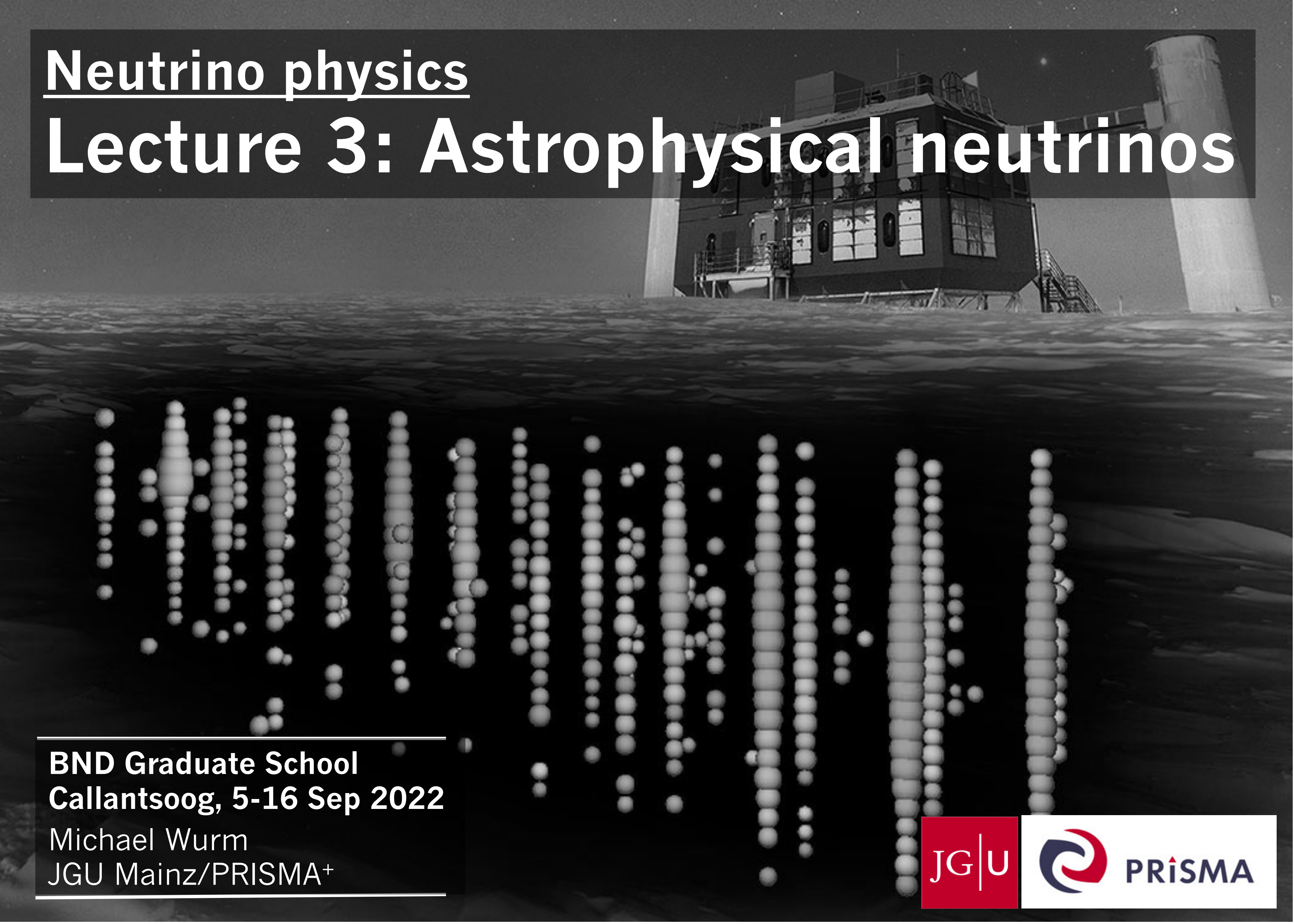
Neutrino physics

Lecture 3: Astrophysical neutrinos



BND Graduate School
Callantsoog, 5-16 Sep 2022

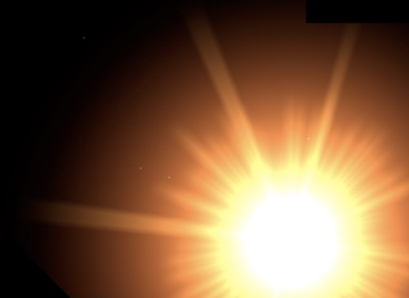
Michael Wurm
JGU Mainz/PRISMA^{+}

Astrophysical neutrino sources

Supernova neutrinos
collapse of Fe core
of a heavy (>8$M_\odot$) star

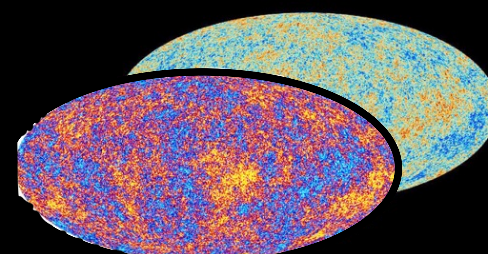
Diffuse Supernova neutrinos
from all core-collapse SNe
throughout the Universe

Extragalactic neutrinos
from cosmic accelerators
(AGNs, GRBs ...?)



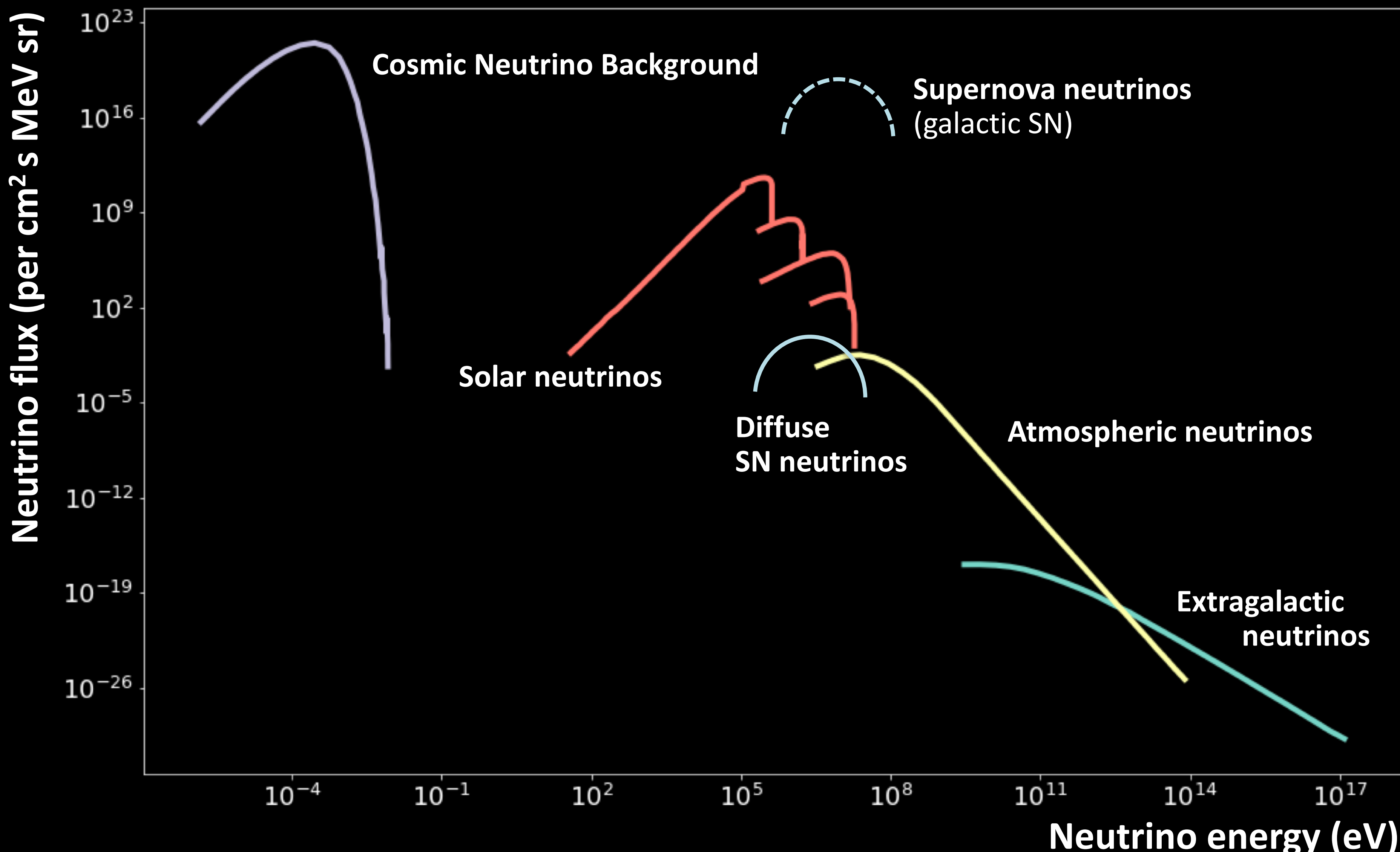
Solar neutrinos
pp/CNO fusion chains

Cosmic Neutrino Background
from the Big Bang (cf. CMB)



Geoneutrinos
radioactive decays of U,Th,K
in Earth crust/mantle

Energy spectrum of astrophysical ν's



LECTURE QUIZ

Question 8

Before we go off to speak about astrophysical neutrinos: What is the pre-dominant flavor of geo-neutrinos emitted in radioactive decays?

E : e

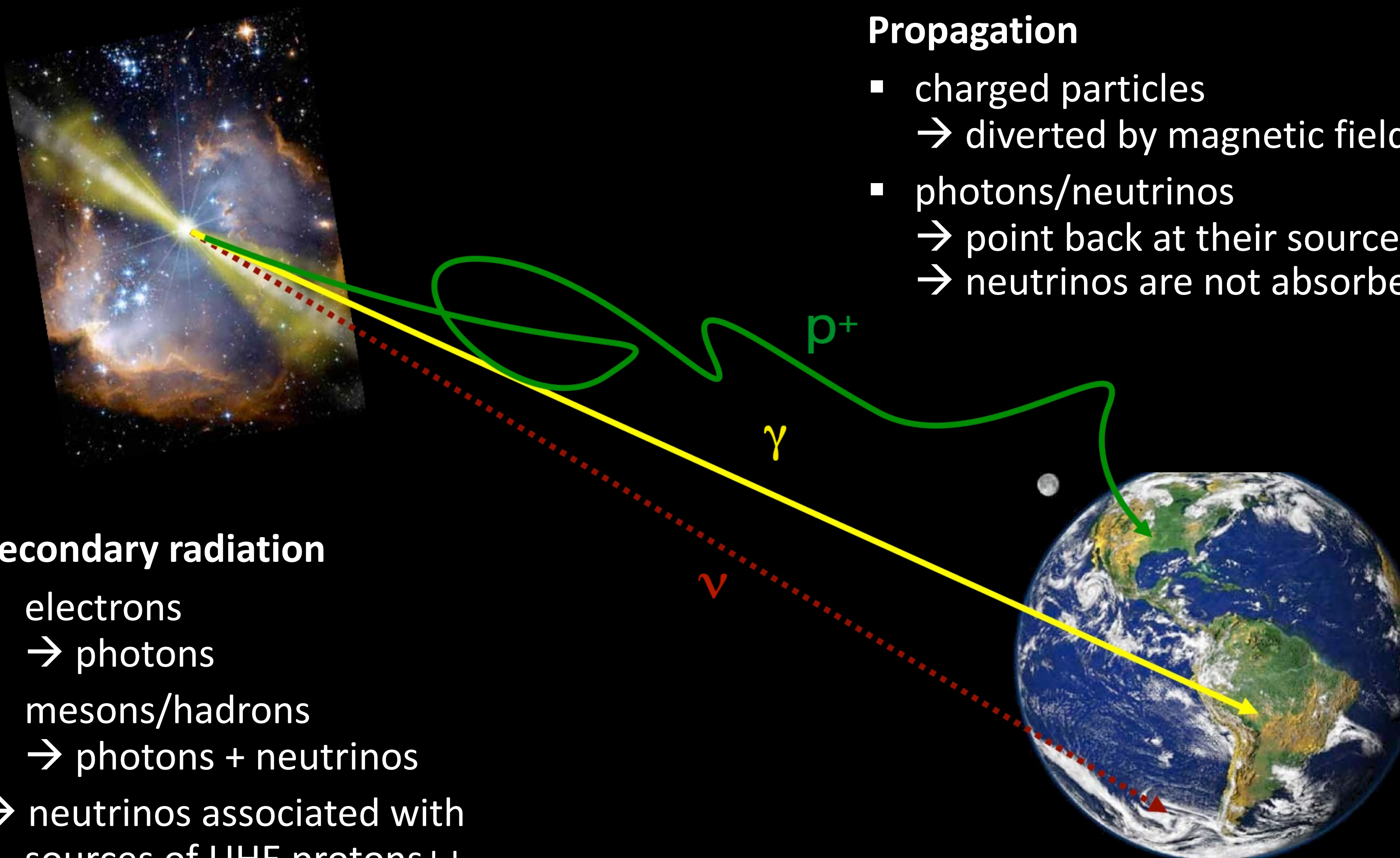
M : μ

T : τ

Note down the **10th letter** of the solution word.

Observation of high-energy Cosmic Rays

[S.Böser]



Propagation

- charged particles
  → diverted by magnetic fields
- photons/neutrinos
  → point back at their source
  → neutrinos are not absorbed

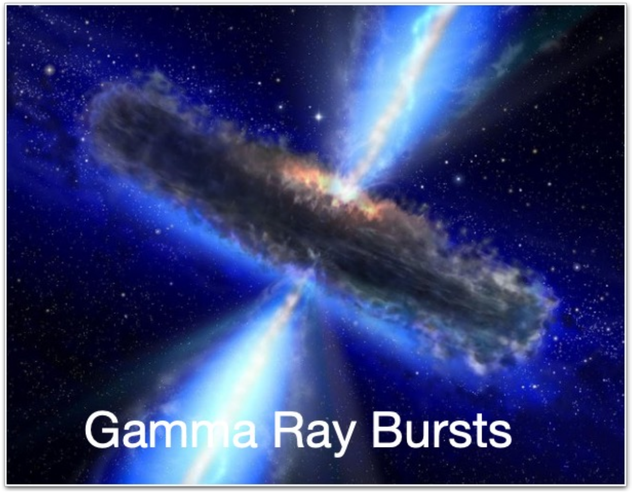
Secondary radiation

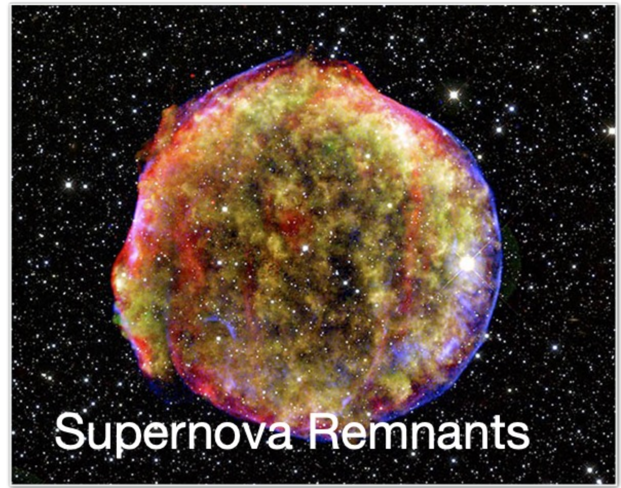
- electrons
  → photons
- mesons/hadrons
  → photons + neutrinos

→ neutrinos associated with sources of UHE protons++

Extragalatic sources of HE neutrinos

[S.Böser]





- **total energy:** up to 10^{45} J
- **Fermi acceleration:** protons with energies up to 10^{19} eV
- **Interactions with matter** in/around cosmic accelarators

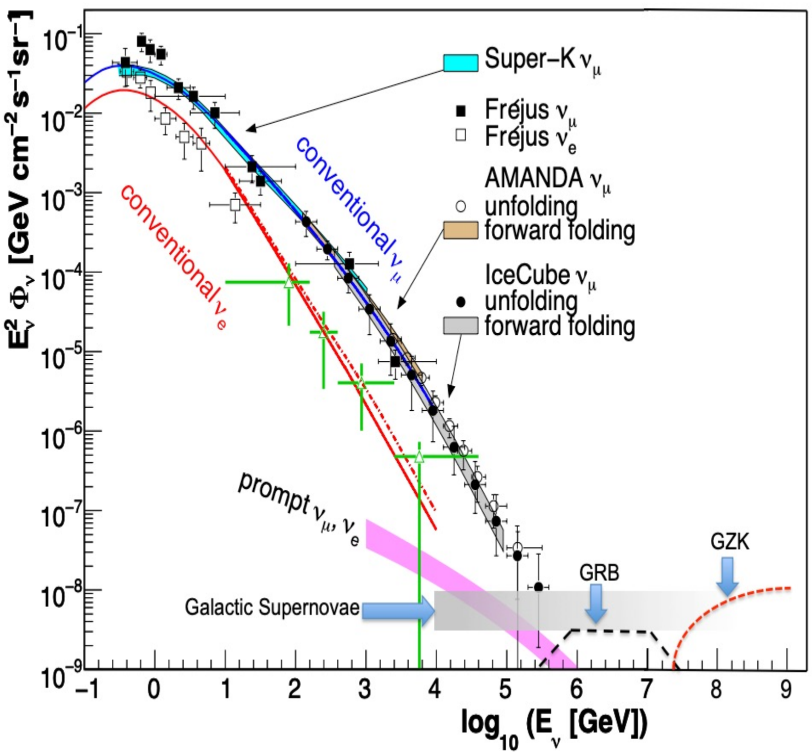
$$p + p \rightarrow \pi, K, \ldots$$

$$\hookrightarrow \pi \rightarrow \mu + \nu_\mu$$

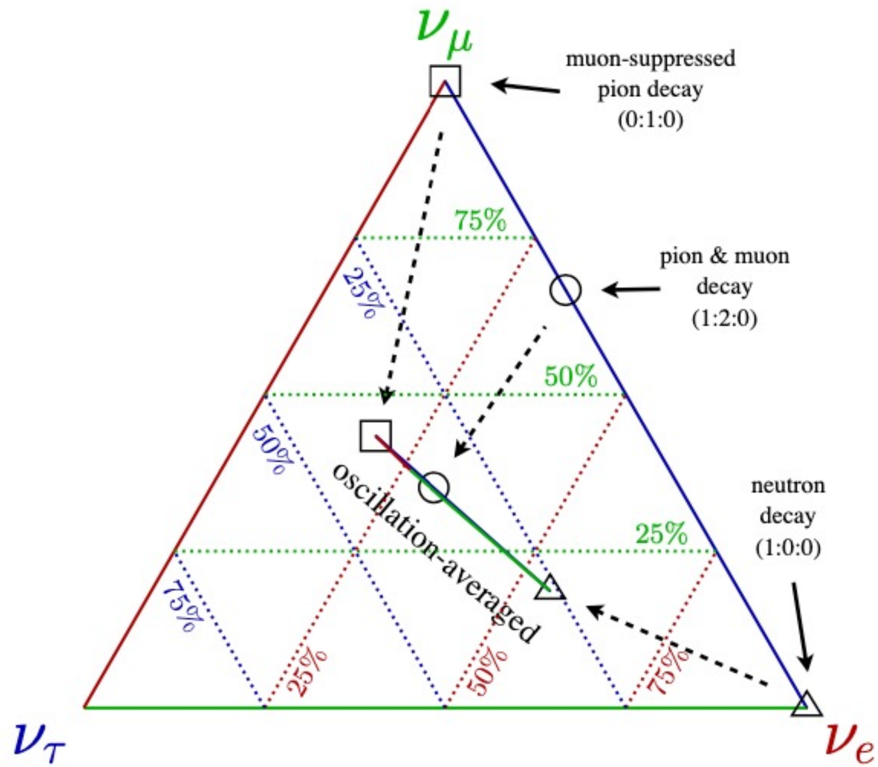
$$\hookrightarrow \mu \rightarrow e + \nu_e + \nu_\mu$$

Expected signal of HE neutrinos

Spectrum

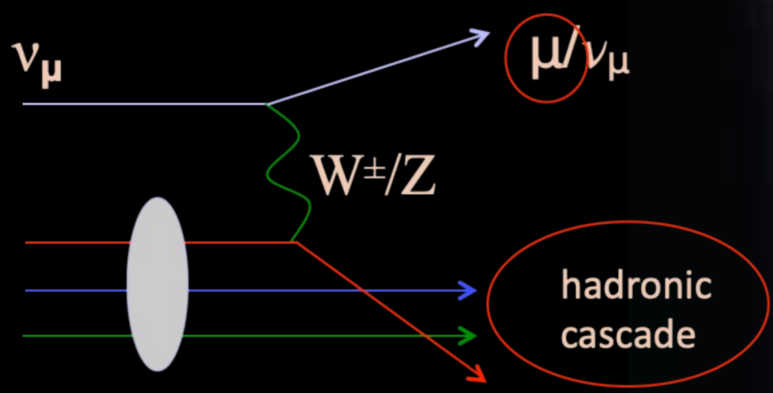


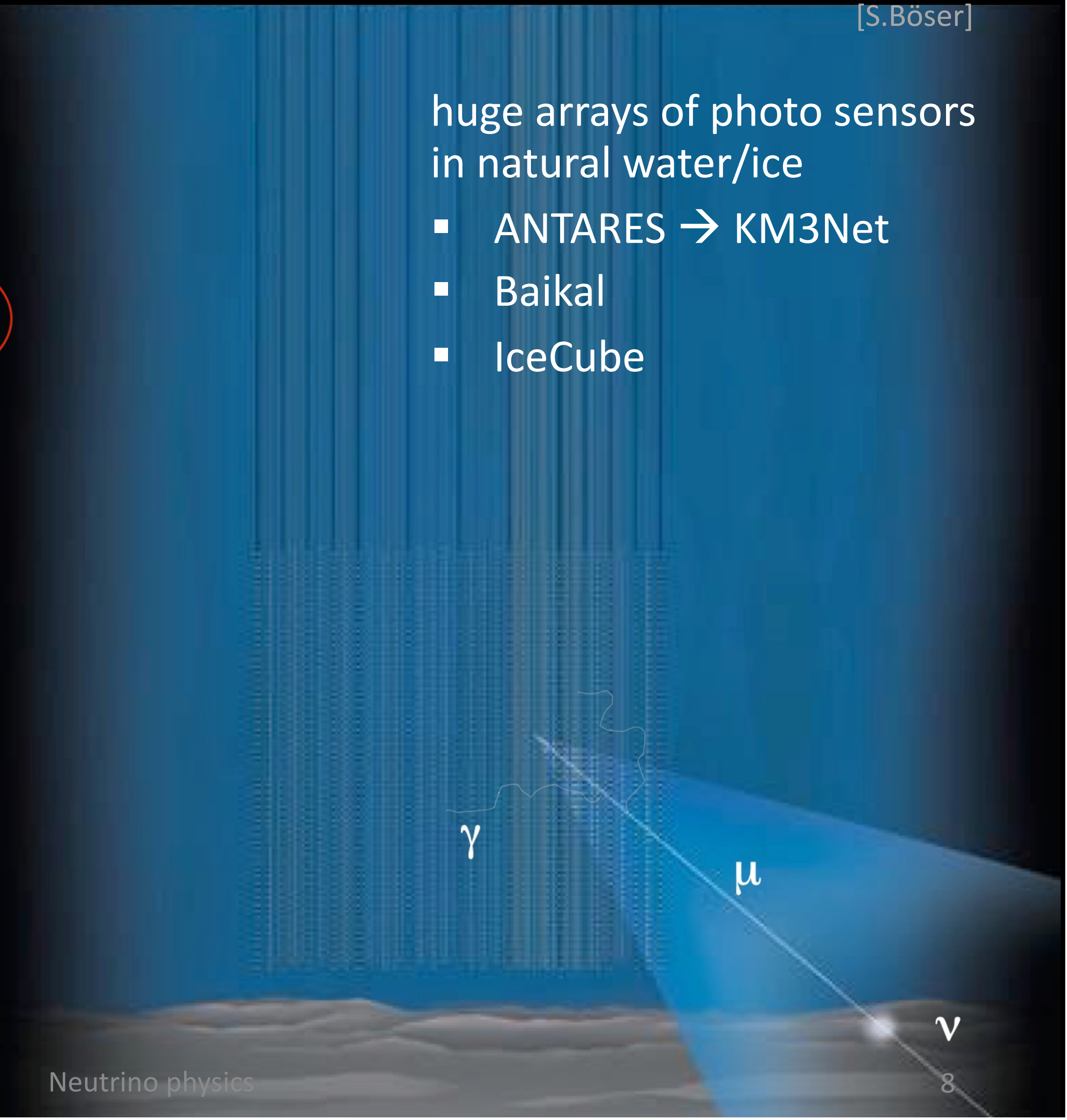
Flavor Composition



- **atmospheric neutrinos** cover signal at low energies → energy range >100TeV
- **fluxes are very low:** detector size of km^3
- **neutrino flavors** depend on production process → flavor sensitivity

Neutrino telescopes





huge arrays of photo sensors in natural water/ice

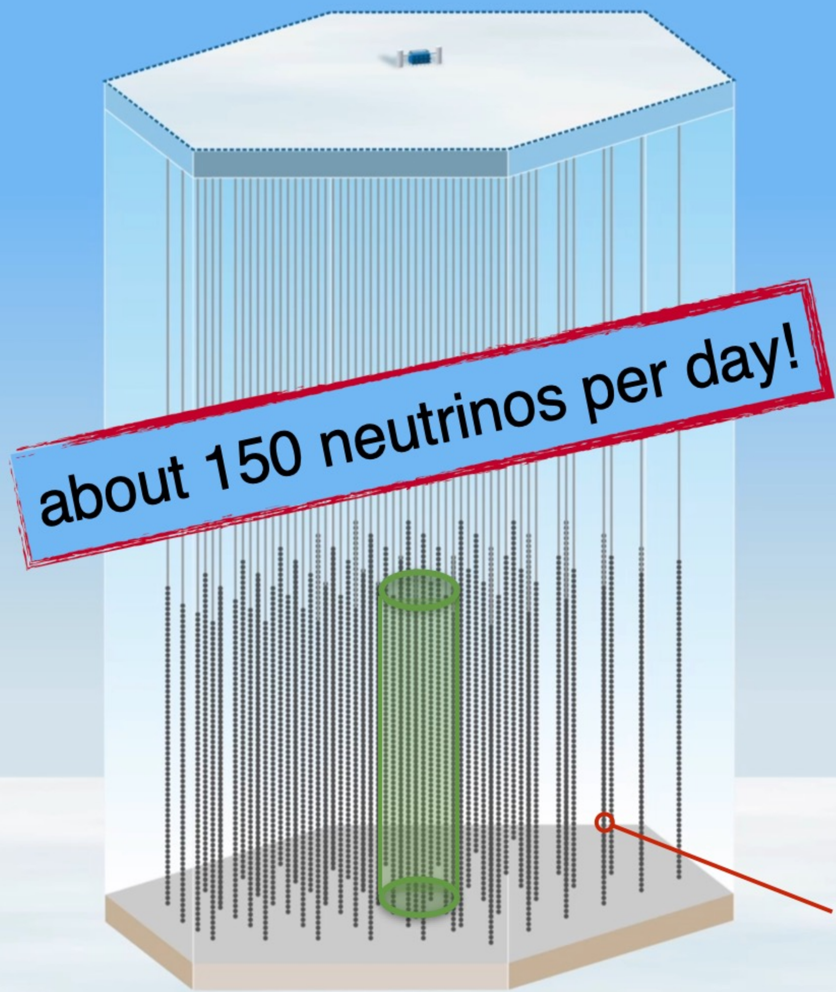
- ANTARES → KM3Net
- Baikal
- IceCube

Neutrino interactions

- ν_μ charged-current interactions
  → long muon track
- all others
  → particle cascades

Icecube Neutrino Telescope

[S.Böser]



IceCube

- located at geographical South Pole
- Depth: 1450m ↔ 2450m
- Distance: ↕17m : ↔125m
  - Energy threshold ~100 GeV

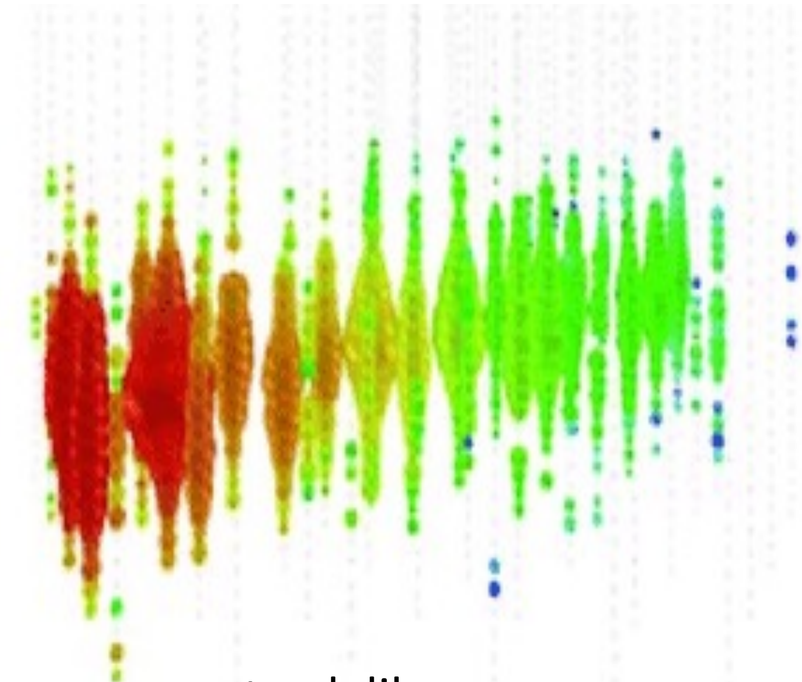
IceCube DeepCore

- Distance: ↕6m : ↔25-40m
  - Energy threshold ~10GeV

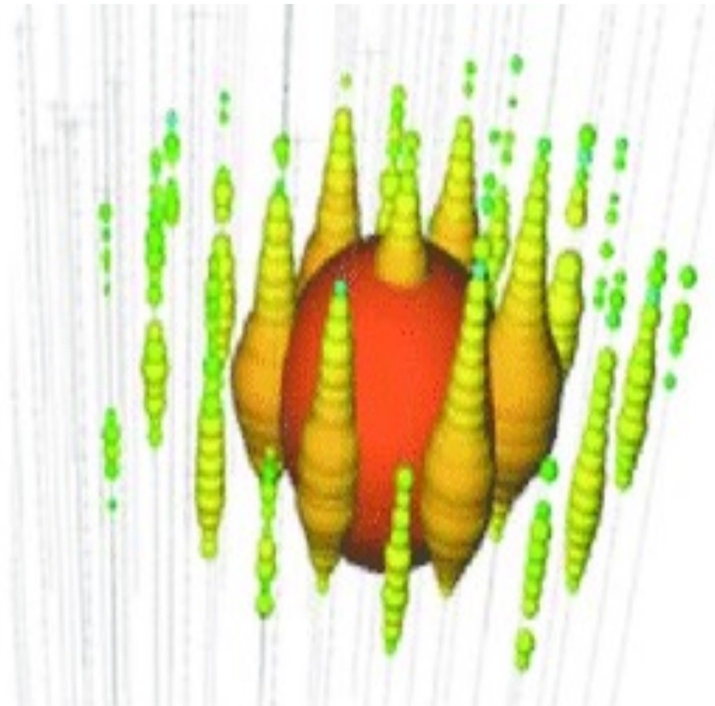
Digital Optical Modules (DOMs)

- 5160 10” PMTs on 85 strings

IceCube Event Displays

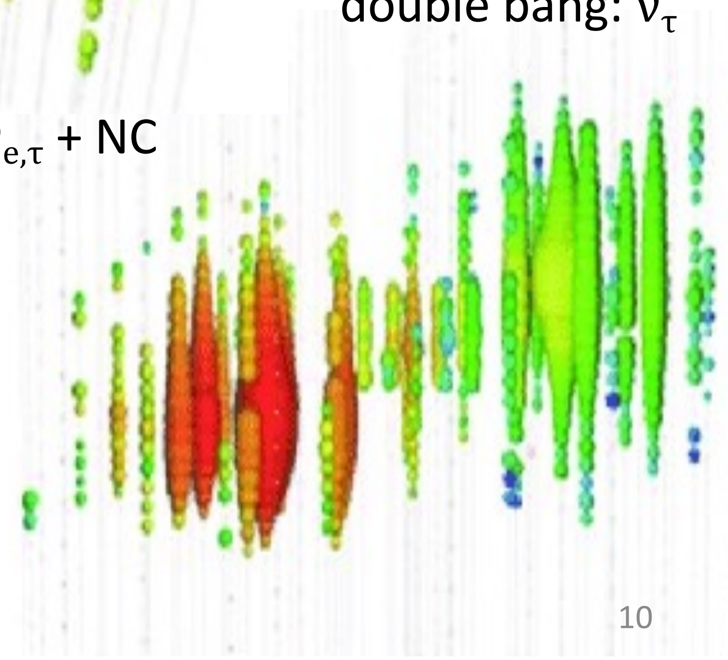


track-like: ν_μ



shower-like: $\nu_{e,\tau}$ + NC

double bang: ν_τ



Signal and Backgrounds

[S.Böser]

Astrophysical neutrinos

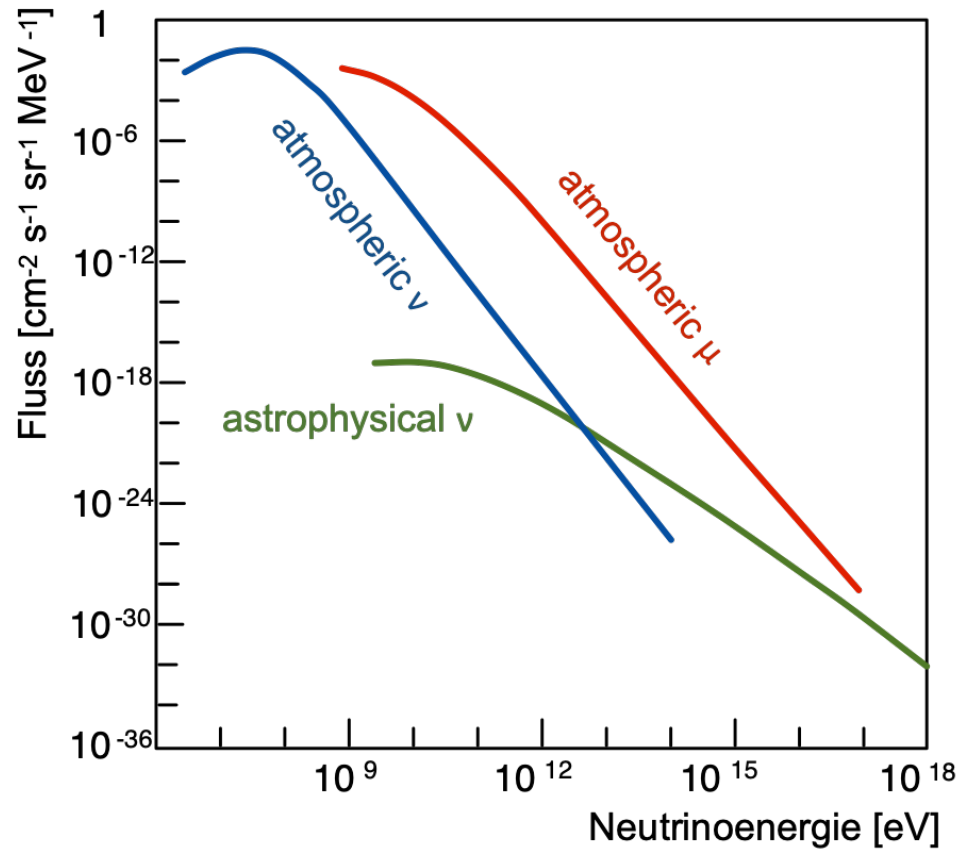
- **from sources of cosmic rays**
- **about 10 per year**

Atmospheric neutrinos

- secondary production from interactions of cosmic rays in the atmopshere
- about 150 per day

Atmospheric („cosmic“) muons

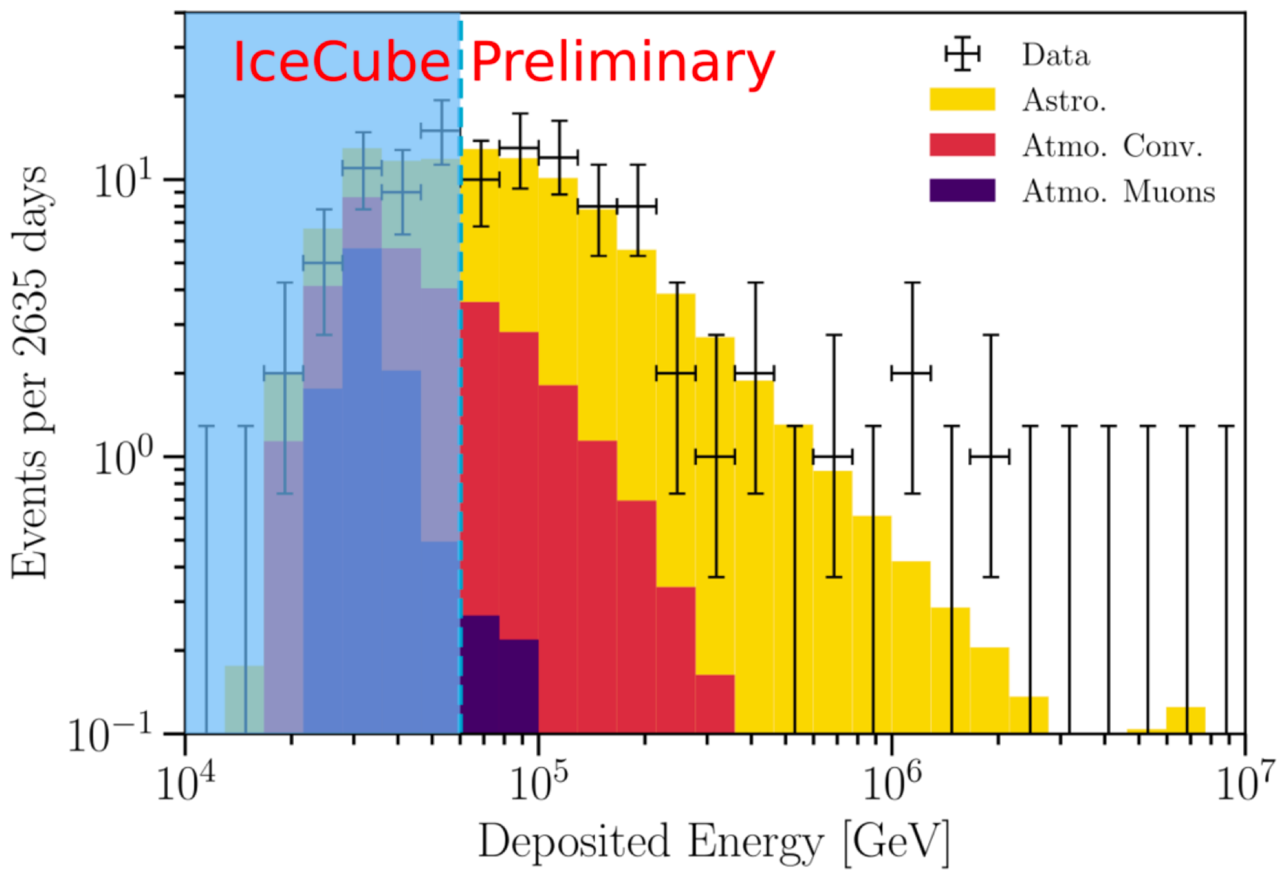
- created with atmospheric neutrinos
- very high rate, but only from above



→ **signature: upward-going tracks at highest energies**

IceCube result on Diffuse Flux

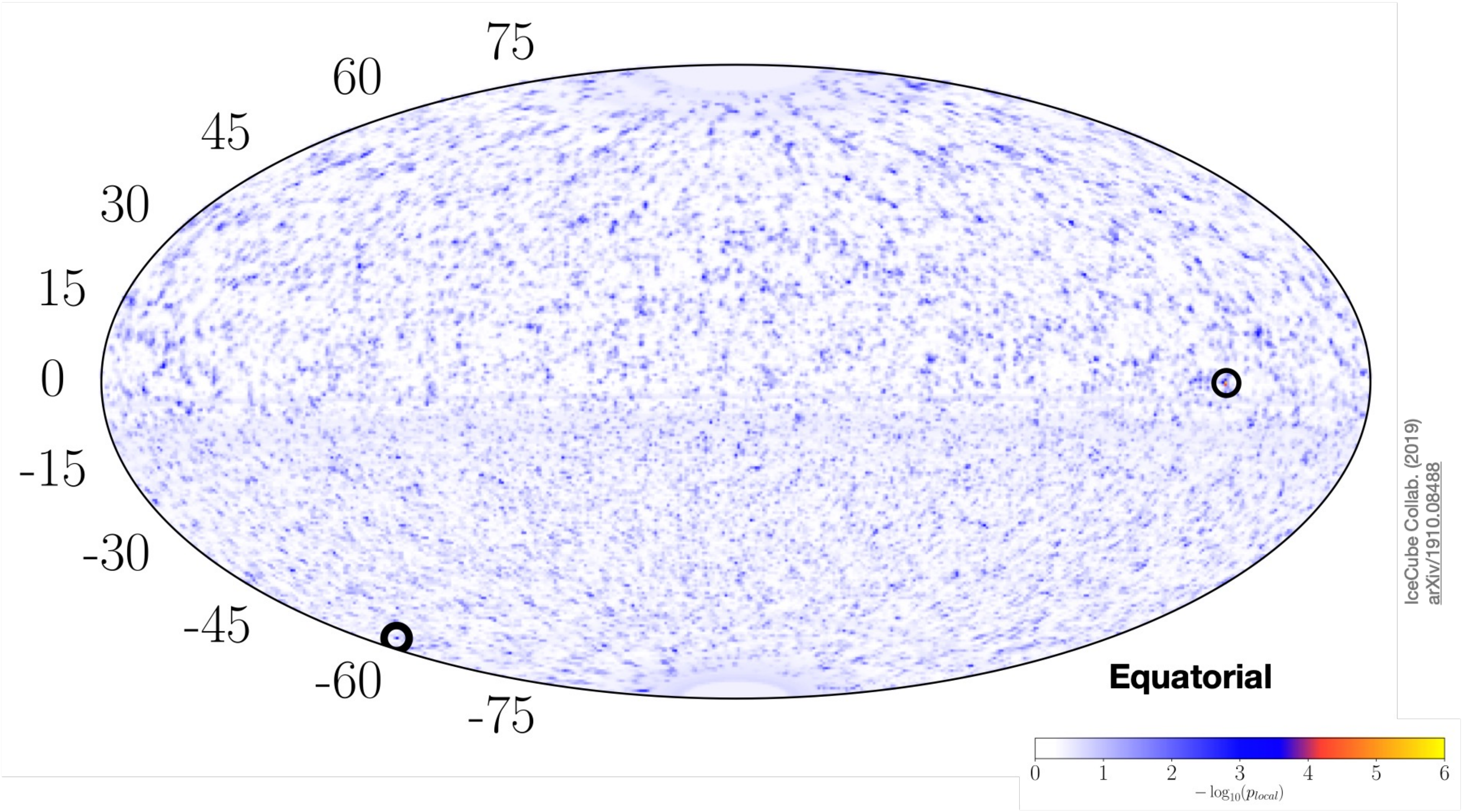
[S.Böser]



→ **first detection in 2014, now well established signal**

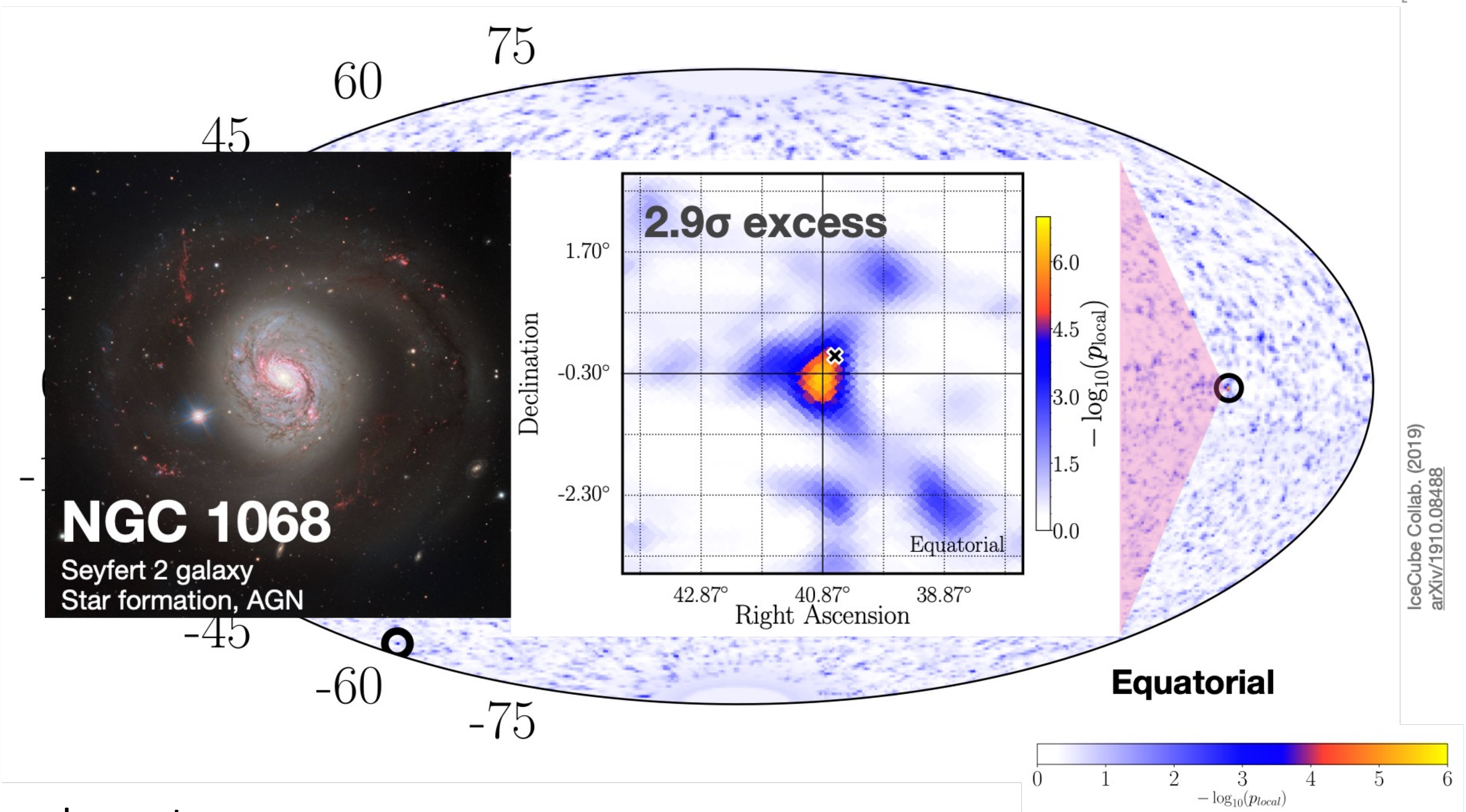
Search for point sources

[S.Böser]



Search for point sources

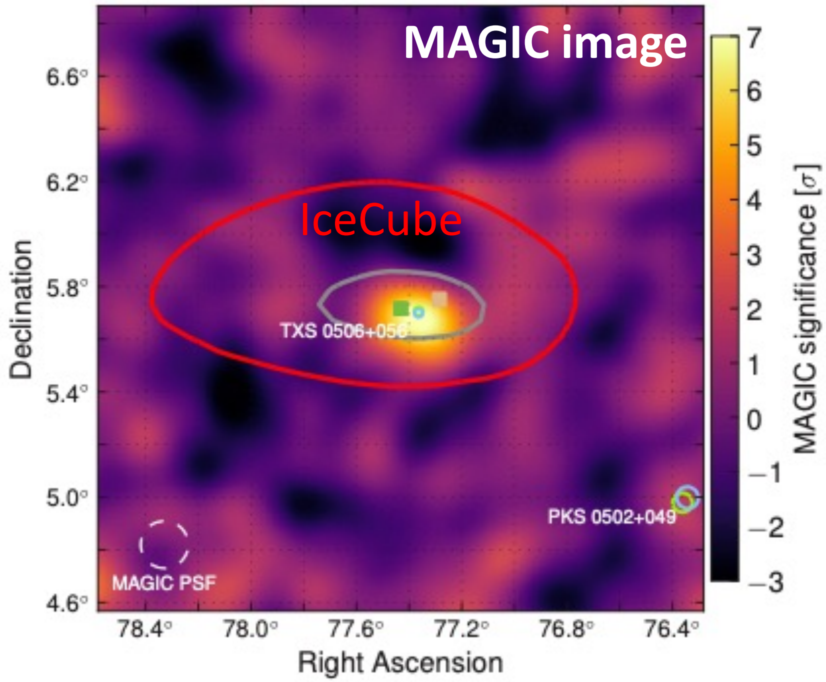
[S.Böser]



Largest excess:

- post-trial significance is 2.9σ
- close to active galaxy NGC 1068

IceCube-170922A



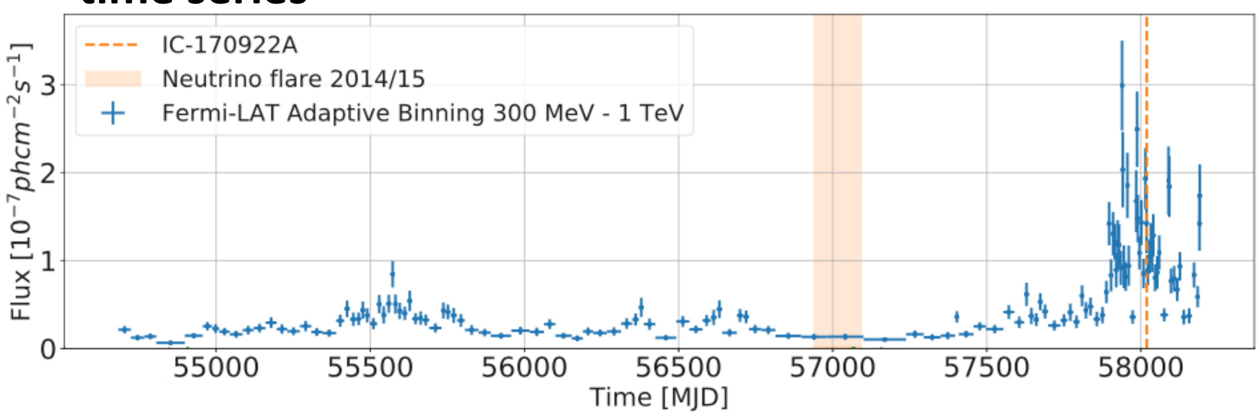
IceCube observation

- single ν_μ with 290 TeV
- at these energies, 56.5% of ν's are of cosmic origin
- reconstructed direction: gamma-ray blazar TXS 0506+056
- some earlier low-energy neutrinos from the same source

Gamma-ray observations

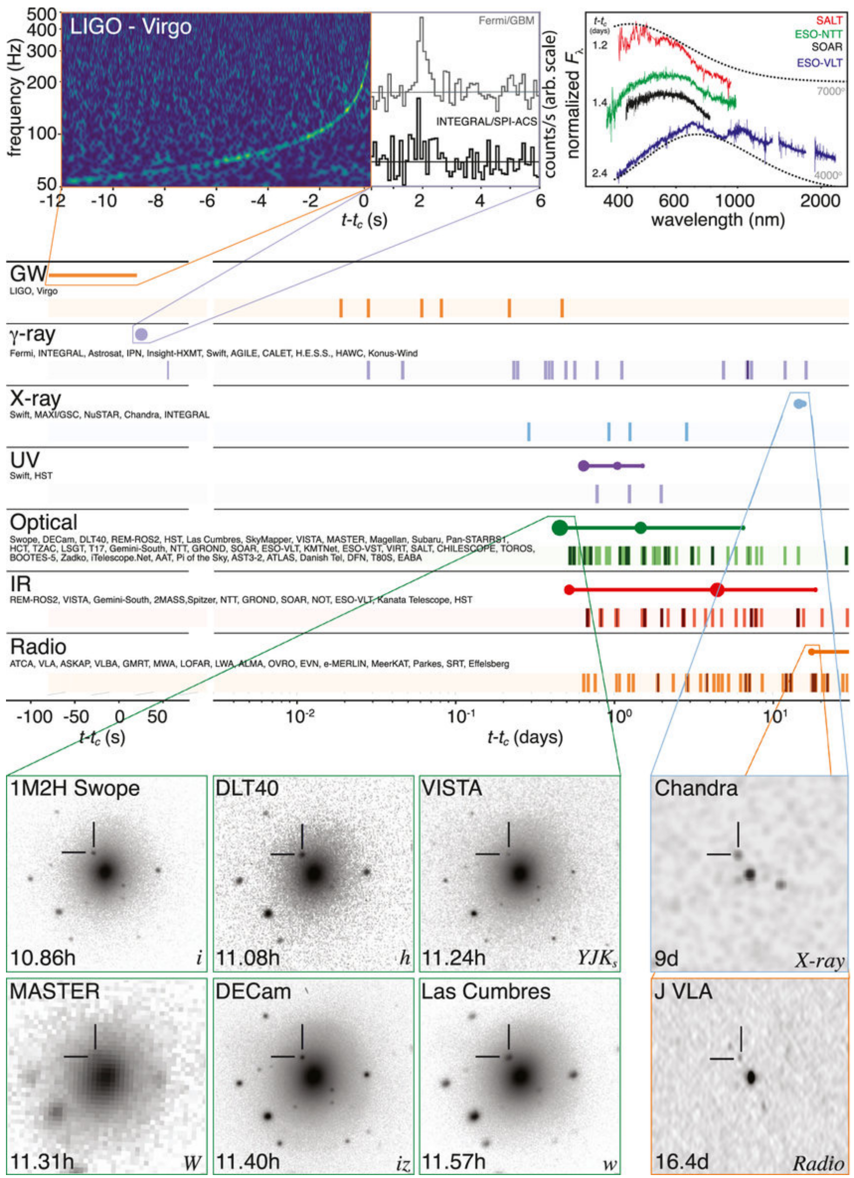
- Fermi & MAGIC reported flares from the same source

time series



→ statistical correlation: >3σ

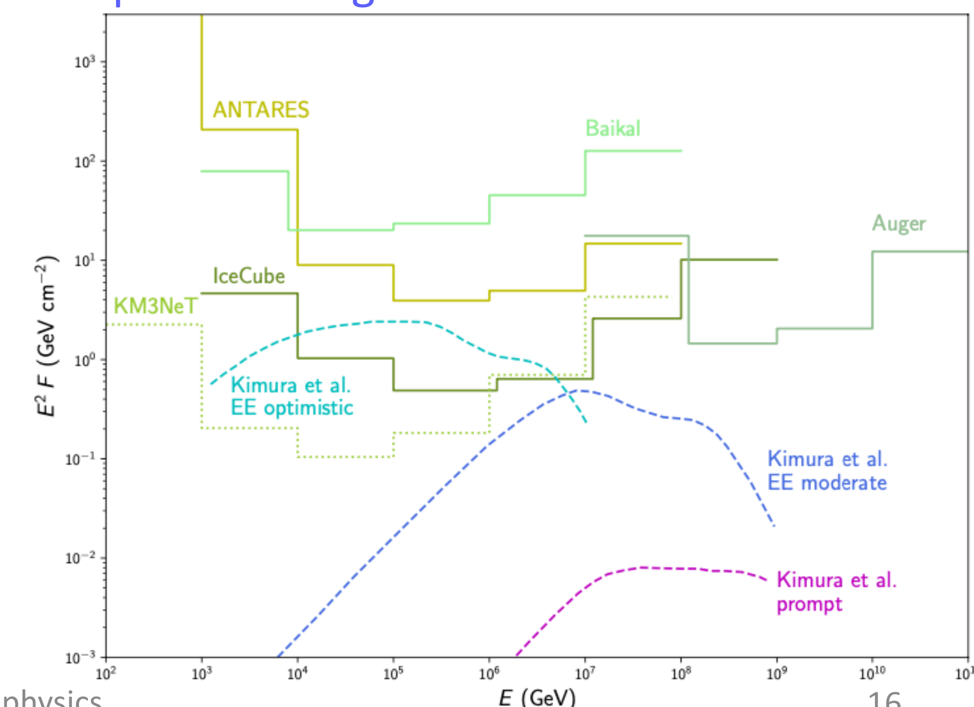
ν's from neutron star merger GW170817?



NS-NS merger/Kilonova

- gravitational wave signal
- Gamma Ray Burst
- follow-up observations in all wavelengths
- but: no neutrino signal observed

predicted signal & neutrino sensitivities



LECTURE QUIZ

Question 9

What is the signature of electron neutrino interactions in IceCube?

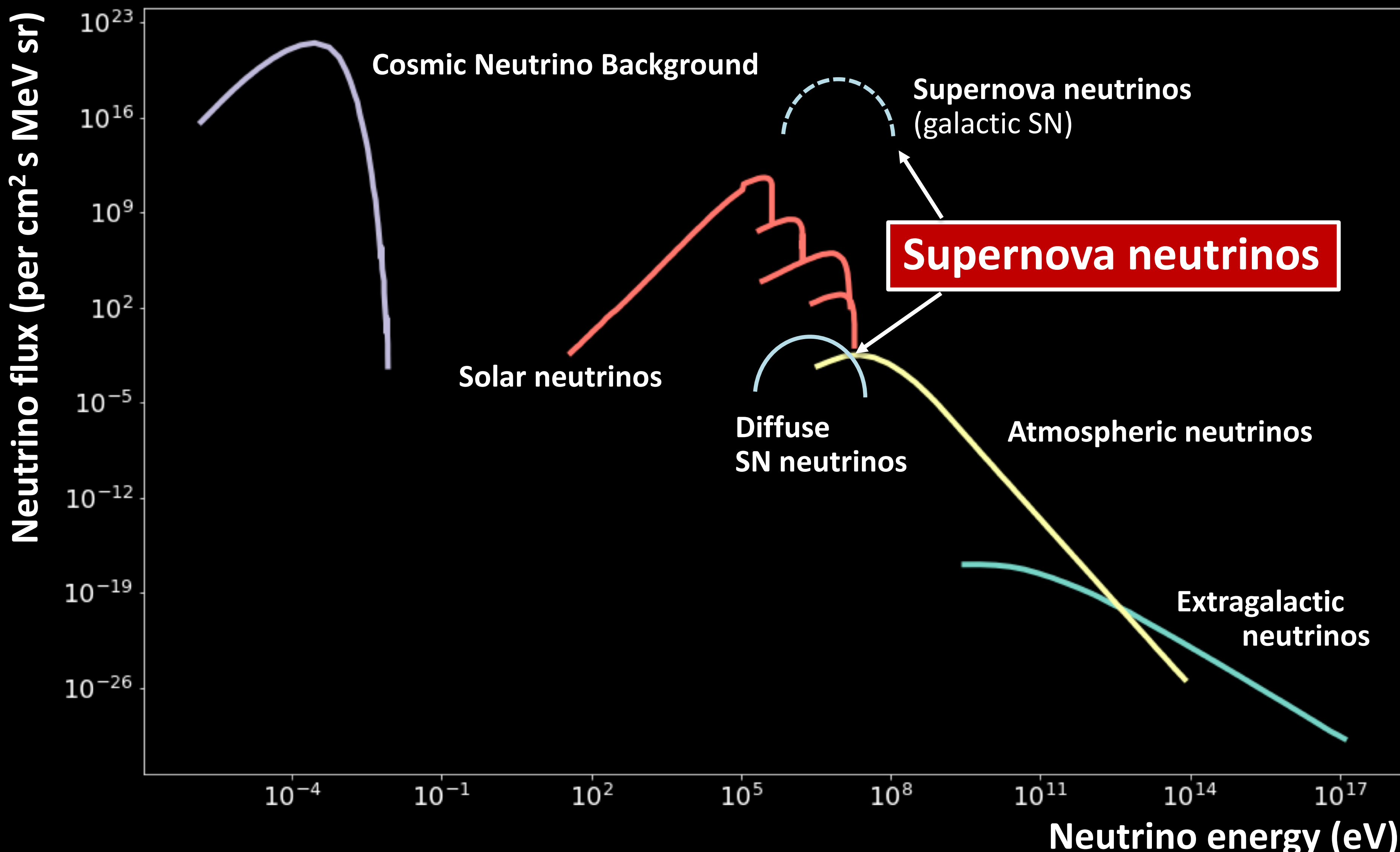
M : track-like

N : shower-like

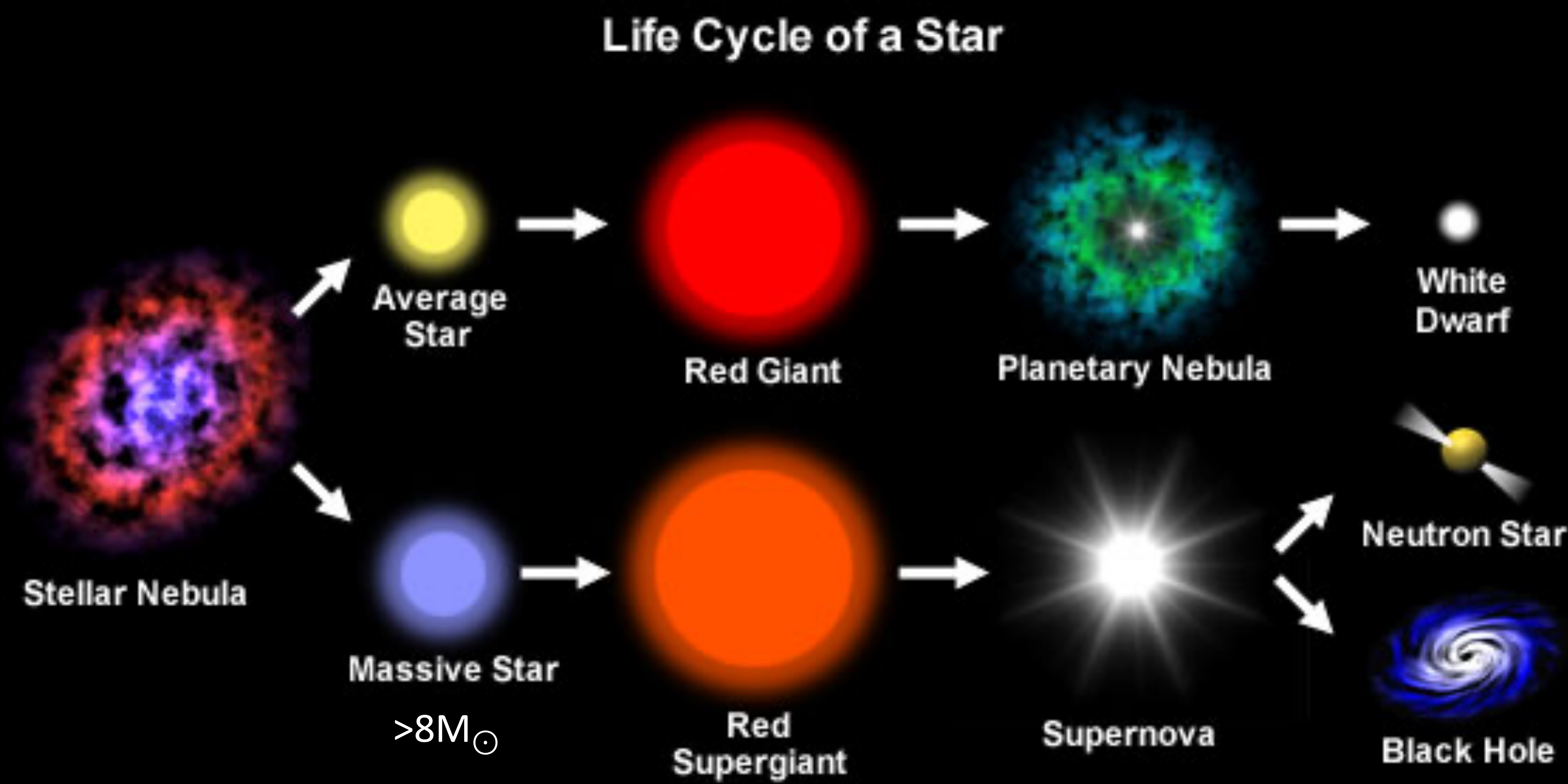
O : double-bang

Note down the **6th letter** of the solution word.

Energy spectrum of astrophysical ν's

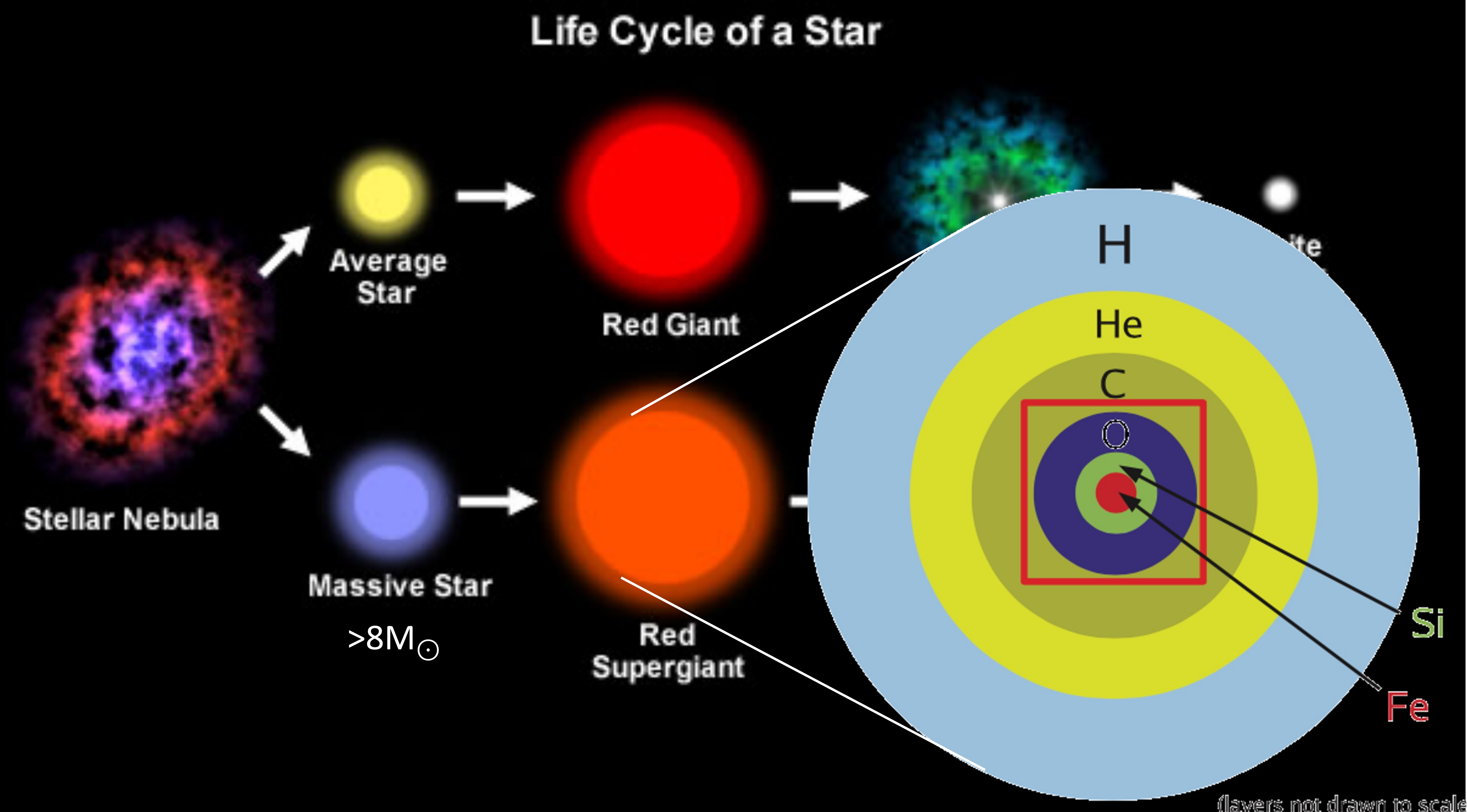


Core-collapse Supernovae



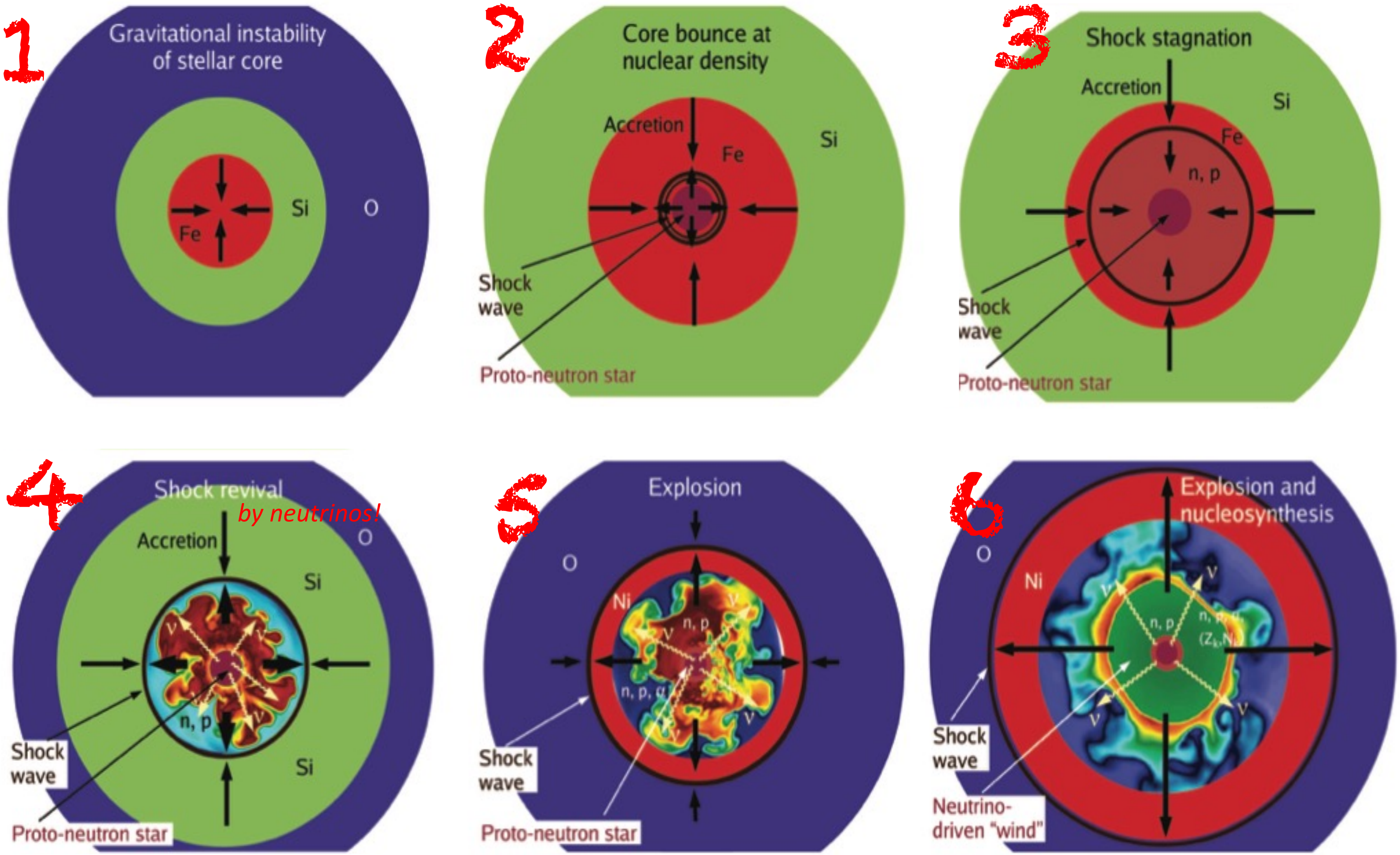
$>8M_\odot$

Core-collapse Supernovae

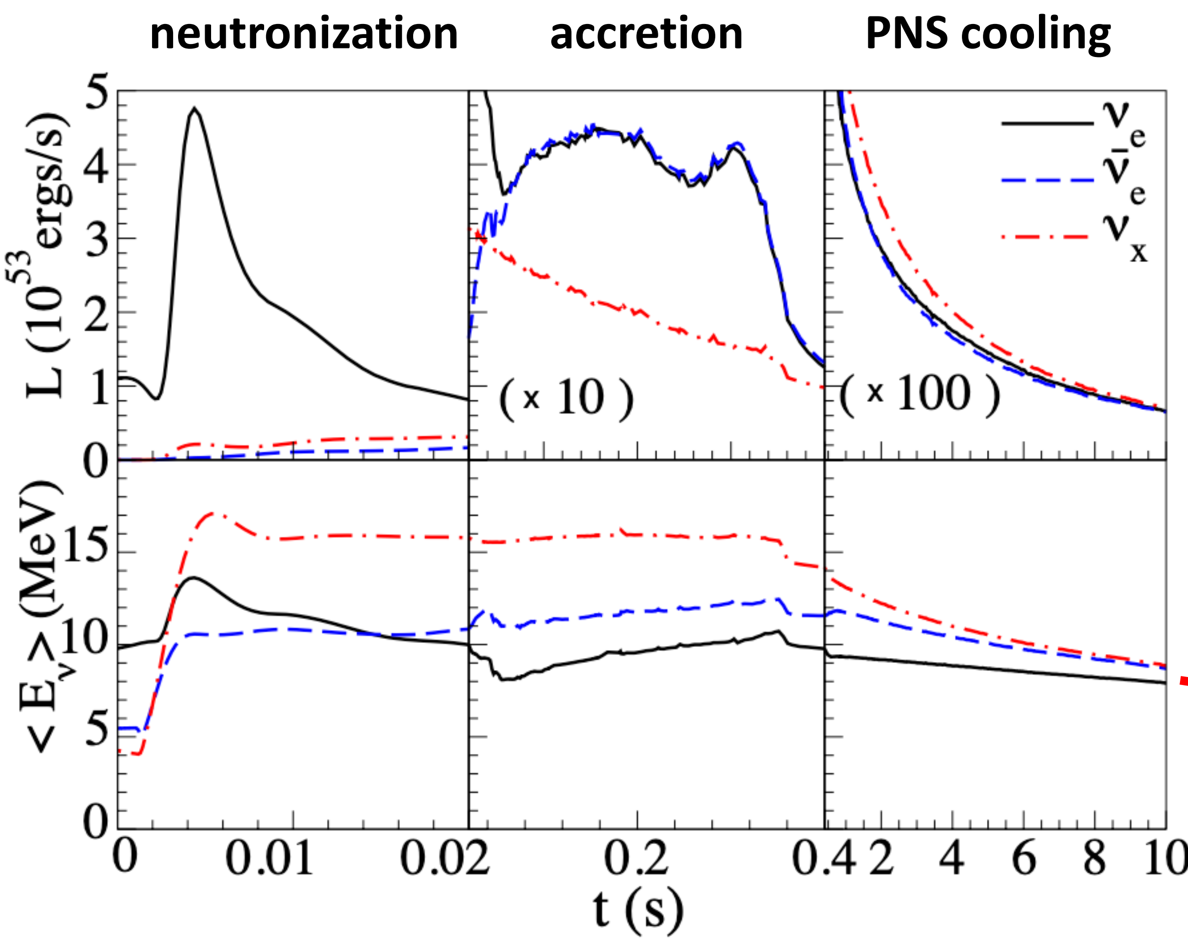


Stalled explosion model

[Janka]



Supernova neutrino emission

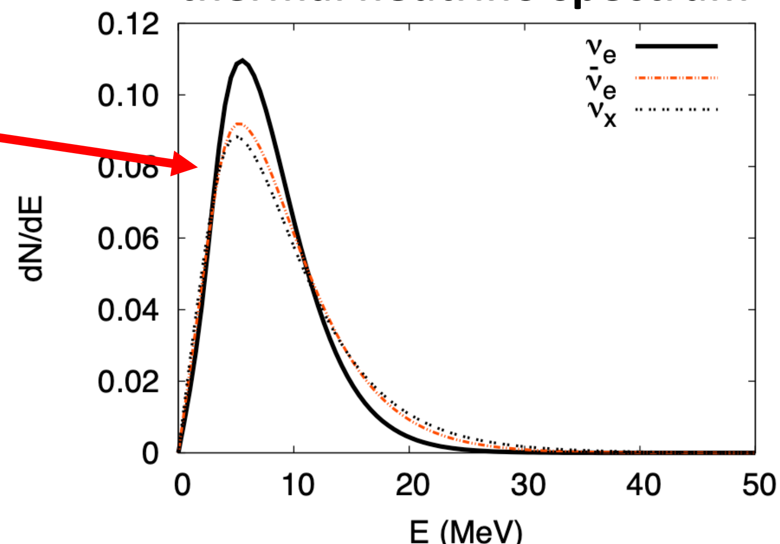


phases of the emission

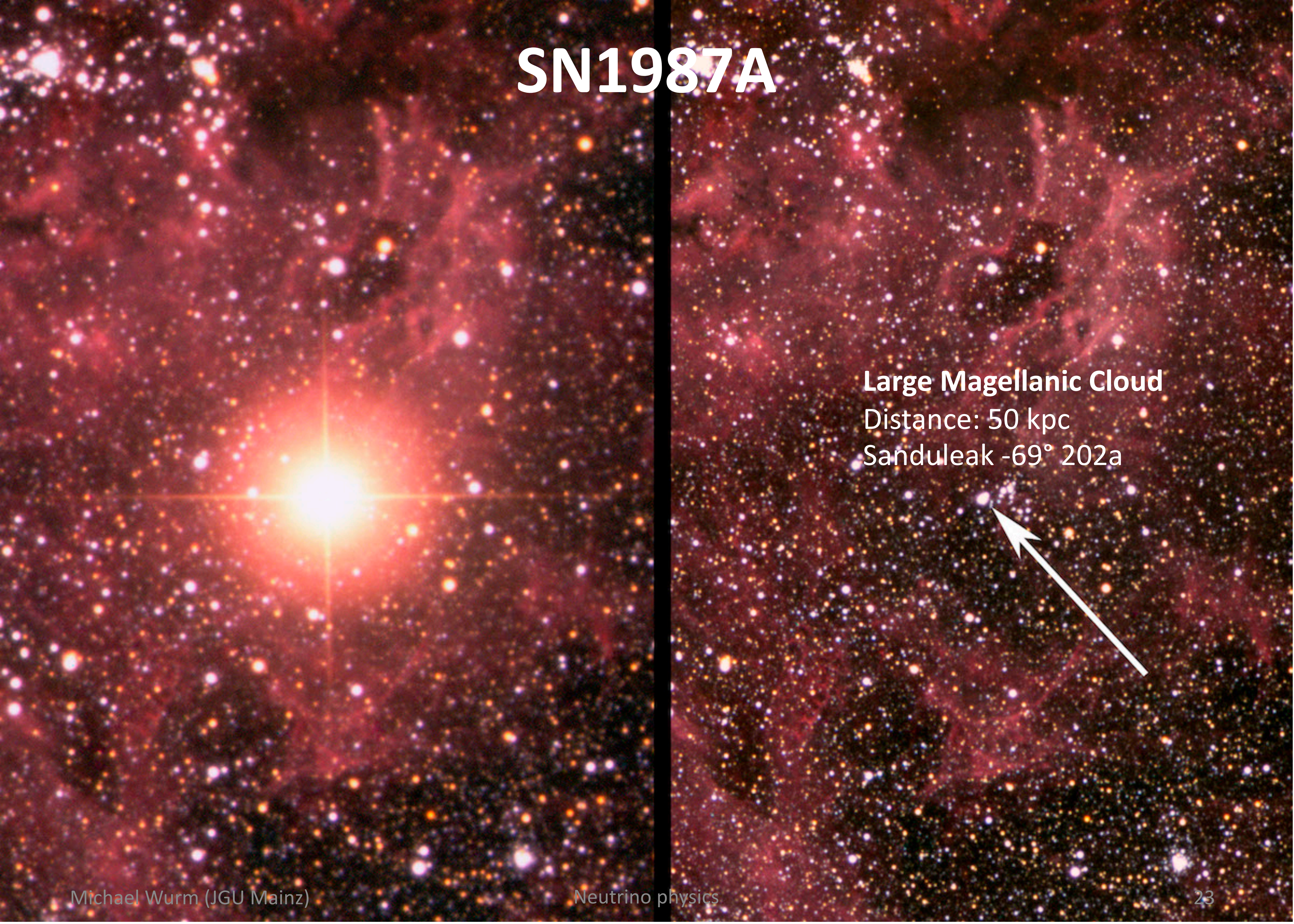
- neutronization burst:
  $p + e^- \rightarrow n + \nu_e$
- accretion phase: $\nu_e + \bar{\nu}_e$
- proto-neutron star cooling:
  ν pair production (all flavors!)

→ 99% of gravitational binding energy released via neutrinos

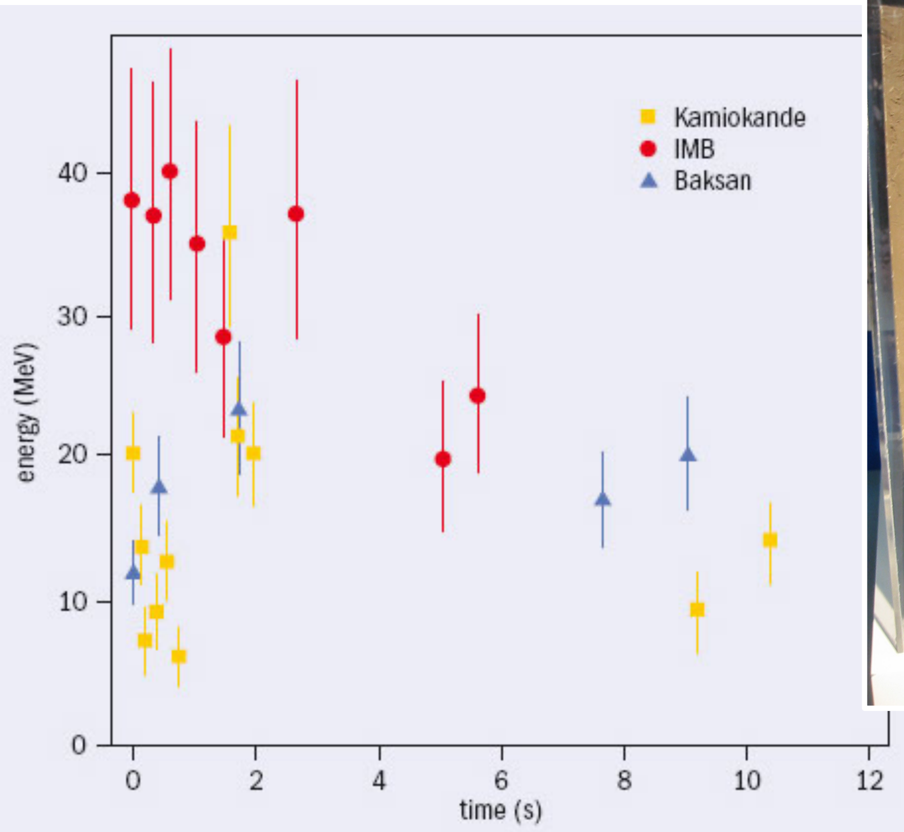
thermal neutrino spectrum



SN1987A



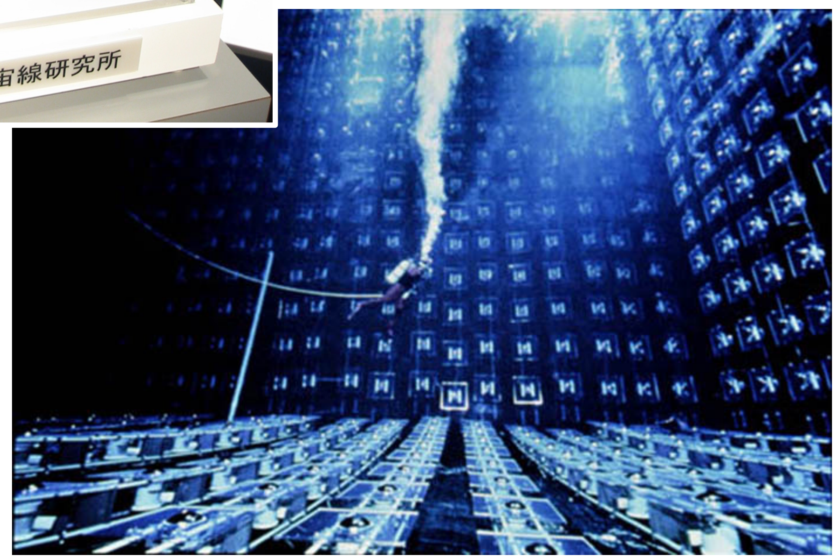
Detected neutrino signal



Kamiokande: 3kt water Ch.

Baksan: 300t liquid scintillator

IMB: 8kt water Cherenkov



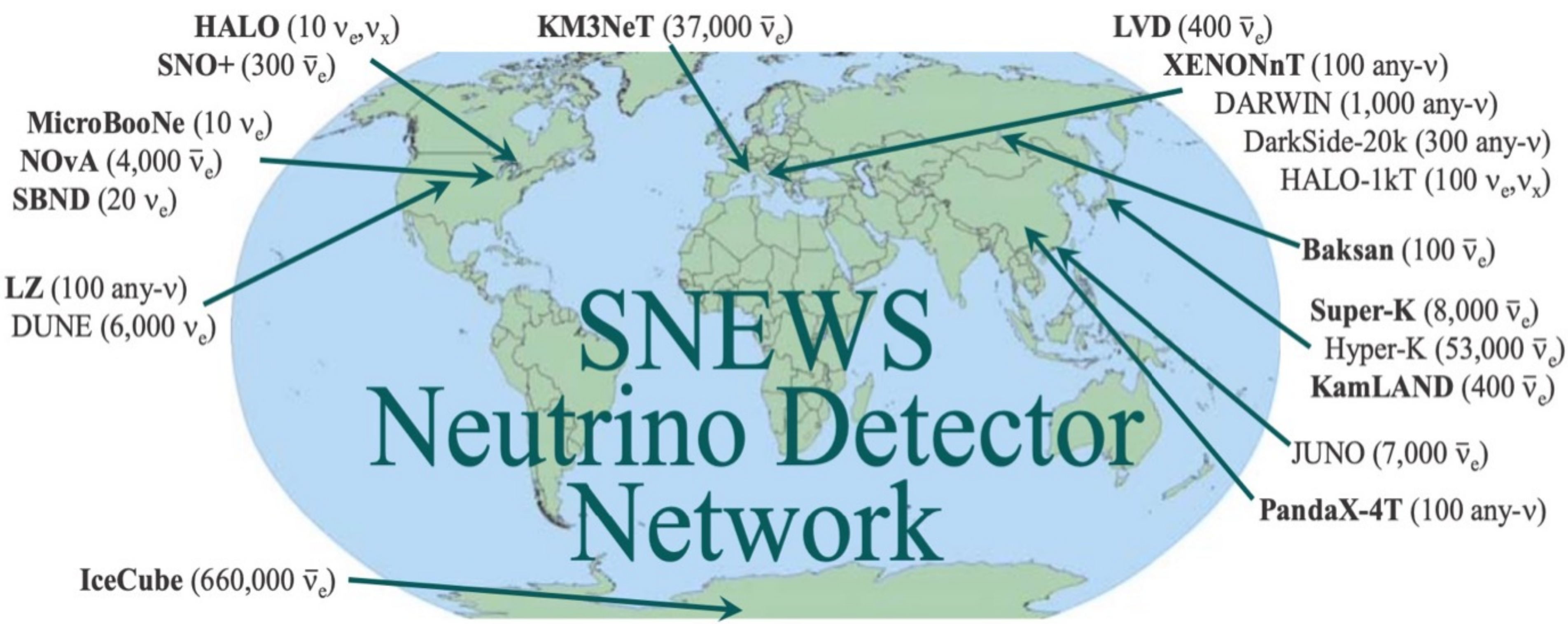
→ **20 events that confirm that the basic core-collapse SN scenario is OK**

ν luminosity, energy, duration match predictions

SN neutrino signal today

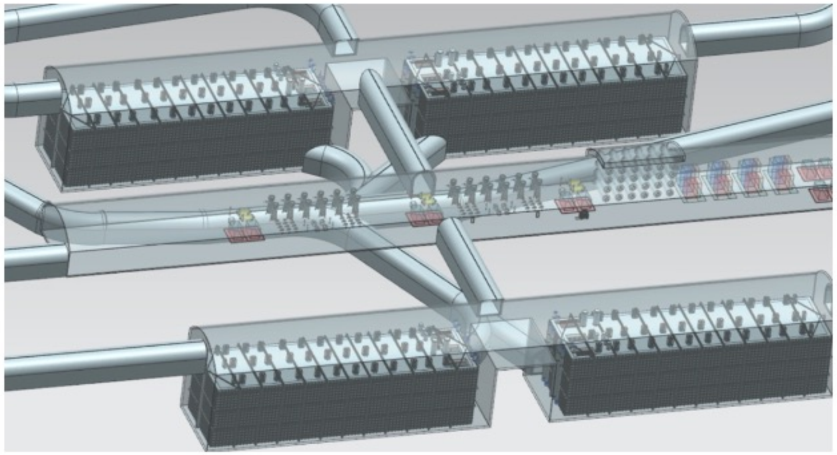
- **10+ large neutrino detectors** will detect 10,000s of events
- provide neutrino energy and flavor resolution
- accurate timing of signal start and pointing capability (triangulation)

→ **SNEWS: Supernova Neutrino Early Warning System**

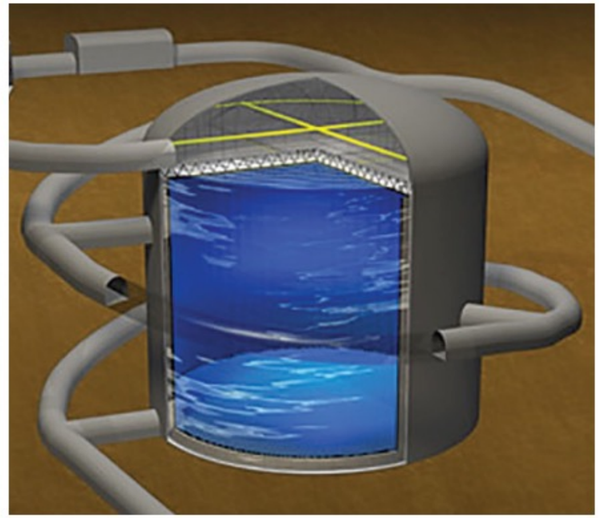


SN neutrino signal tomorrow

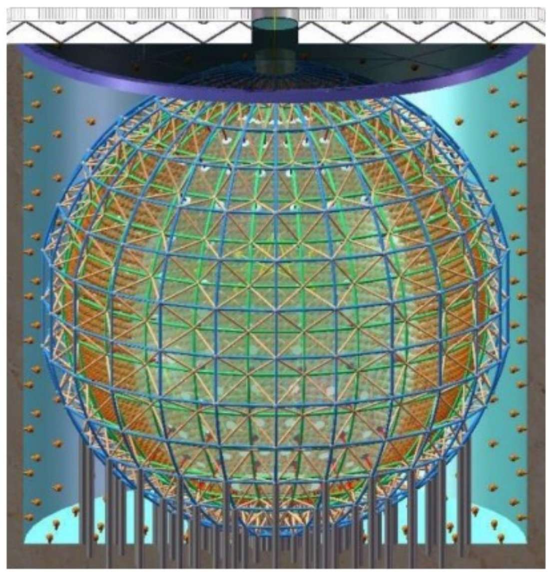
[Scholberg]



DUNE
40 kton argon
USA



Hyper-Kamiokande
260 kton water
Japan

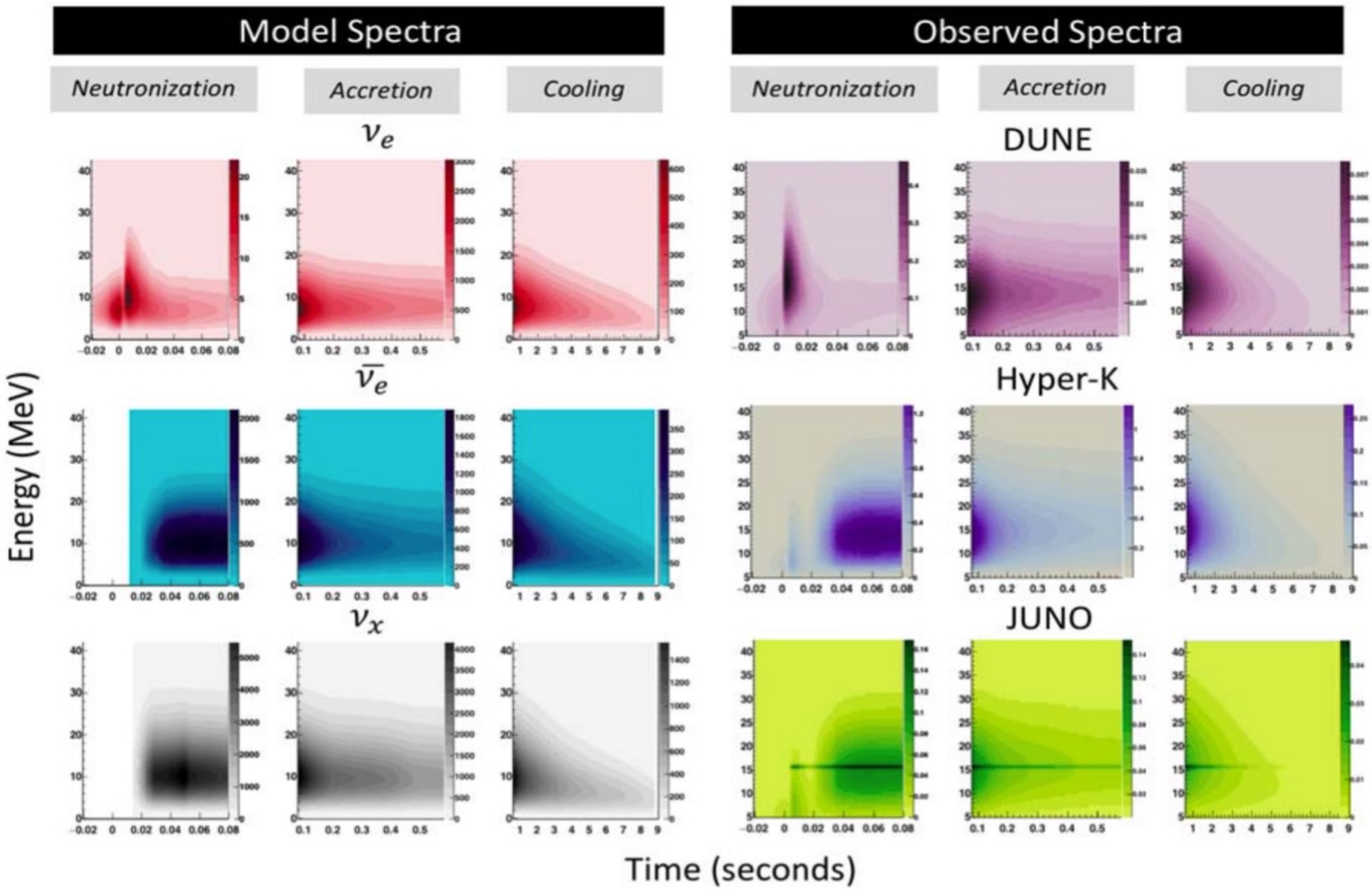


JUNO
20 kton scintillator (hydrocarbon)
China

SN neutrino signal tomorrow

[Scholberg]

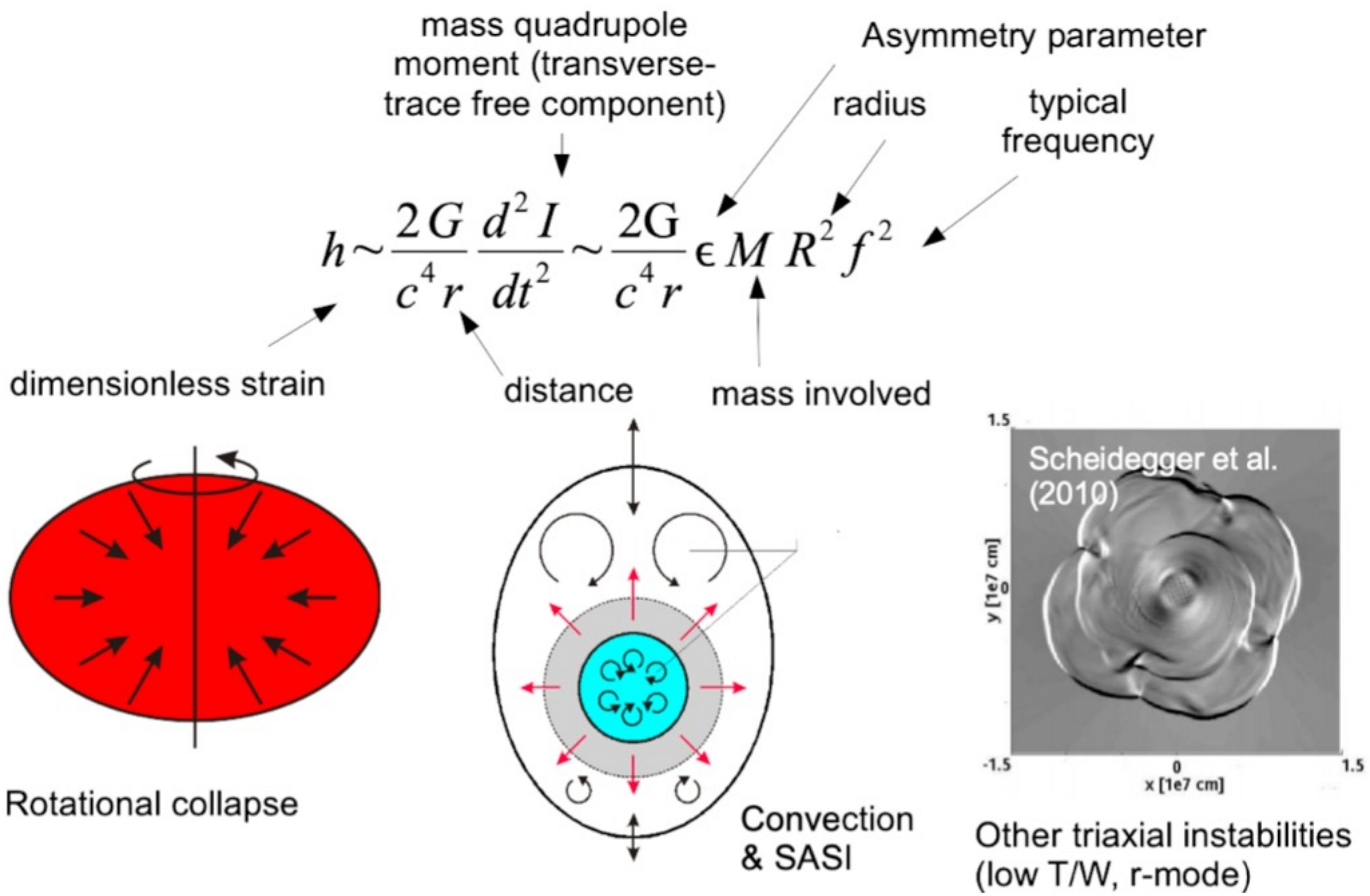
large-scale detectors with different flavor sensitivities provide detailed picture:



Gravitational waves from ccSNe

[B.Müller]

asymmetric movements of stellar matter in collapse produce GWs

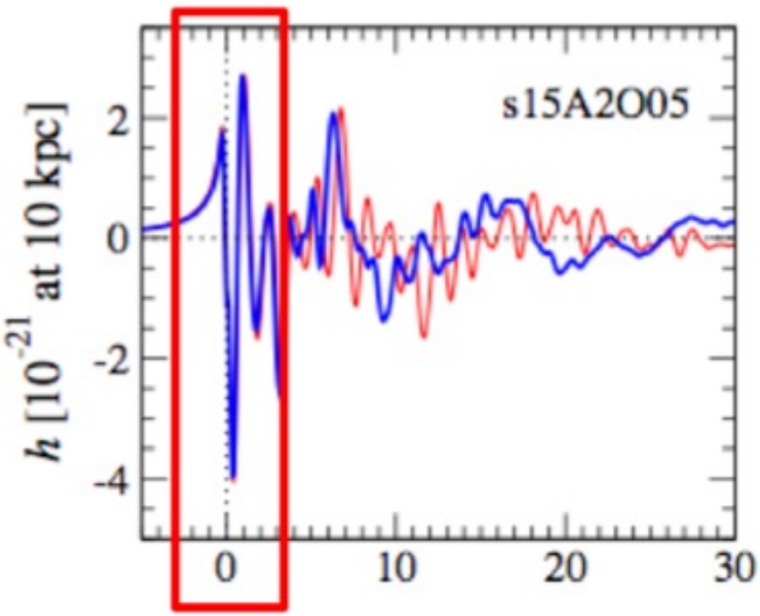


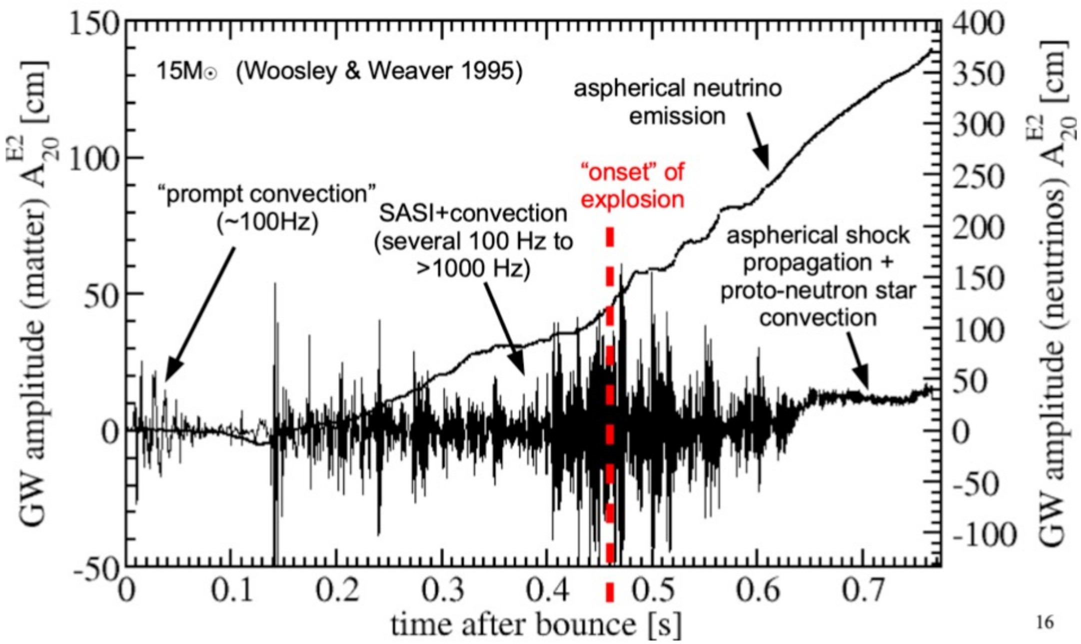
$$h \sim \frac{2G}{c^4 r} \frac{d^2 I}{dt^2} \sim \frac{2G}{c^4 r} \epsilon M R^2 f^2$$

Expected phases for GW signal

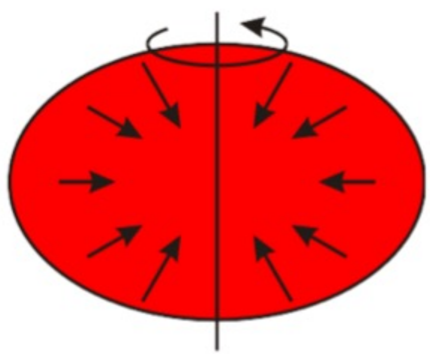
[B.Müller]

GW generation expected during **initial bounce** and **accretion phase**

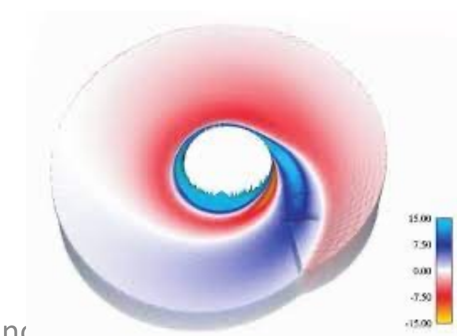


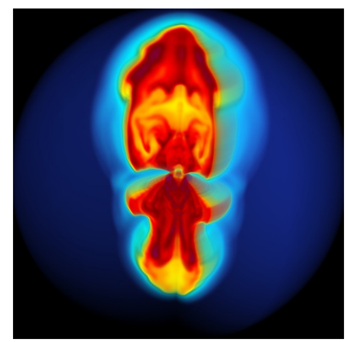


rotational bounce



Standing Accretion Shock Instability (SASI)

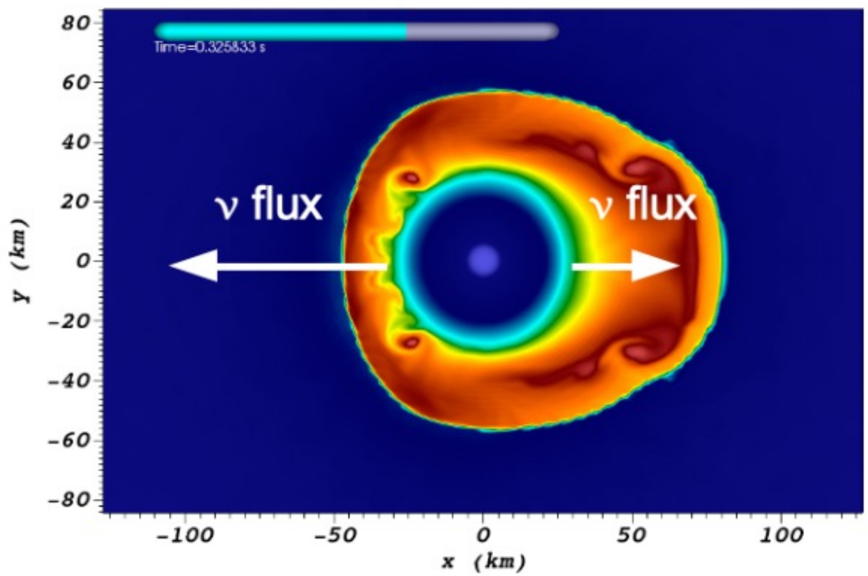


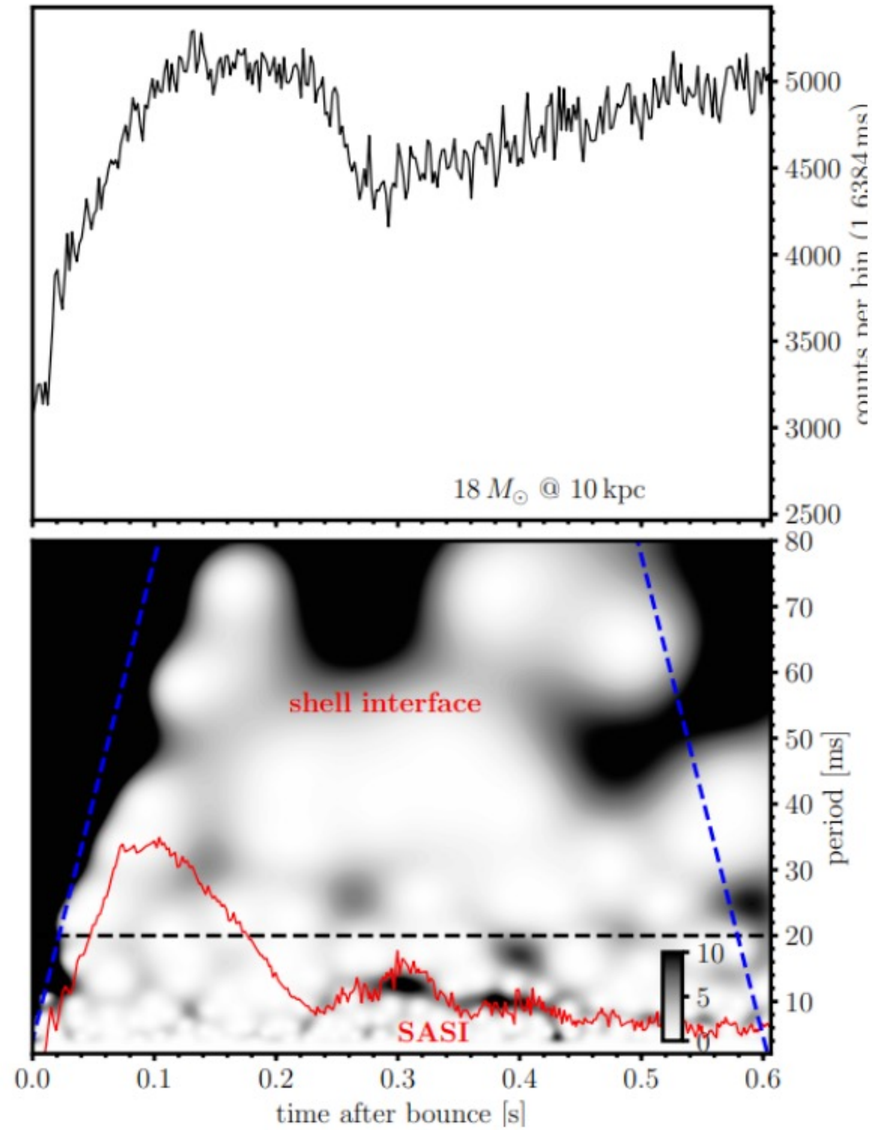


SASI shows as well in neutrino signal!

[B.Müller]

sloshing motion of SN envelope influences neutrino production and propagation:



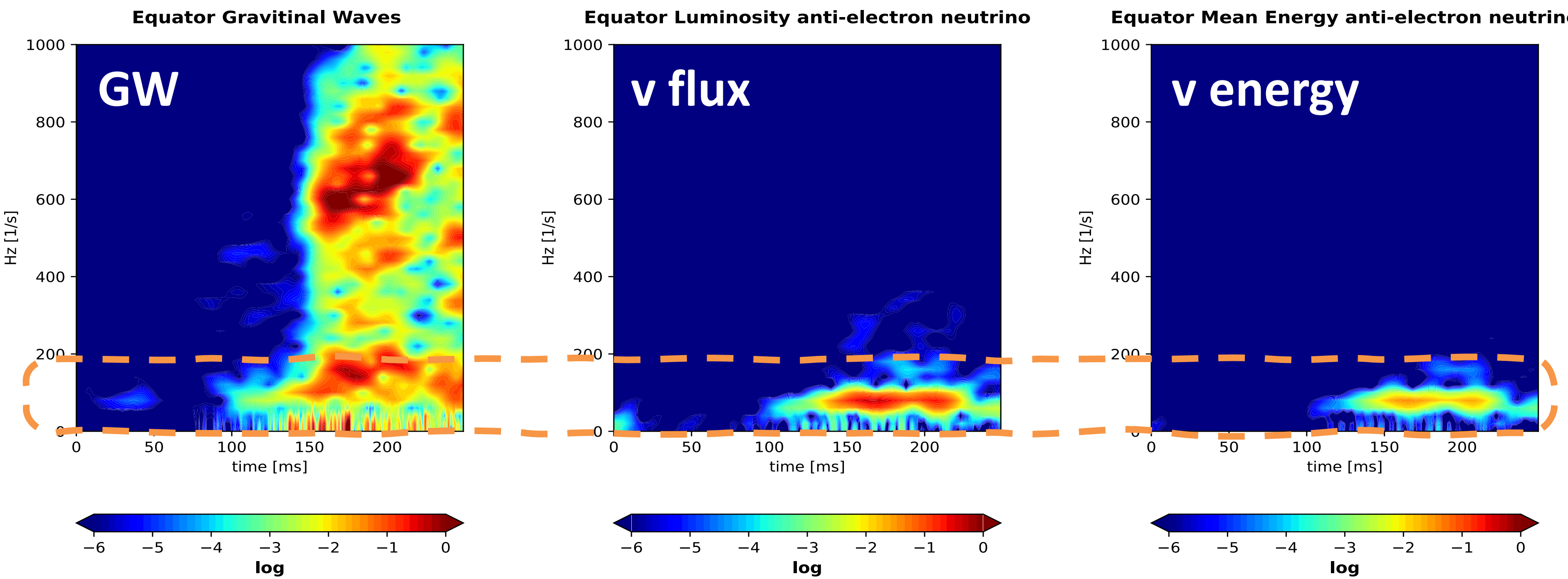


→ time correlation with GWs

Correlations in the ν+GW signals

[D.Maksimovic]

spectrograms of GW and neutrino data show similar features (in simulations):



- **time-stable modulation bands** caused by SASI during the accretion phase
- **GW** feature modulations at **double frequencies** compared to neutrinos
- relative amplitudes depend on orientation of SASI, equation of state of the proto neutron star etc. → resolve degenerate information about the collapse

LECTURE QUIZ

Question 10

What is the predominant mode of neutrino production in core-collapse Supernovae?

U : neutronization

V : mass accretion

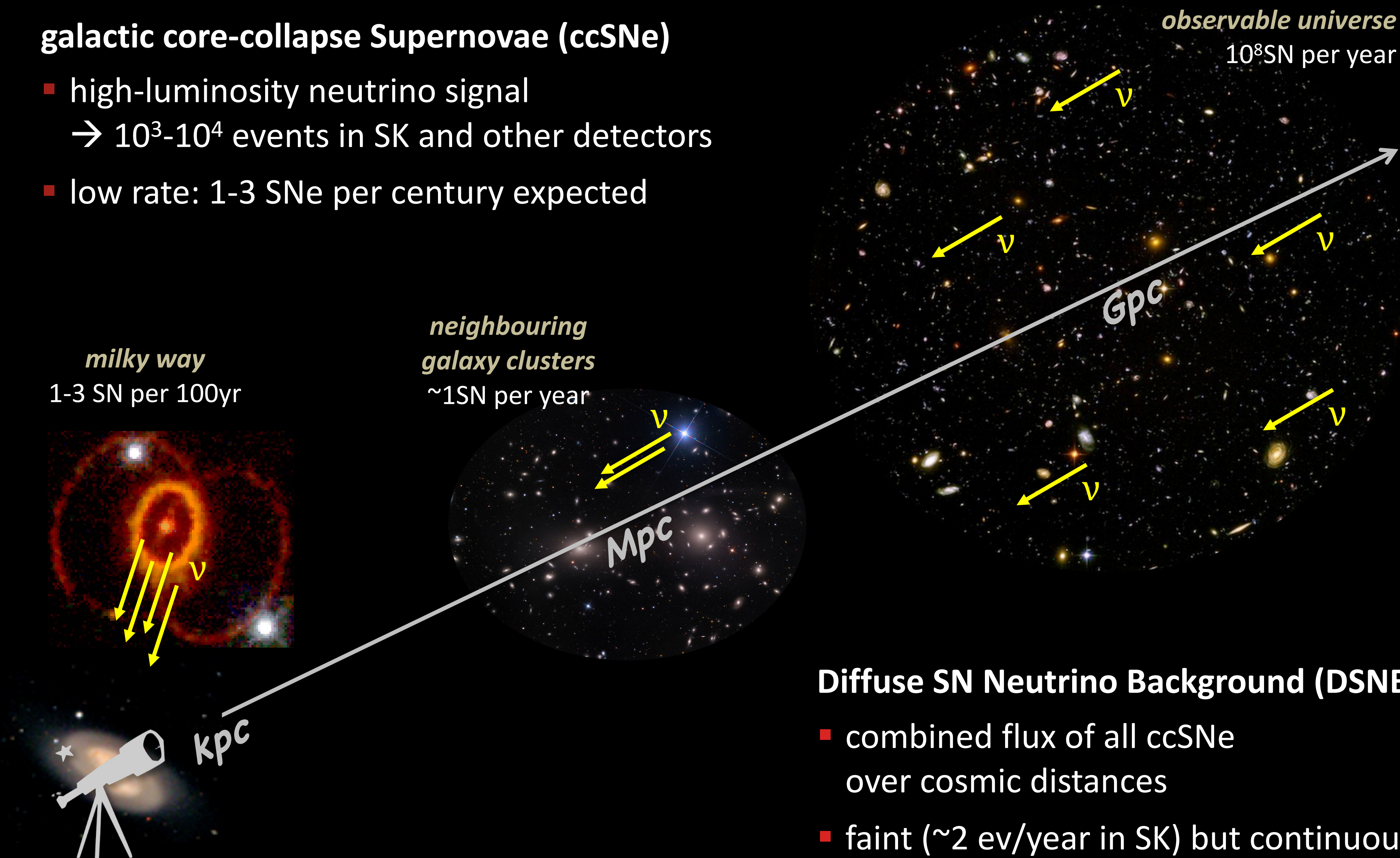
W : pair production

Note down the **second letter** of the solution word.

Diffuse Supernova Neutrinos

galactic core-collapse Supernovae (ccSNe)

- high-luminosity neutrino signal
  → 10^3-10^4 events in SK and other detectors
- low rate: 1-3 SNe per century expected



Diffuse SN Neutrino Background (DSNB)

- combined flux of all ccSNe
  over cosmic distances
- faint (~2 ev/year in SK) but continuous

Why is the DSNB interesting?

→ discovery of the only „permanent“ SN neutrino signal

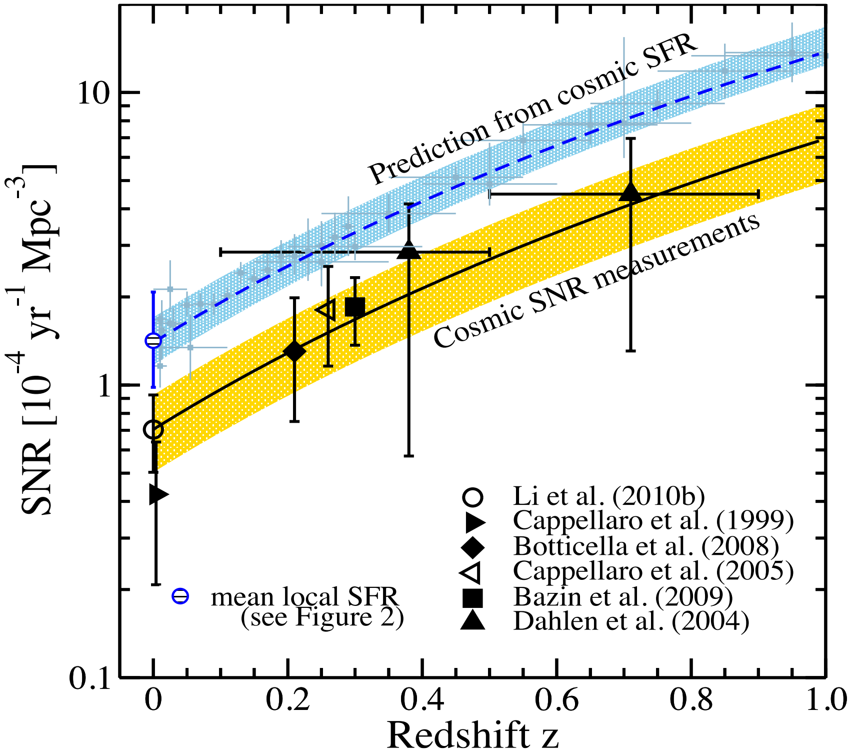
→ signal normalization

- redshift-dependent SN rate
- fraction of hidden/failed Sne

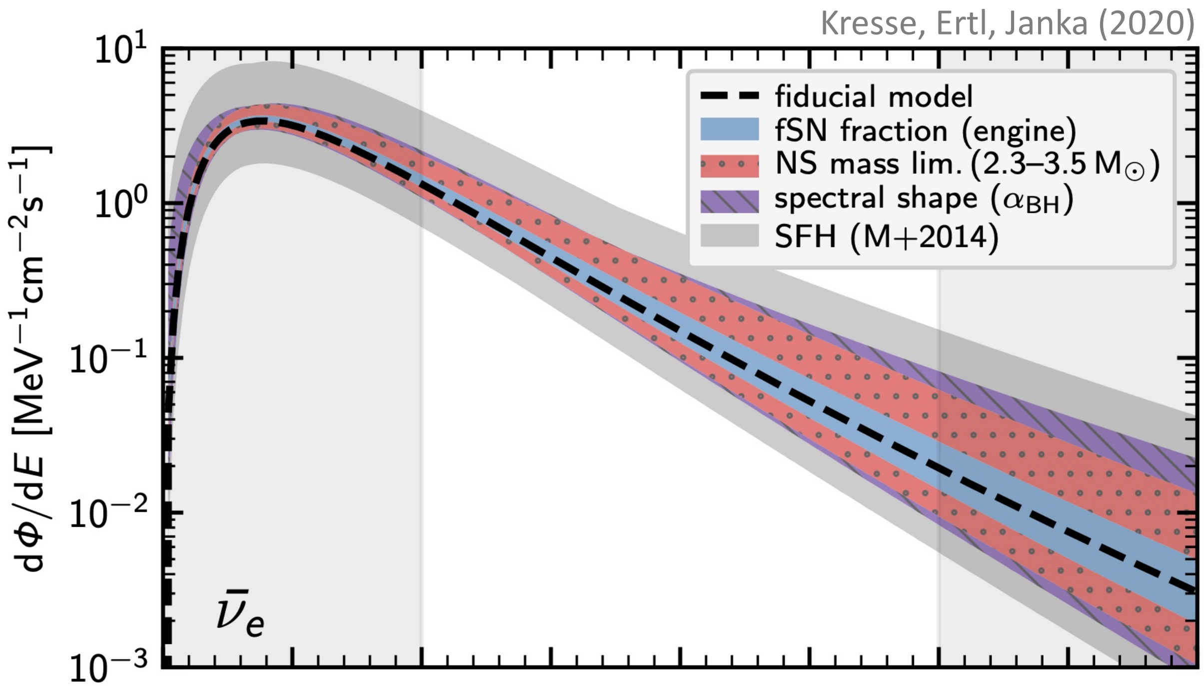
→ spectral shape

- large variability in PNS temperatures expected → average SN neutrino spectrum
- astrophysical parameters, e.g. neutron star equation of state

Beacom



Expected DSNB Signal

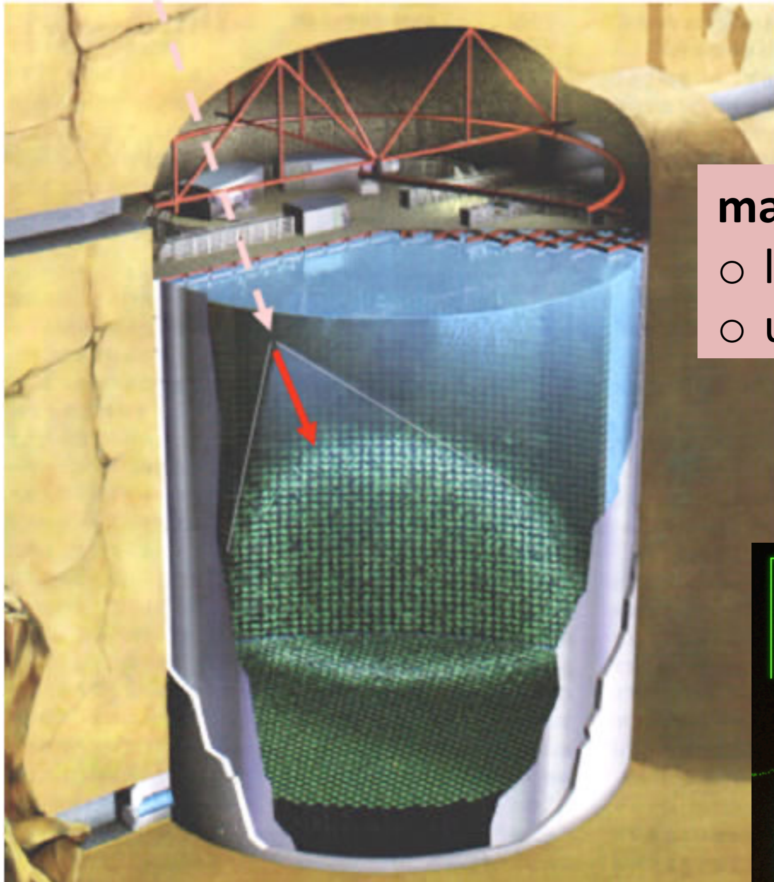


uncertainties shown here:

- fraction of failed SN
- mass limit of neutron stars
- spectral shape of black-hole forming SN
- normalization of Star Formation Rate

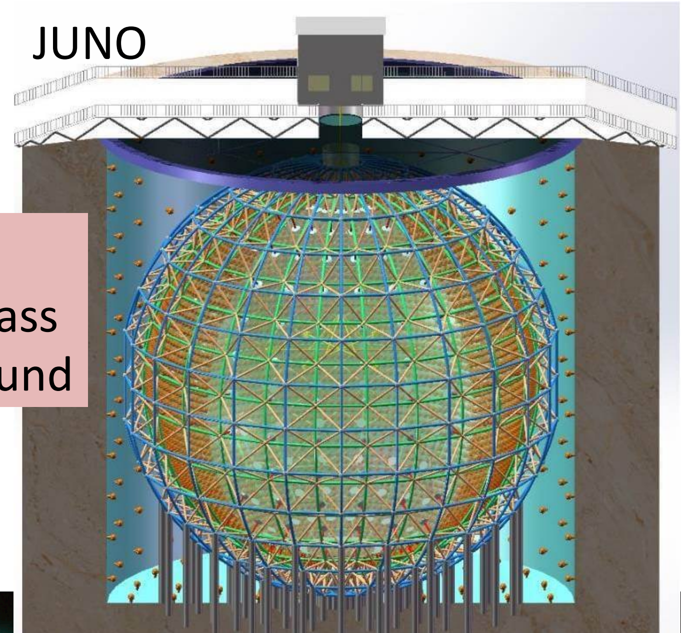
- DSNB flux predictions feature large intrinsic uncertainties
- predictions by many different groups
  → no substantial differences on flux/spectral shape

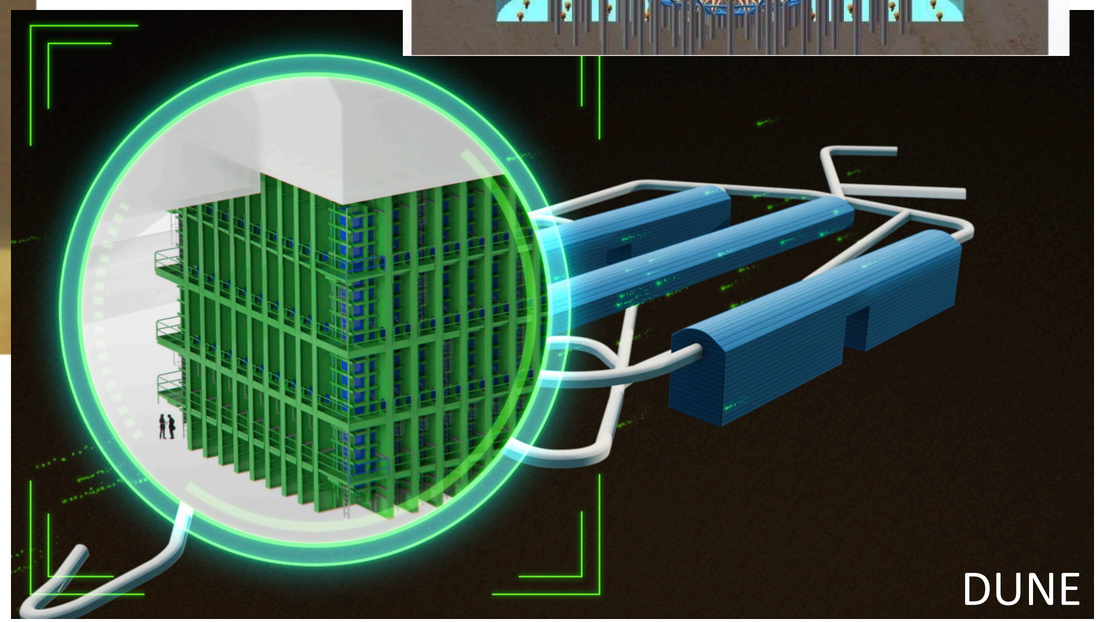
Detectors for DSNB search



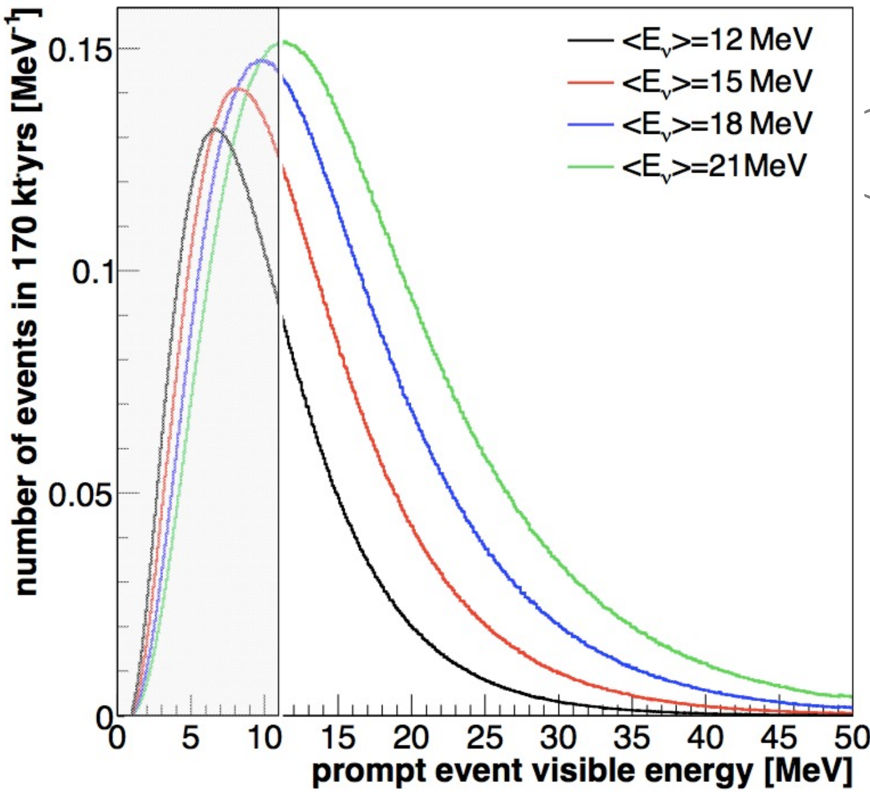
Super-Kamiokande

main requirements:
- large detection mass
- ultra-low background





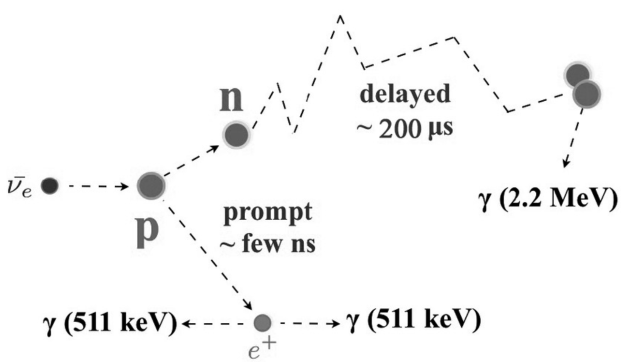
Detecting the DSNB $\bar{\nu}_e$ component



JUNO (2015)

- DSNB flux: ~10^2 /cm^{2}s
- equipartition between ν flavors
- best possibility for detection in water and liquid scintillator (LS)

  $\bar{\nu}_e$ via **inverse beta decay** on free protons (H)
- expected event rate:
  1—2 events per 10 kt·yrs

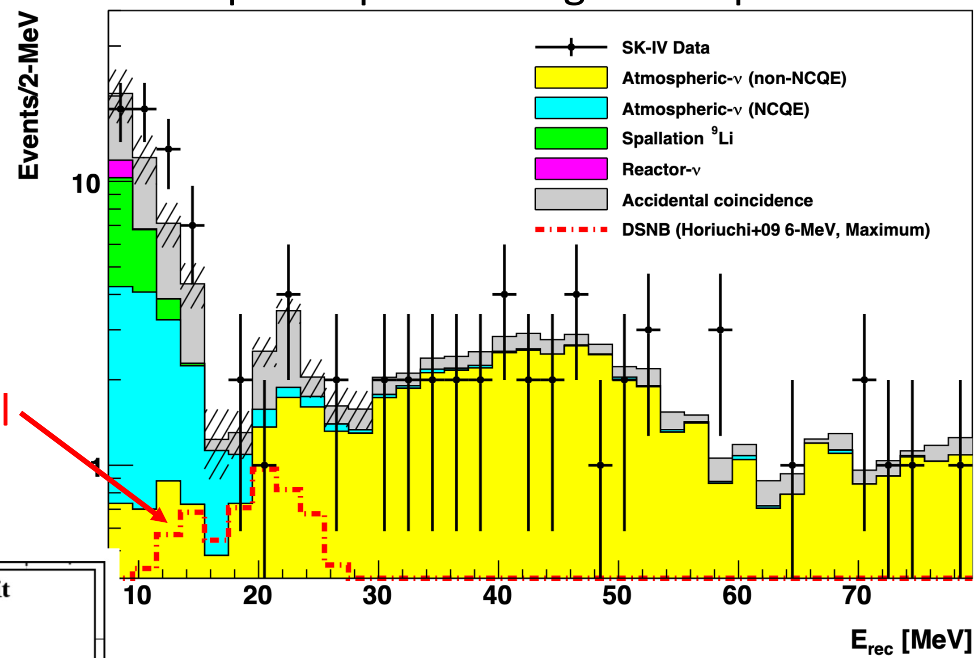


main detector requirements:
- large target mass
- ultra-low background

Current experimental results

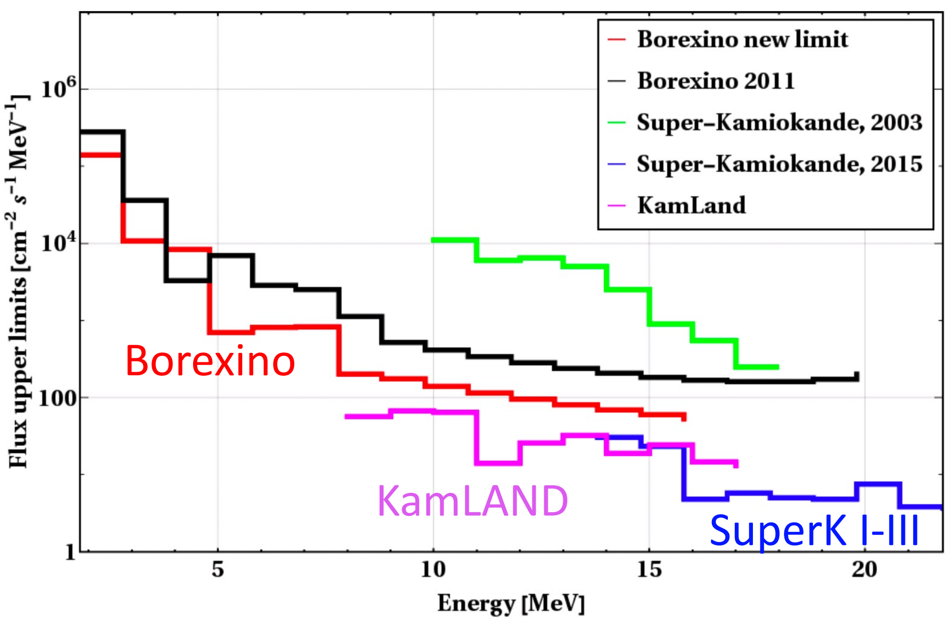
Experiment	Type	Mass
Borexino	LS	270t
KamLAND	LS	1kt
Super-K	WC	22.5kt

Example: Super-K background spectra



Super-Kamiokande (2021)

State of current experimental limits

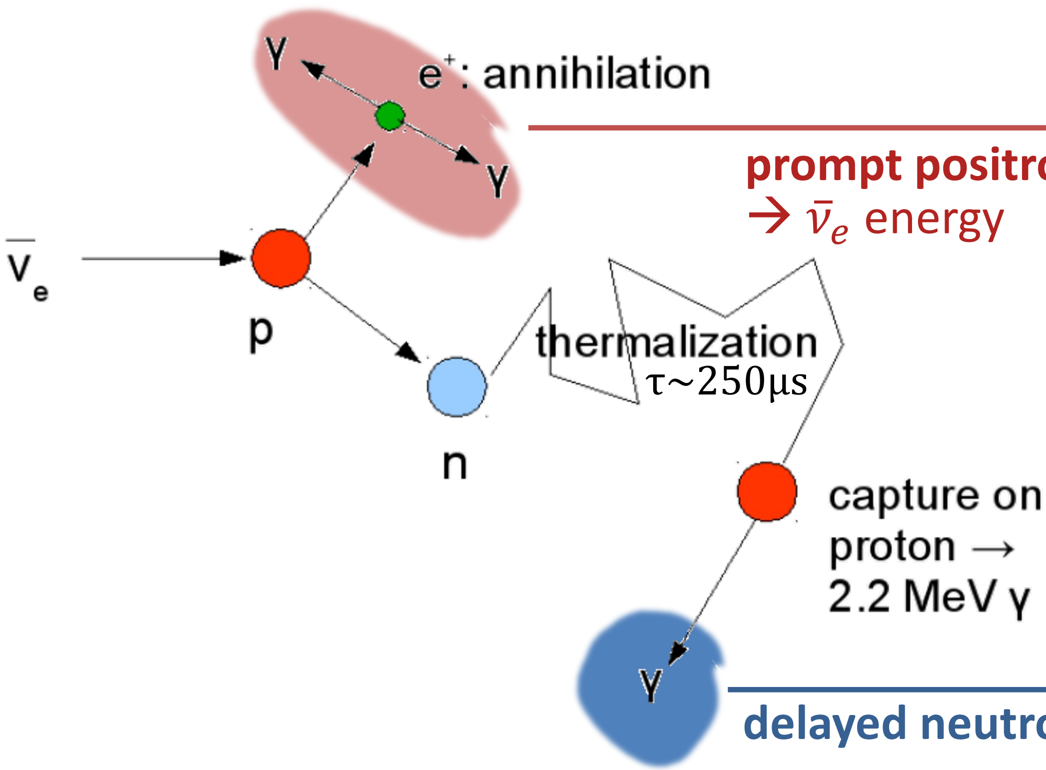


Borexino (2019)

→ current experiments are either too small or feature too much background for a detection

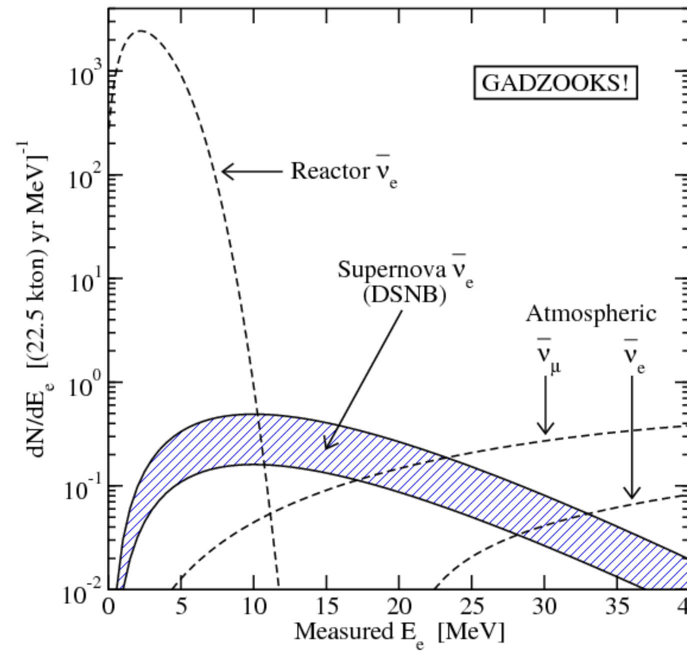
Important improvement: Neutron tag

irreducible backgrounds
detection window 10-30 MeV



prompt positron
→ $\bar{\nu}_e$ energy

delayed neutron



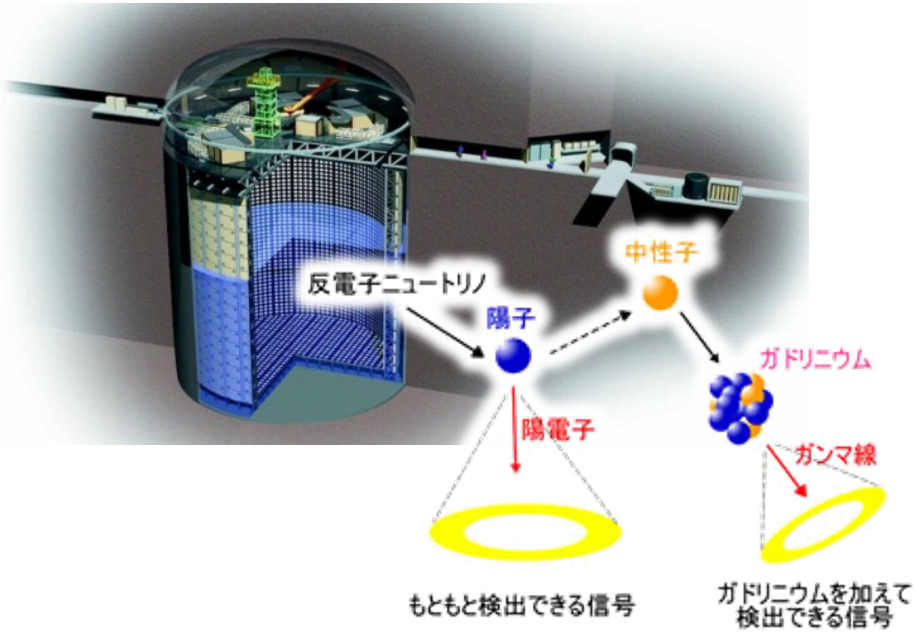
Beacom, Vagins

background discrimination:
removes **single events**
(e.g. invisible muons)

→ **n-detection** inherent to liquid scintillators but hard to achieve in pure water

Detectors with enhanced neutron tagging

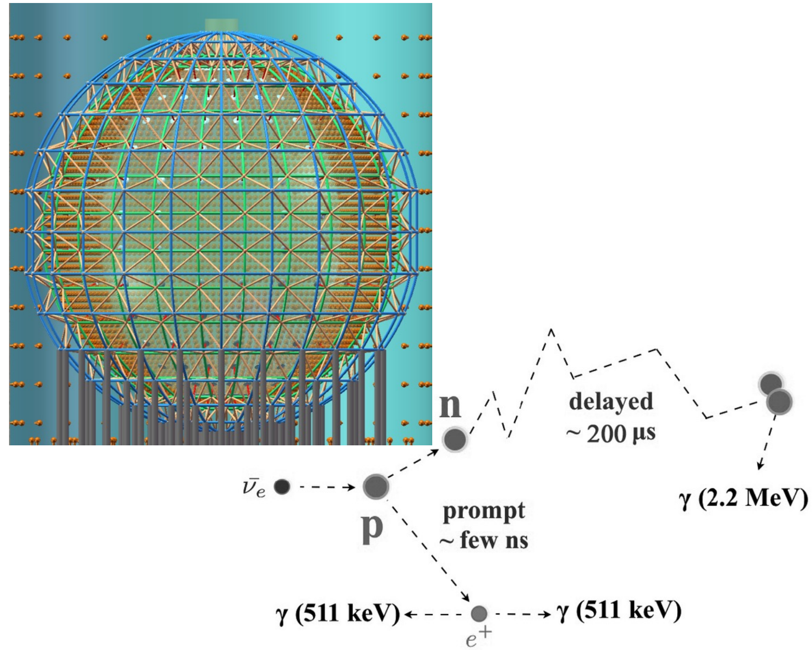
Super-Kamiokande+Gadolinium



- add low concentration of gadolinium (10^{-3})
- **enhanced neutron tag by gamma cascade** (τ~30µs, 4-5 gammas with $\Sigma E_\gamma \approx$8MeV)
- **detection efficiency: 65-80%**

→ running since fall 2020!

JUNO



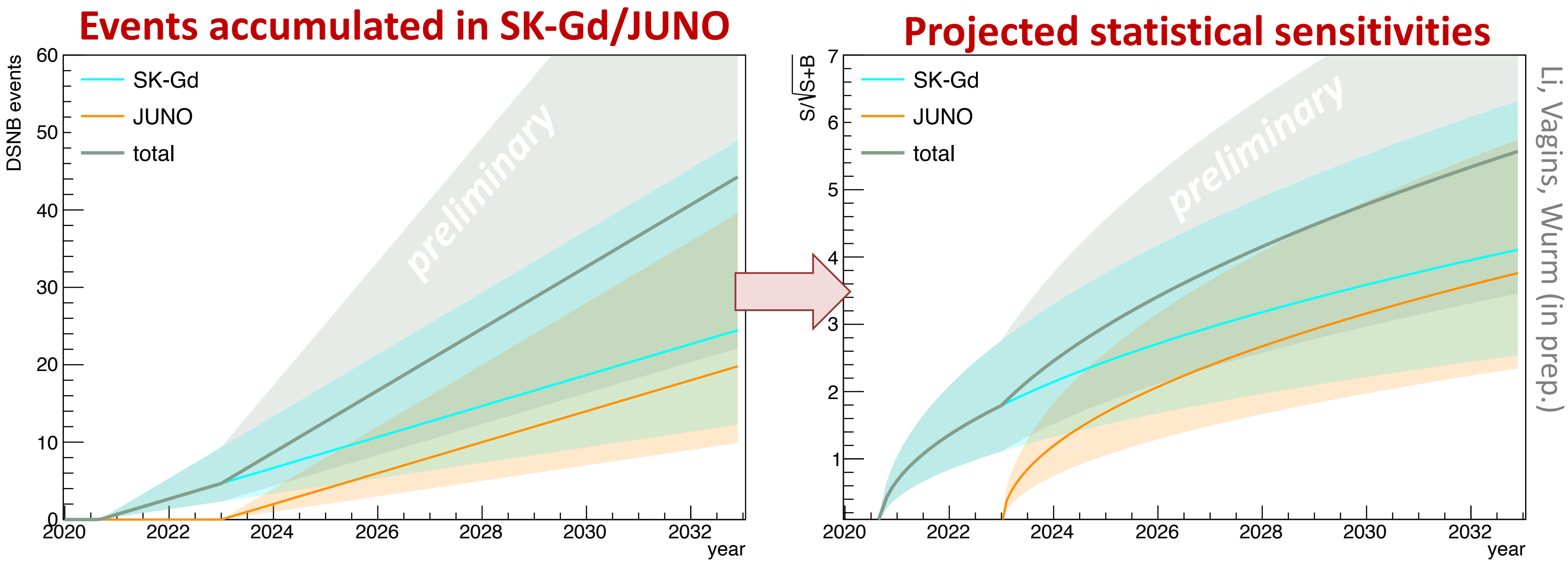
- liquid scintillator: high light yield & low detection threshold
- **large signal by n capture on H**
- **detection efficiency** close to 100%

→ will start in 2023

→ successfully removes all single-event backgrounds – **but:** there are correlated BGs …

First observation of DSNB within 10 years?

SK-Gd started data taking in 2020, JUNO will follow soon → projected DSNB sensitivity?



- after 10 years, sensitivity of individual experiments at 3σ level
- combined sensitivity will reach 5σ level for a positive DSNB detection
- many caveats: DSNB (and BG) rate uncertainty, systematic effects
- but as well synergies: complementary measurements of atm. NC BG in water/scintillator will improve understanding of this background

LECTURE QUIZ

Question 11

How many Diffuse Supernova Neutrinos cross your thumb nail in one second?

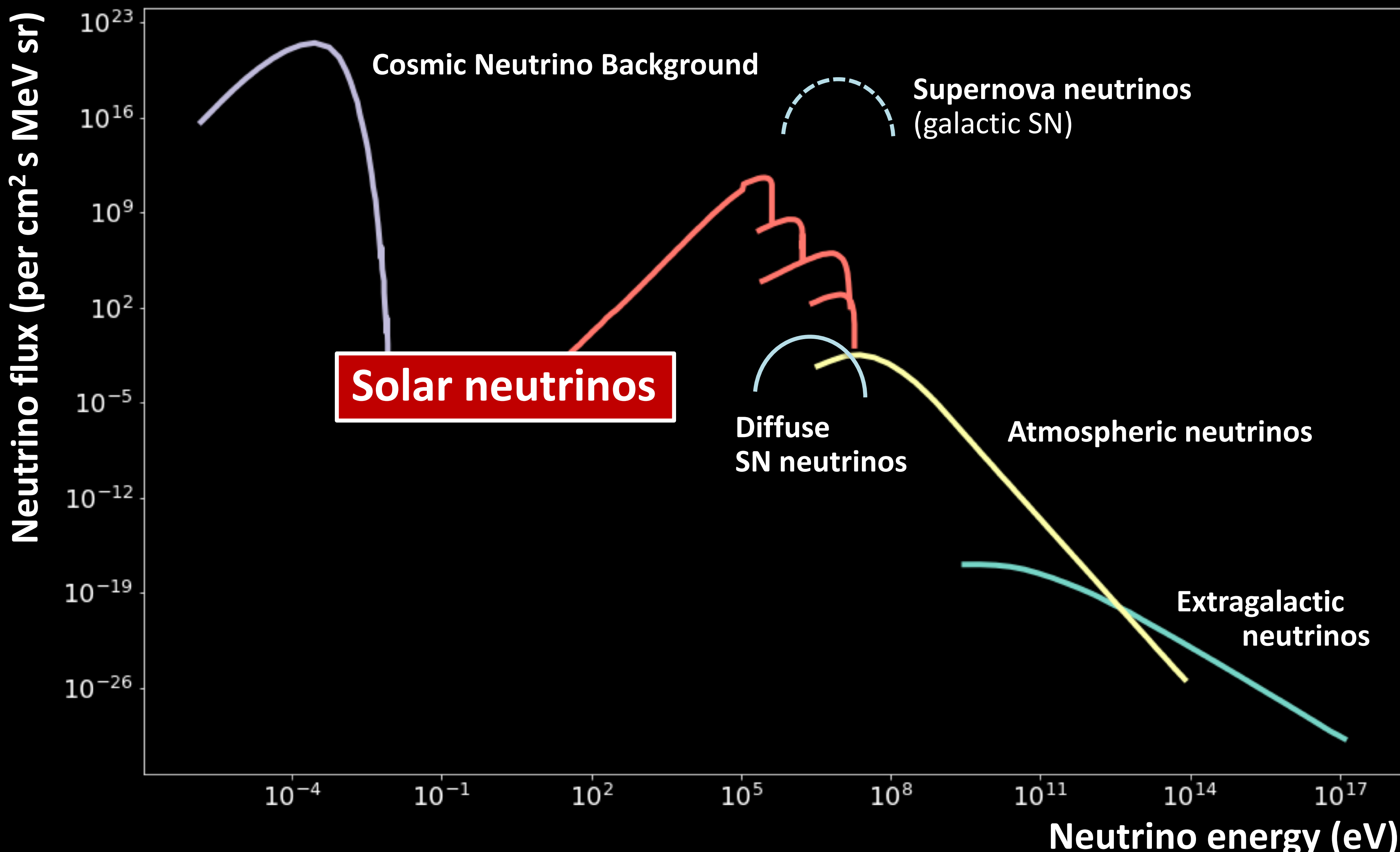
A : 100

B : 1,000

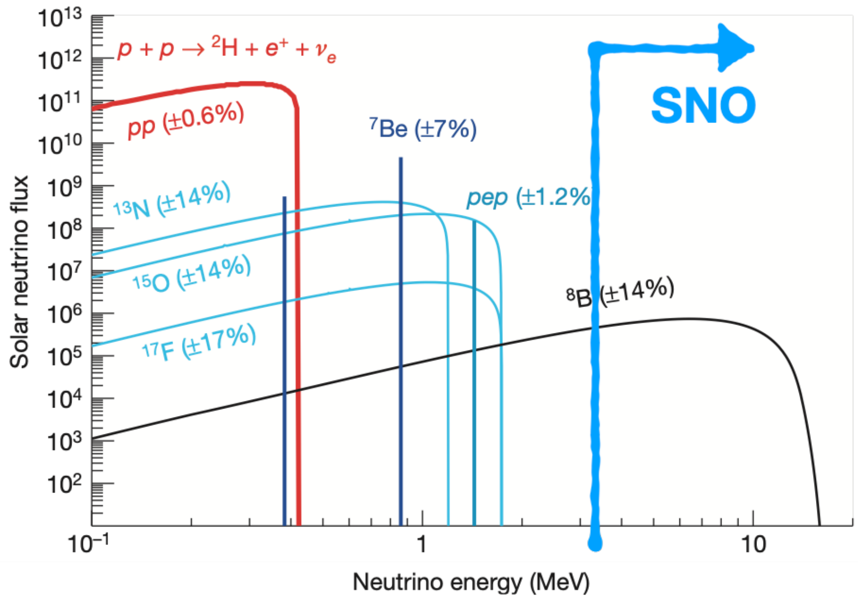
C : 10,000

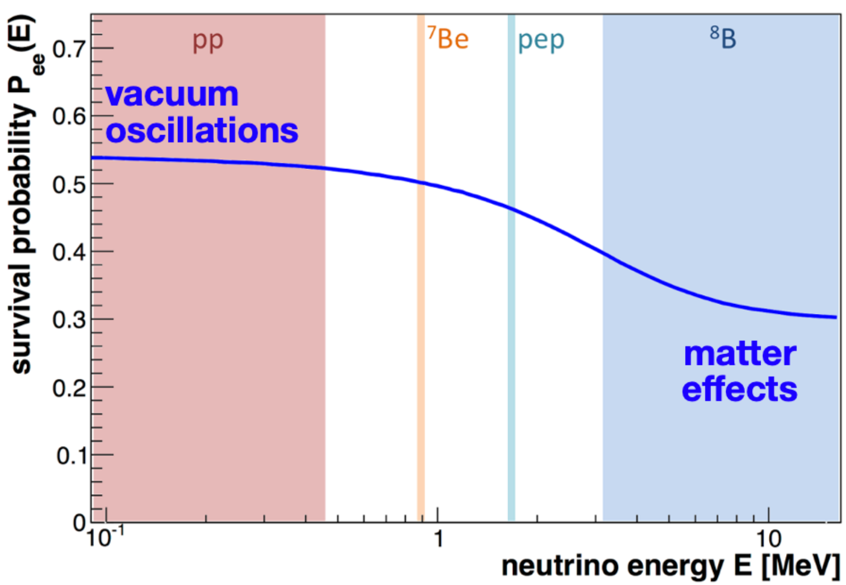
Note down the **third letter** of the solution word.

Energy spectrum of astrophysical ν's



Open questions for solar ν's after SNO results





- SNO measurements only above 5 MeV (later 3.5 MeV) → ^{8}B neutrinos only

→ **Neutrino astronomy**

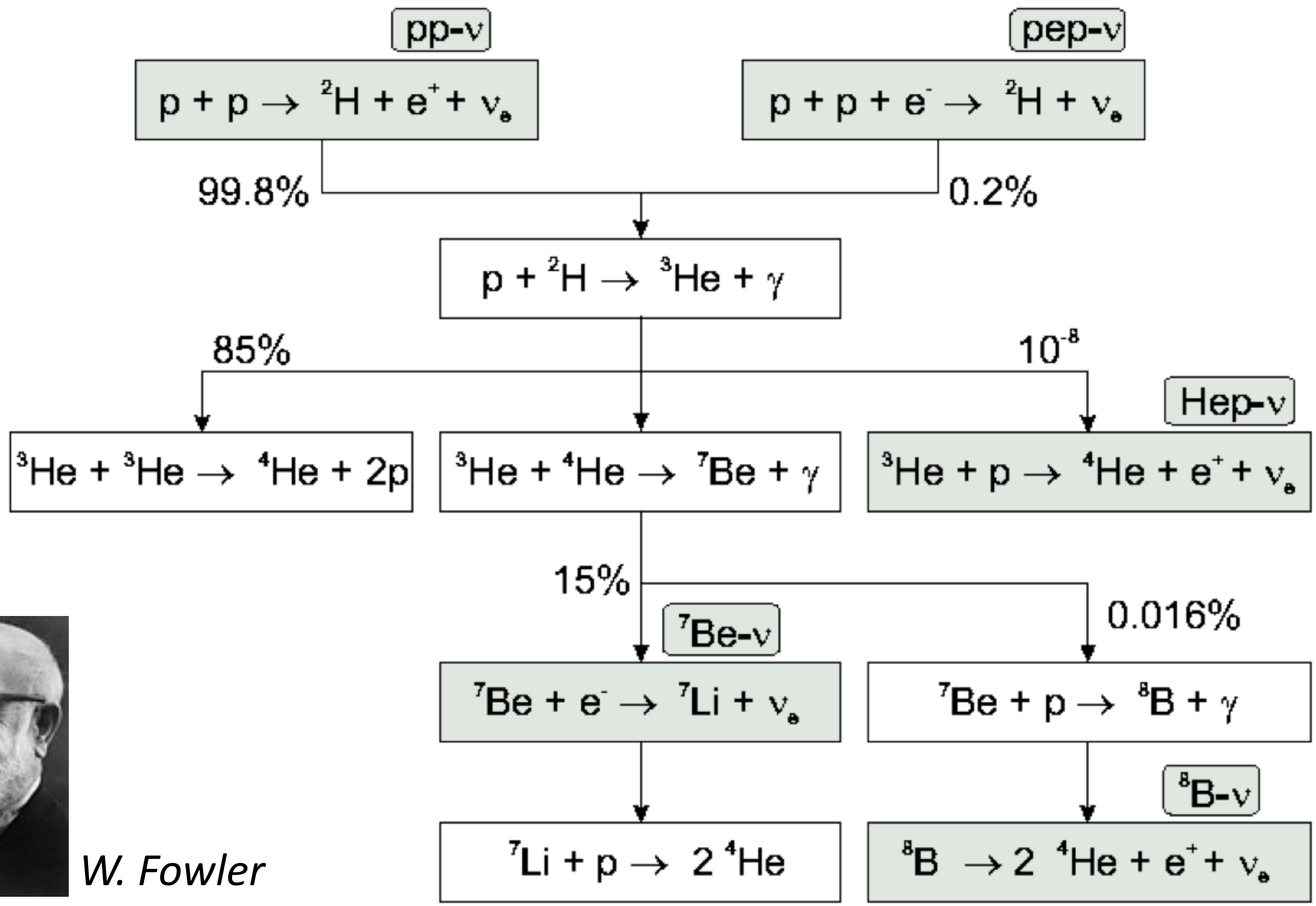
- spectroscopy of neutrinos et low energies to obtain pp reaction rates → precision test of the SSM
- first detection of CNO neutrinos → CNO cycle in Sun/stars?

→ **Neutrino particle physics**

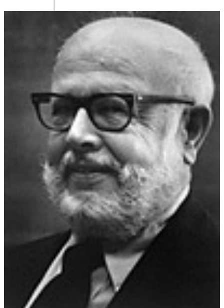
- measuring the energy dependence of solar ν oscillation probabilities → influence of matter effects

Overview of the solar pp-chain

Net fusion reaction: $4p \rightarrow {}^4He + 2e^+ + 2\nu_e$ [+26.7 MeV]



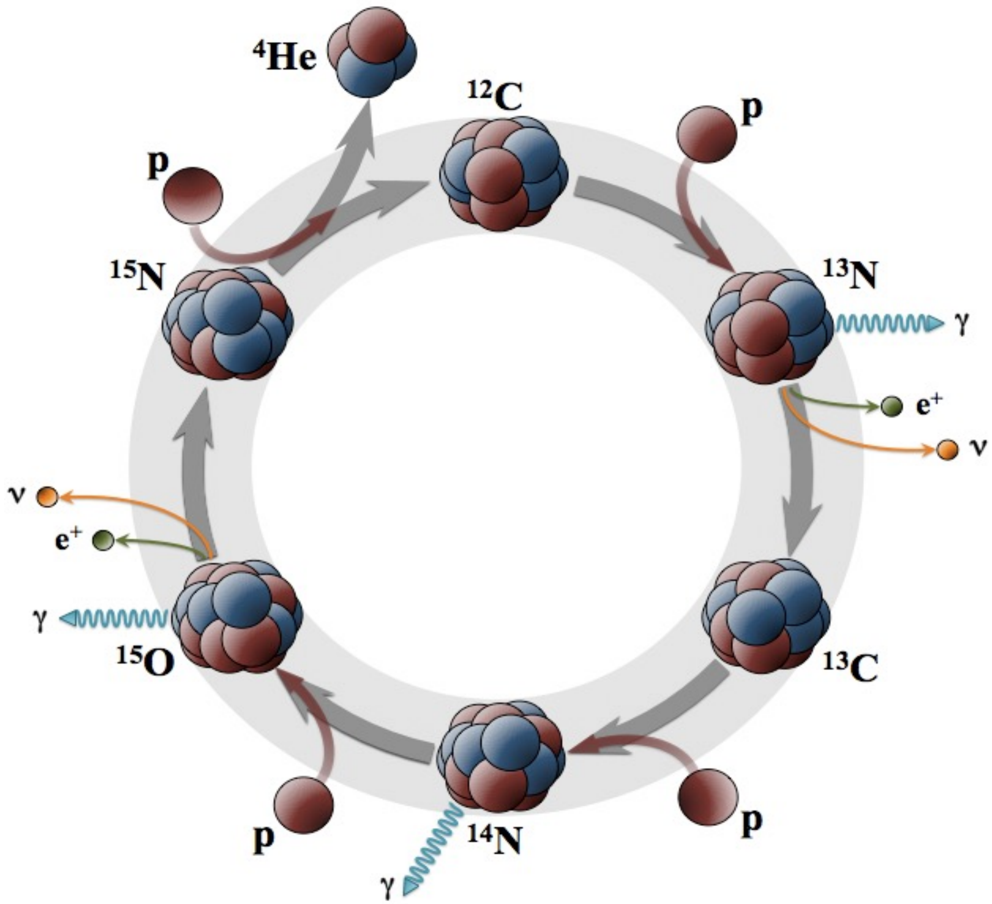
H. Bethe



W. Fowler

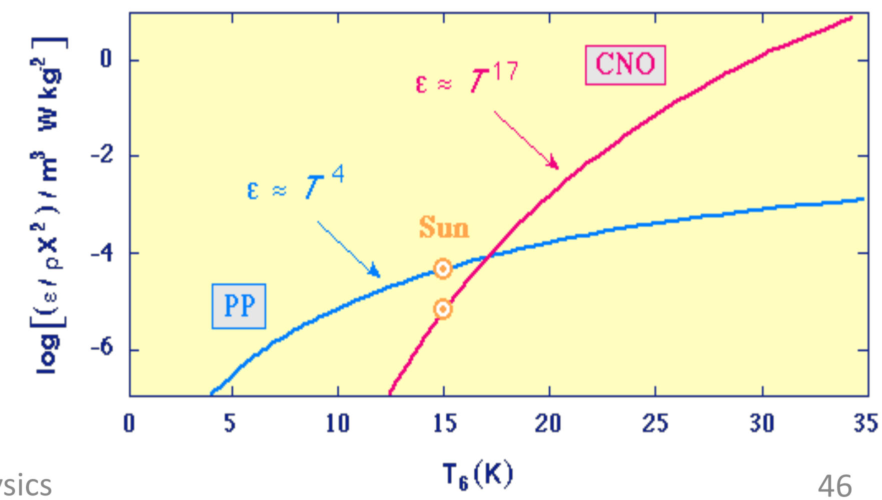
The catalyst CNO cycle

Net fusion reaction: 4p → $^4He + 2e^+ + 2\nu_e$ [+26.7 MeV]



- minor contribution to solar fusion (~1%)
- dominant in heavier and older stars
- relatively large uncertainties in nuclear cross sections

fusion rate vs. solar core temperature



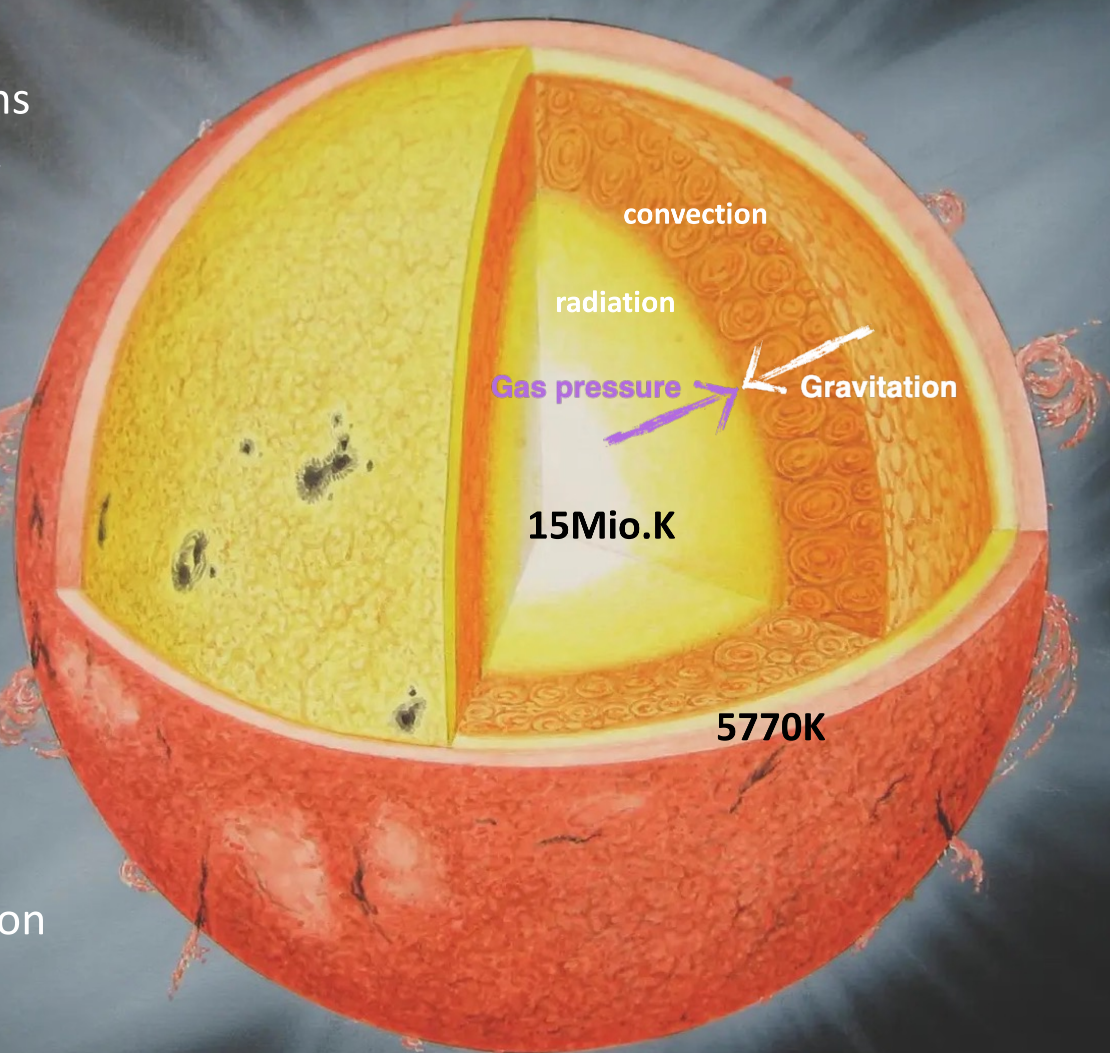
Standard Solar Model (SSM)

Description of the Sun

- Stellar structure equations
  → p, T, ρ as function of R
- Thermodynamics:
  Equation of state
  of solar plasma
- Nuclear physics:
  Cross-sections of
  fusion reactions
- Elemental abundances:
  opacity of solar matter
- Observations:
  surface, age of the Sun

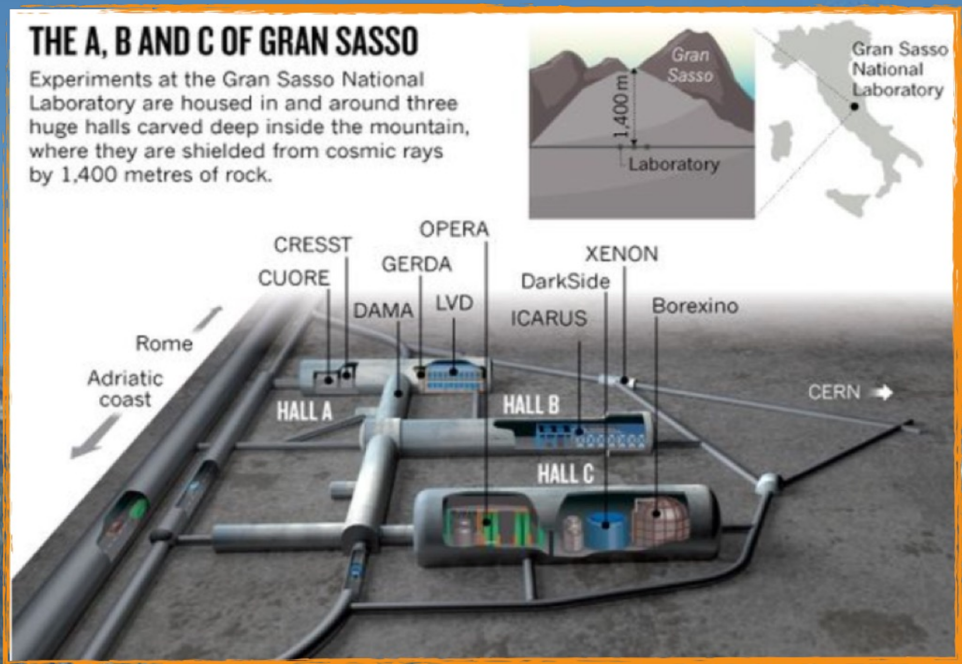
→ structure equations are solved by numeric iteration

→ precise prediction of fusion rates and thus neutrino production rates

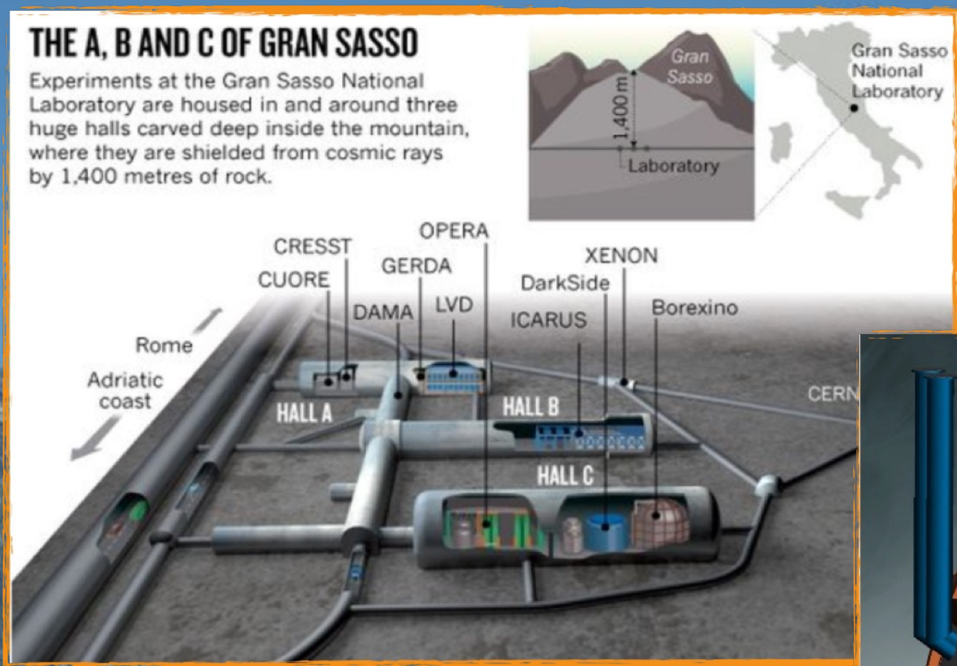


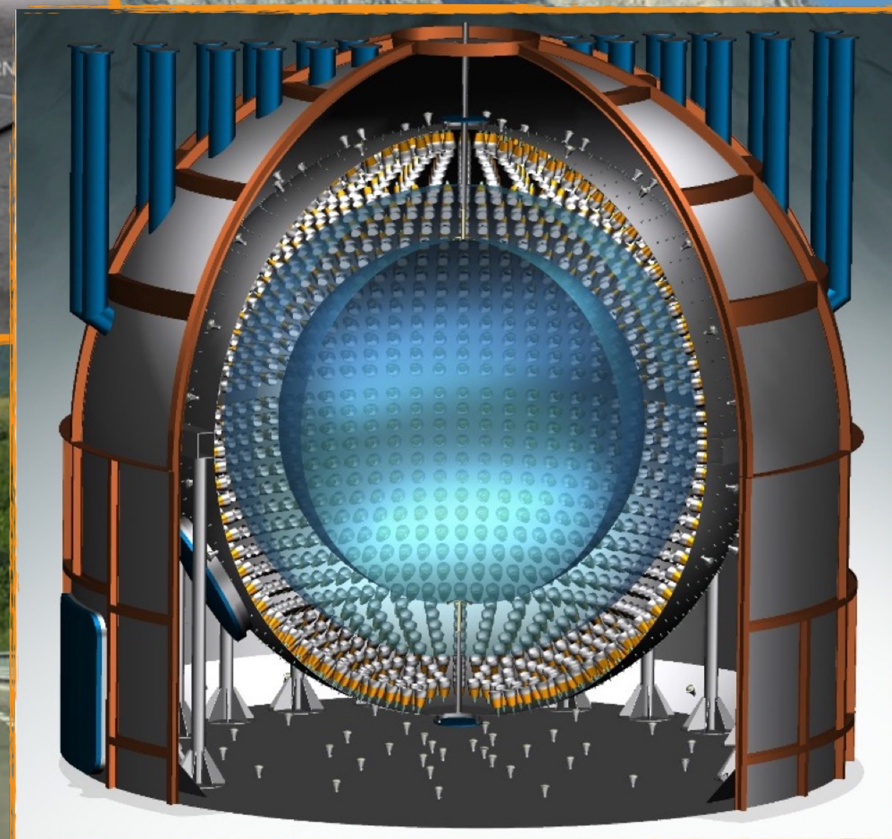
Borexino at Gran Sasso Laboratory

Borexino at Gran Sasso Laboratory



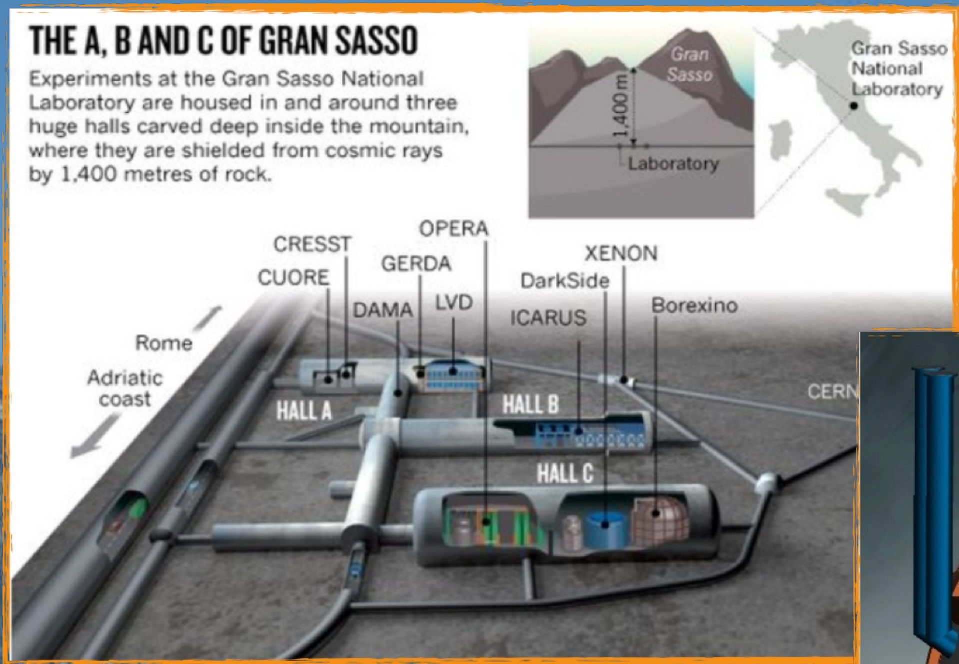
Borexino at Gran Sasso Laboratory

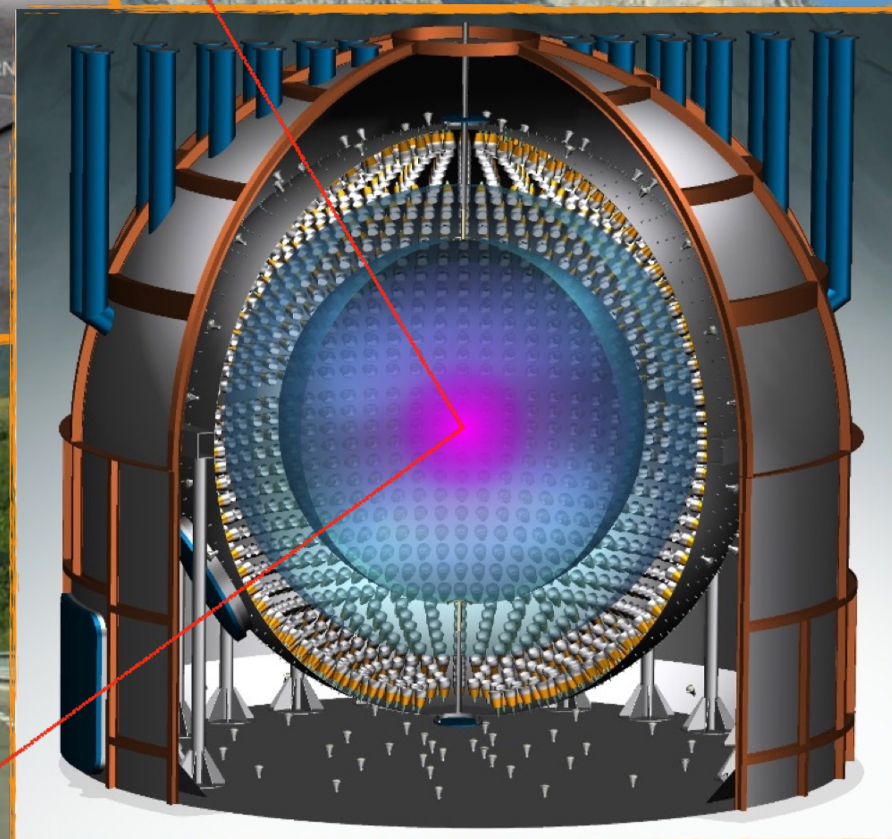




Borexino Detector
Height/Diameter: 18m
Target: Scintillator
Target mass: 270t
Light sensors: 2200 8”-PMTs

Borexino at Gran Sasso Laboratory





Borexino Detector

Height/Diameter: 18m

Target: Scintillator

Target mass: 270t

Light sensors: 2200 8"-PMTs

Inside Borexino

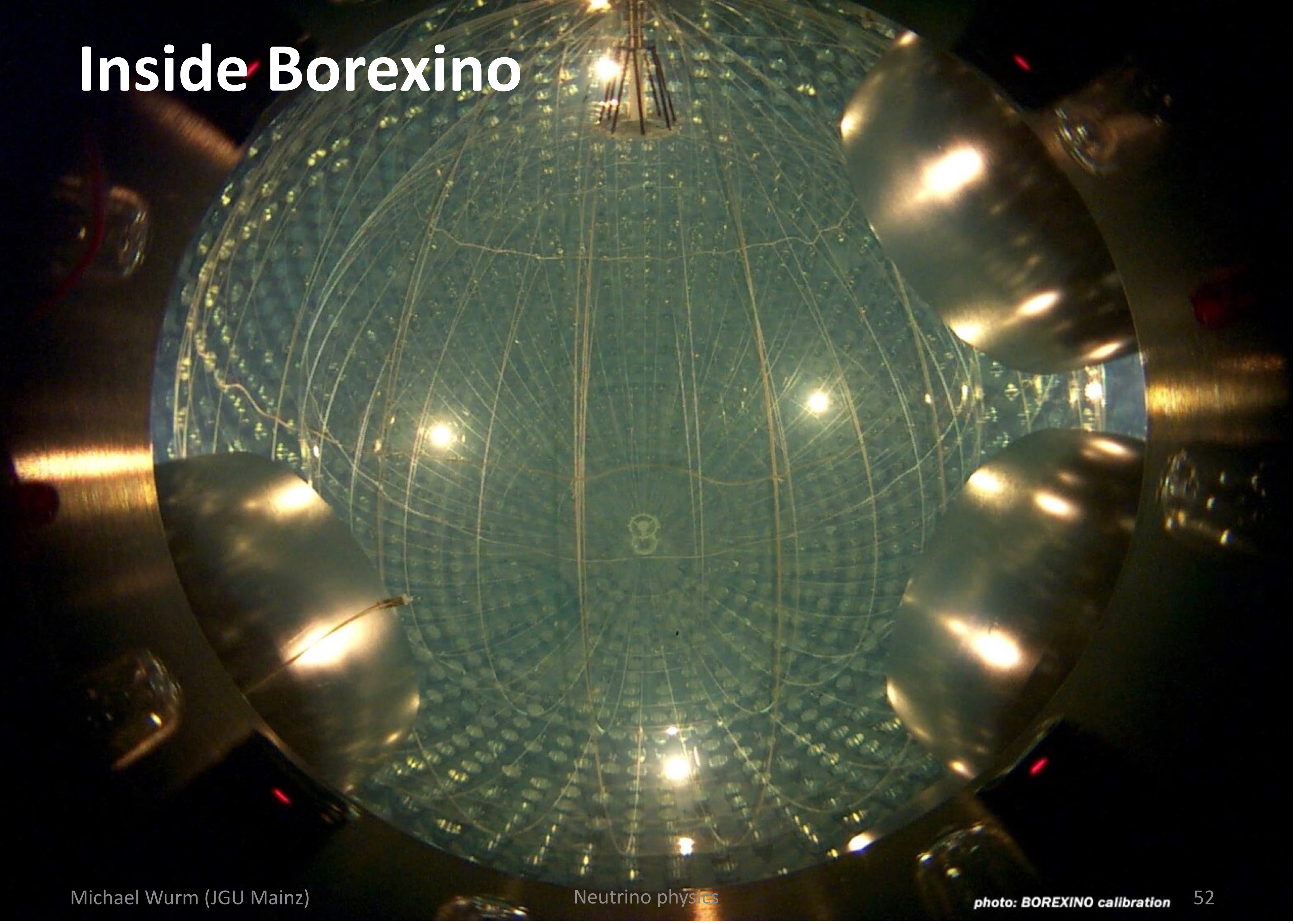


photo: BOREXINO calibration

Inside Borexino

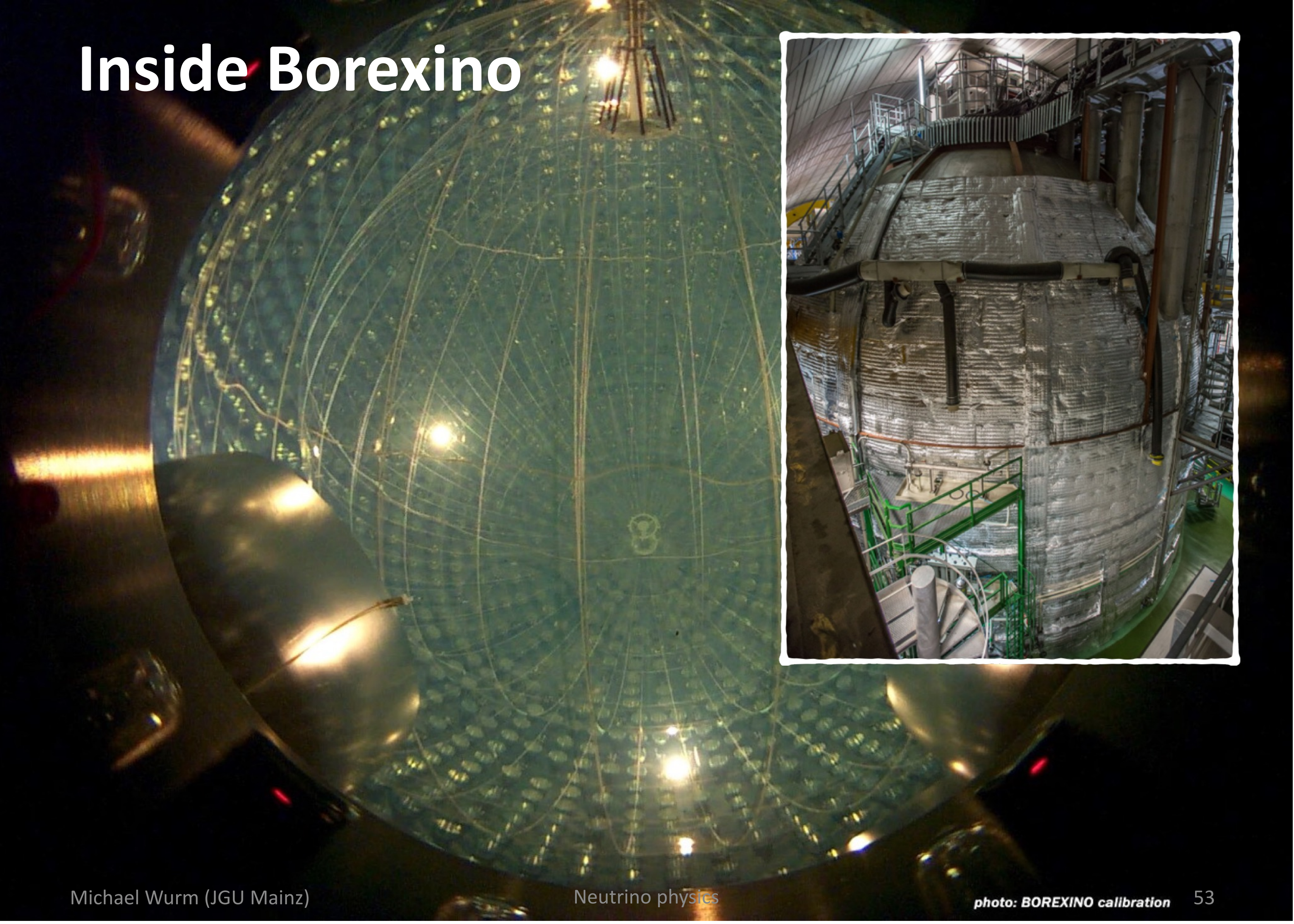


photo: BOREXINO calibration

Inside Borexino

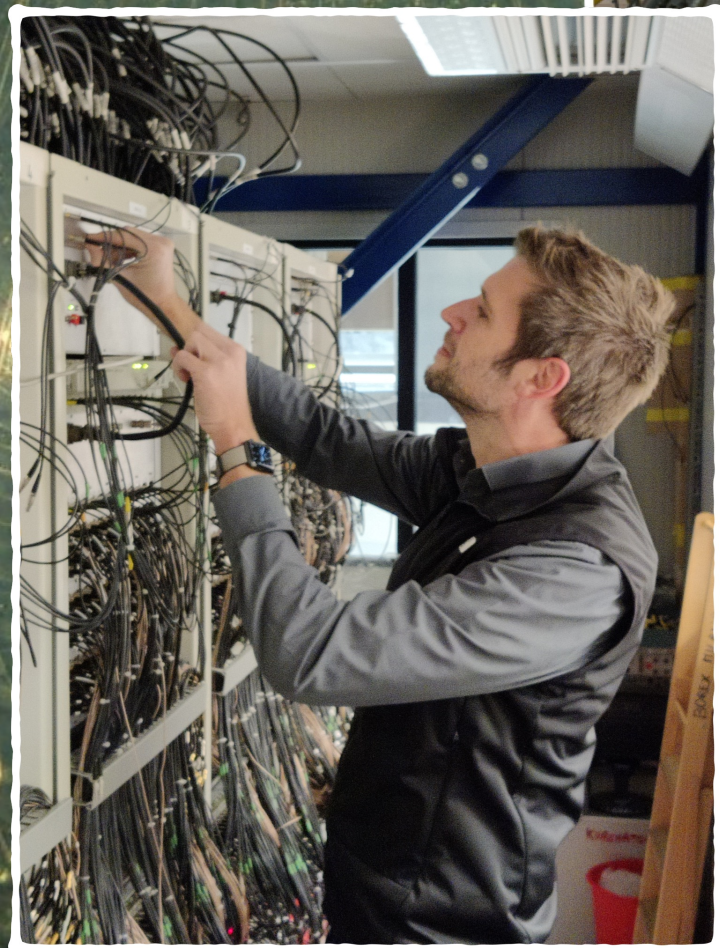
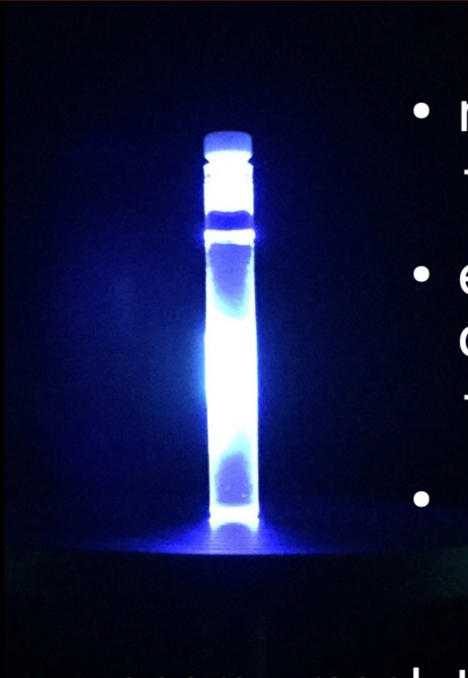
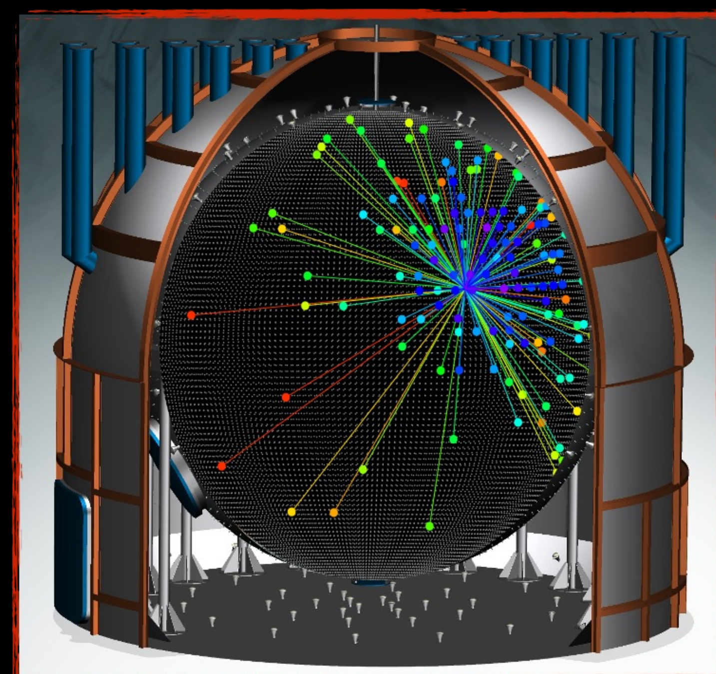


photo: BOREXINO calibration

Neutrino detection in liquid scintillator

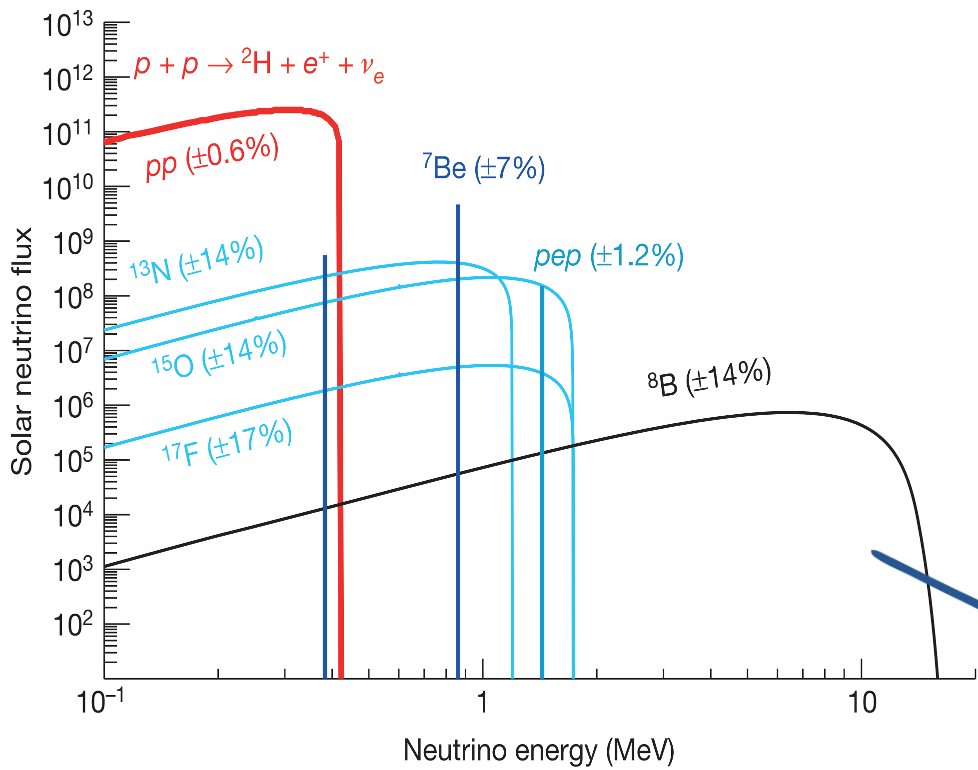


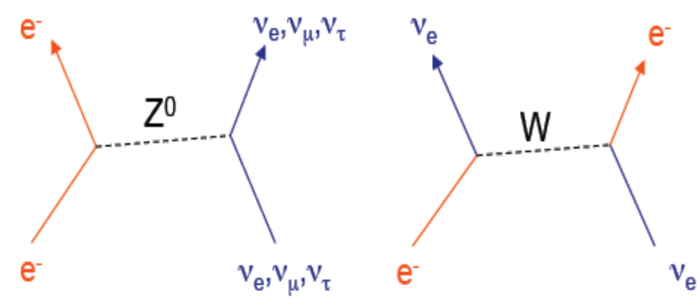
- much greater light yield than Cherenkov effect (x50)
  → better energy resolution
- efficient purification methods for radioactive contaminants: 10^{-18} g/g uranium/thorium in LS
  → low energy threshold (pp neutrinos!)
- transparent and cheap → large-scale detectors

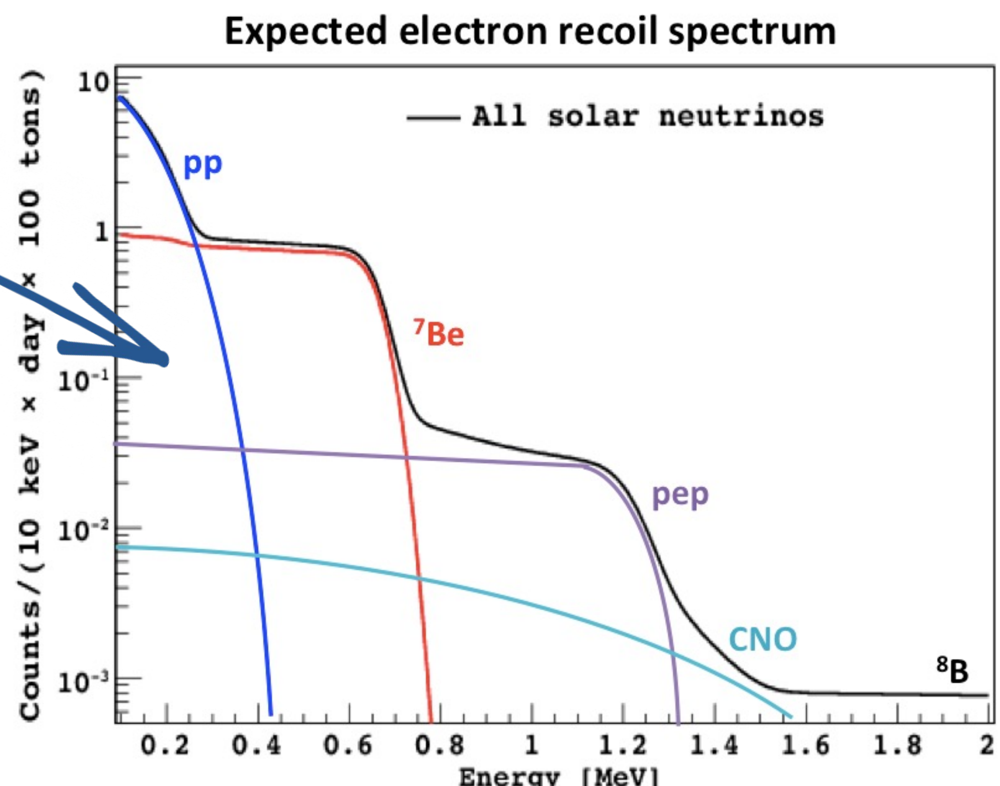


- energy resolution based on number of detected photons:
  isotropic emission: ~10^4/MeV
  detected: Borexino ~500 pe/MeV
  JUNO ~1300 pe/MeV
- vertex reco via photon time-of-flight
- but: no (?) directional resolution

Electron recoil signal in Borexino

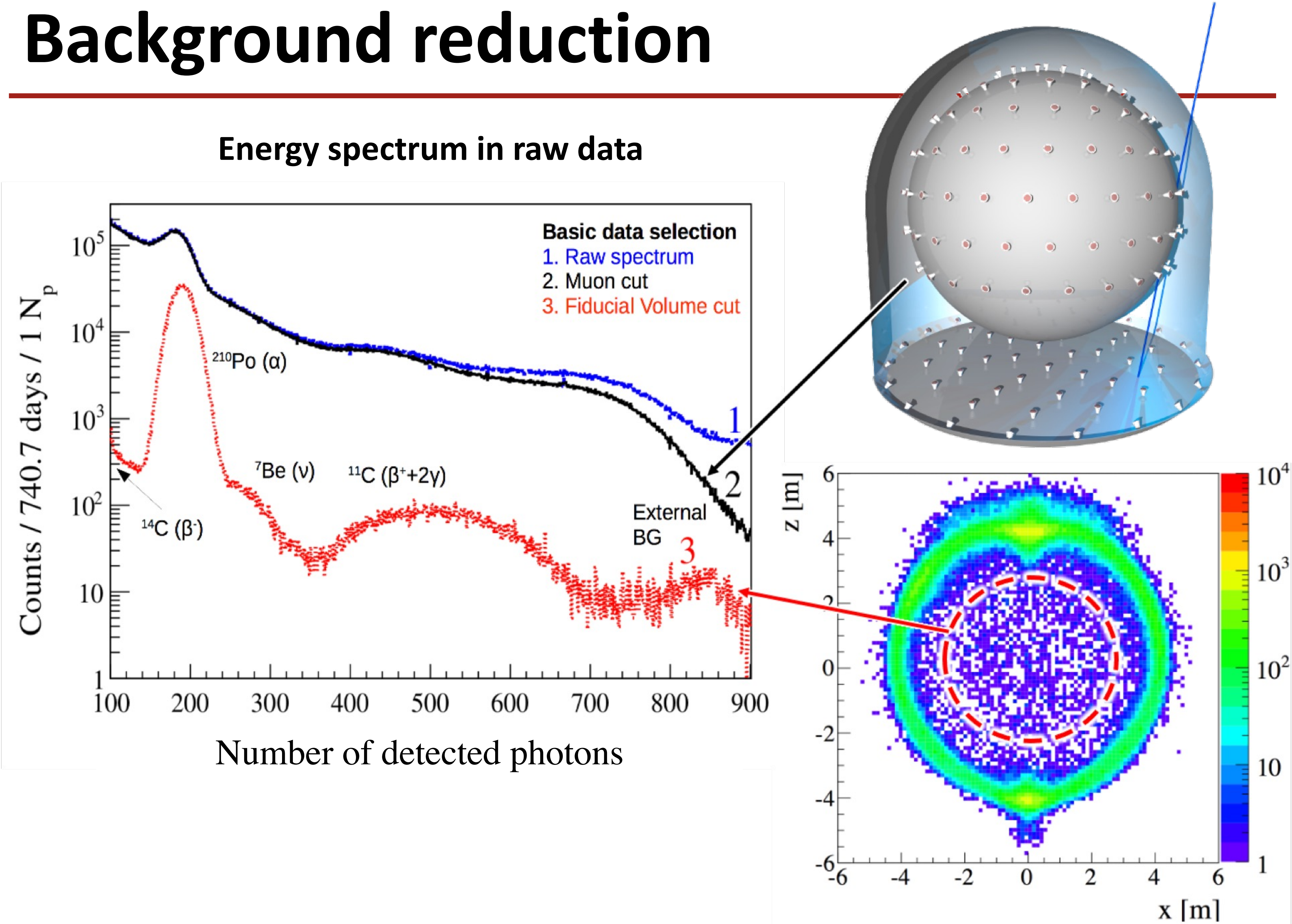






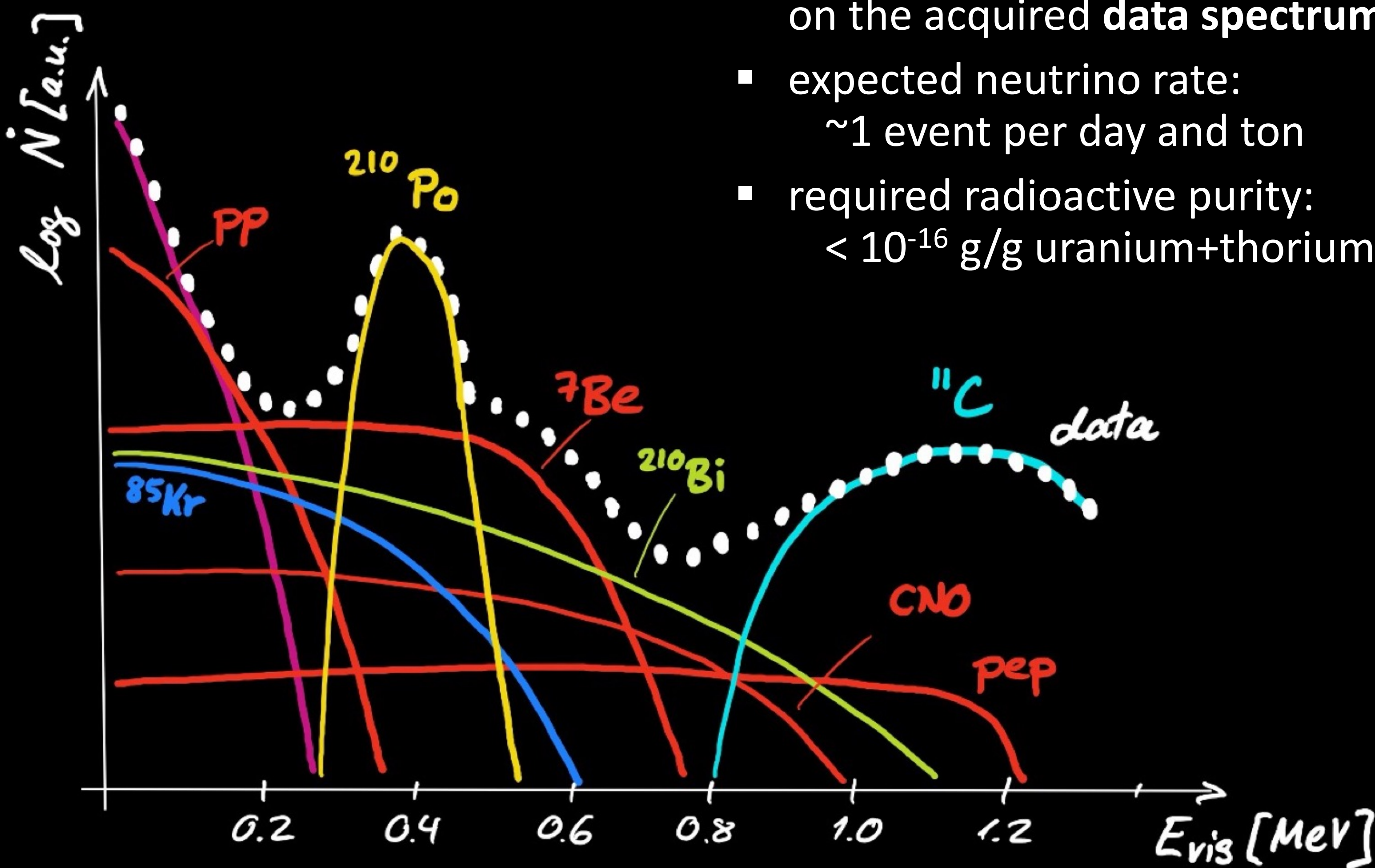
Background reduction

Energy spectrum in raw data

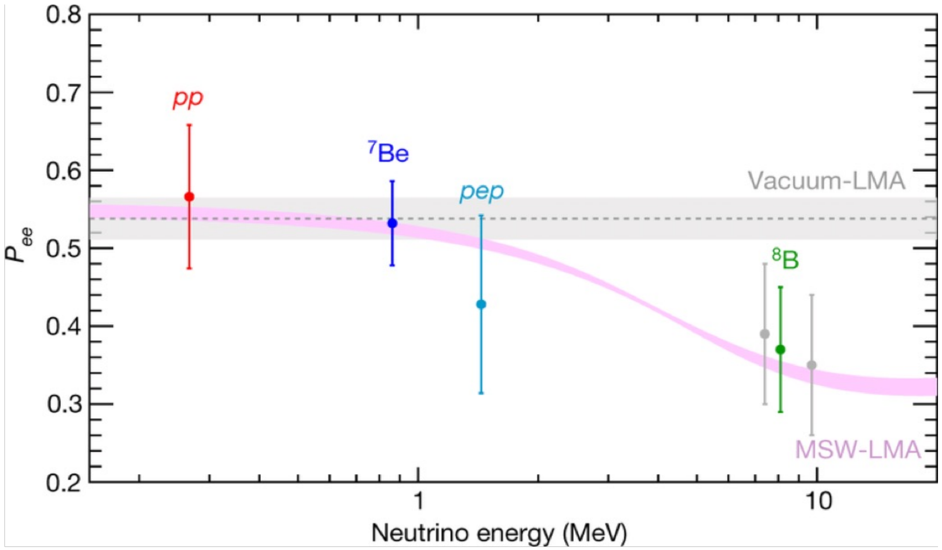


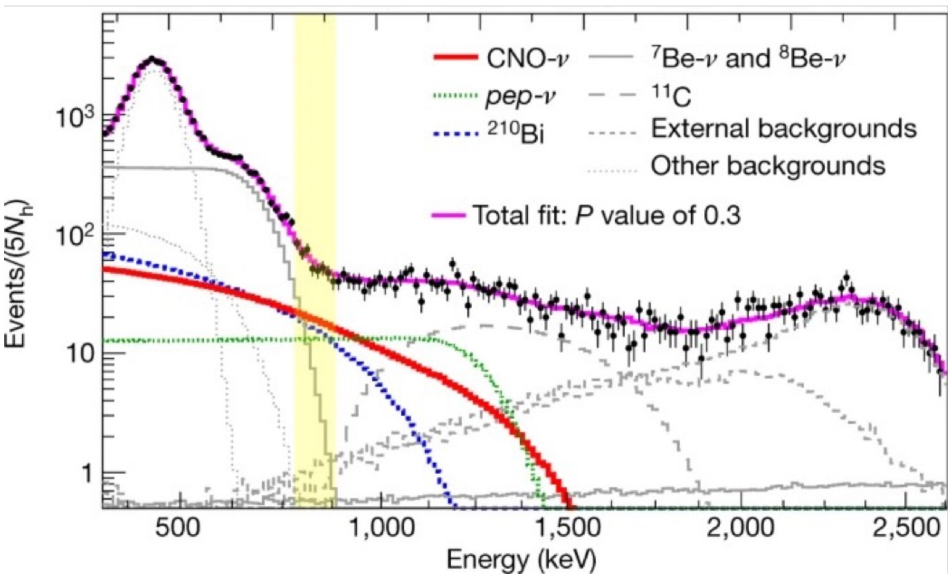
Fit of residual energy spectrum

- Fit of known energy spectra of **neutrino signal** and **radioactive backgrounds** on the acquired **data spectrum**
- expected neutrino rate:
  ~1 event per day and ton
- required radioactive purity:
  < 10^{-16} g/g uranium+thorium in LS



Borexino results on solar neutrinos



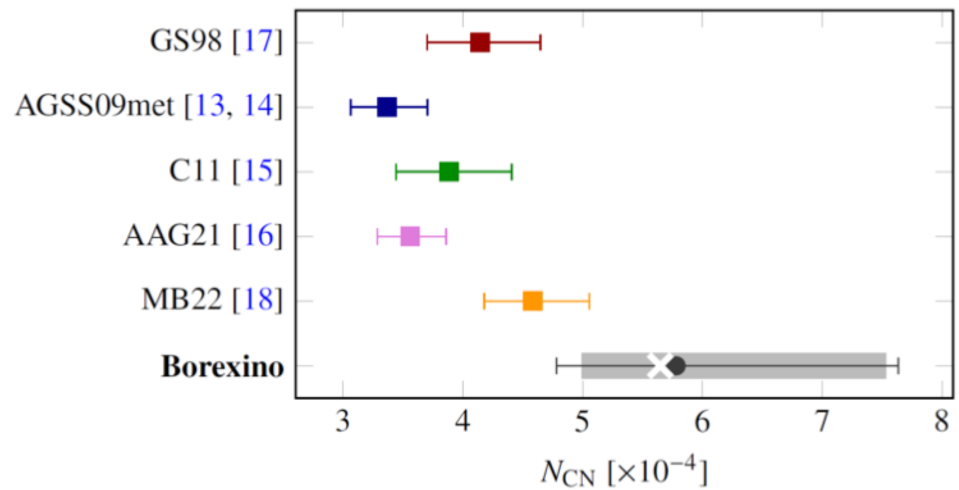


- 2007-2014: ν rate measurements of (almost) all branches of pp-chain

→ confirmation of SSM and vacuum/matter oscillations

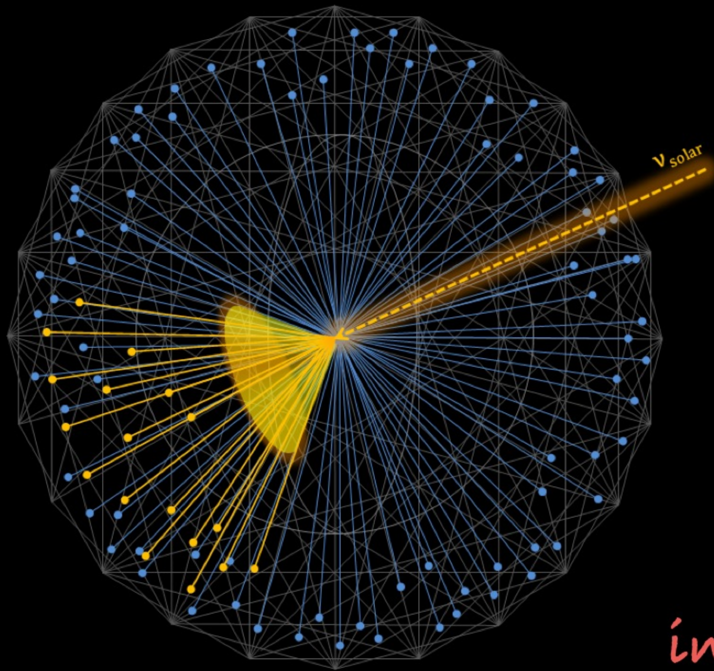
- 2020: first measurement of neutrinos from solar CNO cycle

→ can be related to C,N abundances:

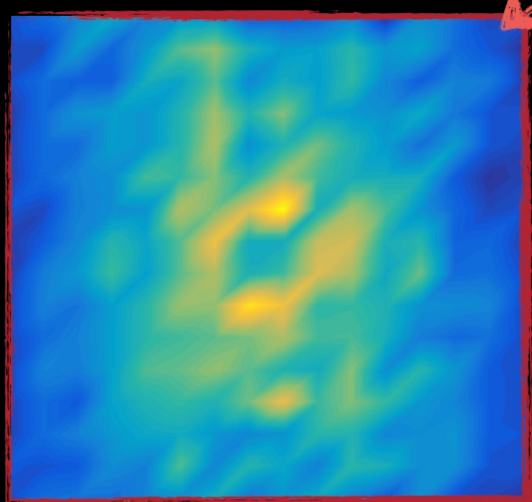


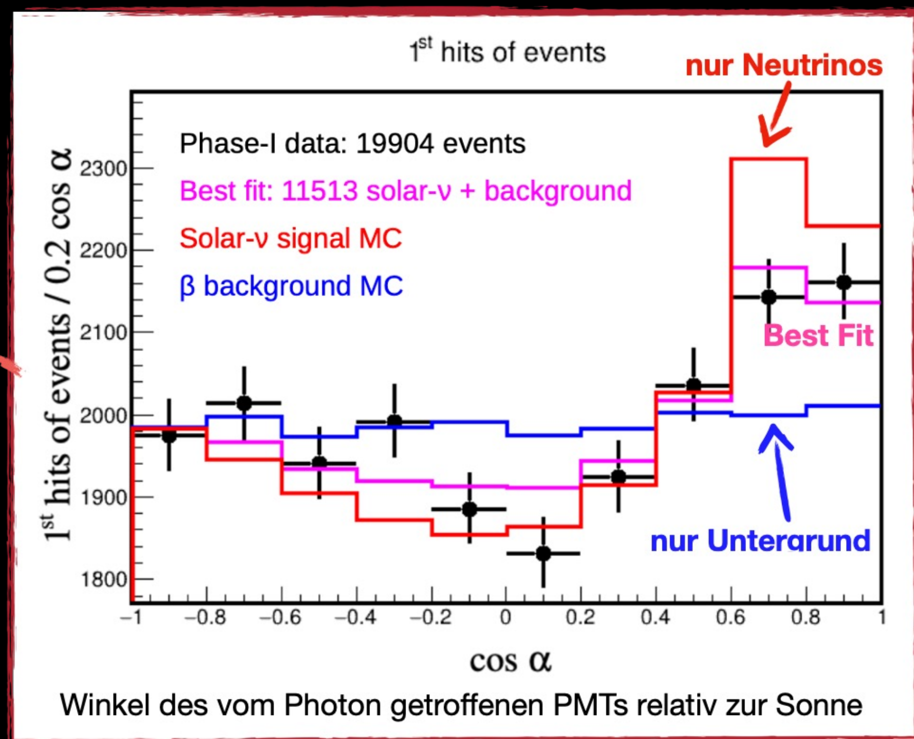
→ Borexino data favors high metallicity

Directional detection of solar neutrinos



- Cherenkov and scintillation signals of electron recoils are superimposed in the detector
- Cherenkov signal too weak to be recognized event-by-event, but superimposed angular hit distributions of many events makes surplus Cherenkov ring visible!



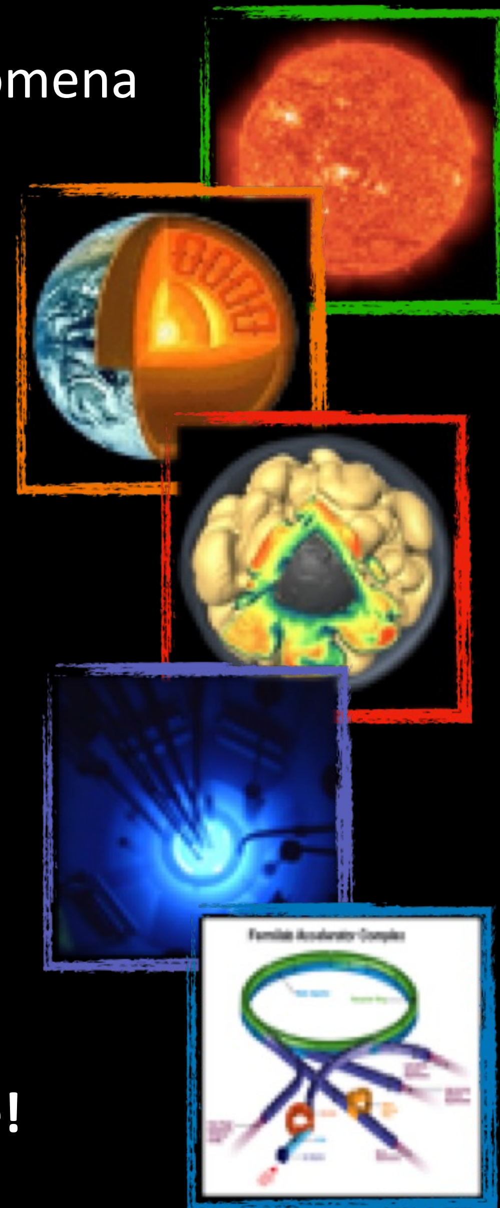


→ future: hybrid Cherenkov/scintillation detectors

Summary of Lecture 3

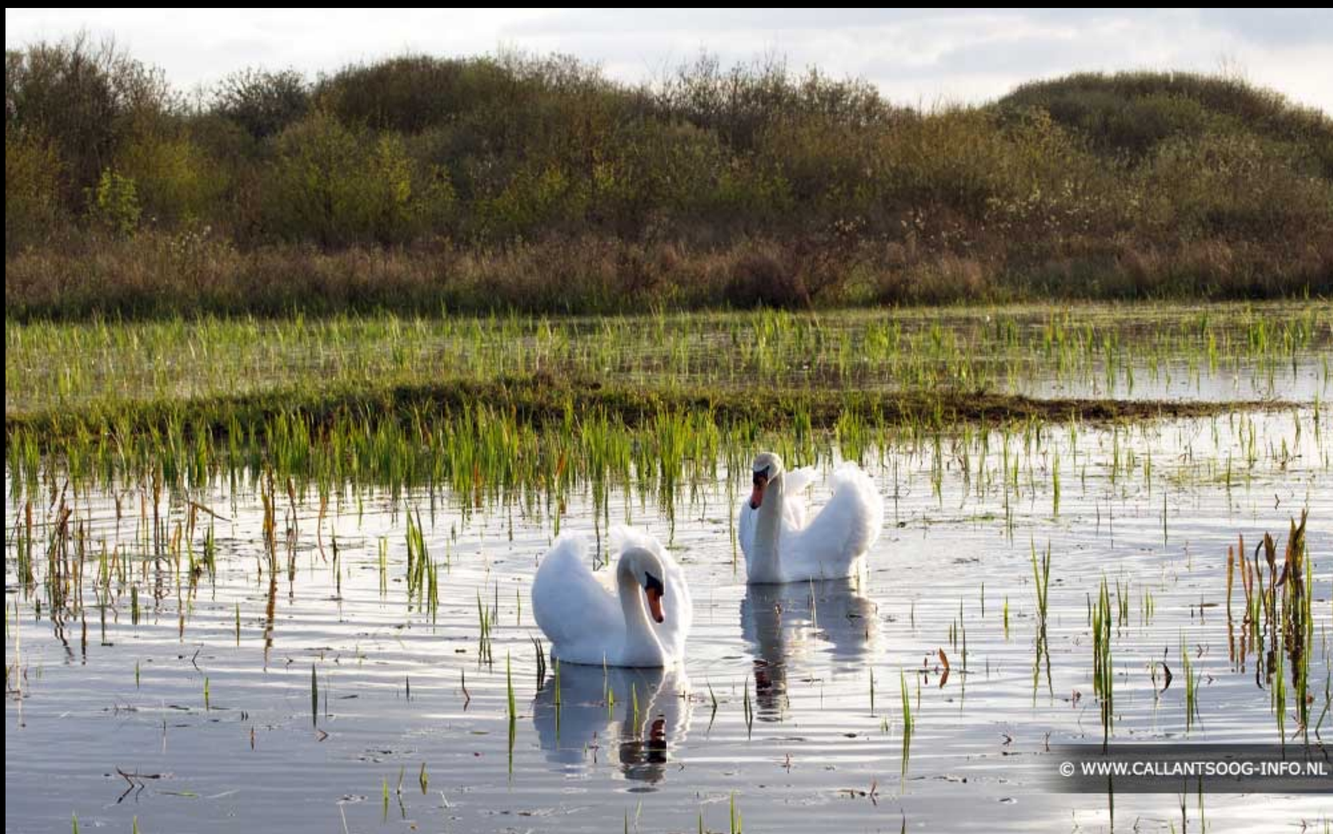
- Neutrinos are unique messengers of astrophysical phenomena
- Different sources (energies, distances, fluxes) require different detection strategies
  - Low energies: Cherenkov, scintillator, liquid argon
  - High energies: large natural water volumes
- Most neutrino experiments are multi-purpose machines, i.e. can study astrophysical sources and ν properties
- Multimessenger observations with optical telescopes, gamma-rays, GWs are still in an early phase

→ (hopefully) many discoveries to come!



LECTURE QUIZ

And the solution word is ...



Thanks for your attention!

Which of the following would be brighter, in terms of the amount of energy delivered to your retina:

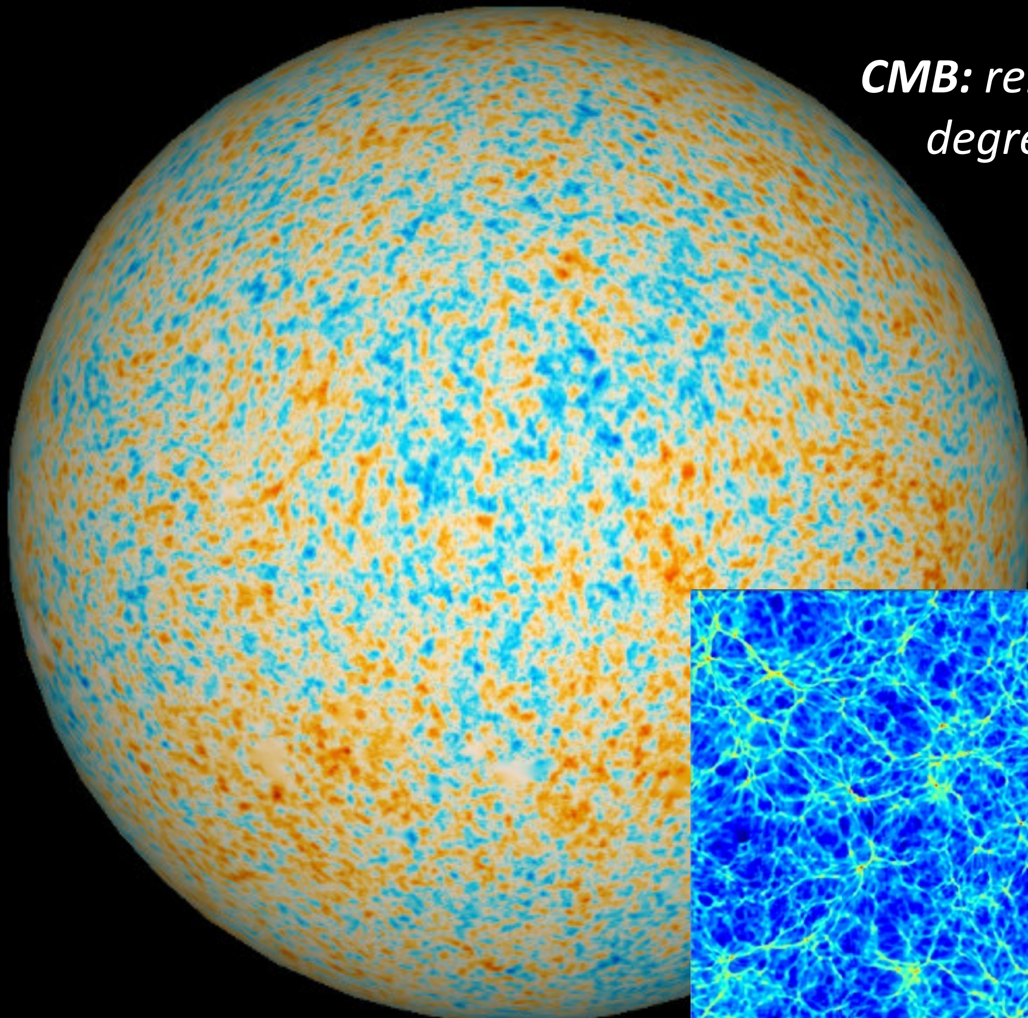
1. A supernova, seen from as far away as the Sun is from the Earth, or
2. The detonation of a hydrogen bomb ***pressed against your eyeball?***

Applying the physicist rule of thumb suggests that the supernova is brighter. And indeed, it is … by ***nine orders of magnitude***.

Questions?

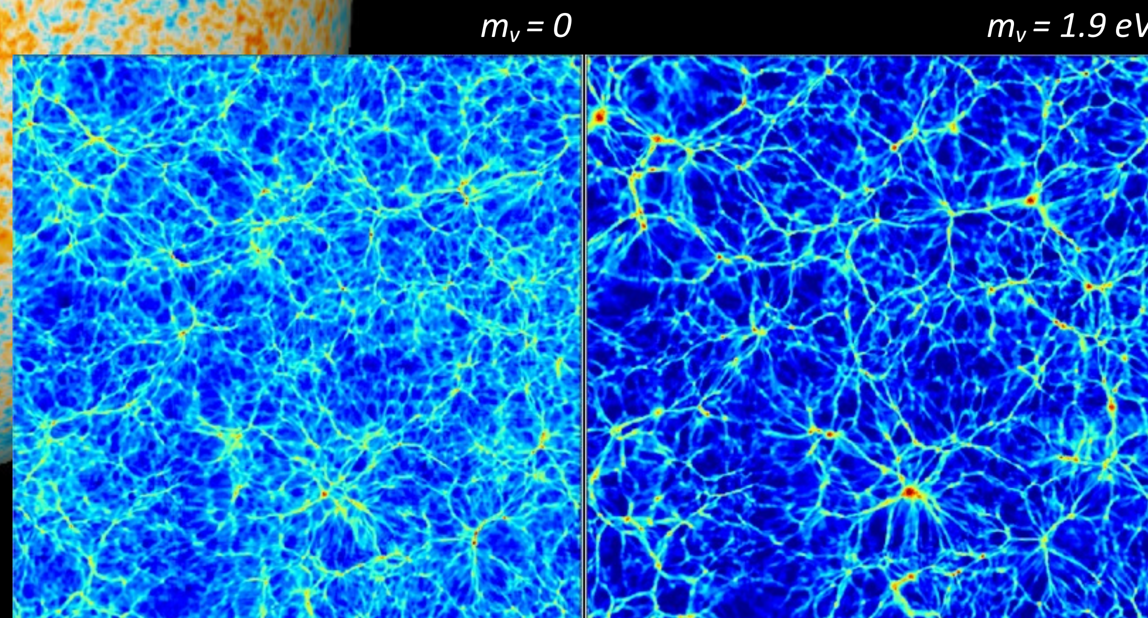
Backup

In conflict: Cosmology



CMB: *relativistic degrees of freedom*

Structure formation: *hot dark matter*



Cosmological constraints on light steriles

Planck, 1502.01589

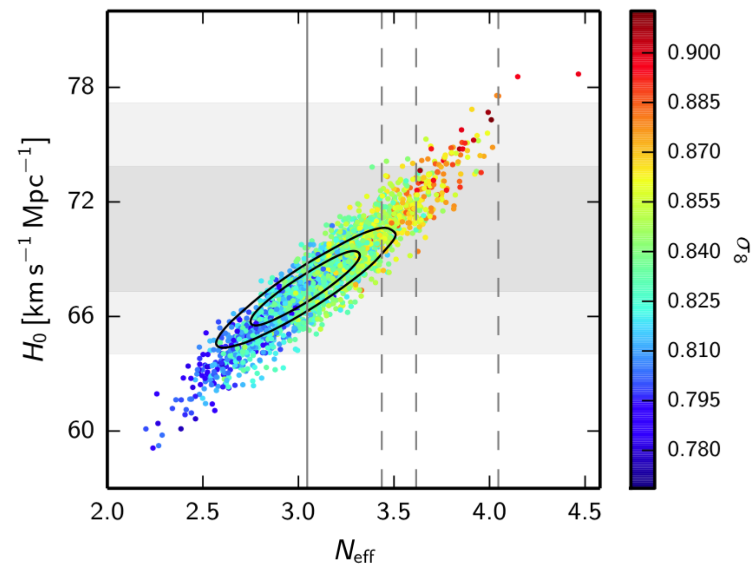
- Cosmological observations able to place stringent bounds on the **number** N_{eff} and **mass sum** Σm_ν of light (i.e. thermalizing) sterile neutrinos

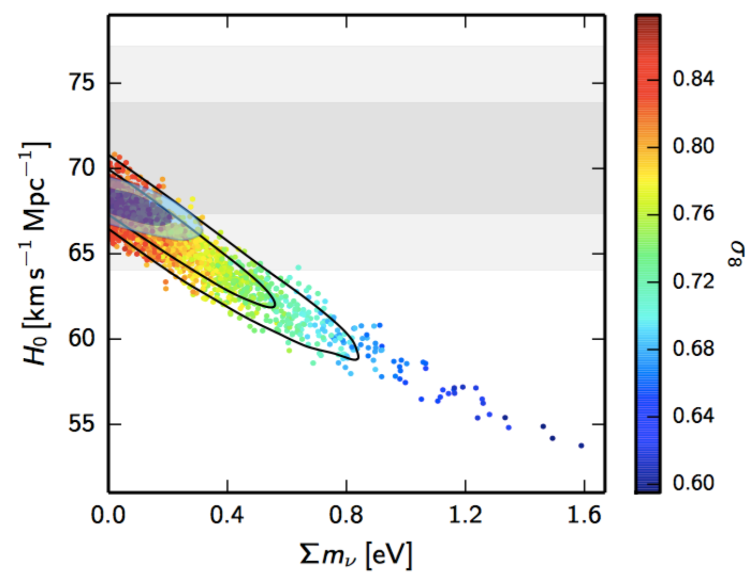
- Most important observables
  - Cosmic Microwave Background
  - Big Bang Nucleosynthesis
  - Large-scale structure

- Bounds from PLANCK (+BAO):
  - $N_{eff} = 2.99 \pm 0.20$
  - $\Sigma m_\nu < 0.49$ (0.17) eV (95% C.L.)

- These limits can be avoided by introducing additional physics, e.g. sterile neutrino self-interactions
  Dasgupta, Kopp [arXiv:1310.6337]

→ still, accommodating sterile ν's needs tuning ...

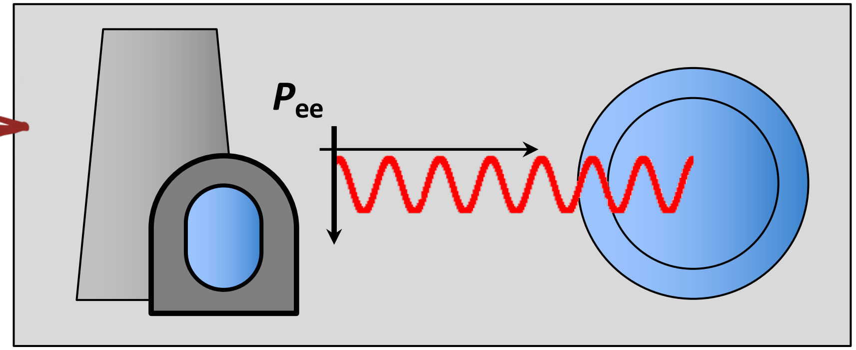




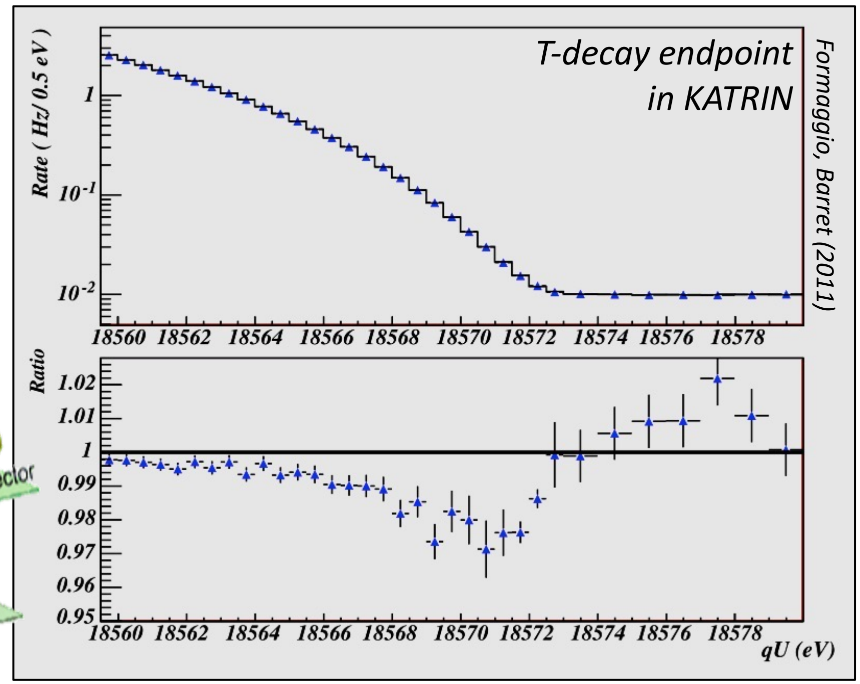
Testing the short-baseline anomalies

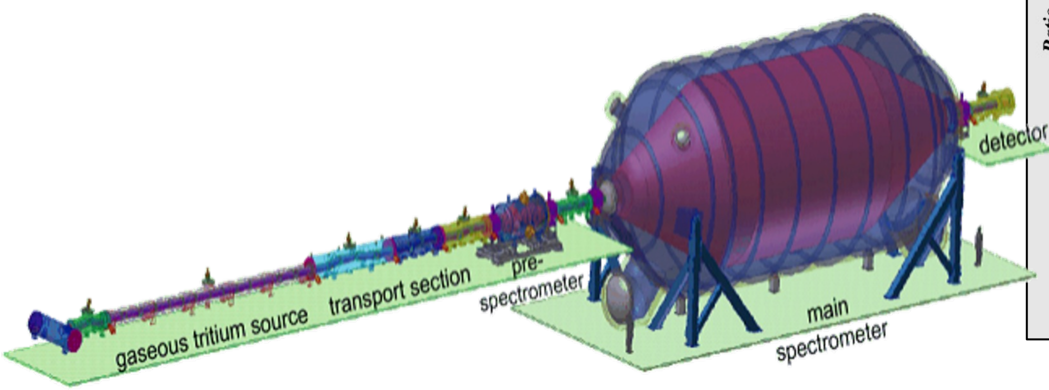
Experimental approaches

- very-short baseline experiments for observing $\nu_e \rightarrow \nu_s$ oscillation disappearance pattern



- β-decay ν mass experiments to find spectral deformation from eV-mass eigenstate ν_4

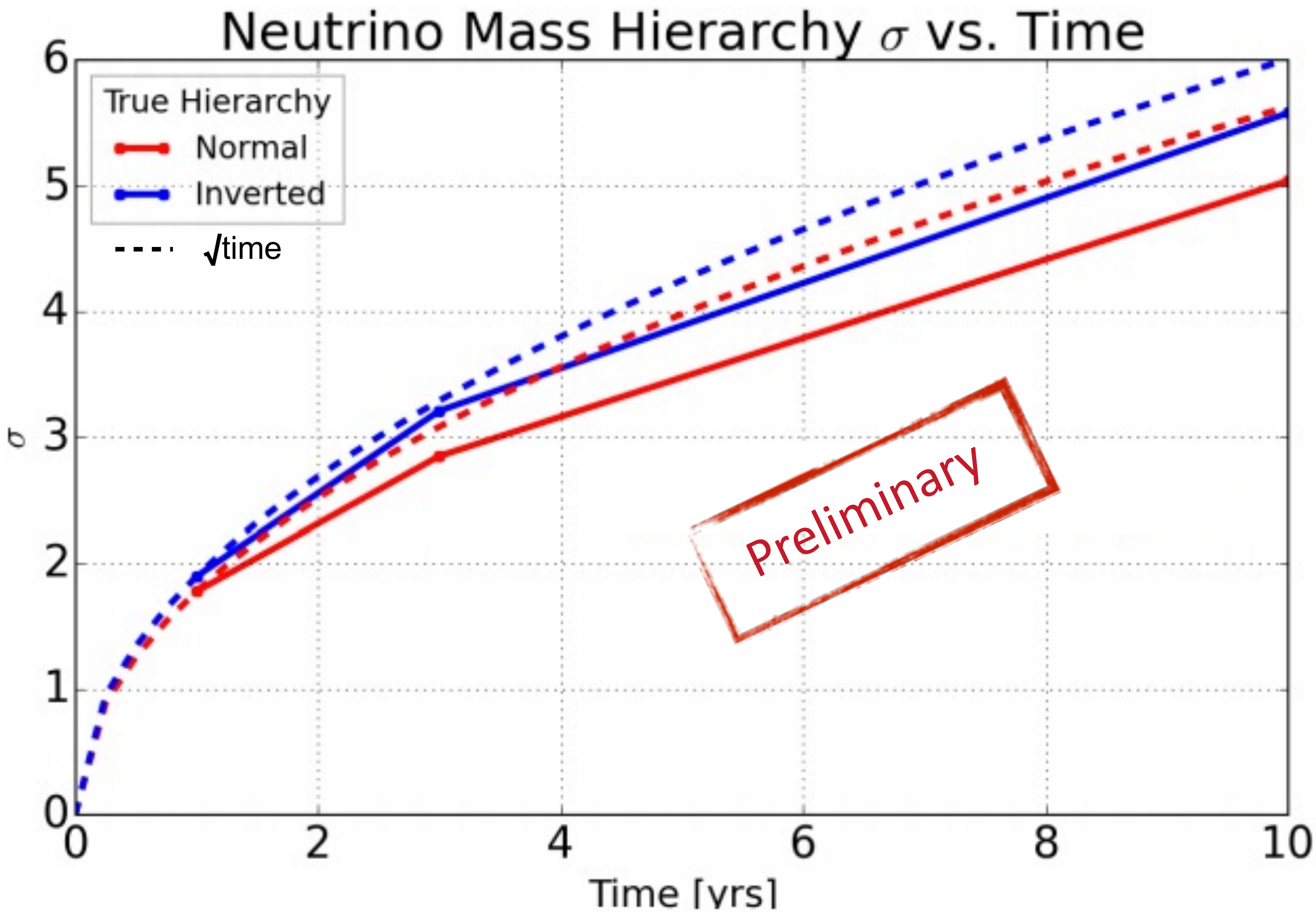




Expected sensitivity

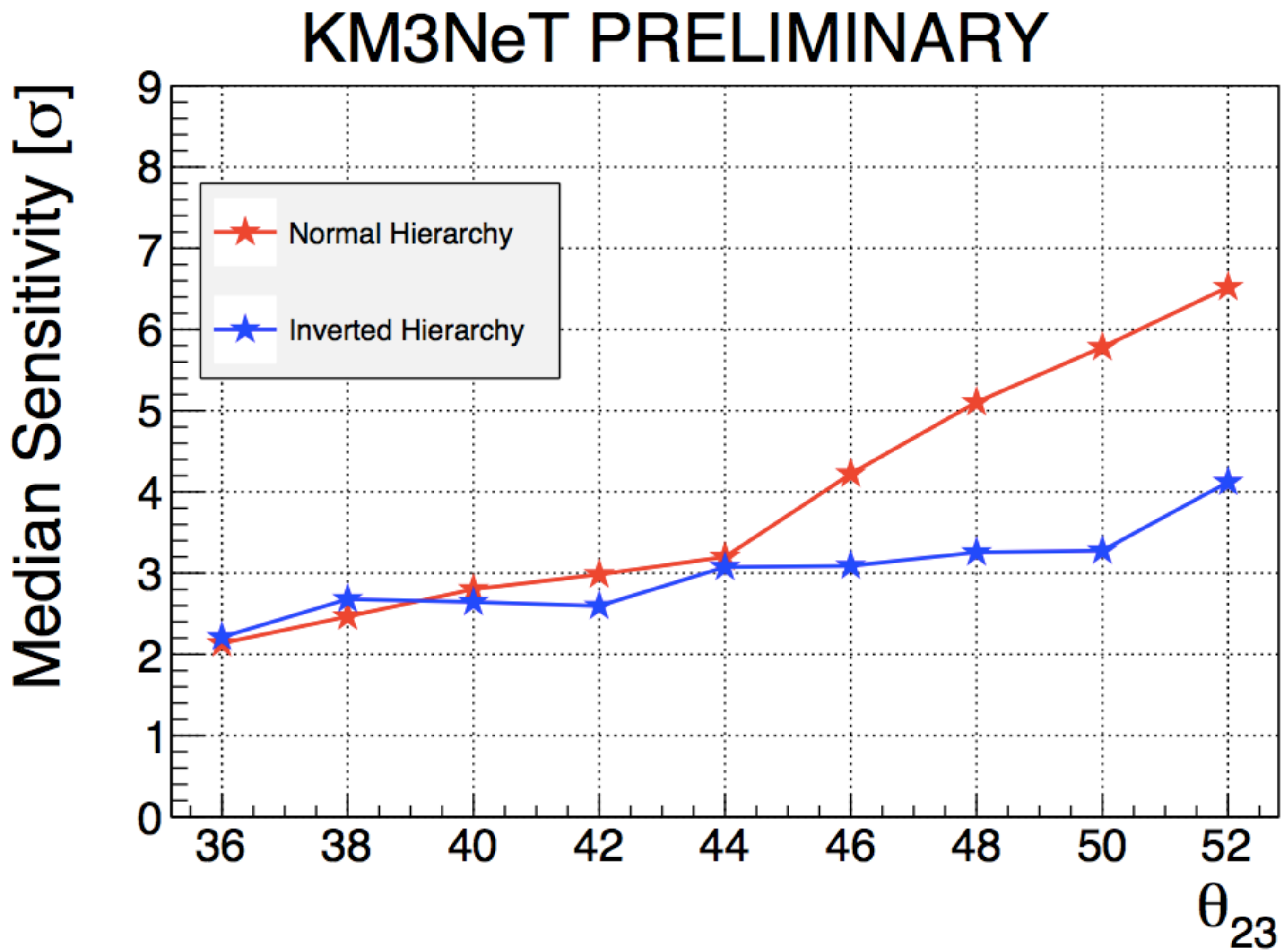
Sebastian Böser

PINGU

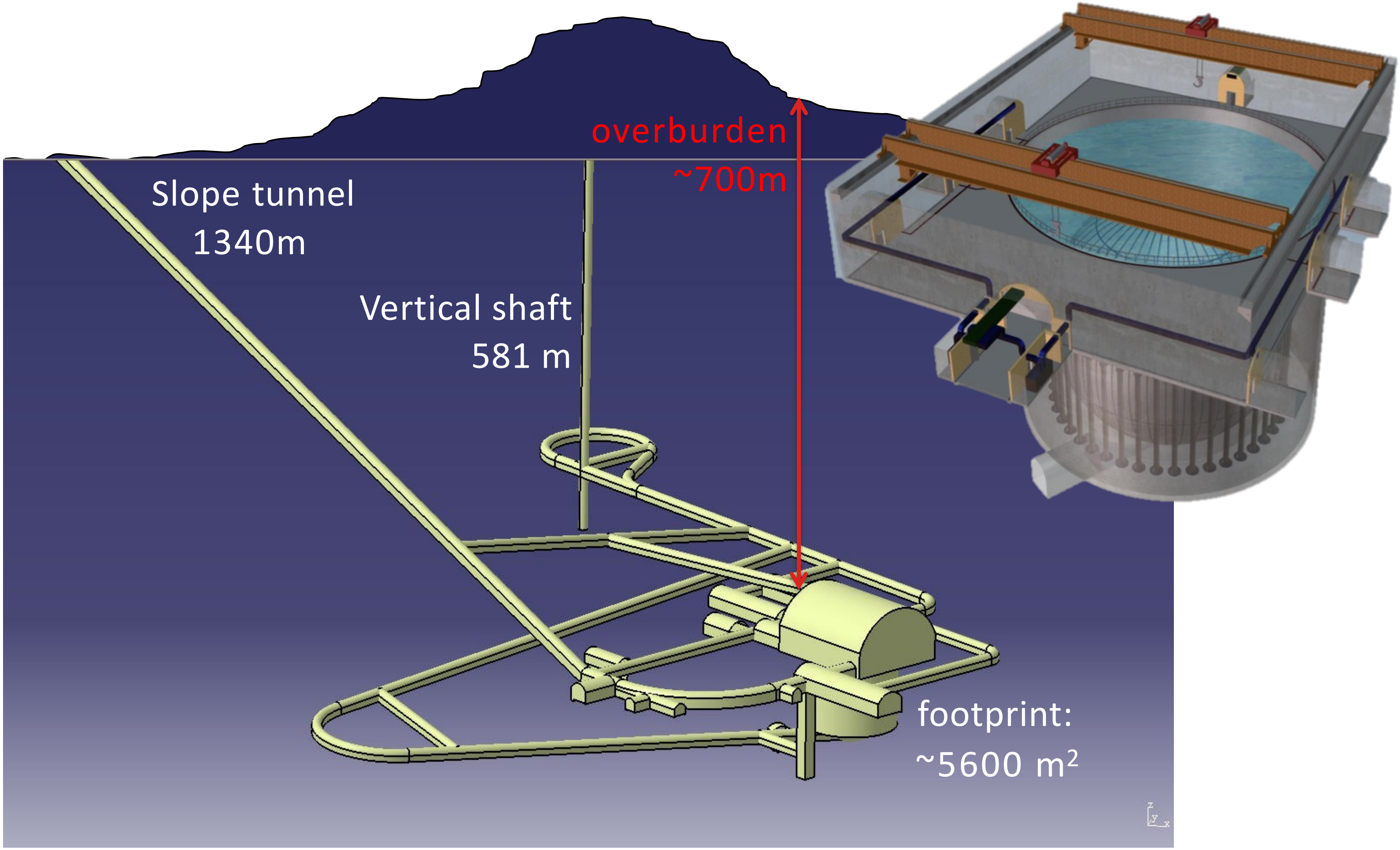


Expected sensitivity

ORCA: δ_{CP}=0, after 3 years

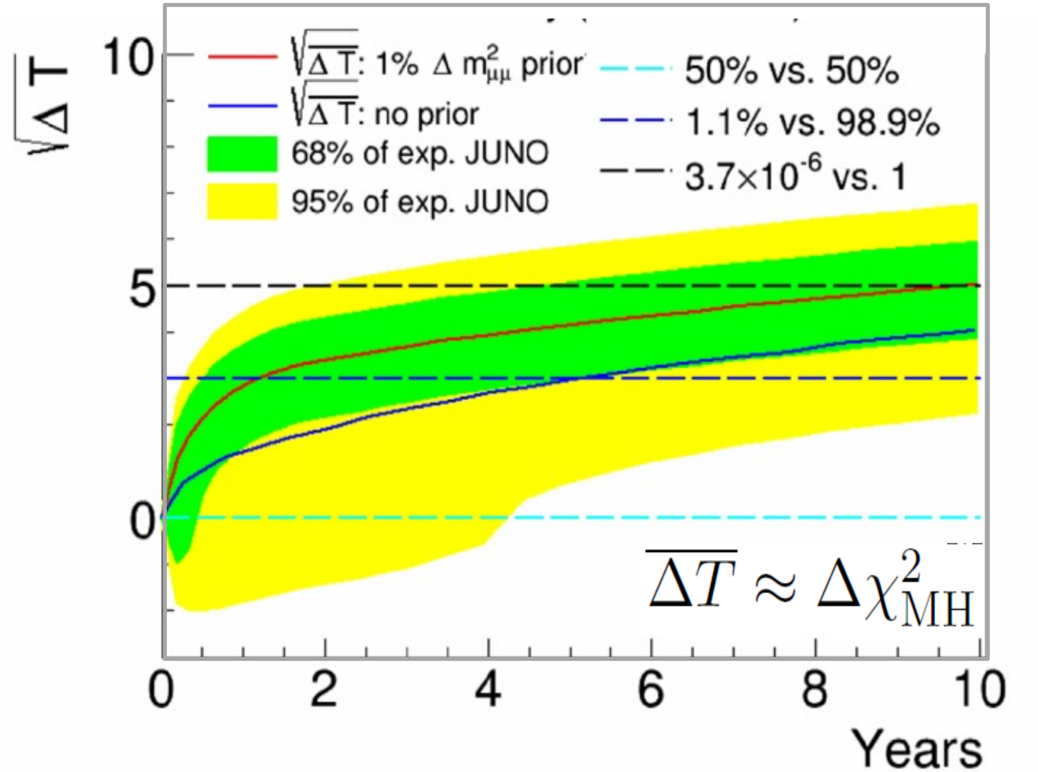


JUNO Underground Laboratory



JUNO Sensitivity

JUNO Yellow Book



central factors:
- E resolution: 3% at 1MeV
- statistics: 100,000 ev

Factors	$\Delta\chi^2$
Statistics only	+16
different core distances	-3
reactor background	-1.7
spectral shape	-1
S/B ratio (rate)	-0.6
S/B ratio (shape)	-0.1
information on $\Delta m^2_{\mu\mu}$	+8

JUNO's expected sensitivity level

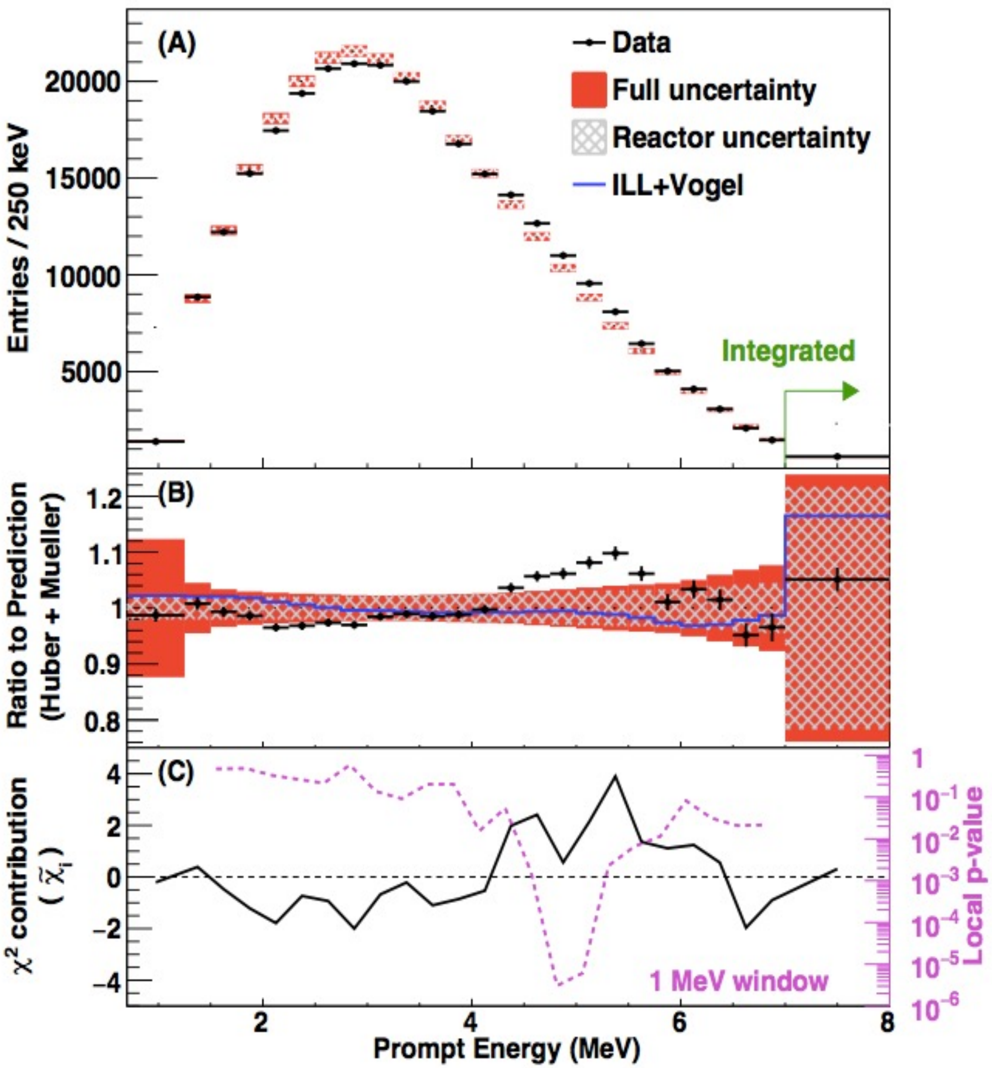
(assuming 3% energy resolution)

- JUNO alone based on 6 years: ~3σ

\+ precise data by T2K/NOvA on $\Delta m^2_{\mu\mu}$: **4σ**

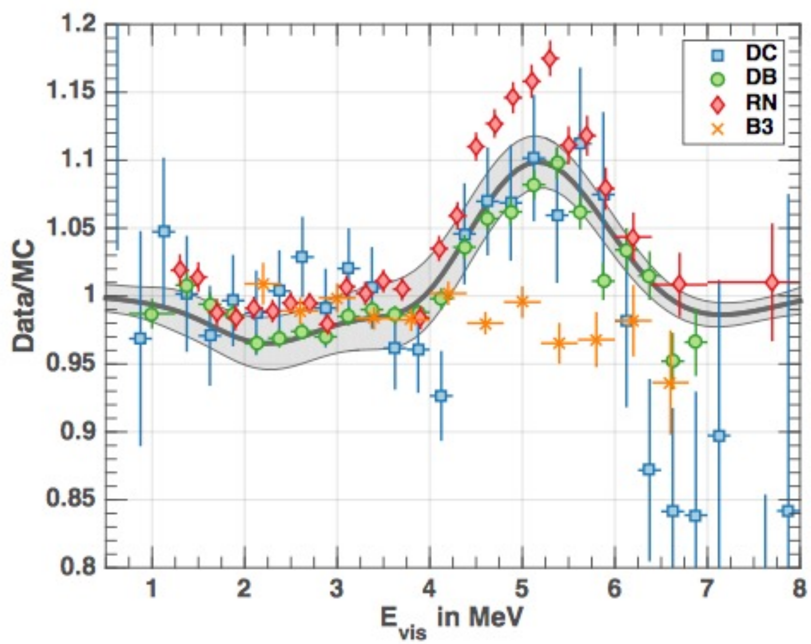
New doubts on understanding of sources 1/2

Daya Bay Near Detector spectrum



- Short-baseline θ_{13} experiments observe a deviation from spectral prediction: „5 MeV bump“
- unknown feature in reactor neutrino spectrum?
- detector calibration issue?

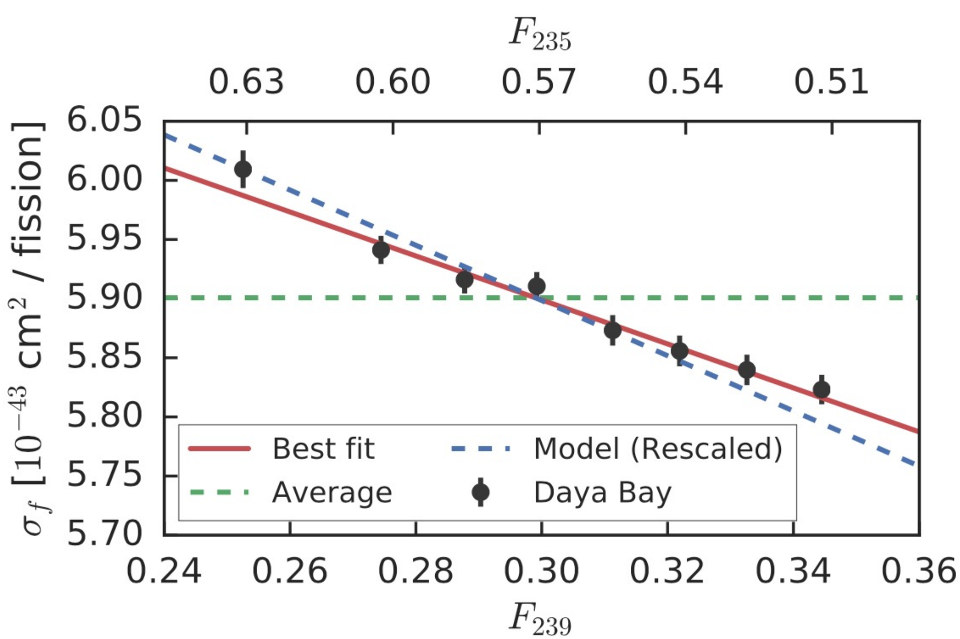
Comparison of experimental spectra

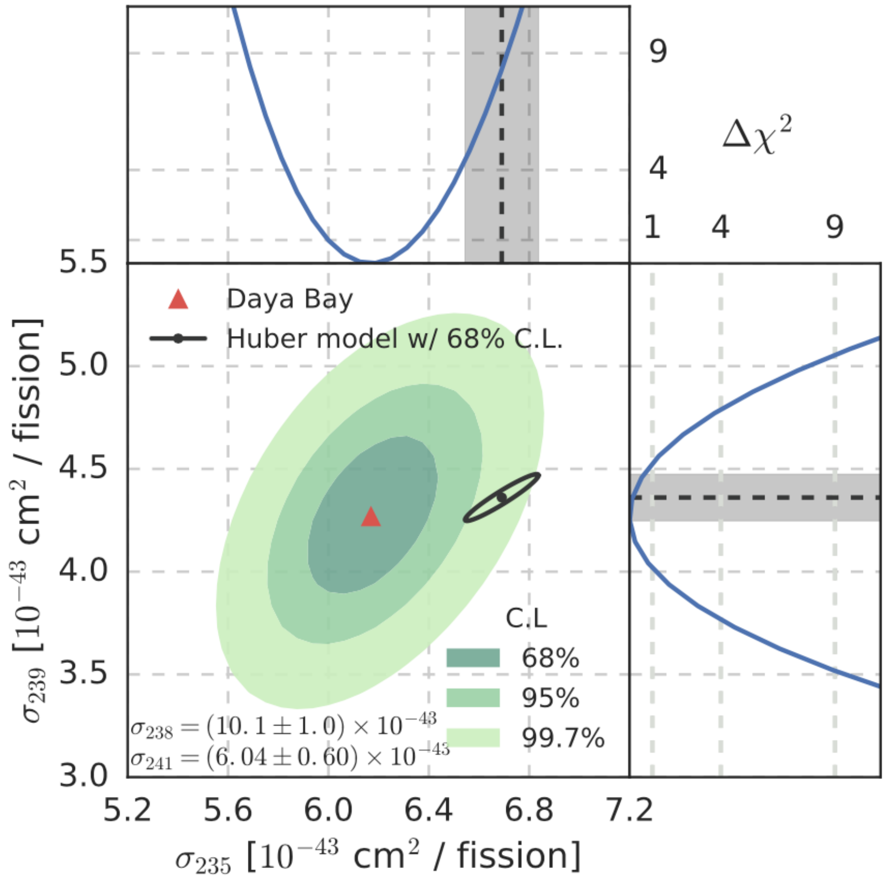


New doubts on understanding of sources 2/2

- **Daya Bay:** dependence of anti-neutrino reaction rates on reactor-burn up shows discrepancy for ^{235}U energy-integrated ν cross-section
- energy-resolved data is inconclusive

IBD rate dependence on core composition





Corresponding energy-integrated X-sections

Gallium anomaly

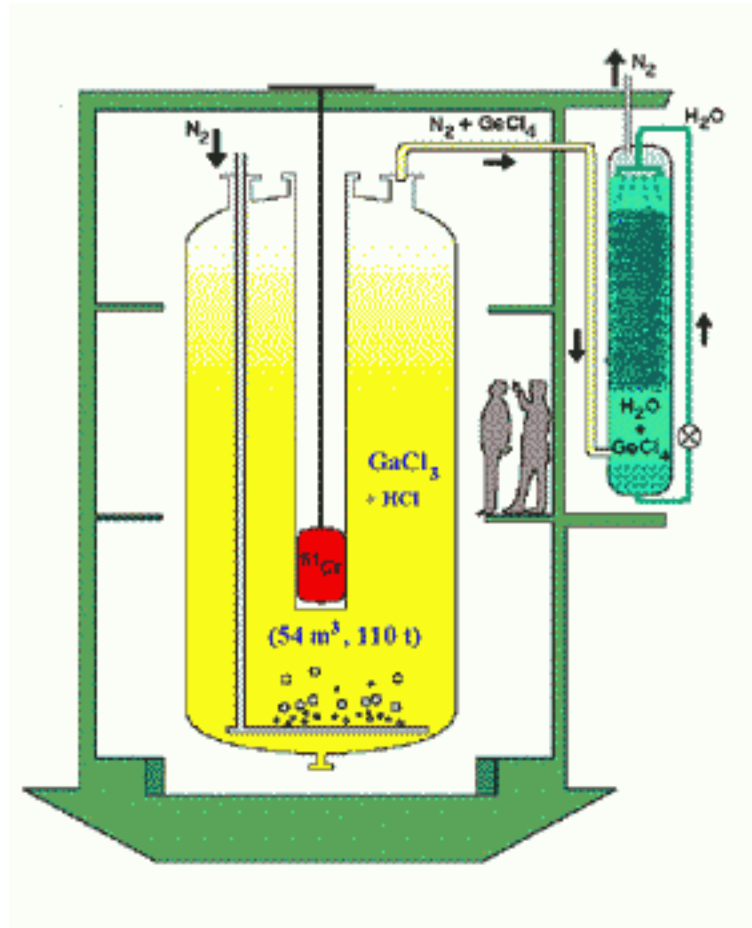
Guinti, 1204.5379

Radioactive ν_e sources inserted in solar radiochemical detectors.

Idea: Test detection efficiency, cross sections etc. for solar ν's.

$$\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-$$

Exp	Source	Ratio (Exp/Th)*
Gallex	^{51}Cr	0.95 ± 0.11
	^{51}Cr	$0.81\ ^{+0.10}_{-0.11}$
SAGE	^{51}Cr	0.95 ± 0.12
	^{27}Ar	0.79 ± 0.08
total		0.86 ± 0.05

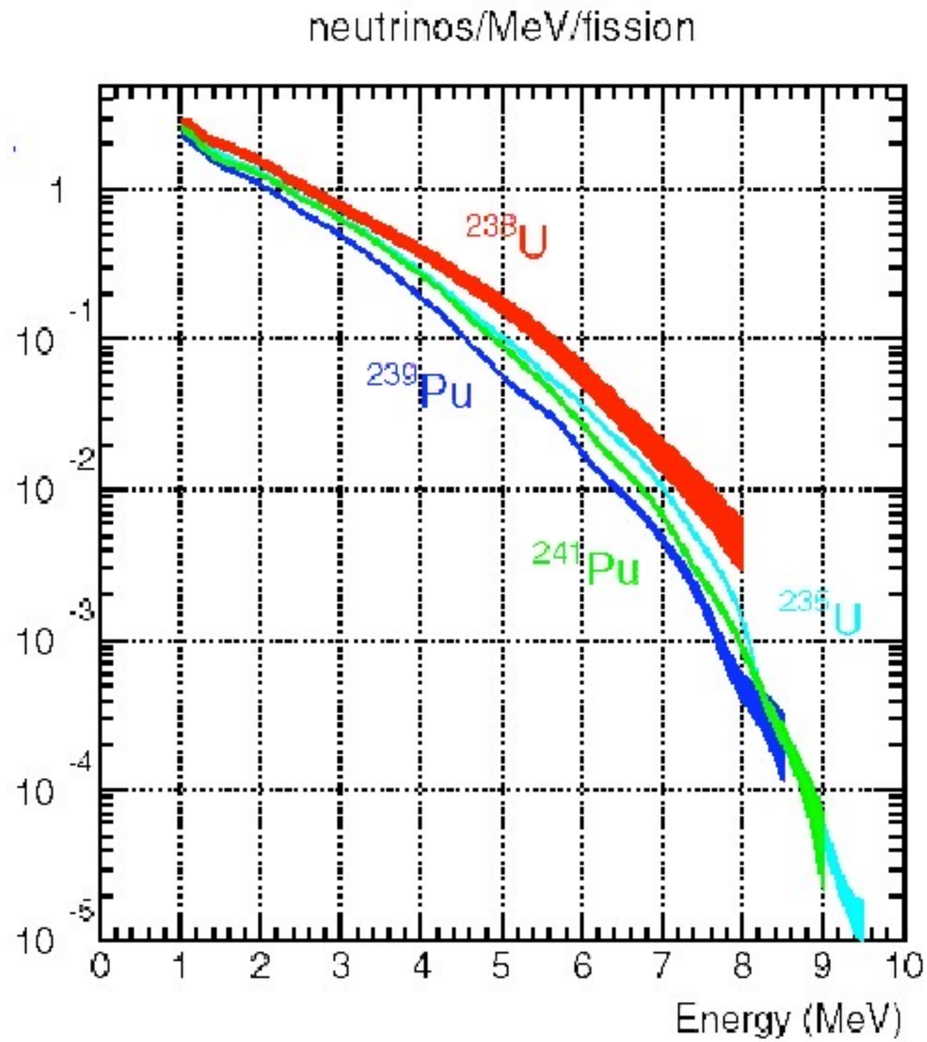


→ compared to prediction, 14% rate deficit observed (2.8σ)

* *cross-sections as calculated by Bahcall*

Reactor antineutrino spectrum

- Four relevant fission elements
  - ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu
  - variable with fuel burn-up
- Effective spectrum from overlaying β-spectra of many fission products
- ν-spectra from spectral inversion of β-decay electron spectra
  - BILL measurements at ILL commonly used reference [arXiv:1405.3501]
- ab-initio calculations of neutrino spectrum very challenging
  fission yields → decay chains → spectra



Re-evaluation of reactor spectrum

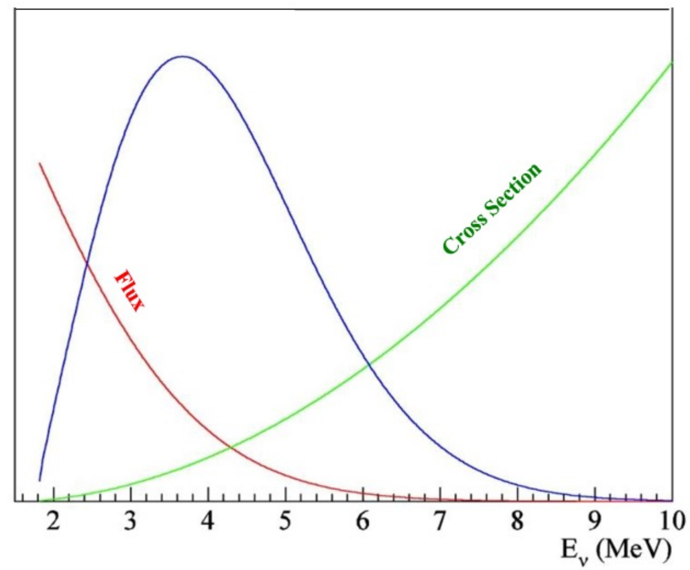
Mueller et al., 1101.2663
Sterile WP, 1204.5379

2011: new spectrum by **Mueller et al.**

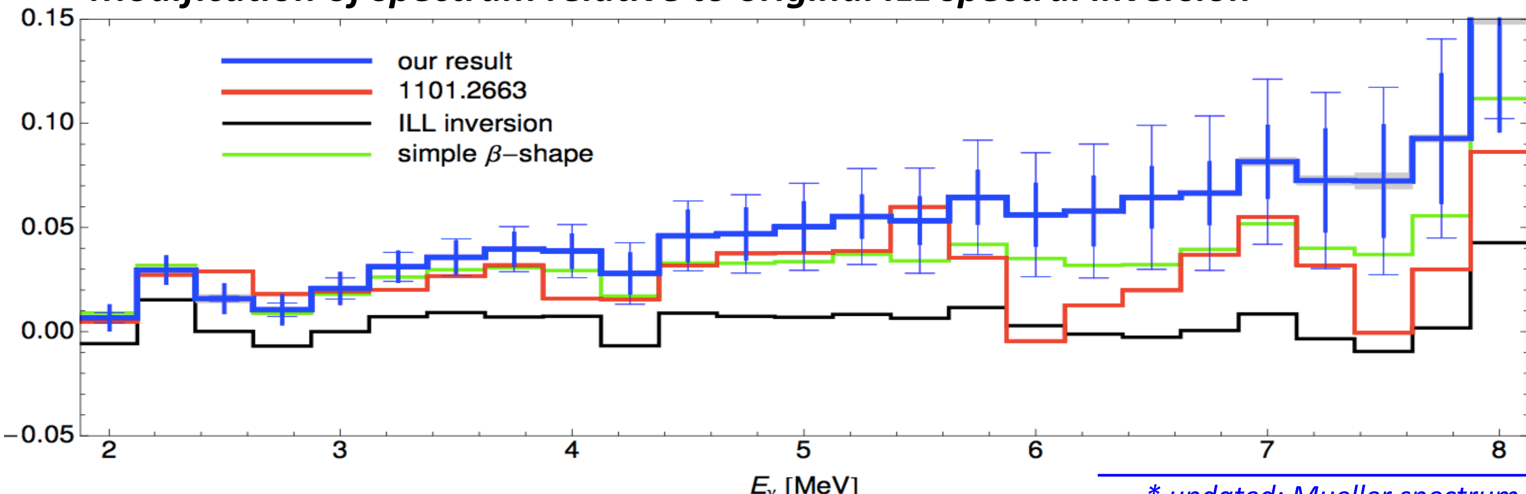
- revision of ILL spectral conversion: *90% ab initio + 10% virtual branches*
- other factors (weak magnetism, $\tau_{neutron}$)

→ **ν spectrum shifts to higher energies**

→ increase of expected rates by ~5% for all reactor neutrino experiments



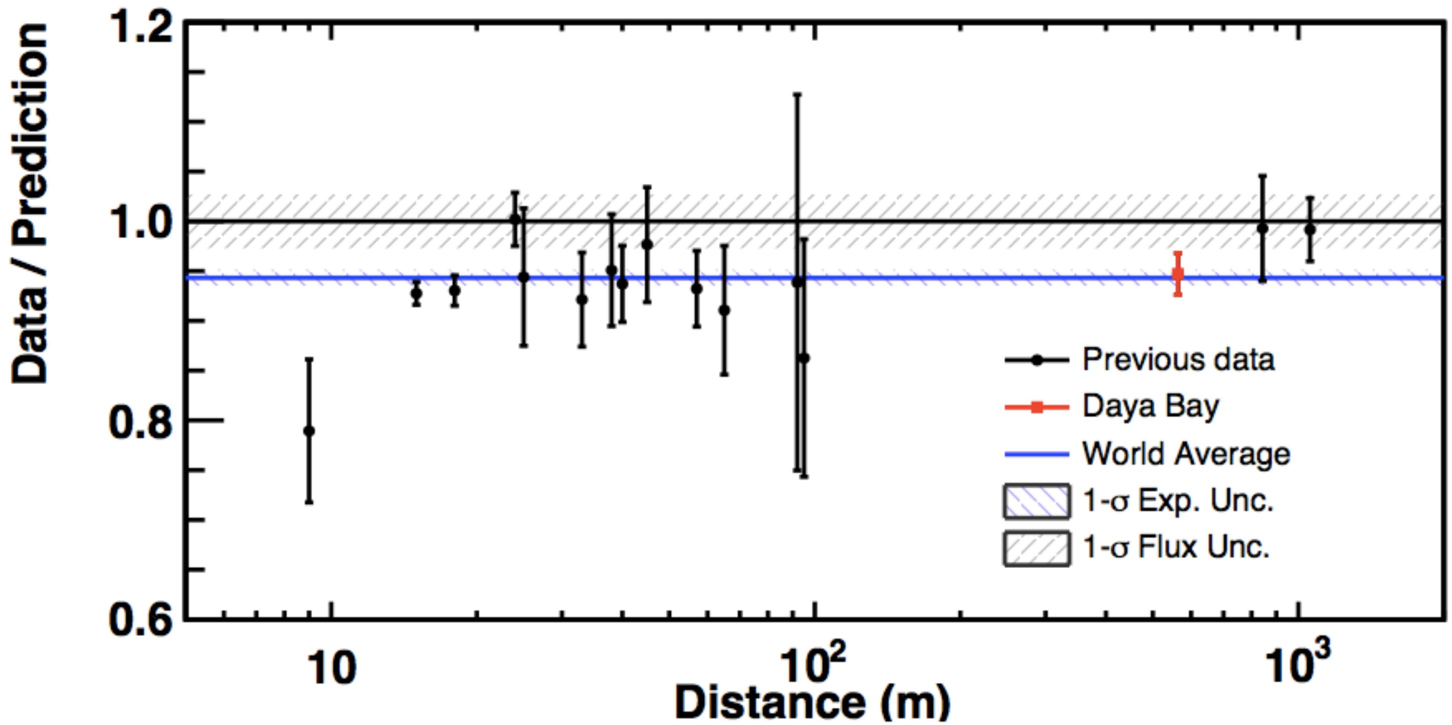
Modification of spectrum relative to original ILL spectral inversion



** updated: Mueller spectrum + new correction from Fermi theory (ν_s whitepaper)*

Reactor antineutrino anomaly

Daya Bay, 1508.04233

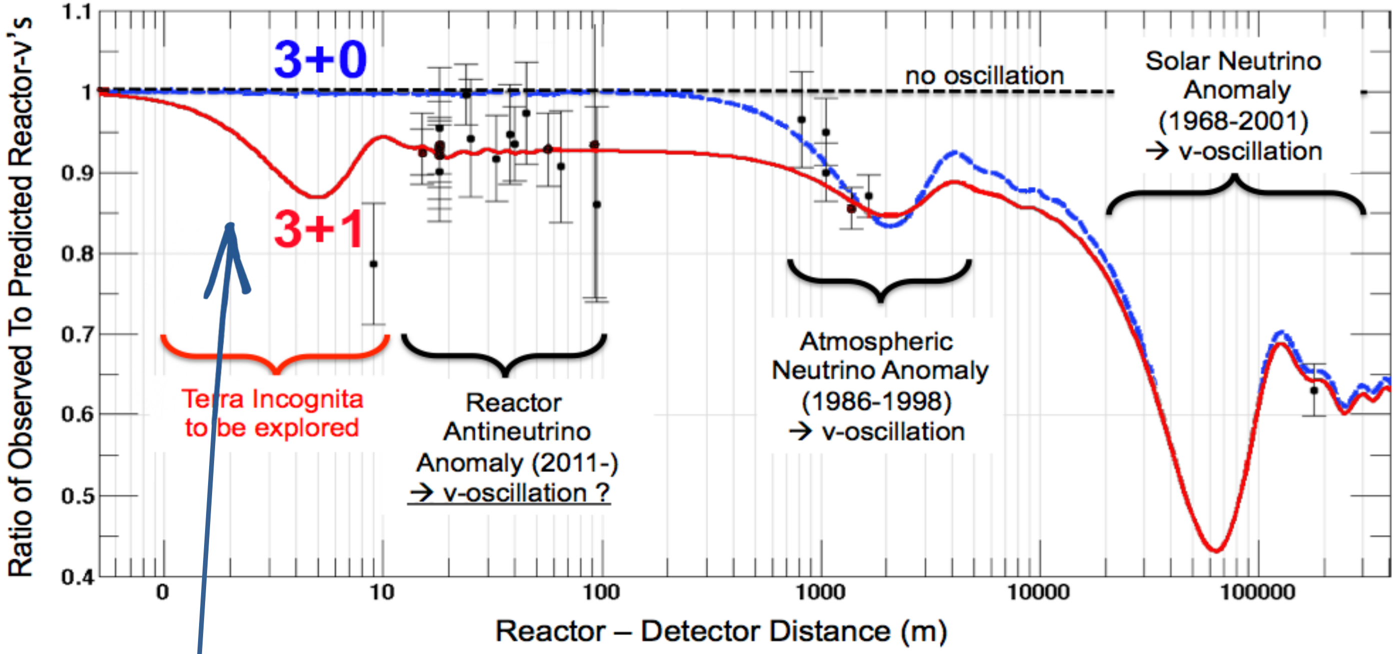


→ average rate of short-baseline (<1km) reactor neutrino experiments shows 6% deficit compared to expectation!

→ significance: ~3σ

Rate deficit → Sterile ν oscillations?

Lasserre



→ possible interpretation in terms of very short-baseline neutrino oscillations:

$$P = 1 - \sin^2(2\theta_{new})\sin^2\left(\frac{\Delta m^2_{new} L}{4E}\right)$$

→ if so, new Δm² value on the order of 1eV²

→ if so, new flavor state must be sterile

Mixing of (3+1) neutrinos

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{11} & U_{12} & U_{13} & U_{14} \\ U_{21} & U_{22} & U_{23} & U_{24} \\ U_{31} & U_{32} & U_{33} & U_{34} \\ U_{41} & U_{42} & U_{43} & U_{44} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

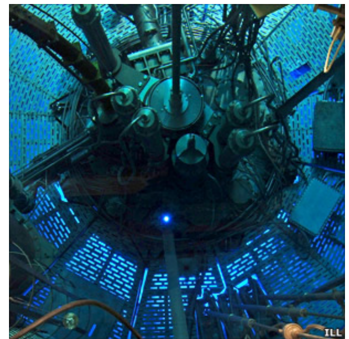
Short-baseline reactor experiments

e.g. STEREO @ ILL Grenoble

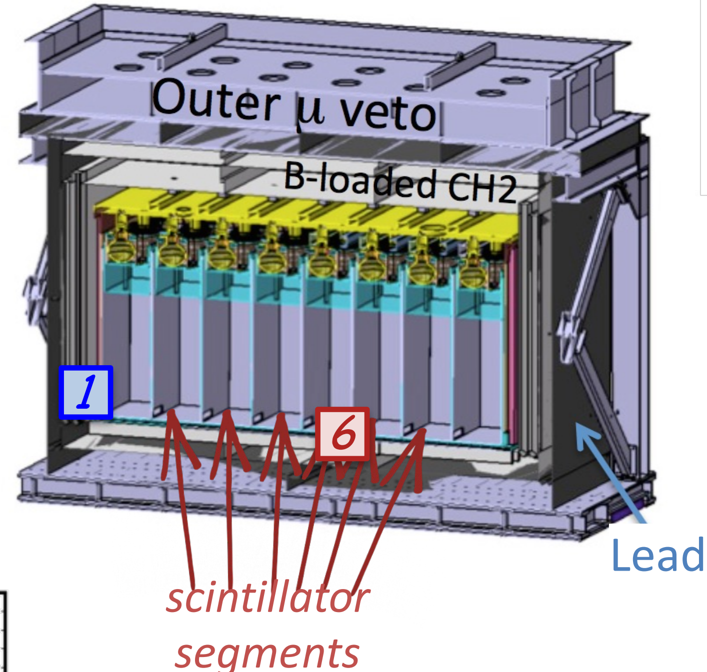
- detector placed close (10m) to compact reactor core (0.8m)
- segmented detector

→ $\bar{\nu}_e$ disappearance from relative spectral deformation

- high background levels

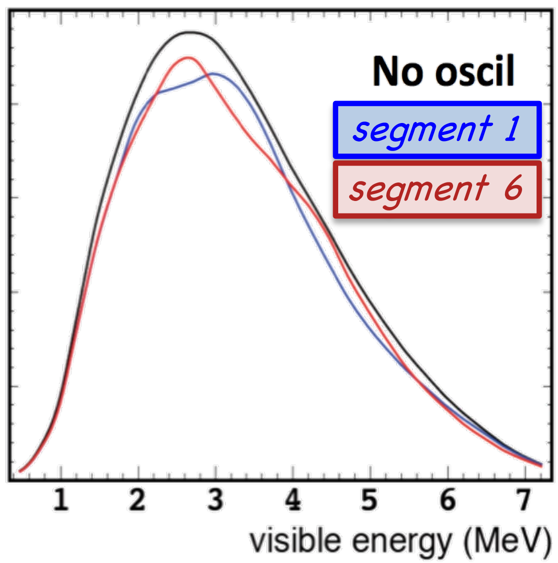


compact reactor core (0.8m)



Many other projects

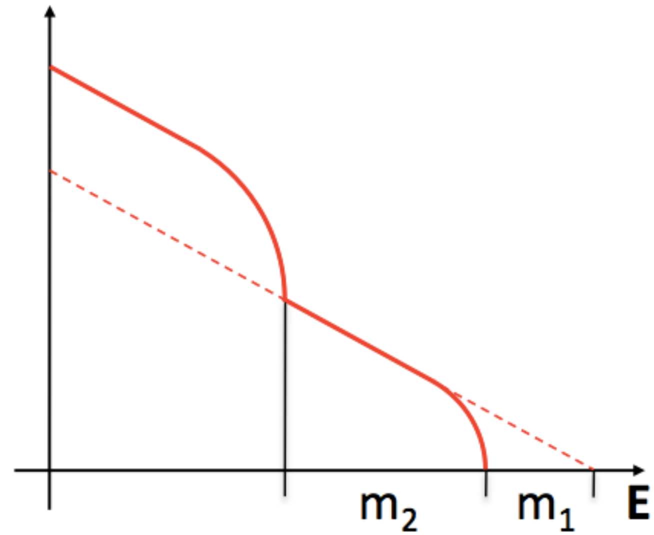
- liquid scintillators:
  NUCIFER (FR)
  Neutrino-4 (RU)
- strips/cubes:
  DANSS (RU)
  PROSPECT (US)
  SOLID (NL)



→ spectral deformation vs. distance (cells)

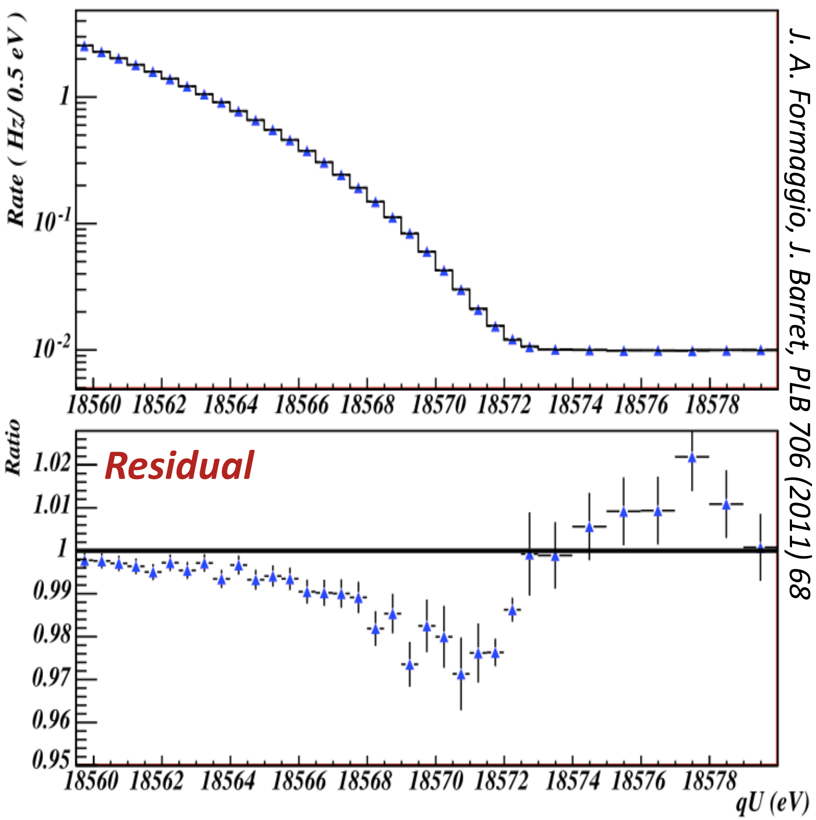
Sterile neutrino search in β-decay

- decay into different mass eigenstates could be distinguished by endpoint measurement
- resolution not sufficient for active ν's: Δm_{31} < 50meV



T decay endpoint:

$\Delta m^2_{41} = 2\ eV^2$, $|U_s|^2 = 0.067$



J. A. Formaggio, J. Barret, PLB 706 (2011) 68

sensitivity to sterile neutrinos

- light steriles: m(ν_4) > 1eV
  large mixing (15%) with ν_e!
  → spectral deformation close to endpoint
- medium steriles: m(ν_4) of $\mathcal{O}$(keV)
  → much larger statistics
  → sensitivity for admixtures $10^{-5} - 10^{-6}$

eV-scale sterile neutrino sensitivity of KATRIN

- "Reactor antineutrino anomaly": $|\Delta m_s^2| > 1.5\ \mathrm{eV}^2, \quad \sin^2(2\theta_s) = 0.14 \pm 0.08 \quad (95\%\ \mathrm{CL})$
- Favoured parameter space can be probed by KATRIN: