TAsP: Theoretical Astroparticle Physics

Responsabile Nazionale: Fiorenza Donato (Torino) - Responsabile Locale TO: Carlo Giunti

12 nodi: BA, FE, LE, LNF, LNGS, NA, PD, PV, PI, RM1, TO, TS (~ 100 members)

6 Staff members:

- Alessandro Cuoco
- Fiorenza Donato
- Nicolao Fornengo
- Carlo Giunti
- Marco Regis
- Marco Taoso

2 Fellini Postdocs:

- Mattia Di Mauro
- Stefano Gariazzo

6 Postdocs:

- Sarah Recchia
- Javier Reynoso
- Andrè Scaffidi
- Jakub Scholtz
- Christoph Ternes
- Elisa Todarello

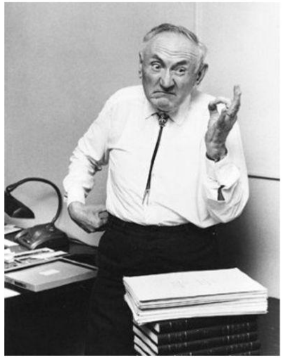
1 PhD Student:

- Luca Orusa

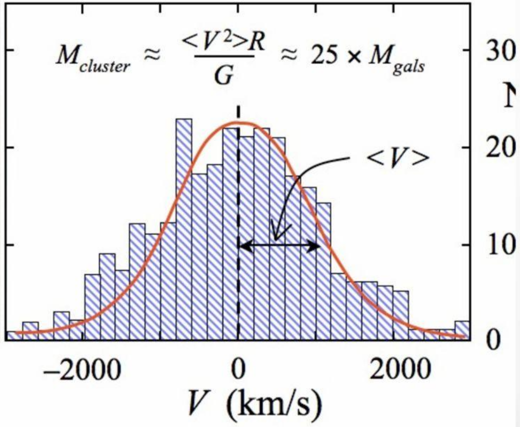
- **Dark Matter & Cosmic radiation:**
  - Anti-matter and anti-leptons in the cosmic radiation
  - Multi-messenger astrophysics with compact and extended sources
  - Hadronic cross section measurements for the production of cosmic rays
  - Phenomenology of DM candidates in the context of BSM theories
  - Cosmological bounds on light particles (dark radiation and dark matter)
  - Axion-like, sterile neutrino and primordial black hole dark matter
- **Neutrinos:**
  - Global data analyses of standard (3ν) and active-sterile neutrino oscillations
  - Phenomenology of BSM neutrino models and non-standard interactions
  - Phenomenology of coherent elastic neutrino-nucleus scattering
  - Cosmological probes of neutrino properties
  - Neutrino decoupling in the early Universe

Evidence for Dark Matter

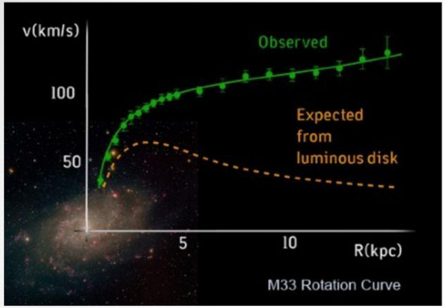
Zwicky, 1933



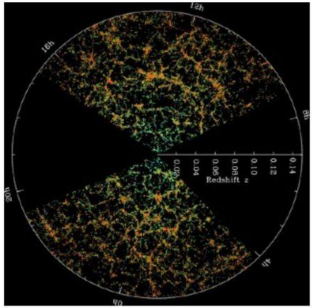
Coma cluster (central part)



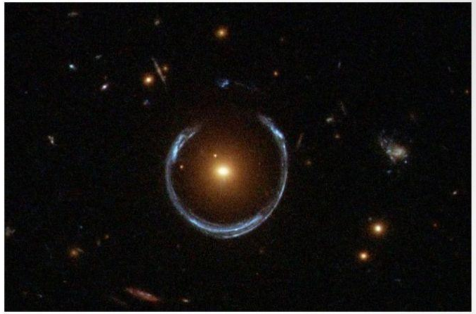
Rotation curves



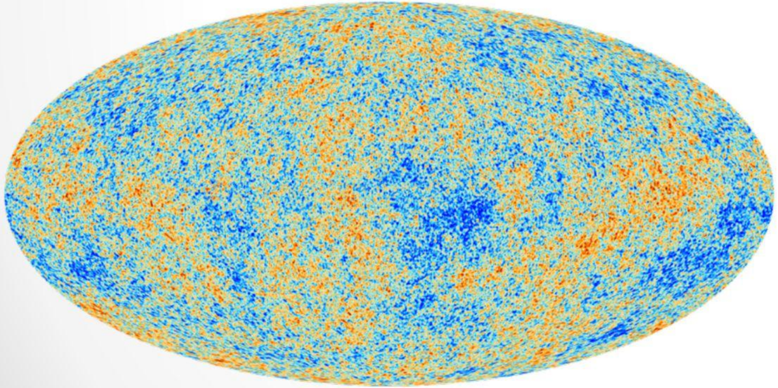
Large scale structure



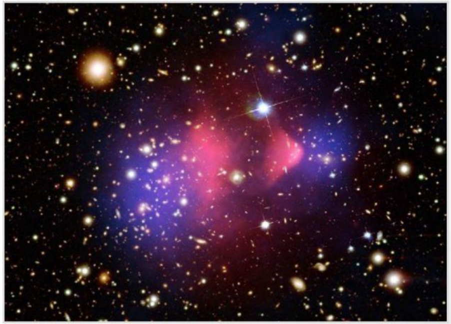
Gravitational lensing



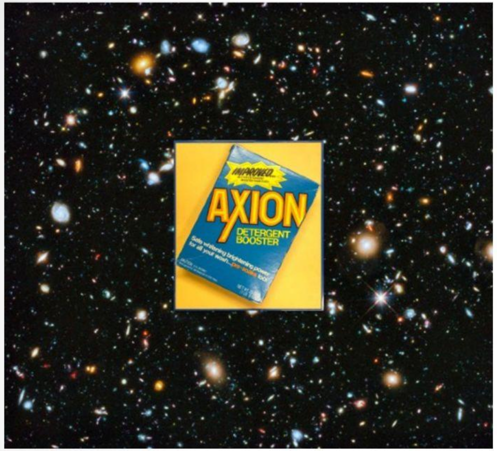
CMB



Bullet cluster

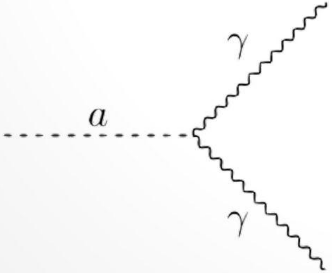


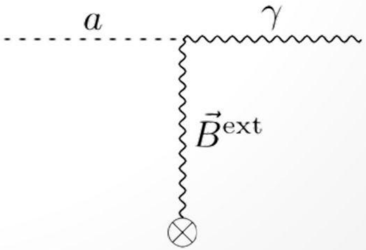
Axion Dark Matter



"A few years before, a supermarket display of brightly colored boxes of a laundry detergent named Axion had caught my eye. It occurred to me that "axion" sounded like the name of a particle and really ought to be one. So when I noticed a new particle that "cleaned up" a problem with an "axial" current, I saw my chance. (I soon learned that Steven Weinberg had also noticed this particle, independently. He had been calling it the "Higglet". He graciously, and I think wisely, agreed to abandon that name)."

Frank Wilczek

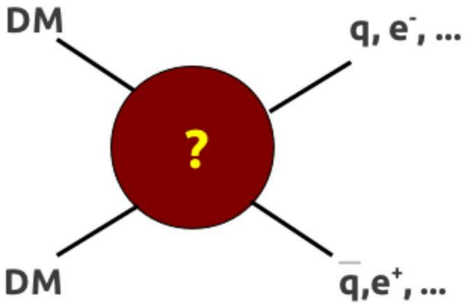


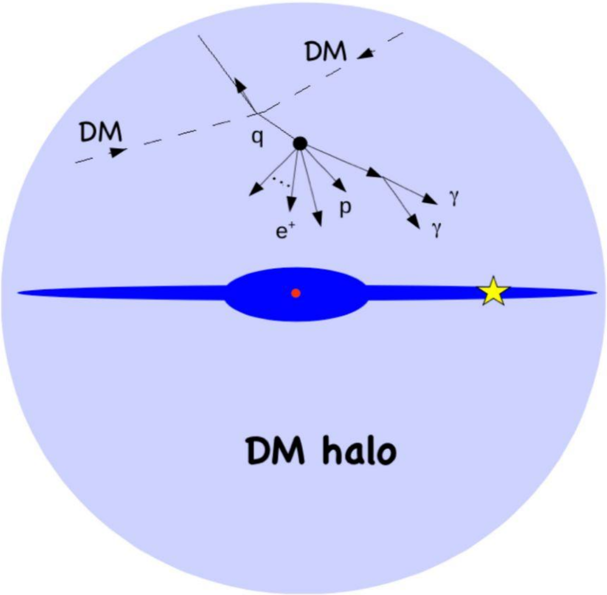


Indirect detection of dark matter

Exploit astrophysical observations to search for the products of dark matter annihilations or decays:

- **photons**
- **neutrinos**
- **anti-matter**: anti-protons, positrons, anti-nuclei

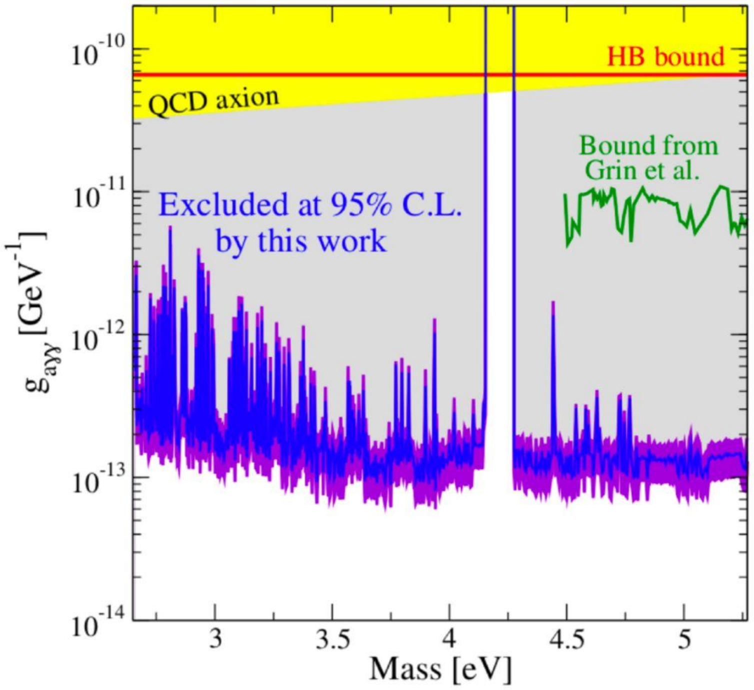


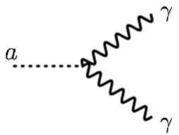


Example 1: Axion-like Particles

We consider dark matter in the form of **axion-like particles**. This dark matter candidate decays into two photons leading to monochromatic photon emissions.
We use observations of the Leo T galaxy from the MUSE instrument and derive bounds on this scenario.

M. Regis, M. Taoso et al. Phys.Lett.B 814 (2021) 136075



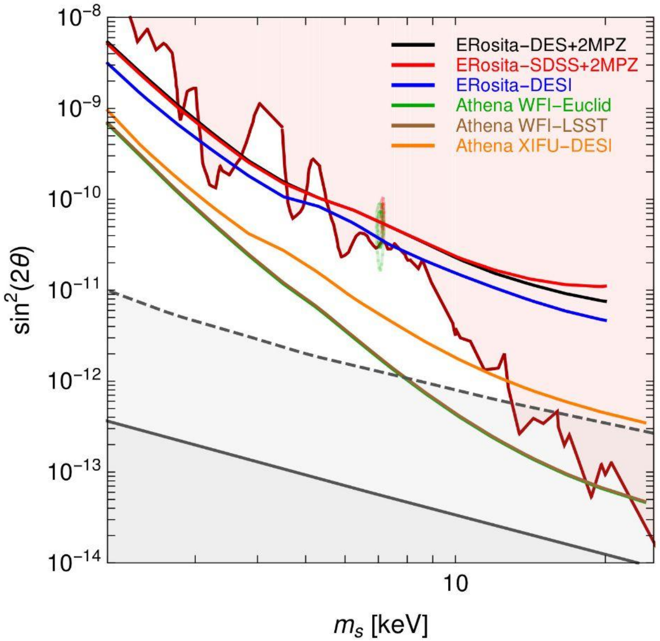


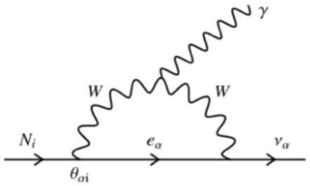
$$\mathcal{L} = \frac{1}{4} g_{a\gamma\gamma}\, a\, F_{\mu\nu} \tilde{F}_{\mu\nu}$$

Example 2: sterile neutrino dark matter

Dark matter in the form of keV scale **sterile neutrinos**. Sterile neutrino decays into an active neutrino and a photon through the mixing with the active states. Such a signal can be searched for with X-ray telescopes. We investigate the sensitivity of future X-ray experiments, exploiting the cross-correlation with catalogs of galaxies.

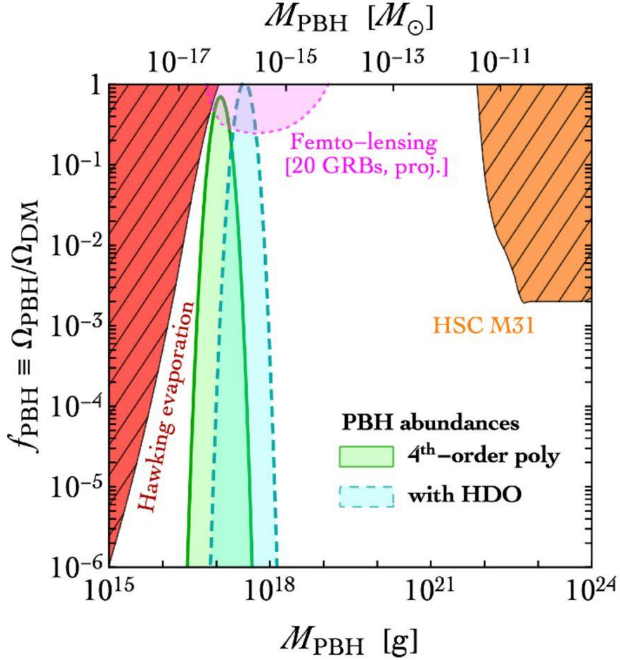
A. Caputo, M. Regis, M. Taoso JCAP 03 (2019) 027





Primordial black holes

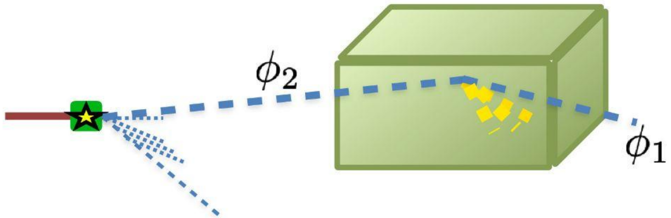
Primordial black holes could be formed from collapse of primordial inhomogeneities in the early Universe before the BBN epoch. We investigate scenarios of **inflation** leading to the formation of PBHs, and analyze the phenomenological consequences in terms of PBHs abundance and gravitational wave signals.

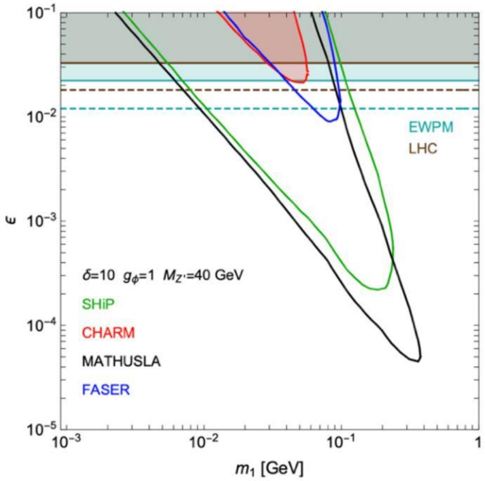


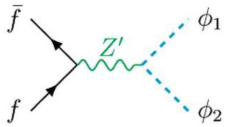
G. Ballesteros, J. Rey, M. Taoso and A. Urbano JCAP 07 (2020) 025

Probing dark sectors with laboratory experiments

Dark sectors could contain dark matter candidates and communicate with the SM via feeble interactions. These scenarios often predict **long-lived particles**, which can be searched for at LHC and with future dedicated facilities, e.g. beam-dump (SHiP) or proposed LHC detectors (FASER, MATHUSLA,…)







E. Bertuzzo, A. Scaffidi and M. Taoso in progress

E. Bertuzzo and M. Taoso JHEP 03 (2021) 272

- Characterization of the cosmic gamma-ray radiation:
    - New mechanisms for non-thermal DM production in the early Universe
      [Scholtz, Fornengo]
    - Cross-correlations with cosmic shear (DM + astro sources)
      [Fornengo, Regis, Camera - ongoing with DES Collab]
    - Cross-correlations with cosmic voids (DM + astro sources)
      [Fornengo, Pinetti, Arcari]
    - Source number counts below Fermi detection limit with machine learning techniques
      [Fornengo, Cuoco, Amerio]
    - Gamma-ray anisotropies
      [Fornengo, Regis, Pinetti, +]
    - Investigation of CTA capabilities for DM studies
      [Fornengo, Cuoco, Pinetti, +]

Jakub Scholtz // Postdoc

Kick-alignment [2012.14907] (Rodrigo Alonso + JS)

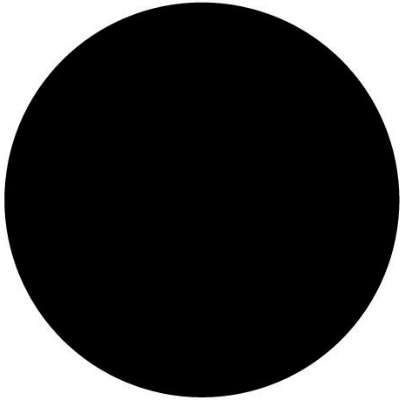
- Spontaneous Baryogenesis (1980s) is possible due to:

$$\mathcal{O} = \frac{\partial_\mu \phi}{f} \bar{\psi} \gamma_\mu \psi = \frac{\partial_\mu \phi}{f} J^\mu_{B,L}$$

- We can flip it (and reverse it) and use the potential generated by the non-zero baryon number to generate non-zero $\partial_0 \phi$ – i.e. we give the ϕ a kick.
- This kick means we pushed energy into the ϕ field – we have generated something and if the ϕ is the DM particle – voilà.
- The truth is far more complicated and you need to do a bit more model building. But the nice thing is that it tells you: with a small baryon asymmetry, small dark matter abundance is natural (which is what we observe).

Generalities

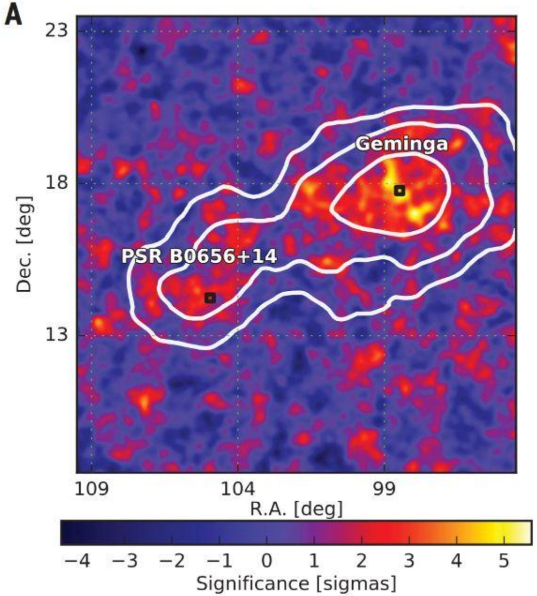
- Recent work:
  - Resurrecting the Fraternal Twin WIMP Miracle
  - What if Planet 9 is a Primordial Black Hole?
  - Out-of-the-box Baryogenesis During Relaxation
- Current Projects:
  - Generating Dark Matter through interactions between oscillations and Decoherence
  - Using computers to detect Cosmic Rays and Nefarious activities
- Summary: I like coming up with new mechanisms and looking for unused datasets



Cosmic-ray Physics: a multi messenger approach

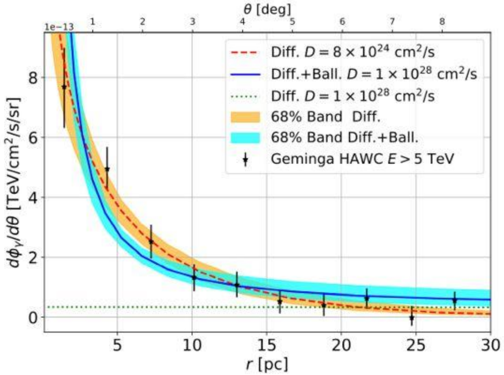
Does the Geminga, Monogem and PSR J0622+3749 γ-ray halos imply slow diffusion around pulsars?

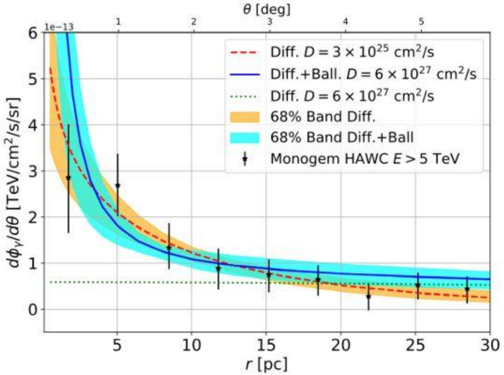
S. Recchia,[1,2] M. Di Mauro,[2] F. A. Aharonian,[3,4] L. Orusa,[1,2] F. Donato,[1,2] S. Gabici,[5] and S. Manconi[6]



Science 358 (2017) no.6365, 911-914

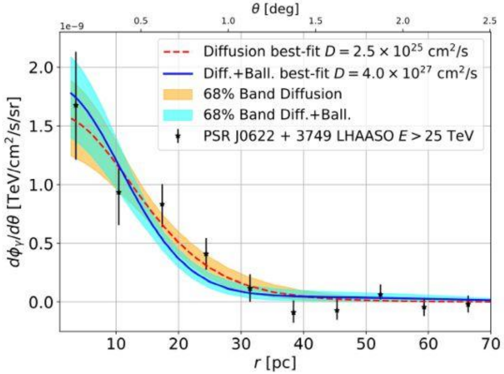
Map of the significance for the detection of Geminga and Monogem by HAWC.





Fit to the surface brightness (flux as a function of angle) for three sources (see labels). Data are from HAWC and LHAASO.

Conclusions:
It is possible to fit well the angular distribution of photons with a scenario with a small diffusion but also with the average Galactic strength assuming ballistic propagation.



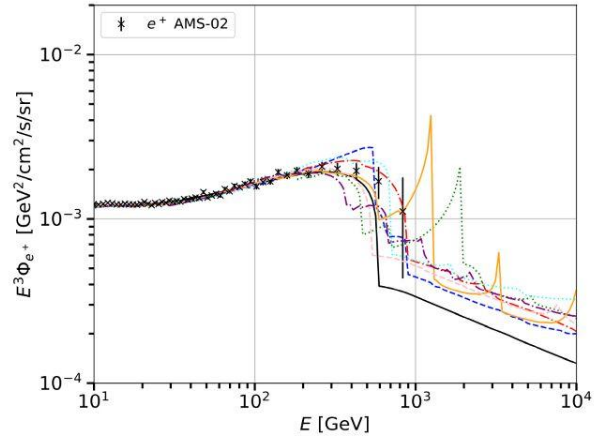
Cosmic-ray Physics: using astrophysics and particle physics

Constraining positron emission from pulsar populations with AMS-02 data

Luca Orusa,[a,b] Silvia Manconi,[c] Fiorenza Donato[a,b] and Mattia Di Mauro[b]

Conclusions:
By assuming a realistic population of Galactic pulsars and propagation parameters compatible with B/C ratio, we have found good fits to the AMS-02 data. The total contribution of positrons is dominated by a few pulsars which are relatively close and powerful.

Fit to the AMS-02 data for positrons with simulated populations of pulsars in the Milky Way. Here we show the simulations that best fit the data.

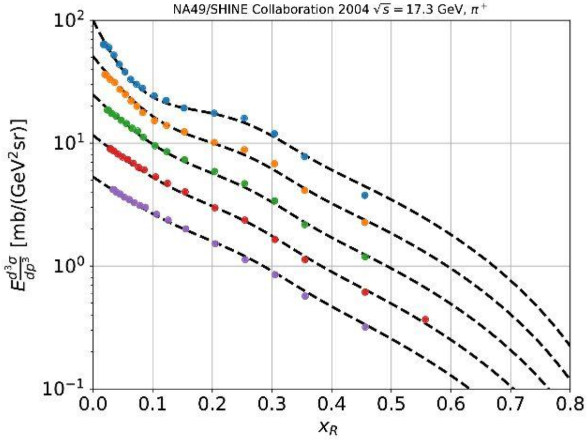


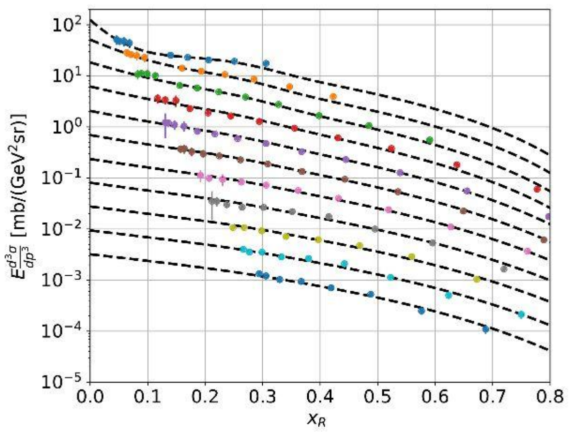
Production cross section of electrons and positrons

Orusa, Di Mauro, Donato, Korsemeir.

Analysis ongoing…..

Best fit to the NA49 and NA61 data for the pion plus production from proton proton collisions. They are reported as function of XR and for different pt values.
We find good fits to the data by adding contribution not precisely account for before such as resonances and hyperons.





Indirect detection of dark matter

Multimessenger constraints on the dark matter interpretation of the *Fermi*-LAT Galactic center excess

PRD 103, 123005 (2021)

Mattia Di Mauro
Istituto Nazionale di Fisica Nucleare, via P. Giuria, 1, 10125 Torino, Italy

Martin Wolfgang Winkler
Stockholm University and The Oskar Klein Centre for Cosmoparticle Physics, Alba Nova, 10691 Stockholm, Sweden

Dissecting the Inner Galaxy with γ-Ray Pixel Count Statistics

F. Calore,[1,*] F. Donato,[2,3,†] and S. Manconi[4,‡]

Phys.Rev.Lett. 127 (2021) 16, 161102

- A dark matter contribution to the positron, antiproton, gamma ray emission from the Milky Way is tightly constrained. Few models are consistent with current data.
- A bulge population of pulsars is a possible interpretation of the Fermi-LAT Galactic center excess.

Future projects

- **Cosmic-ray positrons:**
  - Analyse future TeV gamma-ray data from HAWC and LHAASO to derive the strength of the diffusion around Galactic sources.
    - Is it inhibited (much smaller than the average of the Galaxy)?
    - Is it compatible with the Galactic average (the ballistic propagation should be taken into account)?
  - Fit the positron data with a refined prediction for the secondary production (due to the collision of cosmic rays with interstellar medium atoms).
    - Are the new cross sections we derive compatible with the low-energy data?
    - How much can we constrain dark matter channel annihilating or decaying into leptons?
- **Cosmic Antideuteron and antihelium.**
  - GAPS with soon make the first flights.
  - Improve the coalescence models and implement refined model for the solar modulations.
- **Beyond Standard model theories for dark matter.**
  - Perform combined indirect dark matter search in cosmic particle data using physically motivated particle physics models (dark matter simplified models or beyond the standard model theories.)

Decoupling of relic neutrinos in the early universe

Towards a precision calculation of the effective number of neutrinos N_{eff} in the Standard Model. Part II. Neutrino decoupling in the presence of flavour oscillations and finite-temperature QED

arXiv:2012.02726

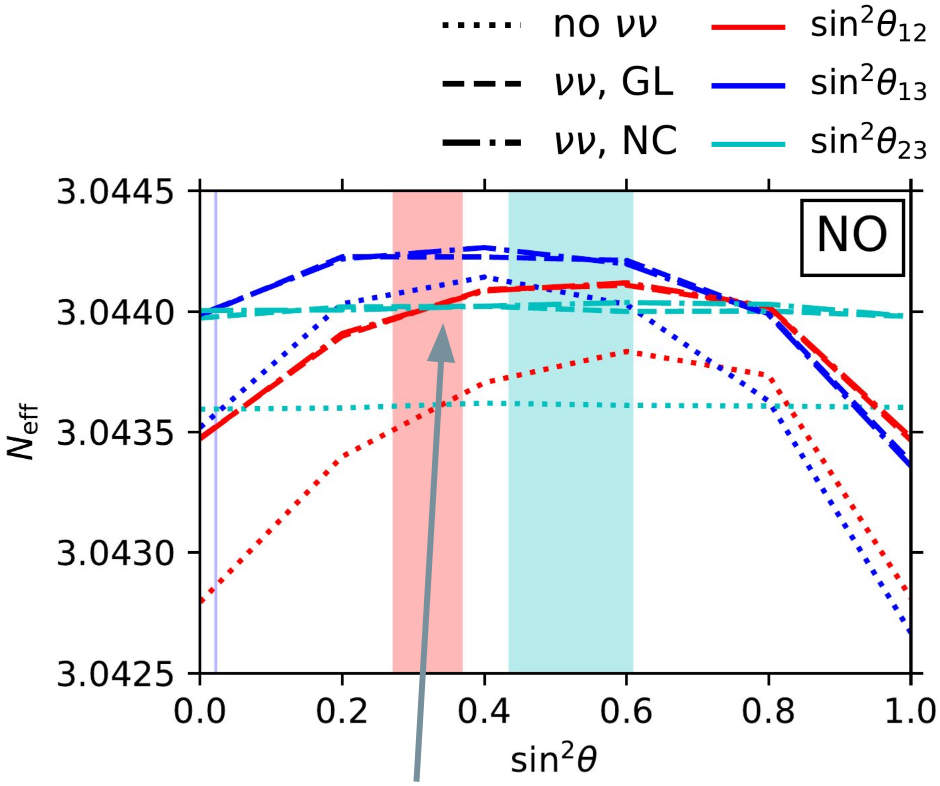
JCAP04(2021)

Jack J. Bennett,[a] Gilles Buldgen,[b] Pablo F. de Salas,[c] Marco Drewes,[b] Stefano Gariazzo,[d,e] Sergio Pastor[e] and Yvonne Y.Y. Wong[a]

New recommended value: **Neff=3.044**

numerical + theoretical error at the level of 0.0001

Public code:
https://bitbucket.org/ahep_cosmo/fortepiano_public



Effect of neutrino oscillations below 0.0001

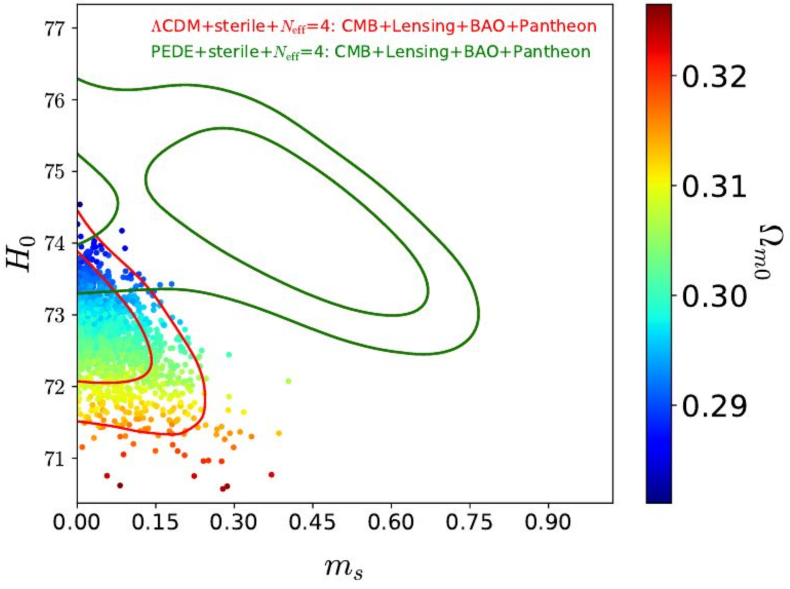
More studies ongoing (effects of non-standard physics, …)

Constraining sterile neutrino properties from cosmology

Minimal dark energy: key to sterile neutrino and Hubble constant tensions?

Eleonora Di Valentino,[1,*] Stefano Gariazzo,[2,†] Carlo Giunti,[2,‡]
Olga Mena,[3,§] Supriya Pan,[4,¶] and Weiqiang Yang[5,**]

arXiv:2110.03990v1

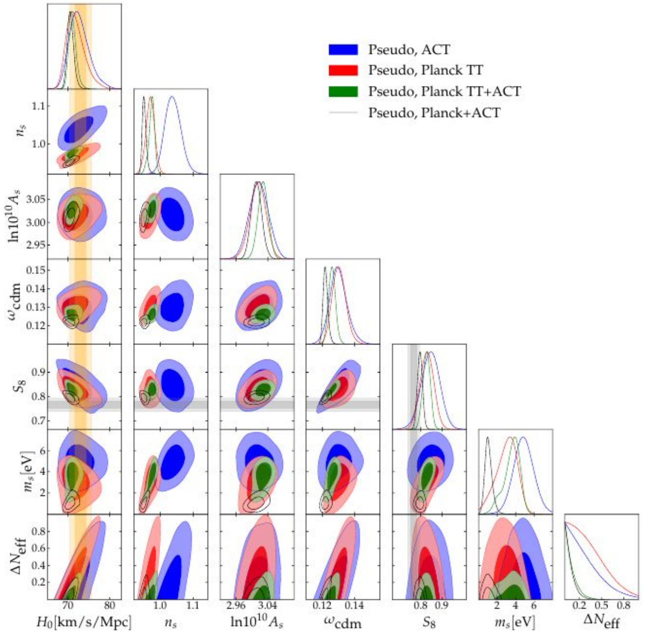


can non-standard dark energy reconcile Hubble tension and sterile neutrino properties?

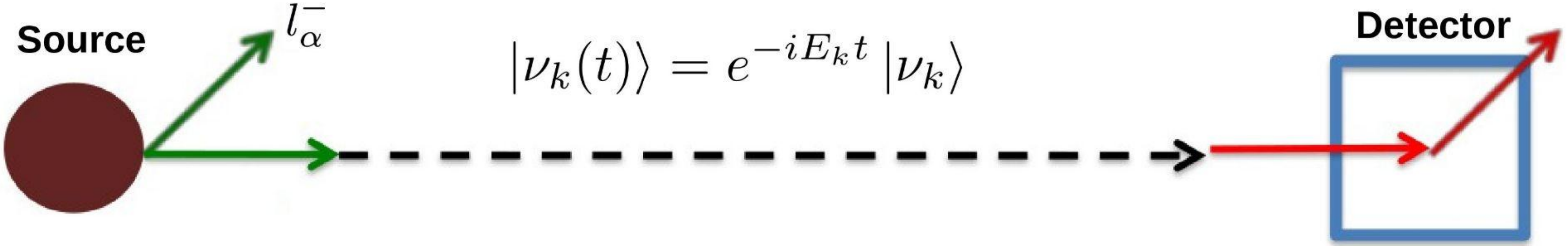
Pseudoscalar sterile neutrino self-interactions in light of Planck, SPT and ACT data

Mattia Atzori Corona,[a,b] Riccardo Murgia,[c] Matteo Cadeddu,[b] Maria Archidiacono,[d,e] Stefano Gariazzo,[f] Carlo Giunti,[f] Steen Hannestad,[g] Thomas Tram[g]

in preparation!



Neutrino oscillations



$$|\nu_k(t)\rangle = e^{-iE_k t}\,|\nu_k\rangle$$

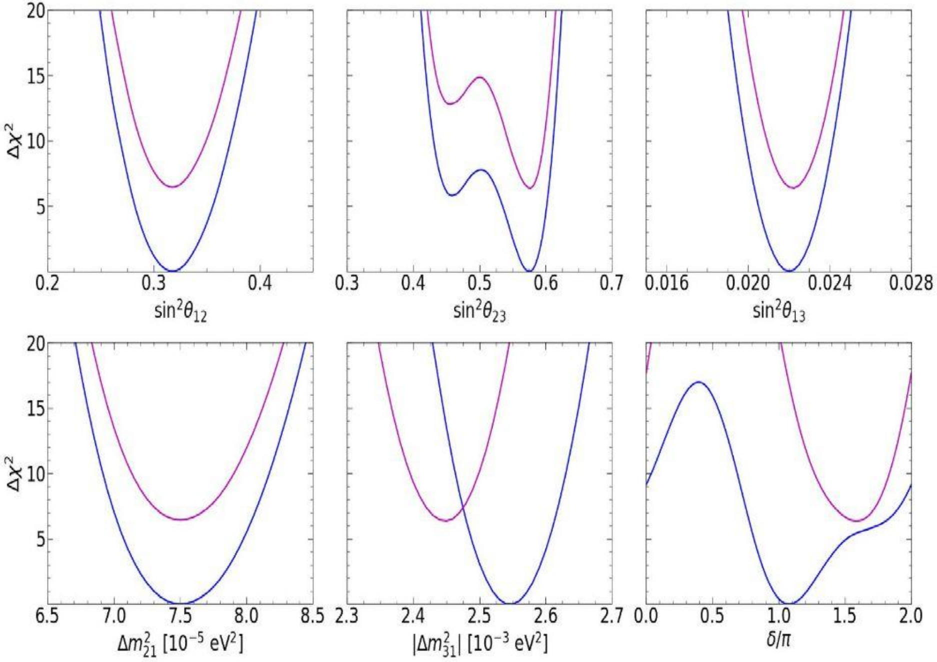
$$|\nu_\alpha\rangle = \sum_k U_{\alpha k}^* \,|\nu_k\rangle$$

$$A_{\nu_\alpha \to \nu_\beta}(t) \equiv \langle \nu_\beta | \nu_\alpha(t)\rangle = \sum_k U_{\alpha k}^*\, U_{\beta k}\, e^{-iE_k t}$$

$$P_{\nu_\alpha \to \nu_\beta}(t) = \left| A_{\nu_\alpha \to \nu_\beta}(t) \right|^2 = \sum_{k,j} U_{\alpha k}^*\, U_{\beta k}\, U_{\alpha j}\, U_{\beta j}^*\, e^{-i(E_k - E_j)t}$$

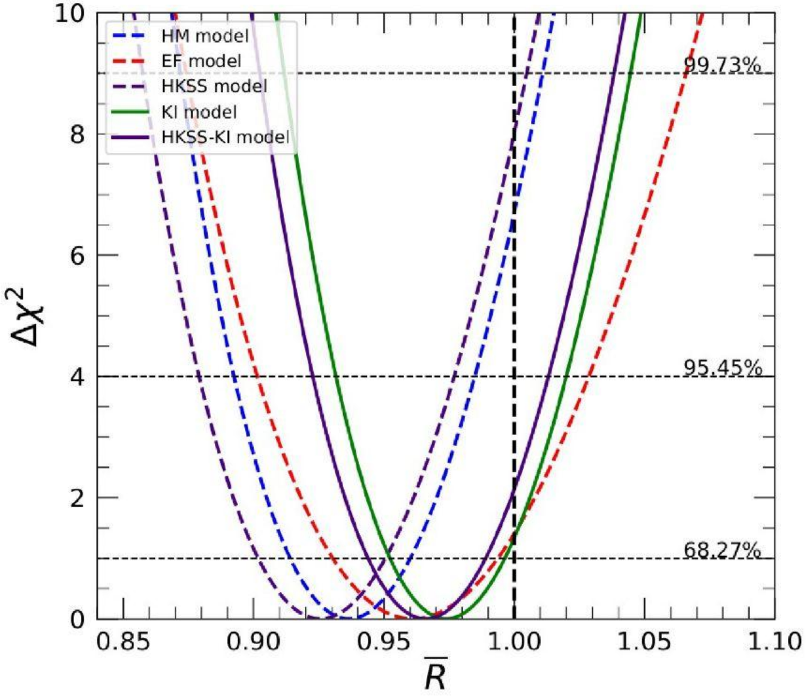
Global Fit

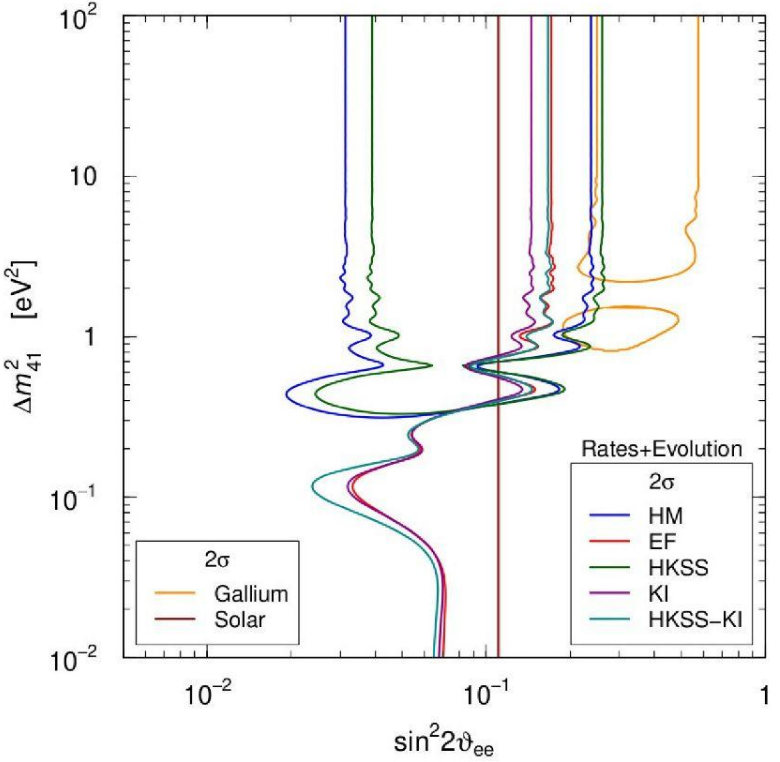
Ternes, Gariazzo, et al, 2006.11237, JHEP 2021



parameter	best fit $\pm 1\sigma$	2σ range	3σ range
$\Delta m^2_{21}[10^{-5}\mathrm{eV}^2]$	$7.50^{+0.22}_{-0.20}$	7.12–7.93	6.94–8.14
$\lvert\Delta m^2_{31}\rvert[10^{-3}\mathrm{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.49–2.60	2.47–2.63
$\lvert\Delta m^2_{31}\rvert[10^{-3}\mathrm{eV}^2]$ (IO)	$2.45^{+0.02}_{-0.03}$	2.39–2.50	2.37–2.53
$\sin^2\theta_{12}/10^{-1}$	3.18 ± 0.16	2.86–3.52	2.71–3.69
$\sin^2\theta_{23}/10^{-1}$ (NO)	5.74 ± 0.14	5.41–5.99	4.34–6.10
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.78^{+0.10}_{-0.17}$	5.41–5.98	4.33–6.08
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.200^{+0.069}_{-0.062}$	2.069–2.337	2.000–2.405
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.225^{+0.064}_{-0.070}$	2.086–2.356	2.018–2.424
δ/π (NO)	$1.08^{+0.13}_{-0.12}$	0.84–1.42	0.71–1.99
δ/π (IO)	$1.58^{+0.15}_{-0.16}$	1.26–1.85	1.11–1.96

The reactor antineutrino anomaly

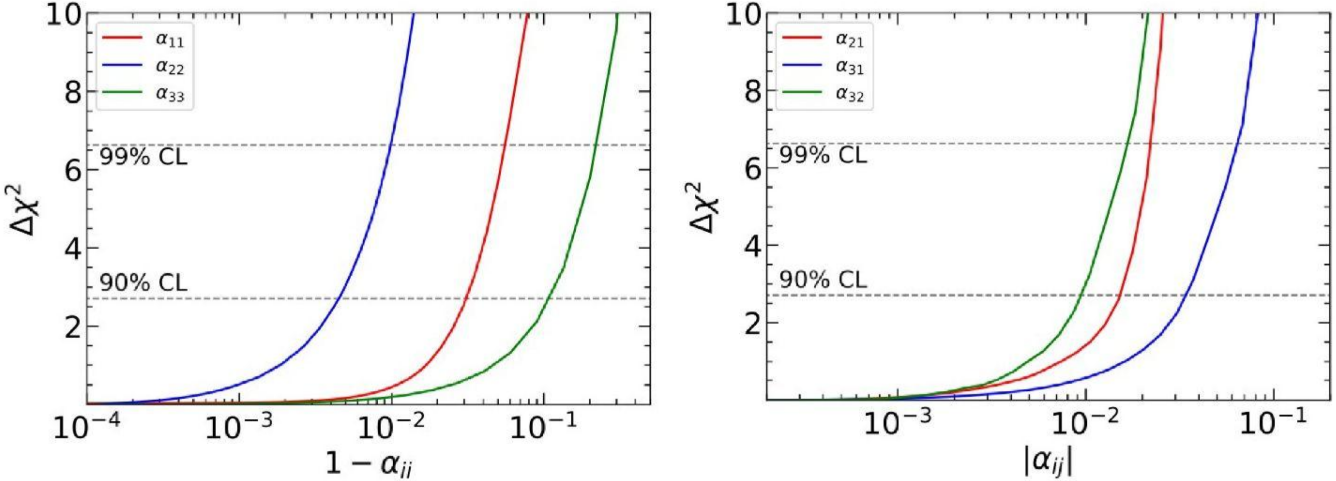




Giunti, Li, Ternes, Xin, 2110.06820

Unitarity of the lepton mixing matrix

$$U^{n\times n} = \begin{pmatrix} N & S \\ V & T \end{pmatrix}$$



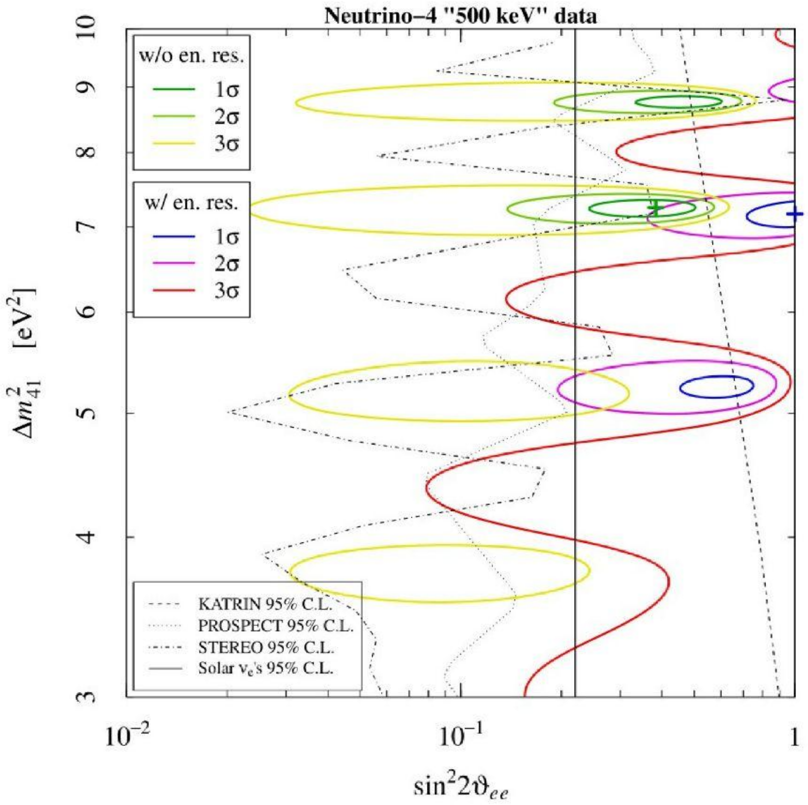
$$N = N^{NP} U = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U$$

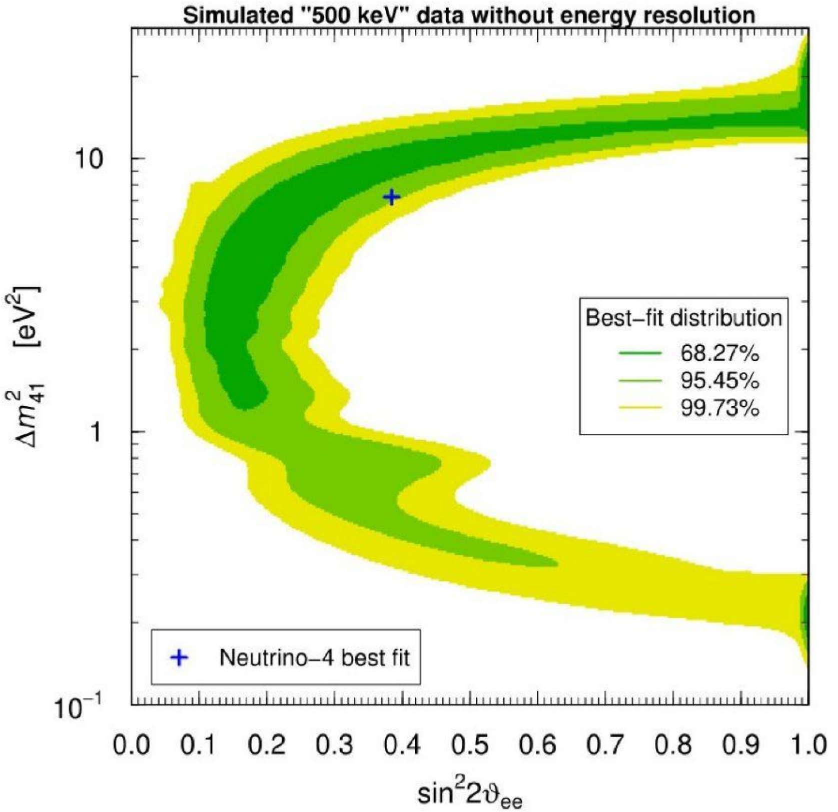
TABLE I. Bounds on the nonunitarity parameters obtained in this analysis.

Parameter	90% C.L.	99% C.L.
$1-\alpha_{11}$	<0.031	<0.056
$1-\alpha_{22}$	<0.005	<0.010
$1-\alpha_{33}$	<0.110	<0.220
$\|\alpha_{21}\|$	<0.013	<0.023
$\|\alpha_{31}\|$	<0.033	<0.065
$\|\alpha_{32}\|$	<0.009	<0.017

Forero, Giunti, Ternes, Tortola, 2103.01998, PRD 2021

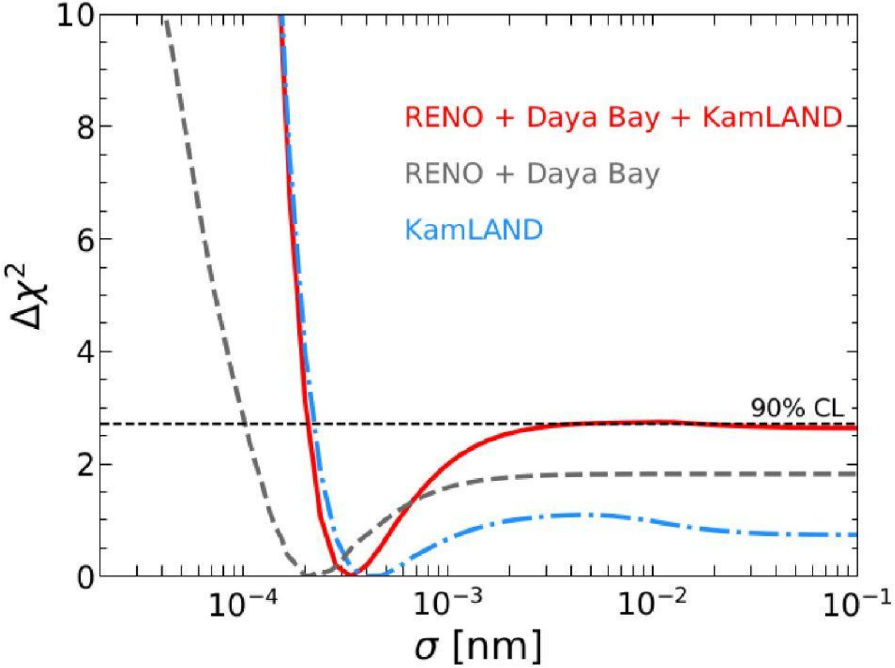
Neutrino-4 anomalv





Giunti, Li, Ternes, Zhang, 2101.06785, PLB 2021

Neutrino decoherence at reactor experiments

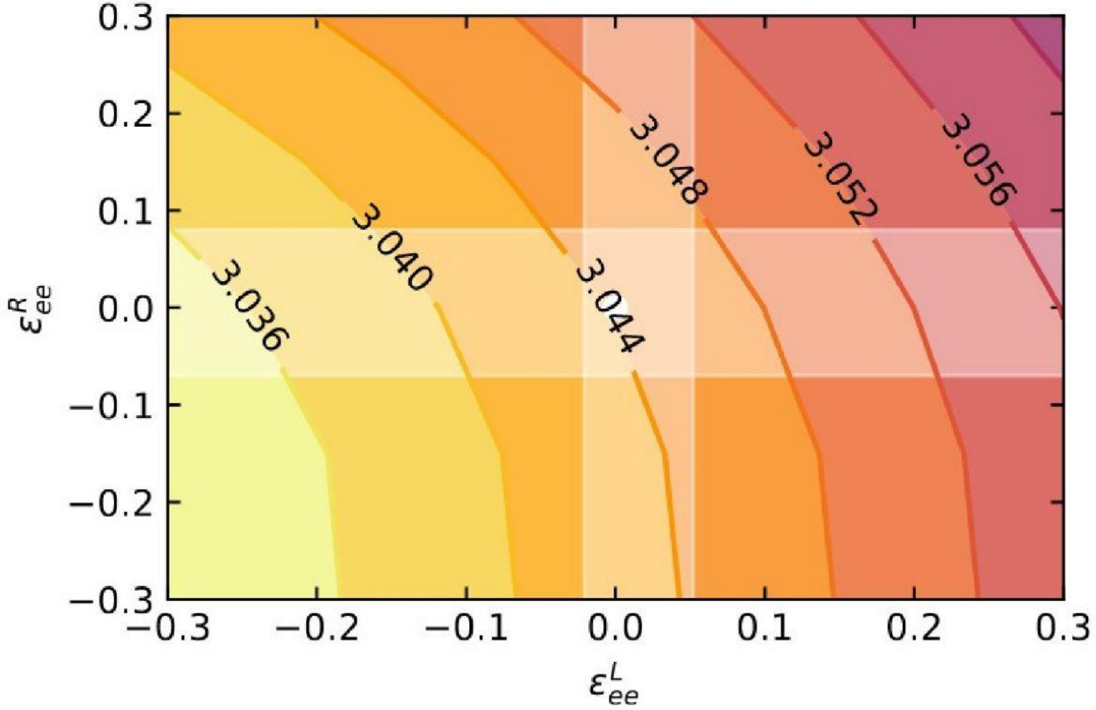


We computed the effects of wave-packet-separation decoherence on the oscillations of reactor antineutrinos

We can bound the wave packet width to be at least ~2e-4 nm

de Gouvea, De Romeri, Ternes, 2104.05806, JHEP 2021

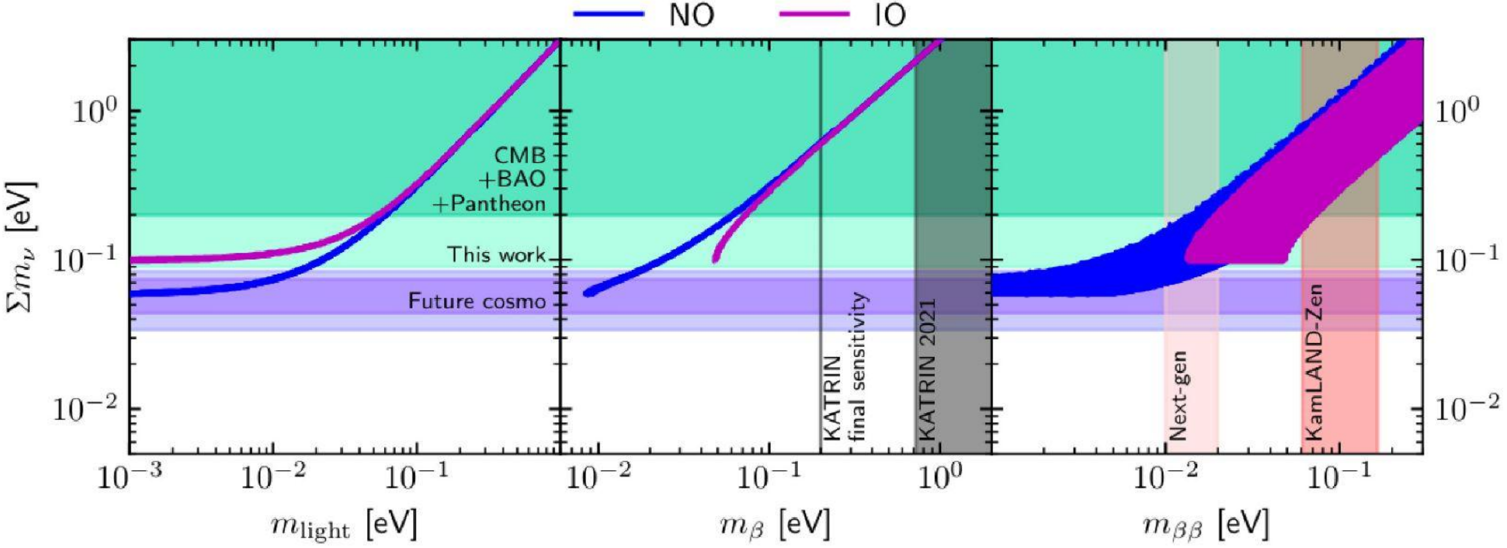
Neutrino NSI and Cosmology



NSI modify both flavour oscillations through matter effects, and the annihilation and scattering between neutrinos and electrons and positrons in the thermal plasma and effect the effective number of neutrinos

de Salas, Gariazzo, Martinez-Mirave, Pastor, Tortola, 2105.08168, PLB 2021

Sum of neutrino masses



$$\sum m_\nu < 0.09 \text{ eV at } 95\% \text{ CL}$$

Most up-to-date limits on the sum of neutrino masses. Cosmology is able to disfavor inverted neutrino mass ordering

Di Valentino, Gariazzo, Mena, 2106.15267, PRD 2021


Grazie!
electron-neutrino
muon neutrino
tau-neutrino