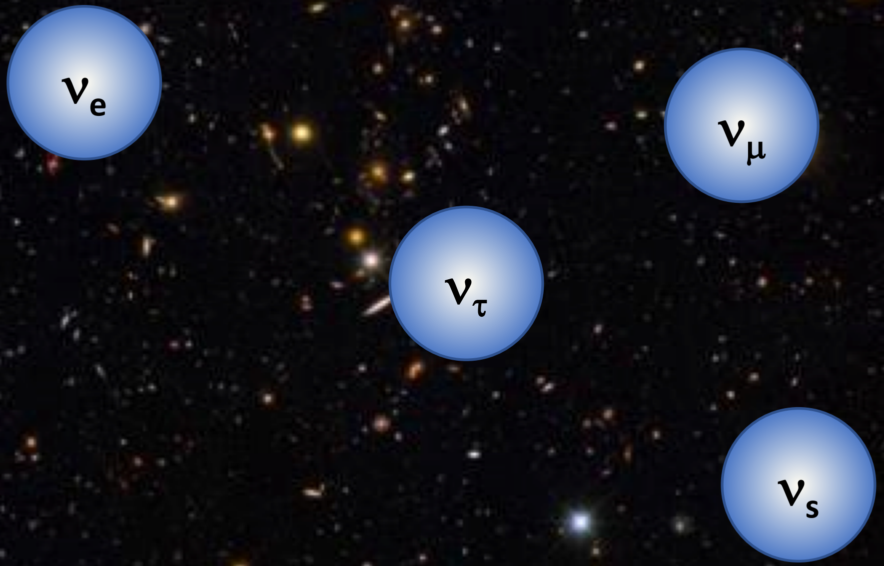
Town Meeting



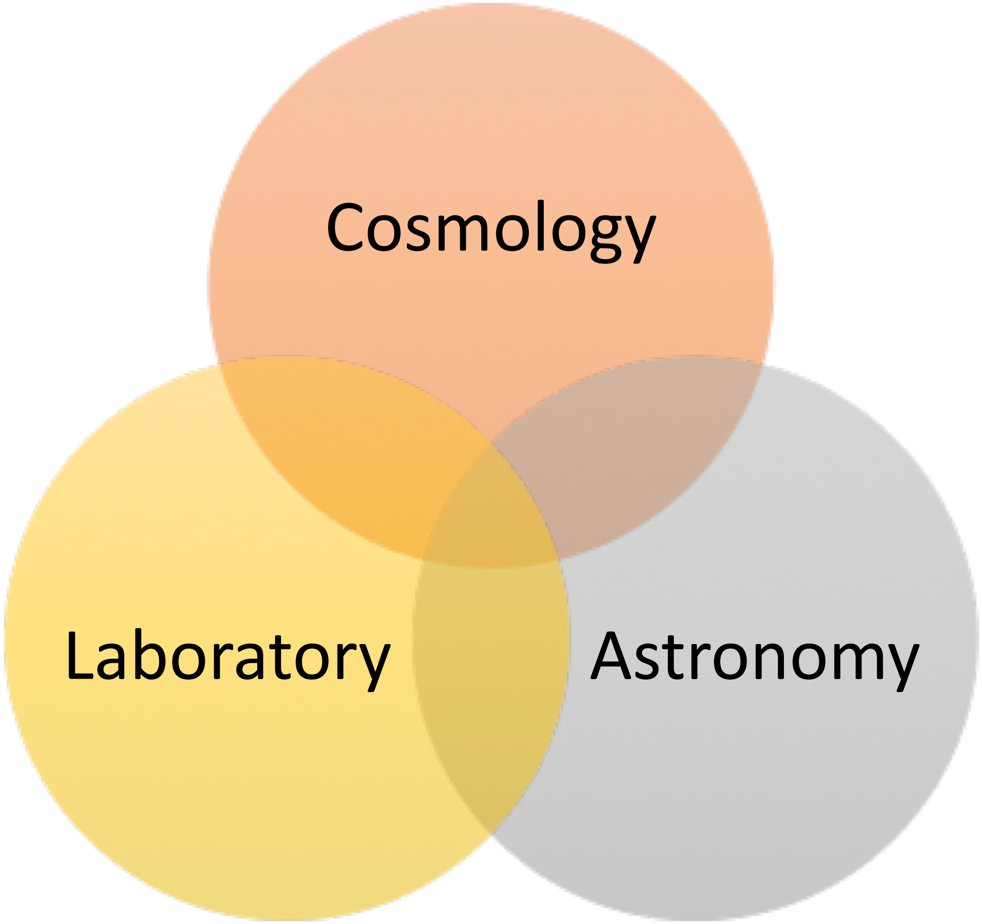
Panel 3: "Neutrinos and the Universe”

Alexey Boyarsky, Steen Hannestad, Marek Kowalski, Julien Lesgourgues, Luis Labarga, Susanne Mertens, Mikhail Shaposhnikov

October 24, 2018

Questions

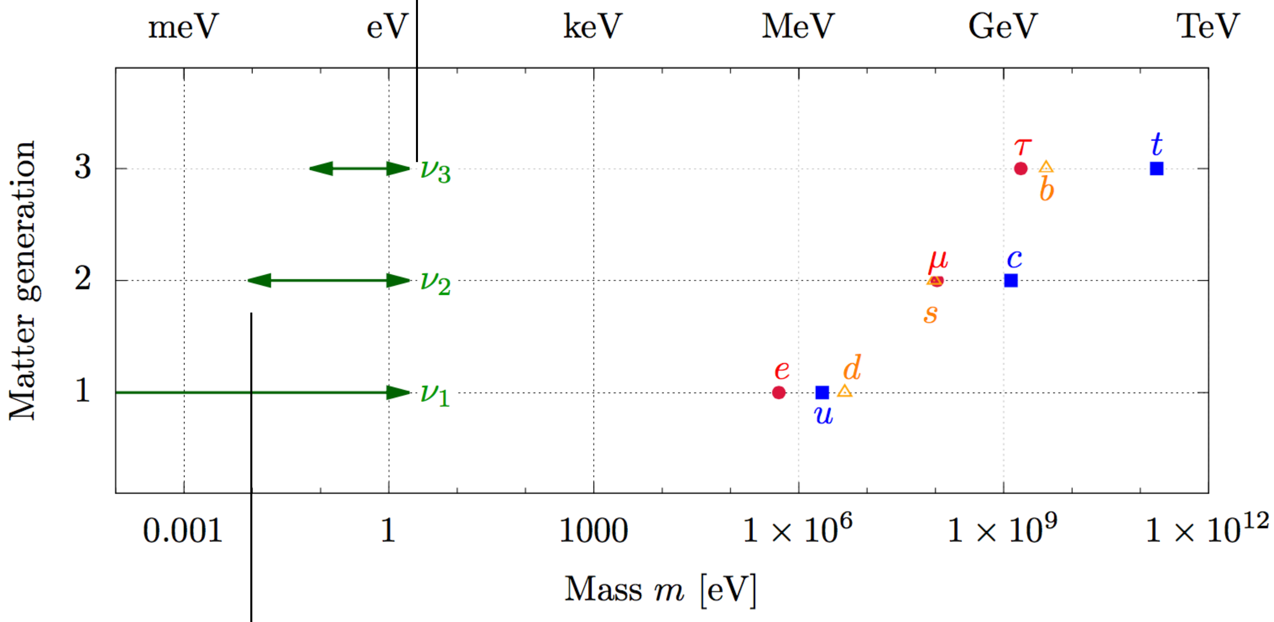
- What is the neutrino mass?
- How can we explain the baryon asymmetry of the universe?
- Sterile neutrinos as dark matter?
- What is the number of light neutrino species?
- What is the origin of UHE neutrinos?



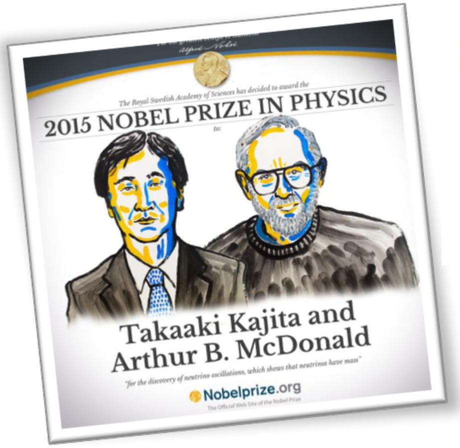
Susanne Mertens

Neutrino Mass

Upper bound
from laboratory measurements

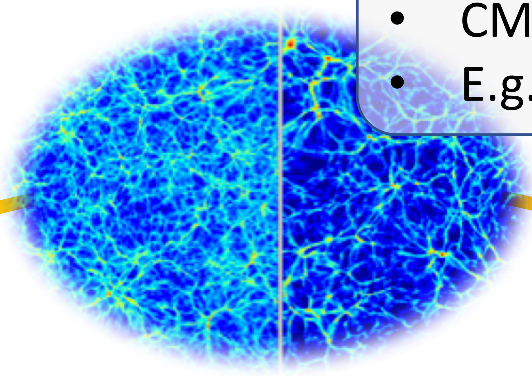


Lower bound
from oscillation experiments



Neutrino mass probes

Cosmology
- CMB, BAO, LSS
- E.g. LiteBIRD, CMB-S4, DESI BAO, Euclid, etc.



Astronomy
- Supernova explosions
- E.g. Hyper-K, Juno, Dune, IceCube, etc.

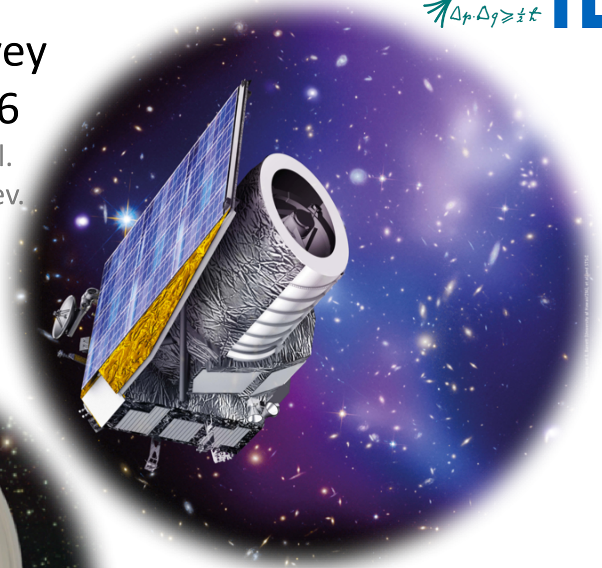
Laboratory
- Single and double beta decay
- E.g. $0\nu\beta\beta$ exp., KATRIN, ECHo, etc.

Cosmology: Future

LiteBIRD
CMB-polarization
2020 – 2025
A. Suzuki et al. doi:10.1007/s10909-018-1947-7 arXiv:1801.06987

CMB-S4
CMB-lensing
2020 – 2024
K. N. Abazajian et al. [CMB-S4 Collaboration], arXiv:1610.02743

DESI-BAO
Galaxy survey
2019 – 2024
A. Aghamousa et al. [DESI], arXiv:1611.00036



EUCLID
Galaxy survey
2021 – 2026
L. Amendola et al. [Euclid], Living Rev. Rel. 16 (2013) 6v

Cosmic Microwave Background

- $\sigma(\sum m_\nu) \sim 0.05$ eV

+ Baryonic acoustic oscillations

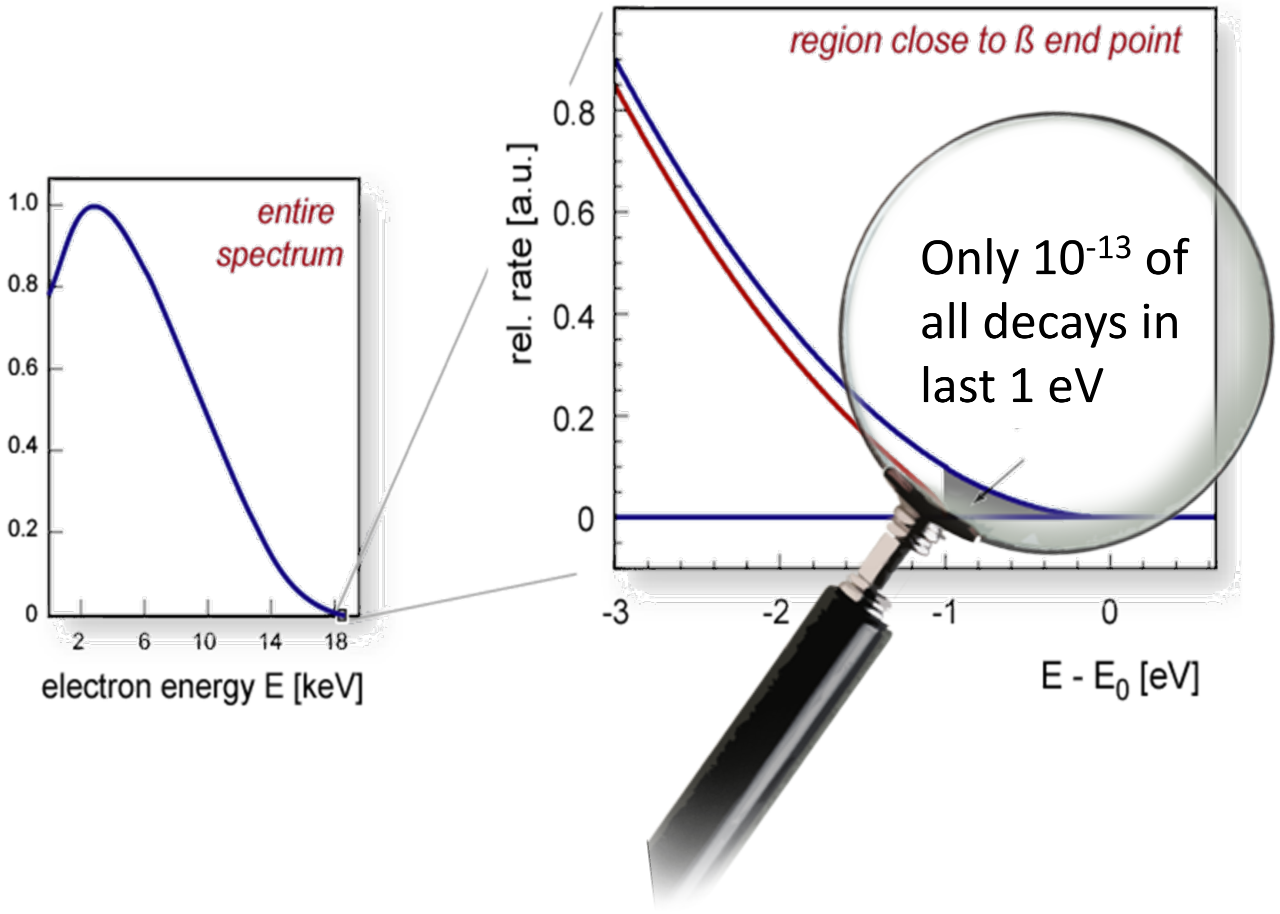
- $\sigma(\sum m_\nu) \sim 0.02$ eV

+ + Late-time structure formation

- $\sigma(\sum m_\nu) \sim 0.01$ eV

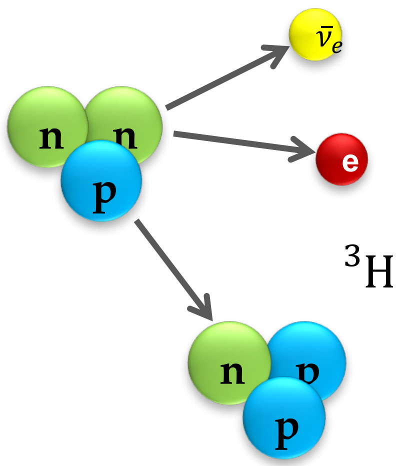
Laboratory: Idea

- Kinematic determination of the neutrino mass
- Non-zero neutrino mass reduces the endpoint and distorts the spectrum
- Challenges:
  - High signal rate:
    low endpoint, short half-life
  - Low background
  - Excellent energy resolution (~ 1 eV)
  - Precise understanding of spectral shape



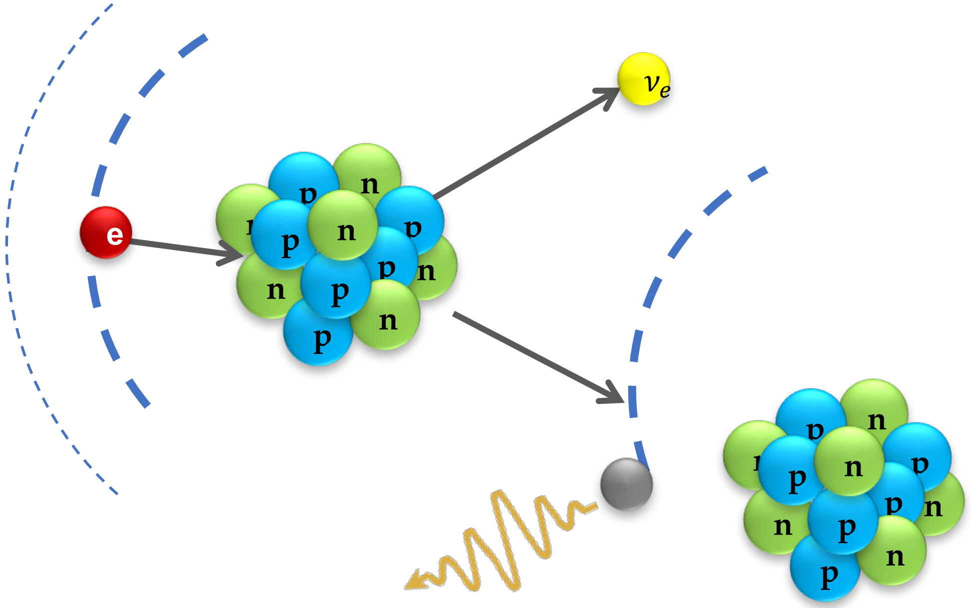
Susanne Mertens

Laboratory: Probes



$$^{3}\mathrm{H} \rightarrow \, ^{3}\mathrm{He}^{+} + e^{-} + \bar{\nu}_e$$

$$^{163}\mathrm{Ho} \rightarrow \, ^{163}\mathrm{Dy}^{*} + \nu_e$$
$$^{163}\mathrm{Dy}^{*} \rightarrow \, ^{163}\mathrm{Dy} + E_C$$



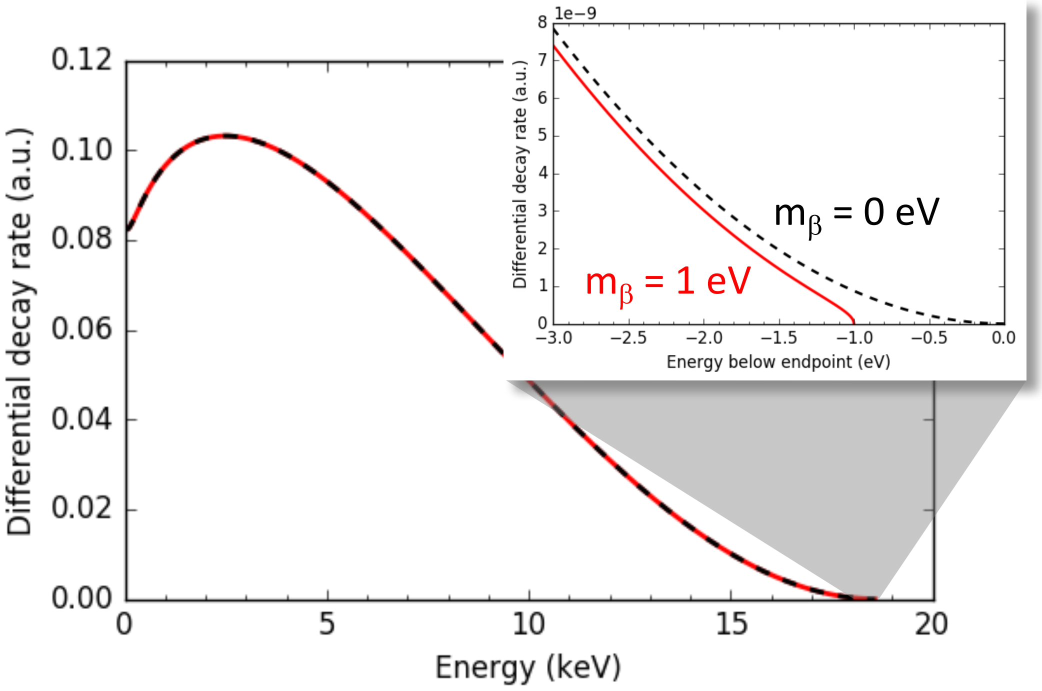
Super-allowed beta-decay of tritium

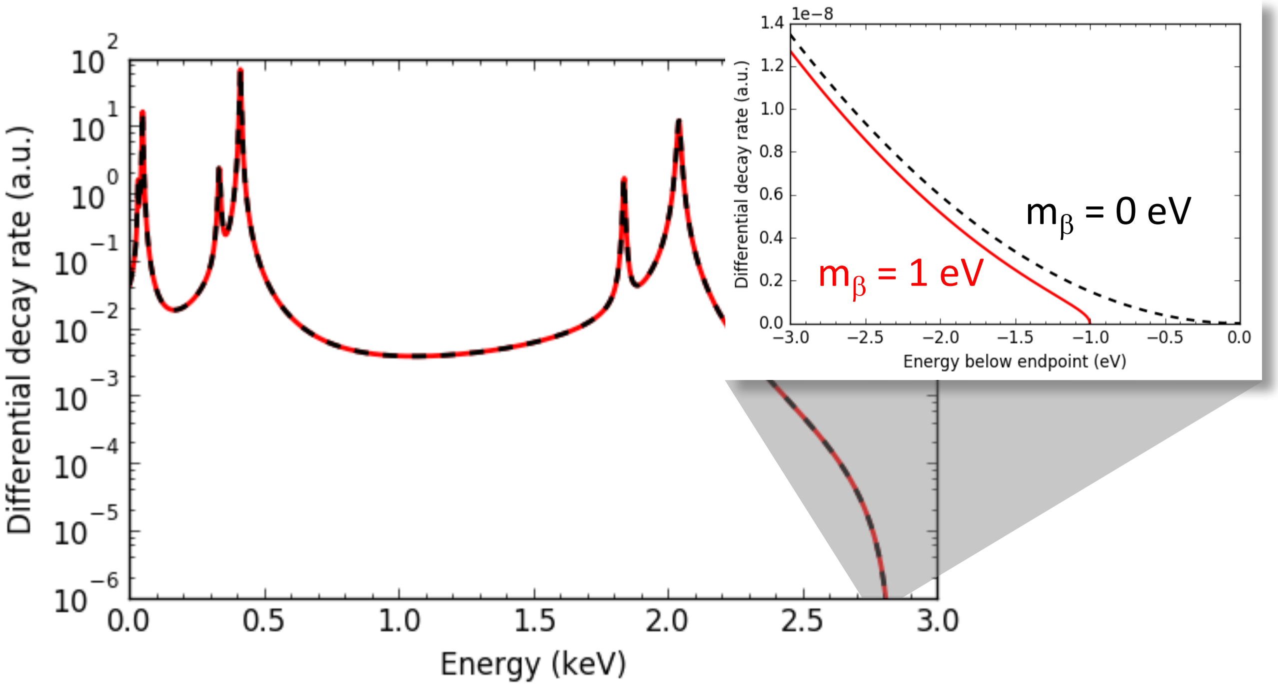
- $T_{1/2}$ = 12.3 years
- E_0=18.6 keV

Electron capture of 163-holmium

- $T_{1/2}$ = 4500 years
- E_0=2.8 keV

Laboratory: Probes





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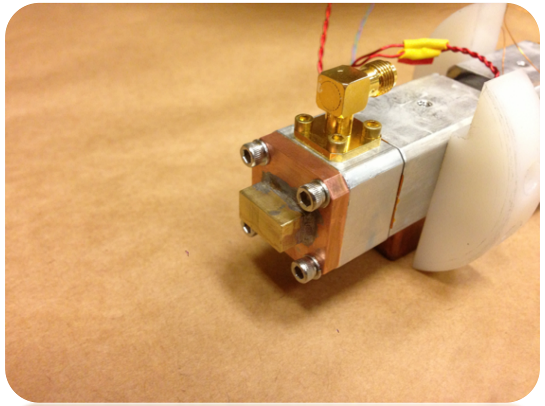
Laboratory: Experiments

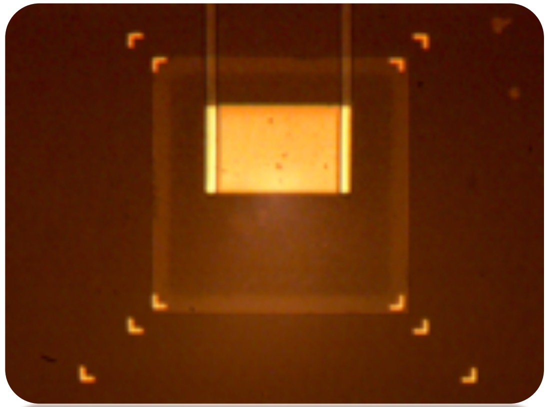
Tritium

MAC-E-Filter
(KATRIN)



Cyclotron Radiation
Emission Spectroscopy
(Project-8)

Holmium



Micro-Calorimetry
(HoLMES, ECHo,
NuMecs)

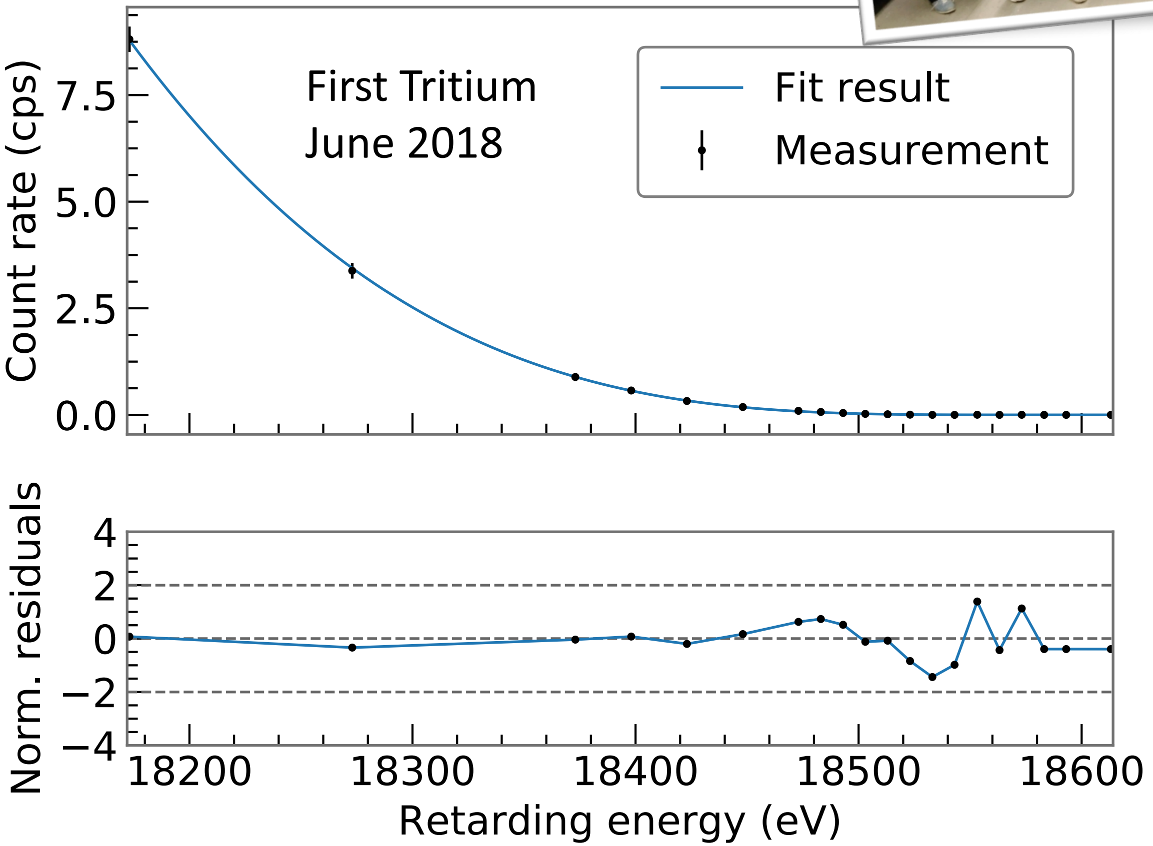
G. Drexlin V. Hannen, S. Mertens, and C. Weinheimer Adv. High Energy Physics 2013
L. Gastaldo et al 2014 J. Low Temp. Phys. 176 876
B. Alpert et al 2015 Eu. Phys. J. C 7 112
B. Monreal and J. A. Formaggio 2009 Phys. Rev. D 80

Laboratory: Experiments

Tritium

KATRIN

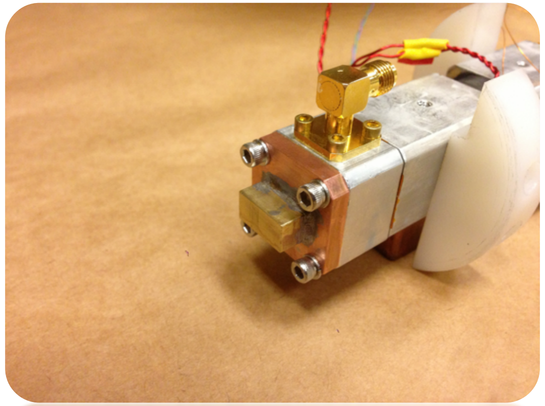
- First Tritium in June 2018
- Start nu-mass measurement: March 2019
- **Goal: 200 meV after 5 calendar years in 2023**



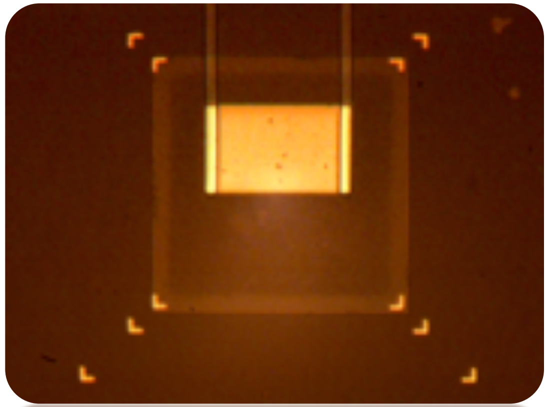
Laboratory: Experiments

Further future: Ptolemy project (arXiv:1810.06703)

Tritium



Holmium



KATRIN

- First Tritium in June 2018
- Start nu-mass measurement: March 2019
- **Goal: 200 meV after 5 calendar years in 2023**
- New ideas: e.g. time of flight mode

Project-8

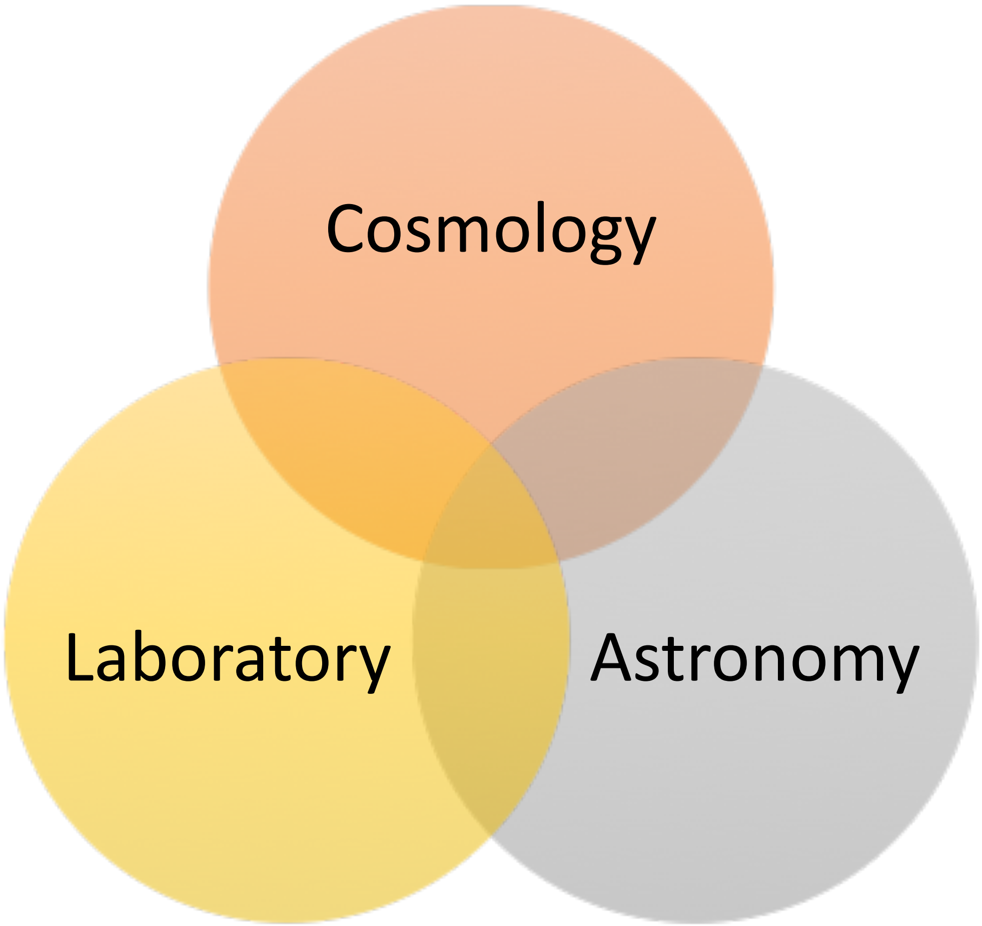
- Proof of principle in 2015
- Tritium measurements just started
- Advantage: Scalability
- **Goal: 40 meV with atomic tritium source**

ECHo, Holmes

- High-statistics Ho-spectra recorded
- Advantage: Scalability
- **Goal: Sub-eV sensitivity in 2021**

Questions

- What is the neutrino mass?
- **How can we explain the baryon asymmetry of the universe?**
- **Sterile neutrinos as dark matter?**
- **What is the number of light neutrino species?**
- What is the origin of UHE neutrinos?

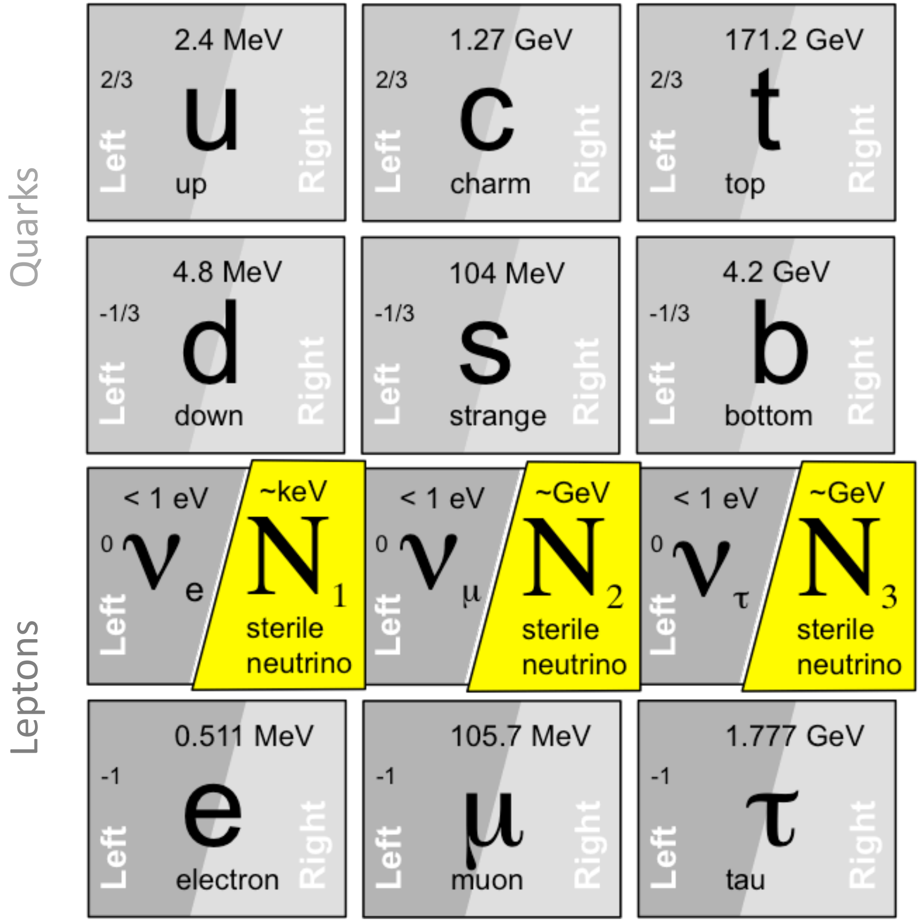


Nu-mass and **Beyond**

Introduction of **right-handed neutrinos** to the Standard Model of Particle Physics:

- Natural way to explain neutrino mass
- New (almost sterile) neutrino mass eigenstates (of arbitrary scale)

➢ Rich phenomenology



L. Canetti, M. Drewes, and M. Shaposhnikov, PRL **110** 061801 (2013)

Nu-mass and **Beyond**

Heavy sterile neutrinos (> GeV)

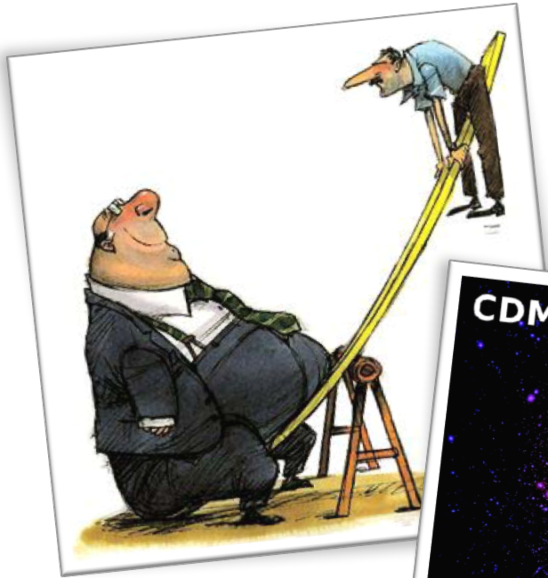
- Lightness of neutrinos
  + Baryonic asymmetry of the universe

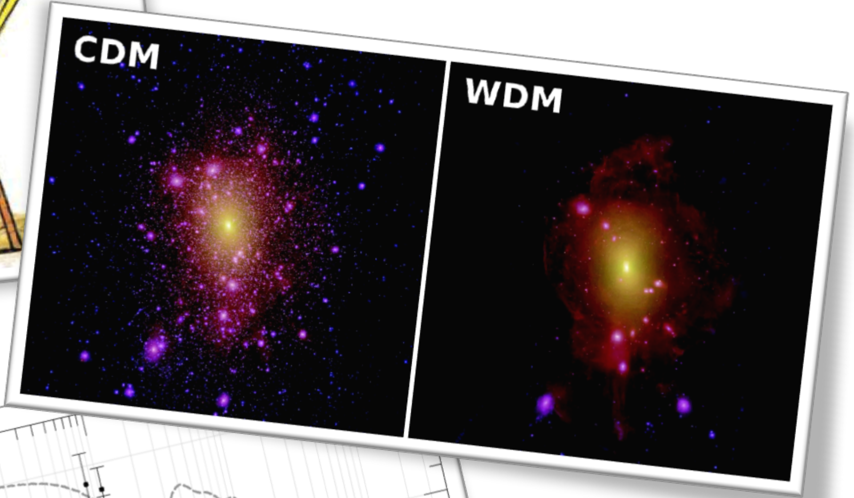
KeV-scale sterile neutrinos (~ 1 - 50 keV)

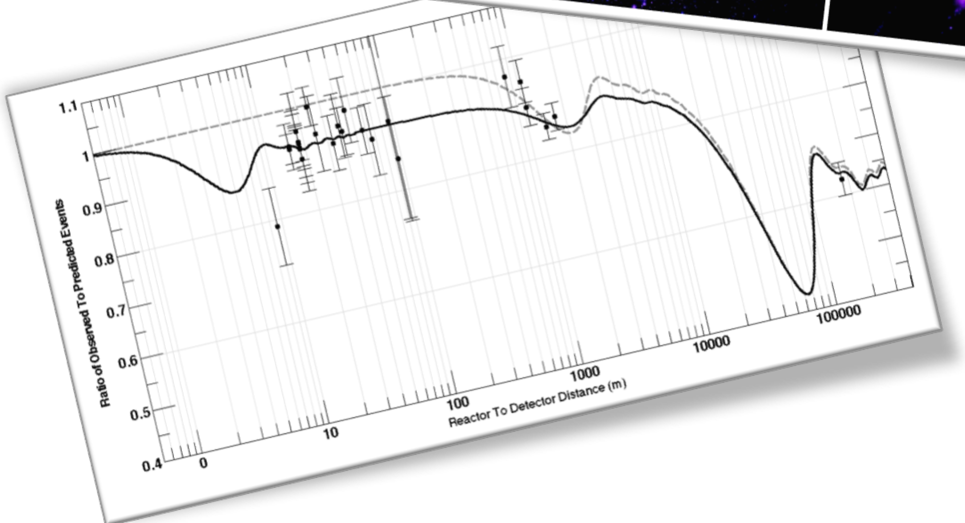
- Dark matter candidate

Light sterile neutrinos (~1 eV)

- Short-baseline neutrino oscillation anomalies







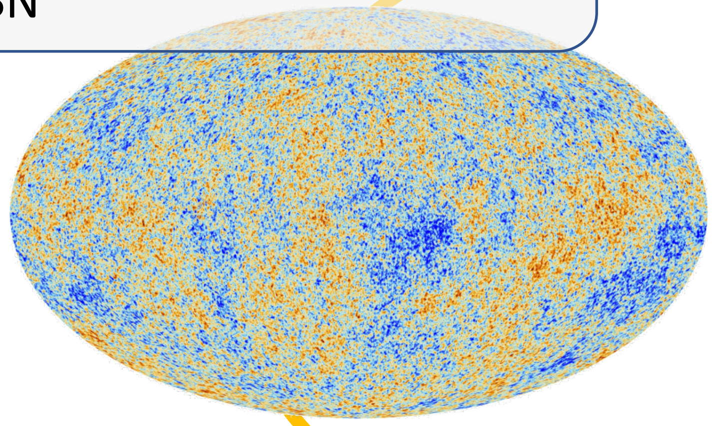
Baryon asymmetry: Probes

Cosmology

- Baryon-to-photon ratio
- CMB, BBN

Laboratory

- Search for relatively light Majorana leptons
- Measurement of the CP-phases in neutrino mixing
- Search for neutrinoless double beta decay



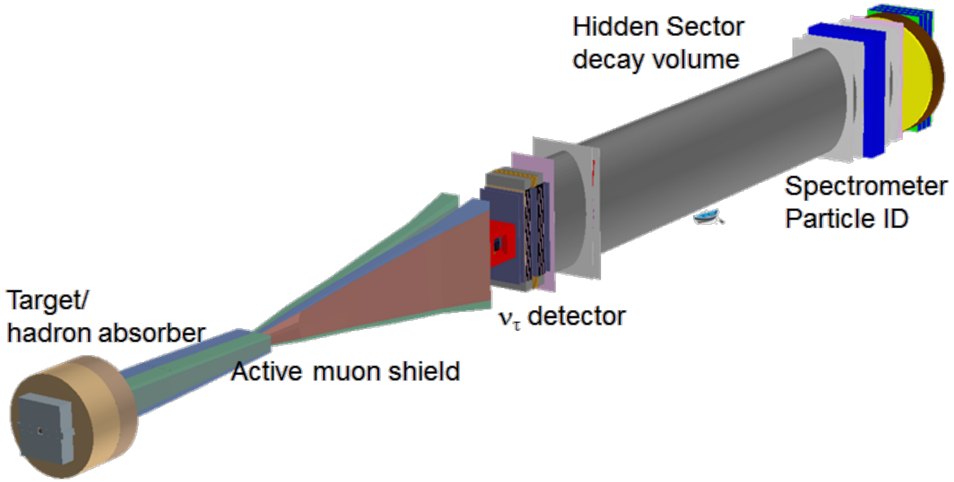
Search for "light" Majorana leptons

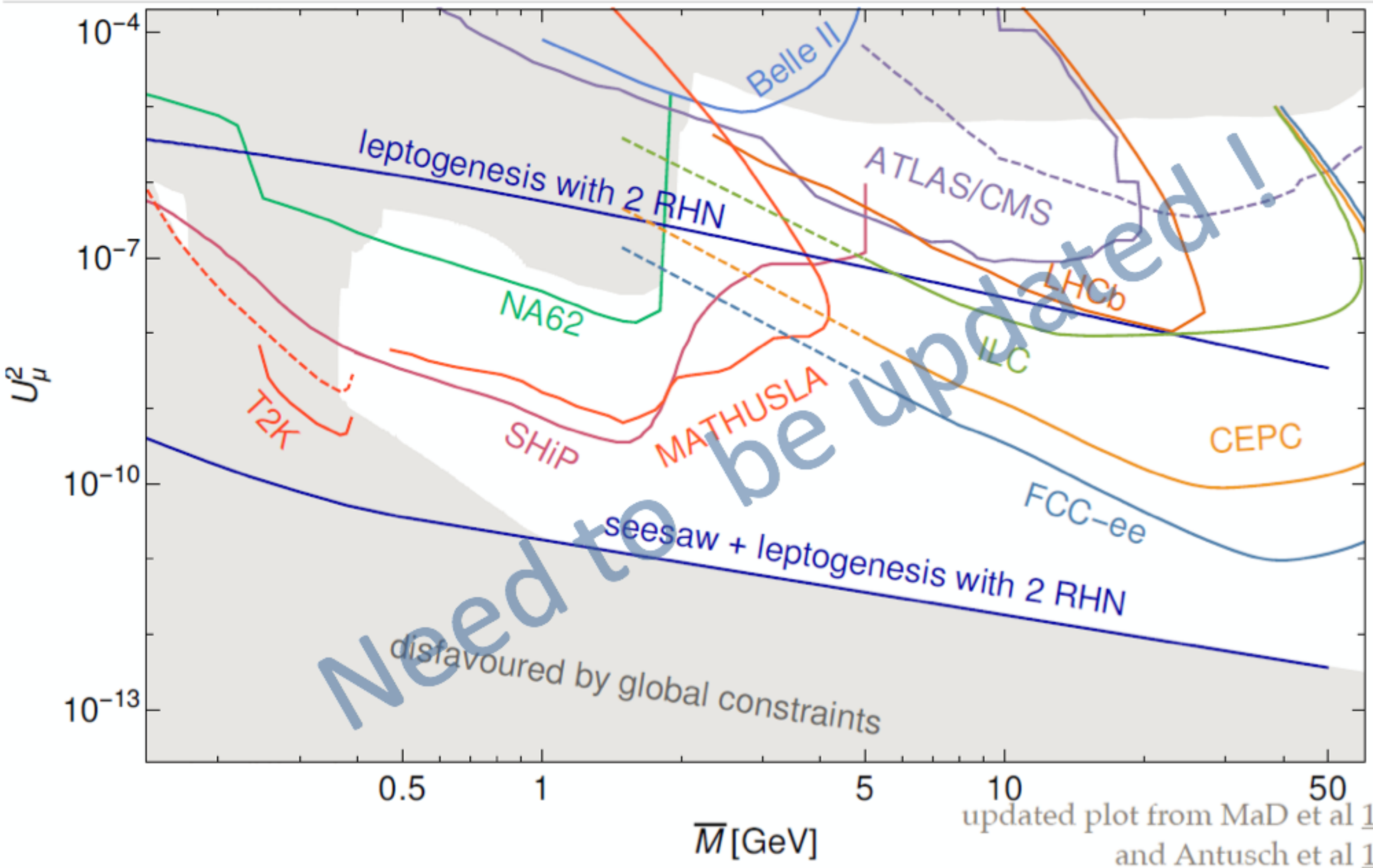
High energy frontier (GeV – TeV)

- e.g. Future Circular Collider

High intensity frontier (~ GeV)

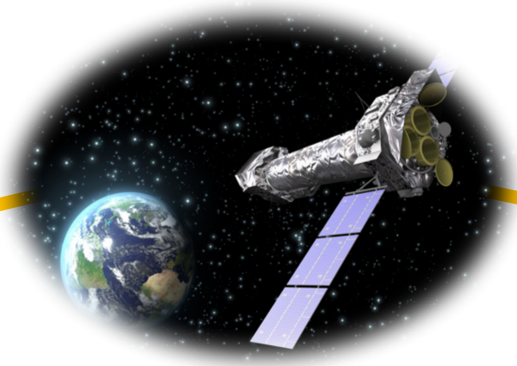
- e.g. ShiP





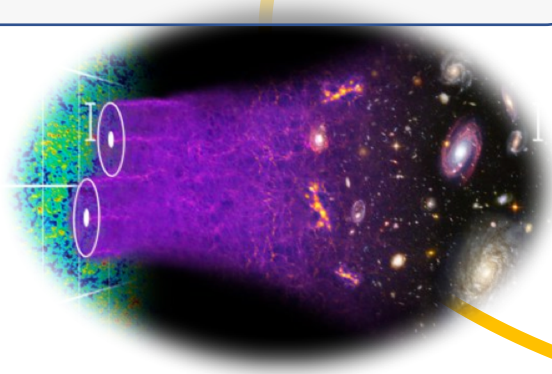
updated plot from MaD et al 1609.09069
and Antusch et al 1710.03744
cf. also Cai et al 1711.02180

Sterile neutrino dark matter: Probes



Astronomy
- Mono-energetic x-ray detection
- e.g. Chandra, XMM Newton, Athena X-IFU

Cosmology (Warm dark matter)
- Galactic structures via Lyman-alpha
- BBN
- e.g. BOSS

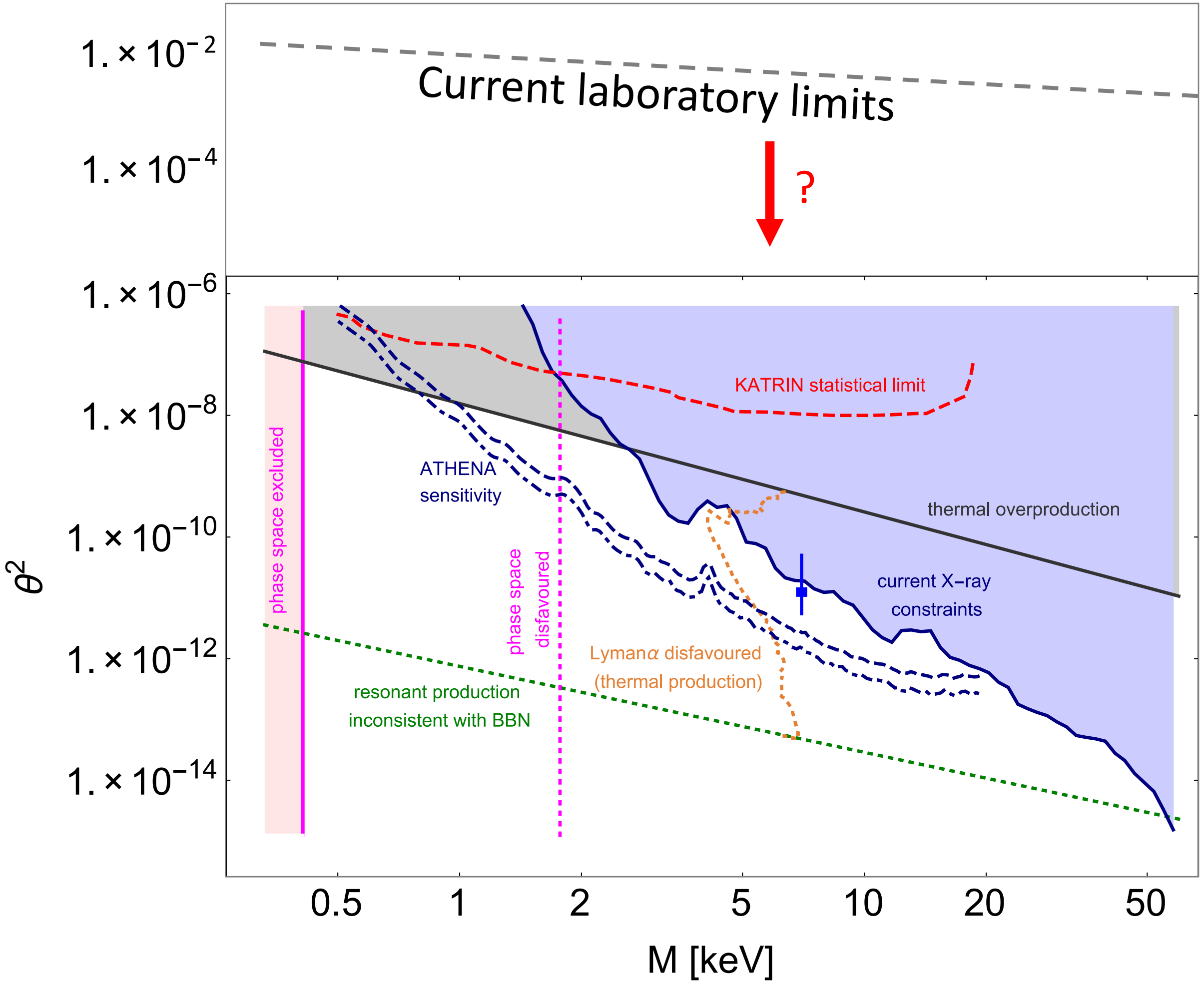


Laboratory
- Direct Detection
- Kinematics of beta decay
- e.g. KATRIN/TRISTAN

Boyarsky, M. Drewes, T. Lasserre, S. Mertens and O. Ruchayskiy, Rep. Prog. Nucl. Part. Phys. [arXiv:1807.07938 [hep-ph]]

Sterile neutrino dark matter: Probes

- Strong limits (and hints) from astrophysical and cosmological probes
- New ideas for laboratory experiments:
  - Direct detection via
    - Inverse beta decay
      Y. F. Li and Z.-z. Xing, *Phys. Lett.,* vol. 695, 2011.
      T. Lasserre, K. Altenmueller, et al., *arXiv:1609.04671 [hep-ex],* 2016.
    - Elastic Scattering
      M. D. Campos and W. Rodejohann, *Phys. Rev.,* vol. D94, 2016.
  - Kinematics of beta decay:
    - Full kinematic reconstruction
      F. Bezrukov and M. Shaposhnikov, *Phys. Rev. D,* vol. 75, 2007.
      P. Smith, arXiv:1607.06876, 2017
    - Spectral analysis
      S. Mertens et al., *J. Cosmol. Astropart. Phys.,* vol. 02, 2015



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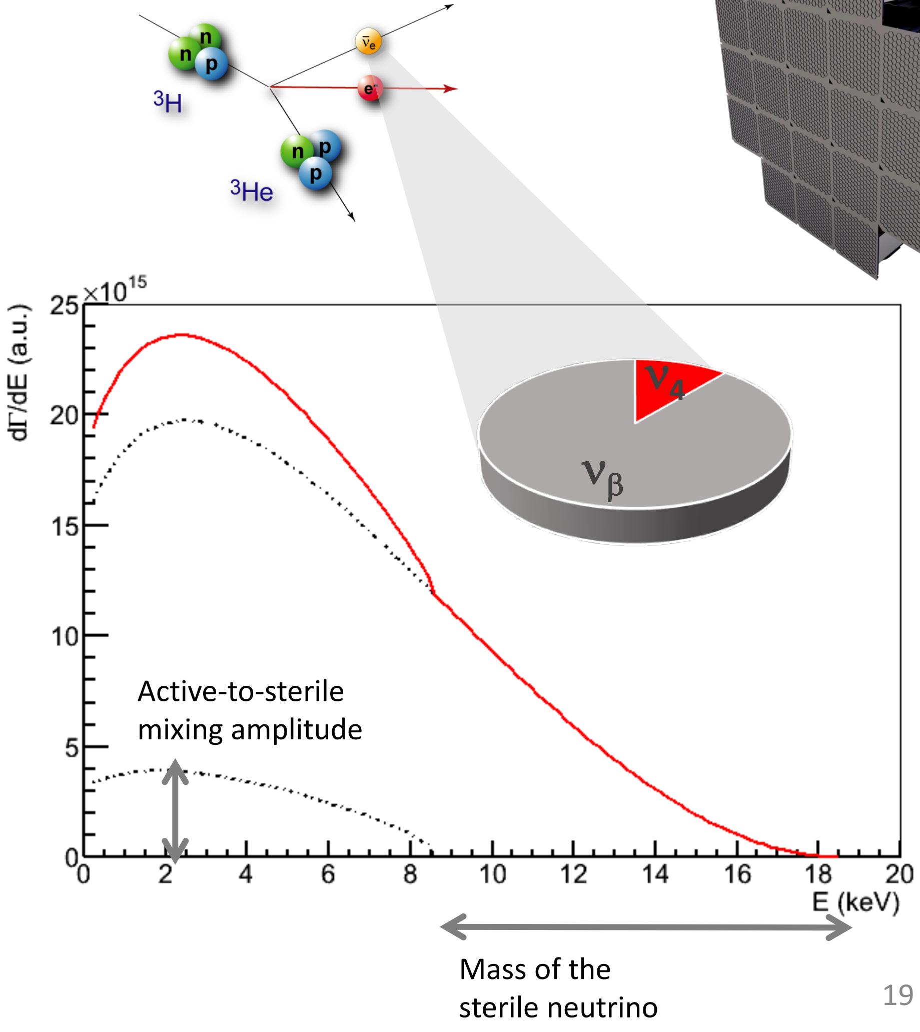
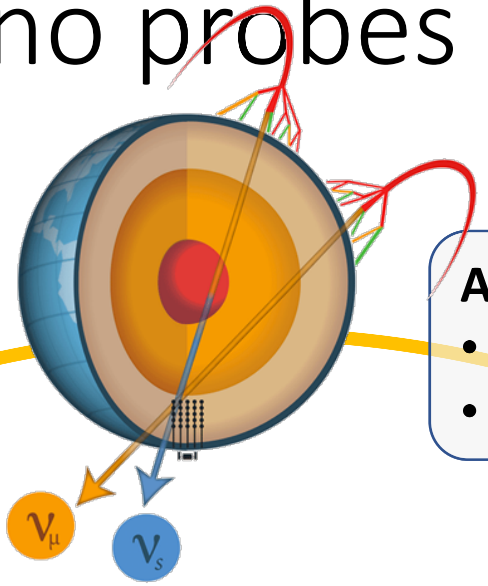
      P. Smith, arXiv:1607.06876, 2017
    - Spectral analysis
      S. Mertens et al., *J. Cosmol. Astropart. Phys.*, vol. 02, 2015

TRISTAN project



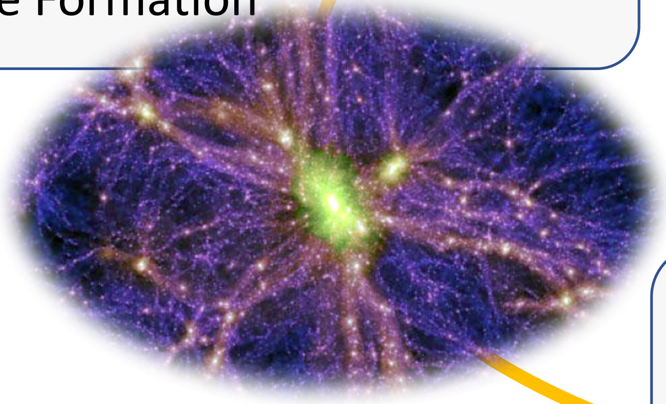
Boyarsky, M. Drewes, T. Lasserre, S. Mertens and O. Ruchayskiy, Rep. Prog. Nucl. Part. Phys. [arXiv:1807.07938 [hep-ph]]

Light sterile neutrino probes



Astronomy
- Atmospheric muon neutrino oscillation
- e.g. IceCube, Hyper-Kamiokande

Cosmology (N_{eff})
- BBN
- Structure Formation



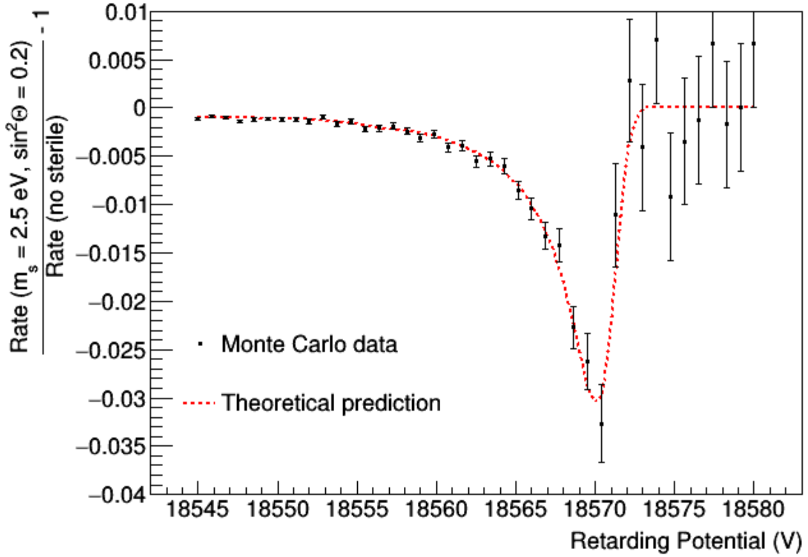
Laboratory
- Short-baseline oscillation
- Kinematics of beta decay

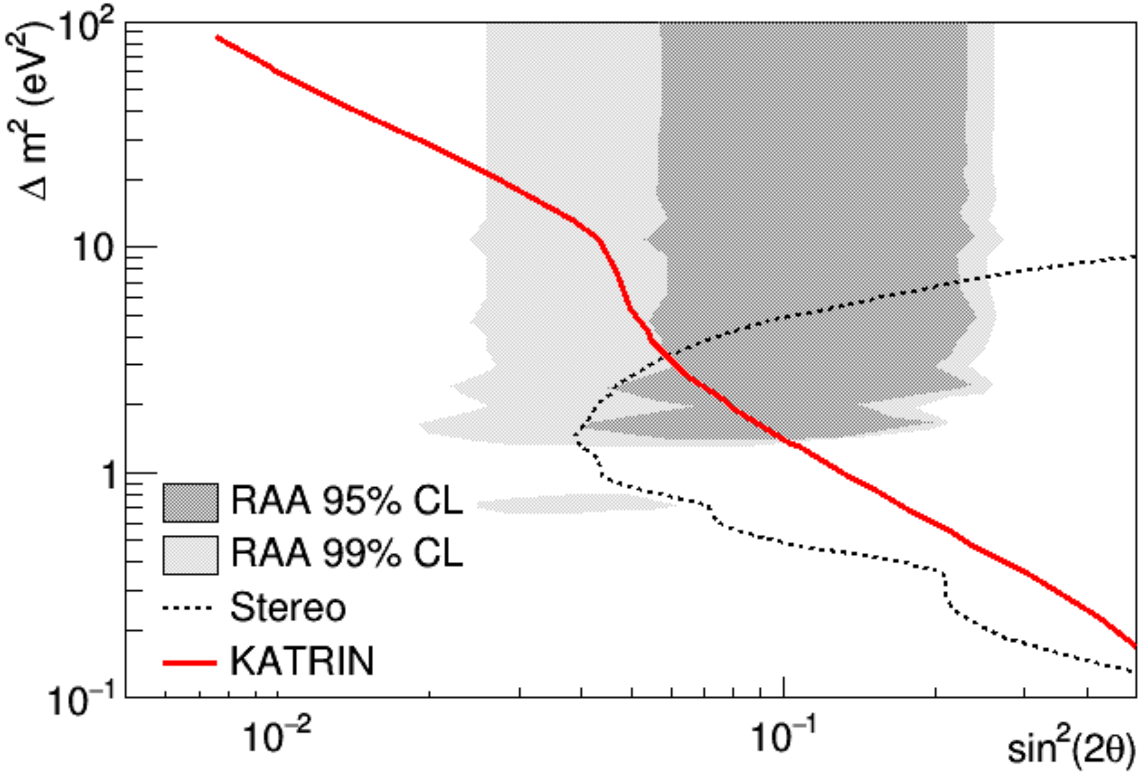
e.g. Stereo, KATRIN, ECHo

IceCube Collab. Phys. Rev. Lett. 117, 071801 (2016)
K. Abe *et al.* (SK Collaboration) Phys. Rev. D **91**, 052019
T. Brinckmann et al. arXiv:1808.05955 [astro-ph.CO]

Light sterile ν's and β-decay experiments

- Light sterile neutrino search can be considered for all direct nu-mass experiments
- Complementarity to oscillation experiments
- High sensitivity for $\Delta m^2 > 3$ eV^2
- Comes "for free"…





A. Formaggio and J. Barrett 2011, Phys. Lett. B, 706, 168–71
Sejersen-Riis and S. Hannestad 2011, JCAP 02 1475
L. Gastaldo, C. Giunti, E. M. Zavanin 2016, JHEP 2016 6 61

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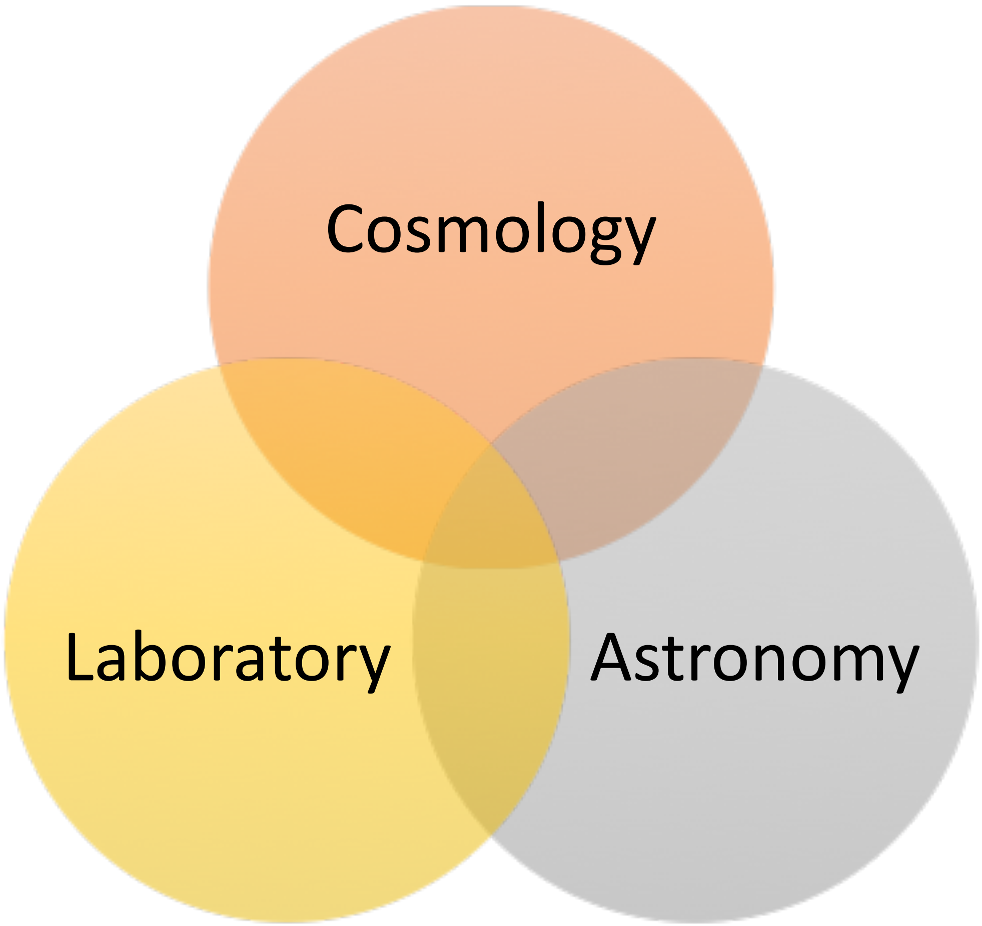


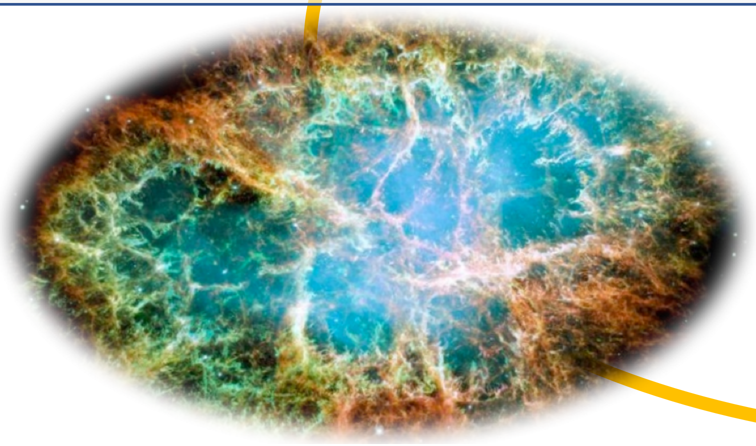
Neutrino astronomy: Probes

High-energy astronomy

- Highest energy cosmic rays
- IceCube-Gen-2, KM3Net (ARCA + ORCA), Gigaton Volume Detector (Baikal-GVD)

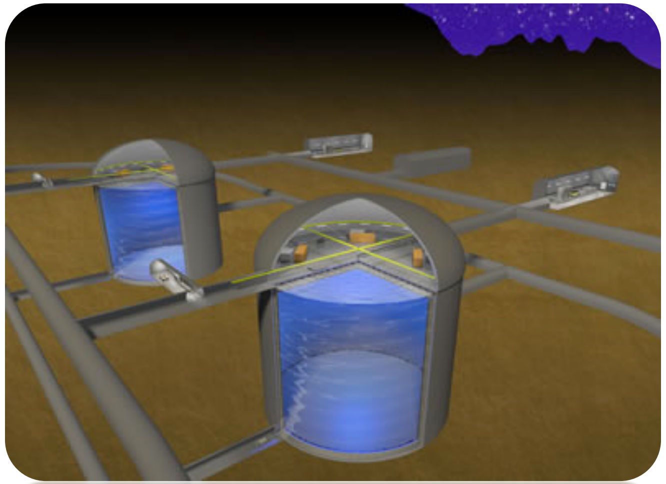
Low energy astronomy

- Supernovae, diffuse supernova background
- SuperK-Gd, Hyper-K, DUNE, JUNO, IceCube

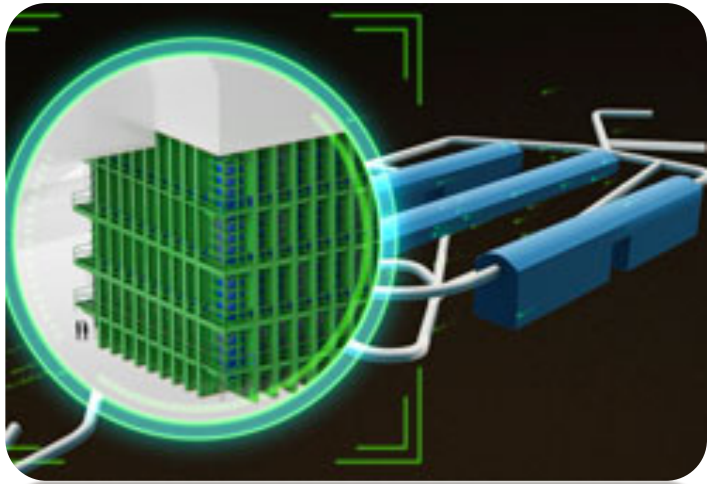


K. Abe et al. [Hyper-Kamiokande proto-Collaboration], arXiv:1805.04163
R. Acciarri et al. [DUNE Collaboration], arXiv:1512.061411
F. An et al. [JUNO Collaboration], arXiv:1507.056132

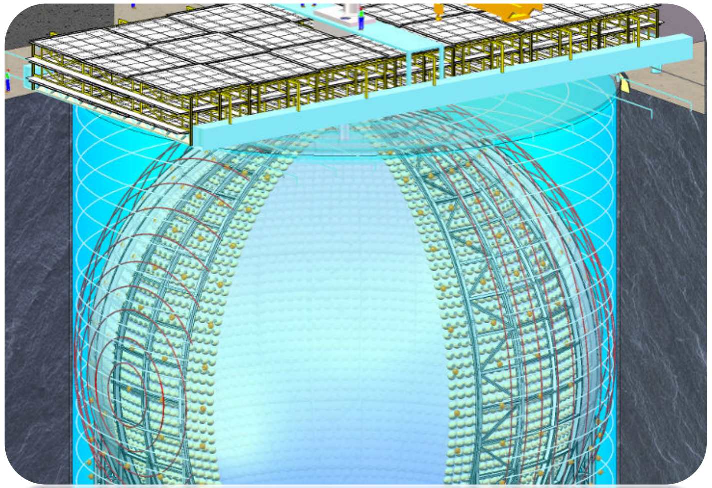
LE neutrino astronomy



Hyper-Kamiokande
- Water
- Start construction in 2020
- Expected operation in 2026
- 55k anti- ν_e (10kpc SN)
- 70 events (10 years DSNB)



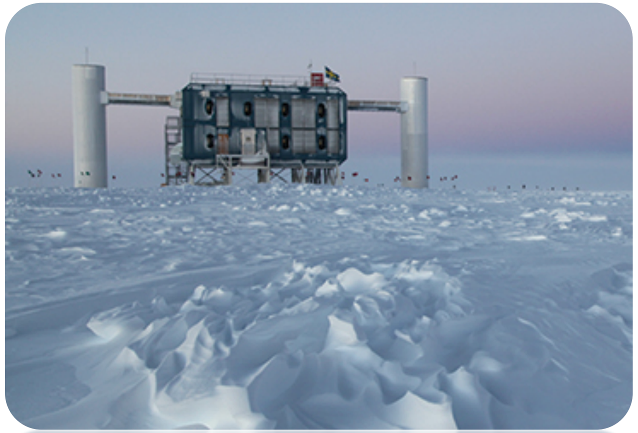
DUNE
- Liquid Argon
- Constructed started 2017
- start of operation [20 kt] 2024
- 3k ν_e (10kpc SN)
- 46 events (10 years DSNB)



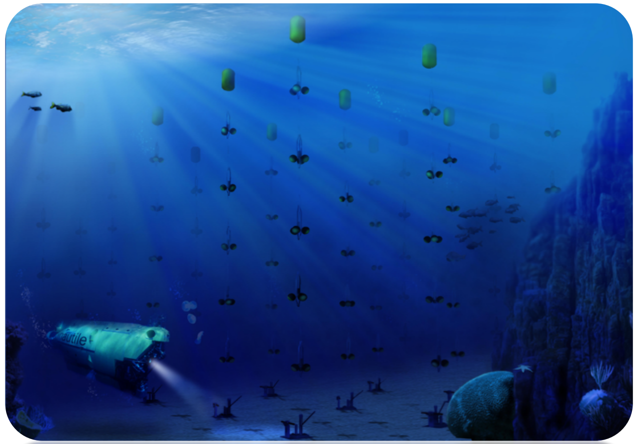
JUNO
- Liquid scintillator
- Construction started 2014
- start of operation 2021
- 5k anti- ν_e (10kpc SN)
- 30 events (10 years DSNB)

Complementarity!

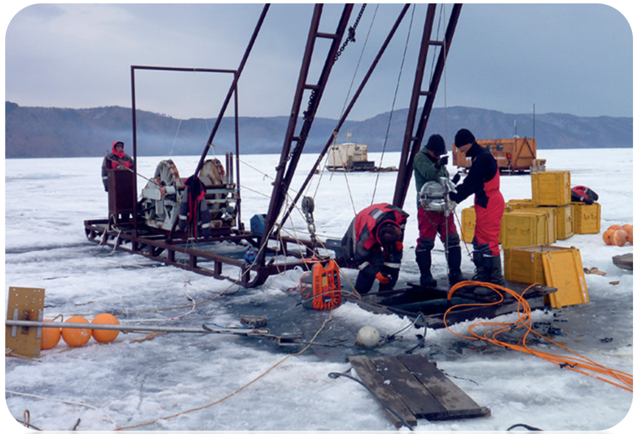
HE neutrino astronomy: Current



IceCube
- 2013: neutrinos of cosmic origin
- 2018: detection of blazar (multi-messenger signal)



KM3-Net
- Under construction
- 3 out of 230 DUs installed

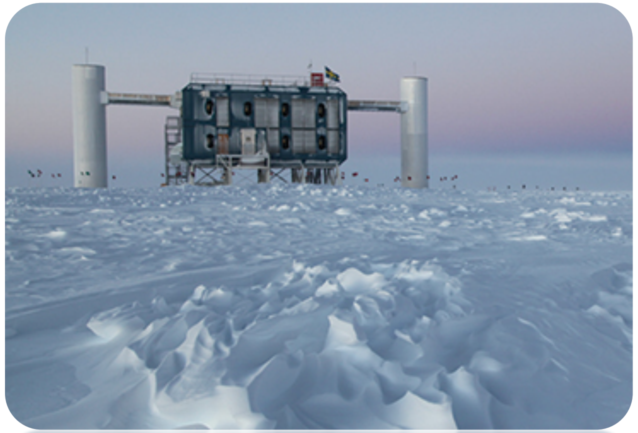


Baikal-GVD
- Under construction
- ~3 clusters
  = 800 optical modules installed

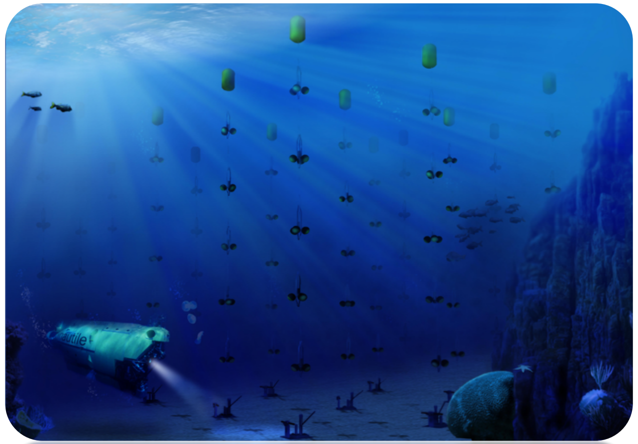
M. G. Aartsen et al. [IceCube Collaboration], Science 361 (2018) no.6398, 147

HE neutrino astronomy: Future

Radio instrumentation for very high energy
e.g. ARA/ARIANNA, GRAND



IceCube
- 2013: neutrinos of cosmic origin
- 2018: observation of blazar (first multi-messenger signal)



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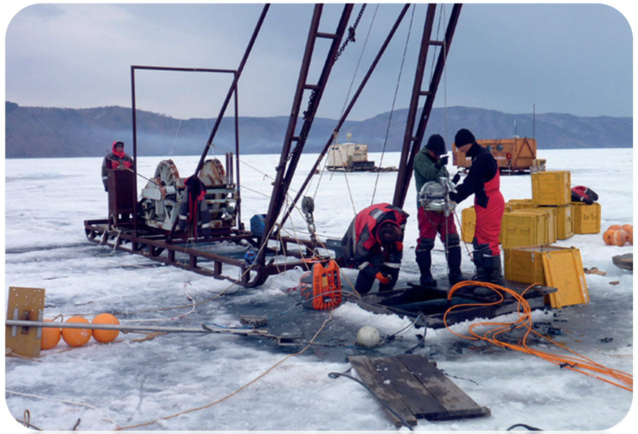


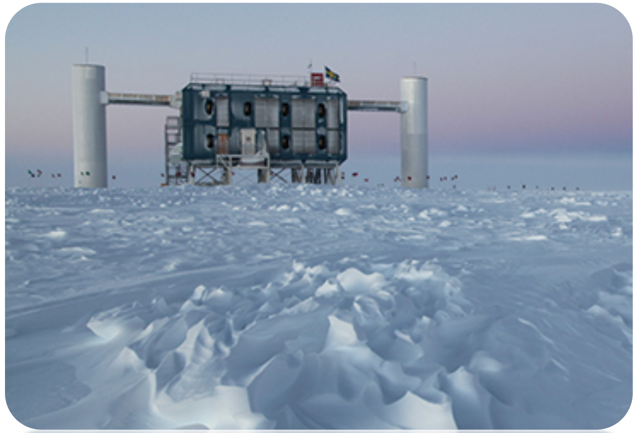
Baikal-GVD
- Under construction
- ~3 clusters
  = 800 optical modules installed

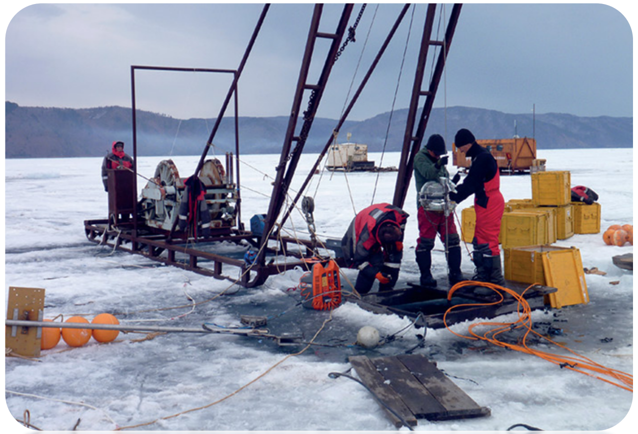
- IceCube-Gen2 (8 km^2)
- IceCube-Upgrade (low energy)

- ARCA (1.2 km^3)
- ORCA (low energy)

- 2021: ~0.5 km^3 (8 clusters)
- Final: 1.4 km^3 (27 clusters)

Neutrino astronomy: Future





Future missions:

- identify and understand the sources of the highest energy cosmic rays
- obtain a unique multi-messenger view of active galaxies and the explosion of stars
- investigate galactic sources and cosmic ray propagation
- test nuclear, neutrino and BSM physics

Neutrino mass:

- Impressive perspectives of cosmology-based neutrino mass probes
- Direct measurements are needed: KATRIN starts in March-19, new ideas allow to reach hierarchical mass regime

Leptogenesis:

- Future high intensity experiment can test existence of light Majorana particles
- CP-violation → Hyper-K, DUNE

Sterile neutrino dark matter

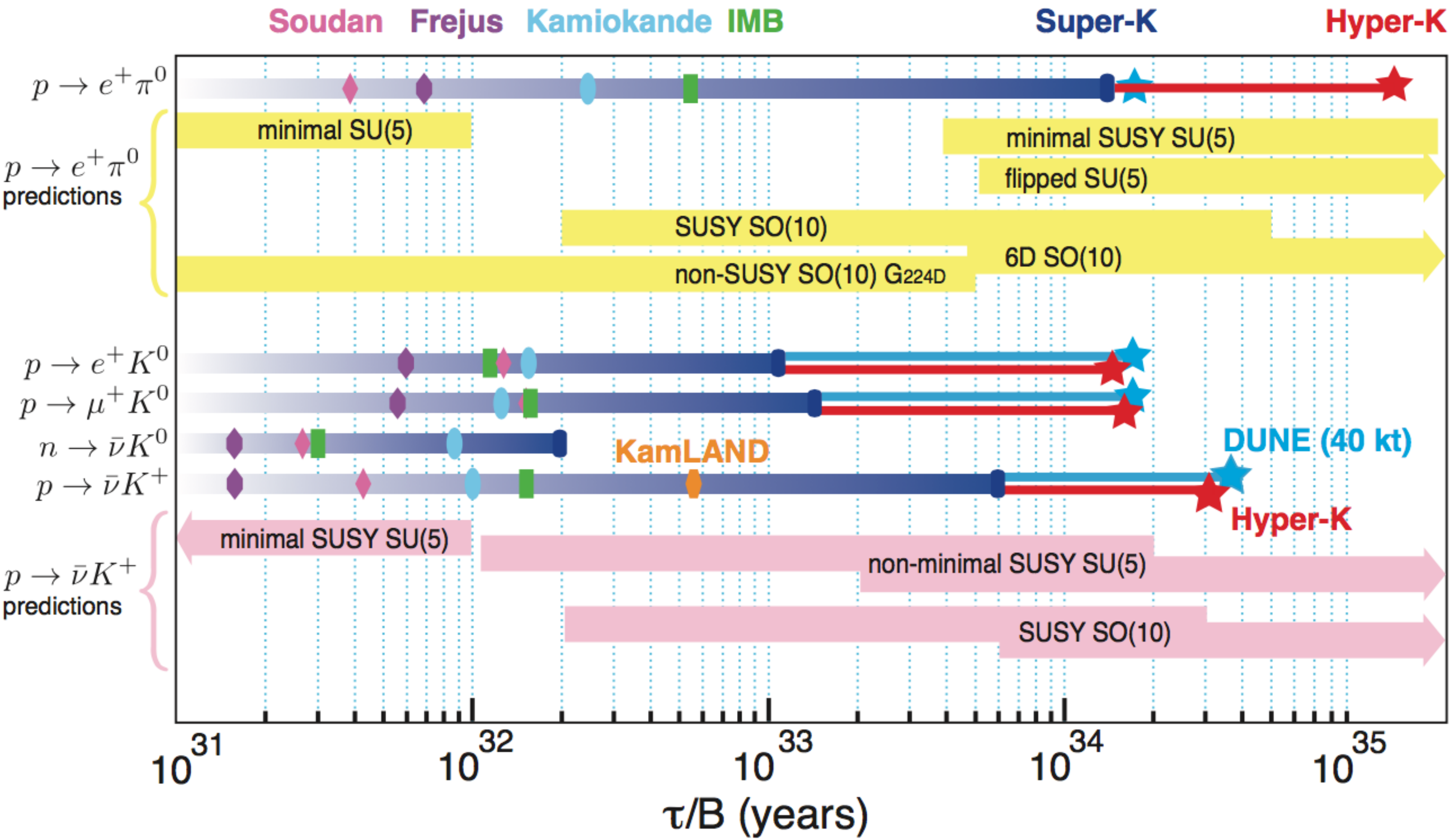
- Strong cosmology and astronomy limits (holistic analysis of all experimental data needed)
- New ideas for laboratory searches (largely unexplored)

Light sterile neutrinos

- Drastic impact on cosmology if hints are experimentally confirmed
- Direct nu-mass experiment provide complementary information

Neutrino astronomy

- Need complementarity of HK, DUNE, JUNO, IceCube, etc. for galactic SN and diffuse SN background
- Km3NeT, IceCube-Gen2, etc. will provide a novel window to the very high energy Universe



Soudan Frejus Kamiokande IMB Super-K Hyper-K
$p \to e^+\pi^0$
$p \to e^+\pi^0$ predictions
minimal SU(5)
minimal SUSY SU(5)
flipped SU(5)
SUSY SO(10)
6D SO(10)
non-SUSY SO(10) G224D
$p \to e^+K^0$
$p \to \mu^+K^0$
$n \to \bar{\nu}K^0$
$p \to \bar{\nu}K^+$
KamLAND
DUNE (40 kt)
Hyper-K
$p \to \bar{\nu}K^+$ predictions
minimal SUSY SU(5)
non-minimal SUSY SU(5)
SUSY SO(10)
10^{31} 10^{32} 10^{33} 10^{34} 10^{35}
τ/B (years)