European Strategy for Particle Physics

ESPP: Dark Matter, Neutrinos & Cosmic Messengers

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EUROPEAN PHYSICAL SOCIETY
EPS HEP2025 MARSEILLE
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EPS-HEP CONFERENCE
07-11 JULY, 2025
PALAIS DU PHARO
MARSEILLE, FRANCE

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
AGENCIA ESTATAL DE INVESTIGACIÓN
GENERALITAT VALENCIANA
AsYmmetry Essential Asymmetries of Nature

Unfairly brief account of a challenging exercise by two WGs:

Neutrinos & Cosmic Messengers (~61 inputs)

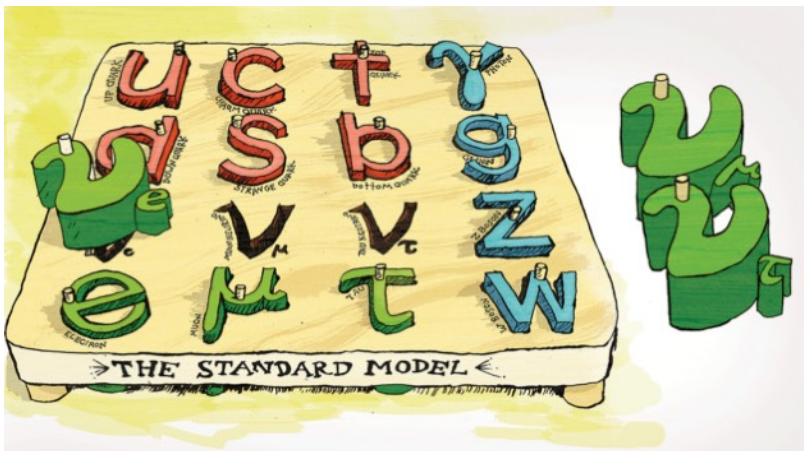
Members: S. Bolognesi, S. Dolan, V. Domcke, I. Esteban, J. Formaggio, M.C González-García, A. Heijboer, PH, A. Ianni, J. Kopp, E. Resconi, M. Scott, V. Sordini

Dark Matter & Dark Sectors (114 inputs)

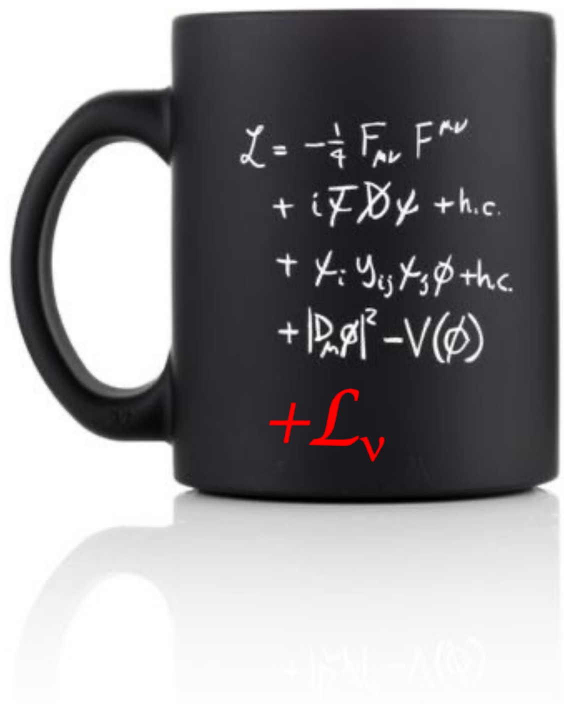
Members:
A. Chou, C. Doglioni, E. Castorina, F. Calore, M. McCullough,J. Monroe, J. Pradler,J.Vogel, M.Ovchynnikov,
B. M. D'Onofrio,P. Agnes,T. Pollmann,Y. Ema

Open Questions in Physics:massive neutrinos

Neutrino physics = νSM in the making



$\mathcal{L}_\nu$ = new Higgs-Lepton couplings+…



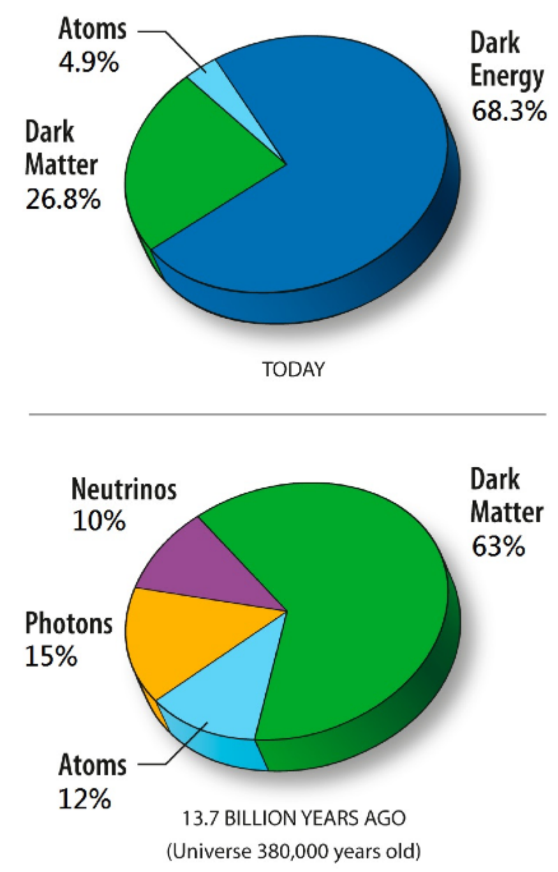
Open Questions in Physics: Baryons

$$\mathcal{L}_{\rm SM} + \text{ Gravity} \neq \text{Cosmos}$$

Baryons<-> matter-antimatter asymmetry

new sources of CP violation+new non-equilibrium dynamics in the Early Universe (eg. more weakly interacting particles,...) generic in

$$\mathcal{L}_\nu$$

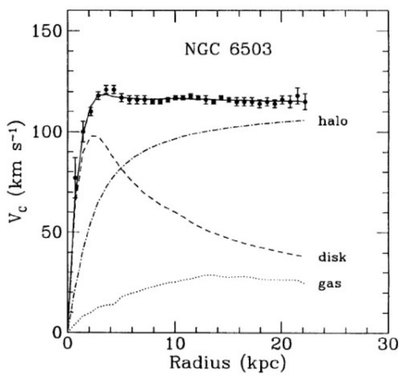


Open Questions in Physics: Dark Matter

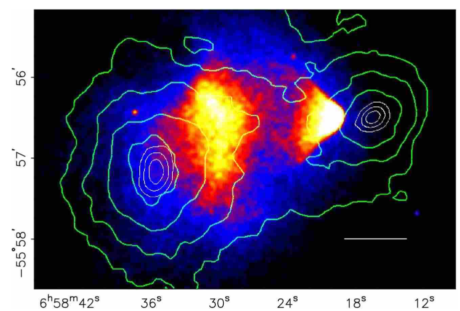
$$\mathcal{L}_{\rm SM} + \text{ Gravity} \neq \text{Cosmos}$$

A consistent need of a gravitating non-relativistic, non-interacting matter component across scales

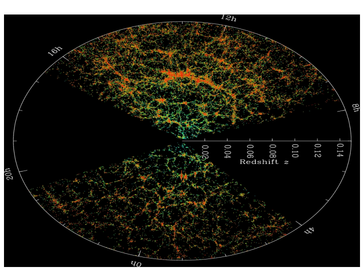
@Galaxy



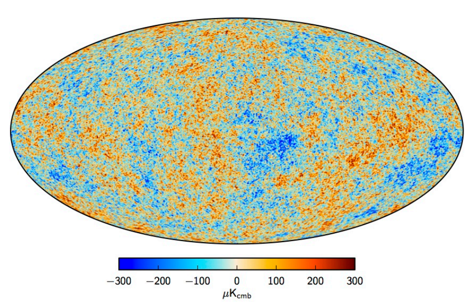
@GalaxyCluster

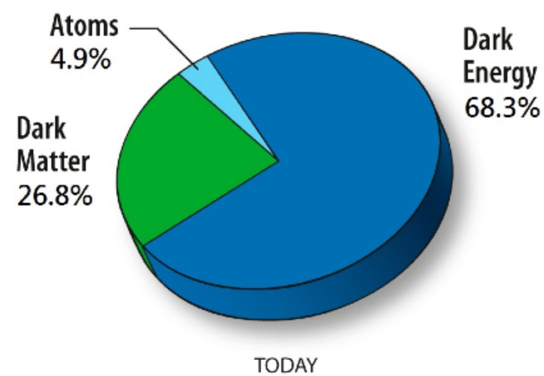


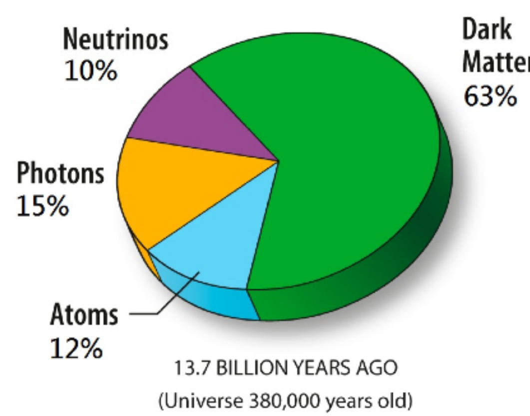
@LSS



@CMB





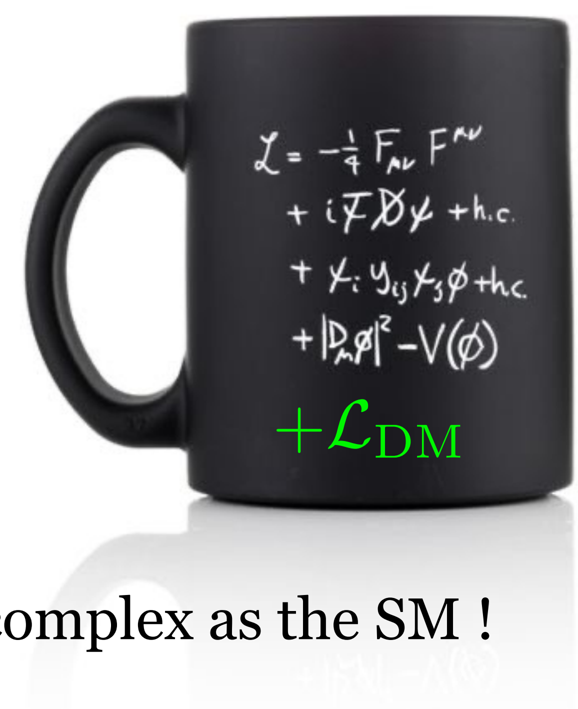


Open Questions in Physics:Dark Matter

Dark Matter physics = DSM in the making

$$\rho_\chi = n_\chi m_\chi \simeq 0.4\text{GeV}/\text{cm}^3 \quad \text{(locally)}$$

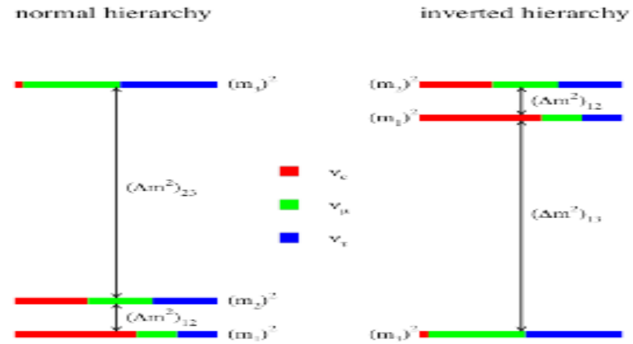
$$\mathcal{L}_{\text{DM}} = \mathcal{O}(\chi, .., \text{SM})$$



Dark sector could be as rich, diverse, complex as the SM !

Massive Neutrinos

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \ldots) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



NO/NH IO/IH

NuFit 6.0, JHEP 12 (2024) 216

IC24 with SK atmospheric data

	Normal Ordering (best fit) bfp $\pm 1\sigma$		3σ range
$\sin^2\theta_{12}$	$0.308^{+0.012}_{-0.011}$	3.7%	75 $\to$ 0.345
$\theta_{12}/^\circ$	$33.68^{+0.73}_{-0.70}$	2.1%	63 $\to$ 35.95
$\sin^2\theta_{23}$	$0.470^{+0.017}_{-0.013}$	5.0%	35 $\to$ 0.585
$\theta_{23}/^\circ$	$43.3^{+1.0}_{-0.8}$	3.1%	.3 $\to$ 49.9
$\sin^2\theta_{13}$	$0.02215^{+0.00056}_{-0.00058}$	2.3%	30 $\to$ 0.02388
$\theta_{13}/^\circ$	$8.56^{+0.11}_{-0.11}$	1.3%	19 $\to$ 8.89
$\delta_{CP}/^\circ$	212^{+26}_{-41}	16.4%	24 $\to$ 364
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.49^{+0.19}_{-0.19}$	2.5%	92 $\to$ 8.05
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.513^{+0.021}_{-0.019}$	0.8%	51 $\to$ +2.578

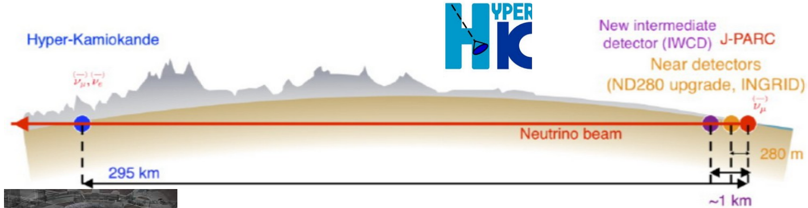
See also F. Capozzi et al., Phys. Rev. D 104, 8, 083031
5 P. F. de Salas et al., JHEP 02, 071 (2021) 16/06/2025

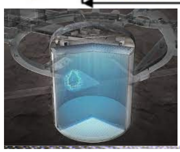
Major open questions for future oscillation experiments:

- neutrino ordering
- CP violation
- ≤% precision in all parameters

New Neutrino Oscillation Experiments

- Two new complementary LBL accelerator neutrino projects:

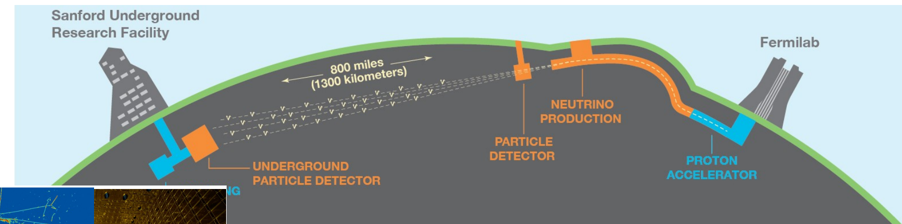


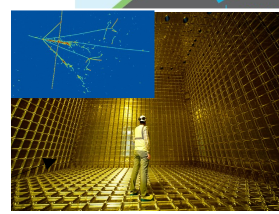


SuperKamiokande
volume x8
(water Cherencov)

T2K beam
X2.6 power

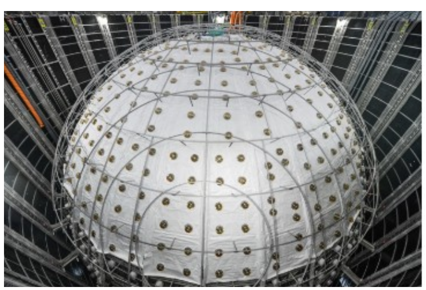
>2028





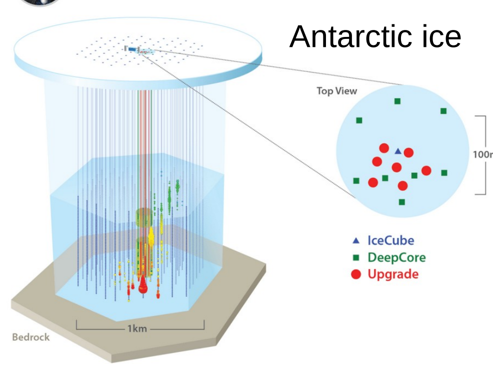
>2031

- One new reactor neutrino project:

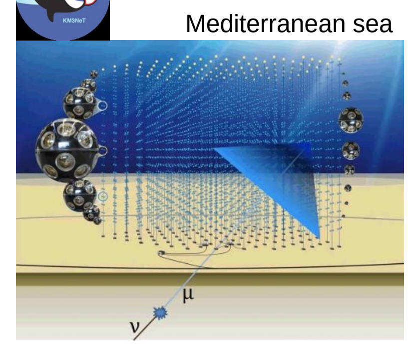


20kTon liquid scintillator
Starting data taking now!

- Two atmospheric neutrino projects:



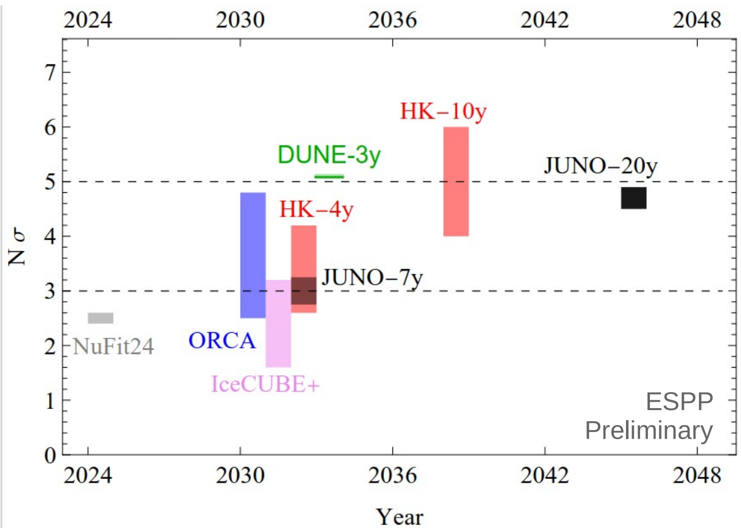
IceCube DeepCore 10Mton +
Upgrade 2MTon



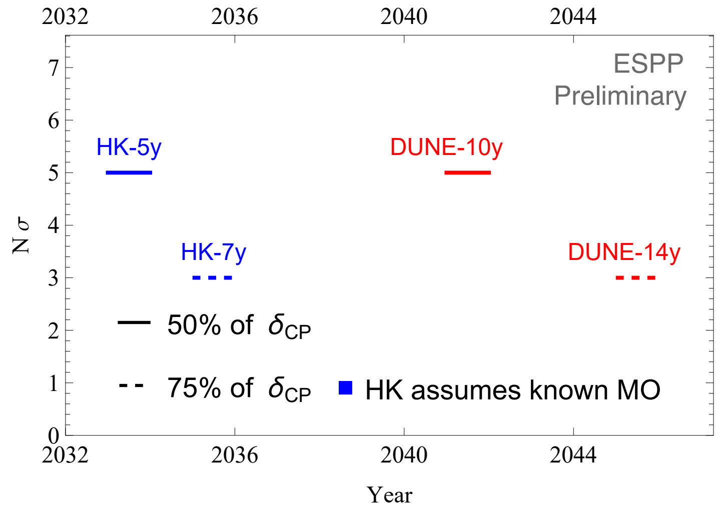
Km3Net: deploying on-going
→ ORCA 7MTon

Neutrino Oscillation Experiments: major discoveries in next decade

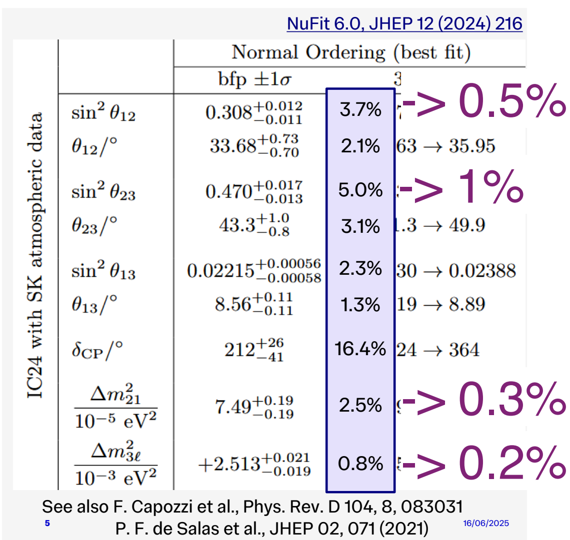
Mass ordering



Leptonic CP violation



<% precision in mixings/masses



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$\theta_{23}/^\circ$	$43.3^{+1.0}_{-0.8}$	3.1%	1.3 → 49.9
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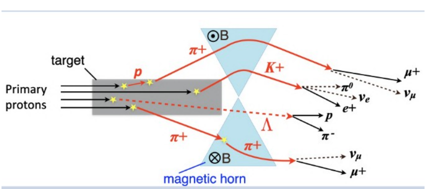
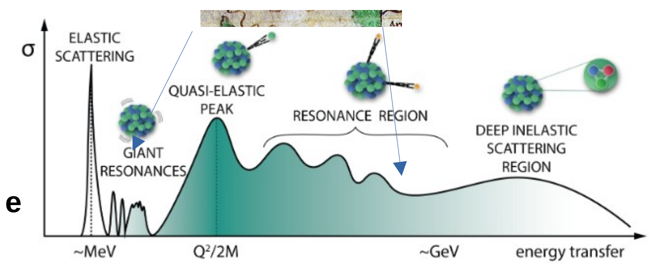
See also F. Capozzi et al., Phys. Rev. D 104, 8, 083031
P. F. de Salas et al., JHEP 02, 071 (2021)

5 16/06/2025

Challenges: systematics in fluxes & xsec!





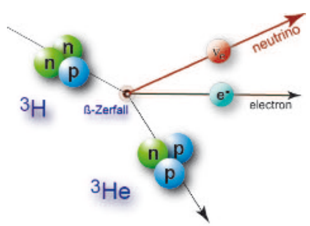
Dedicated projects@accelerators:

NA61/SHINE, NuScope, NuSTORM,…

Neutrino mass scale

$$m_{\nu_e} = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

β-decay/e-capture



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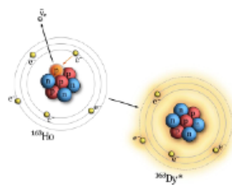
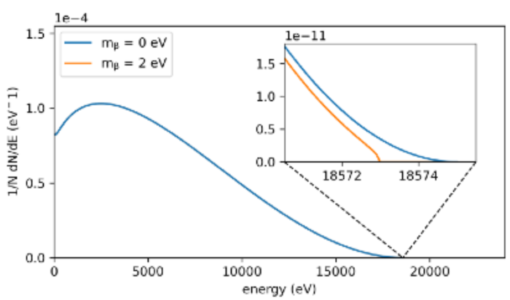
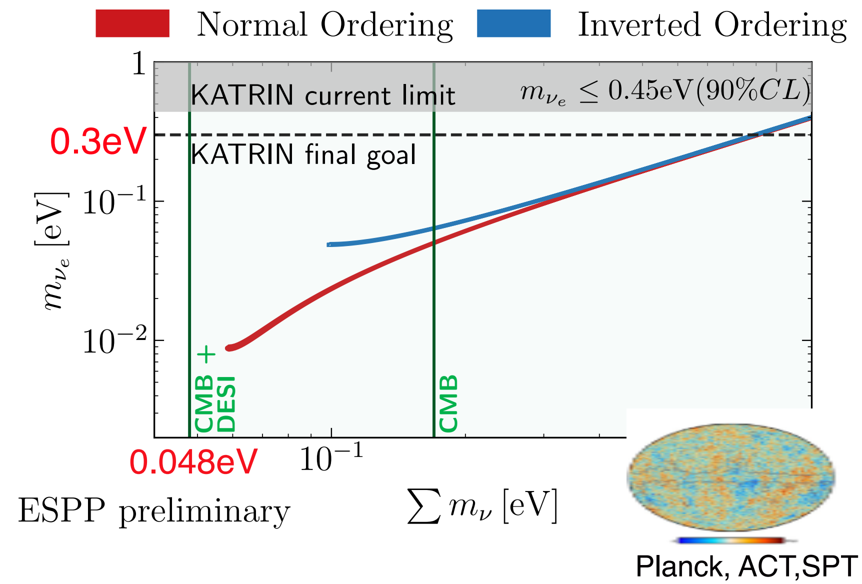
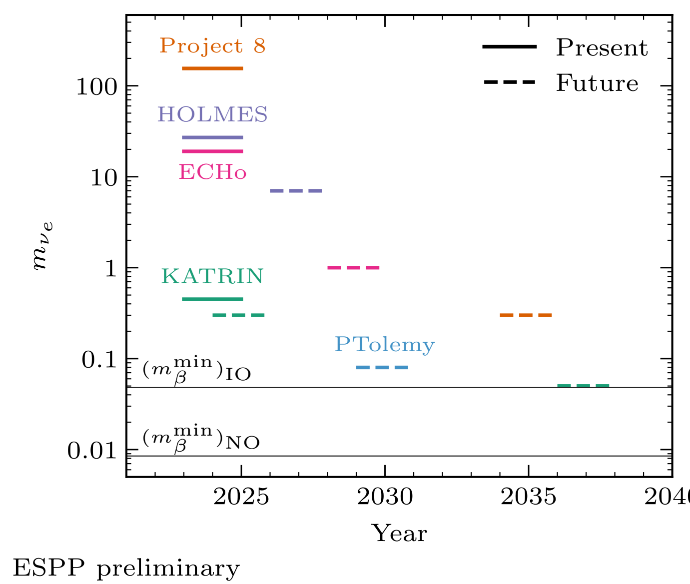






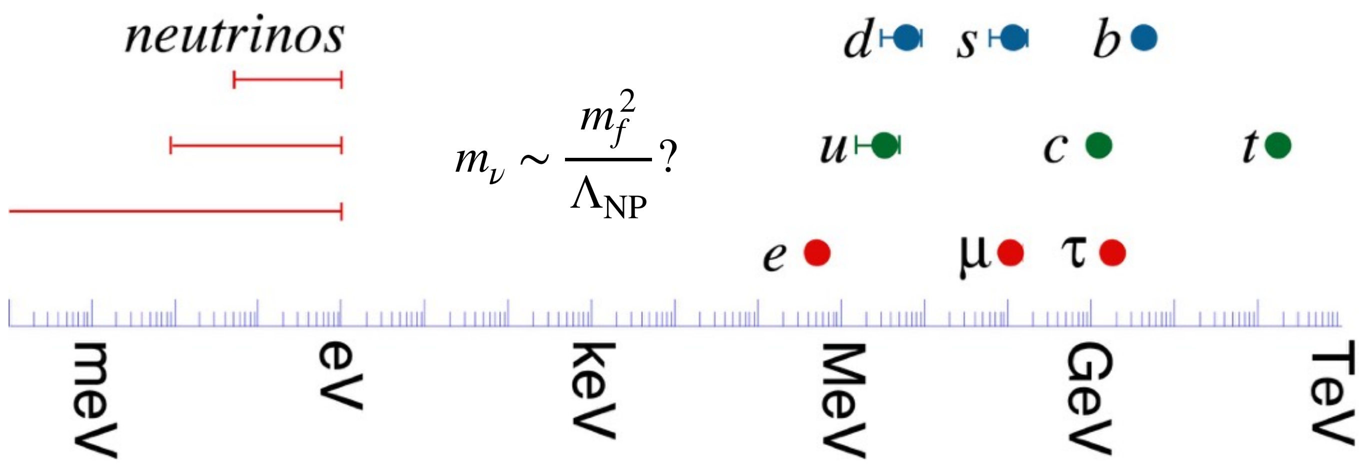


Laboratory Challenges: atomic tritium, ab-initio e-capture, scalability

Cosmology: strong limit driven by tension of LCDM with data !

Neutrinos exploration of new physics

Neutrino masses suggest the existence of a new physics scale

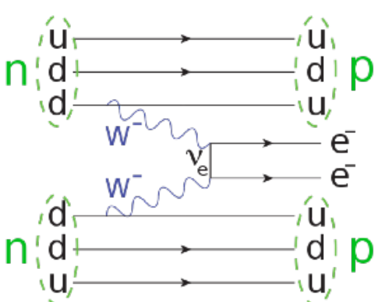


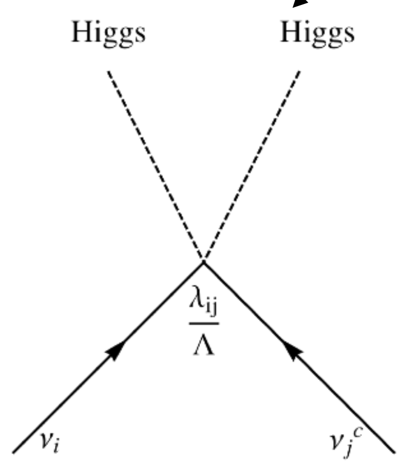
Neutrino Exploration of New Physics

Neutrino Experiments = Huge detectors + Low Background + Intense Beam Dumps

$$\mathcal{L}_{\rm SMEFT} = \underbrace{\sum_i \frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)}}_{\text{6 operator}} + \underbrace{\sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)}}_{\text{2499 operators(59 B,L,FC)}} + \ldots$$

$\beta\beta 0\nu$

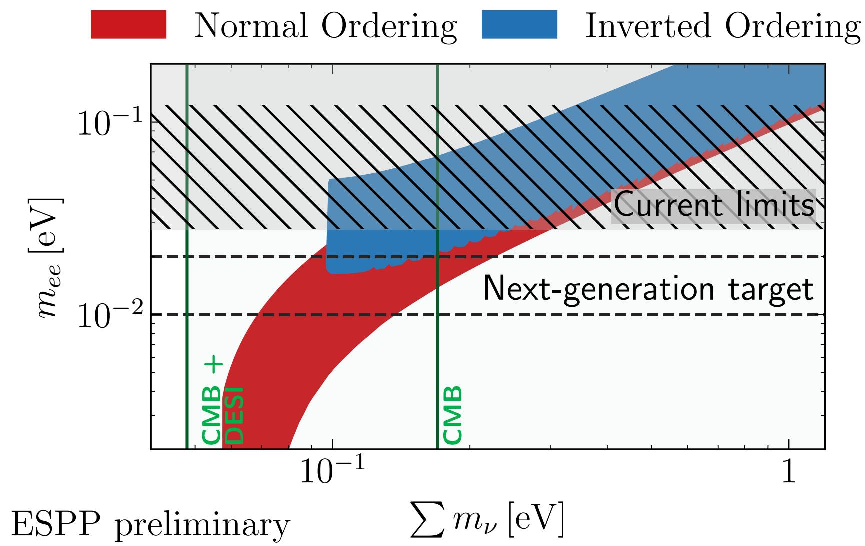




Baryon # violating,
Non-standard Nu interactions,
Non-unitarity PMNS,...

Neutrinoless Double Beta Decay: $\Lambda_{\rm NP}$

$$T^{-1}_{2\beta 0\nu} \simeq \underbrace{G^{0\nu}}_{\text{Phase}} \underbrace{\left|M^{0\nu}\right|^2}_{\text{Nuclear M.E.}} \underbrace{\left|\sum_i \left(V^{ei}_{MNS}\right)^2 m_i\right|^2}_{|m_{ee}|^2}$$



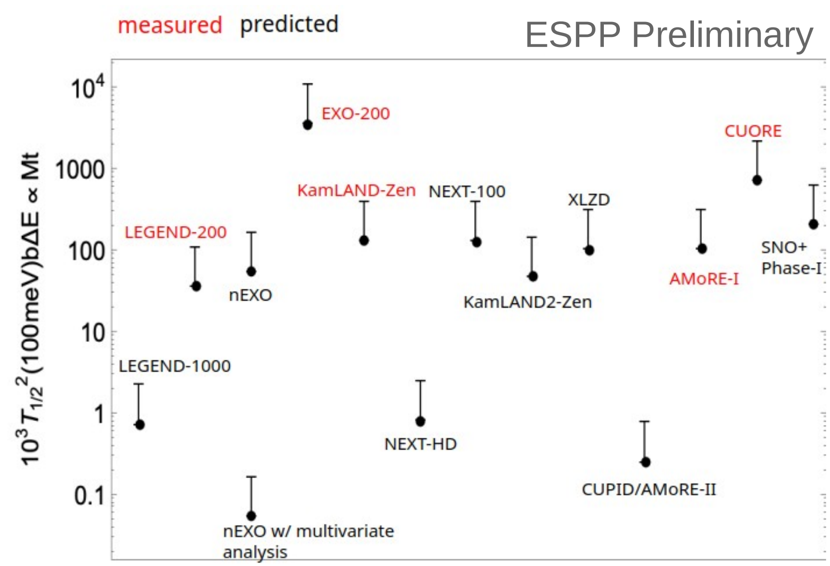
Different isotopes/technologies/challenges:

Te Liquid Scin. SNO+

Xe Liquid Scin. Kamland-Zen
liquid Xe TPC nEXO
gas Xe TPC NEXT*

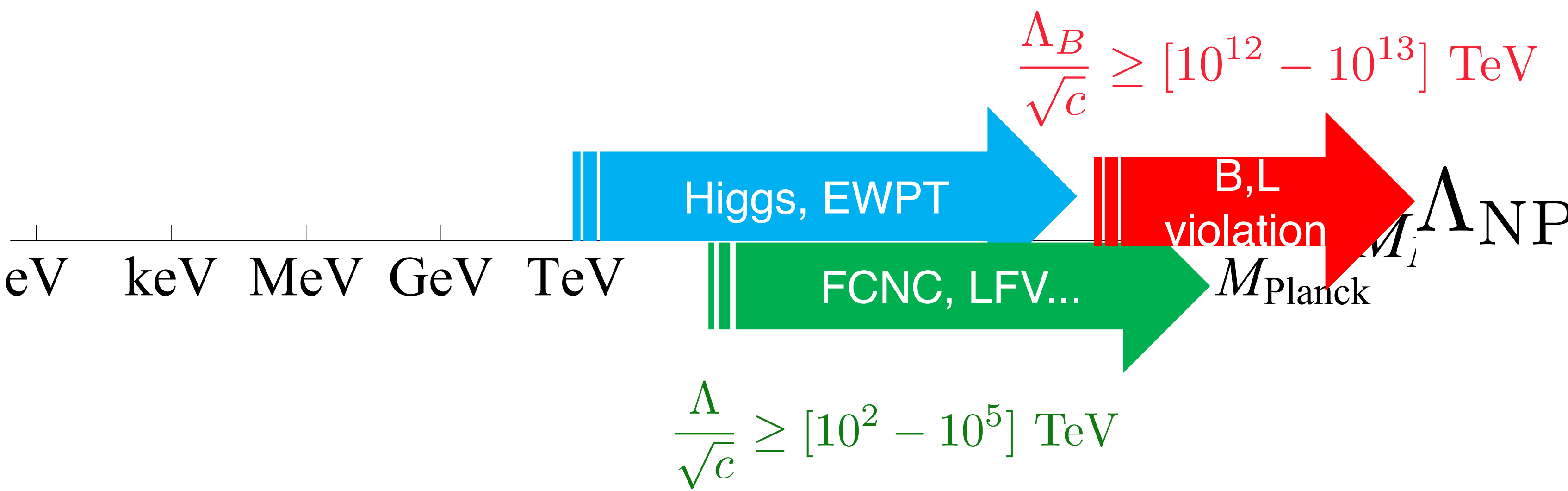
Ge Legend*

Mo bolometers: CUPID*, Amore



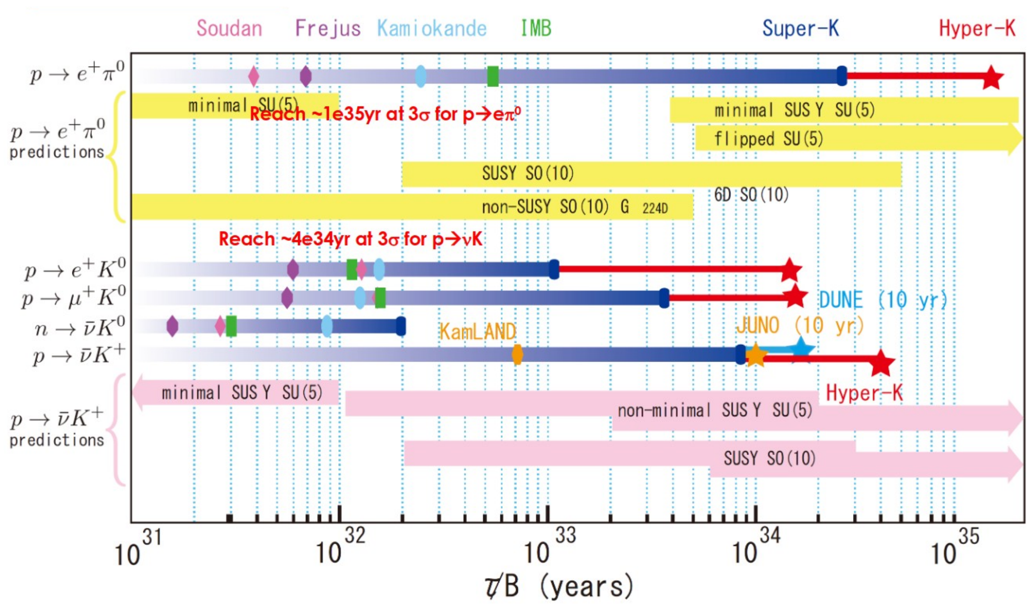
* in underground labs in Europe

p-decay & B violating processes

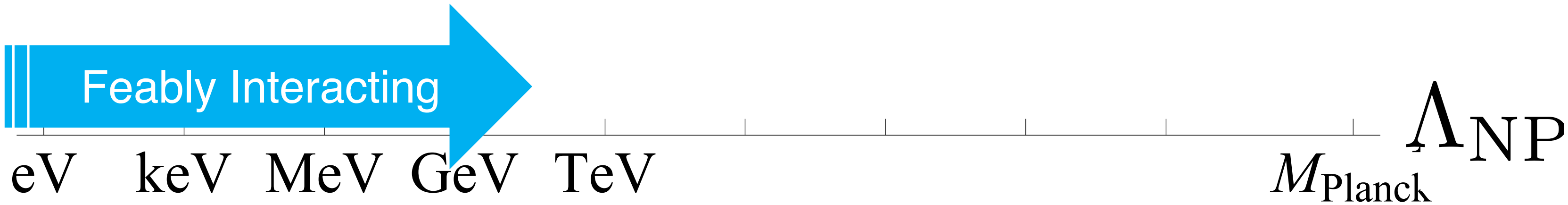


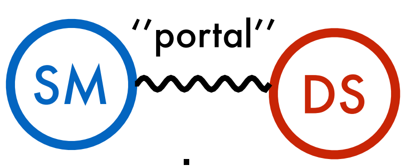
Neutrino experiments have provided the most stringent limits to SMEFT via B violating searches: p-decay, n-nbar oscillations,

$$\tau_p > 10^{34} y \to 10^{35} y$$



Neutrino Exploration of New Physics





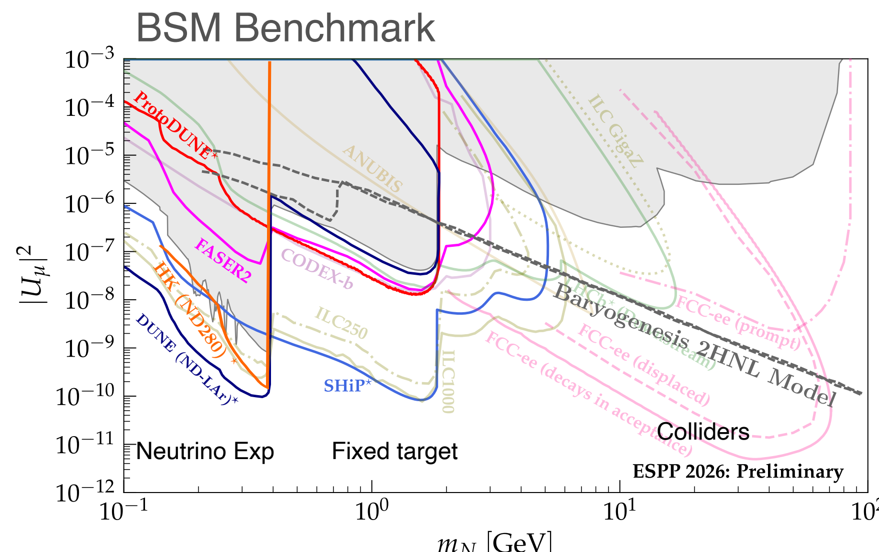
$\epsilon B_{\mu\nu} F'^{\mu\nu}$: dark photon portal,

$|H|^2 S, |H|^2 S^2$: Higgs portal,

$L H N_R$: neutrino (HNL) portal,

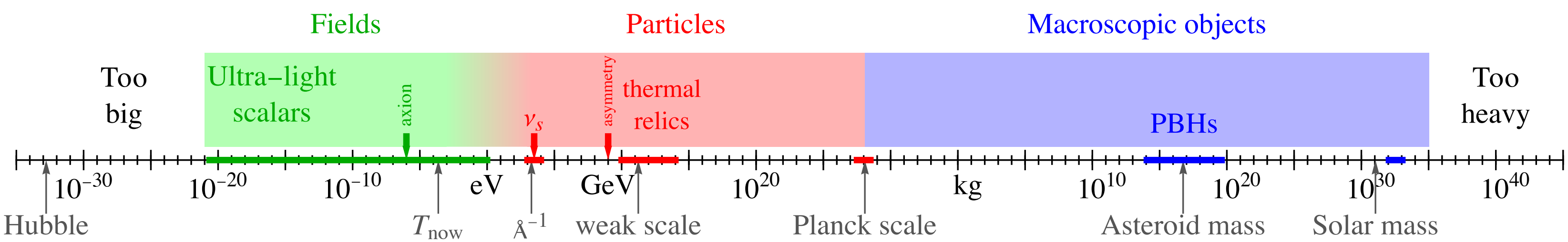
Neutrino Portal = Low scale Type I seesaw

- Light neutrino masses+ heavier neutrinos (light sterile neutrinos or HNLs)
- Generation of a matter/antimatter asymmetry, implications in cosmology, stellar evolution, etc



Dark Matter

Models of DM has been proposed at widely different scales

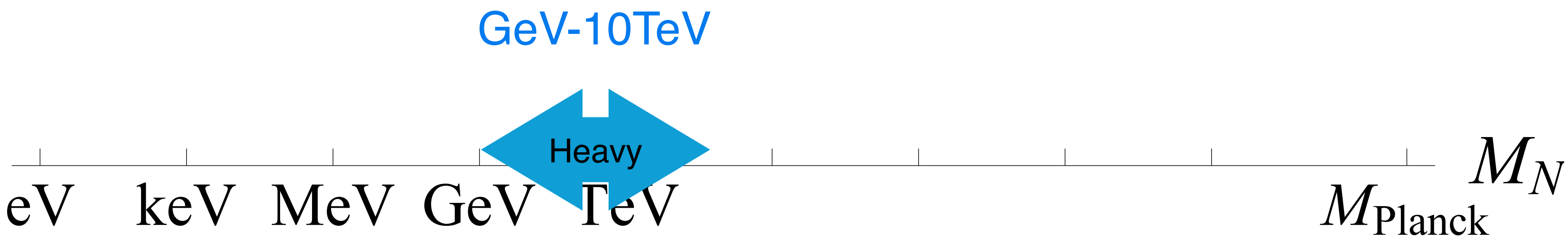


Cirelli et al, 2406.01705

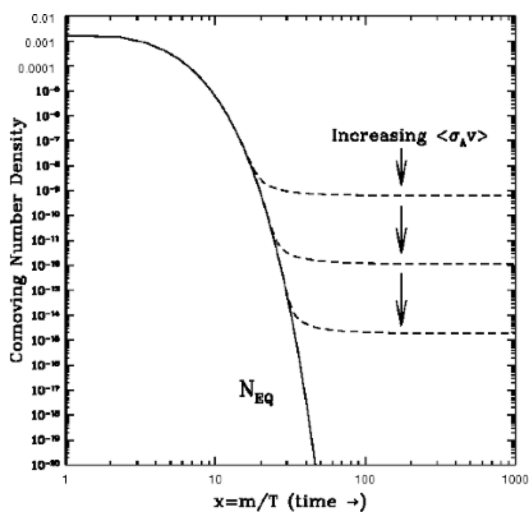
Most relevant for particle physics are those below Planck scale:

1. Ultralight mass range $m_\chi \lesssim \text{eV}$.
2. Light mass range $\text{keV} \lesssim m_\chi \lesssim \text{GeV}$.
3. Heavy mass range $\text{GeV} \lesssim m_\chi \lesssim 10\,\text{TeV}$.
4. Ultraheavy mass range $\text{TeV} \ll m_\chi$

Dark Matter: WIMP Benchmark

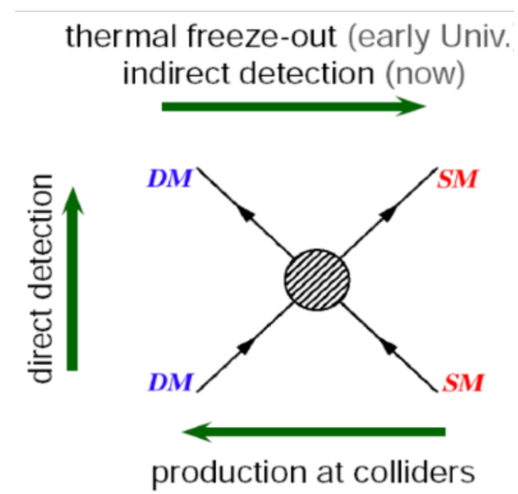


Standard Thermal Freeze-out

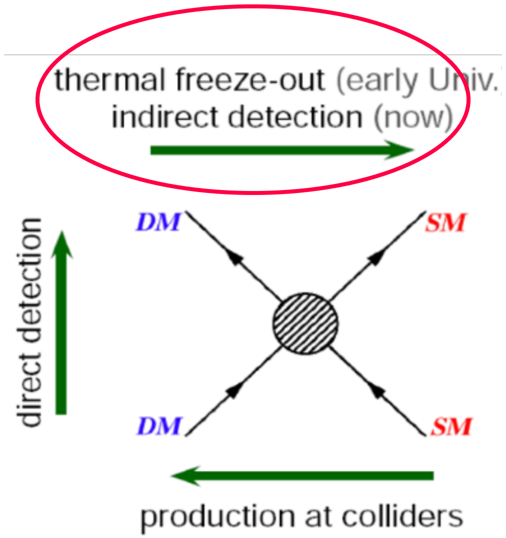


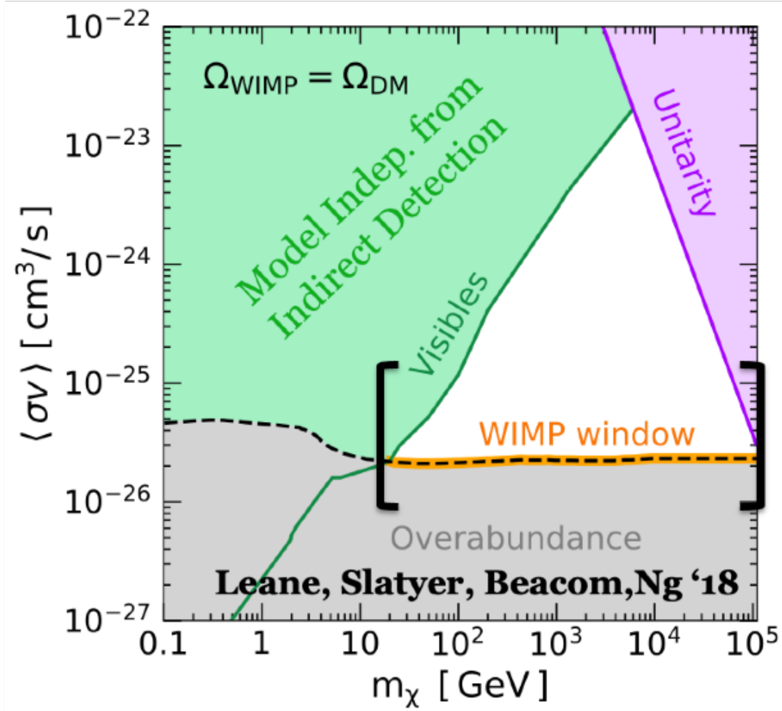
$$\Omega_{DM} h^2 \propto \frac{1}{\langle \sigma v \rangle}$$

$$\begin{aligned} \langle \sigma v \rangle &\sim 10^{-26} cm^3/s \\ &\sim \alpha^2 \left(\frac{m_\chi}{100\mathrm{GeV}}\right)^{-2} \end{aligned}$$

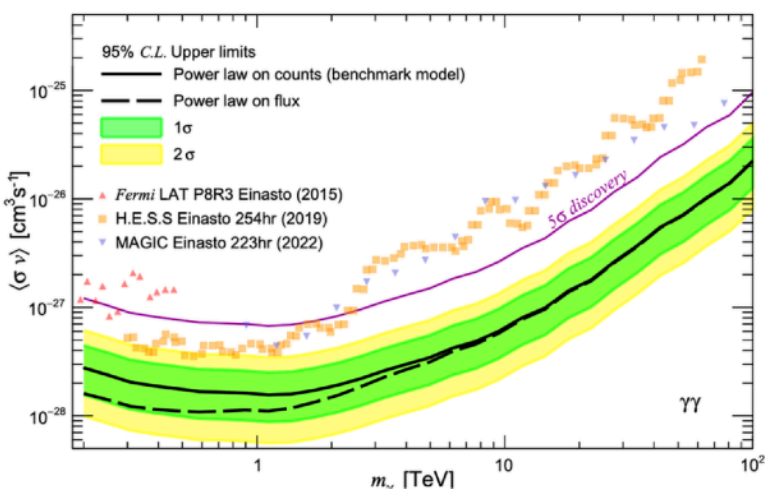


WIMP window closing:indirect detection





CTA Collab 2403.04857



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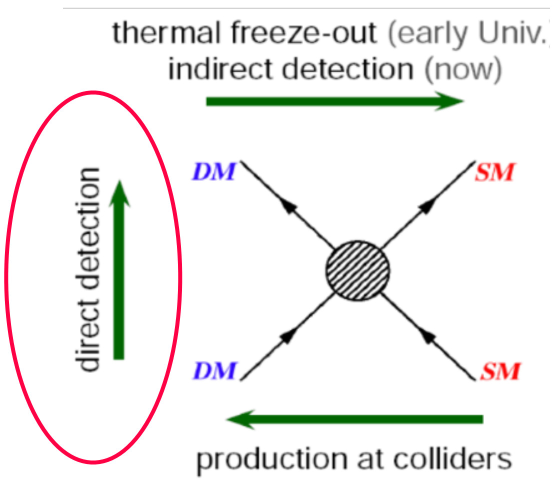
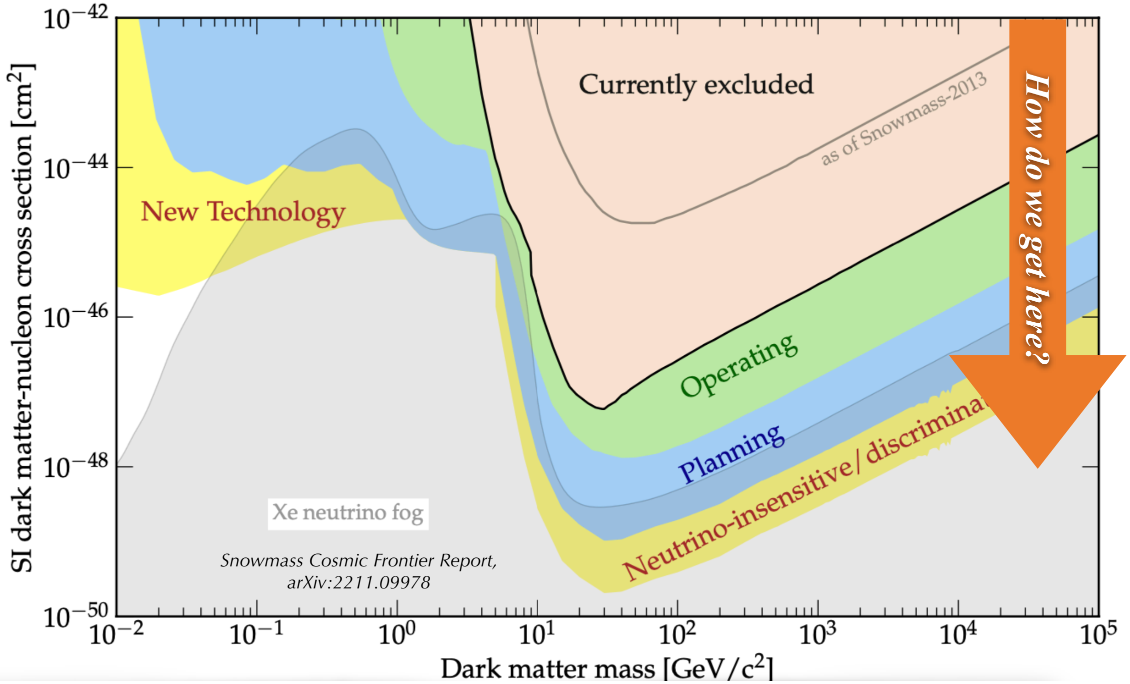
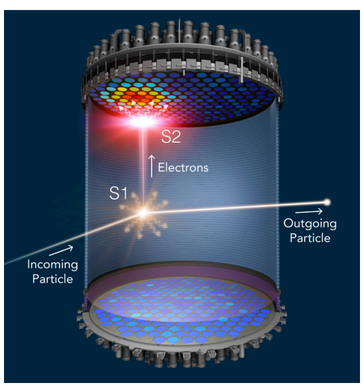
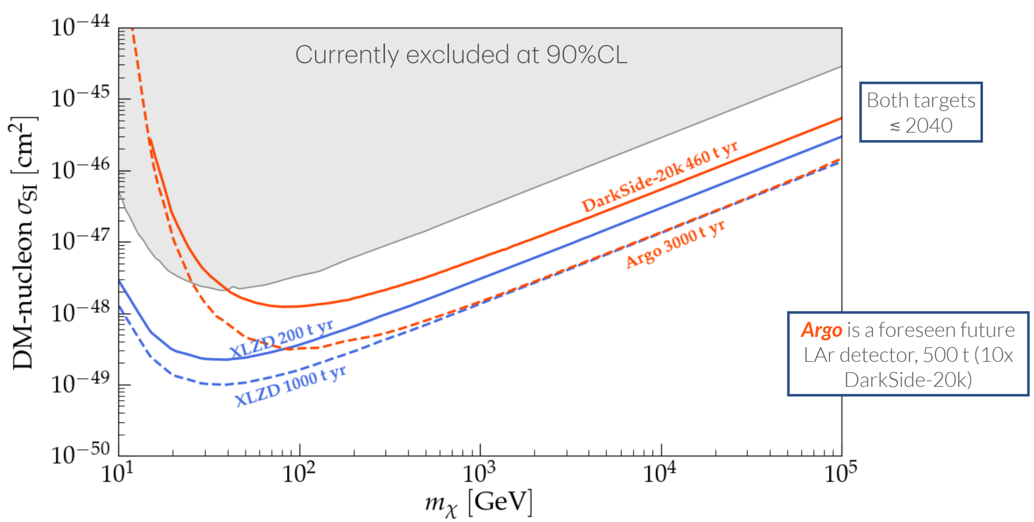


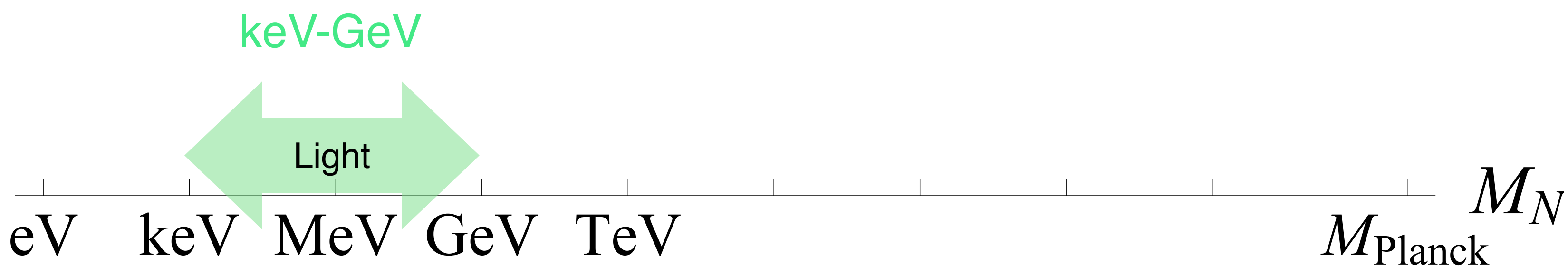


Noble Liquids (Xe, Ar)

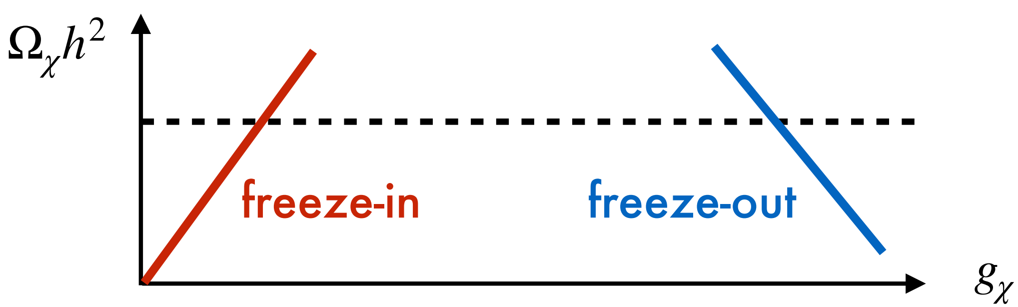


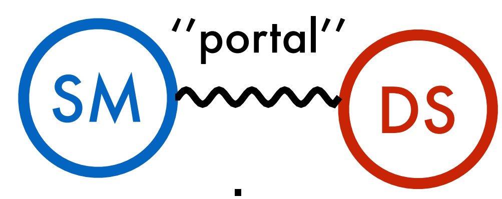


Dark Matter: Light Dark Matter Benchmark



Lighter and feably-coupled DM require alternative production mechanisms and detector tecnologies





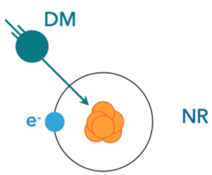
$\epsilon B_{\mu\nu} F'^{\mu\nu}$: dark photon portal,

$|H|^2 S, |H|^2 S^2$: Higgs portal,

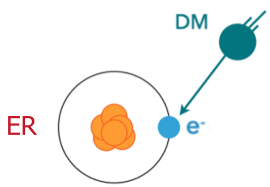
LHN_R : neutrino (HNL) portal,

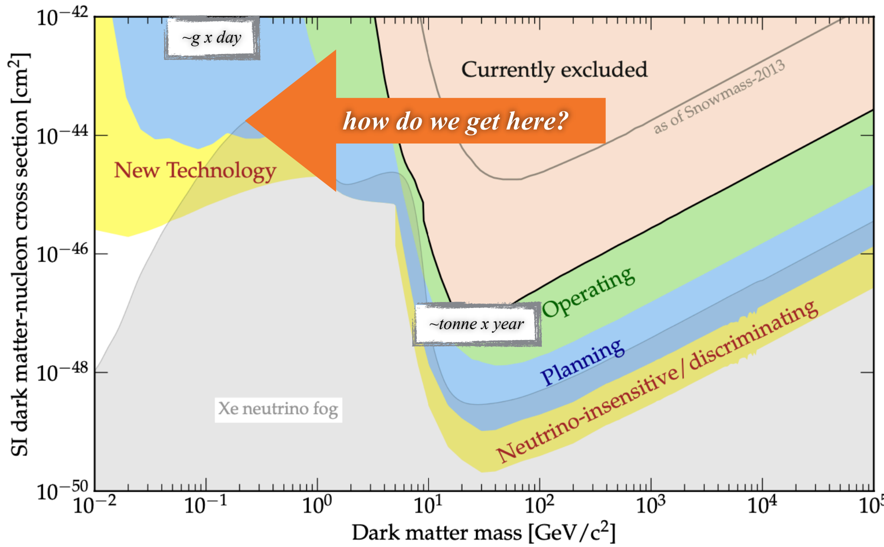
$aF\tilde{F}$: axion-like particle (ALP) portal.

Light DM: direct detection

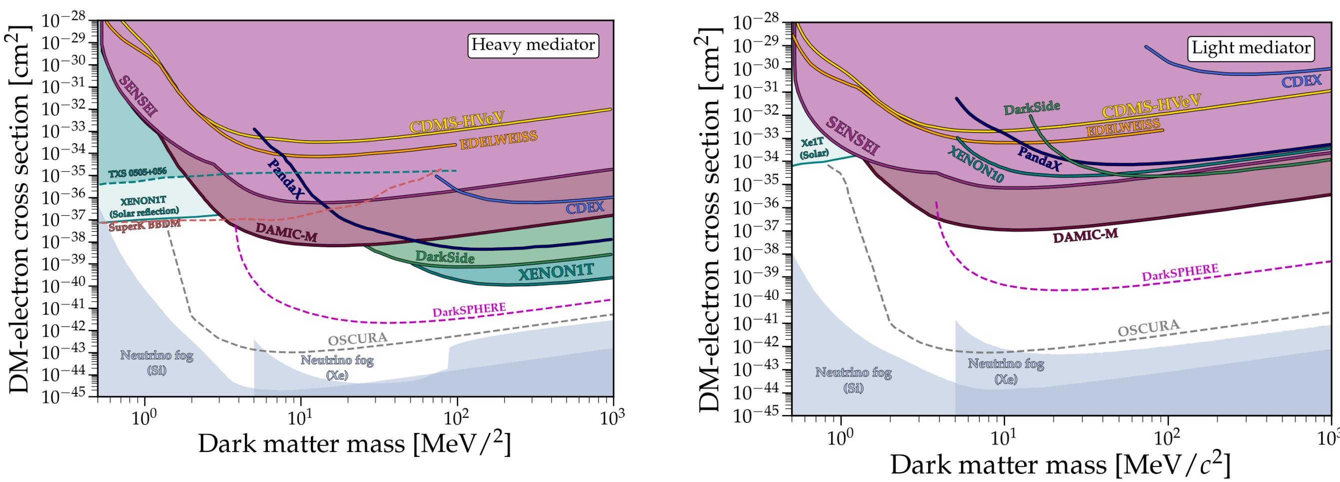


+ inelastic (Migdal)



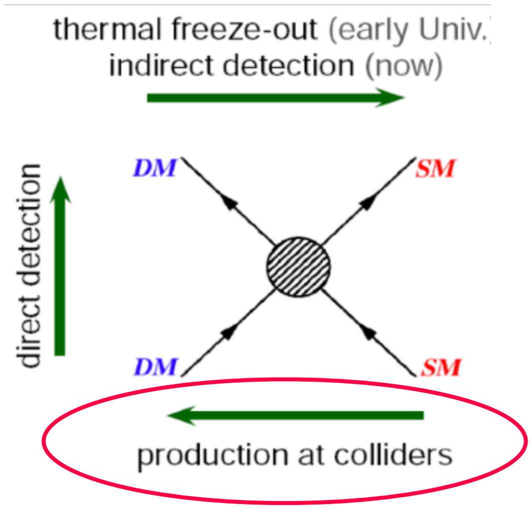


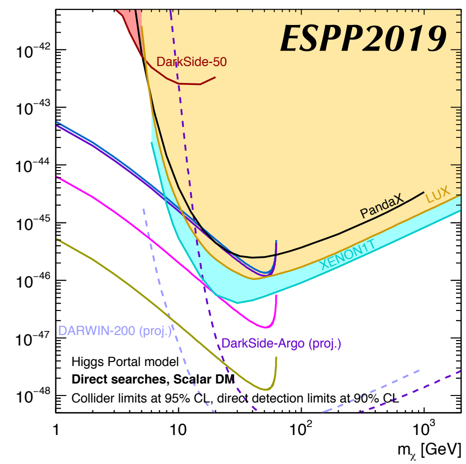
New analysis strategies, and novel technologies for dedicated experiments

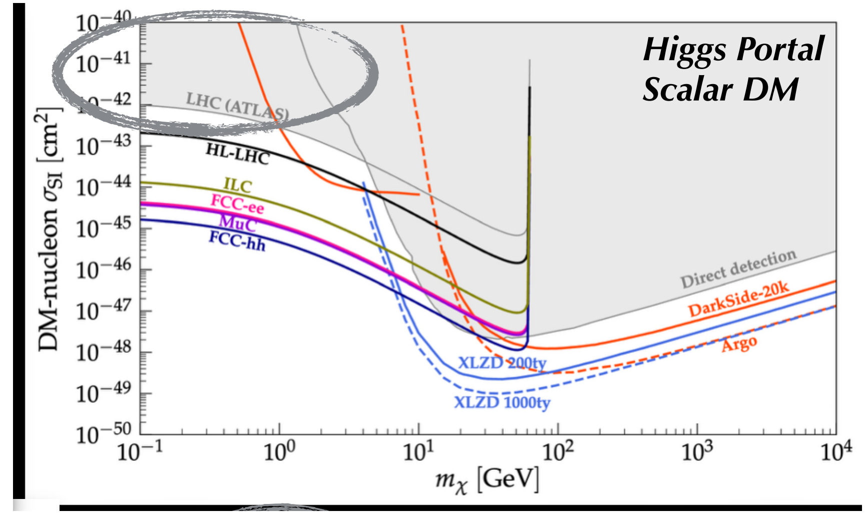


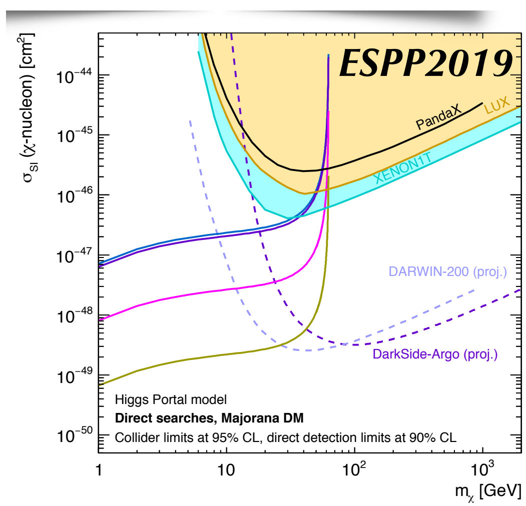
C. O'Hare, https://github.com/cajohare

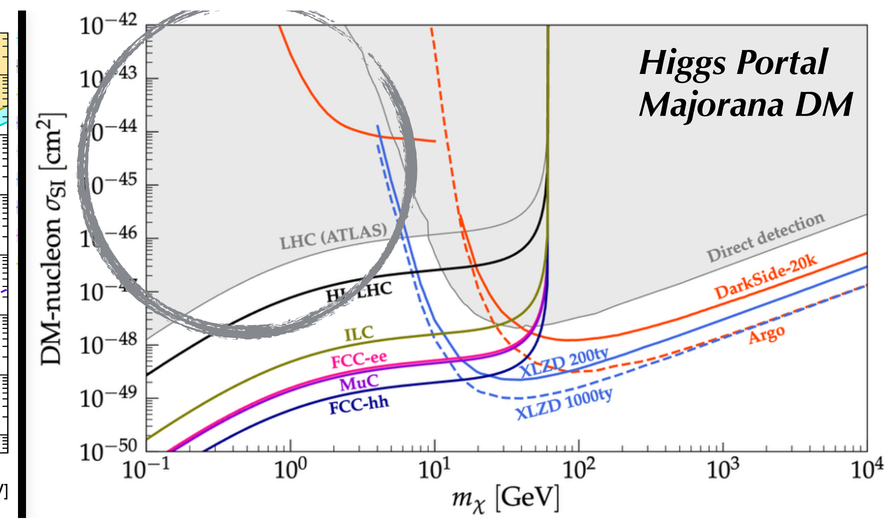
Collider complementarity



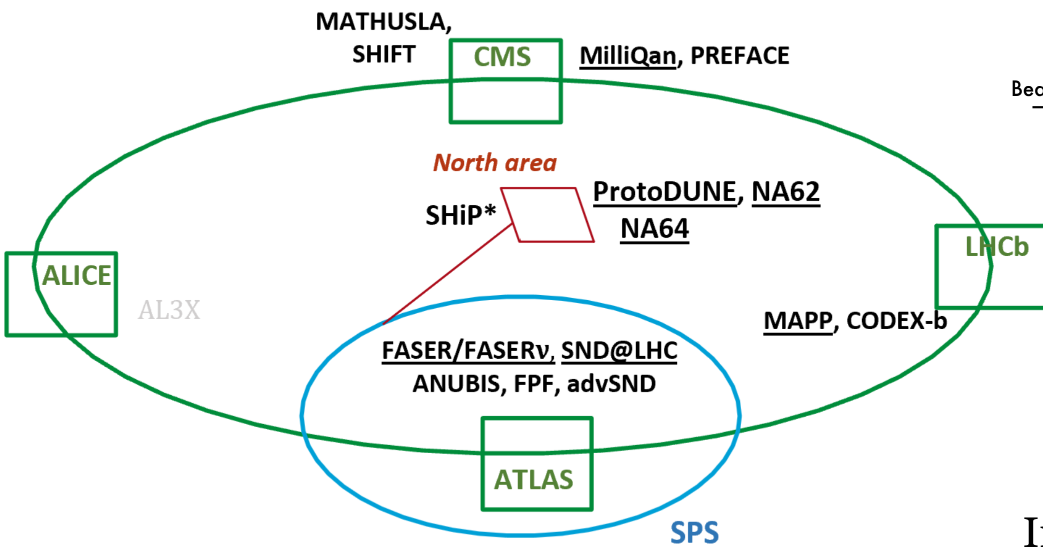


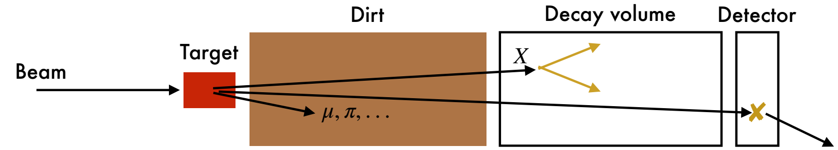




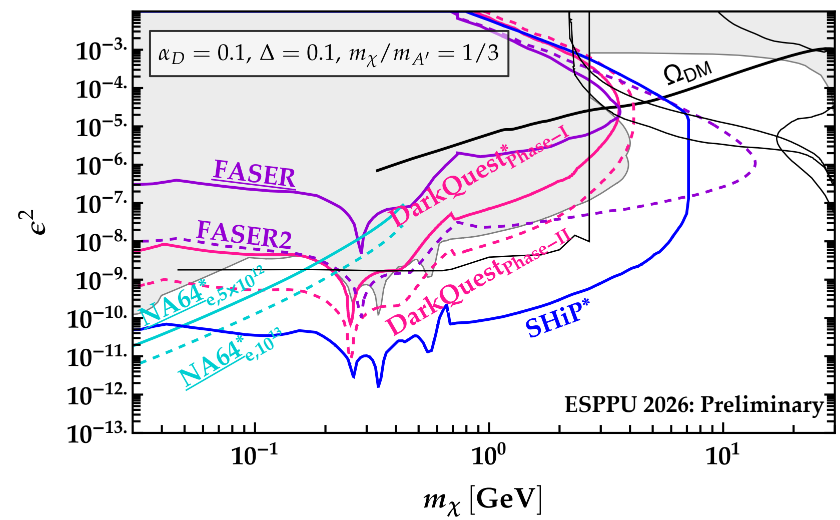


Fixed Target+LHC FPF complementarity

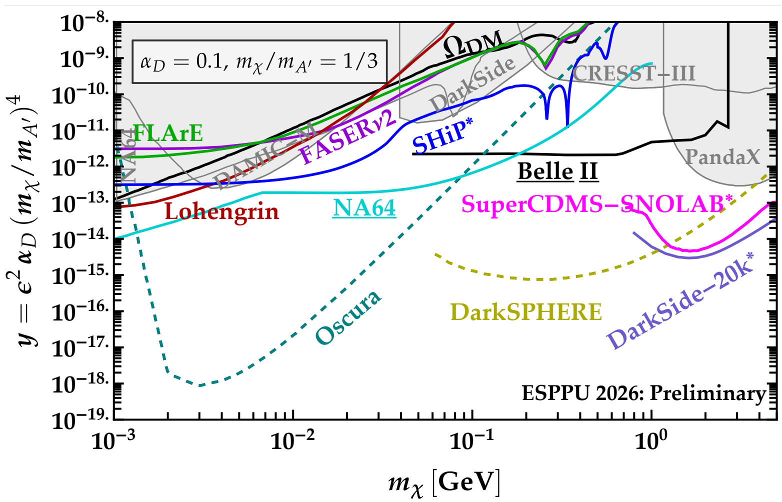




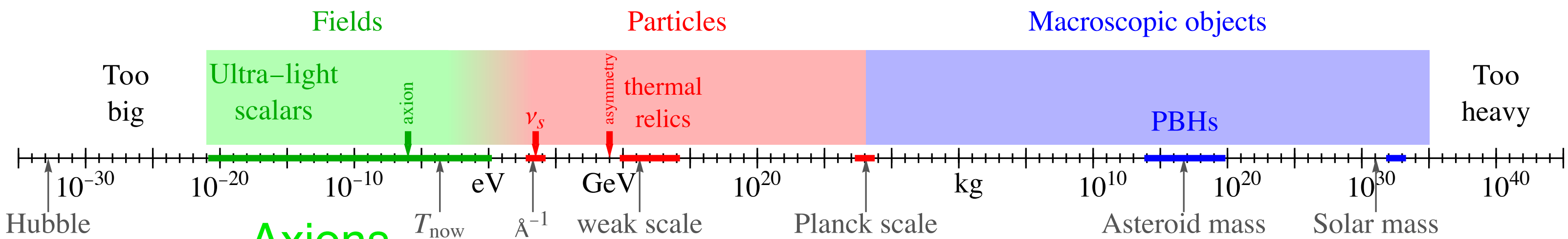
Inelastic DM Vector Portal



Elastic DM Vector Portal

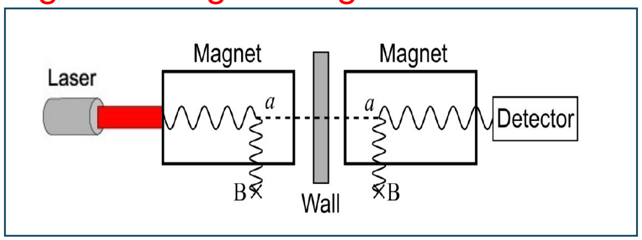


Dark Matter: Ultralight DM benchmark (< eV)

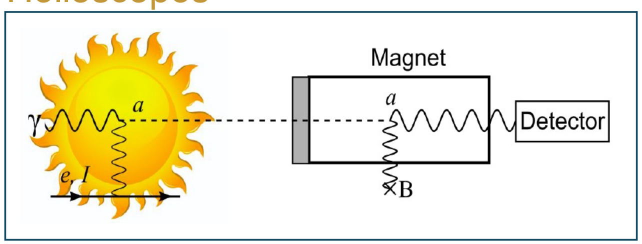


Axions

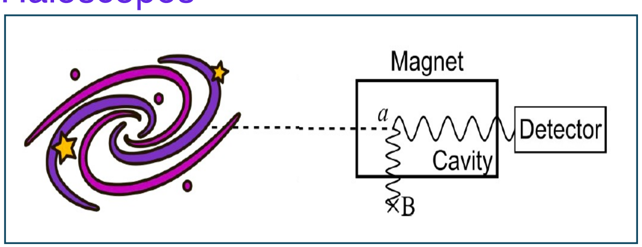
Light-Shining-Through-Wall

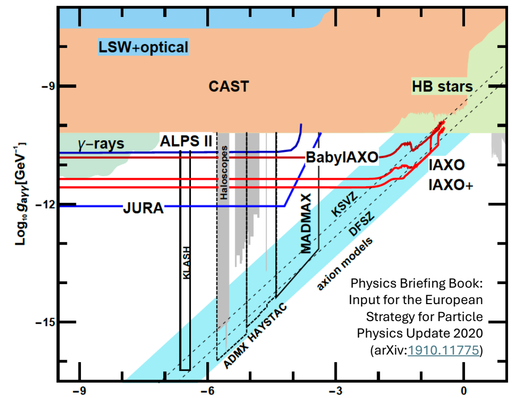


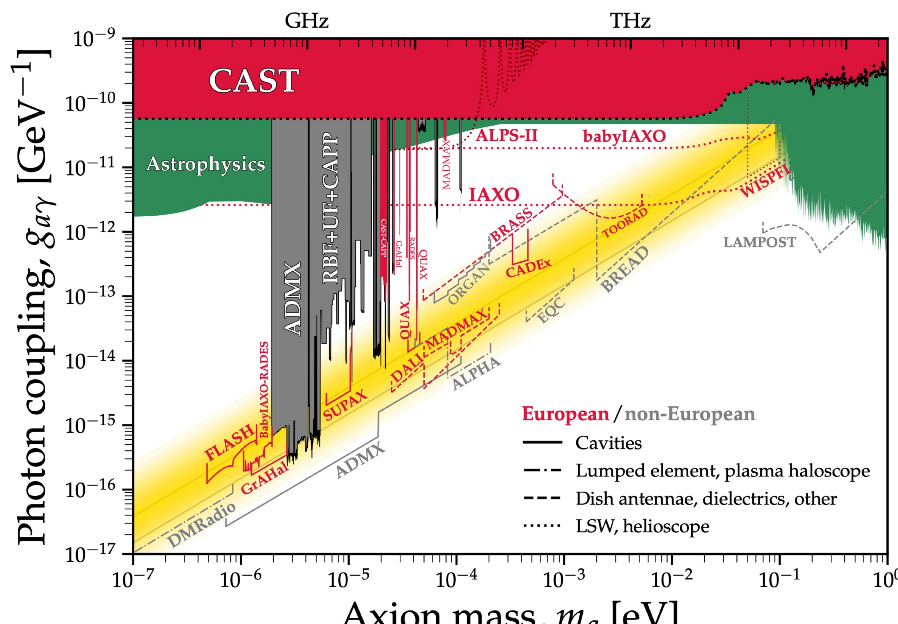
Helioscopes



Haloscopes

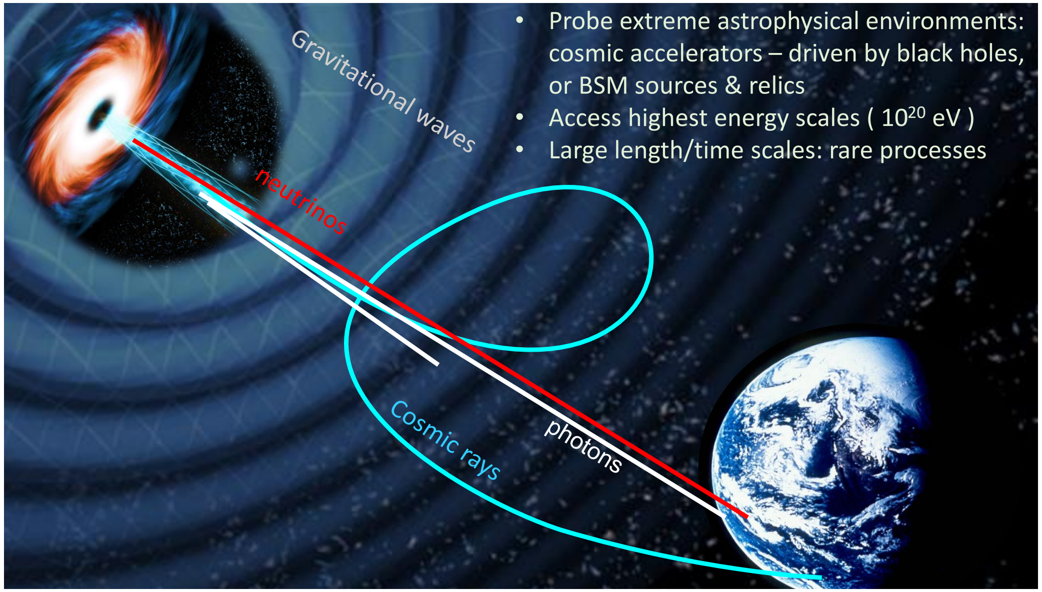


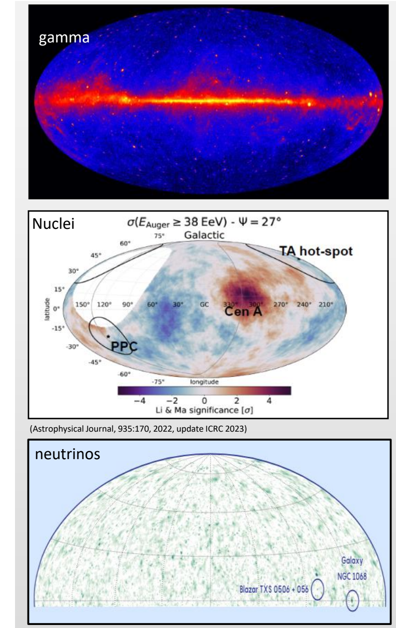


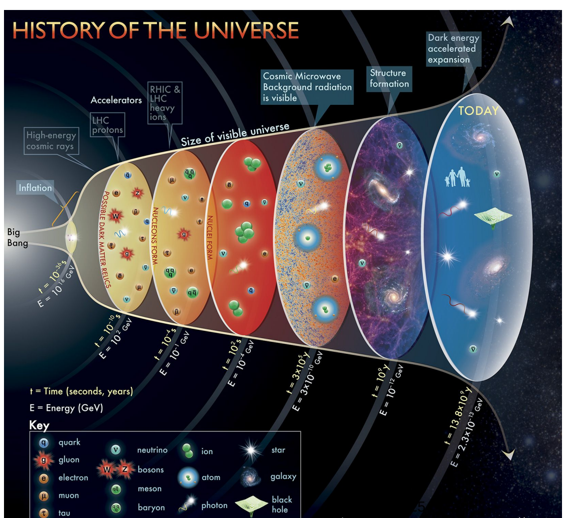


Cosmic Messengers (CRs, em, ν, GWs)

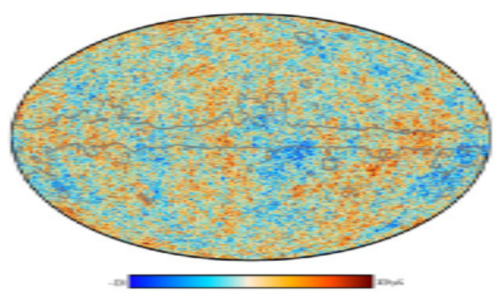
Astrophysical messengers





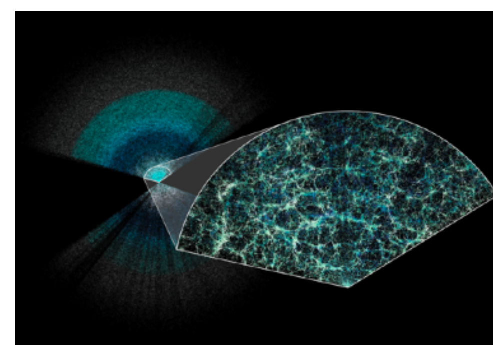


and Cosmic Relics



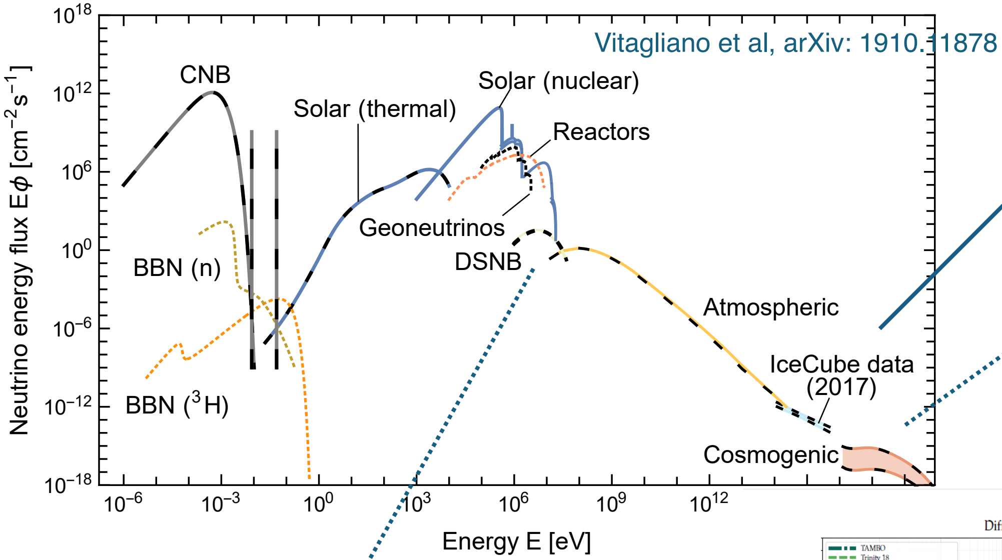
CMB

LSS



Neutrinos as cosmic messengers

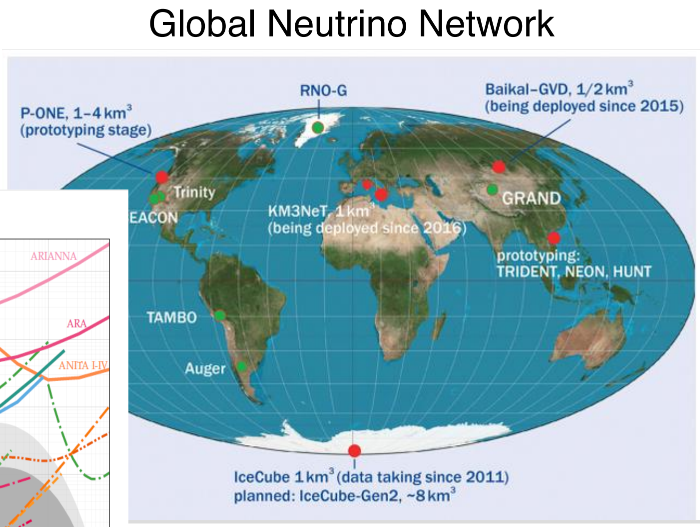
Cosmic neutrinos have been instrumental in establishing ν properties (solar, atmospheric, cosmic ν) and a model of the sun. Neutrinos at the highest energies are starting to point to sources. Other known neutrino fluxes await discovery (DSNB, cosmogenic,…)

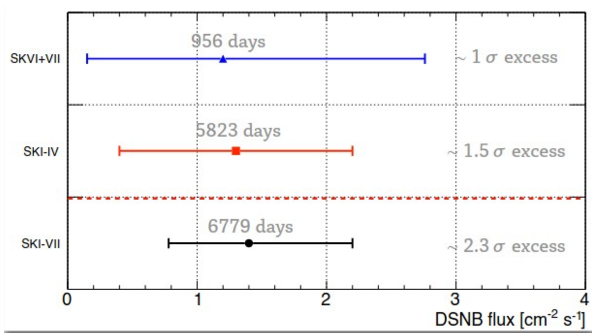


HE Cosmic Neutrinos (PeV)

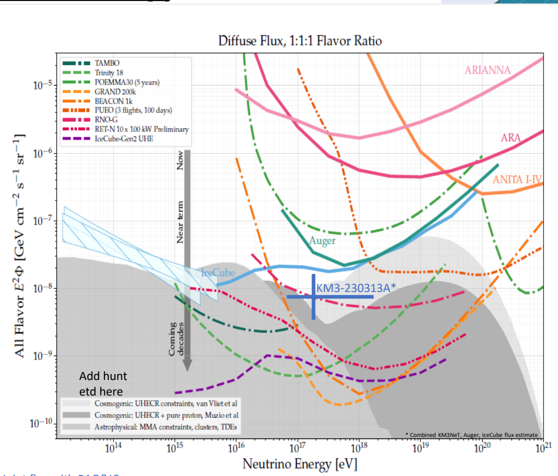
- Running: IceCube, KM3NET-ARCA, GVD
- Under construction: P-One

UHE Cosmic Neutrinos (PeV-EeV+)



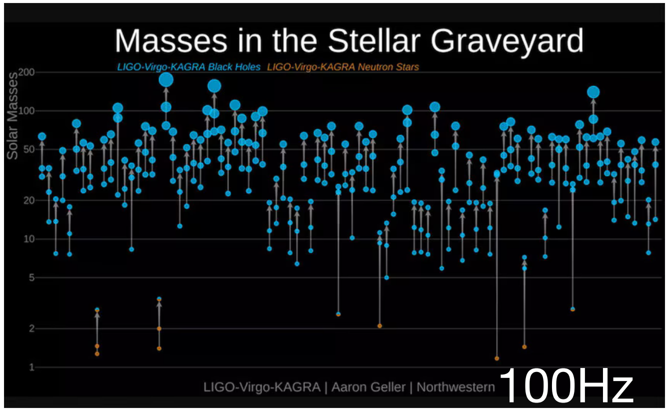


DSNB around the corner ?

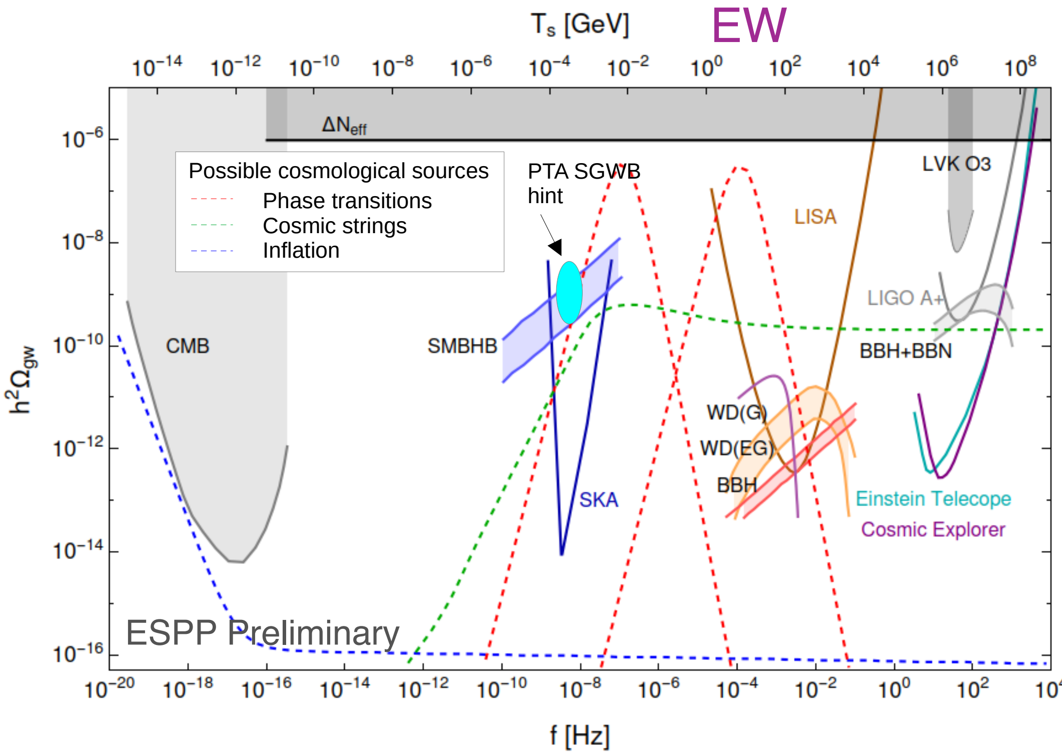


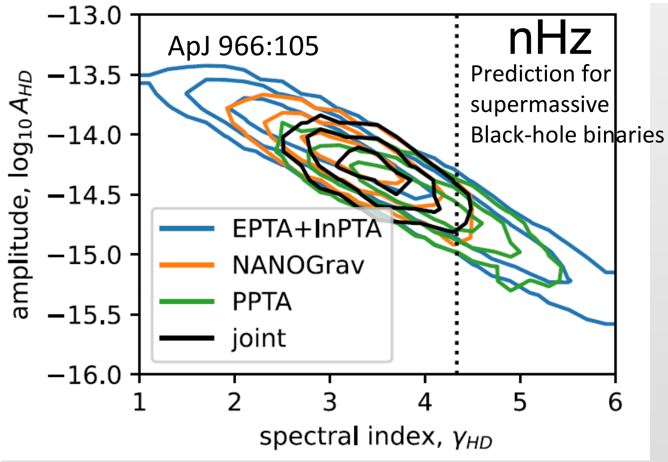
New detection strategies for the highest energies: radar, radio,lunar

Gravitational Waves as cosmic messengers

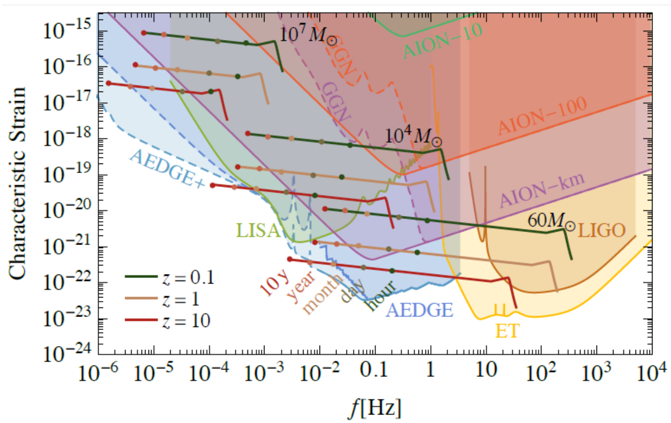


Prospects for Stochastic Gravitational Wave Background Searches





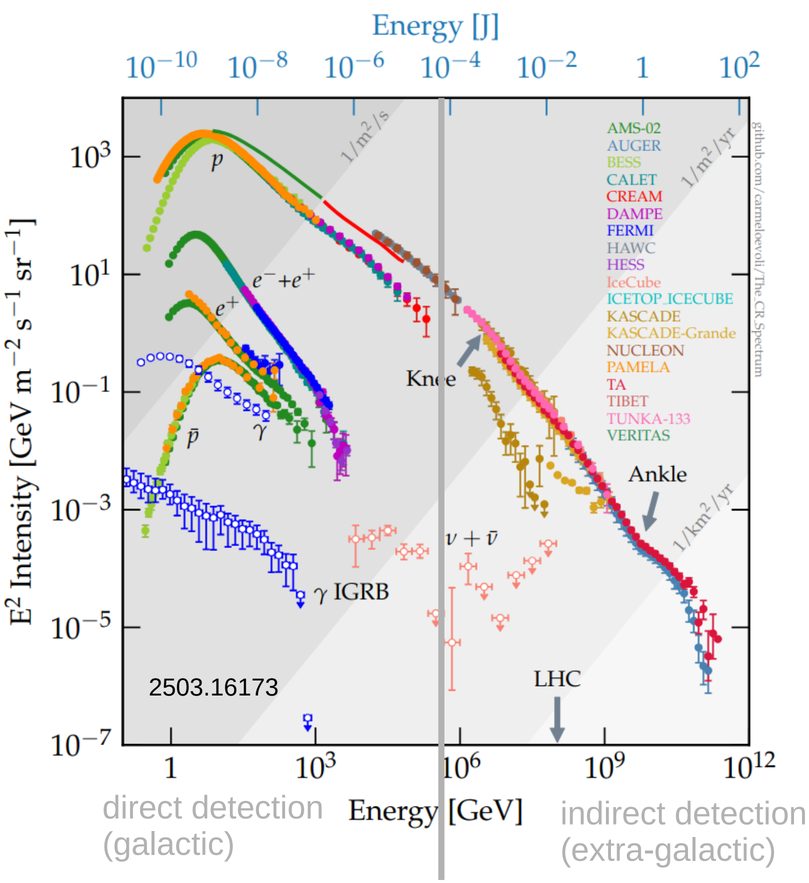
Extending spectral coverage:
atom interferometers +
R&D for higher frequencies…

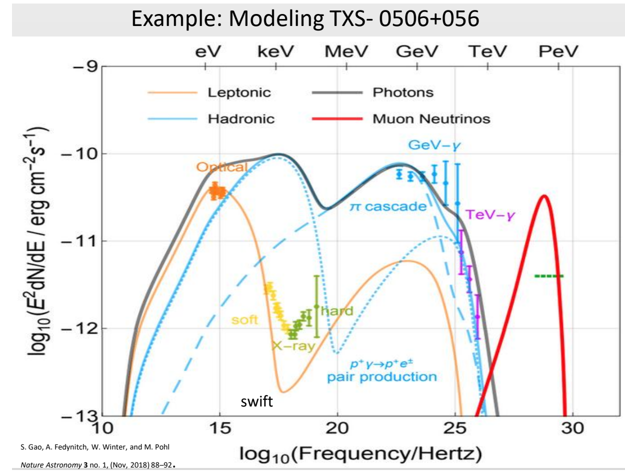


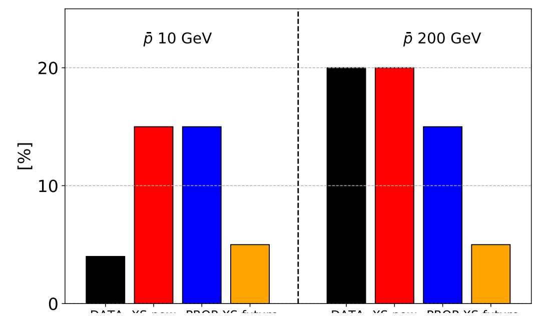
Stochastic GW ?

Understanding cosmic accelerators

- Spectrum at all CMs and energies crucial for modelling cosmic accelerators







Particle	Reaction	Measurement	$\sqrt{s}$	Sought precision
$\overline{p}$	$p + p \rightarrow \overline{p} + X$	σ_{inv}	5 to 100 GeV	$< 3\%$
	$p + He \rightarrow \overline{p} + X$			$< 5\%$
	$p + p \rightarrow \overline{\Lambda} + X$			$< 10\%$
	$p + He \rightarrow \overline{\Lambda} + X$			$< 10\%$
	$p + p \rightarrow \overline{n} + X$			$< 5\%$
	$p + n \rightarrow \overline{p} + X$			$< 5\%$

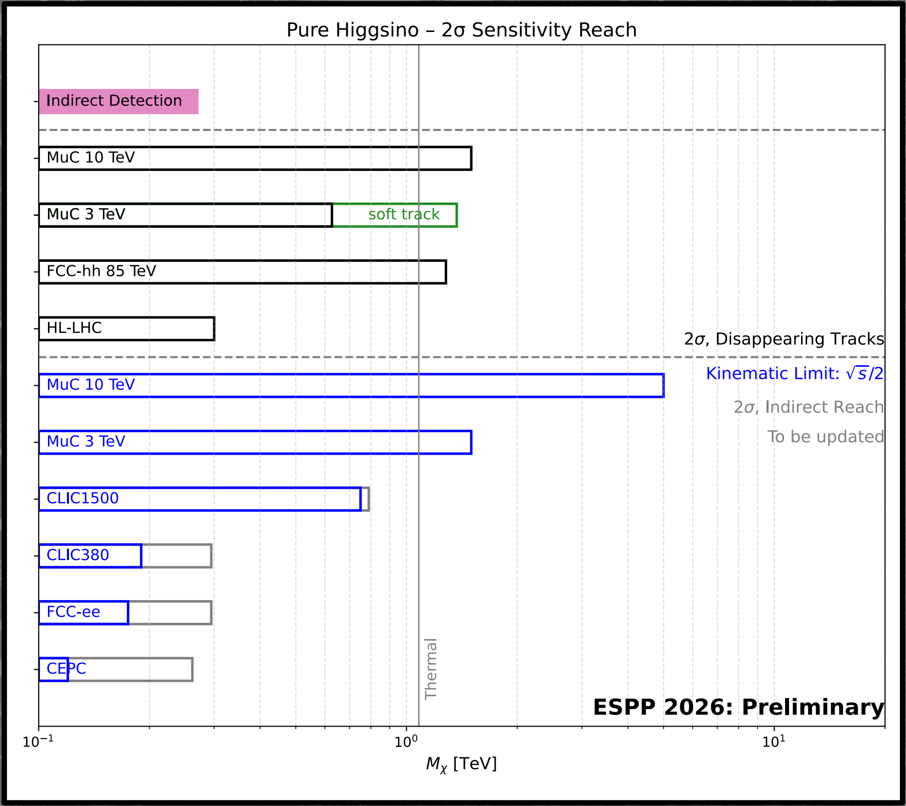
- Synergies w accelerator physics: need to understand particle/antiparticle production and propagation (LHCb-SMOG, ALICE, AMBER, NA61/SHINE, n-TOF, TOTEM, FASER, SND, FPF)

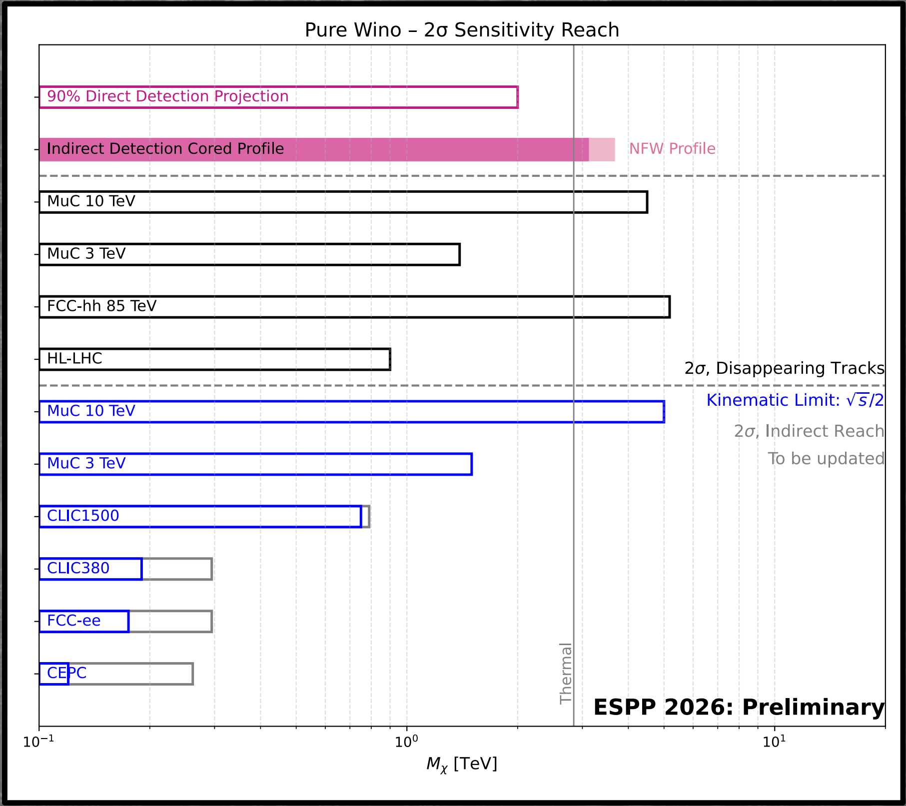
Conclusions

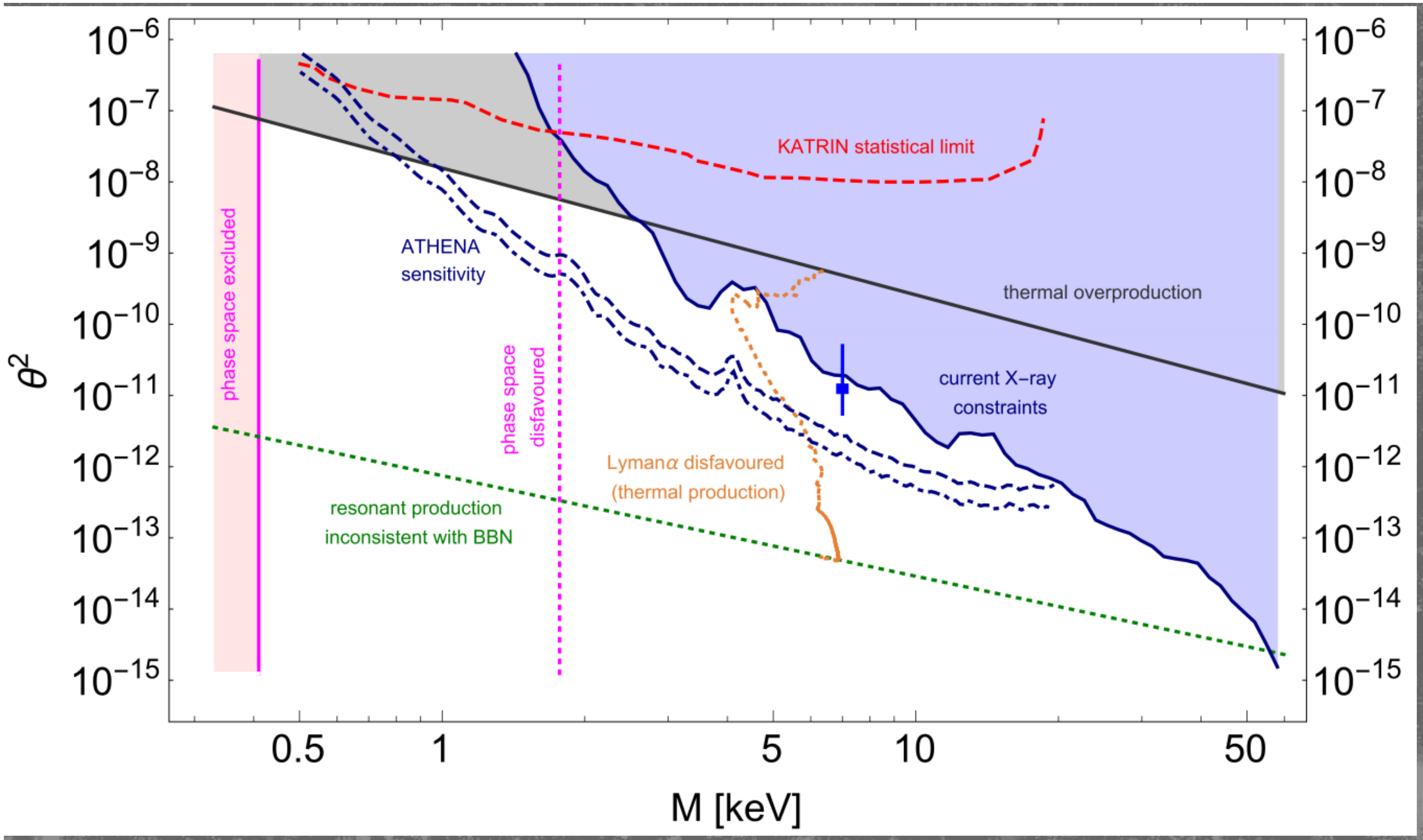
- The extension of the SM with massive neutrinos is incomplete: links to new physics and the matter-antimatter asymmetry compelling
- Neutrino experiments are unique facilities to search for new physics (both at high energy and feably interacting sectors): eg. proton decay, light sterile neutrinos, heavy neutral leptons,..
- Dark Matter remains the biggest conundrum in our understanding of the cosmos. A dark extension of the SM could take many faces: diversity and complementarity of experimental approaches is crucial (new avenues in direct DM detection, cosmic messengers and colliders/accelerators)
- Cosmic messengers provide essential information on neutrino and dark matter properties, and are unique probes of the most powerful cosmic accelerators. Cosmic relics/backgrounds from the Big Bang (eg. BBN,CMB,LSS) provide a window on the Early Universe (future CνB and GWB can bring us to pre-BBN times)
- Neutrino/Dark Matter/Cosmic messenger & collider/accelerator science not only target the same fundamental physics questions, but can complement and enhanced each other's physics reach
- There are also strong technological synergies: cryogenics, detector technologies, large project management, data simulation and analysis methods & tools.

A flourishing experimental program is underway: major discoveries and high-impact science expected in the next decade. Any discovery will require confirmation by different experiments and techniques with independent systematics !

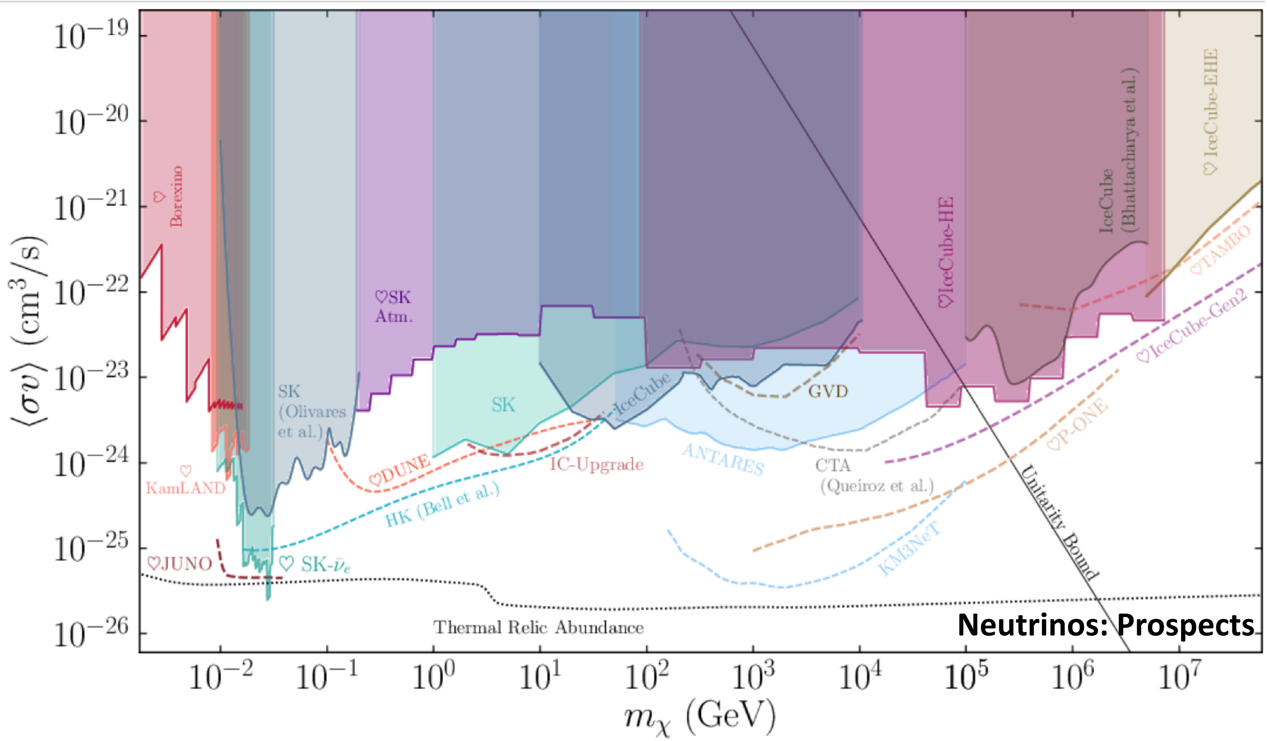
Fate of the Ino







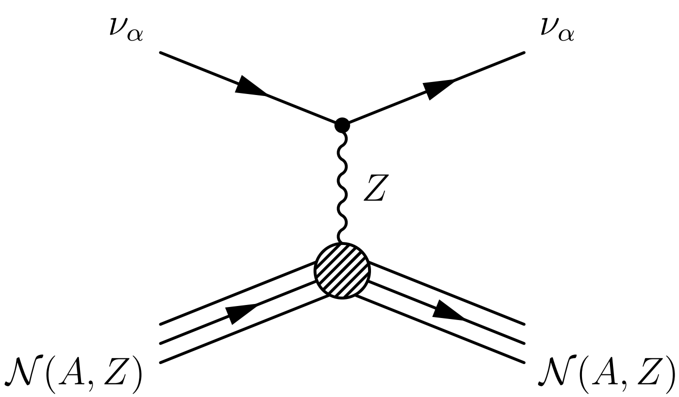
Boyarsky+ 1807.07938



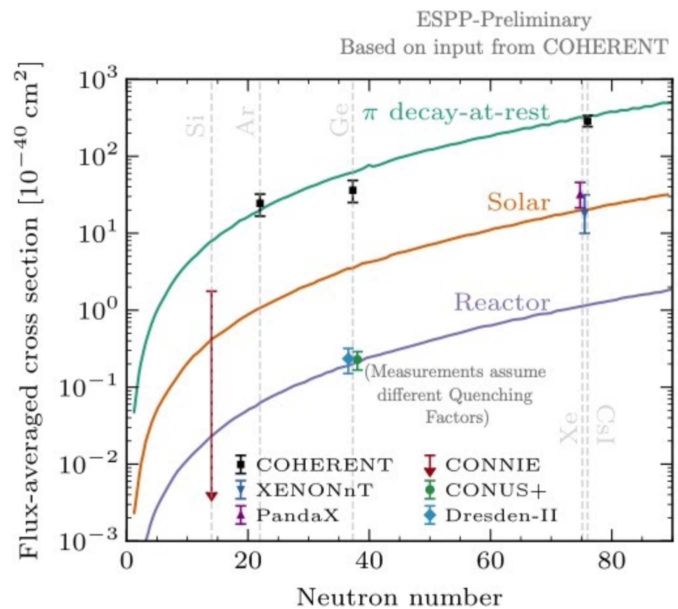
Neutrinos: Prospects
⟨σv⟩ (cm³/s)
m_χ (GeV)
10⁻¹⁹
10⁻²⁰
10⁻²¹
10⁻²²
10⁻²³
10⁻²⁴
10⁻²⁵
10⁻²⁶
10⁻²
10⁻¹
10⁰
10¹
10²
10³
10⁴
10⁵
10⁶
10⁷
♡ Borexino
♡ KamLAND
♡JUNO
♡ SK-$\bar{\nu}_e$
SK (Olivares et al.)
♡SK Atm.
SK
♡DUNE
HK (Bell et al.)
IC-Upgrade
IceCube
ANTARES
GVD
CTA (Queiroz et al.)
KM3NeT
♡IceCube-HE
IceCube (Bhattacharya et al.)
♡ IceCube-EHE
♡TAMBO
♡IceCube-Gen2
♡P-ONE
Unitarity Bound
Thermal Relic Abundance

New explorations in neutrino physics

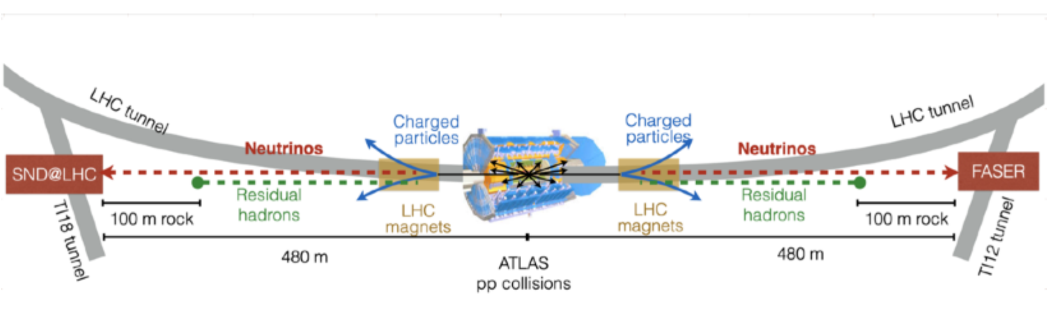
Coherent Neutrino Scattering $E\nu < 50$MeV (nuclear recoils < keV)



D. Freedman '74



O(100 evts) TeV-neutrinos from the LHC detected by FASER & SND

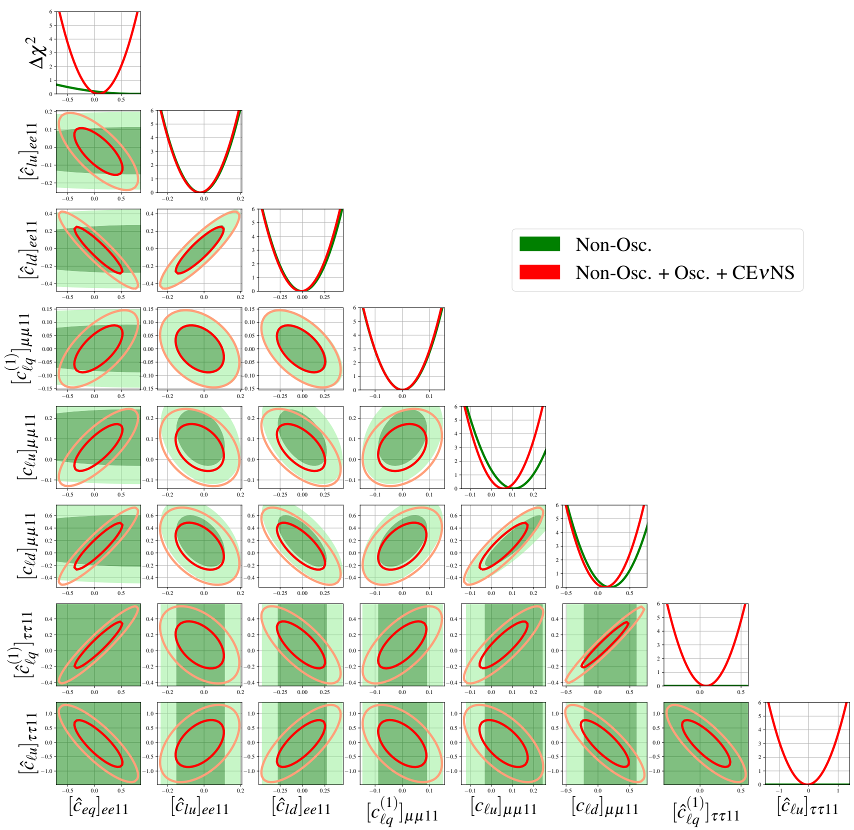


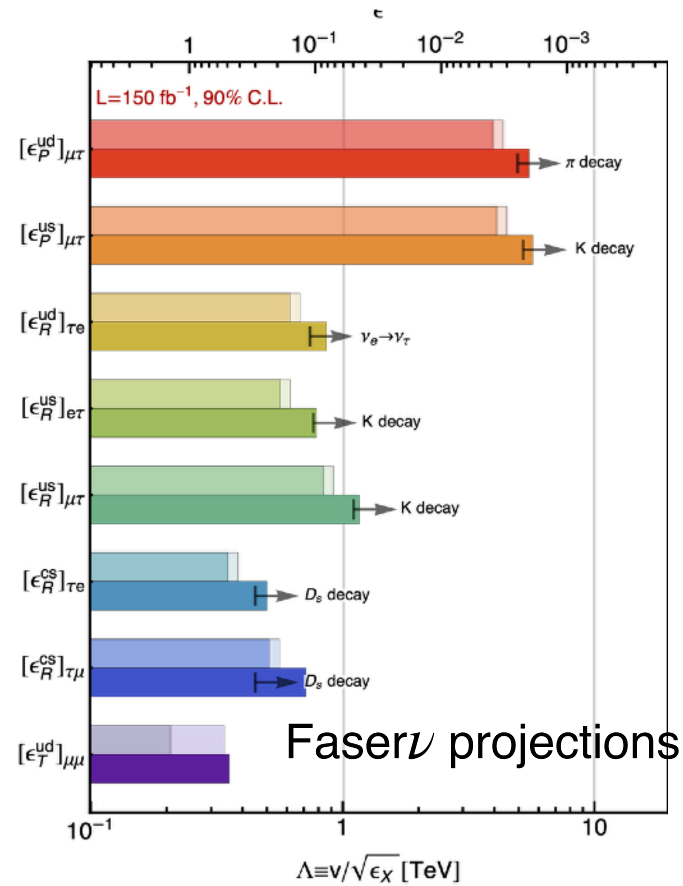
Complementary to Icecube/KM3NET

- σ_ν@TeV
- Neutrino flux: forward charm production, gluon PDF
- LFU

SMEFT: non-standard neutrino interactions

The most general d=6 SMEFT is very complex and constraining it from data under no flavour assumptions a daunting task: neutrino constraints are important !





Coloma et al arXiv: 2411.00090
Bresó-Pla et al arXiv: 2301.07036

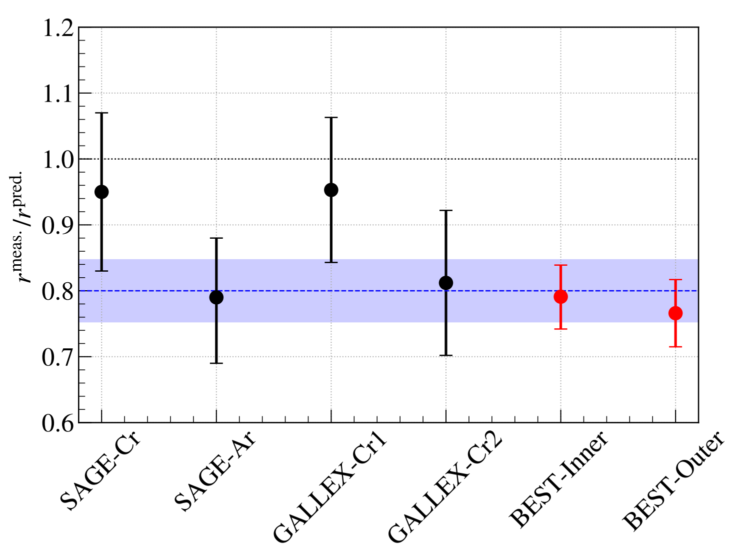
Falkowski et al arXiv:2105.12136

-> J. Kopp parallel talk

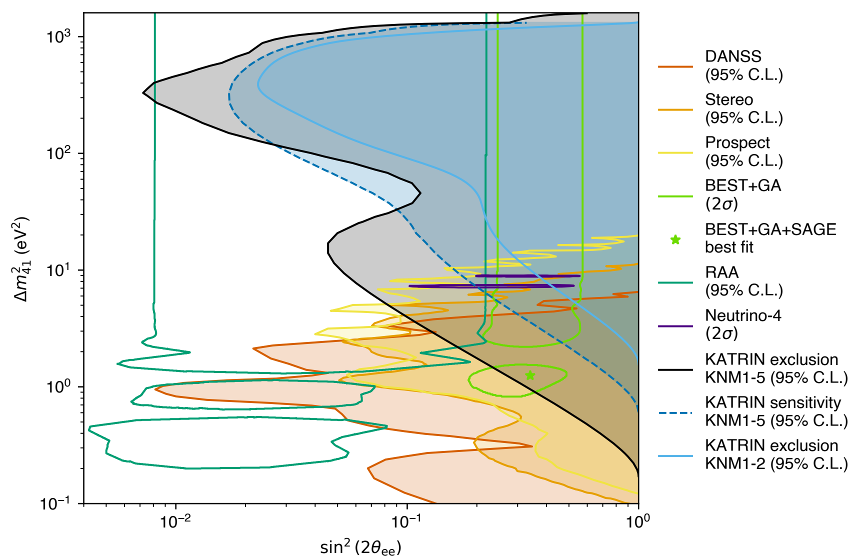
Light Sterile Neutrinos

Standard explanation to neutrino anomalies: LSND/MiniBoone, Reactor, Gallium,...

- MiniBoone/MicroBoone: tensions arising in data (more by SBN@FNAL)
- Reactor anomaly dissolving in flux systematics
- L/E dependence not observed by 5/6 experiments (NEOS, STEREO, PROSPECT, DANSS, SOLID, Neutrino4)
- Gallium anomaly still there but light sterile neutrino explanation excluded by KATRIN !



Barinov et al, 2201.07364



Acharya et al, 2503.18667