Solar WISPs

Light DM Beyond WIMPs Workshop: from Theory to detection

Hagoshrim, Israel, 31st May 2015

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Universidad de Zaragoza (Spain)

Outline

- Sun as a laboratory for fundamental physics

- Light DM particles : axions and HPs

- Solar flux

- Solar constraints

- Helioscopes

Modeling the Sun

Basic parameters

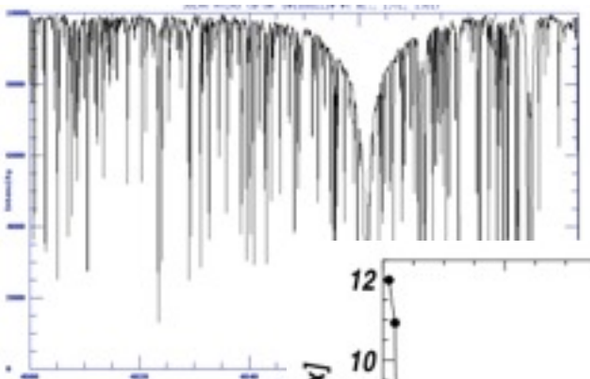
Luminosity

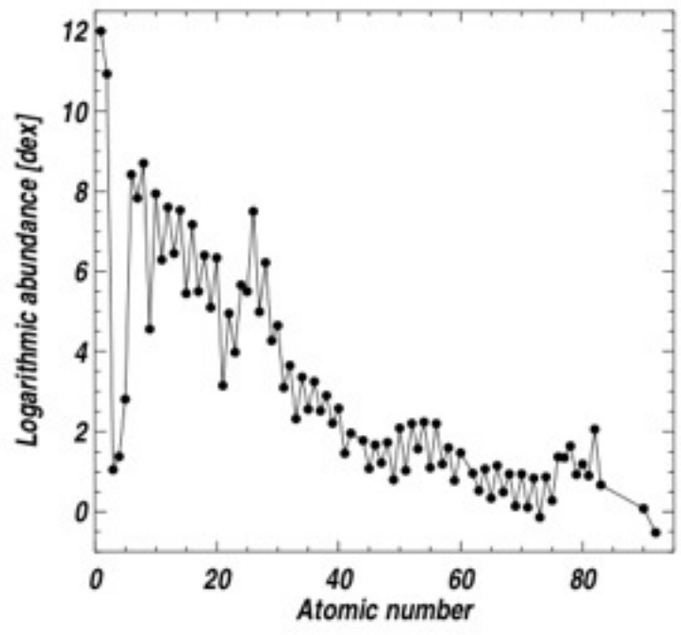
Radius

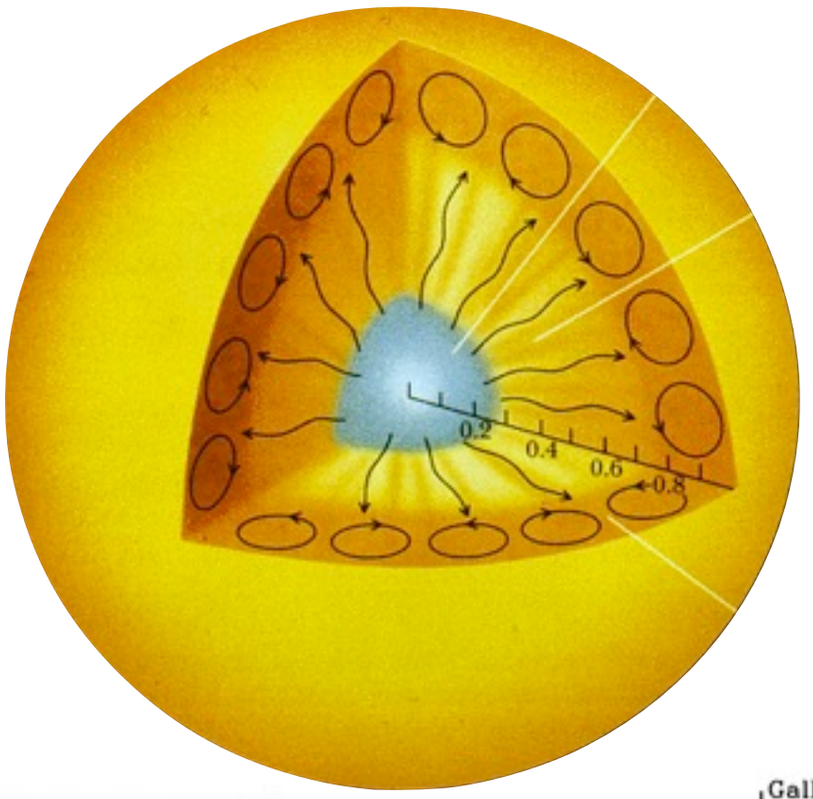
Mass

Metallicity

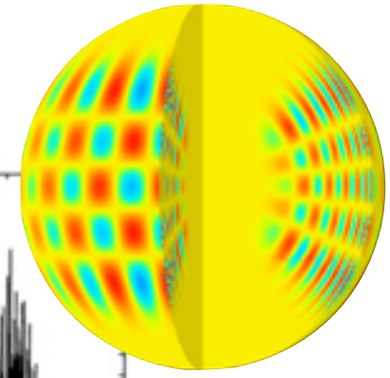
Composition

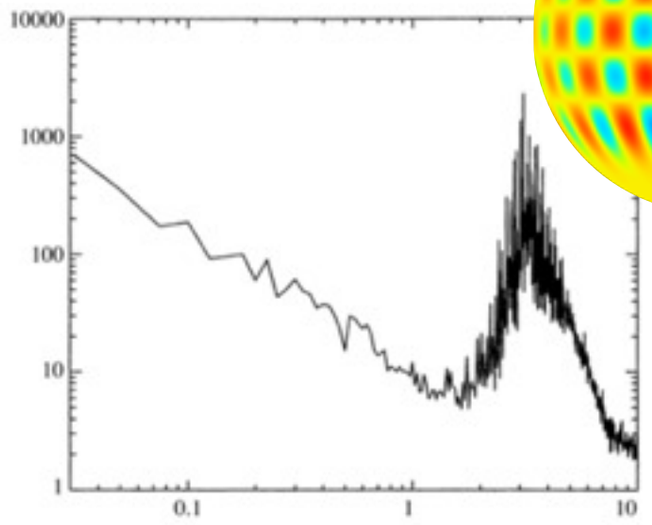






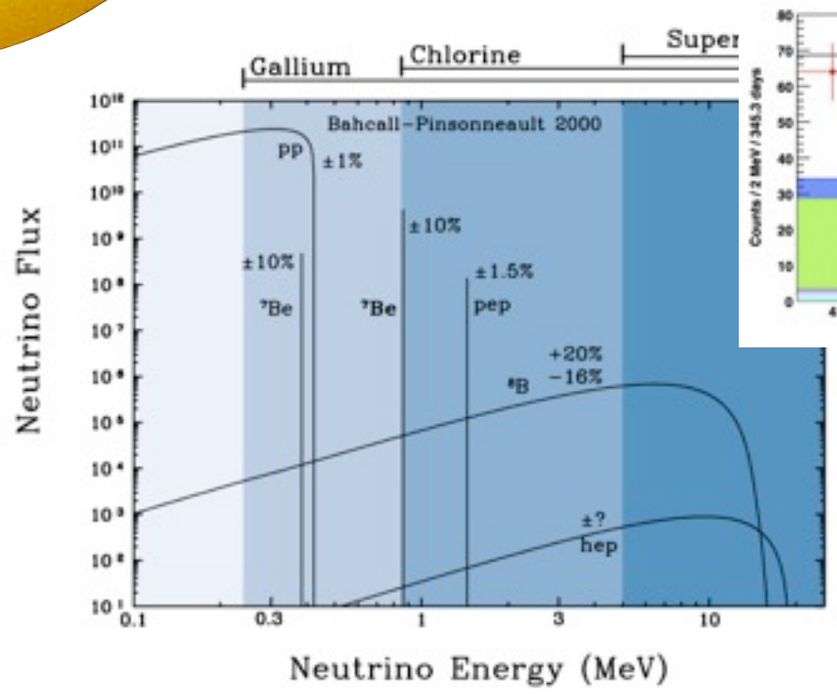
Helioseismology

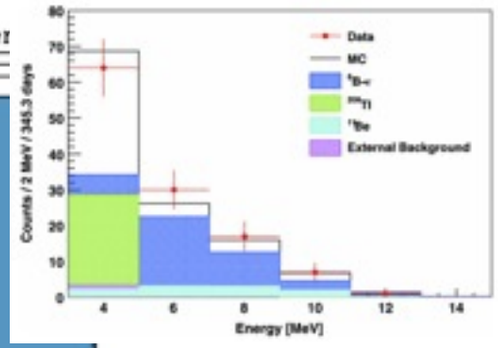




ν[mHz]

Neutrino fluxes



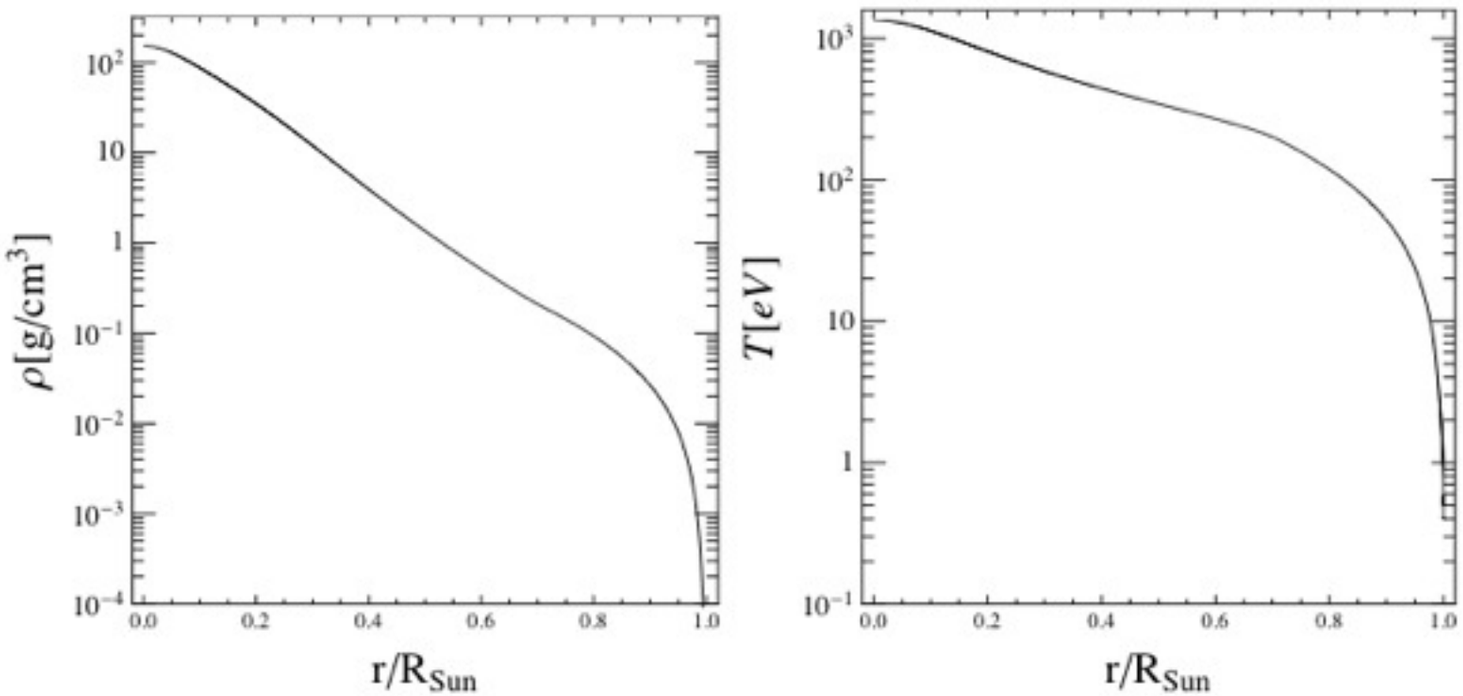


Accurate solar models but...

Models of Solar interior agree quite nicely ...

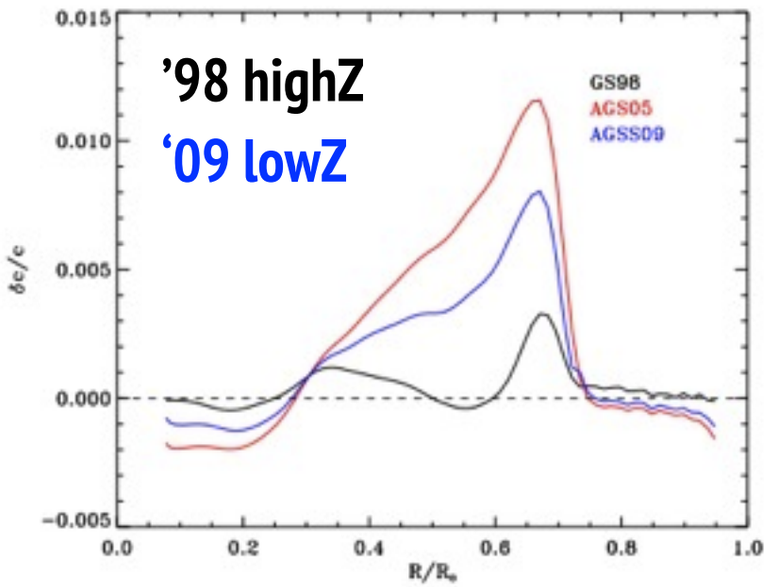
1: numerical evolution of stellar structure until now

2: Inversion of oscillation frequencies



However, a small discrepancy persists: solar abundance problem

observed -model



Sun as a particle lab

- WISPs are emitted by plasma interactions -> New direct Energy loss
- Eloss provided by faster nuclear reactions $4\mathrm{p} \rightarrow \mathrm{He} + 2\nu + \mathrm{E}$

but we still have to observe the same external parameters L, R, He and Z abundances, etc...

Presolar He abundance needs to be smaller

core Temperature needs being larger reaction rates are $\propto T^{\mathrm{laaaaarge}}$

favors pplII chain , i.e more $^{8}\mathrm{B}\,\nu's$ search for large neutrino fluxes!

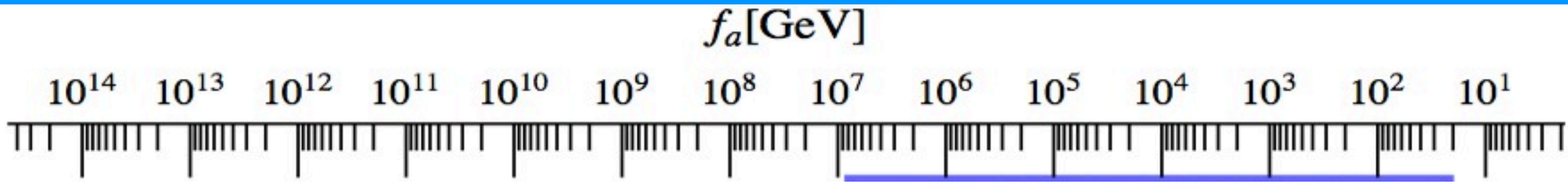
T-profile and soundspeed change search for deviations of soundspeed profile!

Sun as a particle source

but what particles are we interested in?

light DM candidates ... ?

light DM 1 : Axions

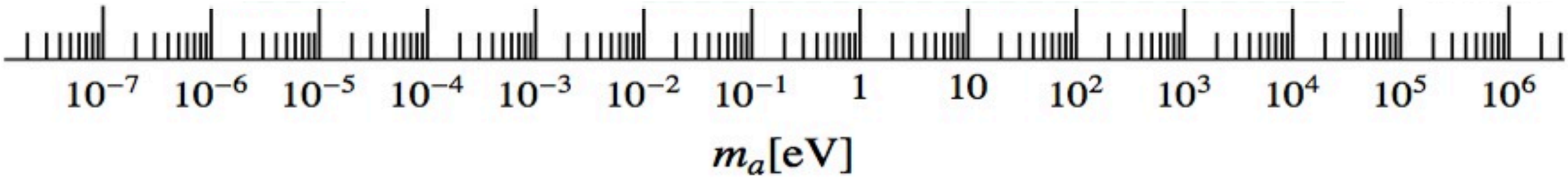


- Axion DM scenarios

excluded | ok | sub

excluded | ? | tuned

tuned (anthropic?) | ok | tuned



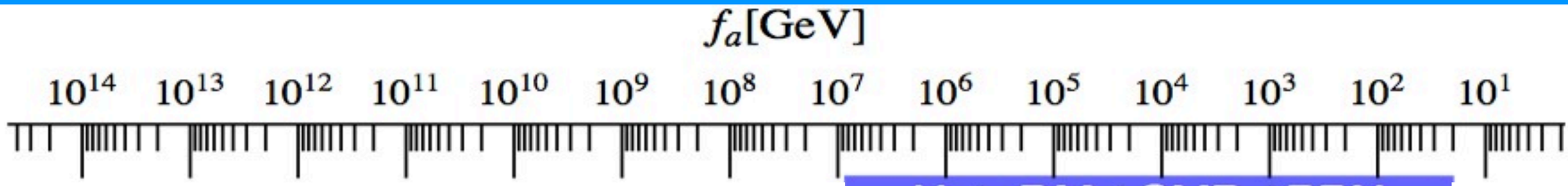
Post-inflation PQ (N=1)
strings+unstable DW's

Post inflation PQ (N>1)
strings+long-lived DWs

Pre inflation PQ

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

light DM 1 : Axions



Hot–DM / CMB / BBN

- Axion DM scenarios

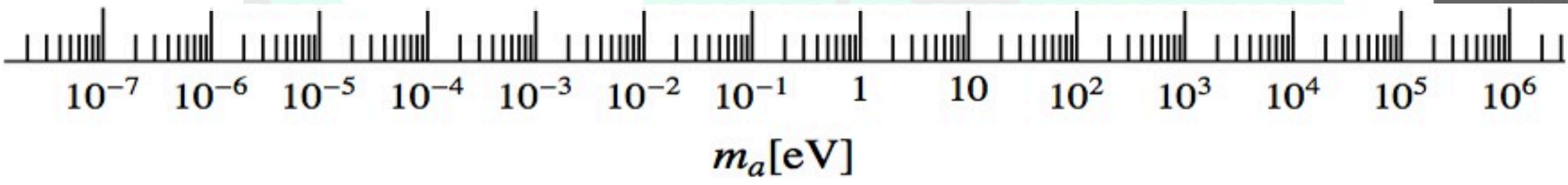
Burst Duration | SK | SN1987A

excluded | ok | sub ? | (g_{ae}) | Globular Clusters ($g_{a\gamma}$)

excluded | ? | tuned | White Dwarfs (g_{ae})

tuned (anthropic?) | ok | tuned | (g_{ae}) | Solar Neutrino flux ($g_{a\gamma}$)

ADMX | ADMX – II | IAXO | CAST | Telescope | Beam Dump



Post-inflation PQ (N=1)
strings+unstable DW's

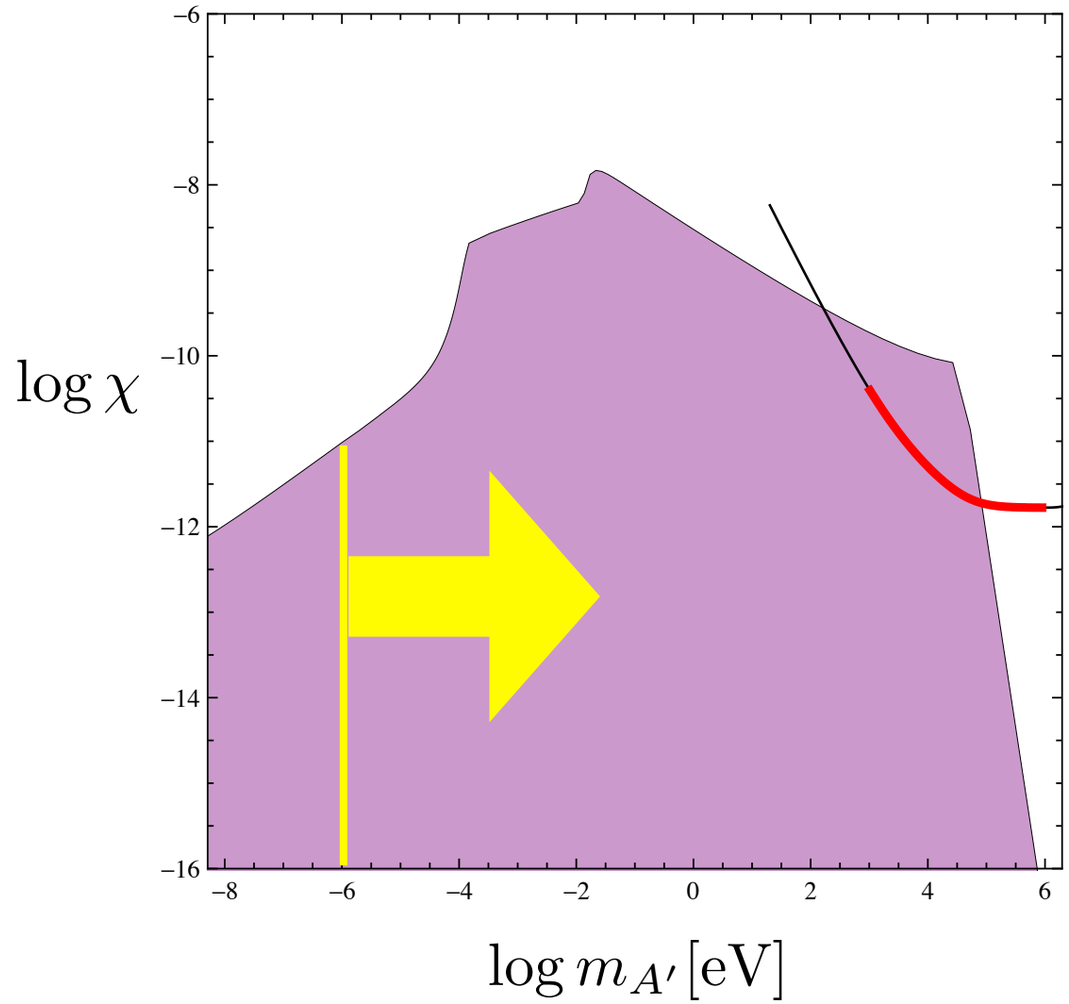
Post inflation PQ (N>1)
strings+long-lived DWs

Pre inflation PQ

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

light DM 2 : Hidden Photons $\mathcal{L} \ni -\frac{\chi}{2} F_{\mu\nu} F'^{\mu\nu}$

- HP DM scenarios



thermal (resonant)

$\Omega h^2 \propto \chi^2$

Inflation L-modes

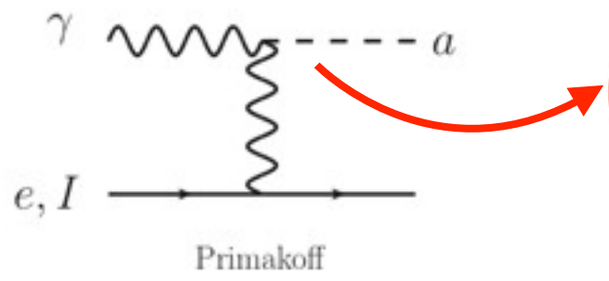
$\Omega h^2 \propto \sqrt{m} H_I^2$

Pre-inflation?

$\Omega h^2 \propto ?$

Axions from the Sun

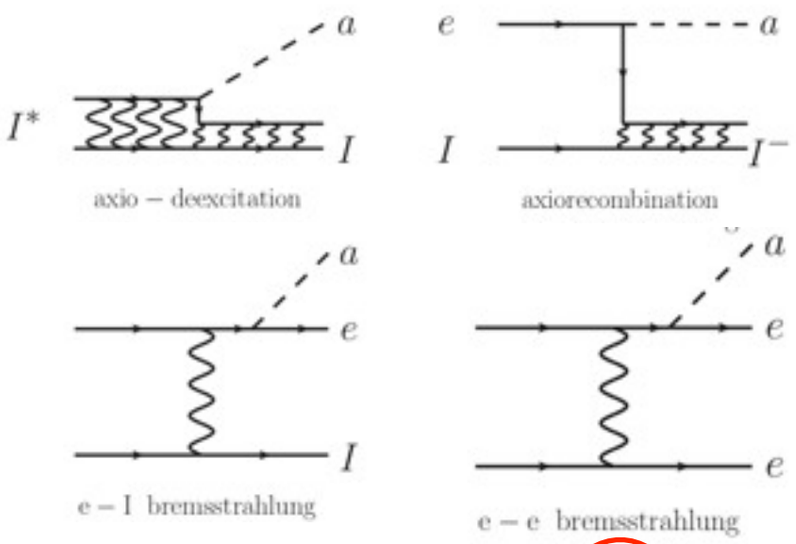
Hadronic axions

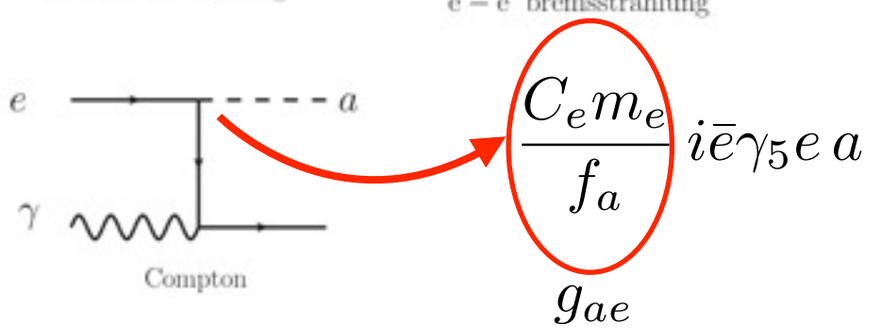


$$\frac{C_\gamma \alpha}{2\pi f_a} \frac{F_{\mu\nu}\widetilde{F}^{\mu\nu}}{4} a$$

$$g_{a\gamma}$$

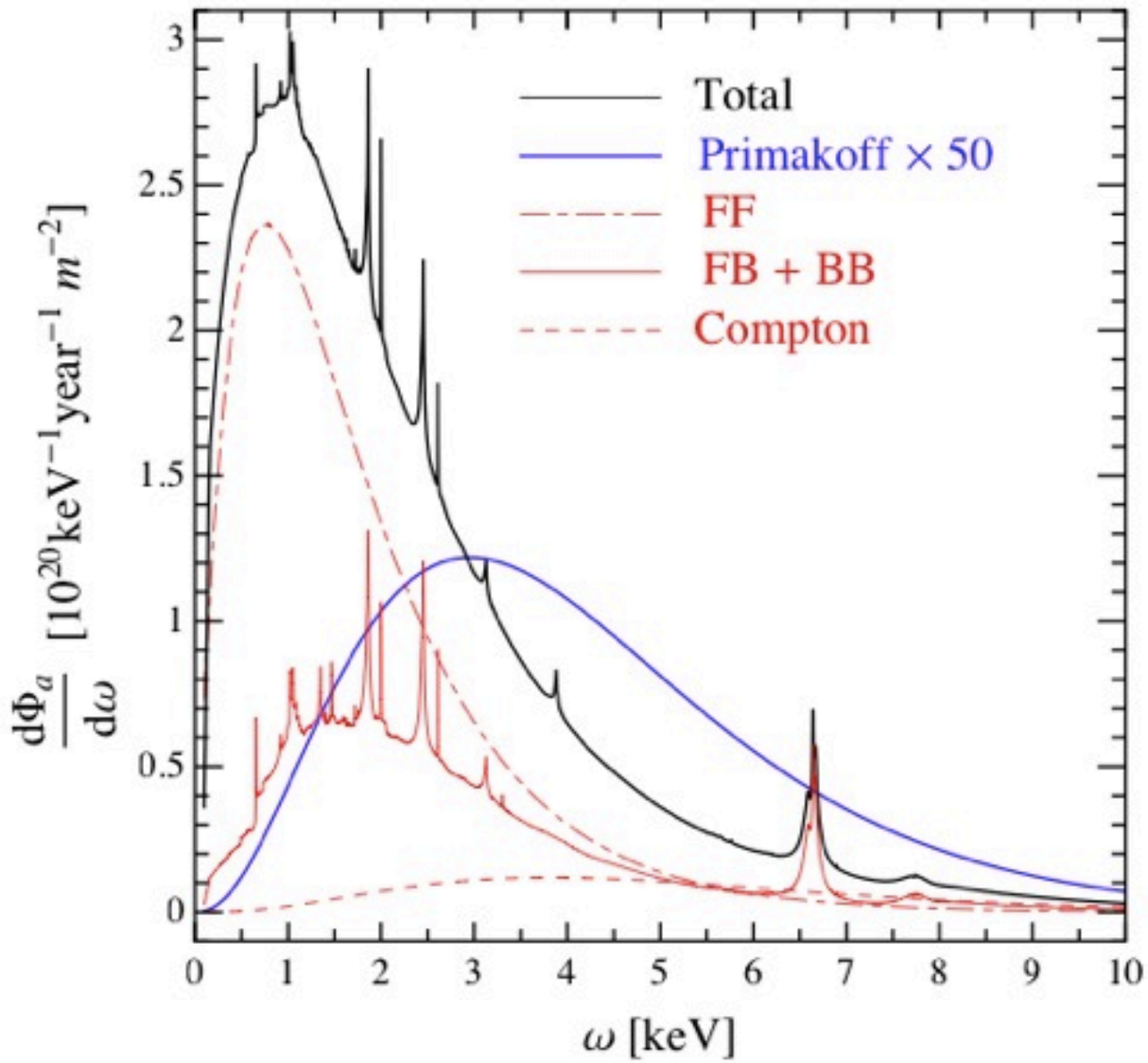
Non hadronic (electron coupling)





$$\frac{C_e m_e}{f_a} i\bar{e}\gamma_5 e\, a$$

$$g_{ae}$$



$$g_{ae} = 10^{-13}$$

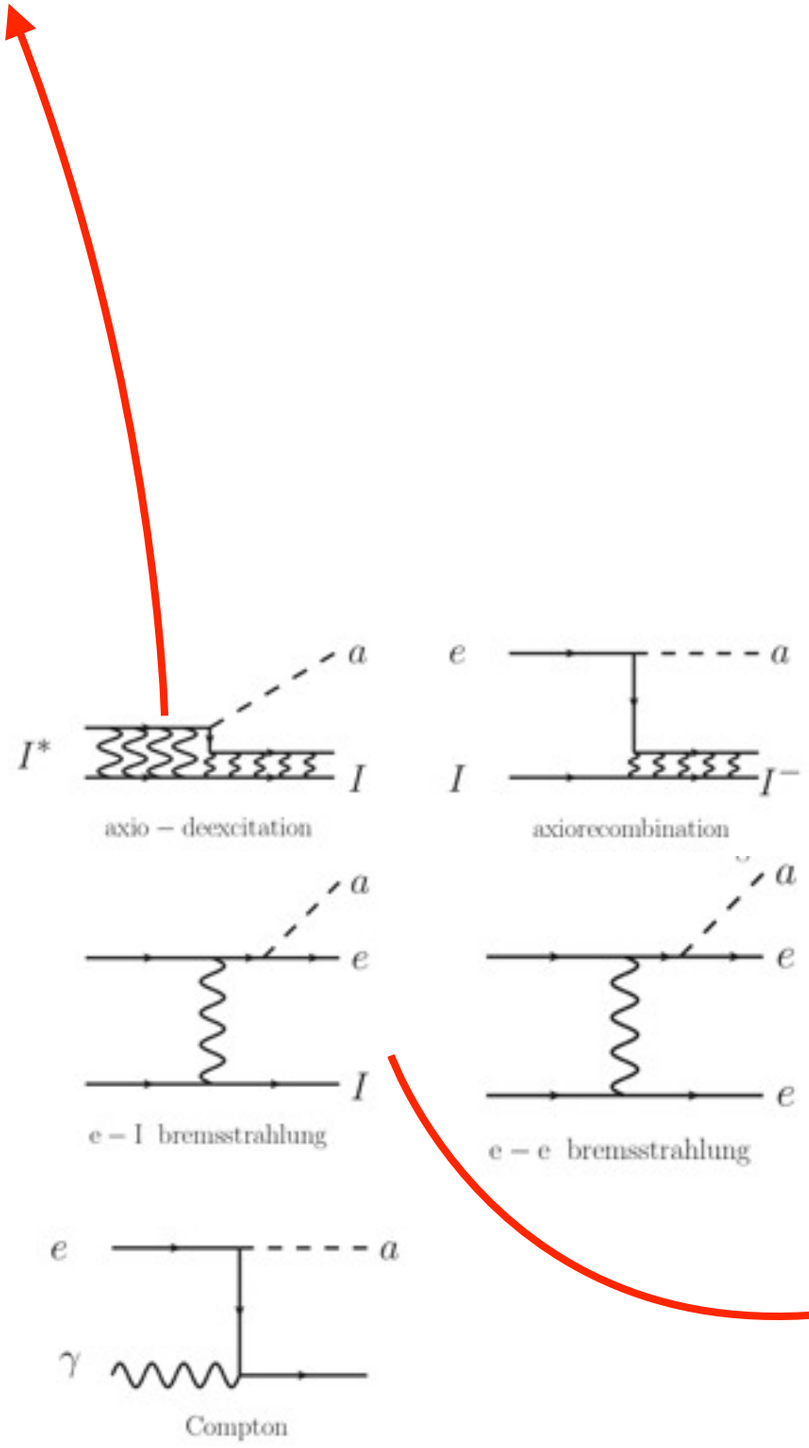
$$g_{a\gamma} = 10^{-12}$$

typical of non-hadronic meV mass axions

the A from ABC axions

Redondo JCAP12(2013)008

Atomic de-excitation and recombination : cumbersome atomic physics (all Z) in a plasma (E-levels, f-factors, etc...)



Solution!

axion emission ⟷ photon emission

$$\frac{\sum_{s_i,s_f}|\mathcal{M}(e_i\to e_f+a)|^2}{\frac{1}{2}\sum_{\epsilon}\sum_{s_i,s_f}|\mathcal{M}(e_i\to e_f+\gamma)|^2}=\frac{1}{2}\frac{g_{ae}^2}{e^2}\frac{\omega^2}{m_e^2}$$

(approximations: NR, sep,multipole)

Dimopoulos '86, Pospelov '08

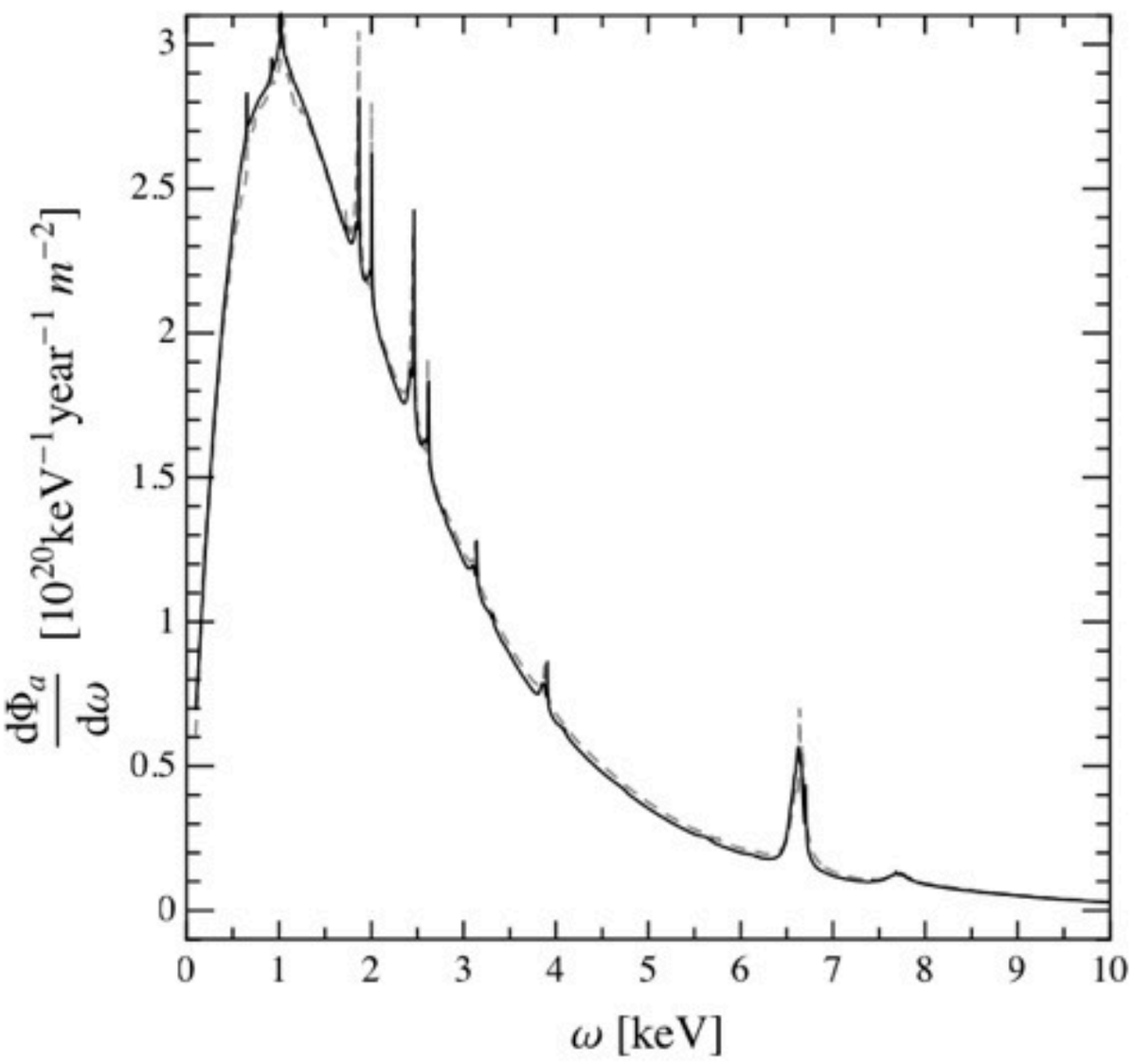
and ... in local thermal equilibrium

photon emission ⟷ photon absorption (opacity!!)

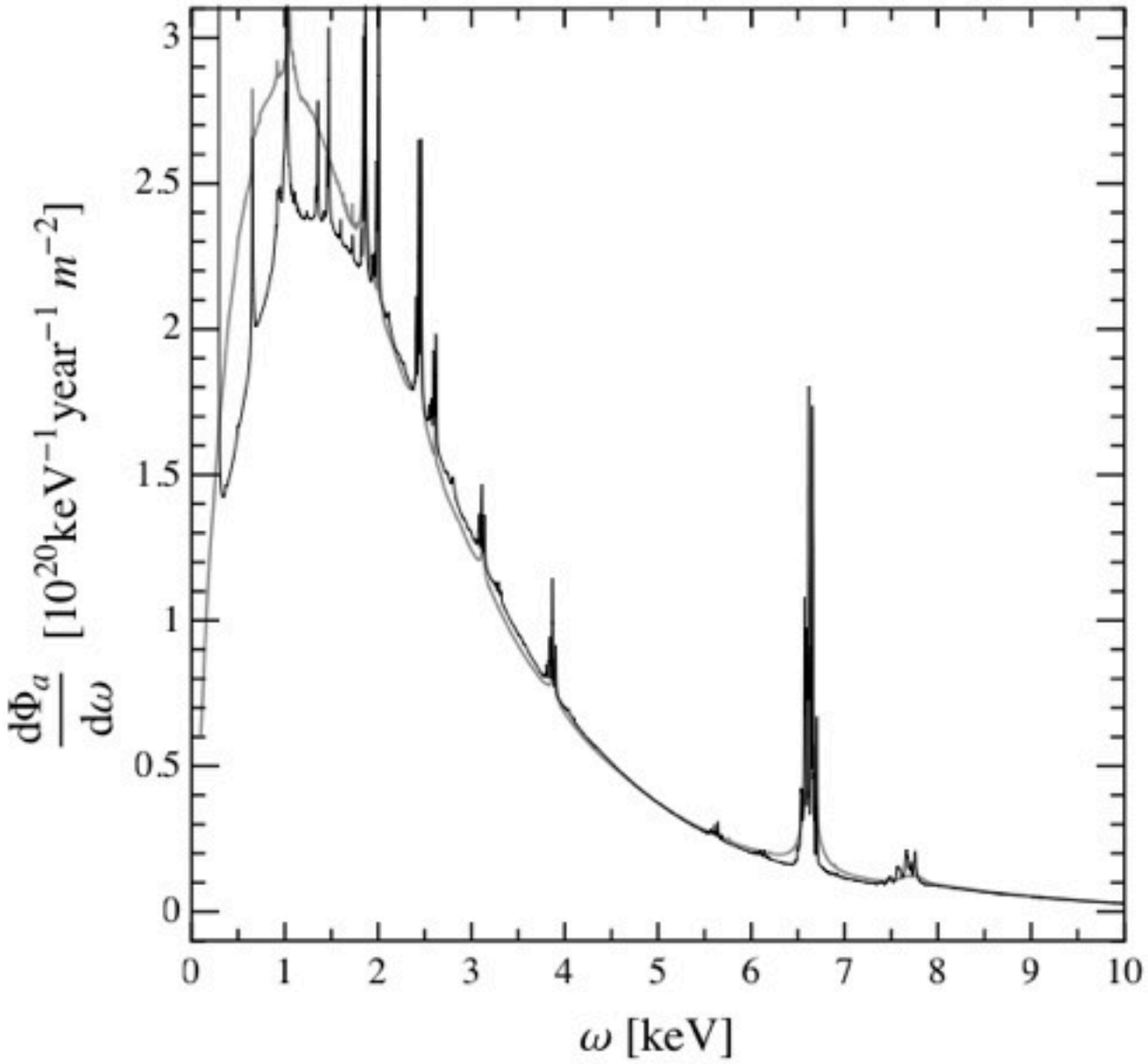
$$\Gamma_\gamma^{\rm Abs}=e^{\frac{E}{T}}\Gamma_\gamma^{\rm Prod}$$

Can be also used with Bresmstrahlung to cross check

different opacity codes



OP vs LEDCOP

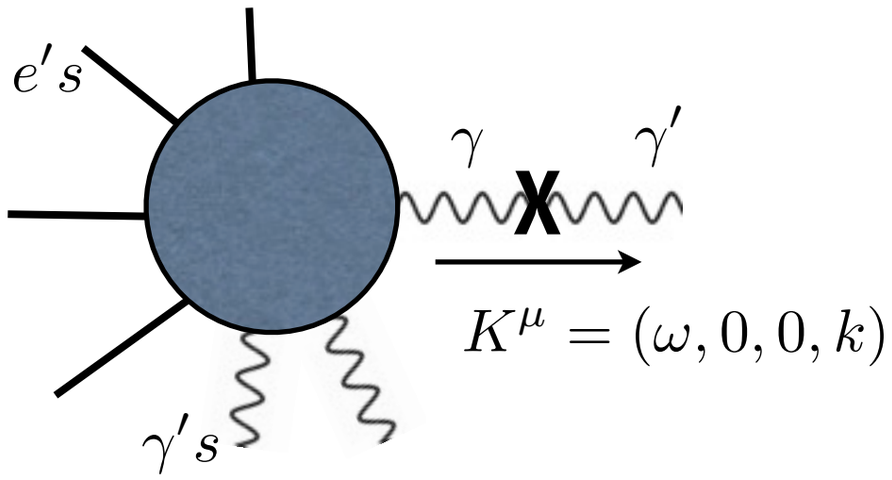


OP vs OPAS

HPs from the Sun

Redondo 08, An 13, Raffelt 13

HPs are produced in photon-oscillations



$$M(i \to f + \gamma') = M(i \to f + \gamma)\frac{1}{K^2 - \Pi}(\chi K^2)$$

$K^2 = m^2$

Medium effects

Transverse polarization

$$\Gamma^{\rm Prod}_{\gamma'_T} = \Gamma^{\rm Prod}_{\gamma_T} \times \frac{\chi^2 m^4}{(m^2 - {\rm Re}\Pi_{\rm T})^2 + ({\rm Im}\Pi_T)^2}$$

Longitudinal polarization

(Isotropic, NR medium $|M_L|^2 = |M_T|^2 \frac{K^2}{\omega^2}$, $\Pi_L = \Pi_T \frac{K^2}{\omega^2}$)

$$\Gamma^{\rm Prod}_{\gamma'_L} = \Gamma^{\rm Prod}_{\gamma_L} \times \frac{\chi^2 m^4}{(m^2 - {\rm Re}\Pi_{\rm L})^2 + ({\rm Im}\Pi_L)^2} = \Gamma^{\rm Prod}_{\gamma_T} \times \frac{\chi^2 m^2 \omega^2}{(\omega^2 - {\rm Re}\Pi_{\rm T})^2 + ({\rm Im}\Pi_T)^2}$$

A model of refraction and absorption

Redondo 08, An 13, Raffelt 13

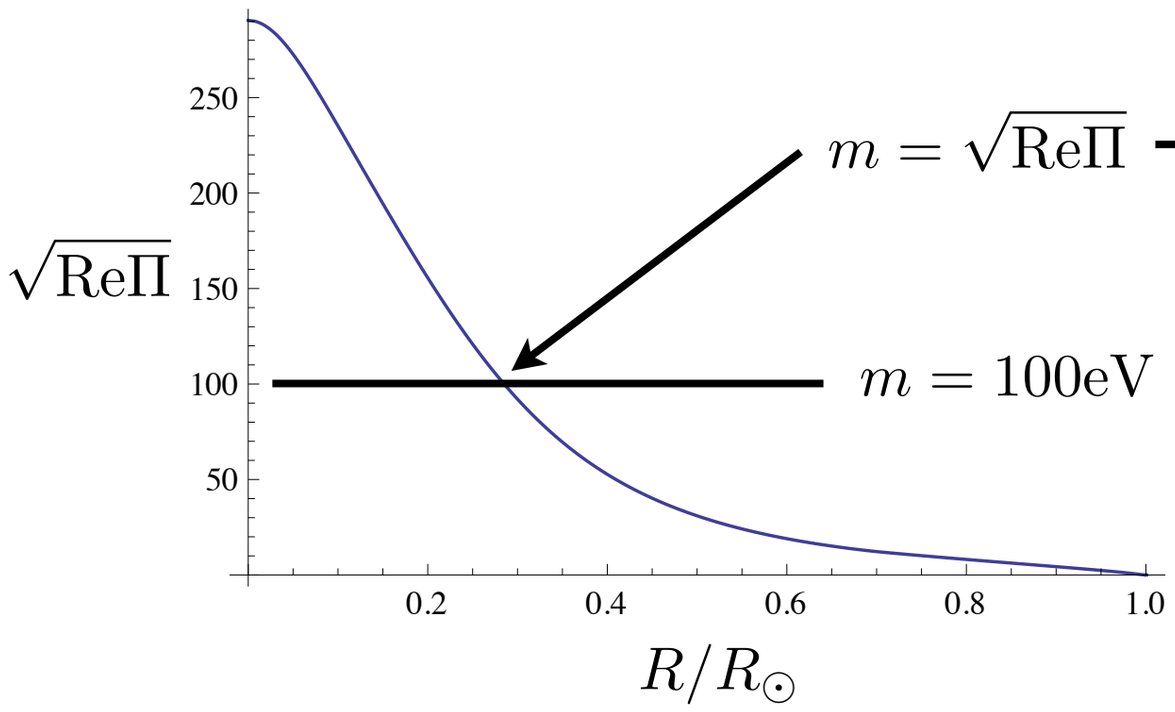
We need Π_T inside the Sun to compute the emission

$$\Pi = \mathrm{Re}\Pi + i\mathrm{Im}\Pi \quad \equiv m_\gamma^2 + i\omega(\Gamma^{\mathrm{A}} - \Gamma^{\mathrm{E}})$$

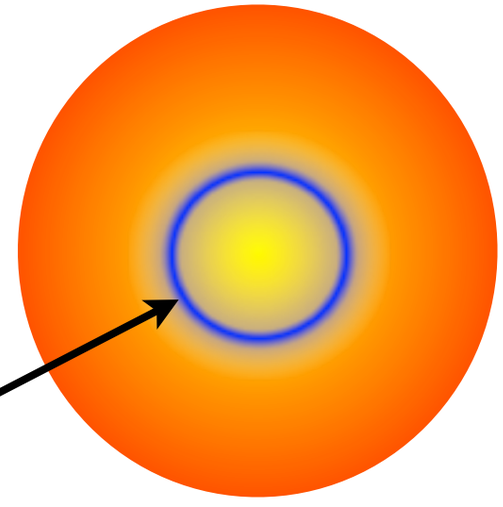
refraction absorption(emission)

Refraction: $$\mathrm{Re}\Pi = \frac{4\pi\alpha n_e}{m_e} + \sim \frac{4\pi\alpha n_{\mathrm{H}}}{m_e} \sum_r \frac{\omega^2(\omega^2 - \omega_r^2)}{(\omega^2 - \omega_r^2)^2 + (\omega\gamma_r)^2} + \ldots$$

free electrons (>0) neutral H Z, KK...



resonant (on-shell) conversion of T-modes (all Energies!)



T-HP emission

A model of refraction and absorption

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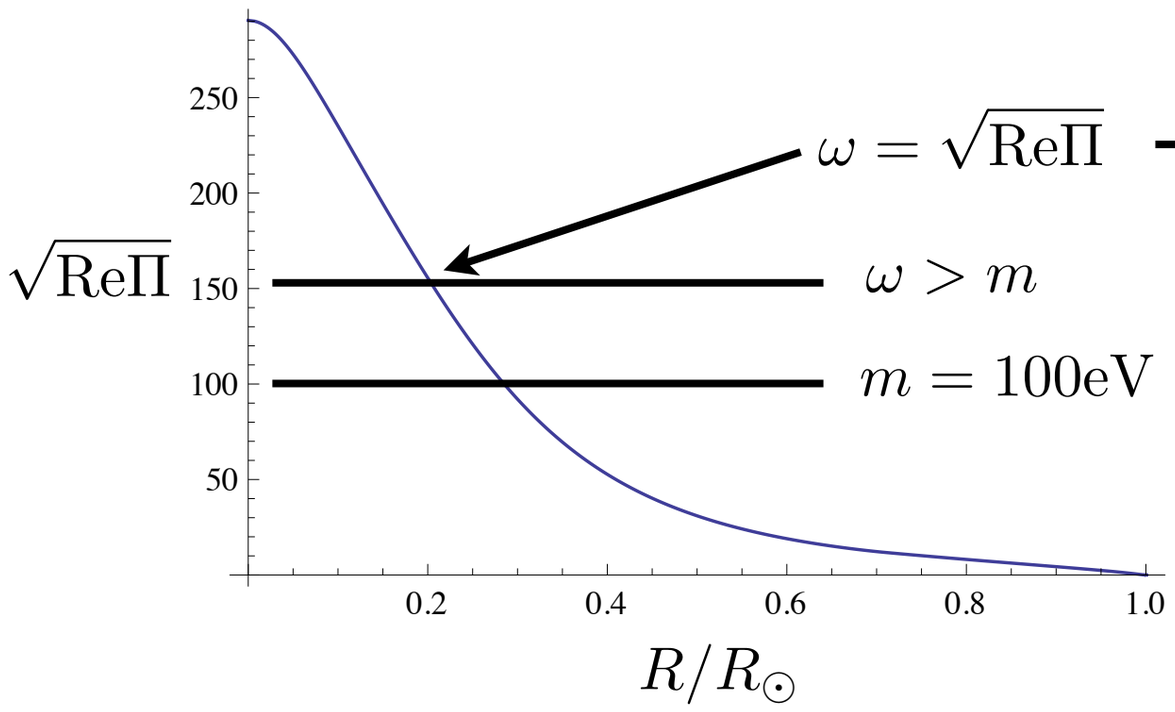
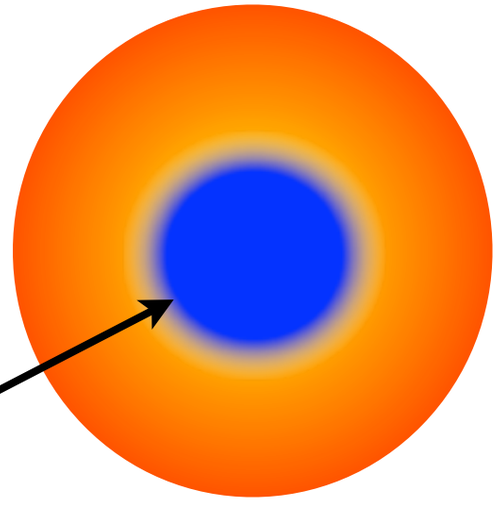
free electrons (>0) neutral H Z, KK...



resonant (on-shell) conversion of L-modes (one energy)



L-HP emission

A model of refraction and absorption

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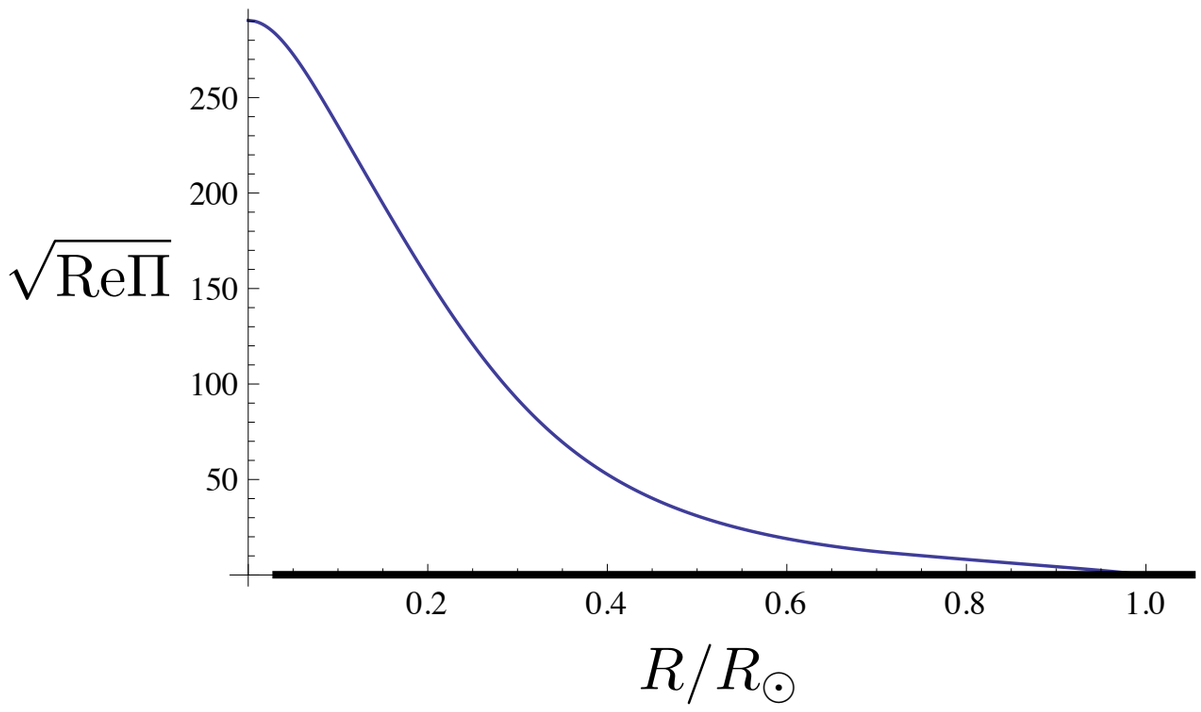
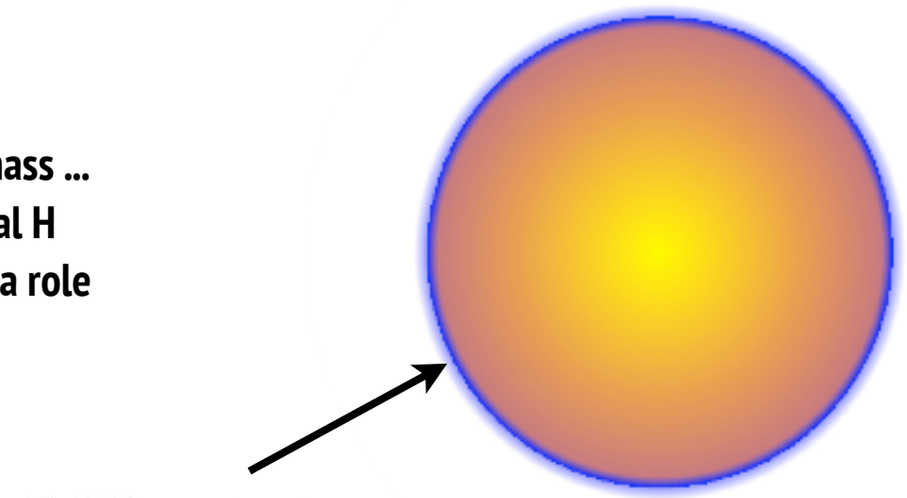
free electrons (>0) neutral H Z, KK...

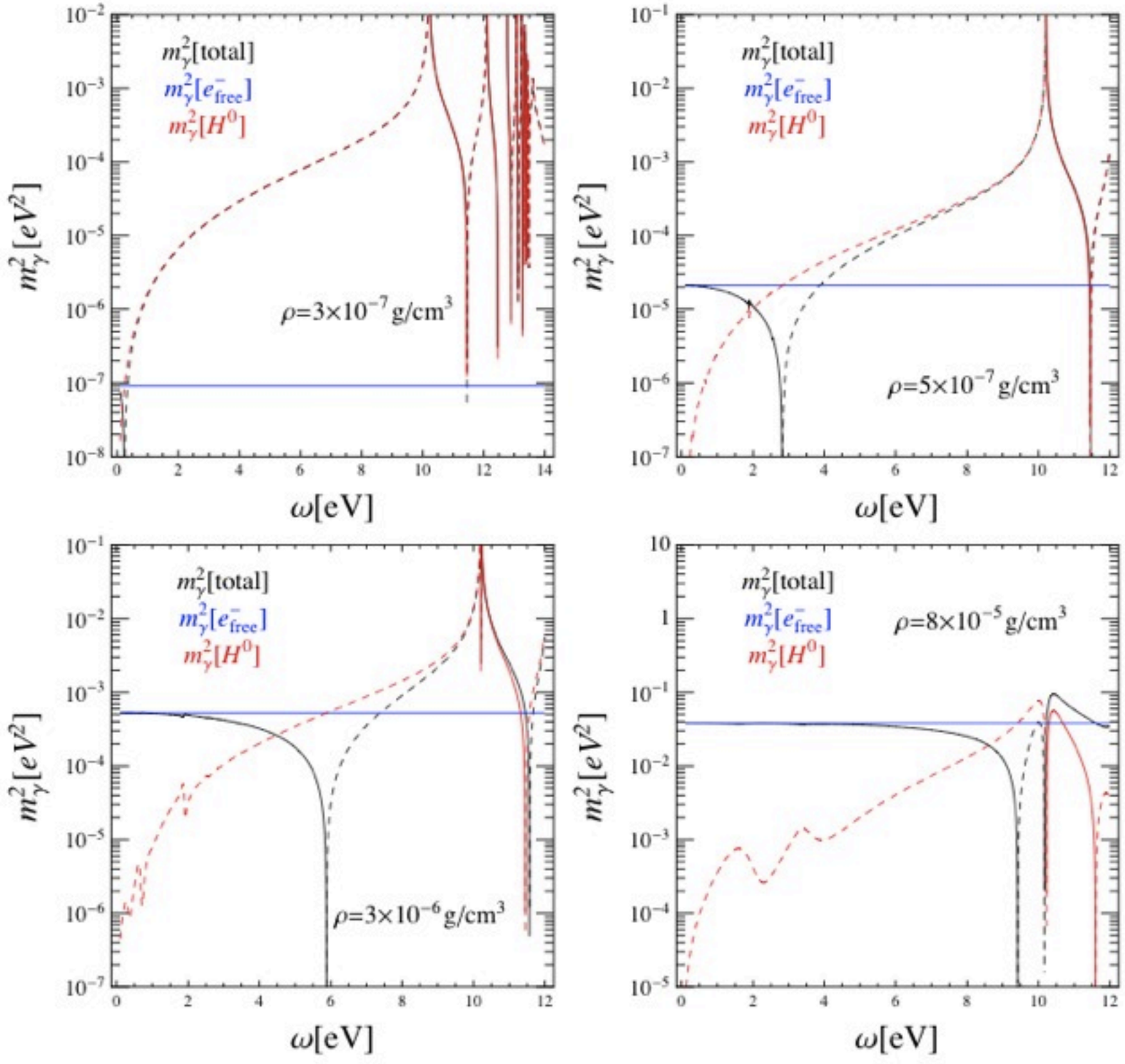


low mass ...
neutral H
plays a role



A model of refraction and absorption

At low temperatures, densities



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We need Π_T inside the Sun to compute the emission

$$\Pi = \mathrm{Re}\Pi + i\mathrm{Im}\Pi$$

refraction absorption(emission)

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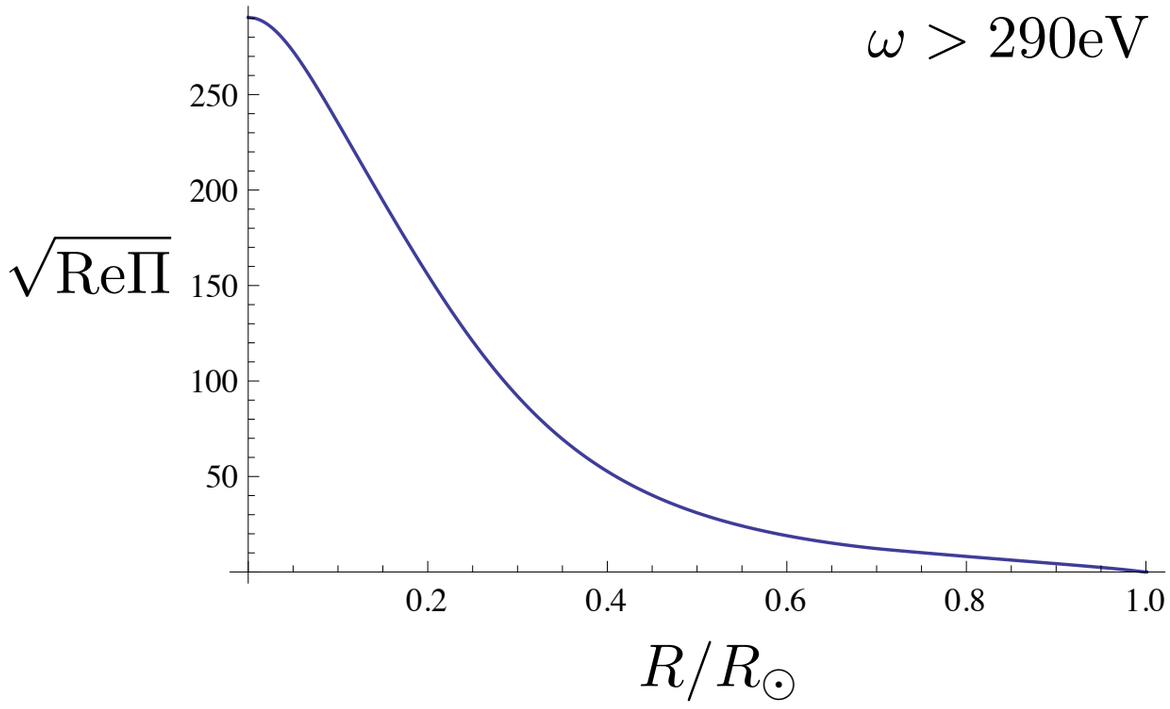
free electrons (>0) neutral H Z, KK...

$m > 290\mathrm{eV}$ resonant (on-shell) conversion not possible (T and L)

$\omega > 290\mathrm{eV}$ resonant (on-shell) conversion not possible (L)



$$\Gamma^{\mathrm{Prod}}_{\gamma'_T} \sim \Gamma^{\mathrm{Prod}}_{\gamma_T} \times \chi^2$$

$$\Gamma^{\mathrm{Prod}}_{\gamma'_L} \sim \Gamma^{\mathrm{Prod}}_{\gamma_T} \times \chi^2 \frac{m^2}{\omega^2}$$

A model of refraction and absorption

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free electrons (>0) neutral H Z, KK...

Absorption/E: $$\mathrm{Im}\Pi = \Pi^{\mathrm{Bremsstrahlung}} + \Pi^{\mathrm{Compton}} + \Pi^{\mathrm{Atomic,H}} + \Pi^{\mathrm{Atomic,Z}} + \ldots$$

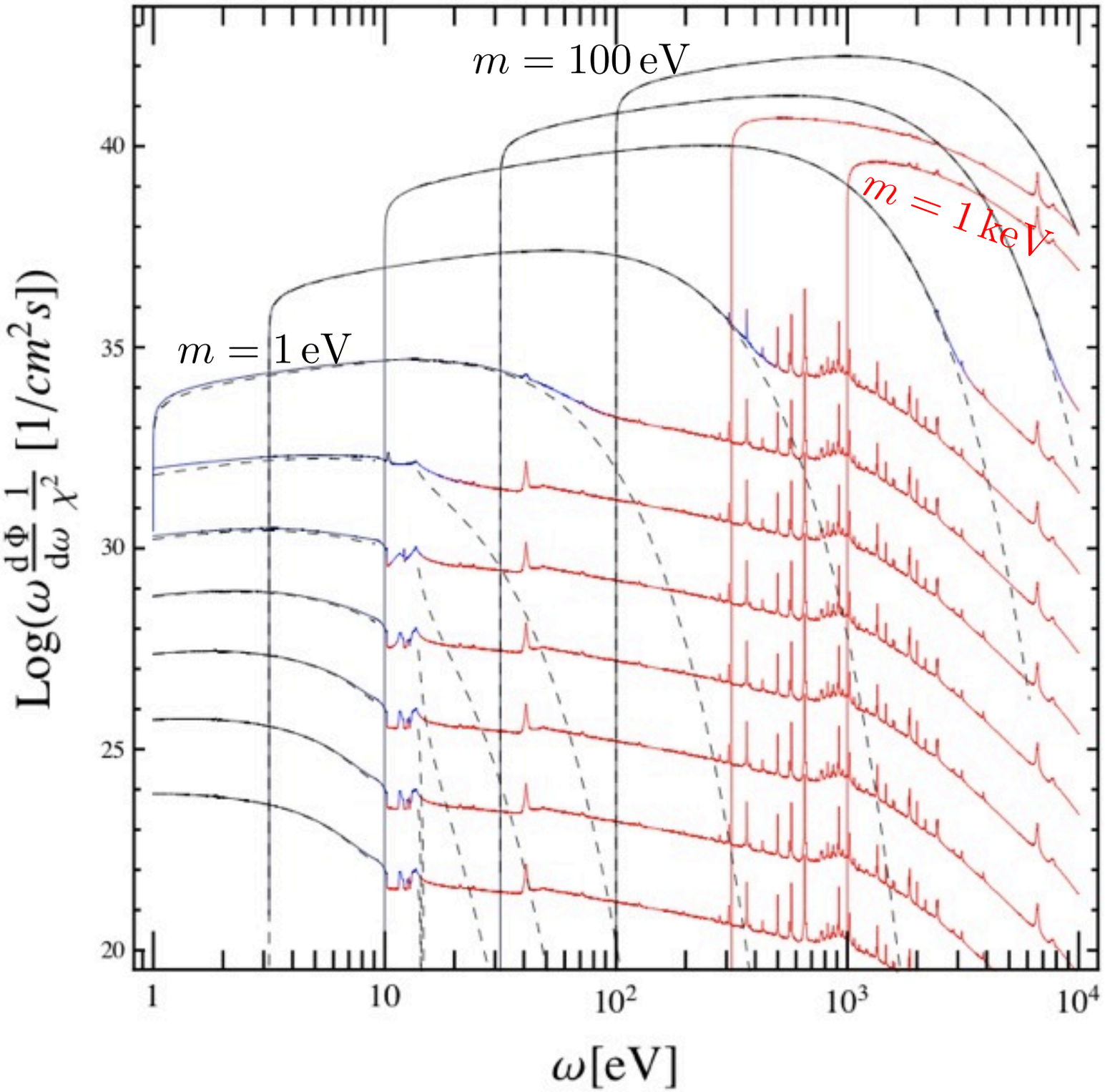
standard formulas calculated taken from OP

Completely irrelevant for the Sun-average emission

$$\int dr \frac{\Gamma(r)}{(m^2 - \mathrm{Re}\Pi(r))^2 + (\omega\Gamma(r))^2} \times \ldots$$ = independent of Γ

Atlas of solar HP emission: T-modes

Redondo arXiv:1501.07292

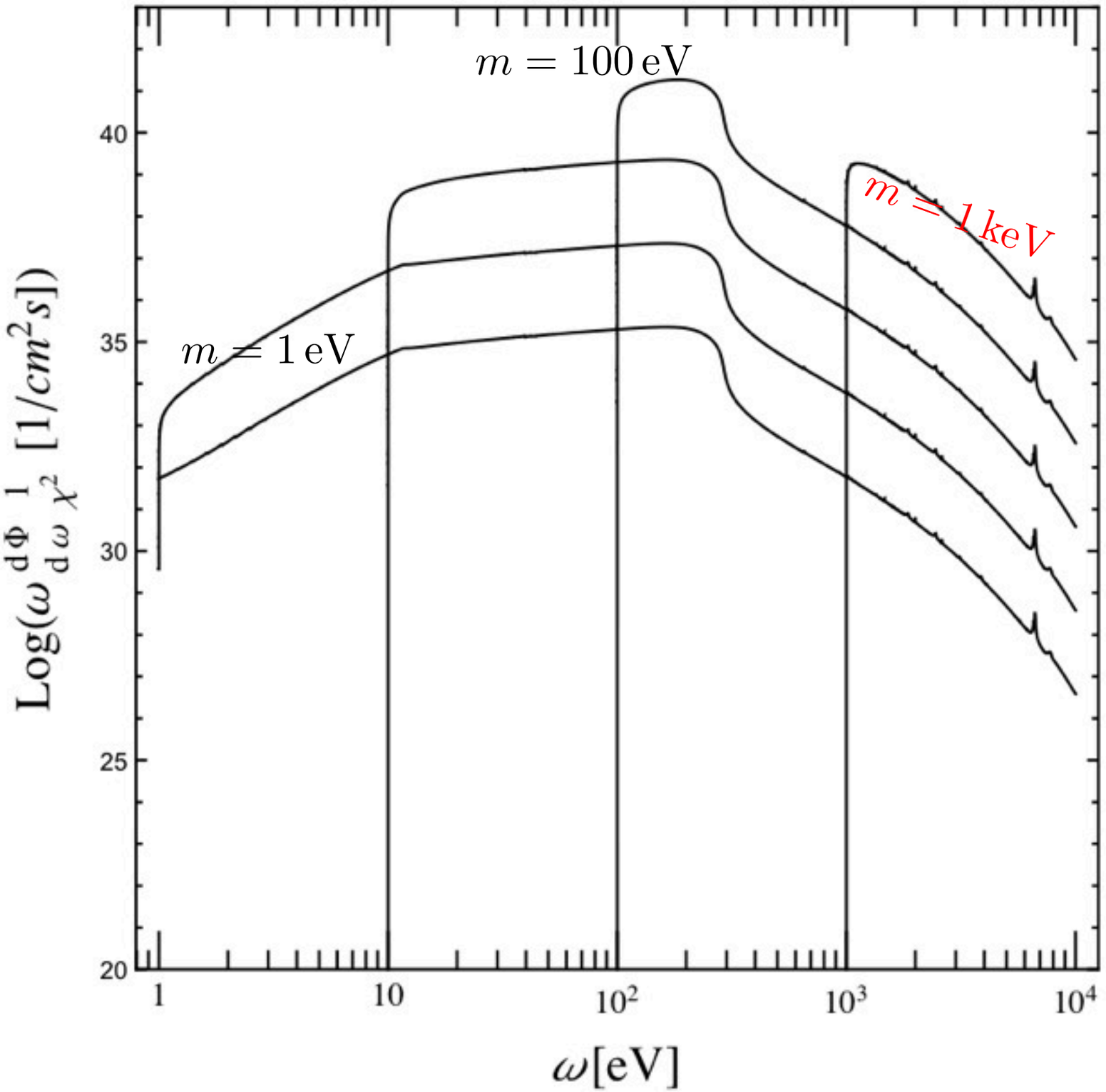


resonant

non-resonant

Atlas of solar HP emission: L-modes

Redondo arXiv:1501.07292



Atlas of solar HP emission: L-modes

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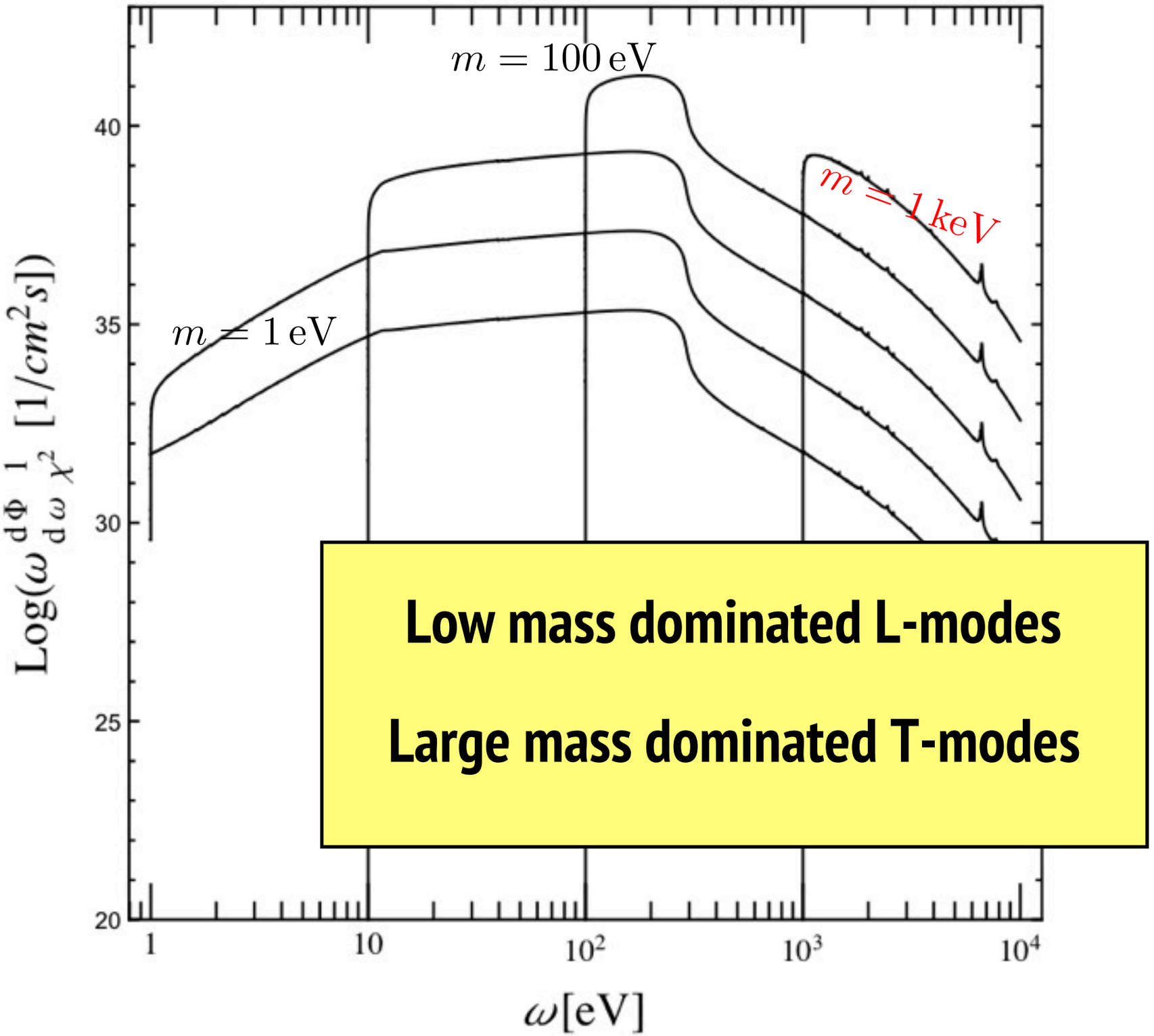


Low mass dominated L-modes

Large mass dominated T-modes

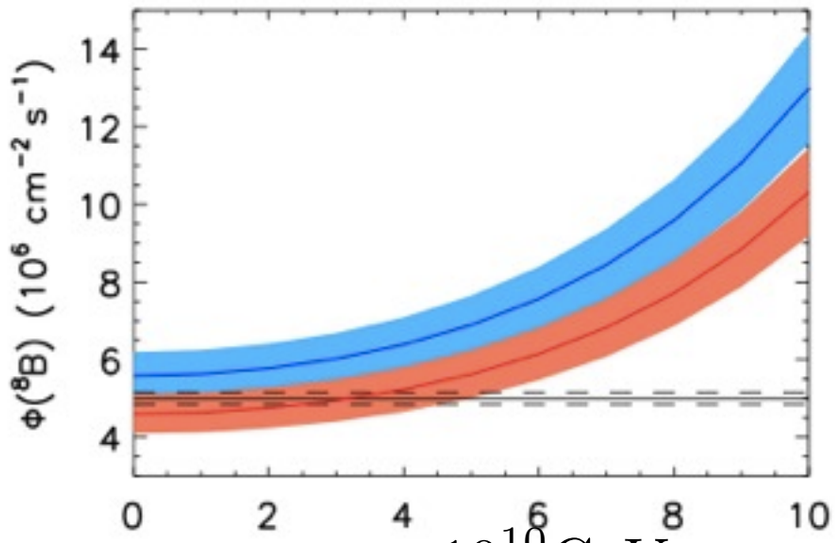
Constraining Solar Axions

... An 13, Raffelt 13, Vinyoles arXiv:1501.01639

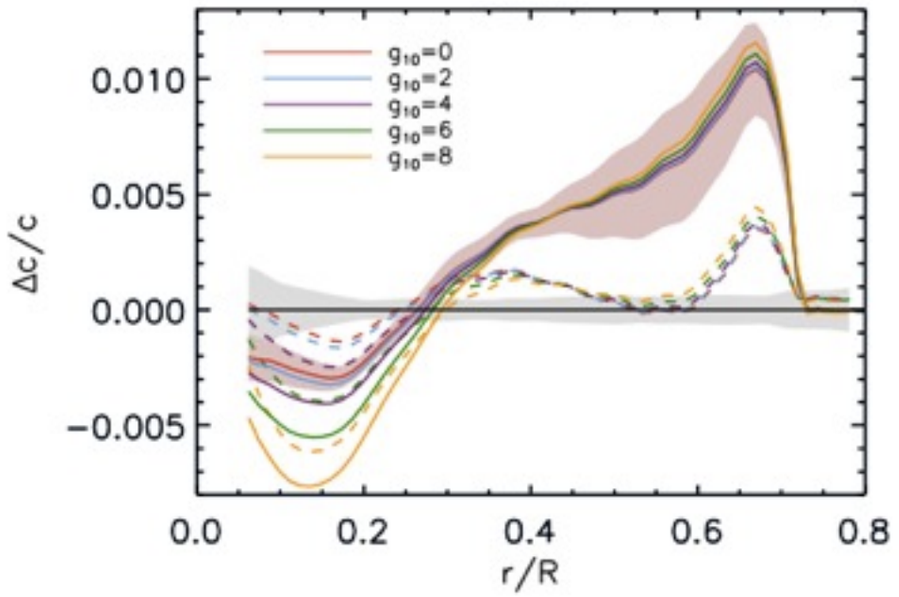
Solar models with Axion (hadronic, L-HP emission)

Axions

Solar 8B neutrino flux

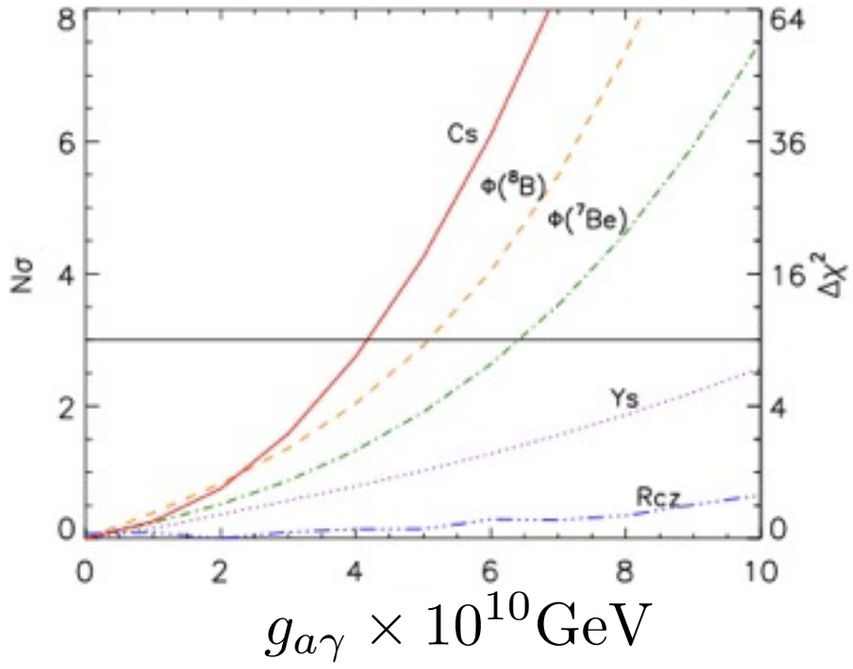


sound speed profile (obs-model)

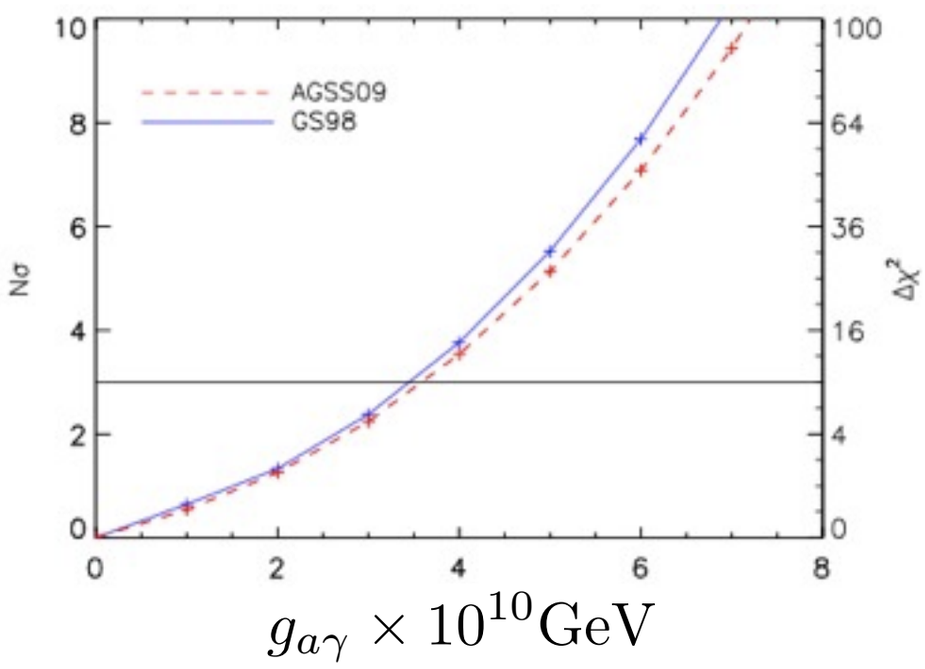


solid (AG09),
dashed (GS98)

individual chi^2



total chi^2



Constraining Solar Axions

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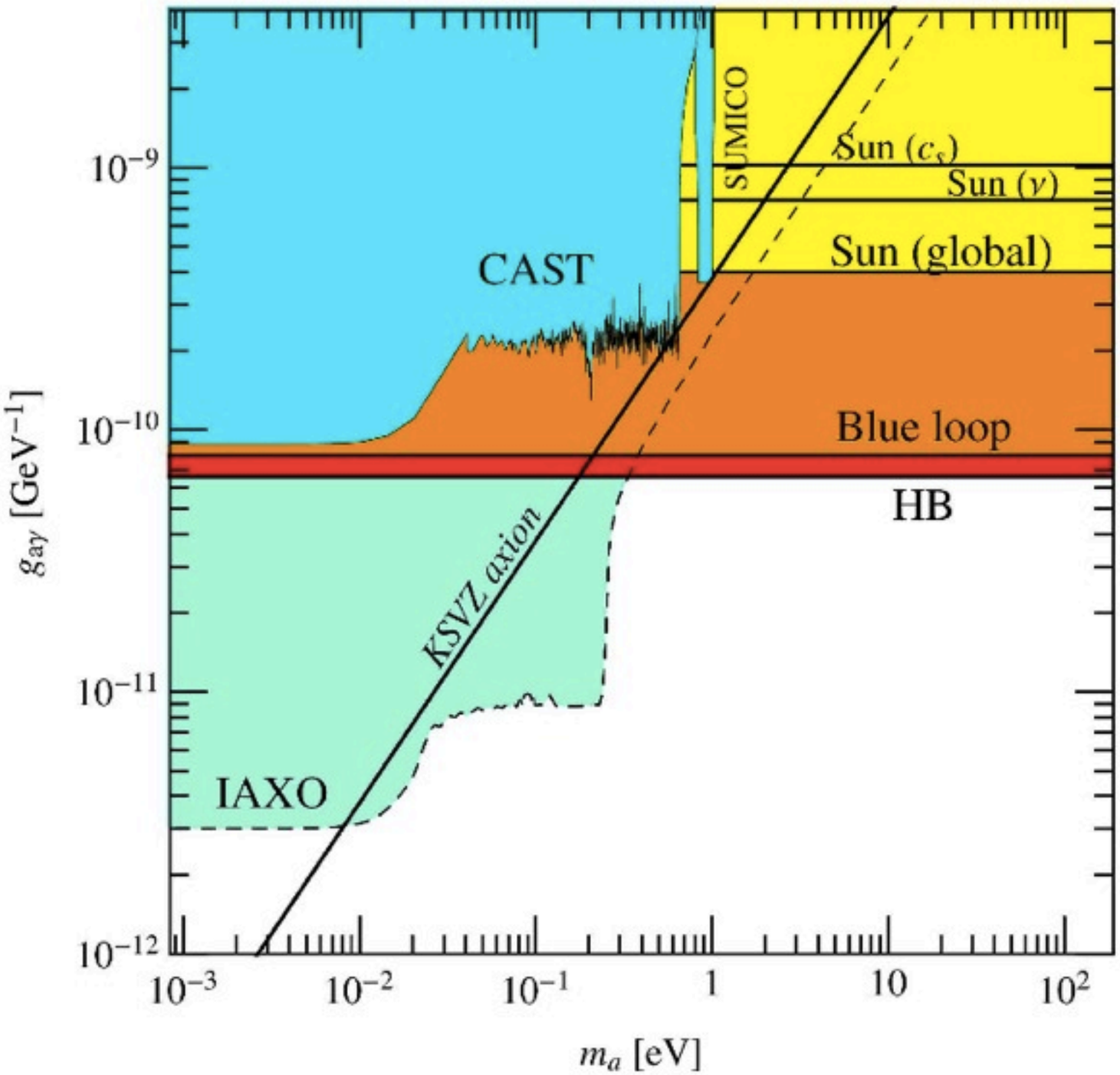
Solar models with Axion (hadronic, L-HP emission)

Axions



→ old

→ new cons.

→ stronger :-(

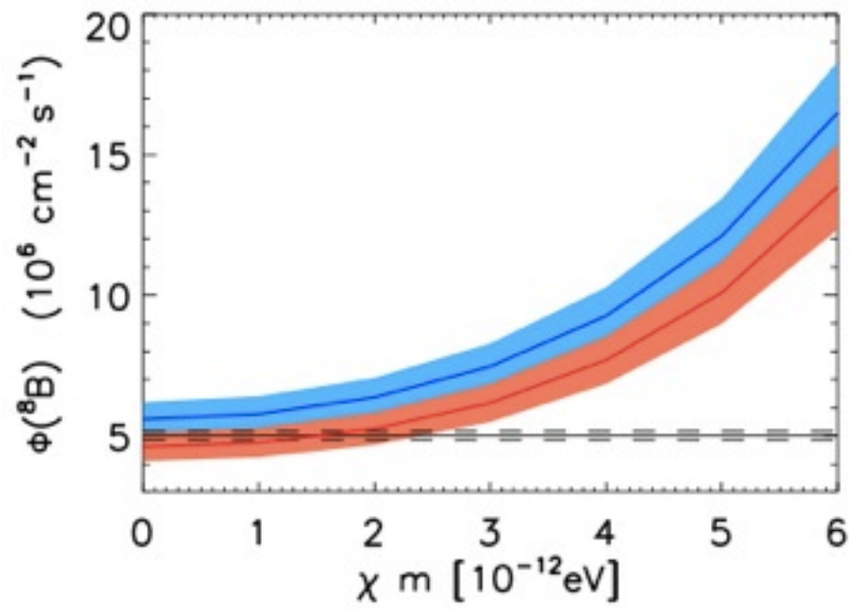
Constraining Solar HPs

... An 13, Raffelt 13, Vinyoles arXiv:1501.01639

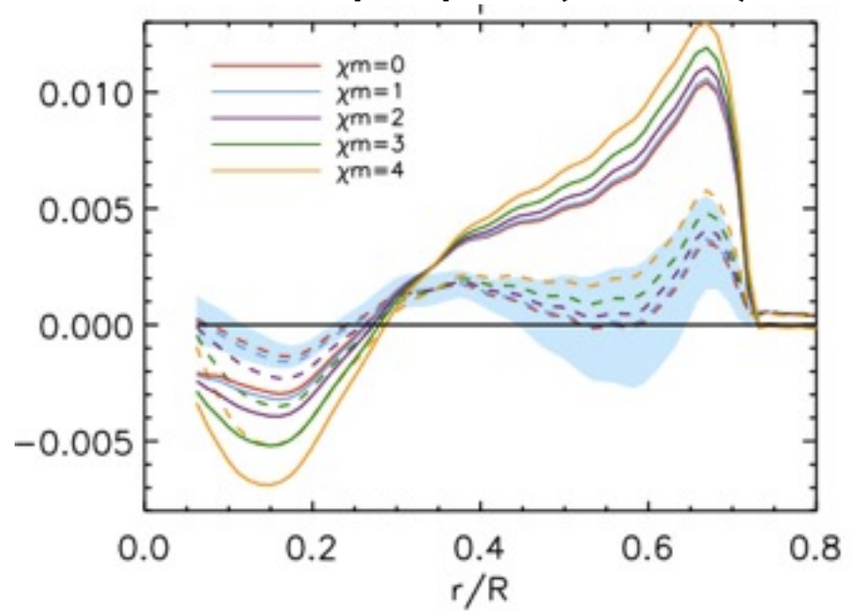
Solar models with Axion (hadronic, L-HP emission)

L-HPs

Solar 8B neutrino flux

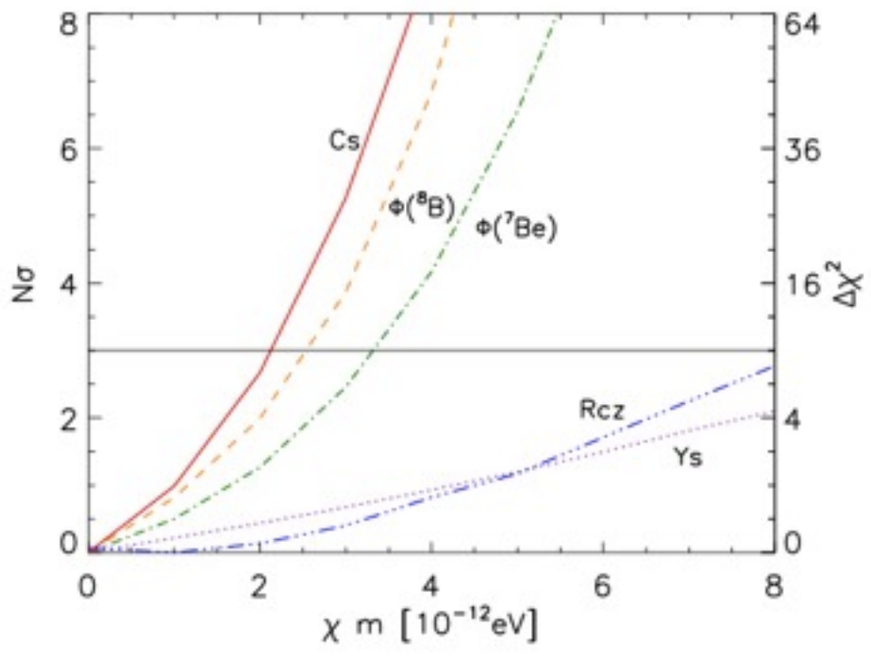


sound speed profile (obs-model)

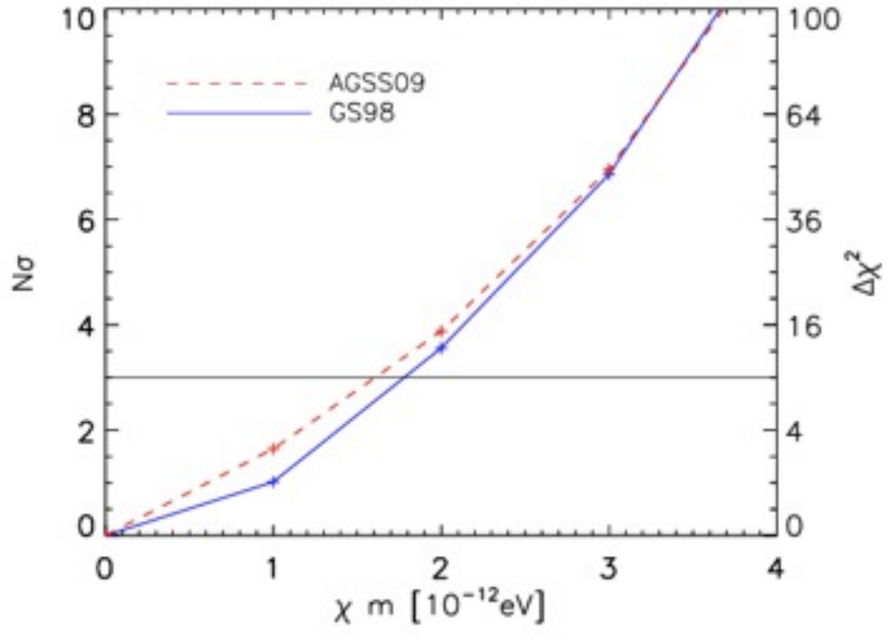


solid (AG09),
dashed (GS98)

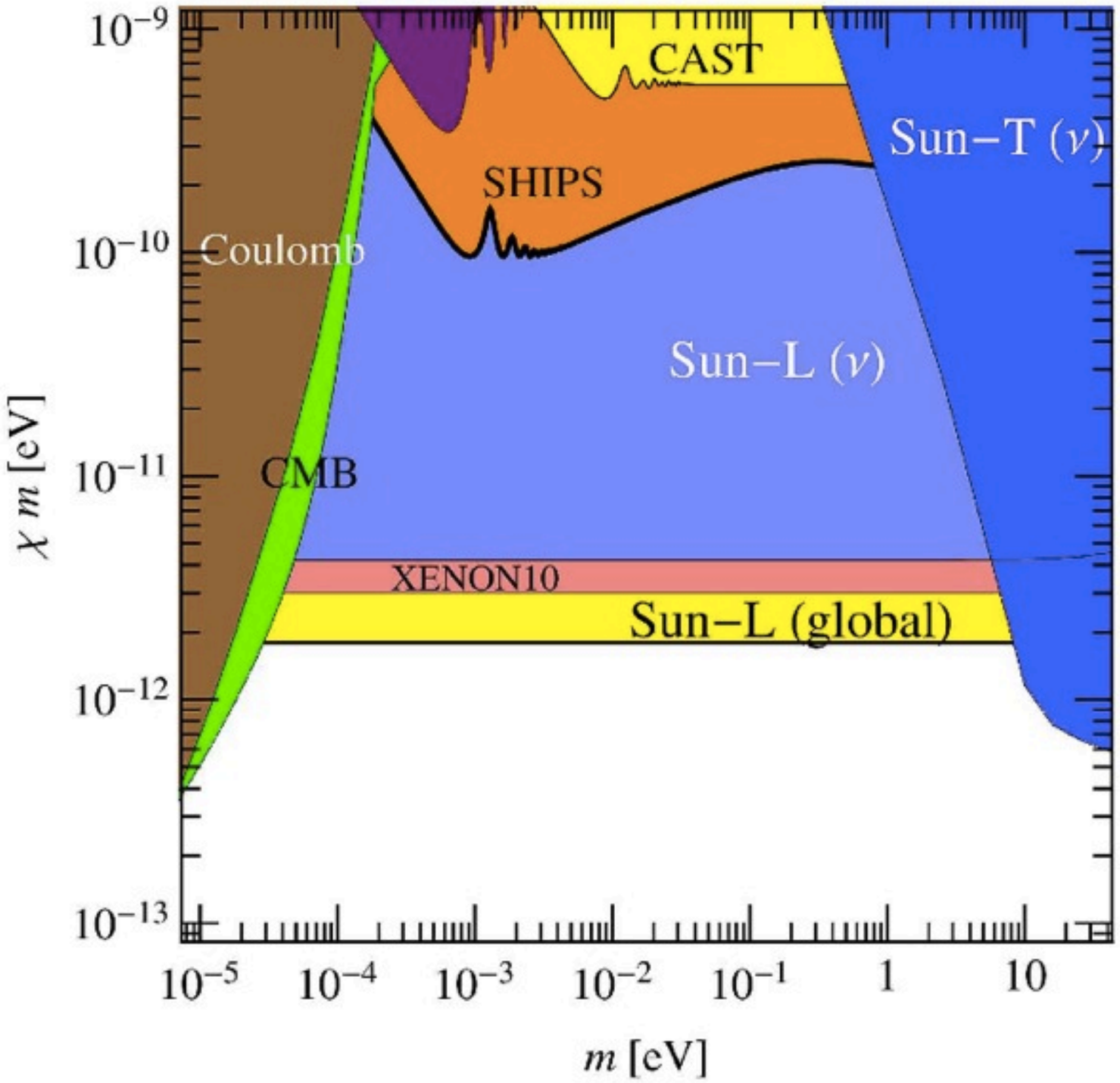
individual chi^2



total chi^2



Constraining Solar HPs



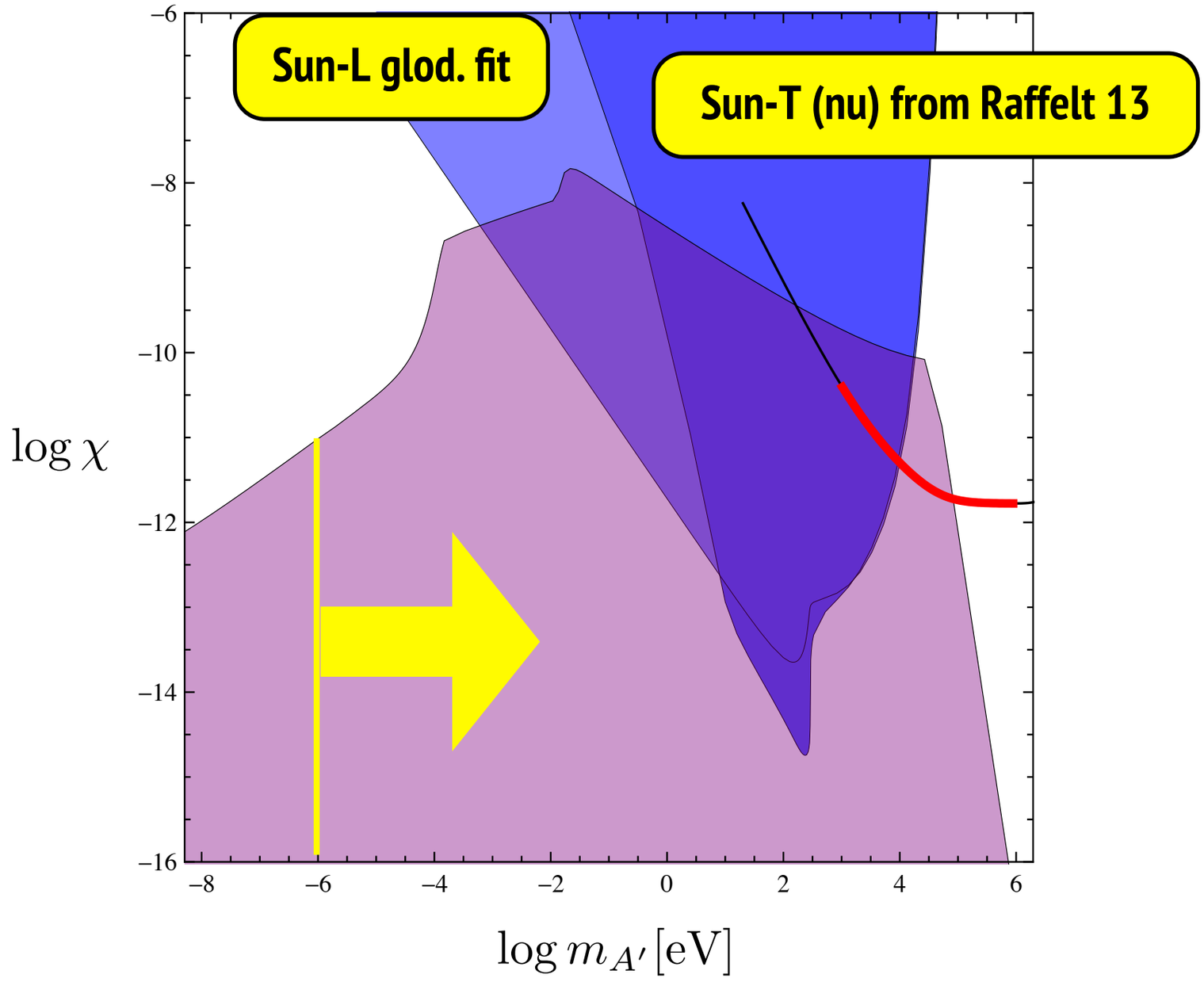
→ old

→ new cons.

caveat ... solar abundance issue

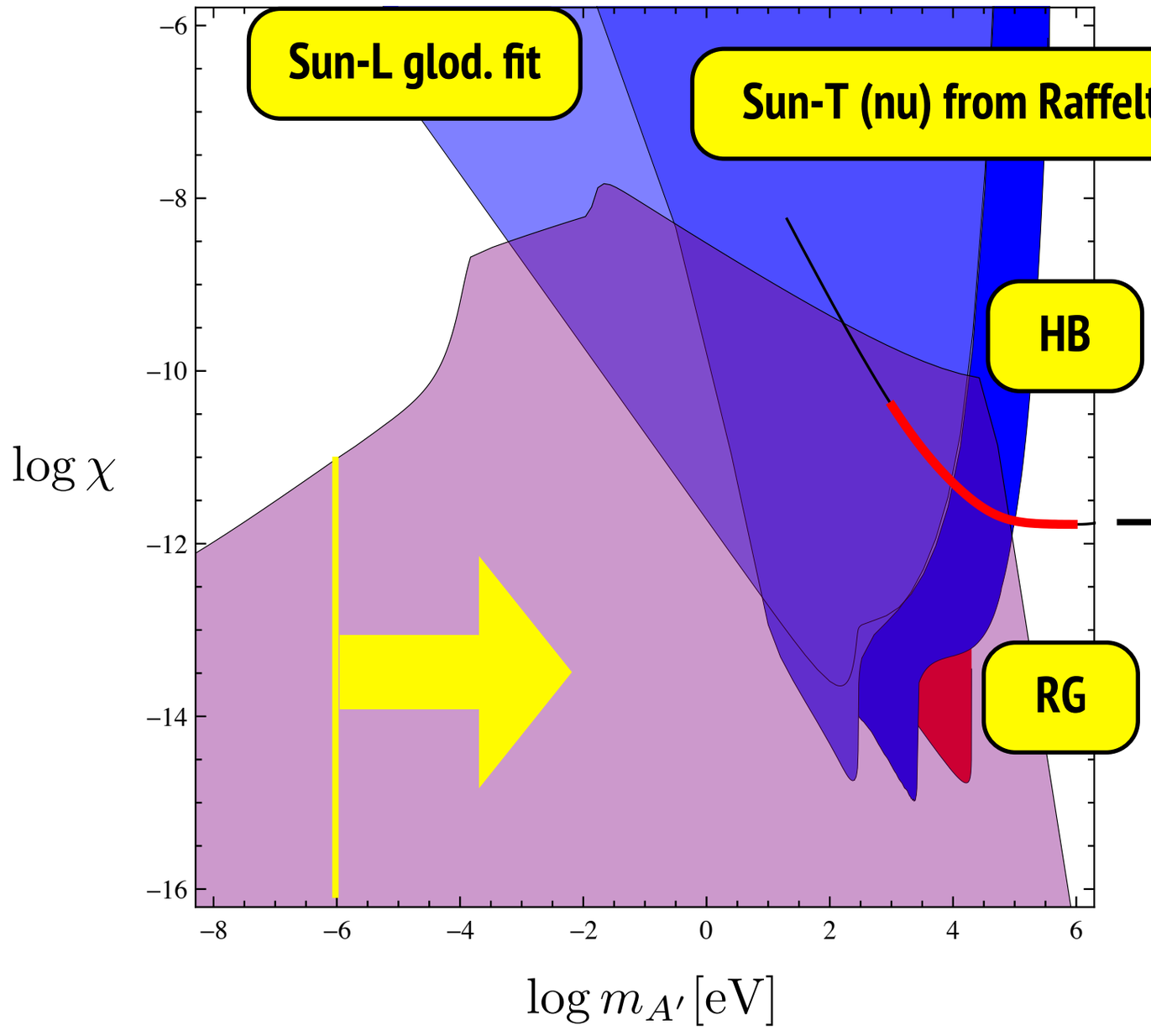
Constraining Solar HPs

... An 13, Raffelt 13, Vinyoles arXiv:1501.01639



Constraining HPs from HB and RG

... An 13, Raffelt 13, Vinyoles arXiv:1501.01639

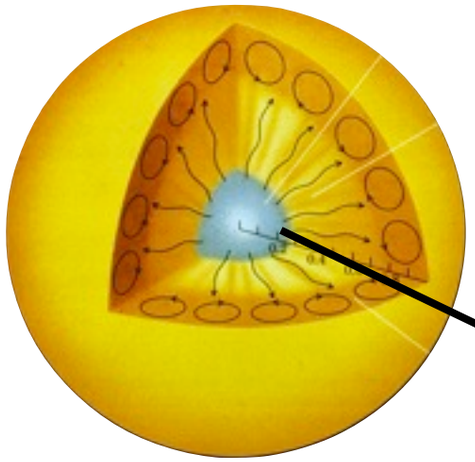


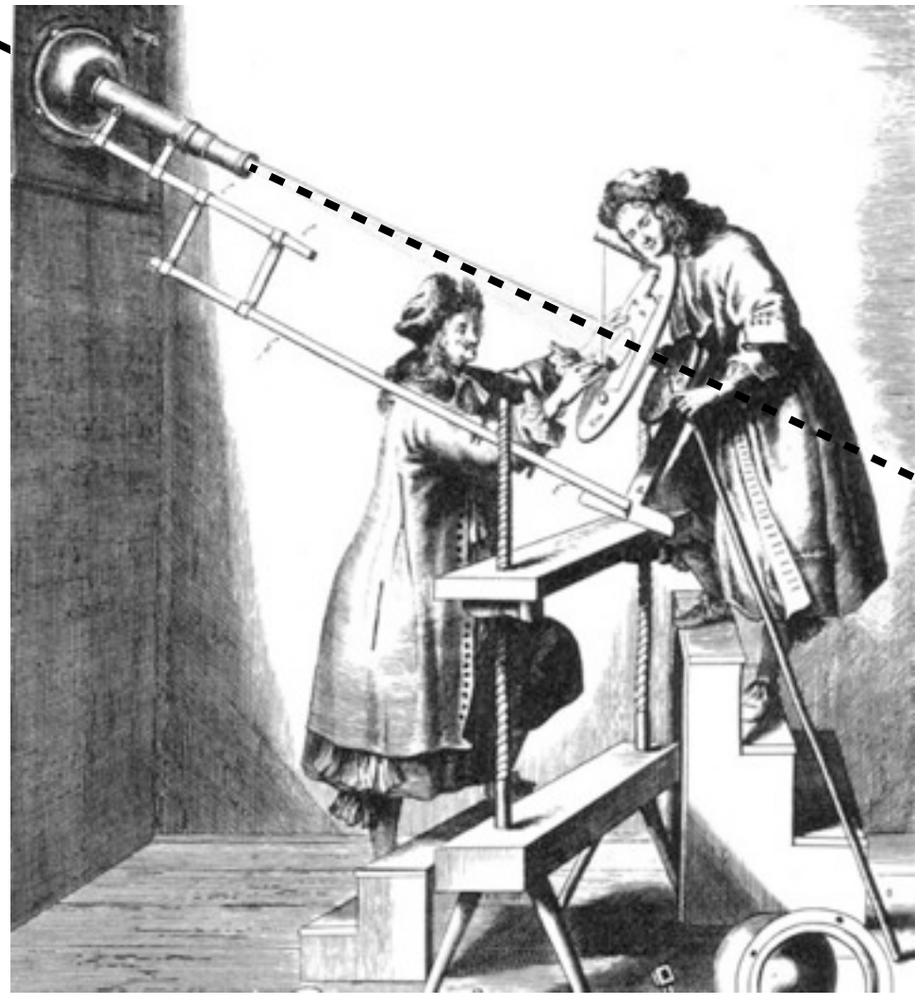
Thermal DM excluded

(also by DD)

Helioscopes

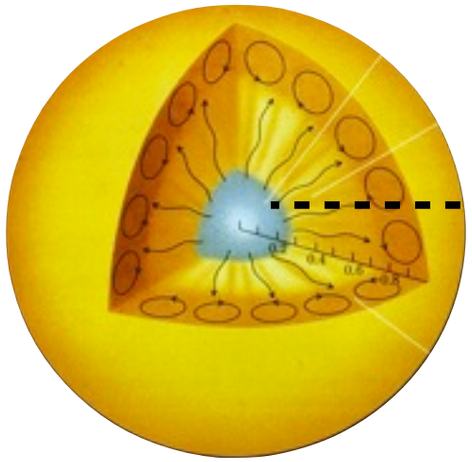
Detect solar WISPs with Earth-bound Experiments

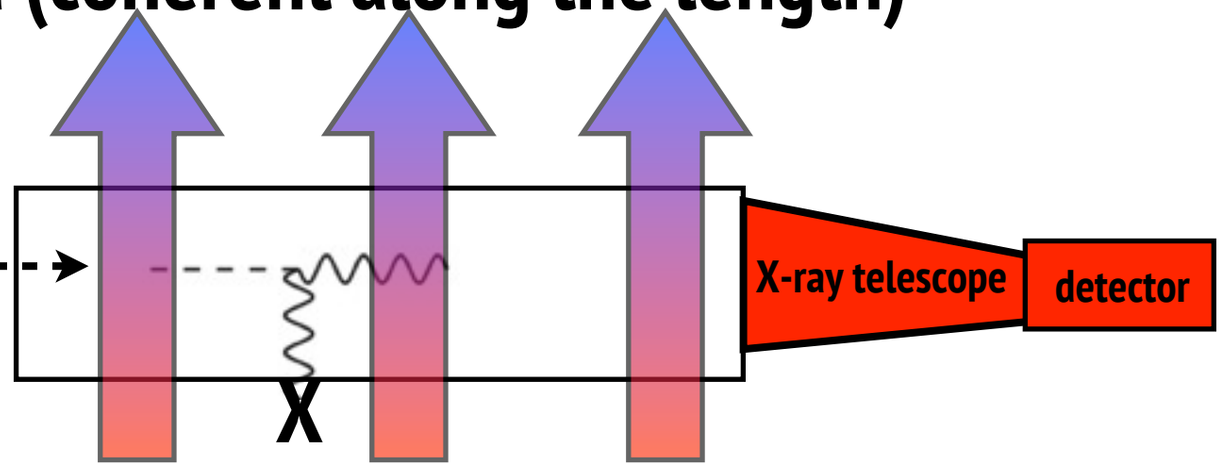




Axion Helioscopes

Detect solar Axions in a strong B-field (coherent along the length)

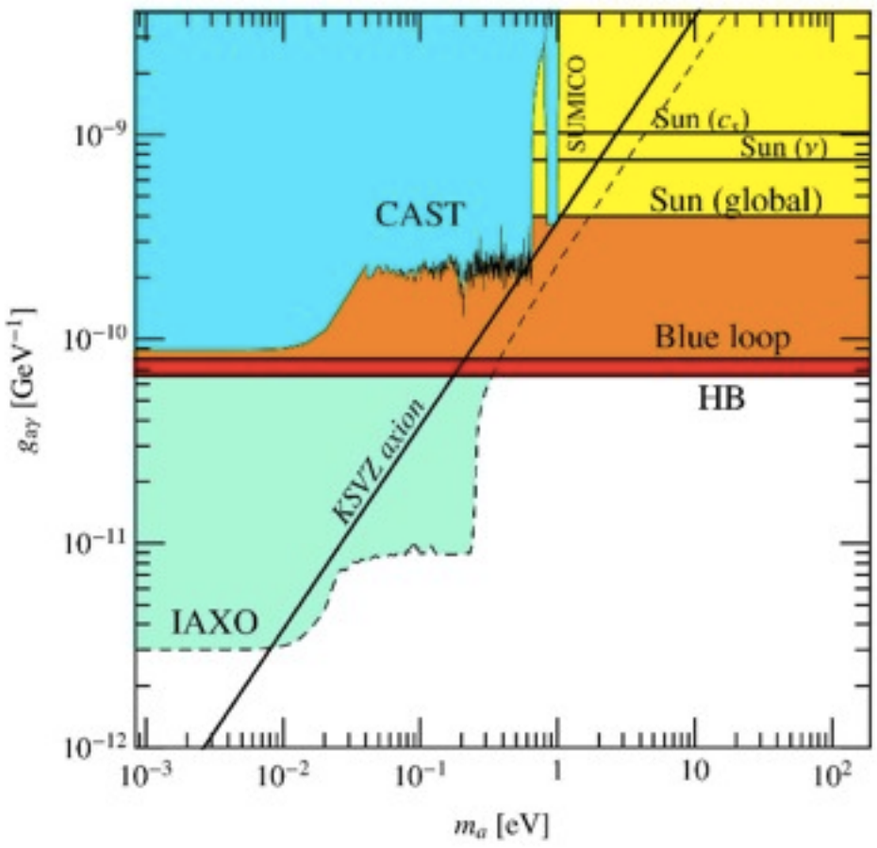




$$P(a \to \gamma) = \frac{g_{a\gamma}^2 B^2 \omega^2}{m_a^4} \sin^2\left(\frac{m_a^2 L}{4\omega}\right)$$

CAST (LHC dipole 9.3 m, 9T)

hadronic axions



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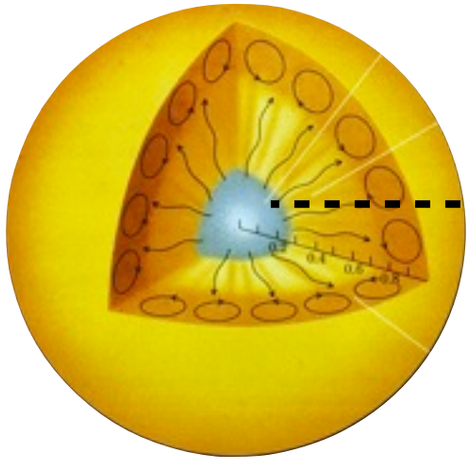

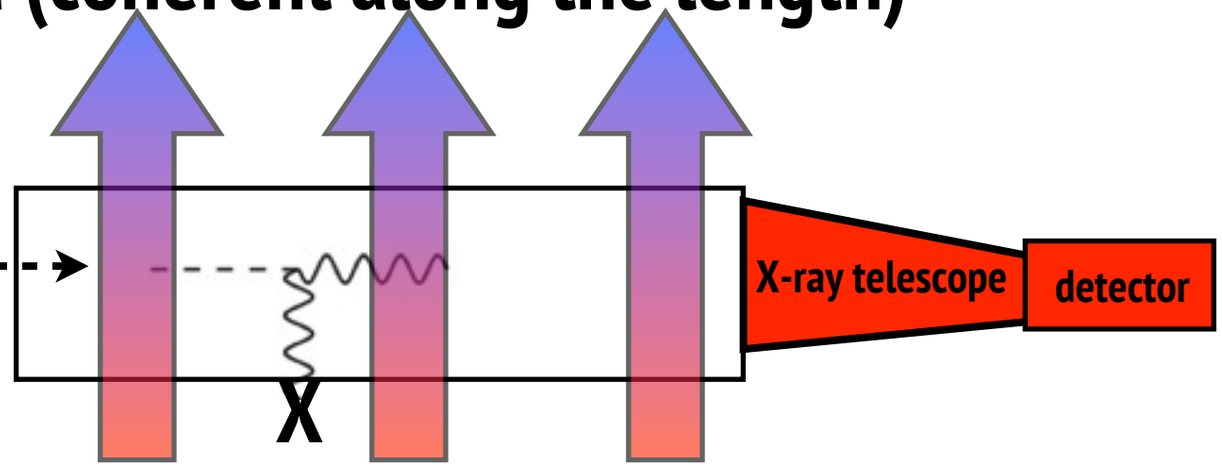

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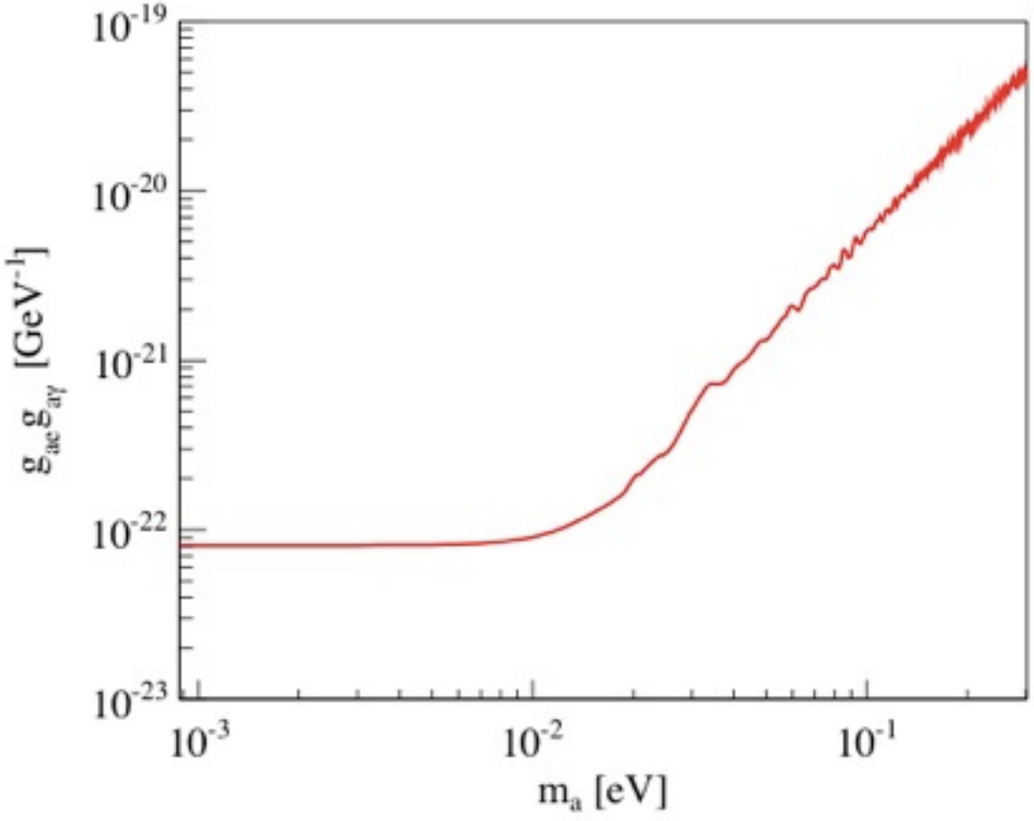
non-hadronic axions

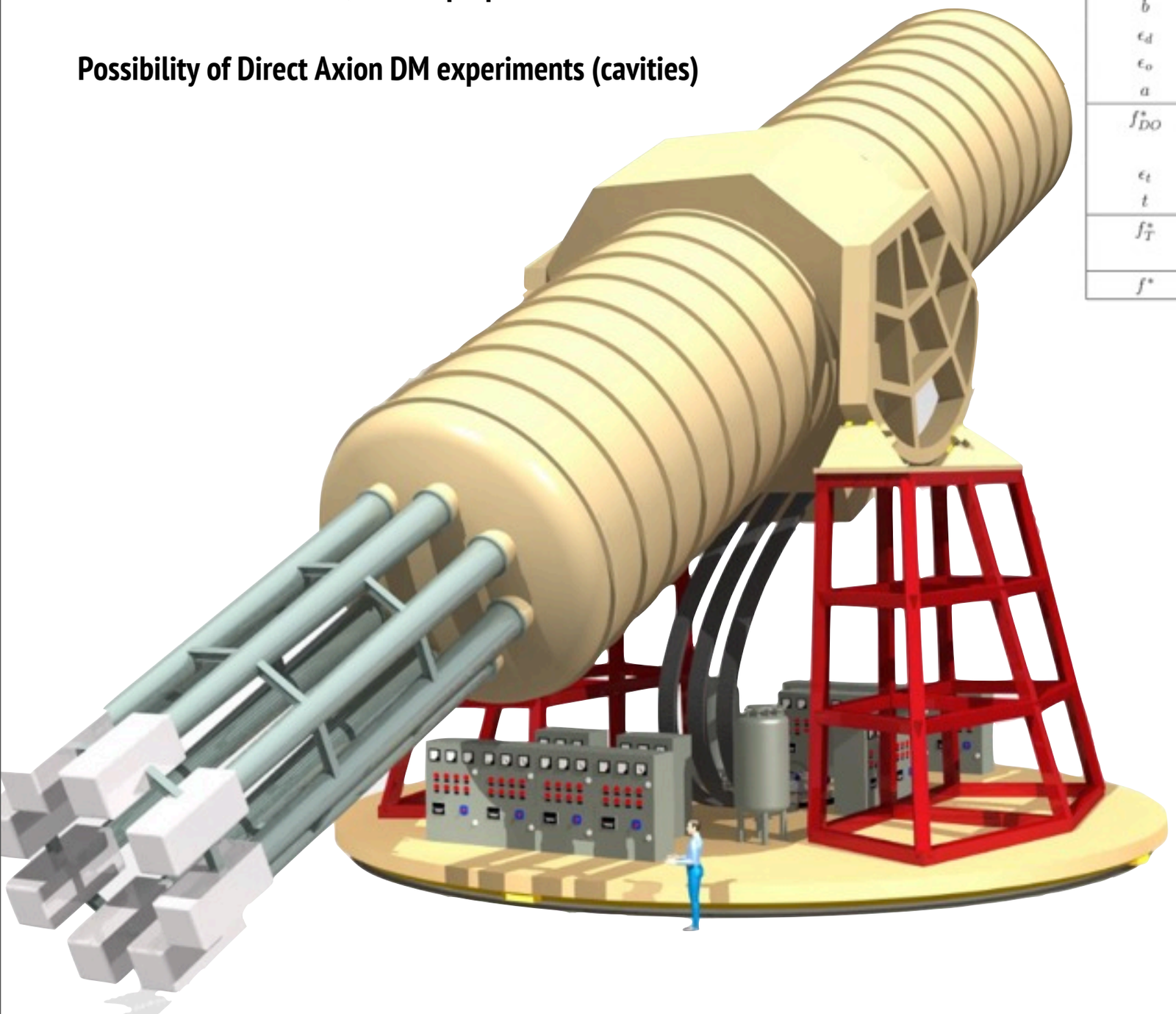


Next generation (proposed) IAXO

Boost parameters to the maximum

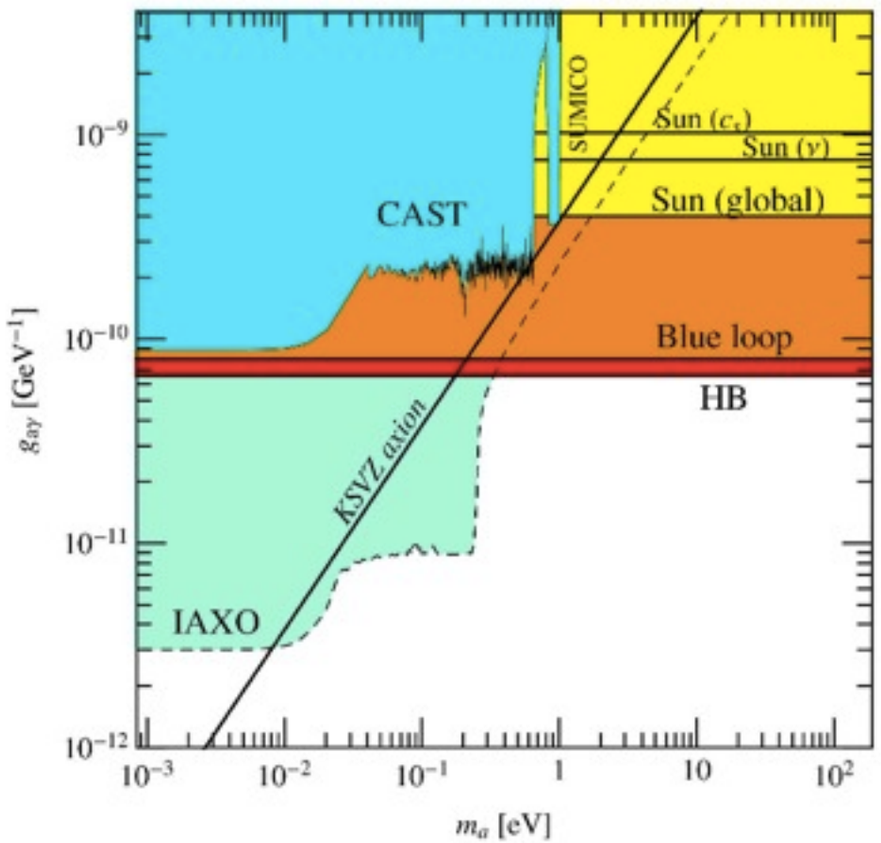
Conceptual design report IAXO 2014 JINST 9 T05002
LOI submitted to CERN, TDR in preparation

Possibility of Direct Axion DM experiments (cavities)



Parameter	Unit	CAST-I	NGAH 1	NGAH 2	NGAH 3	NGAH 4
B	T	9	3	3	4	5
L	m	9.26	12	15	15	20
A	m^2	2×0.0015	1.7	2.6	2.6	4.0
f^*_M		1	100	260	450	1900
b	$\frac{10^{-5}\,c}{keV\,cm^2\,s}$	~ 4	3×10^{-2}	10^{-2}	3×10^{-3}	10^{-3}
ϵ_d		0.5–0.9	0.7	0.7	0.7	0.7
ϵ_o		0.3	0.3	0.3	0.6	0.6
a	cm^2	0.15	3	2	1	1
f^*_{DO}		1	6	14	40	40
ϵ_t		0.12	0.3	0.3	0.5	0.5
t	year	~ 1	3	3	3	3
f^*_T		1	2.7	2.7	3.5	3.5
f^*		1	1.6×10^3	9.8×10^3	6.3×10^4	2.7×10^5

hadronic axions



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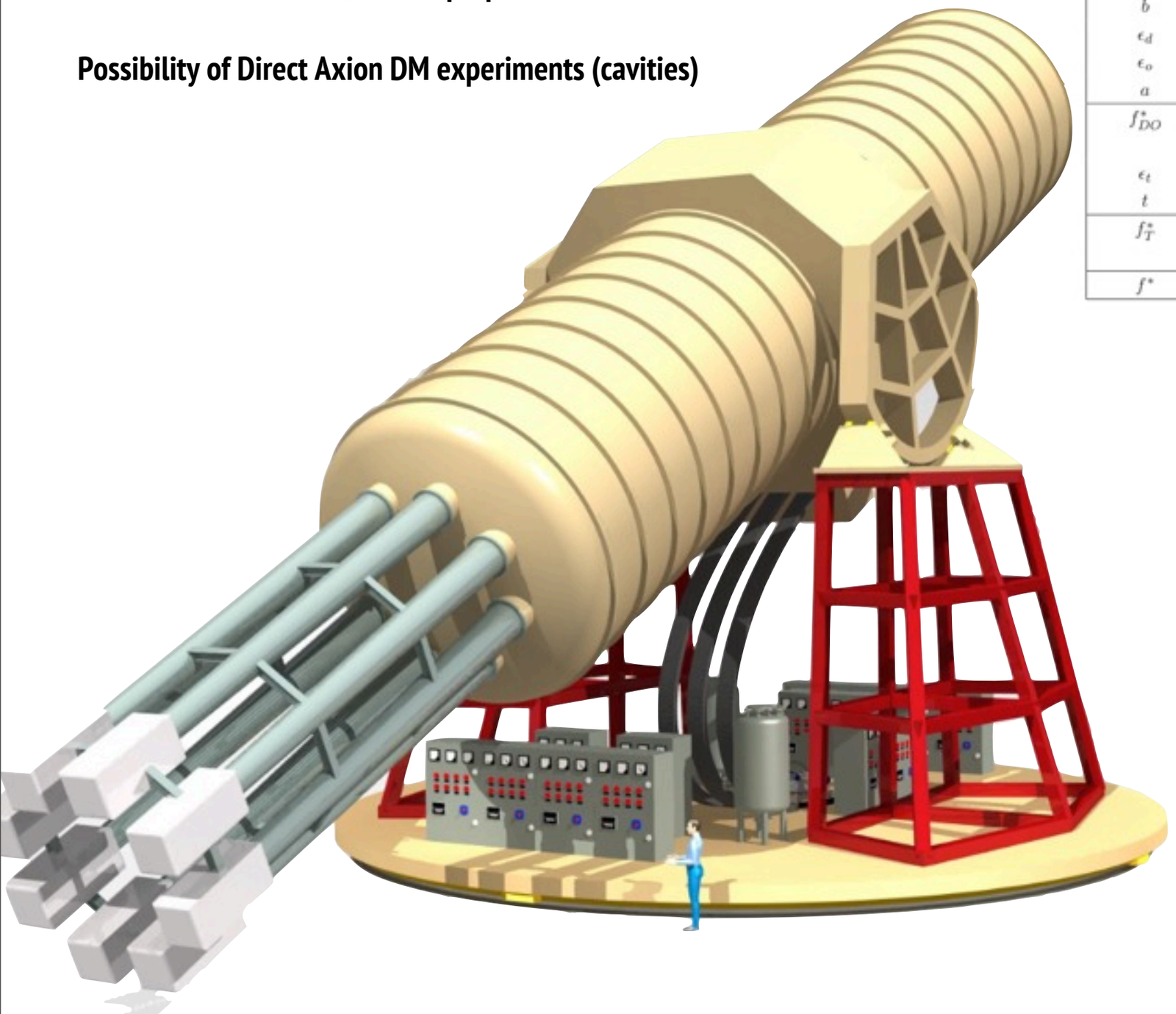

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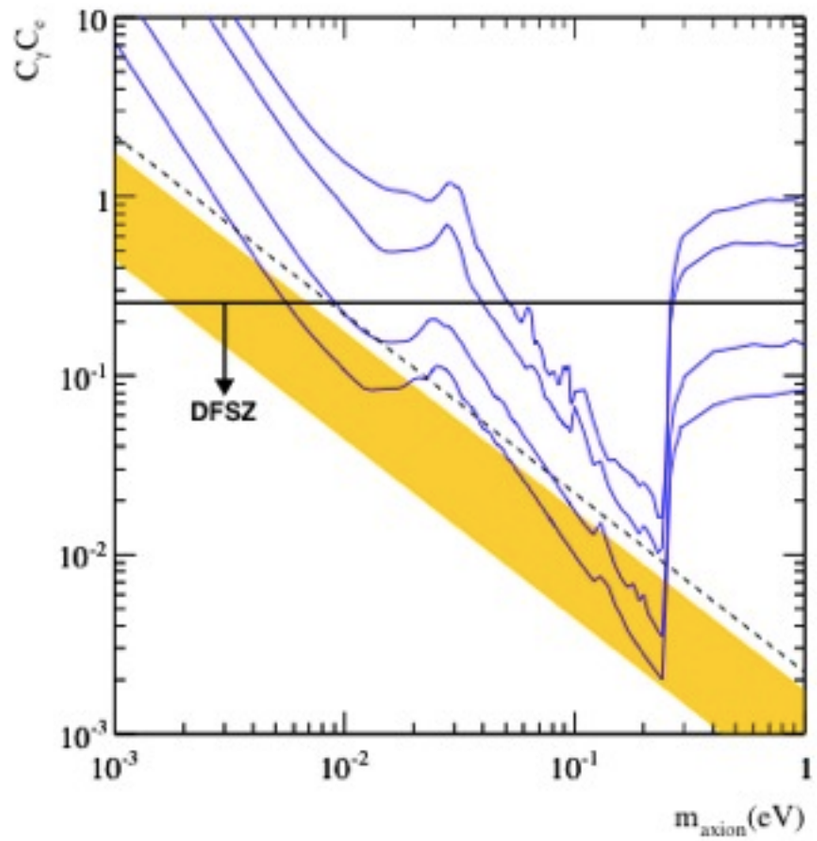
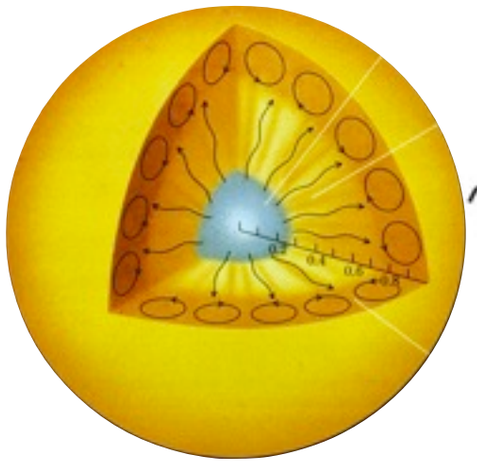
f^*		1	1.6×10^3	9.8×10^3	6.3×10^4	2.7×10^5

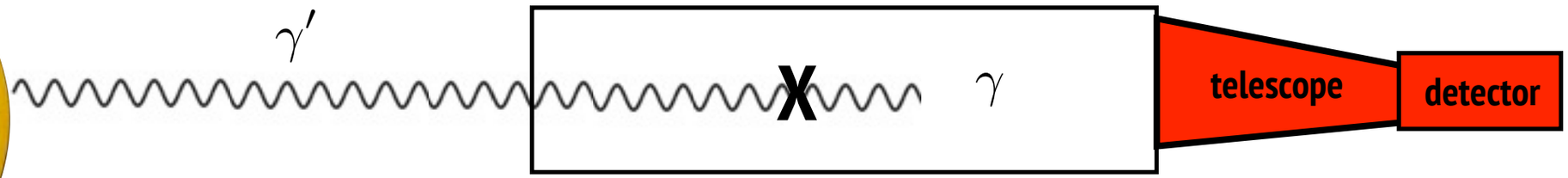
non-hadronic axions



HP Helioscopes

Detect solar HPs in vacuum vessel (only T-modes)





$$P(\gamma' \to \gamma) = 4\chi^2 \sin^2\left(\frac{m_{A'}^2 L}{4\omega}\right)$$

CAST

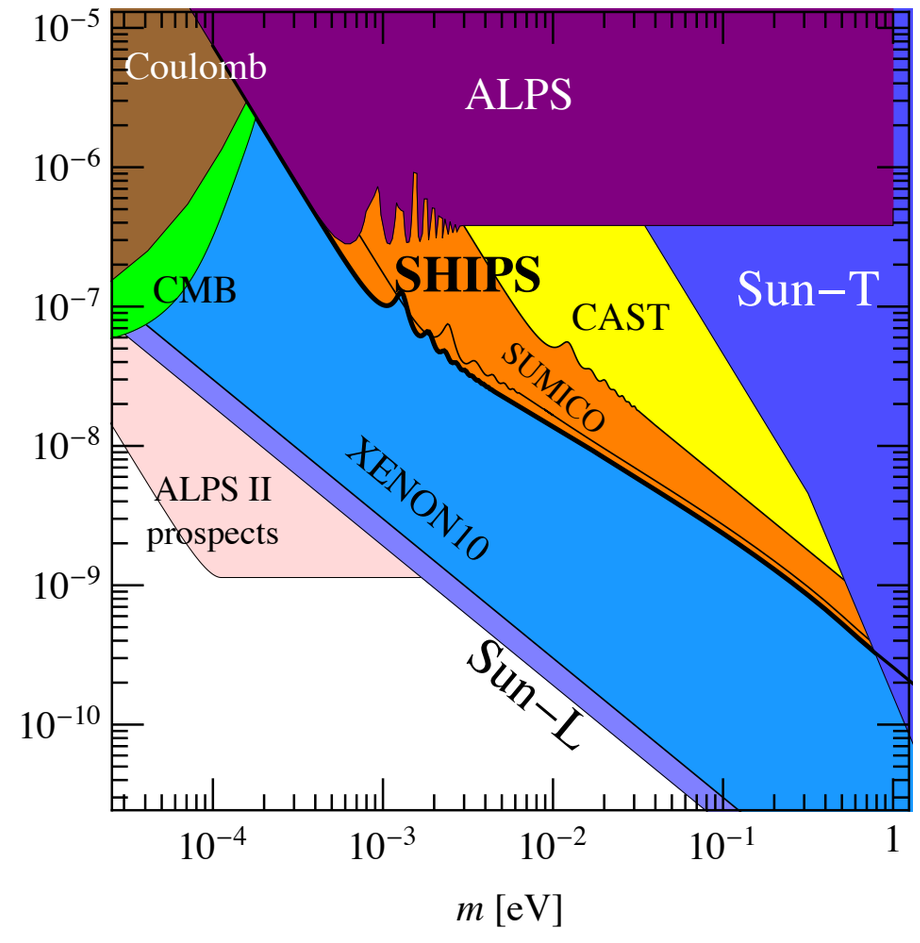
Redondo '08

SUMICO (visible)

Inoue '13

SHIPS (dedicated visible)

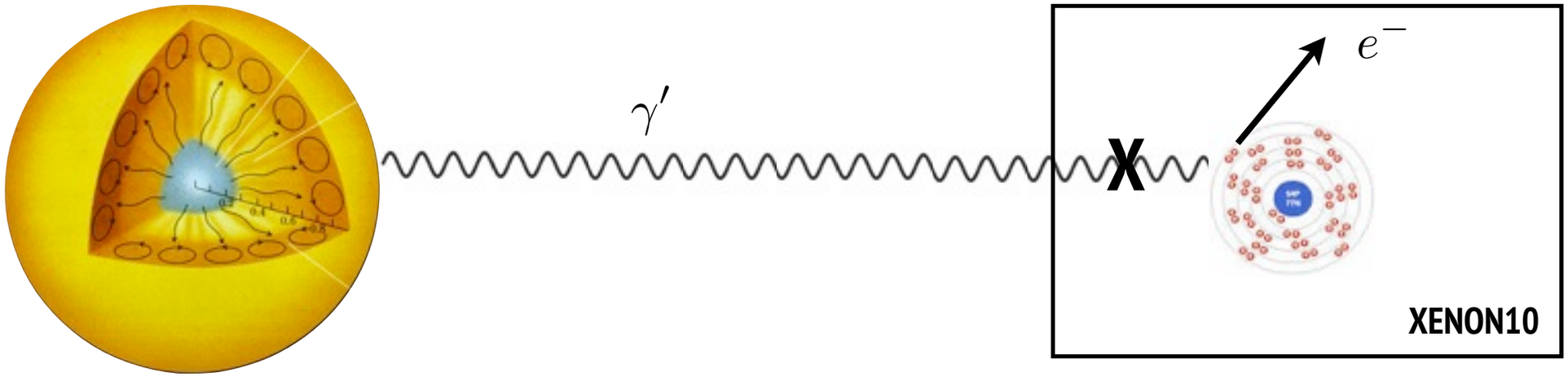
Schwartz '15



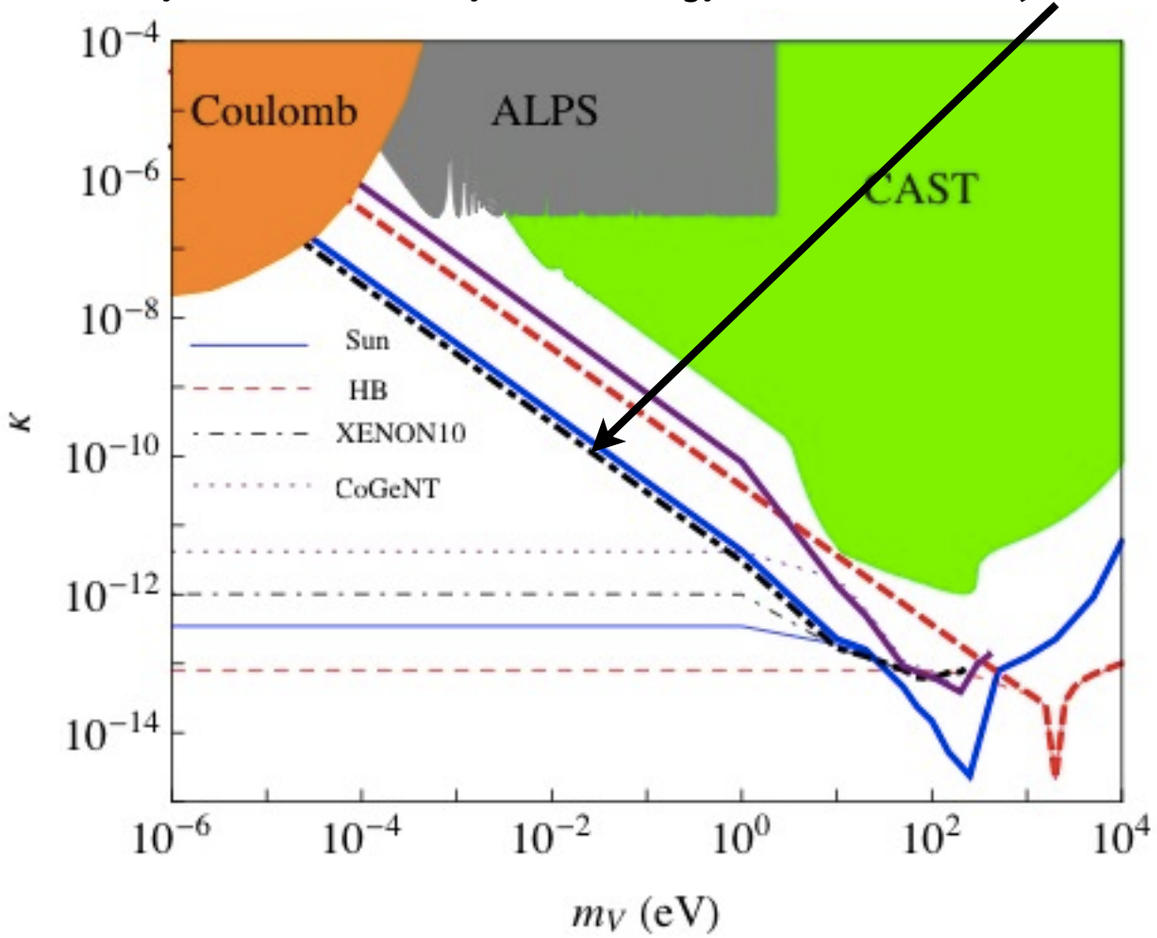
HP Helioscopes

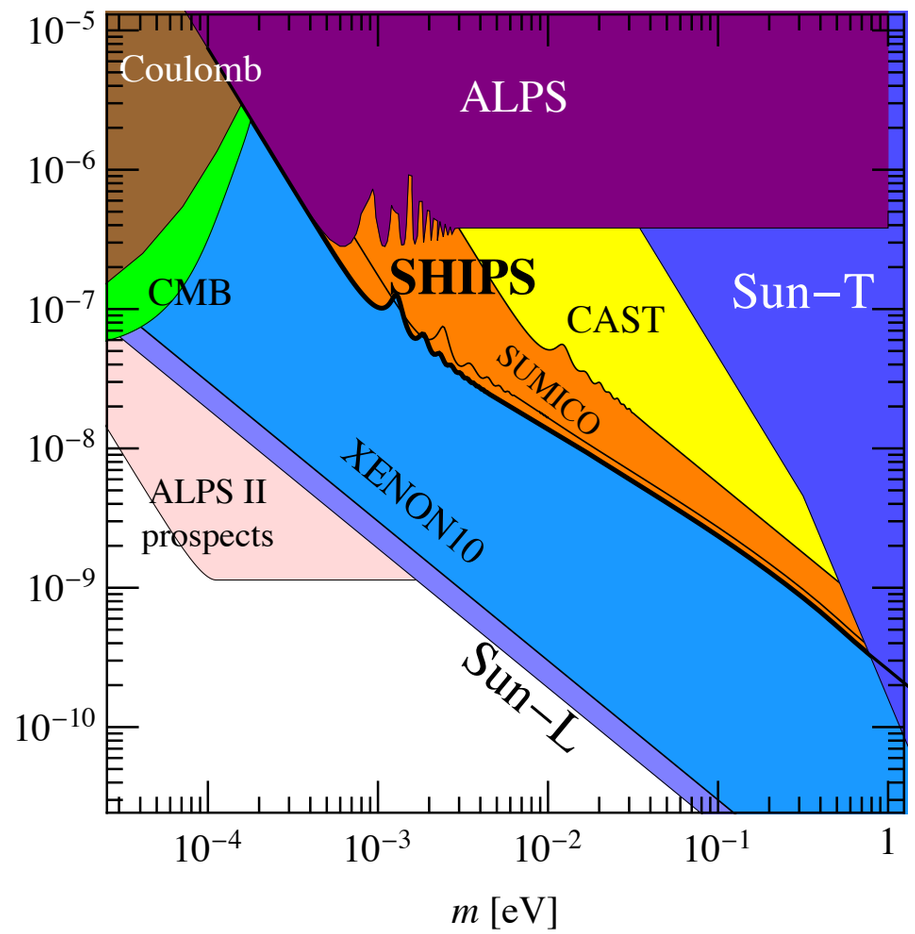
Detect solar HPs in with DM detectors

An '13



Very conservative analysis low-energy ionisation events (XENON10)

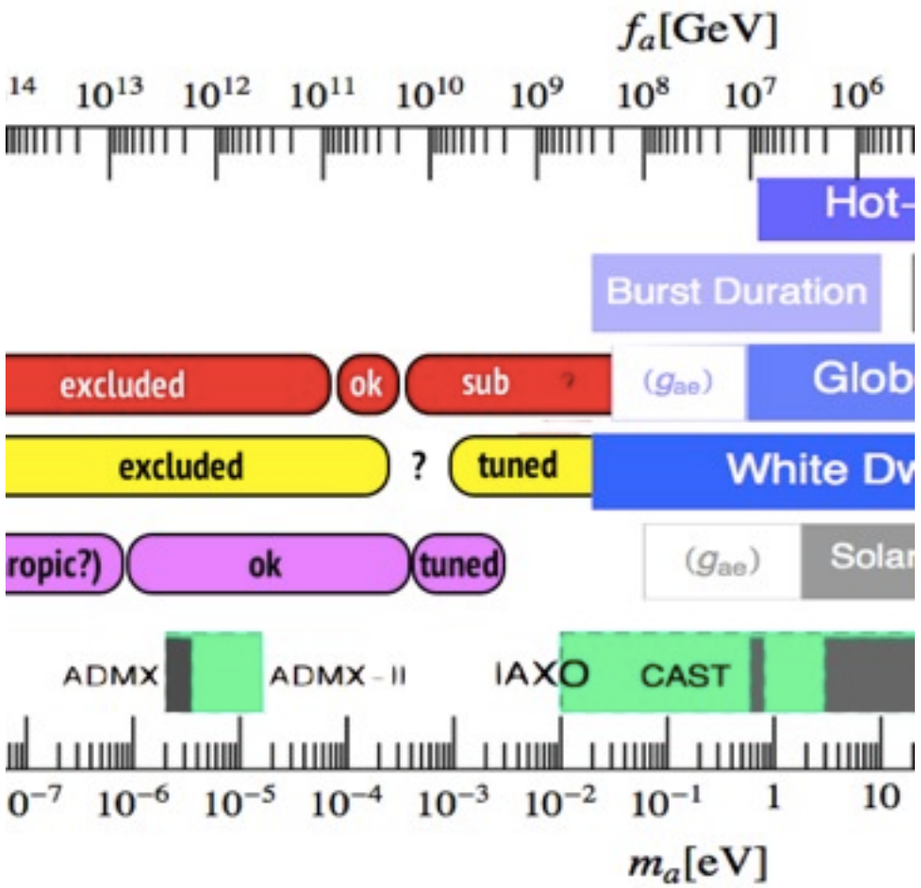




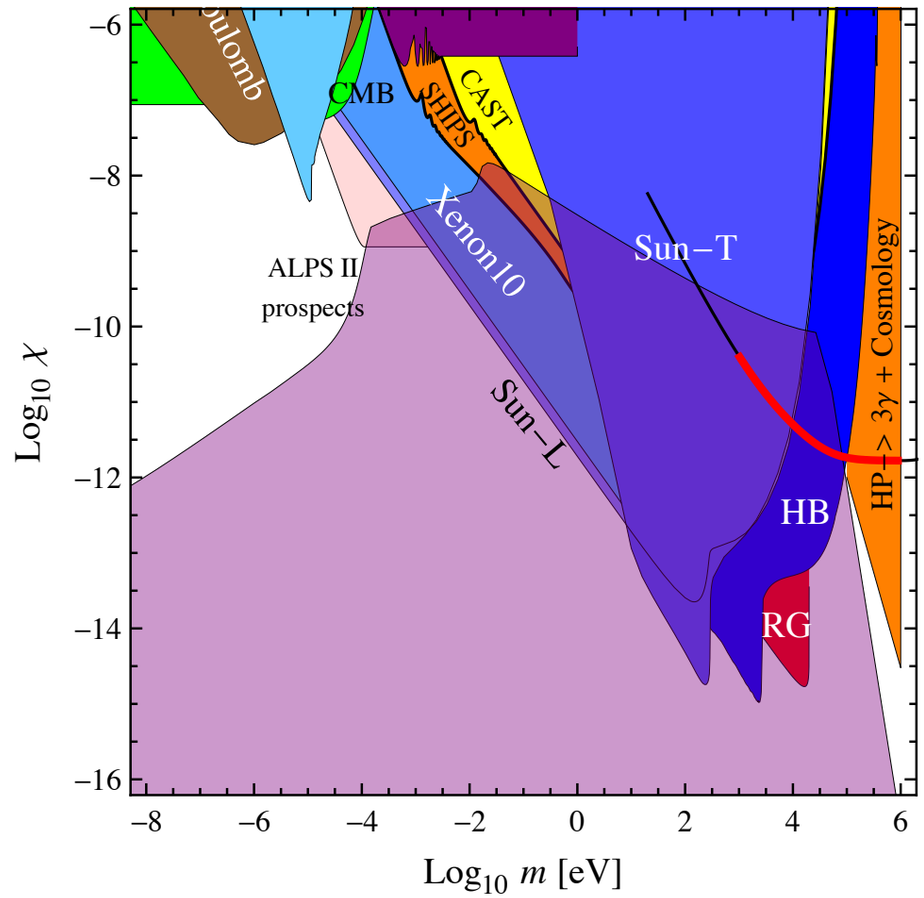
Conclusions

- Sun as a laboratory can help us finding light DM candidates

meV mass axions with IAXO



HPs with DM detectors &or solar precision fits



- Nice complementarity but we need more DD experiments!

Many things are happening... ask me!