The rise of neutrinos - Introduction

Thomas Hambye, ULB-PhysTh

the 3 observed neutrinos $\nu_{e,\mu,\tau}$ are elusive particles

→ they are very light particles which feel only the weak interactions many neutrino sources in the Universe…

Solar ν

Atmospheric ν

Astrophysical ν

Supernovae ν

Cosmological ν

Geo-ν

many neutrino sources in the Universe…

…from which neutrinos can easily escape straight to neutrino detector

…allowing to point the production site and probe inner dynamics of sources

Solar ν

understanding Sun dynamics and associ-ated nuclear physics

Supernovae ν

supernovae dynamics

Geo-ν

interior of the Earth physics

Atmospheric ν

Astrophysical ν

diffuse flux

+ point sources

Gamma-Ray Bursts,

Tidal Disruption Events,

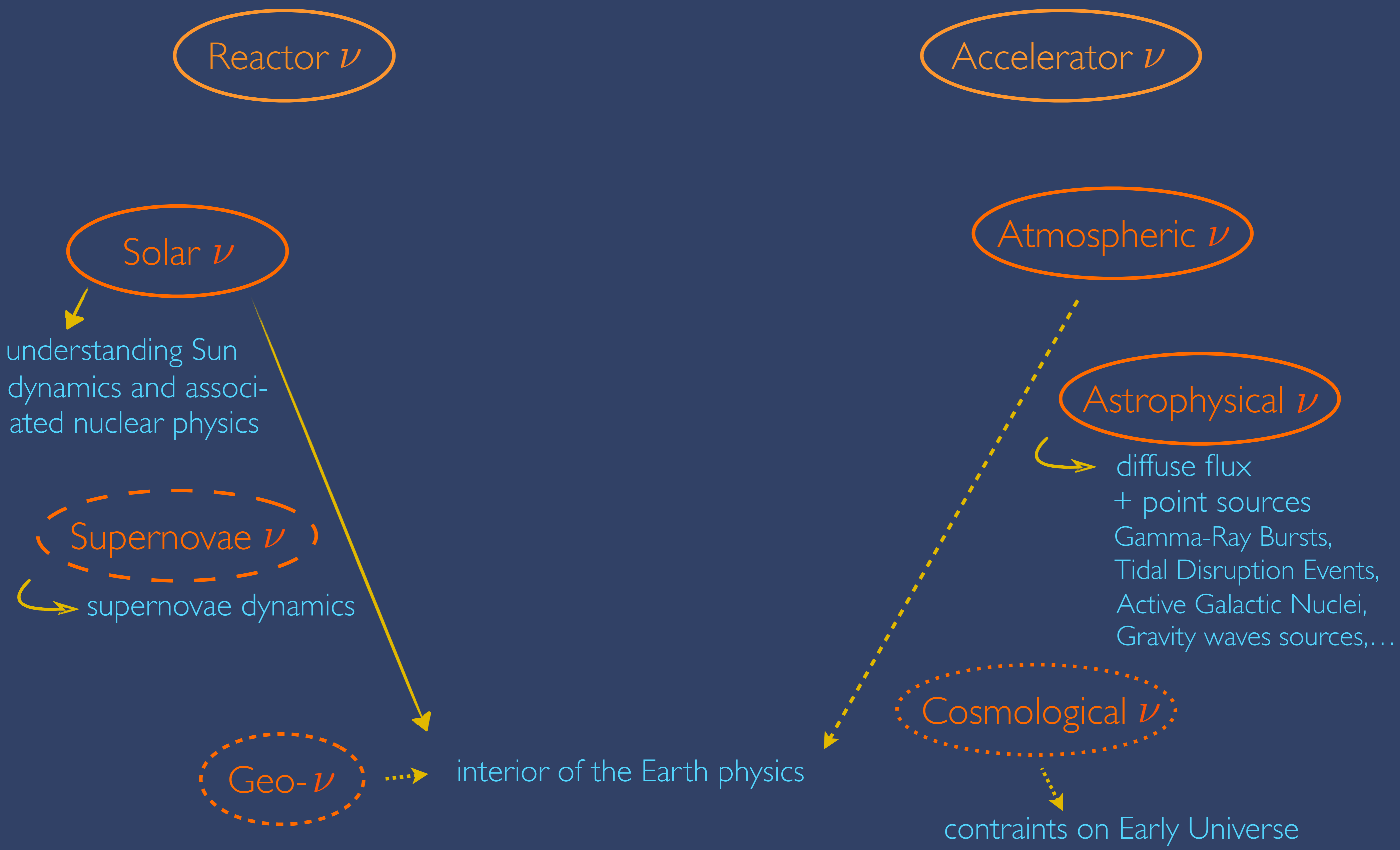
Active Galactic Nuclei,

Gravity waves sources,…

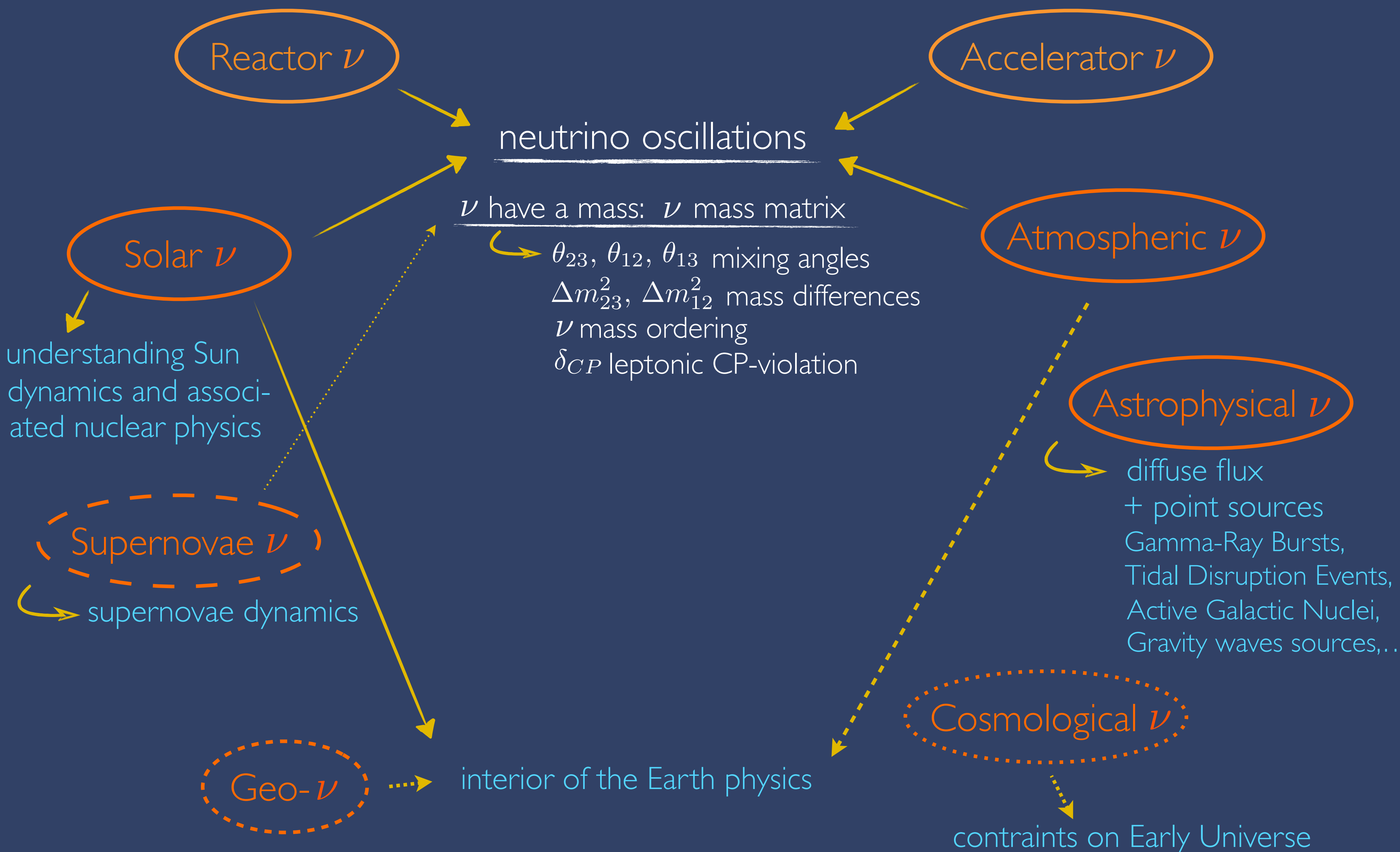
Cosmological ν

contraints on Early Universe

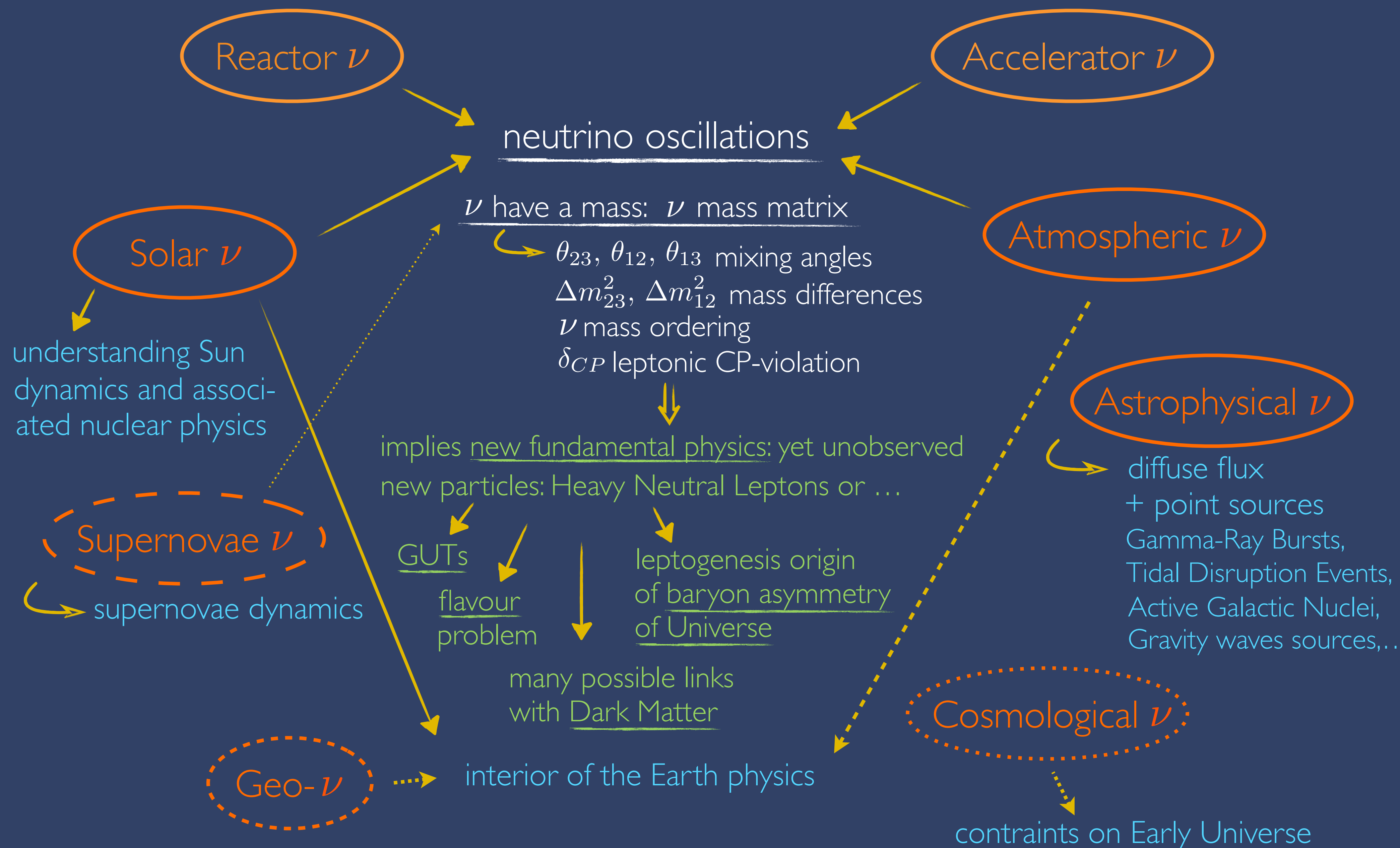
+ man-made neutrino sources…



neutrino oscillations have been established from 4 types of neutrino sources



neutrino oscillations: Beyond the SM physics



+ many non oscillation ways to probe BSM physics from ν physics, proton decay, …

neutrino physics in Belgium: EOS and beyond see Joscha's talk

CMS experiment: searches for Heavy Neutral Leptons

Theory part: CMS-UGent, UCL, ULB meetings

Reactor ν

Accelerator ν

neutrino oscillations

ν have a mass: ν mass matrix

$\theta_{23}, \theta_{12}, \theta_{13}$ mixing angles

$\Delta m^2_{23}, \Delta m^2_{12}$ mass differences

ν mass ordering

δ_{CP} leptonic CP-violation

$\Downarrow$

implies new fundamental physics: yet unobserved new particles: Heavy Neutral Leptons or …

GUTs

flavour problem

leptogenesis origin of baryon asymmetry of Universe

many possible links with Dark Matter

Solar ν

understanding Sun dynamics and associ-ated nuclear physics

Supernovae ν

supernovae dynamics

Atmospheric ν

Astrophysical ν

diffuse flux

+ point sources

Gamma-Ray Bursts,

Tidal Disruption Events,

Active Galactic Nuclei,

Gravity waves sources,…

Cosmological ν

contraints on Early Universe

Geo-ν

interior of the Earth physics

+ many non oscillation ways to probe BSM physics from ν physics, proton decay

see Marta's talk

SOLID experiment: reactor anomalies at very short distance + searches for Heavy Neutral Leptons

Reactor ν

Accelerator ν

neutrino oscillations

ν have a mass: ν mass matrix

$\theta_{23}, \theta_{12}, \theta_{13}$ mixing angles

$\Delta m^2_{23}, \Delta m^2_{12}$ mass differences

ν mass ordering

δ_{CP} leptonic CP-violation

$\Downarrow$

implies new fundamental physics: yet unobserved new particles: Heavy Neutral Leptons or …

Theory part: Solid-UAntwerp, ULB, UCL meetings

GUTs

flavour problem

leptogenesis origin of baryon asymmetry of Universe

many possible links with Dark Matter

Solar ν

understanding Sun dynamics and associ-ated nuclear physics

Atmospheric ν

Astrophysical ν

diffuse flux
+ point sources
Gamma-Ray Bursts,
Tidal Disruption Events,
Active Galactic Nuclei,
Gravity waves sources,…

Supernovae ν

supernovae dynamics

Geo-ν

interior of the Earth physics

Cosmological ν

contraints on Early Universe

+ many non oscillation ways to probe BSM physics from ν physics, proton decay

see Marta's talk

JUNO experiment: multi-purpose large ~20 kton neutrino detector

~50 km reactor neutrino baseline

Reactor ν

Accelerator ν

neutrino oscillations

ν have a mass: ν mass matrix

- θ_{23}, θ_{12}, θ_{13} mixing angles
- Δm^2_{23}, Δm^2_{12} mass differences
- ν mass ordering
- δ_{CP} leptonic CP-violation

$\Downarrow$

implies new fundamental physics: yet unobserved new particles: Heavy Neutral Leptons or …

GUTs

flavour problem

leptogenesis origin of baryon asymmetry of Universe

many possible links with Dark Matter

Solar ν

understanding Sun dynamics and associated nuclear physics

Supernovae ν

supernovae dynamics

Atmospheric ν

Astrophysical ν

diffuse flux
+ point sources
Gamma-Ray Bursts,
Tidal Disruption Events,
Active Galactic Nuclei,
Gravity waves sources,…

Cosmological ν

contraints on Early Universe

Geo-ν

interior of the Earth physics

+ many non oscillation ways to probe BSM physics from ν physics, proton decay

IceCube experiment: high energy neutrino observatory

+ Future: IceCube-Gen2, KM3Net

Reactor ν

Accelerator ν

neutrino oscillations

ν have a mass: ν mass matrix

- θ_{23}, θ_{12}, θ_{13} mixing angles
- Δm^2_{23}, Δm^2_{12} mass differences
- ν mass ordering
- δ_{CP} leptonic CP-violation

$\Downarrow$

implies new fundamental physics: yet unobserved new particles: Heavy Neutral Leptons or …

- GUTs
- flavour problem
- leptogenesis origin of baryon asymmetry of Universe

many possible links with Dark Matter

Solar ν

understanding Sun dynamics and associ-ated nuclear physics

Atmospheric ν

Astrophysical ν

- diffuse flux
- + point sources
- Gamma-Ray Bursts,
- Tidal Disruption Events,
- Active Galactic Nuclei,
- Gravity waves sources,…

Supernovae ν

supernovae dynamics

Geo-ν

interior of the Earth physics

Cosmological ν

contraints on Early Universe

+ many non oscillation ways to probe BSM physics from ν physics, proton decay

First dedicated search for Dark Matter induced neutrino-lines at neutrino telescopes

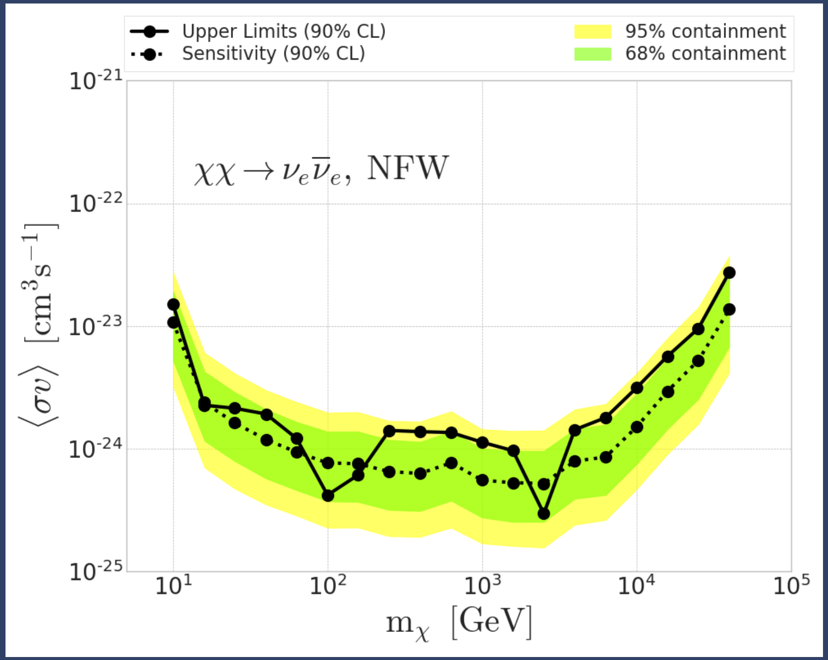
If DM (in the Galactic center, …) annihilate or decay into 2 neutrinos:

monochromatic flux of neutrinos: DM smoking gun!

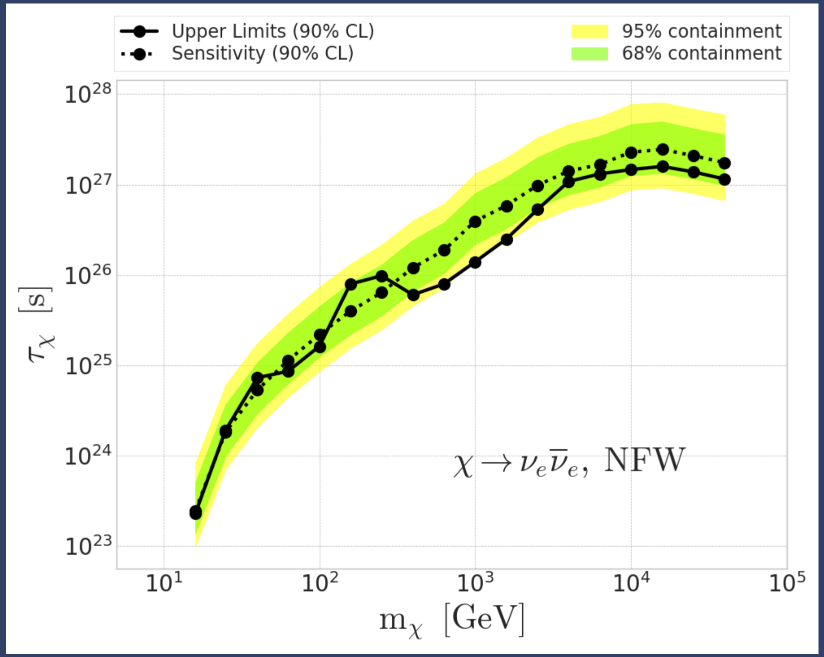
Dedicated double binning IceCube analysis (energy + angle):

ULB IIHE+ ULB PhysTh

Annihilation



Decay



Theory neutrino activities:

- neutrino mass origin, baryogenesis new model building
  main leptogenesis alternative elaboration, high/low scale ULB, UCL
- detailed QFT study of HNL low energy origin of neutrino masses and baryogenesis UCL, ULB
- DM-neutrino connections ULB, UCL
  neutrino lines DM models, seesaw induced DM decay, etc

implies new fundamental physics: yet unobserved new particles: Heavy Neutral Leptons or …

GUTs

flavour problem

leptogenesis origin of baryon asymmetry of Universe

many possible links with Dark Matter

+ many non oscillation ways to probe BSM physics from ν physics, proton decay,…

Reactor ν

Accelerator ν

neutrino oscillations

ν have a mass: ν mass matrix

$\theta_{23}, \theta_{12}, \theta_{13}$ mixing angles

$\Delta m^2_{23}, \Delta m^2_{12}$ mass differences

ν mass ordering

δ_{CP} leptonic CP-violation

Solar ν

understanding Sun dynamics and associ-ated nuclear physics

Atmospheric ν

Astrophysical ν

diffuse flux
+ point sources
Gamma-Ray Bursts,
Tidal Disruption Events,
Active Galactic Nuclei,
Gravity waves sources,…

Supernovae ν

supernovae dynamics

Geo-ν

interior of the Earth phys

Young Scientist Session: The rise of neutrinos:

Joscha Knolle (EOS/BOF postdoc at UGent):

"Search for Heavy Neutral Leptons in CMS"

Marta Colomer (postdoc at ULB-IIHE)

"Neutrinos at reactor experiments - JUNO and Solid"

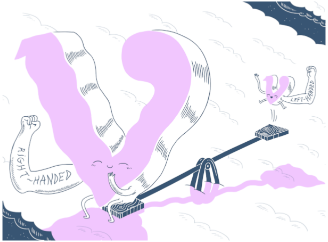
A Decade of Discoveries in High Energy Physics
Brussels Town Hall, March 09, 2023

Searches for heavy neutral leptons with the CMS experiment at the CERN LHC

Joscha Knolle

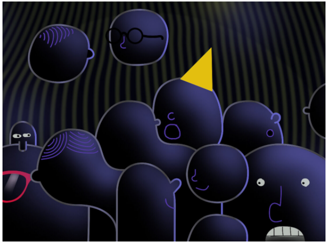
GHENT UNIVERSITY

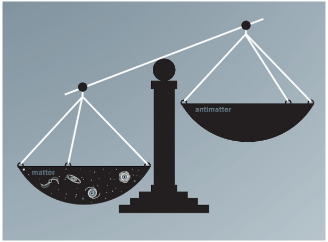
Heavy neutral leptons



see-saw mechanism?

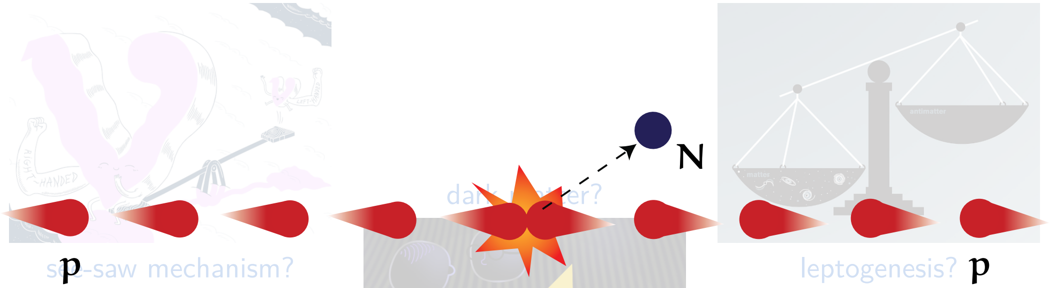
dark matter?





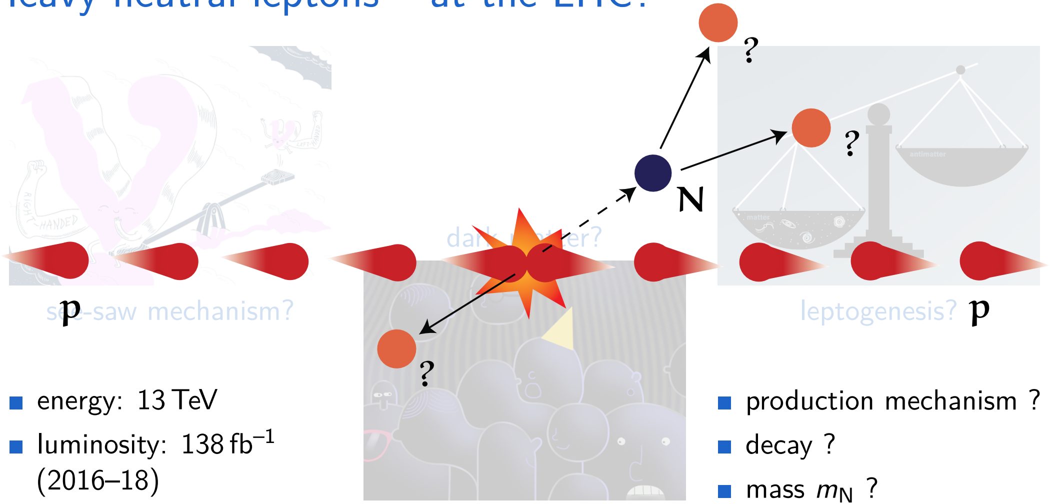
leptogenesis?

Heavy neutral leptons – at the LHC?



- energy: 13 TeV
- luminosity: 138 fb^{-1} (2016–18)

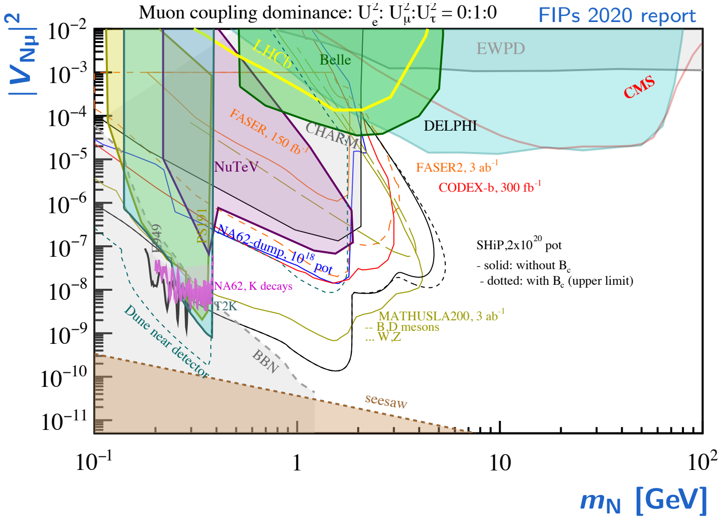
Heavy neutral leptons – at the LHC?



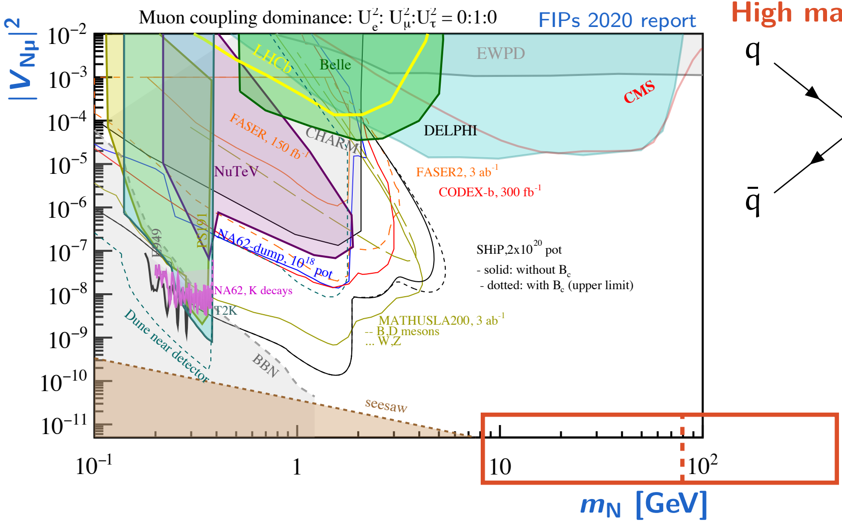
- energy: 13 TeV
- luminosity: 138 fb^{-1} (2016–18)

- production mechanism ?
- decay ?
- mass m_{N} ?
- coupling $|V_{\text{N}\ell}|^2$?

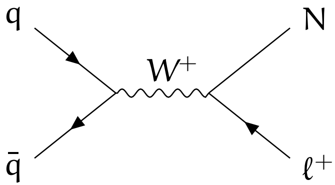
HNLs at experiments



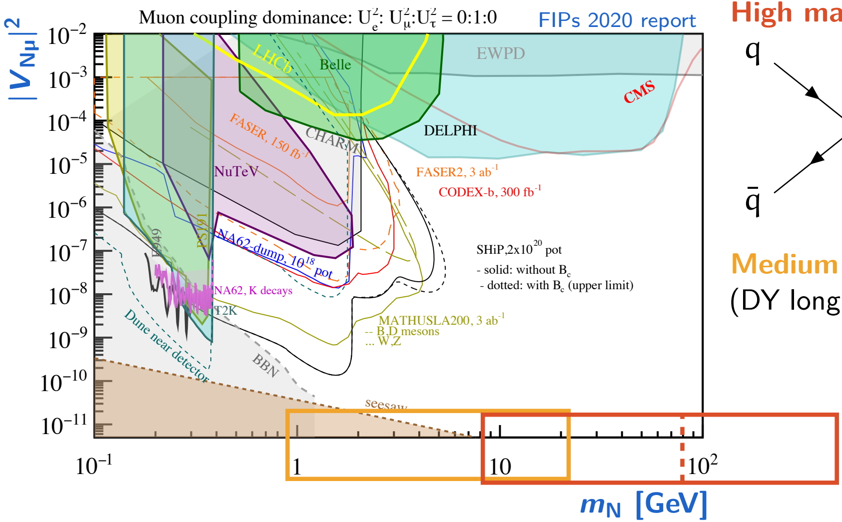
HNLs at experiments



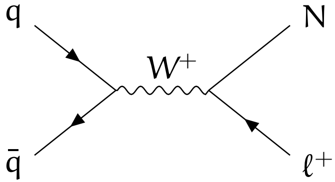
High mass (DY)



HNLs at experiments

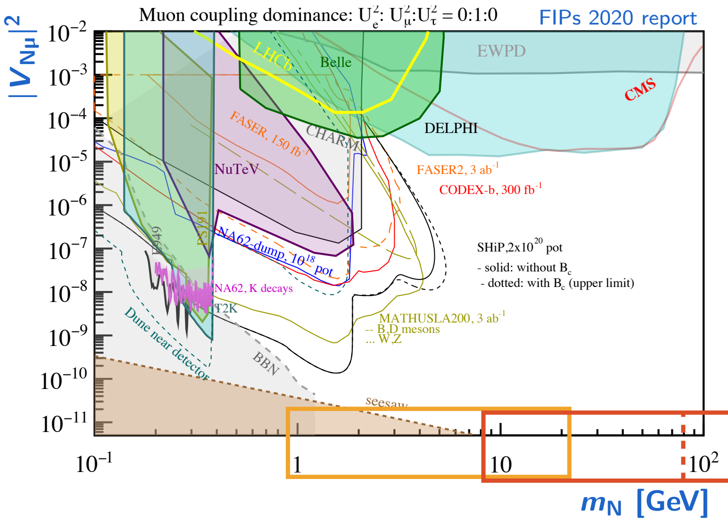


High mass (DY)

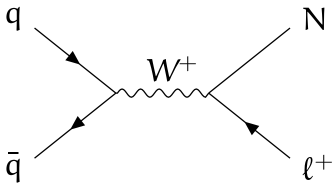


Medium mass
(DY longlived)

HNLs at experiments



High mass (DY)

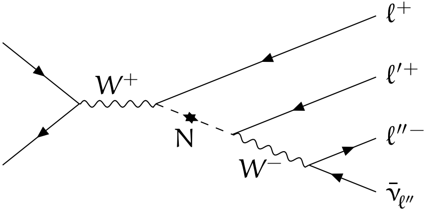


Medium mass (DY longlived)

Highest mass (VBF)

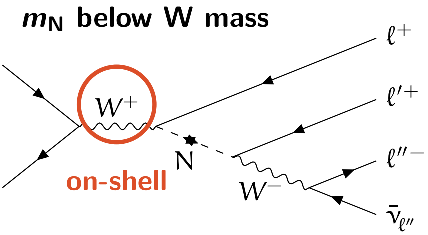
Phys. Rev. Lett. 120 (2018) 221801

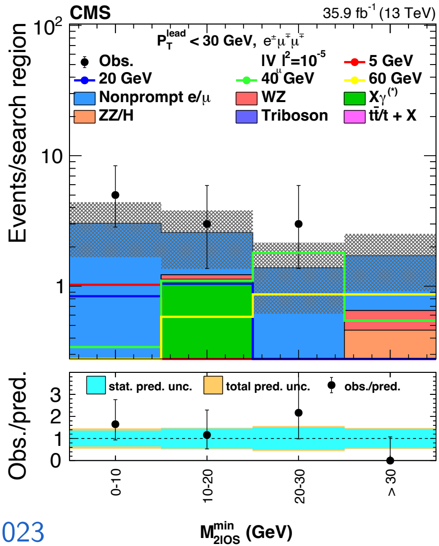
High mass search: trilepton signature



Phys. Rev. Lett. 120 (2018) 221801

High mass search: trilepton signature

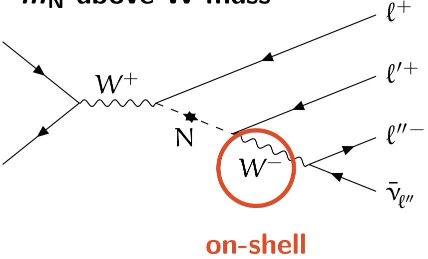


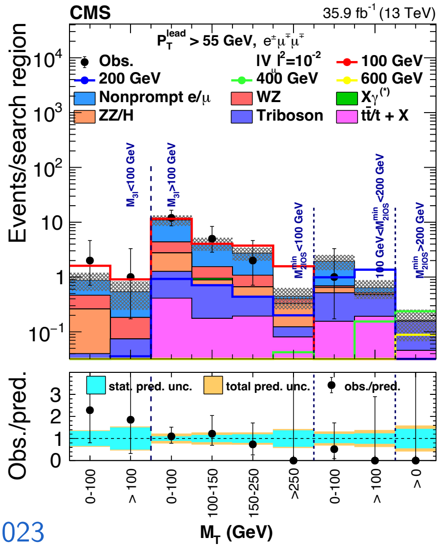


Phys. Rev. Lett. 120 (2018) 221801

High mass search: trilepton signature

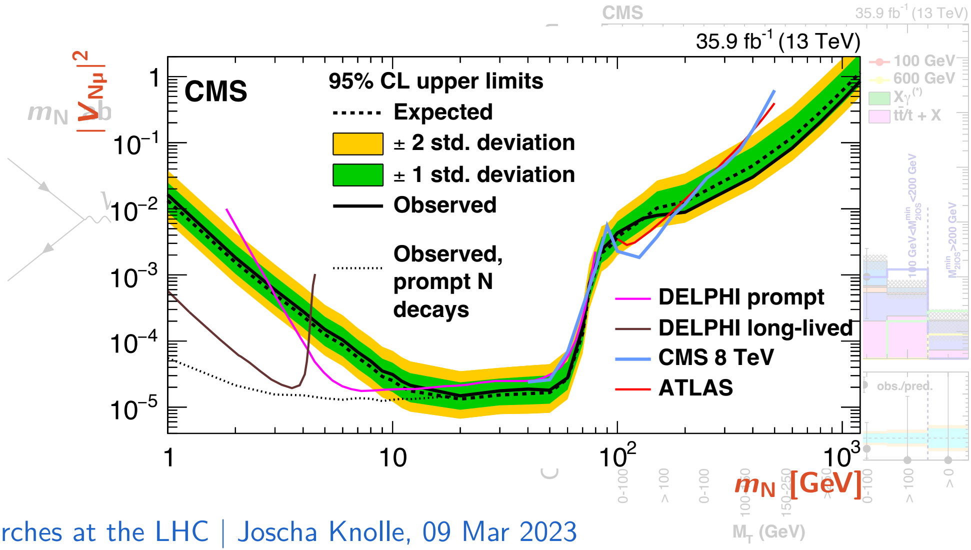
m_N above W mass





Phys. Rev. Lett. 120 (2018) 221801

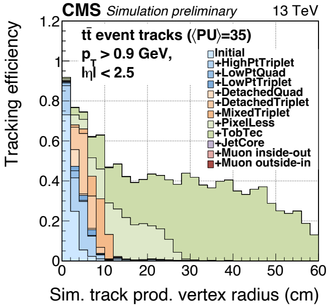
High mass search: trilepton signature



JHEP 07 (2022) 081

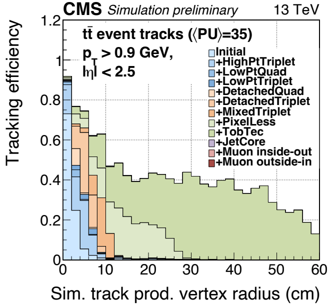
Medium mass search: longlived signature

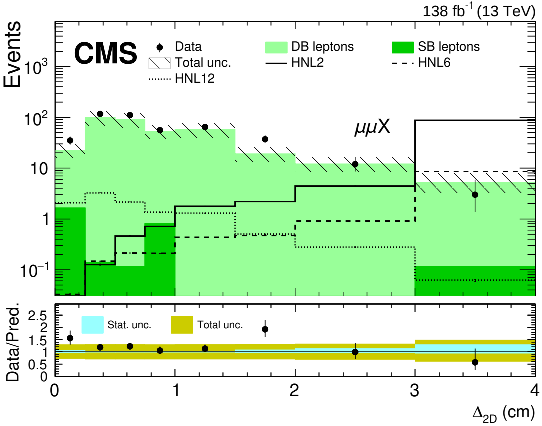
$$\tau_N \propto m_N^{-5} \, |V_{N\ell}|^{-2}$$



Medium mass search: longlived signature

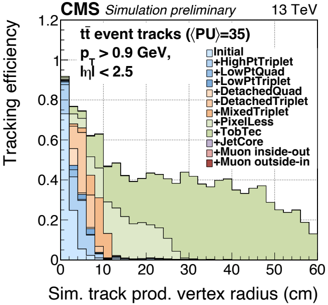
$$\tau_N \propto m_N^{-5} \, |V_{N\ell}|^{-2}$$

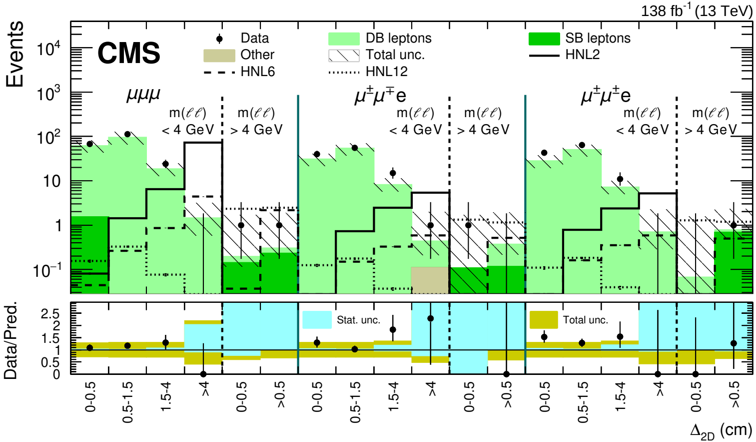




Medium mass search: longlived signature

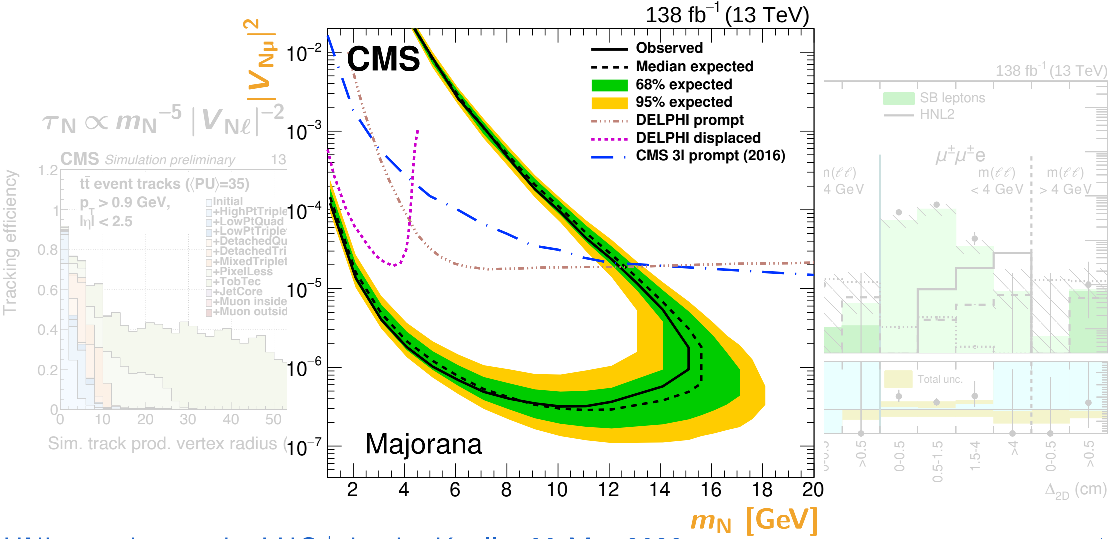
$$\tau_N \propto m_N^{-5} \, |V_{N\ell}|^{-2}$$





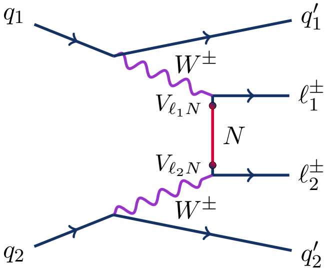
JHEP 07 (2022) 081

Medium mass search: longlived signature

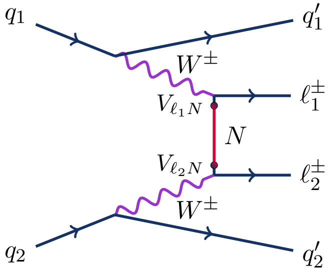


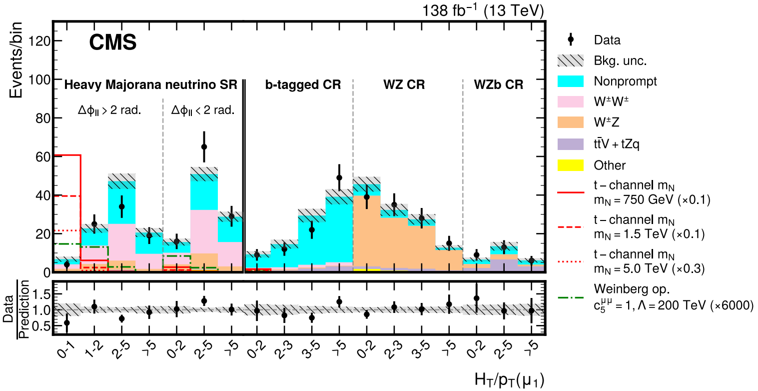
arXiv:2206.08956 (accepted by PRL)

Highest mass search: t-channel VBF



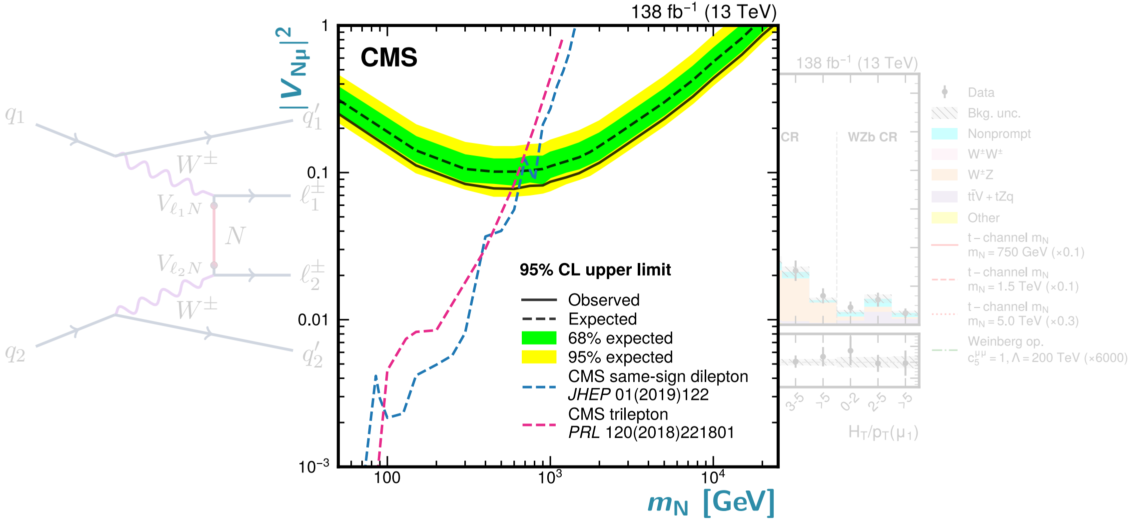
Highest mass search: t-channel VBF



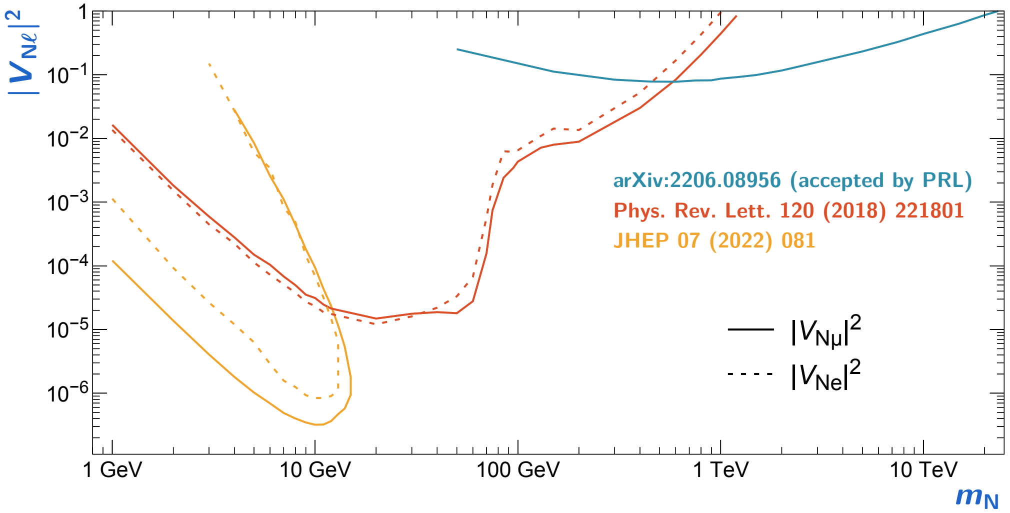


arXiv:2206.08956 (accepted by PRL)

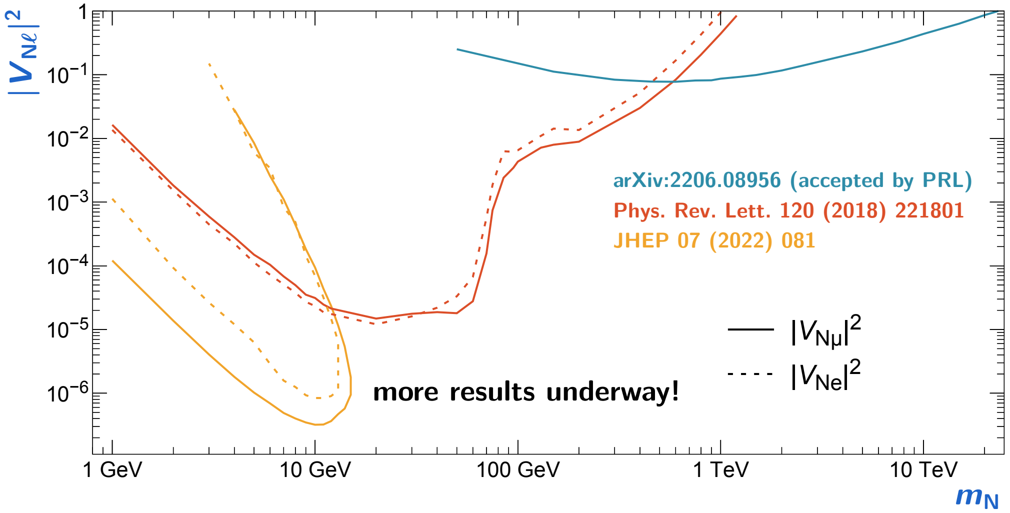
Highest mass search: *t*-channel VBF



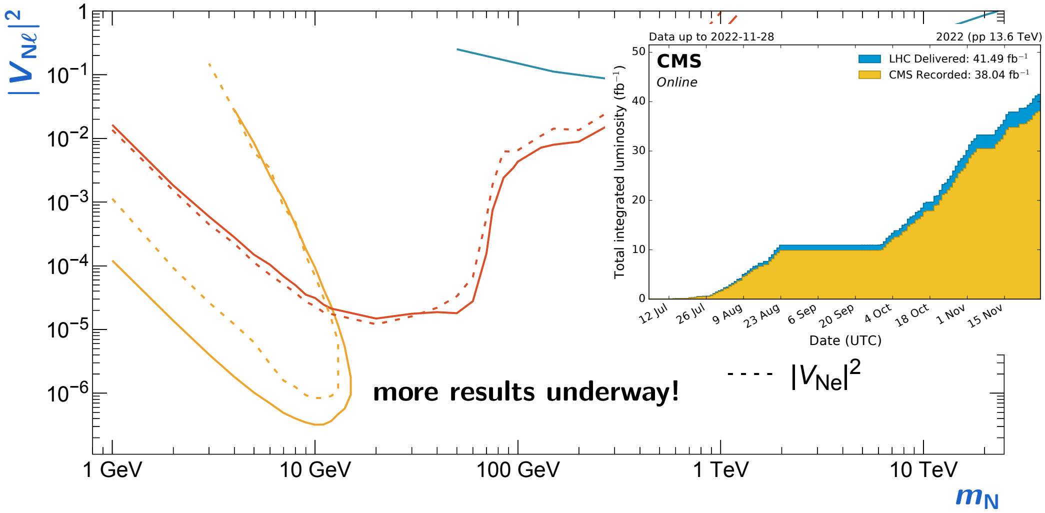
Summary of CMS limits on HNL production

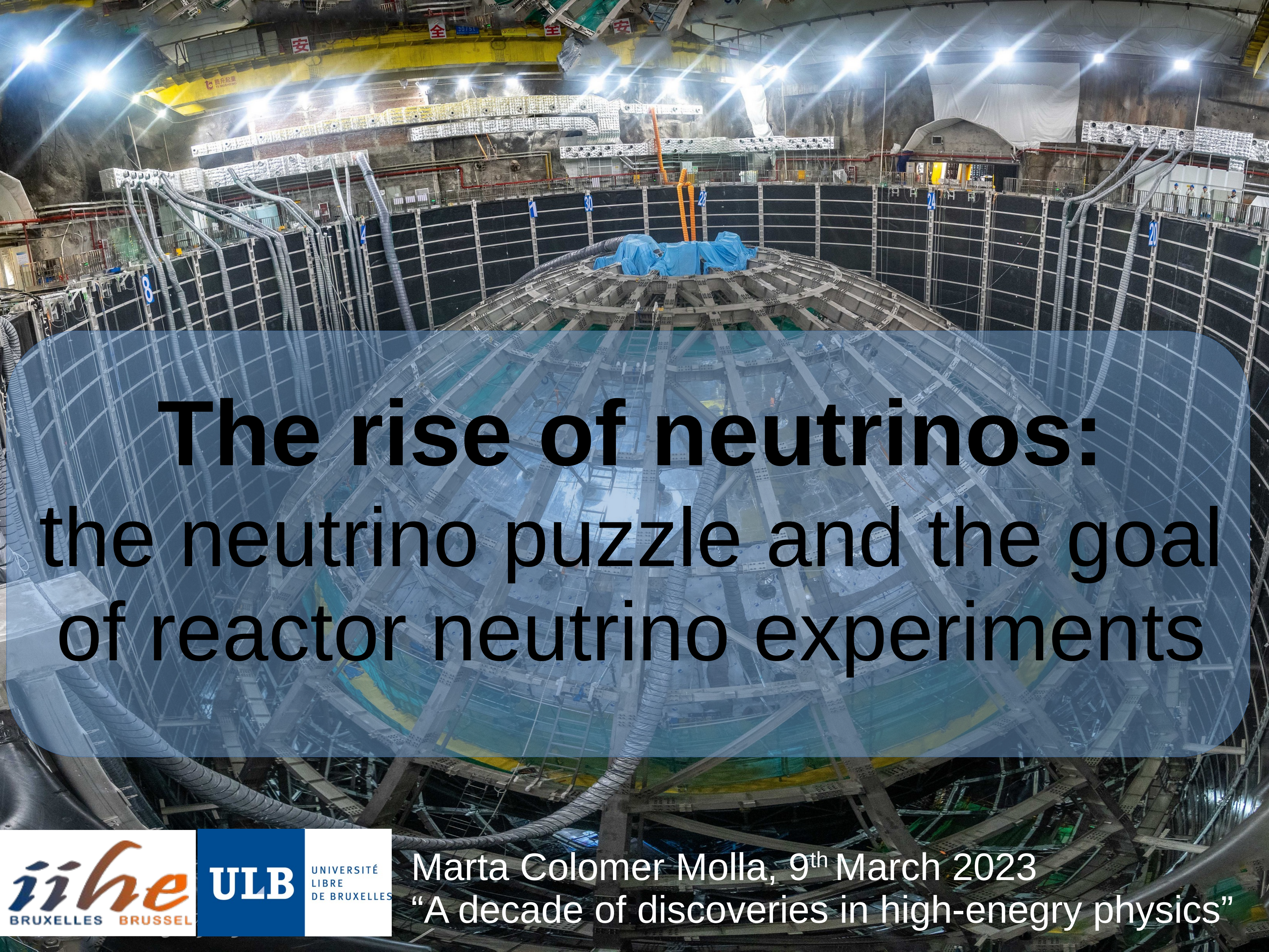


Summary of CMS limits on HNL production



Summary of CMS limits on HNL production





The rise of neutrinos:

the neutrino puzzle and the goal of reactor neutrino experiments

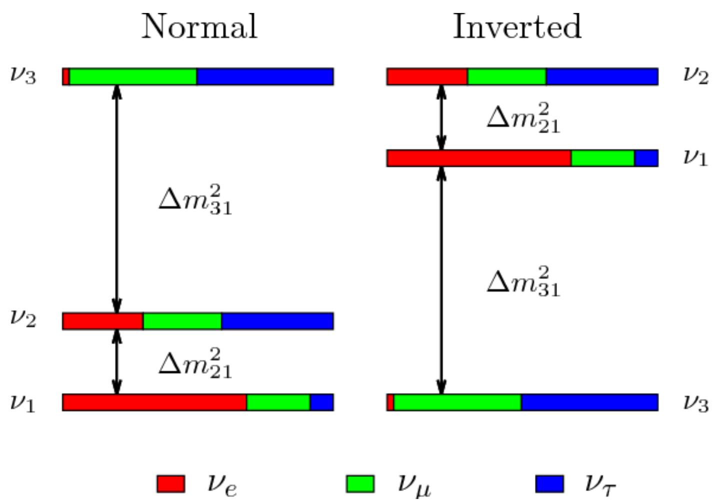
Marta Colomer Molla, 9th March 2023
“A decade of discoveries in high-enegry physics”

The neutrino puzzle: where can reactor neutrinos help?

24 years after the discovery of neutrino oscillations, many unknowns remain:

- What is the neutrino mass ordering?
- What is the he absolute neutrino mass?
- What is the neutrino nature: Dirac or Majorana?
- What is the value of CP phase (δ)?
- How many effective neutrino flavors exist? (sterile neutrinos?)

- **What is the neutrino mass ordering (NMO)?**



Two complementary approaches:

- Matter-enhanced oscillations with accelerator or atmospheric neutrinos
- Vacuum oscillations with reactor neutrinos, independent of matter effects ($\sin^2\theta_{23}$, δ)

↓

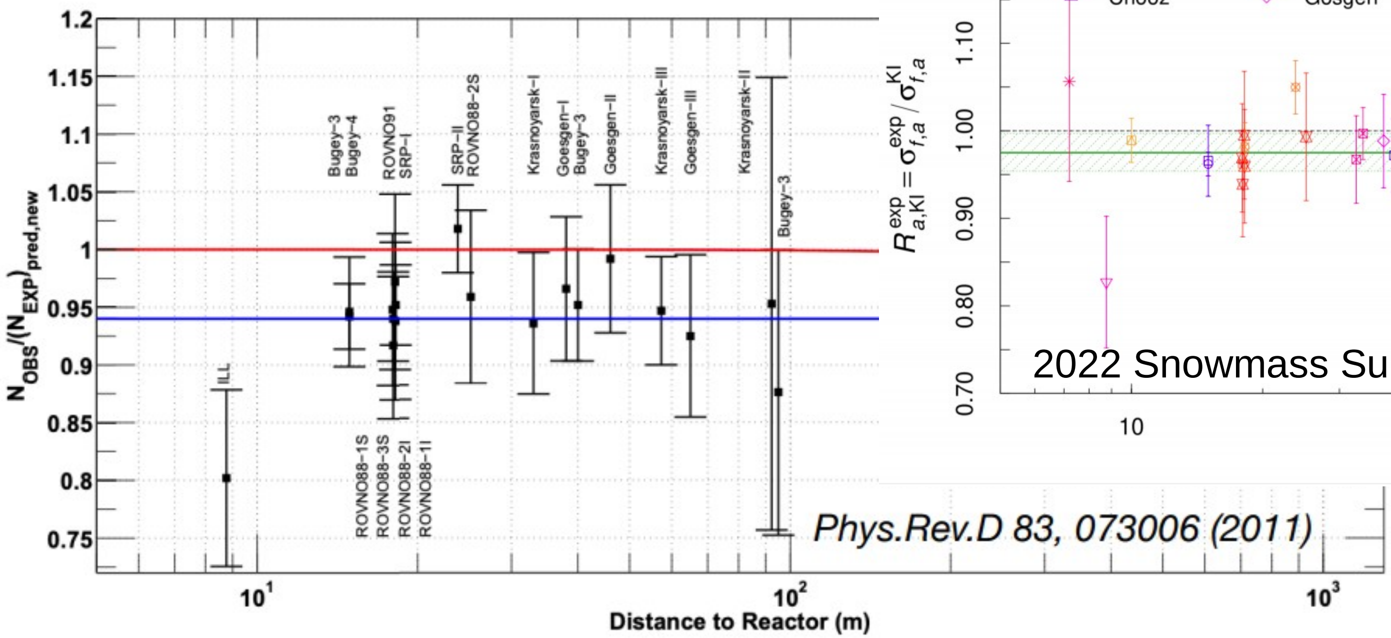
Exploit the synergies between different channels

The neutrino puzzle: where can reactor neutrinos help?

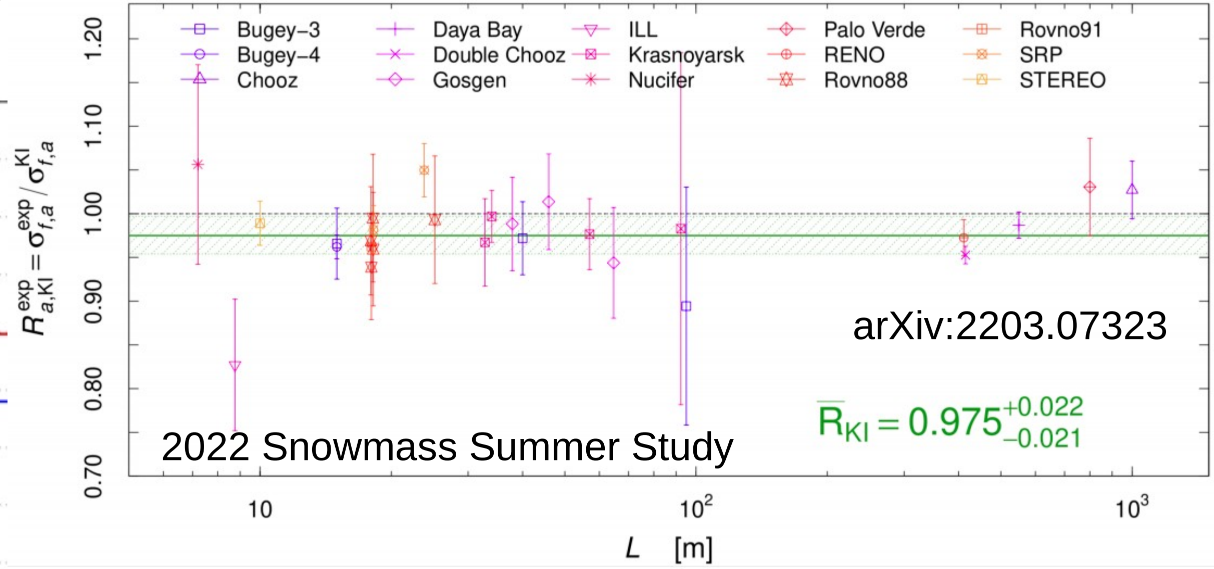
- How many effective neutrino flavors exist? **sterile neutrinos?**

→ **Probe the reactor neutrino anomaly:**

Flux deficit observed by reactor experiments = potential indication of 4th neutrino flavor



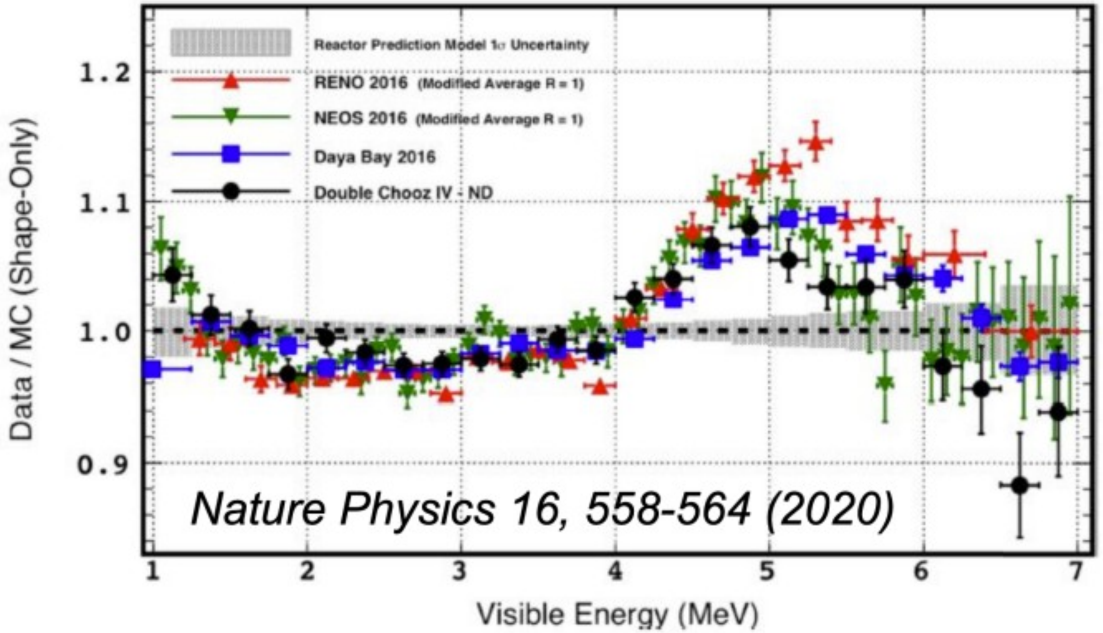
Recent indication: flux deficit may be explained by new ^{235}U measurements



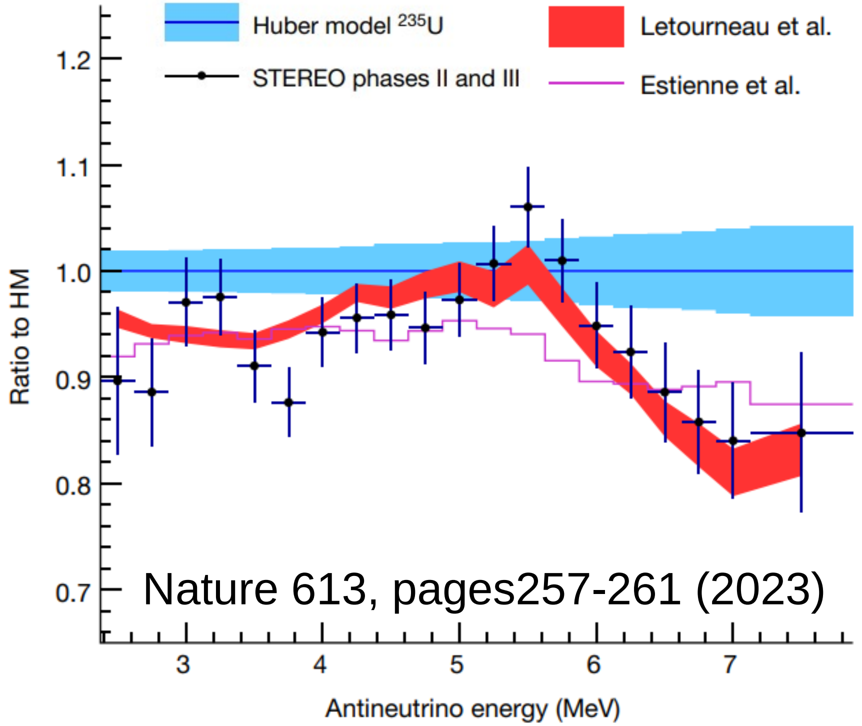
The neutrino puzzle: where can reactor neutrinos help?

- How many effective neutrino flavors exist? (**sterile neutrinos?**)
  - → **Probe the reactor neutrino anomaly:**

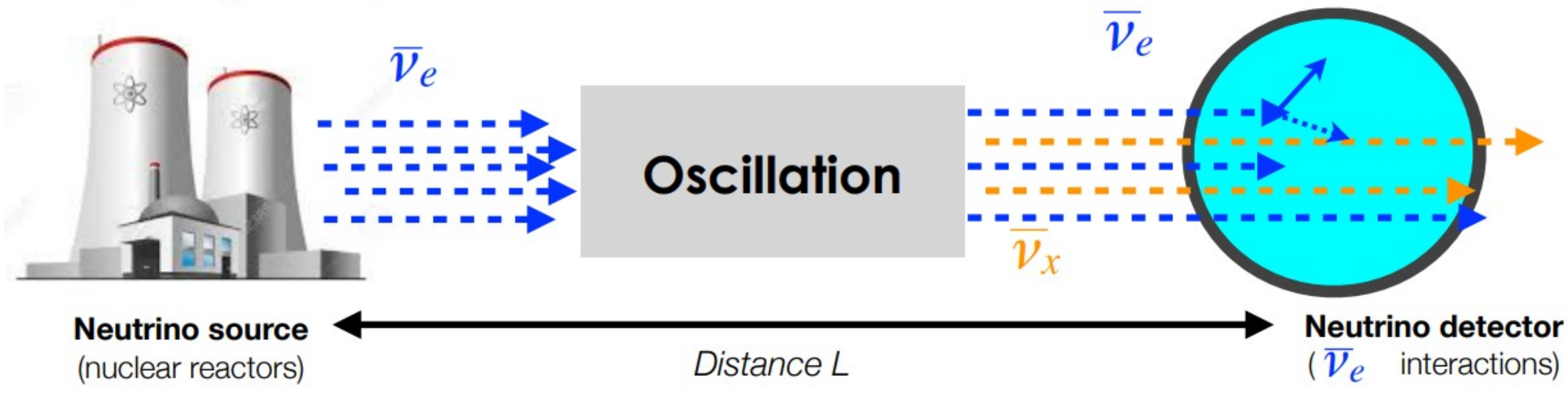
Unexpected bump at ~5 MeV reported by reactor neutrino experiments



Compatible with latest fits by STEREO

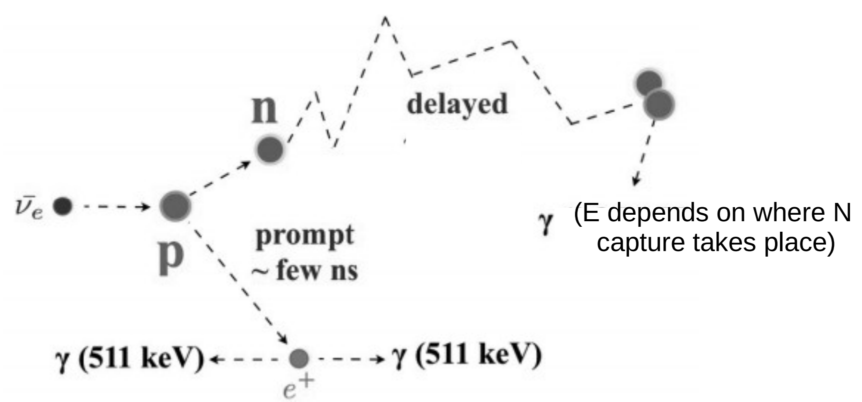


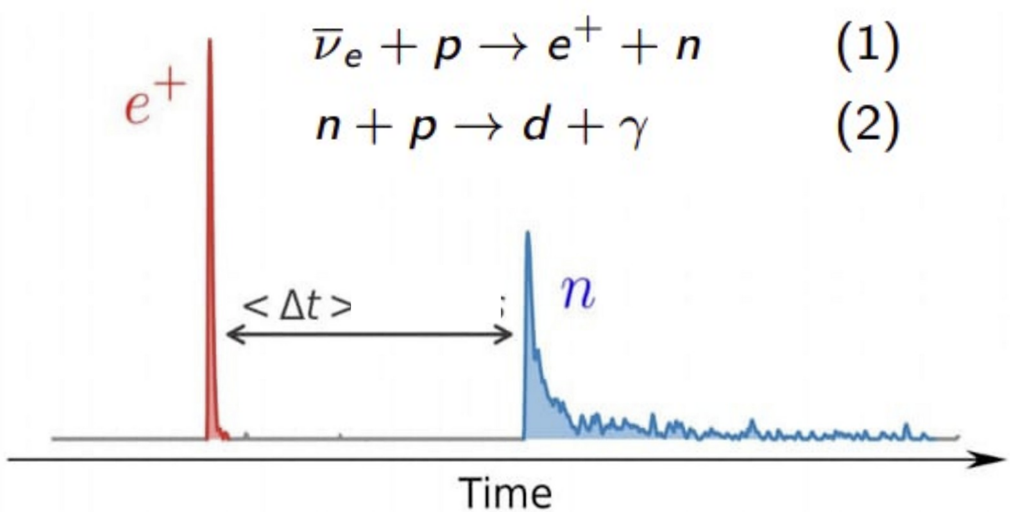
Reactor neutrino detection



Reactor anti-neutrinos are observed by Inverse Beta Decay (IBD):
(1) – Energy deposited by positron (carries neutrino energy)
– Positron annihilation into two gammas (511 keV)
(2) Neutron capture scintillation emission

- Very clear signal: prompt + delay coincidence



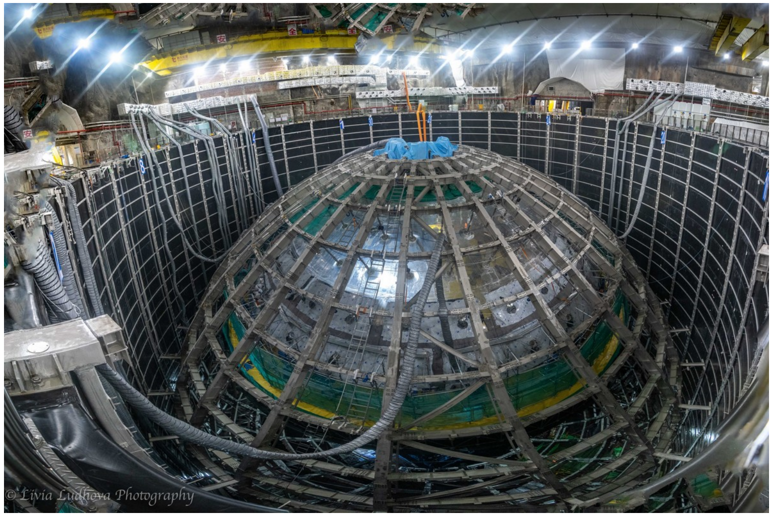


Reactor neutrino detectors

- Belgium is involved in two different reactor neutrino experiments:

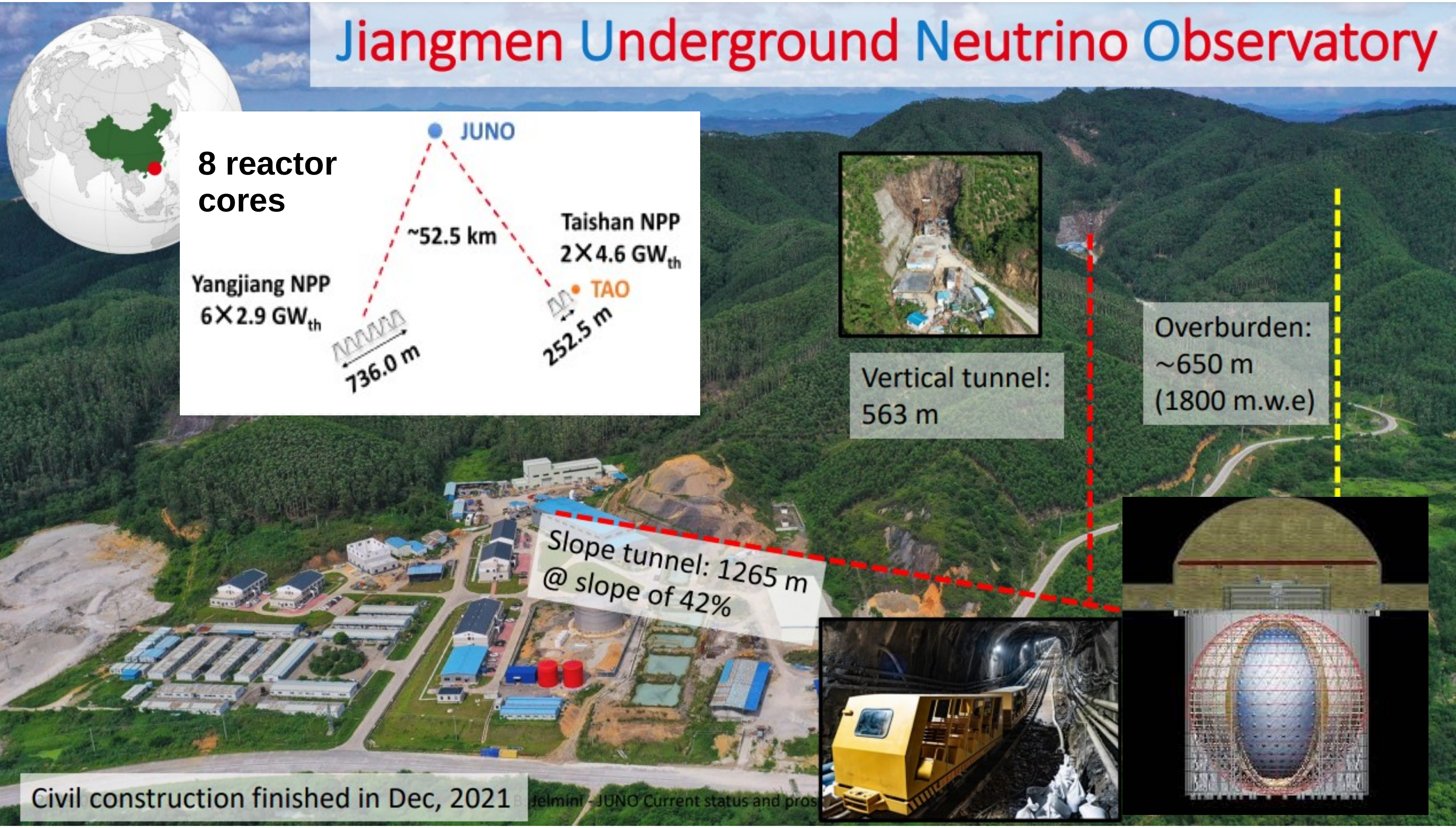
  - JUNO: medium baseline (53 km), under construction in China
  - SoLid: short baseline (6 m), in Belgium, data taking finished

JUNO



SoLid

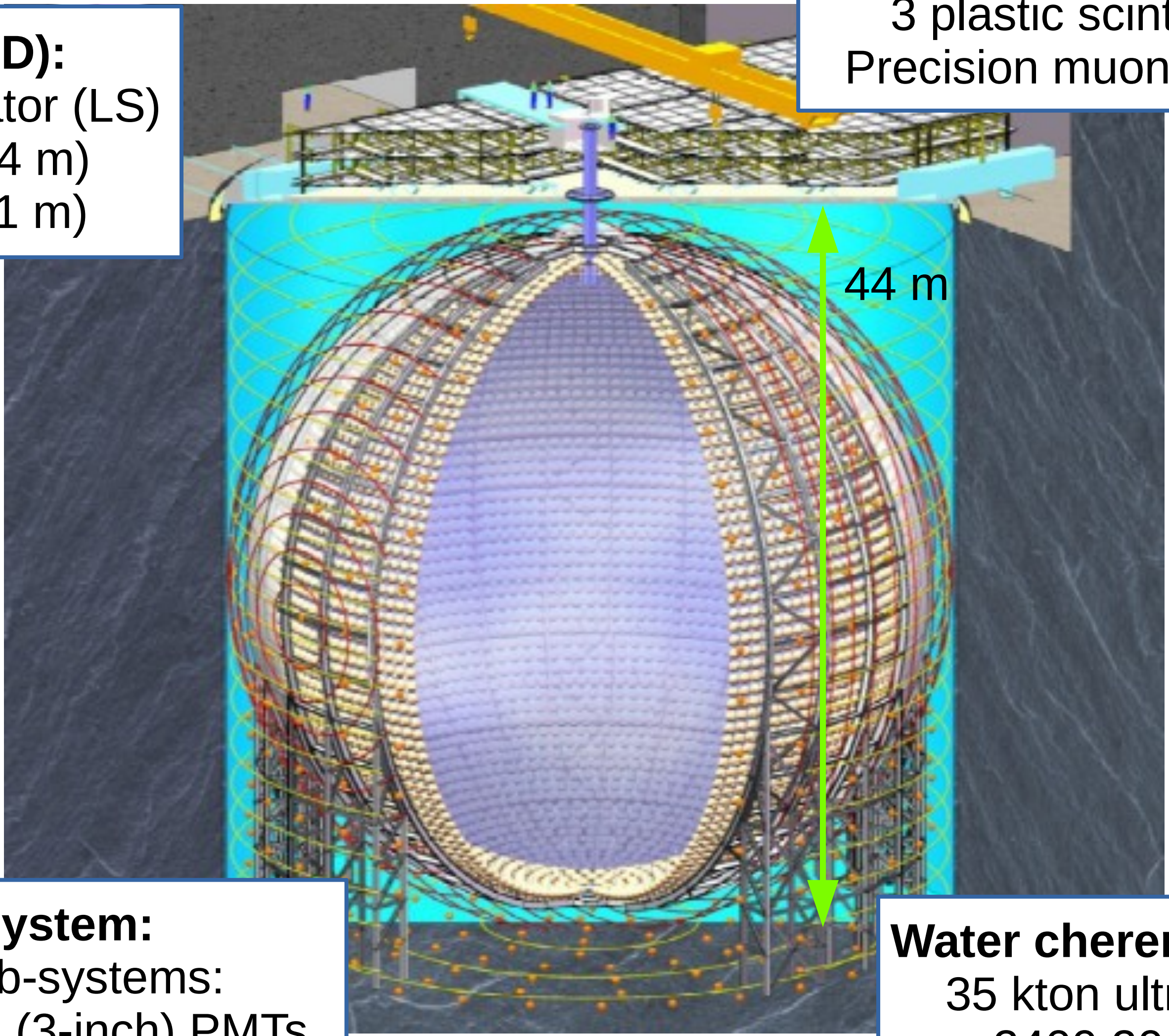
The JUNO detector



The JUNO detector

Central detector (CD):
20 kton of Liquid Scintillator (LS)
Accrylic vessel (ϕ 35.4 m)
Steel structure (ϕ 40.1 m)

Top Tracker:
3 plastic scintillator layers
Precision muon tagging (veto)



Light detection system:
>40000 PMTs in 2 sub-systems:
large (20-inch) and small (3-inch) PMTs

Water cherenkov detector:
35 kton ultra-pure water
2400 20-inch PMTs

JUNO - TAO

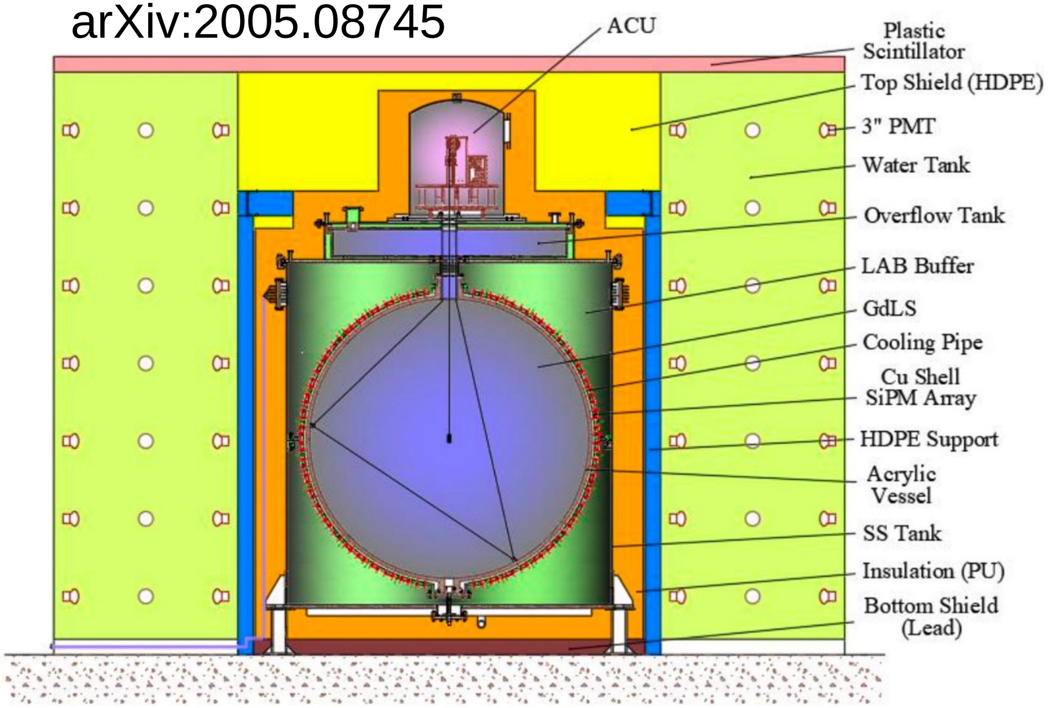
TAO (Taishan anti-neutrino Observatory):

- Close satellite detector of JUNO
- 2.8 kton of liquid scintillator
- Located ~30 m from one nuclear core

Goals:

- ➔ Precise and independent measurement of the reactor neutrino spectrum (with very high statistics)
- ➔ Search for sterile neutrinos

arXiv:2005.08745

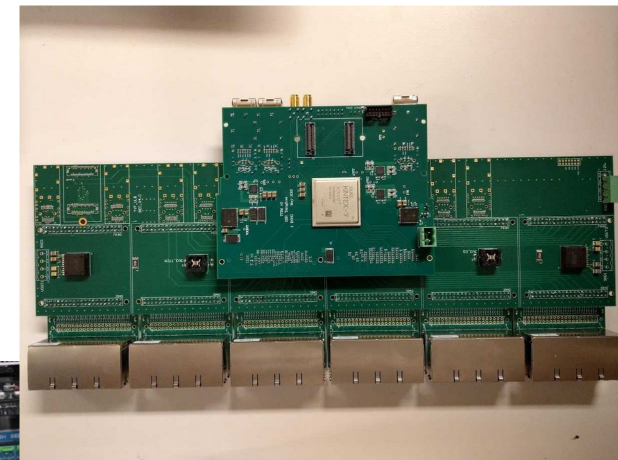


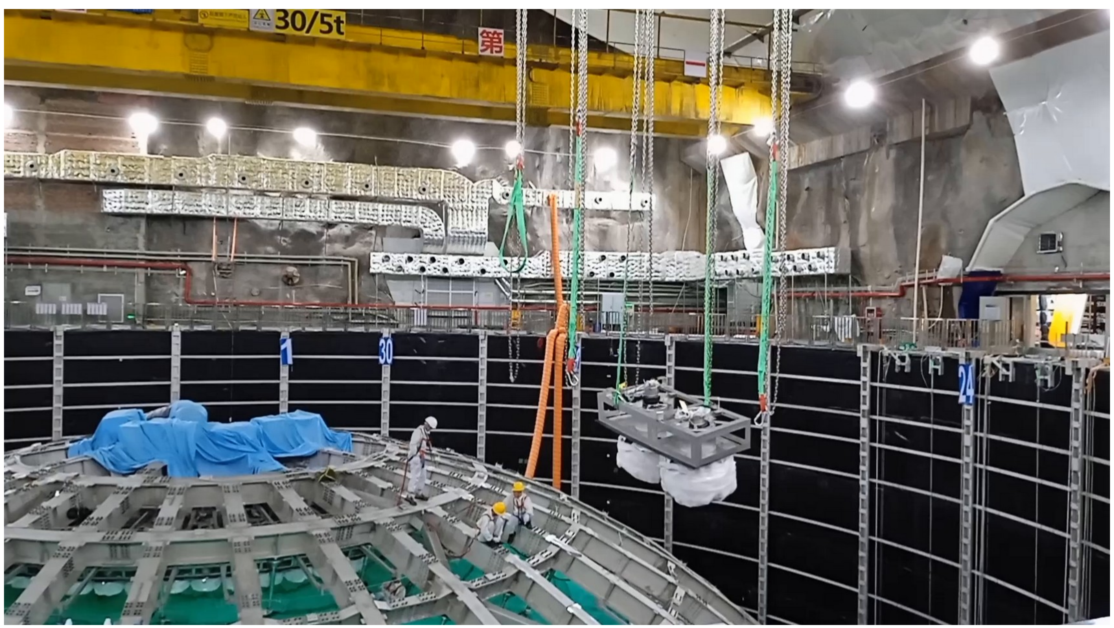
1:1 prototype under construction in China

JUNO: detector status

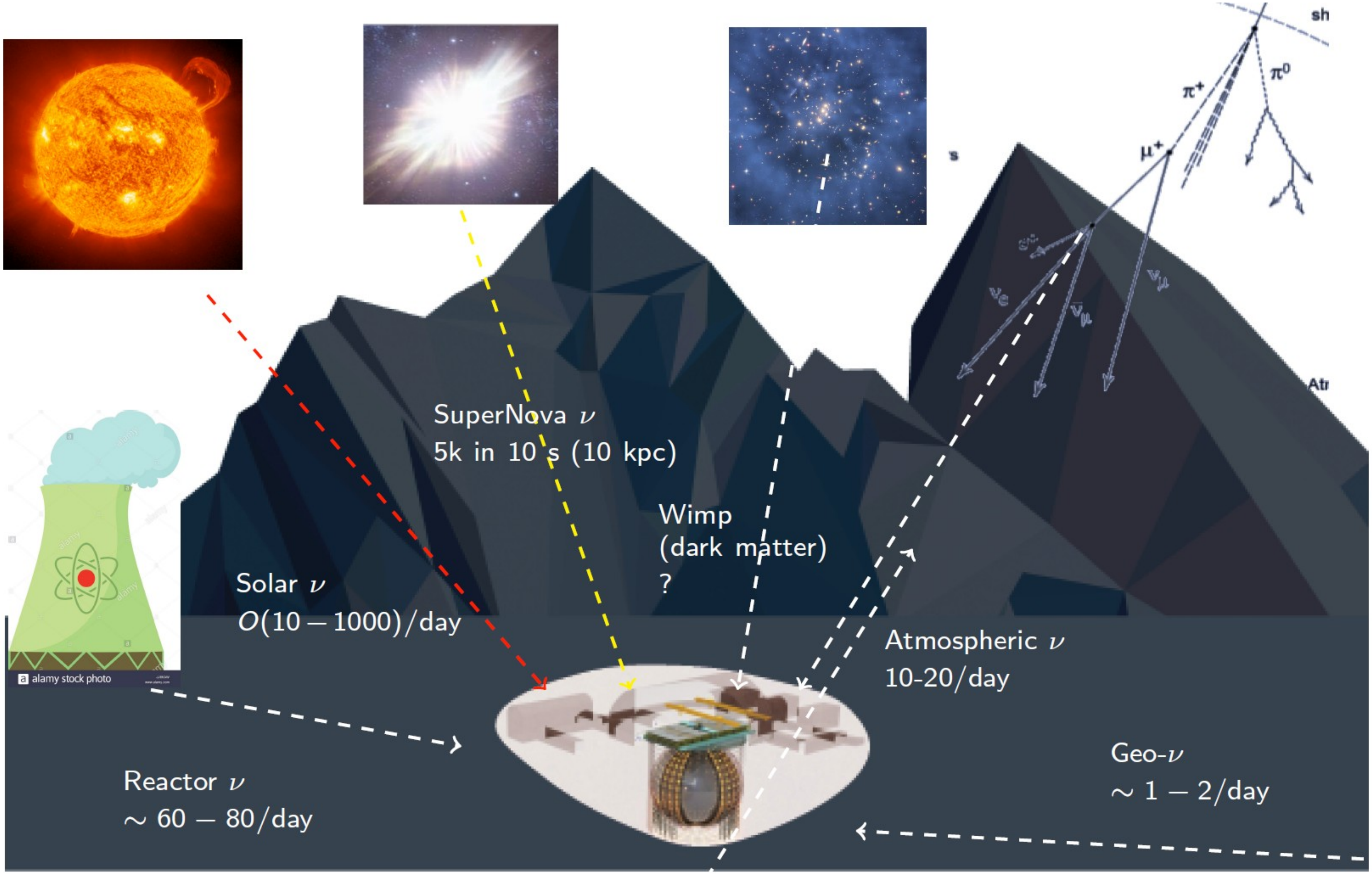
- JUNO electronics being installed:
- ➔ ULB contributed to the design, production and tests of the back-end electronics cards

- ➔ Installation of acrylic sphere and large PMTs ongoing
- ➔ Construction is expected to be finished at the end of the year
- ➔ Filling, commissioning and first physics test run in 2024





JUNO physics program



The JUNO detector

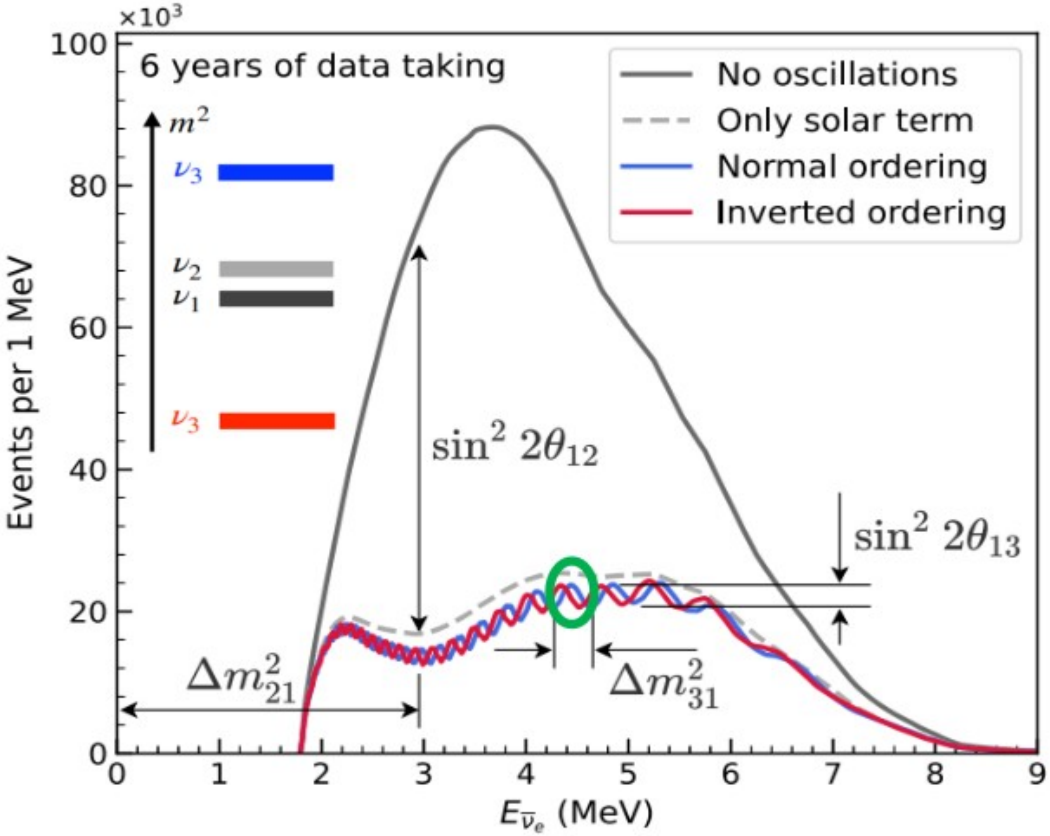
Primary goals:
- precise measurement of oscillation parameters
- determination of the neutrino mass ordering

Requirements:
- High statistics (~10^5 events in 6 yr)
- Energy resolution: ~3% @1MeV
- Energy scale uncertainty < 1%

How?

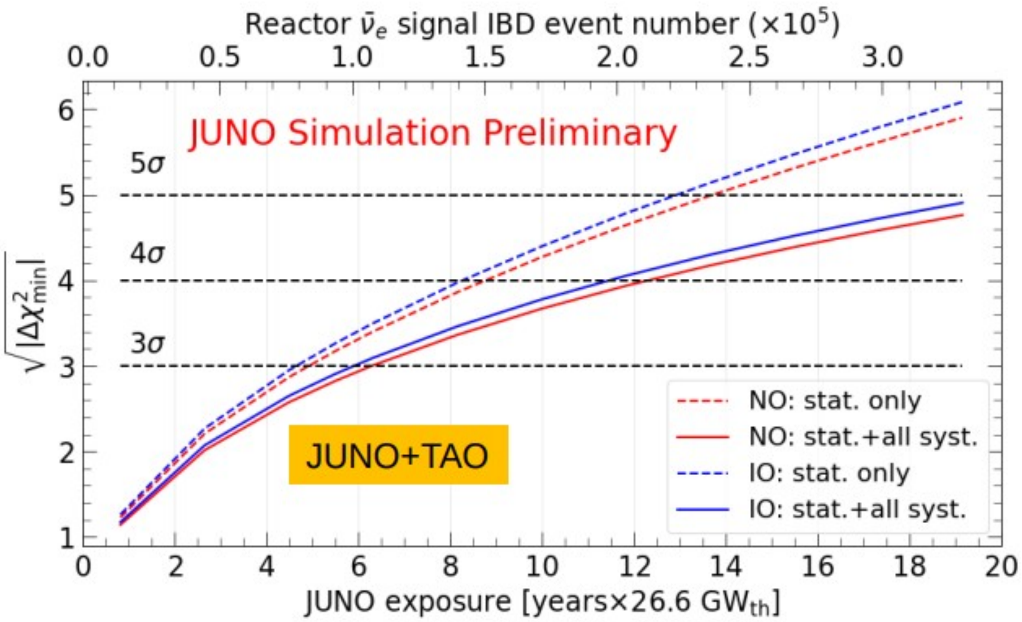
→ **Largest and most precise ever built liquid scintillator (LS) detector**

- Large LS volume (20 kton)
- High LS light yield & transparency
- High PMT coverage and efficiency
- Two complementary PMT systems
- Complementary calibration systems



Reactor neutrino oscillations

Determination of the neutrino mass ordering (NMO) (paper in preparation)

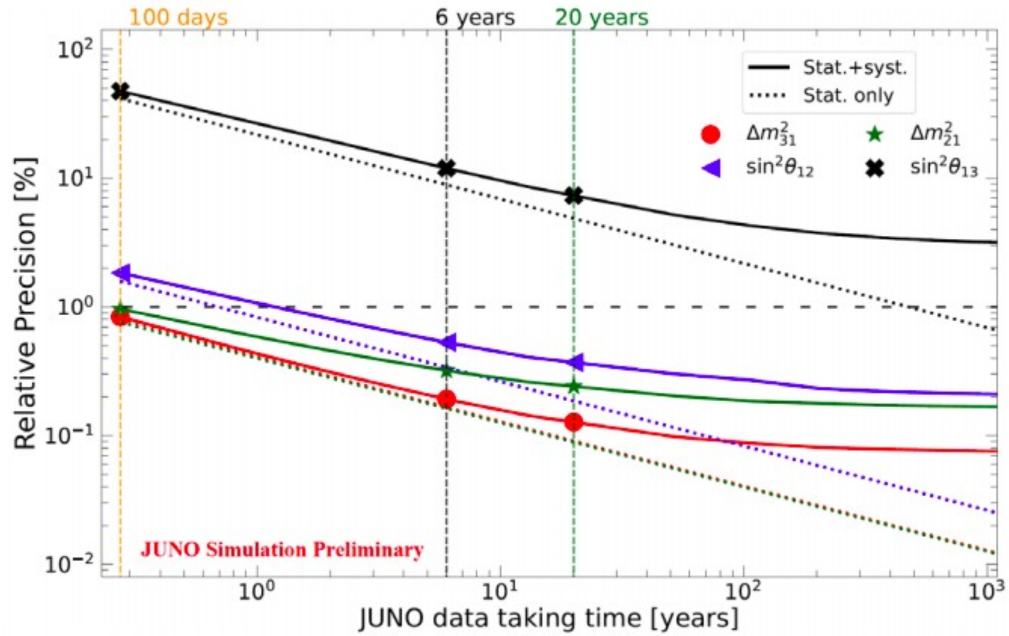


→ Determination of the NMO at 3σ in ~6 yrs

Exquisite spectrum resolution to probe simultaneously Δm^2_{21} and Δm^2_{31} driven oscillations with unprecedented precision

Sub-percent precision measurement of the oscillation parameters Chin. Phys. C 46 (2022)

→ JUNO will reach sub-percent precision level on Δm^2_{21} , Δm^2_{31} (100 days) and $\sin^2\theta_{12}$ (1 year)

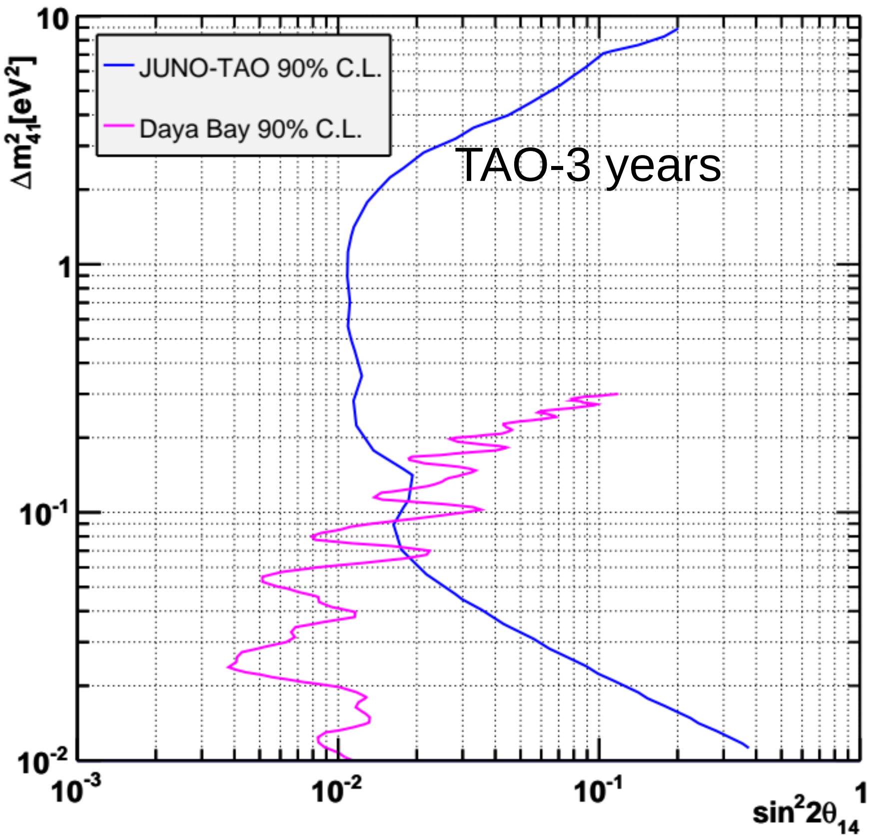


	Δm^2_{31}	Δm^2_{21}	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
PDG 2020	1.4%	2.4%	4.2%	3.2%
JUNO 6 years	~0.2%	~0.3%	~0.5%	~12%

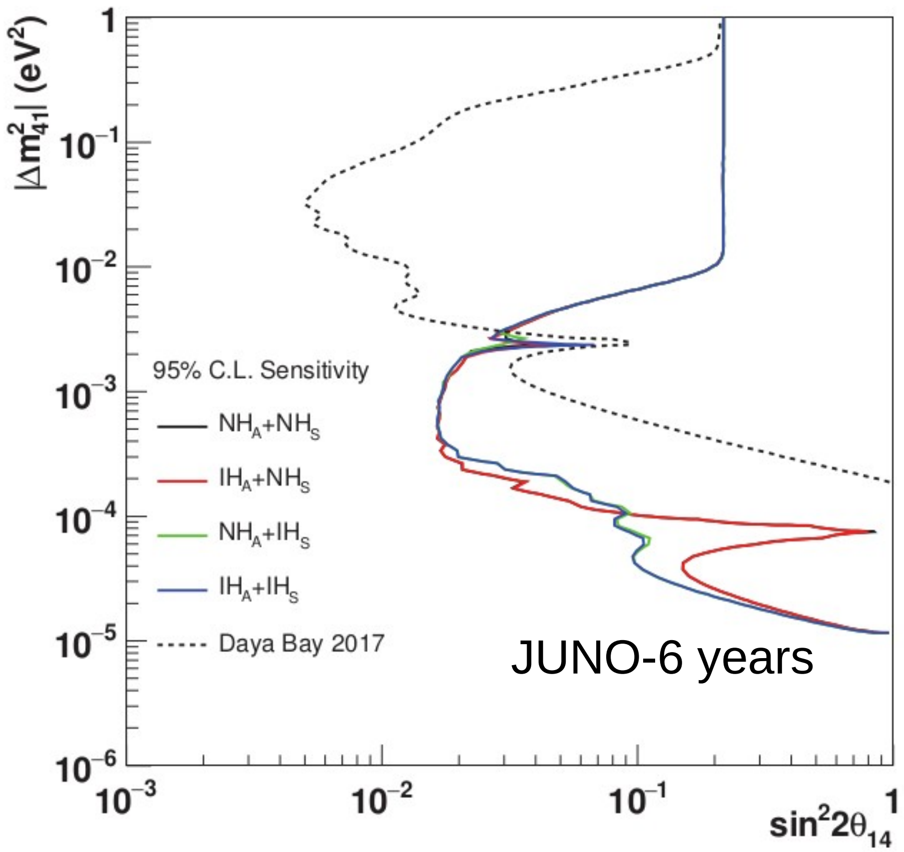
JUNO: sterile neutrino search

Presence of an sterile neutrino → change on the shape of the observed energy spectrum

TAO sensitivity will be competitive in the region
10^{-1} eV^2 < Δm^2_{41} < 10 eV^2



JUNO explores the mass region <10^{-2} eV^2



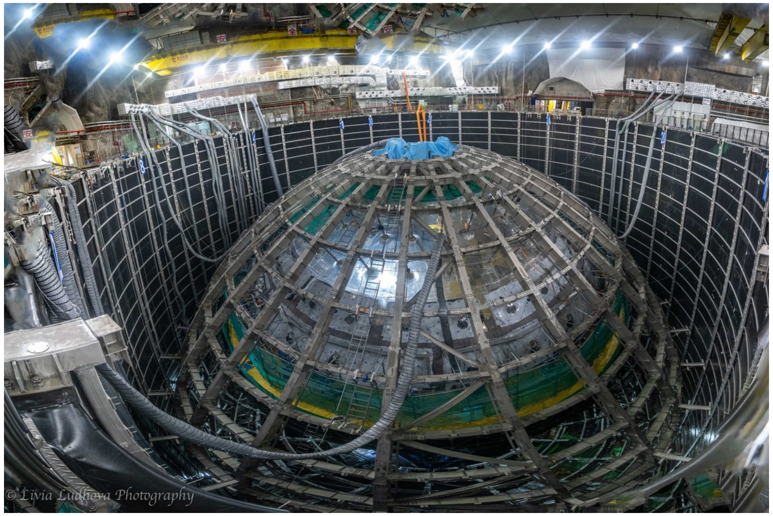
→Expand the space of parameters coverage and extend the exclusion region

Reactor neutrino detectors

- Belgium is involved in two different reactor neutrino experiments:

  - JUNO: medium baseline (53 km), under construction in China
  - SoLid: short baseline (6 m), in Belgium, data taking finished

JUNO

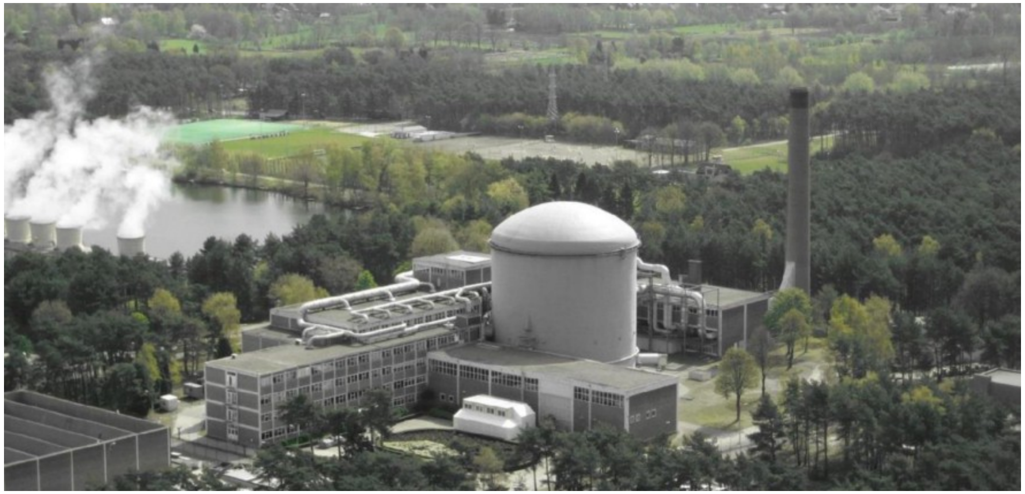


SoLid

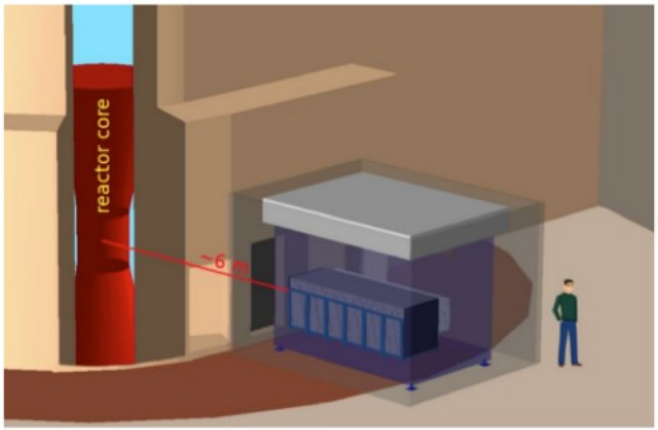
The SoLid experiment

- SoLid (Search for oscillations with Lithium-6 detector) is located in the BR2 nuclear reactor of the SCK· CEN @ Mol, the Belgian National Nuclear Lab
- Reactor with highly enriched ^{235}U (> 93.5%) nuclear fuel
- Low-level reactor background
- Very compact reactor:

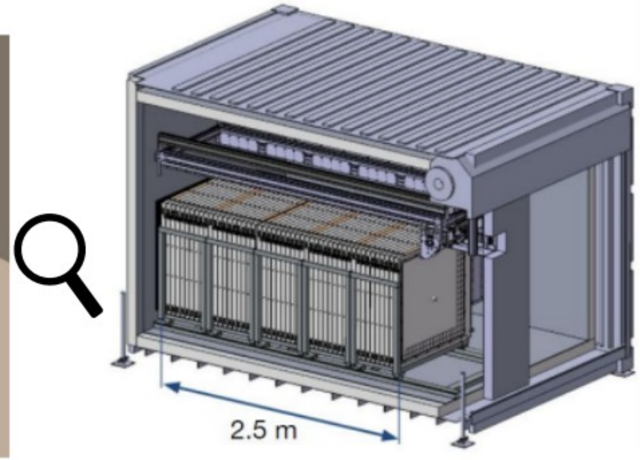
→ detector can be placed ~6 m from the reactor core
- Off periods for background evaluation



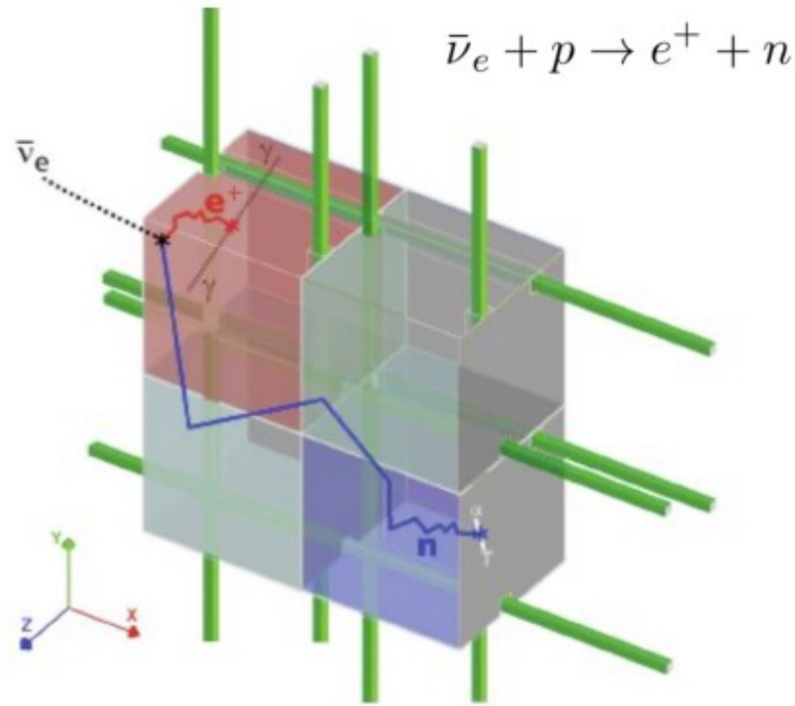
The SoLid experiment

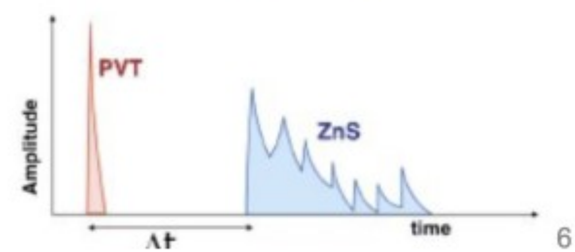


SoLi∂ detector model



SoLi∂ container

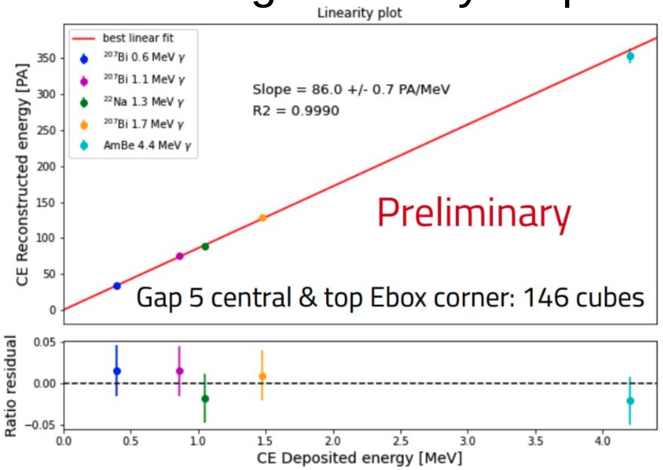




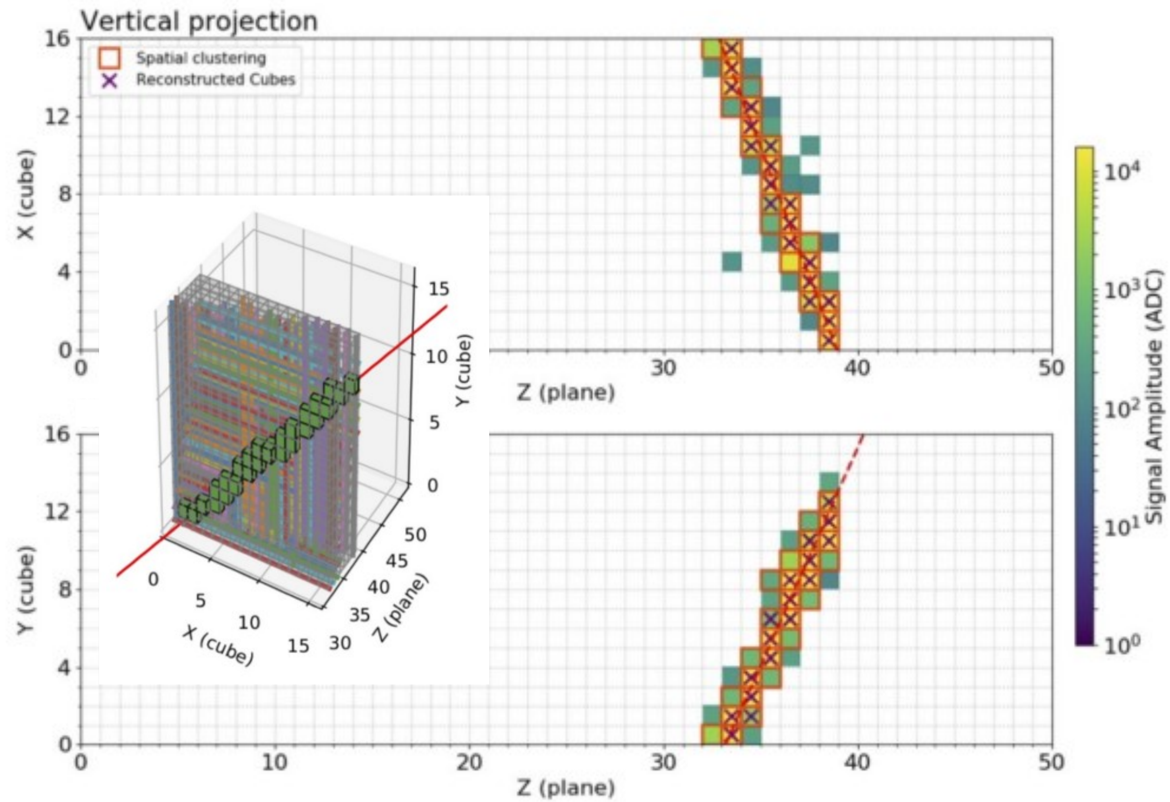
- 5 modules, with a total of ~13k plastic scintillator cubes of 5 cm side
- Signals detected by 3.200 Silicon PMTs
- 1.6 ton fiducial volume (plastic scintillation cubes) for **prompt** IBD signal detection
- ^{6}LiF:ZnS(Ag) sheets to detect **delayed** IBD signal
- Statistics: ~80 IBD events per day

The SoLid experiment

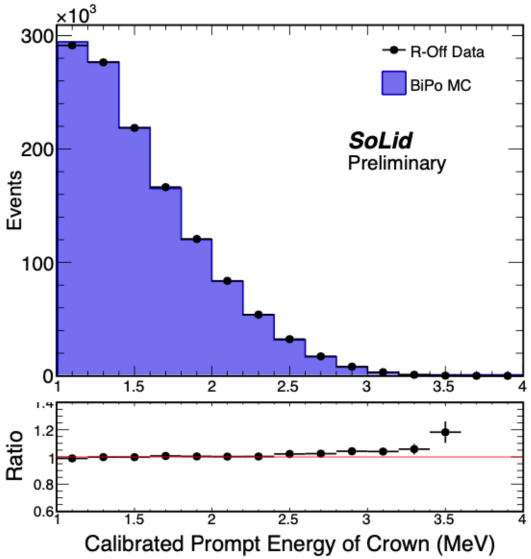
- Good charge linearity response



- Solid can separate e+ from annihilitation gammas:
→ novel calibration and reconstruction methods
- Classify events according to: 0, 1 & 2 gamma category



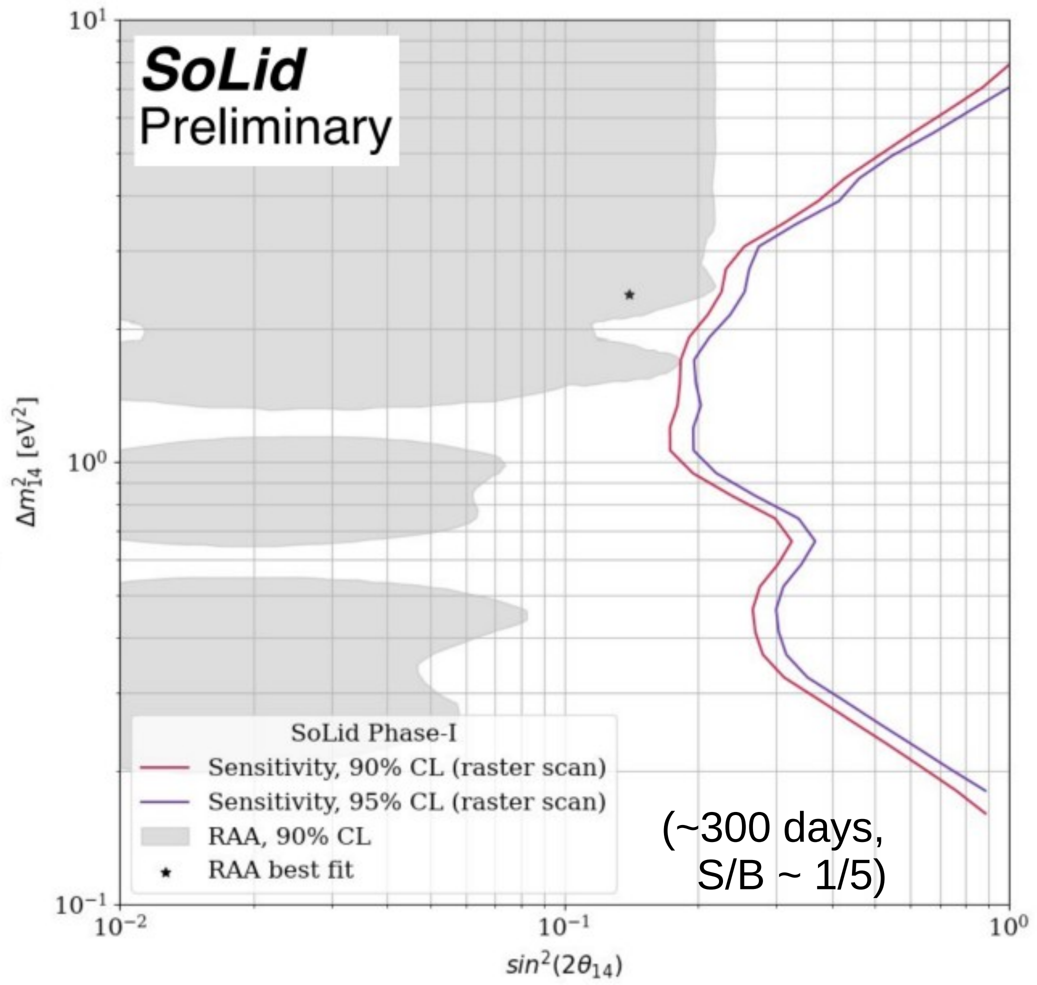
- MC-data tuning: very good agreement



SoLid preliminary results

Goals:
- ➔ Probe the reactor neutrino anomaly at close distance
- ➔ Very precise measurement of the ^{235}U spectrum

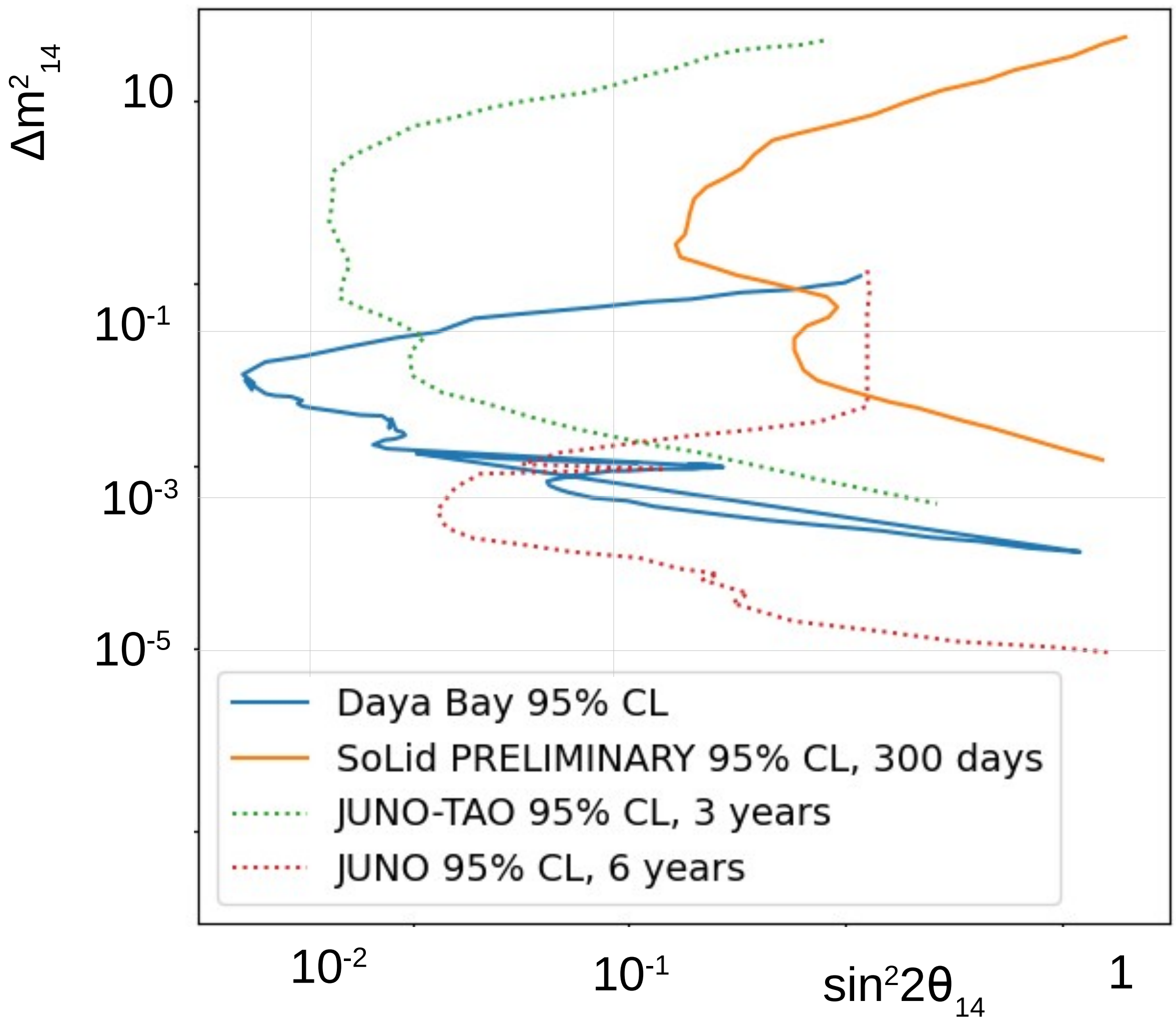
- **Very preliminary result**, yet statistically dominated
- Signal over background improvement: went now from 1/5 to 1/3 with same efficiency
- Preparation of the final release with full dataset ongoing → results soon



Conclusions

- Neutrinos oscillating and being massive = beyond standard model
- Searching for new physics (sterile) requires of complementary detectors and detection channels
- Reactor neutrino experiments are key in these searches
- Belgium is contributing to two major experiments in the field:

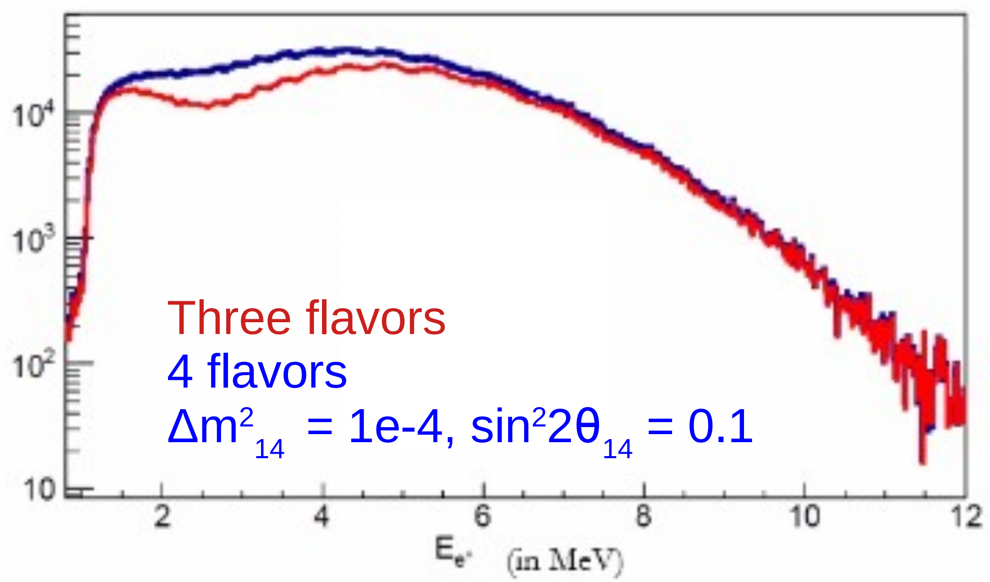
-SoLid, waiting for the results release
-JUNO, waiting for start of data taking

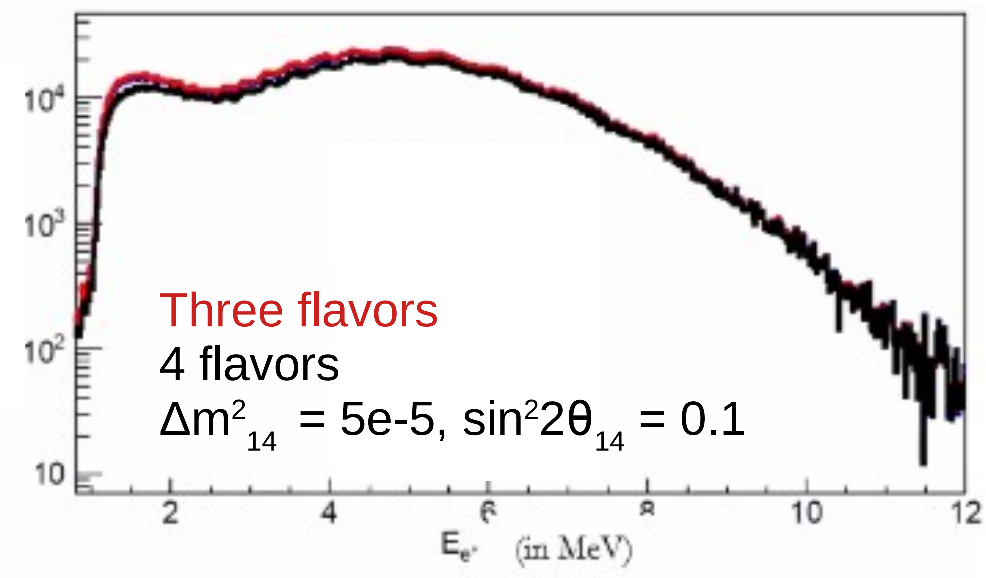


(for illustration of complementarity)

JUNO: sterile neutrino search

- Presence of an sterile neutrino → change on the shape of the observed energy spectrum
- The change with respect to 3 flavors scenario will depend on the oscillation parameters: Δm^2_{14} and $\sin^2 2\theta_{14}$





→ How much of the parameter space can JUNO and JUNO-TAO constrain?