Frascati, LNF, Axions
1 July 2016

WHAT'S NEXT ON AXION (-LIKE) PARTICLES:

BOUNDS AND DISCOVERY OPPORTUNITIES

ALESSANDRO MIRIZZI
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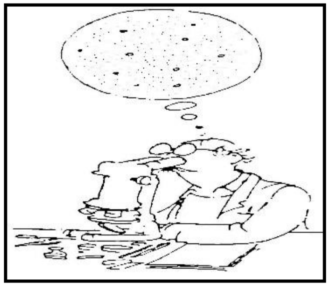
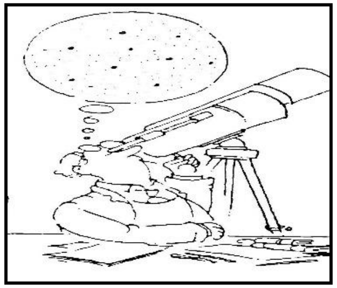
OUTLINE

From Axions to Axion-like particles (ALPs): Theoretical motivations



Laboratory searches of ALPs: bounds and perspectives



ALPs in astrophysics: bounds, hints and discovery potential

The End....

Conclusions

THE STRONG CP PROBLEM

The QCD Lagrangian includes a term which violates CP (and T)

$$\mathcal{L}_{CP} = \theta \frac{\alpha_s}{8\pi} G \cdot \tilde{G}$$

where $\theta = \theta_{QCD} + \arg \ \det \ M_q$

⇨ Prediction of an electric dipole moment for the neutron:

$$|d_n| \approx |\theta| (0.04 - 2.0) \times 10^{-15} e \text{ cm}$$

Present experimental limit : $| d_n | < 2.9 \times 10^{-26} \text{ e cm}$

[Baker et al., hep-ex/0602020]

⇨ $| \theta | < 10^{-10}$ Why so small ?

THE PECCEI-QUINN MECHANISM

[Peccei & Quinn 1977, Wilczek 1978, Weinberg 1978]

- **PQ Symmetry**

Introduce a symmetry that results in a term which **dynamically minimize** θ.

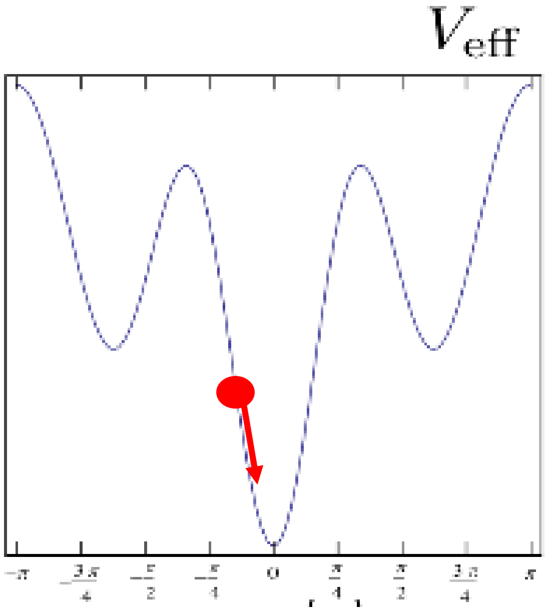
Introduction of a new global $U(1)_{PQ}$ simmetry, spontaneously broken at a scale f_a .

⇒ **Existence of a massless pseudoscalar field a(x), the axion, interacting with the gluon field.**

Re-interpret θ as a dynamical variable: $\theta \to \frac{a(x)}{f_a}$

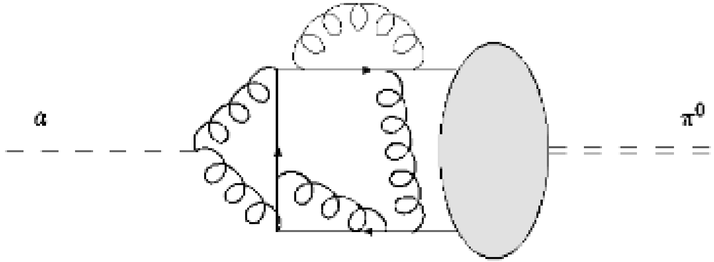
$$\mathcal{L}_\theta \to \mathcal{L}_a = \frac{1}{2}\left(\partial_\mu a\right)^2 - \frac{\alpha_s}{8\pi f_a} a\, G \cdot \tilde{G}$$

At low energy (Λ_{QCD}) the *gga* vertex generates the potential *V(a)* which has its minimun at a_0=0, restoring dynamically CP-simmetry.



Potential (mass term) induced by L_a drives a(x) to CP-conserving minimum

CP-symmetry dynamically restored



Axions generically couple to gluons and mix with π^0

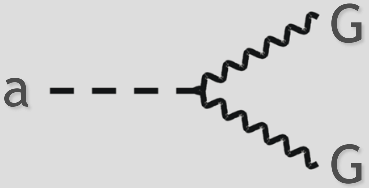
⇒ Axions pick up a small mass

$$m_a \approx \frac{z^{1/2}}{1+z}\frac{f_\pi m_\pi}{f_a} = \frac{6.0\ eV}{f_a/10^6\ GeV}$$

AXION PROPERTIES

Gluon coupling (Generic property)

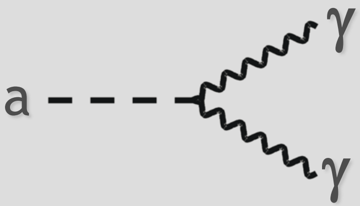
$$L_{aG} = \frac{\alpha_s}{8\pi f_a} G\tilde{G}a$$



Photon coupling

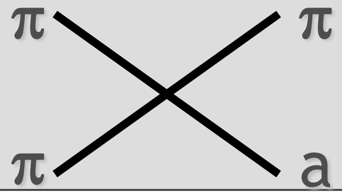
$$L_{a\gamma} = -\frac{g_{a\gamma}}{4} F\tilde{F}a = g_{a\gamma}\vec{E}\cdot\vec{B}a$$

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



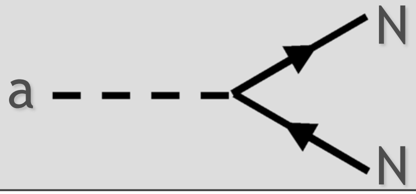
Pion coupling

$$L_{a\pi} = \frac{C_{a\pi}}{f_a f_\pi}\left(\pi^0\pi^+\partial_\mu\pi^- + \ldots\right)\partial^\mu a$$



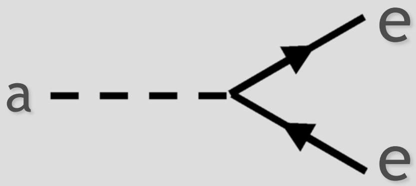
Nucleon coupling (axial vector)

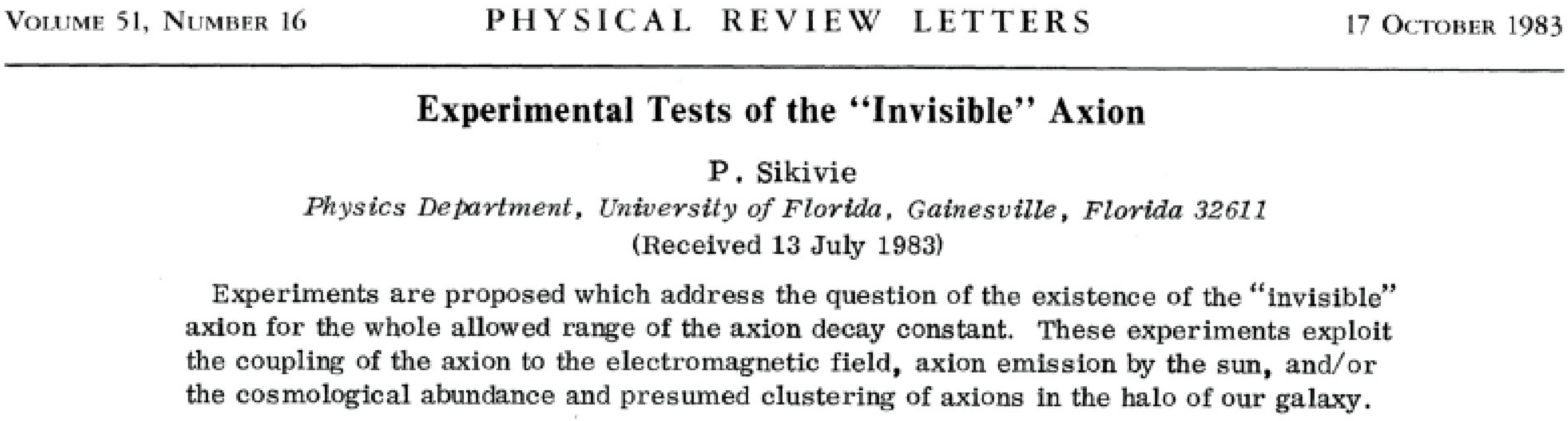
$$L_{aN} = \frac{C_N}{2f_a}\bar{\Psi}_N\gamma^\mu\gamma_5\Psi_N\,\partial_\mu a$$



Electron coupling (optional absent for hadronic axions)

$$L_{ae} = \frac{C_e}{2f_a}\bar{\Psi}_e\gamma^\mu\gamma_5\Psi_e\,\partial_\mu a$$





VOLUME 51, NUMBER 16 PHYSICAL REVIEW LETTERS 17 OCTOBER 1983

Experimental Tests of the "Invisible" Axion

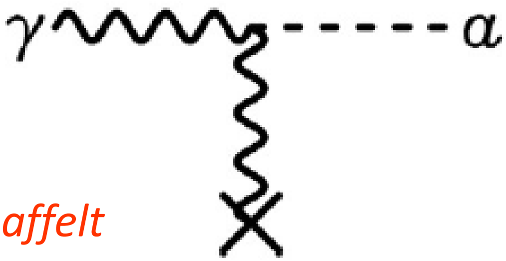
P. Sikivie
Physics Department, University of Florida, Gainesville, Florida 32611

(Received 13 July 1983)

Experiments are proposed which address the question of the existence of the "invisible" axion for the whole allowed range of the axion decay constant. These experiments exploit the coupling of the axion to the electromagnetic field, axion emission by the sun, and/or the cosmological abundance and presumed clustering of axions in the halo of our galaxy.

Primakoff effect:

Axion-photon transition in external static E or B field
(Originally discussed for π^0
by Henri Primakoff 1951)



Pierre Sikivie:

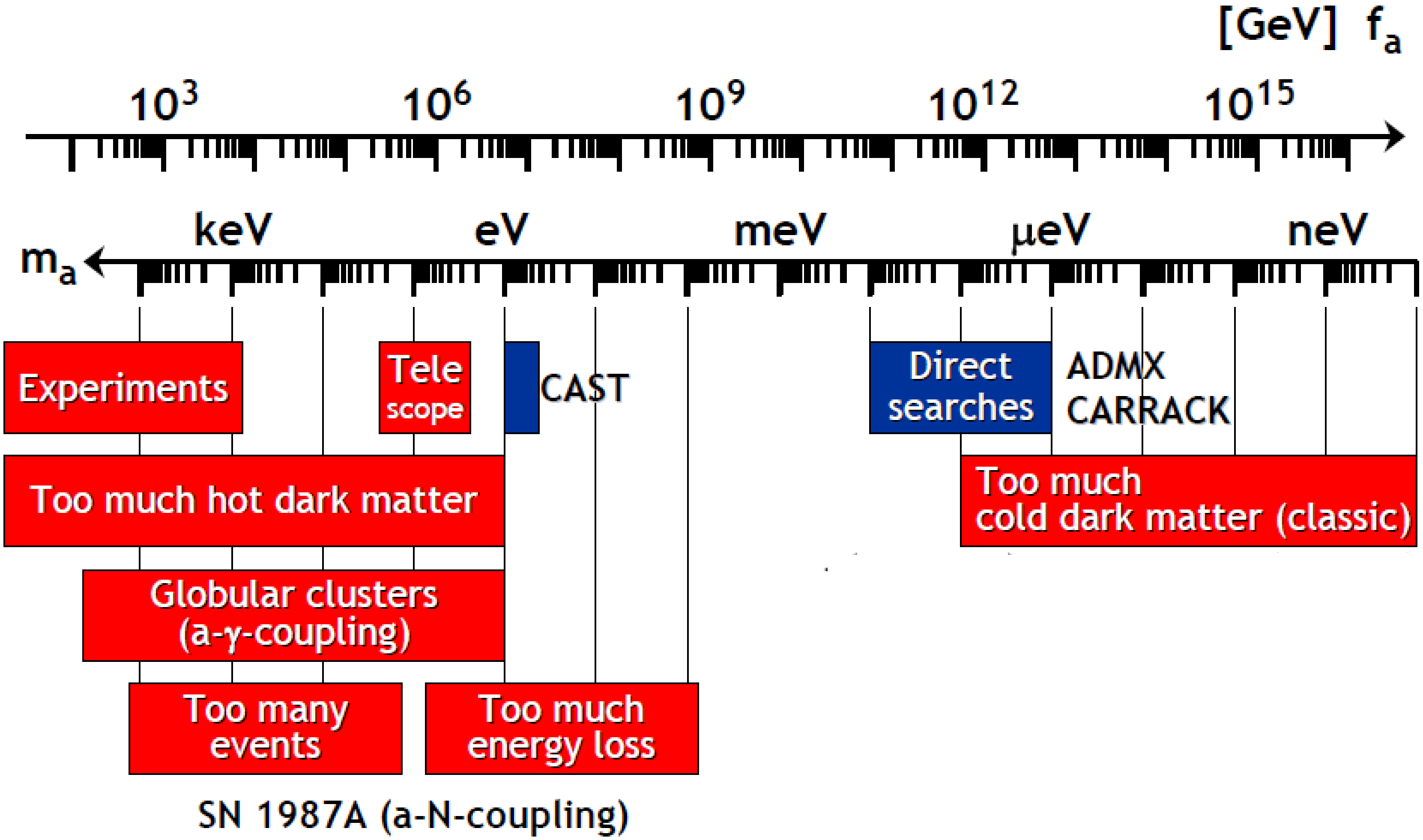
Macroscopic B-field can provide a large coherent transition rate over a big volume (low-mass axions)

- Axion helioscope:
  Look at the Sun through a dipole magnet
- Axion haloscope:
  Look for dark-matter axions with
  A microwave resonant cavity

Slide by G. Raffelt

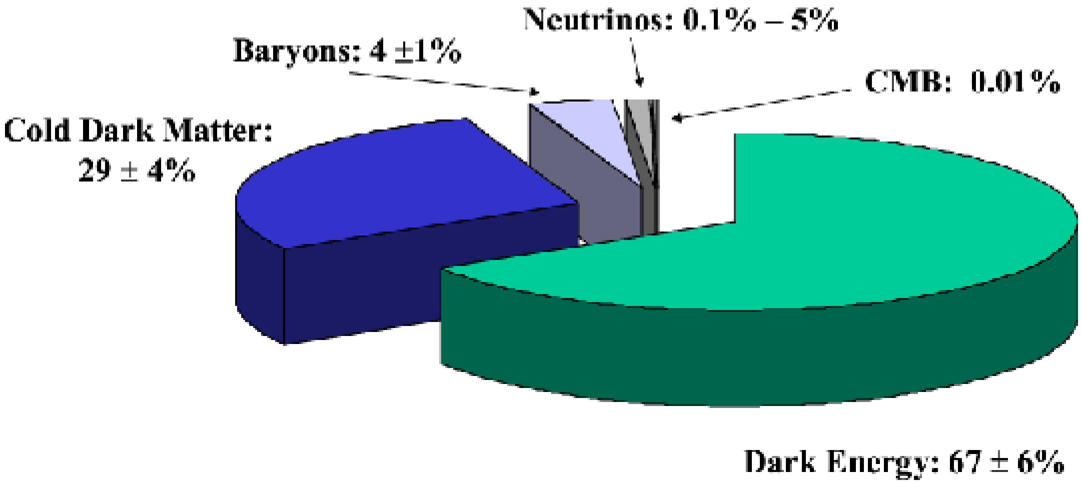
AXION BOUNDS

Raffelt, hep-ph/0611118



DARK MATTER

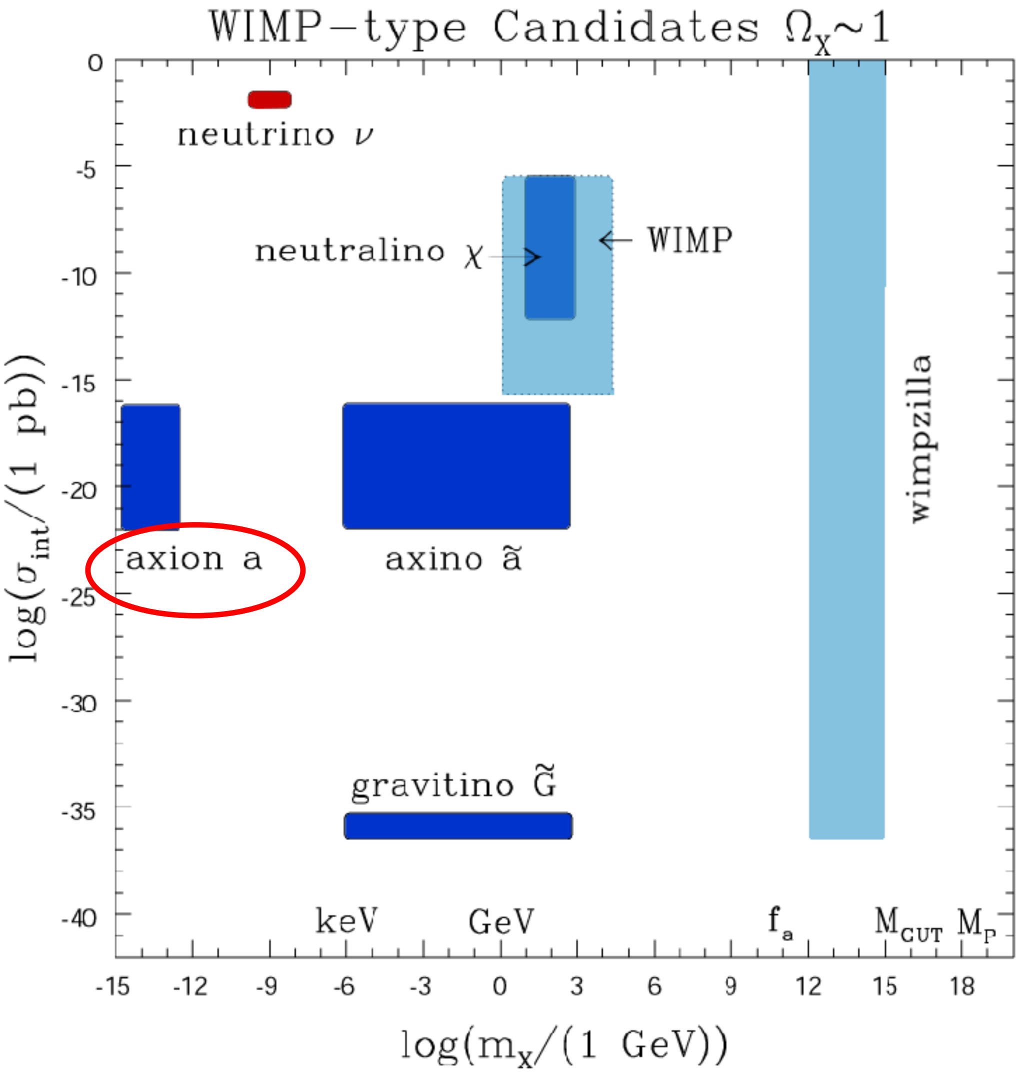
Matter and Energy in the Universe: A strange recipe



Turner and Freedman, astro-ph/0308418

Structure formation requires COLD Dark matter, i.e. particle with small free-streaming length, otherwise the structure formation on scales smaller than this is suppressed.

DARK MATTER CANDIDATES



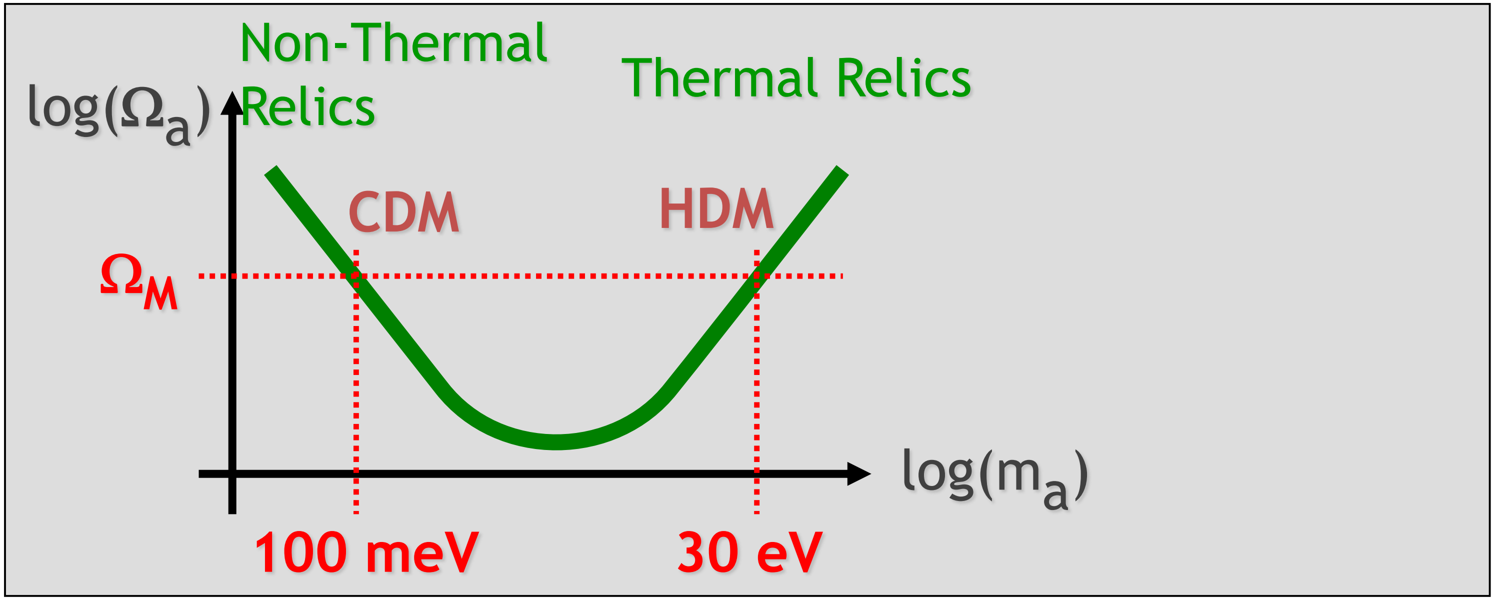
L.Roszkowski, hep-ph/0404052

- Neutrino ν –HDM
- neutralino χ
- generic “WIMP”
- axion a
- axino $\tilde{a}$
- gravitino $\tilde{G}$
- wimpzilla

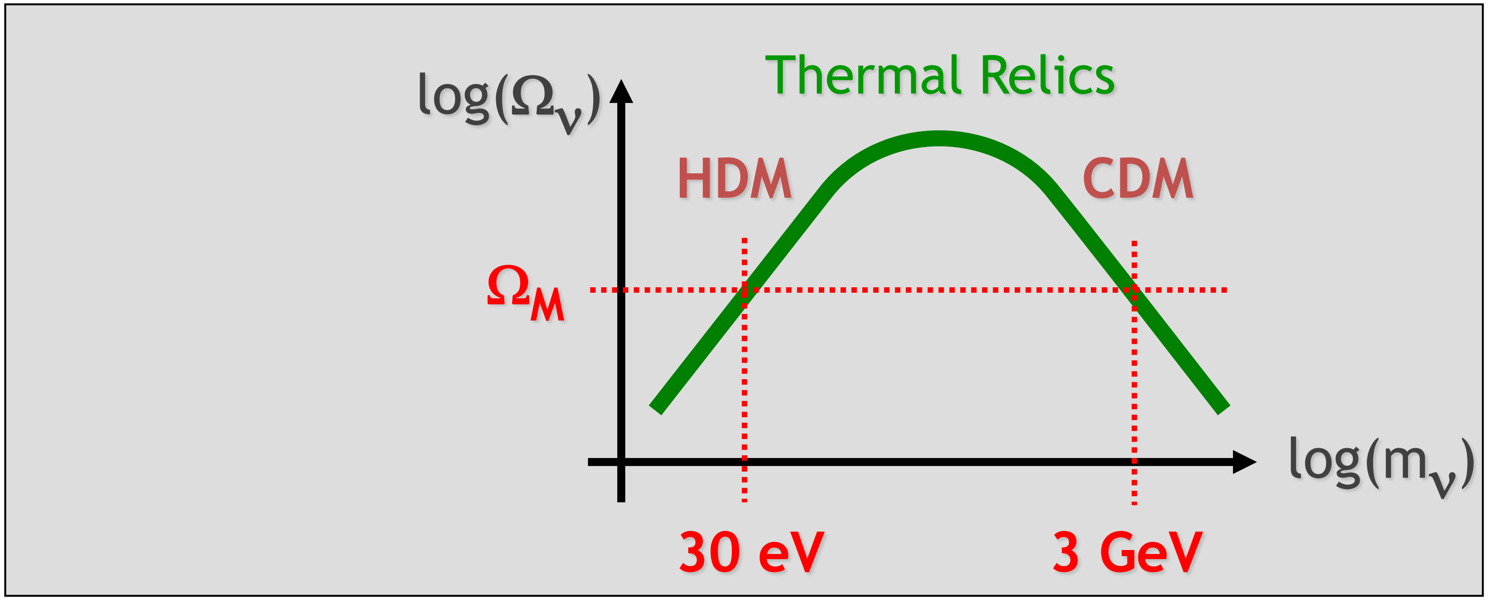
Vastly different ranges of mass and σ, all give $\Omega \sim 1$

DARK-MATTER AXIONS

Axions



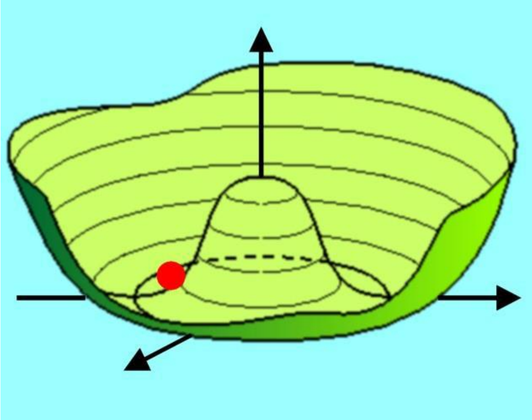
Neutrinos

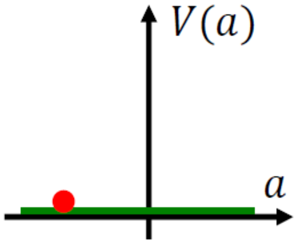


CREATION OF COSMOLOGICAL AXIONS

$T \sim f_a$ (very early universe)

- $U_{PQ}(1)$ spontaneously broken
- Axion fields settles in the "Mexican hat"
- Axion field frozen at initial value $a(t_i) = \theta_i f_a$

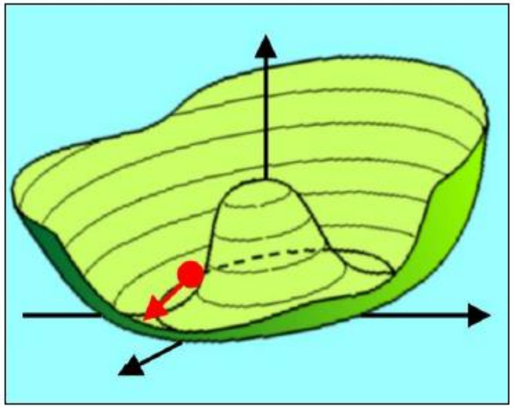


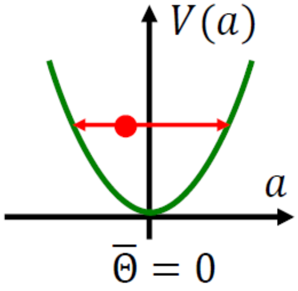


$T \sim 1$ GeV ($H \sim 10^{-9}$ eV)

- Axion mass turns on quickly
- Field start oscillating when $m_a \geq 3H$
- Classical field oscillations (axion at rest)

Vacuum realignment





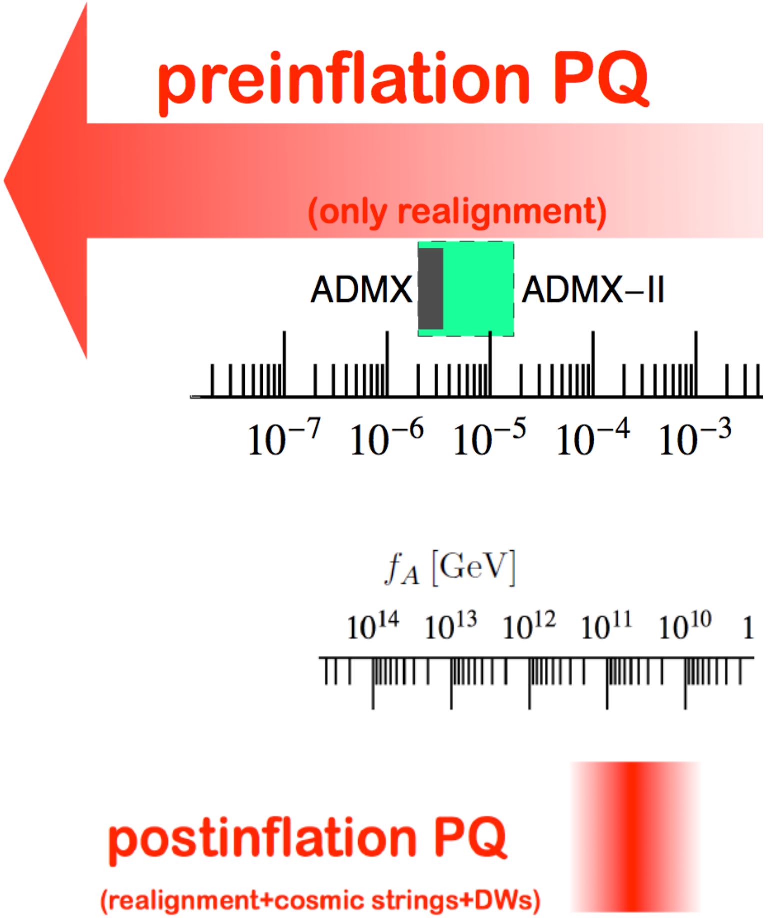
Coherent state of extremely non-relativistic DM, i.e. cold DM.

COSMIC AXION DENSITY

- If inflation after PQ SSB

$$\Omega_a \approx 0.11 \left(\frac{f_a}{5\,x\,10^{11}\,GeV}\right)^{1.184} F\bar{\Theta}_i^2$$
$$= 0.11 \left(\frac{12\,\mu eV}{m_a}\right)^{1.184} F\bar{\Theta}_i^2$$

Θ_i Initial value in a single inflationary patch



- If inflation before PQ SSB

Initial misalignment angles take on different values in different patches of the universe. $\bar{\Theta}_i^2$ is an average of an uniform distributions over possible value

$$\Omega_a \approx 0.11 \left(\frac{40\,\mu eV}{m_a}\right)^{1.184}$$

- Decay of cosmic strings and domain walls may provide additional source for axion CDM

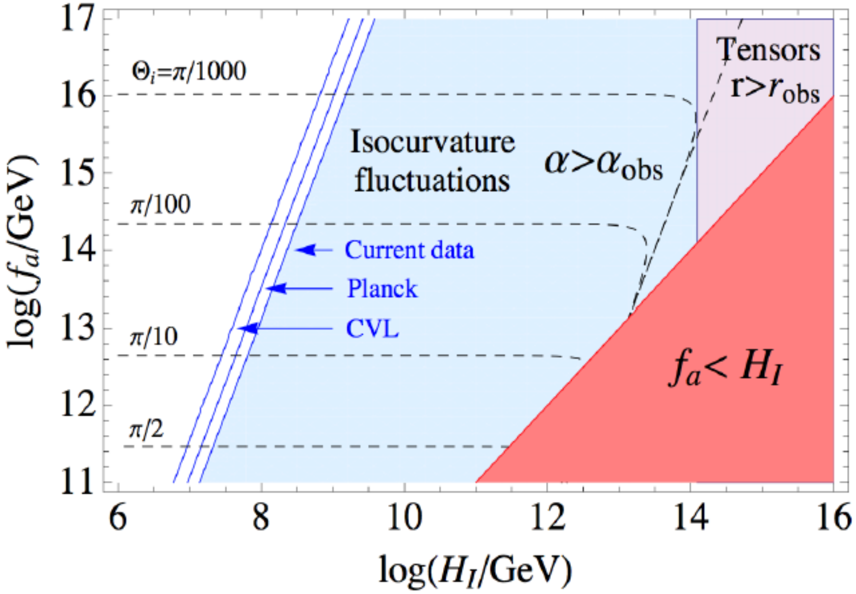
$$\Omega_a \approx 0.11 \left(\frac{400\,\mu eV}{m_a}\right)^{1.184}$$

ISOCURVATURE FLUCTUATIONS

If PQ SSB before inflation, $f_a > H_I$, axion field present during inflation, leading to isocurvature flucutations that are strongly constrained.
From Planck data

$$H_I \leq 0.87 \times 10^7\, GeV \left(\frac{f_a}{10^{11}\, GeV}\right)^{0.408}$$

Only allowed if Hubble scale during inflation smallish



[Hamann,Hannestad,Raffelt,Wong 0904.0647]

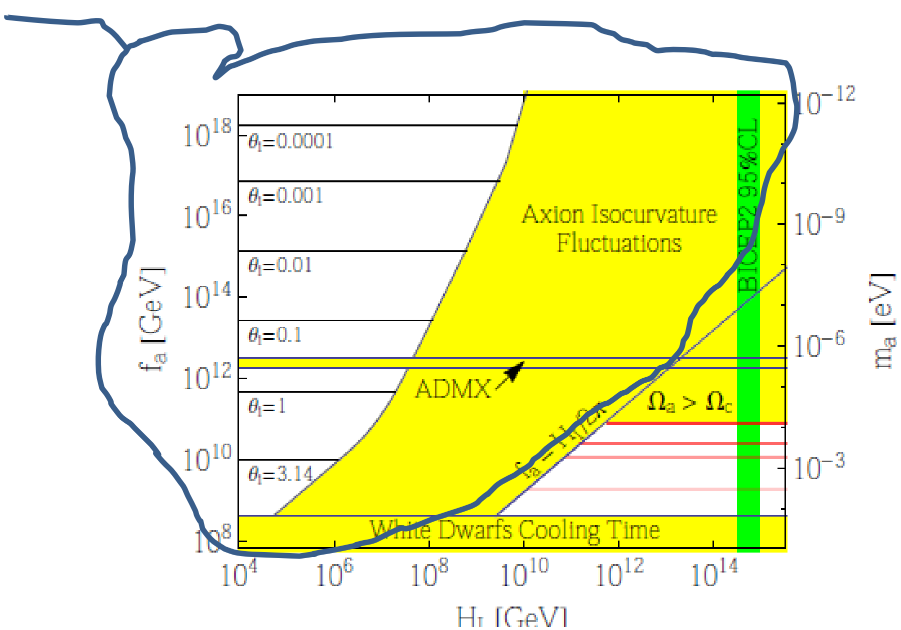
ISOCURVATURE PROBLEM AFTER BICEP2

Detection of tensor/scalar ratio $r = 0.20^{+0.07}_{-0.05}$ from B-mode power spectrum by BICEP2 implies large

$$H_I = \frac{1}{4}\sqrt{\pi A_s r}M_{pl}$$

$$\approx 1.33 \times 10^{14}\, GeV \left(\frac{A_s}{2.4\times10^{-9}}\right)^{1/2}\left(\frac{r}{0.25}\right)^{1/2}$$

Ruled-out



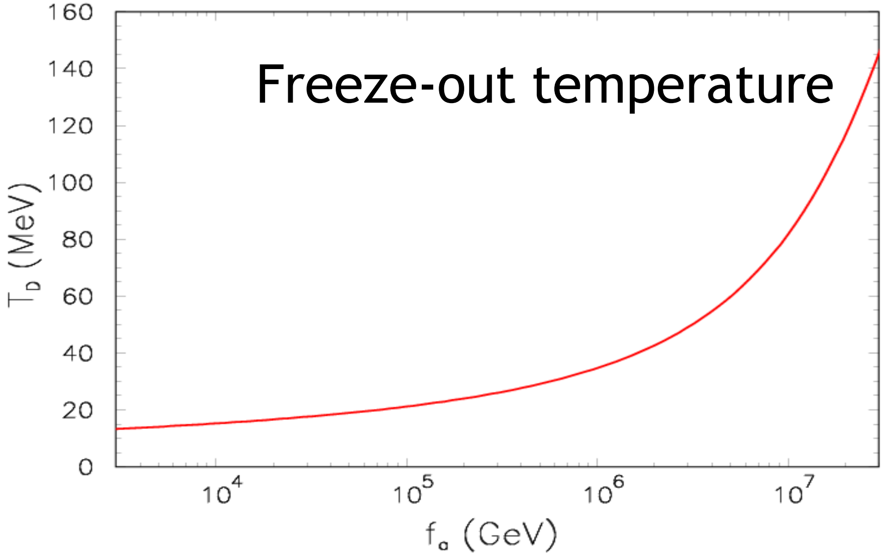
"Half" of the CDM axion parameter space ruled out

Gondolo & Visinelli, 1403.4594

Interpretation of B-modes ruled out after joint Planck/BICEP2 analysis [arXiv:1502.00612]

THERMAL PRODUCTION OF AXIONS

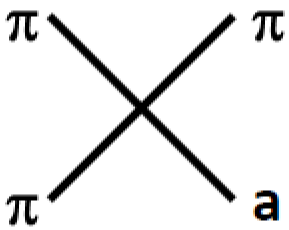
If $f_a < 1.2 \times 10^{12}$ GeV ⟶ there would be a primordial population of axions produced in hot thermal plasma [*Turner (1987), Masso' (2002)*]



If axions were sufficiently strong interacting ($f_a < 3 \times 10^7$ GeV, $m_a > 0.2$ eV) they decouple after QCD phase transition (T < 200 MeV). The most generic interaction process involves hadrons rather than quarks and gluons that would be relevant at earlier epochs.

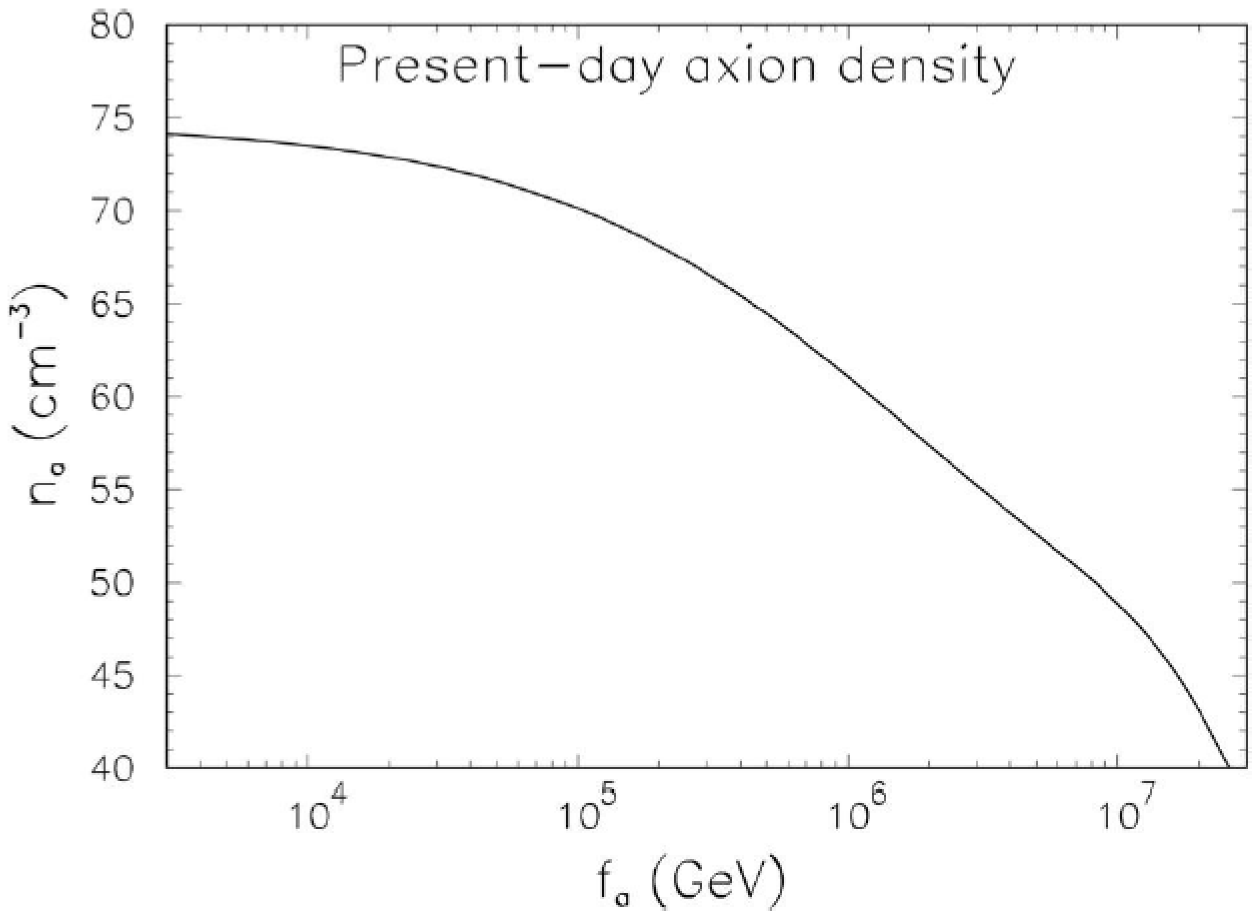
There would be a background of low-mass (~ eV) relic axions

AXIONS HOT DM FROM THERMALIZATION AFTER Λ_{QCD}



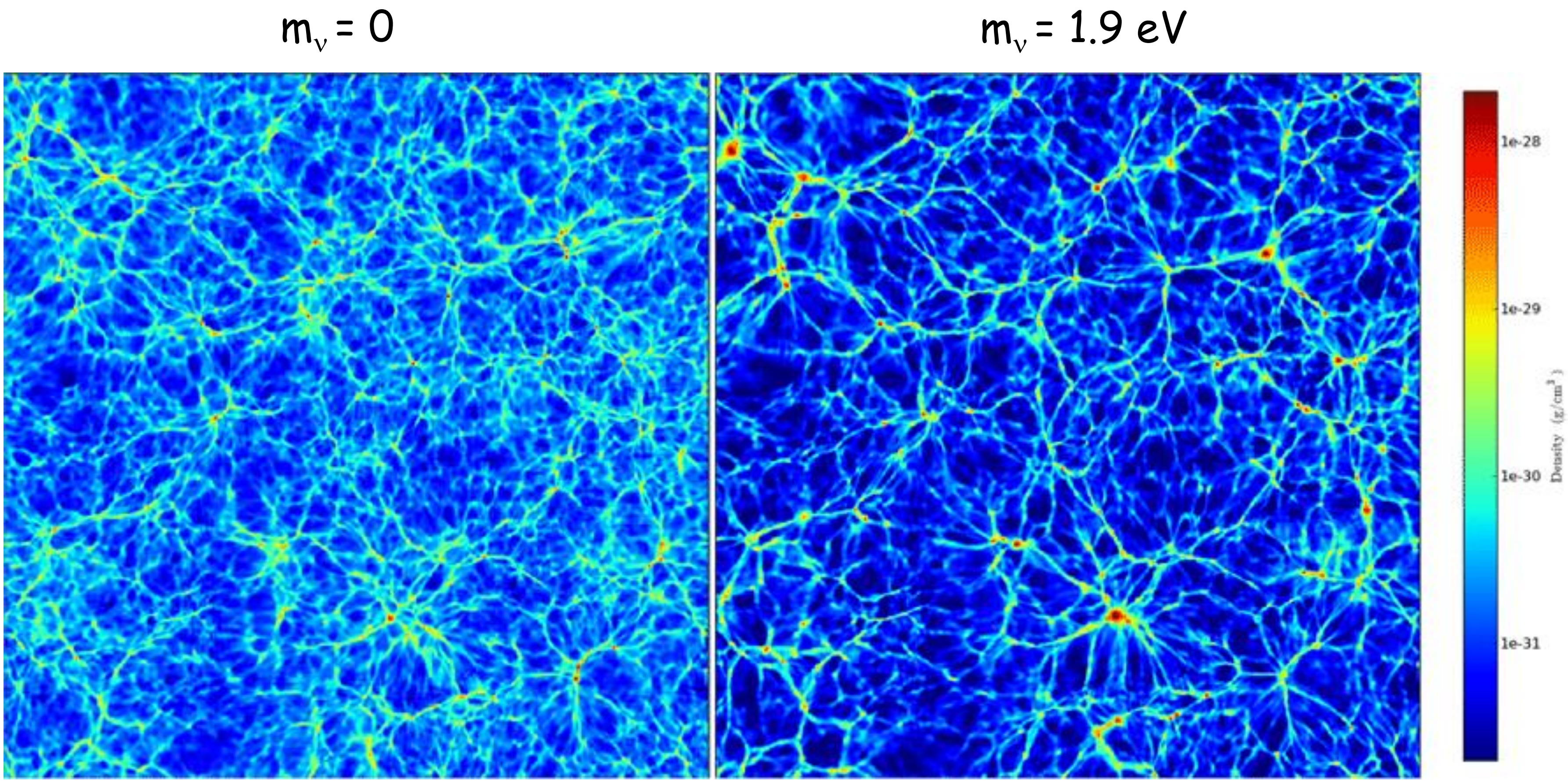
$$L_{a\pi} = \frac{C_{a\pi}}{f_a f_\pi}\left(\pi^0\pi^+\partial_\mu\pi^- + \pi^0\pi^-\partial_\mu\pi^+ - 2\pi^+\pi^-\partial_\mu\pi^0\right)\partial^\mu a$$

Chang & Choi, PLB 316 (1993) 51



Hannestad, Mirizzi & Raffelt, hep-ph/0504059

FORMATION OF STRUCTURE

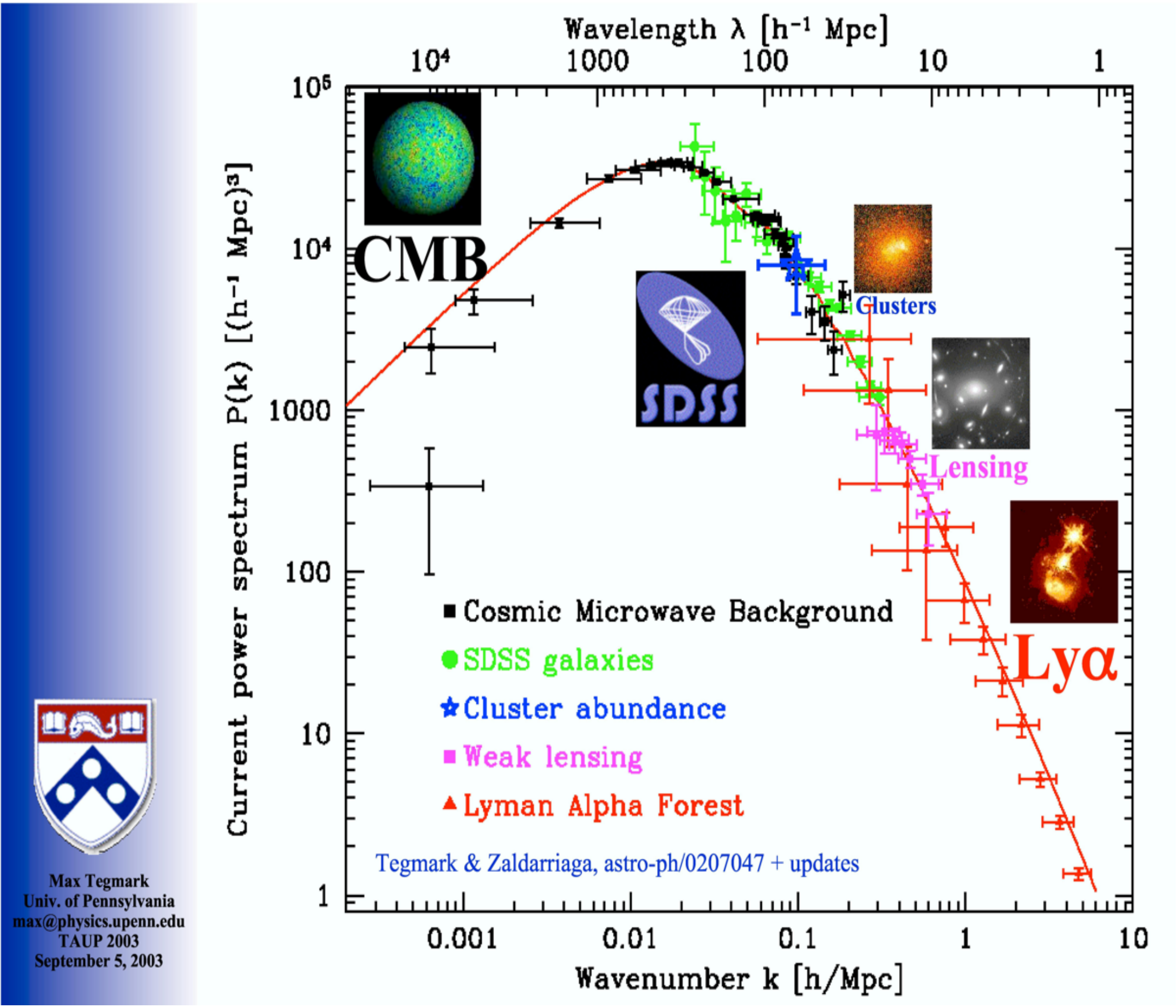


$m_\nu = 0$

$m_\nu = 1.9$ eV

A fraction of HDM suppresses small scale structures

POWER SPECTRUM OF MATTER DENSITY FLUCTUATIONS



Tegmark & Zaldarriaga, astro-ph/0207047 + updates

Max Tegmark
Univ. of Pennsylvania
max@physics.upenn.edu
TAUP 2003
September 5, 2003

Power spectrum

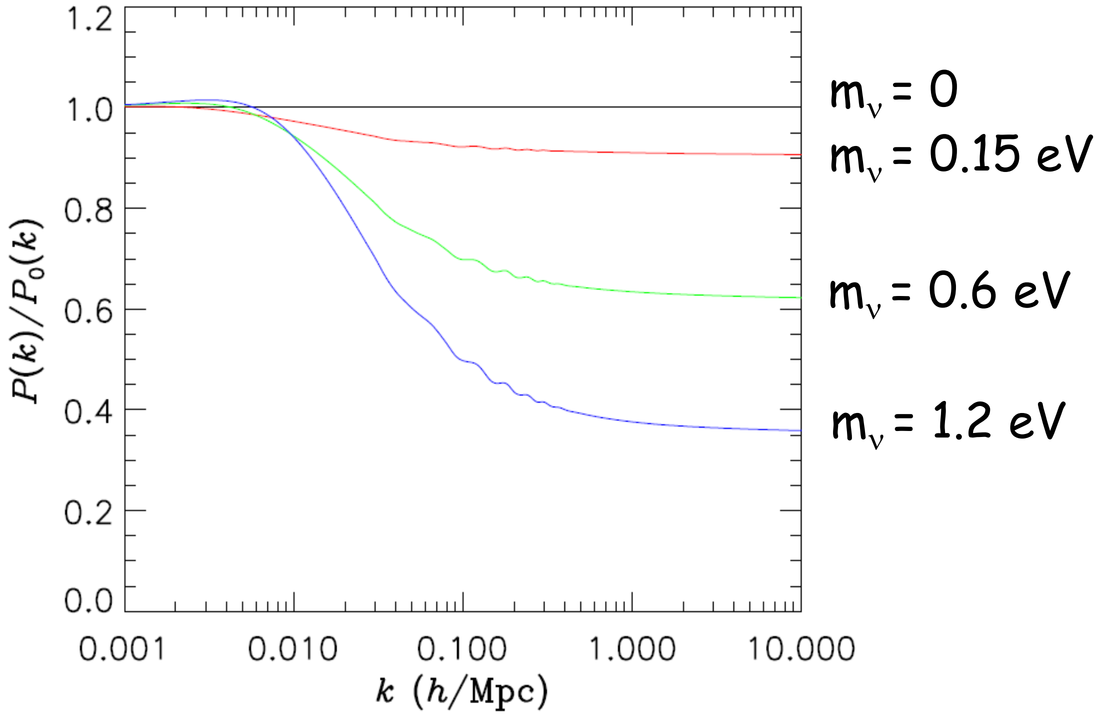
$$P(k) = \left|\delta_k\right|^2$$

Density contrast

$$\delta(\vec{x}) = \frac{\rho(\vec{x}) - \bar{\rho}}{\bar{\rho}}$$

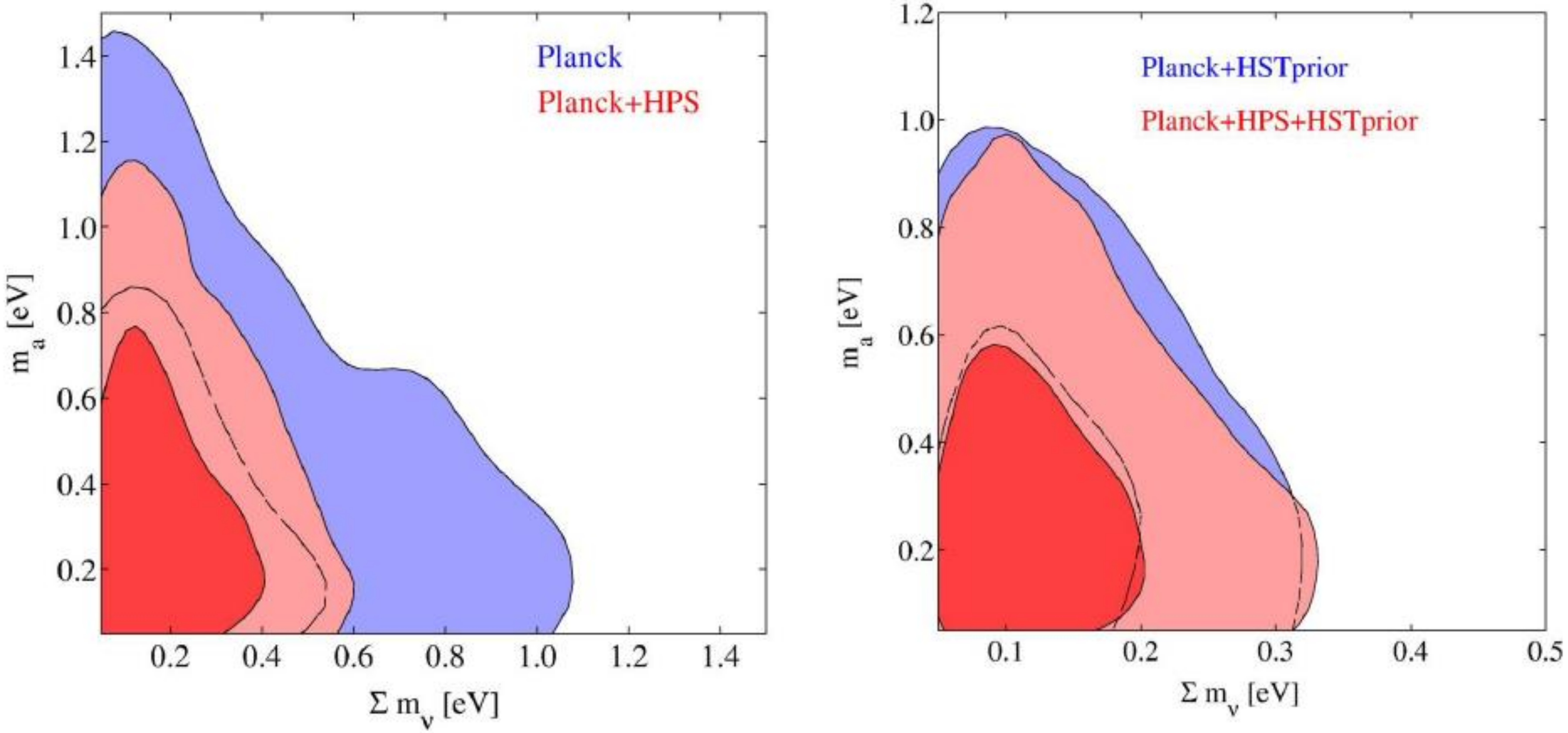
NEUTRINO FREE-STREAMING TRANSFER FUNCTION

Power suppression for $\lambda_{FS} \lesssim 100$ Mpc/h



[Hannestad, 1007.0658]

NEUTRINOS AND AXIONS HOT DM LIMIT AFTER PLANCK



Archidiacono, Hannestad, Mirizzi, Raffelt & Wong, arXiv:1307.0615

FROM AXIONS TO ALPS

There might be much more than a QCD axion:

Axion-like particles (ALPs)

[aka arions, archions…]

Share with the QCD-axion the two-photon vertex $g_{a\gamma}$.
The mass is nearly arbitrary. No relation btw m_a- $g_{a\gamma}$

4D Models

Extra-Dimensions

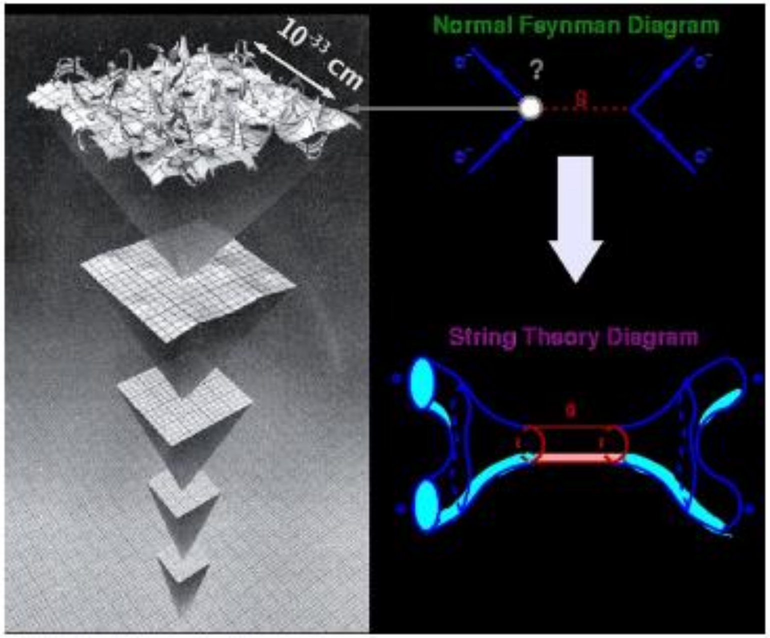
String Theory

….

COEXISTENCE: SUSY & PQ EXTENSION IN STRING THEORY

Particularly strongly motivated extensions of SM based on string theory:

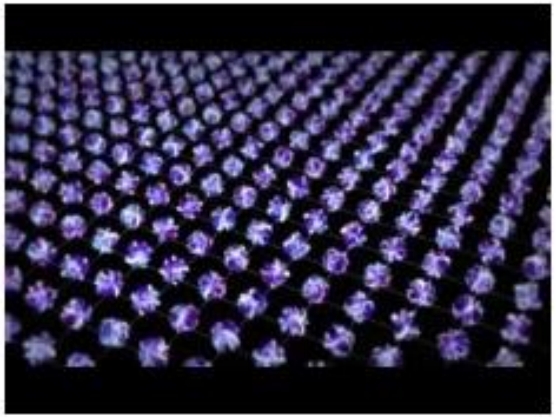
- Attempt to unify SM with gravity
- Quantum gravity



STRING AXIVERSE

- Spectrum of low-energy effective theory in (3+1)-dimensions is supersymmetric and possibly contains several kinds of very weakly interacting slim particles (WISPs): Axion, ALPs (Axion-Like Particles)

- An axiverse - QCD axion plus possibly many ultra-light ALPs whose mass spectrum is logarithmically hierarchical – may naturally arise from strings [*Arvanitaki et al., arXiV: 0905.4702*]



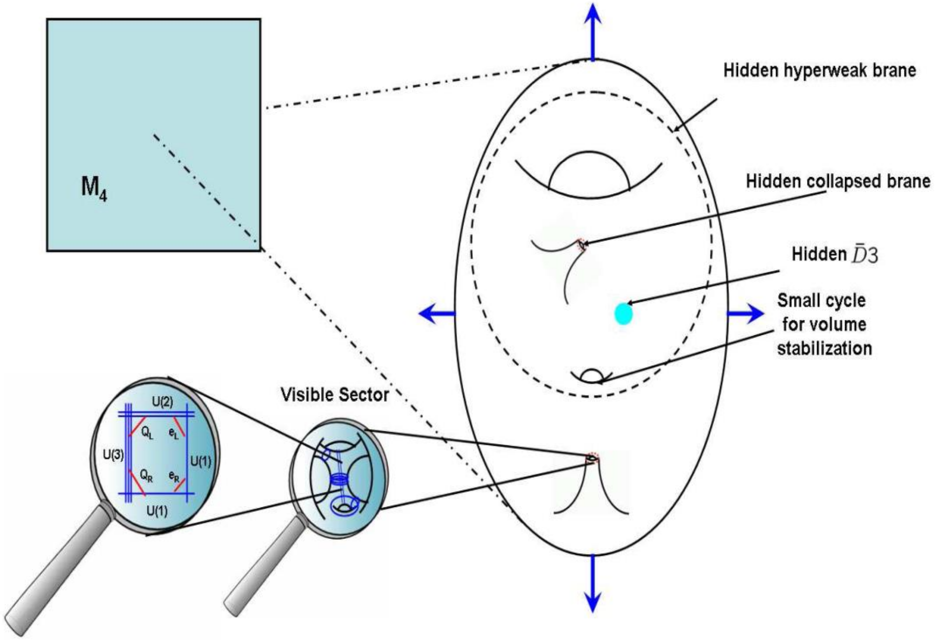
ALPs FROM STRING THEORY

[Witten '87, Conlon '06, Svrcek, Witten '06,….]

- String theory needs Extra Dimensions

Must compactify

- Shape and size deformations of Extra-D correspond to fields: Moduli and Axions Connected to the fundamental scale string scale



Compactification of type II string theories

- *[See J. Jaeckel & A. Ringwald, arXiv:1002.0329 for a review]*
- *[See M. Cicoli, M. Goodsell & A. Ringwald, arXiv:1206.0819 for a specific model in type IIB string]*

AXIONS AND MODULI

- Gauge field terms

$$\mathcal{L} = -\frac{1}{4g^2}F^2 - \frac{\theta}{32\pi^2}F\tilde{F}$$

+ Supersymmetry/supergravity

$$\mathcal{L} = \mathrm{Re}[f(\Phi)]F^2 + \mathrm{Im}[f(\Phi)]F\tilde{F}$$

Scalar moduli coupling

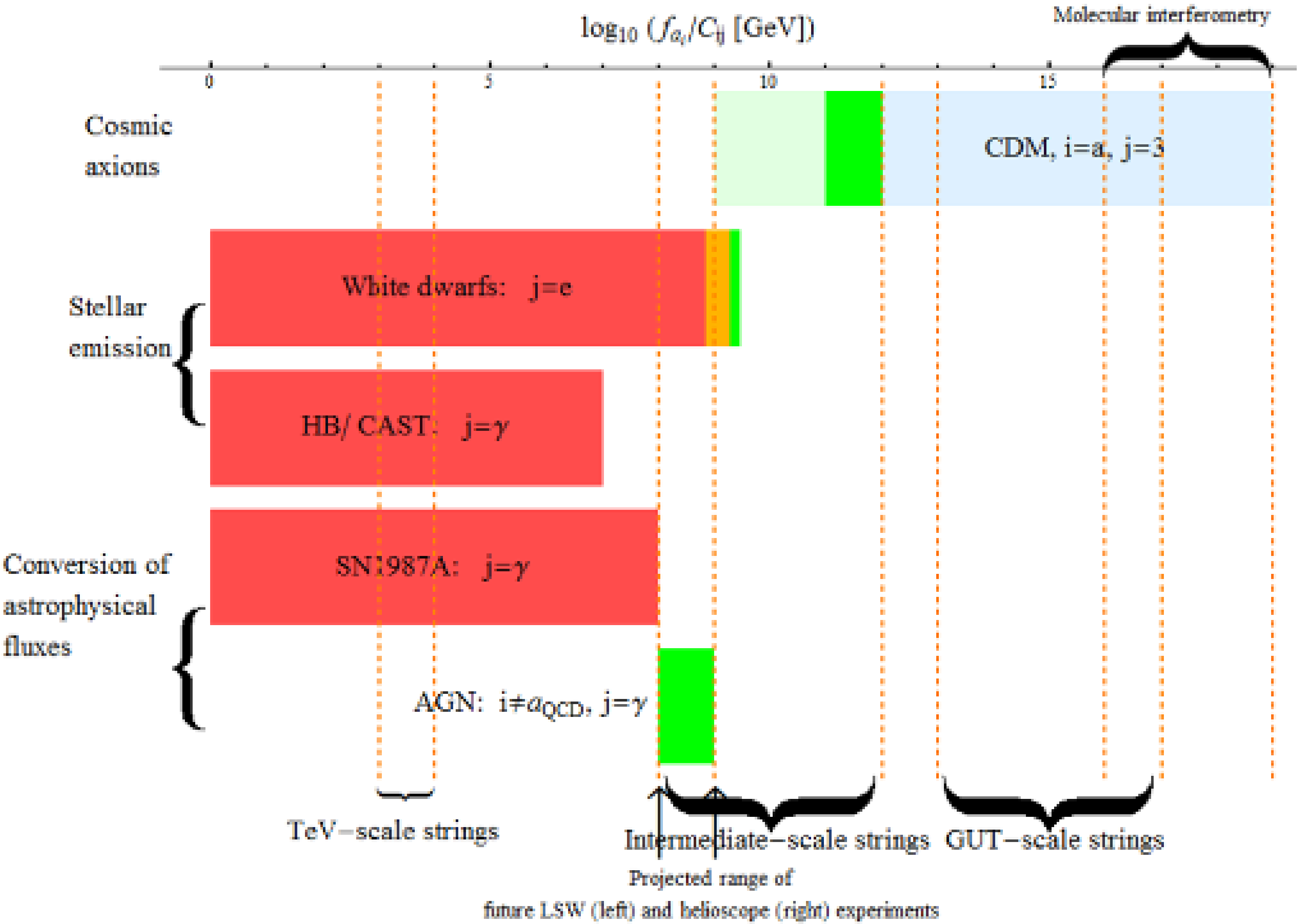
Pseudoscalar ALP coupling

- Gauge couplings always field dependent (no free coupling constants)
- Axions + Moduli always present in String theory

ALPs with an intermediate scale decay constant?

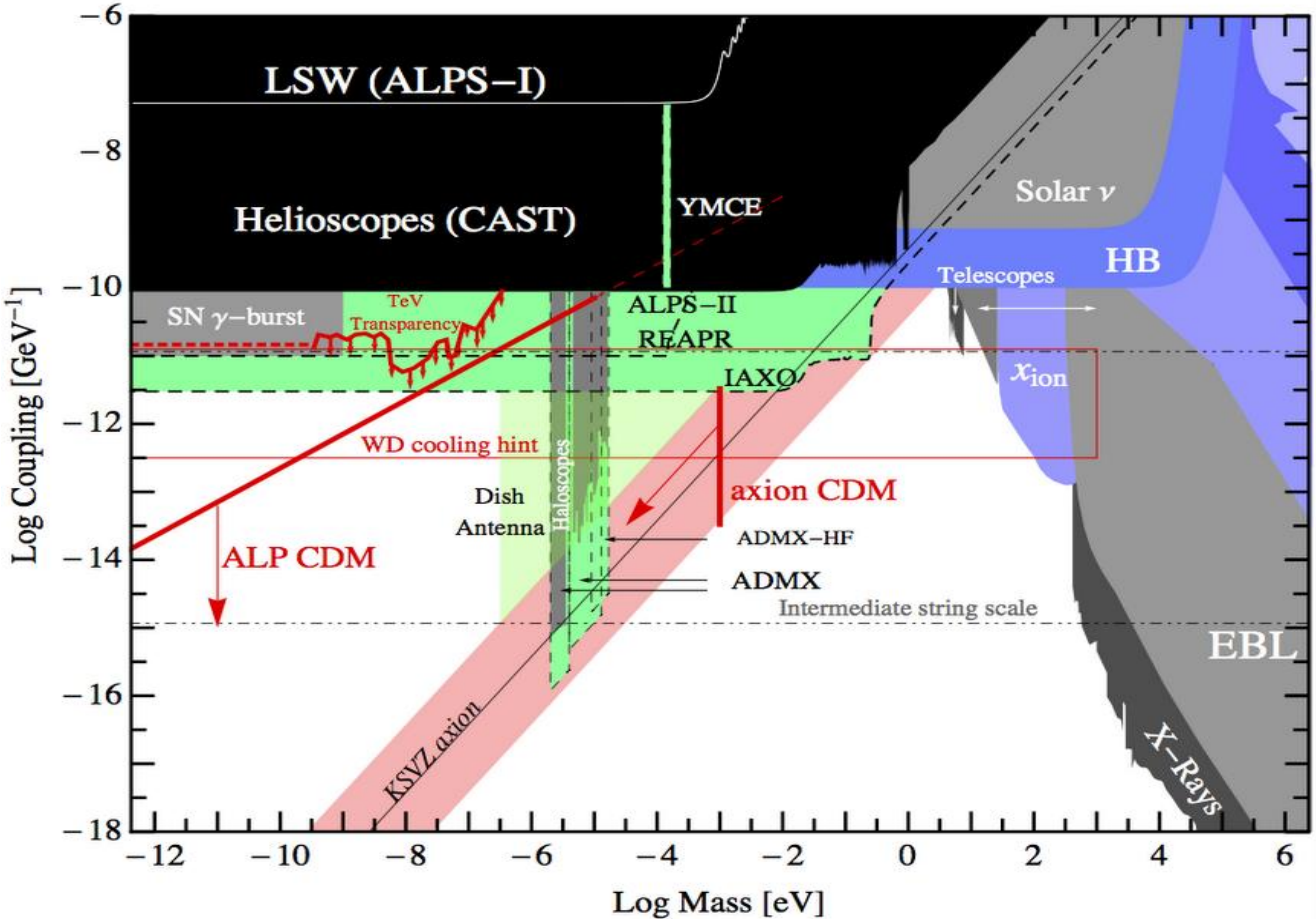
[M. Cicoli, M. Goodsell & A. Ringwald, arXiv:1206.0819]

- Current limits and possible hints from astrophysics and cosmology



CURRENT AND PERSPECTIVE ALP BOUNDS

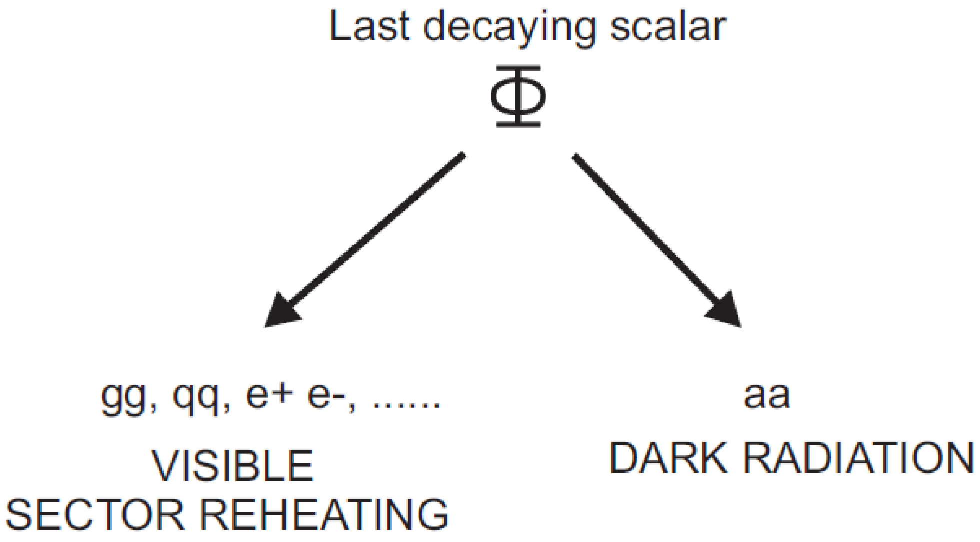
[A. Ringwald, arXiv:1310.1256]



Similar to axions, also ALPs would be produced in the early Universe via the vacuum-realignment mechanism. This would enlarge the parameter space for ALP CDM.

AXIONIC DARK RADIATION ?

[J.Conlon & M.Marsh, arXiv:1304.1804]



Last decaying scalar

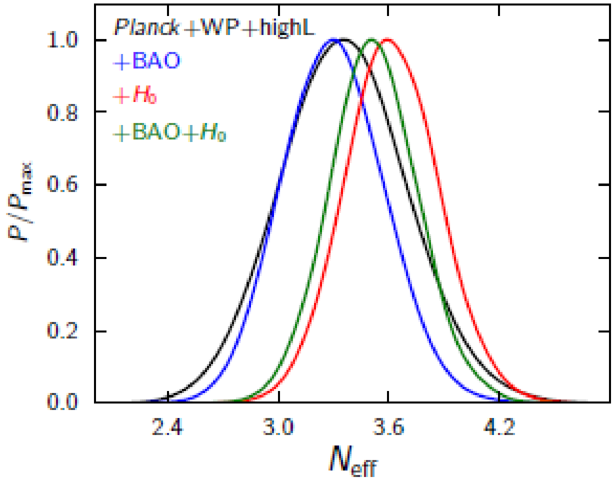
Φ

gg, qq, e+ e-, ……

VISIBLE
SECTOR REHEATING

aa

DARK RADIATION



Planck XVI, 2013

Dark radiation arises from hidden sector decays of moduli

Ideal subject for string phenomenology!

Most axions still linger today as a Cosmic Axion Background with E_{axion}~O(100)eV (X-ray signal from Galaxy Clusters)

DIRECT ALP SEARCHES

Helioscope (Sun)
CAST, Sumico

Haloscope (Galactic DM)
ADMX

Laser polarization
PVLAS, BMV, OSQAR, Q&A

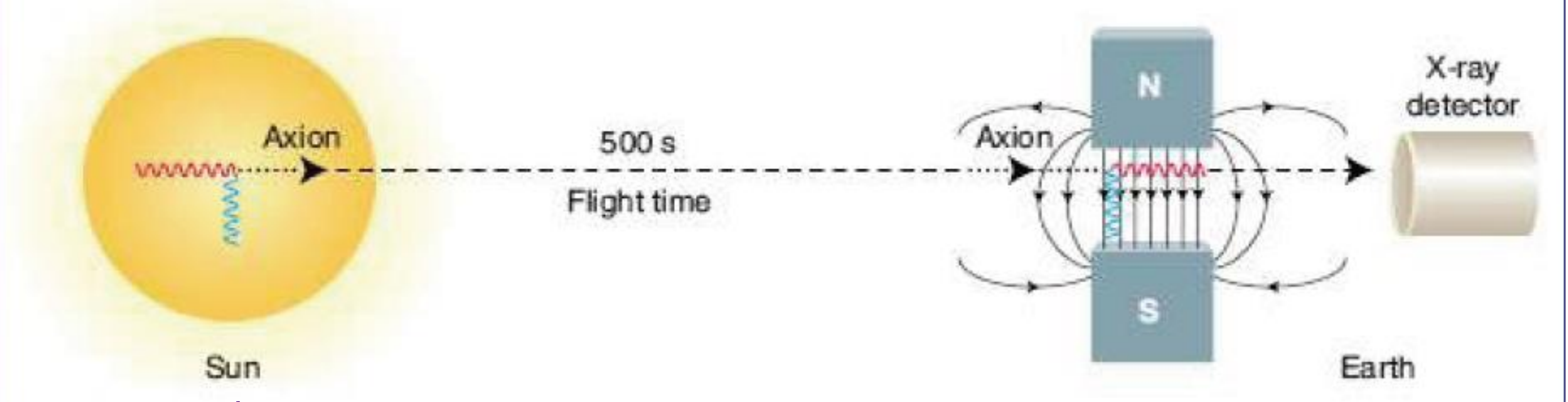
Light shining through a wall
ALPS, BMV, GAMMEV, OSQAR, PVLAS

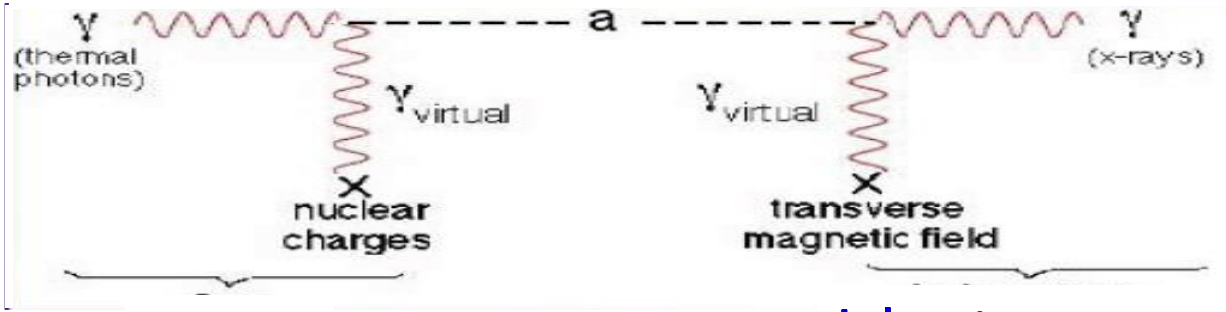
HELIOSCOPES

Searches for solar axions: Axion helioscopes

Primakoff process

Axion-photon oscillation





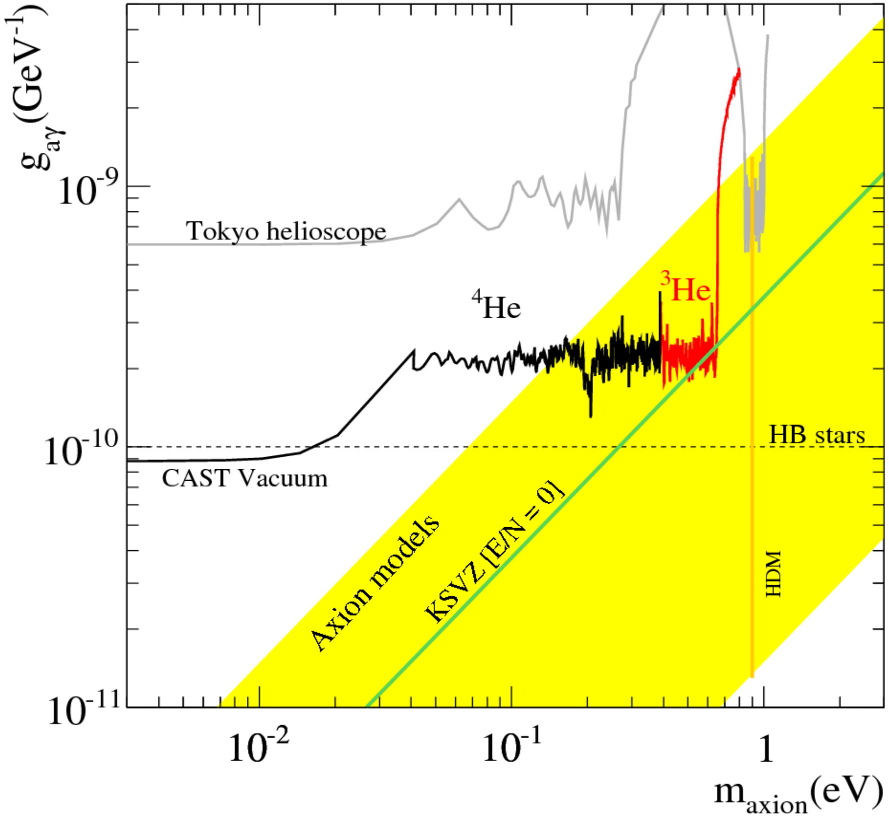
Sun

Laboratory

- Tokyo axion helioscope ⟶ Results since 1998
- CERN Axion Solar Telescope (CAST) ⟶ Data since 2003

CAST @ CERN

CAST ALP BOUND



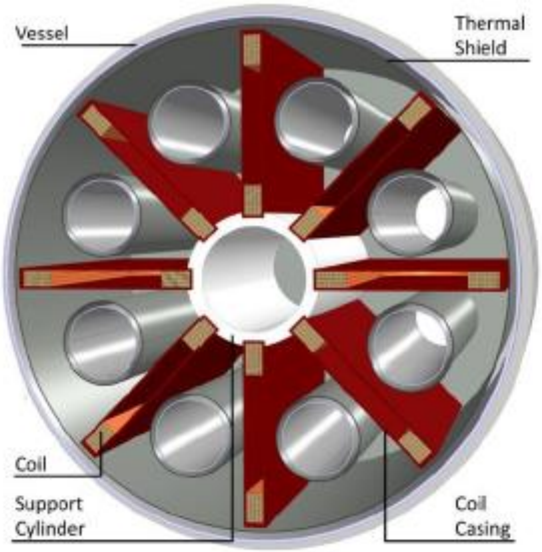
CAST Collaboration:
(arXiv:1106.3919)

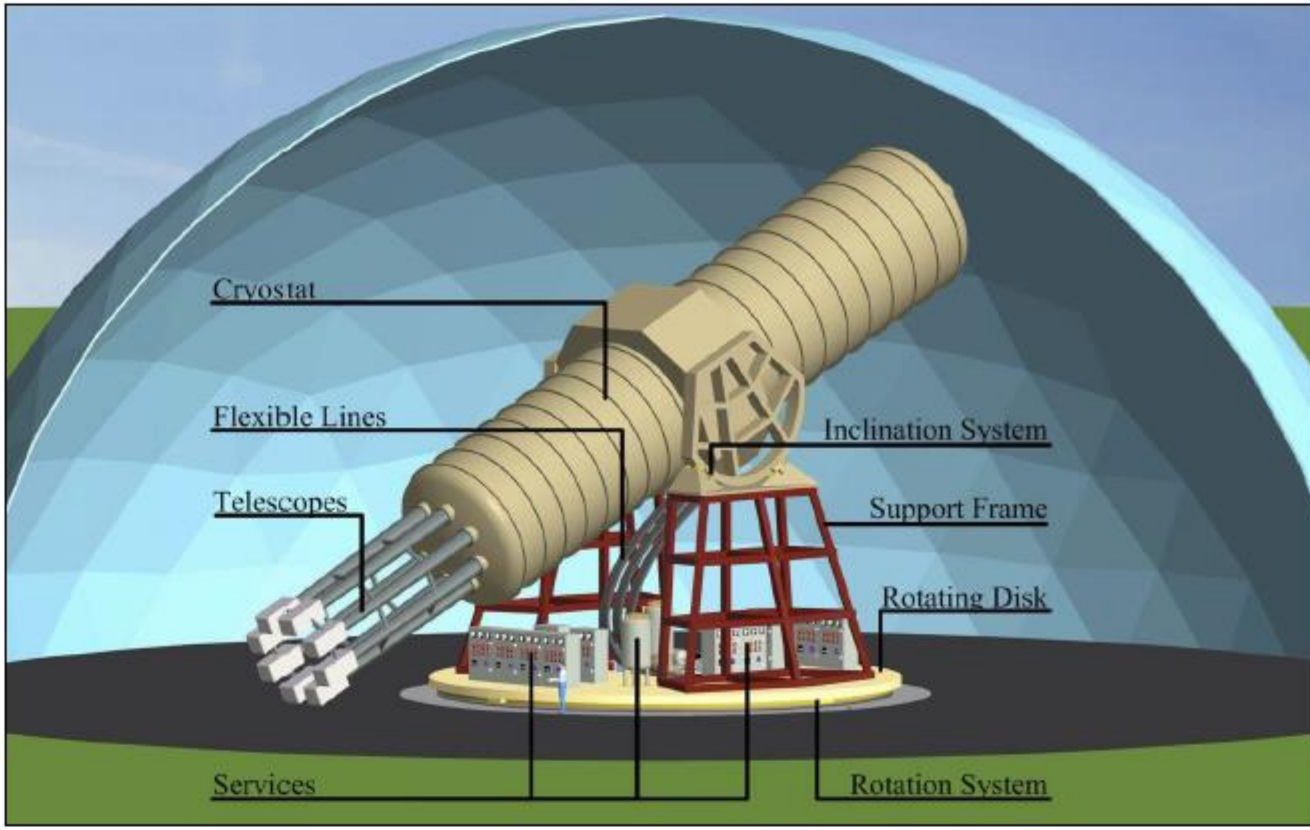
$g_{a\gamma} < 8.8 \times 10^{-11}$ GeV^{-1} at 95% CL
for $m_a < 0.02$ eV

Benchmark for experimental searches

For ultralight ALPs ($m_a \lesssim 10^{-9}$ eV) the stronger limit $g_{a\gamma} \lesssim 10^{-11}$ GeV^{-1} occurs from the SN1987A signal [*see Brockway, Carlson & Raffelt, astro-ph/9605197; Grifolds, Masso' & Toldra, astro-ph/9606028*]

THE INTERNATIONAL AXION OBSERVATORY (IAXO)





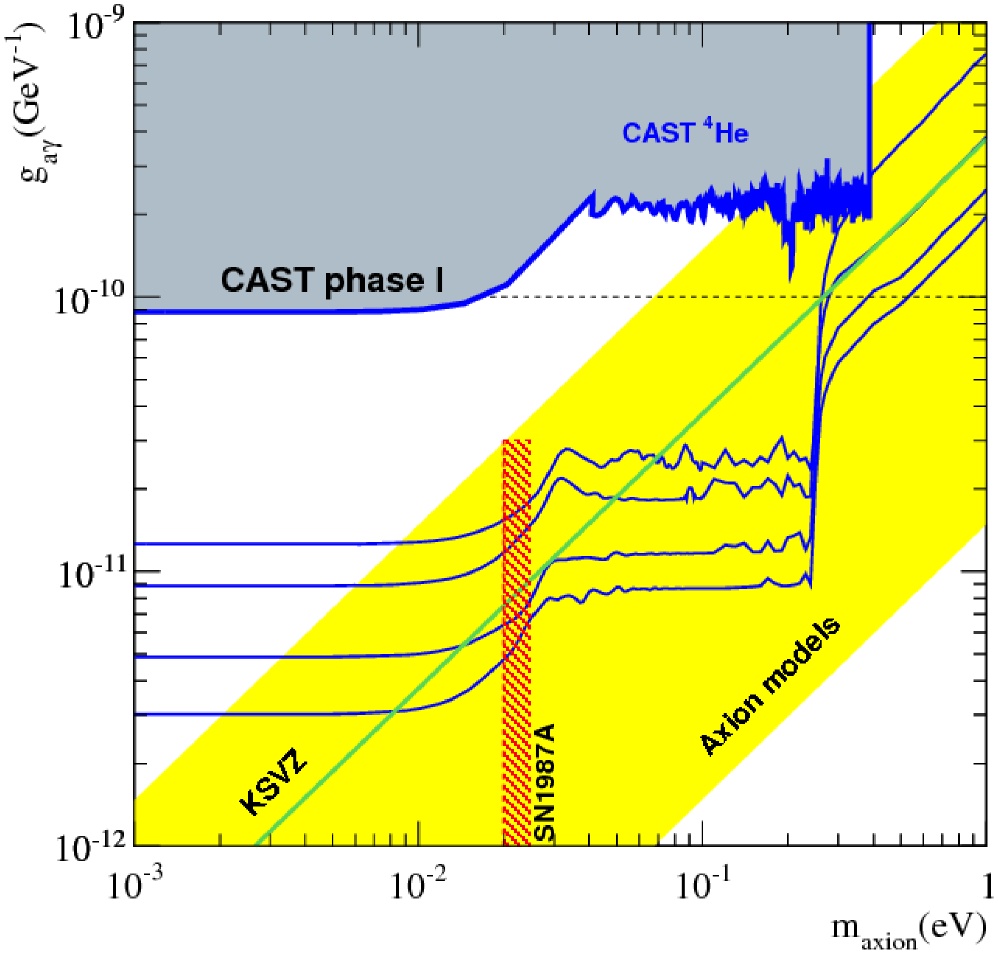
Need new magnet w/

- Much bigger aperture: ~1 m^2 per bore
- Lighter (no iron yoke)
- Bores at T_{room}

- Irastorza et al.: Towards a new generation axion helioscope, arXiv:1103.5334
- Armengaud et al.: Conceptual Design of the International Axion Observatory (IAXO), arXiv:1401.3233

PROSPECT BOUNDS FROM IAXO

[Irastorza et al, , arXiv:1103.5334]



Project of new generation axion helioscope.

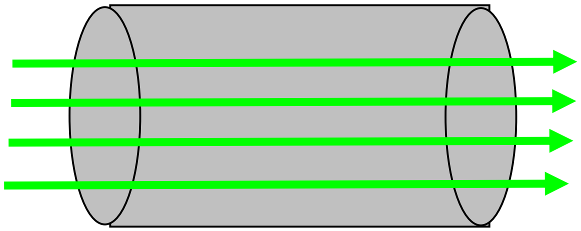
Large improvement in
- Magnetic field volume
- X-ray focusing optics
- Detector bkg reduction

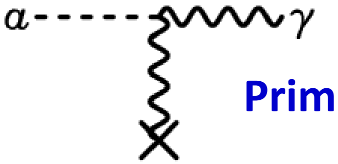
$$g_{a\gamma} \geq 10^{-12}\ \text{GeV}^{-1}$$

SEARCH FOR GALACTIC AXIONS (COLD DARK MATTER)

Axion haloscope (Sikivie 1983)

Microwave resonator



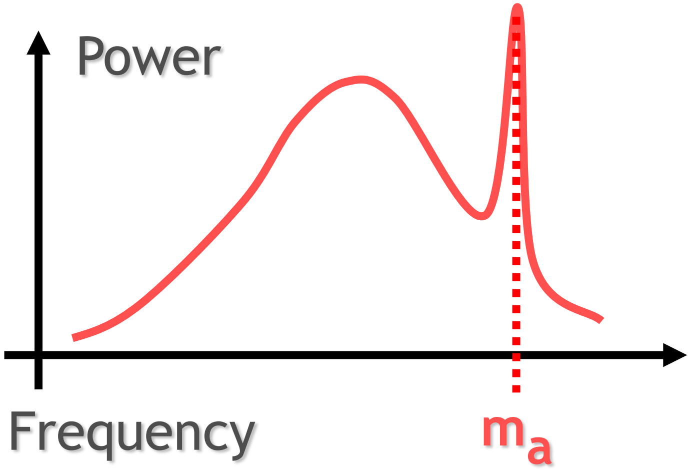


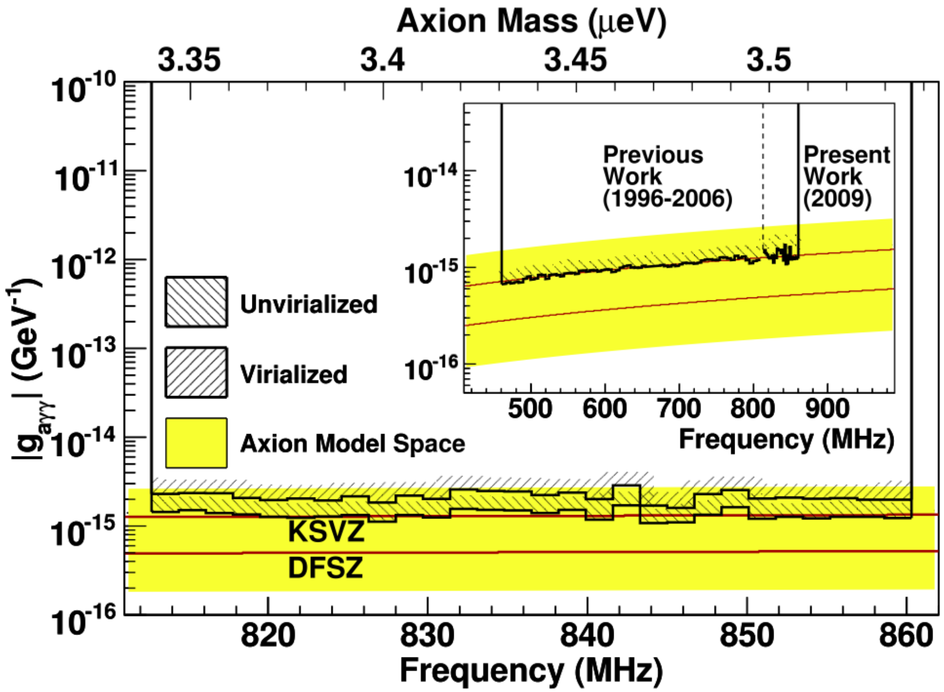
Primakoff conversion

B

DM axions	$m_a = 10\text{-}3000\ \mu\mathrm{eV}$
Velocities in galaxy	$v_a \approx 10^{-3}\ c$
Microwave Energies	$E_a \approx (1 \pm 10^{-6})\ m_a$

Axion Signal



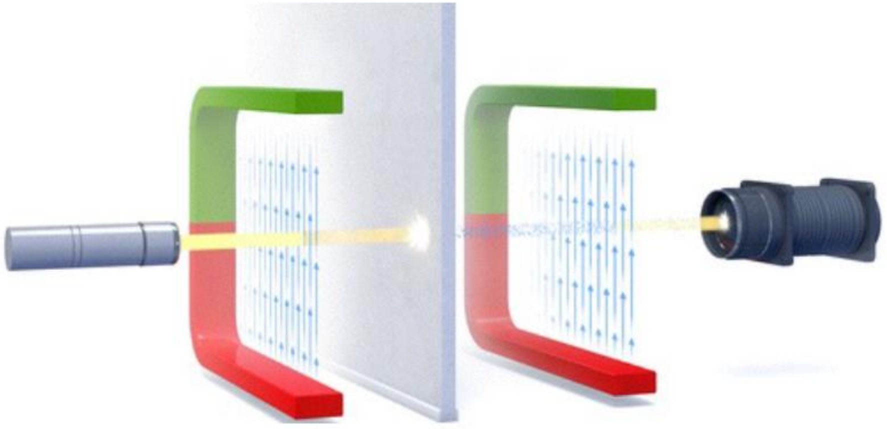


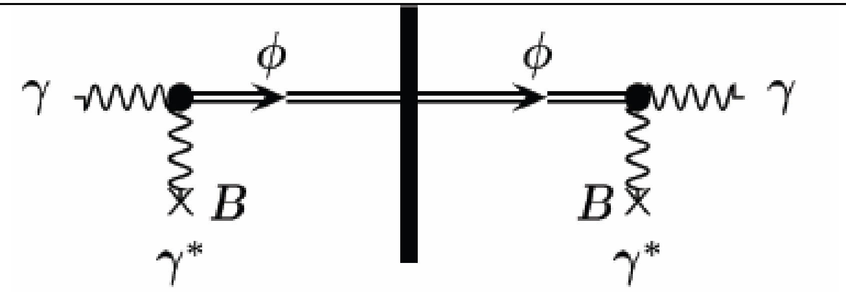
ADMX Collaboration, arXiv:0910.5914

AXION DARK MATTER SEARCH (ADMX)

LIGHT SHINING THROUGH A WALL (LSW) EXPERIMENTS

Search for photon regeneration





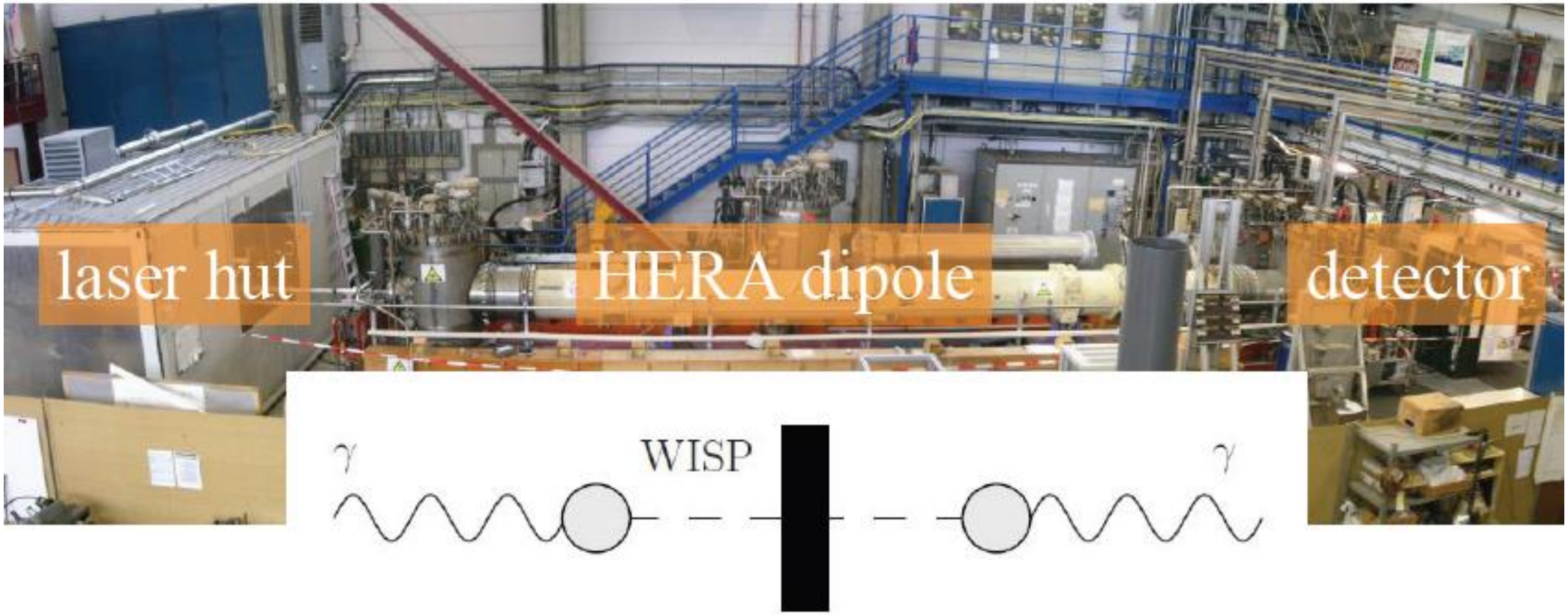
Okun 1982, Skivie 1983, Ansel'm 1985, Van Bibber et al. 1987

Many experiments all around the world: ALPS@DESY, BMV@Tolouse, GammeV@FNAL, LIPPS@Jlab, OSQAR@CERN

ALPS@DESY

[ALPS collaboration, arXiv:0905.4159]

Any Light Particle Search @ DESY



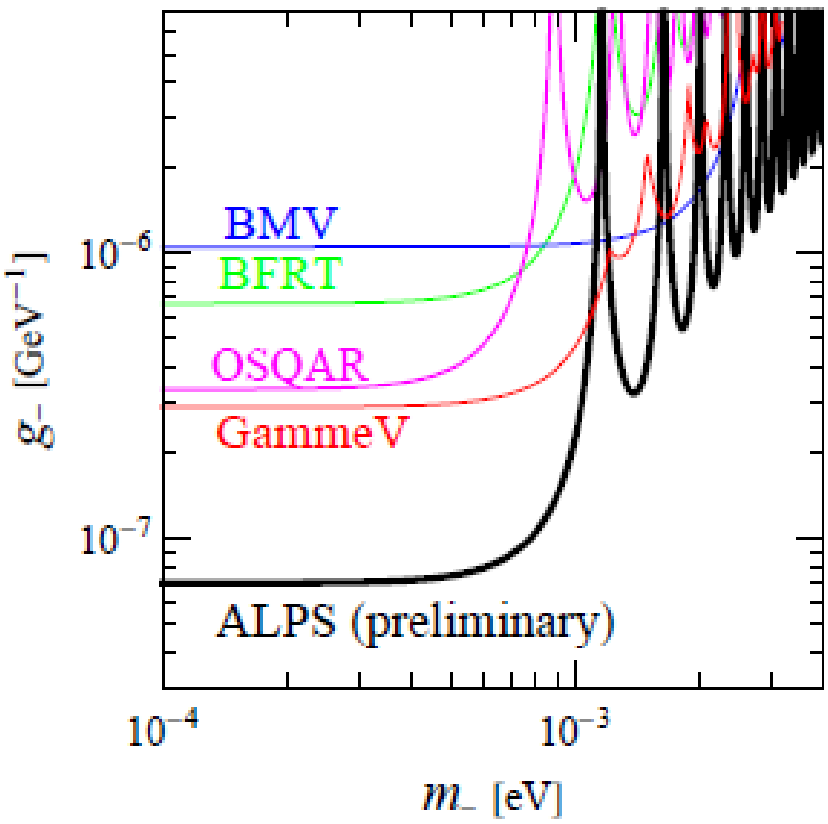
A photon regeneration experiment

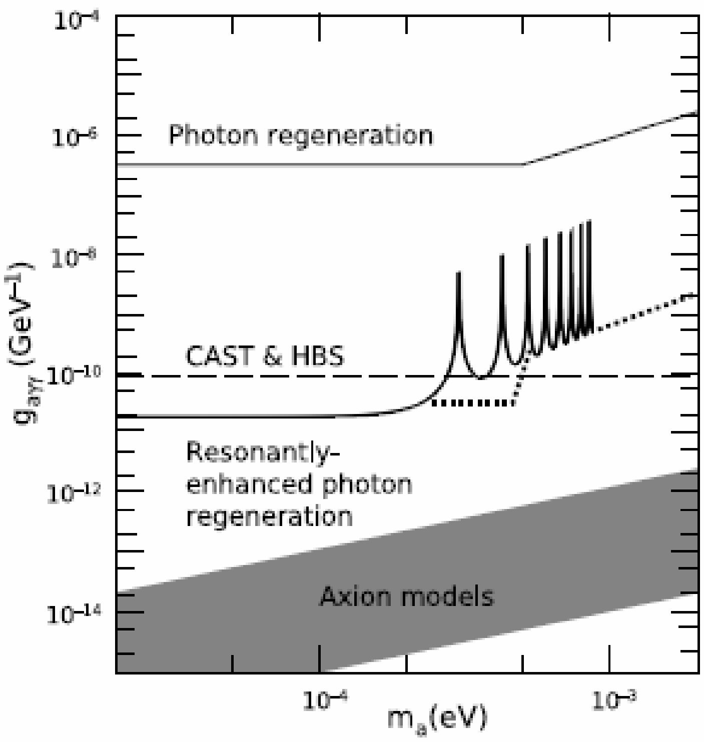
Approved January 2007
Final data run December 2009
(end of first phase)

(Searches also for hidden photons, millicharged particles)

UPPER BOUNDS ON ALPS FROM LSW EXP

[A. Ringwald, arXiv: 1003.2339]



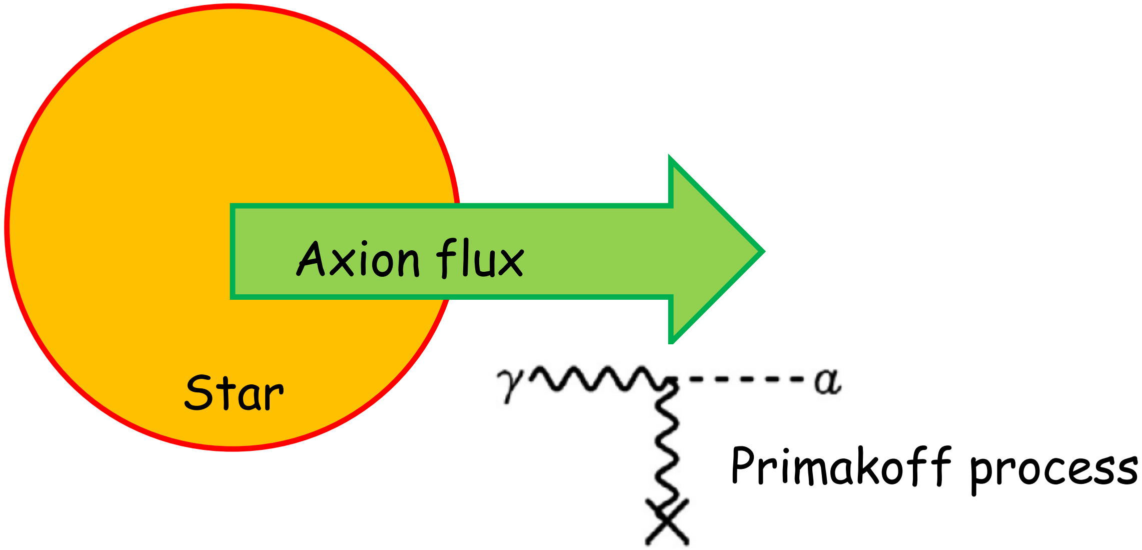


With resonantly enhanced photon regeneration the CAST bound would be beated.

IS IT ALREADY POSSIBLE TO OVERCOME THE "CAST BARRIER"?

YES, WE CAN ....
WITH ASTROPHYSICS !

ASTROPHYSICAL AXION BOUNDS

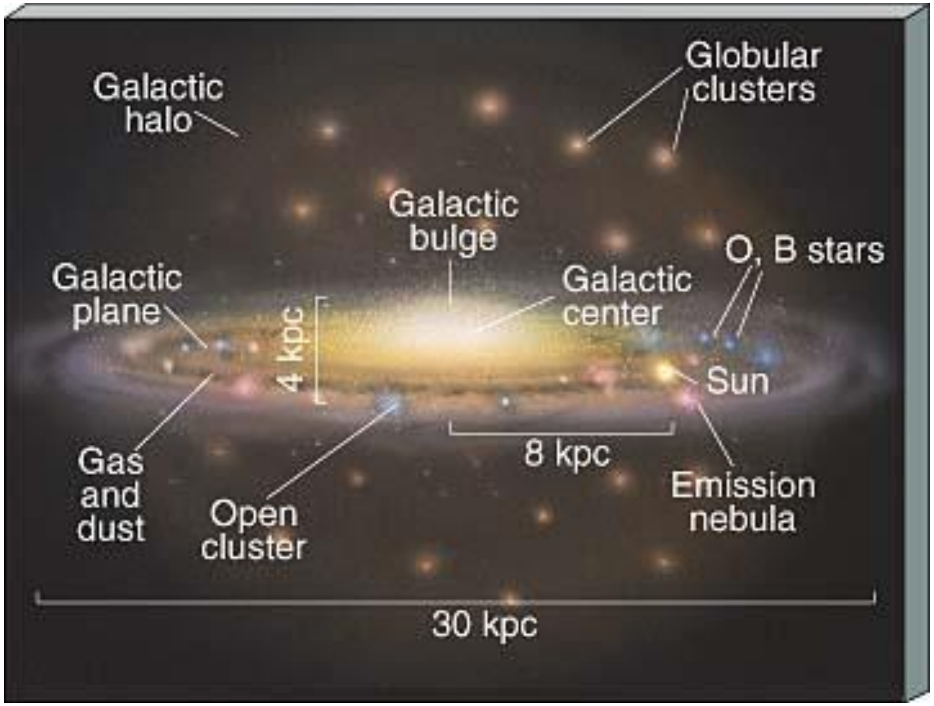


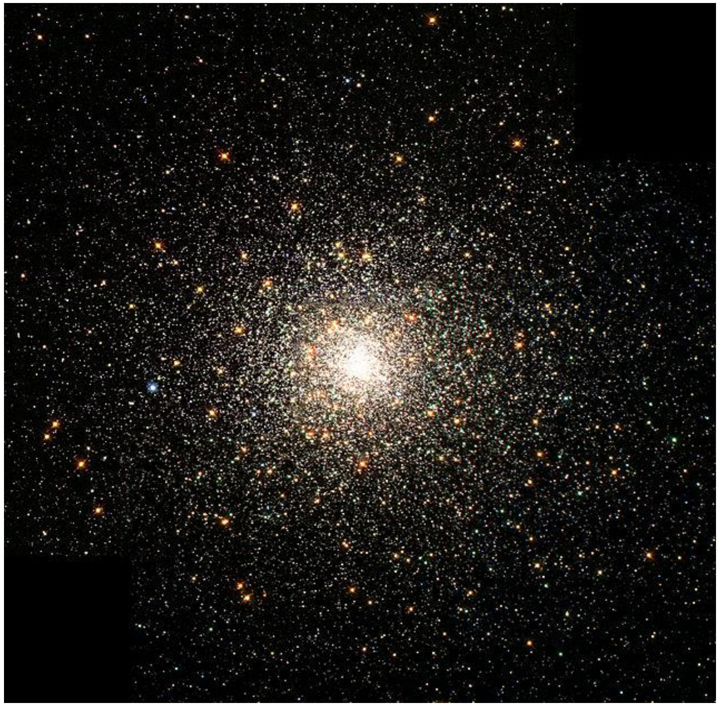
- ALPs have very small mass
- Emission from stellar plasma not suppressed by threshold effect
- New energy-loss channel
- Back-reaction on stellar properties and evolution

Additional energy loss (“cooling”)

- Loss of pressure
- Contraction
- Heating
- Increased nuclear burning

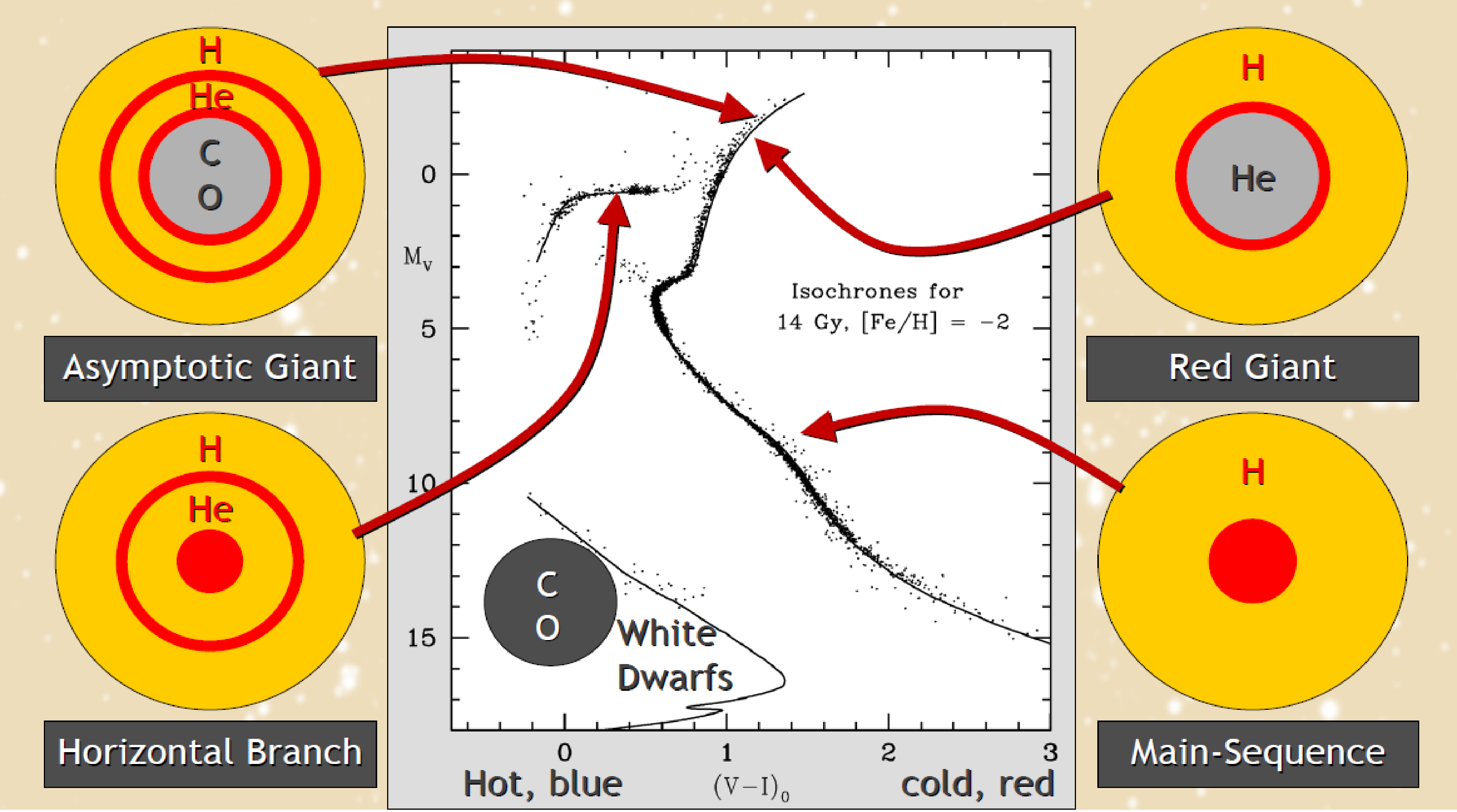
GLOBULAR CLUSTERS





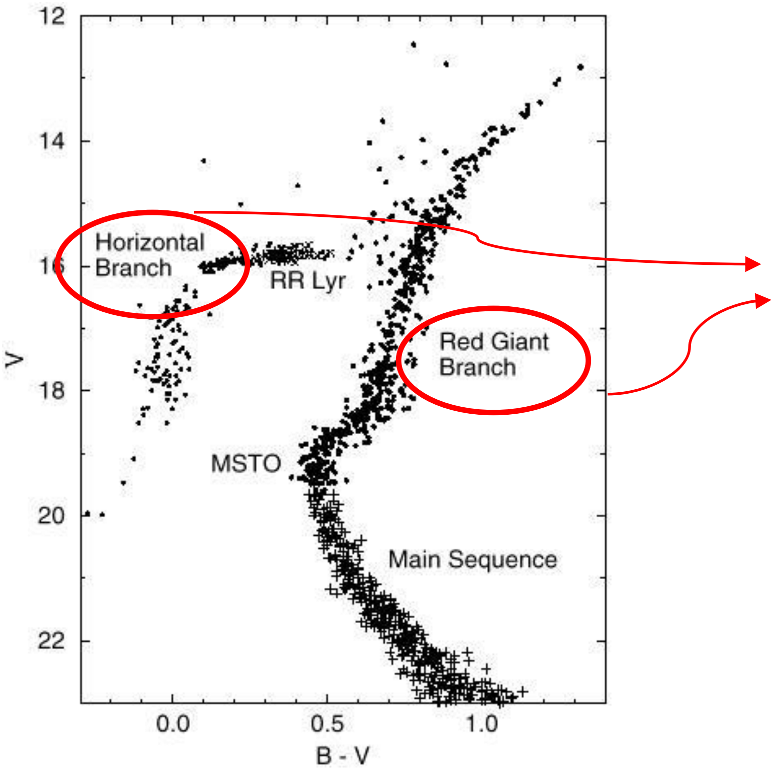
- Globular clusters are gravitationally bound associations of typically 10^6 stars
- The low metallicity is one indicator for their great age
- All stars in a given cluster are coeval; they differ only in their mass

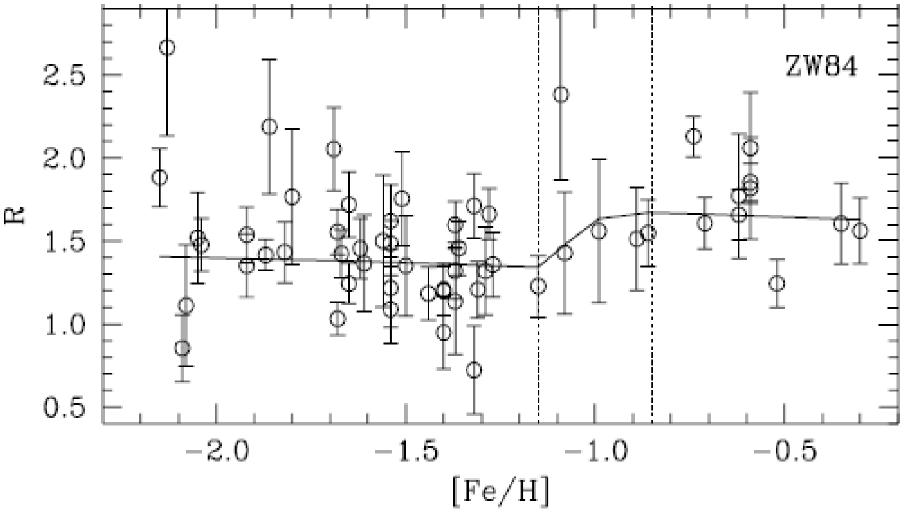
COLOR MAGNITUDE DIAGRAM FOR GLOBULAR CLUSTER



The color-magnitude diagram of a globular cluster represents an “isochrone” of a stellar population. Locus of coeval stars with different initial masses.

HELIUM BURNING LIFETIME OF HB STARS





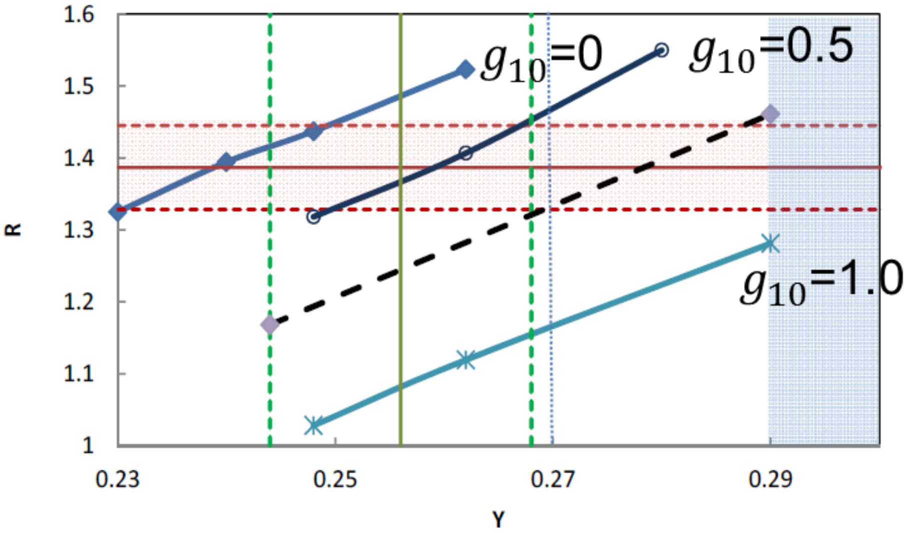
[Salaris et al., astro-ph/0403600]
57 GCs

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

Well reproduced, within 30 %, by models of GC without axions

Axions would reduce the lifetime of stars in HB, while producing negligible change in RGB evolution (Primakoff rate suppressed in degenerate RGB core).
[Raffelt & Deaborn, PRD 36, 2211 (1987)]

HELIUM BURNING LIFETIME OF HB STARS



$$R = 6.26Y - 0.41g_{10}^2 - 0.12$$

We found dependence of R on Helium mass fraction Y, neglected in previous investigations

NEW AXION BOUND FROM GCs

[*Ayala, Dominguez, Giannotti, A.M., Straniero, 1406.6053*]

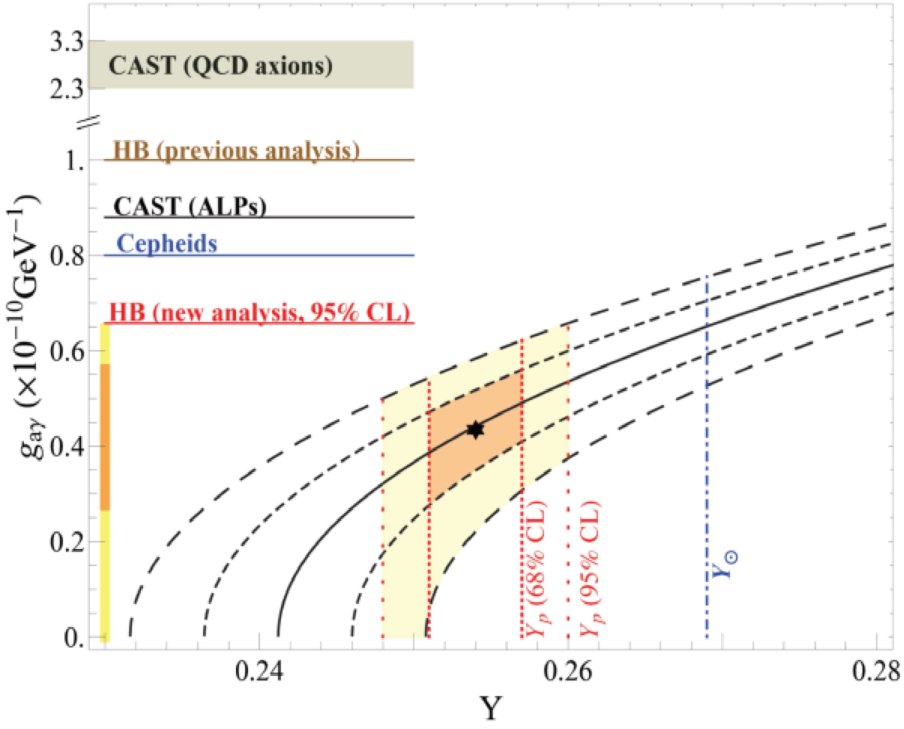


TABLE I: axion-photon coupling bounds

		R	Y	g_{10}
bounds from Y_p	up 95%	1.33	0.260	0.66
-	up 68%	1.36	0.257	0.57
-	central value	1.39	0.254	0.45
-	low 68%	1.42	0.251	0.29
-	low 95%	1.45	0.248	0.00
bounds from $Y_p{}^{\rm SBBN}$	up 95%	1.33	0.2478	0.50
-	up 68%	1.36	0.2475	0.42
-	central value	1.39	0.2472	0.31
-	low 68%	1.42	0.2469	0.15
-	low 95%	1.45	0.2466	0.00
bounds from $Y_\odot$	up 95%	1.33	0.269	0.76
-	up 68%	1.36	0.269	0.71

Taking as benchmark the direction determination of Helium fraction by Izotov et al. (1308.2100) Y_p=0.254±0.003 we find

$$g_{a\gamma} < 0.66 \times 10^{-10} GeV^{-1} \quad (95\ \%\ CL)$$

The strongest bound on $g_{a\gamma}$

SUPERNOVAE

Core collapse SN corresponds to the terminal phase of a massive star [$M \gtrsim 8\, M_\odot$] which becomes unstable at the end of its life. It collapses and ejects its outer mantle in a shock wave driven explosion.

- **ENERGY SCALES:** 99% of the released energy (~ 10^{53} erg) is emitted by ν and $\bar{\nu}$ of all flavors, with typical energies E ~ O(15 MeV).
- **TIME SCALES:** Neutrino emission lasts **~10 s**
- **EXPECTED:** **1-3 SN/century** in our galaxy (d ≈ O (10) kpc).

THREE PHASES OF NEUTRINO EMISSION

[Figure adapted from *Fischer et al. (Basel group), arXiv: 0908.1871*]

10. 8 M_{sun} progenitor mass

(spherically symmetric with Boltzmnann ν transport)

Neutronization burst

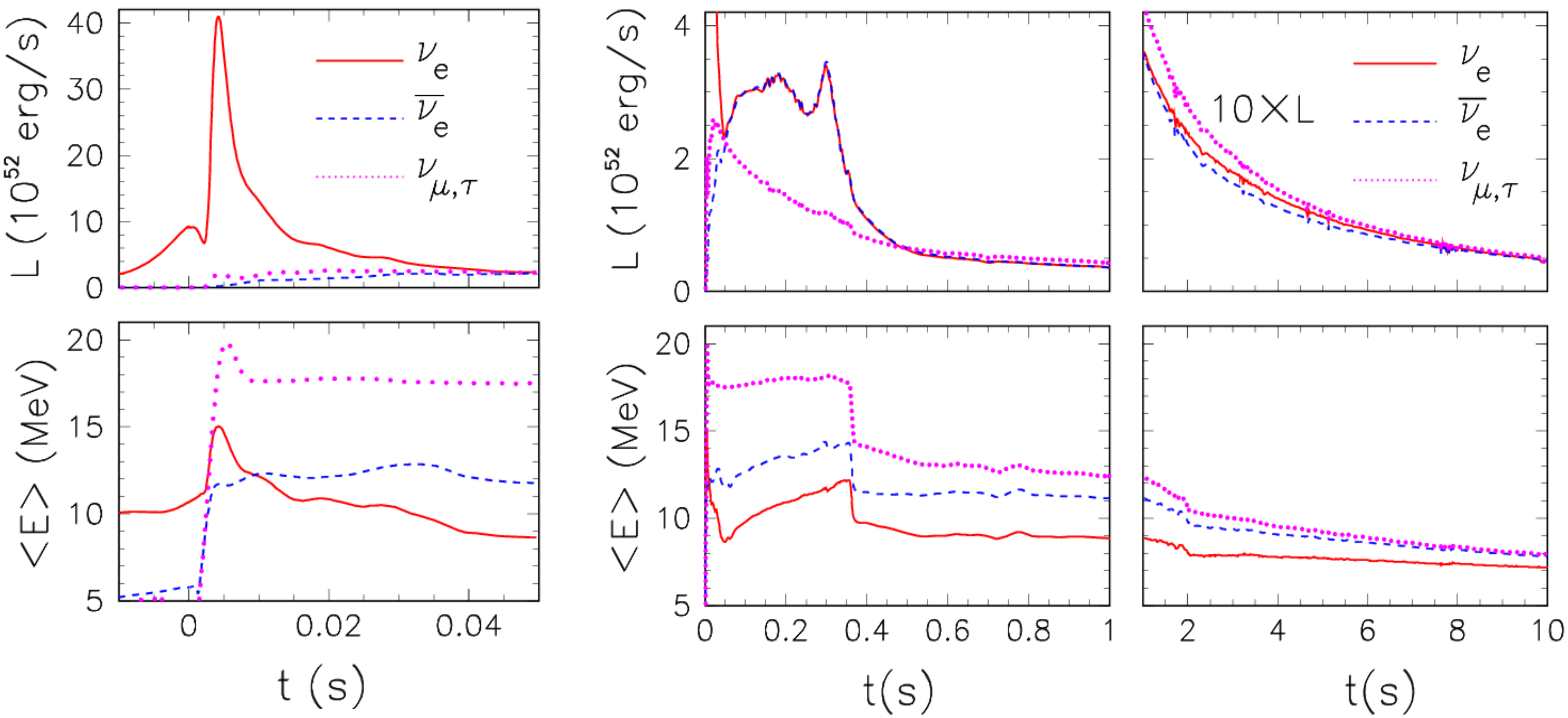
- Shock breakout
- De-leptonization of outer core layers

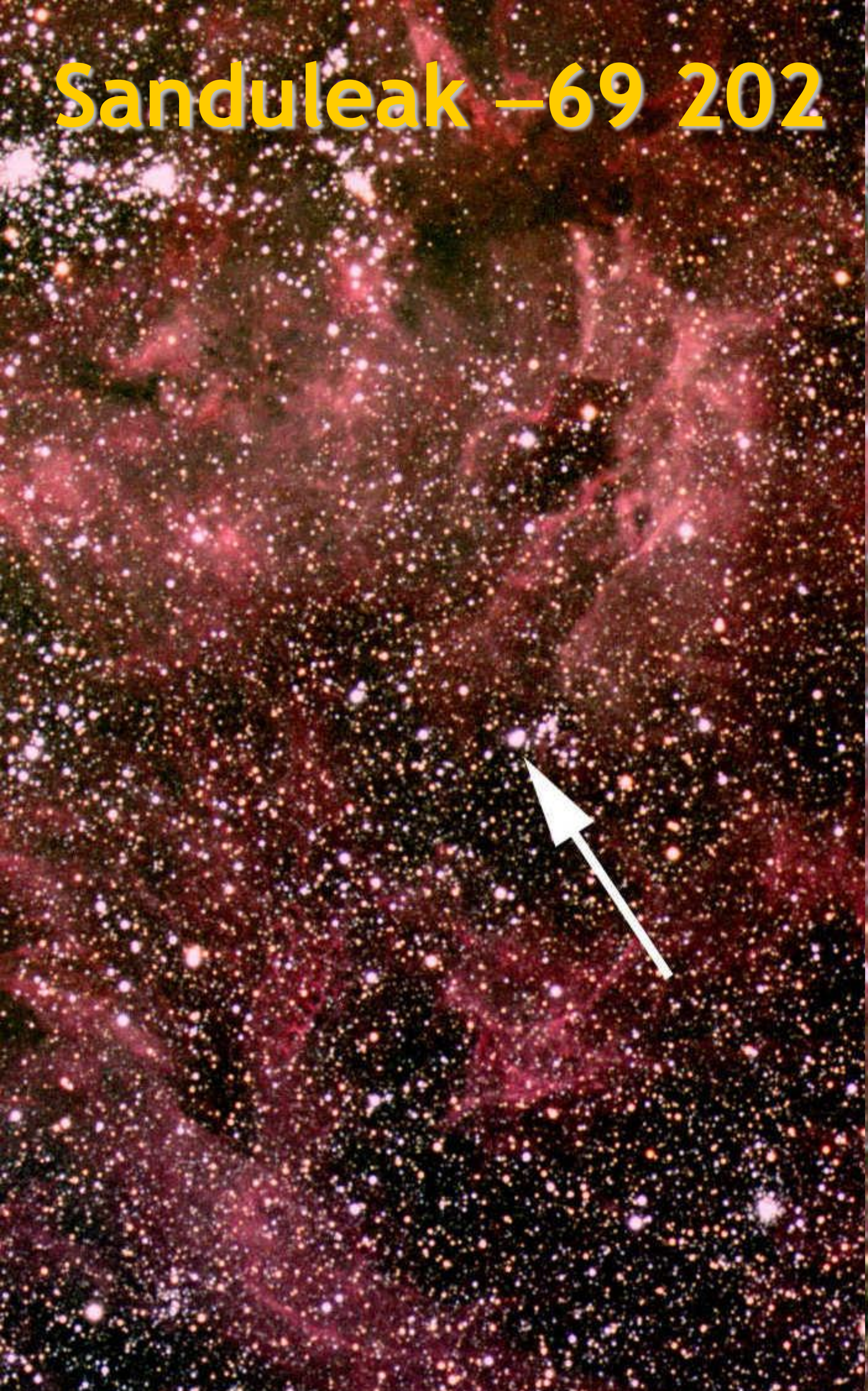
Accretion

- Shock stalls ~ 150 km
- ν powered by infalling matter

Cooling

- Cooling on ν diffusion time scale



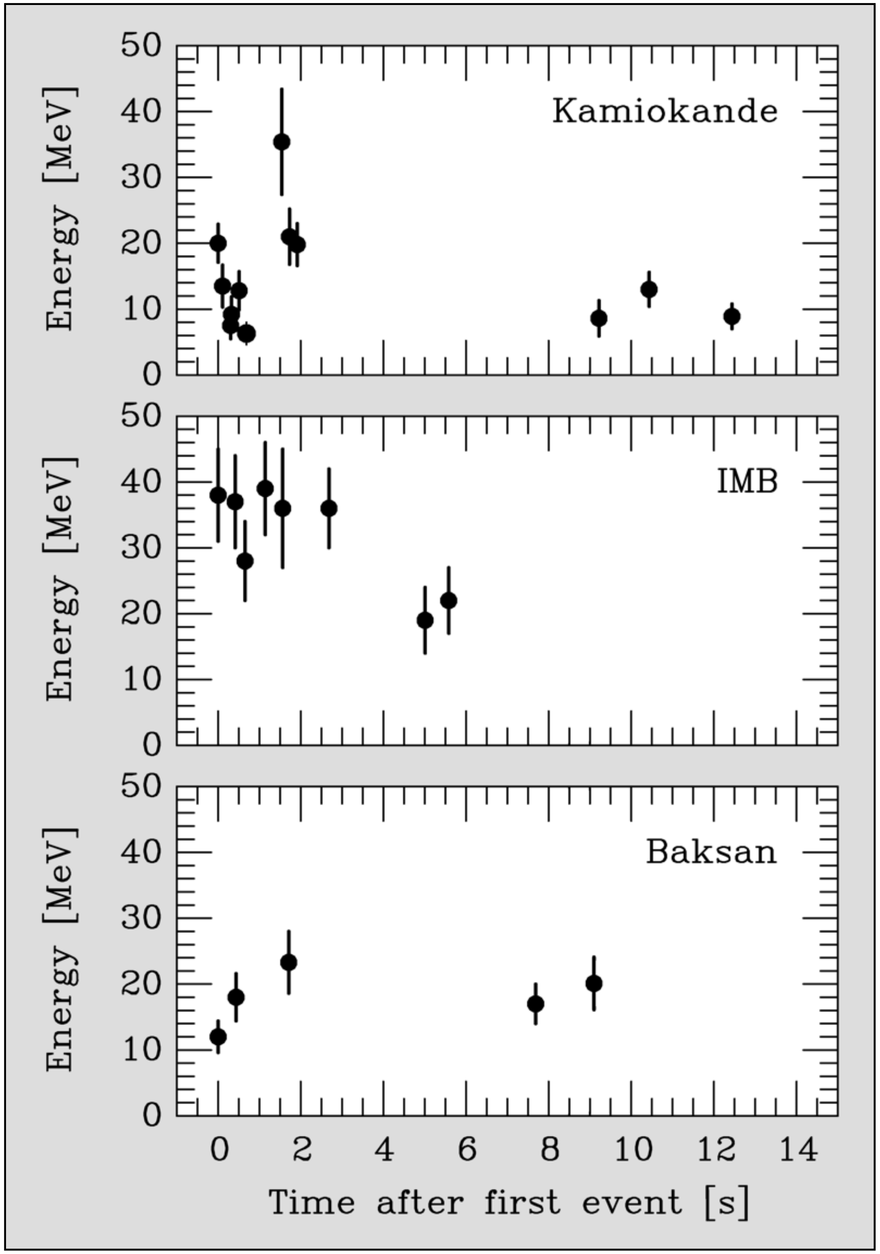


Sanduleak −69 202

Supernova 1987A

23 February 1987

NEUTRINO SIGNAL OF SUPERNOVA 1987A



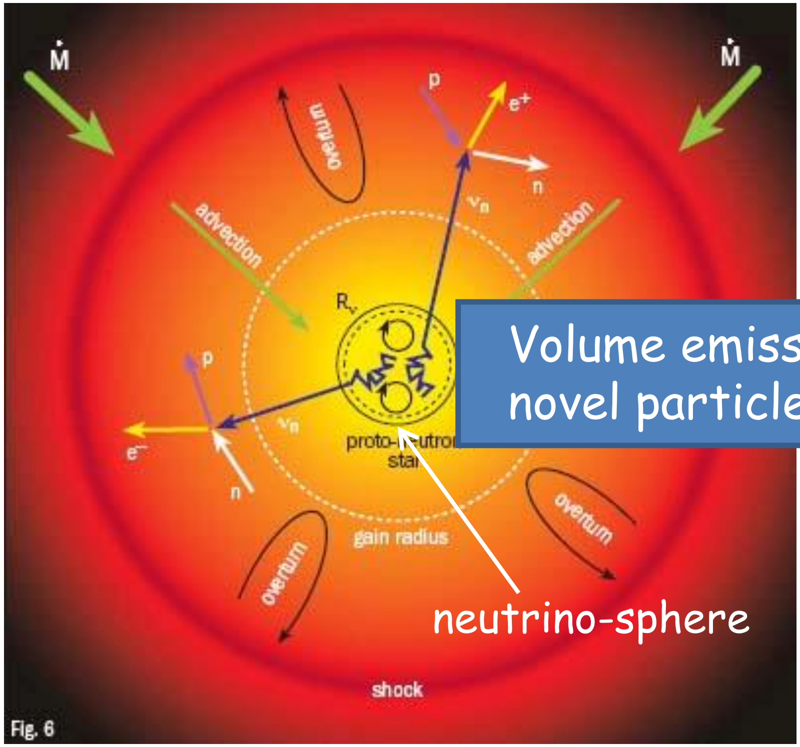
Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ±1 min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty ±50 ms

Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster ~ 0.7/day
Clock uncertainty +2/-54 s

Within clock uncertainties,
signals are contemporaneous

ENERGY-LOSS ARGUMENT



Volume emission of novel particles

neutrino-sphere

Emission of very weakly interacting particles would “steal” energy from the neutrino burst and shorten it.

Assuming that the SN 1987A neutrino burst was not shortened by more than ~$\frac{1}{2}$ leads to an approximate requirement on a novel energy-loss rate of

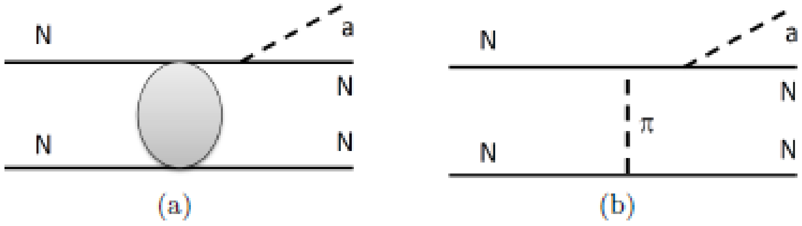
$$\varepsilon_x < 10^{19}\ \mathrm{erg}\ \mathrm{g}^{-1}\ \mathrm{s}^{-1}$$

for $\rho \approx 3 \times 10^{14}\ \mathrm{g\ cm}^{-3}$ and $T \approx 30$ MeV

AXION EMISSION FROM A NUCLEAR MEDIUM

$$NN \to NNa$$

nucleon-nucleon bremsstrahlung



Bulk nuclear interaction One pion exchange

$$\boxed{L_{aN} = \frac{g_{aN}}{2m_N}\overline{N}\gamma_\mu\gamma_5 N\partial^\mu a}$$

$$g_{aN} = C_N \frac{m}{f_a}$$

Non-degenerate energy-loss rate $\varepsilon_a = g_{aN}^2\, 2\times 10^{39}\,\mathrm{erg\,g^{-1}\,s^{-1}}\rho_{15}T_{30}^{3.5}$

$$\begin{pmatrix} T_{30} = T/30\ \mathrm{MeV} \\ \rho_{15} = \rho/10^{15}\mathrm{g\,cm^{-3}} \end{pmatrix}$$

$$\langle\rho_{15}\rangle \approx 0.4$$

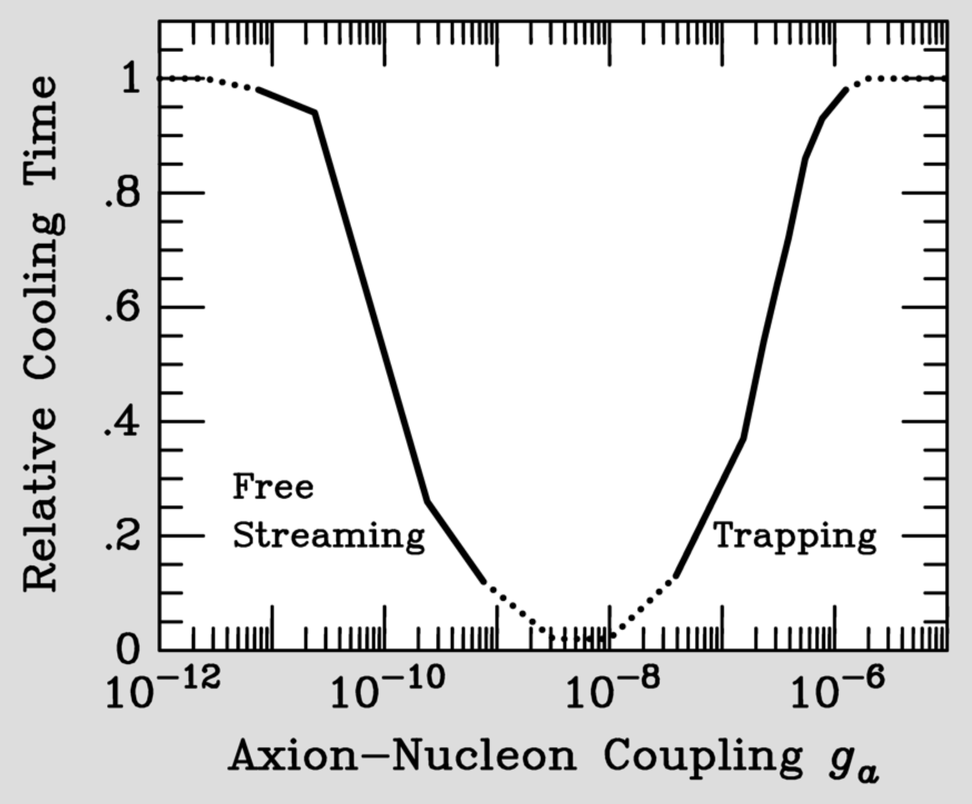
$$\langle T_{30}^{3.5}\rangle \approx 1.4$$

$$\Rightarrow \quad g_{aN} < 9\times 10^{-10}$$

SN 1987A AXION LIMITS

Free streaming
[Burrows, Turner & Brinkmann, PRD 39:1020,1989]

Volume emission of axions



Trapping
[Burrows, Ressell & Turner, PRD 42:3297,1990]

Axion diffusion from an "axion-sphere"

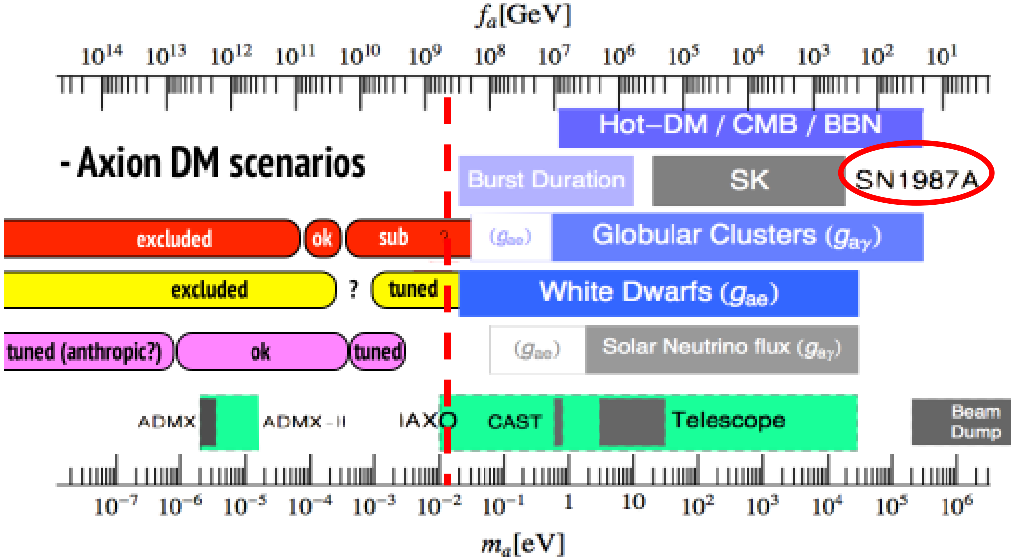
Possible detection in a water Cherenkov detector via oxygen nuclei excitation

Hadronic axion (m_a ~ 1 eV, f_a~10^6 GeV) not excluded by SN 1987A. Possible hot-dark matter candidate. The "hadronic axion window" is closed by cosmological mass bounds.

WHAT WE LEARNT FROM SN 1987A?

- General confirmation of core-collapse paradigm (total energy, spectra, time scale)

- No unexpected energy-loss channel: Restrictive limits on axions…but we a lot of uncertainties….



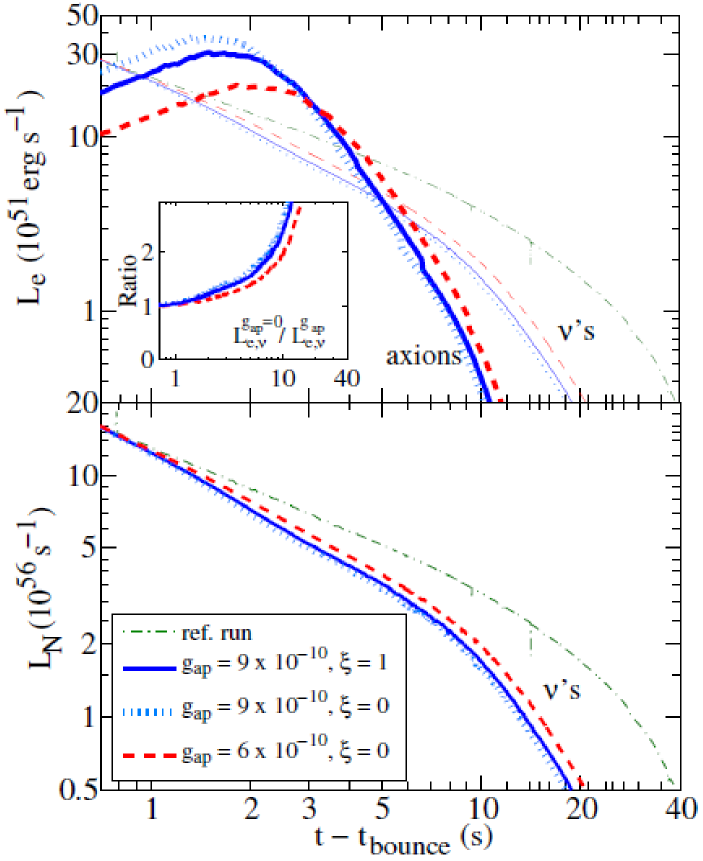
- Improving Energy-Loss Limits with Next Supernova?
  Sensitivity comparable to IAXO one. Important for hadronic axions where WD bounds are absent.

A REAPPRISAL OF AXION EMISSION WITH STATE OF ART SIMULATIONS

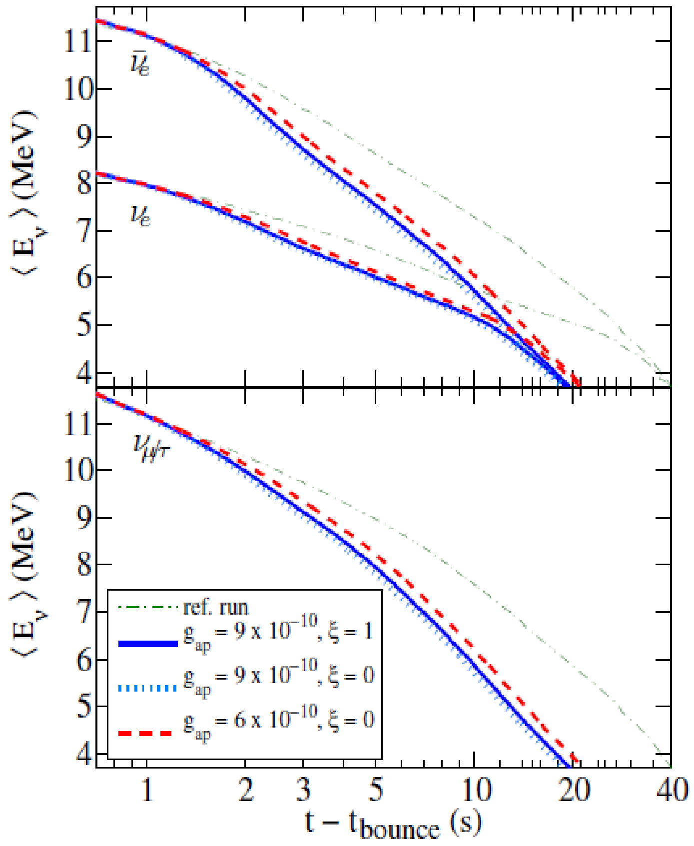
[Fischer, Chakraborty, Giannotti A.M. , Payez & Ringwald, 1605.08780]

18 M_{sun} progenitor mass

(spherically symmetric with Boltzmnann ν transport)



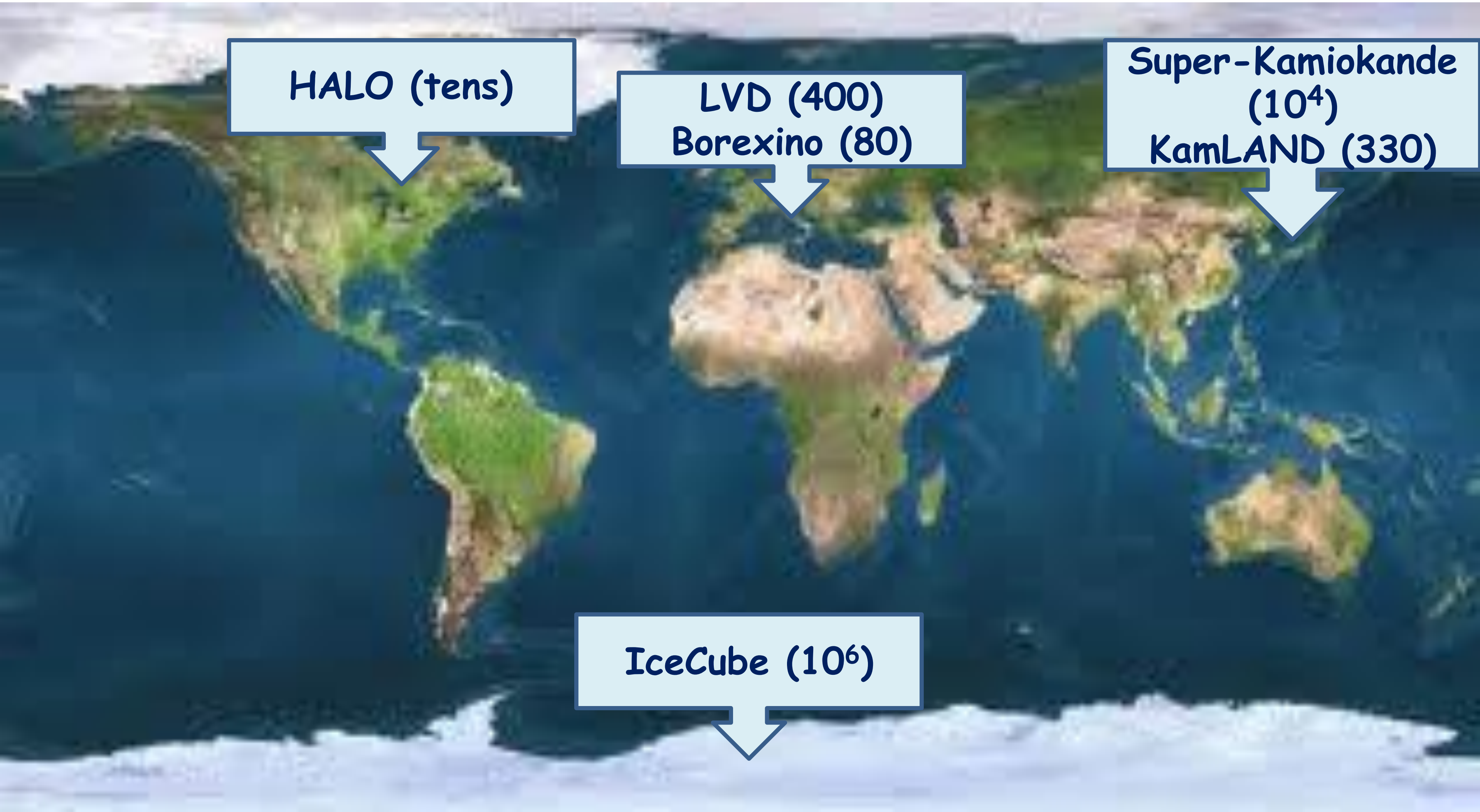
(a) Energy and number luminosities



(b) Average neutrino energies

KSVZ hadronic axion model (g_{an} =0)

Large Detectors for Supernova Neutrinos



HALO (tens)

LVD (400)
Borexino (80)

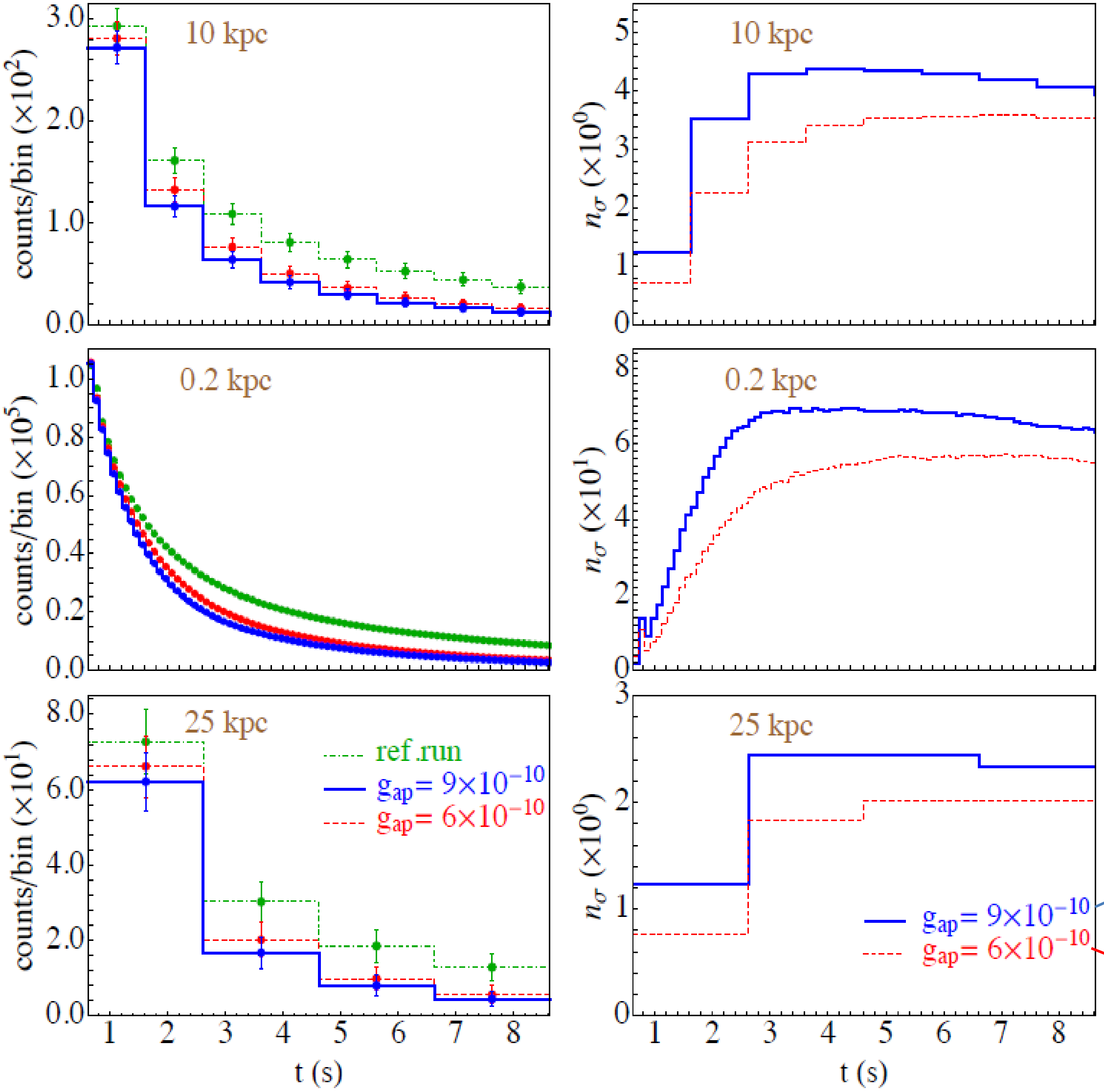
Super-Kamiokande (10^4)
KamLAND (330)

IceCube (10^6)

In brackets events for a “fiducial SN” at distance 10 kpc

IMPACT ON NEUTRINO SIGNAL

@ Super-Kamiokande



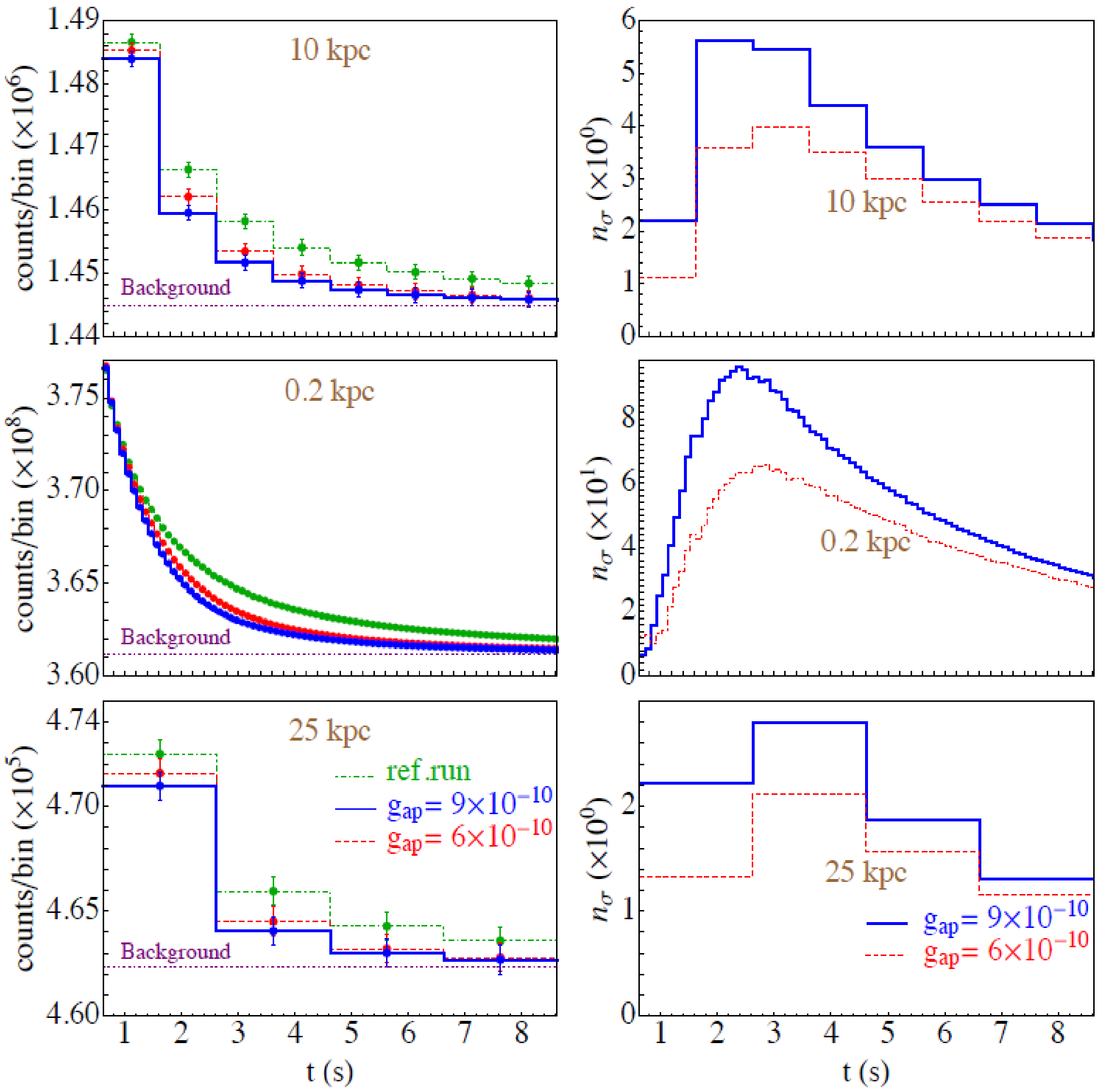
(~ GC)

(Betelgeuse)

$m_a = 3 \times 10^{-2}\, eV,$
$f_a = 4.8 \times 10^{8} GeV$

$m_a = 8 \times 10^{-2}\, eV,$
$f_a = 7.3 \times 10^{8} GeV$

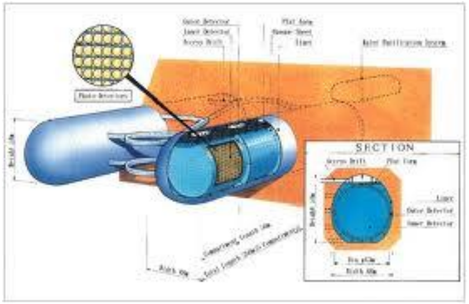
@ Icecube


10 kpc
Background
counts/bin (×10^6)
1.49
1.48
1.47
1.46
1.45
1.44
n_σ (×10^0)
10 kpc
0.2 kpc
Background
counts/bin (×10^8)
3.75
3.70
3.65
3.60
n_σ (×10^1)
0.2 kpc
25 kpc
ref.run
$g_{ap}= 9\times10^{-10}$
$g_{ap}= 6\times10^{-10}$
Background
counts/bin (×10^5)
4.74
4.70
4.65
4.60
n_σ (×10^0)
25 kpc
$g_{ap}= 9\times10^{-10}$
$g_{ap}= 6\times10^{-10}$
1 2 3 4 5 6 7 8
t (s)
1 2 3 4 5 6 7 8
t (s)

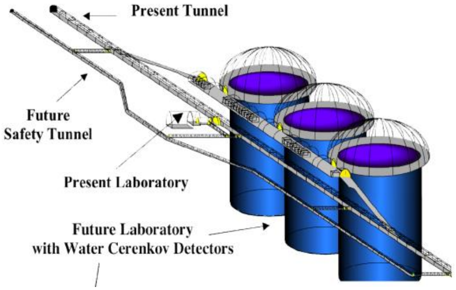
NEXT-GENERATION DETECTORS

Mton scale water Cherenkov detectors

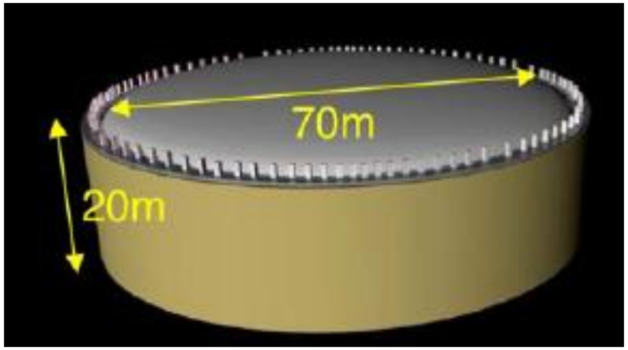
HYPER-
KAMIOKANDE



MEMPHYS



30-100 kton Liquid Argon TPC



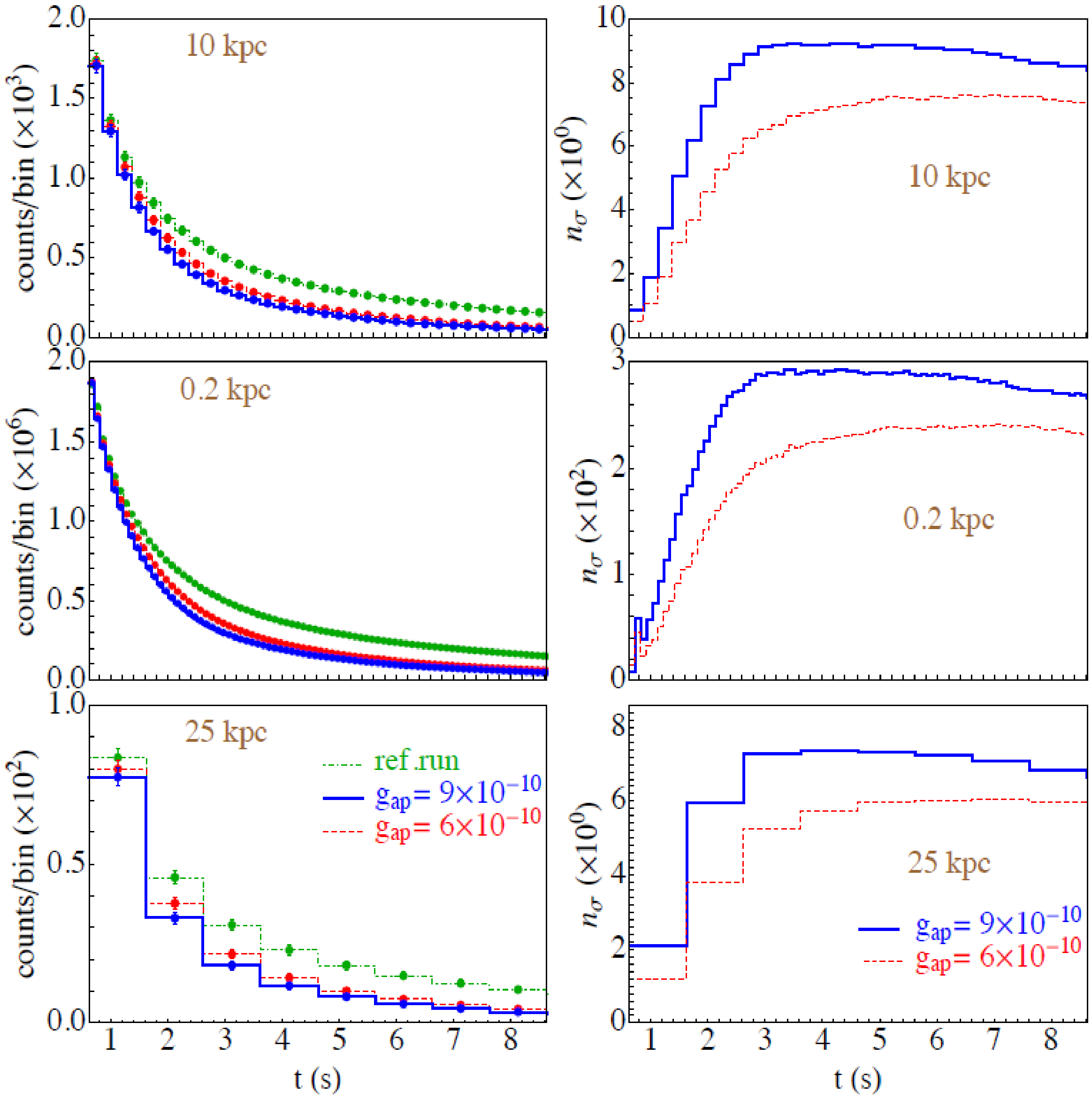
GLACIER, LBNE

20-50 kton scintillator

JUNO

LENA

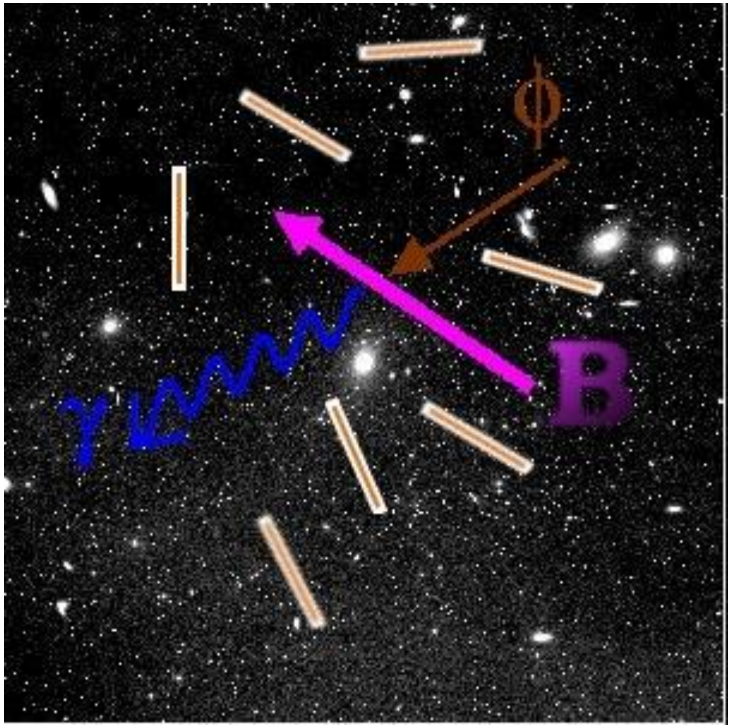
@ 400 kton WC detector



Alessandro Mirizzi

LNF, Frascati, 1 July 2016

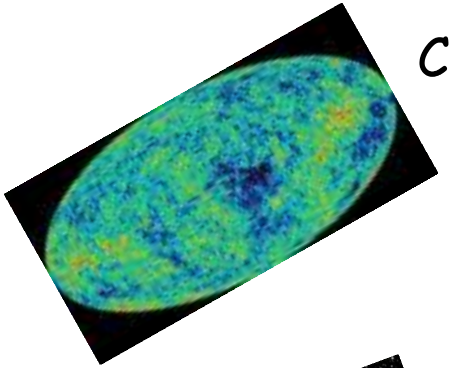
ALPs IN THE SKY?



Photons from cosmic sources can mix with ALPs in the large scale cosmic magnetic fields.

In the last recent years, different contraints and hints of ultralight ALP have emerged from various astrophysical observations.

WHERE TO LOOK FOR ALPs?

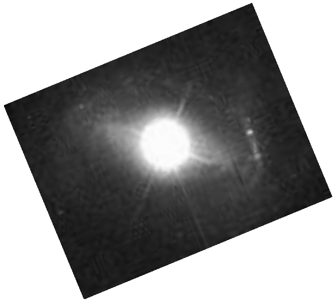


CMB (and diffuse radiations)

GRB

SNe

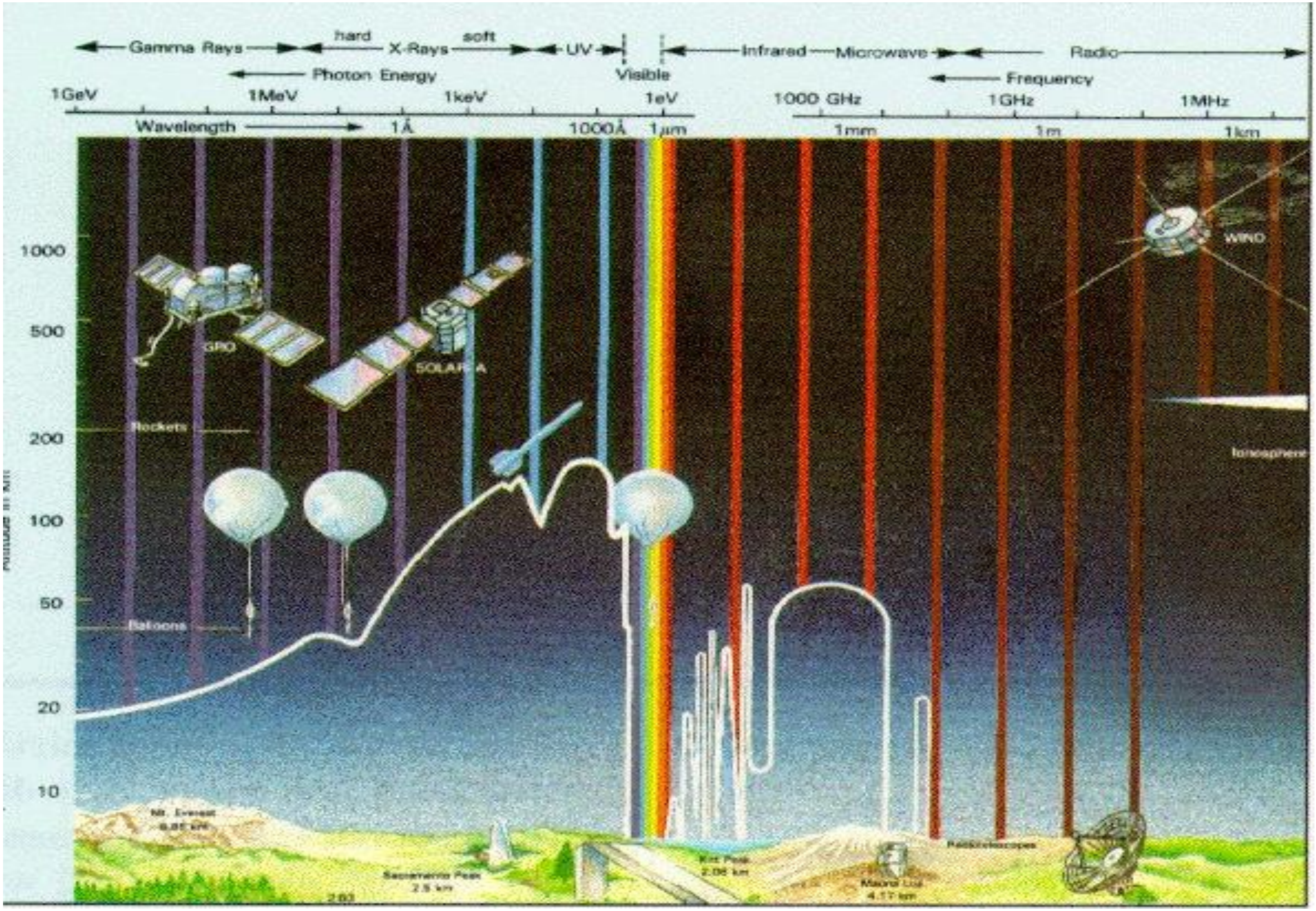
AGN



QSO

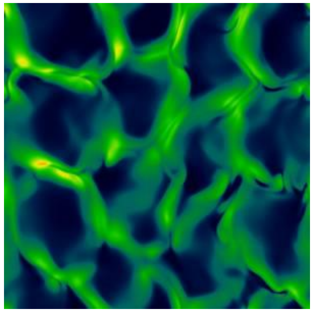
Magnetars

VHE Cosmic rays

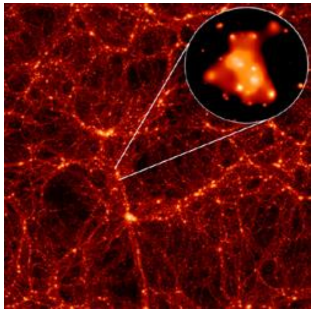


Astrophysical signatures of ALPs over 16 order of magnitudes !

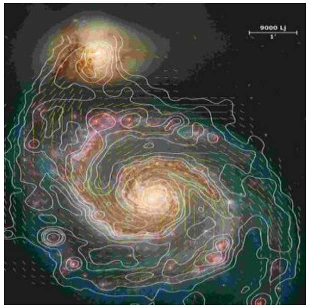
COSMIC MAGNETIC FIELDS



Intergalactic magnetic field. Turbulent structure. For semplicity often assumed a cell-like structure, with B ≈ 1 nG and coherence length L≈ 1 Mpc. Mean electron density $n_e \approx 10^{-7}$ cm^{-3}, i.e. plasma density $\omega_{pl} \approx 1.2 \times 10^{-14}$ eV



Intracluster magnetic field. Turbulent structure. Cell-like structure. B ≈ 1 μG and L≈ 10 kpc. Mean electron density $n_e \approx 10^{-3}$ cm^{-3}, i.e. plasma density $\omega_{pl} \approx 1.2 \times 10^{-12}$ eV



Galactic magnetic field. Regular component. B ≈ few μG and L≈ 10 kpc. Mean electron density $n_e \approx 1.1 \times 10^{-2}$ cm^{-3}, i.e. plasma density $\omega_{pl} \approx 4.1 \times 10^{-12}$ eV. (Turbulent component negligible for ALP conversion)

(+ possible B-fields in the sources)

PHOTON-ALP MIXING

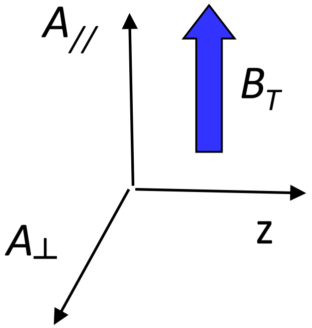
[Raffelt & Stodolsky, PRD 37, 1237 (1988)]

ALPs and photons oscillate into each other in an external magnetic field due to the interaction term

$$L_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}_{\mu\nu} a = g_{a\gamma} \vec{E} \cdot \vec{B} a$$

For propagation in the z-direction and very relativistic ALPs, one obtains a "Schrödinger equation"

$$\left[\omega + \begin{pmatrix} \Delta_{\perp} & \Delta_R & 0 \\ \Delta_R & \Delta_{//} & \Delta_{a\gamma} \\ 0 & \Delta_{a\gamma} & \Delta_a \end{pmatrix} - i\partial_z \right] \begin{pmatrix} A_{\perp} \\ A_{//} \\ a \end{pmatrix} = 0$$



If one ignores a possible Faraday rotation effect (Δ_R=0), $A_\perp$ decouples, and the lower part represents a 2 × 2 mixing problem

INPUT PARAMETERS

$$\left[\omega+\begin{pmatrix}\Delta_{pl} & \Delta_{a\gamma}\\ \Delta_{a\gamma} & \Delta_{a}\end{pmatrix}-i\partial_z\right]\begin{pmatrix}A_{//}\\ a\end{pmatrix}=0$$

→ **Photon-axion mixing**

where

- $\Delta_{a\gamma} \quad = \frac{1}{2} g_{a\gamma} B_T \simeq 1.52 \times 10^{-2} \left(\frac{g_{a\gamma}}{10^{-11}\mathrm{GeV}^{-1}}\right)\left(\frac{B_T}{10^{-9}\,\mathrm{G}}\right) \mathrm{Mpc}^{-1}\,,$
- $\Delta_{a} \quad = -\frac{m_a^2}{2E} \simeq -7.8 \times 10^{-4} \left(\frac{m_a}{10^{-10}\mathrm{eV}}\right)^2 \left(\frac{E}{\mathrm{TeV}}\right)^{-1} \mathrm{Mpc}^{-1}\,,$
- $\Delta_{\mathrm{pl}} \quad = \frac{\omega_{\mathrm{pl}}^2}{2E} \simeq -1.1 \times 10^{-11} \left(\frac{E}{\mathrm{TeV}}\right)^{-1} \left(\frac{n_e}{10^{-7}\,\mathrm{cm}^{-3}}\right) \mathrm{Mpc}^{-1}\,,$

$$\omega_{pl}^2 = \frac{4\pi\alpha n_e}{m_e}$$

plasma frequency

PHOTON-ALP CONVERSION PROBABILITY

The probability for a photon emitted in a state $A_{//}$ to convert into an ALP after traveling a distance **s** is given by

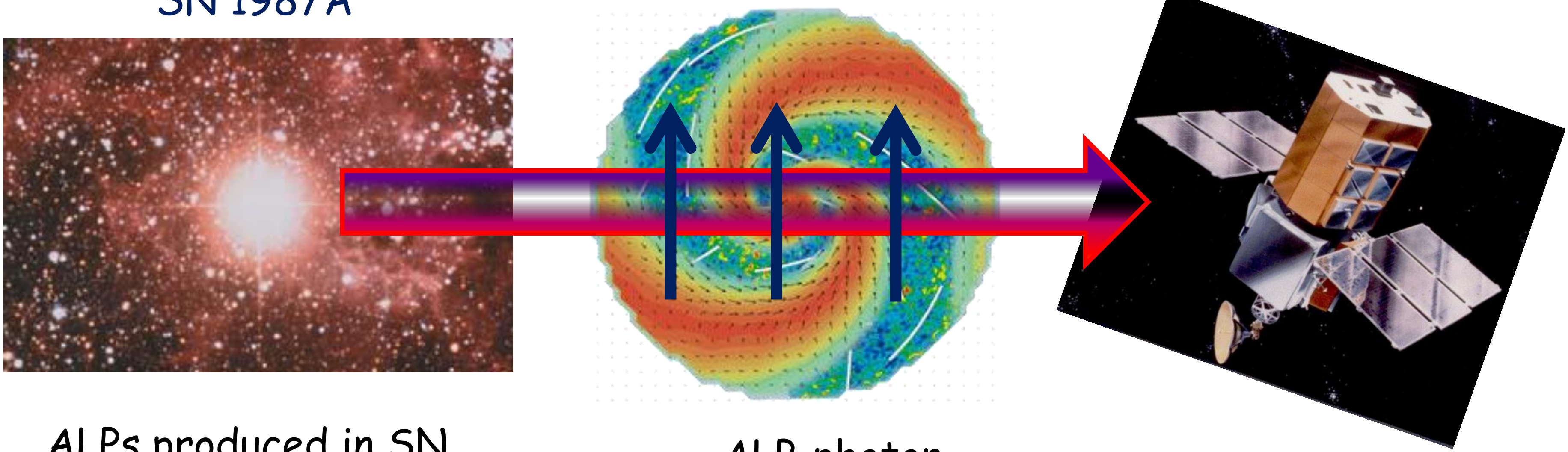
$$P_0(\gamma \to a) = |\langle A_{//}(0)|a(s)\rangle|^2 = \frac{1}{1+\left(\frac{E_*}{E}\right)^2}\sin^2\left(g_{a\gamma}B_T\left[1+\left(\frac{E_*}{E}\right)^2\right]^{1/2}\frac{s}{2}\right)$$

in terms of the critical energy

$$E_* \equiv \frac{|m_a^2-\omega_{pl}^2|}{2g_{a\gamma}B_T} \cong 2.6\cdot 10^{10}\,\frac{|m_a^2-\omega_{pl}^2|}{(10^{-10}\,eV)^2}\left(\frac{10^{-9}\,G}{B_T}\right)\left(\frac{g_{a\gamma}}{10^{-11}\,GeV^{-1}}\right)eV$$

ALPs CONVERSIONS FOR SN 1987A

[*Brockway, Carlson, Raffelt, astro-ph/9605197, Masso and Toldra, astro-ph/9606028*]



SN 1987A

Milky-Way

SMM Satellite

ALPs produced in SN core by Primakoff process

ALP-photon conversions in the Galactic B-fields

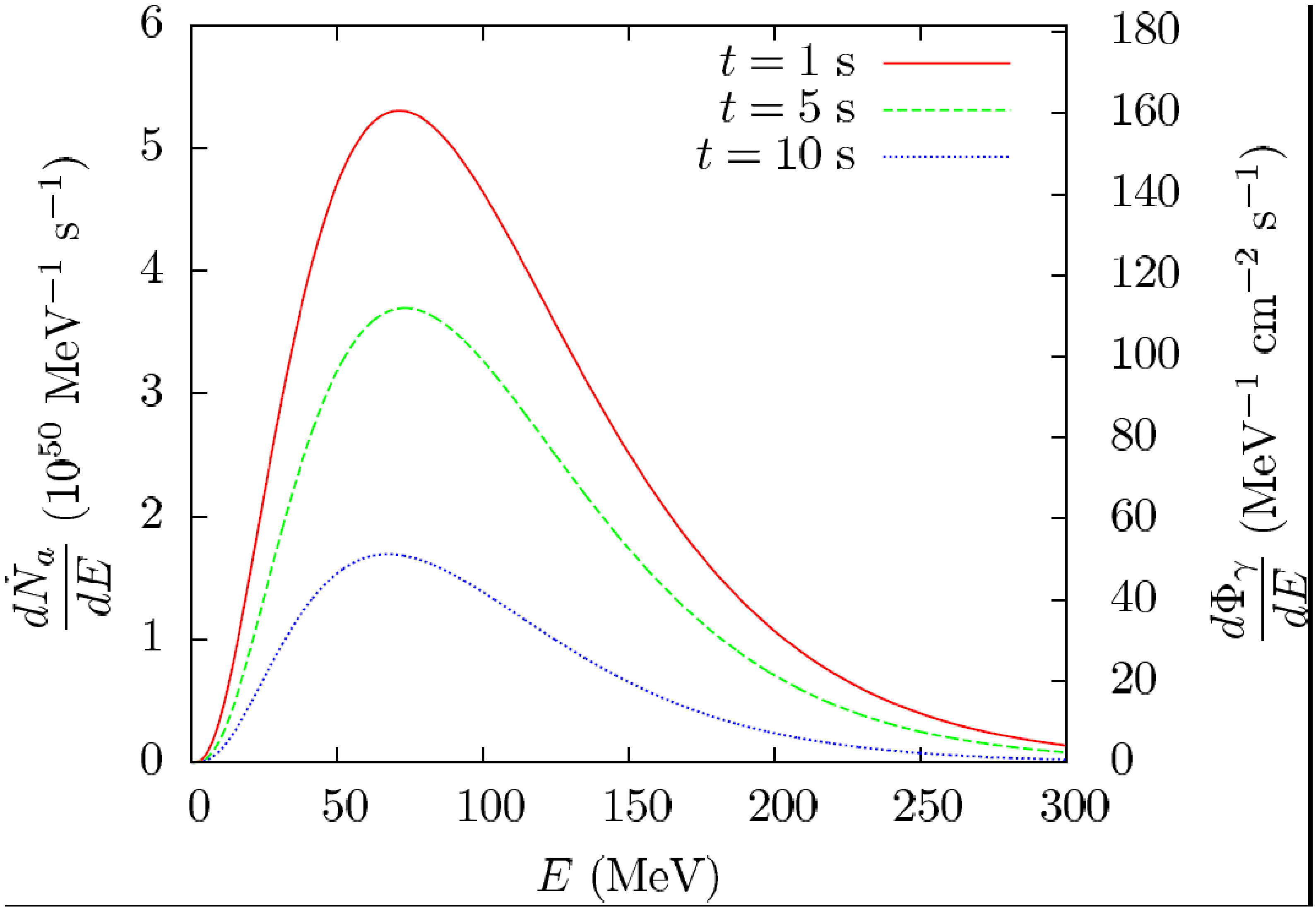
No excess gamma-rays in coincidence with SN 1987A

In [*Payez, Evoli, Fischer, Giannotti, A.M. & Ringwald, 1410.3747*] we revaluate the bound with

- state-of-art models for Sne and Galactic B-fields
- accurate microscopic description of the SN plasma

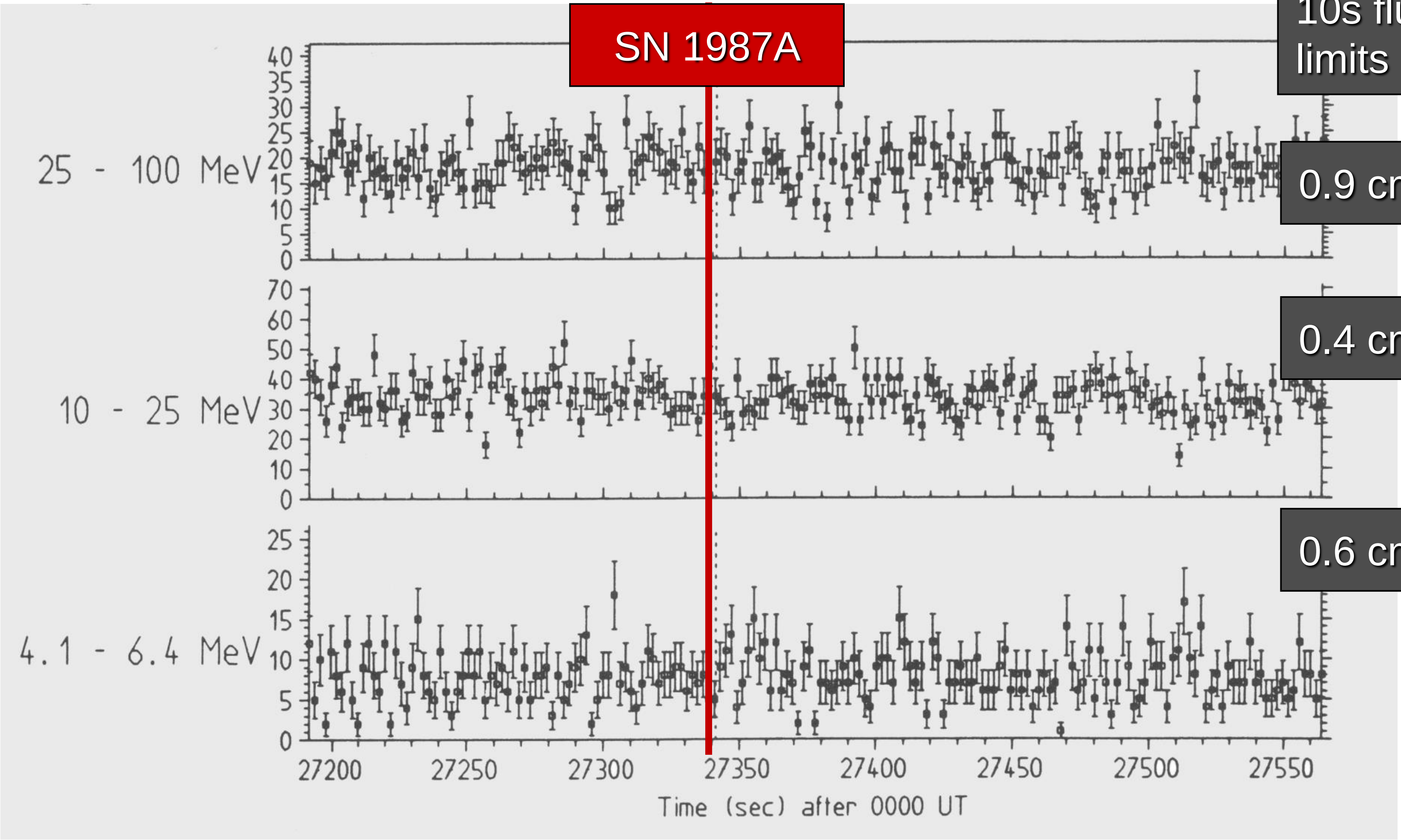
ALP-PHOTON FLUXES FOR SN 1987A

[Payez, Evoli, Fischer, Giannotti, A.M. & Ringwald, 1410.3747]



GAMMA-RAY OBSERVATION FROM SSM SATELLITE

Counts in the GRS instrument on the Solar Maximum Mission Satellite



SN 1987A

10s fluence limits

$0.9\ cm^{-2}$

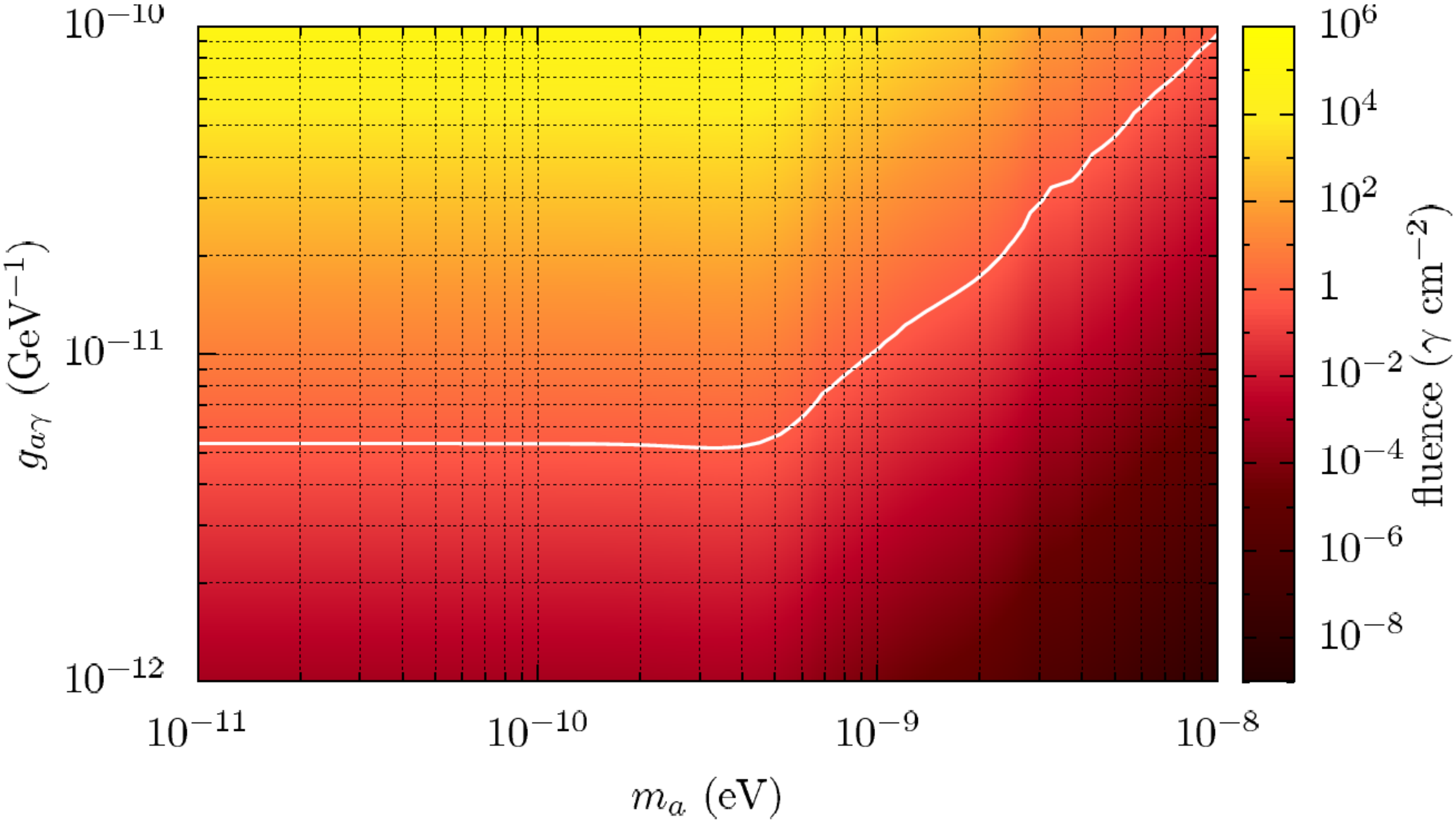
$0.4\ cm^{-2}$

$0.6\ cm^{-2}$

$$F(g_{a\gamma}) = 7.02 \times 10^4 \left(\frac{g_{a\gamma}}{10^{-10} GeV^{-1}}\right)^4 \gamma cm^{-2}$$

NEW BOUND ON ALPs FROM SN 1987 A

[*Payez, Evoli, Fischer, Giannotti, A.M. & Ringwald, 1410.3747*]



$$g_{a\gamma} \le 5.3 \times 10^{-12}\ GeV^{-1} \quad \text{for} \quad m_a < 4.4 \times 10^{-10}\text{eV}$$

SN1987A provides the strongest bound on ALP-photon coversions for ultralight ALPs

WHAT'S FROM SN 20XXA ?

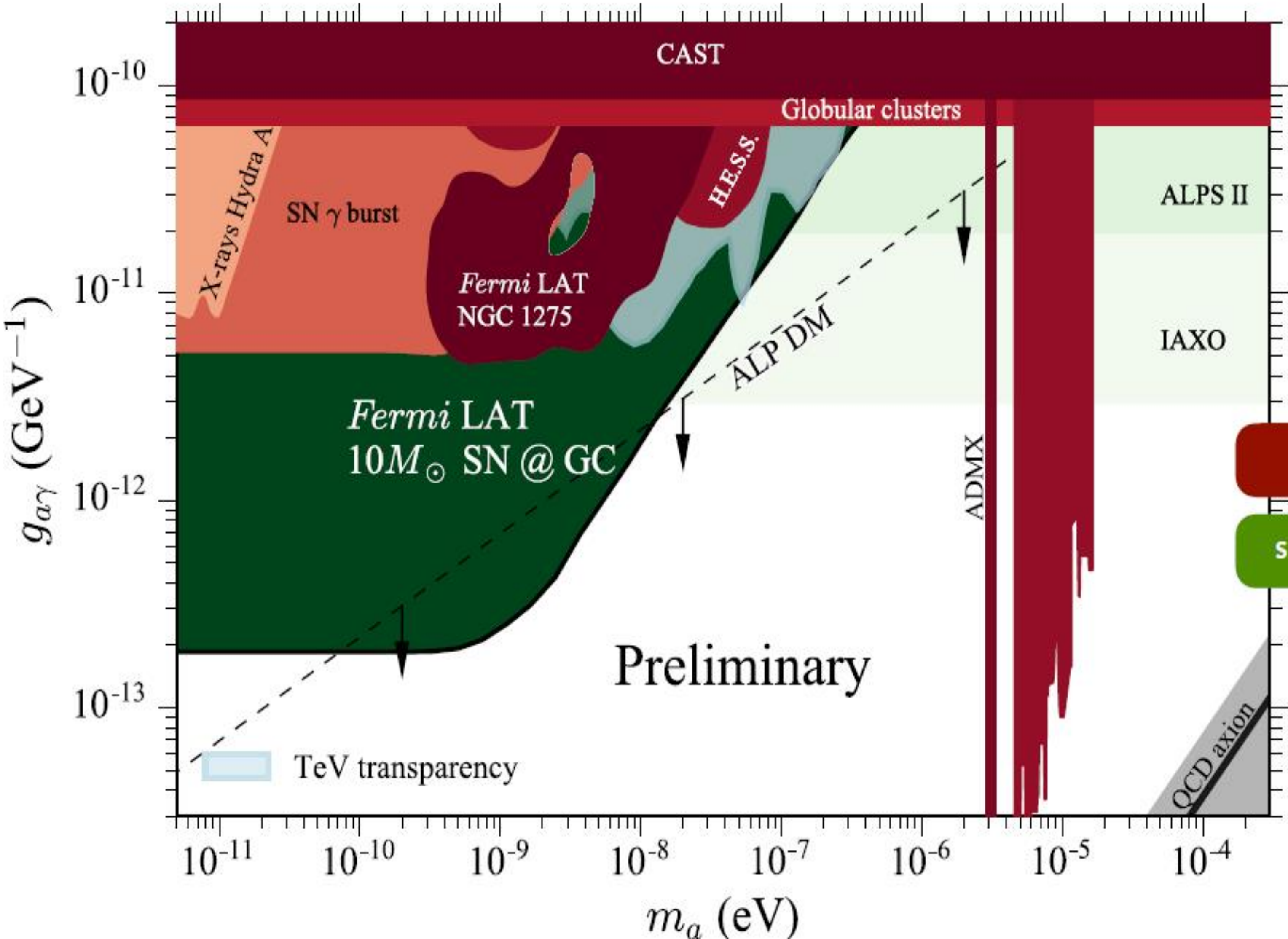
FERMI-LAT AS GALACTIC SN ALP-SCOPE

[Meyer, Giannotti, A.M., Conrad & Sanchez-Conde, to appear soon]

Alessandro Mirizzi

LNF, Frascati, 1 July 2016

Comparing the Sensitivity with other Limits

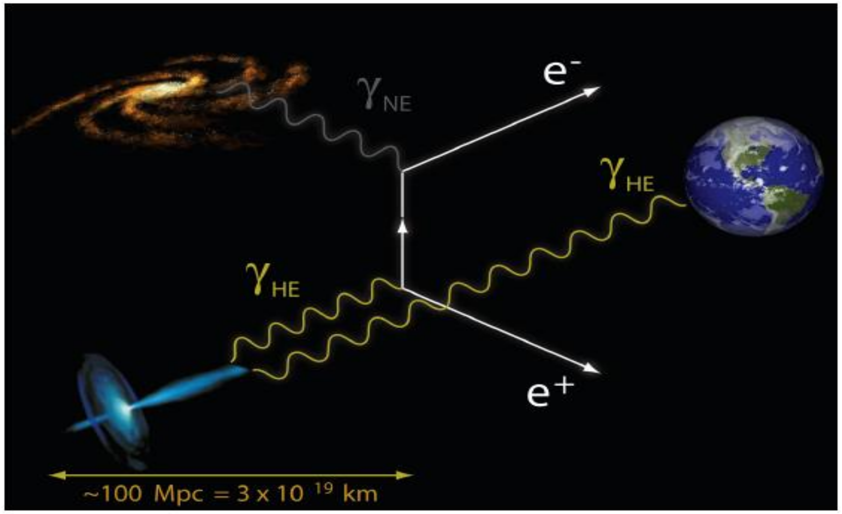


Limits

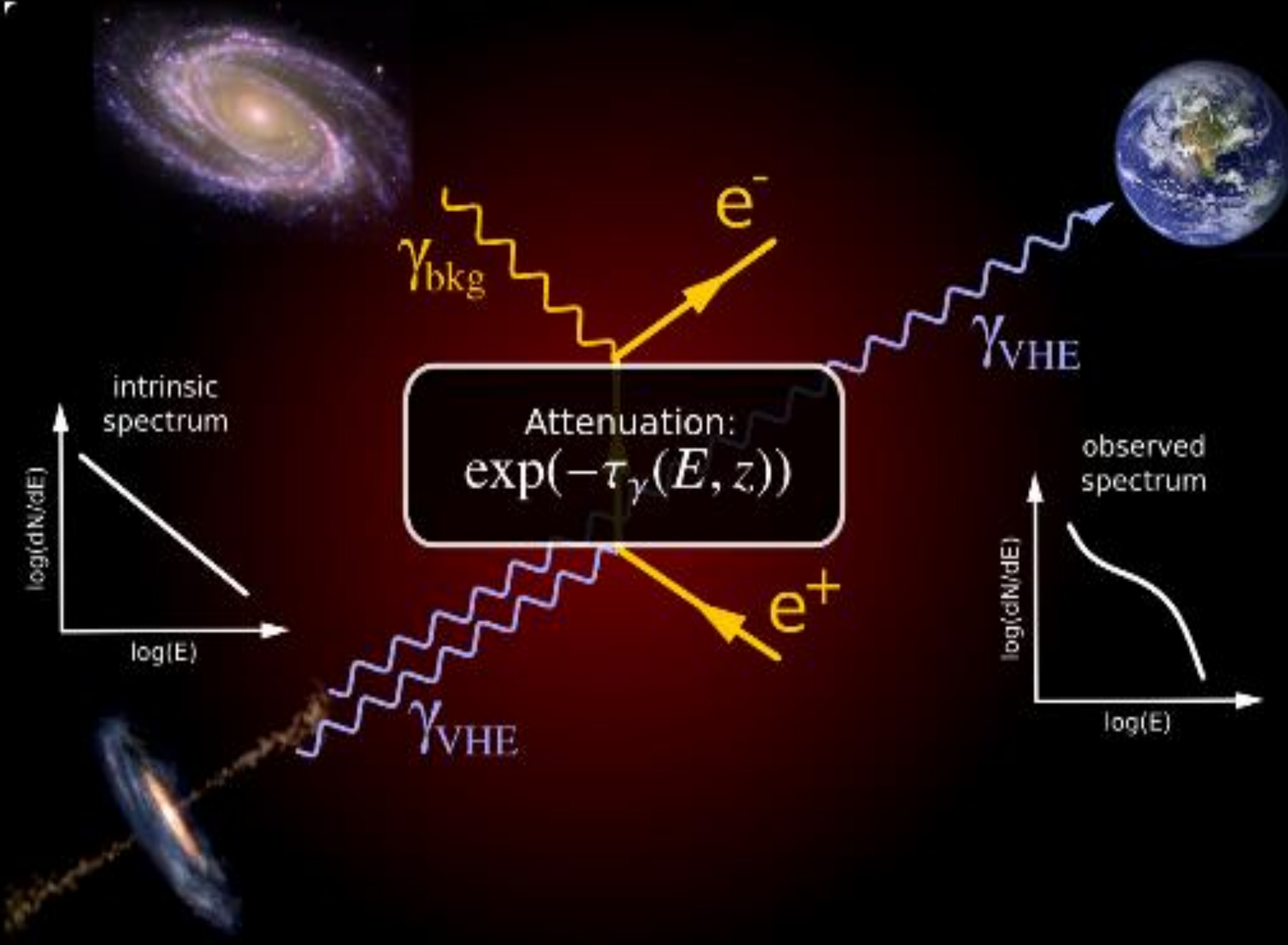
Sensitivities

A COSMOLOGICAL PUZZLE: HOW TRANSPARENT IS THE UNIVERSE?

VHE photons from distant sources (hard) scatter off background photons (soft) thereby disappearing into electron-positron pairs.



The dominant contribution to cosmic opacity comes from the extragalactic background light (EBL) produced by galaxies. Stellar evolution models + deep galaxy counts yield the spectral density of the EBL



Attenuation:

$$\exp(-\tau_\gamma(E,z))$$

VHE PHOTONS ABSORPTION

VHE photon propagation is controlled by the optical depth

$$\Phi_{\gamma}^{obs} = T_{\gamma}\Phi_{\gamma}^{0} = e^{-\tau_{\gamma}}\Phi_{\gamma}^{0}$$

$$\tau_{\gamma} = \frac{d}{\lambda_{\gamma}(E)}$$

Optical depth

$$\lambda_{\gamma}(E) = \frac{1}{n(E)\sigma(\gamma\gamma \to e^{+}e^{-})}$$

Mean free path

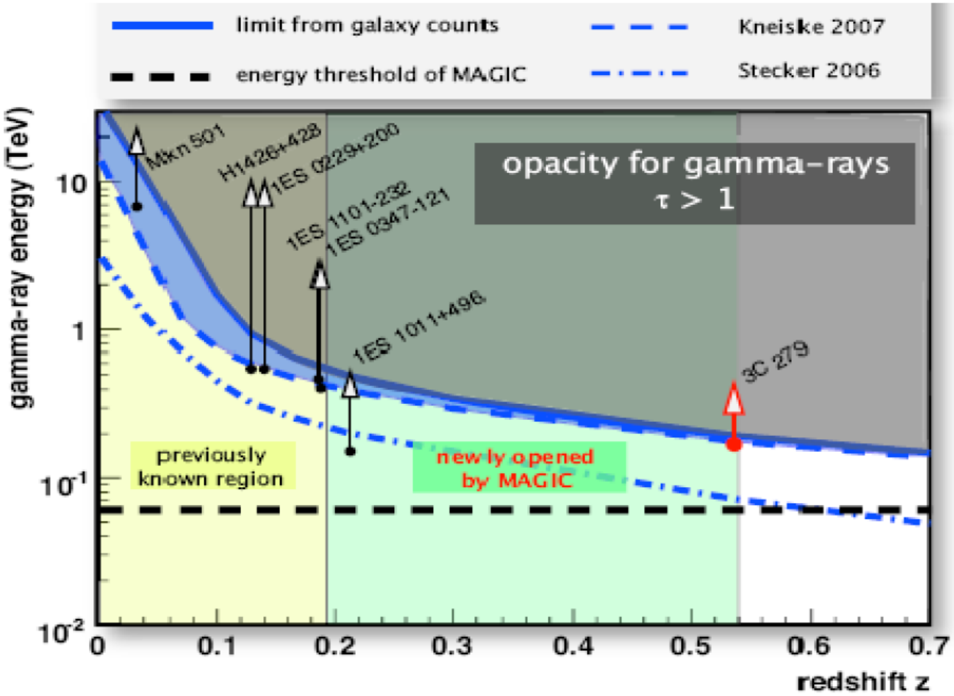
Two crucial consequences emerge:

- Observed flux should be EXPONENTIALLY suppressed at LARGE distances, so that very far-away sources should become INVISIBLE.
- Observed flux should be EXPONENTIALLY suppressed at VHE, so that it should be MUCH STEEPER than the emitted one.

OBSERVATIONS DISPROVE BOTH EXPECTATIONS!

VHE PHOTONS FROM DISTANT SOURCES

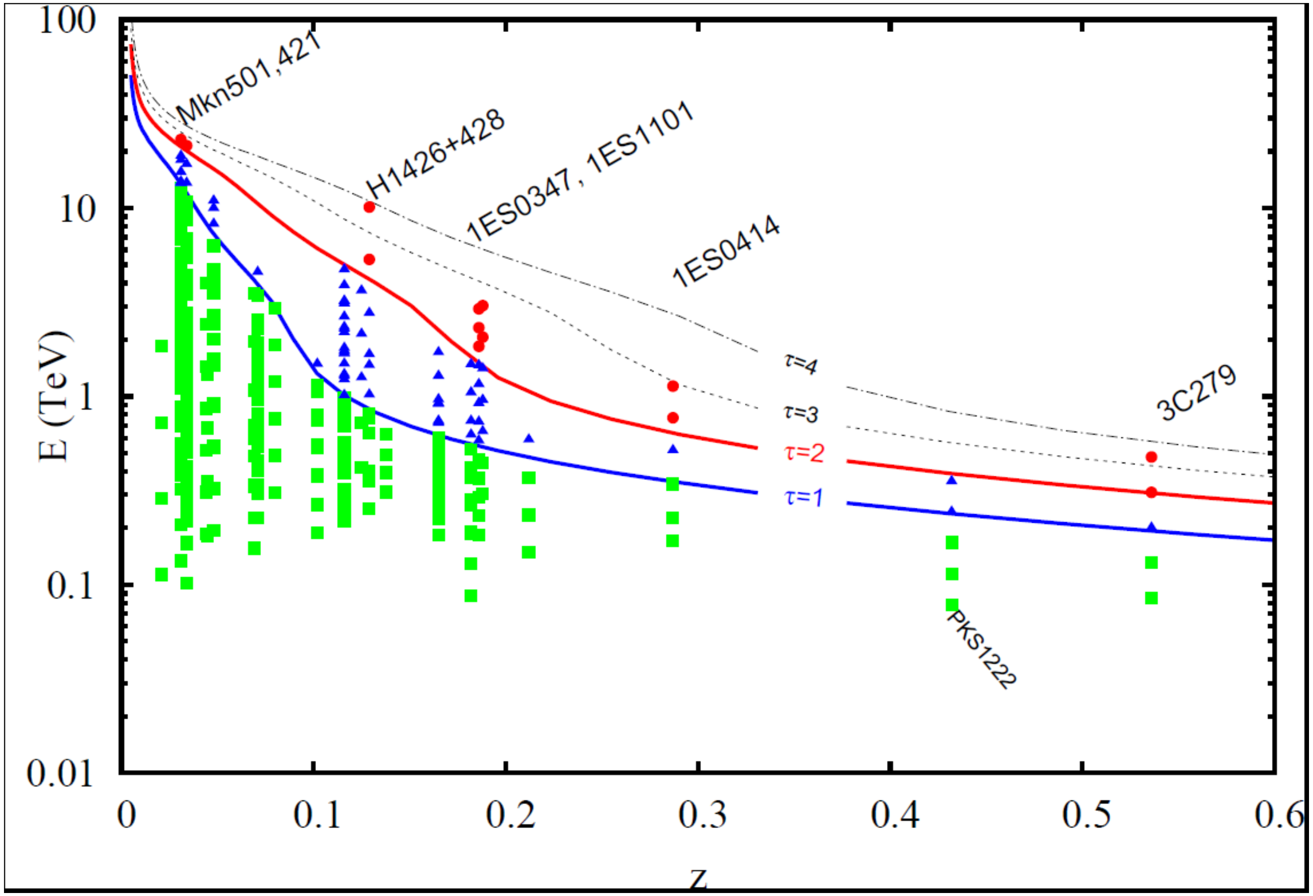
- First indication in 2006 from H.E.S.S. at E = 1 - 2 TeV for 2 sources AGN H2356-309 at z = 0.165, AGN 1ES1101-232 at z = 0.186.
- Stronger evidence in 2007 from MAGIC at E = 400 - 600 GeV for 1 source: AGN 3C 279 at z = 0.536. This source should have been VERY HARDLY VISIBLE at VHE. Yet, signal HAS been detected by MAGIC, with a spectrum QUITE SIMILAR to that of nearby AGN



MAGIC Collaboration, arXiv:0807.2822

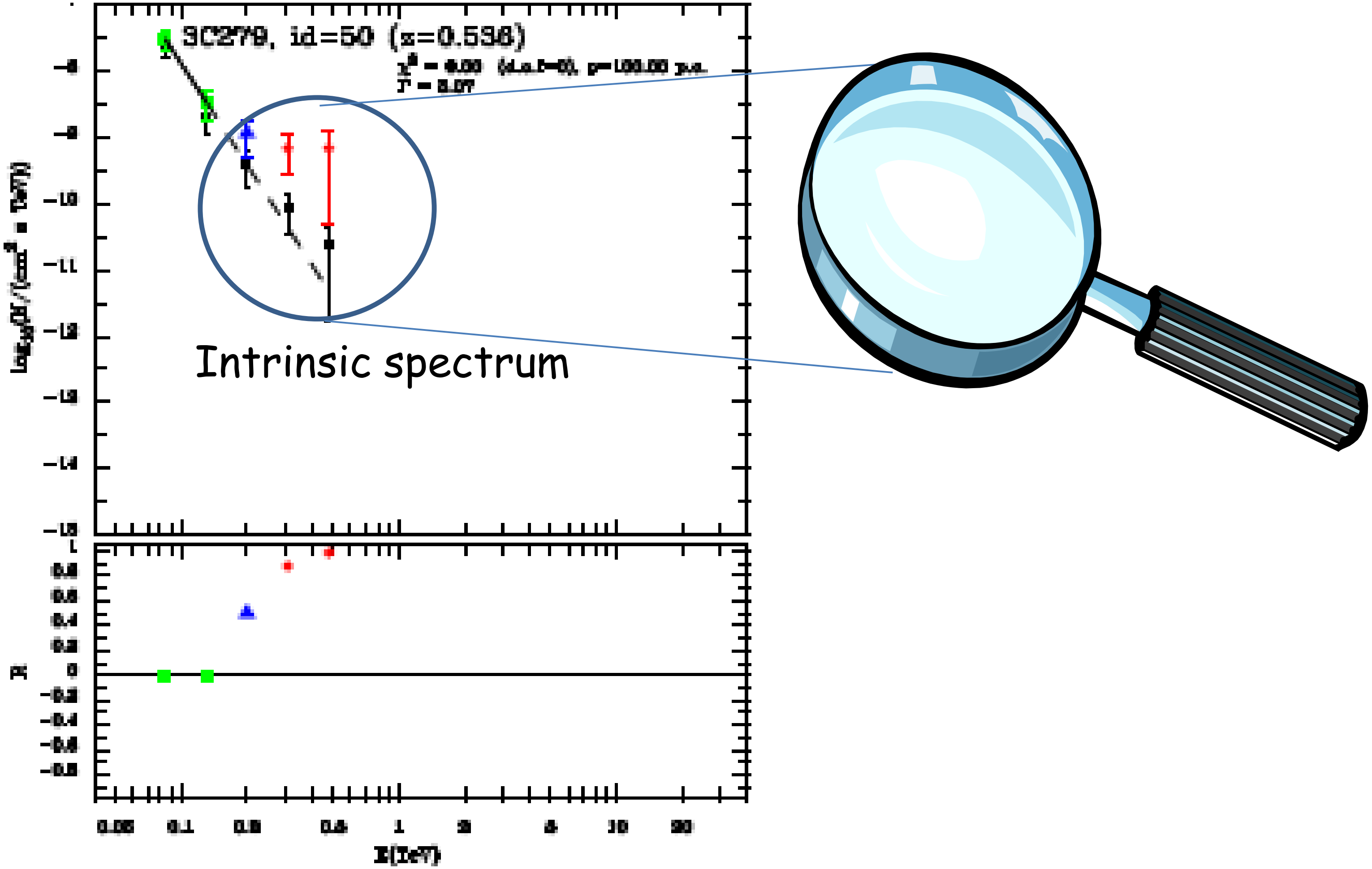
LARGE SAMPLE OF VHE SPECTRA

[Horns & Meyer, arXiV: 1201.4711]



50 spectra of 25 sources with known red-shift with 389 individual differential spectral points.

SEARCH FOR A SPECTRAL HARDENING



7 spectra cover the range from $\tau<1$ to $\tau>2$.

In all these sources an upturn of the absorption-corrected spectrum is visible at this transition with a 4.2 σ significance !

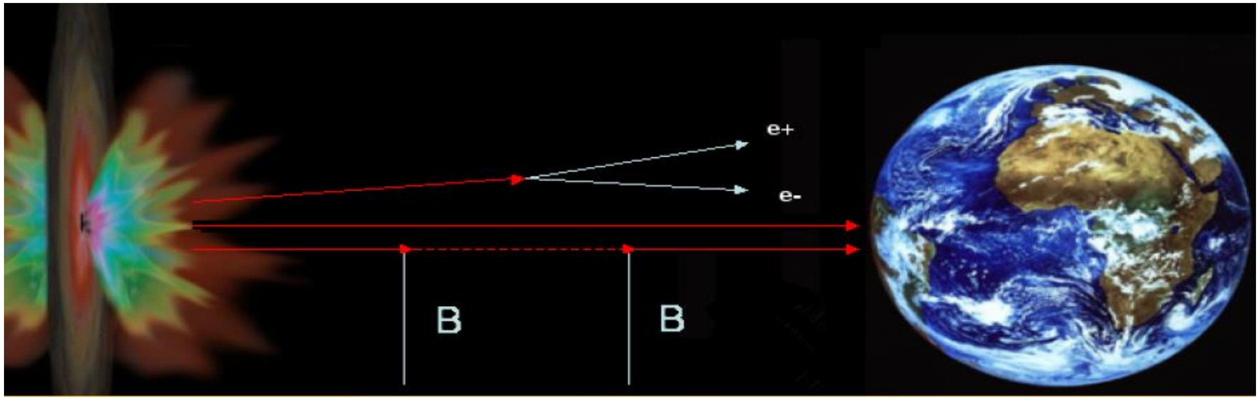
WHAT IS GOING ON?

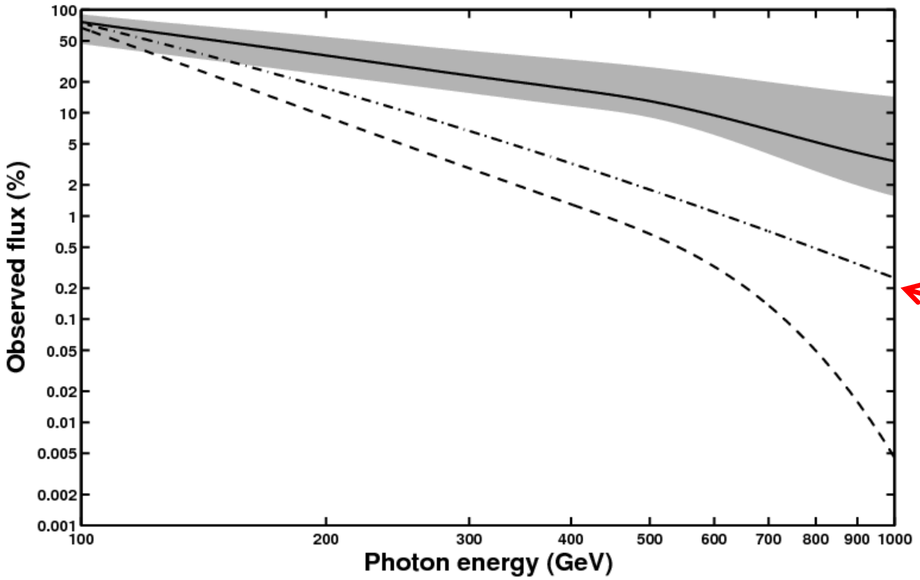
- Unconventional AGN models (harder initial spectra)? Fail to explain ALL other AGNs. There is indication of hardening only at $\tau > 2$.
- Lower EBL? Would be in contradiction with the lower limits from galaxy number counts.
- Secondary γ-ray emission? UHE γ-rays of $E < 50$ EeV crossing cosmological distances and interacting with the EBL close to Earth, generate secondary photons. Does not explain the broad-band γ-ray variability of distant blazars.
- New Physics: breakdown of Lorentz invariance modifying photon dispersion relation at VHE? Would work only in specific models (e.g. D-branes). Perhaps too radical

Or …is there a genie in the bottle?

THE ALP (AXION-LIKE PARTICLE) HYPOTHESIS

If photon-ALP oscillations take place in intergalactic magnetic fields, photons can reach the observer even if distance from source >> mean free path, since ALPs are not absorbed !! *[De Angelis, Mansutti & Roncadelli, arXiv: 0707.4312]*





With ALPs

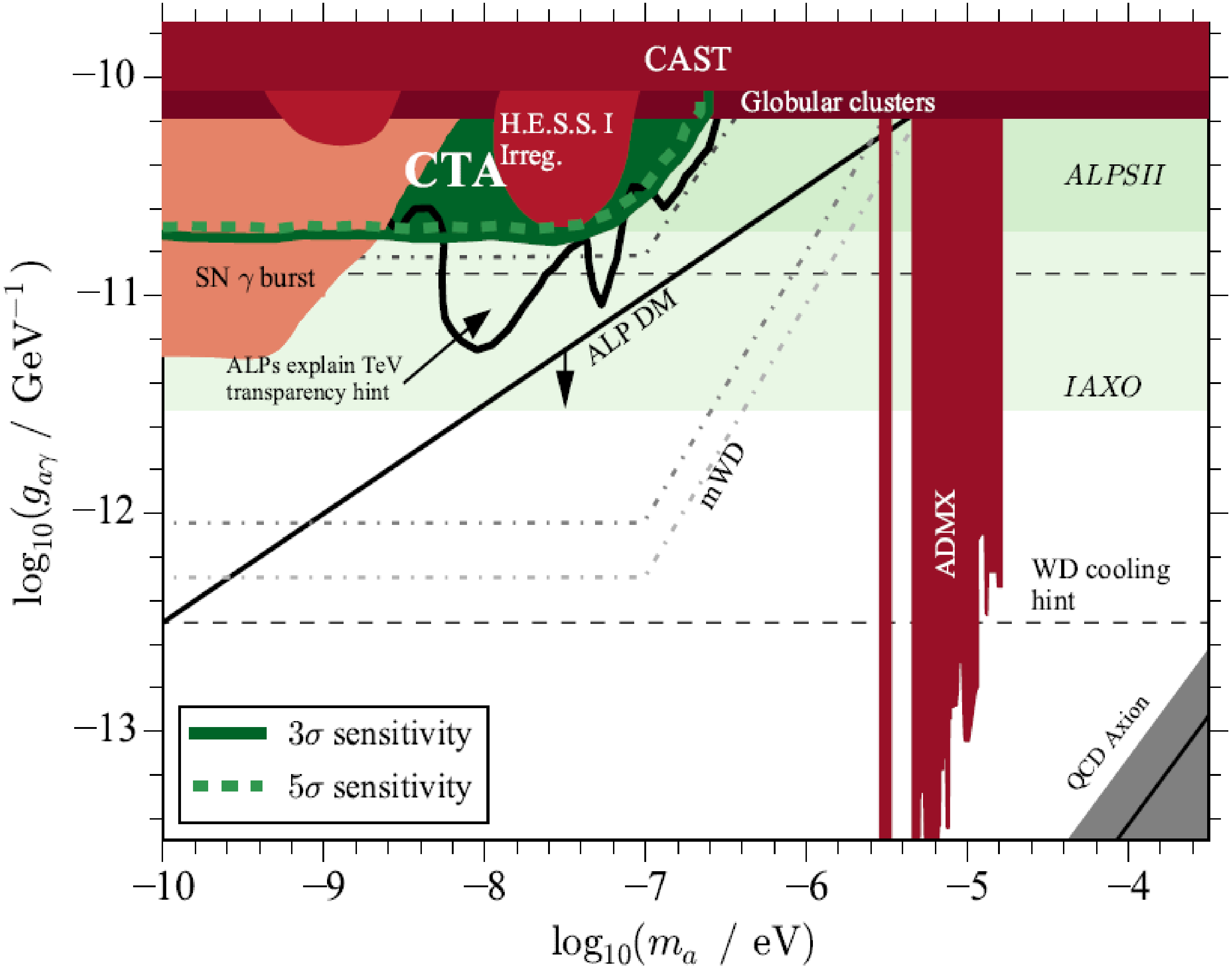
no ALPs

ALPS AND TEV PHOTONS TRANSPARENCY

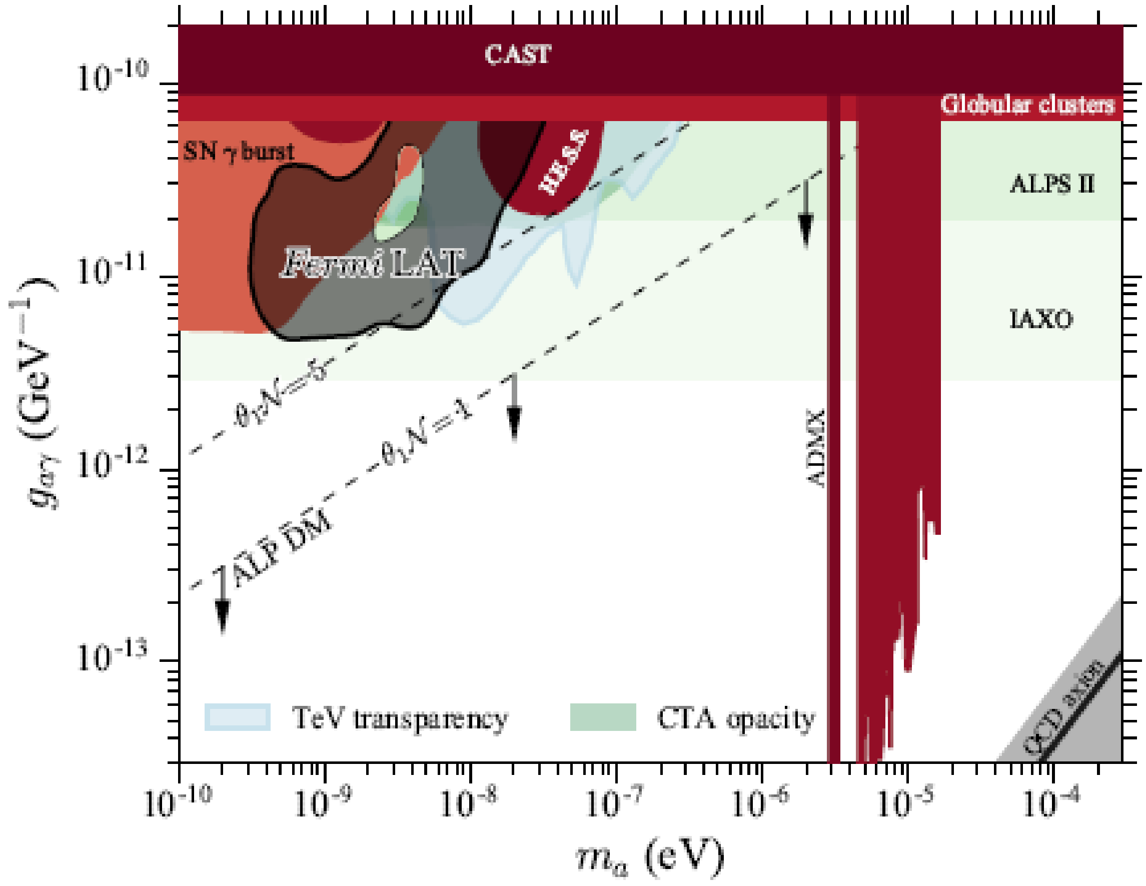
- *De Angelis, Mansutti & Roncadelli, arXiv: 0707.4312*
- *Simet, Hooper & Serpico, arXiv: 0712.2825*
- *Sanchez-Conde, Paneque, Bloom, Prada & Dominguez, arXiv:0905.3270*
- *A.M. & Montanino, arXiv: 0911.0015*
- *Hooper, arXiv: 1007.4862*
- *Dominguez, Sanchez-Conde & Prada, arXiv:1106.1860*
- *De Angelis, Galanti & Roncadelli, arXiv: 1106.1132*
- *Tavecchio, Roncadelli, Galanti & Bonnoli, arXiv: 1202.6529*
- *Horns, Maccione, Meyer, A.M. & Montanino, arXiv: 1207.0776*

SENSITIVITY ON $g_{a\gamma}$ FROM VHE PHOTONS

[Meyer, Horns, Raue, arXiV:1302.1208, Conrad & Meyer, arXiV:1410 1556]



CONSTRAINING THE MODEL



Recent Fermi-LAT analysis of γ-spectrum of NGC 1275 in Perseus cluster + SN 1987A bound strongly constrain the parameter space for the model [*Fermi collab., 1603.06978*]

CONCLUSIONS

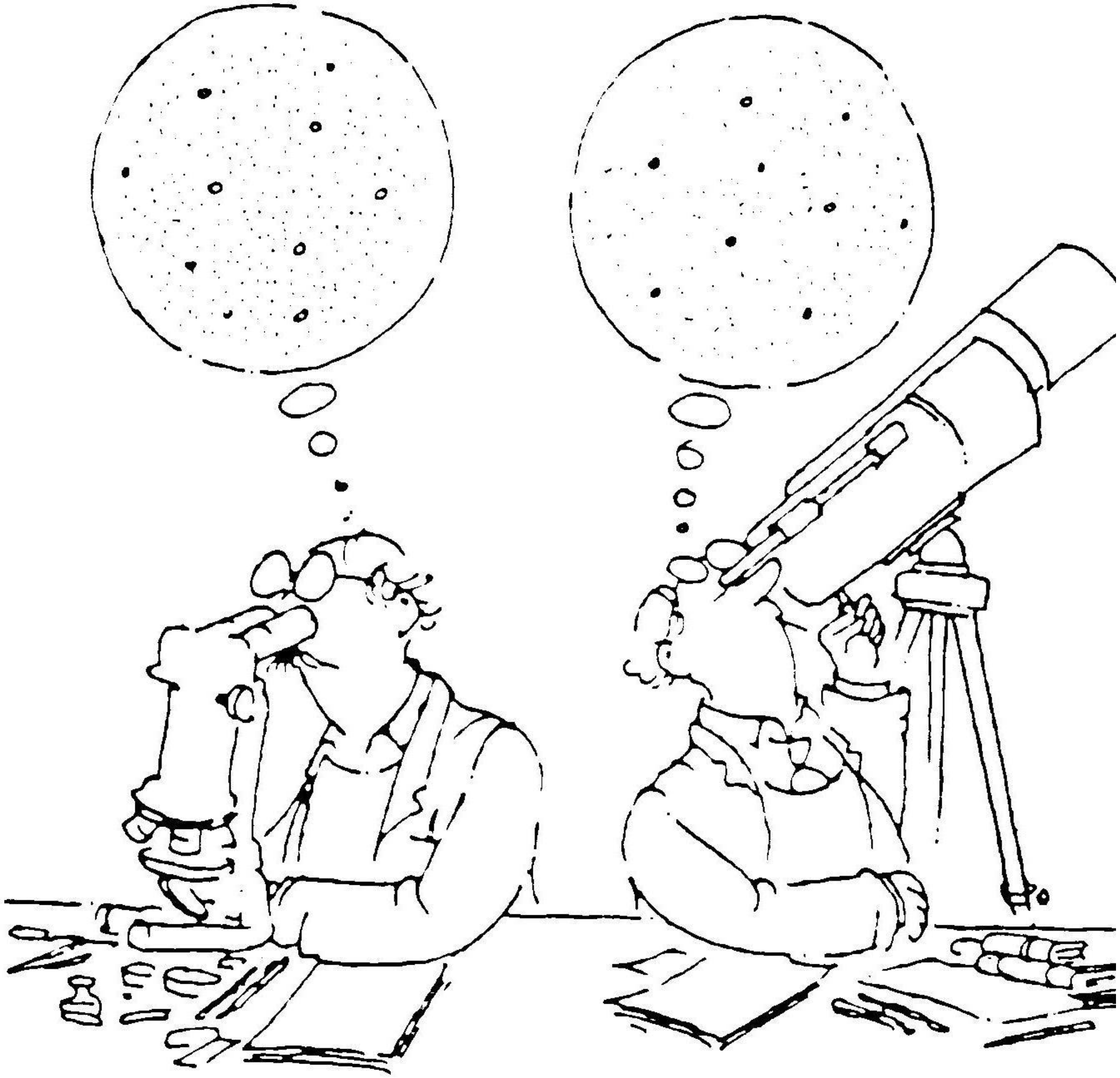
The hunt for axions and ALPs is open !!

Various lab experiments with different techniques and increasing sensitivity aim to touch an unprobed part of the ALP parameter space.

ALP discovery/bounds may provide unique information on the underlying fundamental theory behind them.

Cosmology and Astrophysics already give (for free!) complementary bounds and intriguing hints toward ALPs.

Future cosmological and astrophysical data and lab experiments would give a definitive verdict on axions and ALPs.



Stay tuned !