Giulia Pagliaroli & Ofelia Pisanti

PRIN NAT-NET, 27th January 2020, Naples

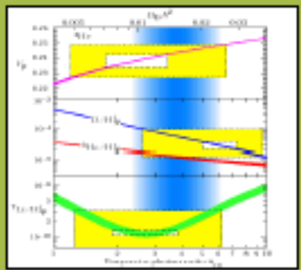
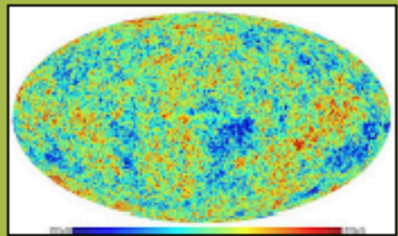
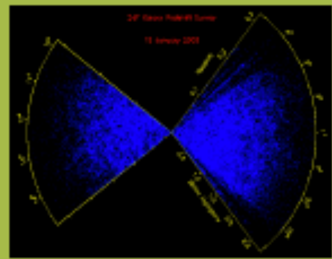
WP3
Sources and fluxes of neutrinos and other messengers

- Relic neutrino detection
- Axions and ALP in astrophysical context
- Issues in BBN neutrinos
- HE neutrinos and MM approach
- Solar neutrino models and low-energy flux detection
- Reference geo-neutrino models
- Core-collapse SN physics

Relic neutrino detection

- G. Mangano, O. Pisanti: Neutrino physics with the PTOLEMY project

CNB indirect evidences

		
Primordial Nucleosynthesis BBN	Cosmic Microwave Background CMB	Formation of Large Scale Structures LSS
$T \sim$ MeV	$T <$ eV	
flavor dependent	Flavor blind	

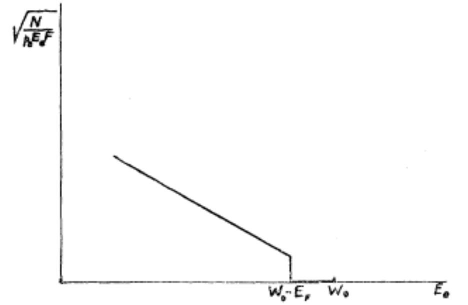


FIG. 1. Shape of the upper end of an allowed Kurie plot to be expected in a β^+ decay if neutrinos are degenerate up to energy E_F, or in a β^- decay if antineutrinos are degenerate.

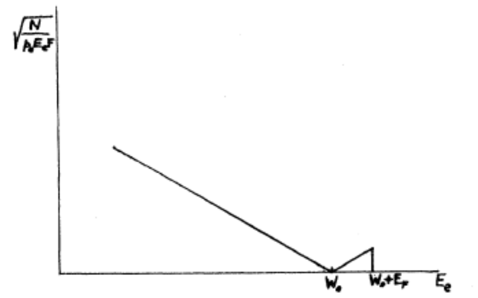
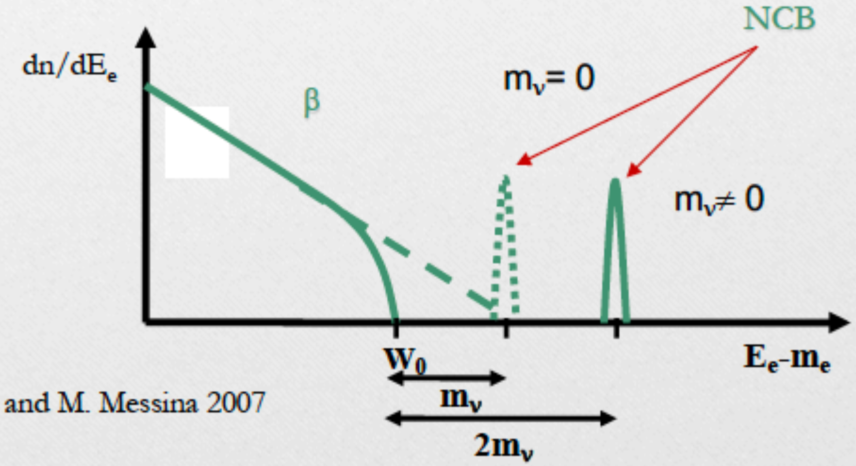


FIG. 2. Shape of the upper end of an allowed Kurie plot to be expected in a β^- decay if neutrinos are degenerate up to energy E_F, or in a β^+ decay if antineutrinos are degenerate.

Weinberg: if neutrinos are degenerate we could observe structures around the beta decaying nuclei endpoint Q

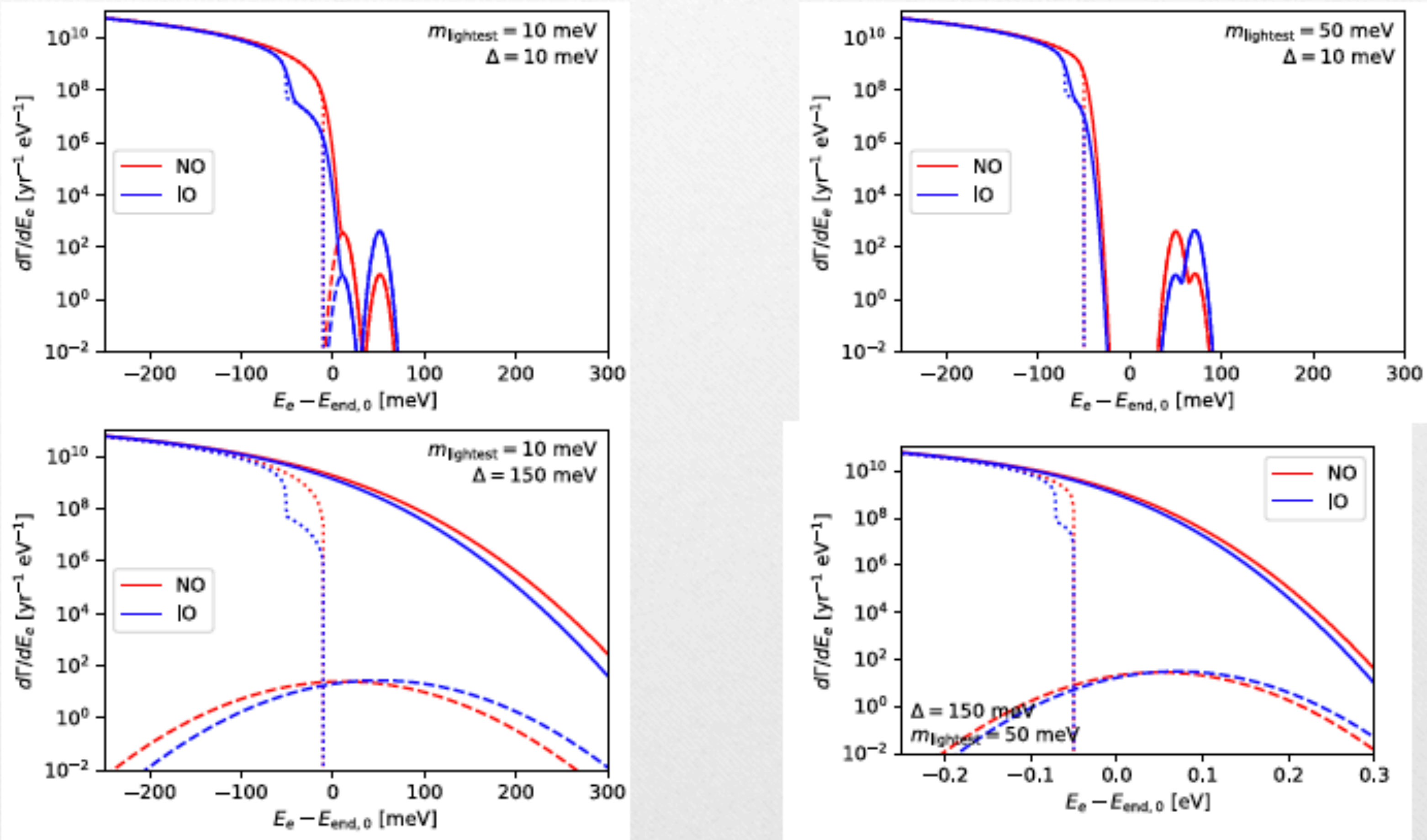
ν's are NOT degenerate but are massive!

2 m_ν gap in electron spectrum around Q



A. Cocco, G.M. and M. Messina 2007

P.F. de Salas, S. Gariazzo, G. Mangano, S. Pastor, O. Pisanti, JCAP 1907 (2019) 047



An ambitious challenge?

Two issues need to be addressed:

1. Signal to background ratio depends on $\sigma_{NCB} v_{\nu} t_{1/2}$.
2. Energy resolution has to be comparable with m_{ν}.

Isotope	Decay	Q_β (keV)	Half-life (s)	$\sigma_{NCB}(v_\nu/c)$ (10^{-41} cm^2)
^{3}H	β^-	18.591	3.8878×10^8	7.84×10^{-4}
^{63}Ni	β^-	66.945	3.1588×10^9	1.38×10^{-6}
^{93}Zr	β^-	60.63	4.952×10^{13}	2.39×10^{-10}
^{106}Ru	β^-	39.4	3.2278×10^7	5.88×10^{-4}
^{107}Pd	β^-	33	2.0512×10^{14}	2.58×10^{-10}
^{187}Re	β^-	2.64	1.3727×10^{18}	4.32×10^{-11}
^{11}C	β^+	960.2	1.226×10^3	4.66×10^{-3}
^{13}N	β^+	1198.5	5.99×10^2	5.3×10^{-3}
^{15}O	β^+	1732	1.224×10^2	9.75×10^{-3}
^{18}F	β^+	633.5	6.809×10^3	2.63×10^{-3}
^{22}Na	β^+	545.6	9.07×10^7	3.04×10^{-7}
^{45}Ti	β^+	1040.4	1.307×10^4	3.87×10^{-4}

PTOLEMY

Pontecorvo Tritium Observatory for Light Early-Universe Massive-Neutrino Yield

$$\nu_e + {}^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^-$$

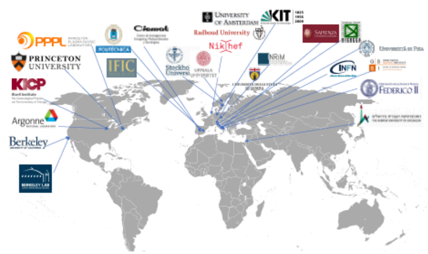
For 1 g of ^{3}H, one expects 10^3-10^5 decay event/s in the measurement bin.

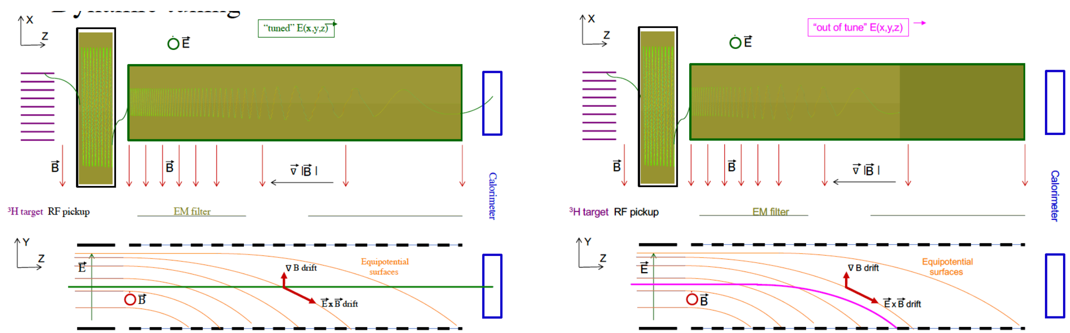
→ We need a filter.

In PTOLEMY the filter concept is based on the reduction of electron transverse kinetic energy due to the climbing of a standing voltage potential. Electric and magnetic fields are designed in such a way that the "wrong electrons" end up on an electrode and the right ones pass.

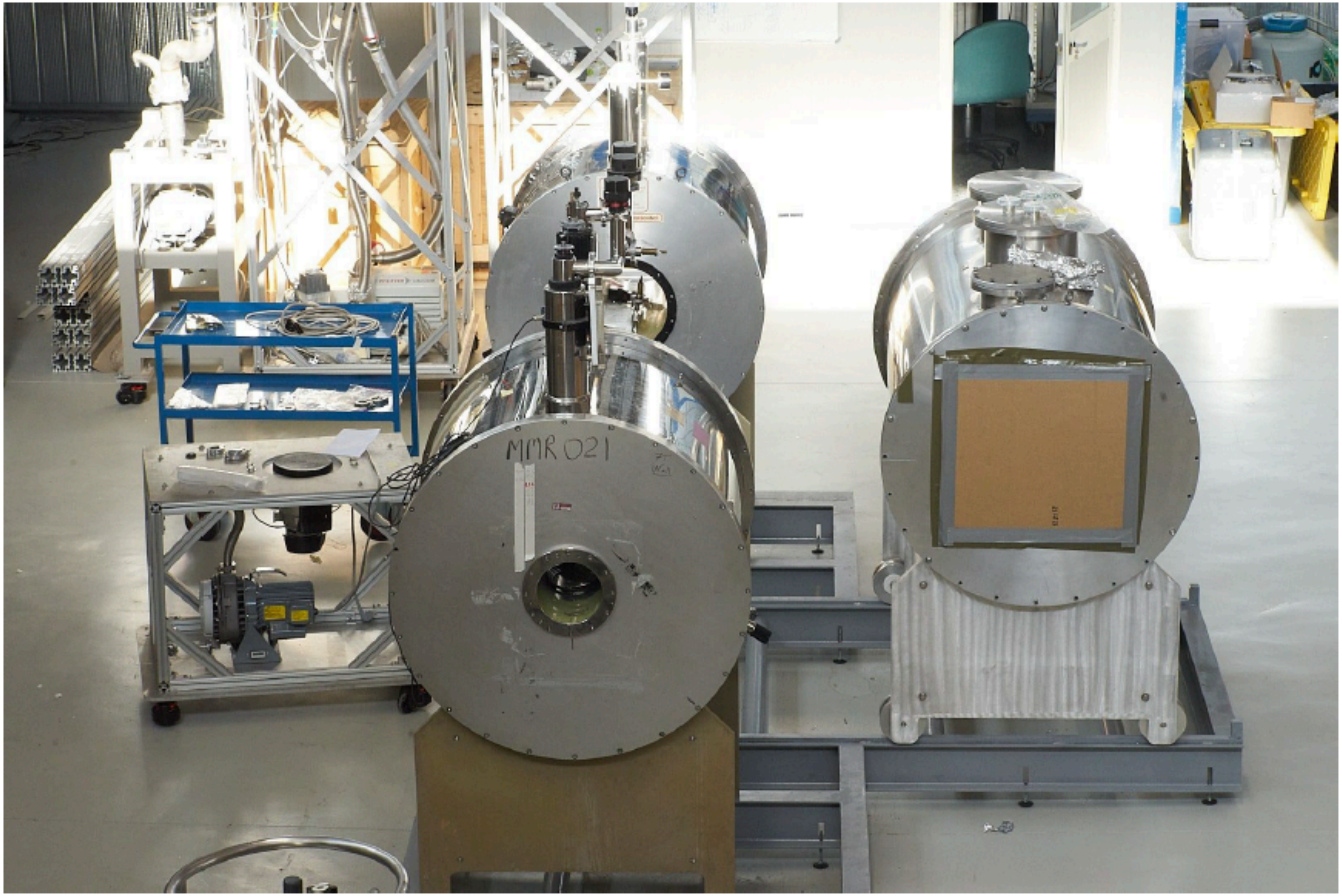
7 countries 23 institutes and 55 physicists

Germany
KIT
Israel
The Racah Institute of Physics
Italy
INFN Laboratori Nazionali del Gran Sasso
GSSI
INRIM Torino
Universita' di Genova and INFN-GE
Universita' di Milano-Bicocca and INFN-Milano-Bicocca
Universita' di Napoli Federico II and INFN-NA
Universita' di Pisa
Universita' di ROMA La Sapienza and INFN-RM1
Universita' di ROMA3 and INFN
Spain
CIEMAT
Consejo Superior de Investigaciones Cientificas (CSIC)
Instituto de Fisica Corpuscular (IFIC)
Universidad Politecnica Madrid
Sweden
Stockolm University
Uppsala University
The Netherland
Nikhef
Univeristy of Amsterdam
USA
Argonne National laboratory(ANL) and Kavli Institute(KICP)
University of California Berkley and Berkley National Laboratory (BNL)
Princeton Plasma Physics laboratory (PPPL)
Princeton University





Work in progress: superconducting magnets and vacuum chamber



Axions and ALP in astrophysical contexts

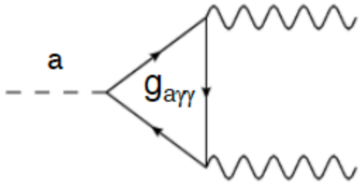
- P. Carenza, T. Fischer, M. Giannotti, G. Guo, G. Martinez-Pinedo, A. Mirizzi: Axion emissivity from a SN
- D. Montanino, F. Vazza, A. Mirizzi, M. Viel: ALP conversions in γ in EG magnetic fields

Why axions?

- A possible solution to the strong CP problem and a possible candidate of DM.

Rybka, TAUP 2019

The Axion has the same quantum numbers as, and mixes with, the π_0. This gives a fairly clear picture of how the axion couplings scale with axion mass.



$$m_A = \frac{f_\pi m_\pi}{f_A}\left(\frac{z}{(1+z+w)(1+z)}\right)^{1/2} \approx \frac{6.0\cdot 10^6}{f_A(GeV)}$$

In the QCD axion particular the axion-photon coupling has very little model dependence. Benchmark models:

scalar + heavy quark → "KSVZ": Ad hoc "hadronic" axion couplings.

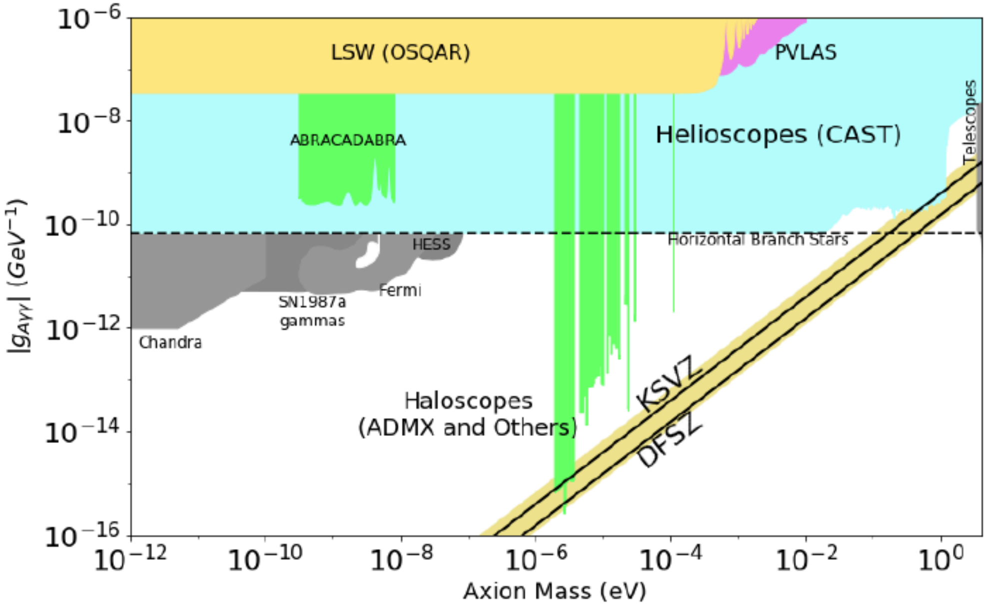
scalar → "DFSZ": Grand unification.

The classic axion-like particle experiments are:

Light Shining Through Walls:
Laser photon-axion mixing
E.g. old: OSQAR, ALPS
future: ALPS-II

Helioscopes:
Axions from the sun
E.g. old: CAST, Sumico
future: IAXO

Haloscopes:
Axion dark matter
E.g. old: ADMX, RBF
future: ADMX G2



Source: PDG

Cadamuro &Redondo

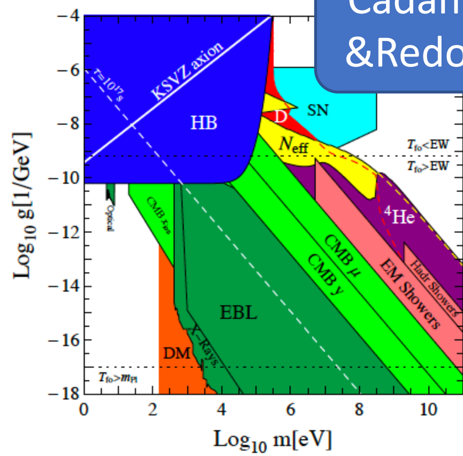


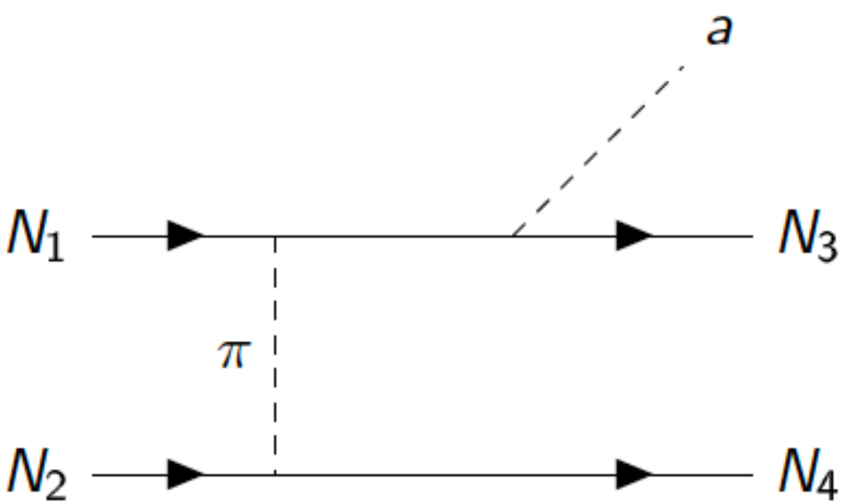
Figure 1. Summary of ALP bounds in the mass-coupling plane. The ALP relic density exceeds the observed value in the region labelled DM. EBL, Optical and X-Rays regions are excluded by the non observation of photons from relic ALP decay. The black-body spectrum of CMB would be unacceptably distorted by ALP decays in the regions labelled CMB. $N_{\rm eff}$, D, Showers and He are described in the text. SN and HB are astrophysical bounds. See [5] for details.

Improved axion emissivity from a supernova via nucleon-nucleon bremsstrahlung

JCAP **1910** (2019) no.10, 016

Carenza, Fischer, Giannotti, Guo, Martinez-Pinedo, Mirizzi

SN axions are produced by nucleon-axion bremsstrahlung



in the One Pion Exchange (OPE) approximation ($m_\pi = 0$), the matrix element is

$$S \times \sum |\mathcal{M}|^2 = \frac{64}{3} g_a^2 m_N^2 \left(\frac{g_A}{2f_\pi}\right)^4$$

where $g_A = 1.26$, $f_\pi = 92.4$ MeV, m_N is the nucleon mass and g_a is the axion-nucleon coupling constant.

Beyond the OPE approximation

The OPE approximation can be improved including the following effects:

- Non-zero pion mass in the propagator$\rightarrow$ $\sqrt{3 m_N T} \sim m_\pi$
- Two-pions exchange$\rightarrow$ Important around $2\mathrm{fm} \simeq 1.5 {m_\pi}^{-1}$
- Effective nucleon mass$\rightarrow$ $m_N^*(\rho)$
- Multiple nucleon scatterings (MS) $\rightarrow$ Nucleon spin fluctuations

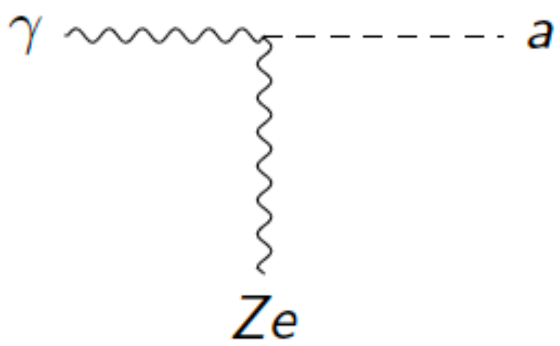
The SN axion bound

Including all the corrections we obtain the following bounds on the axion coupling, mass and Peccei-Quinn scale for KSVZ model

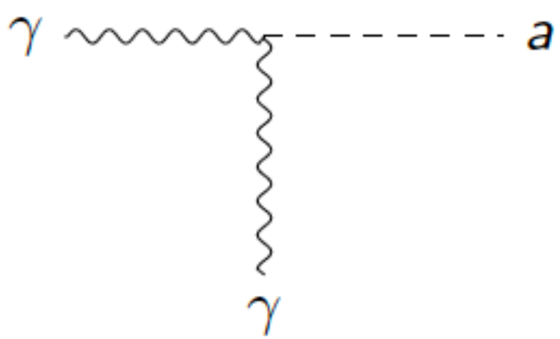
$C_{ap} = -0.47$; $C_{an} = 0$	g_{ap} $(\times 10^{-10})$	m_a (meV)	$f_a (\times 10^8$ GeV)
OPE	4	5	10.4
OPE+MS	5	6	9.7
OPE+corr. (no MS)	11	14	4.2
OPE+corr.+MS	12	15	4.0

Revisiting the HB and SN bound on heavy ALPs

ALPs are produced via Primakoff conversion



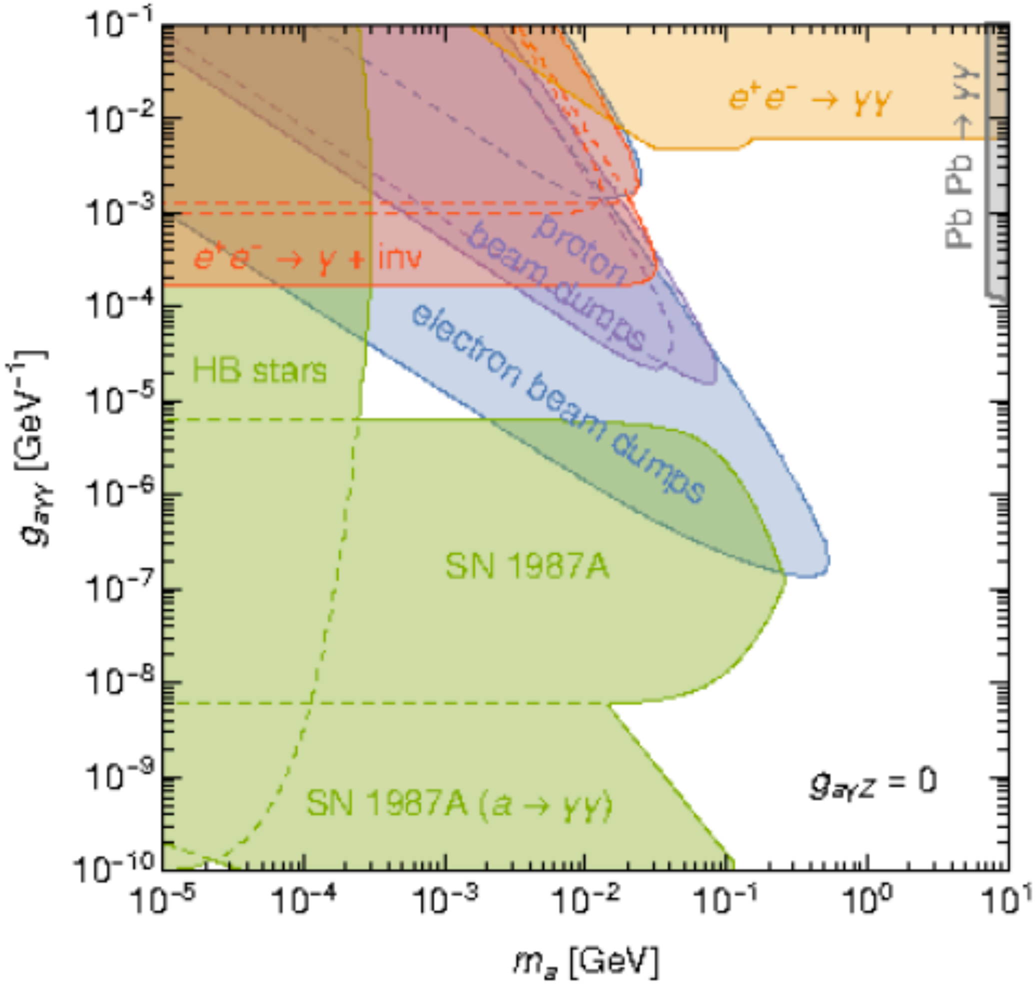
Heavy ALPs ($m_a > 30\,\mathrm{keV}$ in HB and $m_a > 50\,\mathrm{MeV}$ in SN) can be produced by inverse decay



The inverse decay was never considered in literature

Future perspectives

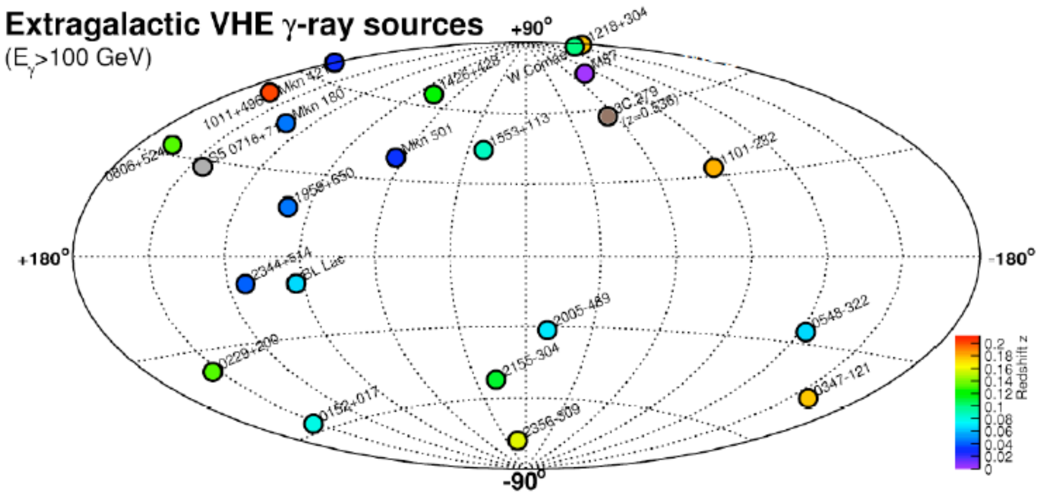
The SN and HB bounds on heavy ALPs are obtained in toy models

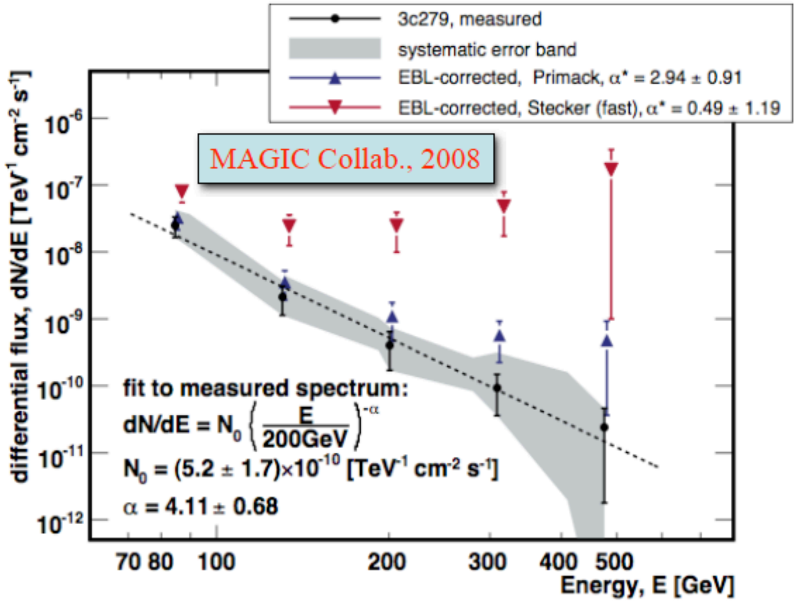


- run HB simulations including ALPs
- revisiting the SN bound in free-streaming and trapping regime

Stochastic conversion of γ into ALP

Very High Energy (VHE) photons (E>100GeV) have been observed from relatively distant sources (up to z~0.6). However, this is a puzzle…





In fact, universe should be opaque to VHE photons due to the scattering on the background photons:

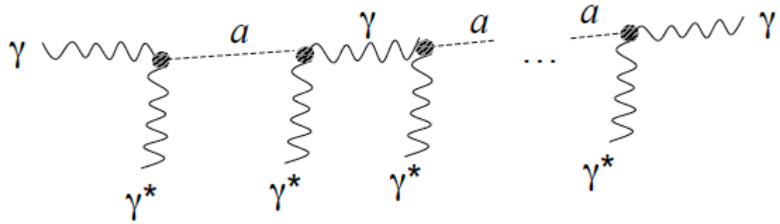
$$\gamma^{\rm VHE} + \gamma^{\rm bgk} \longrightarrow e^+ + e^-$$

EBL corrected spectrum too hard!

A sort of cosmic Light-Shining through Wall effect.

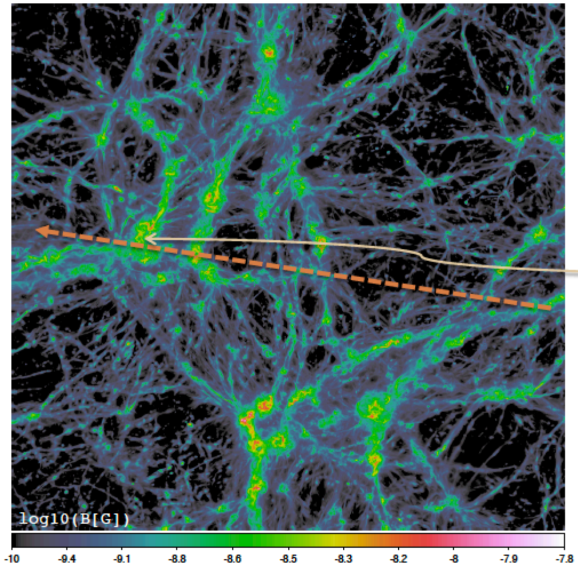
Montanino talk, 2009

Photons propagating in an external magnetic field can undergo to photon-axion oscillations



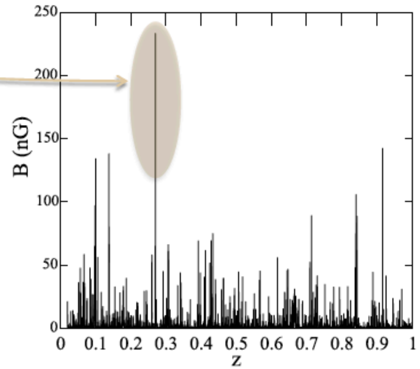
However, extragalactic magnetic fields oversimplified in previous works.

Realistic IGM Fields



Projected magnetic field intensity for 2400^3 simulation of a (50 Mpc)^3 volume at z = 0

- Vazza et al. 2014

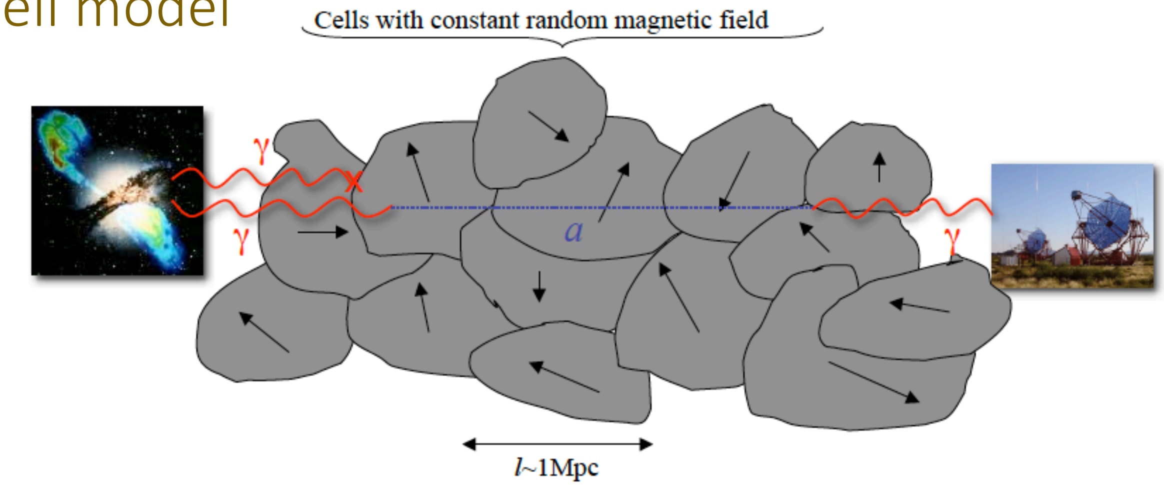


Montanino Vazza Mirizzi Viel, Phys.Rev.Lett. 119 (2017) no.10, 101101

...against...

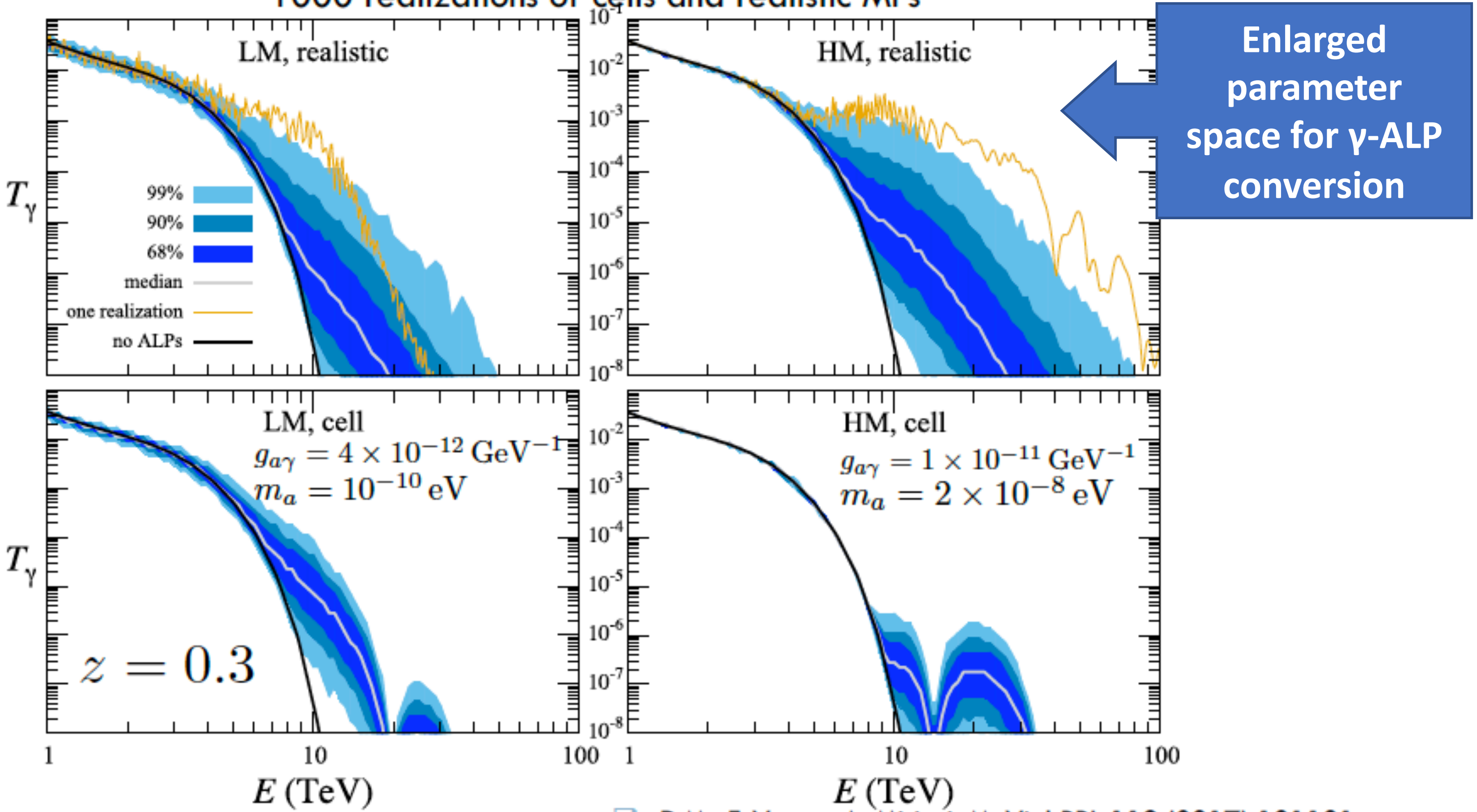
Enhanced γ-ALP conversions

Cell model



Transfer function vs energy

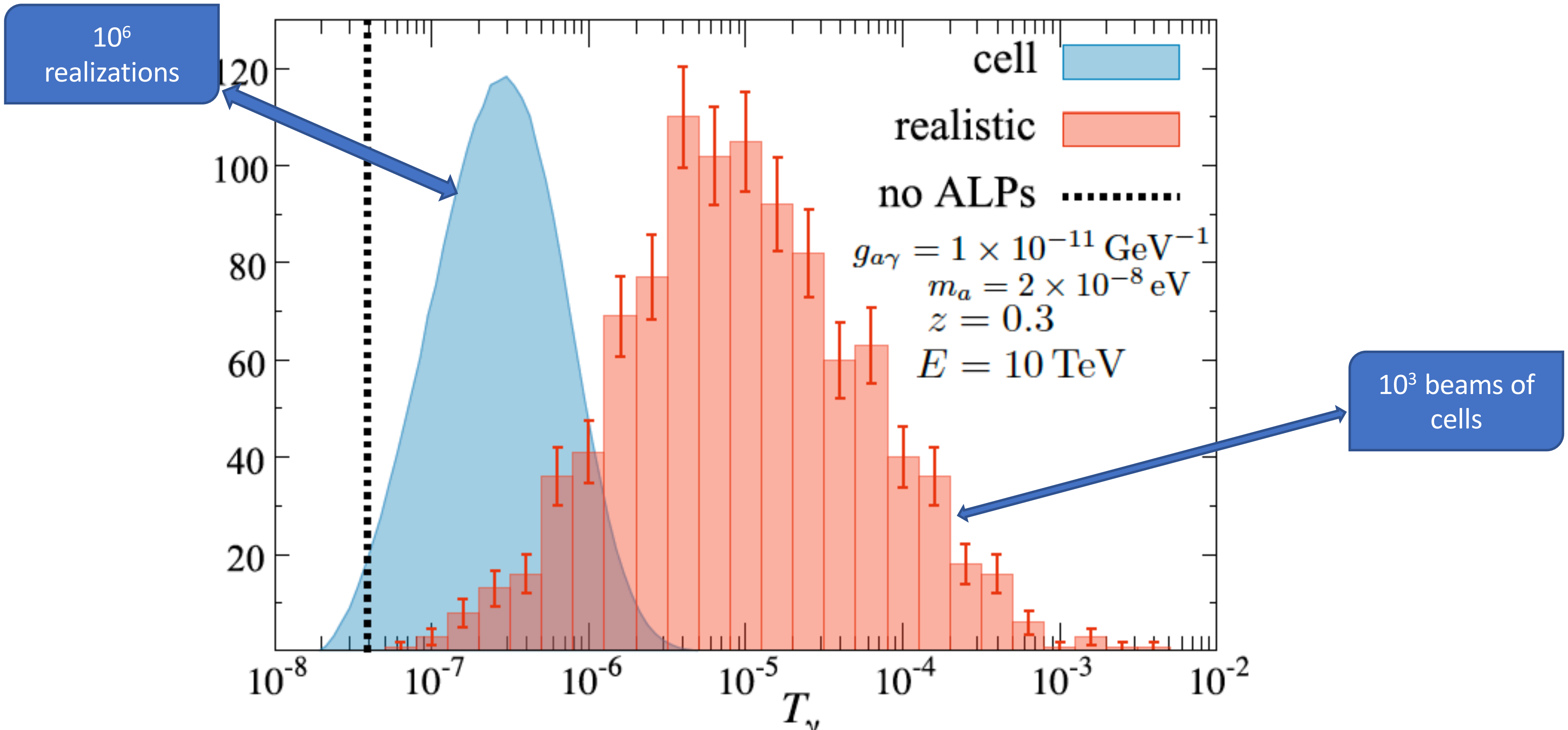
1000 realizations of cells and realistic MFs



- D.M., F. Vazza, A. Mirizzi, M. Viel PRL 119 (2017) 101101

FIG. 4. Photon transfer function T_γ as a function of photon energy for a source at redshift $z = 0.3$ for $m_a = 10^{-10}$ eV and $g_{a\gamma} = 4 \times 10^{-12}$ GeV^{-1} (LM, left panels) and $m_a = 2 \times 10^{-8}$ eV and $g_{a\gamma} = 10^{-11}$ GeV^{-1} (HM, right panels). The upper panels refer to more realistic models of an extragalactic magnetic field, while lower panels are for the cell model. The black curve corresponds to the case of only absorption onto EBL. The solid grey curve represents the median T_γ in the presence of ALPs conversions. The orange curve corresponds to conversions for a particular realization of the extragalactic magnetic field. The shaded band is the envelope of the results on all the possible realizations of the extragalactic magnetic field at 68 % (dark blue), 90 % (blue) and 99 % (light blue) C.L., respectively.

PDF of transfer function



- D.M., F. Vazza, A. Mirizzi, M. Viel PRL 119 (2017) 101101

FIG. 3. Probability distribution functions for the transfer function T_γ for photons emitted from a source at redshift $z = 0.3$, with $E = 10$ TeV and ALPs parameters $m_a = 2\times10^{-8}$ eV and $g_{a\gamma} = 10^{-11}$ GeV^{-1} (HM). Left distribution refers to the cell model, while the right one to the more realistic case. The vertical line corresponds to the no ALPs case.

Issues in BBN neutrinos

- G. Mangano, G. Miele, O. Pisanti: Constraints on N_{eff} from a refined analysis of primordial deuterium

BBN and neutrinos

- Neutrinos are relativistic at BBN times.
- They enter BBN as fuel for the expansion (all flavours) and counterparts in the processes n ⟷ p (only electron neutrinos) ⇒ BBN put constraints on N_{eff} and $\mu_{\nu e}$.
- They decouple just before BBN (~ MeV) ⇒ $T_\nu = T_\gamma$ until e^+e^- annihilation.
- Oscillations are effective just before BBN, with effects depending on neutrino chemical potentials ⇒ BBN put constraints on $\mu_{\nu i}$.

Standard BBN

- Neutrinos are 3 and they count as 3.045.
- Neutrino degeneracy is negligible.

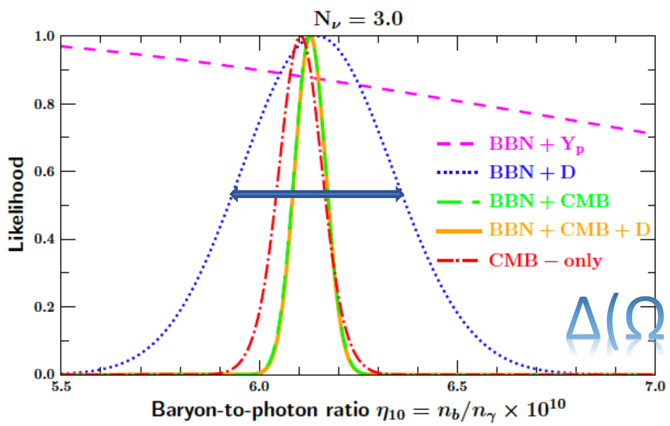
Then, BBN constraints on $\Omega_b h^2$...

Not Standard BBN

- Neutrinos can be more than three (steriles?) and they can count more than 3.045 (neutrino degeneracy?).
- Antonio&Ninetta and Gianpiero&Francesco presentations...

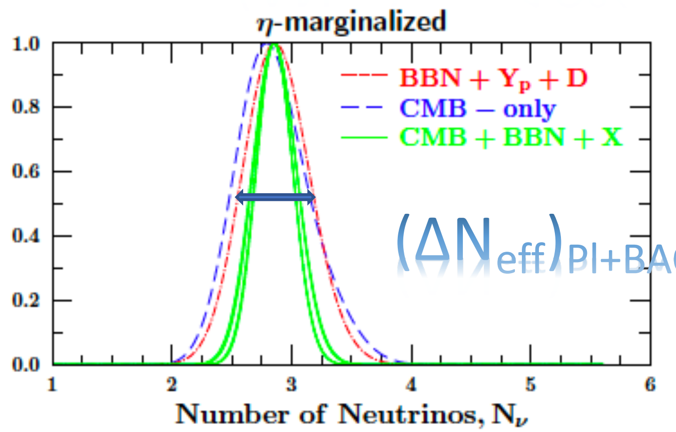
$\Delta(\Omega_b h^2)_{BBN}$=2.7%

$(\Delta N_{eff})_{BBN}$=10%



$\Delta(\Omega_b h^2)_{Pl+BAO}$=1%

Fields et al,
1912.01132
[astro-ph]

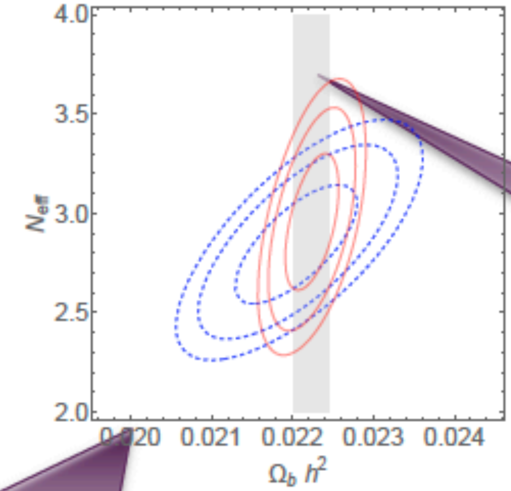


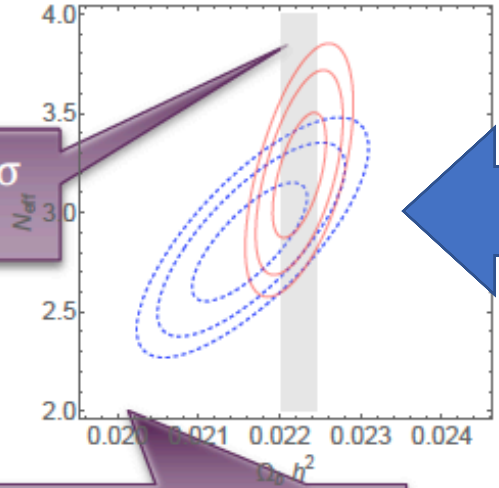
$(\Delta N_{eff})_{Pl+BAO}$=5%

+ BBN/CMB analysis

O. Pisanti, P. Mazzella, G. Miele, G. Mangano, in preparation (see Gianpiero presentation)

- Exp. values:
  - $\Omega_B h^2 = 0.02242 \pm 0.00014$ (Planck 2018)
  - $D/H = (2.527 \pm 0.030)$ (Cooke et al., 2018)
  - $Y_p = 0.2446 \pm 0.0029$ (Peimbert et al., 2016)
- ddn+ddp = PArthENoPE2.1, dpγ = MARCI or MARCII
- D+Planck prior (red) and D+He (only BBN,blue) analyses





Planck 1-σ band

MARCI: $N_{eff} = 2.95 \pm 0.22$

MARCII: $N_{eff} = 3.18 \pm 0.21$

D+Planck

- Neff≃3
- MARCII: slight tension between "D+Planck" and "Only BBN"

BBN/CMB analysis

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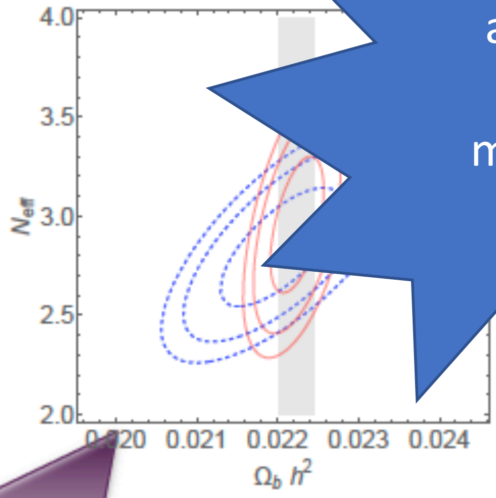
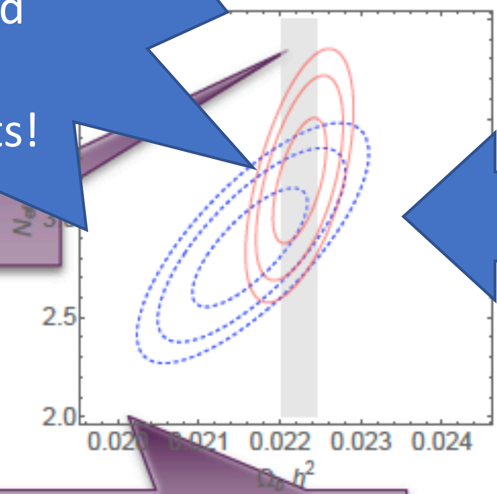
- ddn+ddp = PArthE... ...I or MARCII
- D+Planck prio... ...,blue) analyses

Updated results coming from an analysis based on LUNA measurements!





MARCI: $N_{eff} = 2.95 \pm 0.22$

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D+Planck

- Neff≃3
- MARCII: slight tension between “D+Planck” and “Only BBN”

HE neutrinos and MM approach

- A. Dekker, M. Chianese, S. Ando: DM in NT through APS
- D. Fiorillo, G. Miele, O. Pisanti: Earth-skimming τ at CTA
- A. Ambrosone, M. Chianese, D. Fiorillo, A. Marinelli, G. Miele: Global models of extra-galactic sources
- A. Palladino, C. Mascaretti, F. Vissani: Importance of astrophysical ν_τ
- C. Mascaretti, F. Vissani: Prompt ν and IC

Probing DM in NT

A. Deker, M. Chianese, S. Ando

- IceCube: TG(northern sky)/HESE(full sky) tension on the spectral index of astrophysical ν flux → extragalactic ($\gamma \simeq 2.0$) + galactic components ($\gamma > 2.0$).
- Excess in ν flux at around 100 TeV → DM (or other exotic scenarios)

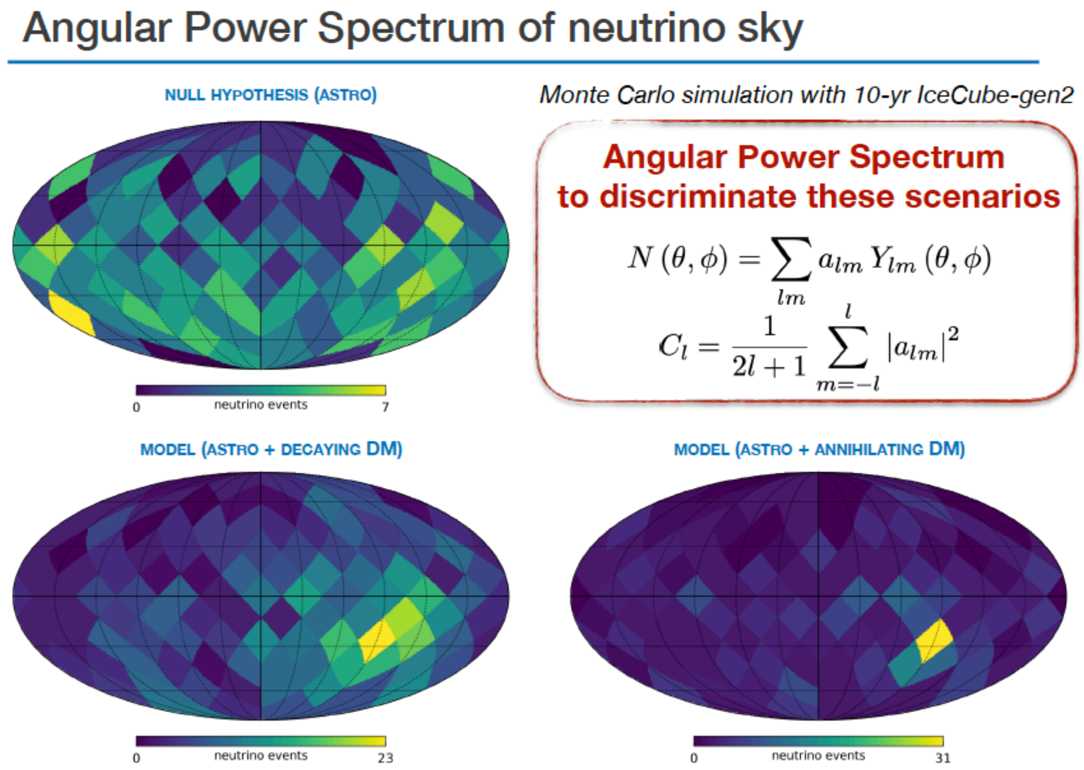
$$N_{\rm tot}(\theta,\phi) = N_{\rm atm} + N_{\rm astro} + N_{\rm DM}$$

$$N_{\rm DM} = N_{\rm DM}^{\rm gal.} + N_{\rm DM}^{\rm ext.gal.}$$

Anisotropy only from galactic DM component (atmospheric anisotropic component negligible above 60 TeV for showers).

$$N(\theta,\phi) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta,\phi)$$

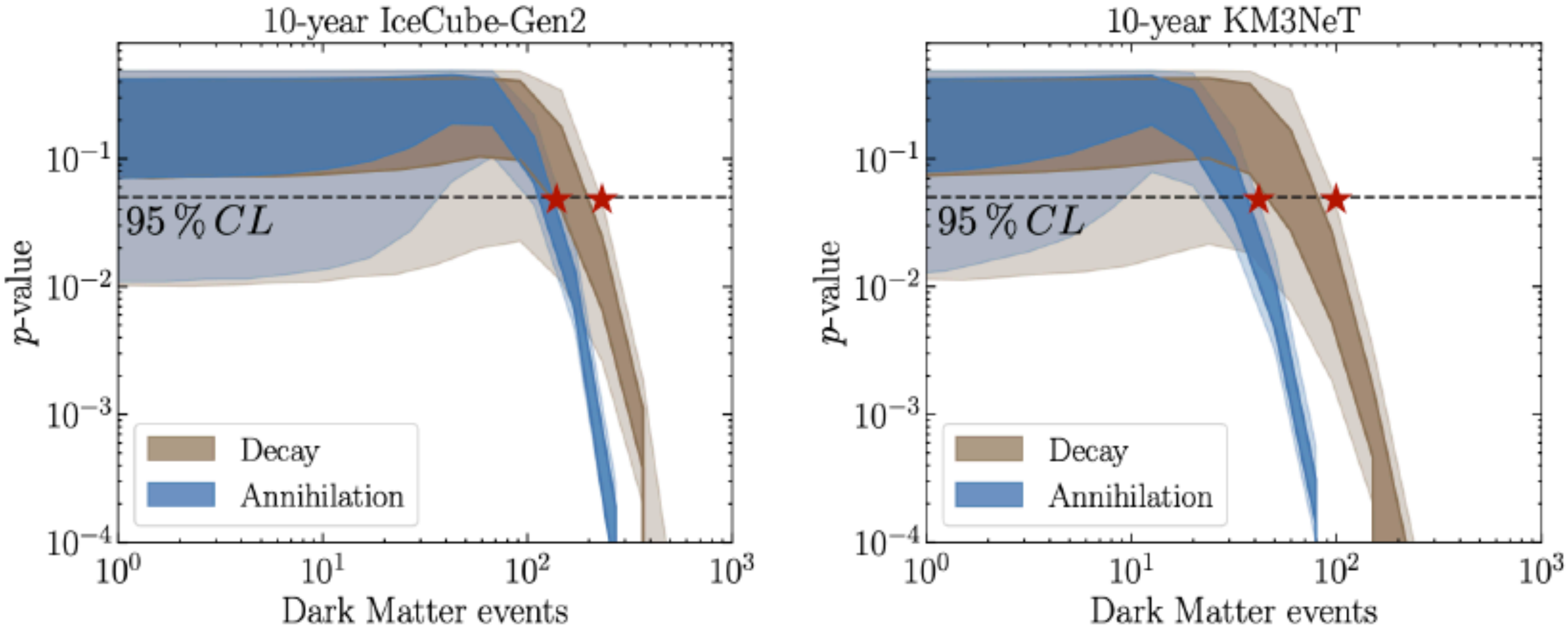
$$C'_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$



Dekker, Chianese, Ando, **arXiv:1910.12917**

Forecast analysis: 10-year

$$p = \min\left[\int_{\chi^2_{\rm data}}^{\infty} d\chi^2 P(\chi^2|\Theta), \int_0^{\chi^2_{\rm data}} d\chi^2 P(\chi^2|\Theta)\right]$$



Model

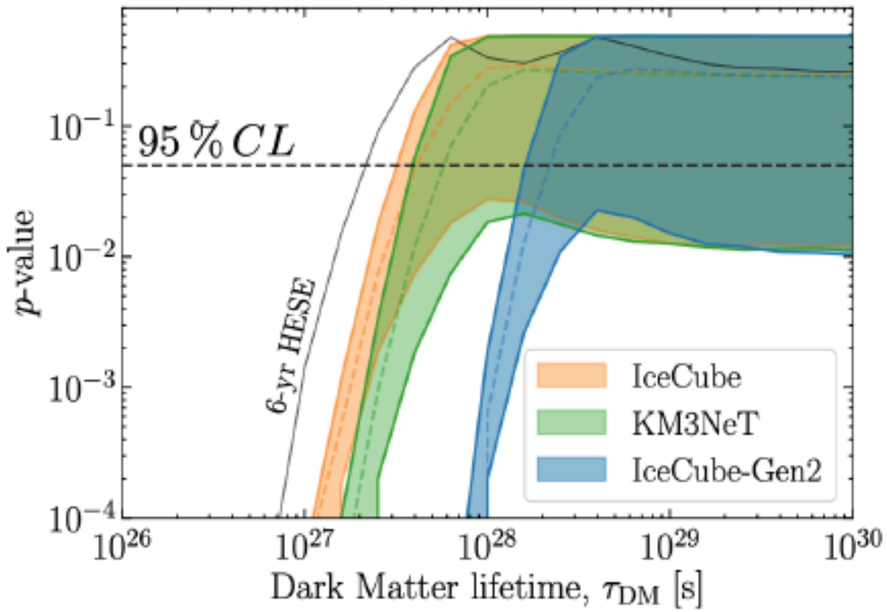
- Decay: $\mathrm{DM} \to \tau^+\tau^- \quad m_{\rm DM} = 400\,\mathrm{TeV}$
- Annihilation: $\mathrm{DM\,DM} \to \tau^+\tau^- \quad m_{\rm DM} = 200\,\mathrm{TeV}$
- NFW and HAI boost factor

Constraints on total DM events from anisotropy

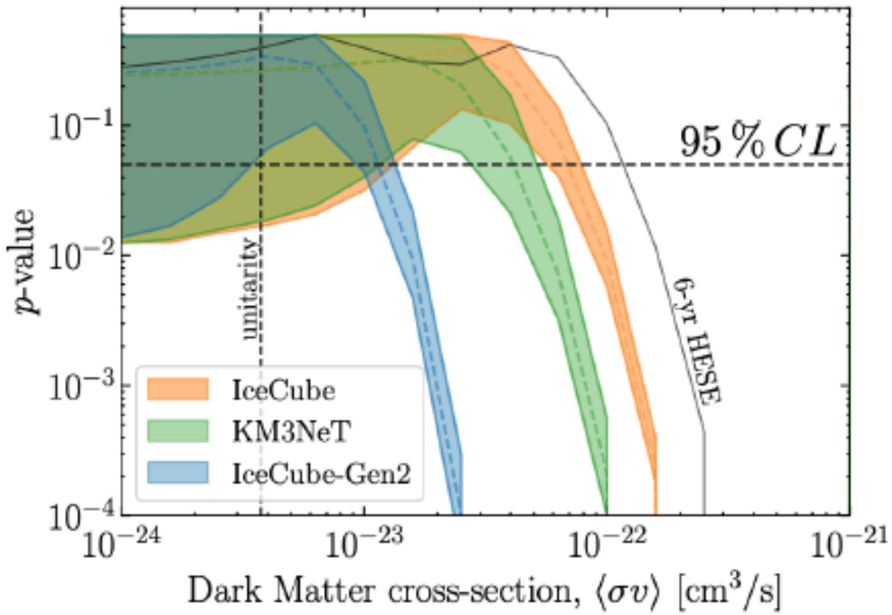
Dekker, Chianese, Ando, ***arXiv:1910.12917***

Forecast analysis: 10-year

DECAY



ANNIHILATION



Model

- Decay: $\mathrm{DM} \to \tau^+\tau^- \quad m_{\rm DM} = 400\,\mathrm{TeV}$
- Annihilation: $\mathrm{DM\,DM} \to \tau^+\tau^- \quad m_{\rm DM} = 200\,\mathrm{TeV}$
- NFW and HAI boost factor

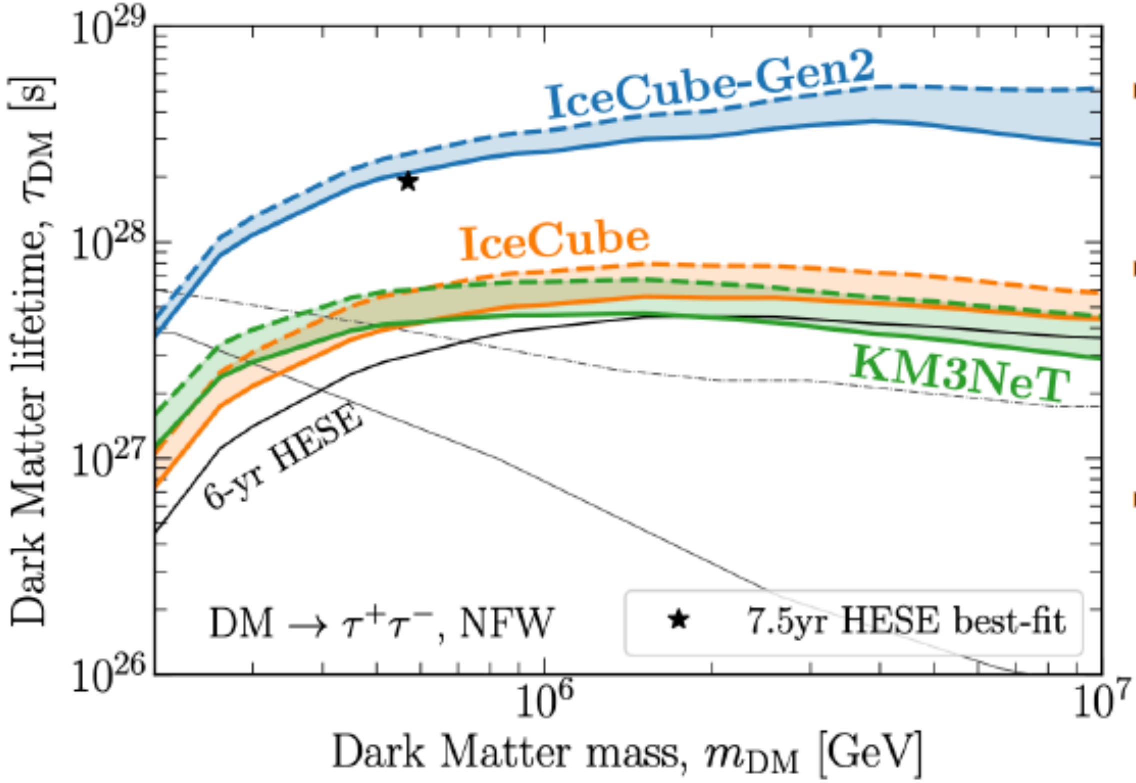
Constraints on total DM events from anisotropy

↓

Constraints on DM lifetime and cross-section

Dekker, Chianese, Ando, ***arXiv:1910.12917***

Decaying Dark Matter



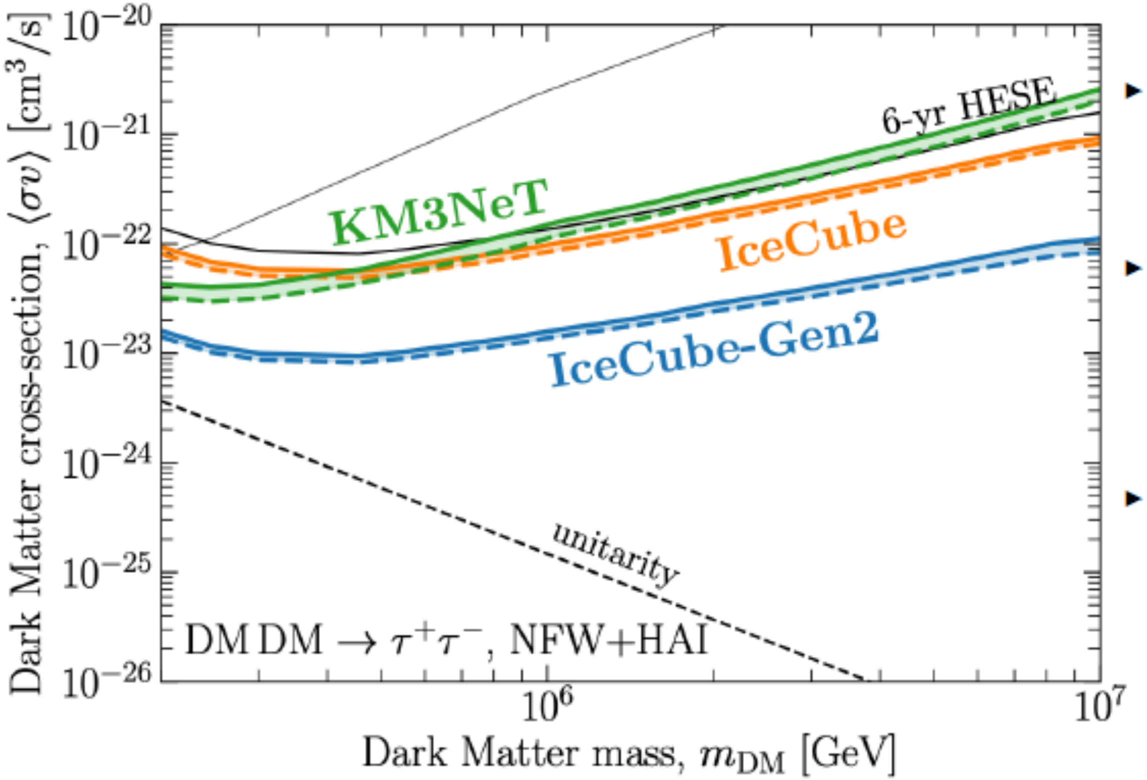
- Exclusion at 95% CL after 10 years of observations
- Bands covering the median and the conservative 95% sensitivity from Monte Carlo
- Gamma-ray constraints shown with grey lines: HAWC (solid) and global (dot-dashed)

*HAWC: Abeysekara et al., **JCAP 1802**; Global: Cohen, Murase, Rodd, Safdi, Soreq, **PRL 119 (2017)***

ICECUBE-GEN2 WILL FIRMLY PROBE THE DARK MATTER HYPOTHESIS

*Dekker, Chianese, Ando, **arXiv:1910.12917***

Annihilating Dark Matter



- Exclusion at 95% CL after 10 years of observations
- Bands covering the median and the conservative 95% sensitivity from Monte Carlo
- Gamma-ray constraints shown with grey lines: HAWC (solid)

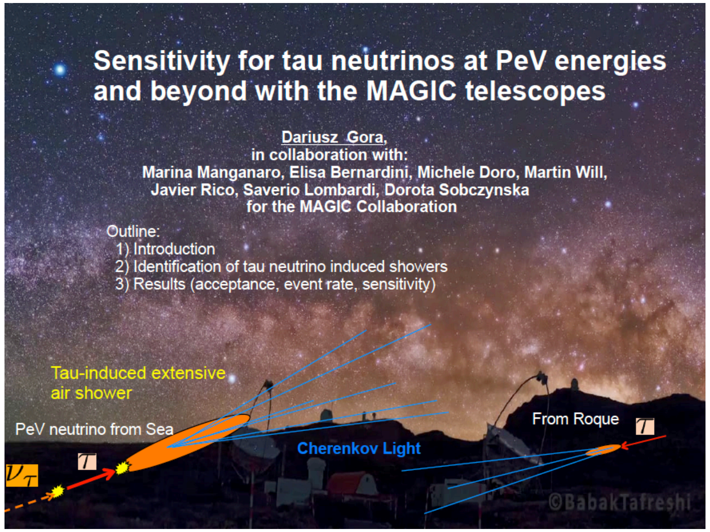
HAWC: *Abeysekara et al.*, ***JCAP 1802***

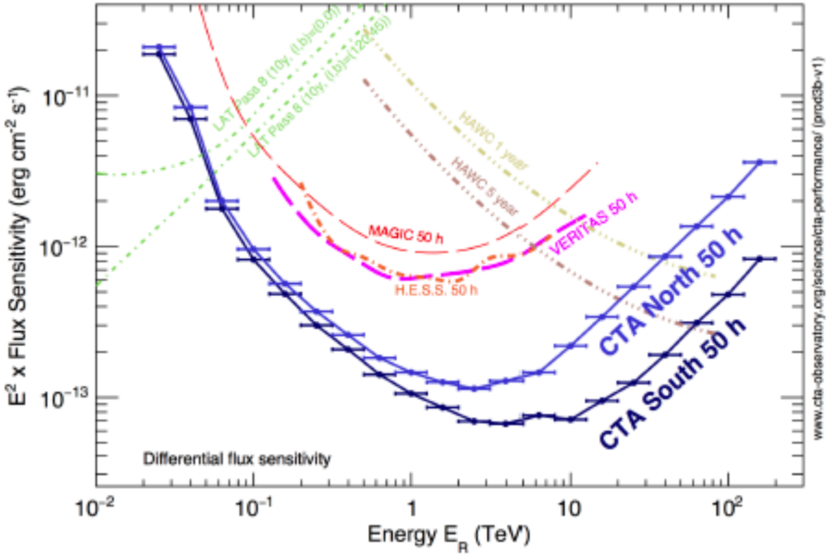
STRONGER CONSTRAINTS WRT GAMMA-RAYS, BUT *UNITARITY*

Dekker, Chianese, Ando, ***arXiv:1910.12917***

IACT and ν_τ

Although optimized for γ primaries, MAGIC is also sensitive to hadronic showers. In particular, since 2007 (ICRC, Merida) the experiment investigated the response to τ coming from the sea.



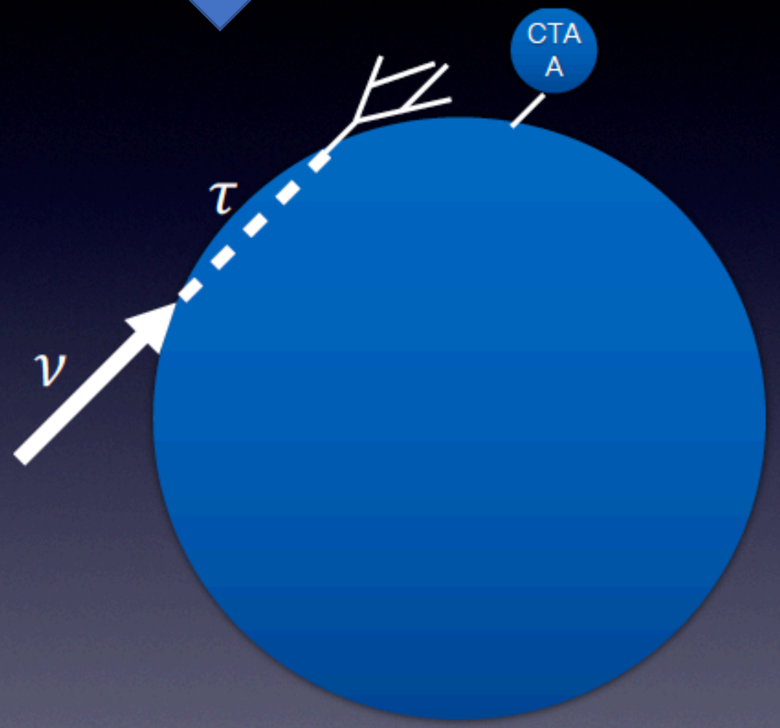


CTA is the next-generation observatory based on IACT technique which will:

1. cover a wider energy range
2. have larger field of view
3. achieve an order of magnitude improvement in sensitivity

Simulation of earth-skimming ν_τ

D. Fiorillo, G. Miele, O. Pisanti



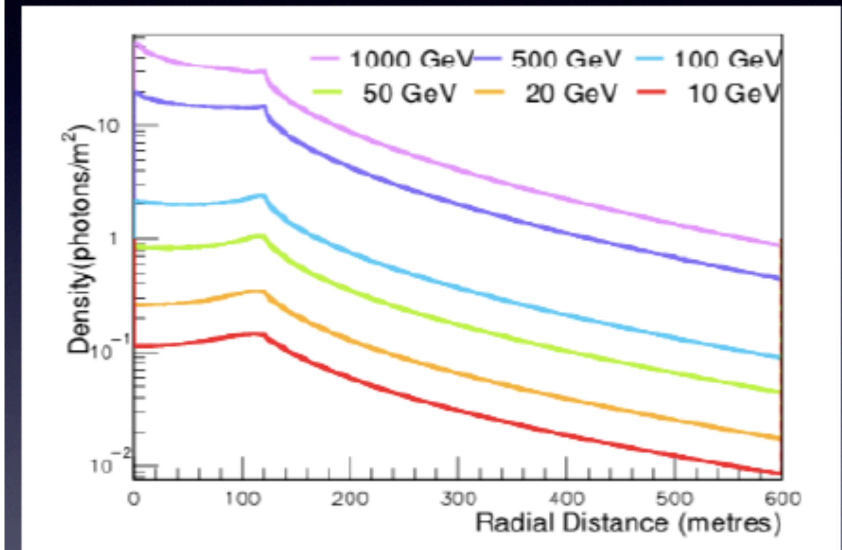
- PARAMETERIZATION OF THE SHOWER FROM A TAUON: taken from the literature
- PARAMETERIZATION OF THE CHERENKOV LIGHT FROM THE SHOWER: obtained through semi analytic means
- PREDICTION FOR THE EXPERIMENT: prediction of effective area, obtained through simulation of the Cherenkov light detected at a telescope

$$\frac{dN}{dt} = \int dE \int d\Omega \frac{d\Phi}{dE d\Omega}(E,\Omega) A_{eff}(E,\Omega)$$

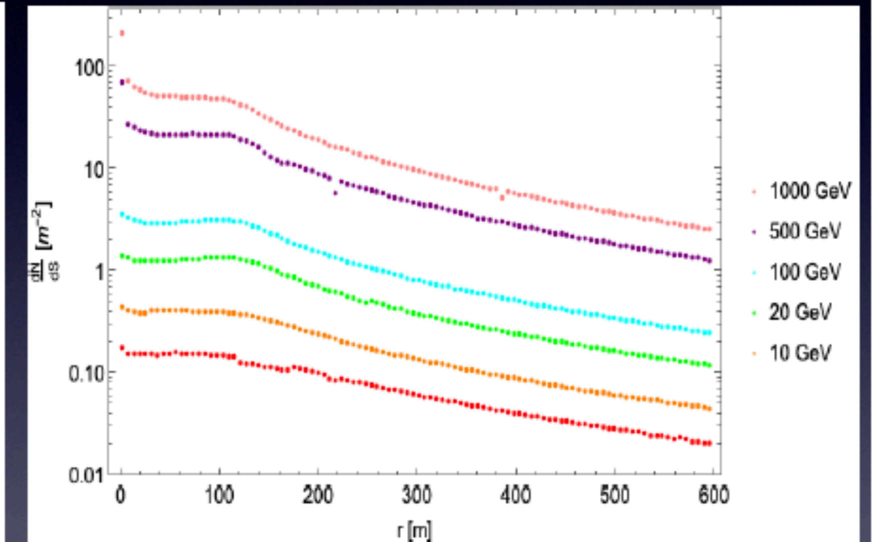
Simulation of earth-skimming ν_τ

Figure 3.14: The average density of Cherenkov photons on the ground (expressed in photons per m^2) as a function of the distance from the shower core for simulated γ-ray showers of various energies at 2200 m of altitude.

Simulations



Semianalytic treatment



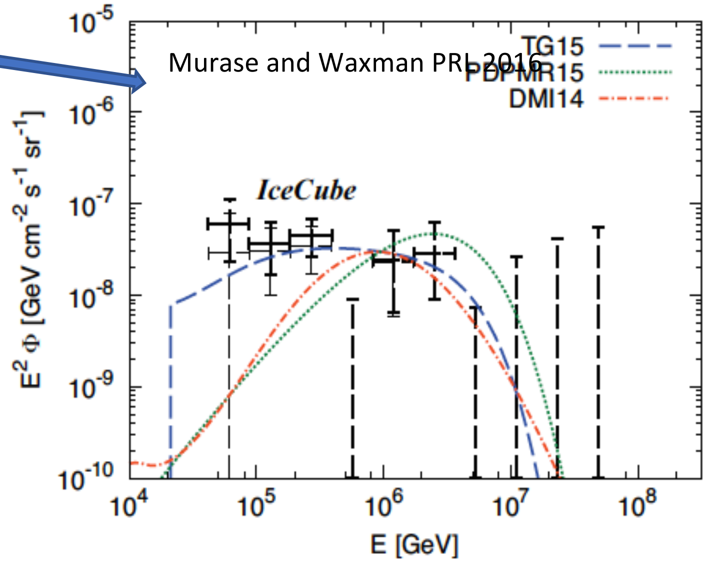
"The development of simulation and atmospheric shower reconstruction tools for the study of future Cherenkov Imaging telescopes", Sajjad

Modelli "globali" di sorgenti extragalattiche + DM

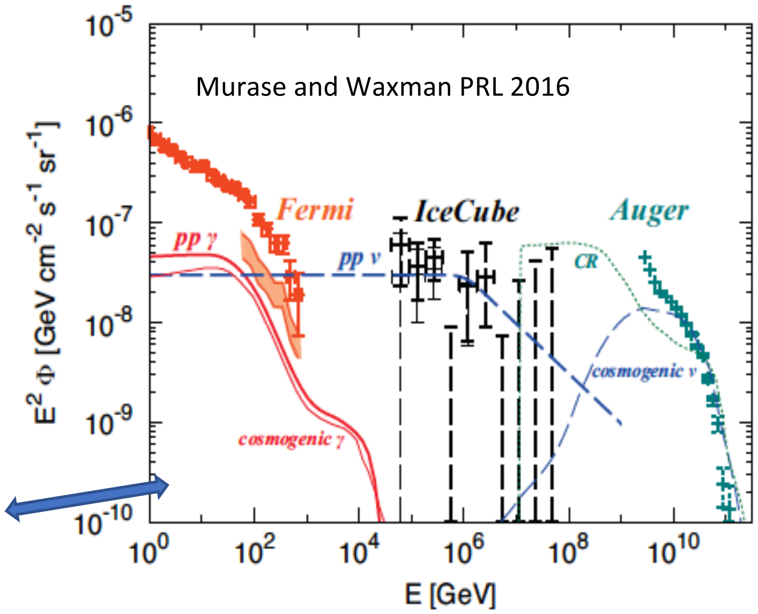
- Studio della popolazione di potenziali sorgenti di neutrini astrofisici suddivisi in "reservoirs" e "acceleratori" e confronto con il flusso misurato da IceCube ⇒ C'è spazio/necessità per una componente di DM?
- Utilizzo dei dati di raggi gamma di Fermi-LAT e dei dati di raggi cosmici ultra energetici da Pierre Auger e Telescope Array per la normalizzazione dei flussi di neutrino aspettati. (Approccio multi-messenger)

Ambrosone, Chianese, Fiorillo, Marinelli, Miele, in preparation

neutrinos from blazars



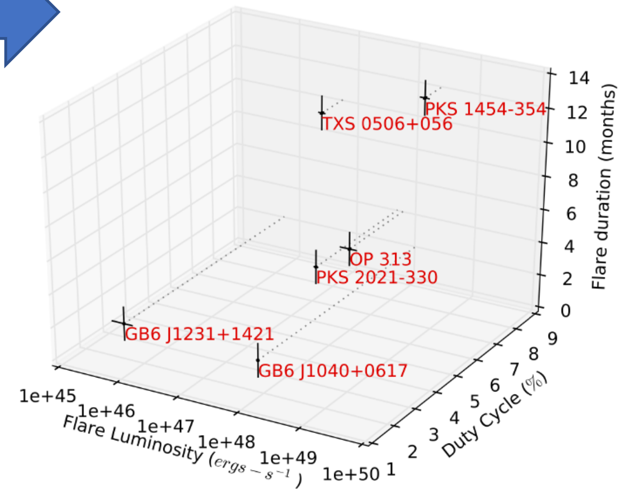
fluxes in the grand-unified model



Modelli di sorgenti extragalattiche + DM

Marinelli, Sacahui, Sharma, Osorio-Archila

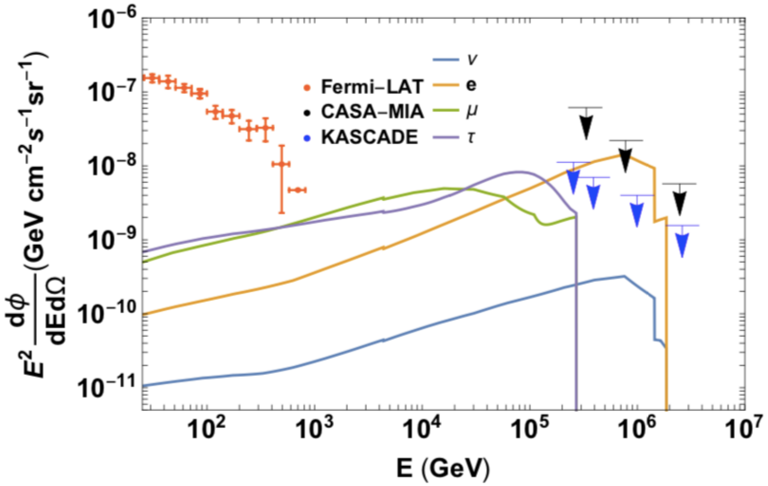
Marinelli et al. arXiv1909.13198



- Stima del contributo adronico degli "acceleratori" utilizzando una simulazione dedicata e un fattore di attività ottenuto dai gamma.
- Approccio semi-analitico per il contributo adronico aspettato dai "reservoir".
- Aggiunta del potenziale flusso di neutrini da decadimento di materia oscura attraverso le simulazioni già utilizzate dal gruppo in precedenza.

Ambrosone, Chianese, Fiorillo, Marinelli, Miele, in preparation

Chianese et al. JCAP 2019



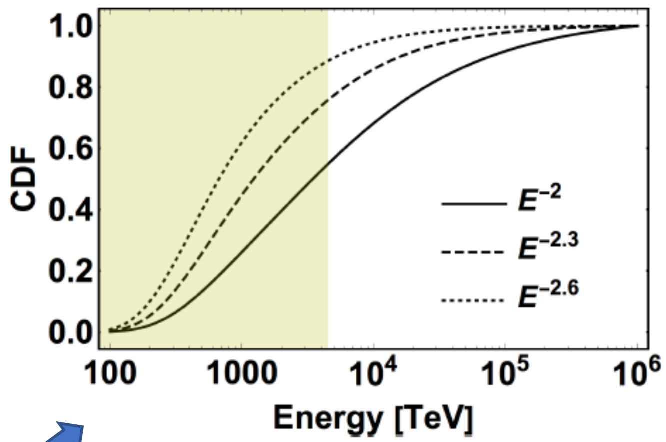
The importance of observing ν_τ

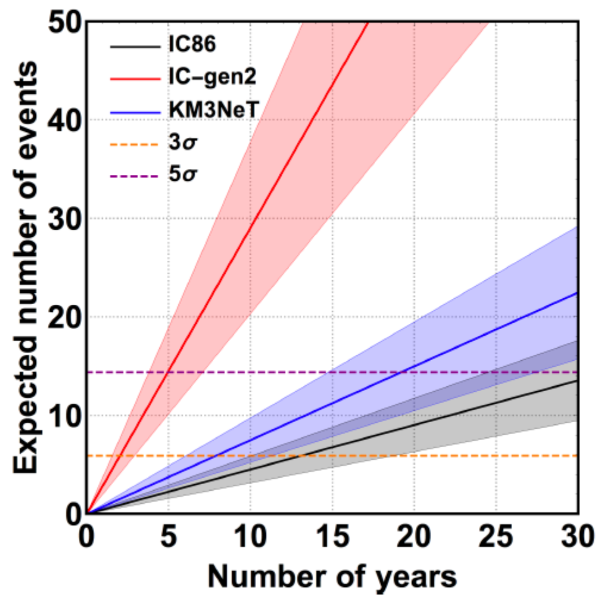
Palladino, Mascaretti, Vissani, JCAP 1808 (2018) 004

- Hadronic processes in sources give rise to ν_e and ν_μ, while ν_τ emerge due to oscillations during propagation.
- In NT ν_τ can be recognized from different topologies (double bang, double pulse → HESE).
- Calculation of the effective areas for double cascades for a generic detector → parent function

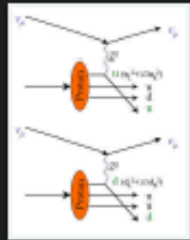
$$P(E_\nu, \alpha) = \frac{\int_0^{E_\nu} E^{-\alpha} A_{\text{eff}}(E_\nu) dE_\nu}{\int_0^{\infty} E^{-\alpha} A_{\text{eff}}(E_\nu) dE_\nu}$$

- From this, the expected yearly rates of distinguishable ν_τ events.

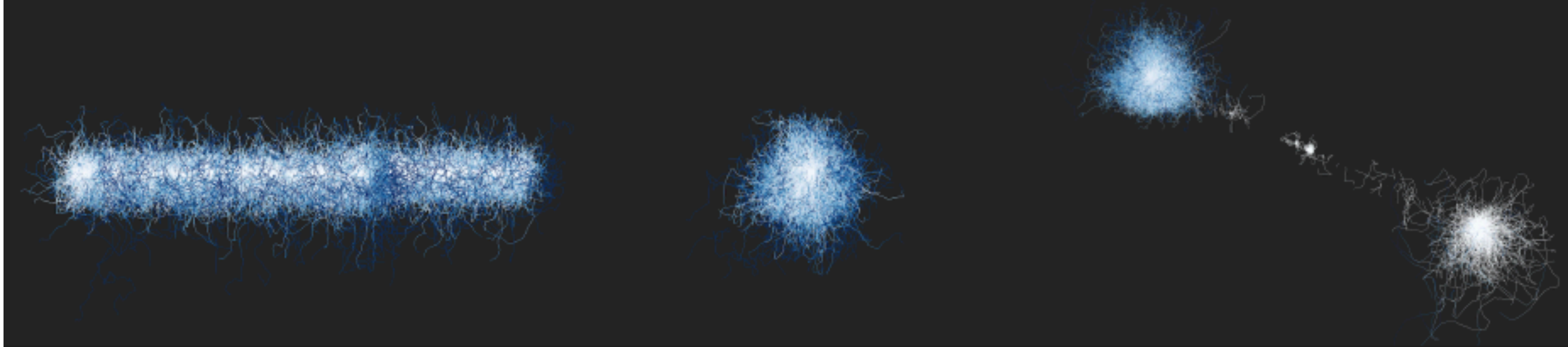


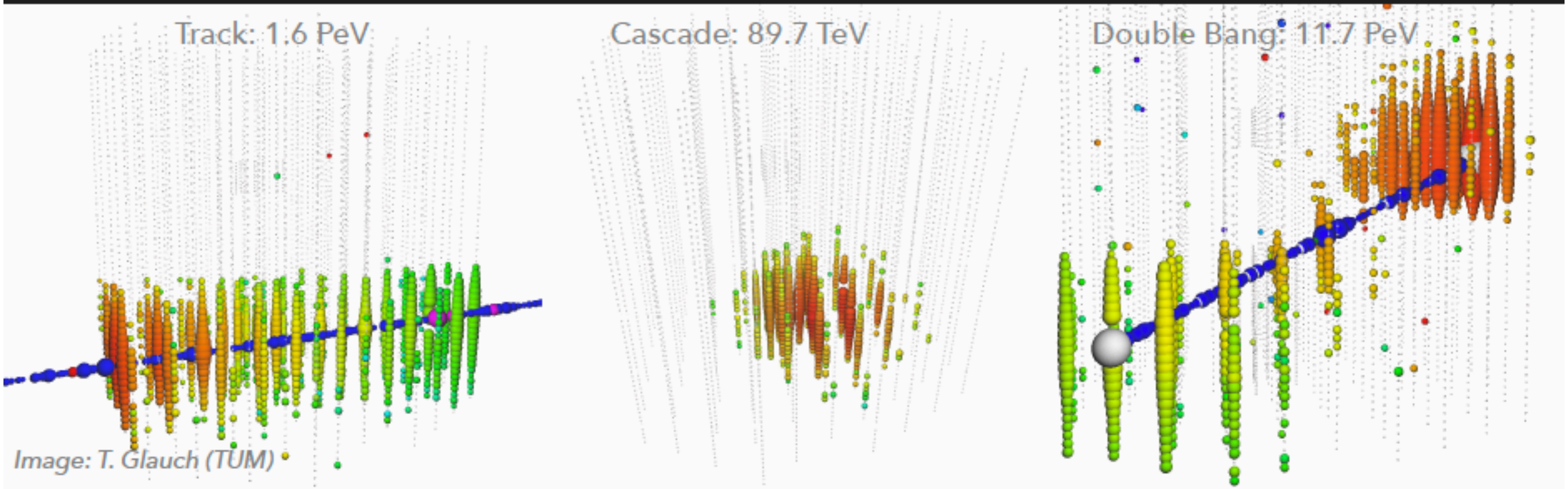


NEUTRINO INTERACTION CHANNELS



Photon path induced by a ν_μ ν_e ν_τ

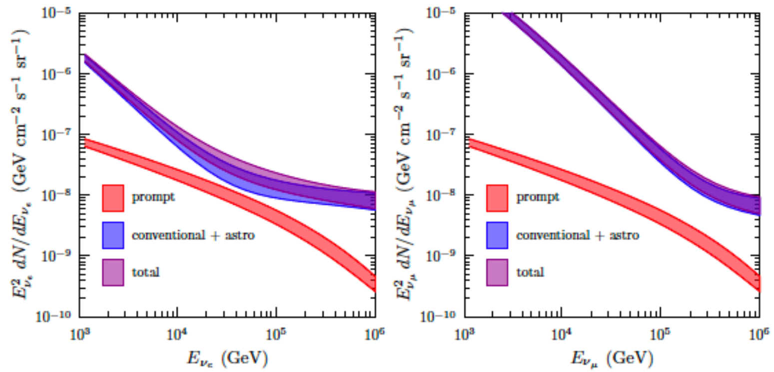


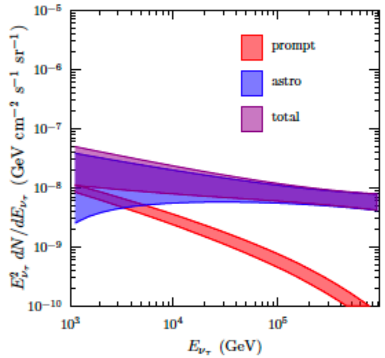


Relevance of prompt neutrinos for IC

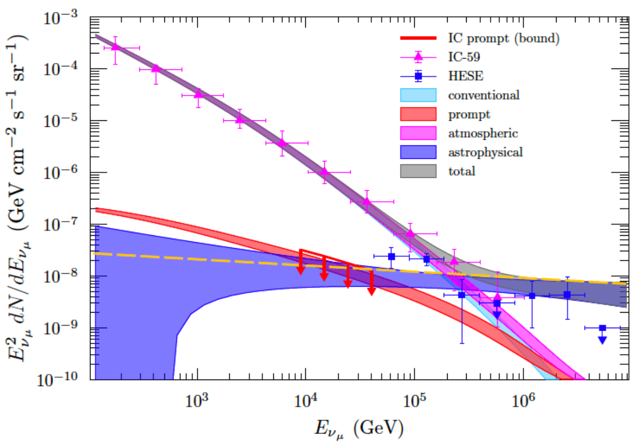
Mascaretti & Vissani, JCAP 1908 (2019) 004

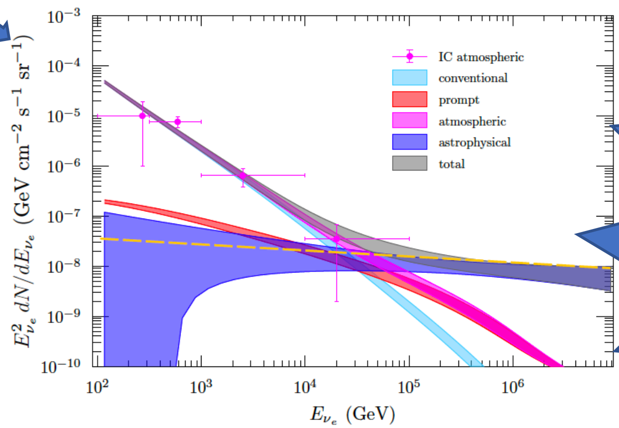
- Atmospheric neutrinos: conventional component from pions and kaons, prompt component from charmed mesons decay.
- Distinguishable spectrum and angular distribution.
- Calculation of the various component of the ν_μ and ν_e flux.





Component	Γ_{ν_e}	Γ_{ν_μ}	Γ_{ν_τ}	Γ_{tot}
Conventional	160–210	420–570	0	580–780
Prompt	20–30	3–5	2–3	25–40
Cosmic	10–40	2–6	5–20	15–65





Prompt ν signal difficult to extract

Diffuse Galactic HEN and Gamma-ray

Giulia Pagliaroli, Francesco Lorenzo Villante, Maddalena Cataldo, Vittoria Vecchiotti

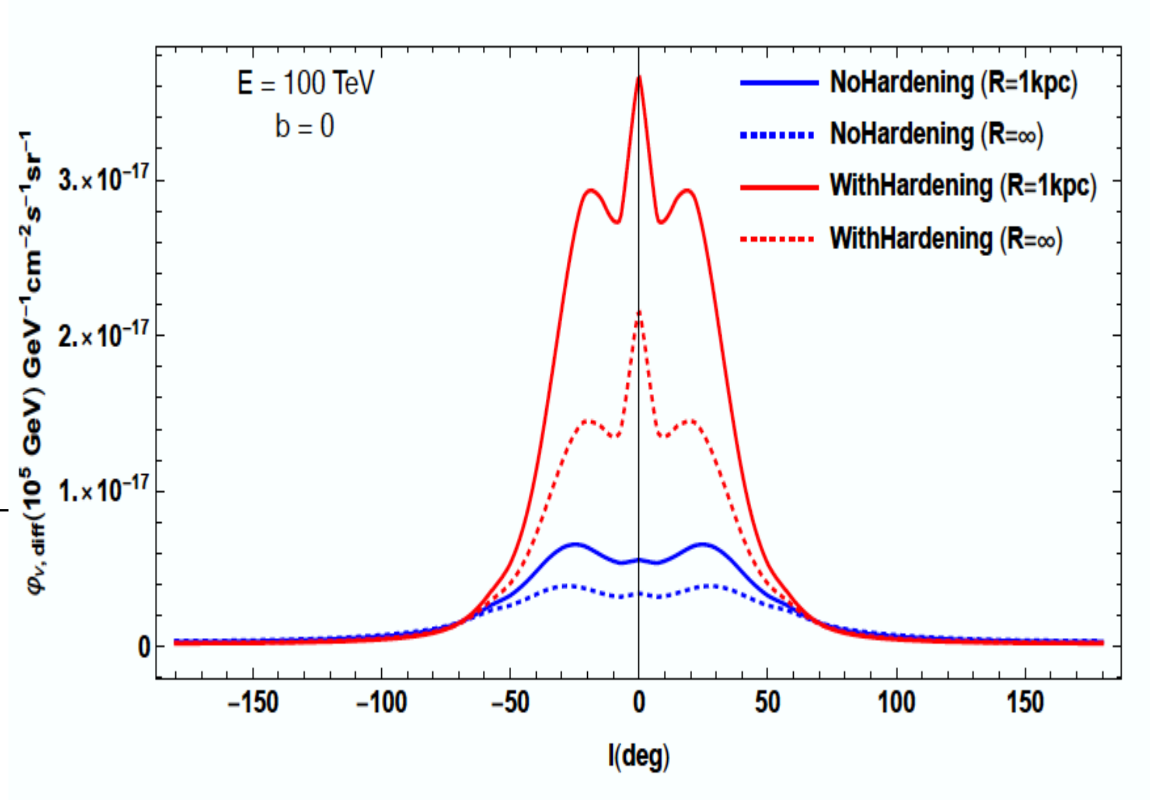
Studio della emissione diffusa prodotta dalla interazione di Raggi Cosmici con il gas presente sul piano galattico: emissione correlata di neutrini e gamma di alta energia per differenti ipotesi sulla distribuzione spaziale e sull'indice spettrale dei raggi cosmici in funzione delle coordinate galattiche.

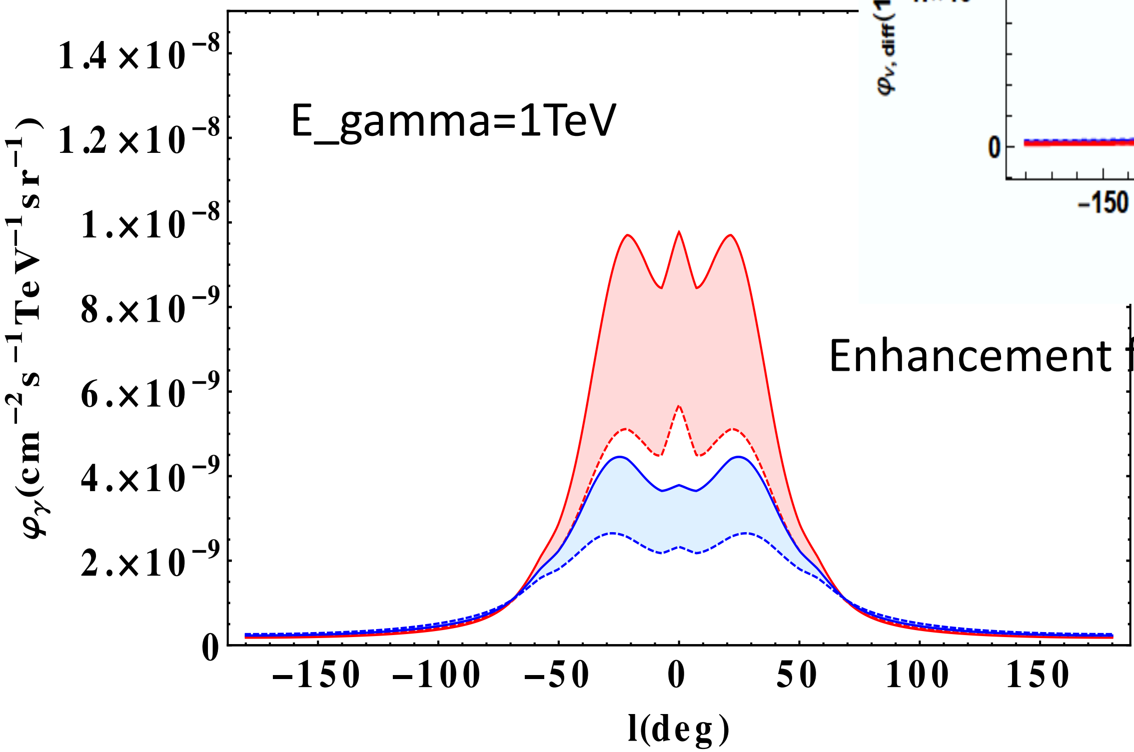
G.Pagliaroli, C.Evoli, F.L.Villante JCAP11(2016)004

Studio della emissione totale galattica data dalla somma dell'emissione diffusa sopra discussa e il contributo da sorgenti sempre per differenti ipotesi sulla distribuzione spaziale e sull'indice spettrale dei raggi cosmici in funzione delle coordinate galattiche. Confronto di questa emissione totale con i dati osservativi dei profili longitudinali di emissione gamma al TeV di HESS, Argo, Milagro e HAWC.

G.Pagliaroli, F.L.Villante JCAP08(2018)035
M.Cataldo, G.Pagliaroli, V.Vecchiotti, F.L.Villante JCAP12(2019)050

Diffuse Fluxes





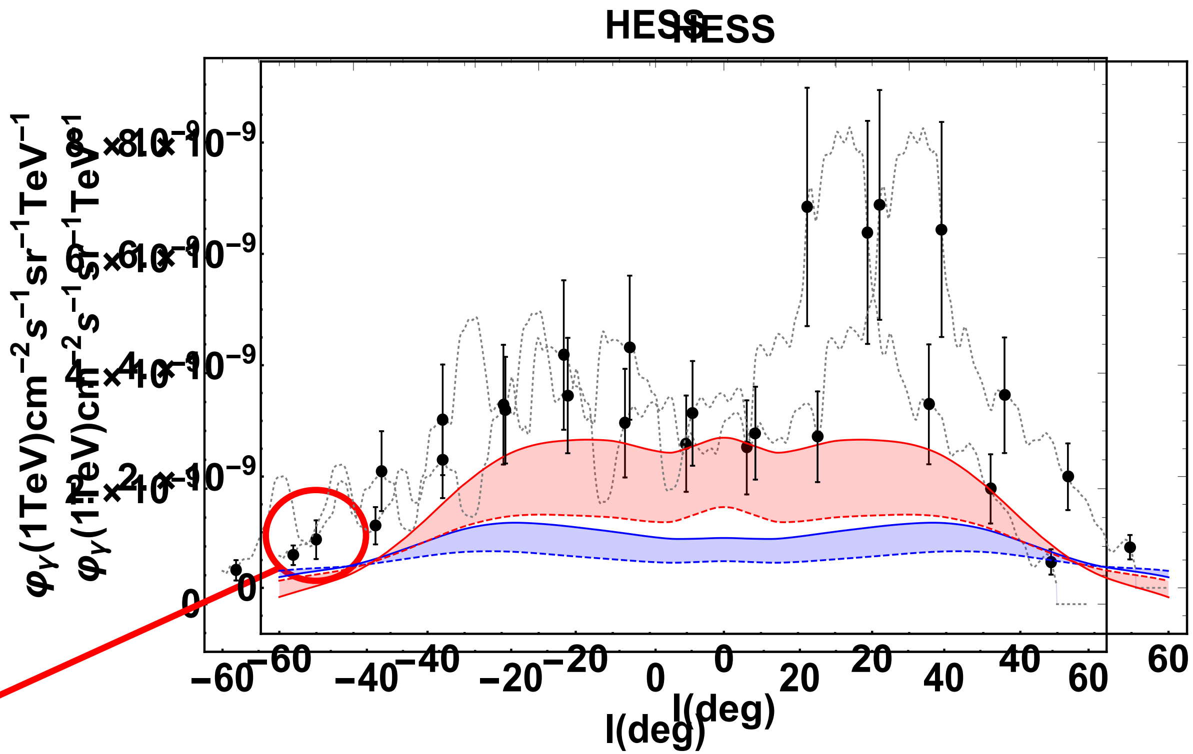
Enhancement factor ~2

Spectral hardening hypothesis
(Red lines)
No hardening (Blue lines)

The TeV Galactic Gamma profile

Error bars = sum in quadrature of statistical
And systematic errors

HESS	30%
HAWC	50%
Argo	27%
Milagro	36%

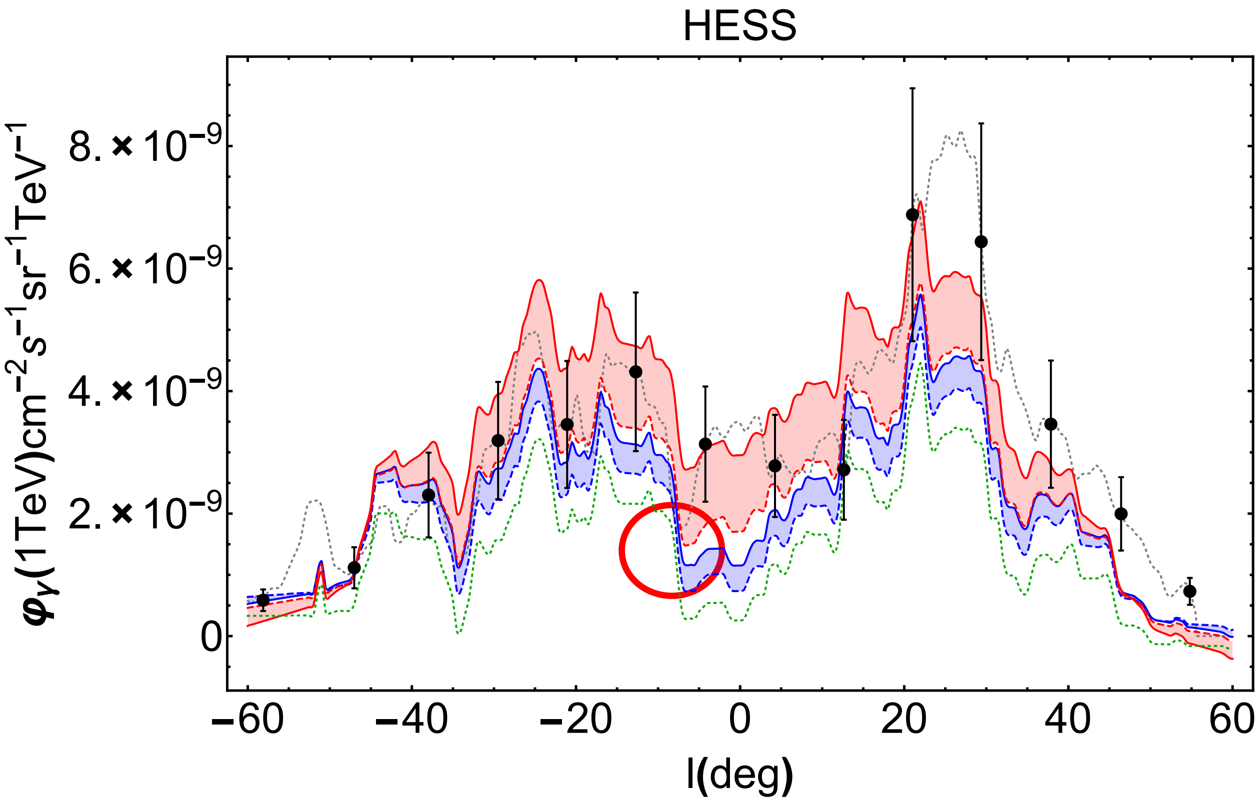


$$\varphi_{\gamma,\text{tot}} = \varphi_{\gamma,\text{diff}} + \varphi_{\gamma,\text{S}} + \varphi_{\gamma,\text{IC}}$$

Diffuse Emission → CRs propagates and interact with interstellar gas

Sources Emission → Gamma rays are emitted nearby the sources

The TeV Galactic Gamma profile



$$\varphi_{\gamma,\mathrm{tot}} = \varphi_{\gamma,\mathrm{diff}} + \varphi^{(r)}_{\gamma,\mathrm{S}} + \varphi^{(unr)}_{\gamma,\mathrm{S}} + \varphi_{\gamma,\mathrm{IC}}$$

104% → 132%

Summary

- On the overall sky the galactic contribution (diffuse flux + source flux) at 100 TeV gives a subdominant contribution to the isotropic HESE flux measured by IceCube: 12-15 %
- In the window -60°<l<60°, |b|<7.5°, galactic flux (diffuse + sources) give a comparable contribution to the isotropic HESE flux. At 100 TeV: 140-230 %
  - An imprint of the CR distribution is present in the TeV gamma diffuse emission and the impact of a spectral hardening is large (can be probed)
  - Diffuse emission with hardening plus Resolved sources saturate the data
  - The unresolved source contribution is not negligible
  - Potential tension of CR spectral hardening with observational data unless HE gamma-ray sources have a luminosity greater than the CRAB

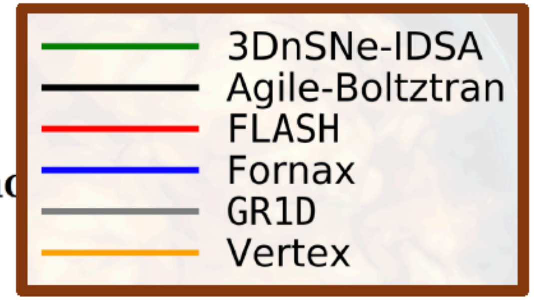
SUPERNOVA neutrinos

tests of core-collapse supernova physics, detection strategy and multi-messengers opportunity

- Mirizzi, R. Glas, H.T.Janka, F. Capozzi, M. Sen, B. Dasgupta, G.Sigl, E.Lisi: fast flavor instabilty in Supernovae
- F. Vissani, A. Gallo Rosso, C. Volpe: Constrain on neutron star properties and neutrino spectra from next galactic CCSN
- A. Mirizzi, Mastrototaro, P. Serpico, A. Esmaili: heavy sterile neutrinos in SNe
- Pagliaroli, O. Halim, V. Fafone, C. Vigorito: Improved

Global effort towards agreement

- Want to demonstrate the community's ability to simulate SN
- Comparison of 6 core-collapse supernova codes
- *Very carefully* control input physics and initial conditions to ensure fair comparison



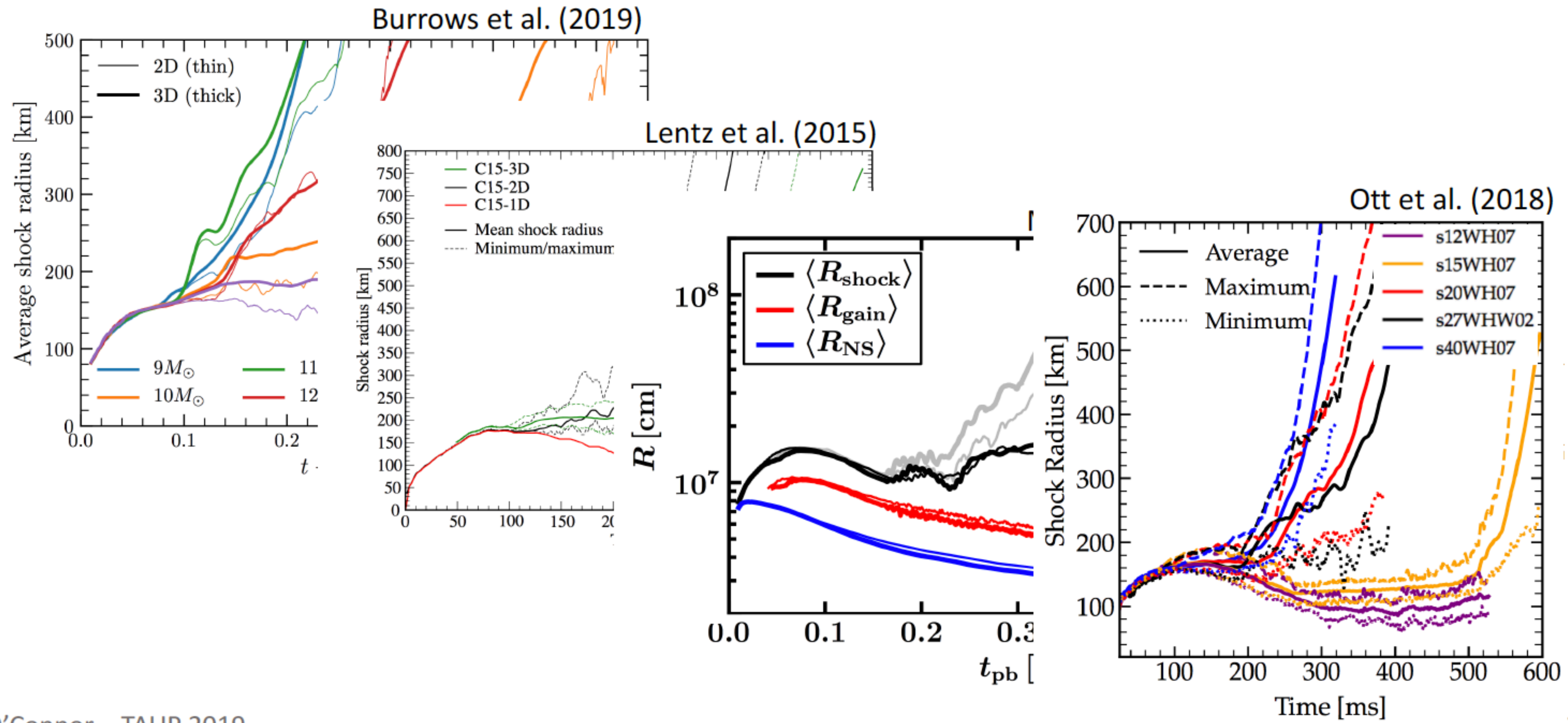
Global Comparison of Core-Collapse Superno[va] Simulations in Spherical Symmetry

Evan O'Connor[1], Robert Bollig[2,3], Adam Burrows[4], Sean Couch[5,6,7,8], Tobias Fischer[9], Hans-Thomas Janka[2], Kei Kotake[10], Eric Lentz[11], Matthias Liebendörfer[12], O. E. Bronson Messer[13,11], Anthony Mezzacappa[11], Tomoya Takiwaki[14], David Vartanyan[4]

Journal of Physics: G 45 10 2018

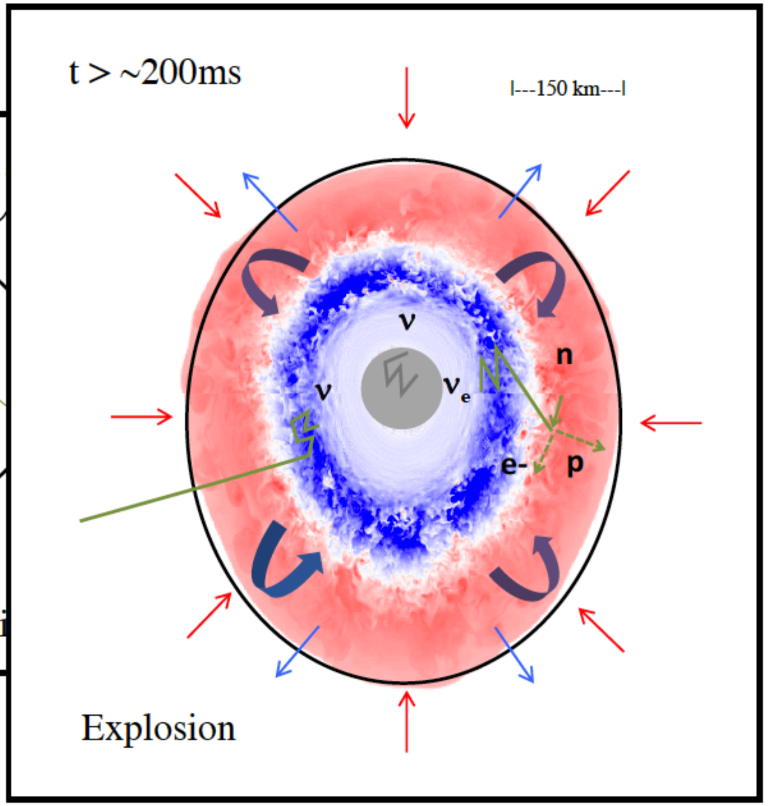
Explosion Successes in multiD – 3D

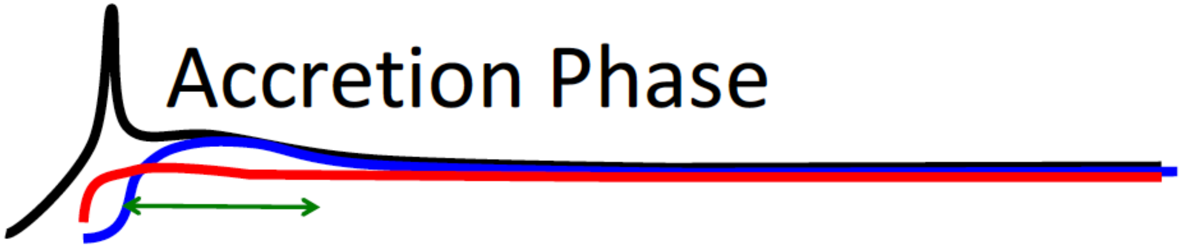
- Similar progenitors
- GR gravity
- Non-rotating



CCSNe: The Stages

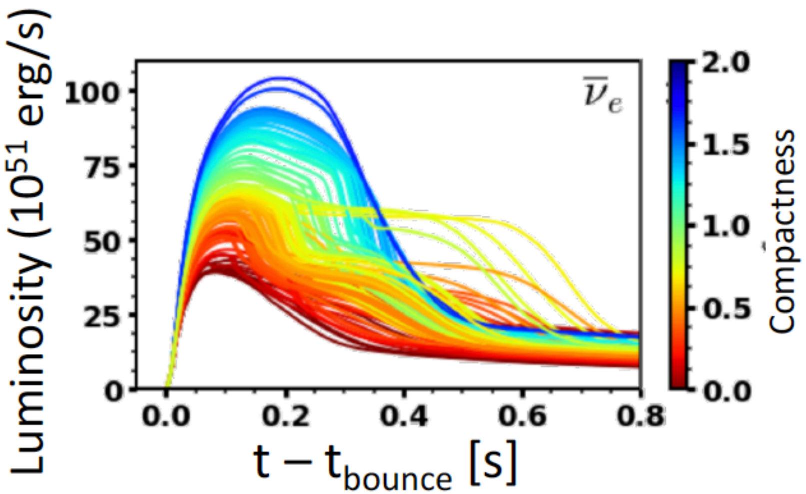
- The prevailing mechanism is the **turbulence-aided neutrino mechanism**
  - Neutrinos from core heat outer layers
  - Drives convection
  - Turbulence pressure support aids heating and drives explosion
- Very successful in 2D*, many successful explosions
- Success in 3D too: fewer simulations

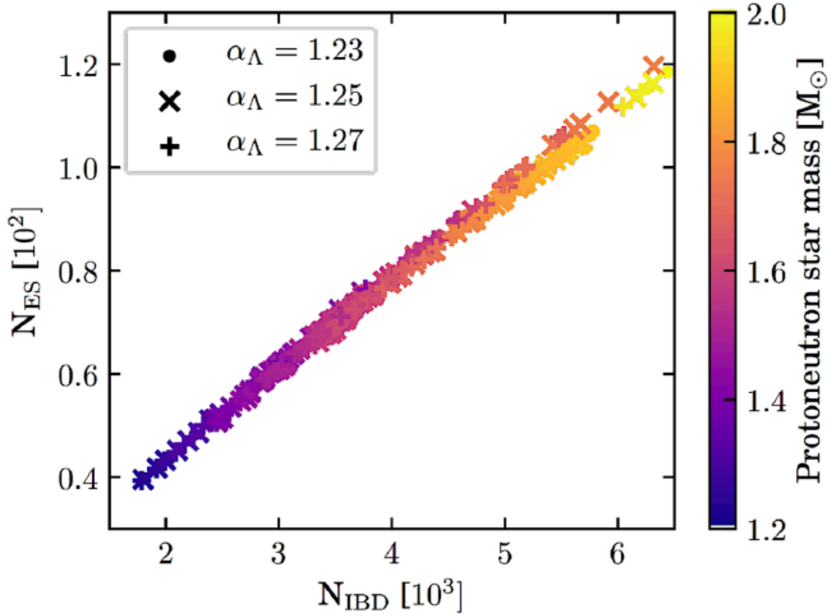




Accretion Phase

200 1D models from
Couch et al. (2019) &
Warren et al. (in prep)

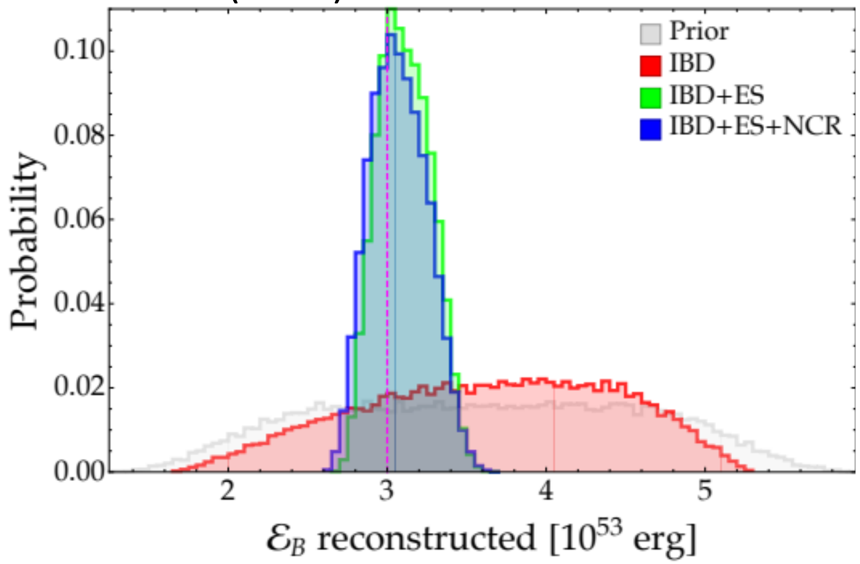


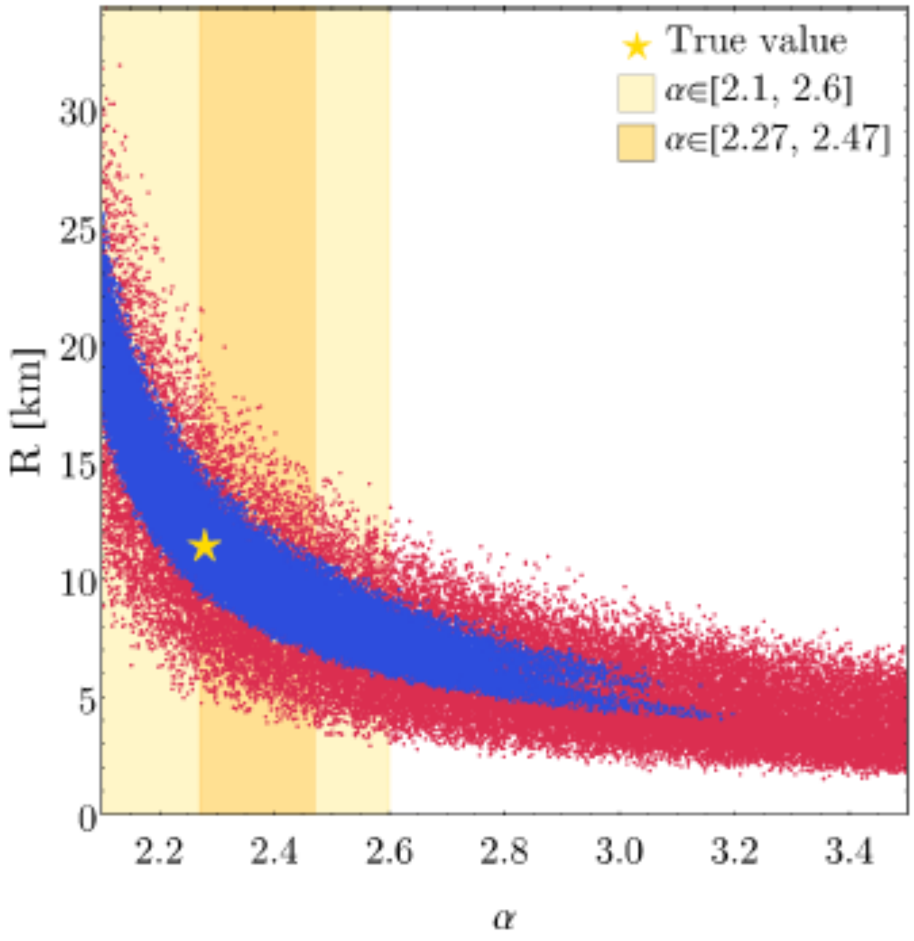


Learn about neutron star mass from neutrino observation of galactic supernova

(Gallo Rosso, Volpe, FV) siamo pronti per la prossima supernova galattica?

A. Gallo Rosso, F. Vissani and M.C. Volpe JCAP 1804 (2018) 040





(a) $\overline{\nu}_e$ species

siamo pronti per la prossima supernova galattica?

una occasione unica che non va sprecata. Cosa impariamo su energia totale; spettri di emissione; distribuzioni di sapore; ecc?

A. Gallo Rosso, S. Abbary, F. Vissani, and M.C. Volpe JCAP 1812 (2018) 006

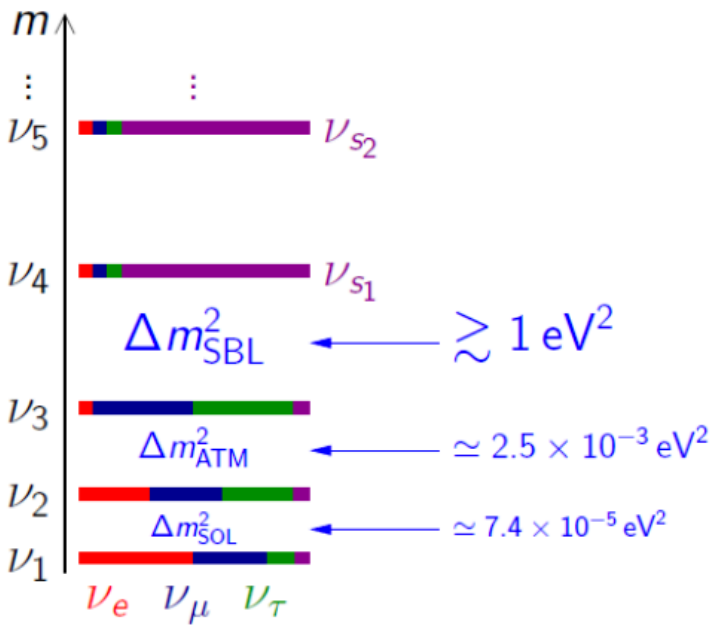
A. Gallo Rosso, F. Vissani and M.C. Volpe JCAP 1711 (2017) 036

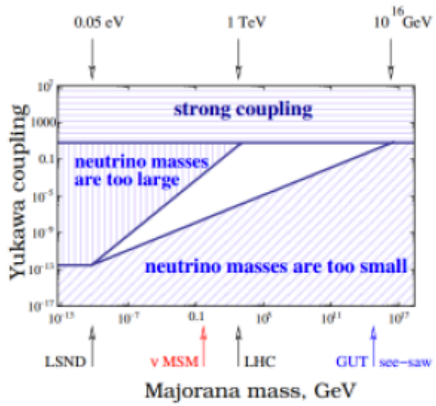
Heavy sterile neutrinos signal in core-collapse supernovae: constraints and signatures

L. Mastrototaro, A. Mirizzi, P. Serpico, A. Esmaili

arXiv: 1910.10249

STERILE NEUTRINOS





	N mass	ν masses	eV ν anomalies	BAU	DM	M_H stability	direct search	experiment
GUT see–saw	10^{10-16} GeV	YES	NO	YES	NO	NO	NO	–
EWSB	10^{2-3} GeV	YES	NO	YES	NO	YES	YES	LHC
ν MSM	keV – GeV	YES	NO	YES	YES	YES	YES	a'la CHARM
ν scale	eV	YES	YES	NO	NO	YES	YES	a'la LSND

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix} .$$

Extra sterile neutrinos with masses $m_s \gg m_a$ and mixed with the active ones through a mixing angle θ_s are predicted in different extensions of the Standard Model

HEAVY STERILE ν EMISSION FROM SNE

- We investigate the possibility that heavy sterile neutrinos ($m \sim O(200)$ MeV and $\sin^2\theta_{\tau 4} = 10^{-8}$, $\sin^2\theta_{e4} = \sin^2\theta_{\mu 4} = 0$) might be produced in supernovae explosion [*Fuller et al, arXiv: 0806.4273 [astro-ph]*]
- In the hot core ν_e, e, p, n are degenerate. The processes that will create sterile neutrino involve only ν_μ, ν_τ.
- We solved the Boltzmann equation for sterile neutrino population, following the technique developed by [*Hannestad et al, arXiv: hep-ph/9506*]

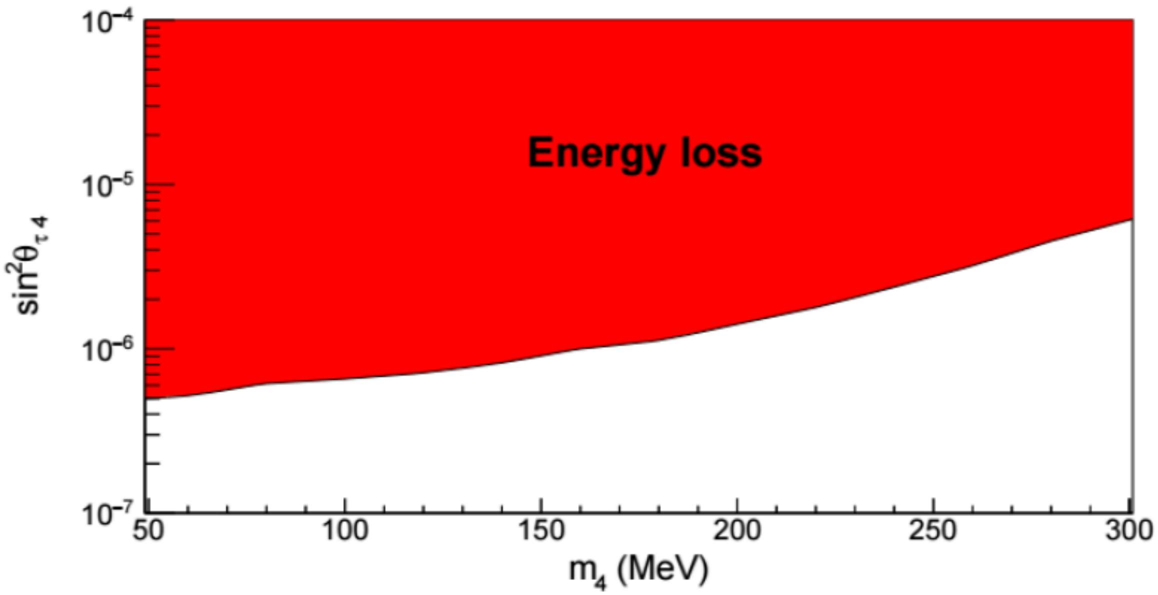
$$\frac{\partial f_s}{\partial t} = \frac{(2\pi)^4}{2E_1} \int d^3\widehat{p_2} d^3\widehat{p_3}\, d^3\widehat{p_4} \Lambda(f_s, f_2, f_3, f_4) S|M|^2 \delta^4(p_1 + p_2 - p_3 - p_4)$$

Process	$\mathrm{S}|\mathrm{M}|^2/(8G_F^2 \sin^2\theta_{\tau 4})$
$\nu_\tau + \bar{\nu}_\tau \to \nu_4 + \bar{\nu}_\tau(\nu_\tau)$	$4u(u - m_4^2)$
$\nu_\mu + \bar{\nu}_\mu \to \nu_4 + \bar{\nu}_\tau(\nu_\tau)$	$u(u - m_4^2)$
$\nu_\tau + \nu_\tau \to \nu_4 + \nu_\tau$	$2s(s - m_4^2)$
$\bar{\nu}_\tau + \bar{\nu}_\tau \to \nu_4 + \bar{\nu}_\tau$	$2s(s - m_4^2)$
$\nu_\mu + \nu_\tau \to \nu_4 + \nu_\mu$	$s(s - m_4^2)$
$\bar{\nu}_\mu + \bar{\nu}_\tau \to \nu_4 + \bar{\nu}_\mu$	$s(s - m_4^2)$
$\nu_\tau + \bar{\nu}_\mu \to \nu_4 + \bar{\nu}_\mu$	$u(u - m_4^2)$
$\bar{\nu}_\tau + \nu_\mu \to \nu_4 + \nu_\mu$	$u(u - m_4^2)$

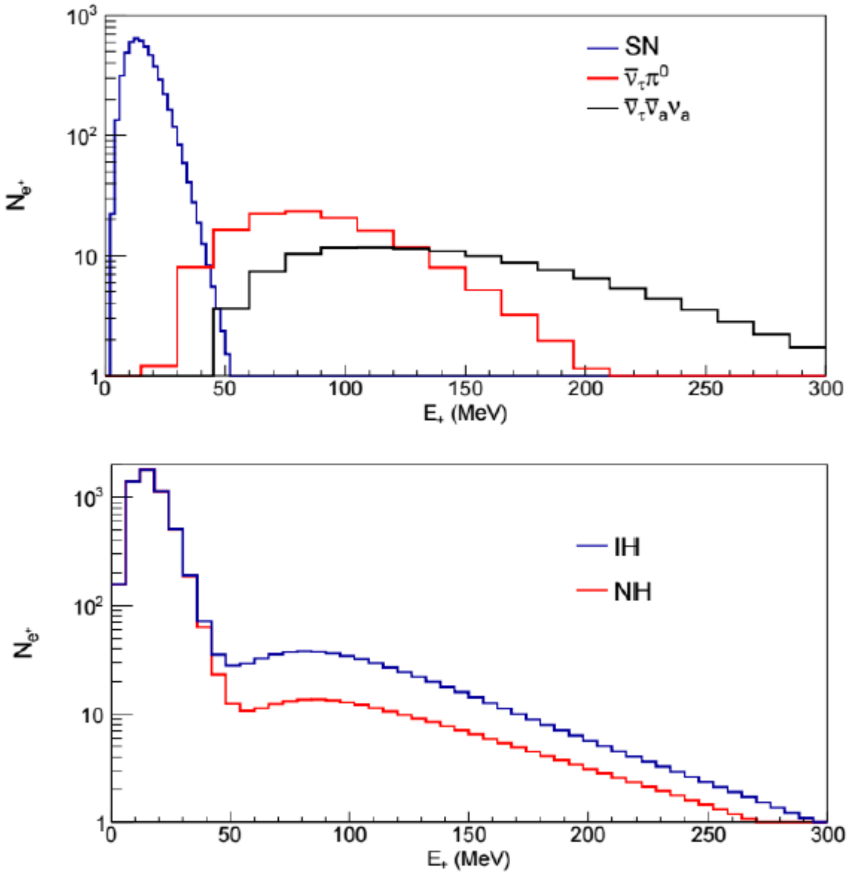
SN 1987A BOUND ON STERILE ν

- The only observed supernova neutrino signal is associated with SN 1987A.
- It sets a limit on the luminosity from exotic particles, that would have caused an excessive energy loss [*Raffelt et al, arXiv: 1102.5124*]

$$L_s \leq 2 \times 10^{52}\ erg/s$$



ACTIVE AND STERILE ν SIGNAL IN SK



	Number of events	
	NH	IH
SN $\bar{\nu}_e$	5280	5640
$\nu_4 \to \pi^0 \bar{\nu}_\tau$	141	470
$\nu_4 \to \nu_\tau \nu_a \bar{\nu}_a$	125	193

The figures refer to the energy distribution of events in Super-Kamiokande detector.

The signature of the existence of ν_s would be a bump in the energy spectrum at $E_\nu \geq 80$ MeV

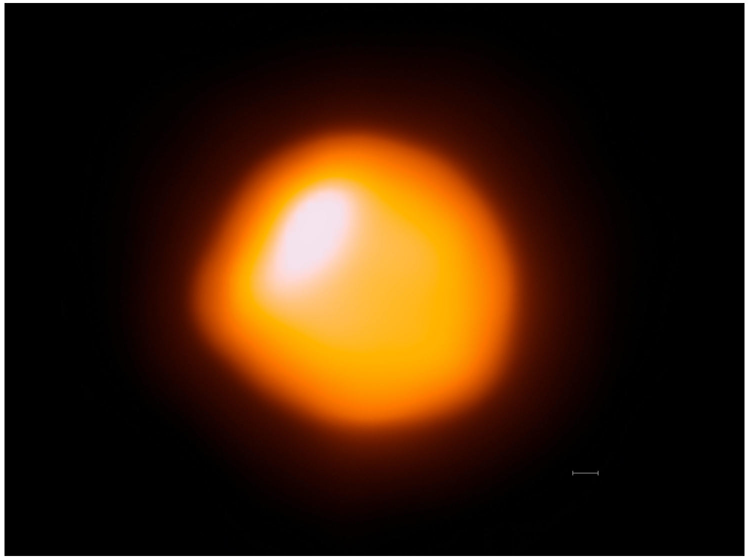
Combined search of Core-collapse SNe with MeV neutrinos and GWs

-Study of new way to disentangle real signal from the noise in order to increase the statistical significance of observed coincidences.

-Study of statistical way to combine GW and neutrinos Data.

Waiting for
Betelgeuse to Explode

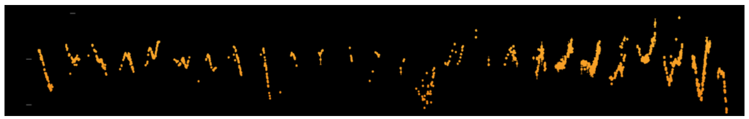
By Jonathan Corum Jan. 9, 2020



A Fading Giant

Around 700 years ago, the red star Betelgeuse began to fade. The light from that unusual dimming is only now reaching Earth, some 700 light-years away.

Betelgeuse is normally one of the 10 brightest stars in the sky, but is now fainter than ever recorded.



GW Emission Mechanisms

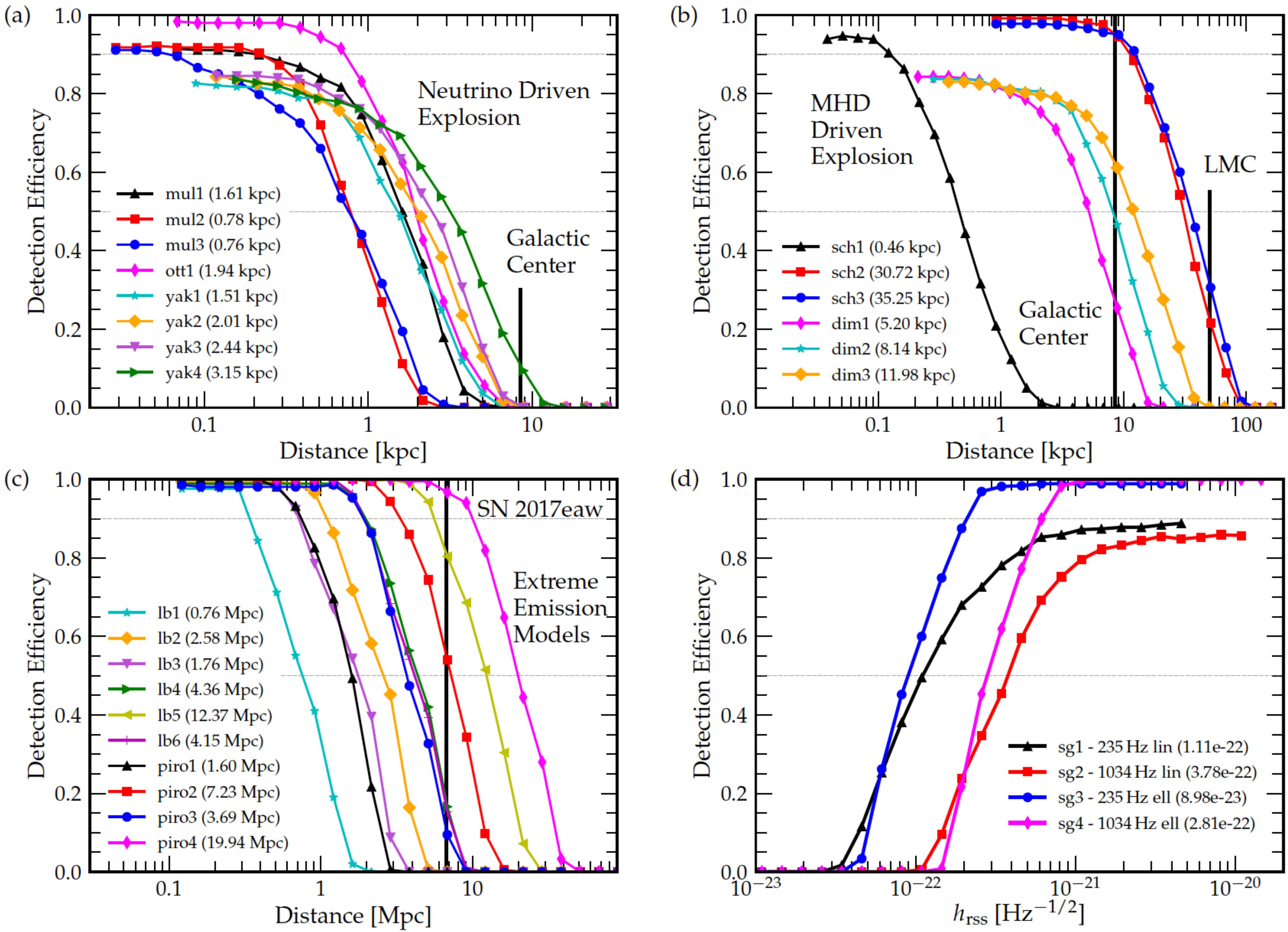
GW Emission Processes
A: PNS core oscillations
B: Rotational 3D instabilities
C: Rotating core collapse and core bounce
D: Post bounce convection and SASI

Dynamical quadrupolar matter distribution

$$h_+ = \frac{G}{c^4}\frac{1}{D}\frac{3}{2}\ddot{I}_{zz}\sin^2\theta$$

Logue *et al.*
Phys.Rev. D86
(2012) 044023

GW Emission Process	Potential Explosion Mechanism		
	MHD Mechanism (rapid rotation)	Neutrino Mechanism (slow/no rotation)	Acoustic Mechanism (slow/no rotation)
Rotating Collapse and Bounce	**strong**	none/weak	none/weak
3D Rotational Instabilities	**strong**	none	none
Convection & SASI	none/weak	weak	weak
PNS *g*-modes	none/weak	none/weak	**strong**


(a)
Neutrino Driven Explosion
Galactic Center
mul1 (1.61 kpc)
mul2 (0.78 kpc)
mul3 (0.76 kpc)
ott1 (1.94 kpc)
yak1 (1.51 kpc)
yak2 (2.01 kpc)
yak3 (2.44 kpc)
yak4 (3.15 kpc)
Detection Efficiency
Distance [kpc]
(b)
MHD Driven Explosion
LMC
Galactic Center
sch1 (0.46 kpc)
sch2 (30.72 kpc)
sch3 (35.25 kpc)
dim1 (5.20 kpc)
dim2 (8.14 kpc)
dim3 (11.98 kpc)
Detection Efficiency
Distance [kpc]
(c)
SN 2017eaw
Extreme Emission Models
lb1 (0.76 Mpc)
lb2 (2.58 Mpc)
lb3 (1.76 Mpc)
lb4 (4.36 Mpc)
lb5 (12.37 Mpc)
lb6 (4.15 Mpc)
piro1 (1.60 Mpc)
piro2 (7.23 Mpc)
piro3 (3.69 Mpc)
piro4 (19.94 Mpc)
Detection Efficiency
Distance [Mpc]
(d)
sg1 - 235 Hz lin (1.11e-22)
sg2 - 1034 Hz lin (3.78e-22)
sg3 - 235 Hz ell (8.98e-23)
sg4 - 1034 Hz ell (2.81e-22)
Detection Efficiency
h_{rss} [$Hz^{-1/2}$]

Joint GW-ν Search

Leonor *et al.*, Class. Quantum Grav. 27 (2010) 084019

False Alarm Rate — GW back. Rate — Neutrino back. Rate — Time coincidence window

$$\text{FAR} = R_{GW}(\eta) \cdot R_{\nu}(\xi) \cdot 2w$$

- **FAR=1/1000 years and at least 2 neutrinos in coincidence with a gravitational wave trigger.**
- w=10 sec to accomodate most emission models

Background-Signal separation

Casentini, Pagliaroli, Vigorito, Fafone,
JCAP 1808 (2018) n.08,010

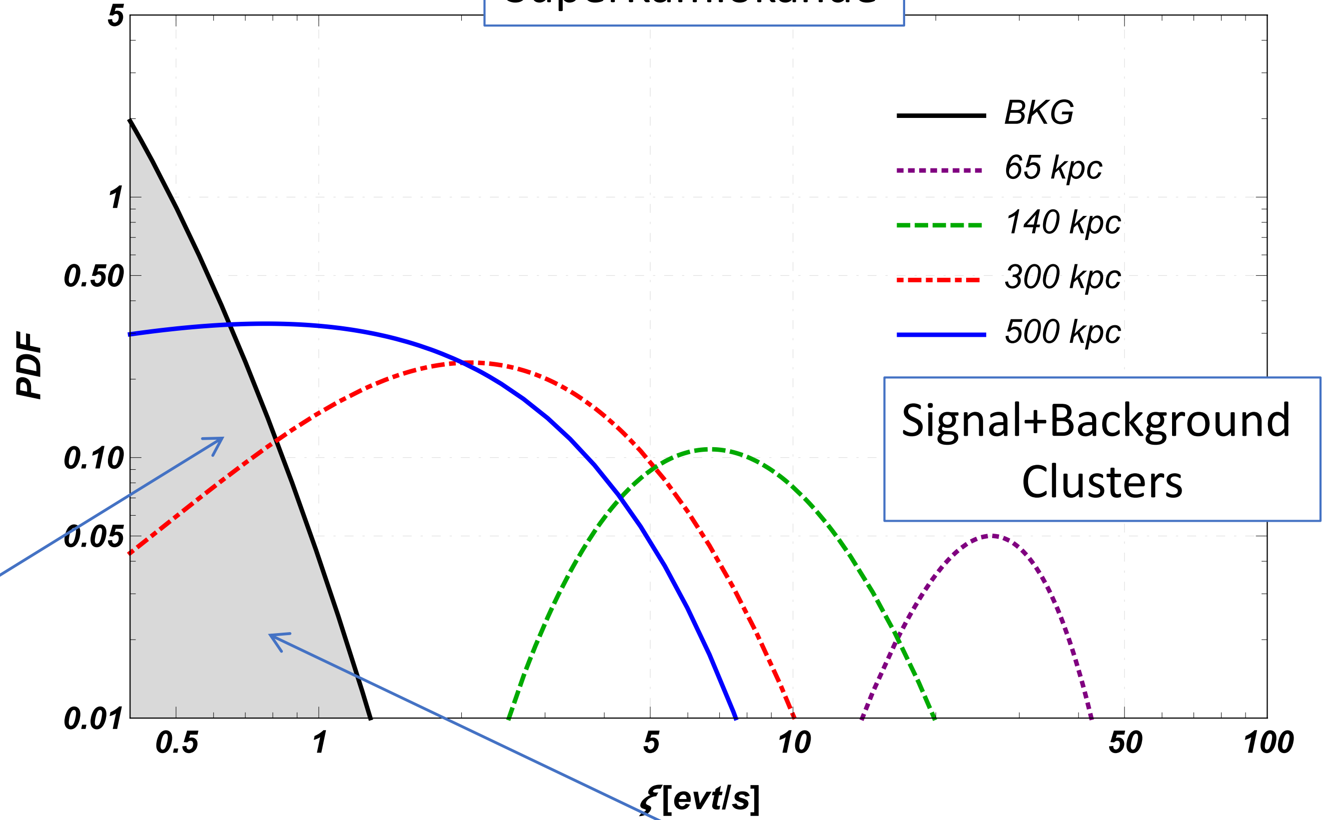
SuperKamiokande

Probability density Distributions

$$\xi_i = \frac{m_i}{\Delta t_i}$$

Pure Background Clusters

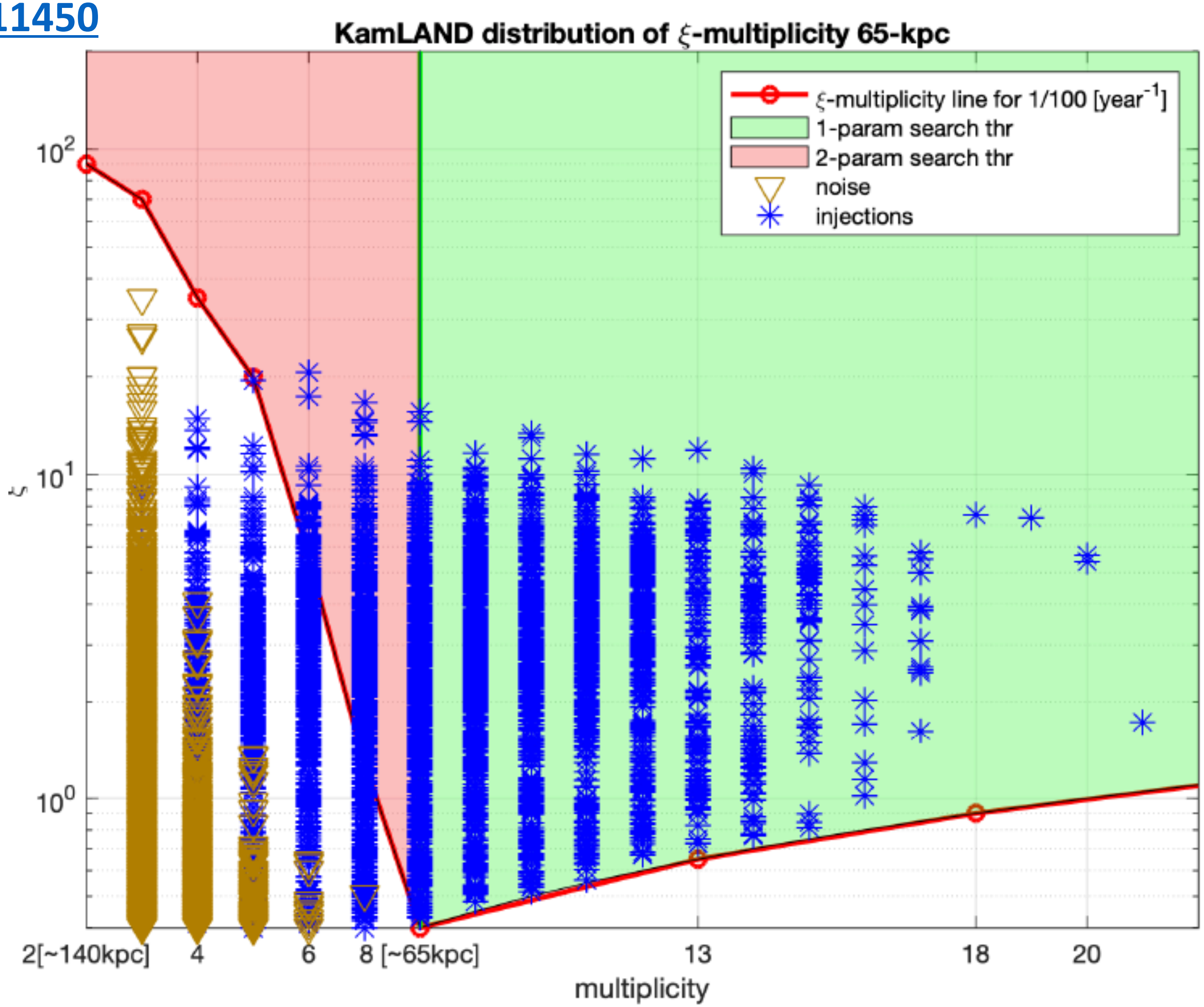
Signal+Background Clusters



$$F_i^{im} = \left[f_i^{im} - 8640 \times \sum_{k=m_i}^{m_i+n;\, n \leq (20\xi - m_i)} P(k) N_k \int_{k/20}^{\xi} f(\xi) d\xi \right] [\text{day}^{-1}].$$

Results with the new FIM

Expanding Core-Collapse Supernova Search Horizon of Neutrino Detectors
O. Halim, C. Vigorito, C. Casentini G.Pagliaroli M. Drago V. Fafone, e-Print:**arXiv:1911.11450**



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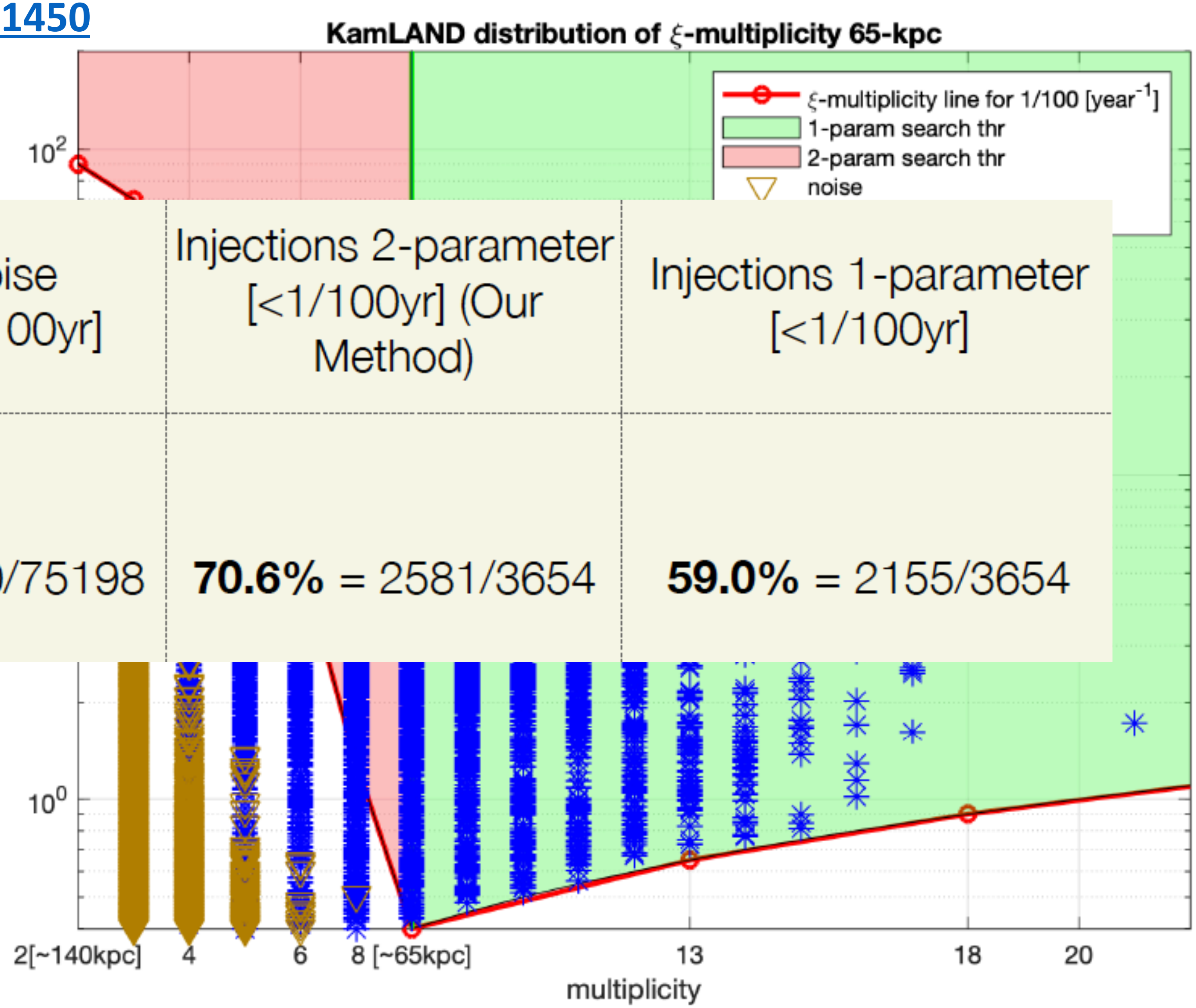


Noise	Noise [<1/100yr]	Injections 2-parameter [<1/100yr] (Our Method)	Injections 1-parameter [<1/100yr]
75198	0% = 0/75198	**70.6%** = 2581/3654	**59.0%** = 2155/3654

Solar neutrinos

"Improvements of solar neutrino models and
low-energy flux detection"

- N. Vinyoles, F. Villante, A. Serenelli, M.Maltoni, C. Pena-Garay, N.Song : A new generation of Standard Solar Models, inference of solar properties from solar neutrinos and helioseismology, CNO measurements
- C. Mascaretti, F. Vissani, Piersanti: Luminosity constrain update, revised Be-e capture
- A. Palazzo: revised cross section ν-Gallium

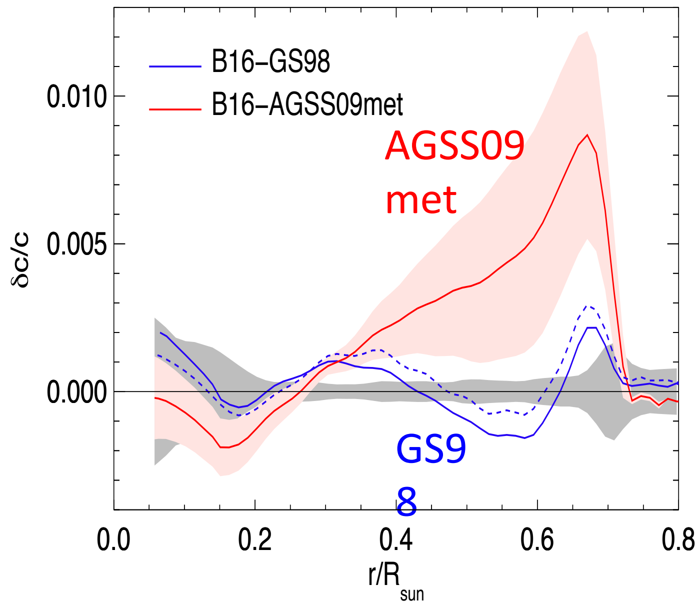
The solar composition problem

The **downward revision** of heavy elements photospheric abundances …

Element	GS98	AGSS09met	δz_i
C	8.52 ± 0.06	8.43 ± 0.05	0.23
N	7.92 ± 0.06	7.83 ± 0.05	0.23
O	8.83 ± 0.06	8.69 ± 0.05	0.38
Ne	8.08 ± 0.06	7.93 ± 0.10	0.41
Mg	7.58 ± 0.01	7.53 ± 0.01	0.12
Si	7.56 ± 0.01	7.51 ± 0.01	0.12
S	7.20 ± 0.06	7.15 ± 0.02	0.12
Fe	7.50 ± 0.01	7.45 ± 0.01	0.12
$(Z/X)_\odot$	0.02292	0.01780	0.29

$$[I/H] \equiv \log(N_I/N_H) + 12$$

Vinyoles et al, ApJ 835 (2017) no.2, 202



… leads to SSMs which **do not correctly reproduce helioseismic observables**

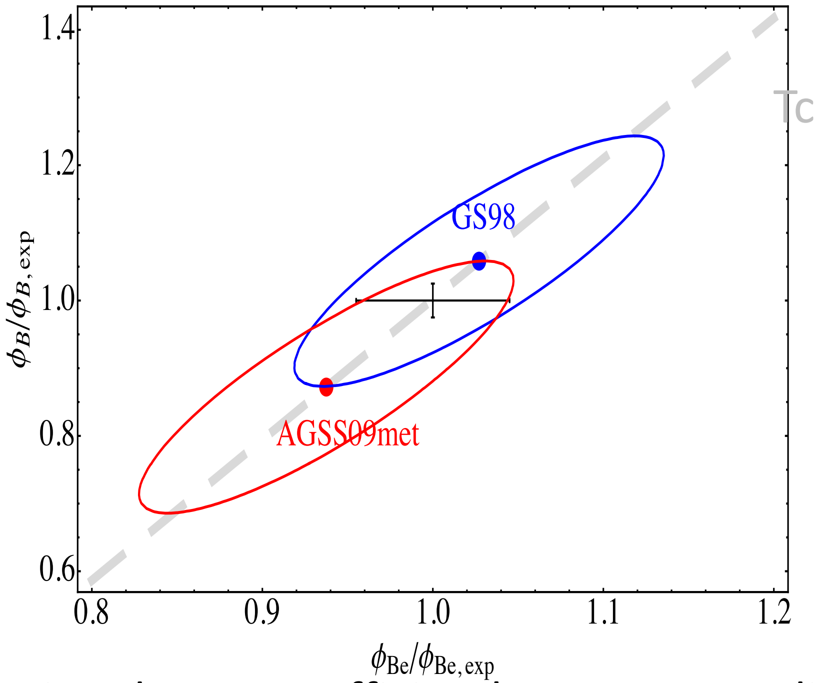
Flux	B16-GS98	B16-AGSS09met	Solar
Y_S	0.2426 ± 0.0059	0.2317 ± 0.0059	0.2485 ± 0.0035
$R_{cz}/R_\odot$	0.7116 ± 0.0048	0.7223 ± 0.0053	0.713 ± 0.001
Φ_{pp}	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.005)$	$5.97^{(1+0.006)}_{(1-0.005)}$
Φ_{Be}	$4.93(1 \pm 0.06)$	$4.50(1 \pm 0.06)$	$4.80^{(1+0.050)}_{(1-0.046)}$
Φ_B	$5.46(1 \pm 0.12)$	$4.50(1 \pm 0.12)$	$5.16^{(1+0.025)}_{(1-0.017)}$
Φ_N	$2.78(1 \pm 0.15)$	$2.04(1 \pm 0.14)$	≤ 13.7
Φ_O	$2.05(1 \pm 0.17)$	$1.44(1 \pm 0.16)$	≤ 2.8

(≈ 2-3σ discrepancies)

Units:
pp: 10^{10} cm ^{2} s^{-1};
Be: 10^{9} cm ^{2} s^{-1};
pep, N, O: 10^{8} cm ^{2} s^{-1};
B, F: 10^{6} cm ^{2} s^{-1};
hep: 10^{3} cm ^{2} s^{-1}

The ^{7}Be and ^{8}B neutrino fluxes

N.Vinyoles et al. ApJ 2017 [arXiv:1611.09867v1]



$\phi_{\mathrm{B}} \propto T_{\mathrm{c}}^{20} \quad \rightarrow \quad (\delta T_{\mathrm{c}})^{\mathrm{GS98}}_{\mathrm{AGSS09}} \leq 1\%$

Solar neutrino data are sufficiently accurate to discriminate GS98-AGSS09met central values. Unfortunately, **theoretical uncertainties dominate the error budget**. These are due to:

- Surface composition
- Environmental parameters: opacity (few %), diffusion coeff. (15%), etc
- Nuclear cross section: S_{17}(4.7%), S_{33}(5.2%), S_{34}(5.4%) dominant error sources

At the moment, **^{7}Be and ^{8}B neutrinos do not determine composition with suff. accuracy**

The solar composition problem

The **solar composition problem** indicates that there is something **wrong** or **unaccounted** in solar models

- Are the new abundances (i.e. the atmospheric model) **wrong**?
- Are properties of the solar matter (e.g. **opacity**) correctly described?
- Is the **chemical evolution** not understood (extra mixing?) or peculiar (accretion?) with respect to other stars?

Note that:
*The Sun provide the **benchmark** for stellar evolution. If there is something wrong in solar models, then this is wrong for all the stars ...*

The interpretation is complicated by the **opacity-composition** degeneracy, i.e.:

*A change of **composition** produces the same effects on the helioseismic observables and neutrino fluxes (except CNO) of a **suitable change of the solar opacity profile $\delta\kappa(r)$***

The importance of CNO neutrinos

- Probe the dominant H-burning mechanism in massive and/or evolved stars
- Permit to break the opacity-composition degeneracy and provide a direct determination of the C+N abundance in the **solar core**:

Indeed, the (strong) dependence on solar environmental parameter (e.g. opacity) can be eliminated by using **B-neutrinos as solar thermometer**. E.g:

$$\delta\phi_{\rm O} - 0.785\,\delta\phi_{\rm B} = \delta X_{\rm CN}^{\rm core} \ \pm 0.4\%({\rm env}) \ \pm 2.6\%({\rm diff}) \ \pm 10\%({\rm nuc})$$

Serenelli et al., PRD 2013

<u>High-Z .vs. Low-Z</u>

$$\delta\phi_{\rm O} = \frac{\phi_{\rm O}^{\rm HZ} - \phi_{\rm O}^{\rm LZ}}{\phi_{\rm O}^{\rm LZ}} \simeq 40\%$$

Beyond solar composition problem (10%):

Using CNO neutrinos to probe for mixing processes in the Sun (and other stars)

$$\delta X_{\rm CN} = \frac{X_{\rm CN}^{\rm core} - X_{\rm CN}^{\rm surf}}{X_{\rm CN,ini}} \simeq 15\%$$

F.Villante

1) Calcolo (e progressivo update) di SSMs (in collaborazione con A. Serenelli):

- http://inspirehep.net/record/1500944, "A new Generation of Standard Solar Models", Vinyoles et al, 2017
- http://inspirehep.net/record/841093, "Linear solar models", Villante 2010

2) Inferenza delle proprieta' del Sole dalle misure di neutrini solari e dalla eliosismologia ed analisi del problema della composizione solare (in collaborazione con A. Serenelli):

- http://inspirehep.net/record/1628937: "Helioseismic and Neutrino Data Driven Reconstruction of Solar Properties", Song et al, 2017
- http://inspirehep.net/record/1449044: "Implications of solar wind measurements for solar models and composition", Serenelli et al., 2016
- http://inspirehep.net/record/1269566: "The chemical composition of the Sun from helioseismic and solar neutrino data", Villante et al., 2014
- http://inspirehep.net/record/859023: "Constraints on the opacity profile of the sun from helioseismic observables and solar neutrino flux measurements", Villante 2010

3) Misure dei flussi di neutrini solari e prospettive di rivelazione dei neutini CNO (ed ecCNO)

- http://inspirehep.net/record/895198: "Comprehensive measurement of CNO;-chain solar neutrinos:", BOREXINO Collaboration, 2018
- http://inspirehep.net/record/1321521: "ecCNO Solar Neutrinos: A Challenge for Gigantic Ultra-Pure Liquid Scintillator Detectors, Villante 2015
- http://inspirehep.net/record/895198: "A Step toward CNO solar neutrinos detection in liquid scintillators", Villante et al, 2011i

c’e’ vita dopo le oscillazioni, e.g. F. Vissani

completare l’esplorazione dei neutrini solari

(Mascaretti, Piersanti, FV)

Luminosity constraint and entangled solar neutrino signals

F. Vissani arXiv:1808.01495

$$\Phi_{\rm pp} + 0.93 \times \Phi_{\rm CNO} = 6.02 \times 10^{10} ({\rm cm}^2\ {\rm s}) \times (1 \pm 0.5\%)$$

F. Vissani Nucl.Phys.Atom.Energy 18 (2017) no.1, 5-12

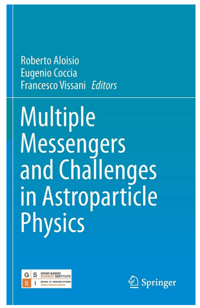
Revised Be+e− rate that increases the B flux up to a maximum of 2.7%

Neutrino Astronomy

una nuova scienza

Antonio Capone, Paolo Lipari and Francesco Vissani

Abstract Neutrino astronomy is a lively discipline that has born at the cross road of particle physics, nuclear physics, and astrophysics. Many low-energy neutrino observatories have demonstrated the possibility of investigating the functioning of the Sun, the terrestrial radiactivity and crucial astrophysical phenomena as the gravitational collapse. There are mounting evidences that extraterrestrial high-energy neutrinos



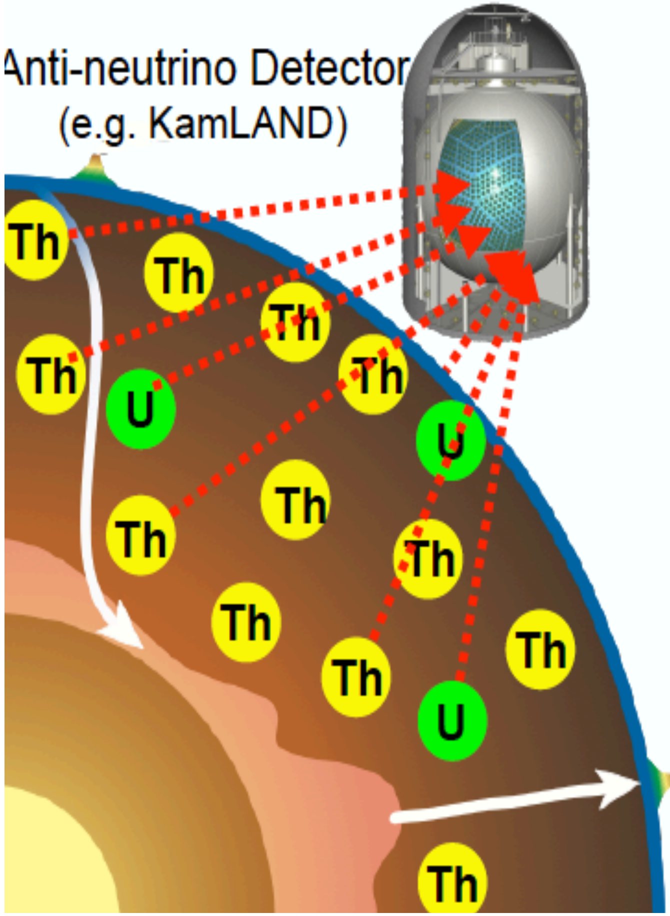
Geo-neutrinos

E. Lisi, M. Baldoncini, F. Mantovani, B. McDonough, V. Strati: Variances and covariances of geo-neutrino signals

Geo-neutrinos

Electron-antineutrinos from natural radioactive decays

$\bar{\nu}_e \ 4.1 \times 10^6/\mathrm{cm}^2/\mathrm{sec}$



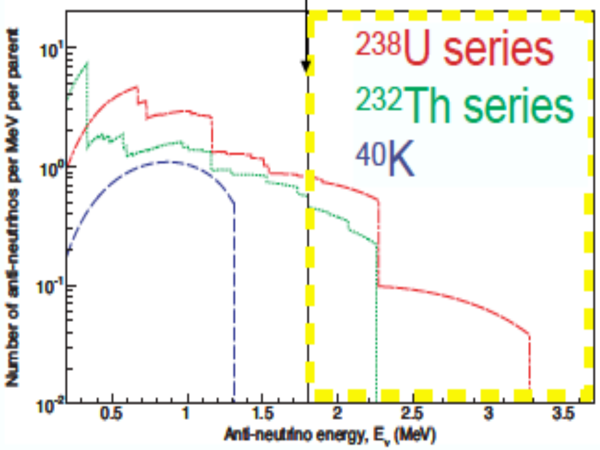
β-decay — geo-neutrinos

$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\alpha + 6\mathrm{e}^- + 6\bar{\nu}_\mathrm{e} + 51.7\,\mathrm{MeV}$$

$$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\alpha + 4\mathrm{e}^- + 4\bar{\nu}_\mathrm{e} + 42.7\,\mathrm{MeV}$$

$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + \mathrm{e}^- + \bar{\nu}_\mathrm{e} + 1.311\,\mathrm{MeV}\ (89.28\%)$$

Energy threshold, 1.8 MeV



inverse β-decay

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- Only geo-neutrinos from U and Th are detectable right now
- ^{40}K geo-neutrinos new detection technology

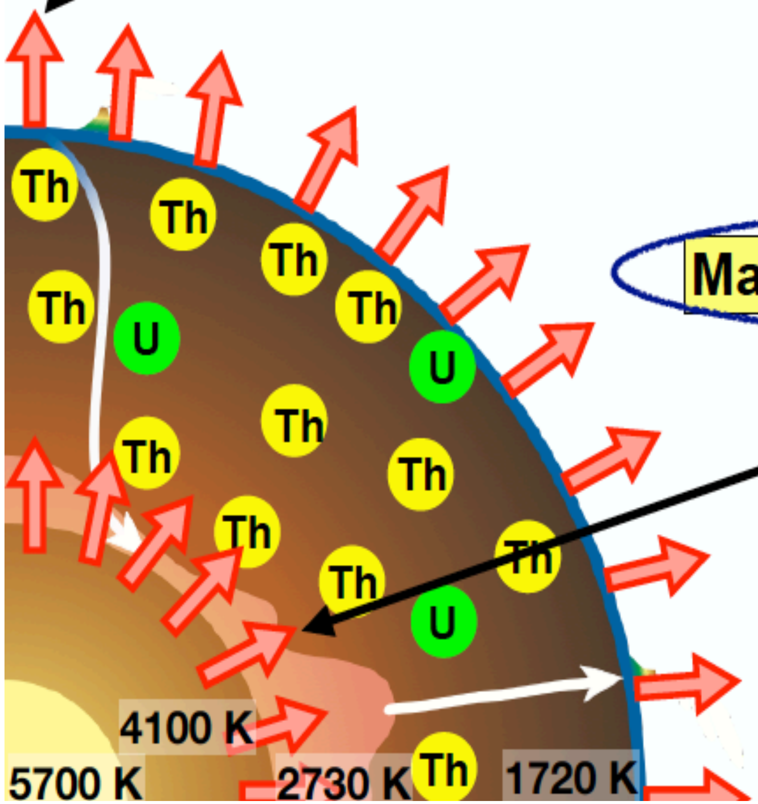
Number of geo $\bar{\nu}_e$ ∝ Amount of U Th, Radiogenic heat

Earth's Heat Budget

Surface heat flow *Measured* =

	Contributions	Source
Crust heat production	*Model*	**Radiogenic**
+ **Mantle cooling**	*??*	Primordial
+ **Mantle heat production**	*??*	**Radiogenic**
+ **CMB※ heat flow**	*??*	Primordial

CMB heat flow = **Core cooling** + **Inner core growth**



Geoneutrinos can define the amount of radiogenic heat

※Core Mantle Boundary

Mantle Contribution

1. Observation - <u>Crust (estimated by model)</u> = Mantle

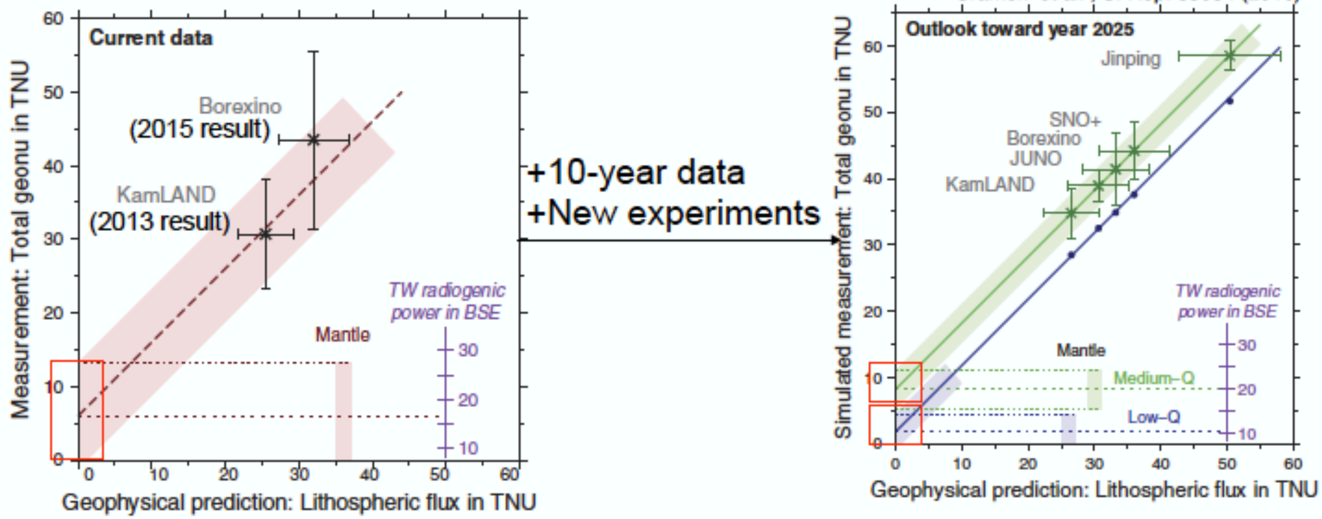
Can not avoid model dependence of crustal signal

2. Multi site measurements

Observation = Crust + Mantle
(y = x + b)

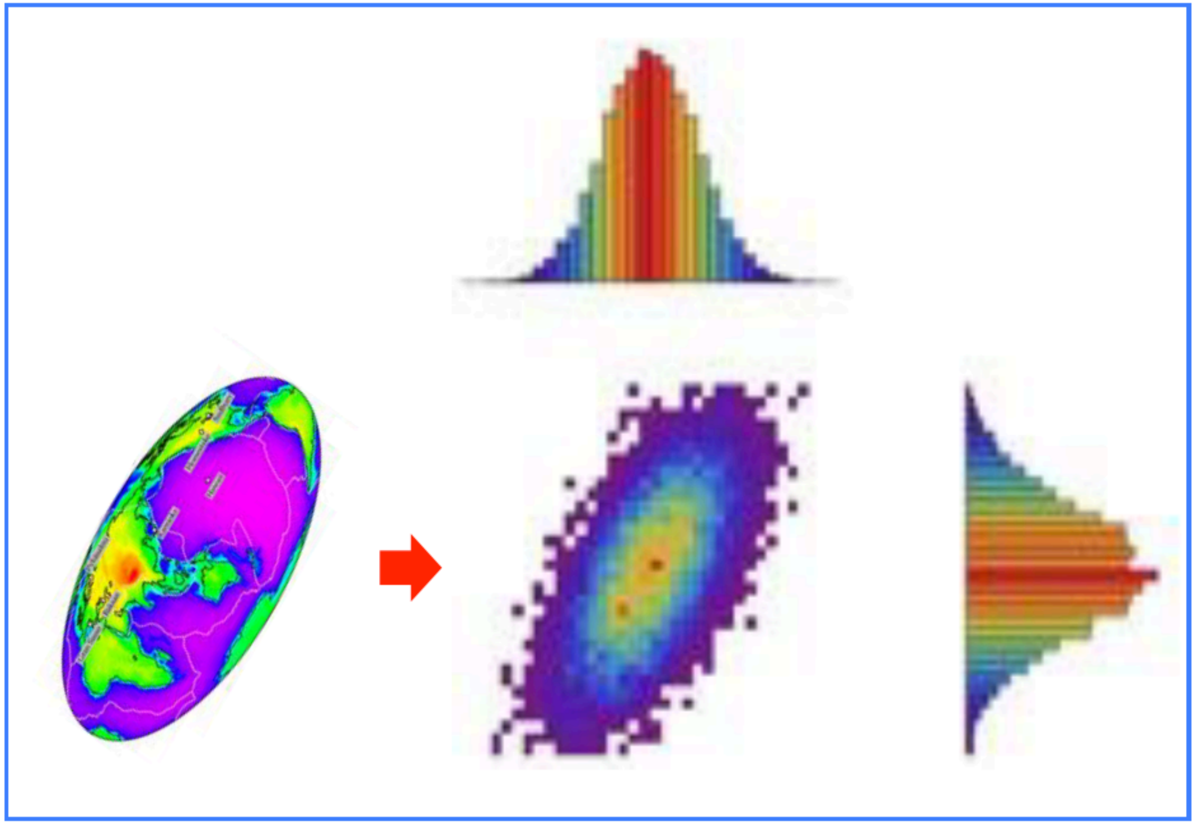
Note : Assuming homogeneous mantle

Šrámek et al. , S. Rep. 33034 (2016)



These are NOT direct measurement of mantle contribution.

Variances and covariances of geoneutrino signals



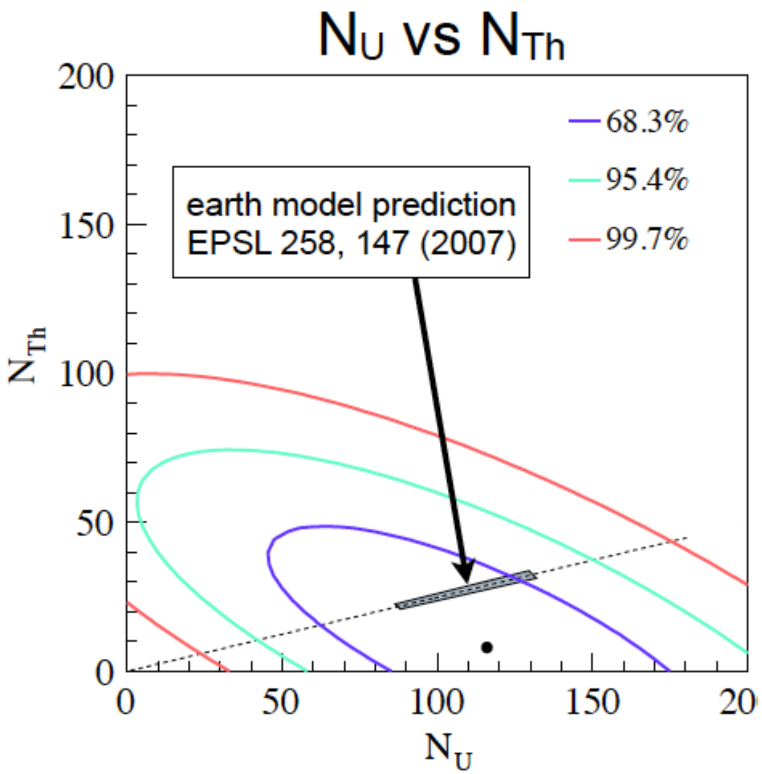
Eligio Lisi, INFN, Bari, Italy

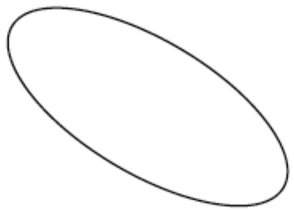
Neutrino Geoscience, Paris, 2015

Ways to improve statistics & modeling (I)

Always deal with (Th, U) signals, not summed Th+U
[There is more info in the joint (Th,U) distributions]

Must take into account (Th,U) covariances. E.g., KamLAND:





(Th,U) data errors:
negative correlation.
If one ↑, the other ↓

(Th,U) model errors:
positive correlation.
Both ↑↑ or ↓↓

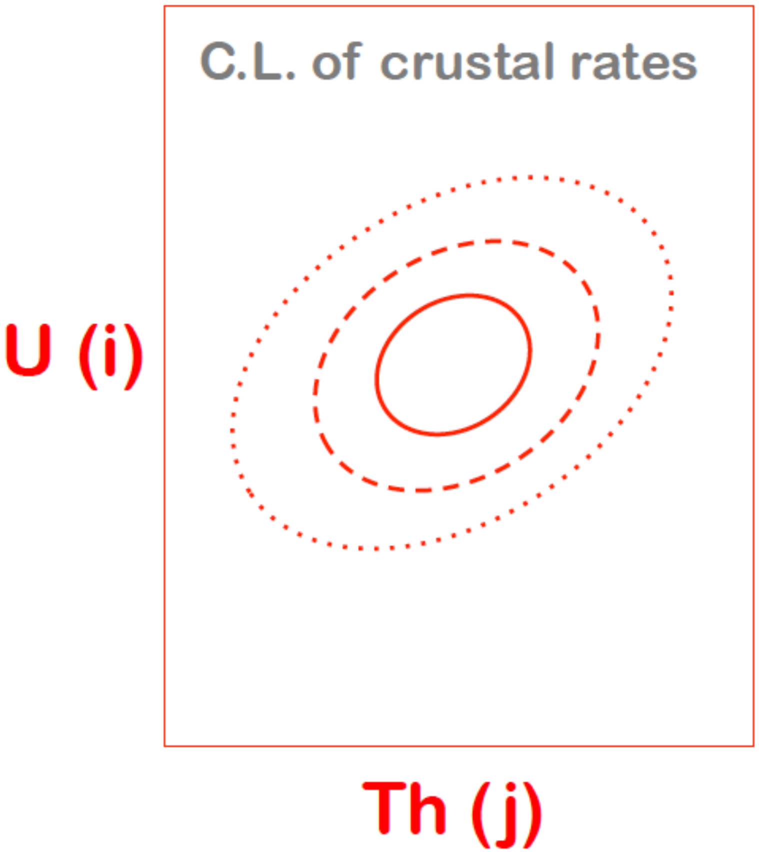
Combine information from more experiments:

$D_1 - C_1 = M_1$
$D_2 - C_2 = M_2$
$D_3 - C_3 = M_3$
...

For isotropic mantle ($M = M_1 = M_2 = M_3 = \ldots$), the M error is then smaller than individual M_i errors

But: combined subtraction is tricky, since the C_i errors are correlated via common crust →

Methodology (no numbers yet – work in progress)



For both i=j (same site) and i≠j (different sites)

Take the best current model for the global crust geometry (vertical and horiz.)

Identify local reservoirs around expt. sites (currently: Gran Sasso, Kamioka, Sudbury)

Identify large sub-reservoirs in the "rest of the crust"

In each of the above reservoirs, assign central values, errors and correlat. to log(Th) and log(U) abundances

[If needed, add volumetric uncertainties]

Declare all the assumptions underlying the above choices, for book-keeping and for future improvements

Based on this model, calculate the Th and U oscillated crust rates and errors at each site.
Provide full, joint distributions of their errors

tentativi Bayesiani di stimare queste covarianze, come in arXiv:1901.01358, non ci convincono. Lo scopo e' quello di fare la migliore inferenza possibile del flusso del mantello per sottrazione (Mantle=Total-Crust) usando dati BX+KL 2019 e state-of-the-art estimates of covariances.