ASTROPHYSICS WITH FEEBLE PARTICLES*

WG3 science cases:
state-of-the-art &
what should be done.

* not only ALPs.

NEW vs STANDARD PHYSICS

Immediate goal: the use of astronomical sources as laboratories to probe new physics.

Future perspective: the use of WISPs as new messengers.

- **Astronomical observables:**
  - Stars - from the Sun to supernova progenitors, including compact remnants (WDs and NSs)
  - Stellar explosions (supernovae)
  - Active galactic nuclei (AGNs, Quasars, Blazars….)
- **TOOLS:**
  - Models of these astronomical sources
  - Accurate measurements: photometry, spectroscopy, astrometry …….

NEW vs STANDARD PHYSICS

- **The general method is simple:**
  1. **identification of astronomical sources much sensitive to the new physics ingredient,**
  2. **comparisons between theoretical predictions (models) and source properties (observations).**
- To be competitive with laboratory experiments, the error budget should be reduced as much as possible.
- **The main issue is the realistic evaluation of all the uncertainties, those affecting both the theoretical predictions and their observational counterparts.**
- The main risk is to underestimate the global error, thus misinterpreting discrepancy between theory and observations

A straightforward example.

- Stellar models are obtained by solving a set of equations describing the physical structure and the chemical evolution.

- For instance, consider the energy balance equation:

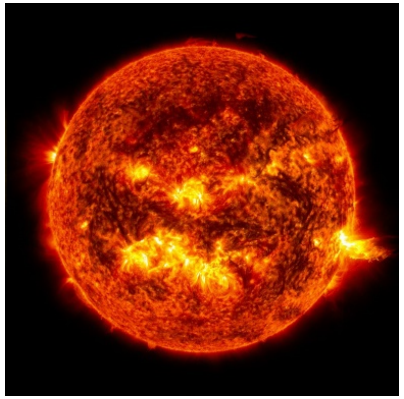
$$\frac{dL}{dr} = (\epsilon_N + \epsilon_g - \epsilon_\nu) 4\pi r^2 \rho \quad \Rightarrow \quad L = \int_0^R \frac{dL}{dr} dr$$

ϵ_N → nuclear energy rate

ϵ_g → gravitational energy rate

ϵ_ν → thermal neutrino energy loss

To be compared to:



Hints of new physics or systematic errors ?

Suppose to find a discrepancy between *theoretical predictions* and *observations*. It may be due to:

- Uncertainties affecting the theoretical recipe and/or the observations
- **Missing physics!!!**

Some example of missing physics:

- **non-vanishing neutrino magnetic moment. It would enhance ϵ_ν**
- **non-standard energy sink: $\epsilon_N + \epsilon_g - \epsilon_\nu - \epsilon_X$**

Some example of theoretical errors:

- **in general, uncertainties affecting $\epsilon_N, \epsilon_g, \epsilon_\nu$ $or\ T(r), \rho(r)$, e.g., unknown low-energy nuclear states may affect fusion cross sections (changing ϵ_N).**

Some example of observational errors:

- **statistical and systematic errors affecting photometry, parallaxes, light extinction**

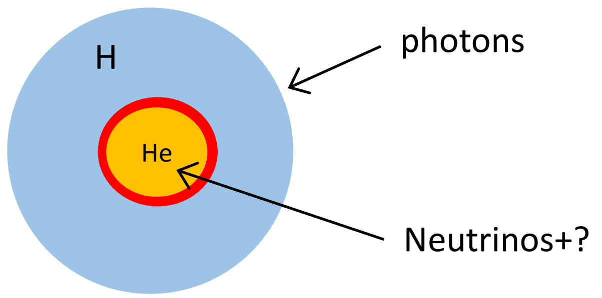
………

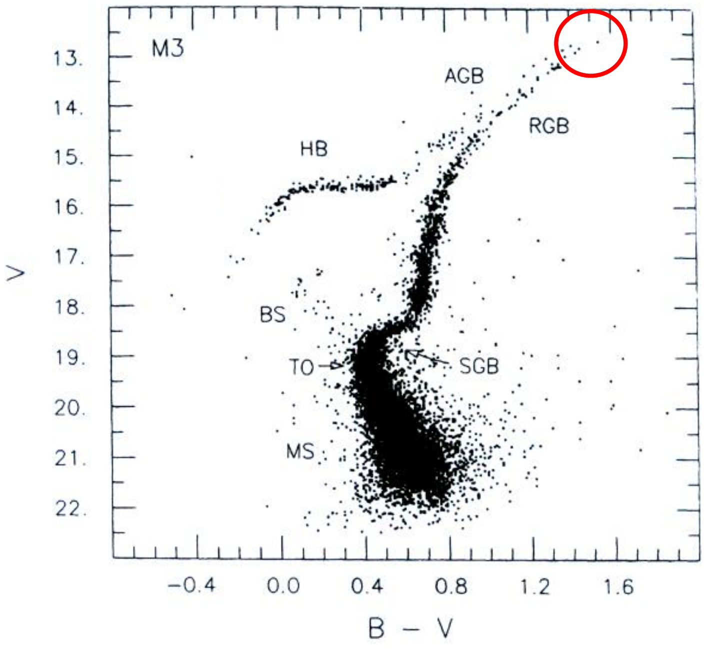
Science cases for WG3: just a few!

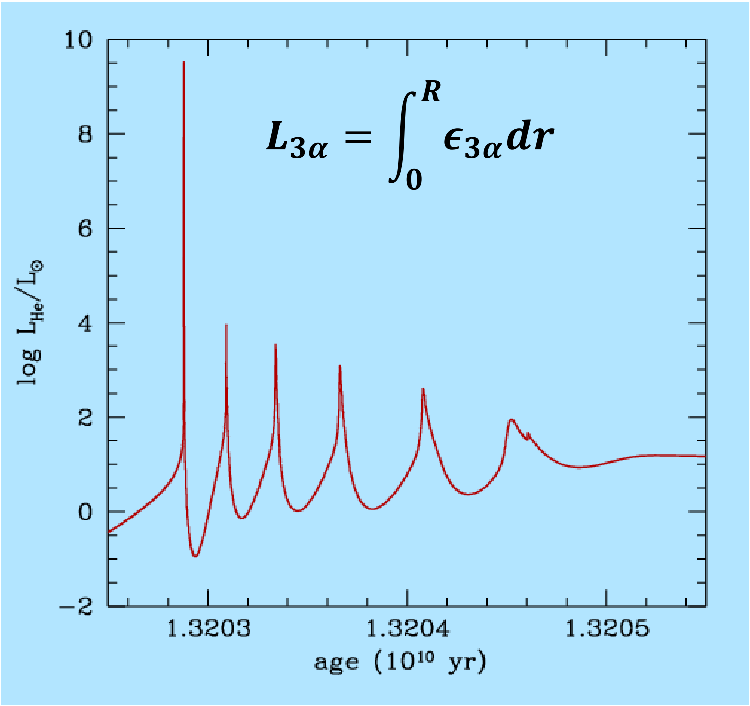
- The Sun (synergy with WG4)
- Globular cluster stars: RGB and HB stars
- Compact remnants of stellar evolution: WDs and NSs
- Final destinies of stellar evolution: SNe and SNe progenitors
- Extragalactic WIMPs sources: Blazars
- Dark matter halos (synergy with WG2)
- ……………………..

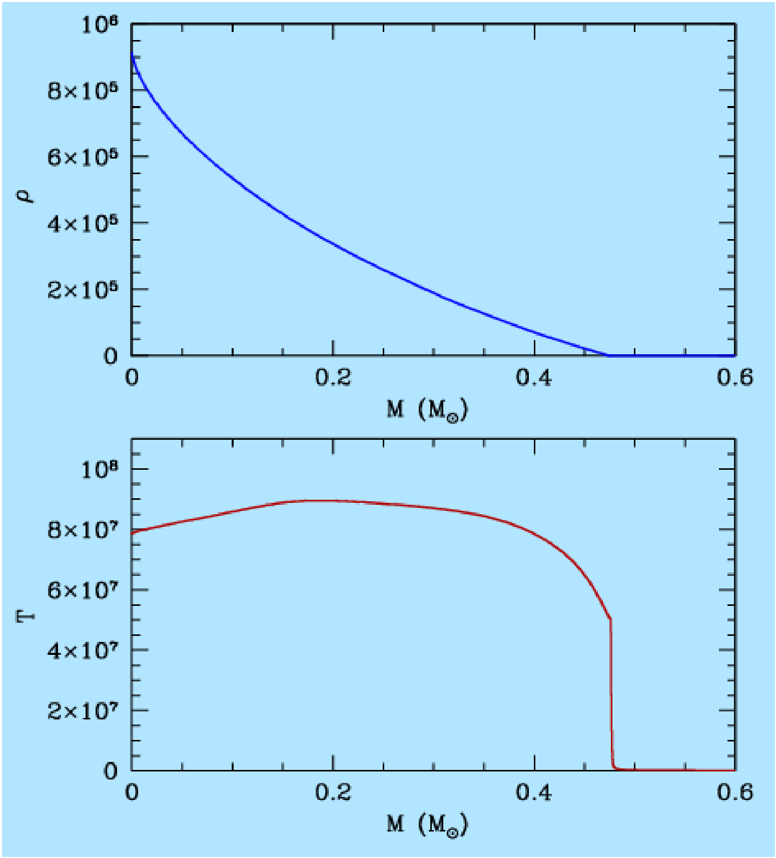
The RGB tip of Globular Clusters

- The tip of the red giant branch (RGB) coincides with the thermonuclear runaway powered by the He ignition (3α) within the degenerate core of a low-mass star (typically 0.8-0.9 M$_\odot$).
- The observable used to constrain the new physics is **the luminosity of the RGB tip**, which is sensitive to concurrent actions of energy sources (nuclear+ gravity) and energy sinks (plasma neutrinos+ bremsstrahlung axions+?).

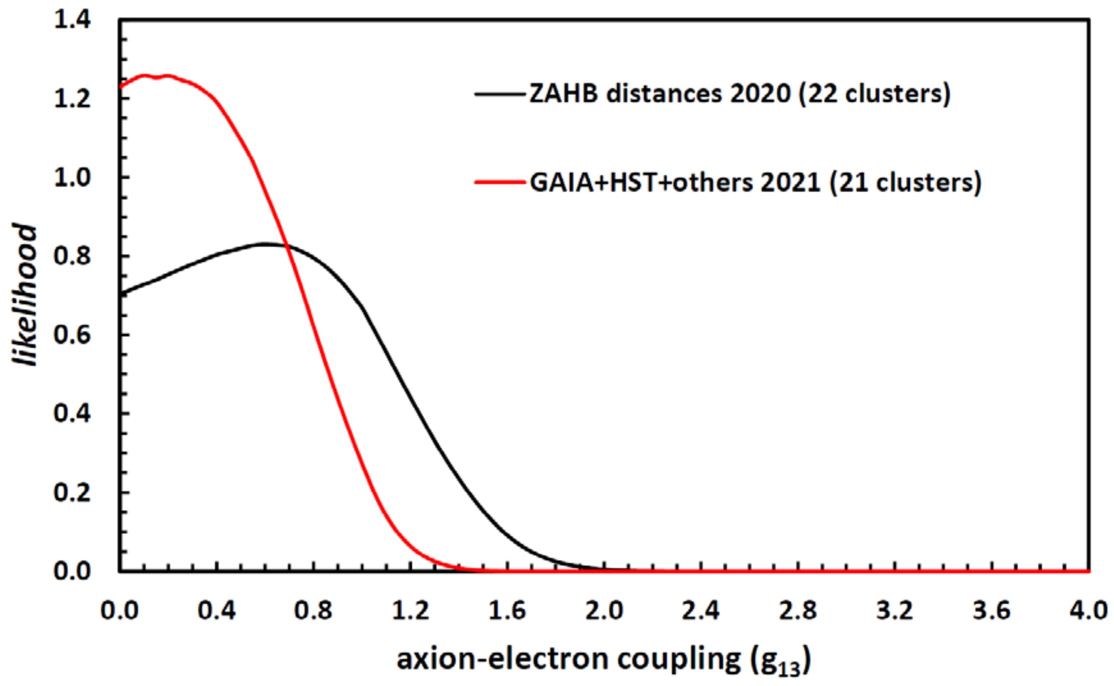


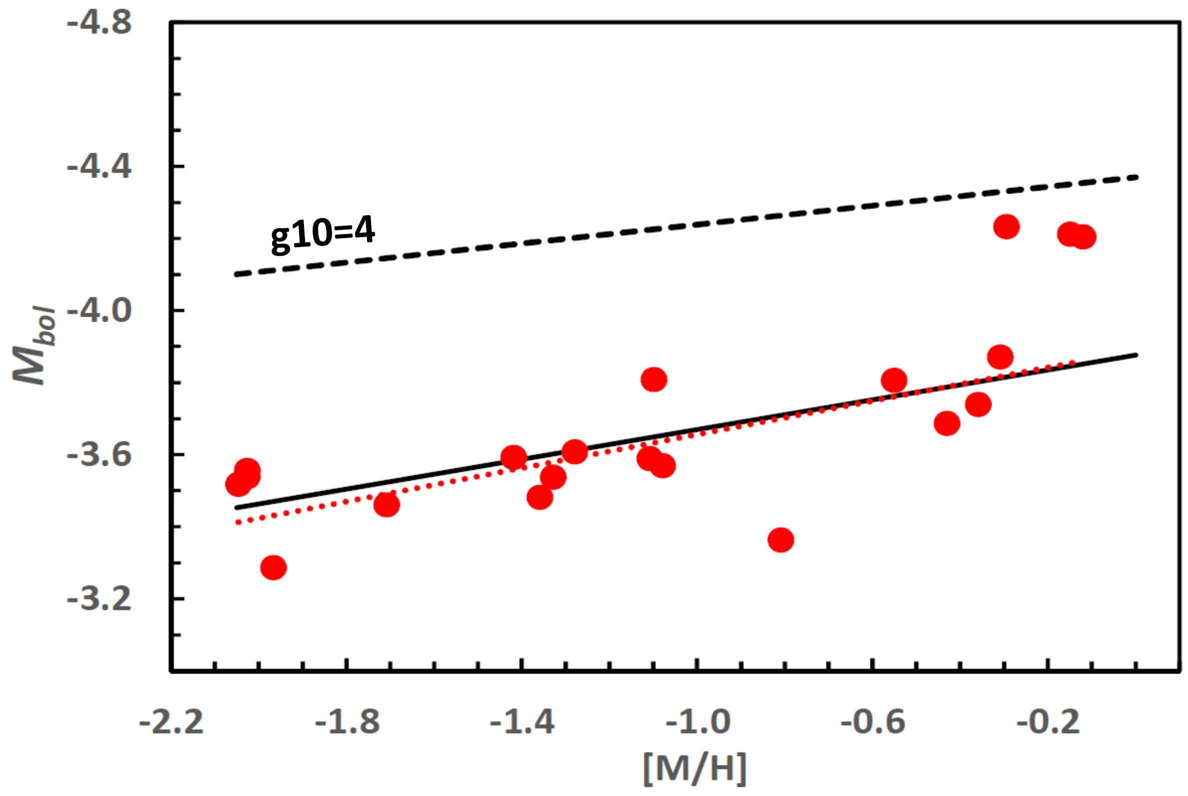






Tools & Methods:
global error analysis
(theory+observations)





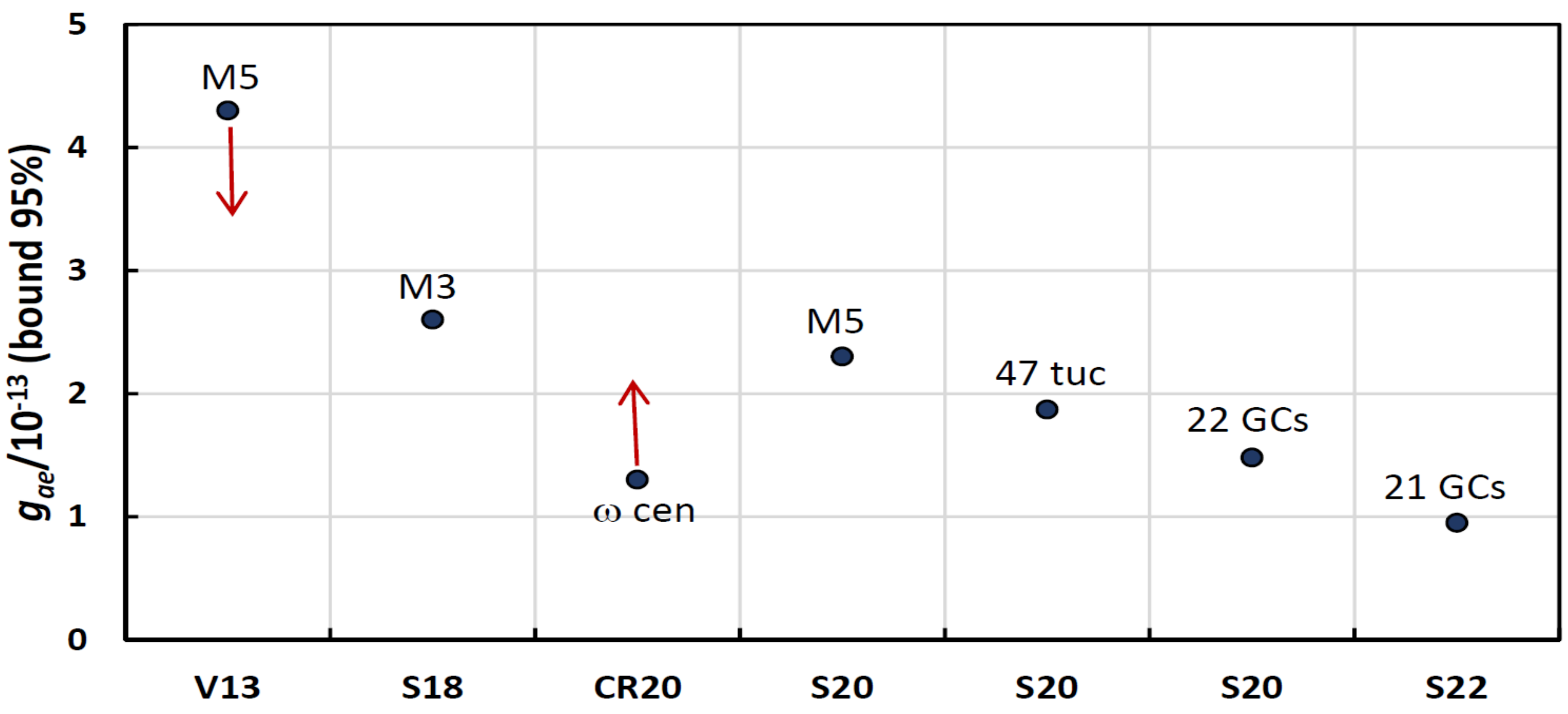
g_{ae} = 0 (black-solid line) and g_{ae} = 4 10^{-13}(black-dashed line). The red-dotted line represents the least square fit of the 21 observed bolometric magnitude.

Result:

hint 68%: $g_{ae}/10^{-13} = 0.10^{+0.22}_{-0.10}$

bound 95%: $g_{ae}/10^{-13} < 0.96$

the most stringent bound for the axion-electron coupling.



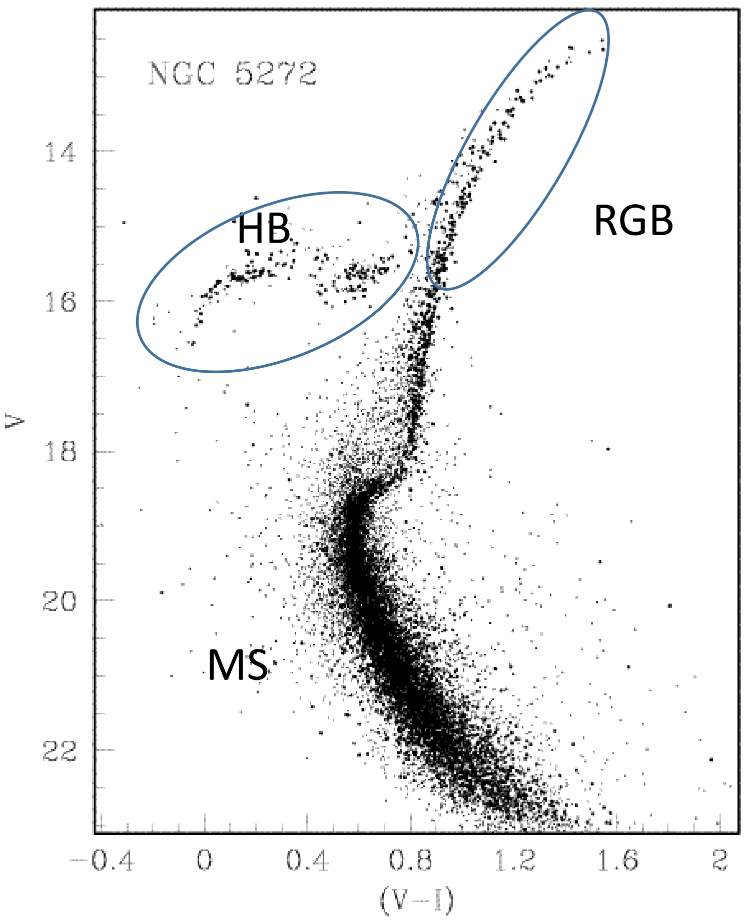
V13=Viaux+ 2013 - S18=Straniero+ 2018 – CR20=Capozzi & Raffelt 2020 – S20= Straniero+ 2020 – S22=present work

Some Remarks:

- V13 underestimate L_{tip} theory, because of the weak 3α screening (no ion-electron couplings).
- CR20 underestimate the ω Cen distance (kinematic), because of the ellipticity of this cluster.
- S20, for 47 tuc use distance from GAIA DR2 parallax. For the others, use ZAHB normalized to 47 tuc.
- S22 revised distances after GAIA DR3 .

$R=N_{HB}/N_{RGB}$ parameter

The number of stars observed in a given portion of the CM diagram is proportional to the time spent by a star in this region. ALPs ***electron coupling (Bremsstrahlung)*** affects ***N_{RGB}***, while **photon coupling (Primakoff**) affects ***N_{HB}*** .

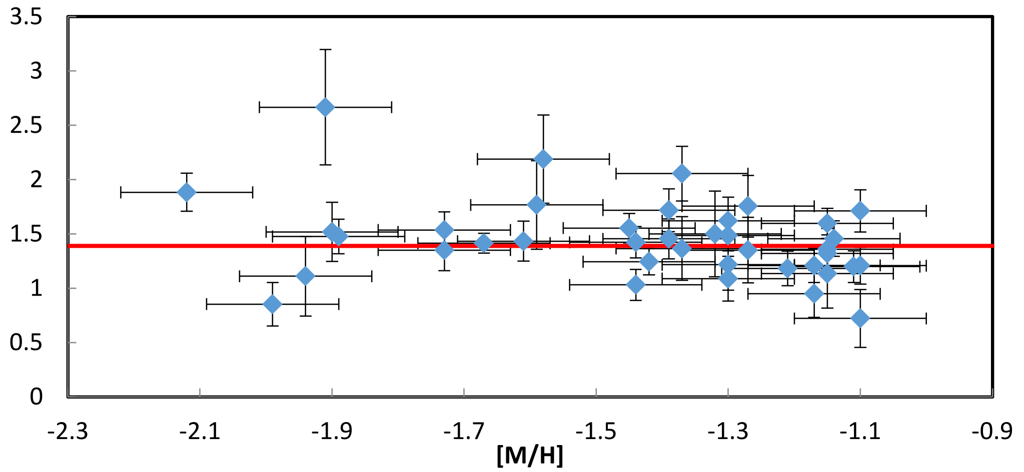


$$R = \frac{N_{HB}}{N_{RGB}}$$

- R does **not depend on metallicity, distance, light absorption and age**.
- R **depends on Y (!!)**

R

39 GCs (from the Salaris et al 2004 catalog)



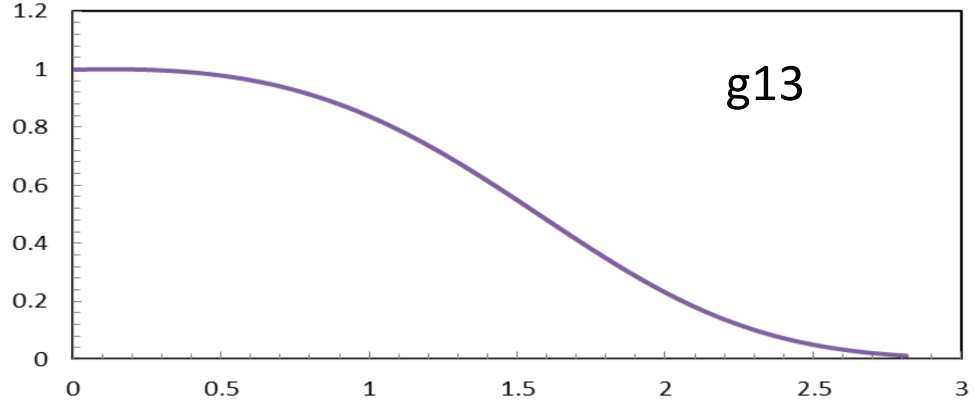
<R> = 1.39±0.03

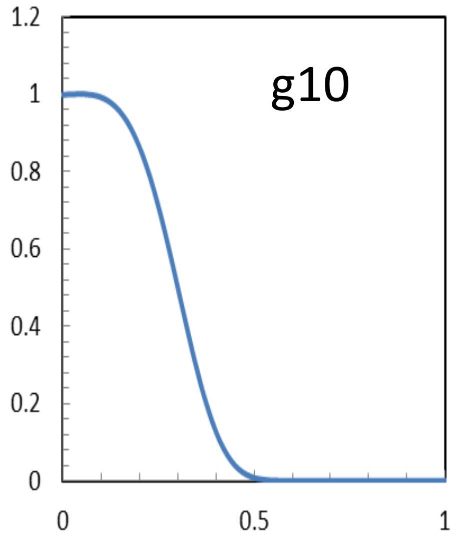
Combined Likelihood:

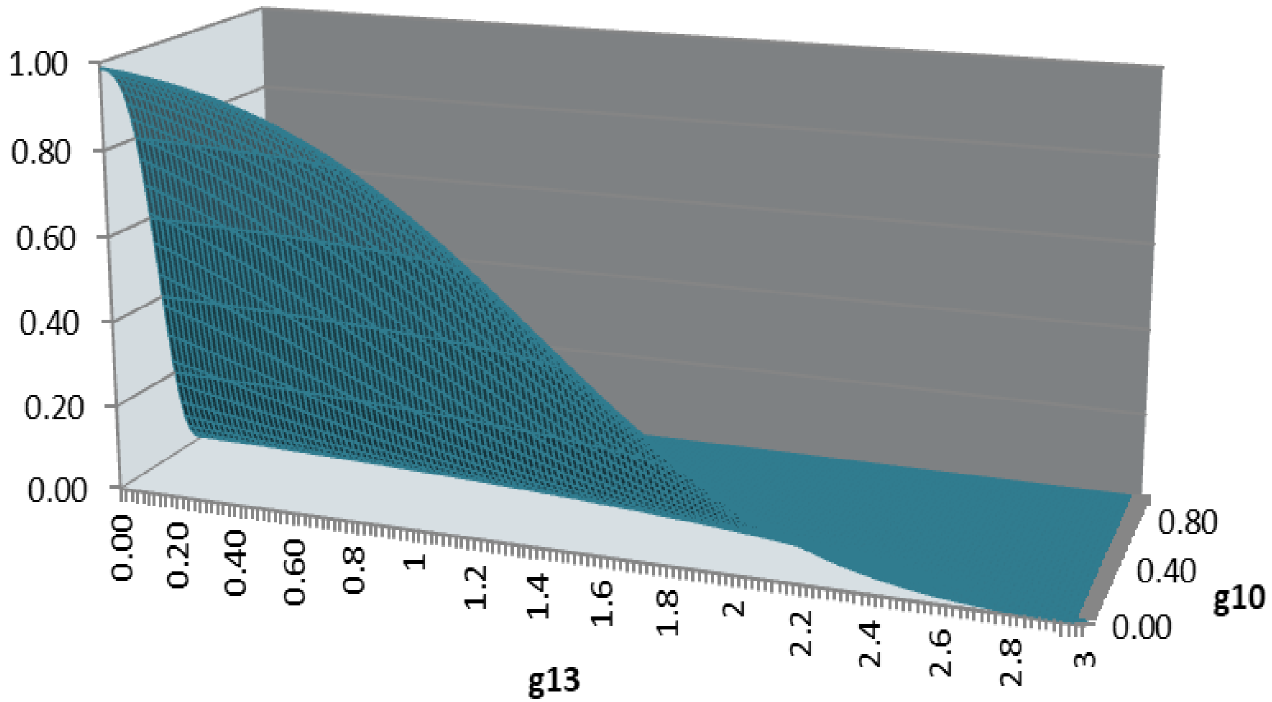
$$L(g13, g10) = \exp\left[-\frac{(R_{th} - R_{ex})^2}{\sigma_{ex}^2 + \sigma_Y^2 + \sigma_{th}^2}\right]$$

Error budget:

R_{ex}	±0.03
Y	**±0.015**
$\mathbf{R_{th}}$	**±0.04**

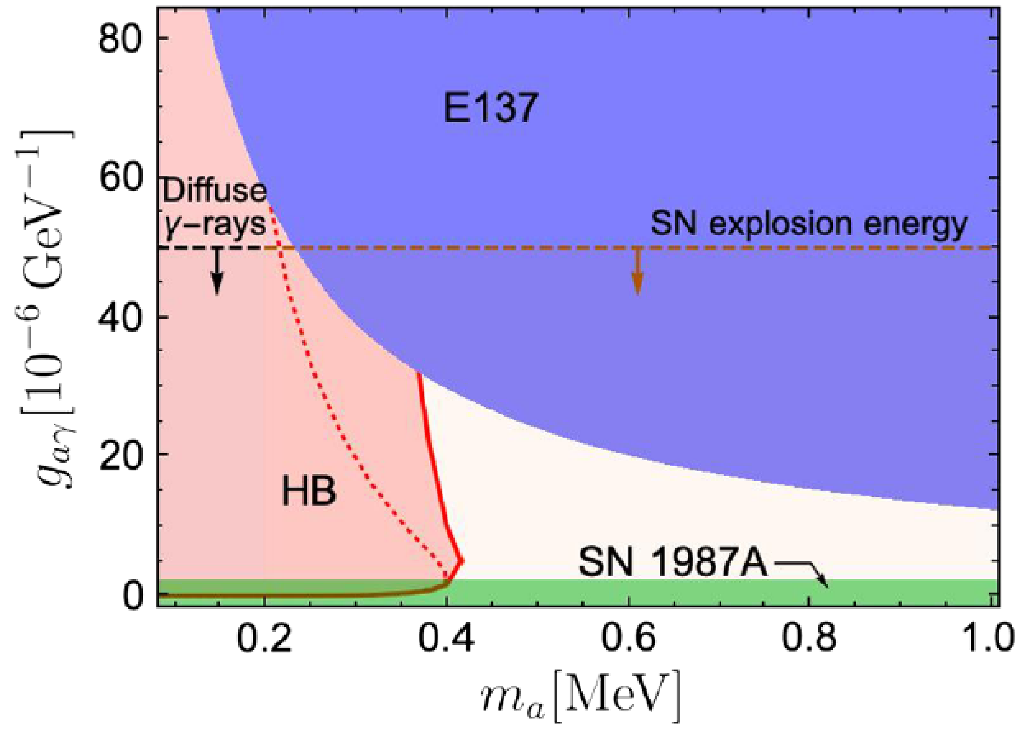






Upper bounds 95% C.L. (m_a< 1 keV) **$g_{a\gamma}$< 6x10^{-11} GeV^{-1} and g_{ae}< 2.6x10^{-13}** *(Ayala et al. 2014 , Straniero et al. 2017).*

For more massive ALPs, ***photon coalescence and ALPs trapping*** *play relevant roles: Carenza et al. 2018, Luente et al. 2022.*



- ***Main issues: He abundance, multiple populations, poor statistics***
- ***Theoretical uncertainty:*** **semiconvection, $^{12}C(\alpha,\gamma)^{16}O$**

White dwarf cooling

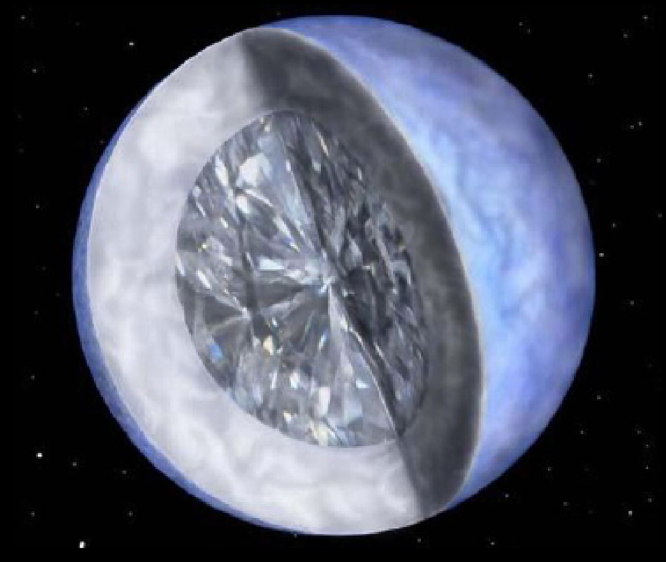
(from a 2016 J. Isern talk)

$$L + L_\nu + (L_e) = -\int_{M_{WD}} c_V \frac{dT_C}{dt} dm - \int_{M_{WD}} T \left(\frac{\partial P}{\partial T}\right)_{V,x} \frac{dV}{dt} dm + (l_s + e_s)\dot{m}_e + (\varepsilon_e)$$

A $L(T_C)$ relationship is necessary to solve this equation
It depends on the properties of the envelope.

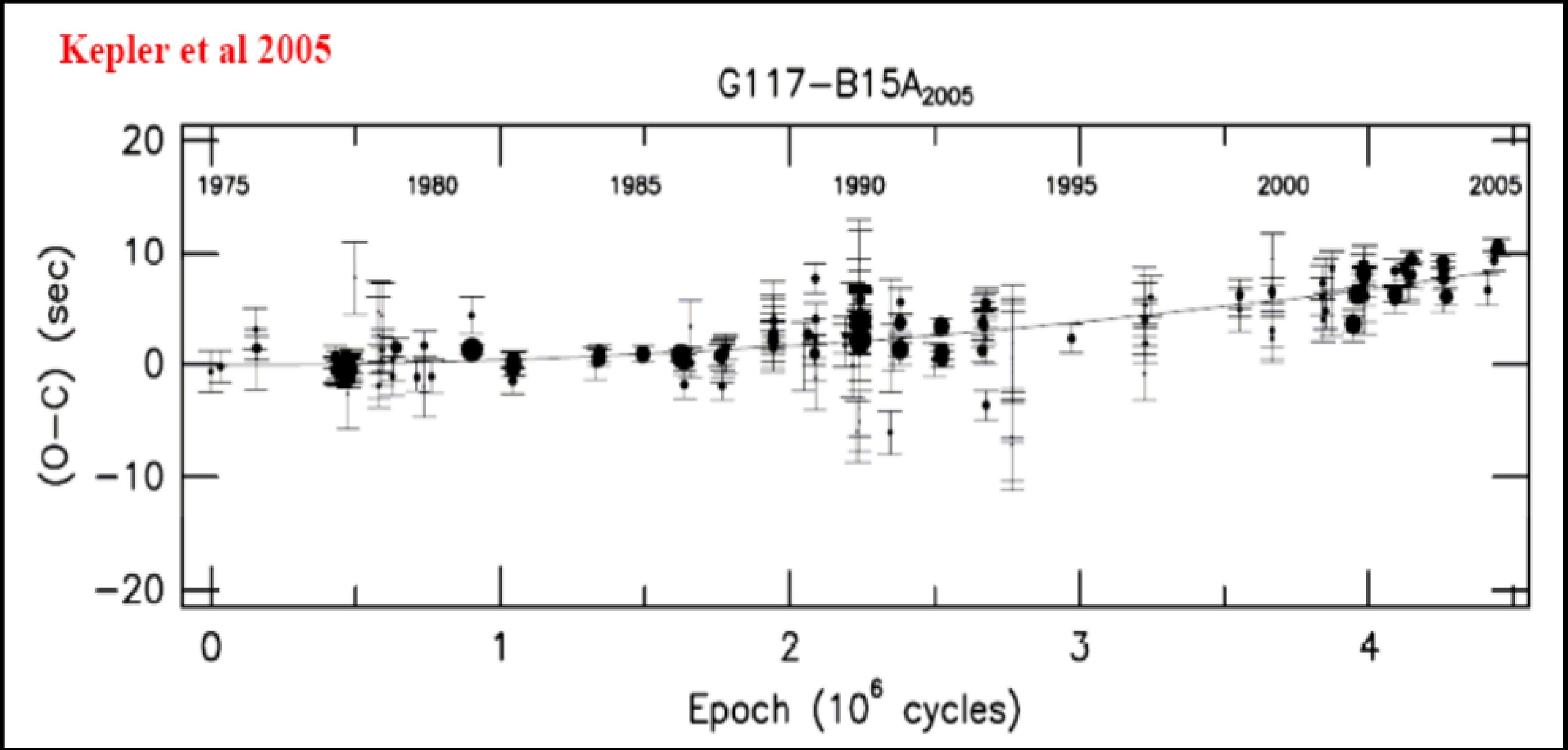
$$L \propto T^\alpha$$

$$\alpha \approx 2.5 - 2.7$$



CO.core/He-envelope/H-envelope

Two ways to test the evolution of WD
From the secular drift of their period of pulsation
From their luminosity function



$$\dot{\Pi} = (12.0 \pm 3.5) \times 10^{-15} \text{ s/s}$$

The first value (Kepler et al'91) was a factor of 2 larger than expected.

Three solutions:

- Observational error
- Whited warfs with "IME" cores
- Exotic source of cooling

The luminosity function

Number of white dwarfs per unit of volume and magnitude versus luminosity

$$n(L) = \int_{M_l}^{M_u} \Phi(M)\Psi\left(T_G - t_{cool} - t_{ps}\right)\tau_{cool}\, dM$$

1.- n(L) is the observed distribution

2.- Φ,Ψ are the IMF and SFR respectively.

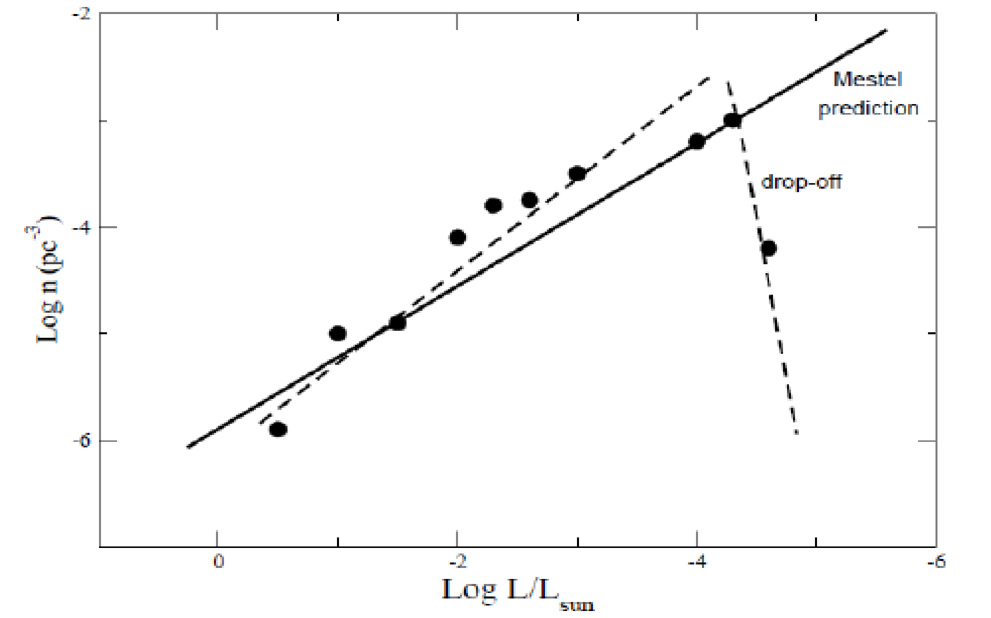
T_G is the age of the Galaxy

3.- t_{cool} is the cooling time

t_{PS} is the lifetime of the progenitor

τ_{cool} is the characteristic cooling time

Hidden an IFMR



If the 3 ingredients are known it is possible to use the WDLF to test new physics

Conclusions:

The recent luminosity functions and the measurement of the secular drift of the pulsation period of DAV suggest that WDs cool down more quickly than expected . But this last result must be revised

Axions or light bosons able to couple to electrons could account for this (m_a ~ 5 meV) extracooling. IAXO could solve the problem

Because of its simplicity, WD could play an important role in the development of new ideas in Physics. Nevertheless, to obtain robust results it will be necessary to remove the uncertainties listed before:

* Extend the observational LF to high and low luminosities
* Obtention of the LF for massive white dwarfs
* Improvement of the cooling models. Envelope is crucial
* Role of binaries
*…

GAIA can provide the necessary precision & accuracy

LSST will probably provide the definitive thrust

SN progenitors.

- The evolution of massive stars during the C burning and beyond is controlled by the thermal neutrino production (Compton) taking place within their core. The same process can also release ALPs.

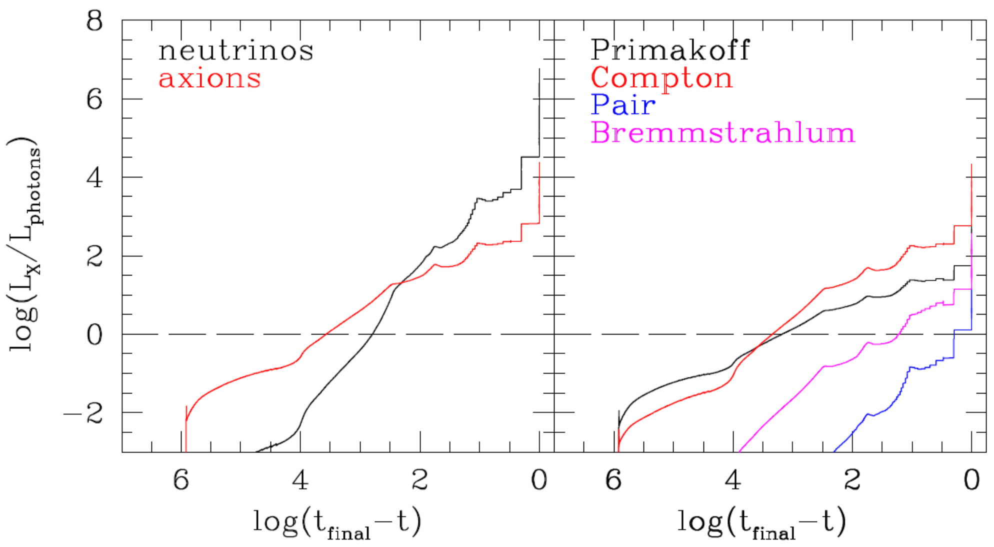


TABLE I. Models of ALP production from Betelgeuse. The stage of stellar evolution is parametrized by the time remaining until the core collapse for Betelgeuse, t_{cc}. See text for the definition of other parameters.

Model	Phase	t_{cc} [yr]	$\log_{10}\frac{L_{eff}}{L_\odot}$	$\log_{10}\frac{T_{eff}}{K}$	Primakoff C^P	Primakoff E_0^P [keV]	Primakoff β^P	Bremsstrahlung C^B	Bremsstrahlung E_0^B [keV]	Bremsstrahlung β^B	Compton C^C	Compton E_0^C [keV]	Compton β^C
0	He burning	155000	4.90	3.572	1.36	50	1.95	1.3×10^{-3}	35.26	1.16	1.39	77.86	3.15
1	Before C burning	23000	5.06	3.552	4.0	80	2.0	2.3×10^{-2}	56.57	1.16	8.55	125.8	3.12
2	Before C burning	13000	5.06	3.552	5.2	99	2.0	6.4×10^{-2}	70.77	1.09	17.39	156.9	3.09
3	Before C burning	10000	5.09	3.549	5.7	110	2.0	8.9×10^{-2}	76.65	1.08	22.49	169.2	3.09
4	Before C burning	6900	5.12	3.546	6.5	120	2.0	0.136	85.15	1.06	31.81	186.4	3.09
5	In C burning	3700	5.14	3.544	7.9	130	2.0	0.249	97.44	1.04	50.62	210.4	3.11
6	In C burning	730	5.16	3.542	12	170	2.0	0.827	129.17	1.02	138.6	269.1	3.17
7	In C burning	480	5.16	3.542	13	180	2.0	0.789	134.54	1.02	153.2	279.9	3.15
8	In C burning	110	5.16	3.542	16	210	2.0	1.79	151.46	1.02	252.7	316.8	3.17
9	In C burning	34	5.16	3.542	21	240	2.0	2.82	181.74	1.00	447.5	363.3	3.22
10	Between C/Ne burning	7.2	5.16	3.542	28	280	2.0	3.77	207.84	0.99	729.2	415.7	3.23
11	In Ne burning	3.6	5.16	3.542	26	320	1.8	3.86	224.45	0.98	856.4	481.2	3.11

Once emitted, ALPs can be converted into photons (X-tays) when traveling within the galactic magnetic field. The signature of this phenomenon can be serched ib the X-ray spectra of galactic supergiants.

TOOLS and Method

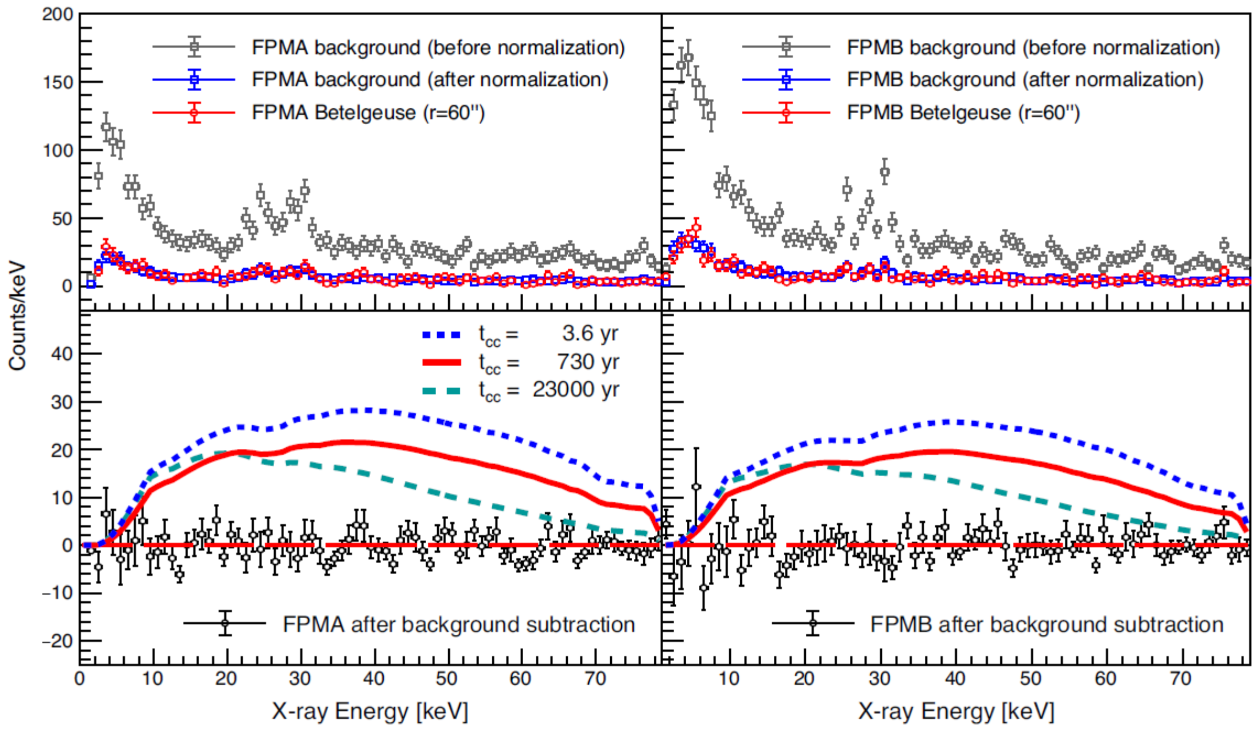
The expected photon flux from a nearby massive star is : →

$$\frac{dN_\gamma}{dEdSdt} = \frac{1}{4\pi d^2}\frac{d\dot{N}_a}{dE}P_{a\gamma}.$$

The ALP-photon conversion probability is [41]

$$P_{a\gamma} = 8.7 \times 10^{-6} g_{11}^2 \left(\frac{B_T}{1\ \mu\mathrm{G}}\right)^2 \left(\frac{d}{197\ \mathrm{pc}}\right)^2 \frac{\sin^2 q}{q^2},$$

where B_T is the transverse magnetic field, q is the momentum transfer, and d is themagnetic field length.



- Top: X-ray spectra from NuSTAR for the Betelgeuse source (red) and background (gray and blue)
- Bottom: Source spectra after subtracting the normalized background. The predicted ALP-produced x-ray spectra assuming B_T = 1.4 μG, mass $m_a=10^{-11}$ eV, and coupling $g_{a\gamma}=1.5 \times 10^{-11}$ GeV−1.

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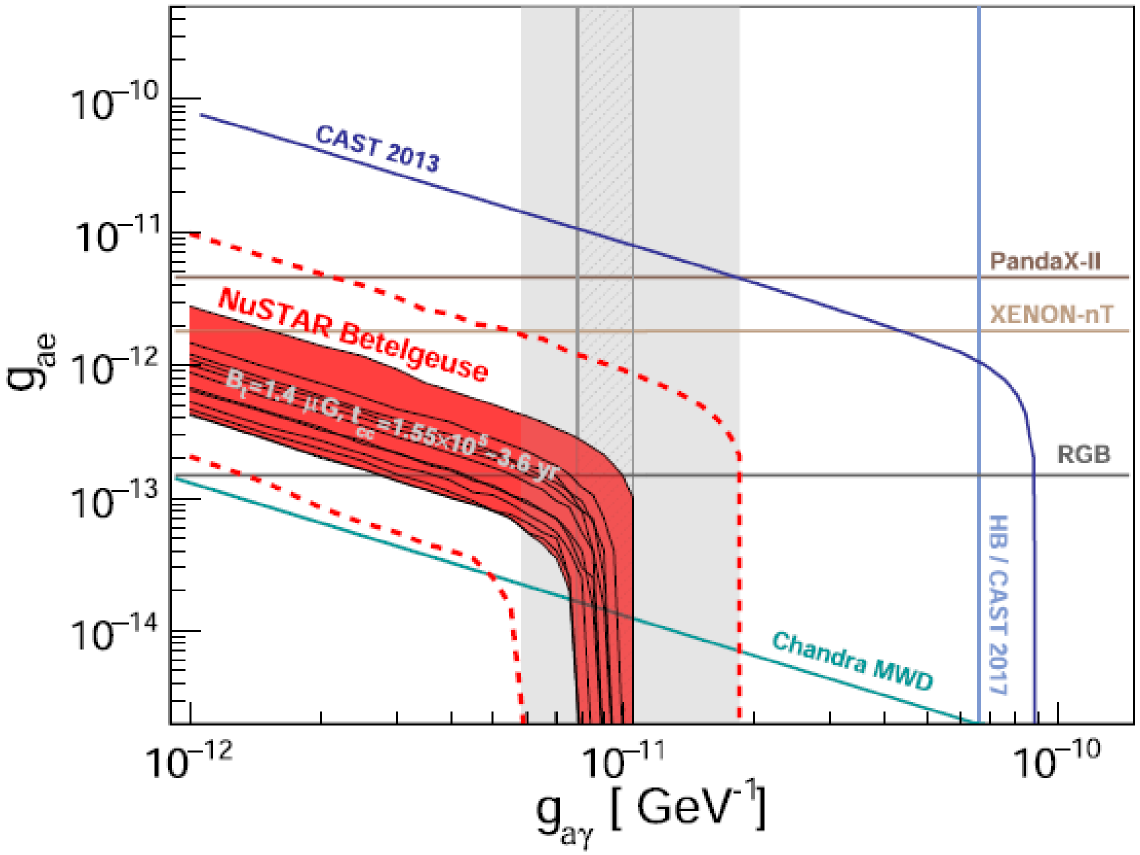
RESULTS

From Mengjiao Xiao et al 2020 and 2022



Perspectives: extend the measure to other nearby red supergiants.

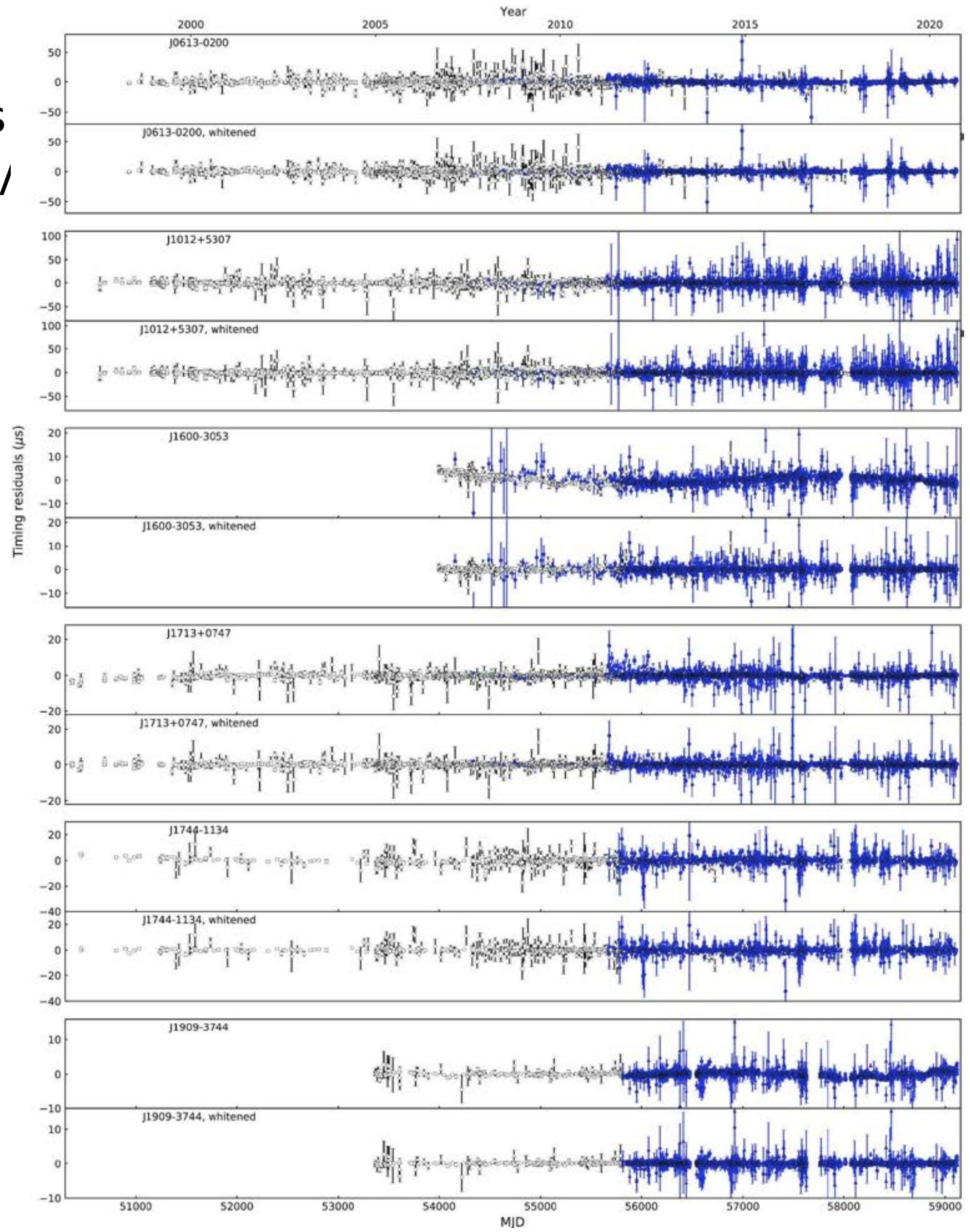
Pulsar timing data (by F. Urban)

- The local distribution of ultra-light dark matter is the coherent superposition of plane waves all with the same frequency. This is true within a patch of size $1/vf$ ~ $1e3/f$ and for a time $1/v^2 f$ ~ 1e6/
- If the dark matter couples to matter, it may produce oscillatory forces on compact bodies, such as pulsars, or on mirrors of laser interferometers.

$$\mathcal{L}_S = \frac{\phi}{\Lambda} R$$

$$\mathcal{L}_V = g\bar{\psi}\gamma^\mu A_\mu \psi$$

$$\mathcal{L}_T = \frac{\alpha}{M_{\rm Pl}} M_{ij} T^{ij}$$



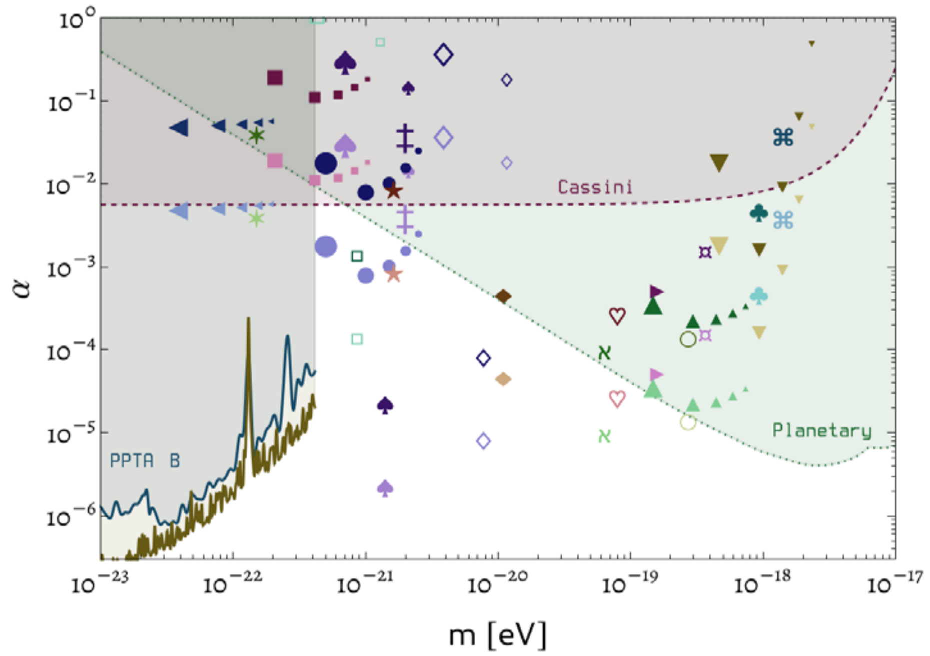
Tools & Methods:

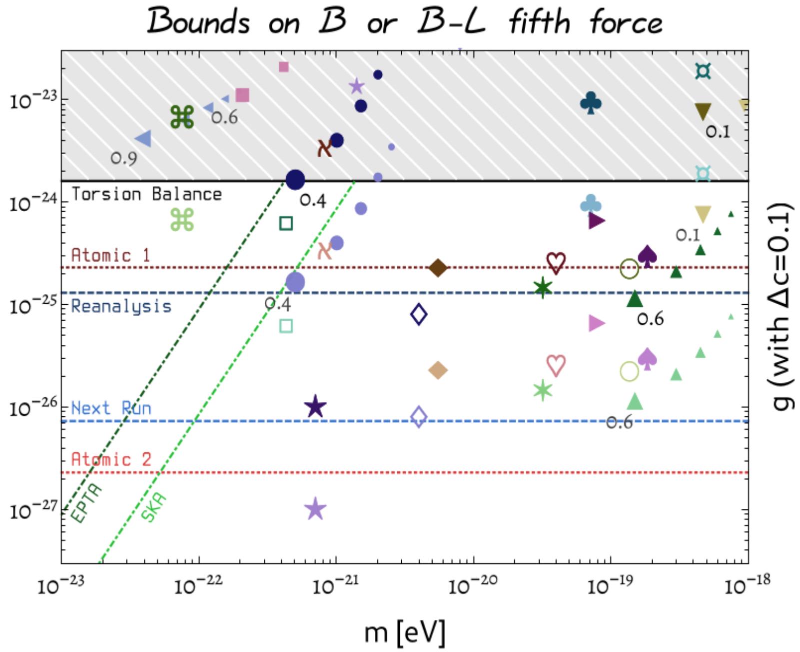
Pulsar timing arrays (PTA), exploits telescopes generally used for radio astronomy to measure the very tiny variations in the times of arrival (ToA) of the pulses emitted by millisecond pulsars (MSP), induced by GWs. The same method may be used to reveal DM-M interactions:

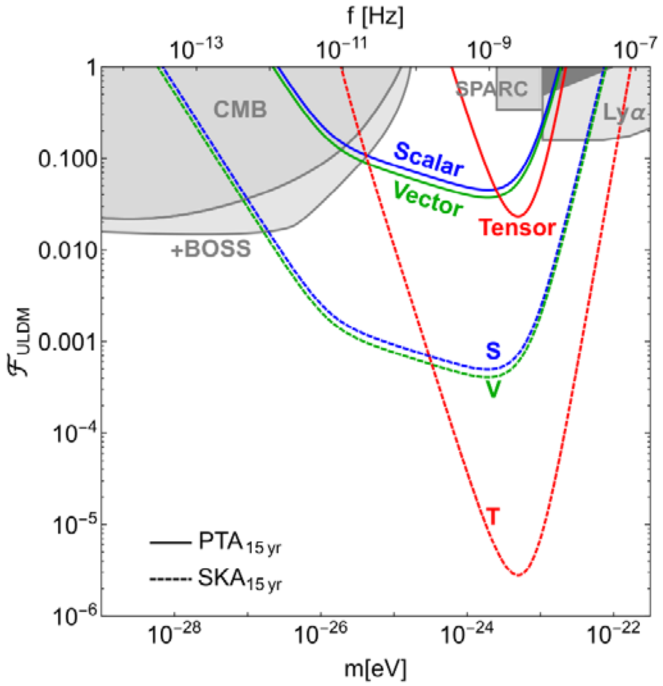
1. When *m~1/P,* the orbit of a binary system experiences secular drift, which we can detected by measuring ToA

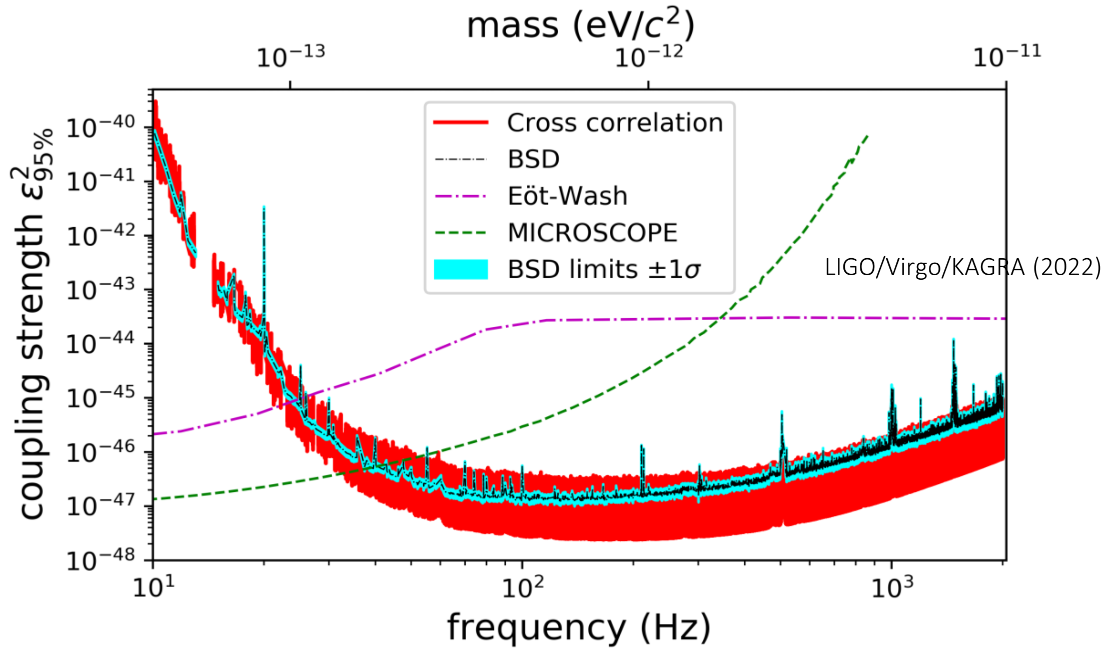
2. Pulsars and the Earth in a pulsar-time-array (PTA) are dragged around by dark matter: this will also show up in ToA data (nHz)

3. Mirrors of a laser interferometer will be subject to the same effect, as they were “immersed” in a continuous massive (scalar, vector, tensor) gravitational wave (mHz to kHz)





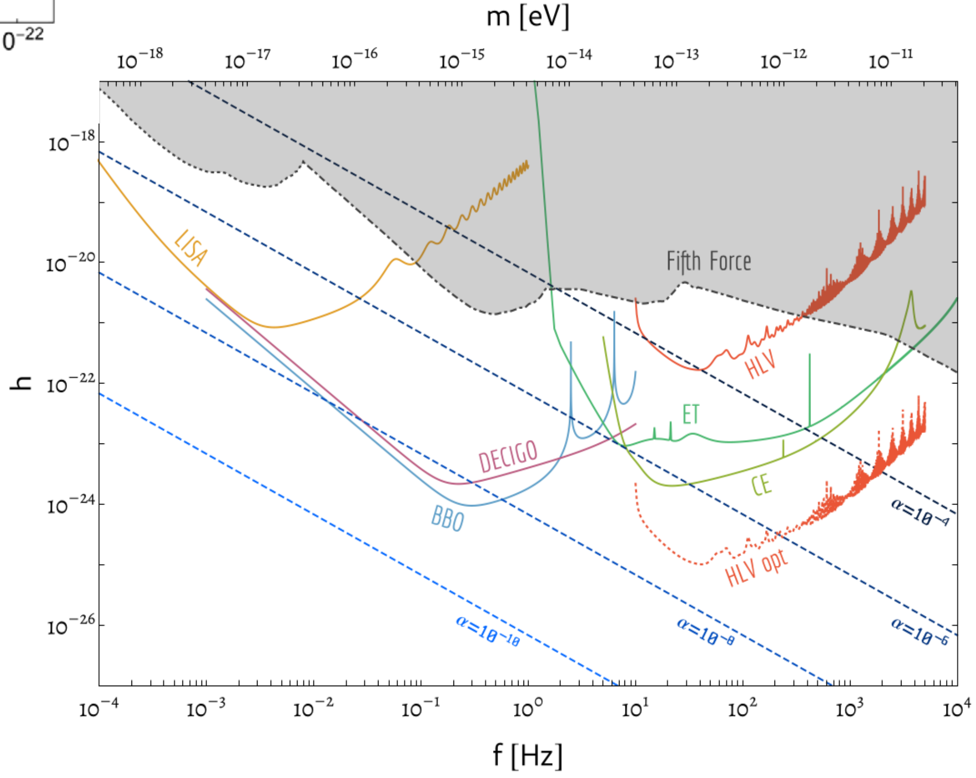




Outlook:

1. ultra-low frequencies

2. interferometers data



D. Blas, D. L. Nacir and S. Sibiryakov, arXiv:1612.06789 [hep-ph]

D. Blas, D. L. Nacir and S. Sibiryakov, arXiv:1910.08544 [gr-qc]

D. López Nacir and FU, arXiv:1807.10491 [astro-ph.CO]

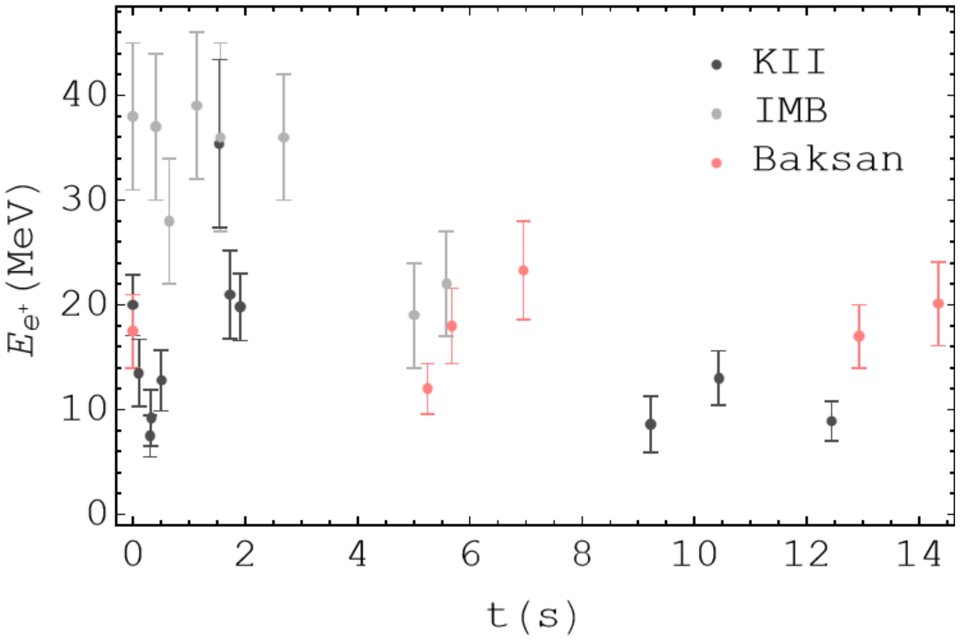
J. M. Armaleo, D. López Nacir and FU, arXiv:1909.13814 [astro-ph.HE]

J. M. Armaleo, D. López Nacir and FU, arXiv:2005.03731 [astro-ph.CO]

J. M. Armaleo, D. López Nacir and FU, arXiv:2012.13997 [astro-ph.CO]

C. Unal, FU and E. D. Kovetz, arXiv:2209.02741 [astro-ph.CO]

Core-collapse Supernovae (by Carenza, Lucente, Vitagliano)

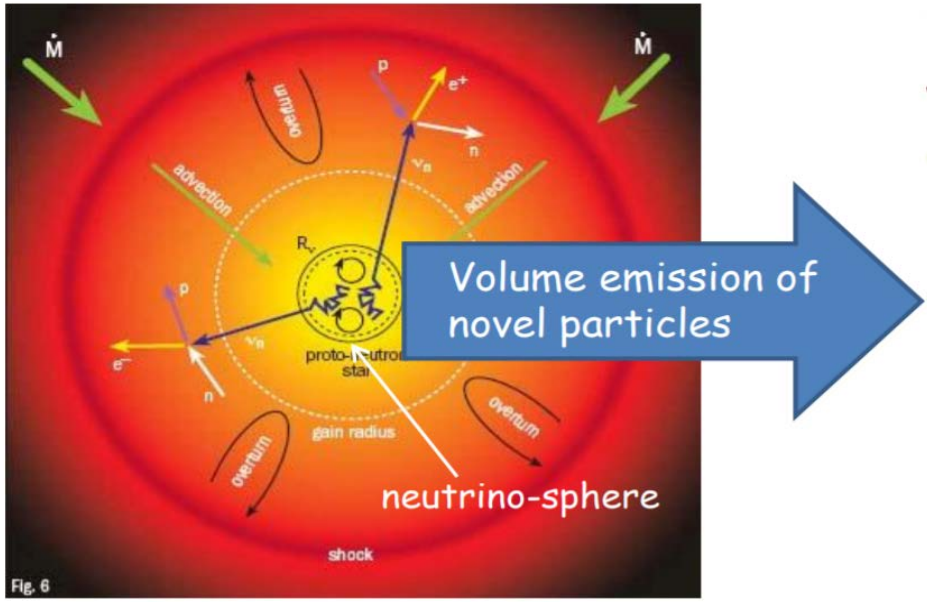


A Core-collapse supernova (SN) is the terminal phase of a massive star [$M \geq 8\ M_{\odot}$].
The 99% of the released energy ($\sim 10^{53}$ erg) is emitted by **neutrinos**.

From **SN 1987** neutrino burst observations:

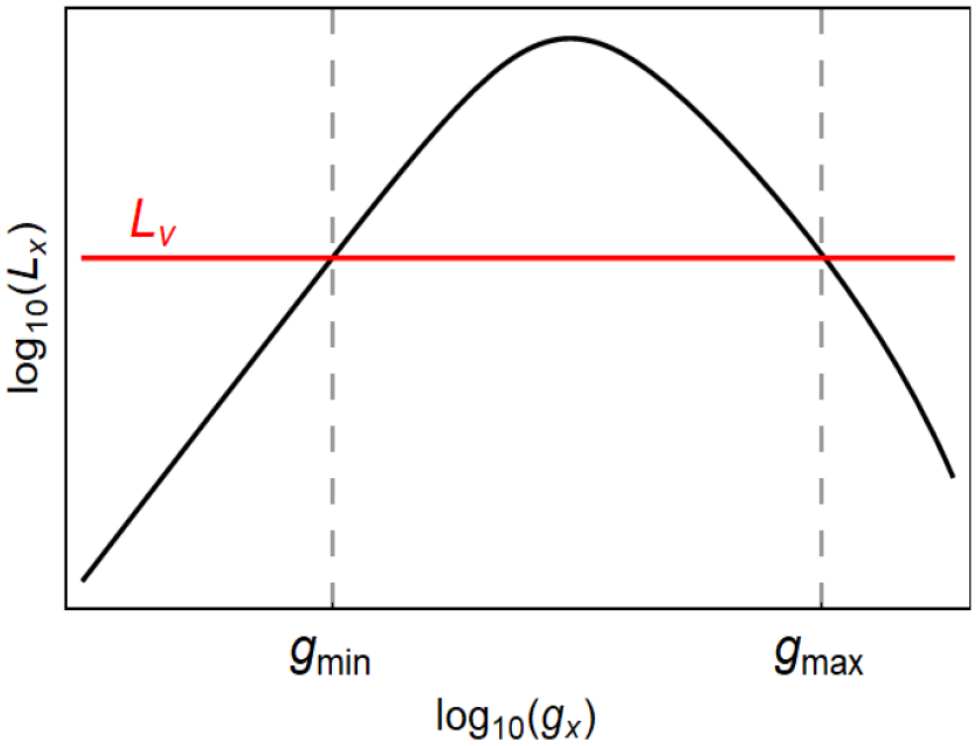
- **Duration** of the burst $\sim$ **10 s**
- $< E_{\nu} > \approx$ **15 MeV**

WISPs production in SNe:
additional ***energy-loss*** channel affecting the duration of the neutrino burst if the axion production is comparable to the neutrino emission **[G. Raffelt, Lect. Notes Phys. 741 (2008)]**.



Cooling bounds on WISPs

The SN cooling argument can be exploited to constrain axions and other WISPs, e.g. sterile neutrinos **[L. Mastrototaro et al., JCAP 01 (2020), 010]** and dark photons **[J.H. Chang et al., JHEP 09 (2018), 051]**.



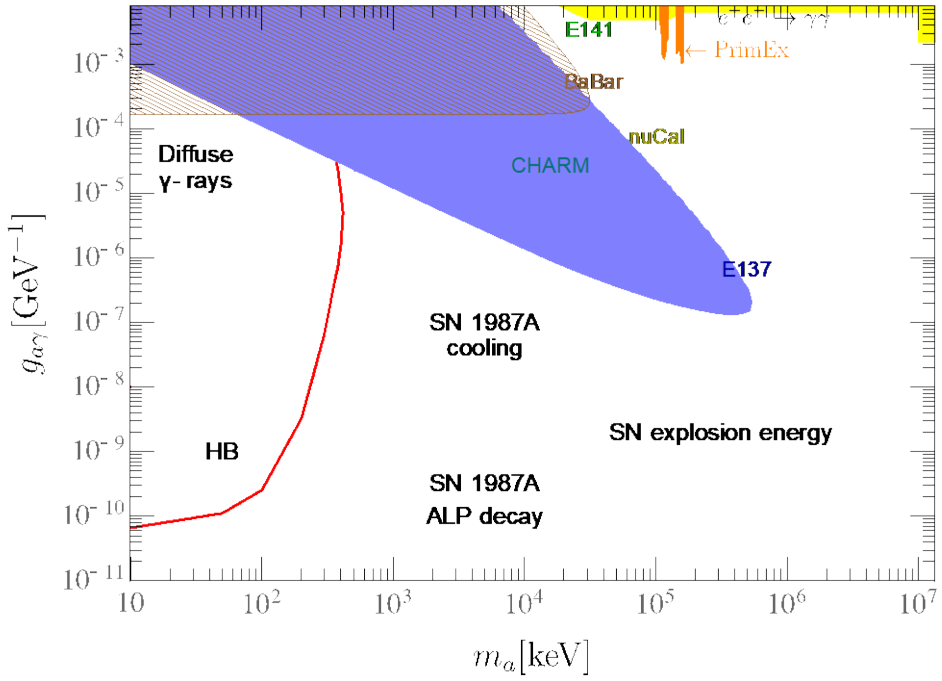
G. Raffelt and D. Seckel, PRL 60 (1988) 1793
A. Caputo et al., JCAP 08 (2022) no.08, 045

For larger values of the coupling WISPs are trapped in the SN core and the axion **luminosity** drops. Couplings $g_{\rm min} < g_x < g_{\rm max}$ are excluded.

From g_{aN}:

$$m_a \lesssim 11 \text{ meV}$$

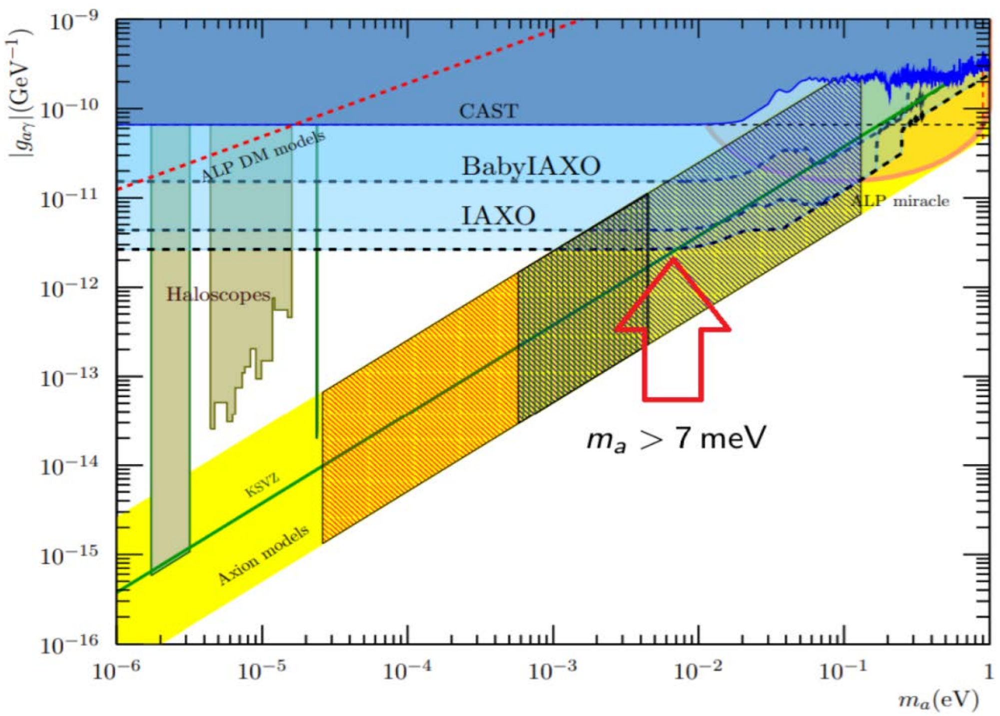
for QCD axions **[P. Carenza et al., JCAP 10 (2019) no.10, 0.16]**



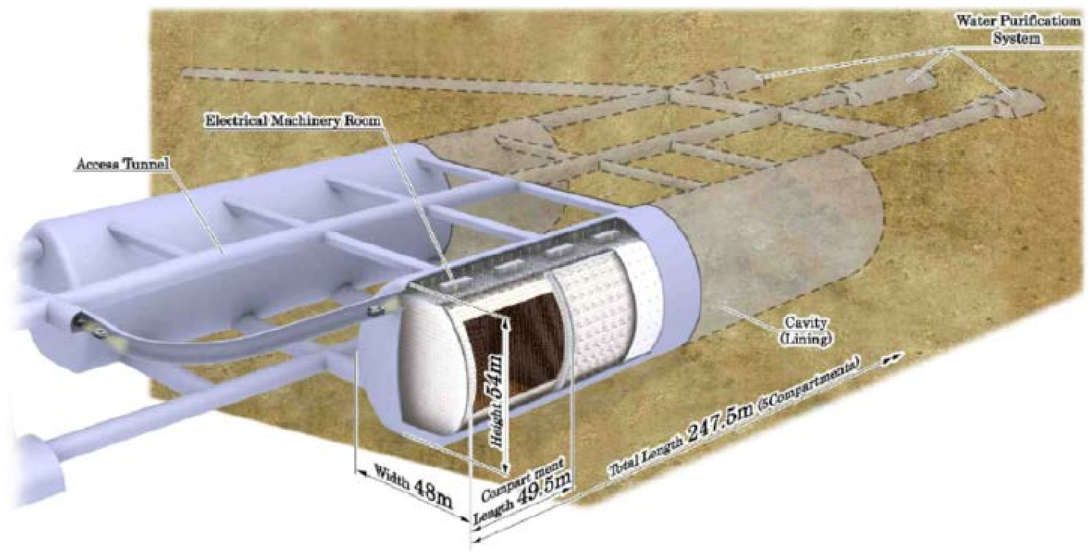
G. Lucente et al., JCAP 12 (2020), 008
A. Caputo et al., Phys. Rev. D 105 (2022) no.3, 035022
A. Caputo et al., Phys Rev. Lett. 128 (2022) no.22, 221103

Future perspectives

The future helioscope IAXO can investigate the QCD axion band from $m_a > 7\,\text{meV}$, the SN bound region **[E. Armengaud et al., JCAP 06 (2019), 047]**.



SN simulations can be revised in the next future by including WISPs self-consistently, to study how they could affect the neutrino signal in the trapping regime.



In the case of a **future Galactic SN explosion**:

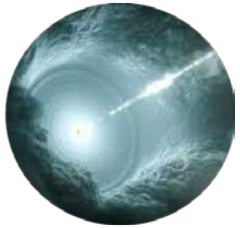
- Possible WISP signal in next-gen large underground neutrino detectors, e.g. HyperKamiokande.
- Possible observation of a WISP-induced gamma-ray signal (need to fill the *MeV sensitivity gap*).

Very high-energy gamma rays (by F. Calore)

- Very high-energy gamma rays can competitively probe ALPs-photon mixing for ALPs masses from neV to ueV.

$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma} \mathbf{E} \cdot \mathbf{B} a$$

- **ALPs sources**: Galactic (e.g. pulsars) and extragalactic (blazars, galaxies) gamma-ray emitters, whose photons are converted *in situ* into ALPs thanks to the strong magnetic fields.

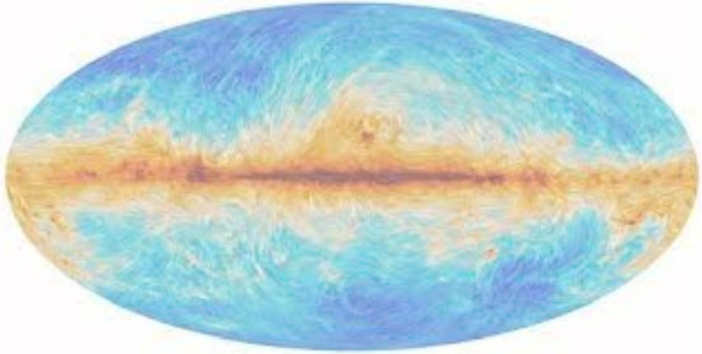


$$\left(\frac{dN_\gamma}{dE}\right)_{\mathrm{P}}$$

In-situ photon spectrum

$$\left(\frac{dN_a}{dE}\right)_{\mathrm{S}} \propto P_{\mathrm{S}}(\gamma \to a) \times \left(\frac{dN_\gamma}{dE}\right)_{\mathrm{P}}$$

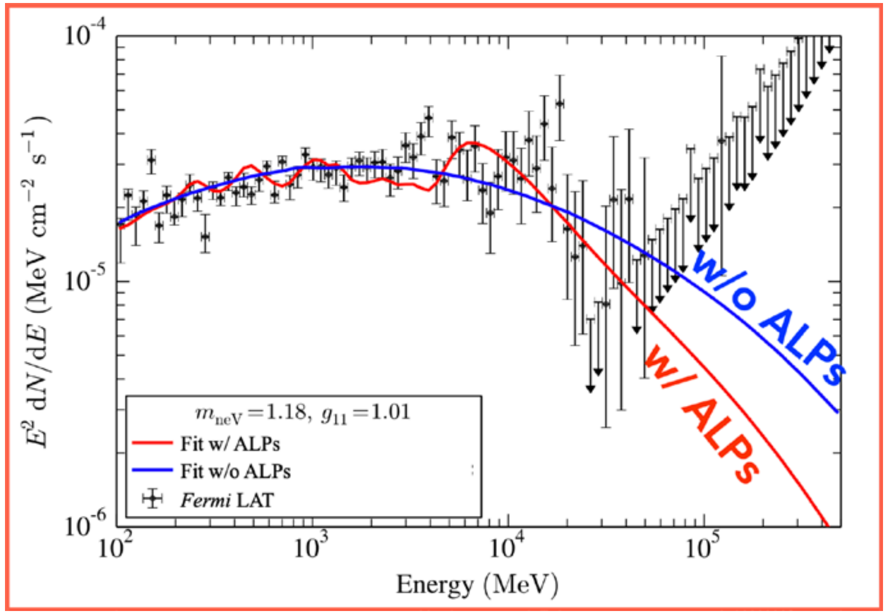
In-situ conversion into ALPs



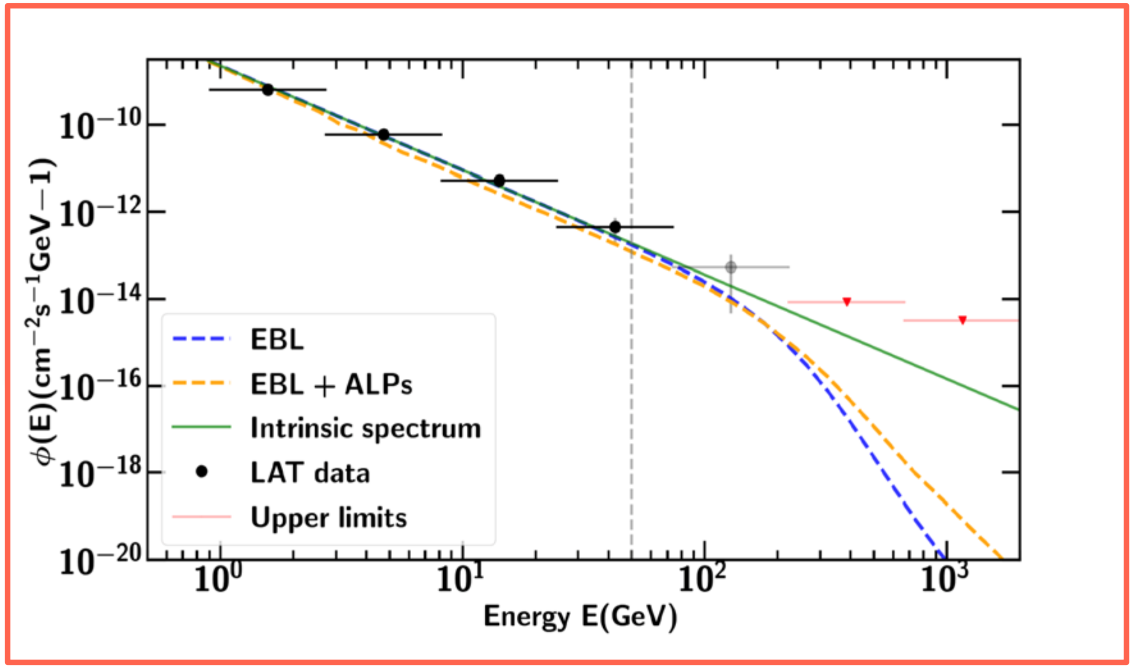
Re-conversion into photons in Galactic B field

Tools & Methods

Observable 1: Search for **spectral distortion** in spectra of Galactic and extragalactic sources (e.g. NGC1275, Mrk421)

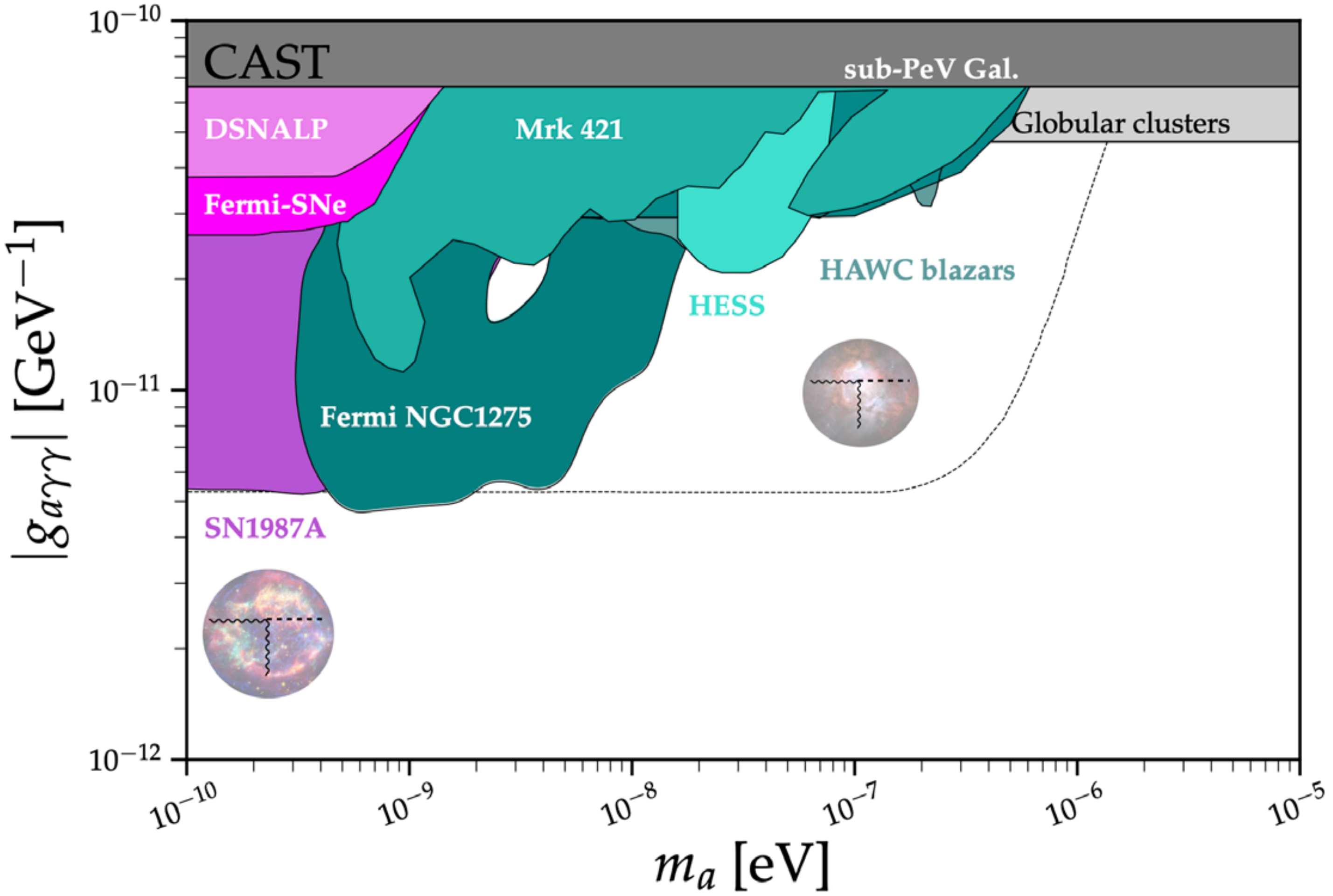


Observable 2: Search for **photons appearance** from photon-ALPs *in source* conversion (HAWC blazars, sub-PeV Gal.)



Common methods:

- Target(s) selection and data analysis
- Spectral analysis w/ and w/o ALPs signal, model comparison
- ALPs modelling: *in source* and Galactic conversion?



Current constraints

Core-collapse Sne

Analysis of diffuse MeV and GeV diffuse backgrounds

Calore+ PRD'20 [2008.11741], Eckner+ PRD'22 [2110.03679]

High-energy gamma-ray sources

NGC1275: Ajello+ PRL'16 [1603.06978]
Mrk421: Li+ PRD'21 [2008.09464]
HAWC blazars: Jacobsen+ [2003.04332]
Sub-PeV Galactic: Eckner&Calore PRD'22 [2204.12487]

Future and challenges:

- Great experimental developments ahead: HAWC, LHAASO, CTA
- Possible synergy with high-energy cosmic neutrinos
- Still large uncertainties affecting *in source* parameters (injection, magnetic field, environment) limit constraining power on ALPs

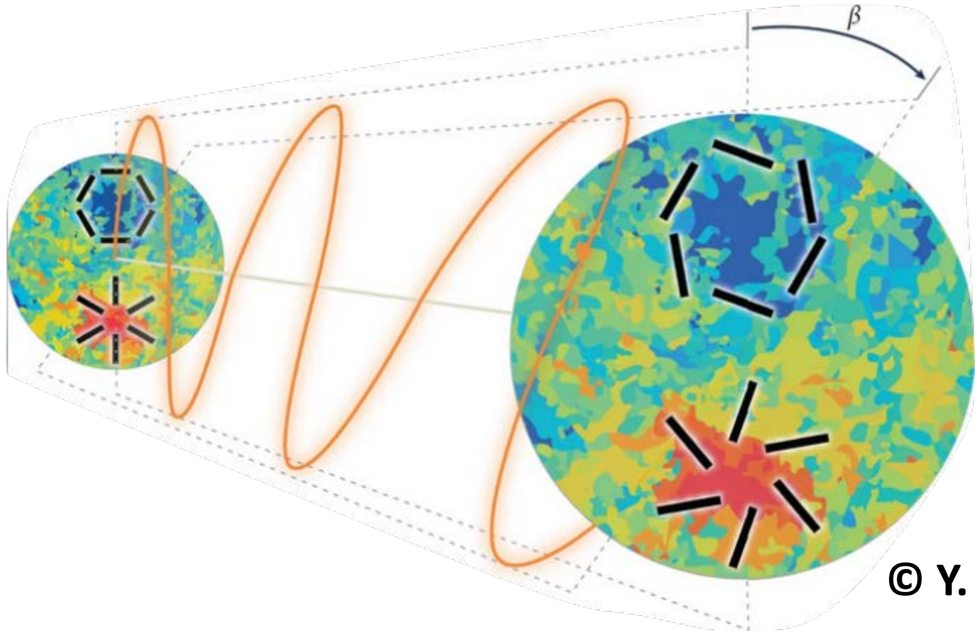
Isotropic cosmic birefringence (by Patricia Diego Palazuelos)

Axion-like particles can couple to electromagnetism through a Chern-Simons interaction

$$\frac{1}{4} g_{\phi\gamma} \phi F_{\mu\nu} \tilde{F}^{\mu\nu}$$

which rotates the plane of linear polarisation clockwise in the sky by an angle

$$\beta = \frac{1}{2} g_{\phi\gamma} \int \frac{\partial \phi}{\partial t} dt$$



© Y. Minami

Look for an isotropic rotation of CMB polarisation that is

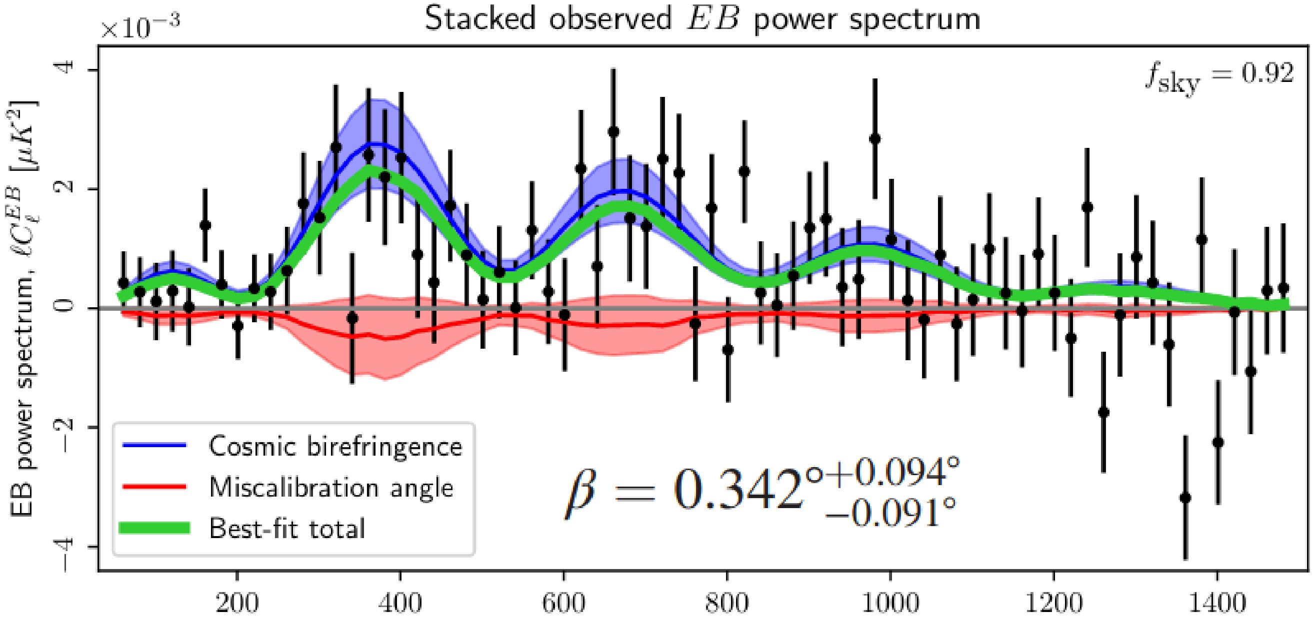
- $\beta(t)$ = constant for 10^{-33}eV ≤ m_φ ≤ 10^{-27}eV
- $\beta(t) \propto \cos(m_\varphi t)$ for 10^{-26}eV ≤ m_φ
  + attenuation of total polarisation intensity

Tools & Methods

Requires calibration of instrumental polarisation angles
- Artificial calibrator
- Astrophysical calibrator (Galactic dust, Crab Nebula)

Likelihood fitting a rotation between Stokes Q&U parameters or E&B modes

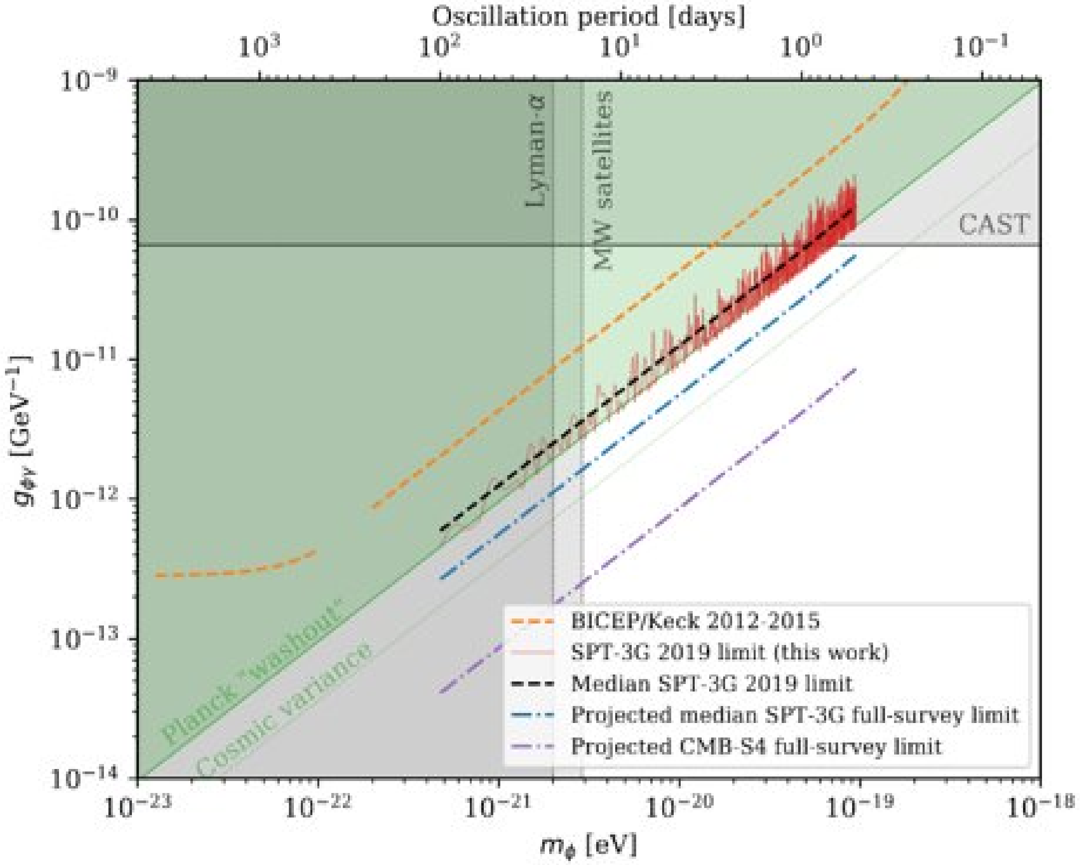
β(t) = constant



Eskilt&Komatsu 2022

Joint analysis of *Planck* and WMAP data
Sensitive to dust EB

β(t) ∝ cos(m_φt)

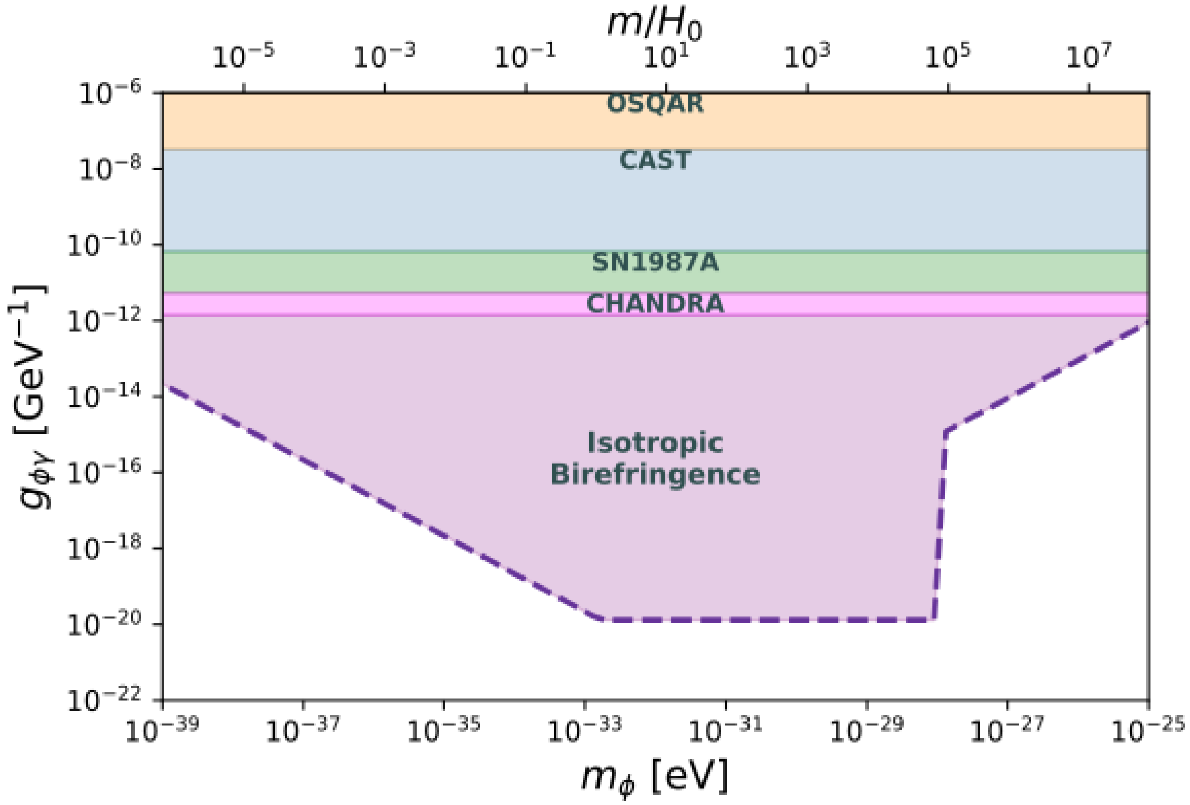


β(t) constraints from SPT-3G data **Ferguson+ 2022**
+ washout constraints from *Planck* data **Fedderke+ 2019**

Future perspective

CMB polarisation can extend axions searches to lower masses

Constraining power that CMB data alone would have were β≈ 0.3° confirmed



What to expect in the near future:

- High-precision CMB polarisation data is on the way (SPT-3G, BICEP3, SO, LiteBIRD)
- Improved artificial calibrators are being deployed [exciting results coming soon from BICEP3!]
- Better understanding of Galactic dust EB

Concluding remarks and quests for WG3.

- The error budget should be maintained under control. It implies ***better models and more accurate observations.***
- ***How can we exploit new astronomical facilities: JWST, EUCLID, VERA RUBIN, ELT, SKA ….. ?***
- ***How can we obtain improved models of potential WIMP sources? Could hardware (e.g., HPC) and software (e.g., machine learning) improve our theoretical predictions ?***
- ***(Epistemology) Just upper bounds or real probes?***

ADDITIONAL SCIENCE CASES

The final fate of Stars: WDs and CCSNe

Inma Domínguez, Maurizio Giannotti, Alessandro Mirizzi & Oscar Straniero

Assume that axions (DFSZ) exist and explore axion impact on:

- **IFMR** (Initial Final Mass Relation) **for WDs**
- **Mup** (the minimum stellar initial mass that experiences carbon burning
  or the maximum initial stellar mass that produces a CO WD)
- **Minimum stellar initial mass for CCSNe, M_{SNIIP}**

For stellar masses that experience the 2nd Dup ($M \geq 4M_{\odot}$),
the growth of the degenerate CO core is halted before
(as the 2nd Dup is anticipated), thus:

- For a given **Minitial** → smaller CO core (**smaller Final/WD mass**).

  The upper part of the IFMR is modified

  The time needed to produce a CO WD with a given mass decreases (as Minitial increases)

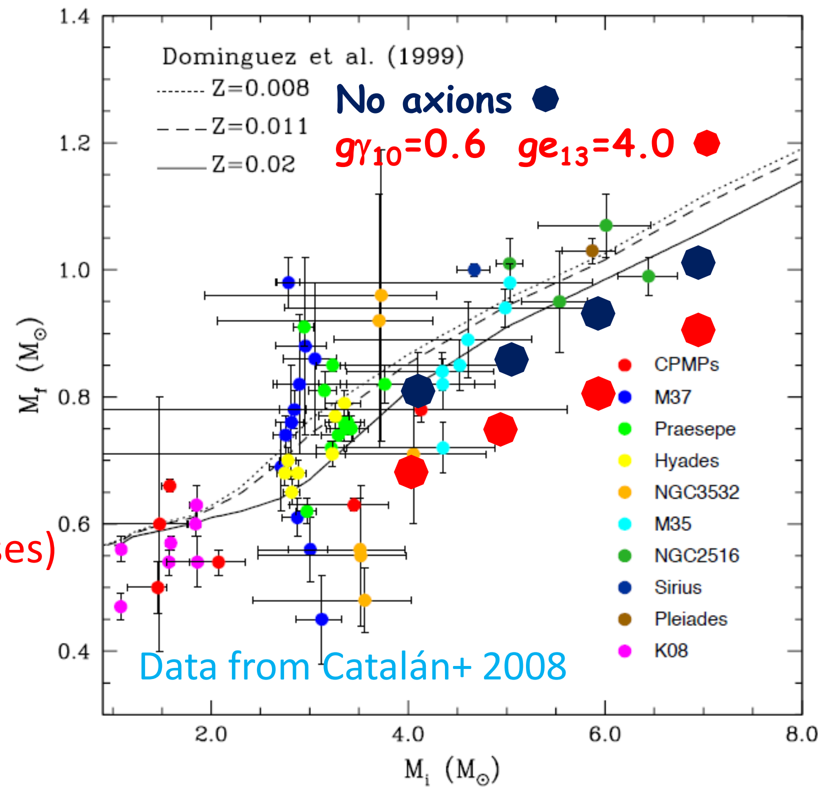
- While **Mup (Minitial) increases** (also, the mass of the CO core needed
  to reach C-ignition conditions slightly increases due to CO core cooling).

- **M_{SNIIP} Minimum initial stellar mass for CCSNe may increase**

  ✓ Precise observables: none

  ✓ Main theoretical uncertainties:
  treatment of convection, rotation & 12C+12C rate

IFMR for WDs



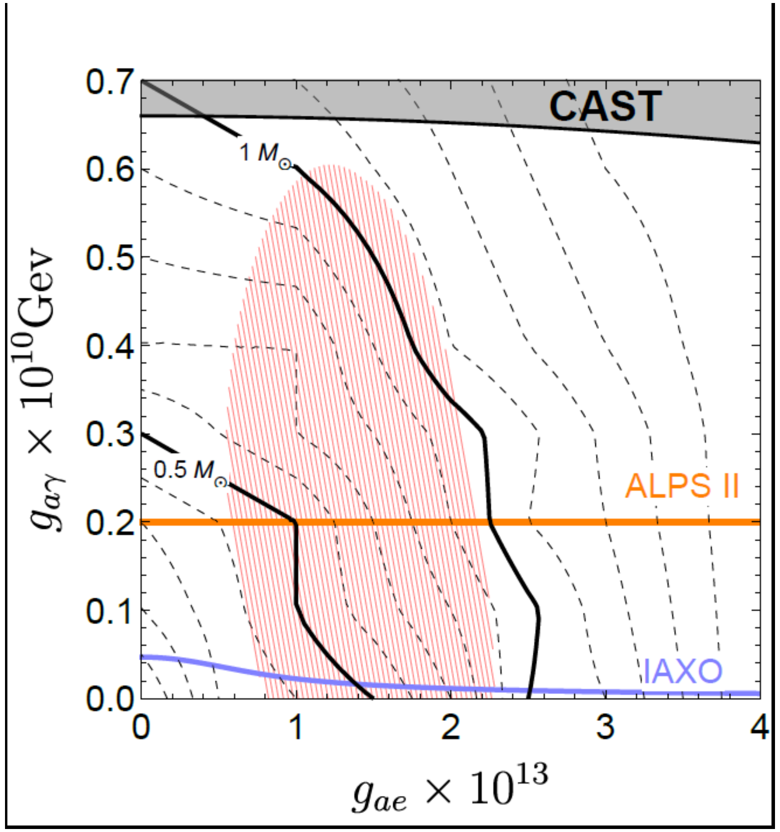
In agreement with
Dominguez, Straniero & Isern 1999
Dolan, Huskens & Volkas 2021

•Tools, Methods & Results:

Stellar evolution numerical simulations including Primakoff, Compton & Bremsstrahlung axion processes → FUNS stellar evolution code Straniero+ 06, Cristallo+ 09,11

Axion rates from Nakawaga+ 1987, 1988; Raffelt & Dearborn 1987, Raffelt & Weiss, 1995, Raffelt 1996 updated by us (Straniero+ 19)

ΔMup (shift up of the minimum mass that experiences carbon burning)



Minimum initial stellar mass for CCSNe

~9.5 $M_\odot$ Based on observed LCs, minimum stelllar mass for SNII-P progenitors
Morozova, Piro & Valenti 2018

Our models without axions experience:

Off-center Ne-ignition **10.0 $M_\odot$**
Central Ne-ignition **11.4 $M_\odot$**

Axions slightly increase those values:
for **$g\gamma_{10}$=0.4 ge_{13}=2.0**
Off-center Ne-ig **10.3 $M_\odot$**
Central Ne-ig **11.8 $M_\odot$**

Not much room for AXIONS unless their impact is "small" **< 0.5** $M_\odot$

Considering **current constraints**

$ge_{13} < 0.96$ (95% CL)
Straniero+ 2022

$g\gamma_{10} < 0.66$ GeV^{-1} (95% CL)
Ayala, Domínguez, Giannotti, Mirizzi, Straniero, 2014
CAST coll. 2017

ΔMup < 1.0 $M_\odot$
ΔM_{SNIIP} < 0.4 $M_\odot$

In Summary...

Touching the IFMR, Mup & M_{SNIIP} may have profound implications...

Our preliminary work shows that the semiempirical IFMR for WDs, Mup & M_{SNIIP} do not need, considering our current understanding, an extra energy sink and thus, if an axion were discovered (ALPSII, IAXO,) with coupling constants that have a sizeable effect (i.e. $\Delta M_{SNIIP} > 0.5\ M_{\odot}$) it will impact on our understanding of stellar evolution !

There are many uncertainties !!

→ Improve observations

i.e. Cluster ages (distances, reddening, Fe/H), more massive WDs in young clusters, SN rates, Delayed Time Distributions for SNe...

→ Improve models

i.e. convection, rotation, nuclear reaction rates, SNe...