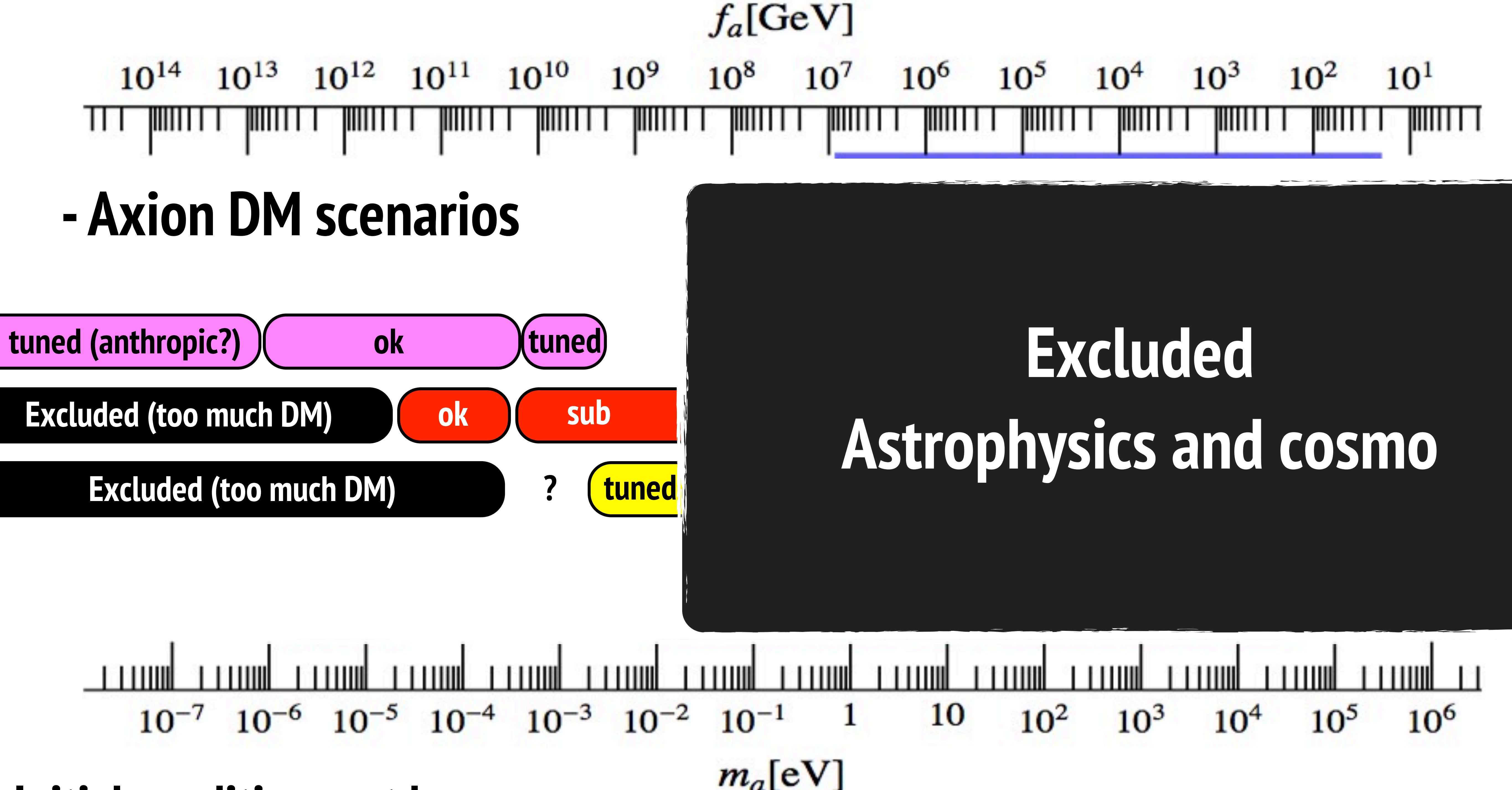
Giannotti et al (arXiv:1512.08108)

	α_{26}	references
G117 - B15A	1.87 ± 0.53	[4]
R548	1.82 ± 1.03	[6]
PG 1351+489	0.52 ± 0.67	[7]
WDLF	0.156 ± 0.068	[8]
RG	0.26 ± 0.28	[12]
HB	0.38 ± 0.3	this work



the meV frontier, astrophysics and dark matter

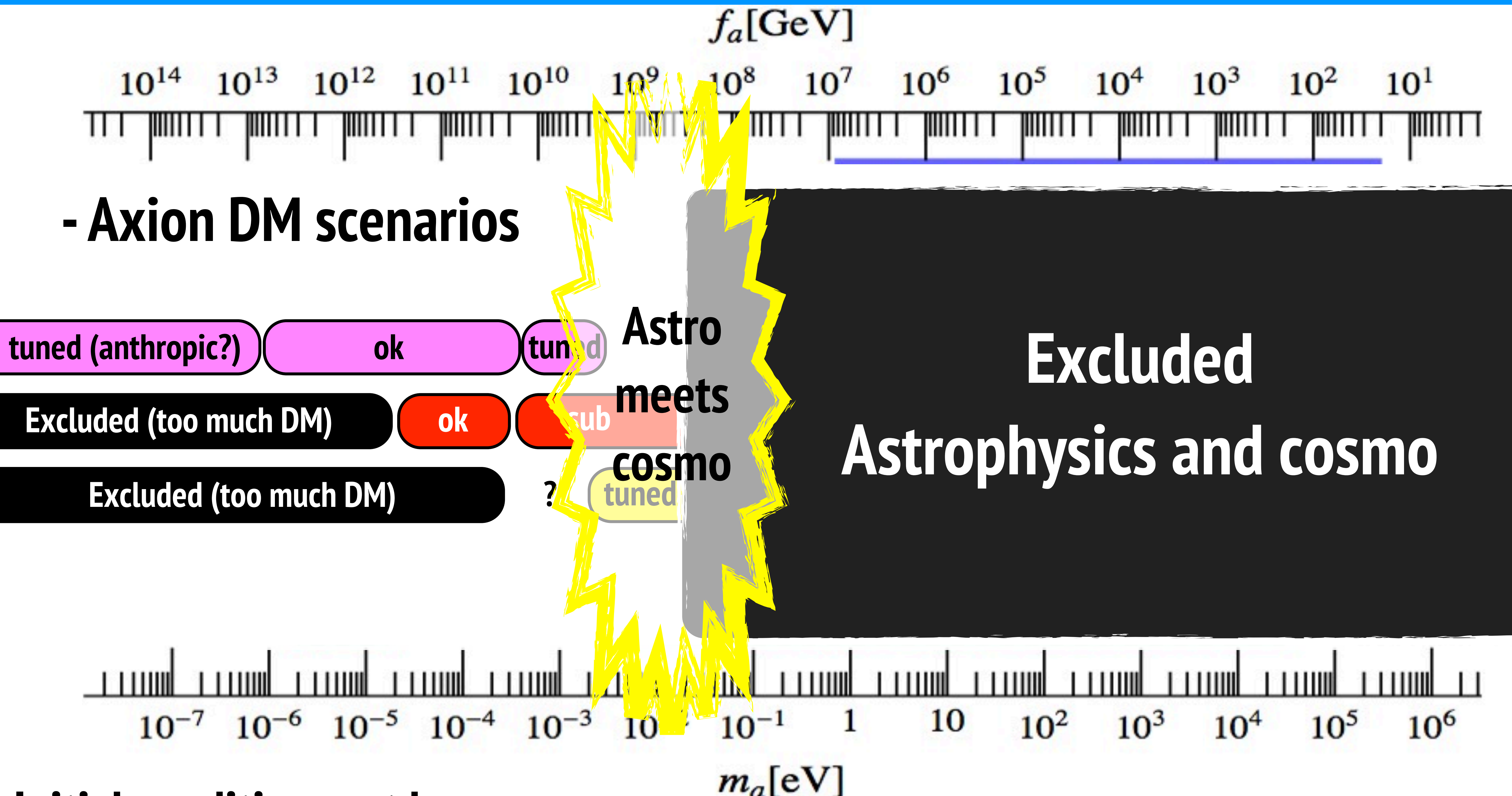
- Axion DM scenarios



Initial conditions set by :

Inflation smooth	Phase transition (N=1)	Phase transition (N>1)
$\Omega_{\rm aDM}h^2 \simeq \theta_I^2 \left(\frac{80\,\mu{\rm eV}}{m_a}\right)^{1.19}$	strings+unstable DW's	strings+long-lived DWs

the meV frontier, astrophysics and dark matter



Initial conditions set by :

Inflation smooth

$$\Omega_{\rm aDM}h^2 \simeq \theta_I^2 \left(\frac{80\,\mu{\rm eV}}{m_a}\right)^{1.19}$$

Phase transition (N=1)

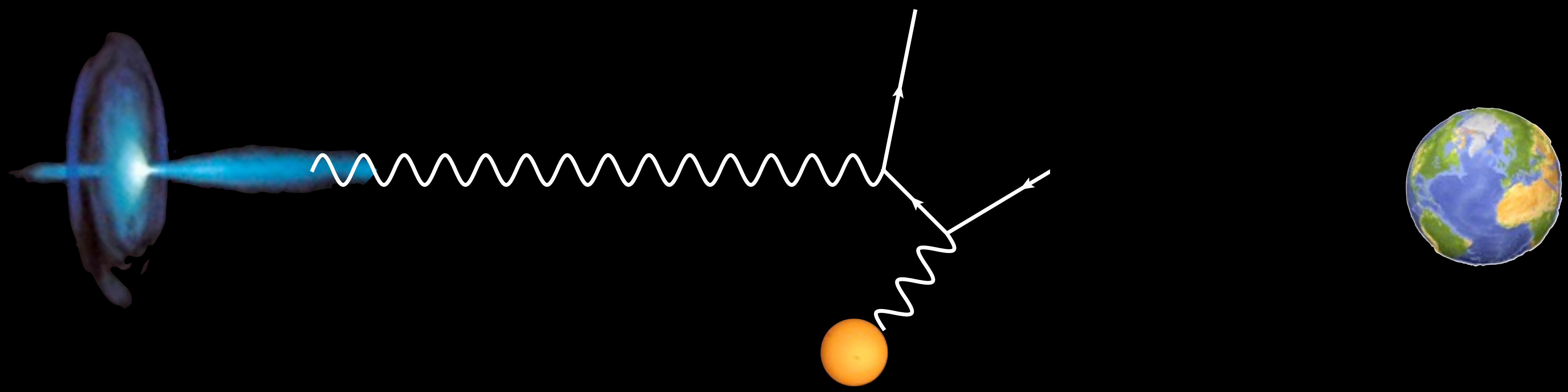
strings+unstable DW's

Phase transition (N>1)

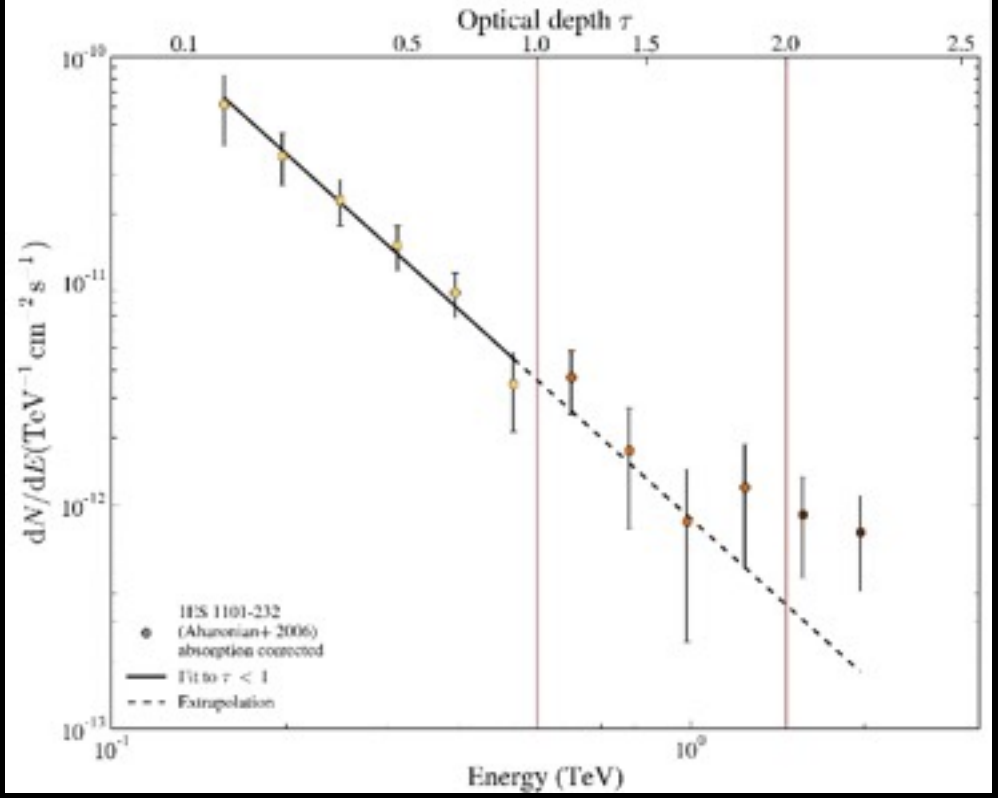
strings+long-lived DWs

Transparency of the Universe

Very High energy gamma rays cannot arrive to Earth



However, they do ...(Roncadelli et al PRD 84, Sanchez-Conde et al JCAP 1111, Horns and Meyer JCAP 1202)

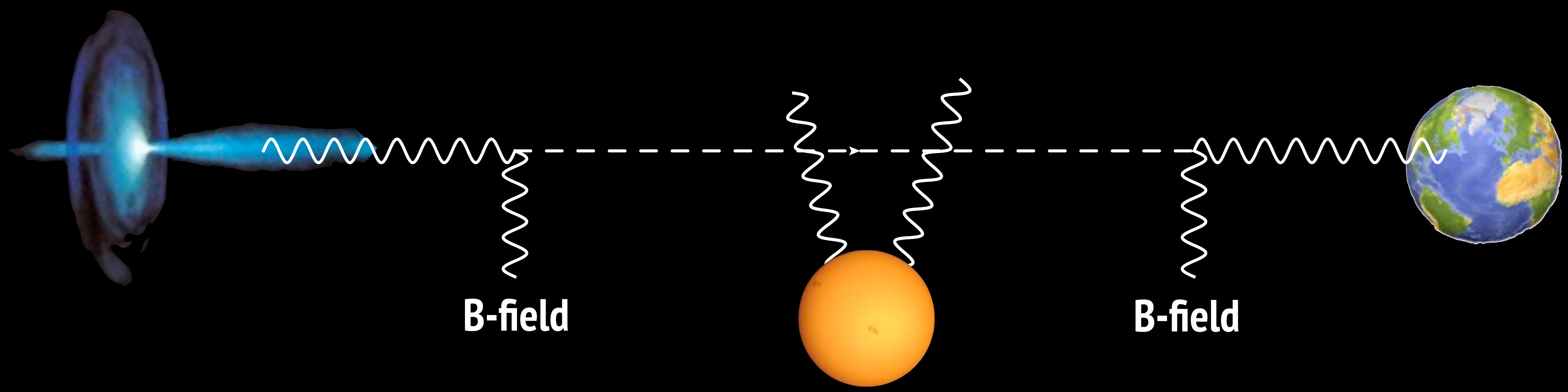


Excess persists at

$$2 - 4\sigma$$

Transparency of the Universe ... due to axion-like particles?

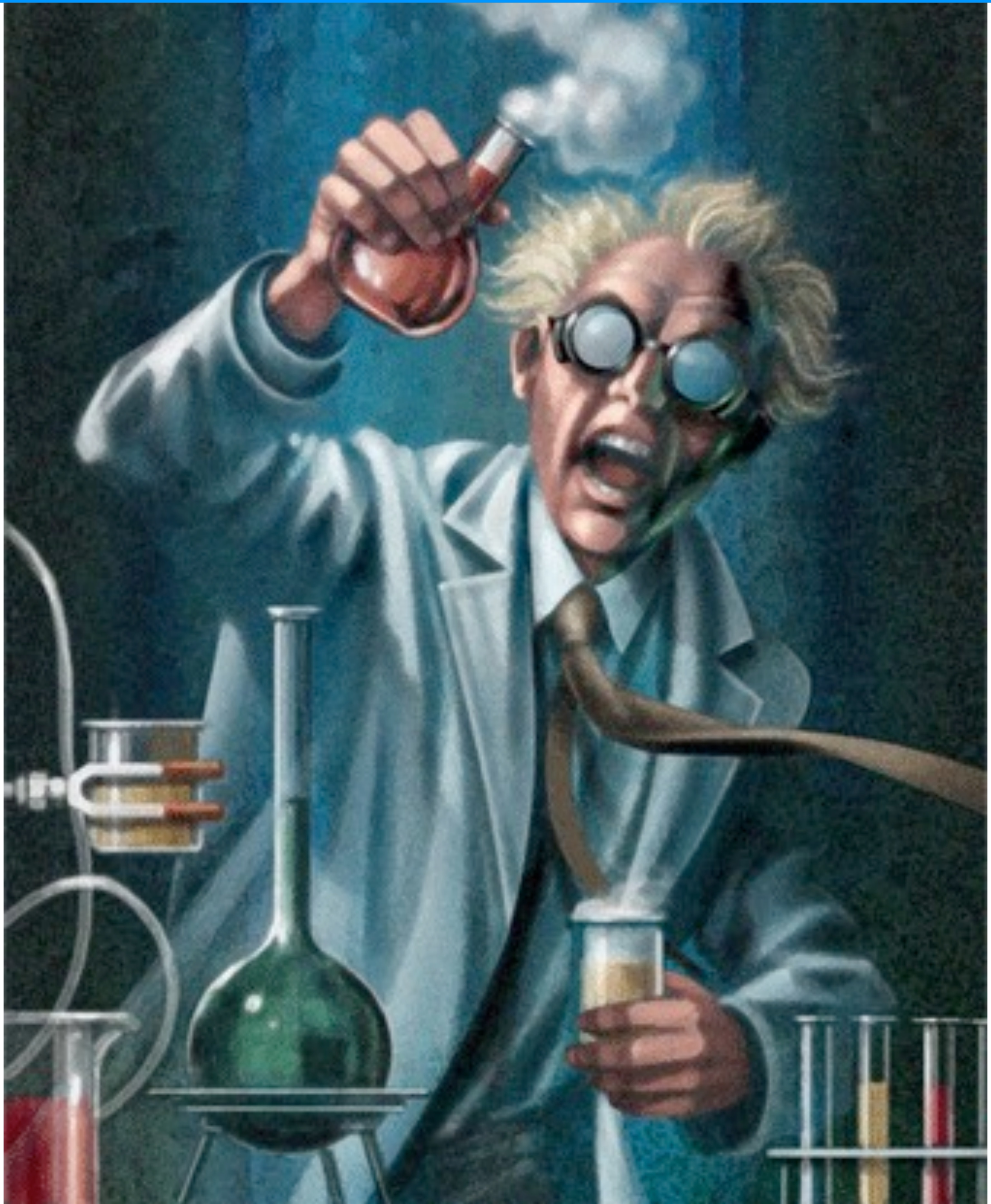
Very High energy gamma rays CAN arrive to Earth converted into axions



-The effect requires couplings $g_{a\gamma} \sim 10^{-11}\mathrm{GeV}^{-1}$ and mass $m \sim 10^{-9}\mathrm{eV}$

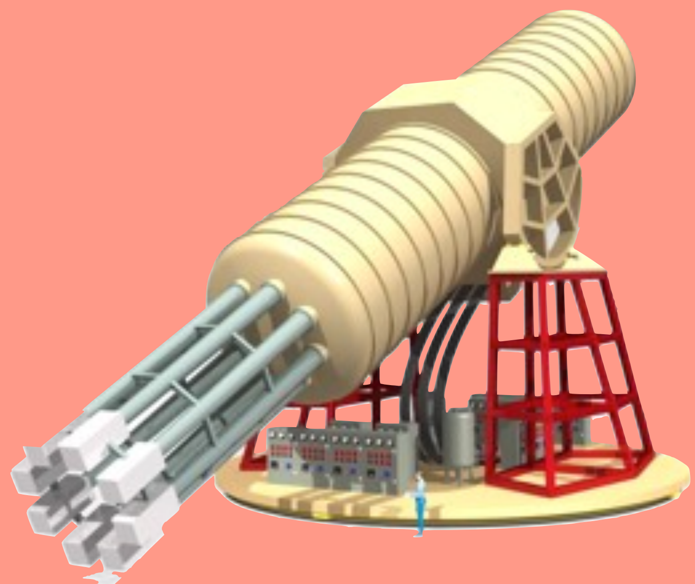
- It cannot be the QCD axion, but it can be an axion-like particle ...
- how can we test it?

Experiments

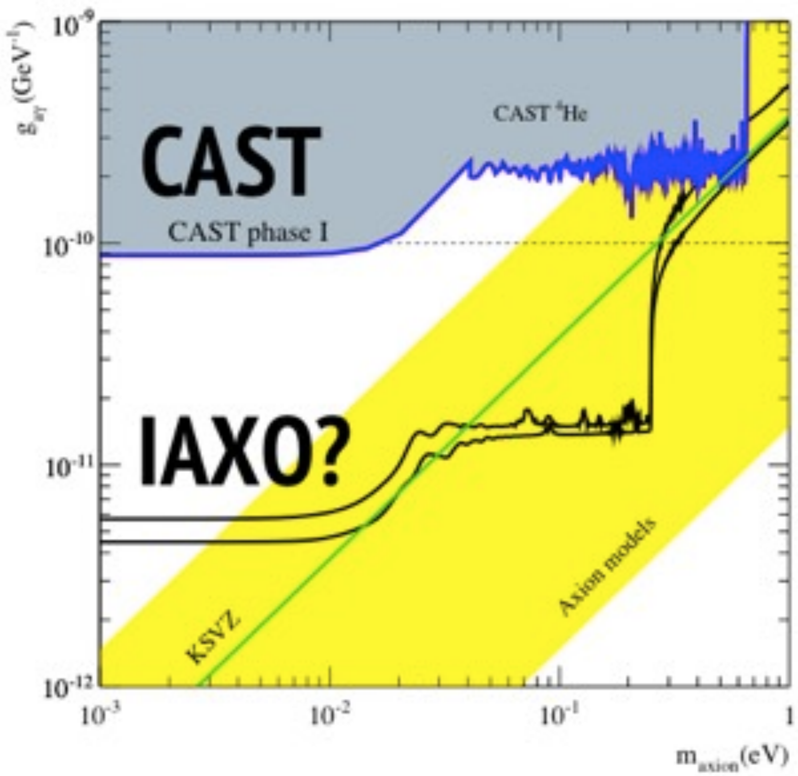


Detecting Axions

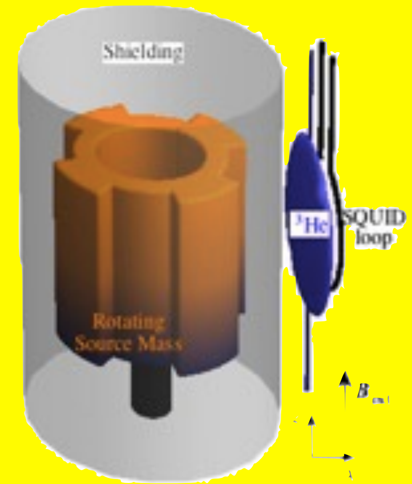
Solar Axions



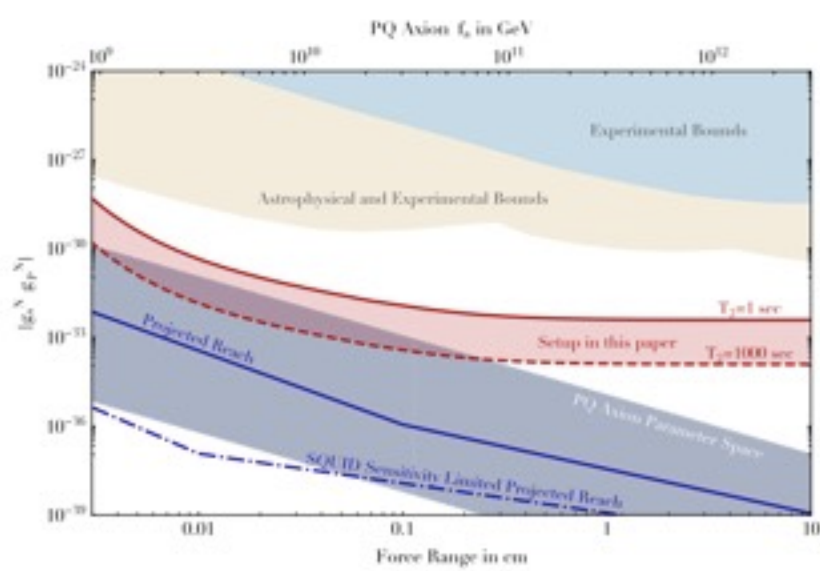
IAXO CDR 2014



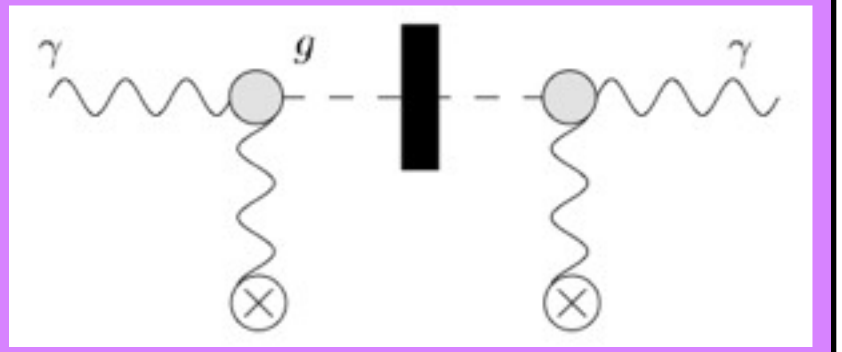
5th forces



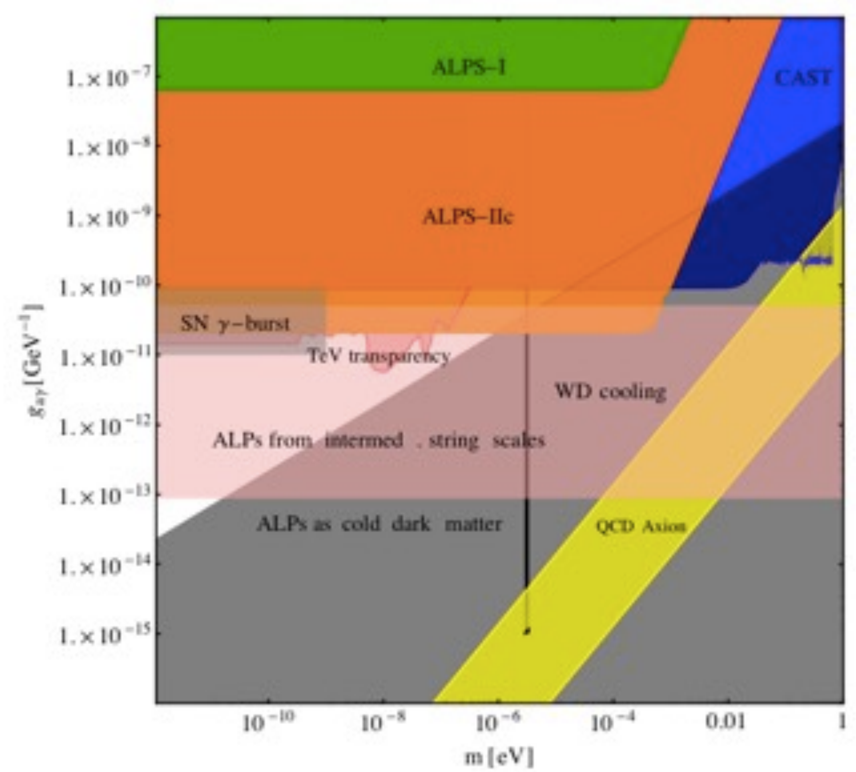
Arvanitaki Geraci PRL 2014



Photon regeneration

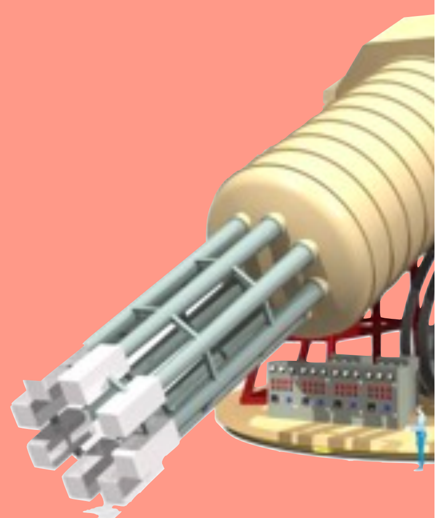


ALPS-II TDR 2013



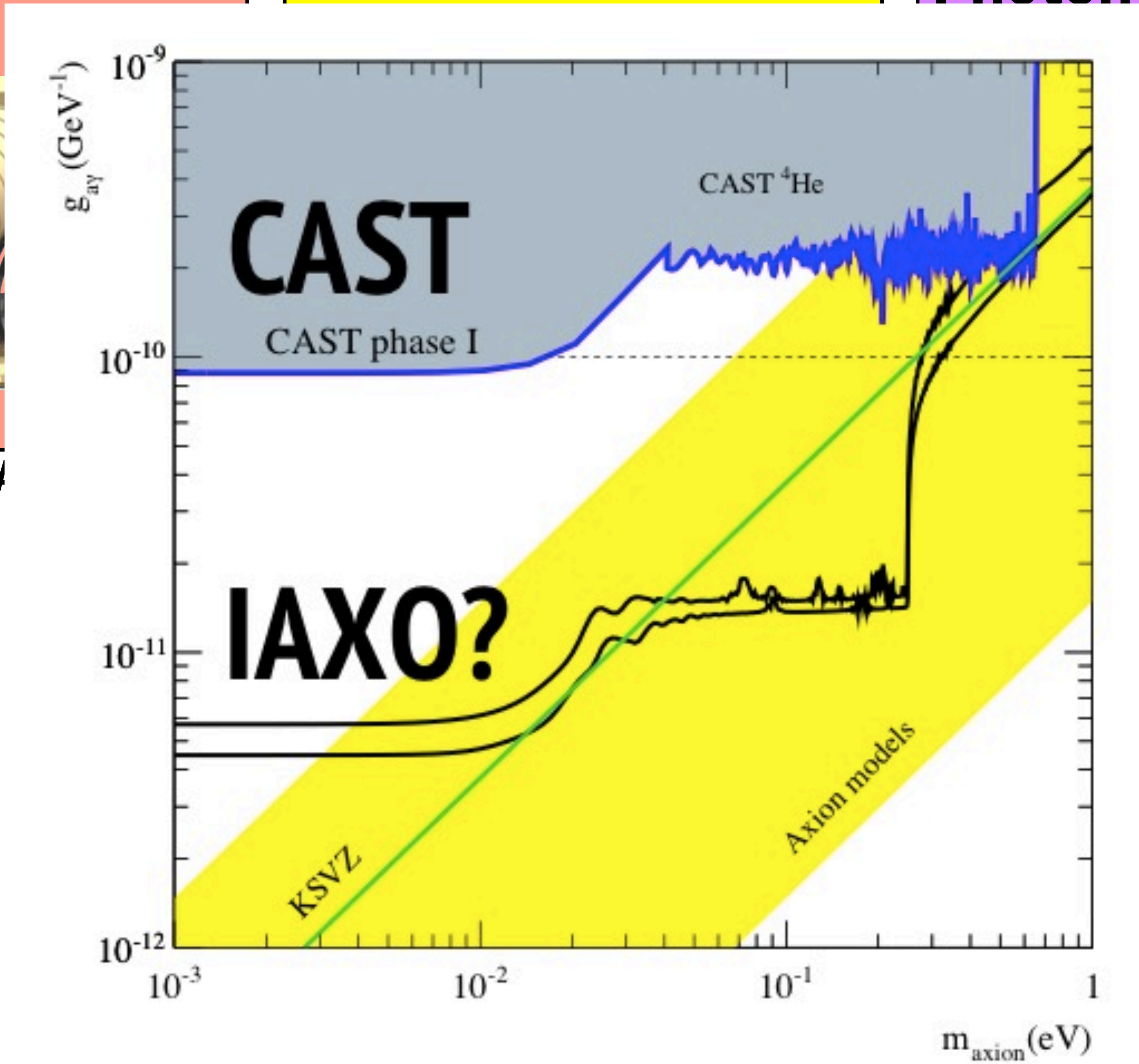
Detecting Axions

Solar Axions

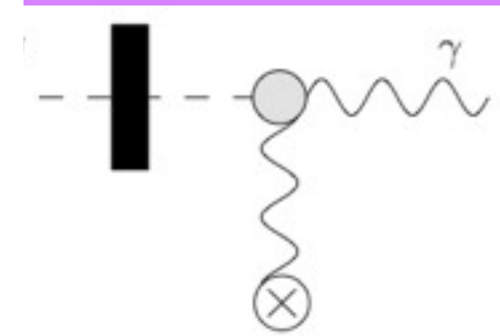


IA

5th forces



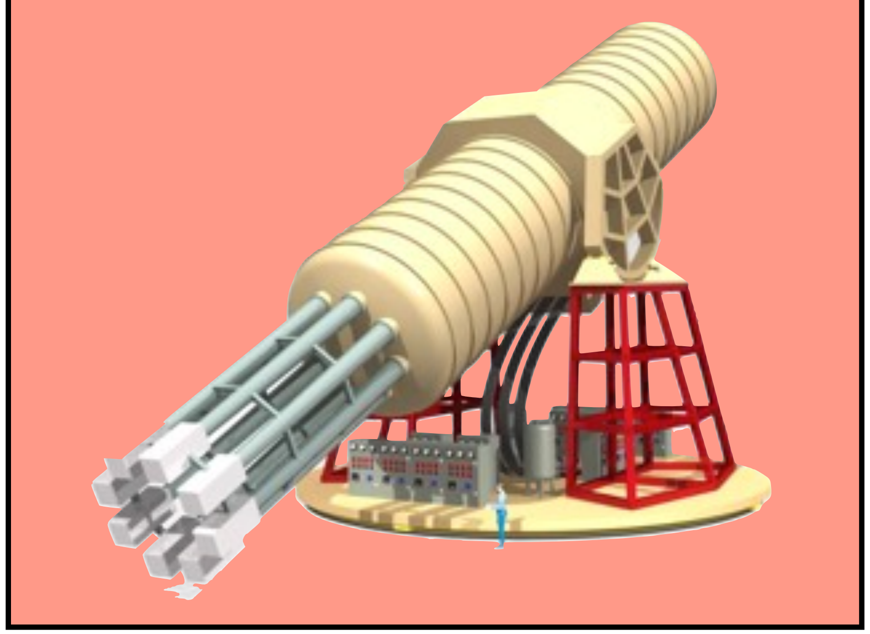
Photon regeneration



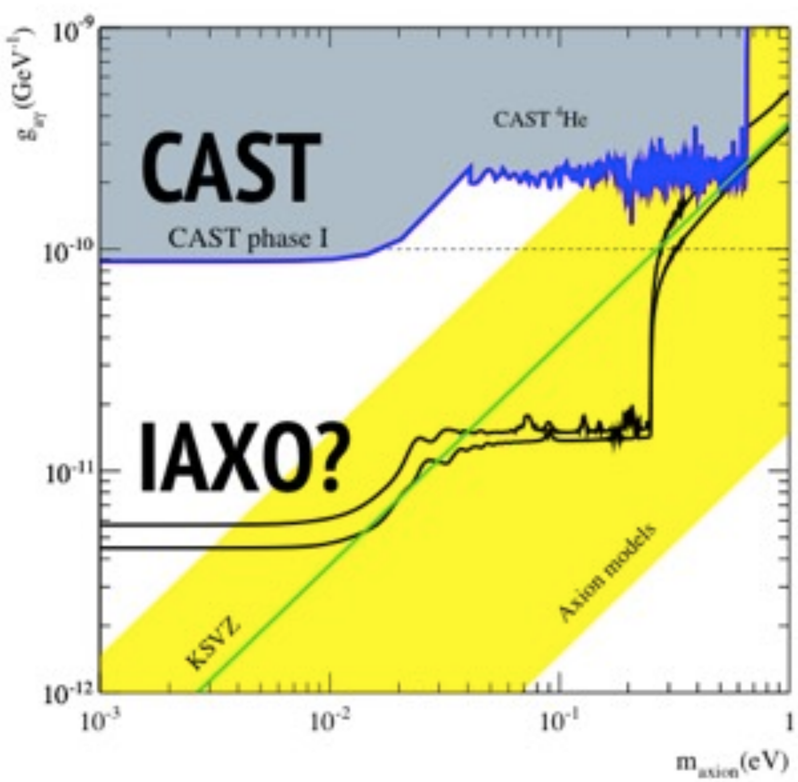
ALPS-II TDR 2013

Detecting Axions

Solar Axions

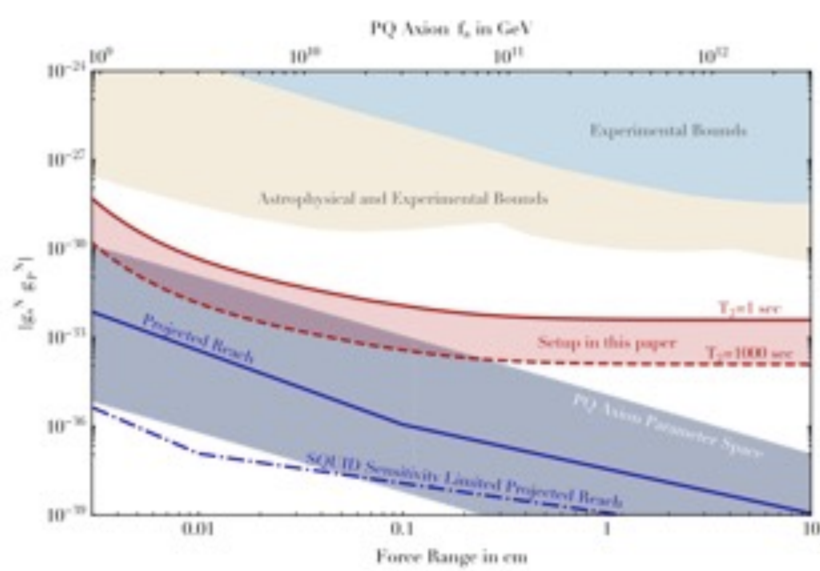


IAXO CDR 2014

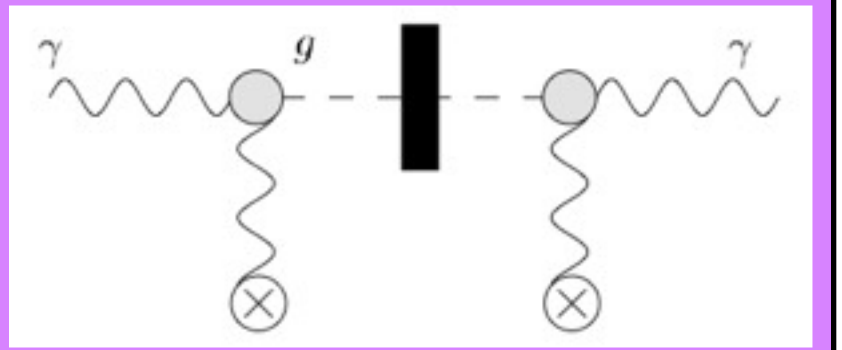


5th forces

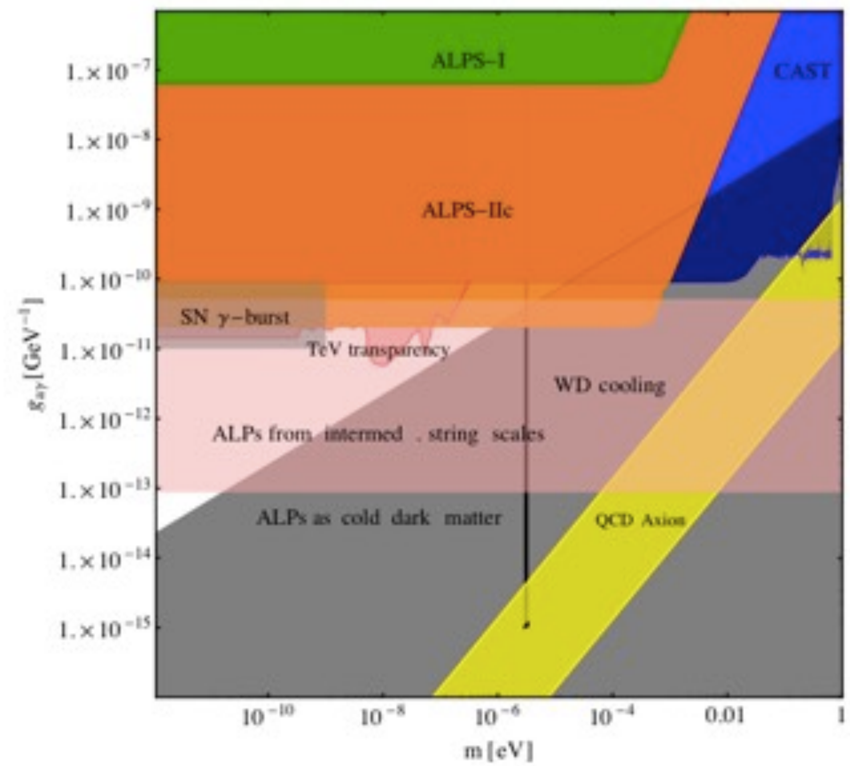
Arvanitaki Geraci PRL 2014



Photon regeneration

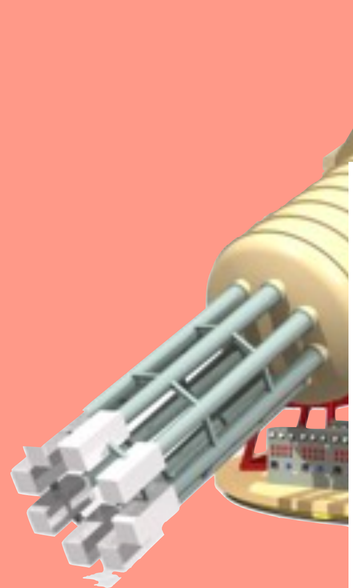


ALPS-II TDR 2013



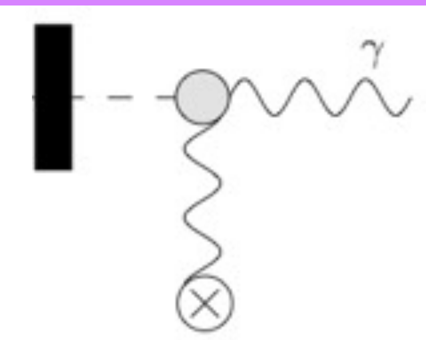
Detecting Axions

Solar Axions

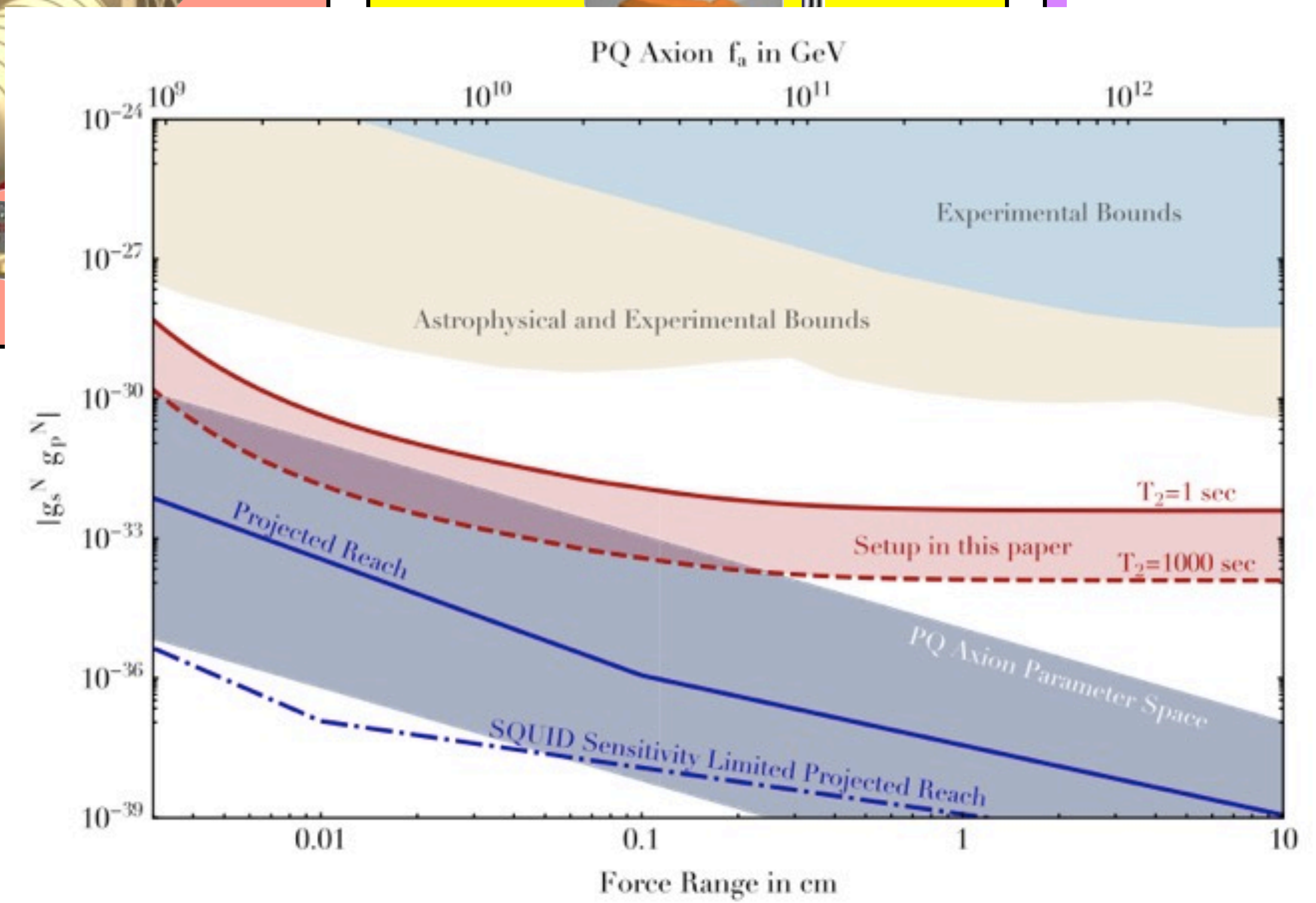


5th forces

Photon regeneration

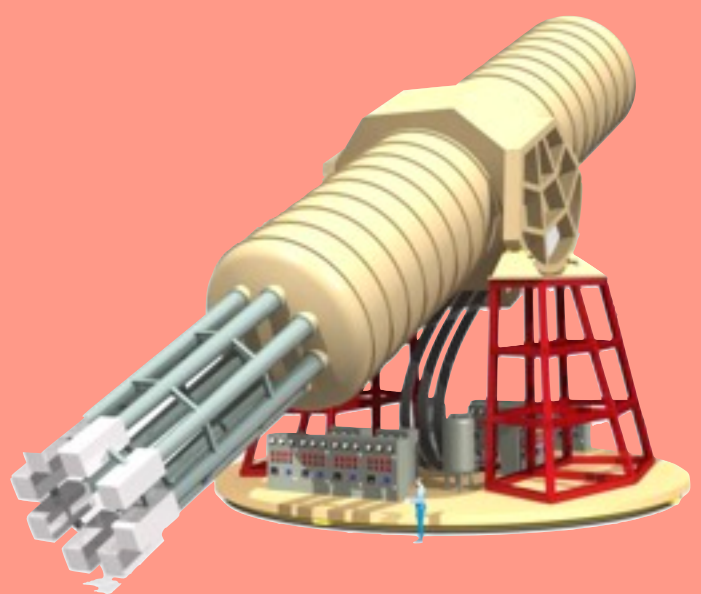


ALPS-II TDR 2013



Detecting Axions

Solar Axions

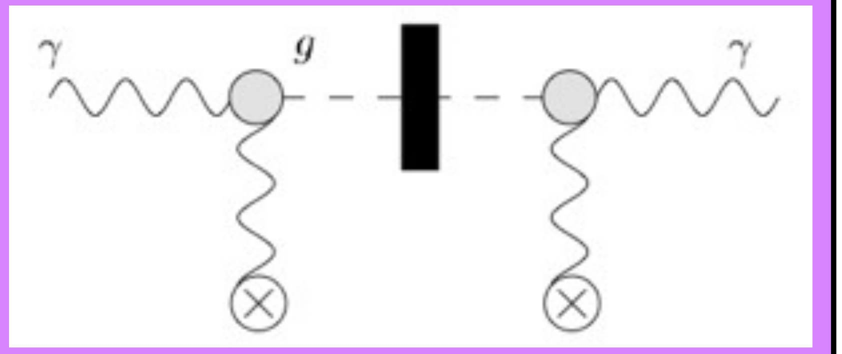


IAXO CDR 2014

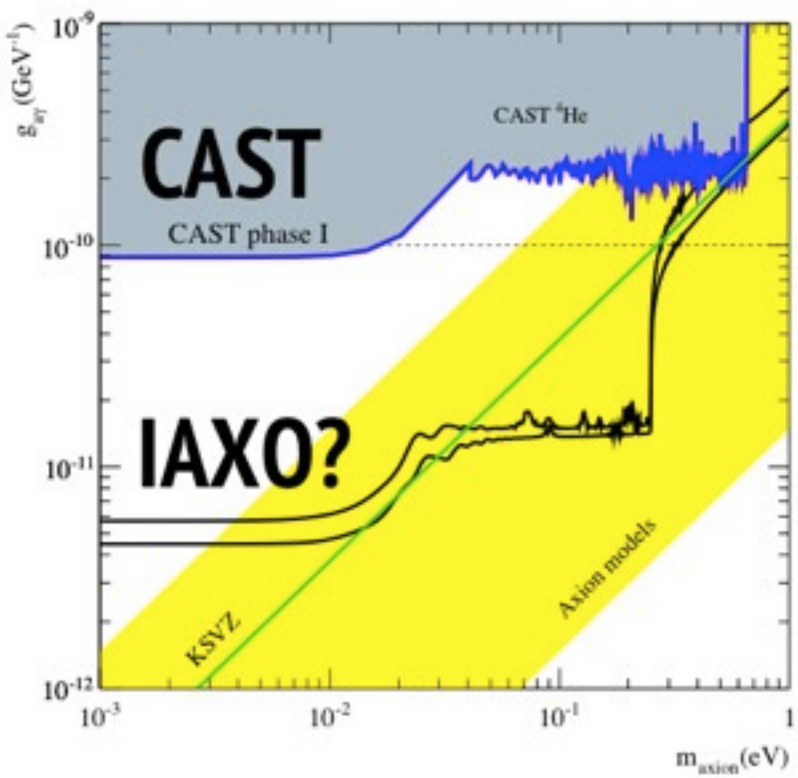
5th forces

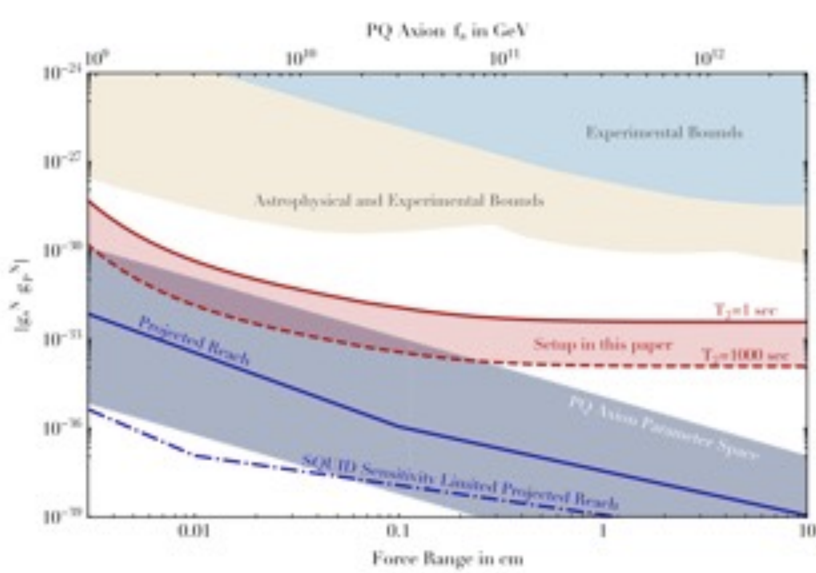
Arvanitaki Geraci PRL 2014

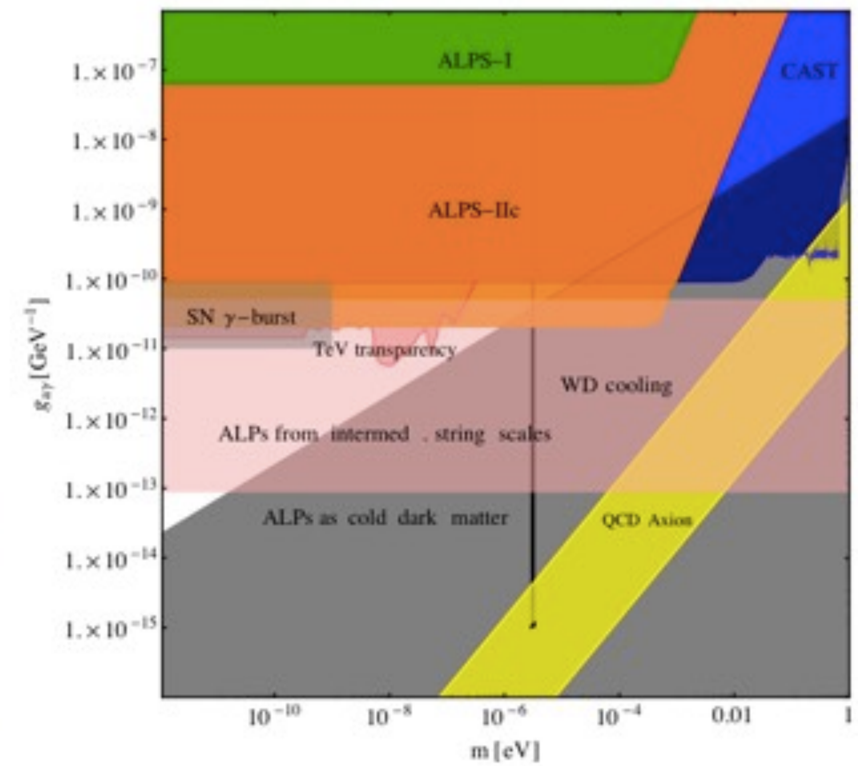
Photon regeneration



ALPS-II TDR 2013

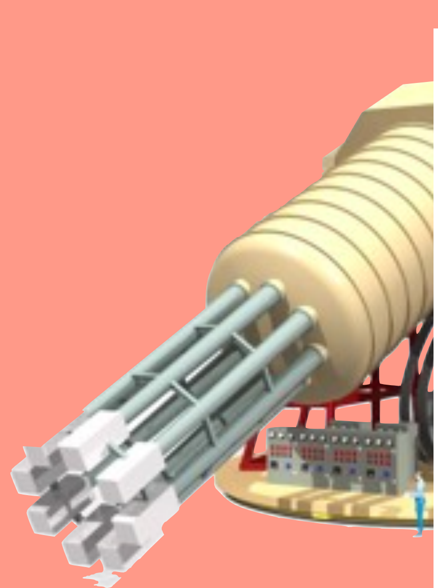






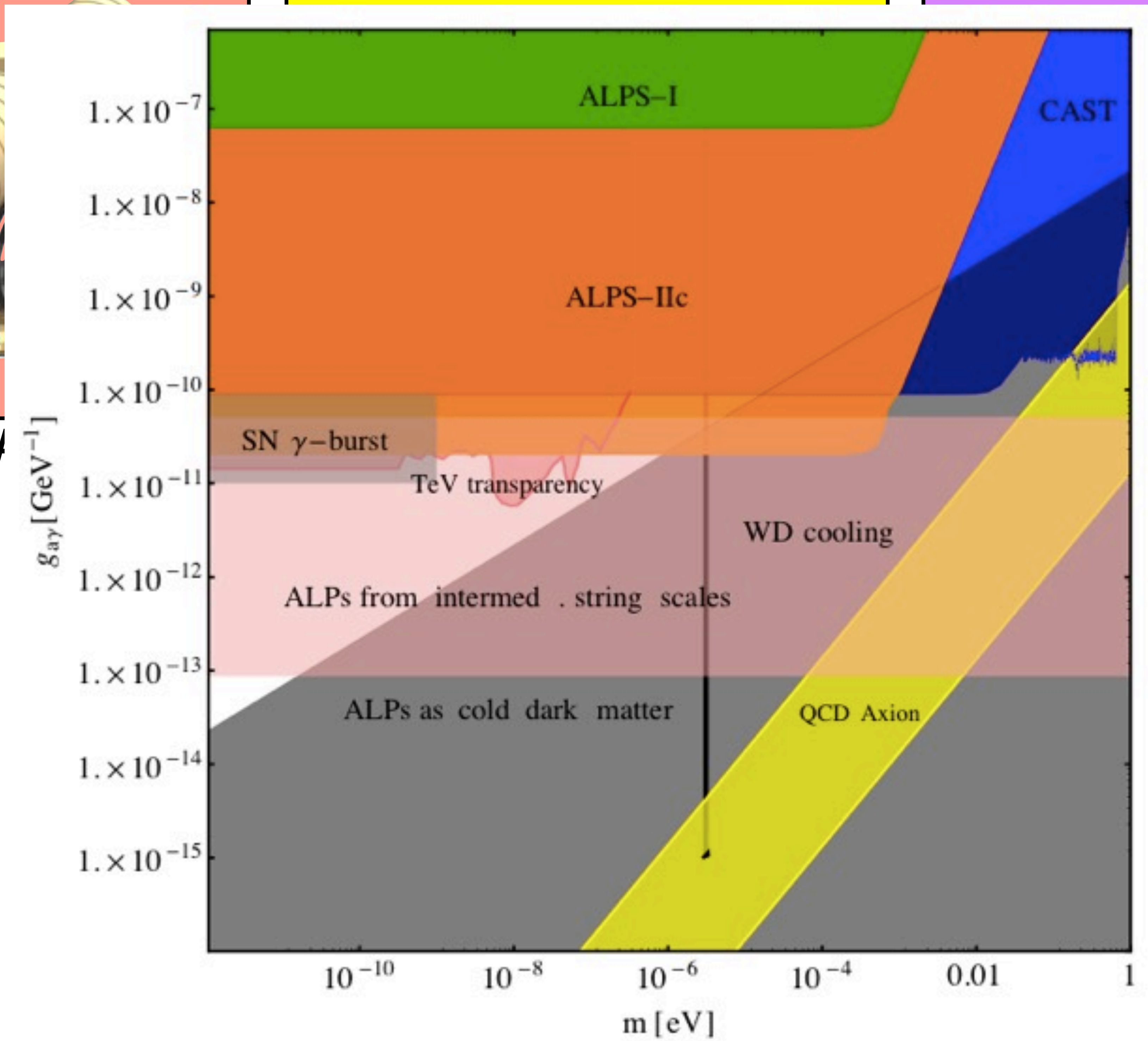
Detecting Axions

Solar Axions

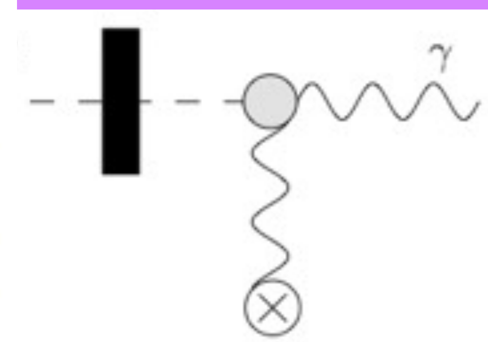


IA

5th forces



Photon regeneration

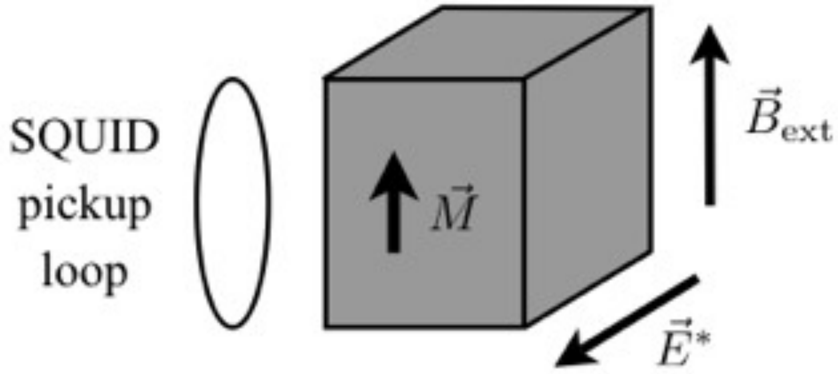


ALPS-II TDR 2013

Dark matter axion experiments

mass neV μeV 0.1 meV

Spin precession



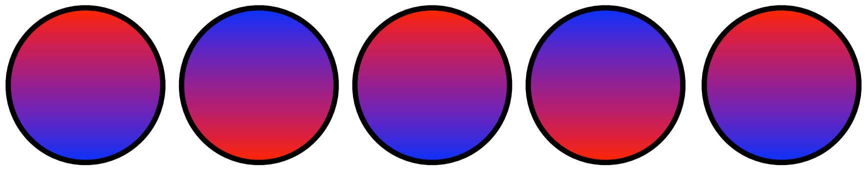
CASPER (Mainz-Berkely)

haloscopes

ADMX, ADMX-HF,Yale, CULTASK, CST-CAPP, MADMAD, RADES ...

Atomic transitions?

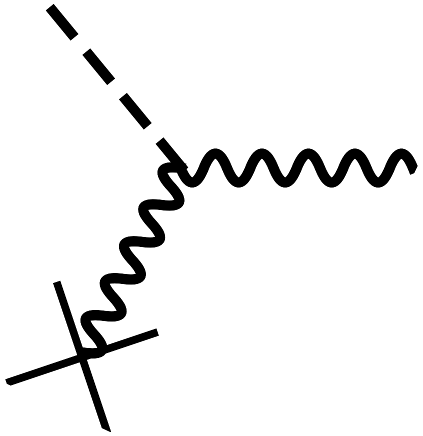
Oscillating EDM



$$d_n \sim \mathcal{O}(10^{-34})\cos(m_a t)[e\,\mathrm{cm}]$$

Graham, Rajendran 2011

Axion-photon conversion

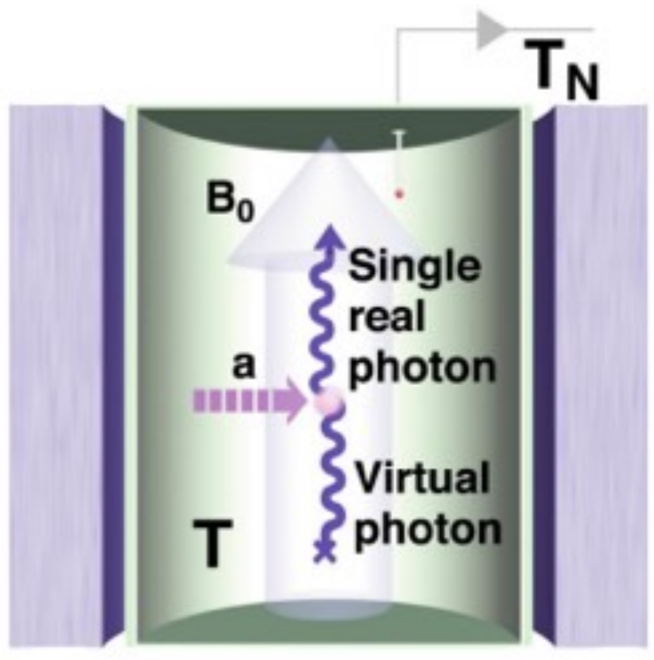


Axion-electron absorption

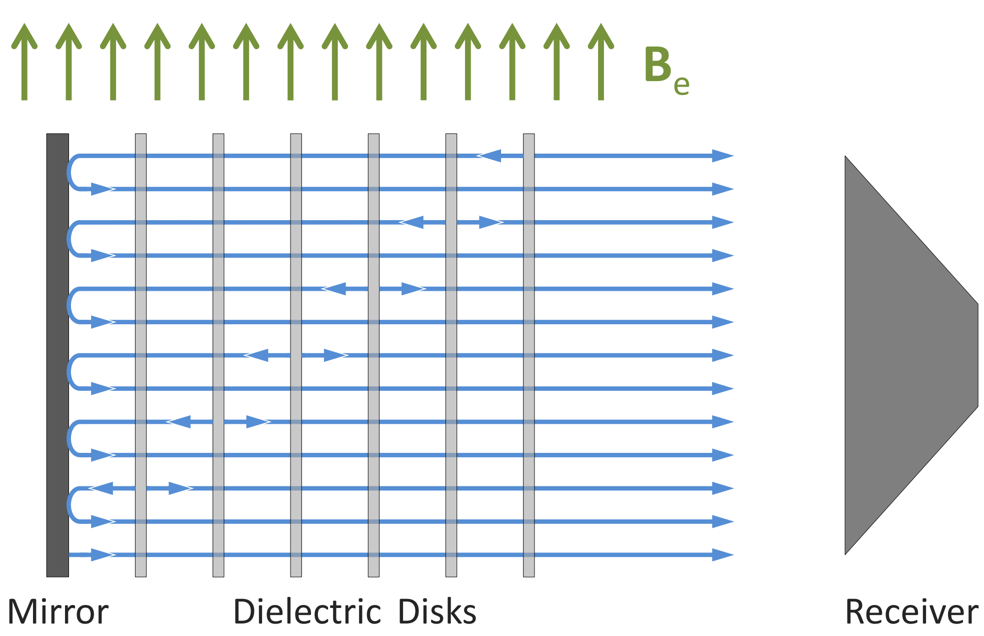
Sikivie 2014

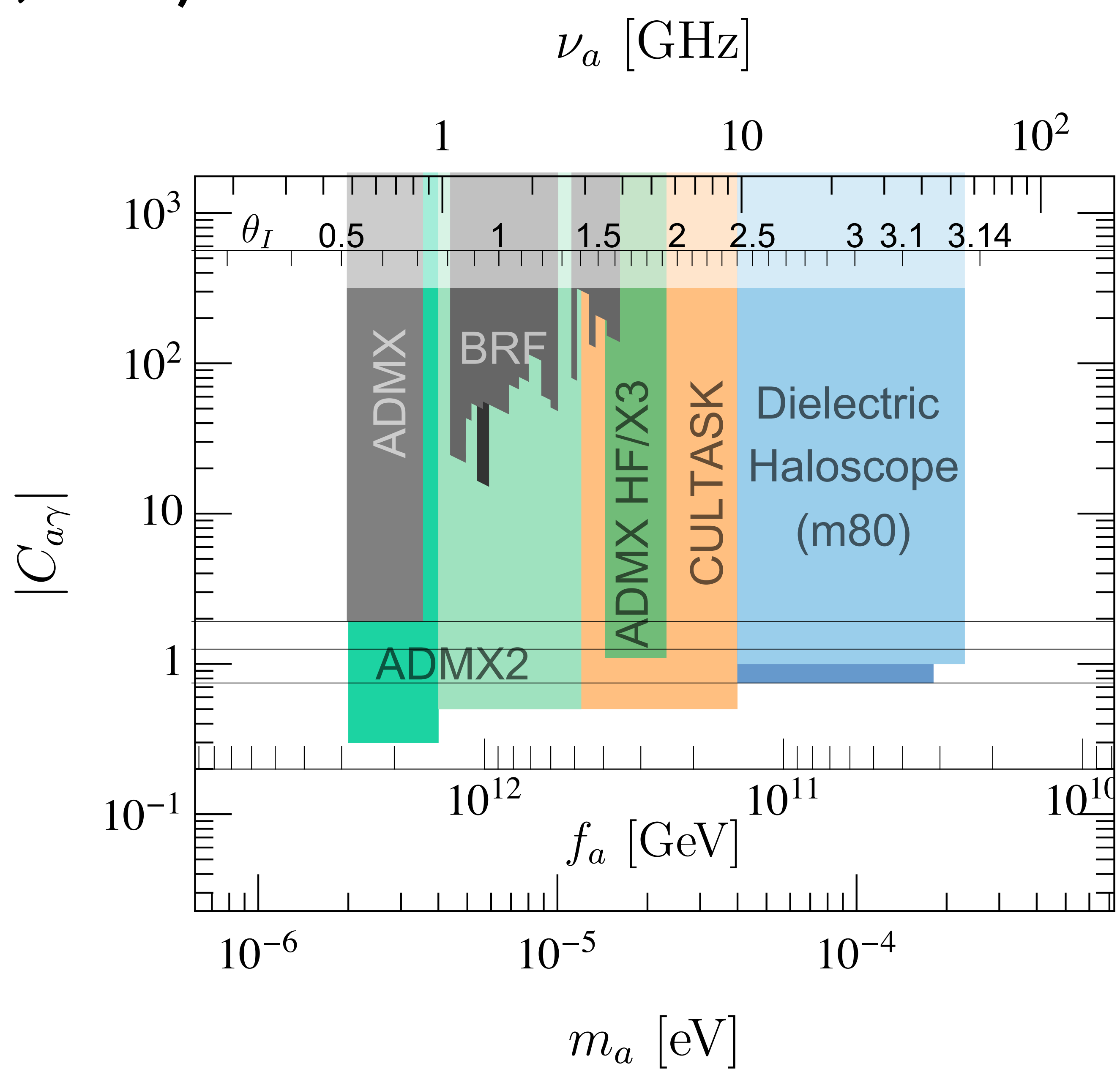
Haloscopes

Resonant cavity (ADMX, Yale, CAPP Korea, RADES)

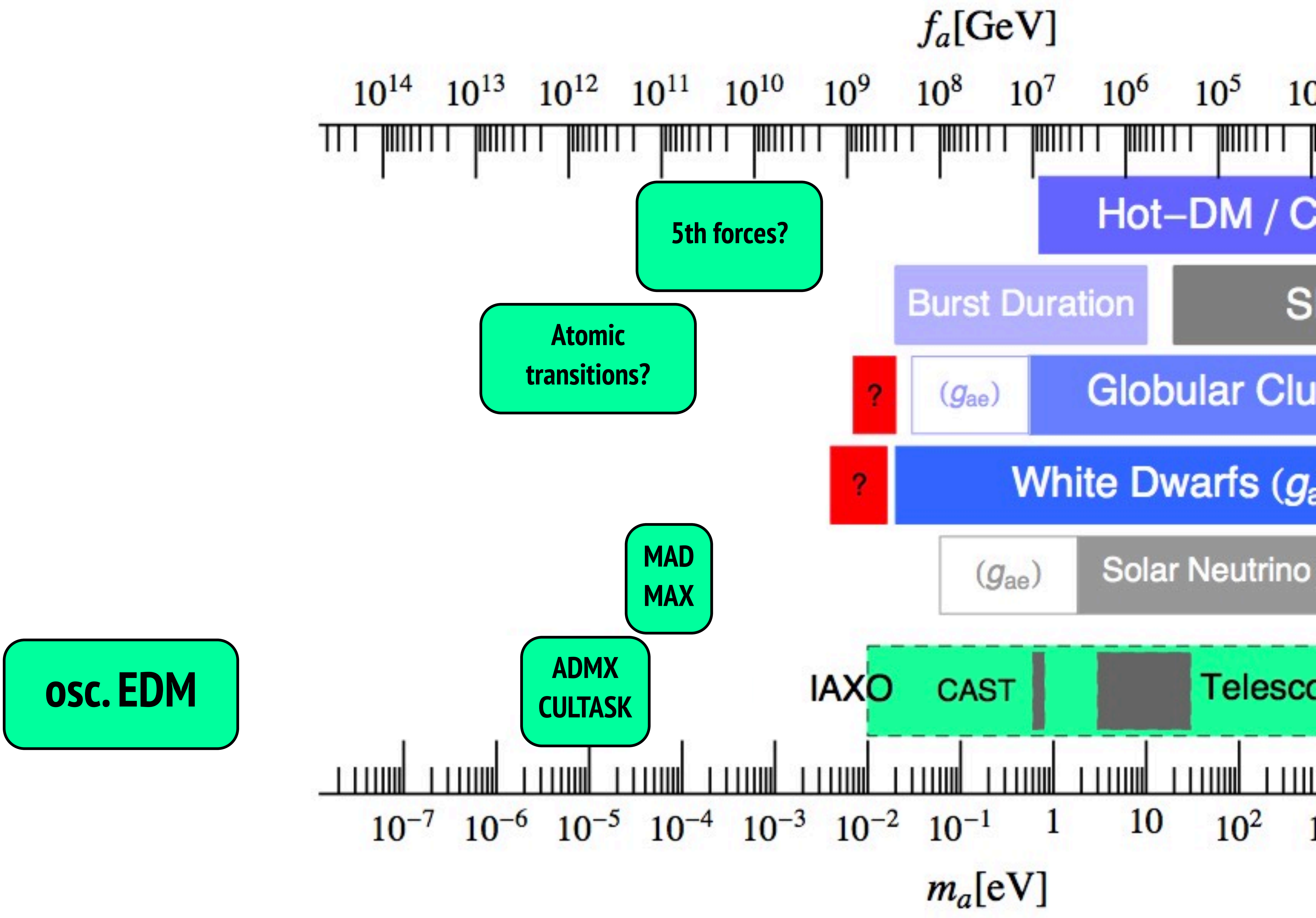


Dielectric haloscope (MADMAX)





A developing picture



Conclusions

- Axions and axion-like particles

offer new theoretical perspectives
dark matter candidates
solutions to astrophysical conundrums

... and are experimentally testable

dark matter experiments
haloscopes & CASPER
solar axions at the meV frontier (dark matter & astro hints)
5th forces

however ... many topics not covered!