Axions and compact objects

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Objets compacts et nouvelle physique,
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A shift of paradigm

- To solve: the hierarchy problem

concretely: why the gravitational force is so much weaker than the other fundamental interactions?

Main candidate,

Supersymmetry : -enlarges Poincaré algebra (new energy scale)

-needs many new particles

-can preserve SM gauge group

- To solve: the strong CP puzzle

concretely: why matter and not anti-matter in our universe?

Main candidate,

'Peccei-Quinn' theory : -enforces CP-symmetry

-needs a new global 'no symmetry'

(anomalous+spontaneously broken)

(new energy scale)

-entangled with SM gauge group :

(careful!)

$$[SU(3)_c \otimes SU(2)_L \otimes U(1)_Y]_{local} \times [U(1)_{\mathcal{B},\mathcal{L},PQ}]_{global}$$

the **QCD axion**: « new » Goldstone bosons combination $\perp Z_L$

QFT Anomalies

Anomalies: classical symmetry broken at the quantum level

Example: « triangle anomalies » in massless QED

$$\mathscr{L}_{QED} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}i\not{D}\psi$$

Two invariances: $\xrightarrow{\text{(Noether theorem)}}$ Two classicaly conserved currents:

- $\psi \to e^{i\theta_V}\psi$
- $\psi \to e^{-i\theta_A\gamma^5}\psi$

$$V^\mu = \bar{\psi}\gamma^\mu\psi\ , \quad \partial_\mu V^\mu = 0$$

$$A^\mu = \bar{\psi}\gamma^\mu\gamma^5\psi\ , \quad \partial_\mu A^\mu = 0$$

$$\Downarrow$$

At the quantum level:

$$V^\mu = \bar{\psi}\gamma^\mu\psi\ , \quad \partial_\mu V^\mu = 0 \quad \text{holds}$$

But axial symmetry is broken :

$$\partial_\mu A^\mu = \frac{1}{8\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

- Fermionic path integral measure is not invariant: [Fujikawa]

$$Z = \int \mathscr{D}\psi\mathscr{D}\bar{\psi}e^{iS}$$

The Strong CP Puzzle in particle physics

$$\mathcal{L}_{QCD} = \bar{q}(i\gamma^\mu D_\mu - m_q \underset{\text{CPV}}{e^{i\theta_{EW}}})q - \frac{1}{4}G_a^{\mu\nu}G^a_{\mu\nu} - \theta_{QCD}\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\underset{\text{CPV}}{\tilde{G}^a_{\mu\nu}}$$

→ 4-component Dirac field

$U(1)_A$ chiral transformation: $q \rightarrow e^{i\gamma^5\theta_{EW}}q$ anomalous symmetry

the measure of the path integral is not invariant under this transformation

axial anomaly shifts quark mass phase to QCD vacuum

$$\mathcal{L}_{QCD} = \bar{q}(i\gamma^\mu D_\mu - m_q)q - \frac{1}{4}G_a^{\mu\nu}G^a_{\mu\nu} - (\overbrace{\theta_{QCD} - \underset{\neq 0}{\theta_{EW}}}^{\bar{\theta}})\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}^a_{\mu\nu}$$

Yukawa coupling to the Higgs are complex $\theta_{CKM} \neq 0$

Why is this strong CP-violation term so puzzling? $\mathcal{L}_{\cancel{CP}} = \bar{\theta}\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}^a_{\mu\nu}$

this induces a huge electric dipole moment for the neutron:

Theory: $|d_n| \sim |\bar{\theta}|10^{-16}e.cm$ vs Experiment: $|d_n| \lesssim 10^{-26}e.cm$

→ $\bar{\theta} < 10^{-10}$

The strong CP problem
=Why is $\bar{\theta}$ so small?

The strong CP problem is really why the combination of QCD and EW parameters make up should be so small...

The Peccei-Quinn axion solution

axial anomaly: $\theta_{EW}^{CPV} \longleftrightarrow \theta_{QCD}^{CPV}$

Solution to the strong CP problem of QCD: add fields such that rotate $\bar{\theta}$ to the phase of a complex SM-singlet scalar who gets a VEV and dynamicaly drives $\bar{\theta} \to 0$

Peccei & Quinn

$$\mathcal{L}_{QCD} = \bar{q}(i\gamma^{\mu} D_{\mu} - m_q e^{i\theta_{EW}})q - \frac{1}{4} G_a^{\mu\nu} G_{\mu\nu}^a - \theta_{QCD} \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}_{\mu\nu}^a$$

1. Introduce a new global anomalous axial $U(1)_{PQ}$ symmetry S.B. at high scale

   ⟶ the low-energy theory has a **Goldstone boson** (the **axion** field)

cf. global vector $U(1)_{\mathcal{B},\mathcal{L}}$

2. Design $\mathcal{L}_{axion}$ such that $Q(q_L) \neq Q(q_R) \longrightarrow$ this makes the $U(1)_{PQ}$ **anomalous** :

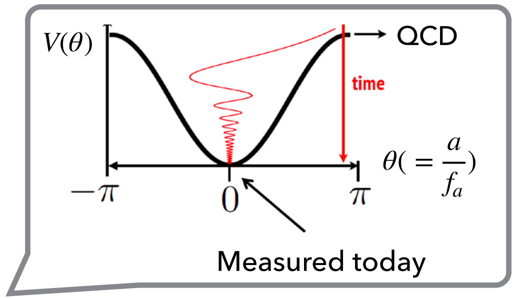
   $\partial_{\mu} J^{\mu} \sim G_{\mu\nu}^a \tilde{G}_a^{\mu\nu}$

   net effect: $\mathcal{L}_{axion} = \mathcal{L}_{QCD} + \frac{a}{v} G_{\mu\nu} \tilde{G}^{\mu\nu} + \ldots$

3. Non-perturbative QCD effects induce:

$$\mathcal{L}_{axion} = \mathcal{L}_{ChPT}(\partial_{\mu} a, \pi, \eta, \eta', \ldots) + V_{eff}(\bar{\theta} + \frac{a}{v}, \pi, \eta, \ldots)$$

$$\sim -\Lambda_{QCD}^4 cos(\bar{\theta} + \frac{a}{v})$$



minimum of the potential: $\bar{\theta} + \frac{<a>}{v} = 0$

CP-violating term cancels!

CP symmetry is dynamically restored!

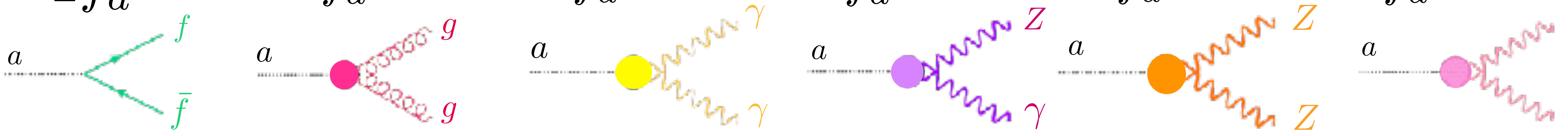
new energy scale!

Axion couplings

Energy

At energies below f_a (SSB):

$$\mathcal{L}_{axion} \supset \frac{\partial_\mu a}{2 f_a} j_a^\mu + \#\frac{a}{f_a} G\tilde{G} + \#\frac{a}{f_a} F\tilde{F} + \#\frac{a}{f_a} Z\tilde{F} + \#\frac{a}{f_a} Z\tilde{Z} + \#\frac{a}{f_a} W\tilde{W}$$



LHC regime
free from (complex) low energy QCD effects
probe different couplings than low energy experiments

electroweak couplings recently computed
do not follow the expected pattern
J.Q. and C. Smith, arXiv:1903.12559, 2006.06778, 2010.13683;
J.Q., C. Smith and P.N.H. Vuong , arXiv:2112.00553

At energies below $\Lambda_{QCD}: a - \eta' - \pi^0 - \eta - \ldots$ mixing

axion mass: $m_a = m_\pi \frac{f_\pi}{f_a} \frac{\sqrt{m_u m_d}}{m_u + m_d} \sim \frac{\Lambda_{QCD}^2}{f_a}$

axion couplings to electrons, nucleons, mesons, photons, ...

(EDMs)

mostly explored:

$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi f_a}\left(\boxed{\frac{E}{N}} - \boxed{1.92}\right)$$

model dep.

model indep.
below confinement

Symmetry breaking in cosmology

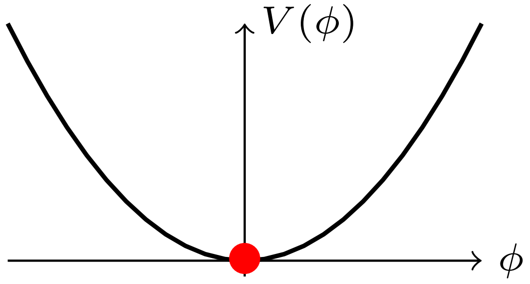
Temperature

$$\delta\phi \sim T$$

$$V_{\rm PQ}(\phi) = \frac{\lambda}{4}(|\phi|^2 - f_a^2)^2$$

$T > f_a$

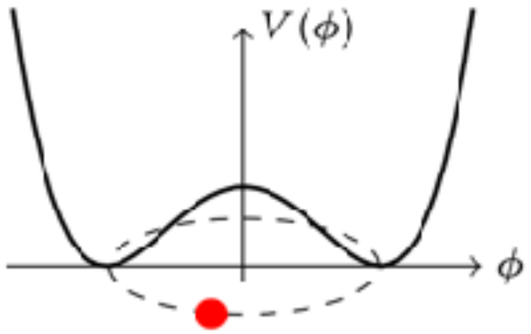
T determines the PQ vev:
$< \phi >= 0$



$T \sim f_a$

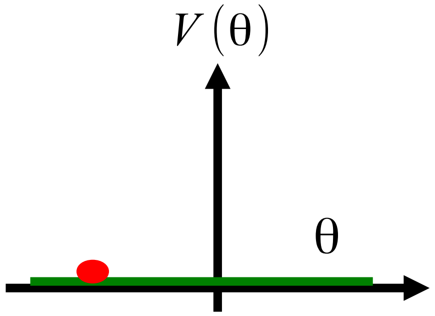
PQ symmetry is spontaneously broken:

$$< \phi >= f_a e^{i\frac{a(x)}{f_a}}$$



The axion is born:

Relic of symmetry breaking



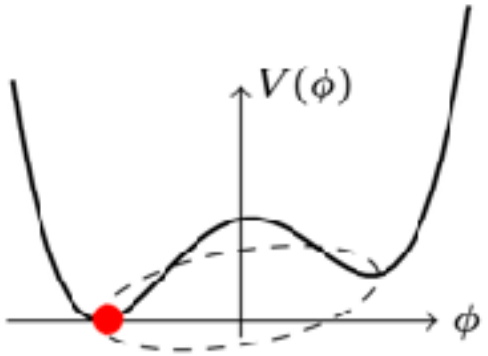
$$\theta = \frac{a}{f_a} \in [-\pi, \pi]$$

$T \sim \Lambda_{QCD}$

PQ symmetry is explicitly broken

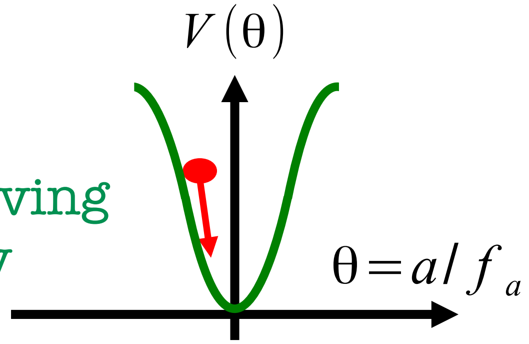
$$m_a^2(T) \begin{cases} \propto T^{-n} & T \gtrsim 100 \text{ MeV} \\ = m_a(T=0) & T \lesssim 100 \text{ MeV} \end{cases}$$

Instanton effects



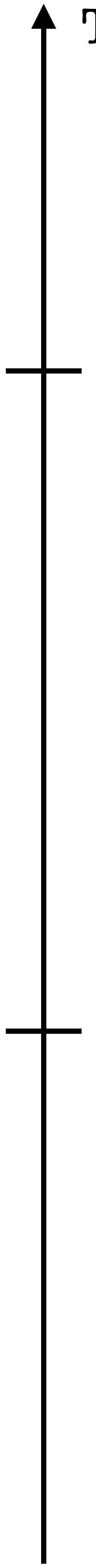
$$+V_{QCD}^{\text{Non-Pert.}} = f_a^2 m_a^2(T)(1 - cos(N_{DW}\theta))$$

CP-concerving theory



Crucial role played by inflation…

Dark matter from vacuum realignment



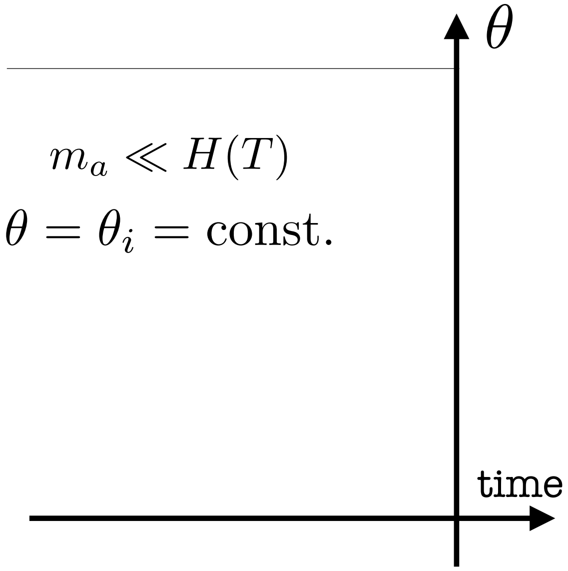
Equation of motion:
(Klein-Gordon)

$$\ddot{\phi} + 3\boxed{H}\dot{\phi} + \boxed{m_a(T)}^2\phi = 0$$

$$H \gg m_a$$

Axion is ‘frozen’ by Hubble friction

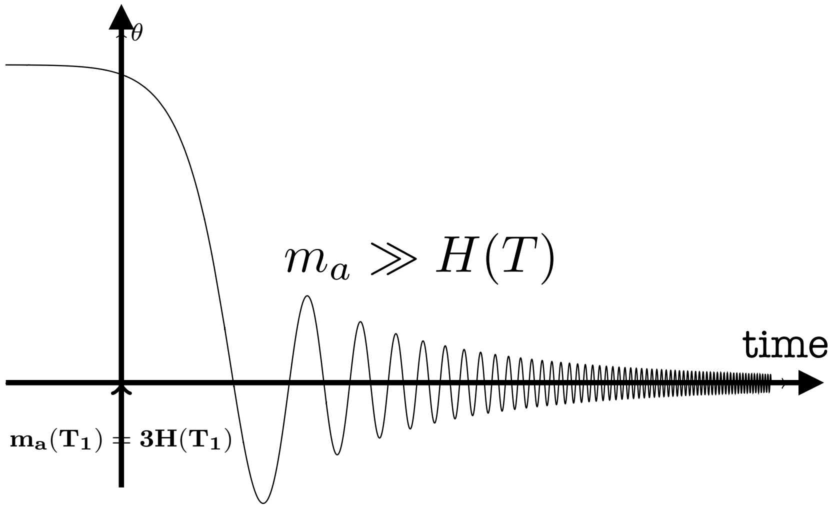
$$\rho_a \sim \text{const}$$
$$w_a \sim -1$$



$$H \ll m_a$$

Coherent oscillations of axion field

$$\rho_a \sim \rho_a(\boxed{a_{\rm osc}})a^{-3}$$



Scalar oscillations behave as matter

$$\boxed{\Omega_a h^2 \approx 0.195\left(\frac{f_a}{10^{12}\,\text{GeV}}\right)^{1.184}\boxed{\theta_{\rm ini}^2}}$$

← 2 scenarios

- Cold Dark Matter!
- Axions are born as non relativistic, classical field oscillations

Initial conditions and inflation

Crucial question: did SSB occur before or after inflation?

$$\boxed{\Omega_a h^2 \approx 0.195 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}} \right)^{1.184} \theta^2_{\mathrm{ini}}}$$

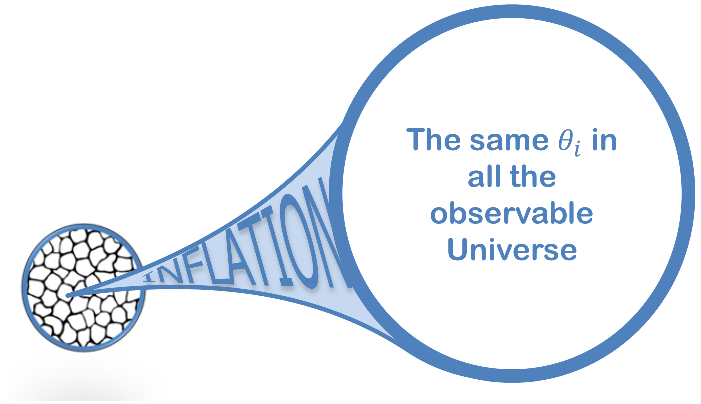
← 2 scenarios

Pre-inflation scenario

$f_a \gtrsim 10^{13}\mathrm{GeV}$

PQ symmetry is broken during inflation and not restored afterwards

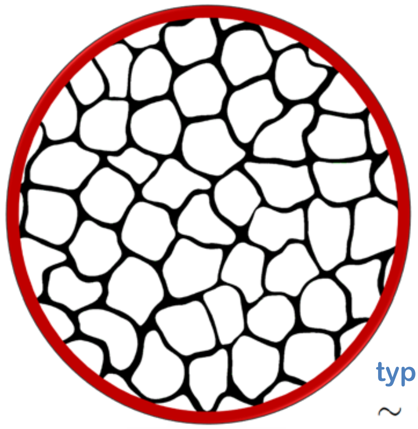
Inflation « selects » one θ_{ini} that is now constant across the observable Universe



Post-inflation scenario

May occur for low f_a

PQ symmetry is broken after inflation



typical size of single patch nowadays: $\sim 0.001(m_A/10\ \mu\mathrm{eV})^{1/2}$ pc

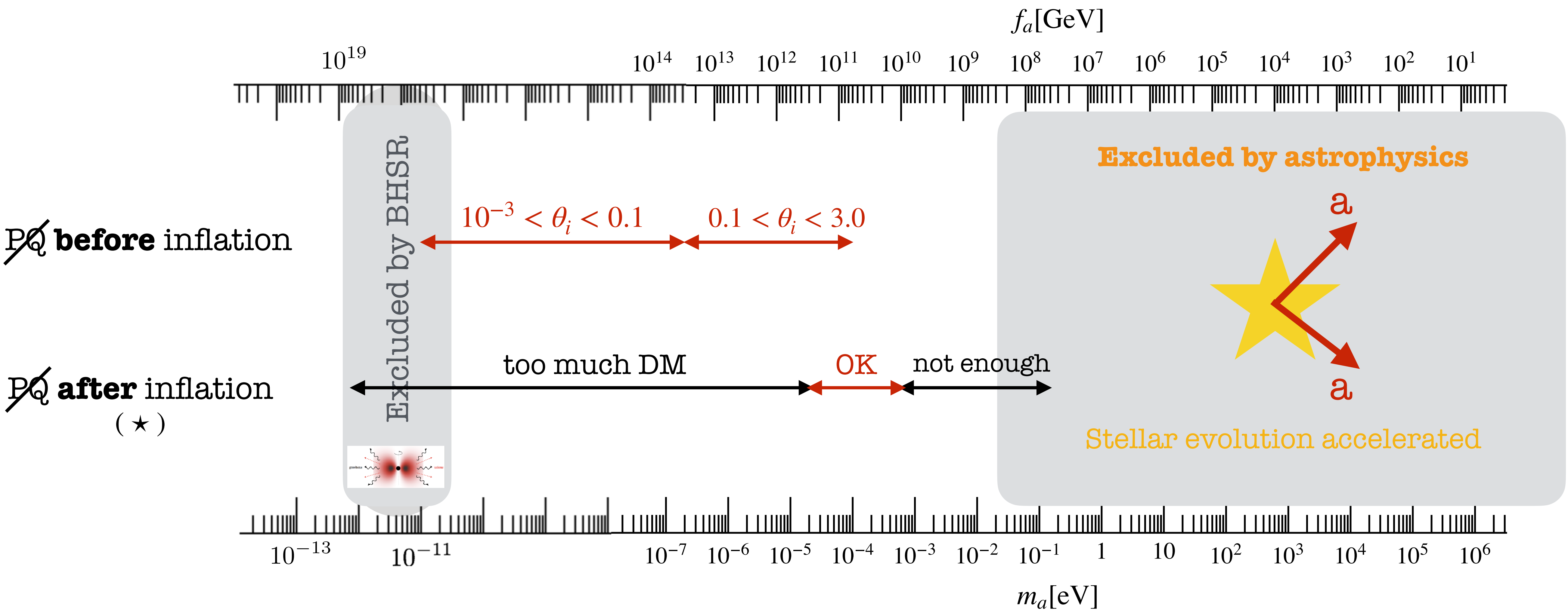
- Many different $-\pi \leq \theta_{ini} \leq \pi$ in the visible « patches » of the universe,
  average field value fixed: $\langle \theta^2_{\mathrm{ini}} \rangle = \frac{1}{2\pi} \int_{-\pi}^{\pi} \theta^2 d\theta = \frac{\pi^2}{3}$

⟶ Ω_a independent of initial conditions

DM relic density, narrow mass window: $\Omega_c h^2 = 0.12$ → $50 \lesssim \frac{m_a}{\mu\mathrm{eV}} \lesssim 200$

Landscape

Axions should be very light and feebly interacting



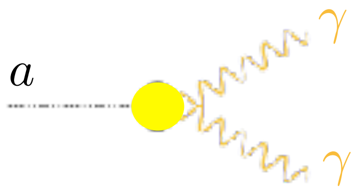
$(\star)$ for $N_{DW} > 1,$ predictions spoiled by topological defects

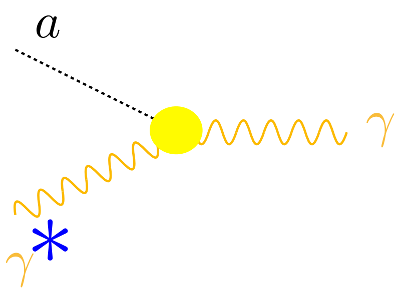
Axion DM constraints from **laboratory** experiments, from **stars** and **cosmos** observations

Axion conversion to photon

$$\mathcal{L}_{axion} \supset \# \frac{a}{f_a} F\tilde{F} \longleftrightarrow \# \frac{a}{f_a} \vec{E}.\vec{B}$$

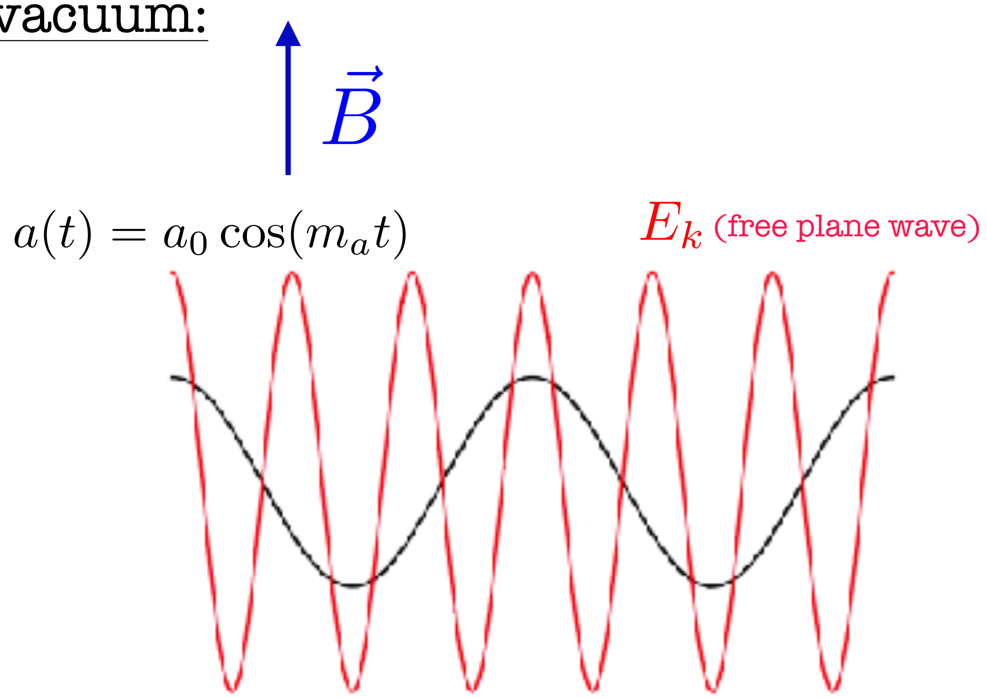
in an external B-field
the axion sources an E-field





Matrix element given by the **overlap** of the **axion** and **virtual photon** wave functions

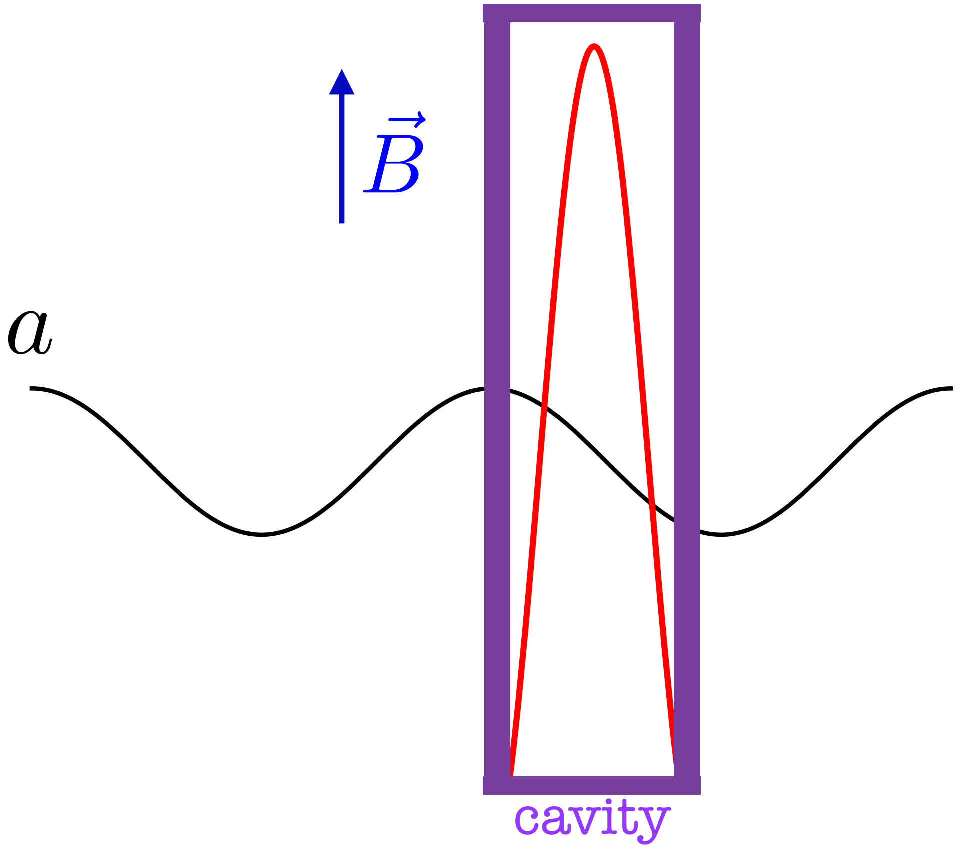
In vacuum:



Oscillatory integral vanishes (moment conservation)
⟶ **no** axion-photon conversion

One needs to modify the free wave function

Inside a cavity: E_k becomes the cavity modes

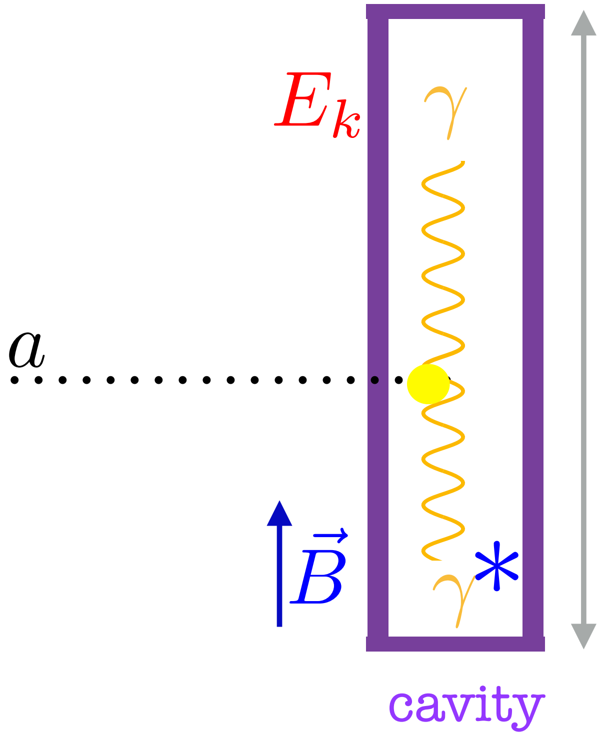


⟶ axion-photon conversion is allowed

Axion haloscope

Amplify resonantly the EM field in a resonant cavity

(forced oscillator)



$\lambda/2 = 0.62\ \mathrm{cm}\ (100\ \mu\mathrm{eV}/m_a)$

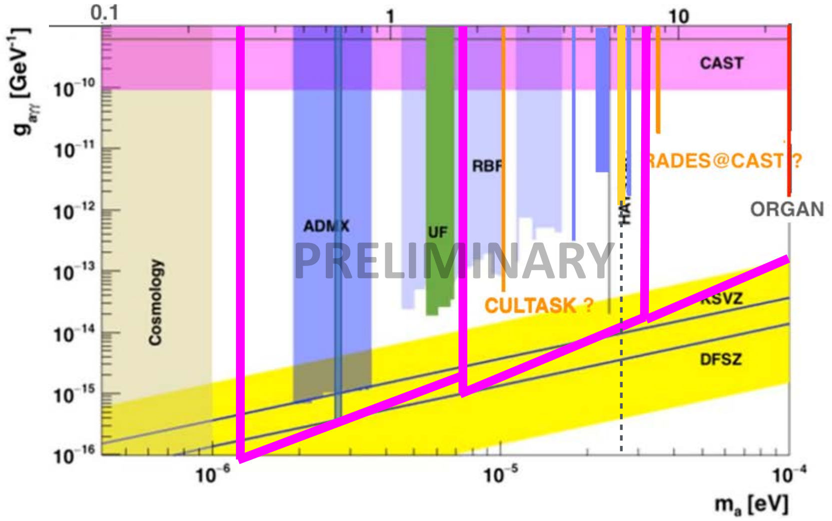
Power extracted from a cavity: $P_{signal} \propto g_{a\gamma}^2 B^2 Q V$ to amplify

$P_{noise} \propto T_{sys}\delta\omega$

GrAHal : the Grenoble Axion Haloscope

1. Hybride Magnet 43 T (34 mm), 40 T (50 mm), 27 T (170mm), 9 T (800 mm) **LNCMI**
2. $T_{sys} \sim 20\mathrm{mK}$ **Institut Néel**
3. quantum amplifiers SQUID &JPA **Institut Néel**

$$g_{a\gamma\gamma}^{\text{1st point}} = 25 \times g_{a\gamma\gamma}^{\text{KSVZ}}$$
$$m_a = 23\mu\text{eV}$$



- New interesting idea : **'plasmon haloscope'** :

-resonance when the **axion** and **plasma** frequencies match

-thin wire metamaterials (~cm spacing ⇒ ~ GHz plasma frequency)

-tuneable with wire spacing ⇒ haloscopes not anymore V limited?

Axion miniclusters

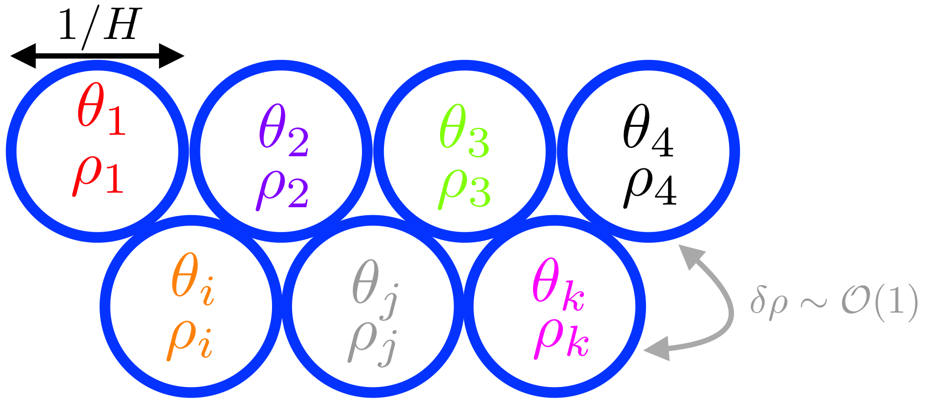
Temperature

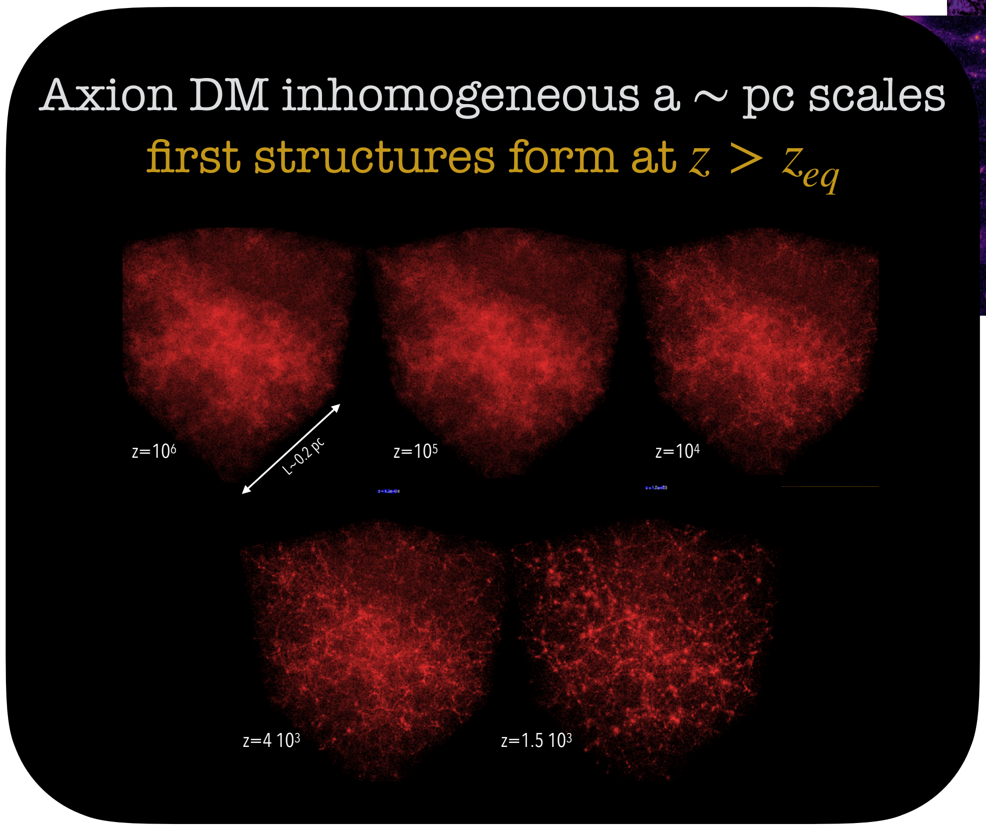
...Inflation occurred already

$T \sim f_a$ SSB of PQ

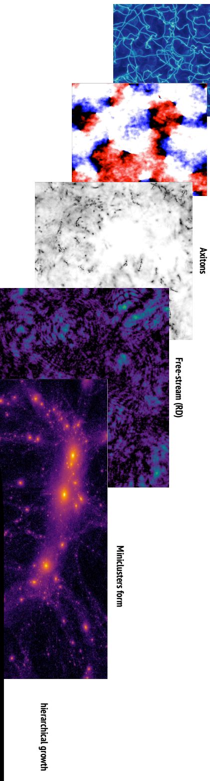
$T \sim \Lambda_{QCD}$ $m_a \neq 0$

$T_{\rm osc}$ $H(T_{\rm osc}) \sim m_a$:




Axion DM inhomogeneous a ~ pc scales

first structures form at $z > z_{eq}$



- density perturbations grow under gravity as usual
- collapsing into gravitationally bound objects known as **miniclusters**
- total axion mass contained within the horizon at $t_{\rm osc}$ sets the characteristic minicluster mass at $z_{\rm eq}$:

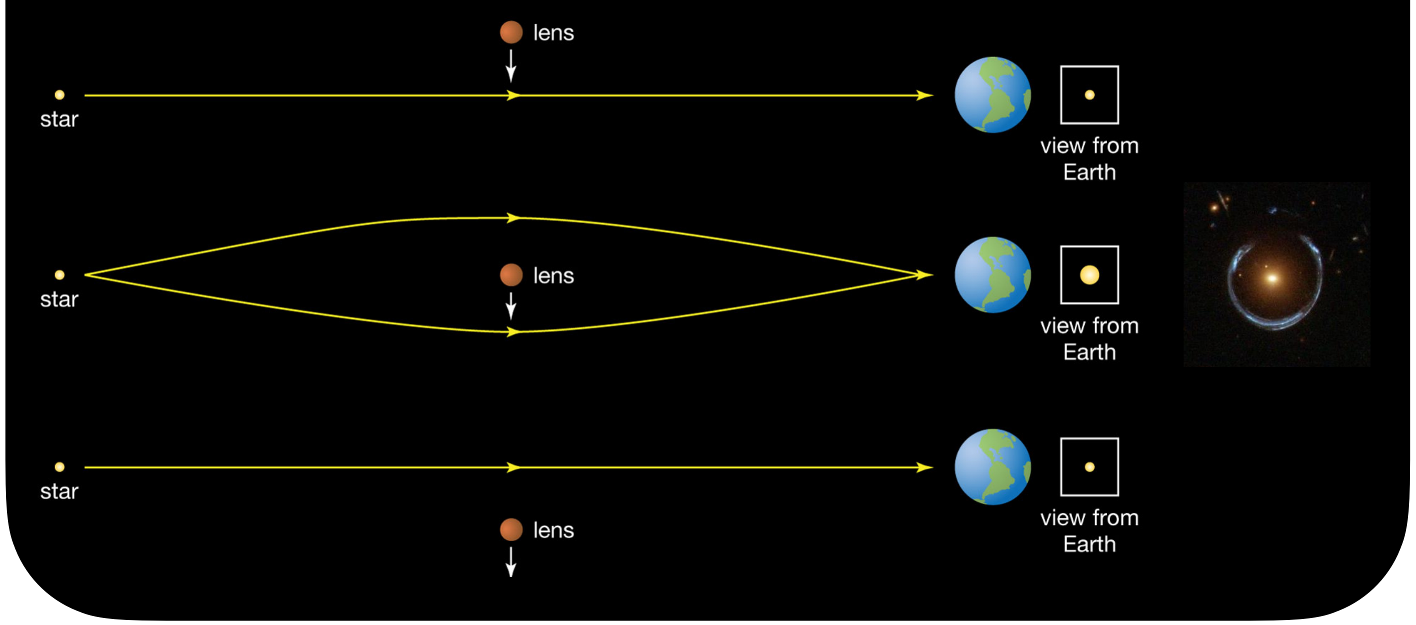
Hogan & Reese (1988)

$$M_0 = \overset{\text{today}}{\bar{\rho}_a} \frac{4}{3}\pi \left(\frac{\pi}{a(T_0)H(T_0)} \right)^3 \begin{cases} M_0 \sim 10^{-12} M_\odot \\ \text{size} \sim 10^7\ \text{km} \\ \sim 10^{25}\ \text{in the Galaxy} \\ \text{through the Earth every} \sim 10^5\ \text{years} \end{cases}$$

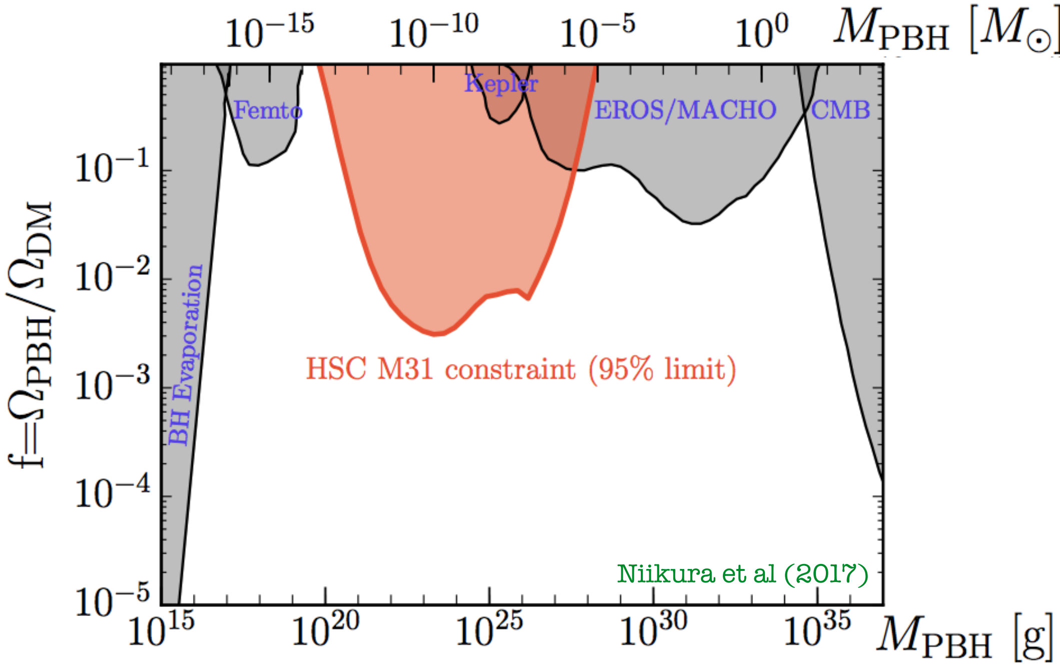
Smaller than smallest WIMP structures ($\sim 10^{-6} M_\odot$)

Detecting axion miniclusters with gravitational microlensing

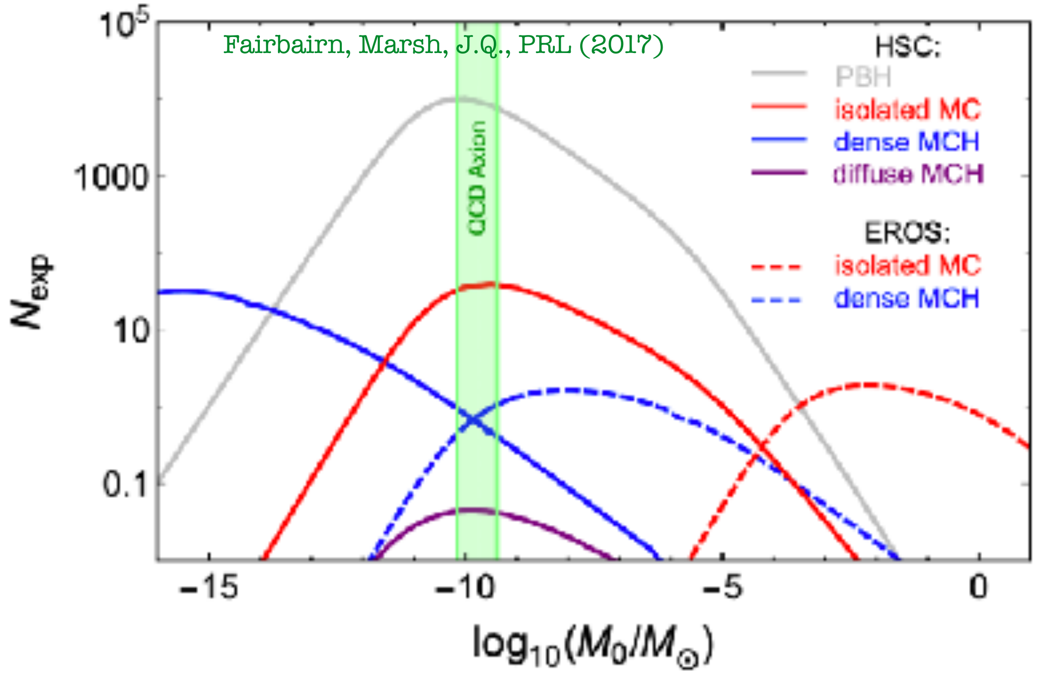
Microlensing: fugitive amplification of a background star which occurs when a compact object passes close to the line of sight to that star.



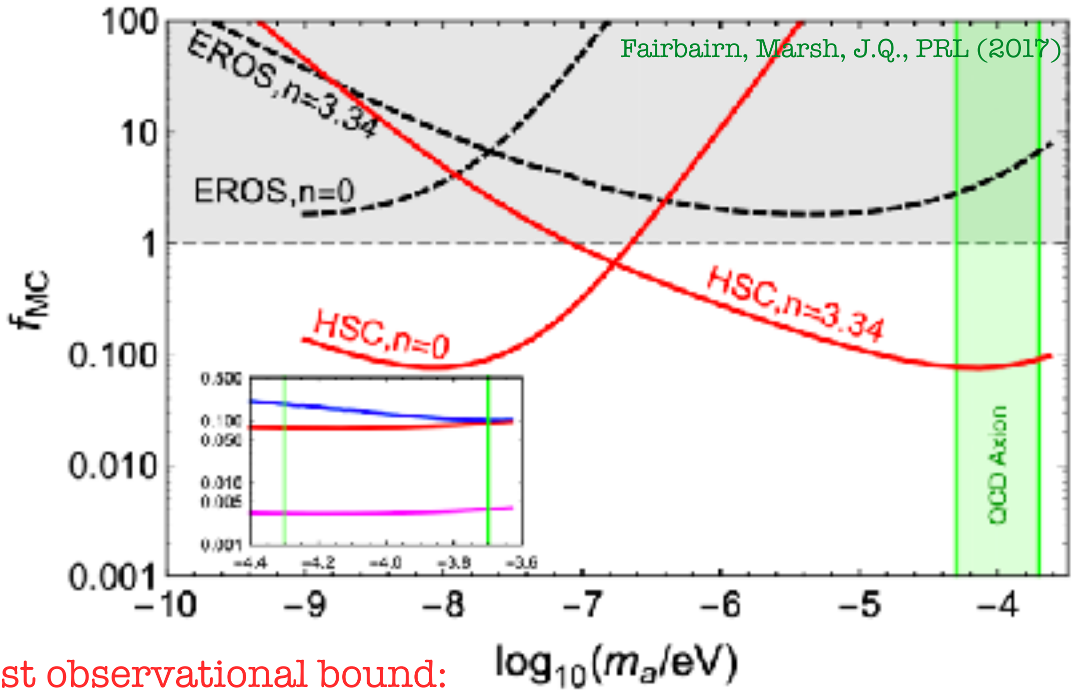
For PBH (point masses), the amount of DM in compact objects is strongly constrained:



Expected microlensing events:



→

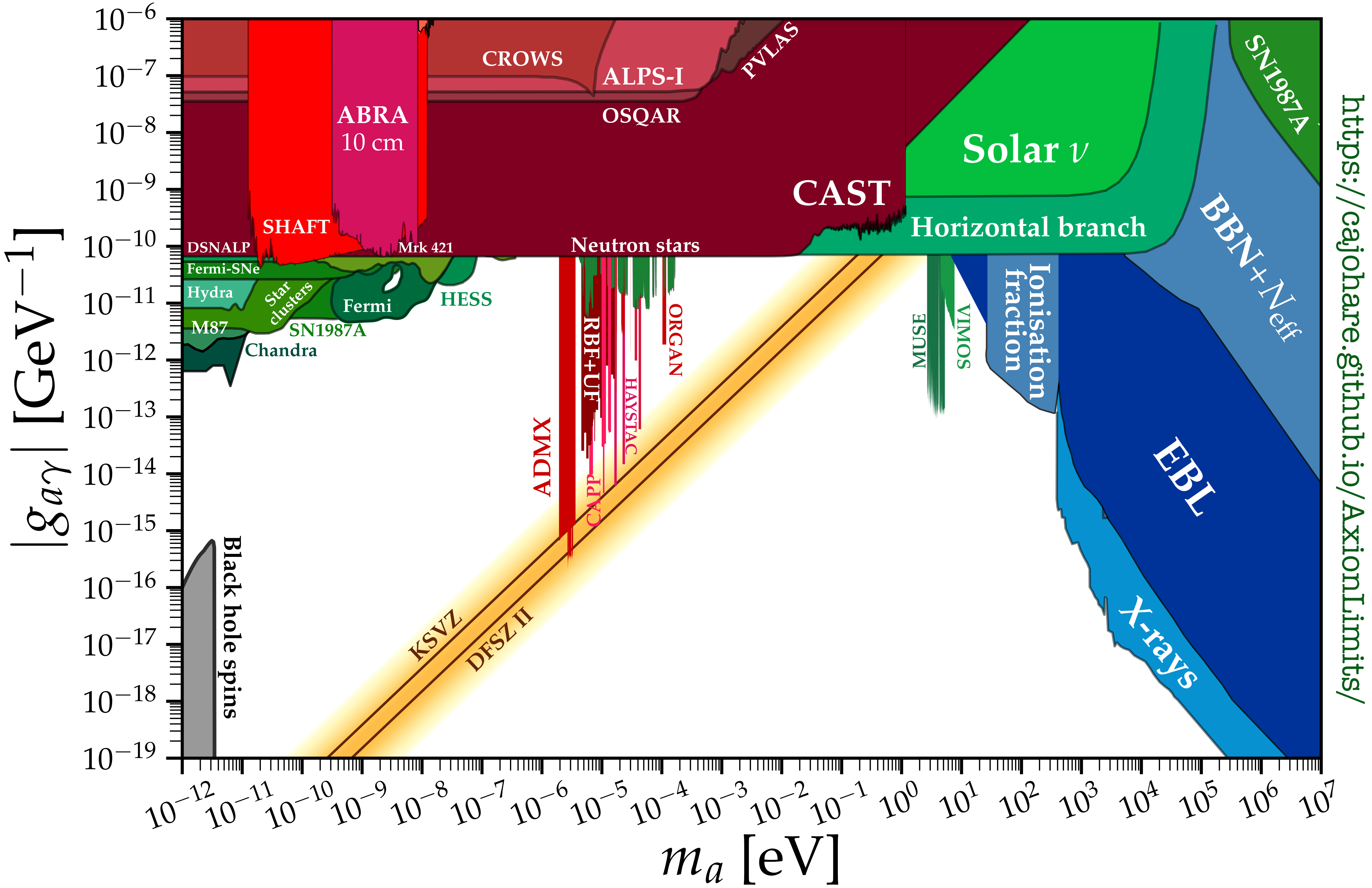


Place the first observational bound:

$$\boxed{f_{\rm MC} \ < \ 0.083(m_a/100\,\mu{\rm eV})^{0.12}}$$

Huge and renewed global effort in axion direct detection. If $f_{\rm MC}$ is high, rare MC encounters → axion DM detection is limited.

Axion limits



Axions in astrophysics

- Axions may couple to photons, electrons and nucleons

- Stars are powerful sources of weakly interacting particles such as gravitons, neutrinos and axions (interior nuclear reactions or thermal processes)

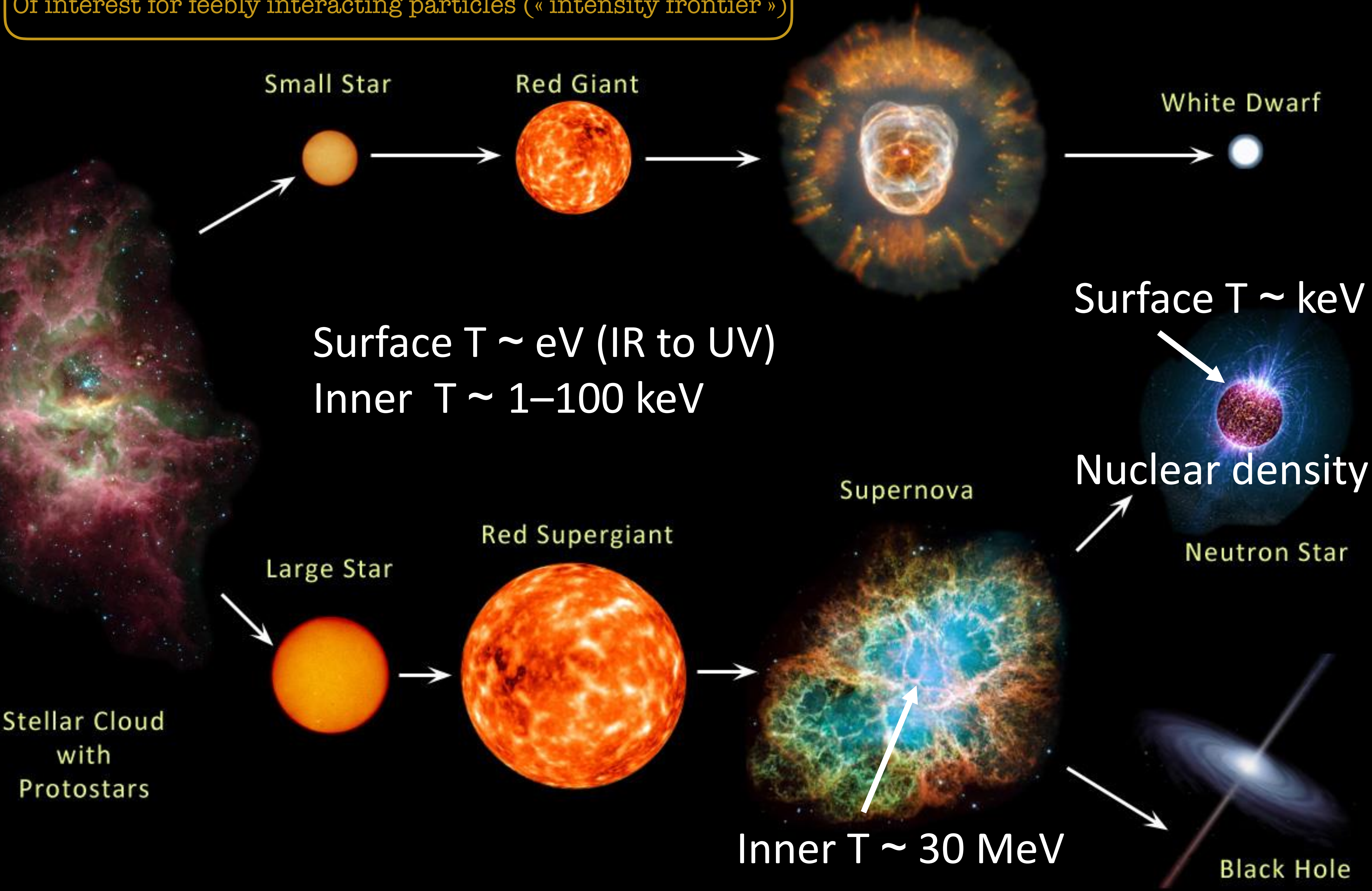
- The properties of stars would change with such a **new energy loss**

- Astrophysical considerations strongly constrain axion properties

- Observable consequences on stars at various stage of their evolution

Particle physics playground

Very low energies (cf. particle physics standards)
Of interest for feebly interacting particles (« intensity frontier »)



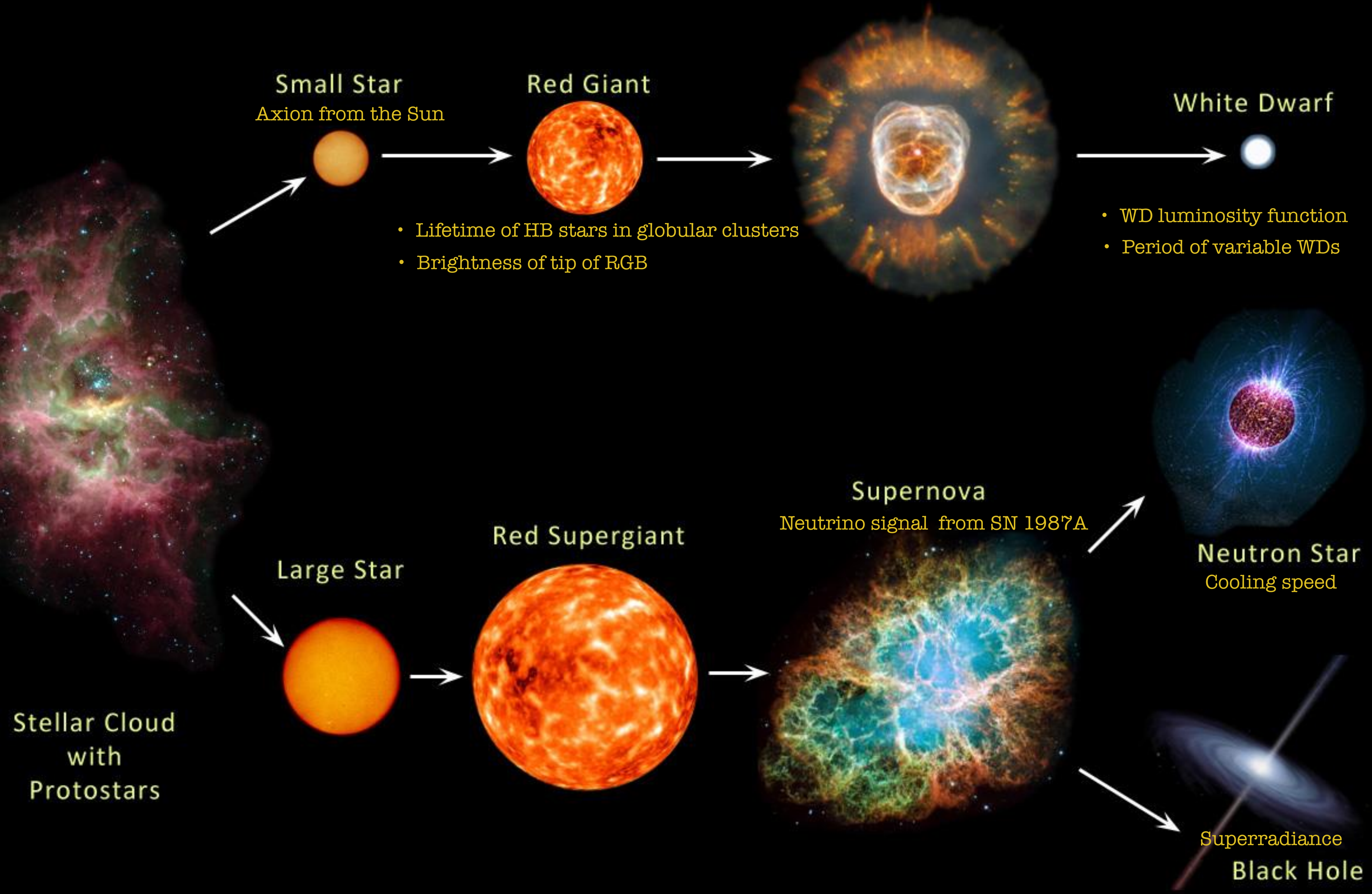
Surface T ~ eV (IR to UV)
Inner T ~ 1–100 keV

Surface T ~ keV

Nuclear density

Inner T ~ 30 MeV

Various axion implications



Stellar Cloud with Protostars

Small Star
Axion from the Sun

Red Giant

- Lifetime of HB stars in globular clusters
- Brightness of tip of RGB

Planetary Nebula

White Dwarf

- WD luminosity function
- Period of variable WDs

Large Star

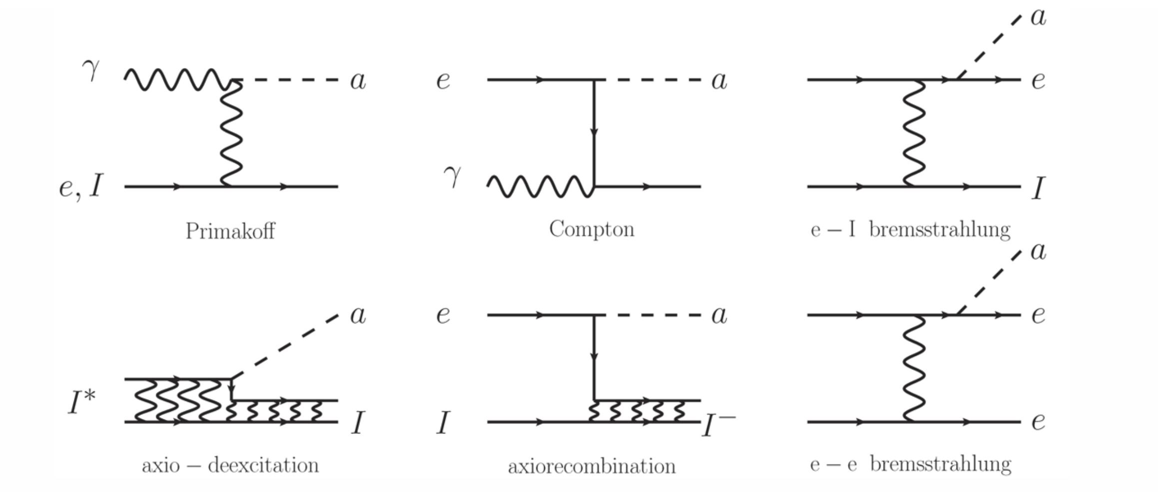
Red Supergiant

Supernova
Neutrino signal from SN 1987A

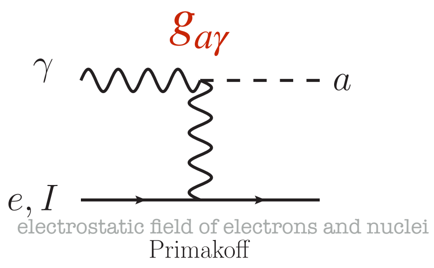
Neutron Star
Cooling speed

Superradiance
Black Hole

Axions and the Sun



Helioscope searches



- Stars produce axions from thermal photons in the fluctuating electromagnetic fields of the stellar plasma

- Robust prediction since it only relies on $g_{a\gamma} \neq 0$ and on well-known solar physics

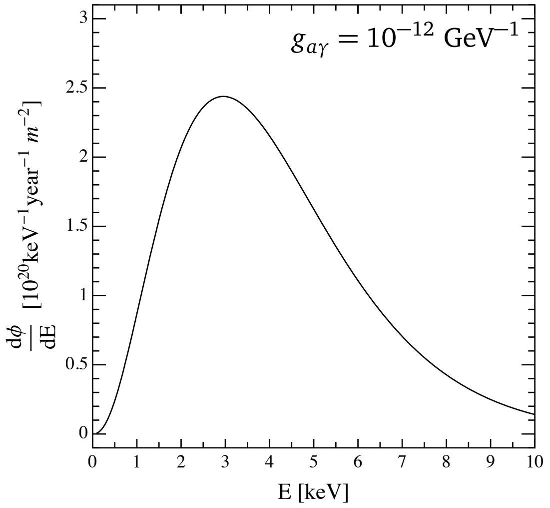
- Produced axions get out of the Sun and travel to the Earth

$$\phi_a \simeq 10^{11}\left(\frac{G_{a\gamma\gamma}}{10^{-10}\mathrm{GeV}^{-1}}\right)^2 \mathrm{cm}^{-2}\mathrm{s}^{-1}, \quad \left(\phi_{\mathrm{solar}\,\nu} \simeq 10^{11}\mathrm{cm}^{-2}\mathrm{s}^{-1}\right)$$

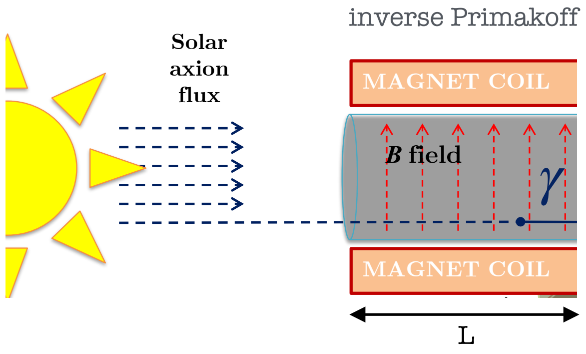
with a characteristic flux:

Maximum of the distribution is at 3.0 keV

Average energy is 4.2 keV



- Helioscope experiments (ex: CAST, SUMICO, IAXO) use this effect to convert these axions back into X-ray photons

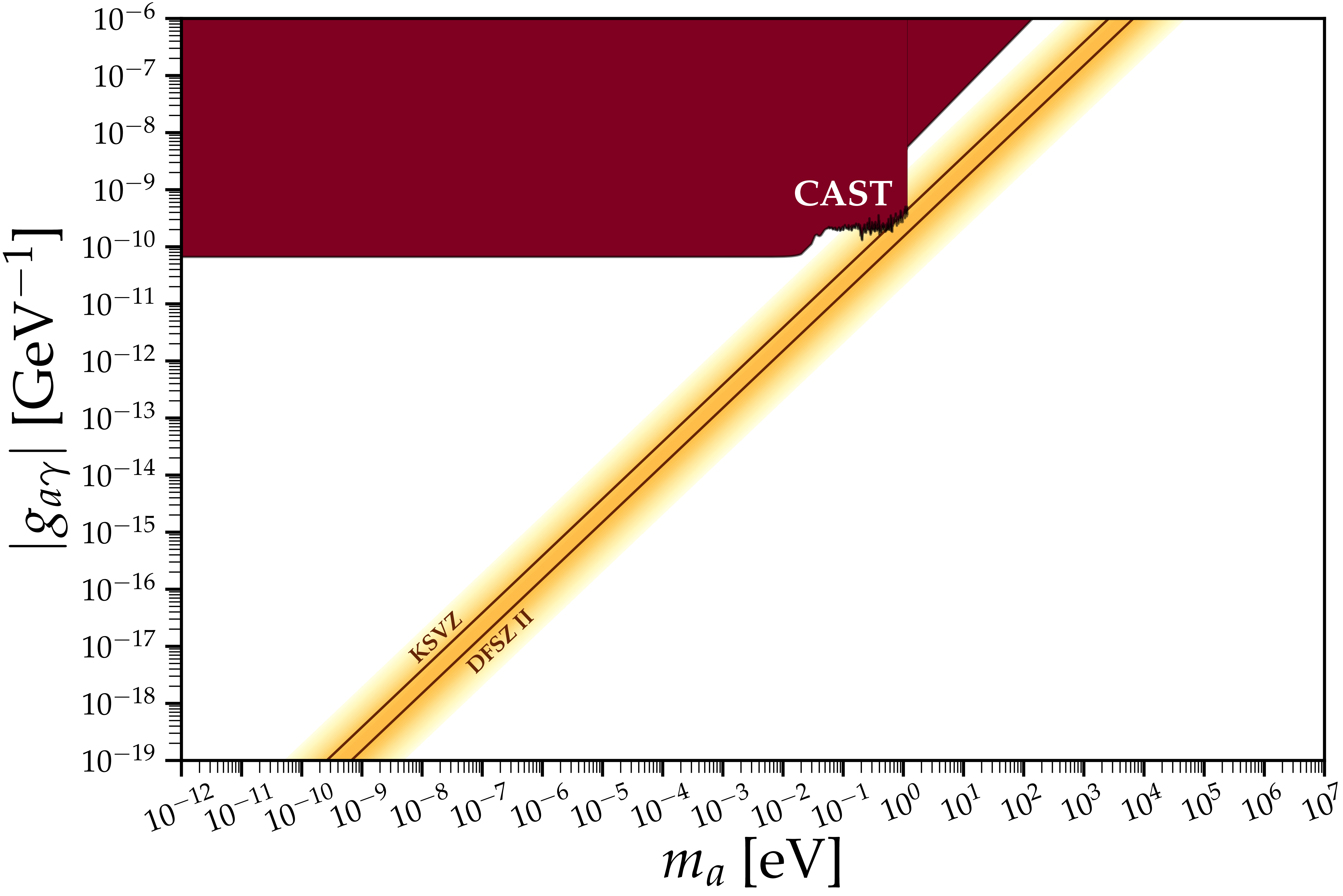


$$P_{a\to\gamma} \sim B_{ext}^2 g_{a\gamma}^2 L^2$$

X-rays

Current constraint (CAST): $g_{a\gamma} \lesssim 10^{-10}\mathrm{GeV}^{-1}$ for $m_a \lesssim 0.01\mathrm{eV}$

For larger masses, the axion-photon transition is suppressed by the energy-momentum mismatch between particles of different mass


CAST
KSVZ
DFSZ II
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-12}
10^{-11}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}

Constraints from the Sun itself

- **Solar age :**

Axion losses lead to an enhanced consumption of nuclear fuel

The standard Sun is halfway through its hydrogen-burning phase so that the solar axion luminosity should not exceed its photon luminosity

an example: the PVLAS experiment (magnetically induced vacuum dichroism)

Possible interpretation of signal by an axion with $g_{a\gamma} \sim 10^{-6}\text{GeV}^{-1}$ and $m_a \sim 1\text{meV}$
Sun's axion luminosity would exceed photon luminosity by a factor 10^6 and the Sun could live only for 10^3 yrs. (**severe constraint** on that PVLAS signature)

- **Helioseismology :**

Integrated effect of axion losses would alter the sound-speed profile which can be diagnosed by helioseismology

Constraint: $g_{a\gamma} \leq 4.1 \times 10^{-10}\text{GeV}^{-1}$

$(L_a \lesssim 0.20 L_\odot)$

H. Schlattl, A. Weiss, G. Raffelt, arXiv:9807476
N. Vinyoles et al., arXiv:1501.01639

- **Solar neutrino flux :**

The energy loss by solar axion emission requires enhanced nuclear burning and thus **increase the temperature** of the Sun. This would **increase the solar ^8B neutrino flux**.

The measure all-flavor ^8B neutrino flux ($\sim 5 \times 10^6 \text{cm}^{-2} s^{-1}$) implies a limit:

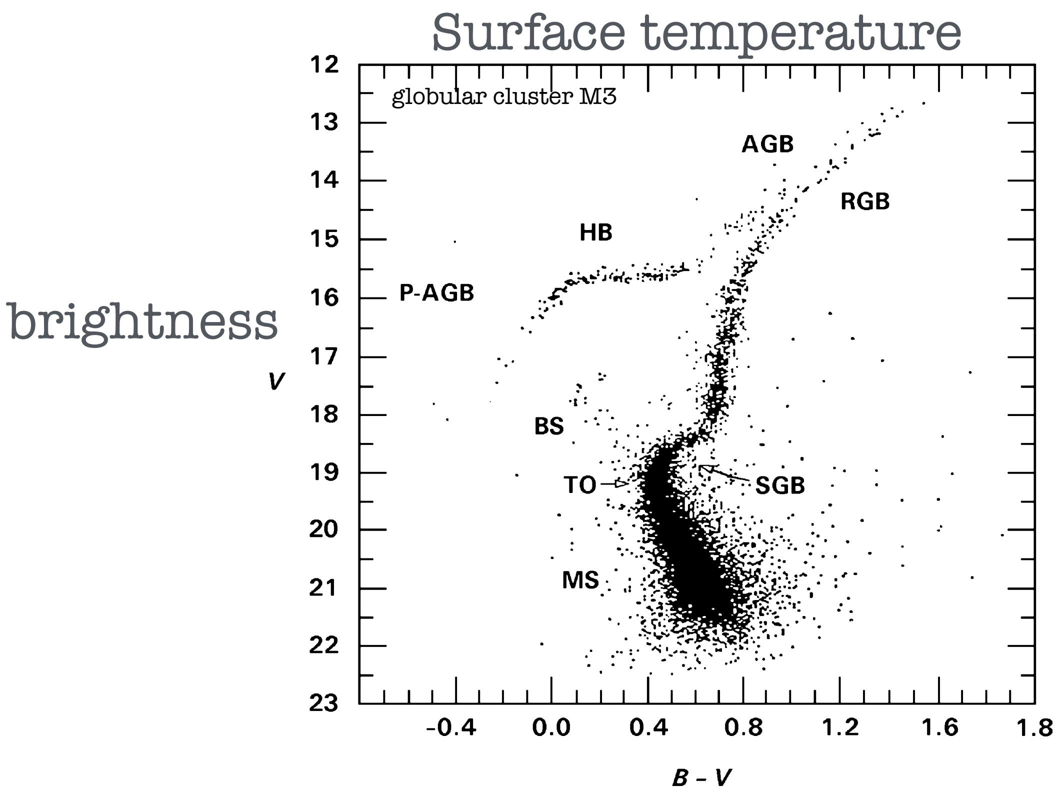
$g_{a\gamma} \lesssim 7 \times 10^{-10}\text{GeV}^{-1}$ $(L_a \lesssim 0.04 L_\odot)$ P. Gondolo, G. Raffelt, arXiv:0807.2926

Major problem of the Sun as an axion source: low temperature of its core...

Globular-Cluster Stars

- This is a gravitationally bound system of stars that formed at the same time and thus differ primarily in their mass.
- It provides a homogeneous population of stars, allowing for detailed tests of stellar-evolution theory.
- The stars surviving since formation have masses somewhat below $1M_\odot$

In « color-magnitude diagram » surface brightness vs. the surface temperature plot, stars appear in characteristic position allowing one to identify their state of evolution :



Main Sequence (MS) : core hydrogen burning

Main-sequence TurnOff (TO) : central hydrogen is exhausted

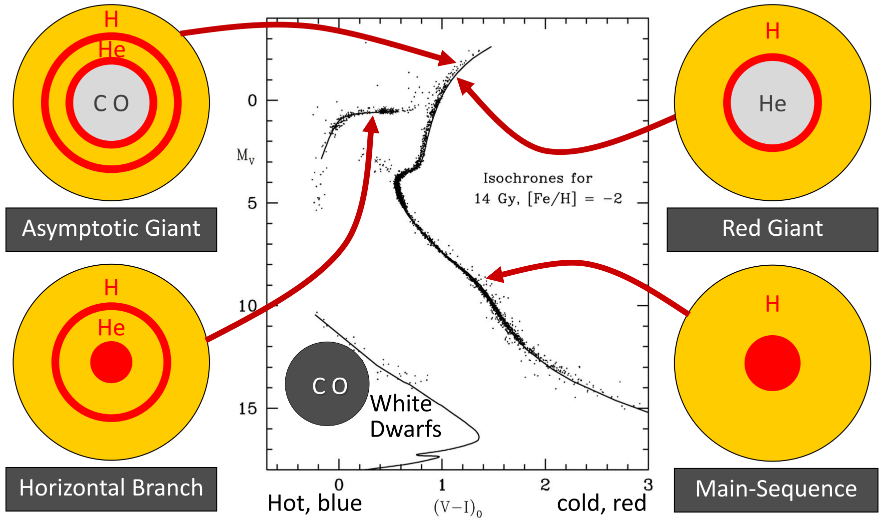
SubGiant Branch (SGB) : hydrogen burning in a thick shell

Red-Giant Branch (RGB) : hydrogen burning in a thin shell with a growing core until helium ignites

Horizontal Branch (HB) : helium burning in the core and hydrogen burning in a shell

Asymptotic Giant Branch (AGB) : helium and hydrogen shell burning

Horizontal-branch stars and the $g_{a\gamma}$ coupling



- The Horizontal-branch (HB) stars are Helium burning stars with low core density and high temperatures

- Axions could be efficiently produced via Primakoff conversion and speed up the evolution of the star in this stage

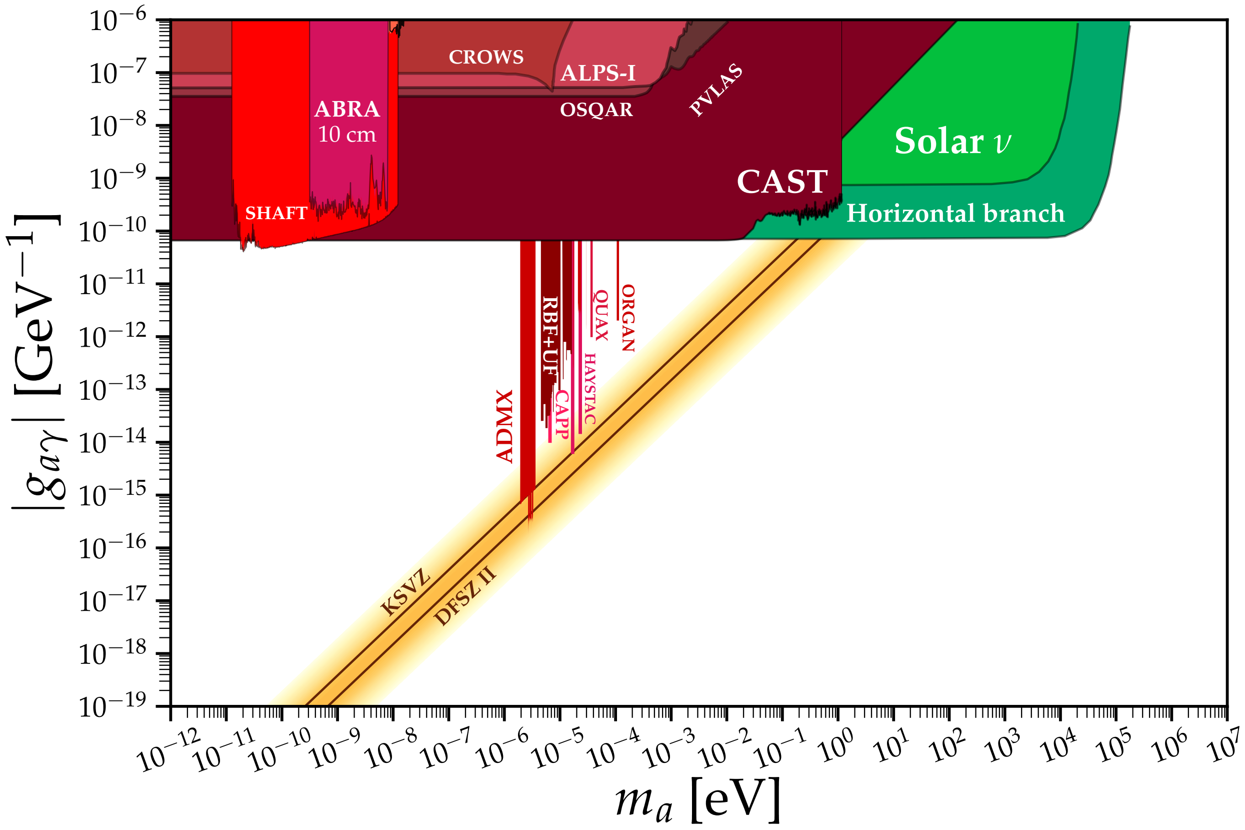
- Observationally, the relevant parameter is the ratio of stars in the HB stage over the ones in the RGB (brighter & preceding)

- A non-zero $g_{a\gamma}$ will deplete the stars at HB with respects to the RGB ones,

$$\text{Constraint: } g_{a\gamma} < 0.66 \times 10^{-10}\ \text{GeV}^{-1}$$

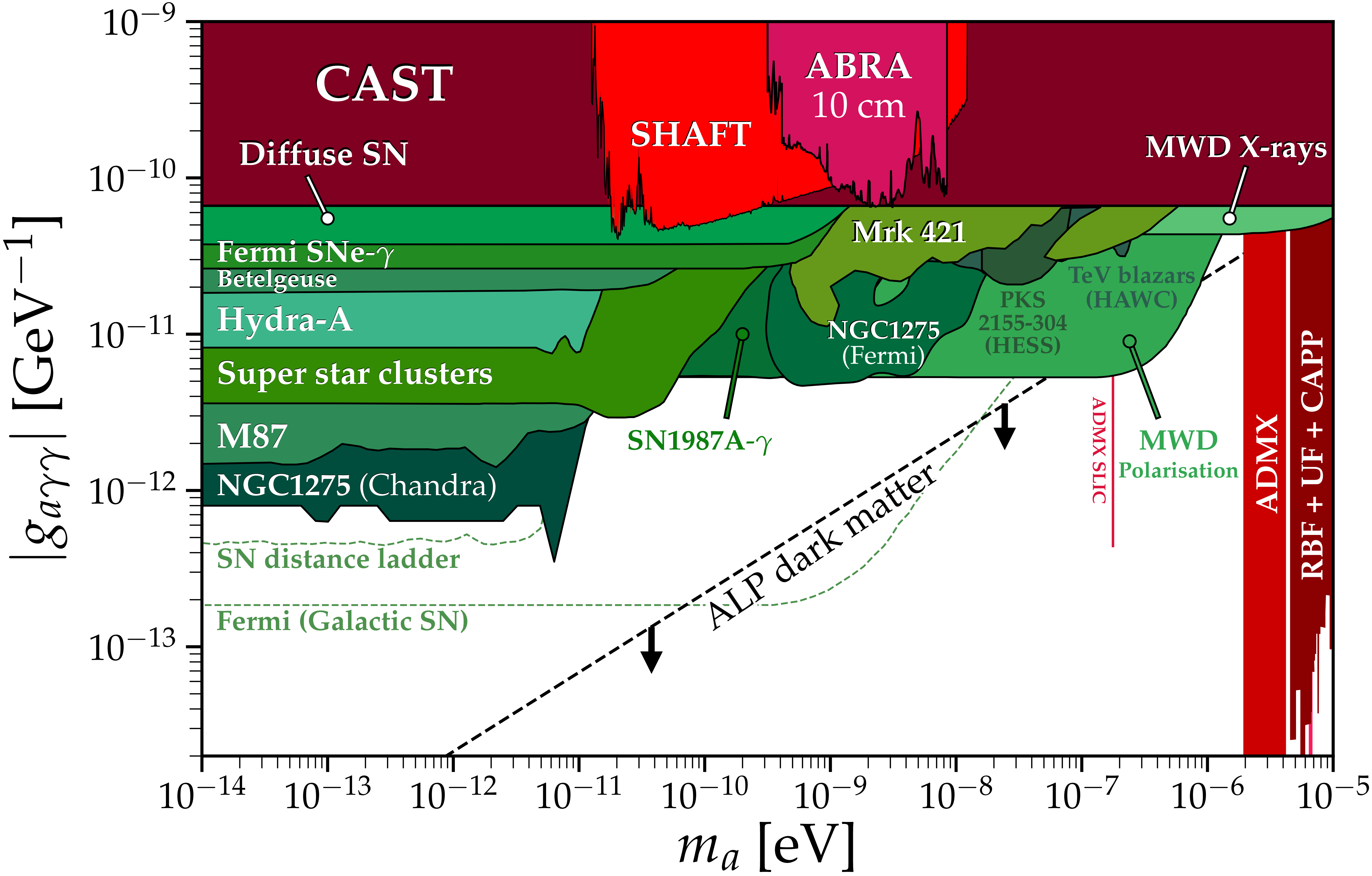
(30 % lifetime reduction)

- Comparable to the CAST limit but applies for higher masses (relevant temperature is ~ 10 keV)



High energy astrophysics limits closeup

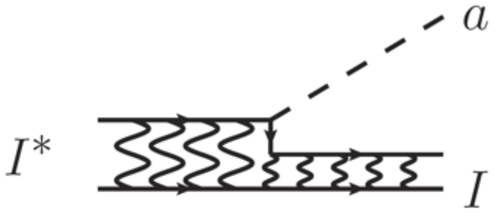
Axion-photon coupling



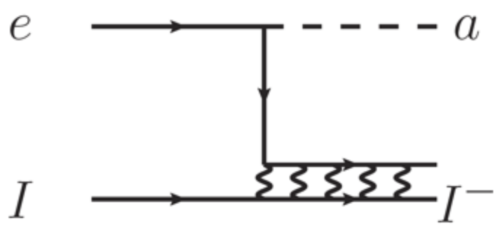
Axion-electron coupling

If axions couple to electrons, a number of additional axion production mechanisms are at play in dense stellar interior:

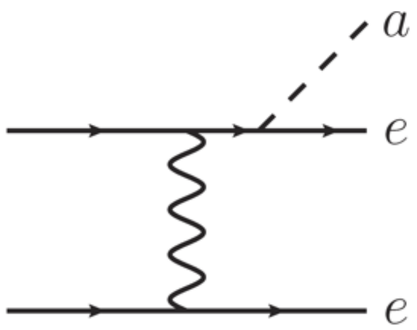
- axion-deexcitation :



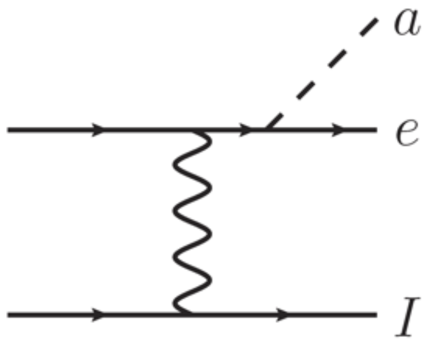
- axio-recombination :



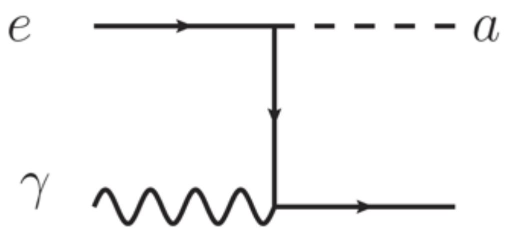
- axion-Bremsstrahlung in electron-electron collisions :



- axion-Bremsstrahlung in electron-ion :



- Compton scattering with emission of an axion :



The most interesting constrains on g_{ae} arise from dense cores of white dwarfs (WD) and RGB stars for which the **bremsstrahlung emission** dominates.

White-dwarf cooling

- WDs are relatively light stars in a late stage of their lifetime when they have exhausted their nuclear energy sources

- They have simple evolution (gravothermal process) governed by the cooling offered by neutrinos and then photons emission

- The presence of an exotic cooling mechanism:

axion luminosity: $L_a \sim 2 \times 10^{-4} L_\odot \left(\frac{g_{ae}}{10^{-13}}\right)^2 \left(\frac{T_c}{10^7\ \mathrm{K}}\right)^4$

Thermal spectrum at $T_C \sim 1\mathrm{keV}$

Surface temperature is a few eV

- Axion cooling could be made efficient in two ways:
  - Look at the distribution of the WDs versus luminosity, cooling speed agrees with expectations, $g_{ae} < 1.5 \times 10^{-13}\ \mathrm{GeV}^{-1}$
  - Direct observation of the period change of single WD variable stars (WDs whose luminosity oscillates due to gravity pulsations within themselves)

Constraint : $g_{ae} \lesssim 10^{-13} \mathrm{GeV}^{-1}$, hint for $g_{ae} = 2.9 \times 10^{-13} \mathrm{GeV}^{-1}$?

Helium ignition of the RGB and the g_{ae} coupling

- Another good observables to constrain g_{ae} is the luminosity of the RGB tip (point of maximum luminosity, when RGB stars reach the condition to ignite Helium, a.k.a the He-Flash)

- RGB stars have a degenerate helium core with a typical density $\rho \sim 10^6 \mathrm{g\ cm}^{-3}$ and $T \sim 10^8$ K. Helium ignites a a critical combination of ρ and T.

- Therefore it can be delayed by axion cooling. This implies that the core grows more massive before helium ignites.

⟶ RGB will extend to brighter stars

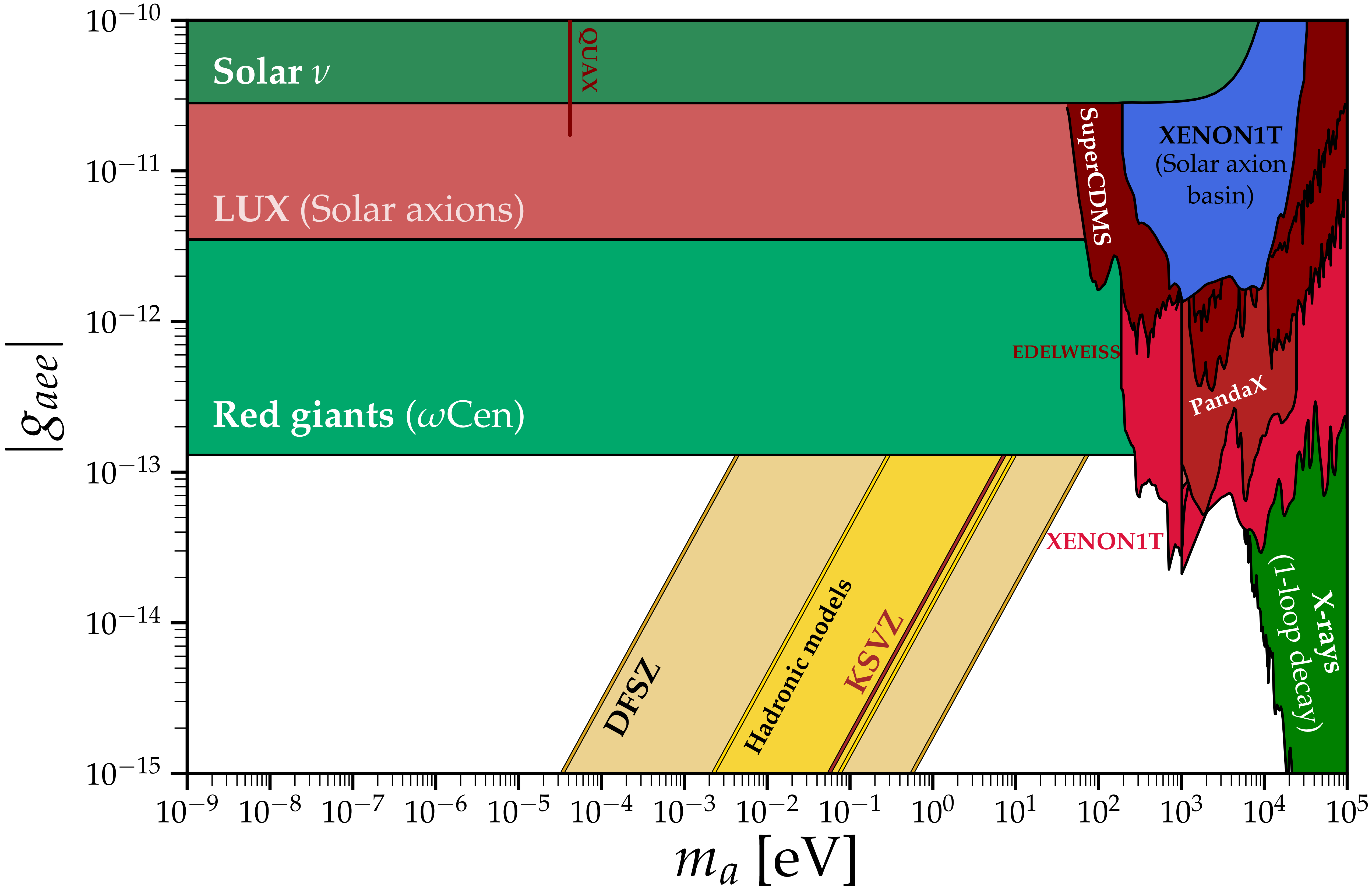
- Remember, that the helium-burning lifetime is useful to constrain $g_{a\gamma}$ because of the Primakoff rate effective in HB stars and suppressed in the RGB cores

- The most efficient axion production mechanisms are the electron bremsstrahlung and the Compton processes

- The helium-ignition argument is useful when the emission rate is larger on the RGB than on the HB,

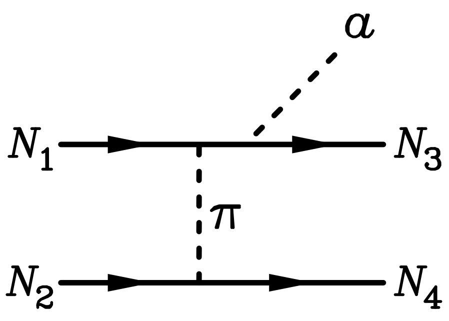
Constraint : $g_{ae} \lesssim 3 \times 10^{-13} \mathrm{GeV}^{-1}$ G. Raffelt and A. Weiss, arXiv:9410205

High energy astrophysics limits closeup
Axion-electron coupling



Axion-nucleon coupling

- If axions or ALPs couple to nucleons, it allows for nuclear transition in the stellar core to emit axions (has been searched for in the Sun)



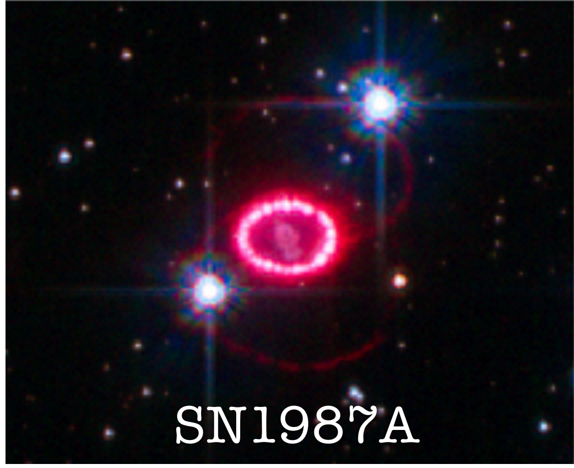
One Pion Exchange (OPE) approximation

- Relevant thermal process is **nucleon bremsstrahlung**.

- This process is efficient at temperatures high enough so that momentum exchange between nucleons is larger than the pion mass.

- This happens only at the cores of **Supernovae** (SN) and **Neutron Stars** (NS).

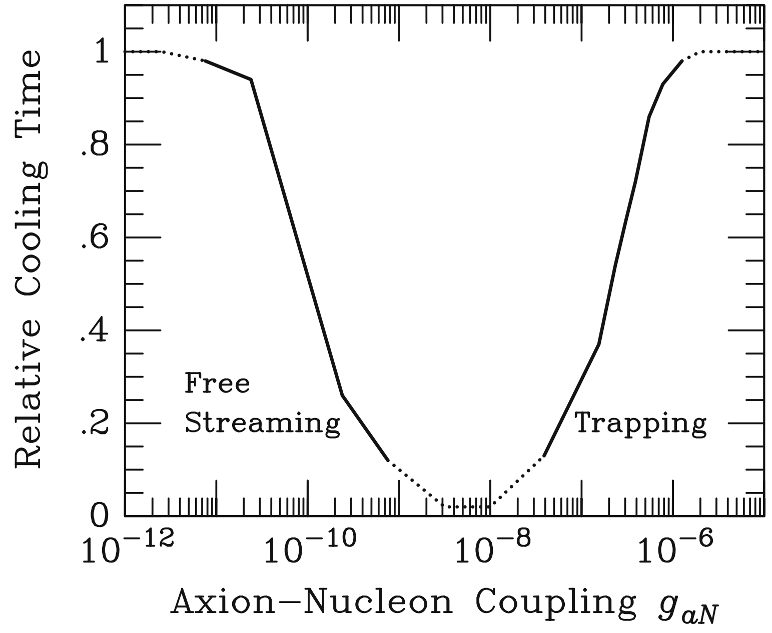
Axion bound from Supernovae



The SN core is an extreme environment

density	temperature	magnetic field
10^{14}g cm^{-3}	30 MeV	10^{15} G

- Strongest constraint on g_{aN} comes from the famous observation of the neutrino signal from the supernovae explosion SN1987A. M. S. Turner, Phys.Rev.Lett. 60 (1988) 1797
- The signal duration depends on the efficiency of the cooling and the observed signal in the few neutrinos detected is compatible with the standard picture that neutrinos dominate as the carrier of the energy released during the explosion.

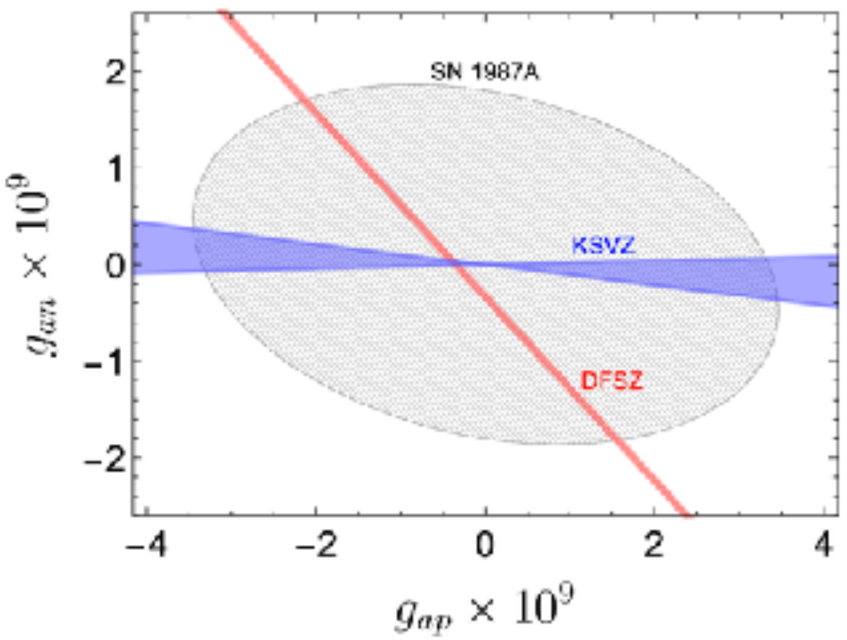


- Axion emission would shorten the neutrino signal:

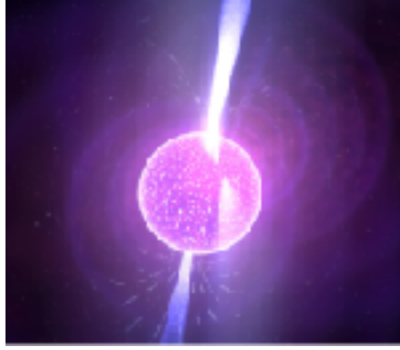
very stringent upper bound for the QCD axion, $m_a \lesssim 20$ meV

(Indicative limit rather than a sharp bound due to considerable uncertainties)

$$g_{an}^2 + 0.29\, g_{ap}^2 + 0.27\, g_{an}\, g_{ap} \lesssim 3.25 \times 10^{-18}$$



Axion bound from Neutron Stars



- Axions may modify NS cooling by being thermally produced within the NS cores and escape the stars due to their weak interactions

- Most previous studies of axion-induces NS cooling have focused on very young NS (proto-NSs) (one from SN1987A are seconds old). What about older NS cooling with ages $\sim 10^5 - 10^6$ years?

- SN1987A studies suffer from self consistent simulation and big uncertainties related to the formation

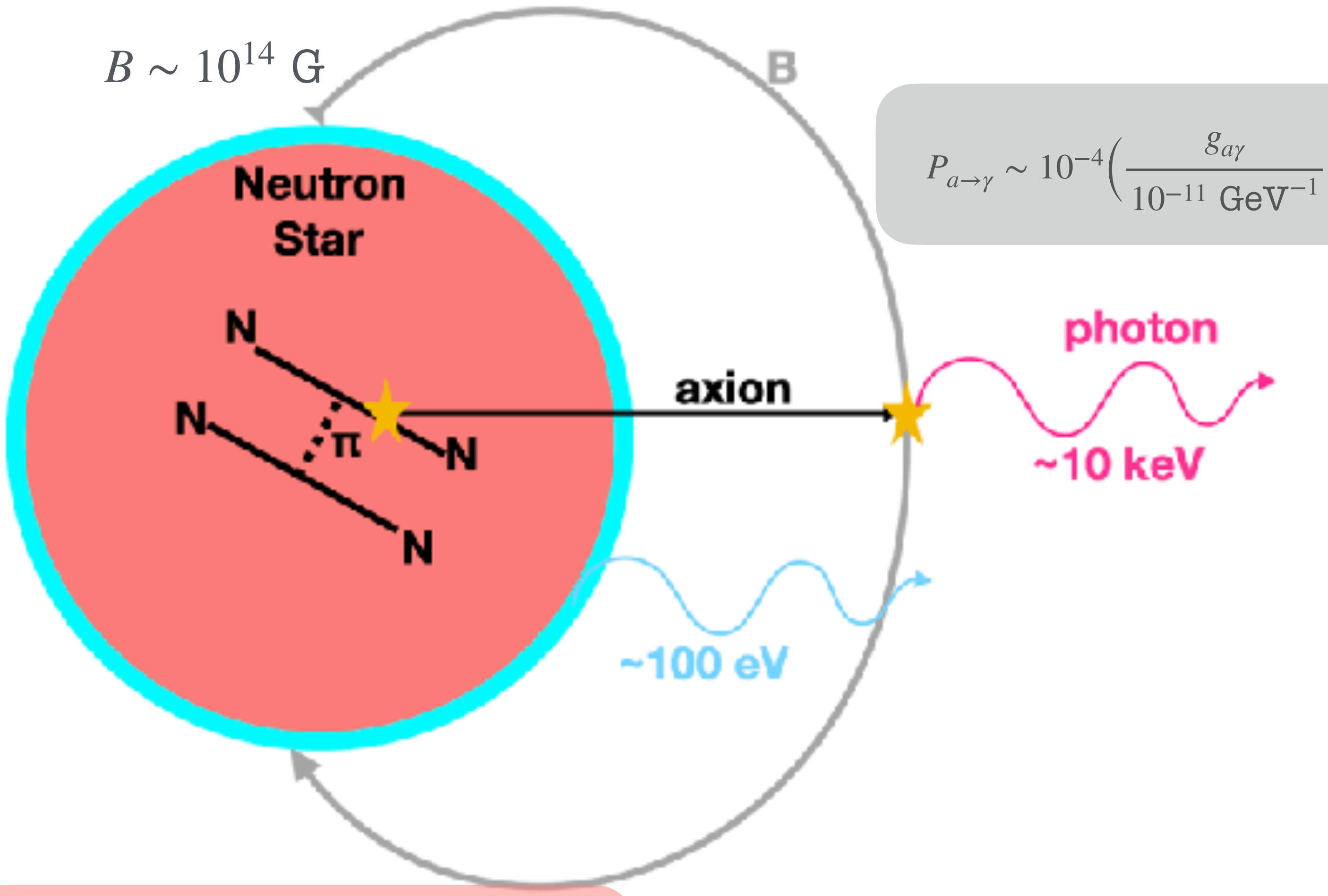
- NSs with ages $\sim 10^5$ yrs live at a unique era, where cooling from **axion bremsstrahlung** emission is maximally important.

  at lower ages neutrino emission plays a more important role since the neutrino (axion) emissivity scales as $\propto T^8 (T^6)$ while at older ages the thermal surface emission dominates the energy loss

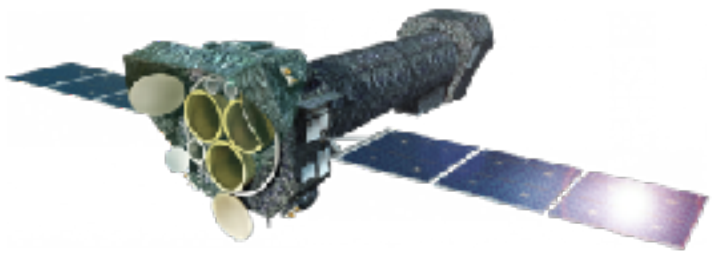
Constraint : $g_{an} \leq 2.8 \times 10^{-10} \mathrm{GeV}^{-1}$ (NS in HESS J1731-347)

- Despite their astronomical distances from Earth, NSs provide competitive environments in which to search for signatures of axion DM because these objects contains enormous magnetic fields ($\sim 10^{15}$ G)

Axion production in NS cores conversion into NS magnetosphere: X-ray searches



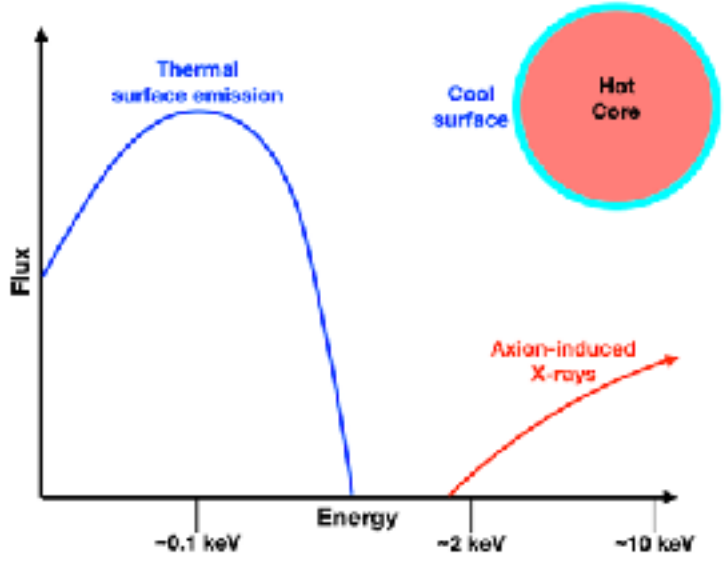
$$P_{a\to\gamma} \sim 10^{-4}\left(\frac{g_{a\gamma}}{10^{-11}\ \text{GeV}^{-1}}\right)^{2}\left(\frac{1\ \text{keV}}{\omega}\right)^{4/5}\left(\frac{B_0}{10^{13}\ \text{G}}\right)^{2/5}\left(\frac{R_{NS}}{10\ \text{km}}\right)^{6/5}$$

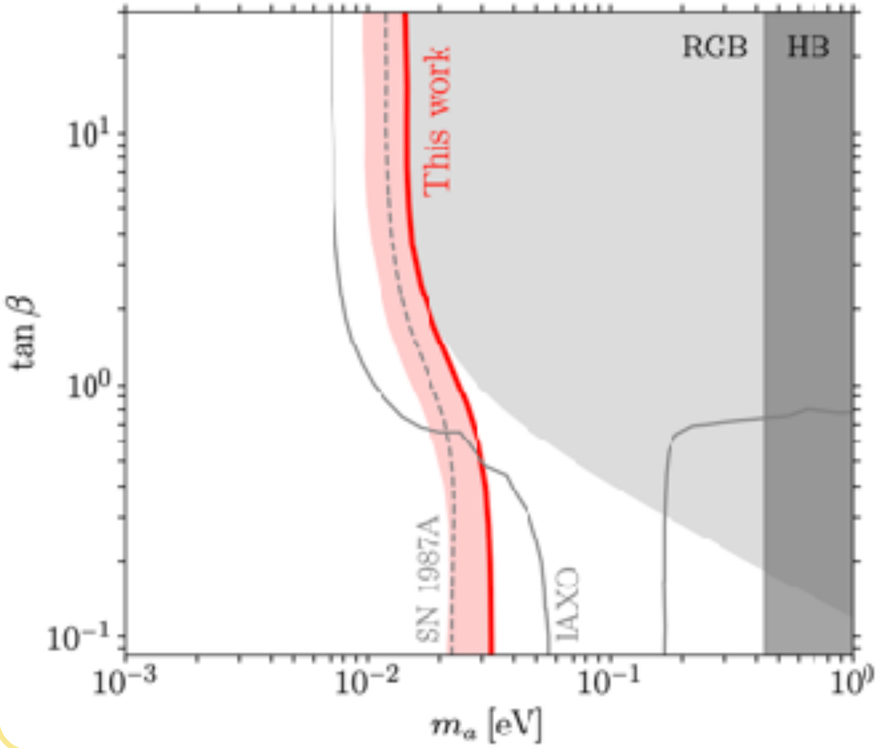


XMM-Newton, Chandra telescopes

$$L_\gamma \propto g_{aN}^2 g_{a\gamma}^2$$

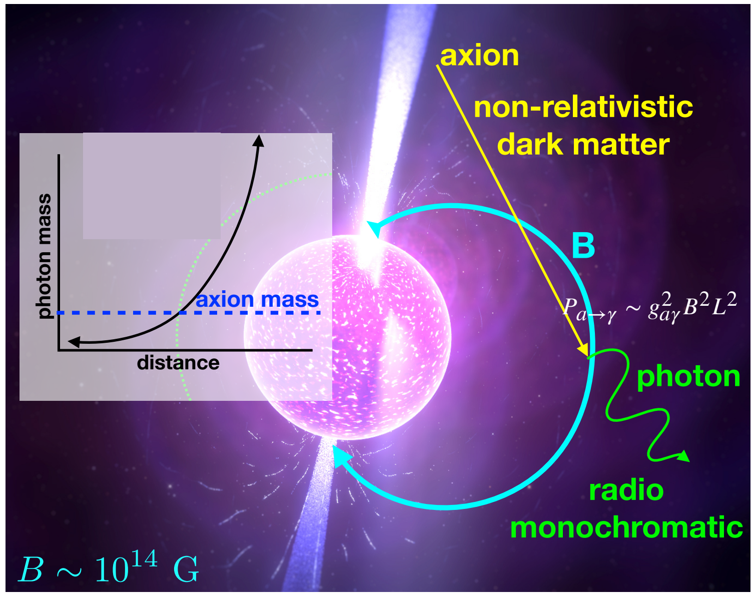
$$L_a \sim 0.05 L_\odot\left(\frac{g_{aN}}{10^{-10}}\right)^{2}\left(\frac{T_c}{10^{8}\ \text{K}}\right)^{6}$$





Buschmann et al., arXiv:2111.09892

Axion production in NS cores conversion into NS magnetosphere: radio searches



radio waves

radio emission propagates to Earth

Expected spectral morphology : $f \sim m_a(1+\mathcal{O}(v^2))/2\pi$ quasi-monochromatic , broadened by astrophysical velocity distribution

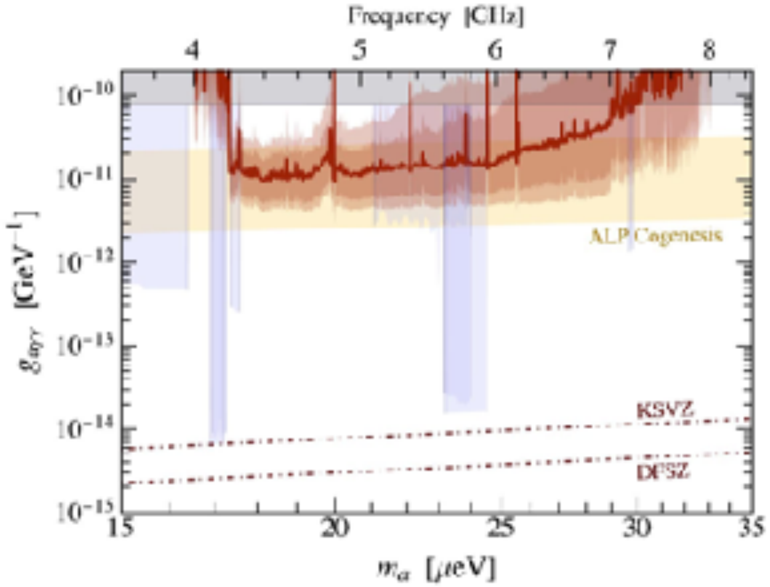

Alex Savello, VLA

- Axion DM may efficiently convert to photons in the magnetospheres of NSs producing nearly monochromatic radio emission:

  This process is resonantly triggered when the plasma frequency induced by the underlying charge distribution approximately matches the axion mass.

- Search for evidence of this process using archival Green Bank Telescope data collected in a survey of the Galactic Center in the C-band by the Breakthrough Listen project (aims to find signatures of extraterrestrial life in the radio band)

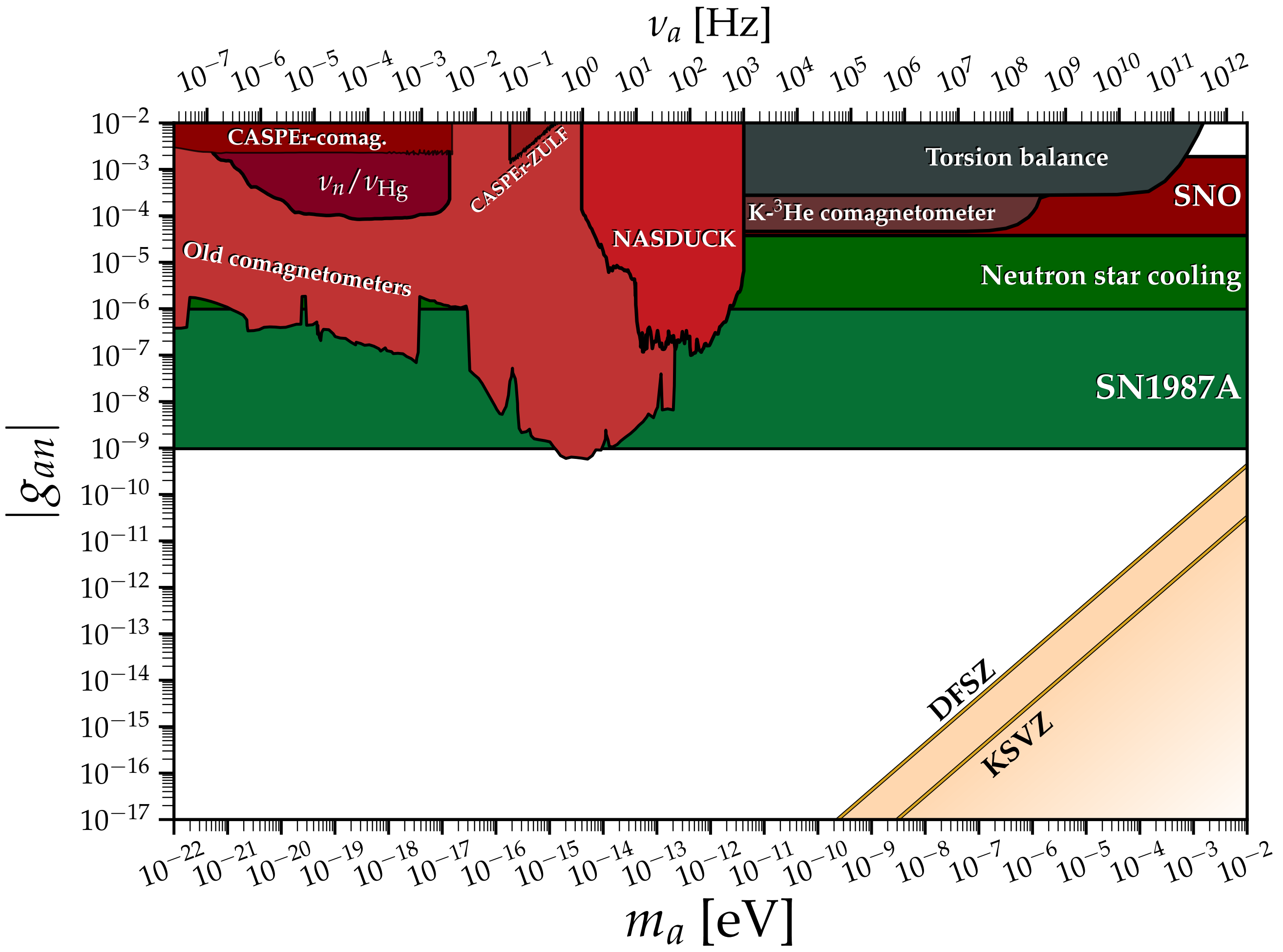
  - Find no evidence for axion DM excluding values down to: $g_{a\gamma} \sim 10^{-11}\mathrm{GeV}^{-1}$ for DM axions with $m_a = 15 - 35\mu\mathrm{eV}$

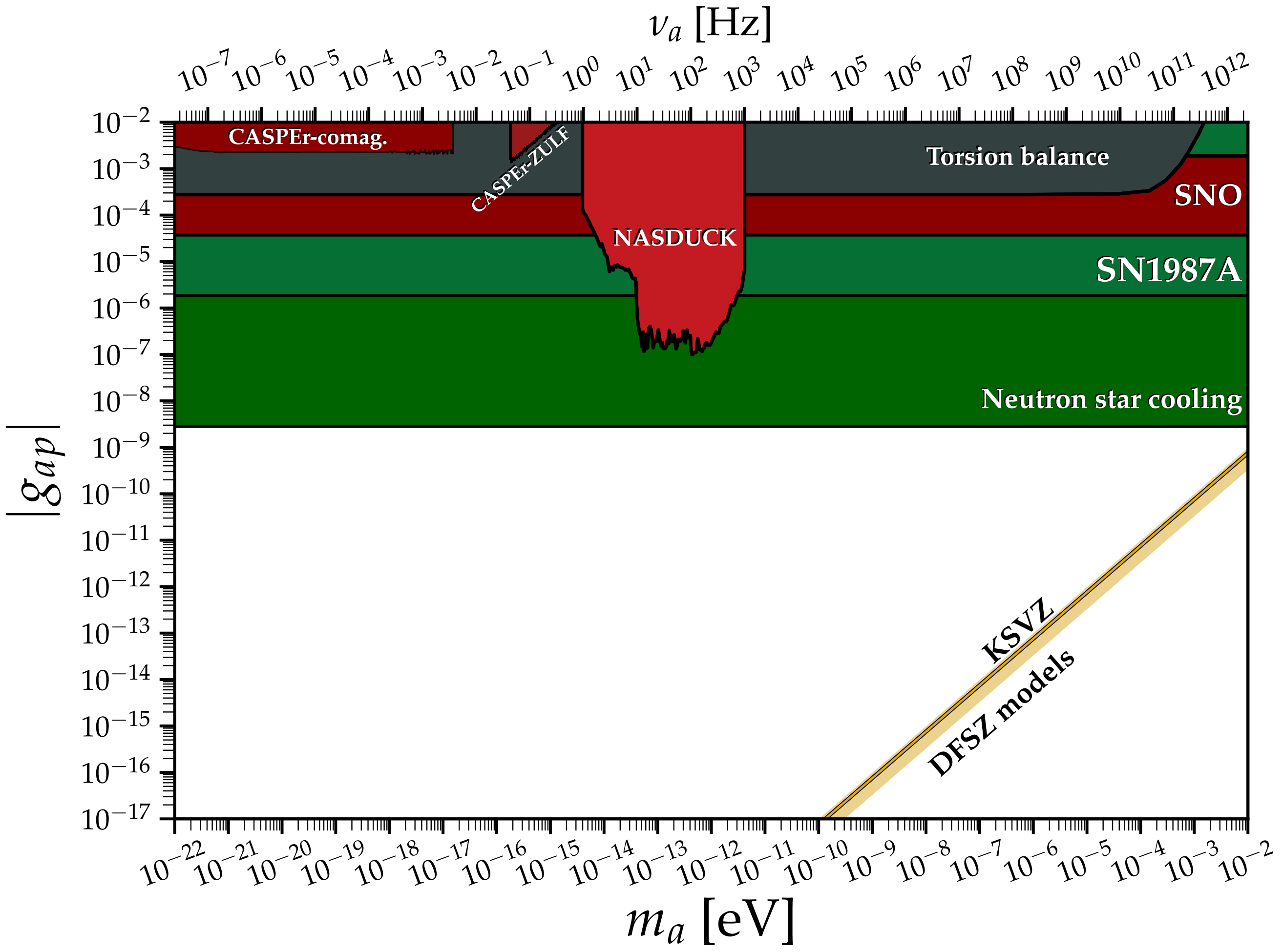


Foster et al., arXiv:2202.08274

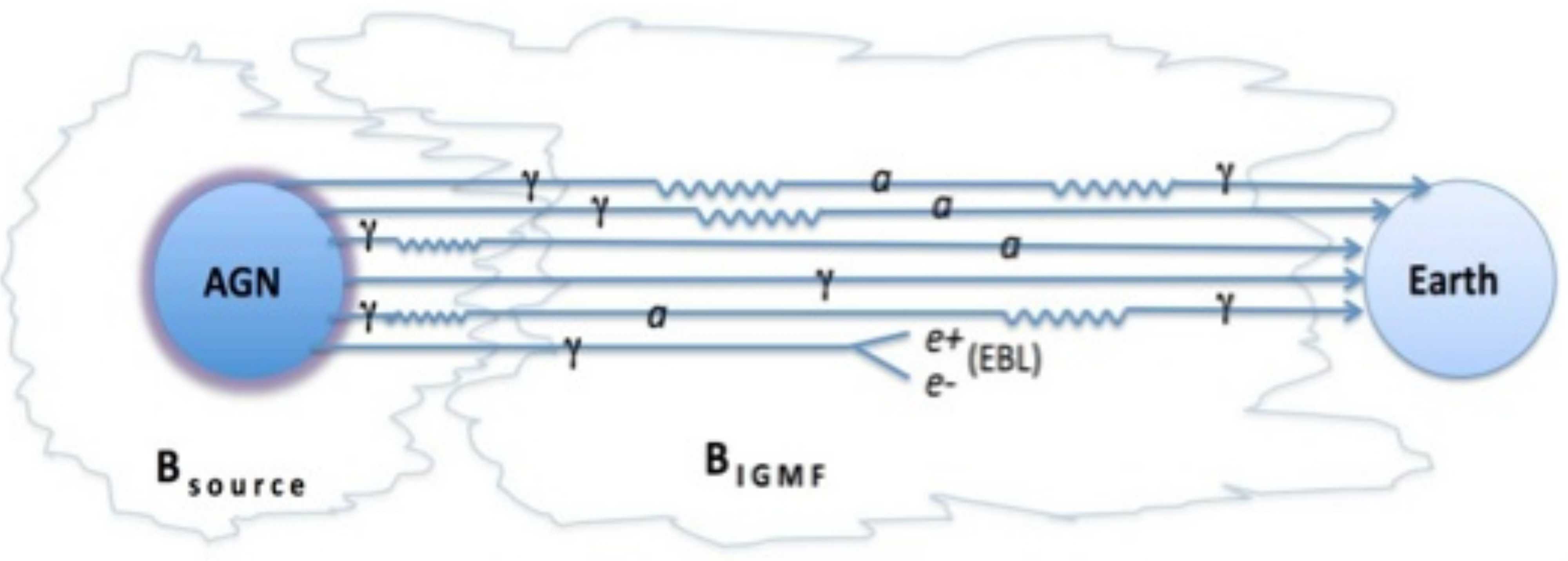
High energy astrophysics limits closeup

Axion-neutron/proton coupling





Photon-axion conversion in intergalactic magnetic field



- Energetic photons from distant sources travel Megaparsec distances through intergalactic magnetic fields to reach Earth

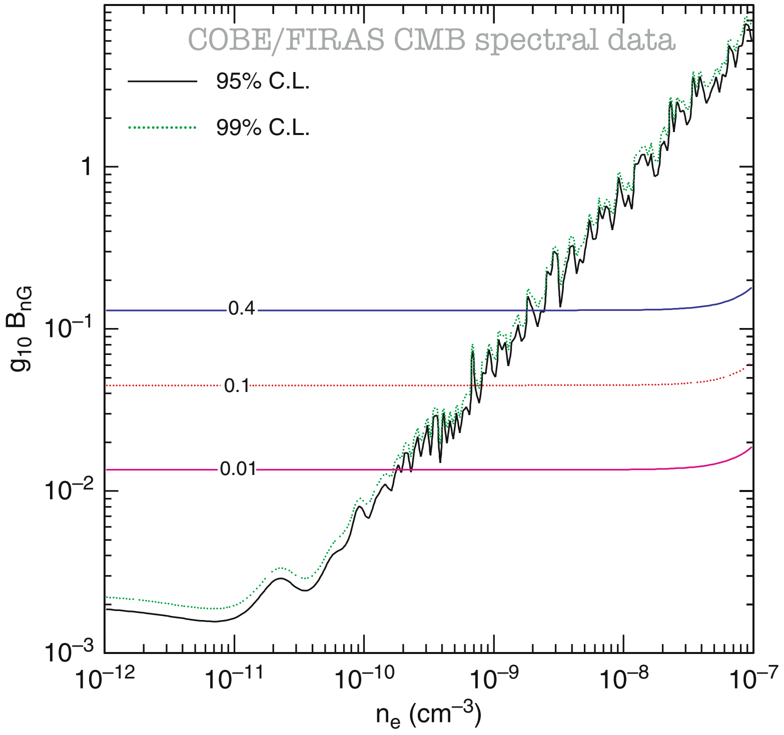
- If conversion to axions is possible, their propagation distance is enhanced

- As the conversion probability is energy-dependent this also leads to a characteristic modulation of the observed gamma and X-ray spectrum

Photon-axion conversion in intergalactic magnetic field

- CMB spectrum distortion:

A. Mirizzi, G. Raffelt, P. Serpico, arXiv:0506078

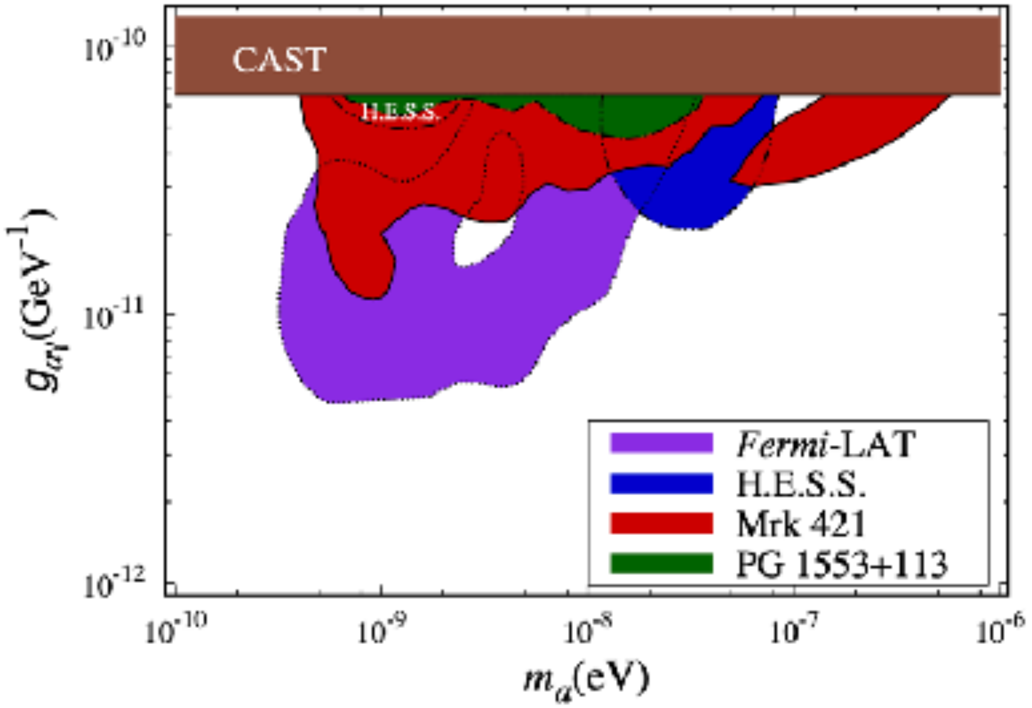


- Quasar spectra distortion:

Photon-axion oscillation add a dispersion due to the energy-dependence of the effect

Blazar Mrk 421 measured by Fermi-LAT :

Li et al. , arXiv:2008.09464



No prompt γ ray burst from Supernova 1987A **Again!**

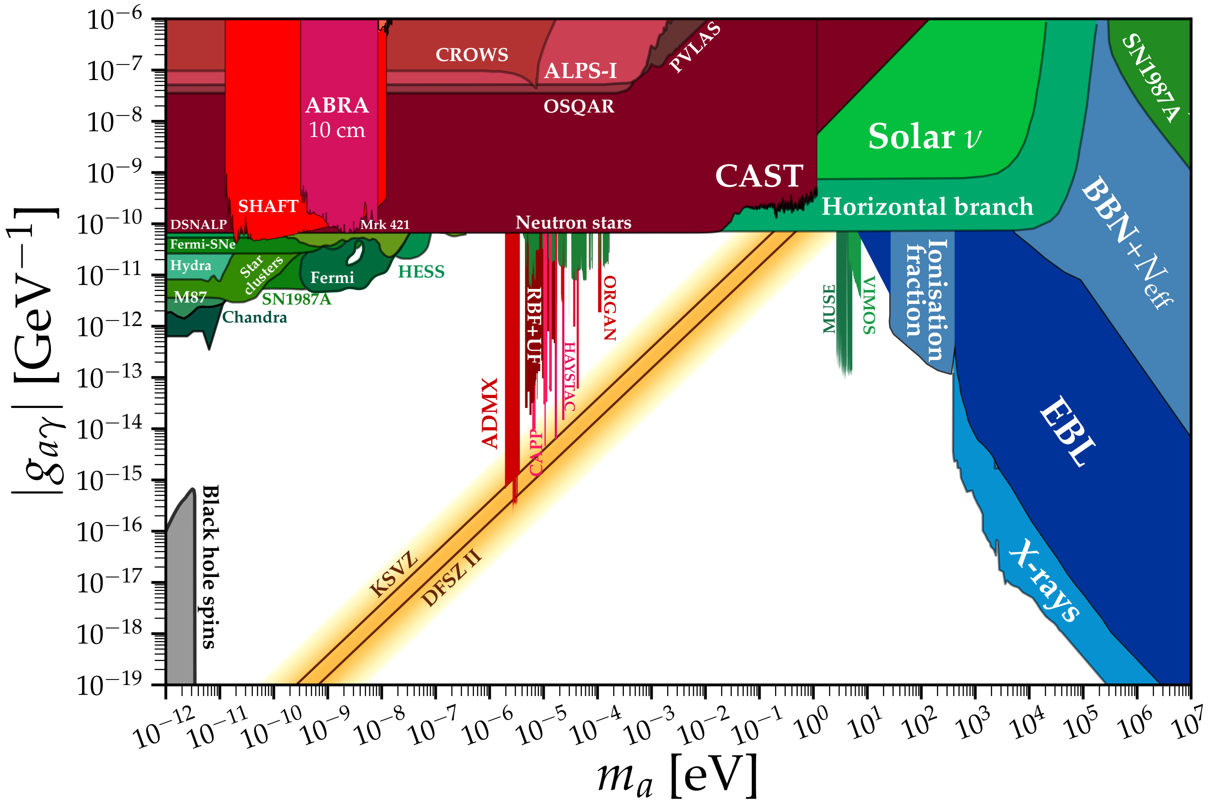
- Axions could be produced during core collapse of Supernovae and escape the explosion

- If they convert back to gamma rays in the Galactic field, a gamma ray burst lasting $\sim 10s$ could be observed in temporal coincidence with the SN neutrino burst

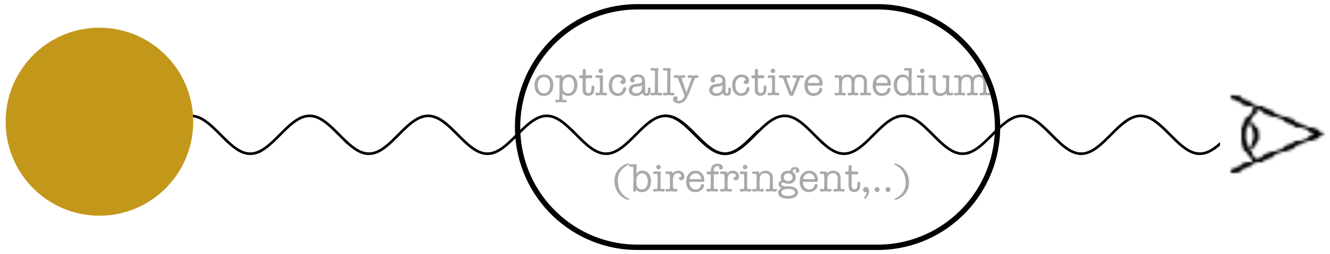
- Needs g_{aN} for production, $g_{a\gamma}$ for conversion in galactic magnetic field

- The non observation of such a gamma ray burst from SN1987A leads to a constraint to $g_{a\gamma}$ to low masses,

$$\text{Constraint}: g_{a\gamma} \lesssim 3 \times 10^{-12}\text{GeV}^{-1} \qquad \text{with } m_a \lesssim 10^{-9}\text{eV}$$



How do photons propagate through axion background?



astrophysical source

axion background

measures

optically active medium

(birefringent,..)

axion electrodynamics:

$$\nabla\cdot\mathbf{E} = \rho - g_{a\gamma\gamma}\mathbf{B}\cdot\nabla a\,,$$

$$\nabla\times\mathbf{B} - \dot{\mathbf{E}} = \mathbf{J} + g_{a\gamma\gamma}\dot{a}\mathbf{B} + g_{a\gamma\gamma}\nabla a\times\mathbf{E}\,,$$

$$\nabla\cdot\mathbf{B} = 0$$

$$\dot{\mathbf{B}} + \nabla\times\mathbf{E} = 0\,.$$

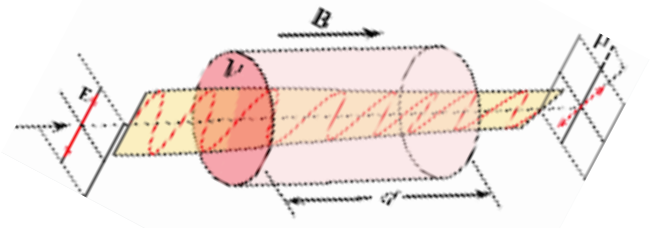
dispersion relation:

$$\omega_\pm \sim k \pm \frac{g_{a\gamma\gamma}}{2}(\partial_t a + \frac{\boldsymbol{k}}{k}.\boldsymbol{\nabla} a) \quad \mp g_{a\gamma\gamma}\omega_p^2\frac{\partial_t a}{4k^2} \quad + \mathcal{O}(g_{a\gamma\gamma}^2)$$

Apply carefully Hamilton's optic

$$v^\pm_{phase} = \frac{\omega^\pm}{k}$$

The Faraday rotation



axion induces photon **polarisation rotation**: Harrari-Sikivie (1992)

$$\theta = \frac{1}{2}\int_{t_i}^{t_f}(\omega_+ - \omega_-)dt$$

$$\theta = \frac{1}{2}\int_{t_i}^{t_f} g_{a\gamma}(\partial_t a + \frac{\boldsymbol{k}}{k}.\boldsymbol{\nabla} a)dt$$

VLT observations of neutron star

$$v^\pm_{group} = \frac{d\omega^\pm}{dk}$$

Group velocity splitting between L/R polarisations:

$$v_g^+ - v_g^- = \pm\frac{g_{a\gamma\gamma}}{4k_0}\frac{\omega_\mathrm{p}^2}{k_0^2}\left[a' - \dot{a}\right]$$

time delay

$$\Delta t_p = \mp\frac{g_{a\gamma\gamma}}{4k_0}\frac{\omega_\mathrm{p}^2}{k_0^2}\int_0^{t_\mathrm{f}} dt'\left[a' - \dot{a}\right]$$

Constraints from :

-Gamma-ray burst

-radio waves from pulsars & fast radio bursts

No refraction at $\mathcal{O}(g_{a\gamma\gamma})$ in absence of plasma

Blas et al. 'No chiral bending of light by axion clumps' (2019) cf. Weinberg (1962)

$$\Delta k^i = \pm\frac{g_{a\gamma\gamma}}{2}\partial_i[a(t_f,\boldsymbol{x}_f) - a(t_i,\boldsymbol{x}_i)]$$

$$\Delta\omega = \mp\frac{g_{a\gamma\gamma}}{2}\partial_0[a(t_f,\boldsymbol{x}_f) - a(t_i,\boldsymbol{x}_i)]$$

Suggests a new way to use atomic clocks to constraints axion DM:

$$\frac{\Delta\omega}{\omega} \sim 10^{-16}\left(\frac{g_{a\gamma\gamma}}{10^{-10}\mathrm{GeV}^{-1}}\right)\left(\frac{1\,\mathrm{GHz}}{\omega}\right)\sqrt{\frac{\rho_\mathrm{DM}}{0.3\,\mathrm{GeV/cm}^3}}$$

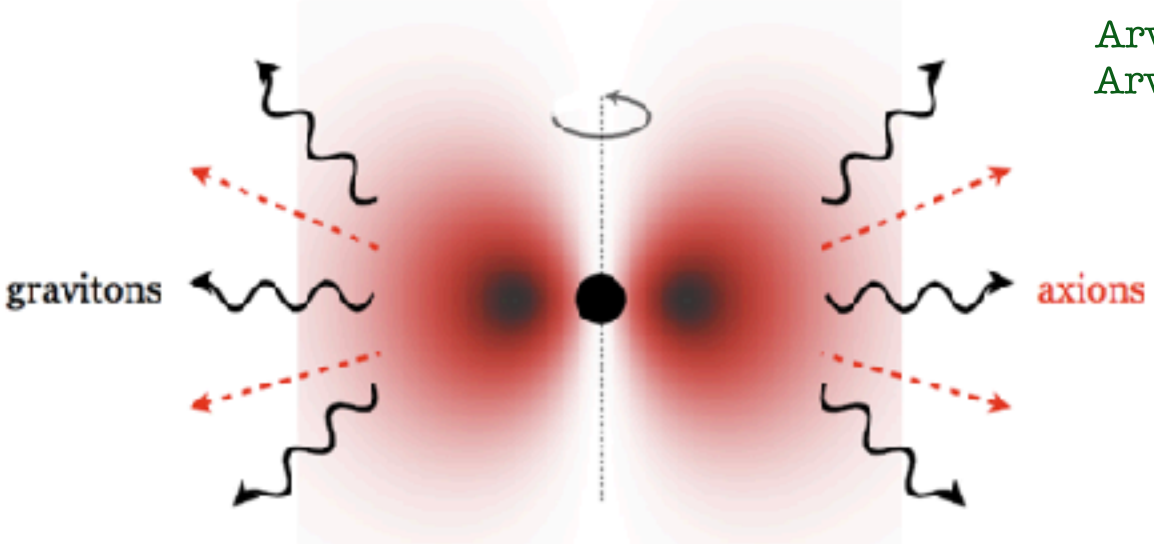
-optical effects should be examined further in specific axion backgrounds

-investigate precision terrestrial optical experiments to probe axion backgrounds

Axion coupling to gravity and black hole superradiance

- Astrophysical considerations can provide insights on the couplings of axions to gravity without assuming any interaction with the SM particles

Arvanitaki et al. arXiv:0506078
Arvanitaki and Dubovsky, arXiv:1004.3558



Spinning BH feeds axion Bose-Einstein condensate which emit gravitons

- Axions form gravitational bound states around BHs whenever their Compton length is of the order of the BHs radii
- The phenomenon of superrandiance guarantees that the axion occupation numbers grow exponentially, providing a way to extract very efficiently energy and angular momentum from the BH
- The axion cloud collapse in what is known as a bosenova producing periodic gravitational waves bursts which should be observable (Advanced LIGO & VIRGO)
- The rate at which the angular momentum is extracted depends on the BH mass, therefore axions could be discovered by observing BH masses and spins,

Current constraints : $6 \times 10^{-13}\text{eV} \leq m_a \leq 10^{-11}\text{eV}$ $6 \times 10^{17}\text{GeV} \leq f_a \leq 10^{9}\ \text{GeV}$

Constraints from the CMB , D. Blas and S. Witte, arXiv:2009.10074
neutron star rotation, F. Day and J. McDonald, arXiv:1904.08341

Conclusions

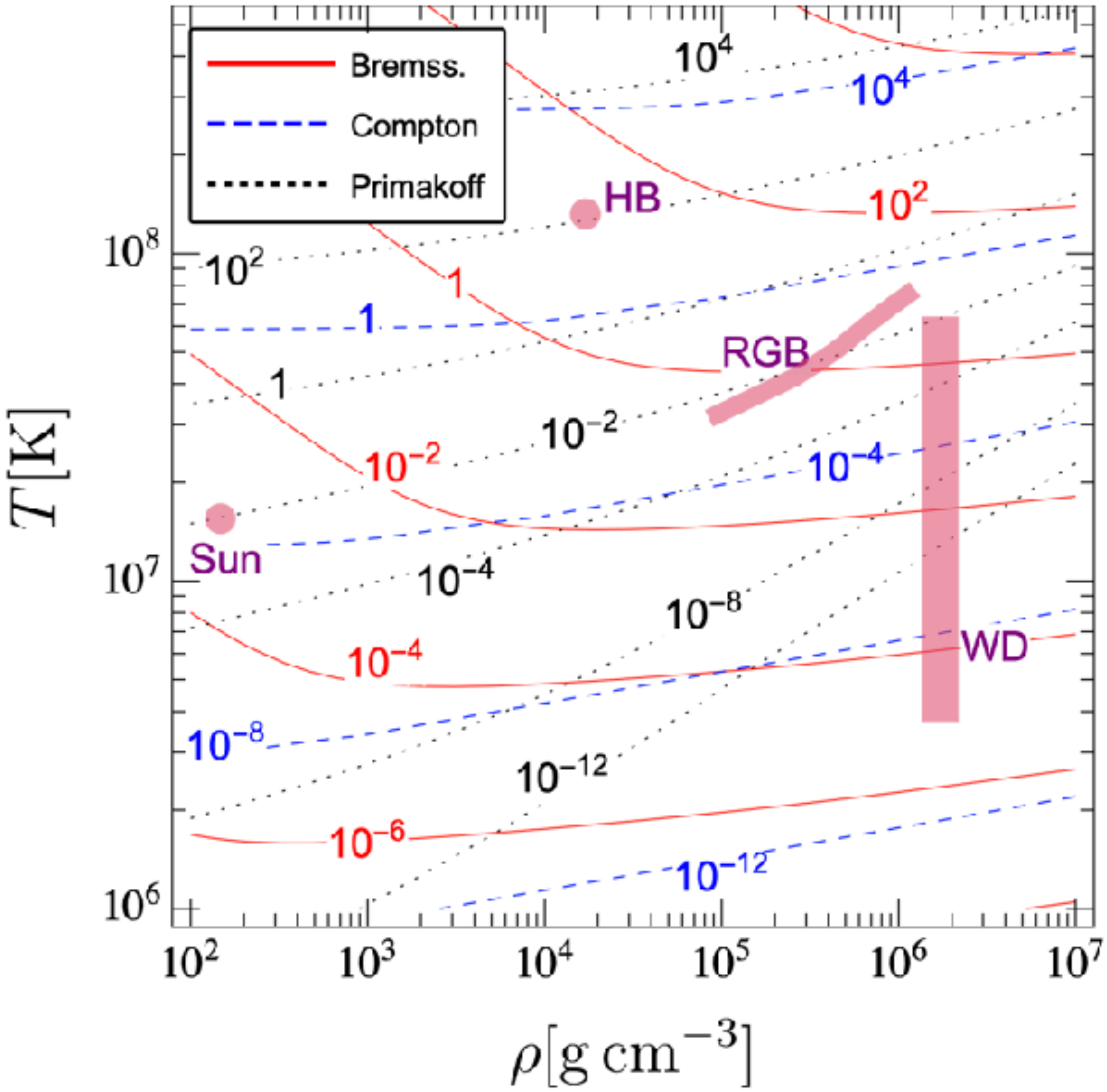
- Axions are generic predictions appearing in extensions of the SM
- They might actually contribute to dark matter, dark radiation or dark energy
- They are actively searched for in many dedicated experiments
- Astrophysics and cosmology provide the most restrictive limits on the axion hypothesis
- If they exist, they could have many effects in astrophysics
  - production in stellar plasma
  - modification of the opacity of the Universe
  - modification of the polarisation of distant sources
  - conversion in any magnetic field

Many new results expected from LSST, GAÏA, ...

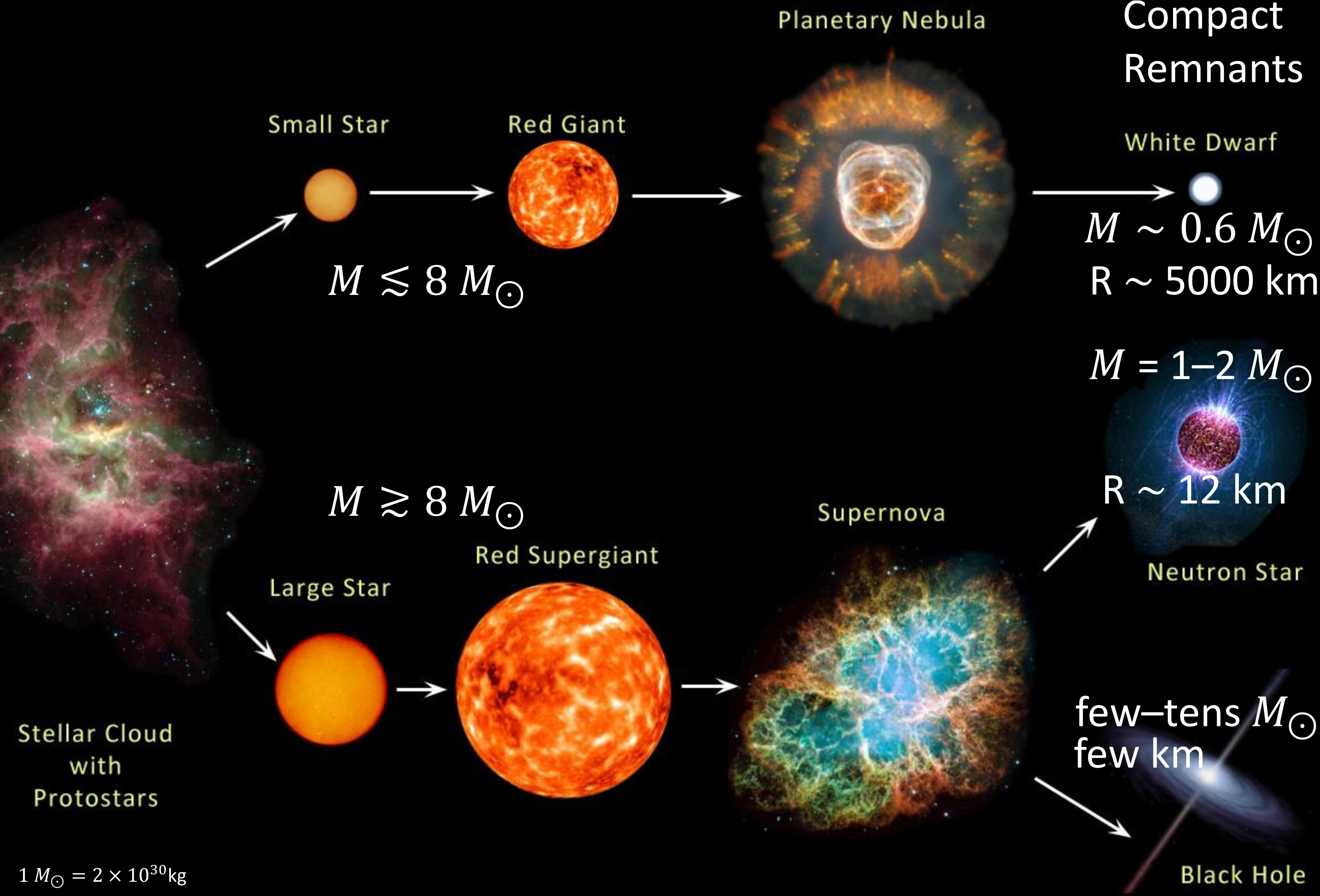
- Axions provide a fascinating interplay between astrophysics, cosmology and particle physics to solve some of the deepest mysteries

Spare slides

From L. Di Luzio et al., arXiv:2003.01100



Evolution of stars



Compact Remnants

Small Star

Red Giant

Planetary Nebula

White Dwarf

$M \sim 0.6\ M_\odot$

R ~ 5000 km

$M \lesssim 8\ M_\odot$

M = 1–2 $M_\odot$

R ~ 12 km

Neutron Star

$M \gtrsim 8\ M_\odot$

Supernova

Red Supergiant

Large Star

few–tens $M_\odot$

few km

Black Hole

Stellar Cloud
with
Protostars

$1\ M_\odot = 2 \times 10^{30}\text{kg}$

Detecting axion dark matter

QFT has two classical limits:

limit of point particles (WIMPs, …)

$\hbar \to 0 \quad \omega, \vec{k} \to \infty$

$E = \hbar\omega$ and $\vec{p} = \hbar\vec{k}$ fixed

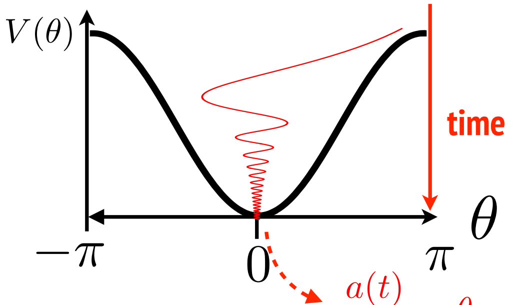
limit of classical fields (axions)

$\hbar \to 0 \quad N \to \infty$

$E = N\hbar\omega$ and $\vec{p} = N\hbar\vec{k}$ fixed

- Local DM density: $\rho_{\rm CDM} \simeq 0.3 \frac{\rm GeV}{\rm cm^3} = m_a n_a$ occupation number is huge

axion behaves as a classical coherent (NR) field:

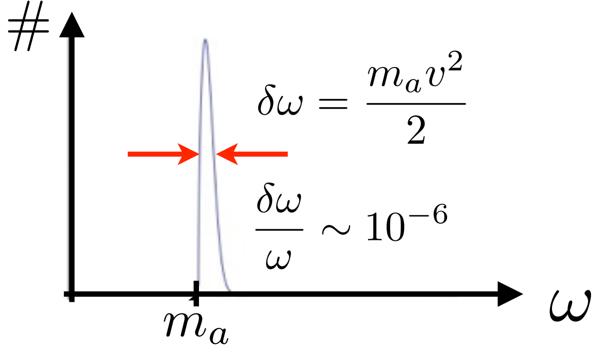


$\frac{a(t)}{f_a} = \theta_0 \cos(m_a t)$

$$\longrightarrow \quad \rho_{\rm CDM} = \frac{1}{2}\dot{a}^2 + \frac{1}{2}m_a^2 a^2 \simeq \frac{1}{2} m_a^2 f_a^2 \theta_0^2 \xrightarrow[\text{axion}]{\text{QCD}} \theta_0 \sim O(10^{-19})$$

- DM halo bounds to our galaxy: $v_a^{\oplus} = v_g \sim 10^{-3}c$

velocity of DM in the galaxy ⇒ the axion spectrum is not monochromatic



$$\omega \simeq m_a(1 + \underbrace{v^2/2}_{\sim 10^{-6}} + \dots)$$

coherence time : $\delta t \sim \frac{1}{\delta\omega} \sim 0.13{\rm ms}\left(\frac{10^{-5}{\rm eV}}{m_a}\right)$

coherence length : $\delta L \sim 20{\rm m}\left(\frac{10^{-5}{\rm eV}}{m_a}\right)$

Fundamental detection strategy: macroscopic coherence leads to coherent enhancement

From theoretical topological defects to cosmological astrophysical objects

Physics left invariant by a $U(1)_{\text{PQ}}$ rotation only if it rotates the QCD angle of $G\tilde{G}$

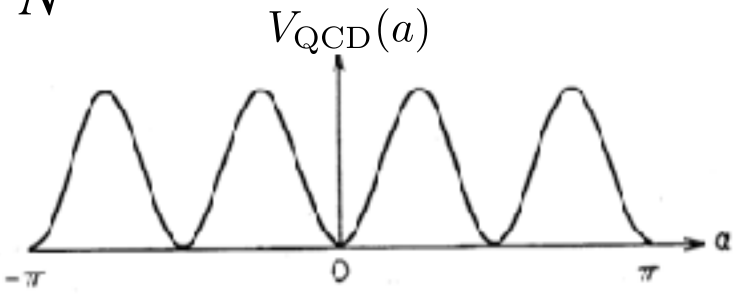
$$\phi \to e^{i\alpha}\phi \qquad \theta_{QCD} \to \theta_{QCD} + \boxed{N}\alpha$$

model dependent

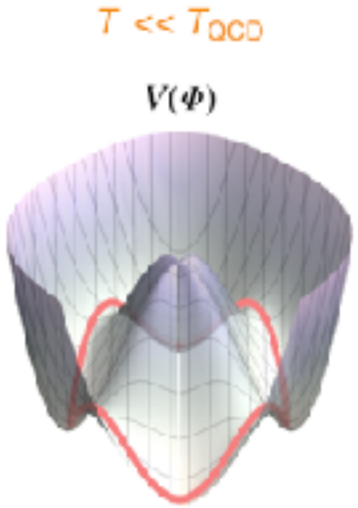
Strong interaction effects break $U(1)_{\text{PQ}}$ but are 2π periodic $\Rightarrow \alpha = \mathbb{Z}\frac{2\pi}{N}$ still a good symmetry

$$\boxed{U(1)_{PQ} \xrightarrow{\text{QCD instantons}} \mathbb{Z}_N}$$

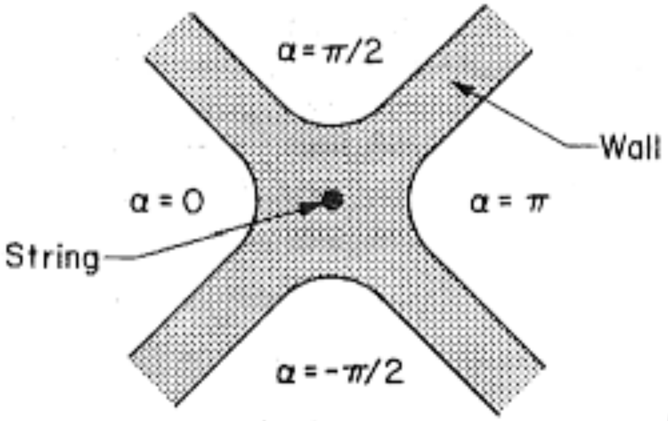
Ex: $N = 4$ axion model
(4 degenerate minima)



In QFT:

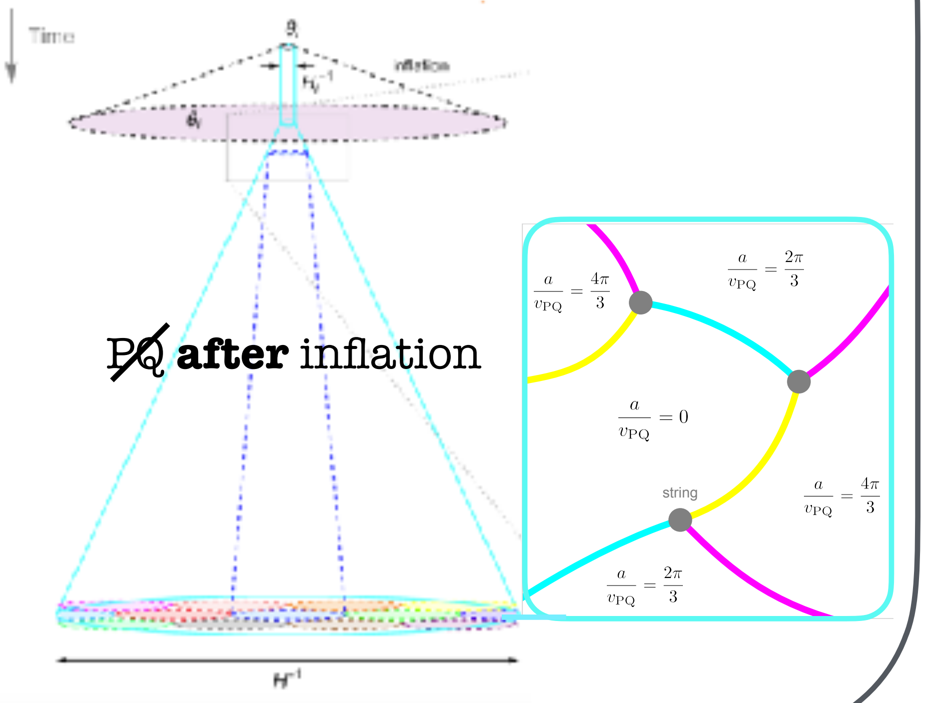


In position space:



$N = 4$ domain walls meet in a string

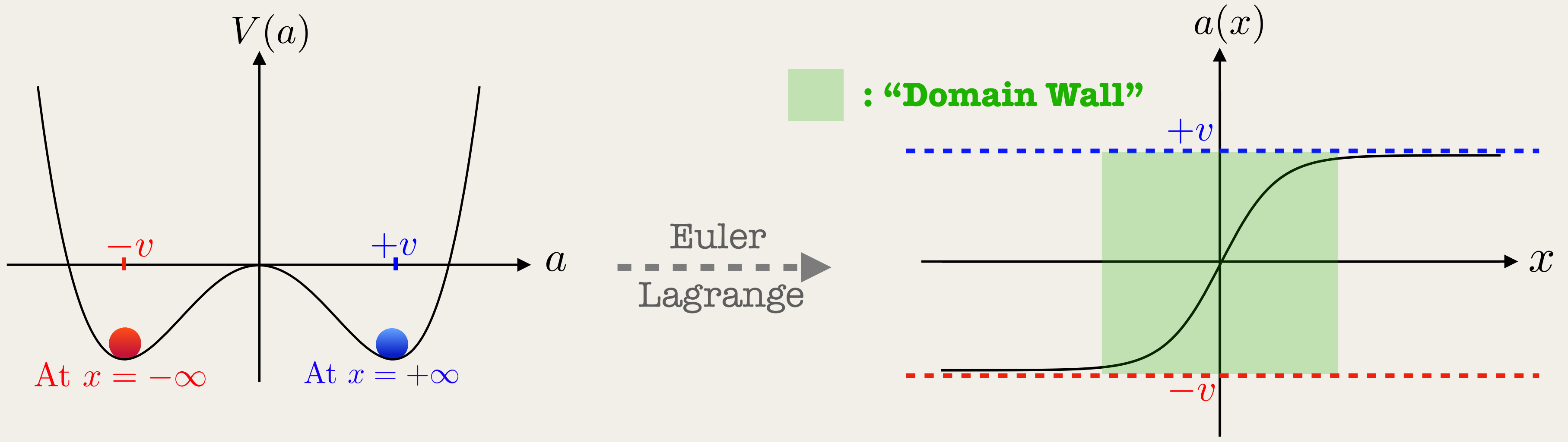
In the early universe:



$\cancel{\text{PQ}}$ **after** inflation

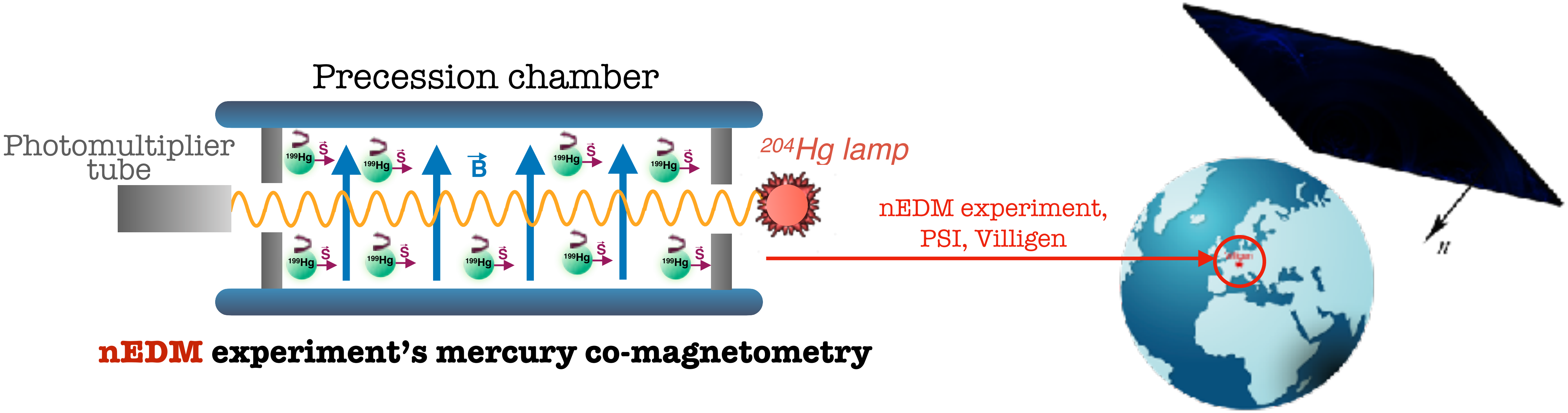
Detecting axion transient with nEDM

Example : $V(a) = -\mu^2 a^2 + \lambda a^4$



$$\mathcal{L}_{\text{int}} = \bar{\psi}\gamma^{\mu}\gamma^{5}\psi \times \frac{\partial_{\mu} a}{f_a} \xrightarrow[\text{limit}]{\text{Non relativistic}} H_{\text{int}} = \sum_{i=e,n,p} 2\vec{s}_i . \left(f_i^{-1} \vec{\nabla} a \right)$$

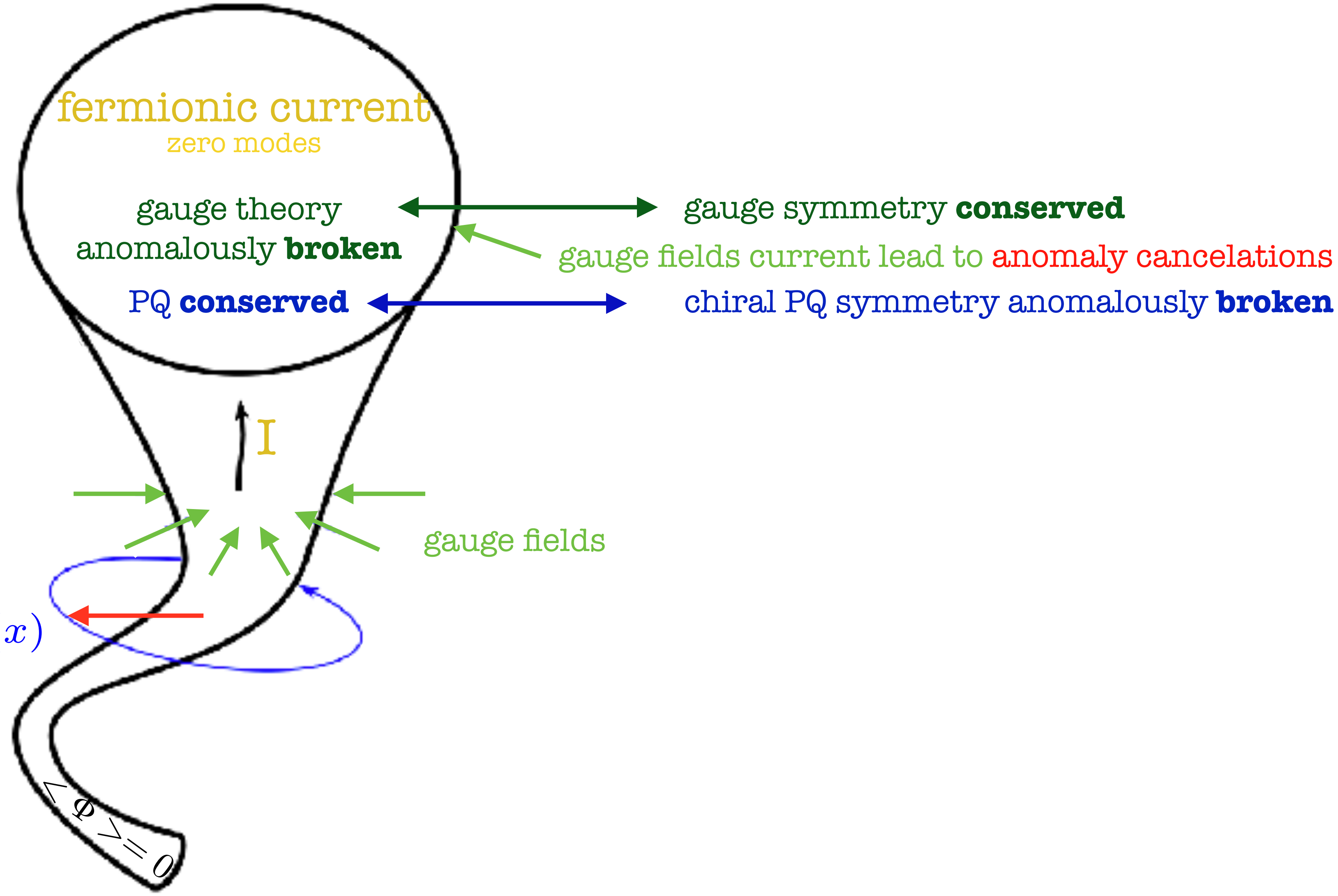
Pseudo-magnetic field



nEDM experiment's mercury co-magnetometry

in collaboration with G. Pignol et K. Martineau (LPSC)

Axion cosmic strings



fermionic current

zero modes

gauge theory anomalously **broken** ⟷ gauge symmetry **conserved**

gauge fields current lead to anomaly cancelations

PQ **conserved** ⟷ chiral PQ symmetry anomalously **broken**

gauge fields

PQ complex scalar field: $\Phi(x) = f(r)e^{i\theta(x)}$

$< \Phi >= f_a$

Axion mixes with SM U(1) symmetries

Interesting model building features to explore

Implications for DM, baryon asymmetry, ...,
still to be explored

Two standard axion models

PQWW axion :

Peccei, Quinn '77
Weinberg '78
Wilczek '78

axion identified with a phase in a 2HDM ($f_a \sim v_{ew}$) : **ruled out**

phenomenology calls for $f_a \gg v_{ew}$ (« invisible axion »)

method: mix it with a complex SM singlet with « big » VEV

KSVZ axion :

Kim '79
Shifman, Vainshtein, Zakharov '80

New « heavy » electrically neutral quark, charged under $U(1)_{PQ}$
+ a new complex scalar singlet

$$\mathscr{L}_{KSVZ} = \mathscr{L}_{SM} + \bar{\Psi}_{L,R} \not{D} \Psi_{L,R} + y \bar{\Psi}_L \Psi_R \phi + V(\phi)$$

DFSZ axion :

Zhitnitskii '80
Dine, Fischler, Srednicki '81

2HDM, SM quarks and leptons are charged under $U(1)_{PQ}$
+ a new complex scalar singlet

Implication for ALPs searches

How to construct a truly **axion-like** basis?

$$\mathcal{L}^{\text{eff}}_{ALP} = \frac{1}{2}(\partial_\mu a^0 \partial^\mu a^0 - m_a^2 a^0 a^0) + \mathcal{L}_{\text{KSVZ}-\text{like}} + \mathcal{L}_{\text{DFSZ}-\text{like}}$$

KSVZ like: New, heavy, electrically neutral quark, charged under $U(1)_{\text{PQ}}$

$$\mathcal{L}^{\text{eff}}_{\text{KSVZ-like}} = \frac{a^0}{16\pi^2 f_a}\left(g_s^2 \mathcal{N}_C G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} + g^2 \mathcal{N}_L W_{\mu\nu}\tilde{W}^{\mu\nu} + g'^2 \mathcal{N}_Y B_{\mu\nu}\tilde{B}^{\mu\nu}\right)$$

- Typically assuming some heavy **vector-like** fermions
- No direct coupling to SM fermions
- Manifestly symmetric under $SU(3)_C \otimes SU(2)_L \otimes U(1)_L$

DFSZ like: 2HDM, SM quarks and leptons are charged under $U(1)_{\text{PQ}}$

$$\mathcal{L}^{\text{eff}}_{\text{DFSZ-like}} = -\frac{i}{f_a} a^0 \sum_{f\,=\,\text{chiral fermions}} m_f \chi^f_A (\bar{\psi}_f \gamma_5 \psi_f)$$

Anomaly cancellation taken into account!

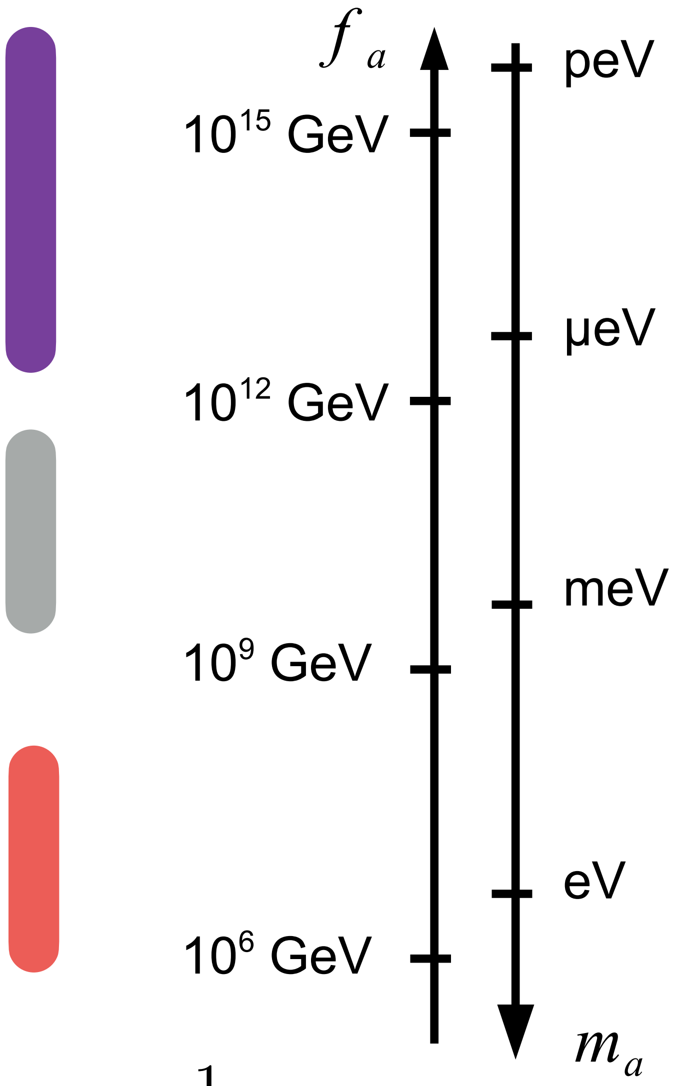
Simple pseudo-scalar couplings

- One should not build EFTs with both **anomalous couplings** and **vectorial-axial fermion couplings** : because of **anomaly cancellations**!
- Effective interactions are not always equal to anomalous interactions!

Three main ways to get a cosmological axion population

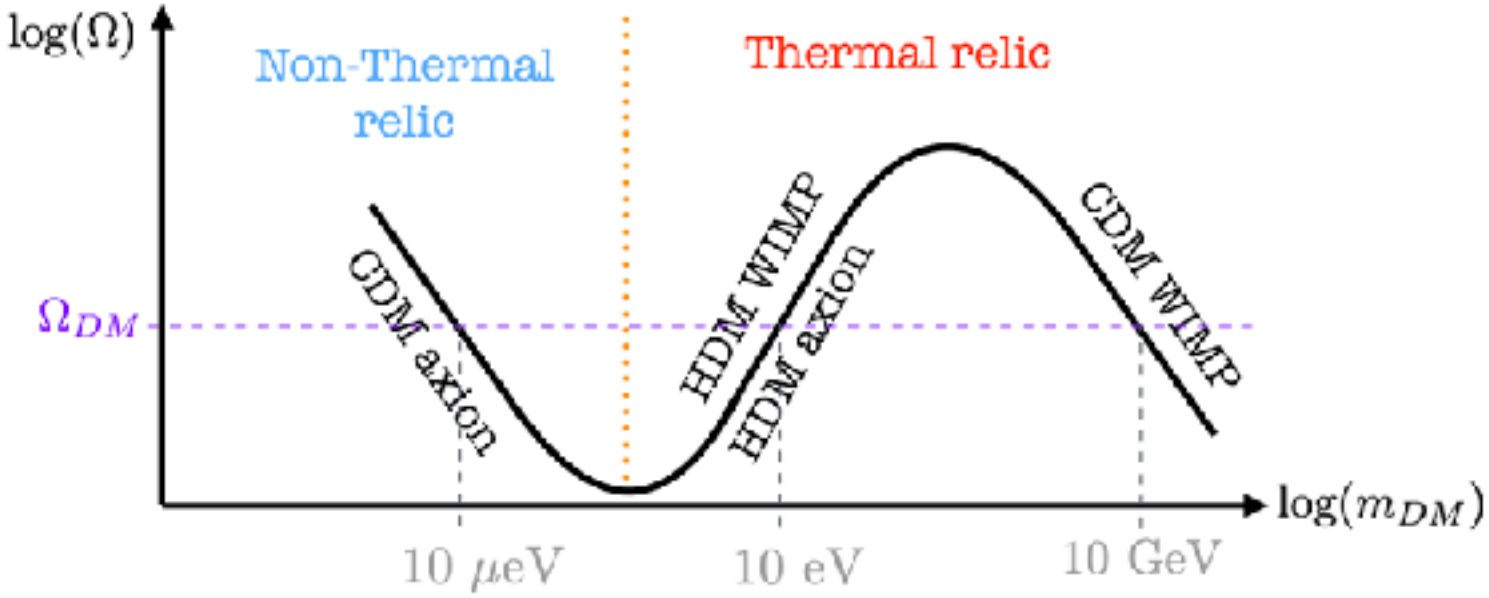
Populations of axions can be hot or cold, particles or coherent fields

- Misalignment mechanism [Cold Field]
- Decay from topological defects (axion strings, DW) [Cold Particles]
- Thermal production (neutrino-like) [Hot Particles]



Production in the early universe via scattering with the cosmic plasma : $\pi + \pi \leftrightarrow \pi + a$

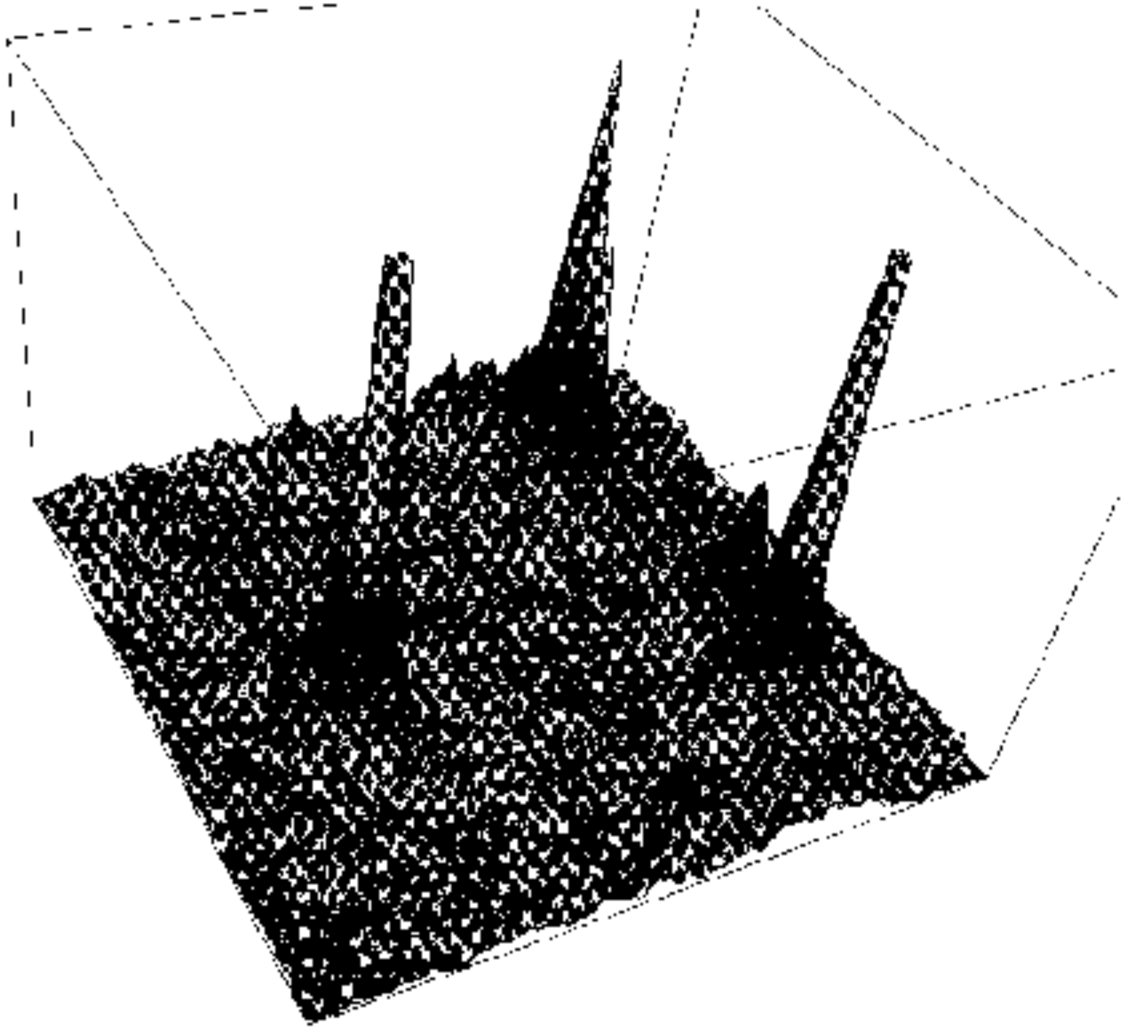
Main process governing thermalisation/decoupling depends on: $c_{\text{axion-X}} \propto \dfrac{1}{f_a}$



Axion miniclusters density

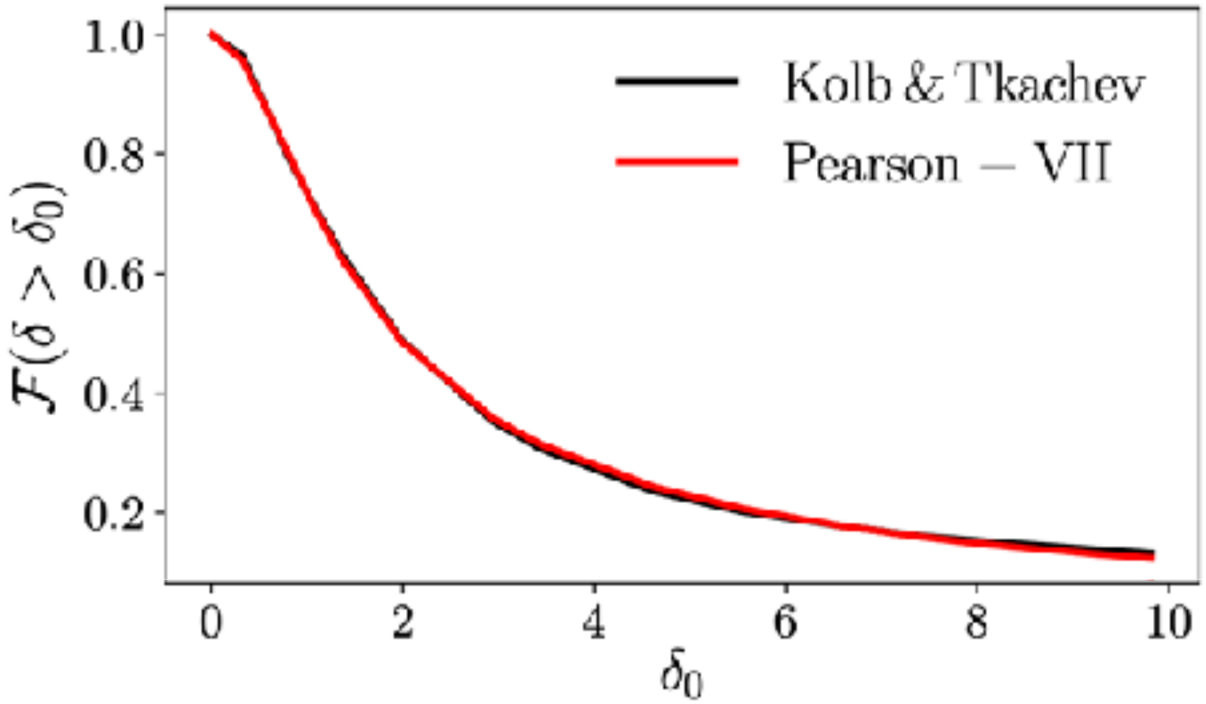
minicluster characteristic density, ρ_{MC}, sets the typical radius, and thus it's concentration

Simulations: Kolb & Tkachev (1990's)



- Minicluster formation simulated without gravity or phase transition

cumulative mass fraction of miniclusters with overdensity parameter δ > δ0



Use spherical collapse :
(consider how regions of large δ collapse when z ≫ zeq)

$$\rho_{MC} = 140\underbrace{\delta^3(1+\delta)}_{\text{initial overdensity parameter}}\bar{\rho}_a(z_{eq})$$

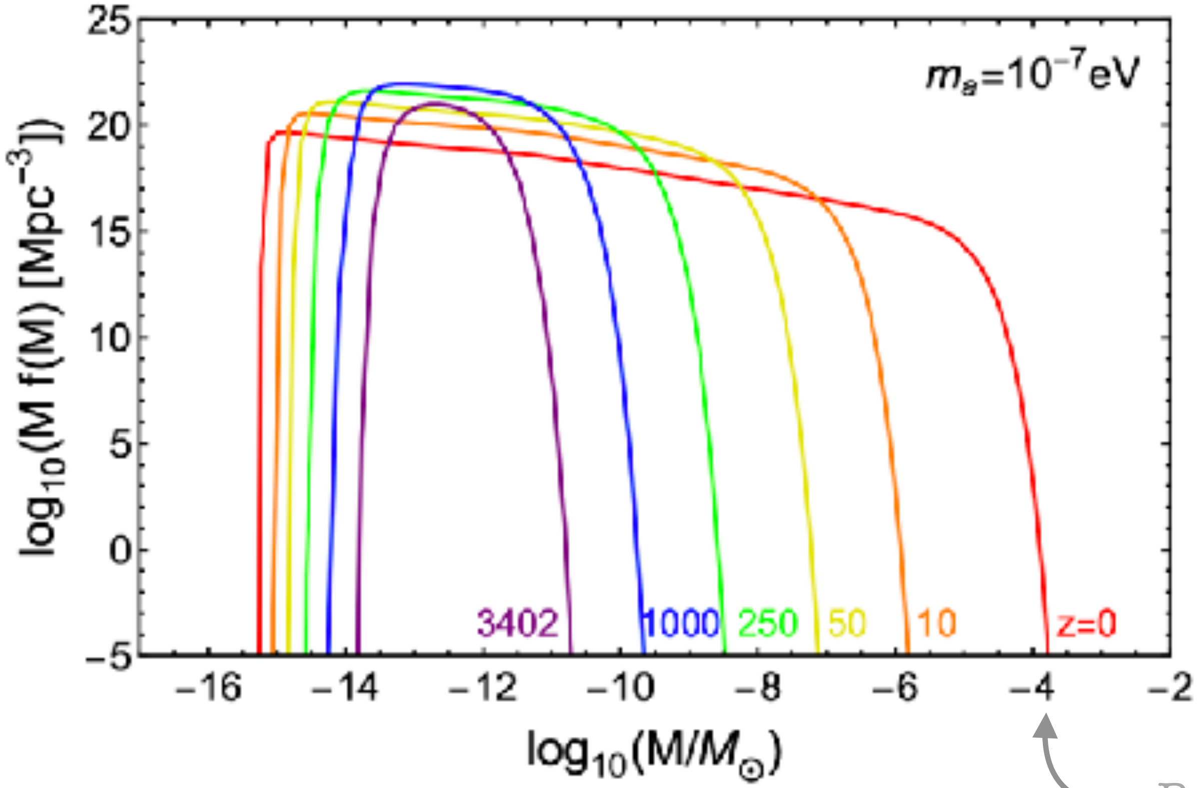
→ We use this to set the concentration of minicluster radial profiles

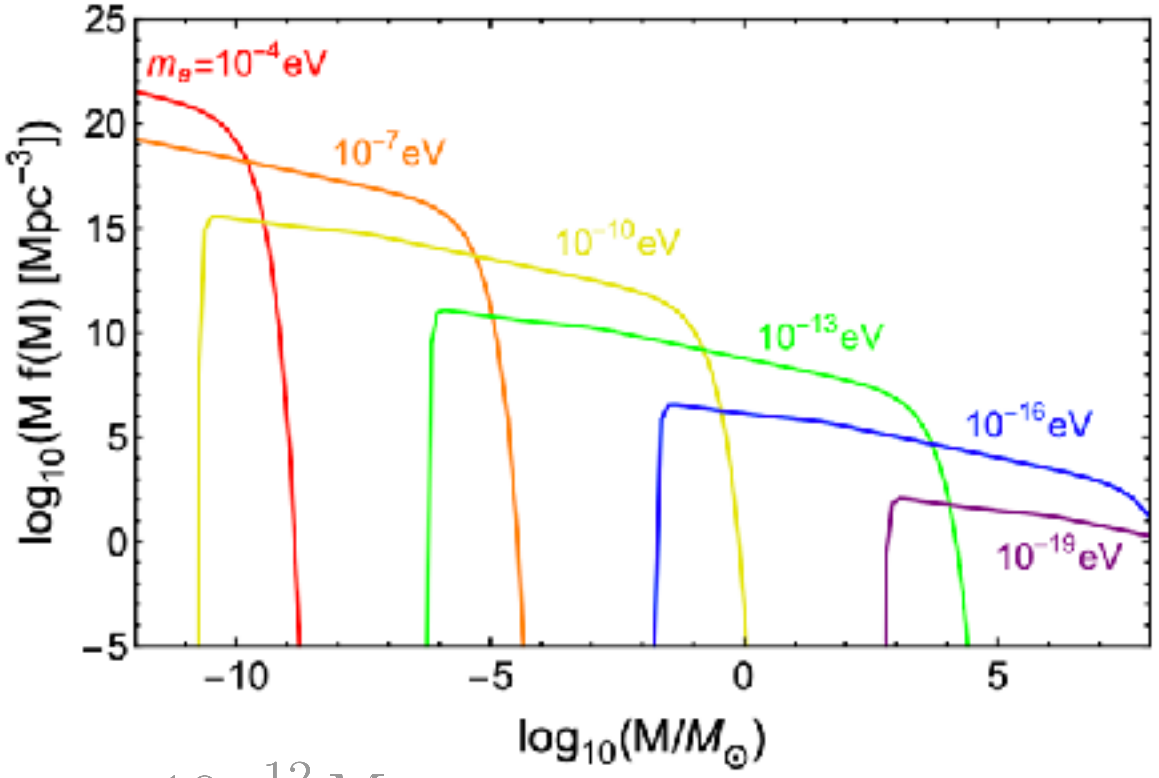
$$\begin{cases} \text{central density} \sim 10^{14}\rho_{\rm DM} \\ \text{size} \sim 10^{-2}\text{pc} \end{cases}$$

The fraction of DM in miniclusters, f_{MC}, is not predicted.
Our goal: constrain f_{MC} observationally.

Axion miniclusters ‘nowadays’

- **initial conditions** for the axion field on **small scales** caused by SSB lead to the **collapse of objects** of mass M_0 around matter-radiation equality.
- once initially formed, go on to **merge into larger bound structures**, which we term “minicluster **halos**”
- behaviour is quite **different from CDM**: the initial conditions are **isocurvature**, structure formation begins much earlier, and the **power spectrum is truncated**.
- We consider the **formation of gravitationally bound structures** from linear density perturbations using the analytic **Press-Schechter formalism**
- Miniclusters halos formed on small scales. Contribute to the **substructure mass function** in the Milky Way.





Reach masses $\gg 10^{-12} M_\odot$

More than 10 orders of magnitude

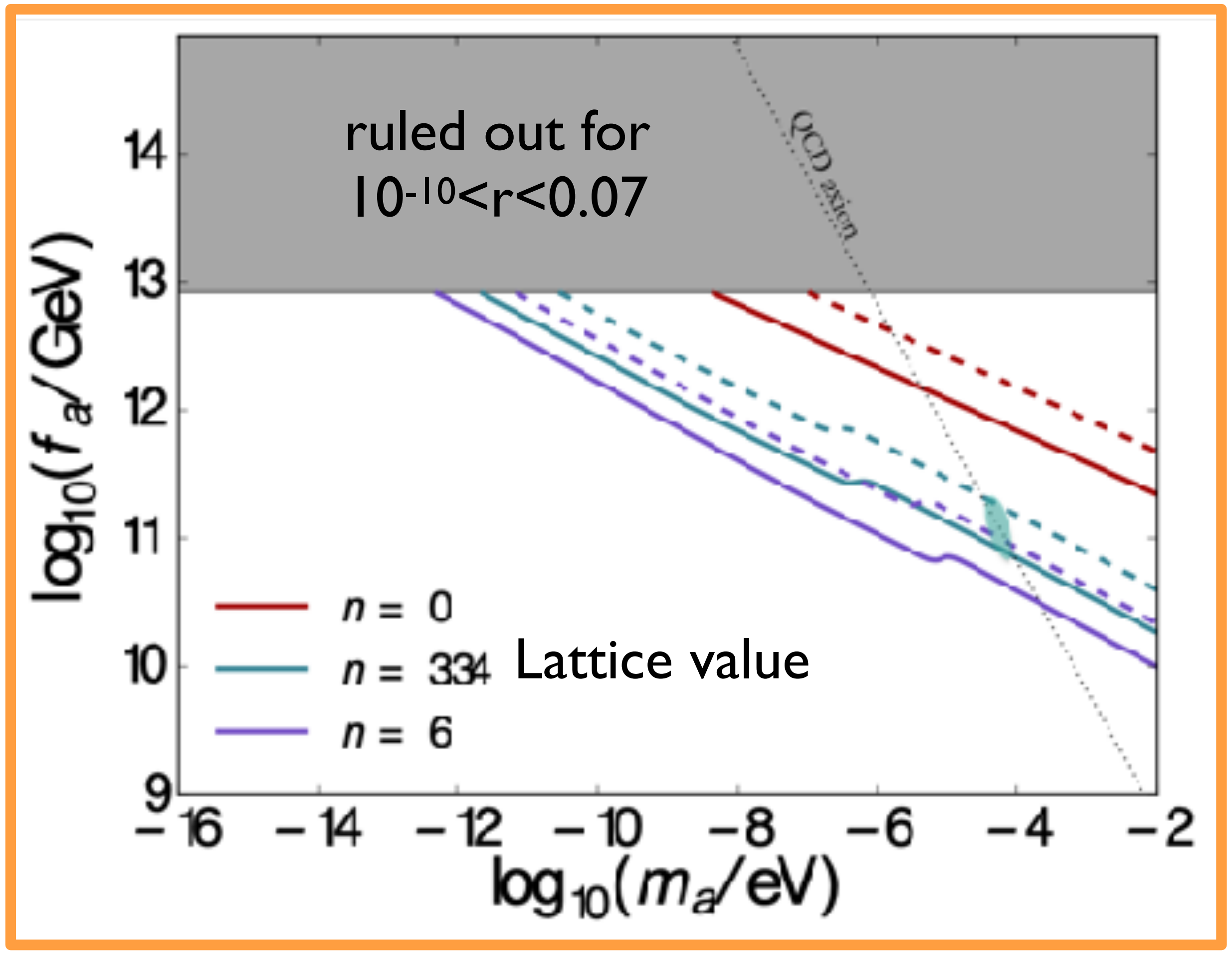
How can we search for miniclusters halos? Like MACHOs?

Fairbairn, Marsh, J.Q., Rozier, PRD (2017)

Axion Relic Density and Minicluster Mass

Axion → matter when $m(T_0)>H(T_0)$. Crucial epoch! Mass in horizon at this time → **minicluster** at z_{eq}: Hogan & Reese (1988)

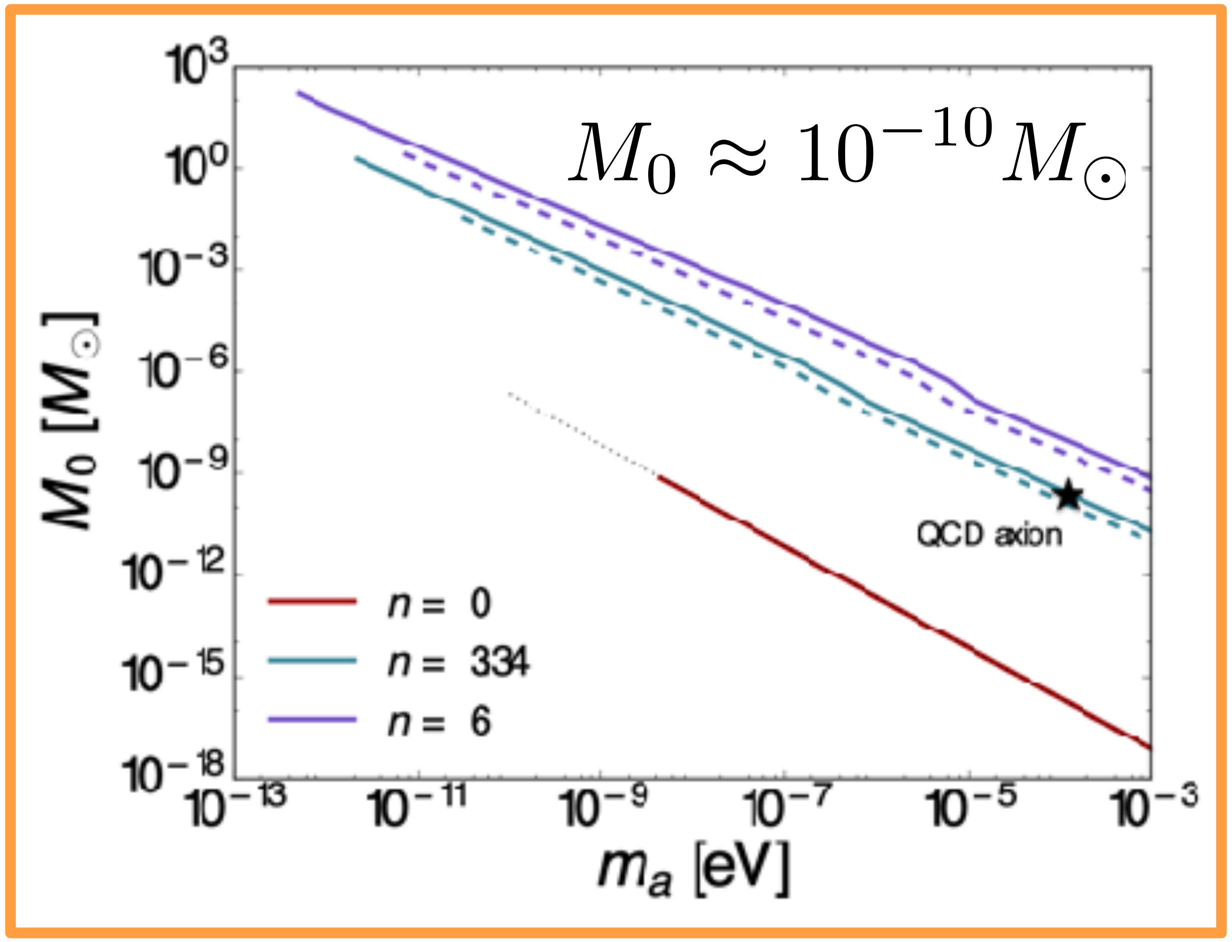
$$\boxed{M_0 = \bar{\rho}_a \frac{4}{3}\pi\left(\frac{\pi}{a(T_0)H(T_0)}\right)^3}$$



DM relic density, $\Omega_c h^2=0.12$.

→ narrow mass window:

$$\boxed{50 \lesssim \frac{m_a}{\mu\mathrm{eV}} \lesssim 200}$$



Lensing with non-pointlike objects

Most haloes are very diffuse and therefore cause no lensing

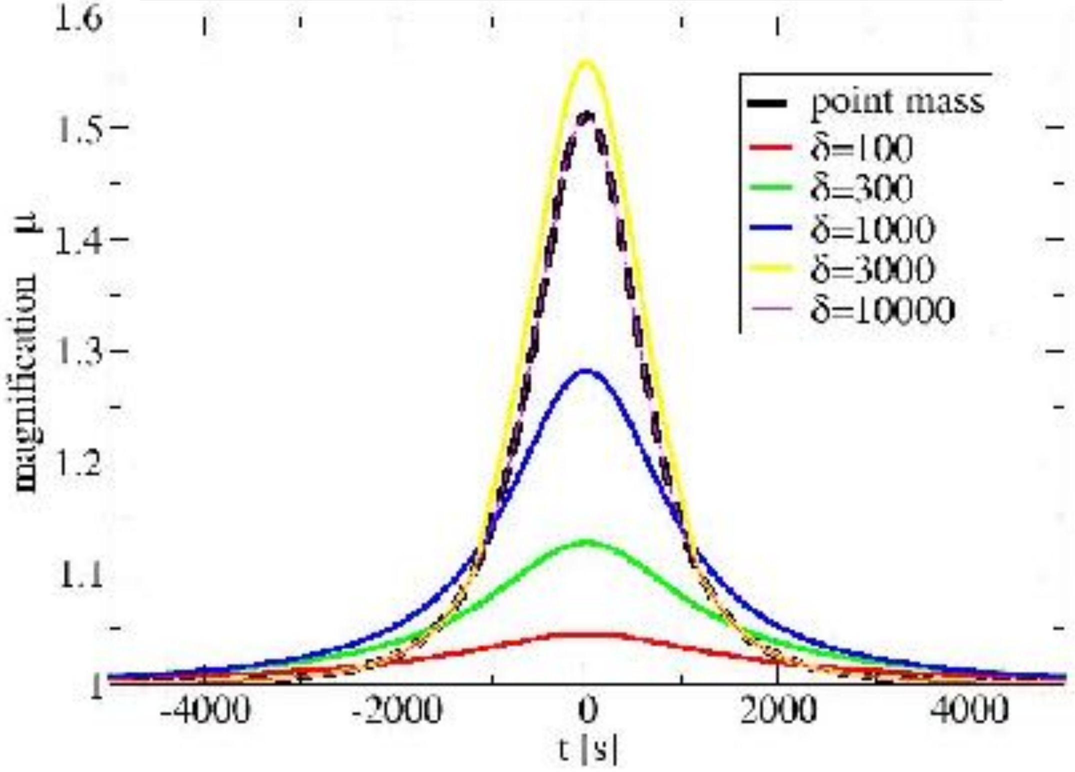
We have distributed density which, while dense, is not a point mass

Model miniclusters as NFW density profile and use eqns:

$$A = [(1-B)(1+B-C)]^{-1}$$

$$C = \frac{1}{\Sigma_c \pi \ell}\frac{\mathrm{d}M(\ell)}{\mathrm{d}\ell}\ ;\ B = \frac{M(\ell)}{\Sigma_c \pi \ell^2}\ ;\ \Sigma_c = \frac{1}{4\pi G d_s x(1-x)}$$

Parametrise the density profile based on initial overdensity δ

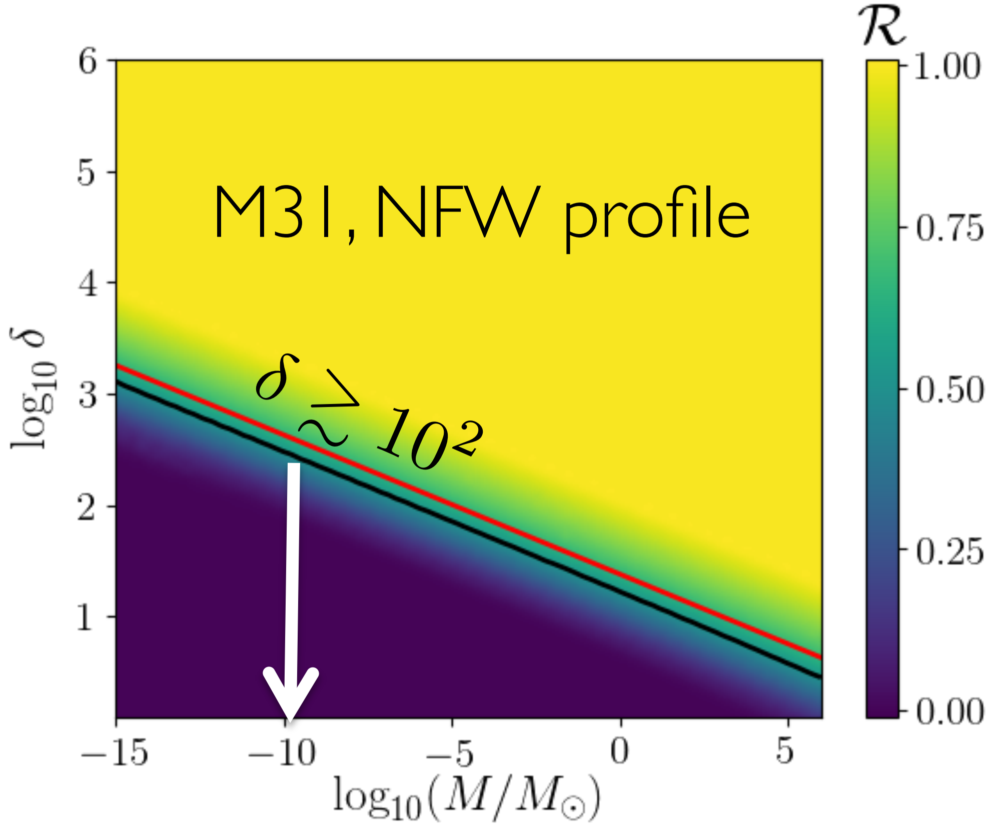


Plot the "light curve" as lens crosses line of sight.

As concentration increases, miniclusters do more lensing.

Effects described by a rescaling of the 'microlensing tube'

$$R_{\rm MC}(x, M, \delta) = \mathcal{R}(\delta, M) R_E(x, M)$$



Behave like point mass when scale radius << R_E

Fairbairn, Marsh, J.Q., Rozier, PRD (2017)

Lensing events depends on density profile and size distribution

Initial conditions: power spectrum

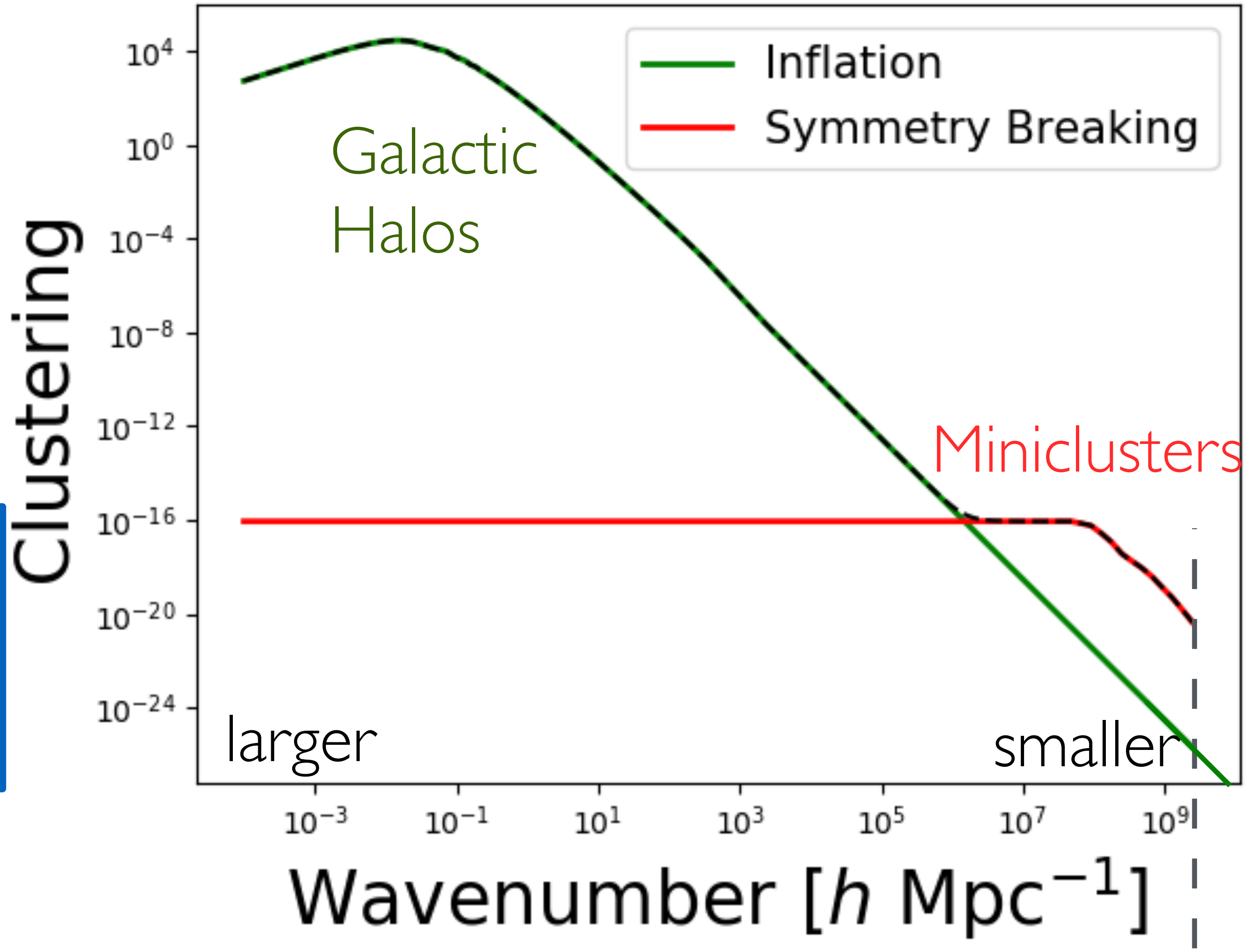
- Miniclusters depart from standard CDM in initial conditions
- Post-inflation symmetry breaking ⟶ large field fluctuations +relics
- This extra source of fluctuations produces axion relics + structure

<u>axion density perturbation:</u>

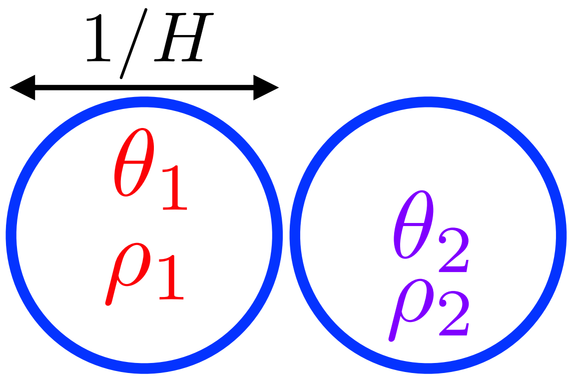
$$\delta_a(\mathbf{r},\tau) = [\rho_a(\mathbf{r},\tau) - \bar{\rho}_a(\tau)]/\bar{\rho}_a(\tau)$$

$$\xi(\mathbf{r}) = \langle \delta(\mathbf{x})\delta(\mathbf{x}+\mathbf{r})\rangle$$

$\xrightarrow{\text{F.T.}}$ Power Spectrum



At τ_0 : the Kibble mechanism assures us that the axion field is fixed to a constant value over each causal horizon, and randomly distributed (white noise) over the different horizons



we can approximate the Power Spectrum by a sharp-k function, cut at the typical (comoving) size of a horizon at τ_0:

$$\boxed{P_k(\tau_0) = P_0\Theta(k_0 - k)}$$

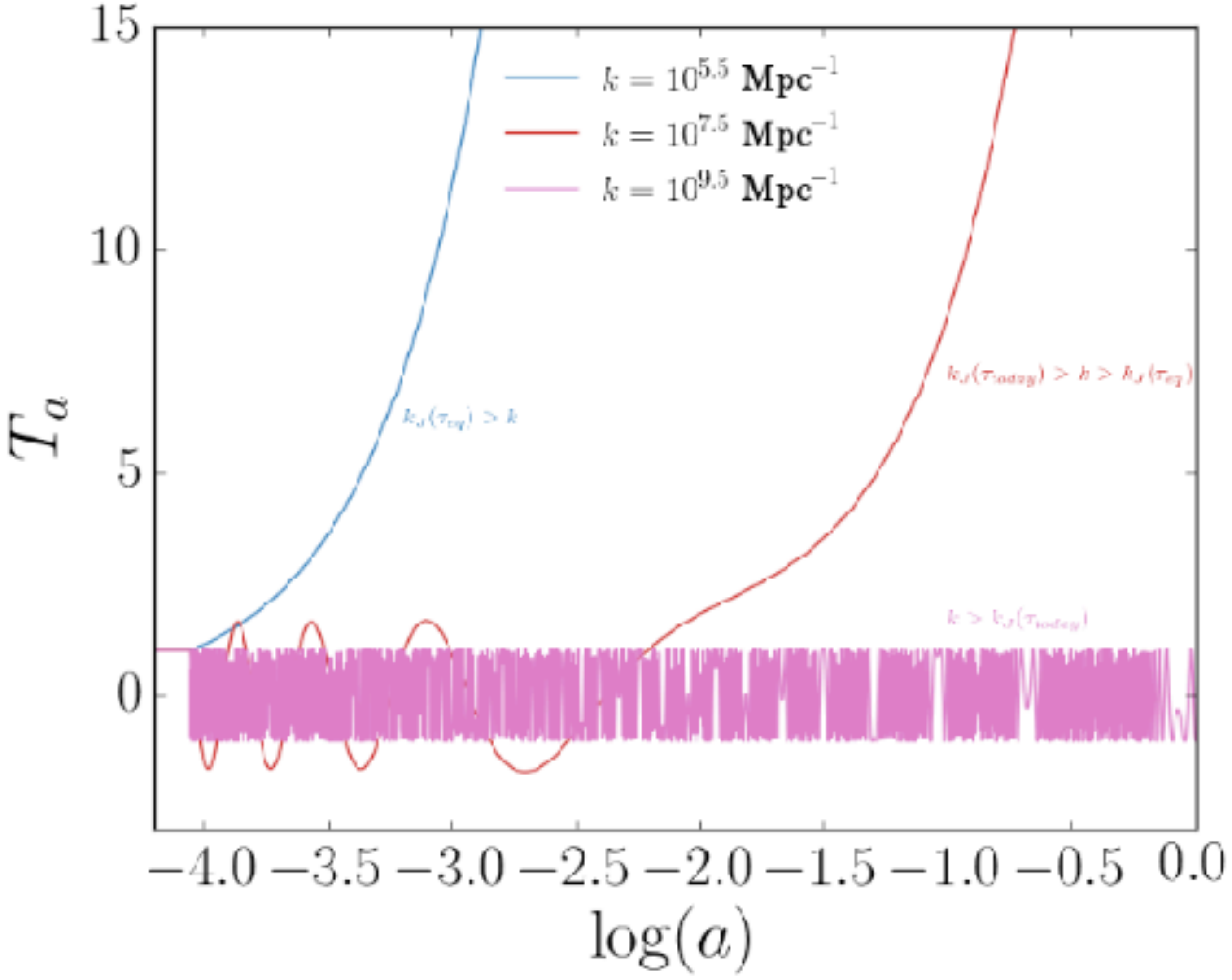
Evolution of density perturbations

The equation of motion for the axion overdensity in an axion-dominated Universe:

$$\delta_a'' + \frac{a'}{a}\delta_a' + \Big(\overset{\text{Pressure}}{k^2 c_s^2} - \underset{\text{Gravity}}{4\pi G a^2 \bar{\rho}_a}\Big)\delta_a = 0$$

Jeans scale: $k_J = (16\pi G a \rho_{a0})^{1/4} m_a^{1/2}$

Pressure = Gravity



- k < kJ (τeq): these modes are already under the Jeans mode at matter-radiation equality, their behaviour is the usual growing/decaying as soon as matter-radiation equality is reached.

- kJ(τeq) < k < kJ(τtoday): these modes are bigger than the Jeans mode at matter-radiation equality, and as kJ increases they cross the Jeans scale. The behaviour of these modes is to oscillate at the beginning of the matter-dominated era, then to follow the usual growing/decaying mode.

- k > kJ(τtoday): these modes are still today physically smaller than the Jeans mode, and still follow the oscillating behaviour.