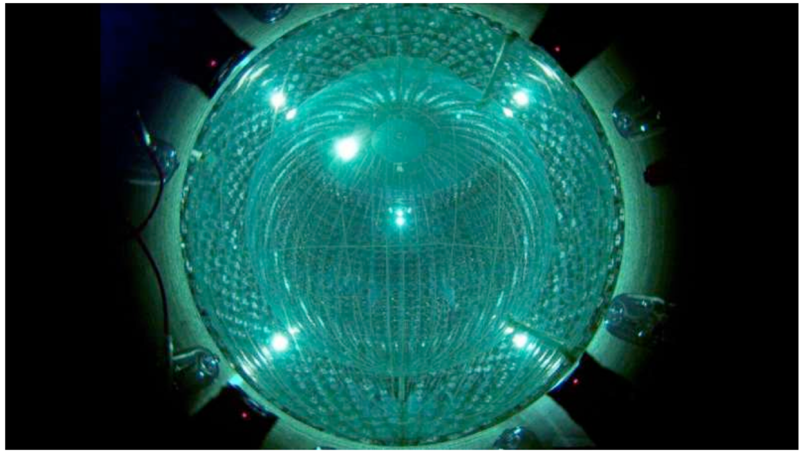
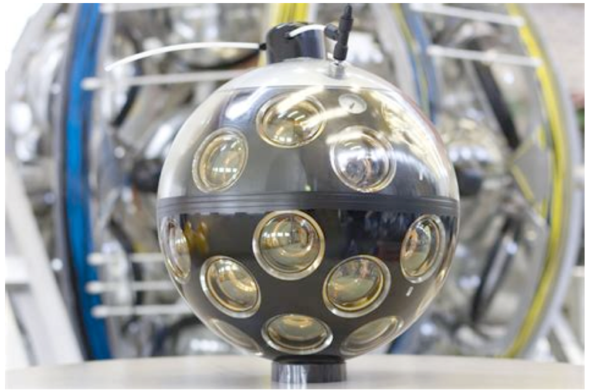
Neutrinos @ INFN:
a leap inside the Commisione Scientifica Nazionale 2





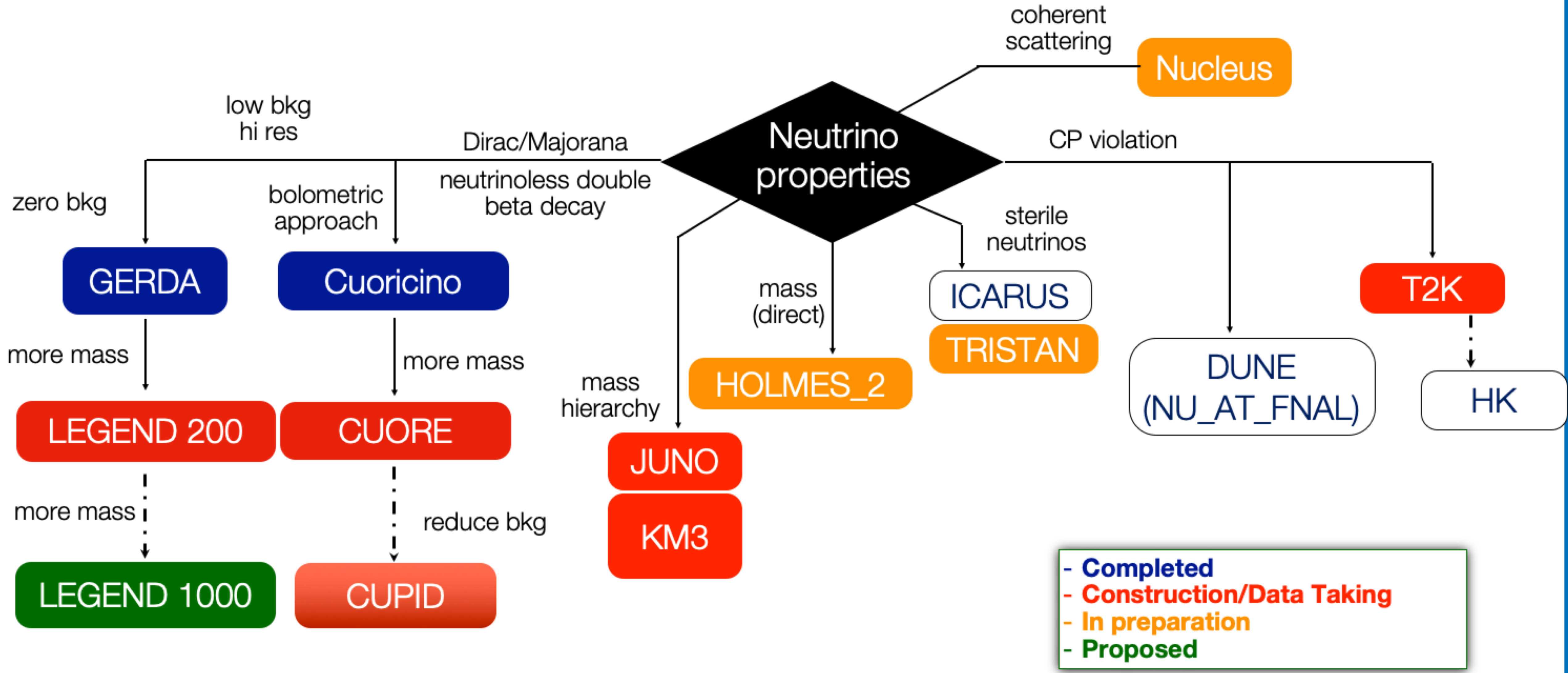
CSN2 INFN: Mission and Organisation

Five research lines

- CSN I – Particle Physics
- CSN II – Astro-particle Physics
- CSN III – Nuclear Physics
- CSN IV – Theoretical high energy physics
- CSN V – Applied nuclear and particle physics

Scientific line CSN2	# exp	FTE	M€
Dark Universe	10+2	171	1.5
Gravity and Quantum Physics	10	236	1.5
Cosmic Radiation	14+1	404	3.6
Neutrino Properties	10(-3)	212	6

CSN2 neutrino properties reasearch line



DUNE, ICARUS, HK: accelerator based experiments moving to CSN1

Measuring neutrino properties

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric and accelerator
$\theta_{23} \approx 50^\circ$
$|\Delta m^2_{32}| \sim 2.5 \times 10^{-3}\text{eV}^2$

Reactor and accelerator
$\theta_{13} \approx 8^\circ$
Accelerator only: $\delta_{CP} = ?$

Solar and reactor
$\theta_{12} \approx 34^\circ$
$\Delta m^2_{12} \sim 7.5 \times 10^{-5}\text{eV}^2$

$0\nu\beta\beta$ experiments

known: mixing parameters
unknown: CP phase and mass hierarchy

known knowns

$\delta m^2/eV^2$	~ 7.34×10^{-5}	$\pm 2.2\%$
$\Delta m^2/eV^2$	~ 2.48×10^{-3}	$\pm 1.3\%$
$\sin^2\theta_{12}$	~ 0.303	$\pm 4.4\%$
$\sin^2\theta_{13}$	~ 0.0225	$\pm 3.8\%$
$\sin^2\theta_{23}$	~ 0.545	$\pm 5.0\%$

known unknowns

δ(CP)
sign(Δm^2)
octant(θ_{23})
absolute ν mass
Dirac/Majorana

Quark sector

CKM

vs.

PMNS NH

Lepton sector

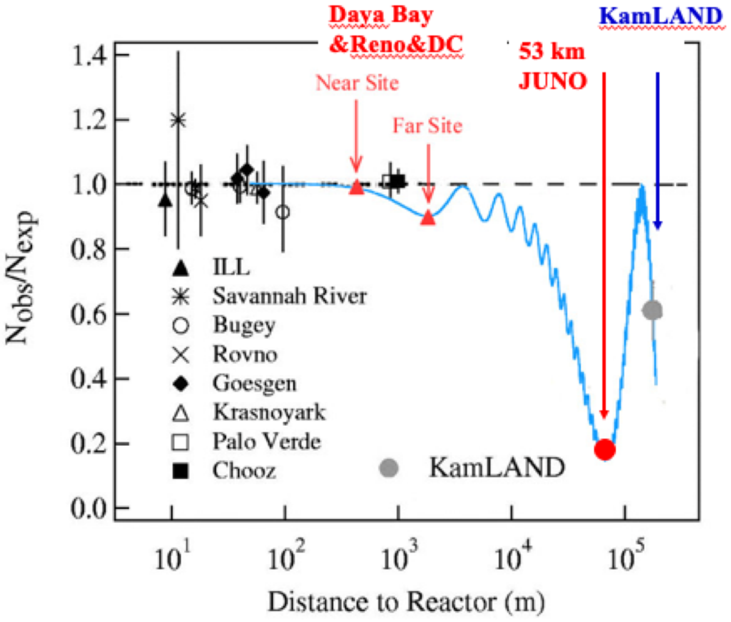
Macrscopic difference between quarks and lepton mixing pattern

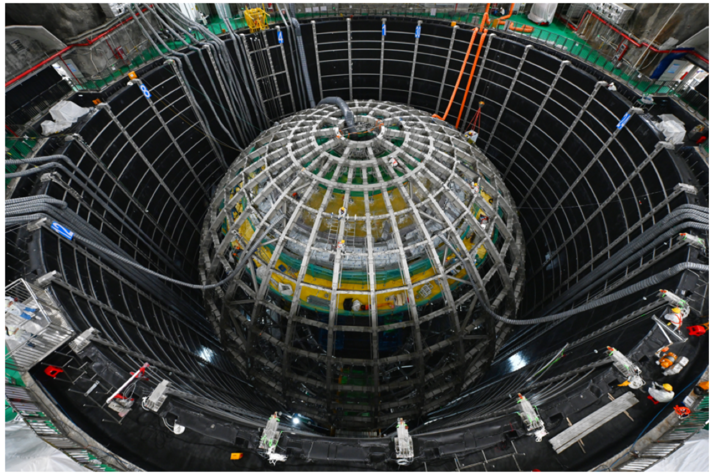
CSN2: Neutrino oscillations experiments

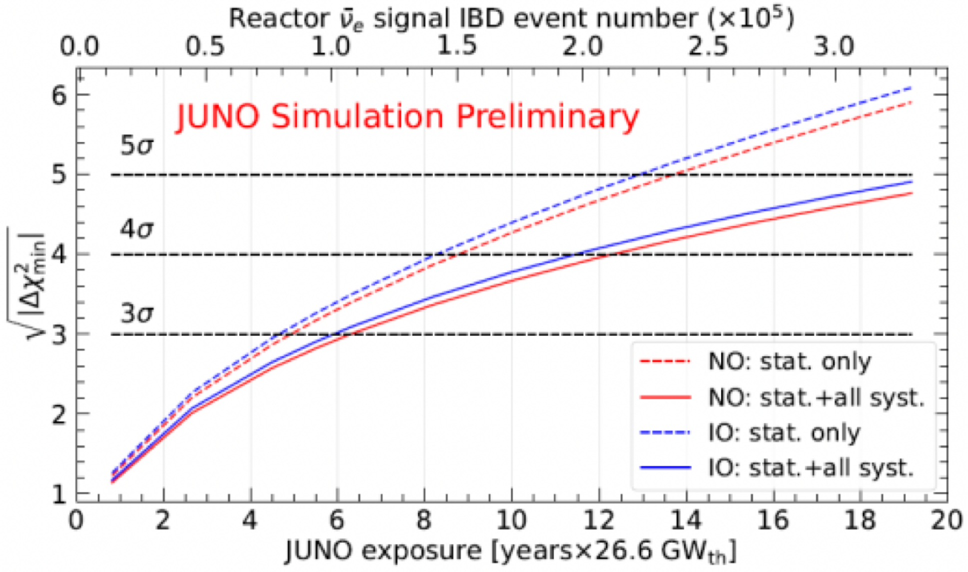
Main goal	source	technique	experiment	By-products
Θ_{23}, Δm^2_{32}	Atmospheric	W. Cherenkov	KM3NeT (ORCA)	MH Θ_{13}, δ_{CP}
δ_{CP}	Accelerator	W. Cherenkov	T2K-HK	Θ_{23}, Δm^2_{32} , Θ_{13} sterile, ν
δ_{CP}, sterile ν, MH	Accelerator	LAr	ICARUS, DUNE	Θ_{23} Δm^2_{32} , Θ_{13}
CEνNS	Reactor	TES	Nucleus	μ_ν, q
MH, Δm^2_{21}, Θ_{12}	Reactor	LS	JUNO	Θ_{13}, Θ_{23}, Δm^2_{32}
Δm^2_{21}, Θ_{12}	Solar	LS	JUNO	μ_ν, q

CSN2: Neutrino mass hierarchy

JUNO The 35 kton Water Cherenkov detector
20 kton LS detector
~3 % energy resolution-the greatest challenge for MH







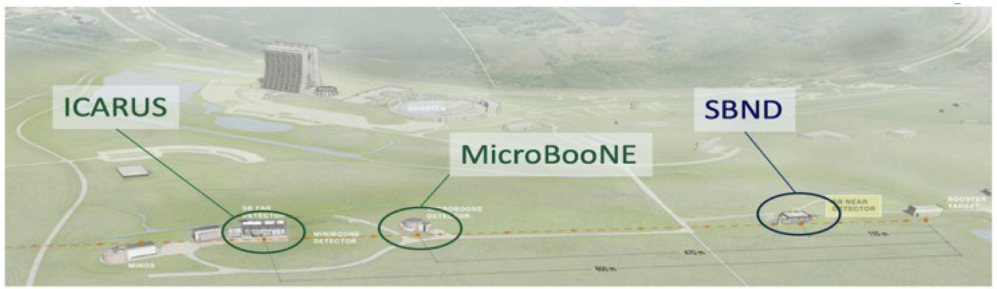
	Δm^2_{31}	Δm^2_{21}	$\sin^2\theta_{12}$
JUNO 6 years	~0.2%	~0.3%	~0.5%
PDG2020	1.4%	2.4%	4.2%

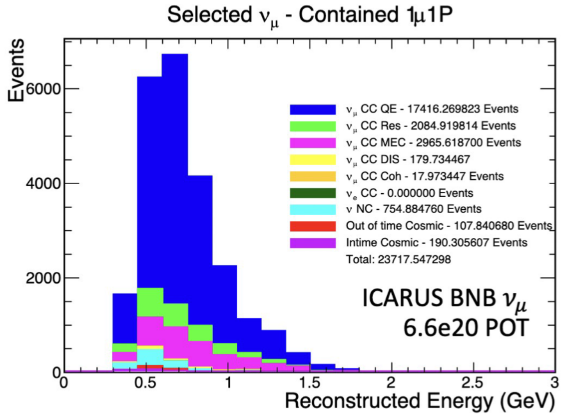
Unprecedented sub percent precision

KM3NeT ORCA expected to enter the game in the next 5 years

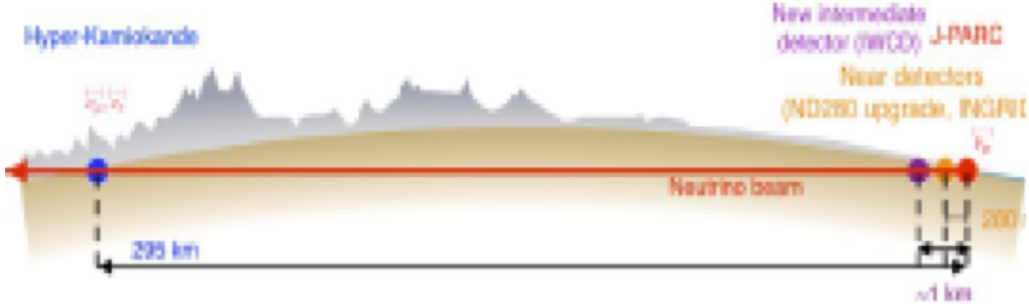
CSN2: Sterile ν and δ_{CP}

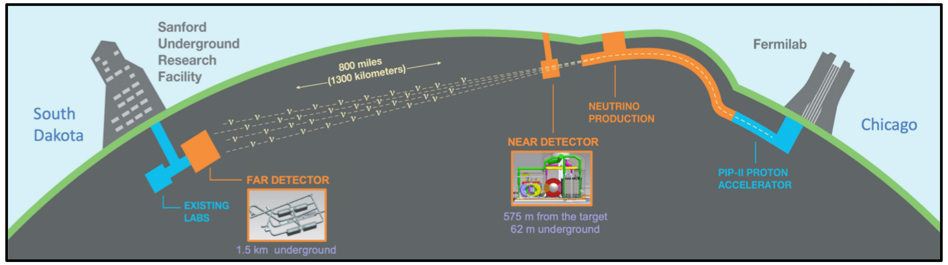
SBN program: BNB beam comparing the ν_e and ν_μ interactions at ICARUS (600m) and SBND(110m)



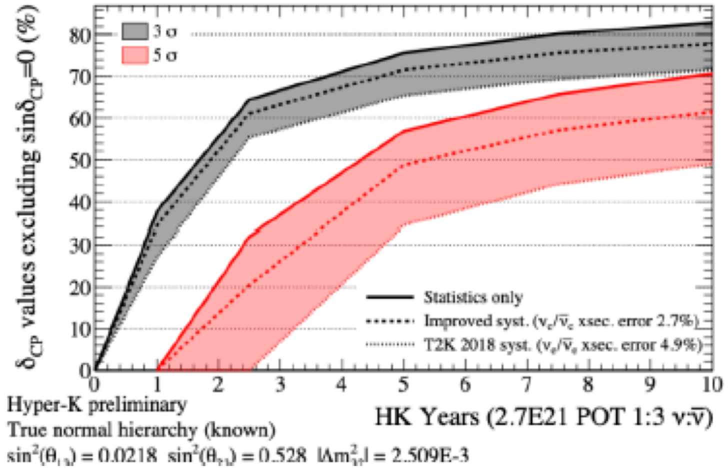


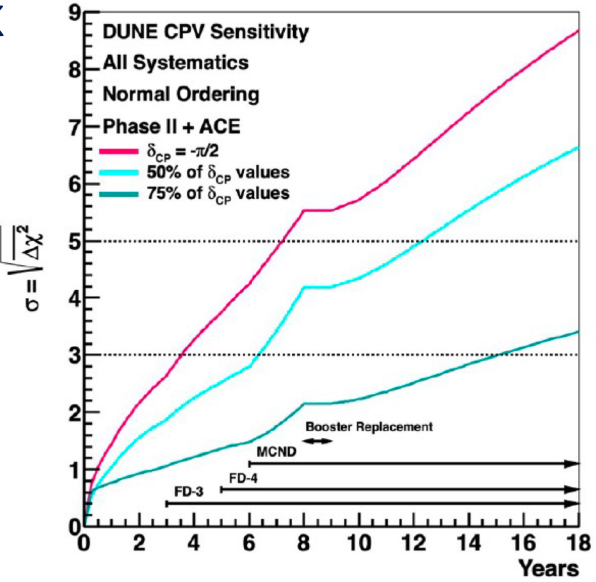
CP violation: normalization of the appearing ν_e → 200/1000 km baselines and "perfect" near detectors
(but also beam monitor a la Enubet !)





From NoVA+T2K to DUNE+HK





CSN2: Neutrinoless beta decay

From Cuore to Cupid

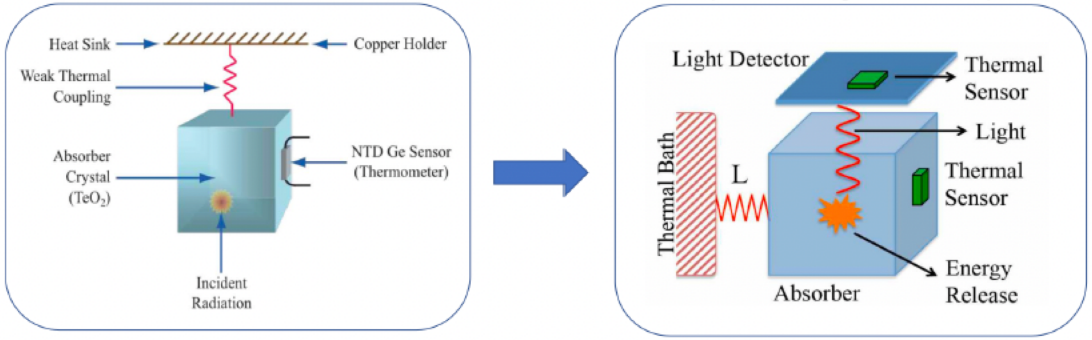
A ton scale high-resolution detector array for the search of 0νββ in the IH

~240 kg of 100Mo

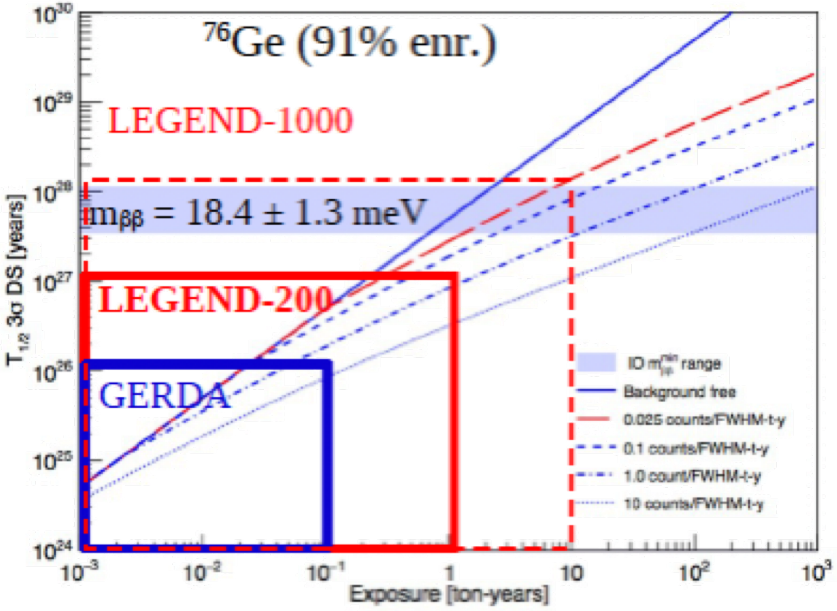
Discovery sensitivity T1/2 > 1.1×10^{27} yr (3σ)
Discovery sensitivity $m_{\beta\beta}$: 12-20 meV (3σ)

CUORE ^{130}Te
pure thermal detector
(bolometer)

CUPID ^{100}Mo
heat + light
(scintillating bolometer)



From Gerda to Legend



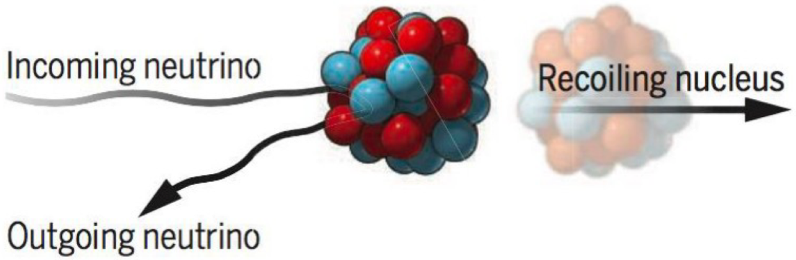
Legend 200 in data taking

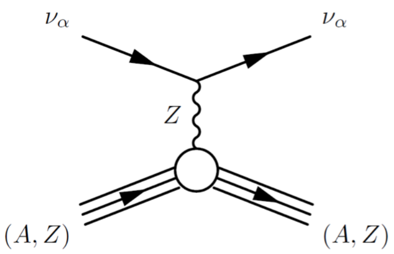
LEGEND-200
search 0νββ to discovery sensitivity: 10^{27} yr

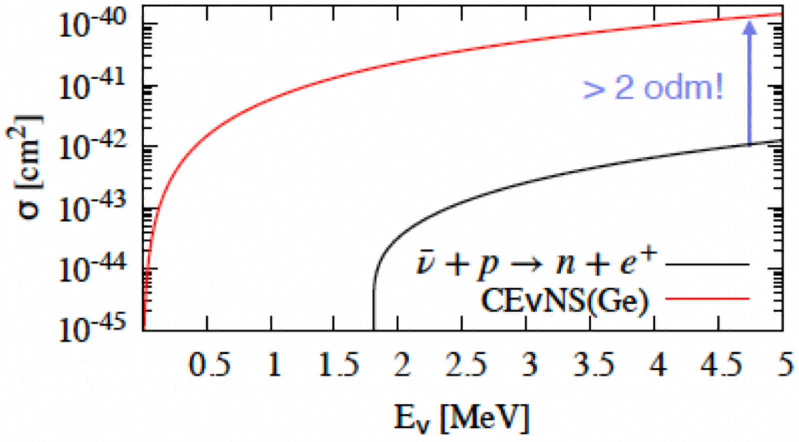
LEGEND-1000
search 0νββ to discovery sensitivity: 10^{28} yr
mββ 34–78 meV (3σ)

CSN2: CEνNS

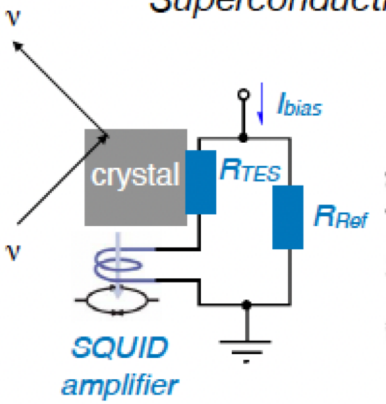
Predicted in 1970, observed in 2017

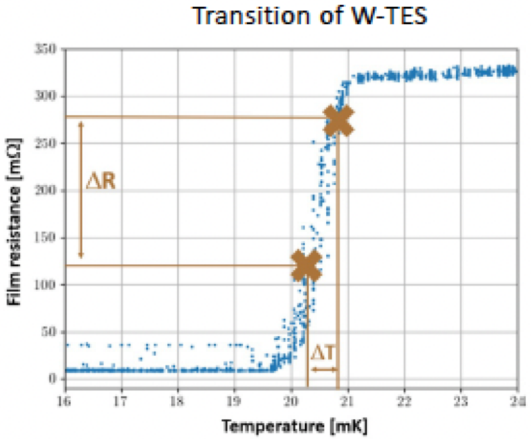


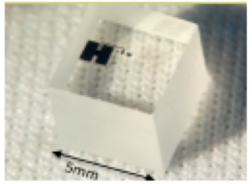


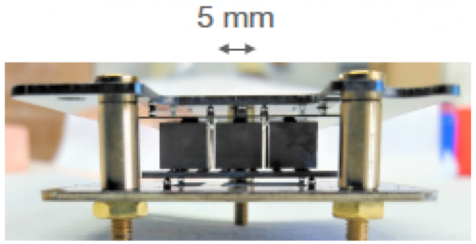


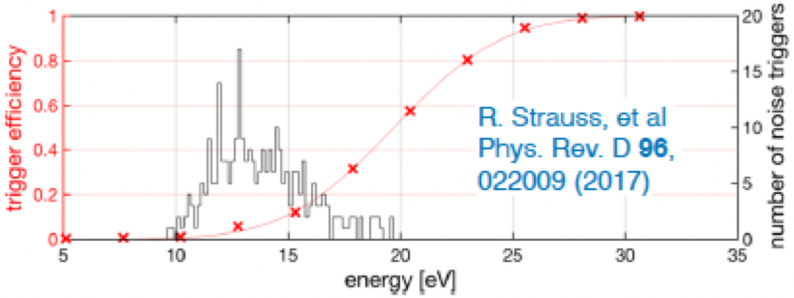
Superconducting thermometers (TES)





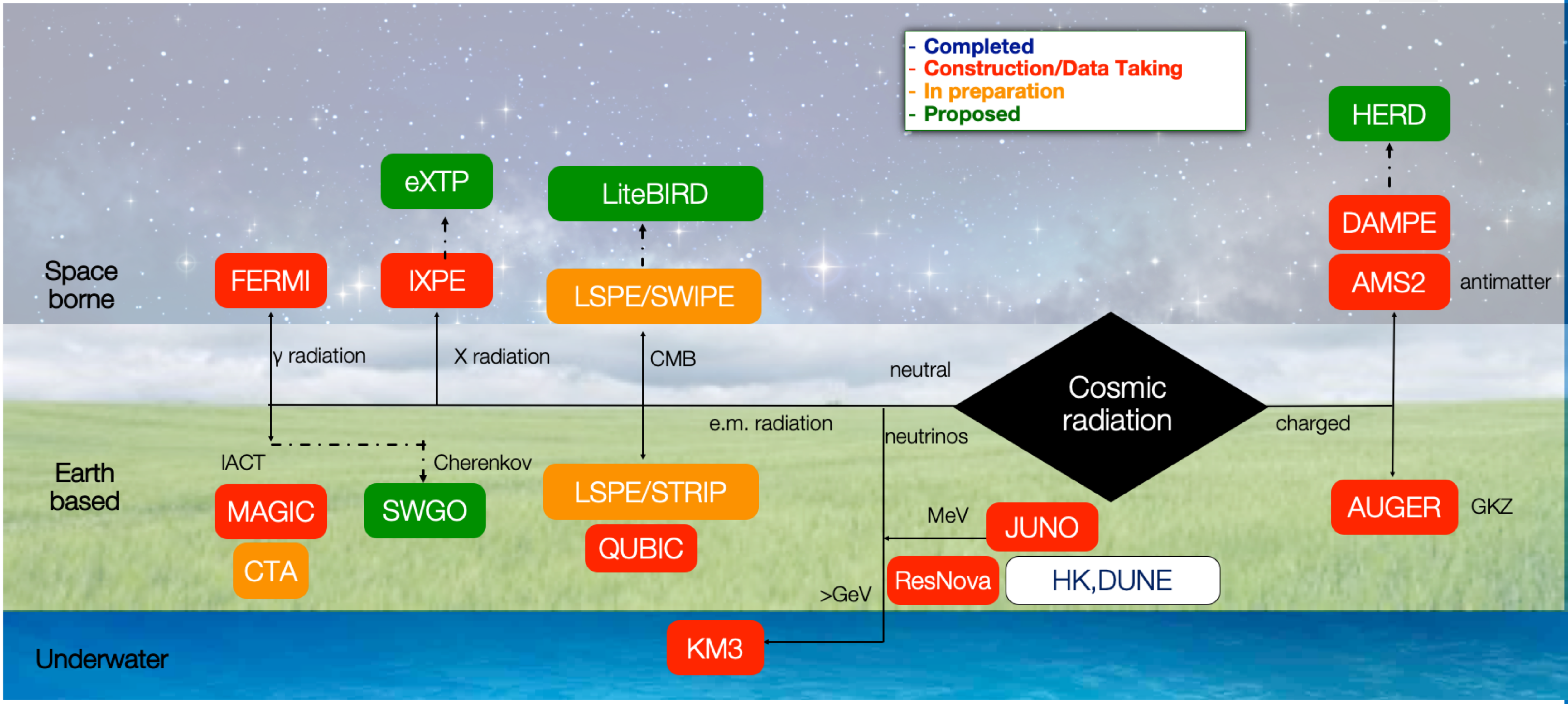






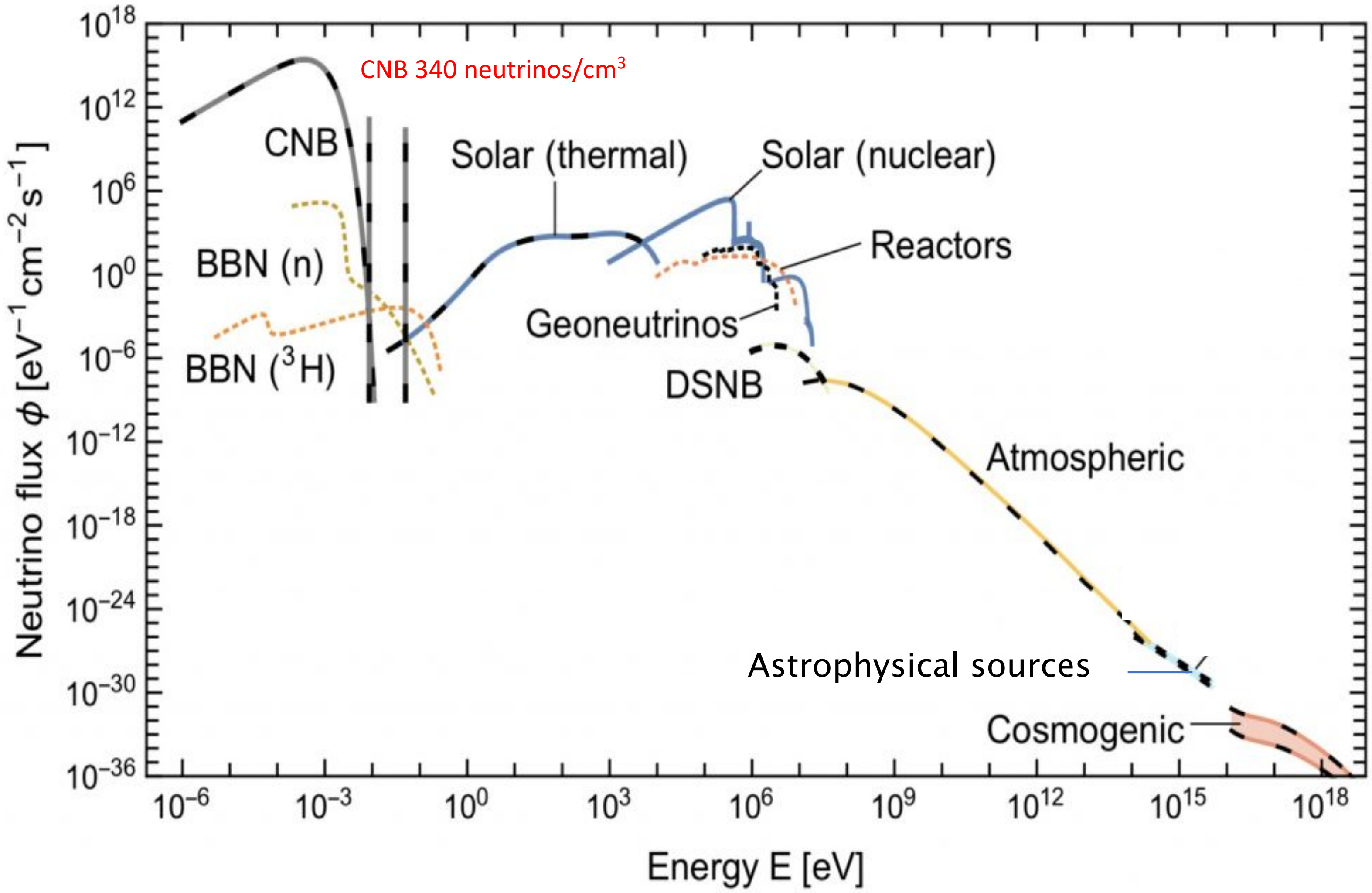
Pro: record-low energy threshold ~ 20 eV

CSN2 cosmic radiation research line



At the dawn of neutrino astronomy

** credit F. Vissani



CSN2 & Neutrino Astronomy: Geo-neutrinos

Geo neutrinos

Radiated Earth power: 47 TW

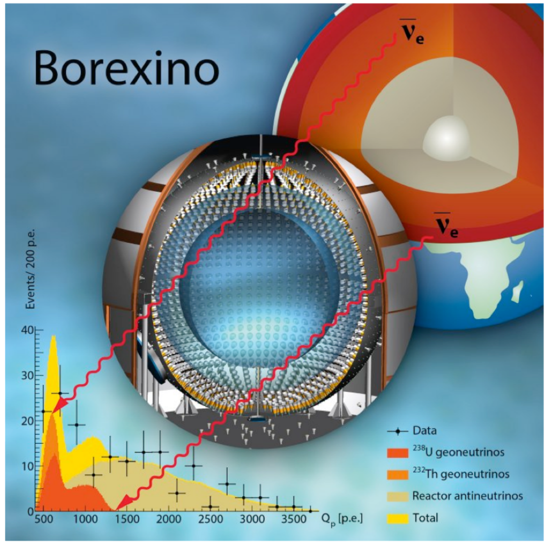
radiogenic between 10 TW and 30 TW

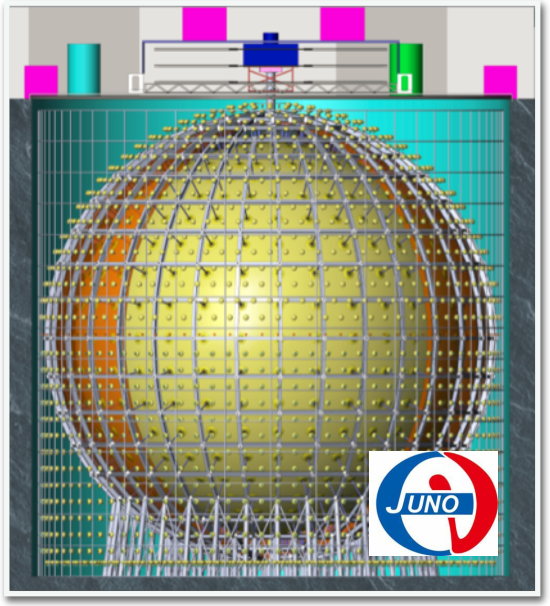
crust (7 TW) , mantle and core (few)

Detection:

Inverse beta decay (IBD) in radio pure scintillators

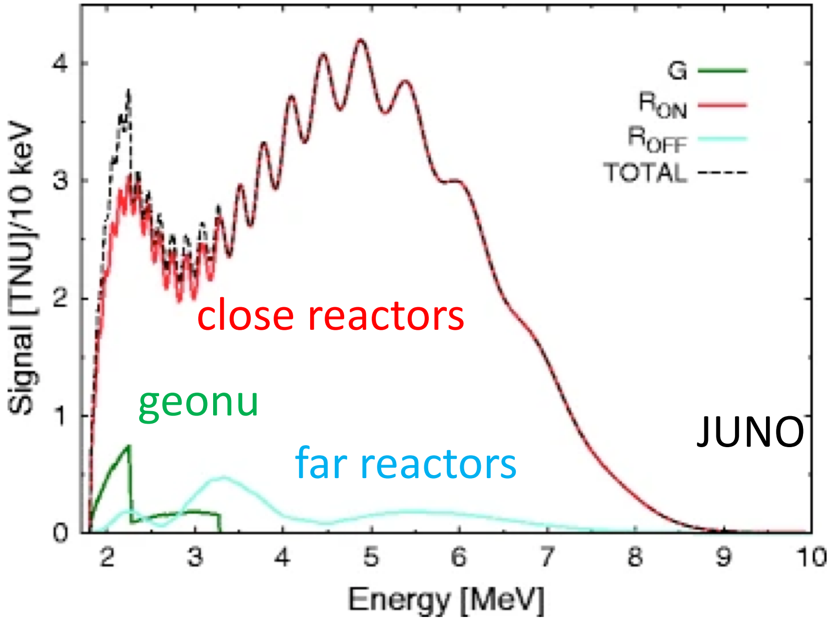
$$\bar{\nu}_e + p \rightarrow n + e^+$$





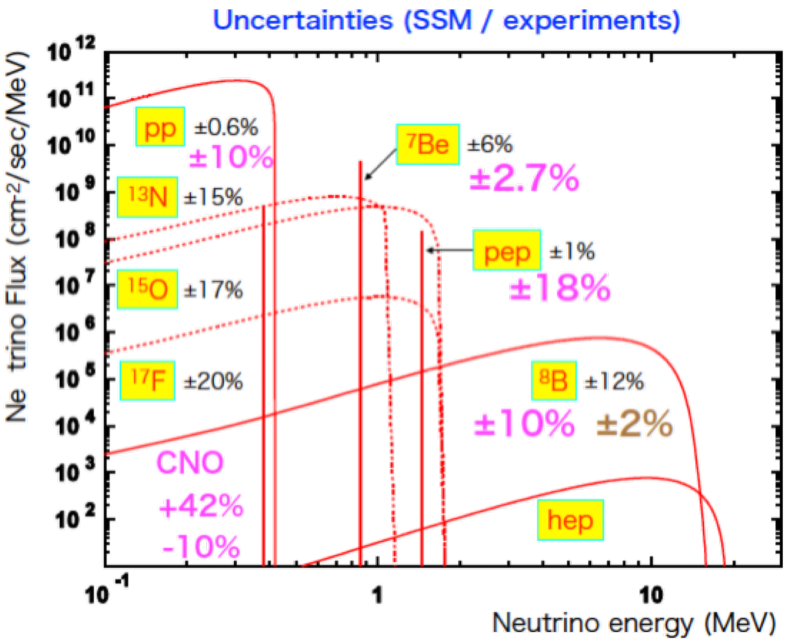
Borexino (2007-2021):
280 T liquid scintillator

Juno
20 kT liquid scintillator

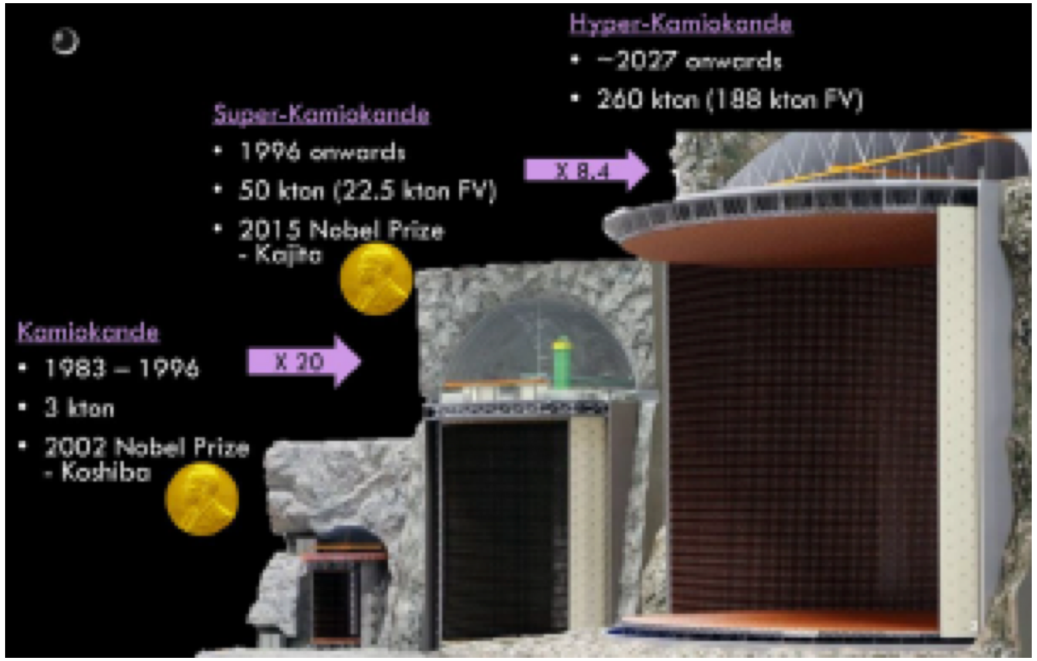


CSN2 & Neutrino Astronomy: Solar Neutrinos

Astrophysical opportunities:
solar metallicity (core temperature/opacity) problem → fundamental for star evolution models
real time sun core astronomy (ν travel time: 10^2 s, gamma travel time: 5×10^{12} s)



The path is paved: JUNO, DUNE, Hyper Kamiokande
SSM tuning with neutrino observations: pp (pep), CNO
Solar (high) metallicity to be confirmed

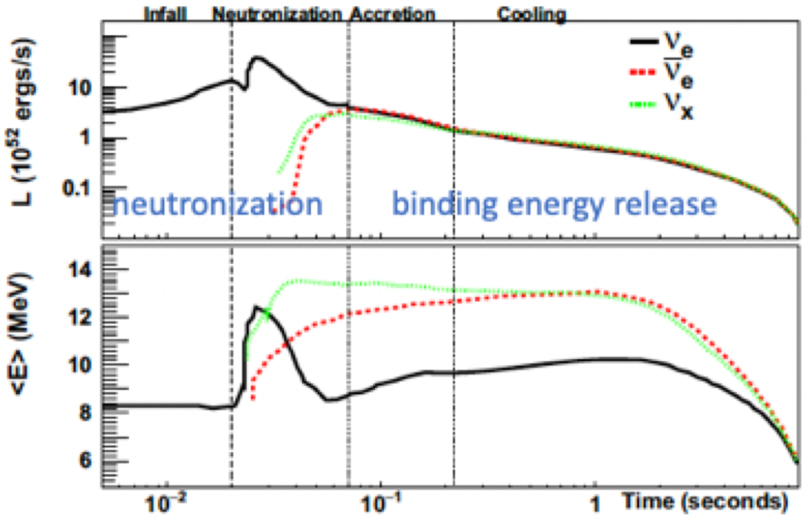


Uncertainties on all neutrinos drastically reduced
Precise measurement of ^{8}B neutrinos
Evidence of CNO neutrinos (7σ)
Sun Metallicity: High Z favoured ($3.1\ \sigma$)

CSN2 & Neutrino Astronomy: SuperNova Neutrinos

Astrophysical opportunities:

- Galactic/close SN detection: SN models test (but also SN TeV neutrinos after few days)
- Diffuse SN neutrino Background detection



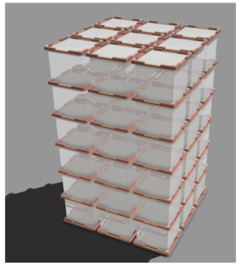
Many detectors ready to catch the signal: Supernova early alert system (SNEWS)

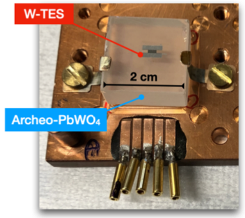
From a Galactic SN (at Earth) ~ 10^{11} ν/cm^2 in 10 seconds

Detector	Events
LVD	300
KM3NeT	$10^{5:6}$
JUNO	6000
DUNE	3000, ν_e signal !
HK:	$\approx$ 200.000 IBD
	$\approx$ 7.500 e^- scattering
	$\approx$ 1.000 ν_e+^{16}O

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

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$





ResNova- ERC @ LNGS

$$\sigma_{CE\nu NS}$$

$(30\ cm)^3$ Archeo$PbWO_4$ crystals

1 keV ~10 counts for a Galactic SN

Diffuse Supernova Background detection

Carry information of star formation rate, energy spectrum of SN burst, neutrinos, and BH formations

Detection of different flavours is crucial for SN modelling

HK

JUNO and DM detectors (XENON) can play a role

CSN2 & Neutrino Astronomy: HE Neutrino Astronomy

Astrophysical opportunities

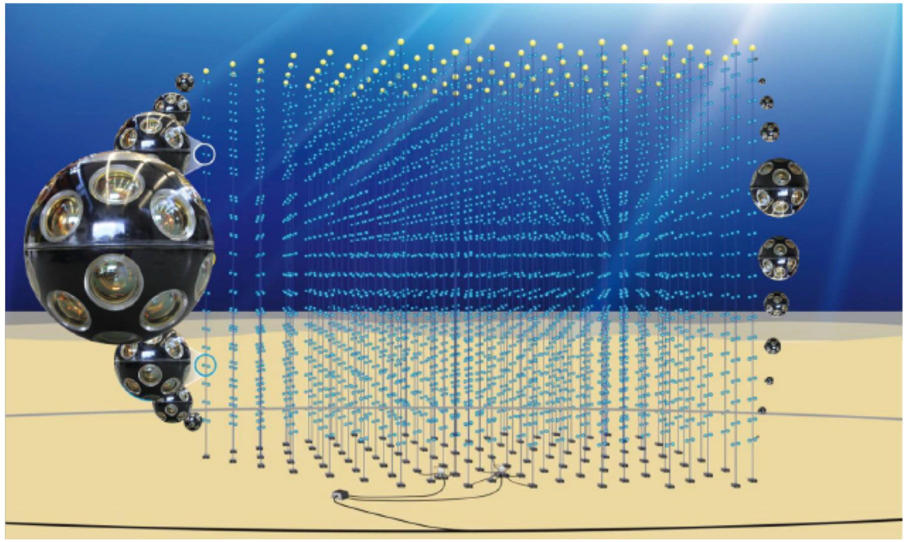
- Diffuse fluxes measurements: atmospheric (CR), galactic, extragalactic
- Point sources identification: sources of Cosmic rays in Galaxy and origin of UHECRs
- HE far universe, cores of the sources

Entering in the HE neutrino astronomy with IceCube:

diffuse flux measurement solid (9s)

4s signals from AGNs and Galaxy

Data from Northern Hemisphere needed for full sky coverage. Reduced light scattering in (sea)water offers optimal pointing accuracy. KM3NeT beyond the ANTARES milestone :



Engineering:

High-re!iability

mass construction

sea operation

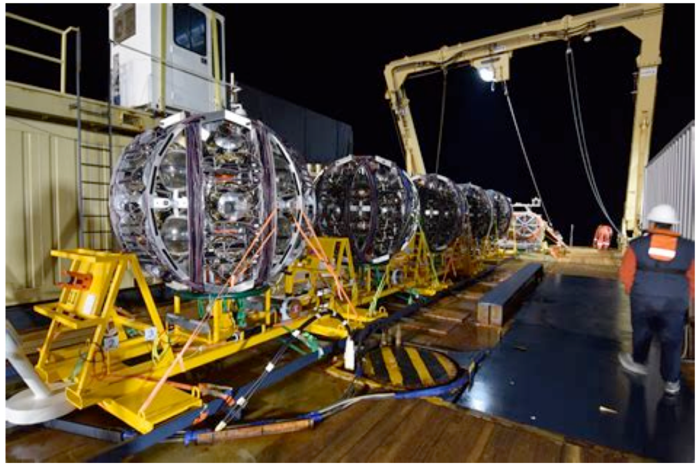
Calibration:

Timing (sub ns)

Positioning (10 cm)

Multi-PMT:

→ now a “standard” for water Cherenkov detectors



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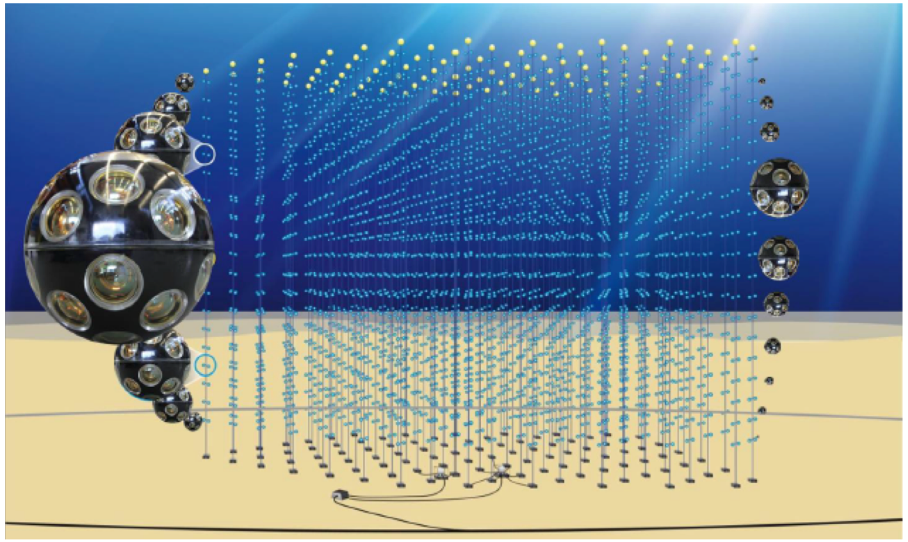

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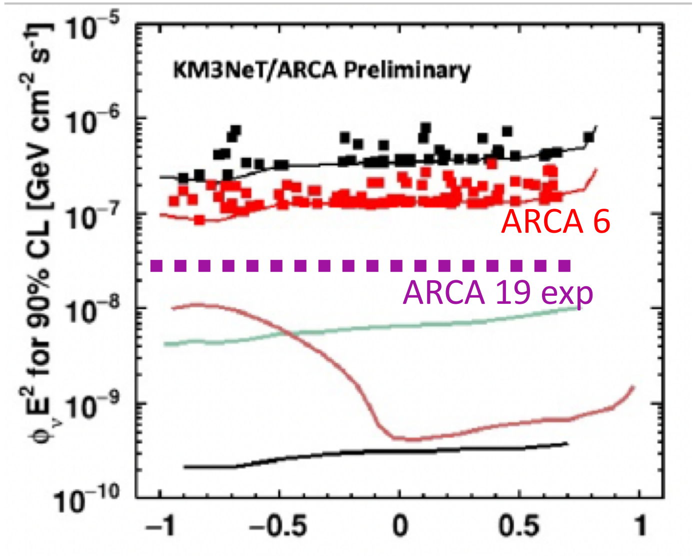

Conclusion

CSN2-INFN is a leading actor in neutrino physics at international level:

Present (with significant contribution) in all key experiment to sound neutrino properties (mass, mass hierarchy, CP violation,…)

CUORE/CUPID, LEGEND
ICARUS/DUNE, JUNO, Hyper-K, KM3NeT

The community is showing growing interest in neutrino astromony from MeV to PeV
JUNO, HK, KM3NeT
CSN2 has also a wide porfolio of experiment to cope with multimessenger astronomy programmes

So long