



The Next Galactic Supernova: A Multi-Messenger Window into Stellar Collapse and New Physics

Nora Valtonen-Mattila

DEATH OF STARS AND BEYOND

$$E_{tot} \sim 10^{53} \text{ erg}$$

Supra-nuclear
densities

End of star's lifecycle

Nucleosynthesis of
heavy elements

Gives birth to neutron
stars and black holes!

Very very hot
(MeV)

DEATH OF STARS AND BEYOND

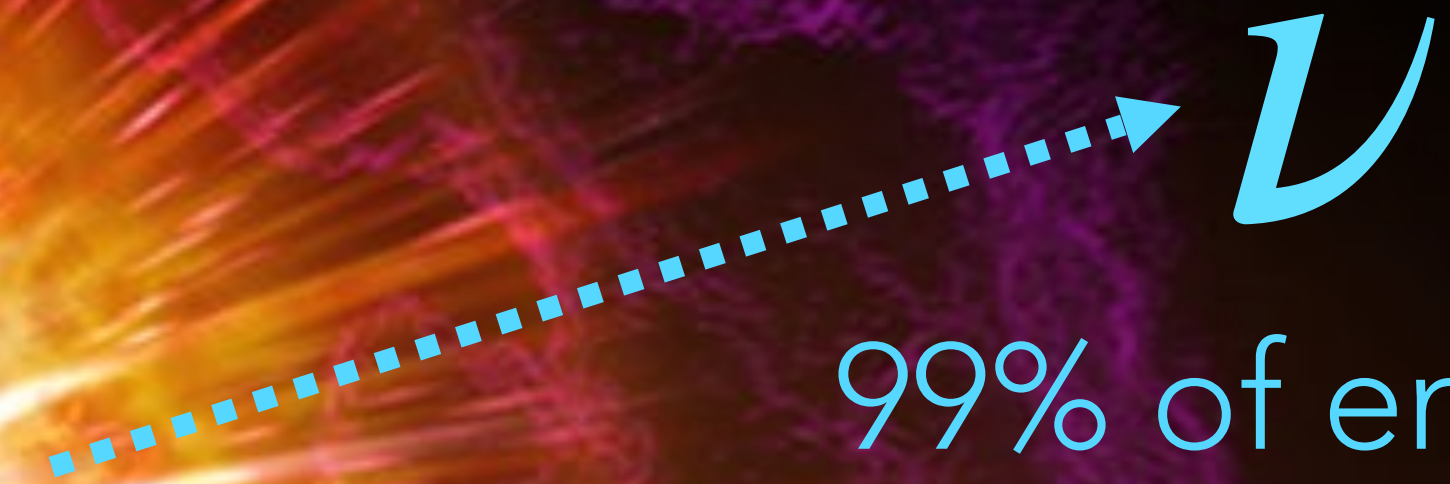
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Supra-nuclear
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99% of energy!
Neutrino luminosity 100
times that of optical

Very very hot
(MeV)

DEATH OF STARS AND BEYOND

$$E_{tot} \sim 10^{53} \text{ erg}$$

Supra-nuclear
densities

End of star's lifecycle

Nucleosynthesis of
heavy elements

**OCCURS ONCE EVERY ~ 40 years in our
Galaxy**

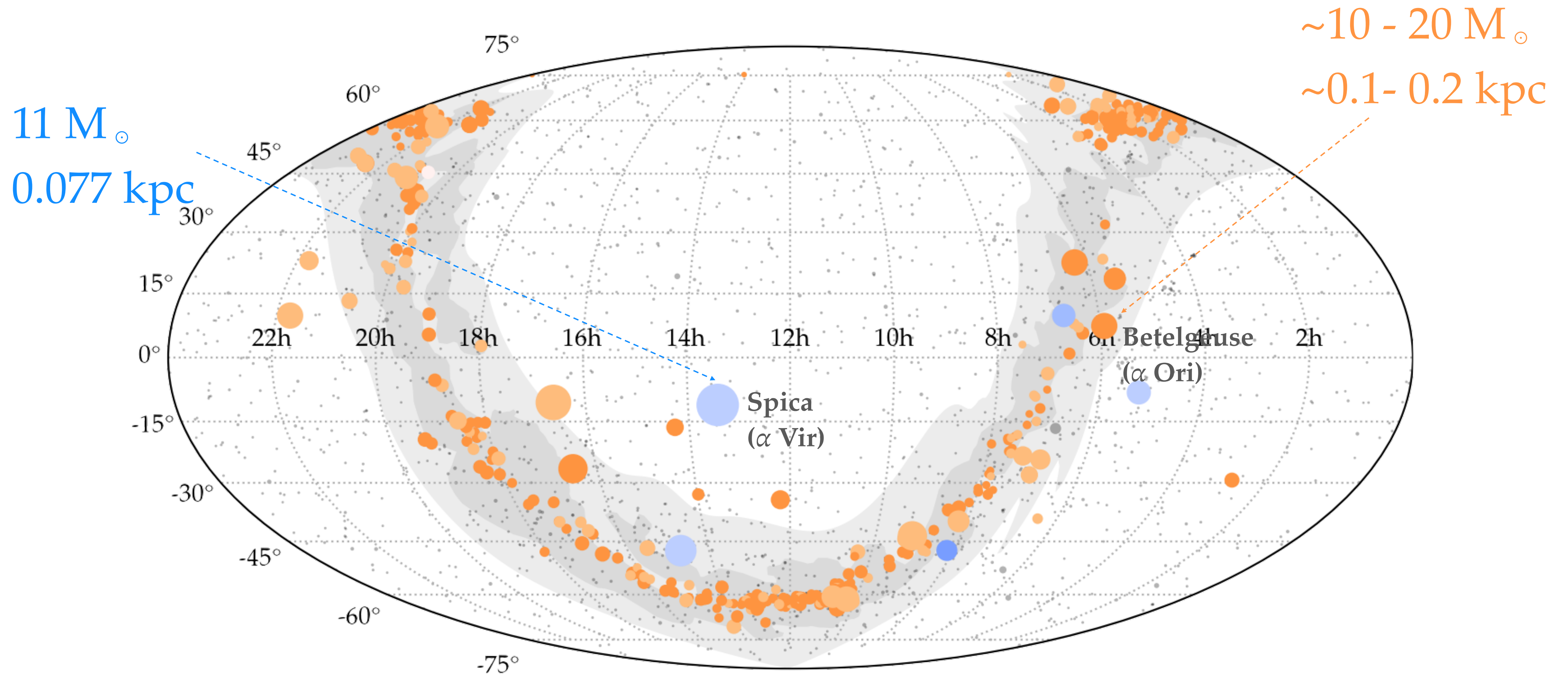
Gives birth to neutron
stars and black holes!

Very very hot
(MeV)

99% of energy!
no luminosity 100
that of optical

ν

VERY NEARBY STARS THAT ARE SN CANDIDATES



See M. Mukhopadhyay+ (ApJ 899:153, 2020), S. Healy+ (MNRAS 529:3630, 2024). [Image credit: SNEWS 2.0.](#)

They all have mass estimates.
Red and blue supergiants

SN 1987A

After explosion



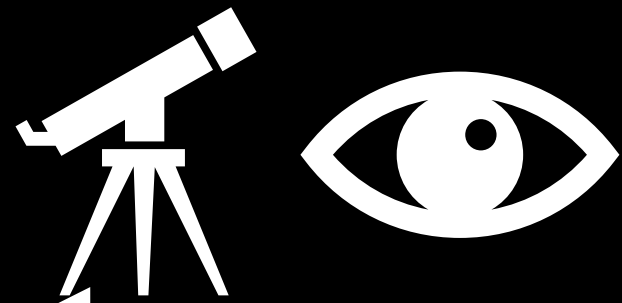
Before explosion



© Australian Astronomical Observatory

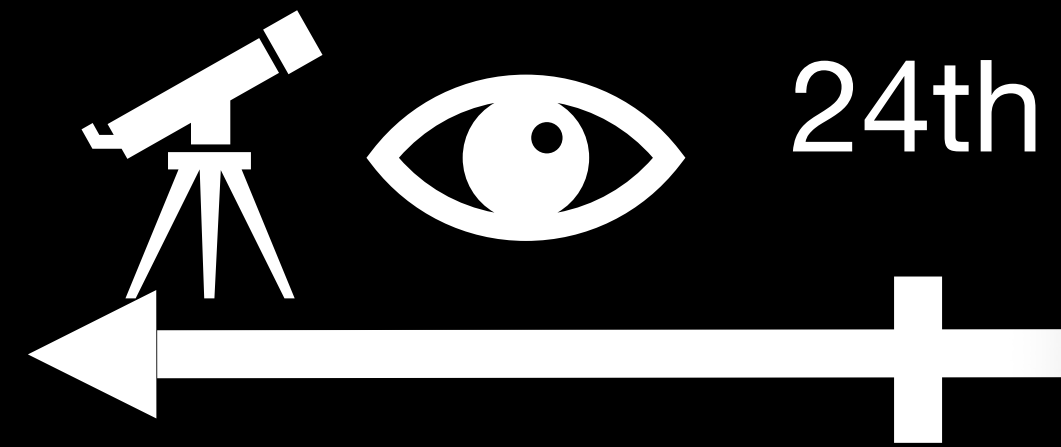
- Blue Supergiant that exploded on the 23rd of February 1987
- Located in Southern Hemisphere (LMC)
- Best studied supernova due to its proximity: closest observed SN in modern times (since 1604)
- To date, only SN to be ever observed via neutrinos (Thermally produced MeV neutrinos)

SN 1987A



23/02/1987

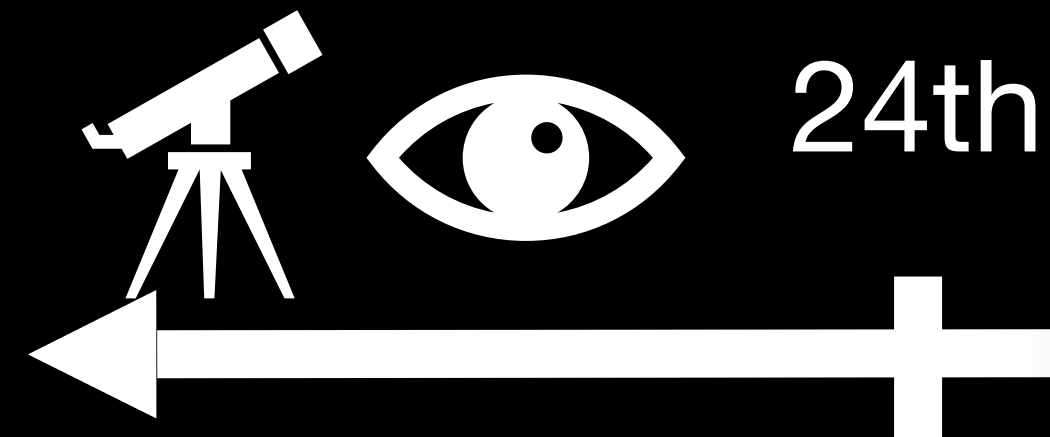
SN 1987A



ESO Observatory in La Silla, Chile

SN 1987A

Prof. Eugene Beier sent to Prof. Yoji Totsuka
at Kamioka-II

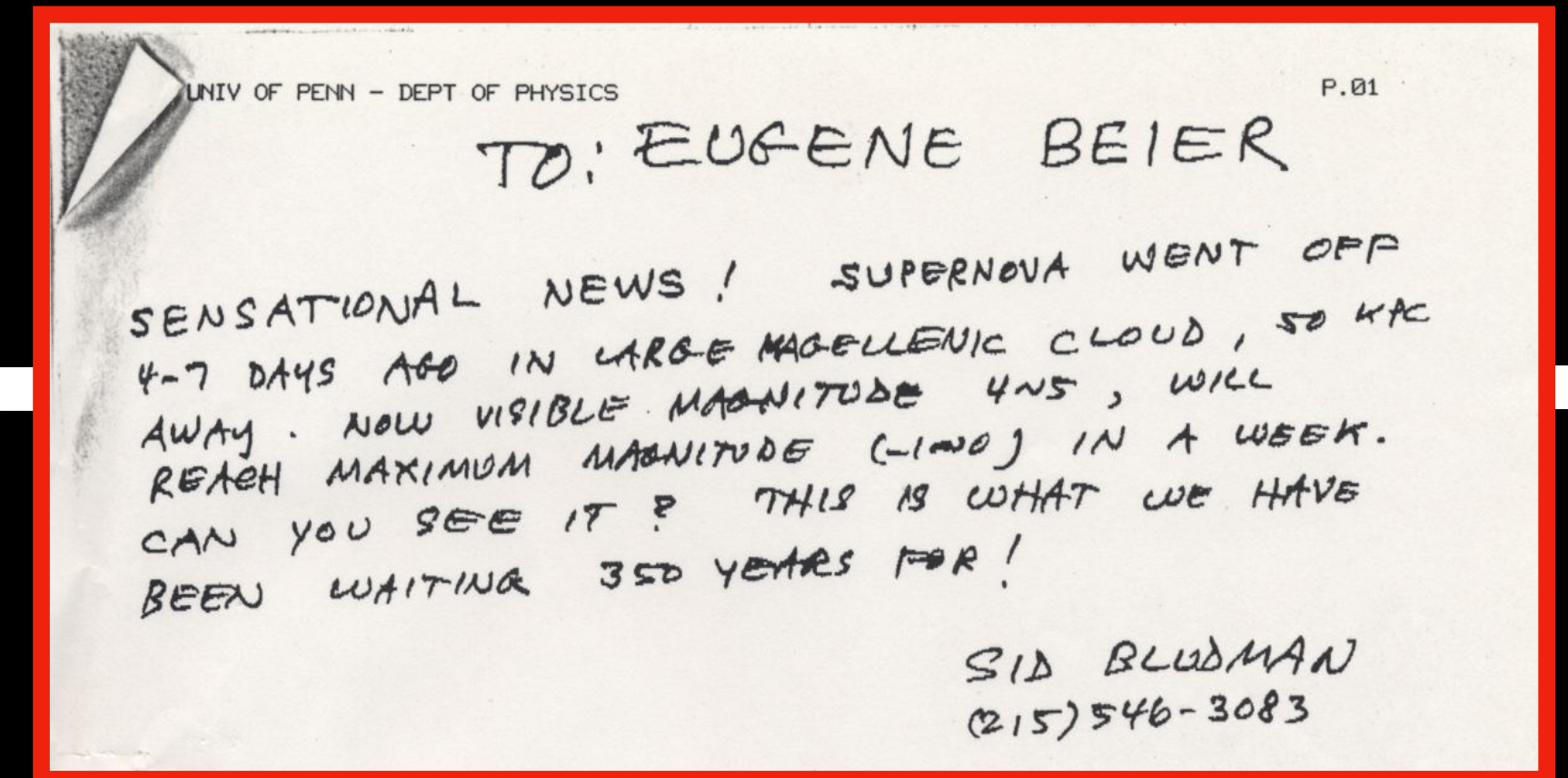


24th

23/02/1987



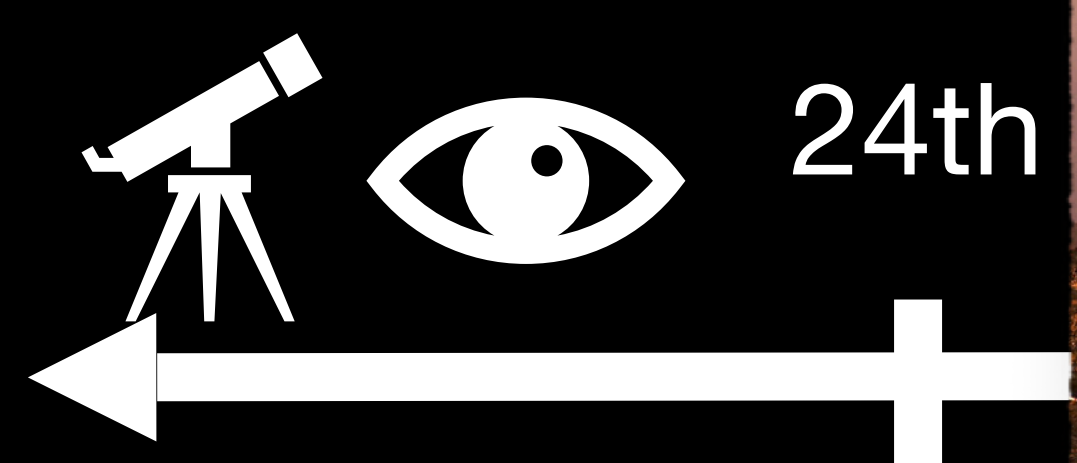
25th



ESO Observatory in La Silla, Chile

SN 1987A

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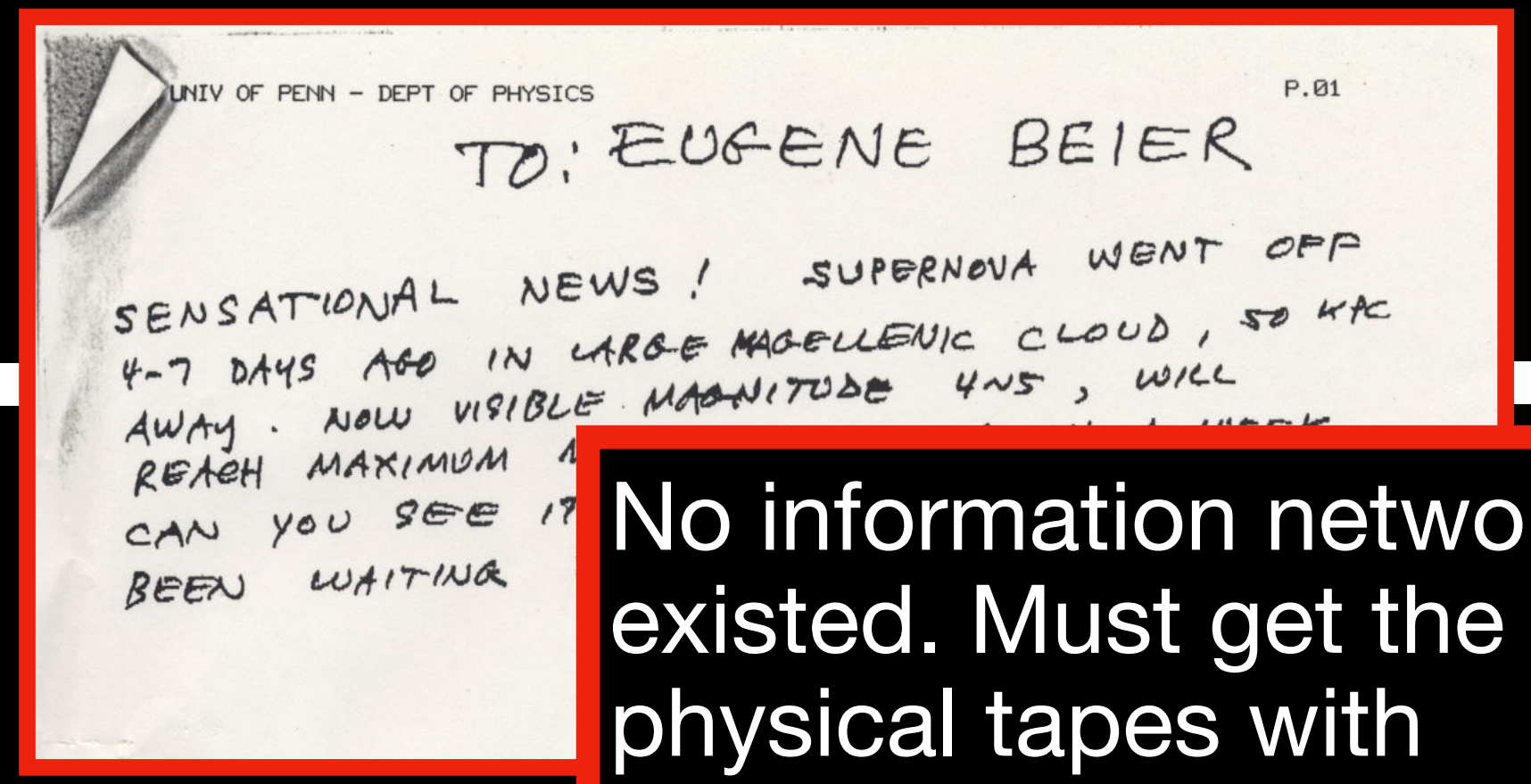
24th

23/02/1987



ESO Observatory in La Silla, Chile

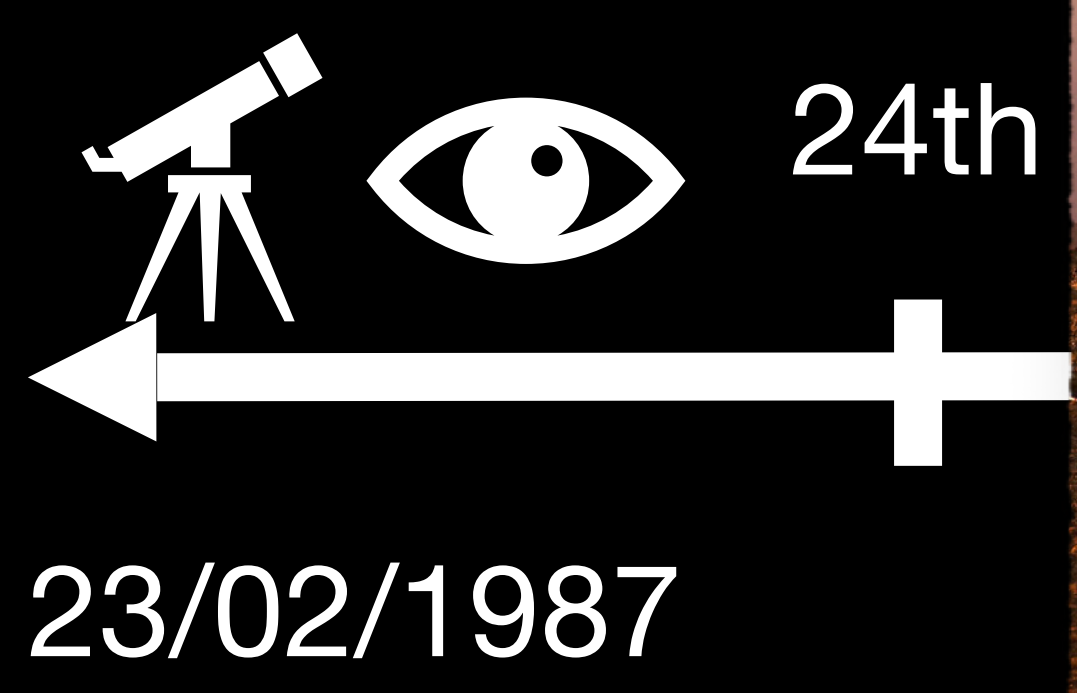
25th



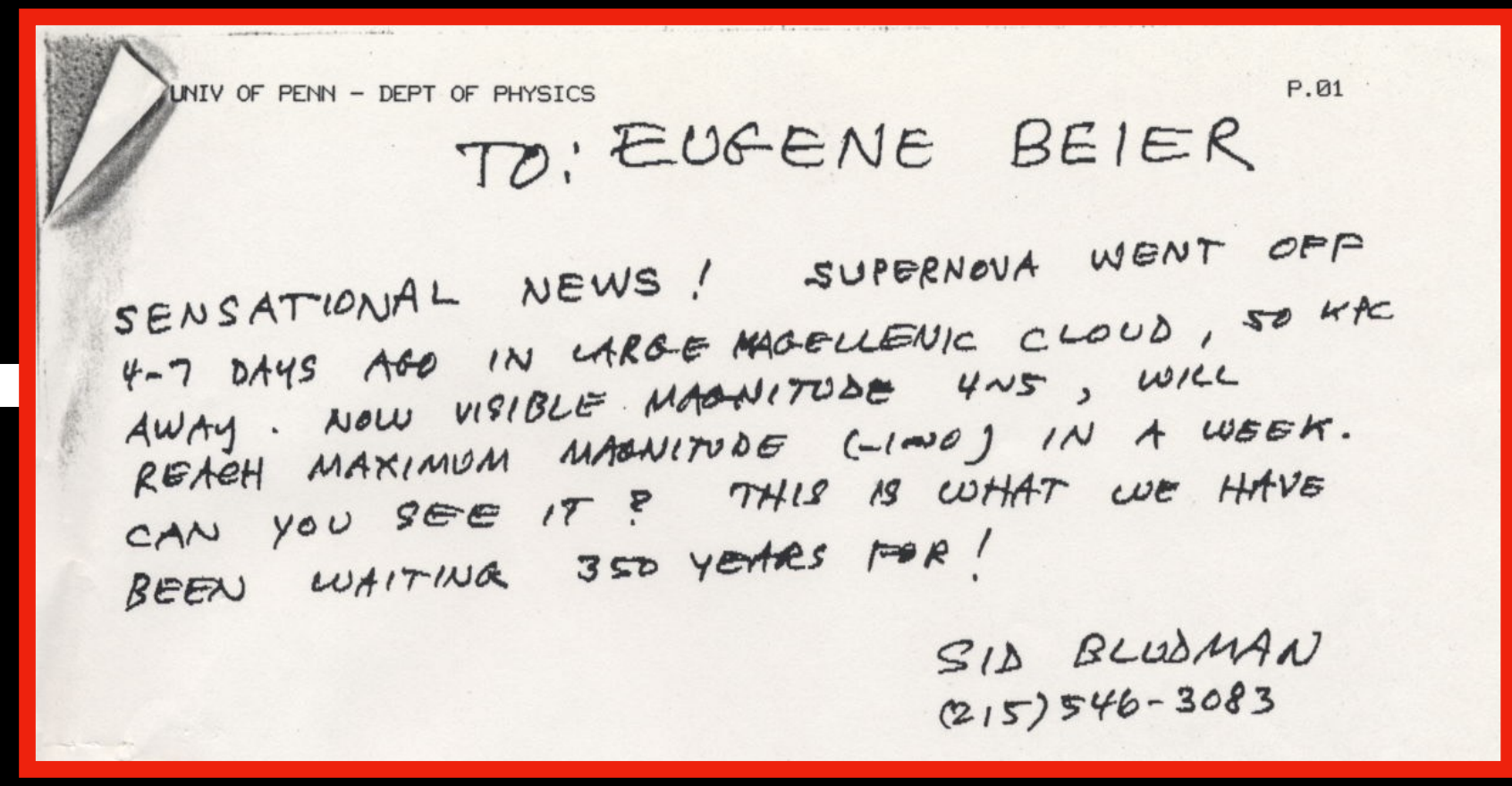
No information network existed. Must get the physical tapes with data!

SN 1987A

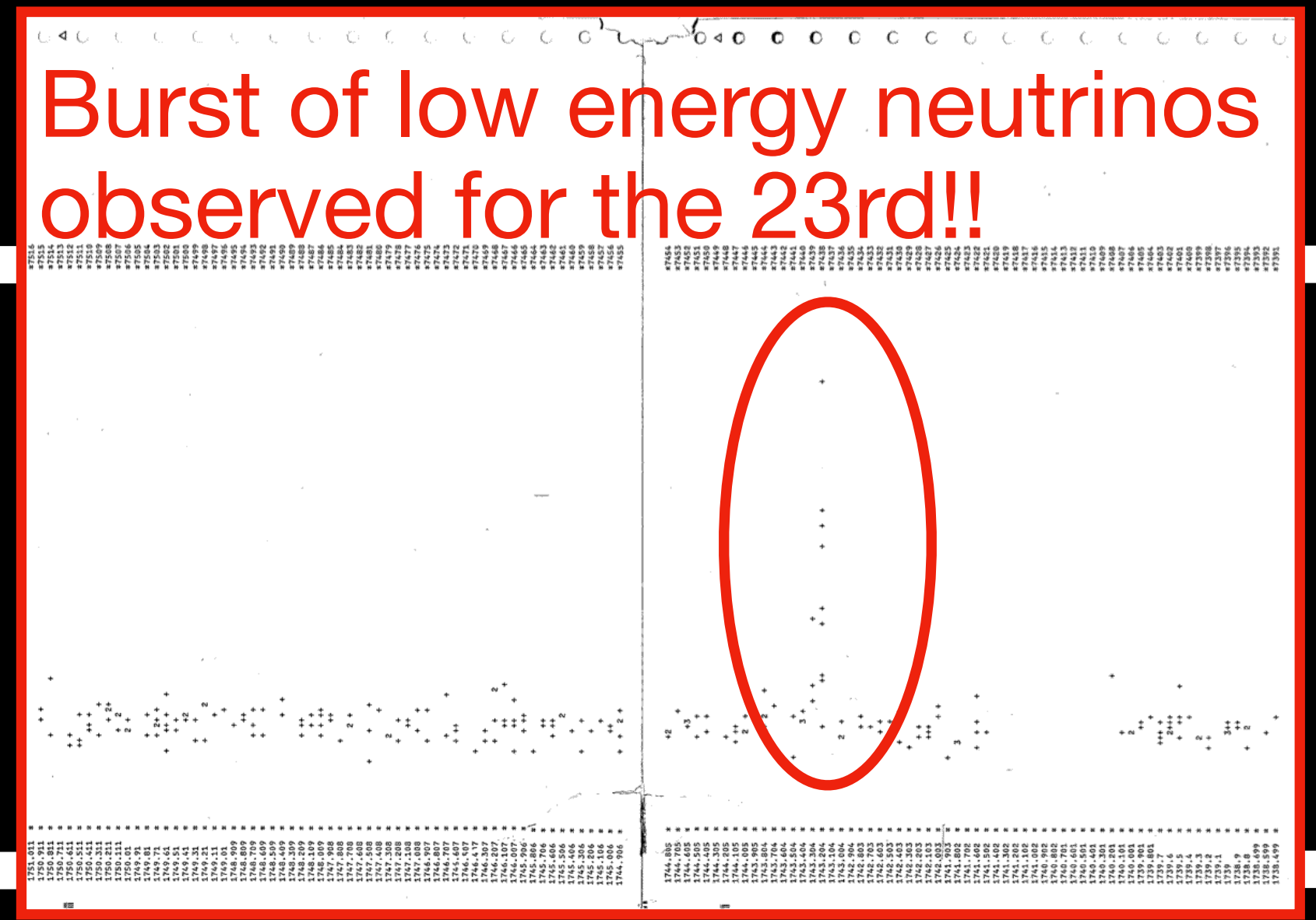
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25th



ESO Observatory in La Silla, Chile



28th



27th

Tapes received, started analysis

SN 1987A

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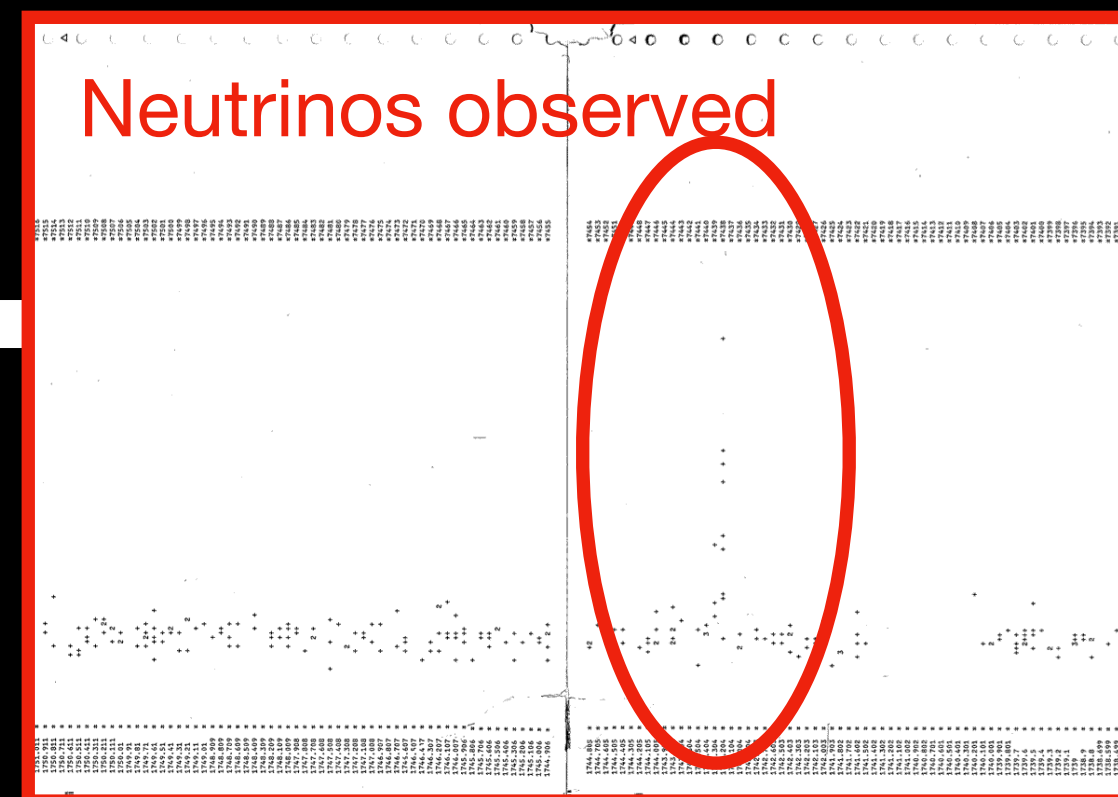
24th
23/02/1987



25th

UNIV OF PENN - DEPT OF PHYSICS P.01
TO: EUGENE BEIER
SENSATIONAL NEWS! SUPERNOVA WENT OFF
4-7 DAYS AGO IN LARGE MAGELLANIC CLOUD, 50 KPC
AWAY. NOW VISIBLE MAGNITUDE 4.5, WILL
REACH MAXIMUM MAGNITUDE (-1.00) IN A WEEK.
CAN YOU SEE IT? THIS IS WHAT WE HAVE
BEEN WAITING 350 YEARS FOR!
SID BLUDMAN
(215) 546-3083

ESO Observatory in La Silla, Chile

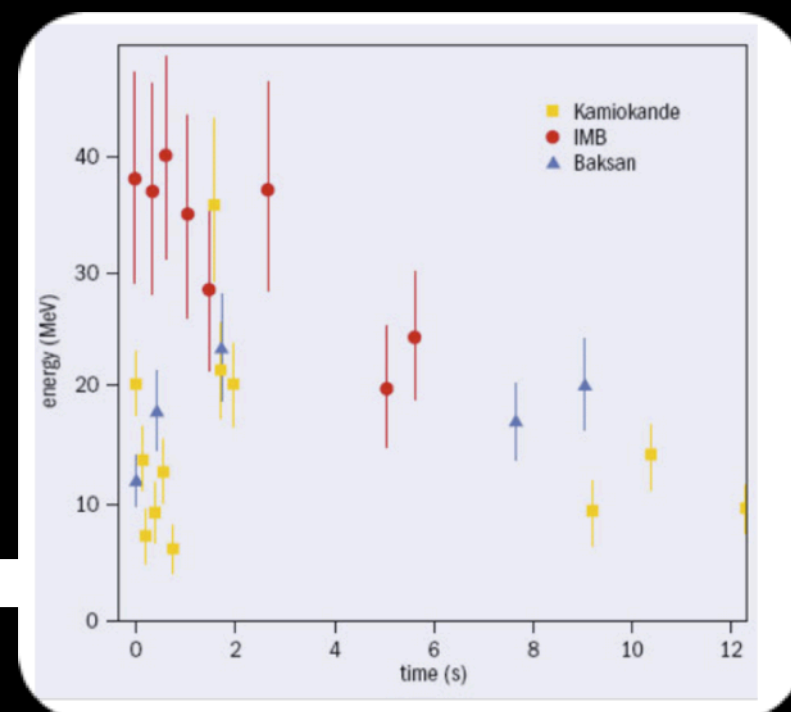


28th



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Baksan and IMB neutrino detectors confirmed the observation of a burst of neutrinos

Few weeks after

SN 1987A

Prof. Eugene Beier sent to Prof. Yoji Totsuka at Kamioka-II

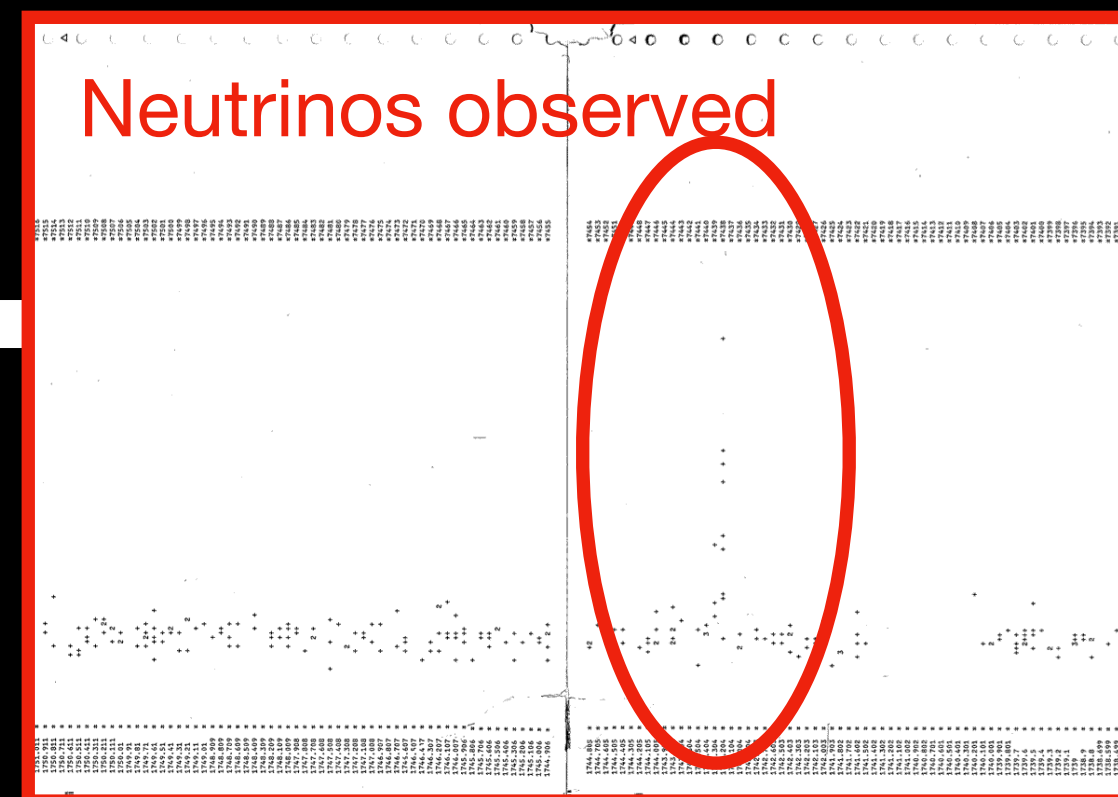
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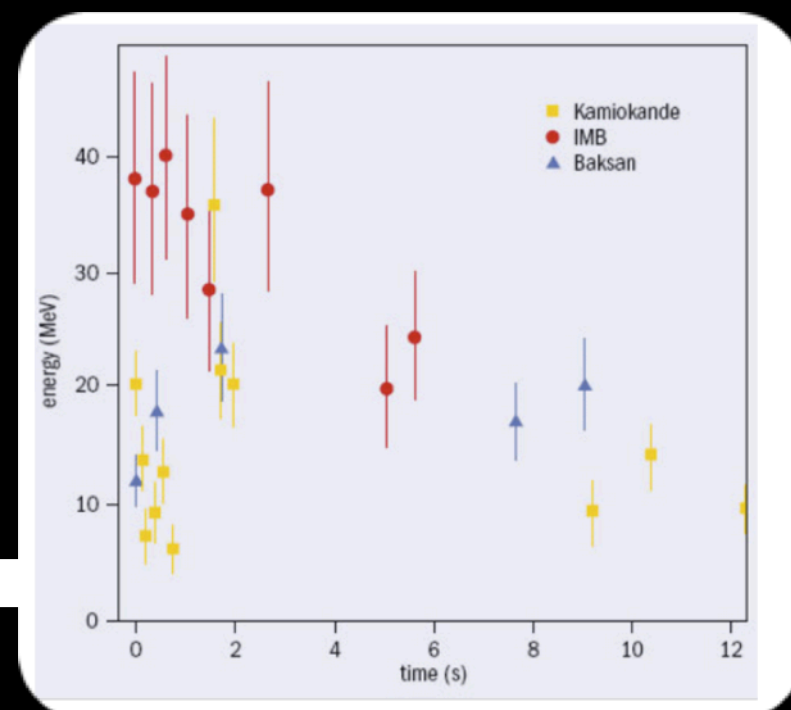


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Tapes received, started analysis

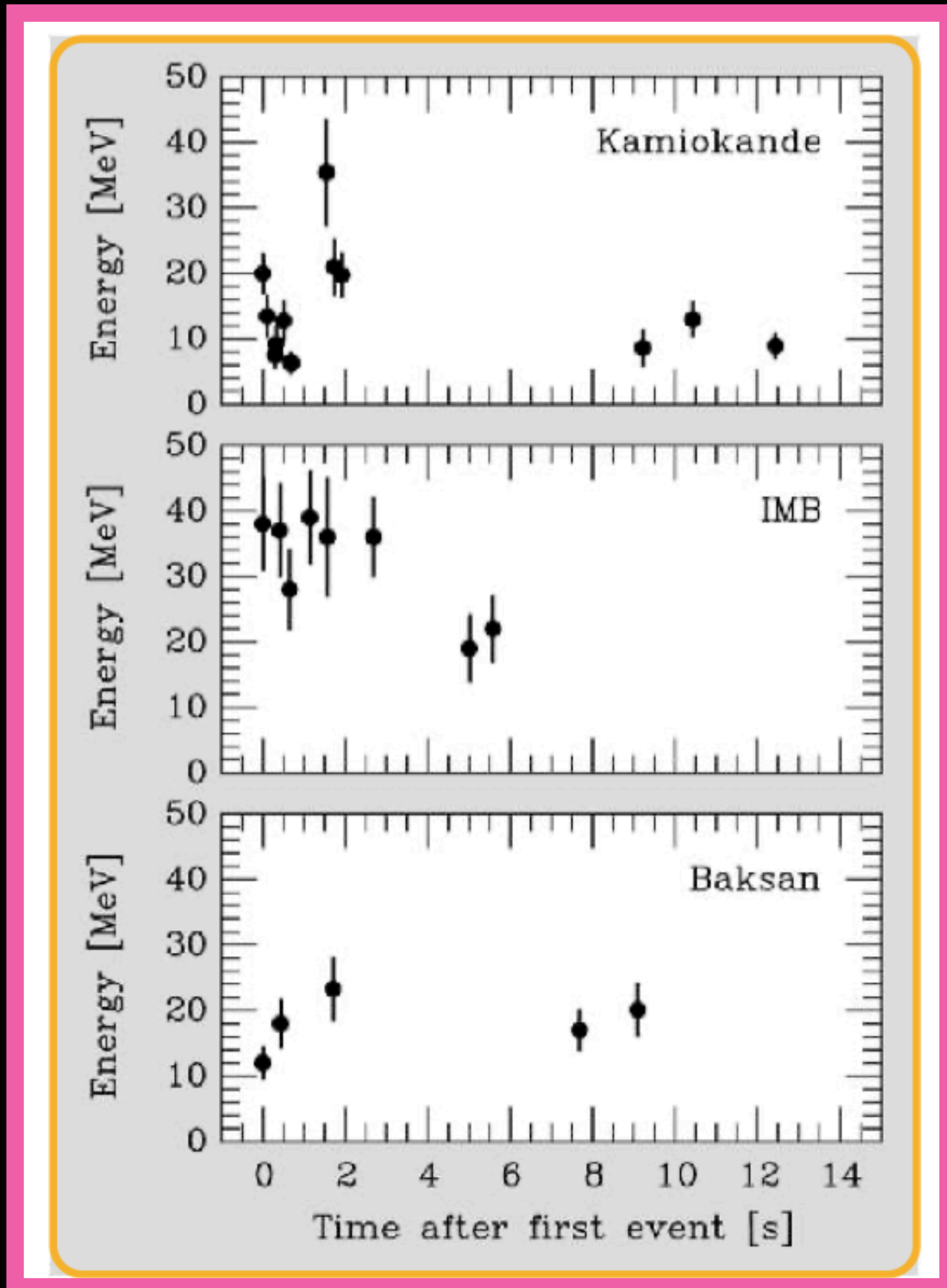


Long campaigns over >30 years
across the entire EM spectrum

We learned a
lot...

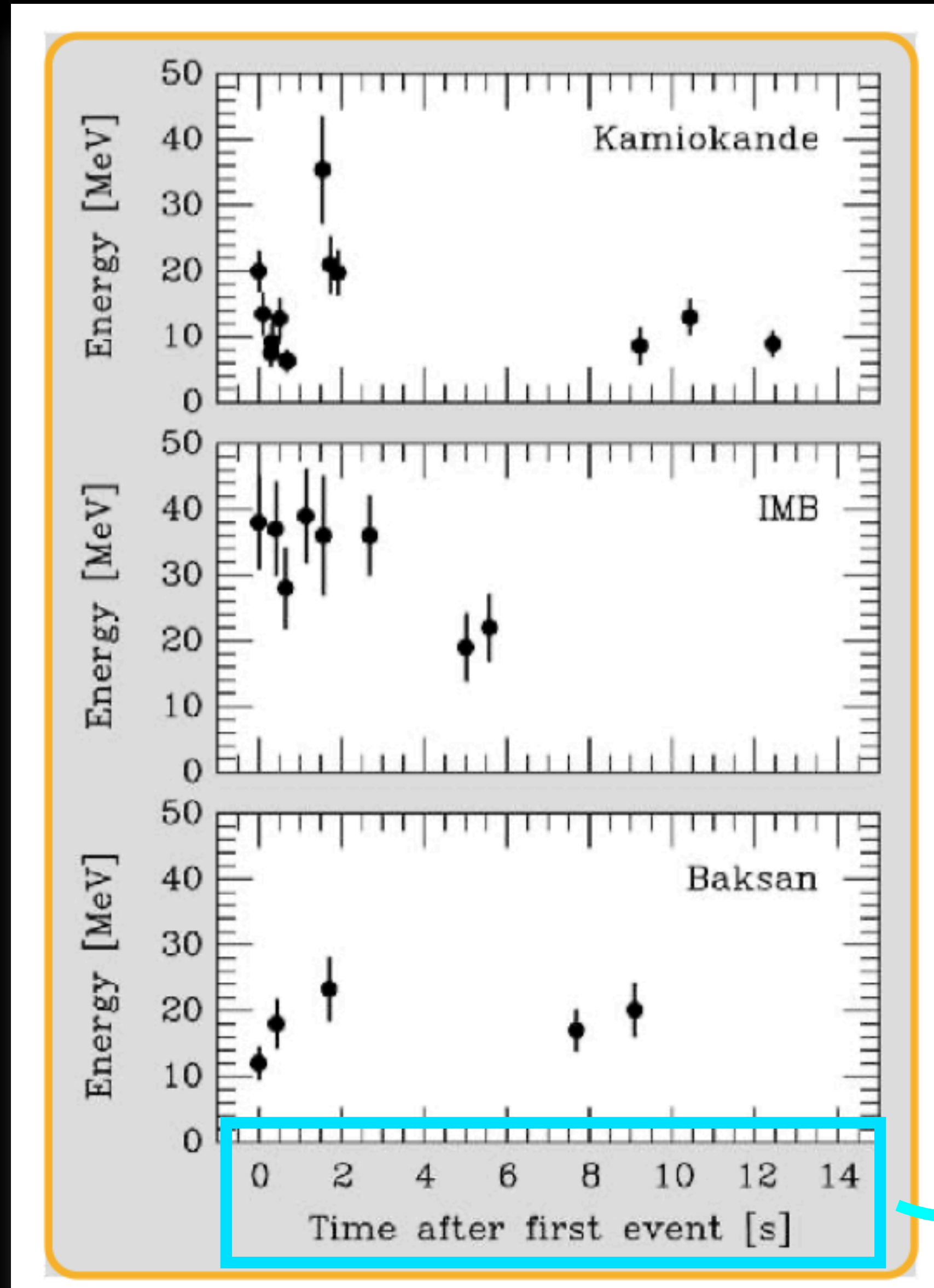
Few weeks after

WHAT DID WE LEARN?



First neutrinos from a transient astrophysical source

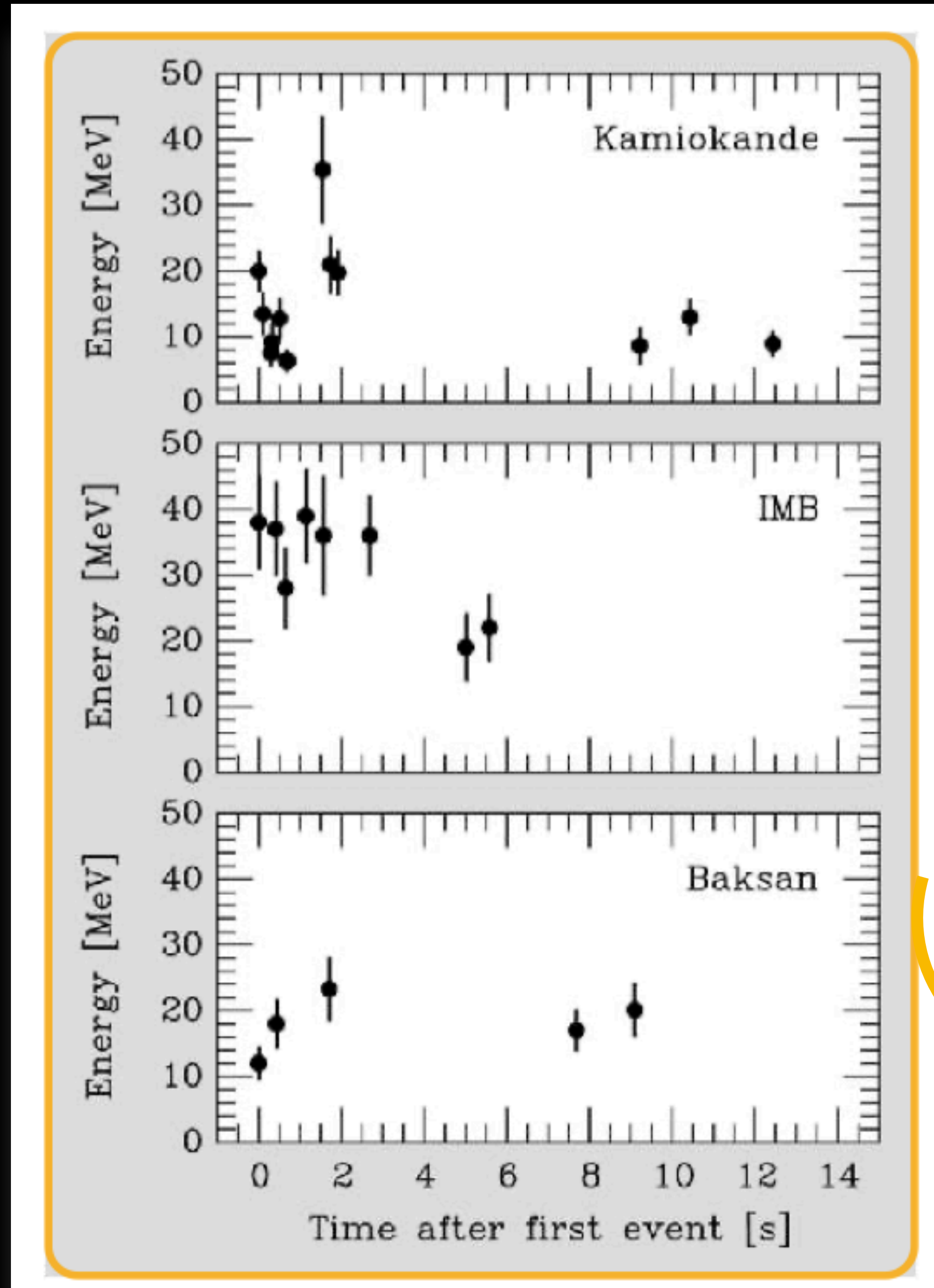
WHAT DID WE LEARN?



First neutrinos from a transient astrophysical source

Time scale matches to proto-neutron star cooling, confirmed star releases most of energy in MeV neutrinos → Stellar evolution

WHAT DID WE LEARN?



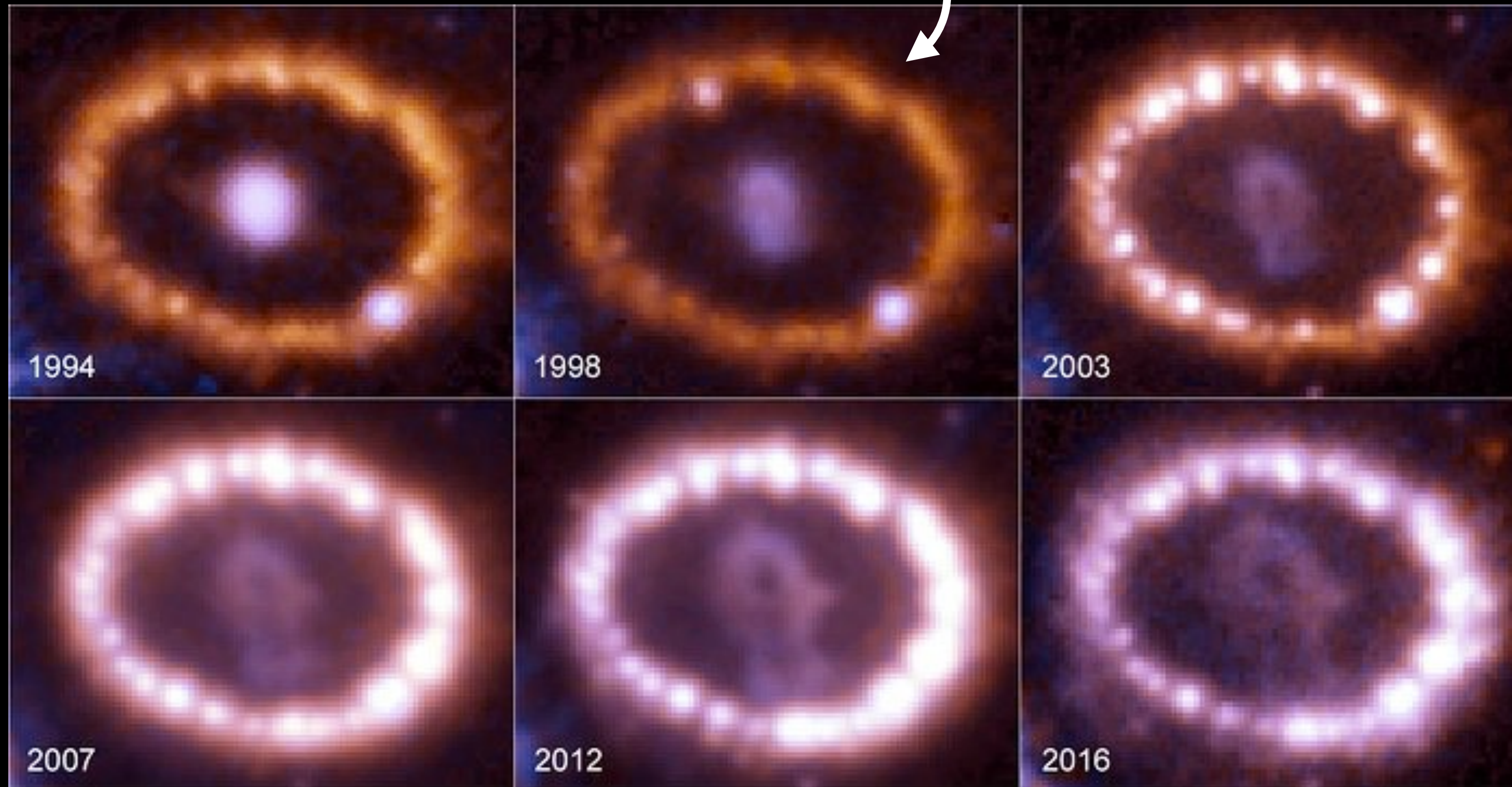
First neutrinos from a transient astrophysical source

Time scale matches to proto-neutron star cooling, confirmed star releases most of energy in MeV neutrinos $\rightarrow$ Stellar evolution

Outside of explosion mechanism $\rightarrow$ bounds on exotic cooling, UL on neutrino mass ($< 12 \text{ eV}/c^2$)

WHAT DID WE LEARN?

Shockwave hitting the matter



The evolution has been tracked for more than 30 years

ELECTROMAGNETIC

Evolution of geometry and debris evolution: SN don't explode symmetrically

- Understanding of shockwave collision (ring)
- Tracked how shock heating creates X-ray, radio, and optical emission
- Observed dust formation and destruction in the expanding debris (CSM)

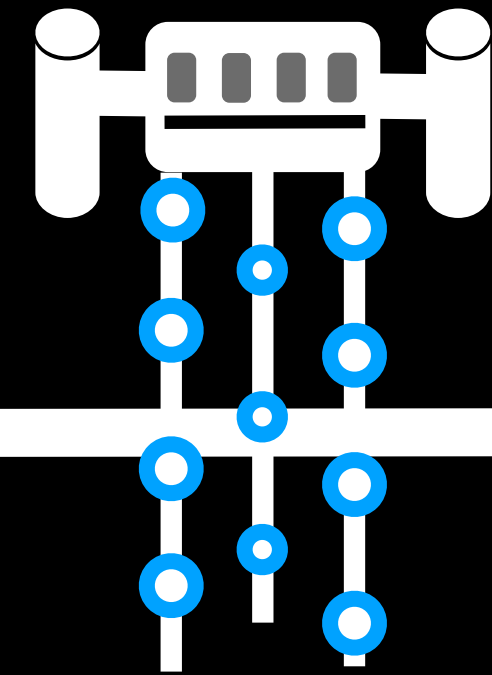
LESSONS

- Successful multi-messenger campaign, albeit slow chain of response
- We learned a lot (much more than I can cover) from a single nearby explosion
- It highlighted the importance of using as many messengers as possible to study astrophysical transients
- We need faster response time and ensure readiness for the next Galactic SN

OUTLINE



Observation of MeV ν



Neutrinos from CCSNe

Putting the pieces together



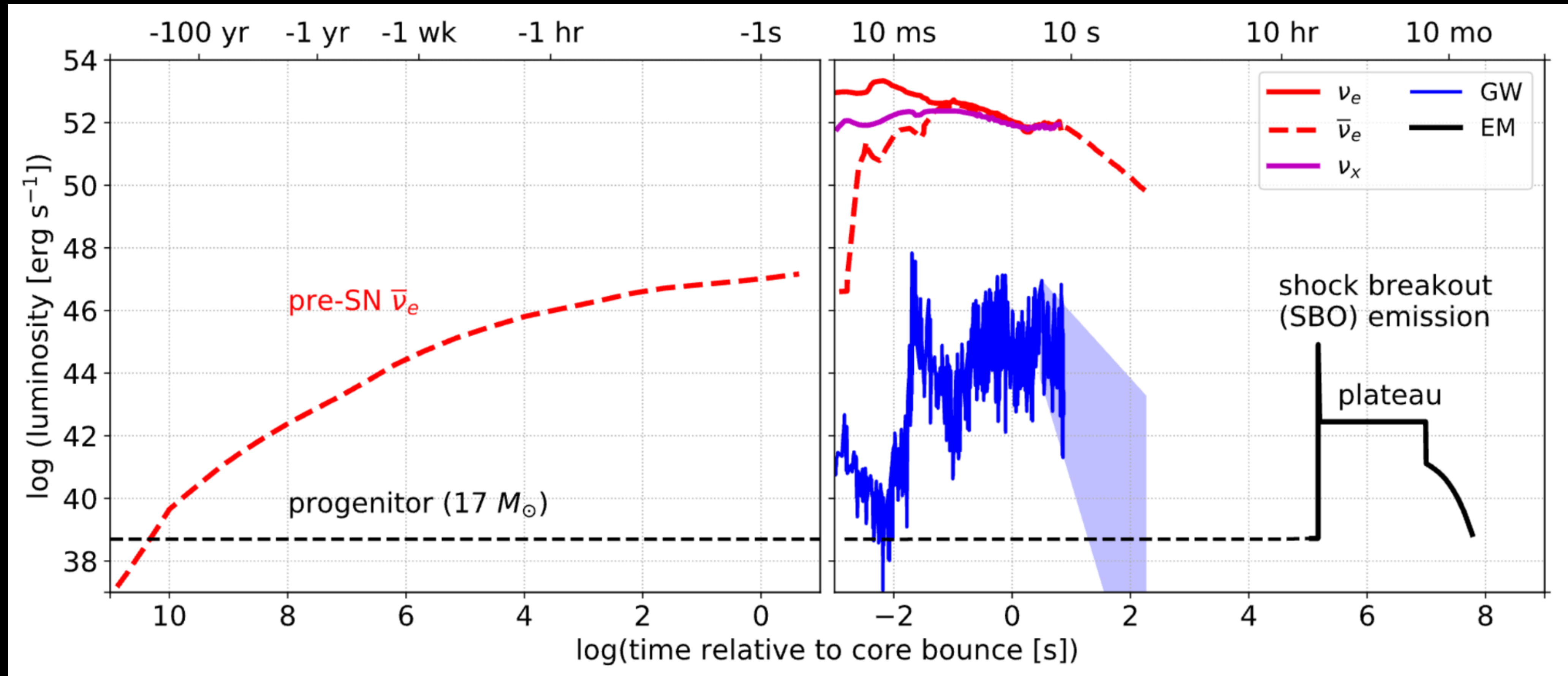
SNEWS
Supernova Early Warning System

Why the next Galactic SN matters



NEUTRINOS FROM SUPERNOVAE

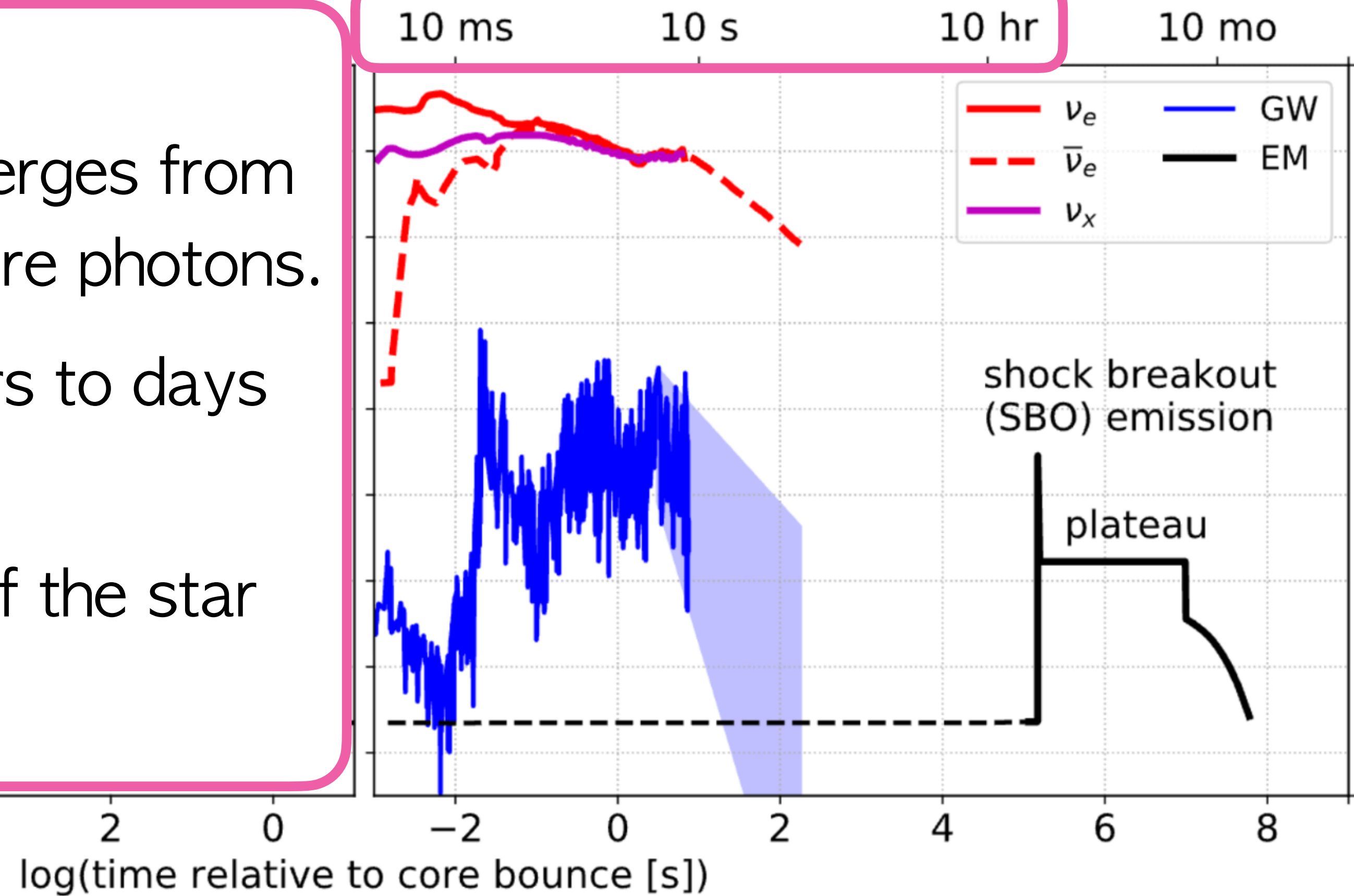
WHY NEUTRINOS?



Adapted from Nakamura et al., MNRAS (2016)

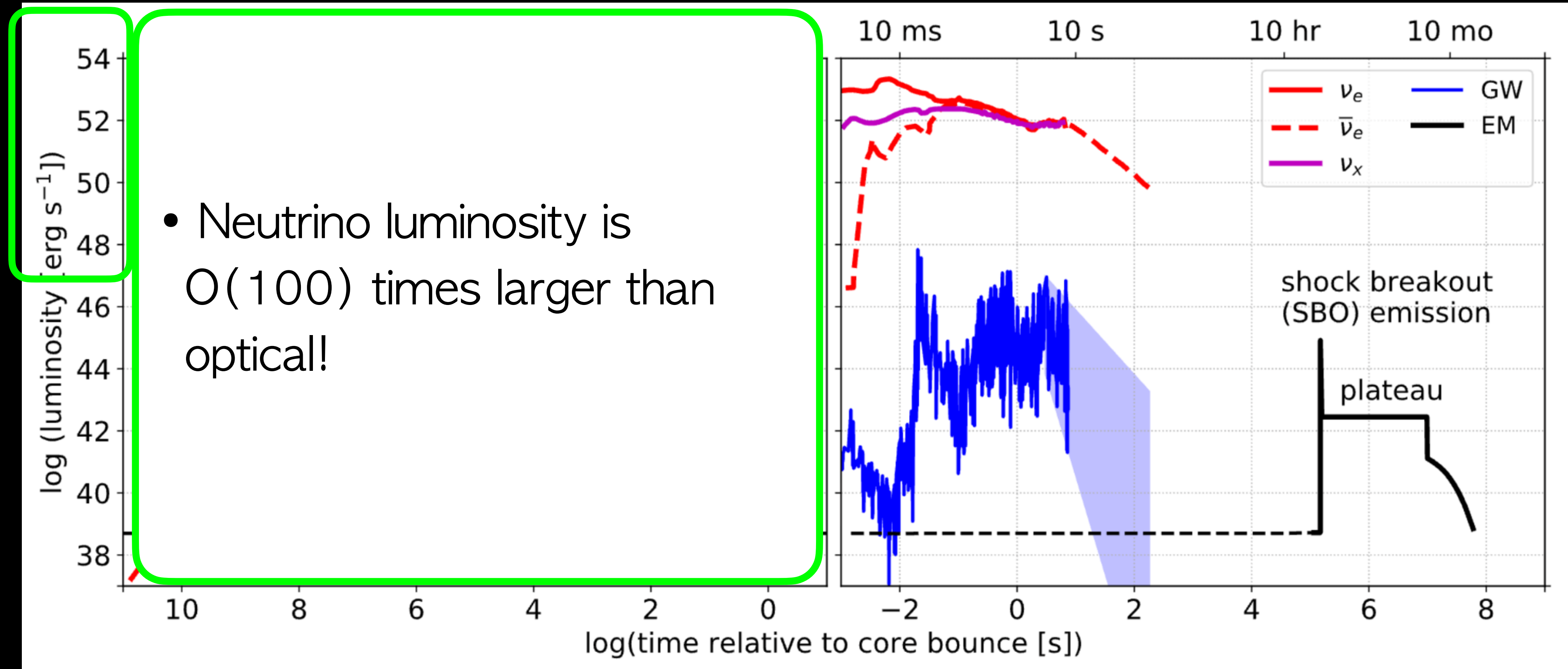
WHY NEUTRINOS?

- The neutrino signal emerges from the core promptly: before photons.
- Photons may take hours to days to emerge.
- Probe deeper regions of the star



Adapted from Nakamura et al., MNRAS (2016)

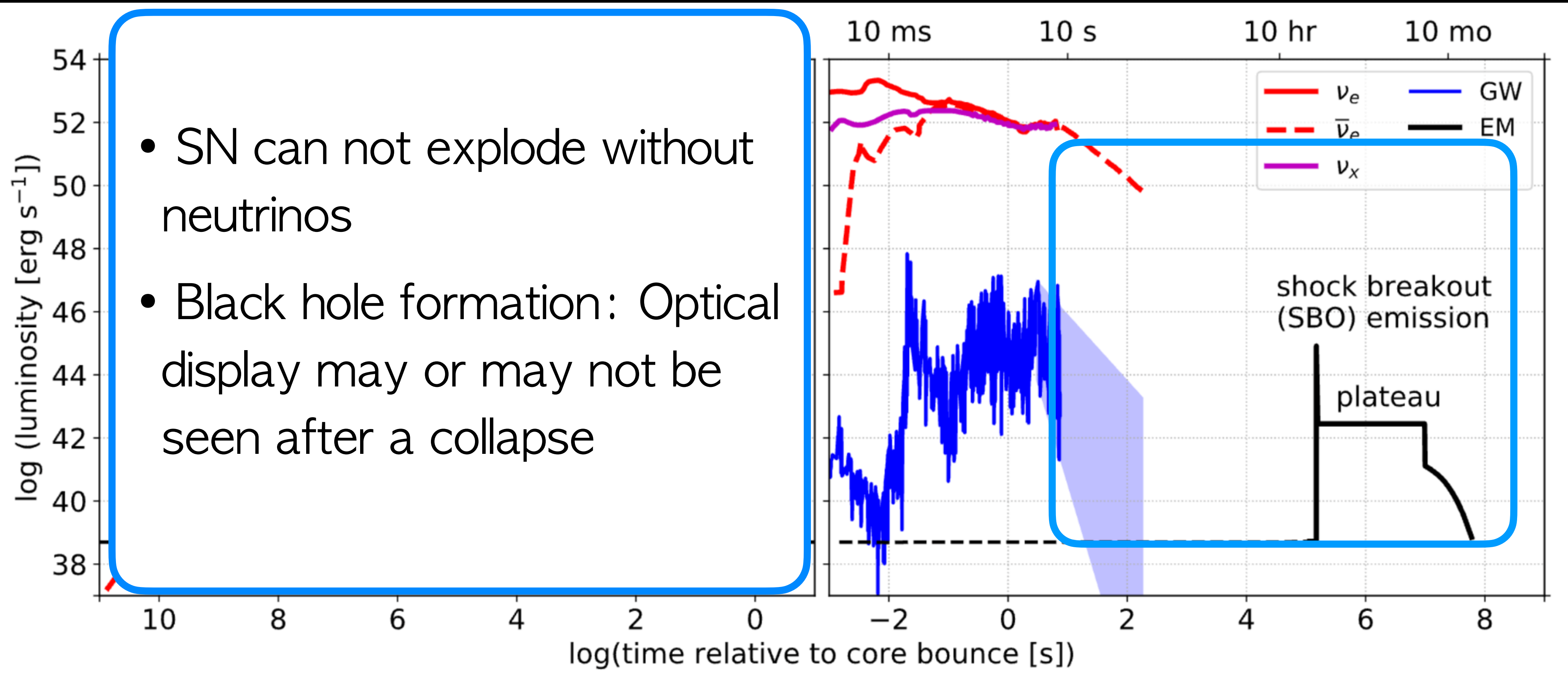
WHY NEUTRINOS?



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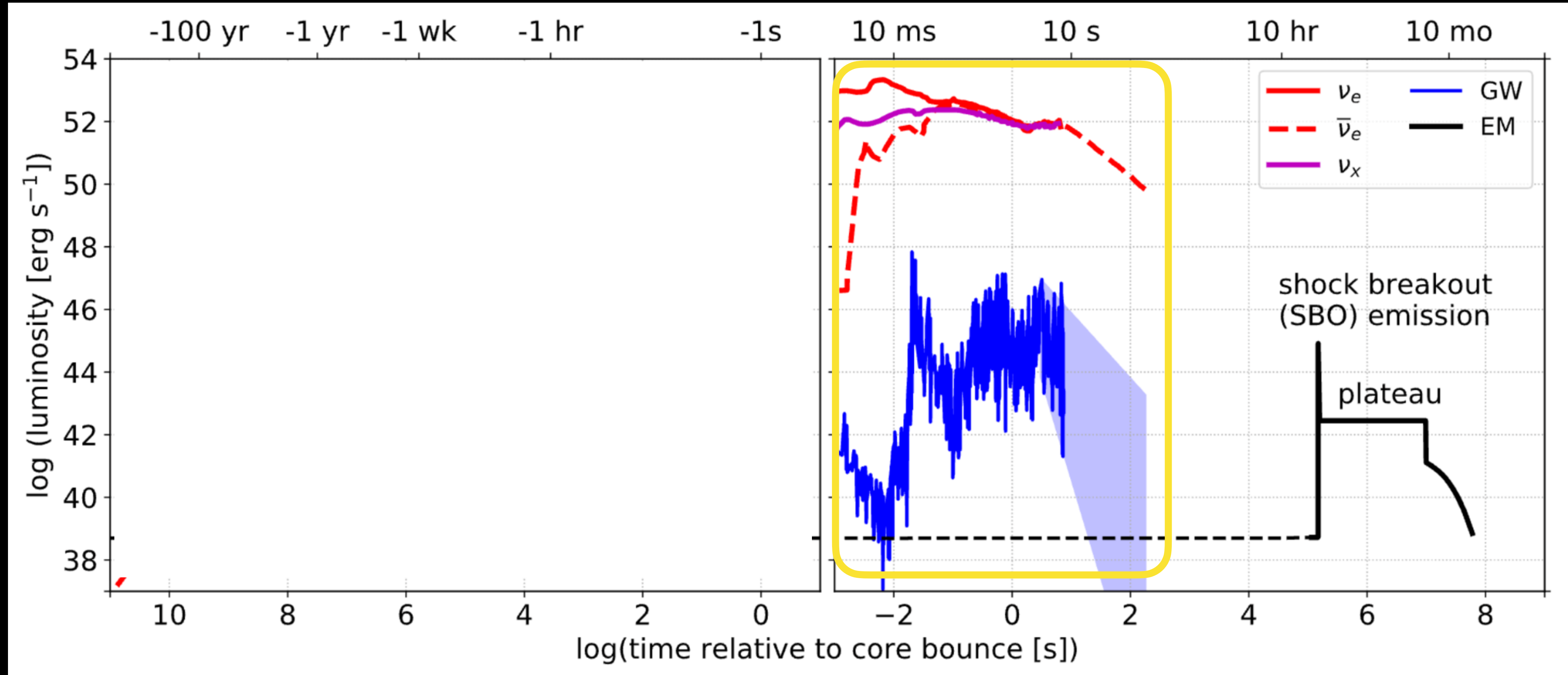
WHY NEUTRINOS?

- SN can not explode without neutrinos
- Black hole formation: Optical display may or may not be seen after a collapse



Adapted from Nakamura et al., MNRAS (2016)

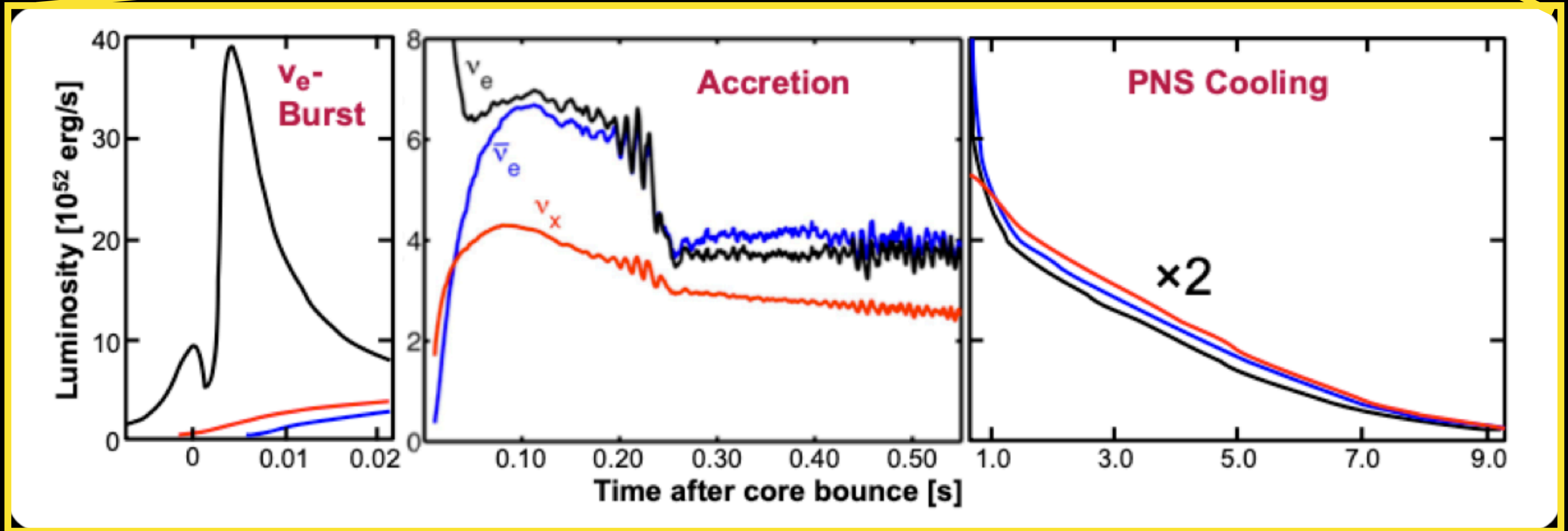
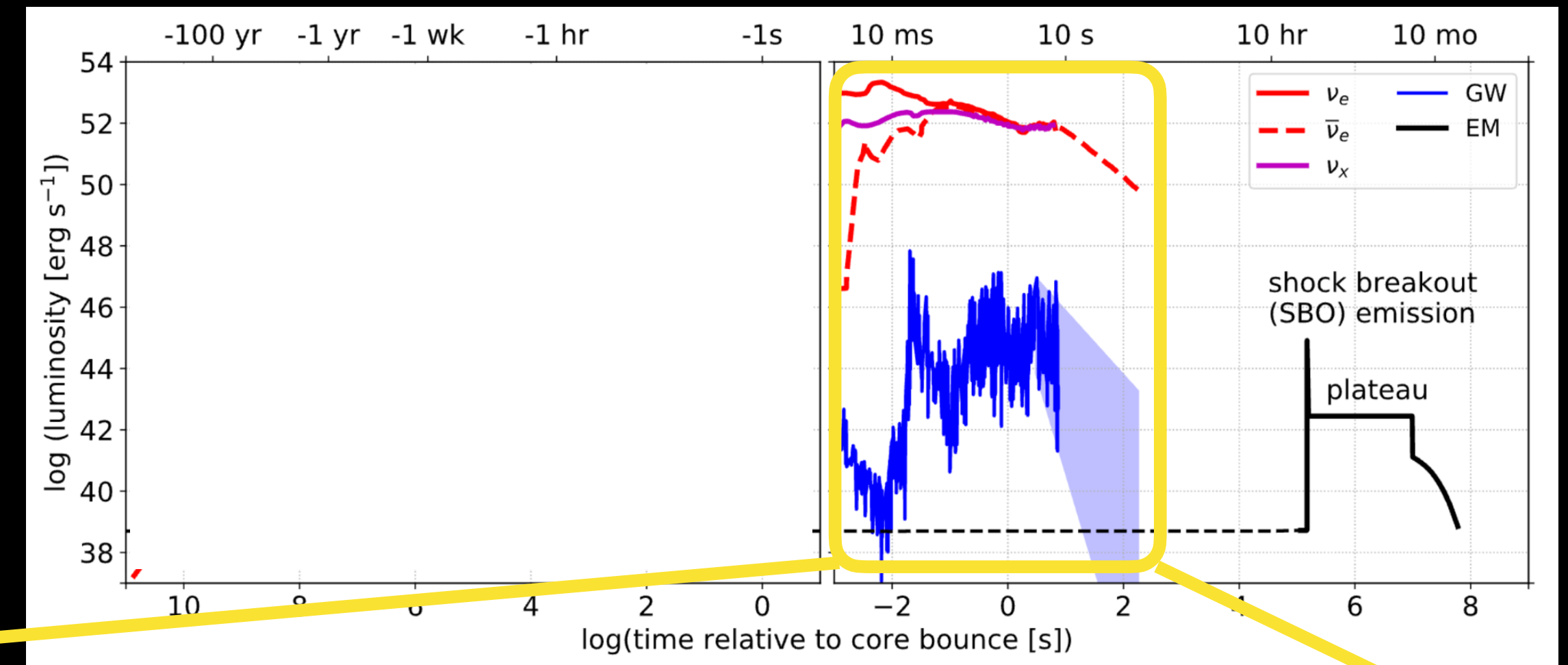
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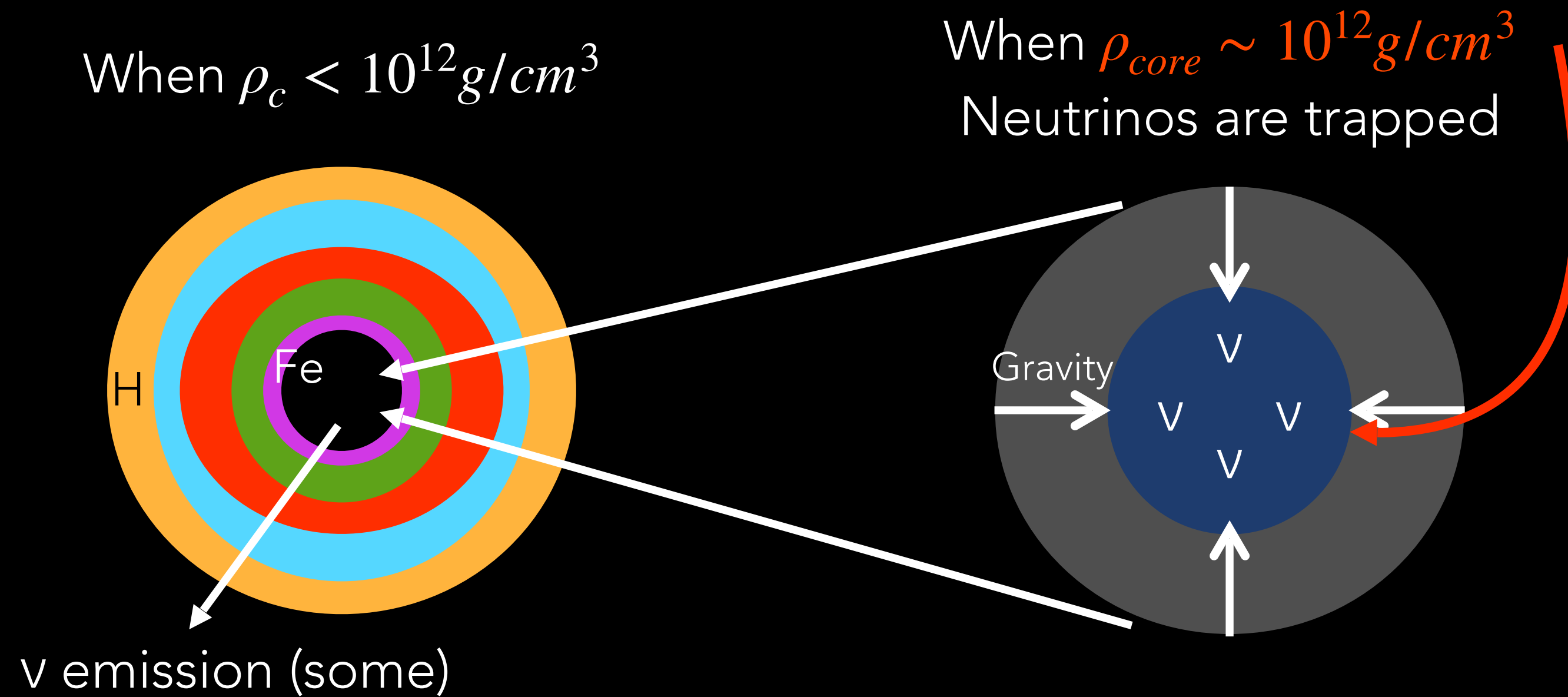
Adapted from Nakamura et al., MNRAS (2016)

WHY NEUTRINOS?

What is core bounce? —> How do you get a core collapse supernova?

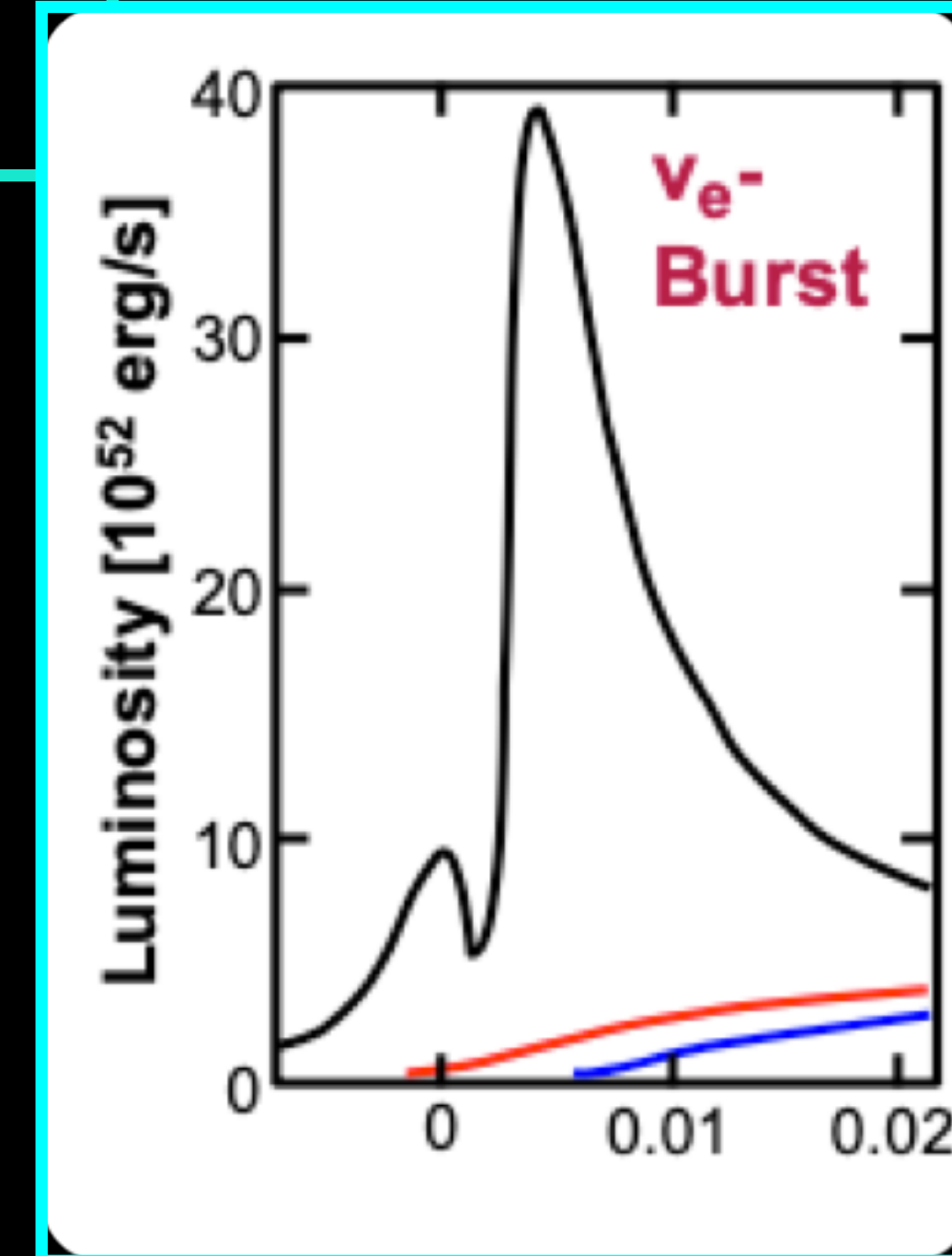
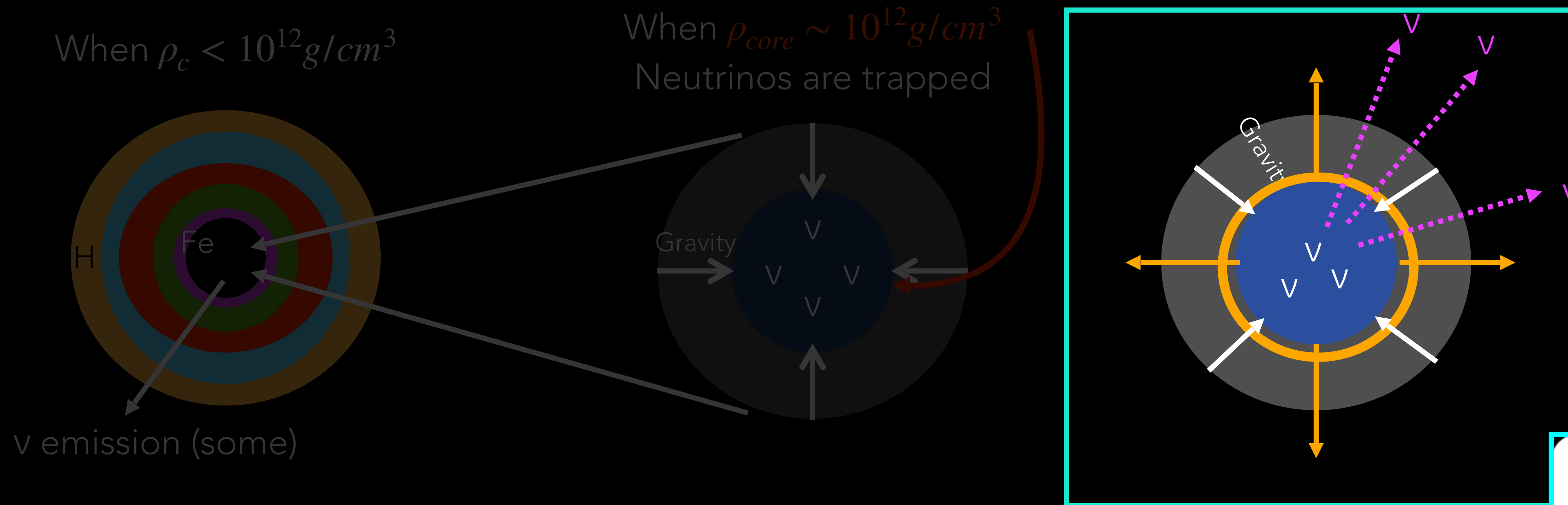


CORE-COLLAPSE SUPERNOVA



- Massive star ($> 8M_{\odot}$) successfully fuses heavy elements until it builds a Fe core.
 - Fusion stops at Fe $\rightarrow$ highest binding energy per nucleon
- Core supported against gravity thanks to electron degeneracy pressure.
 - Keeps growing until a critical mass.
- Core contracts + heats

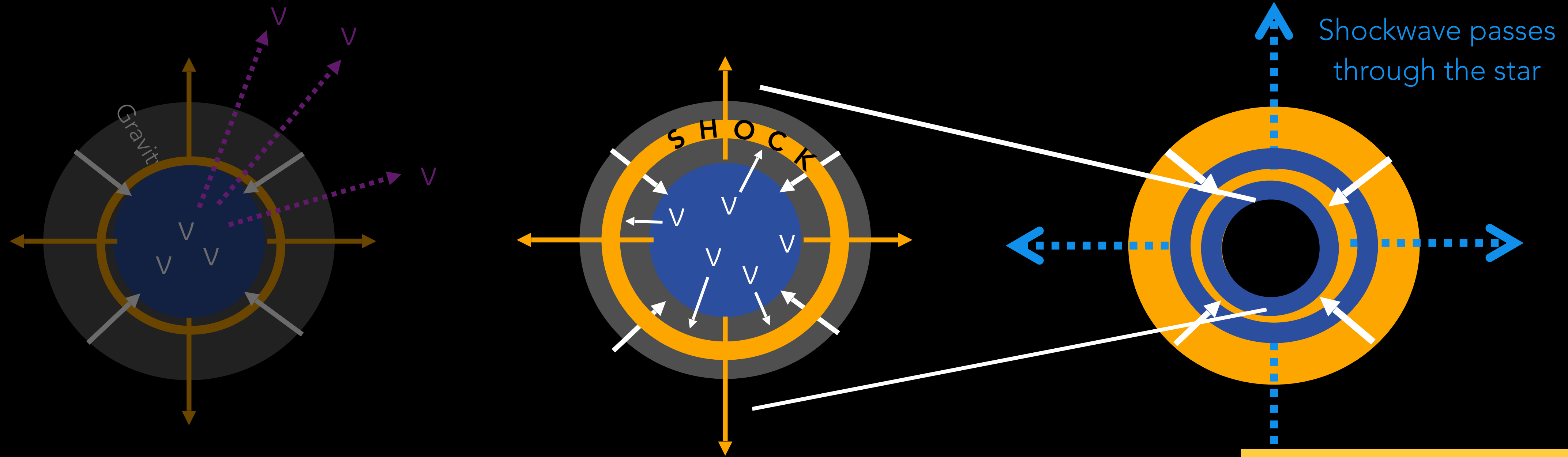
CORE-COLLAPSE SUPERNOVA



Stage I:

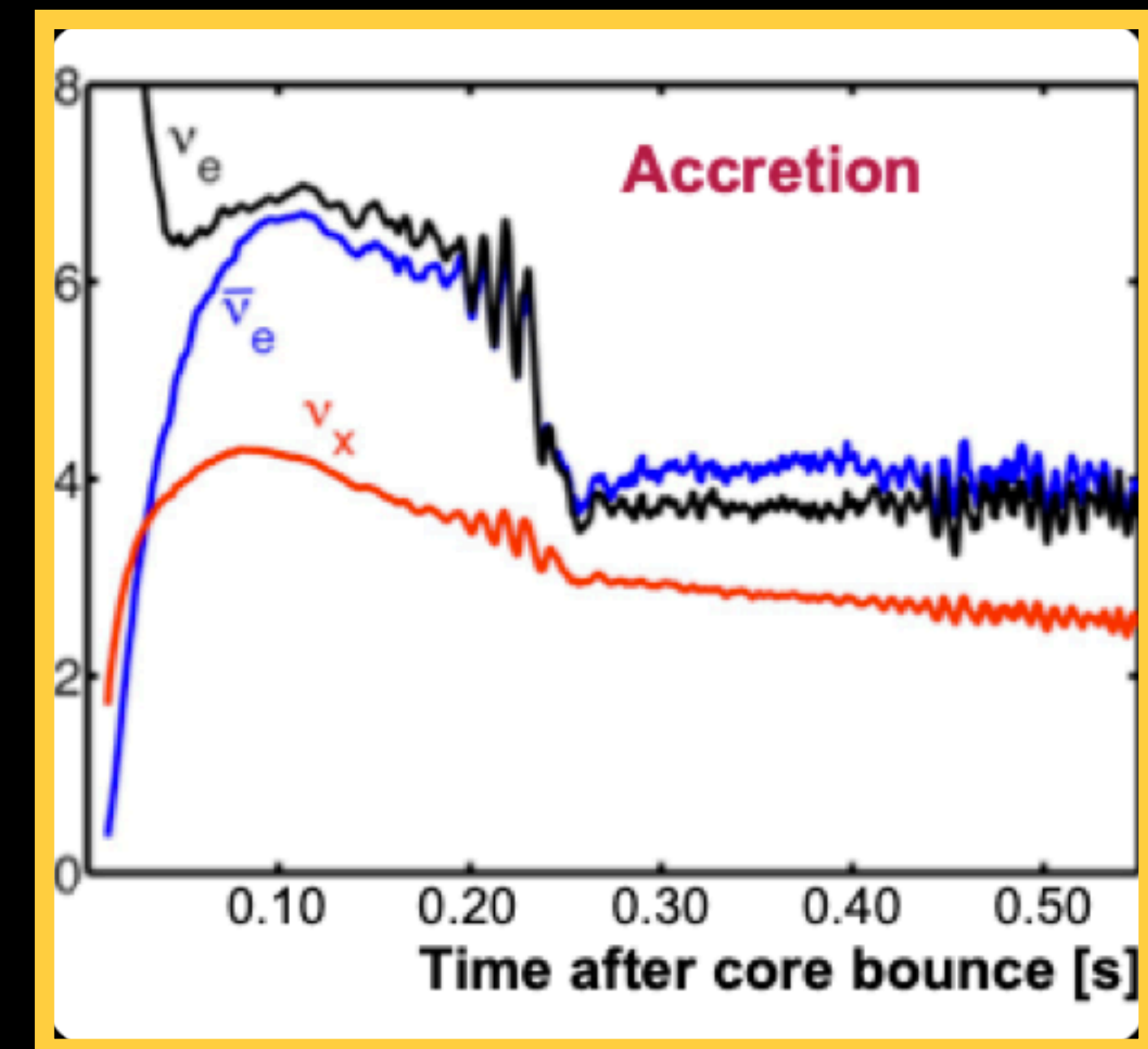
- Photodisintegration on Fe nuclei
 - e^- capture and β -decay
- Reduced electron degeneracy pressure $\rightarrow$ core collapse
- Incompressible core with $\rho_c \approx 10^{14} \text{ g/cm}^3$ forms
- Inner core rebounds $\rightarrow$ Shockwave
- Burst of neutrinos from outer shockwave
- Shockwave insufficient to cause a supernova

CORE-COLLAPSE SUPERNOVA



Stage II: Shock stagnation and revival (accretion phase)

- Energy loss from neutronization burst
- Matter keeps in-falling (accretion)
 - Layers of different neutrino species being formed
- Neutrinos start to heat the shock against the ram pressure of the infall
- Shockwave passes through the star —> Supernova!

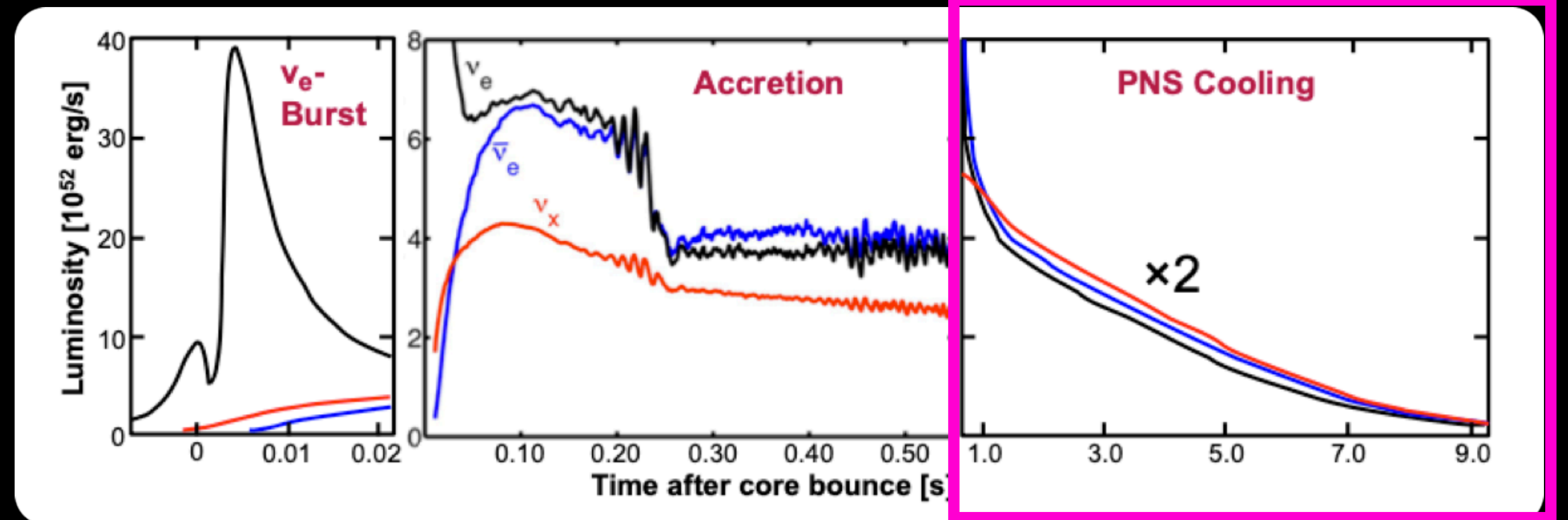
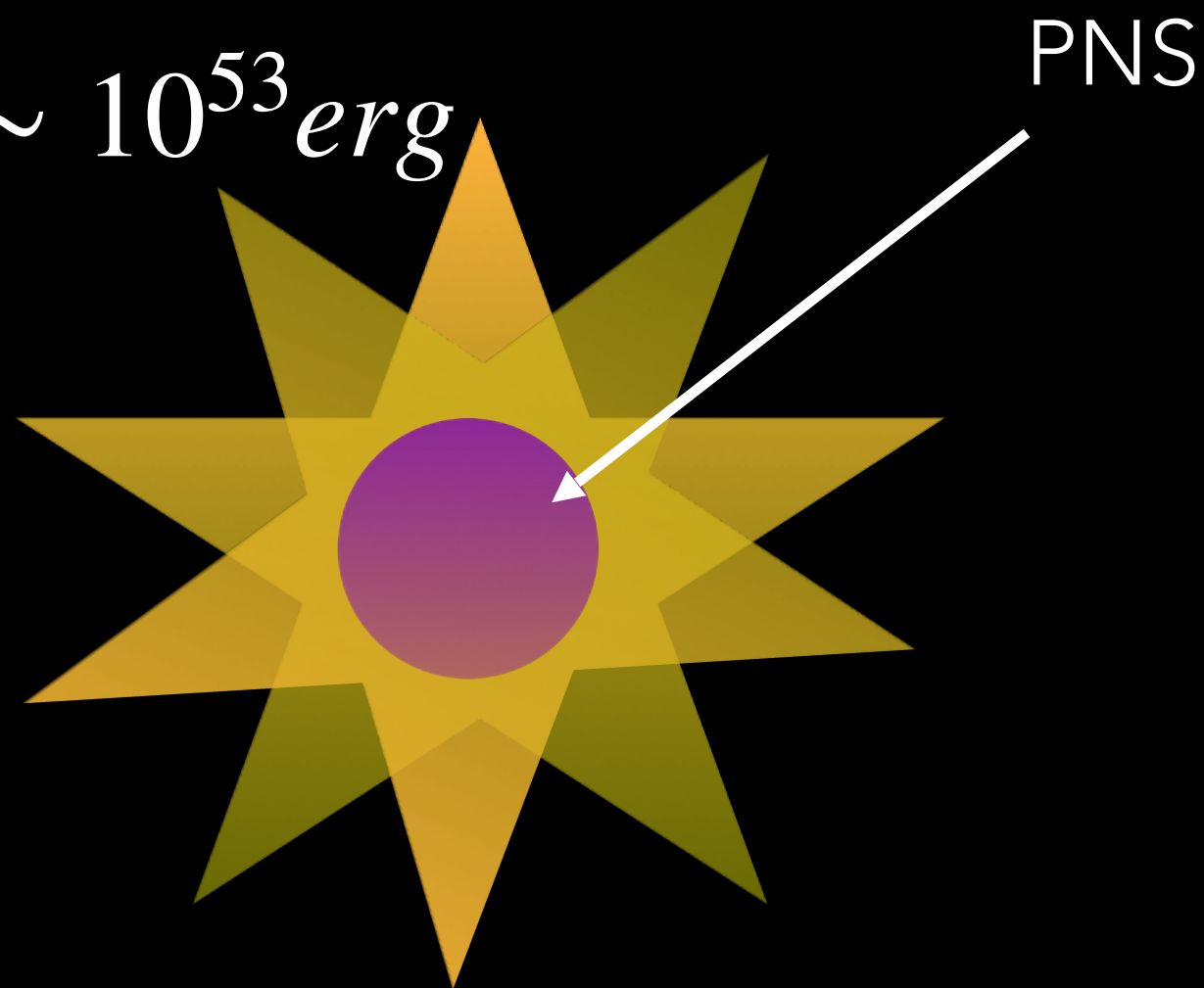


CORE-COLLAPSE SUPERNOVA

Stage III: Proto Neutron Star (PNS) cooling

- Accretion keeps happening around the newly formed PNS
- It keeps on emitting neutrinos
- As less and less matter infall, the PNS keeps cooling down

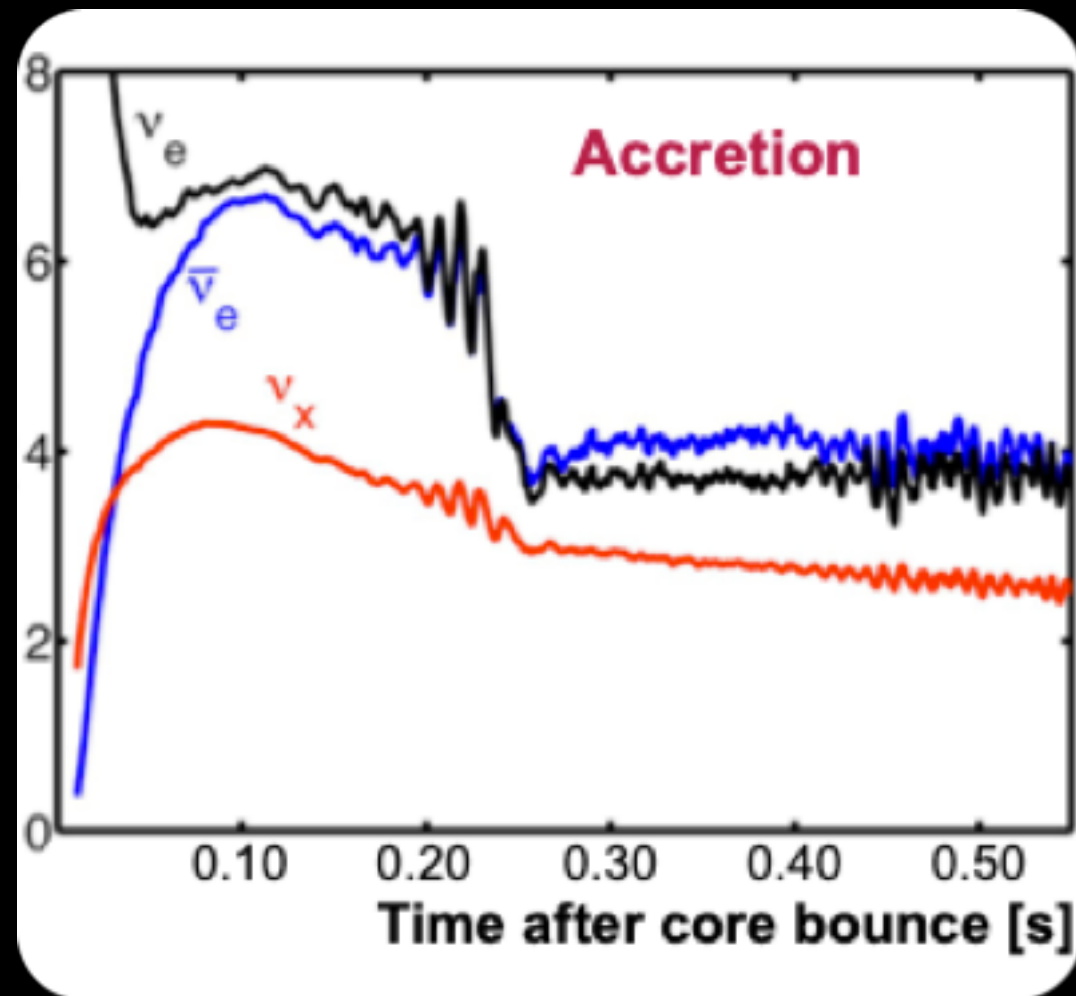
$$E_{tot} \sim 10^{53} \text{ erg}$$



WHAT CAN WE PROBE WITH NEUTRINOS

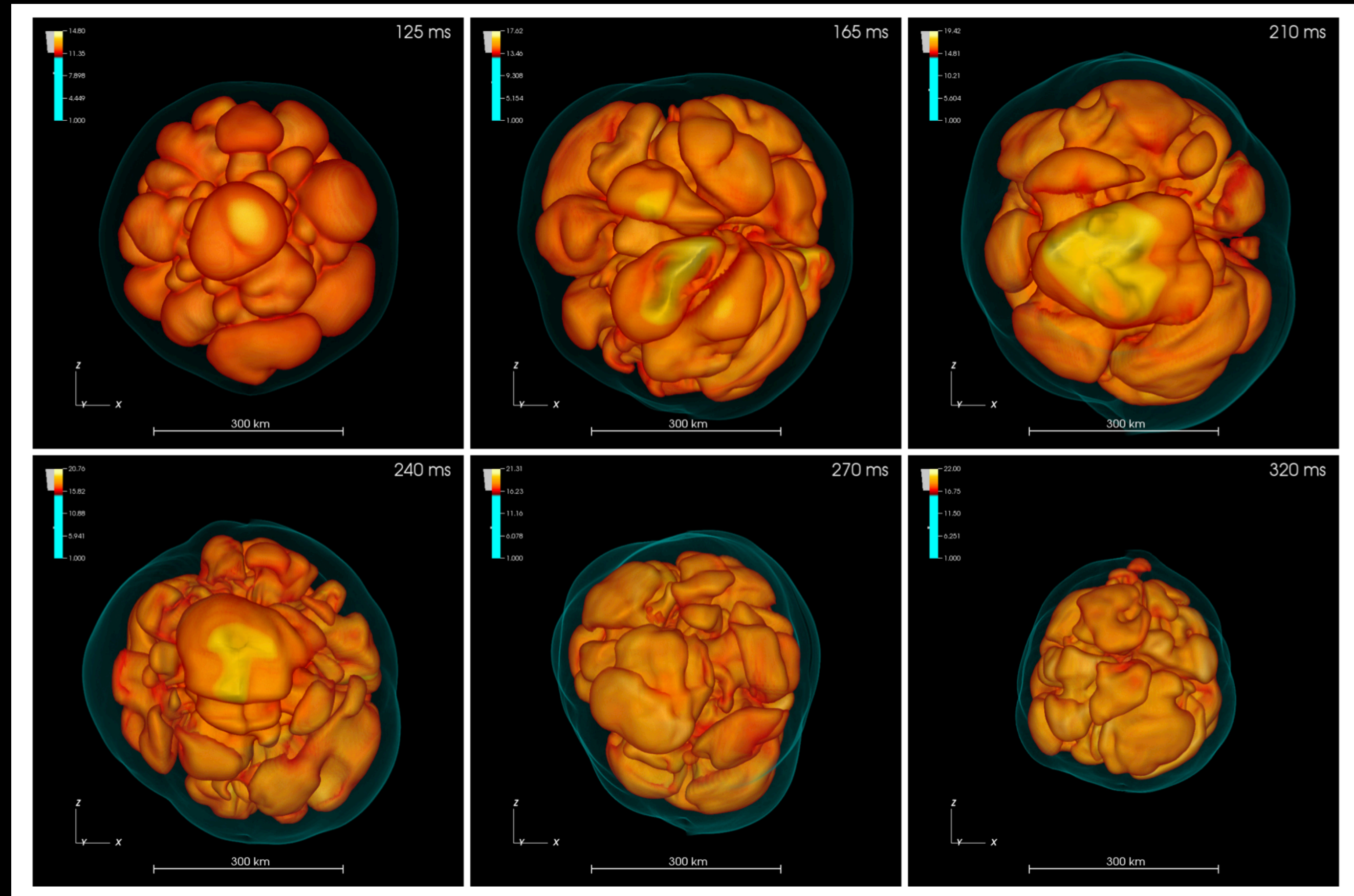
EXPLOSION MECHANISM

Stage II: Accretion



Convection, instability:

Standing Accretion Shock Instability (SASI)



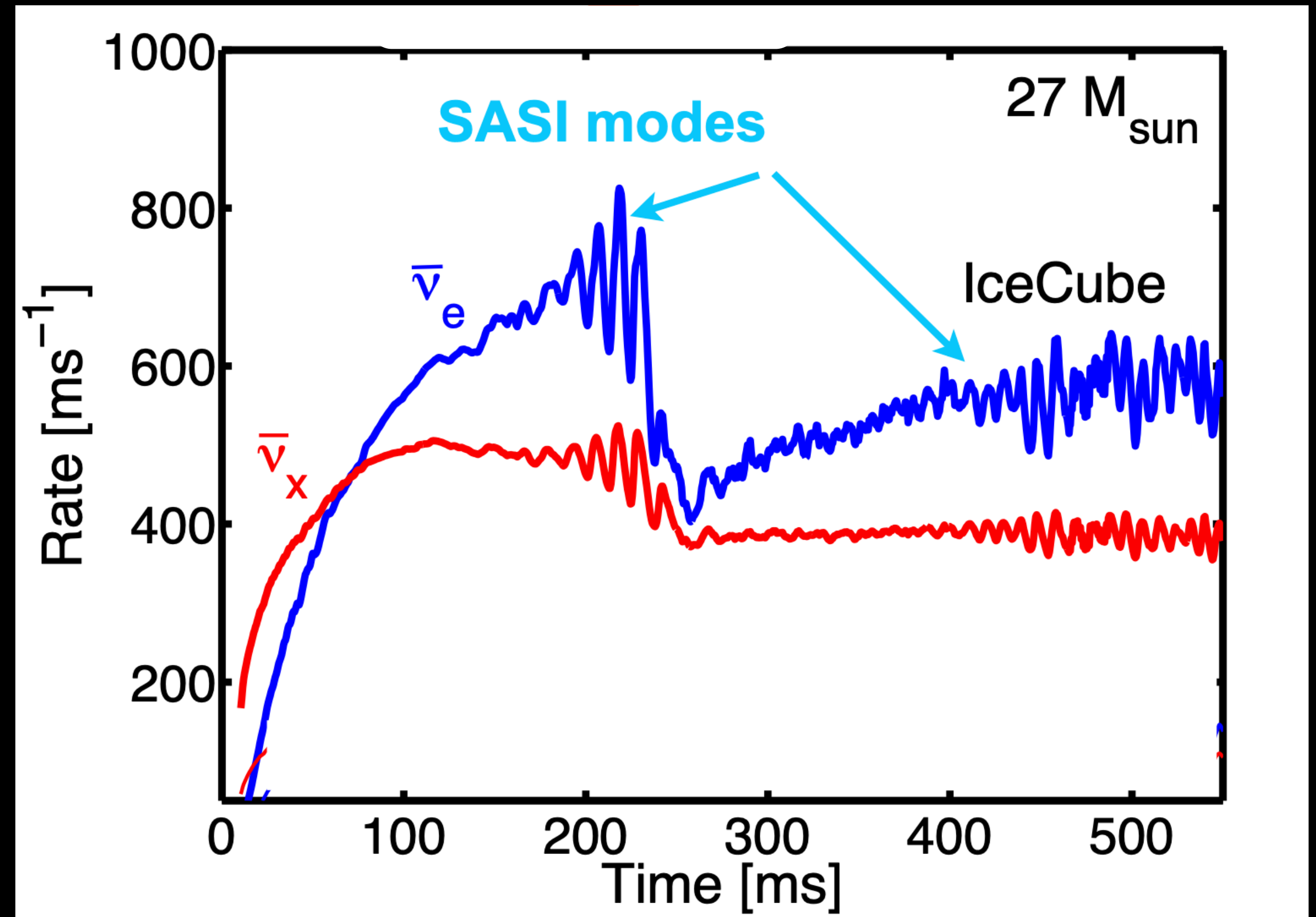
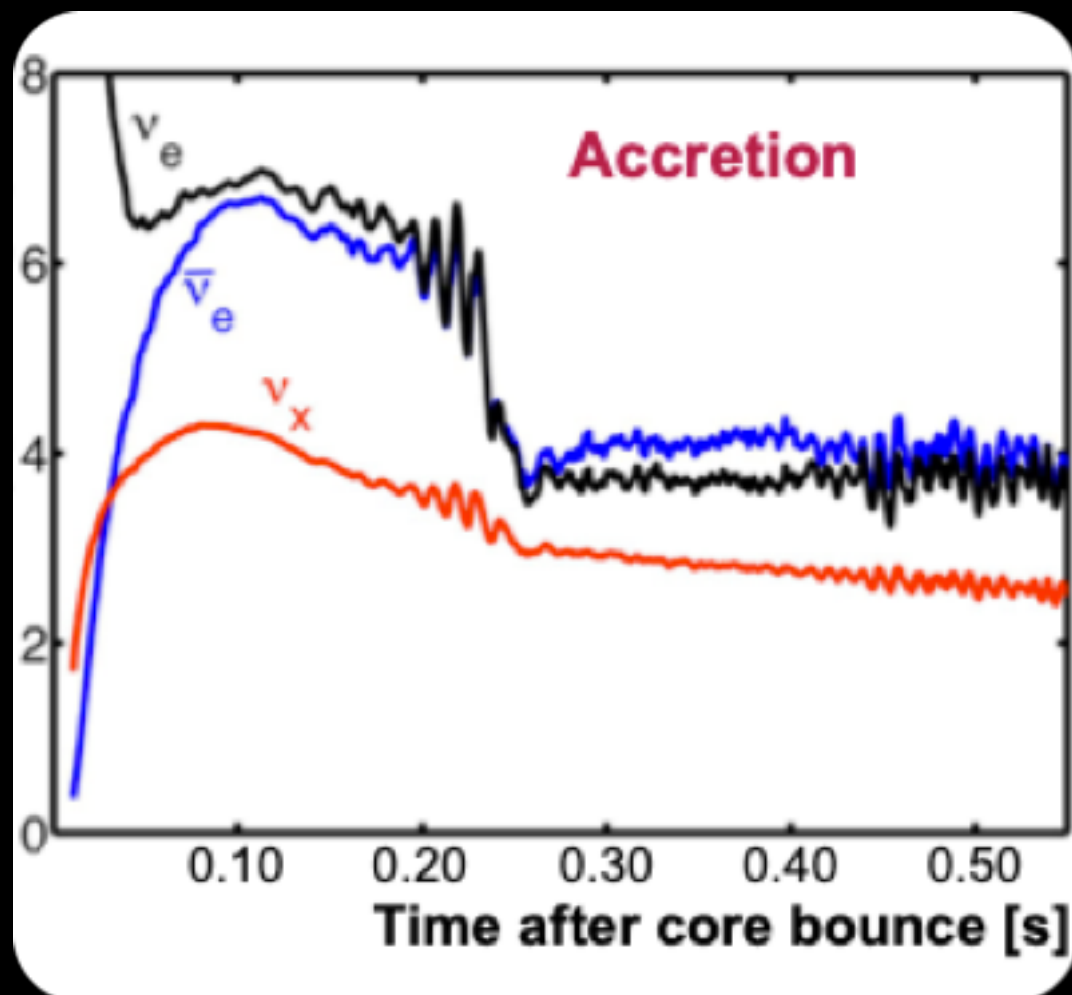
WHAT CAN WE PROBE WITH NEUTRINOS

Convection, instability:

SASI frequency evolution = shock radius evolution

EXPLOSION MECHANISM

Stage II: Accretion



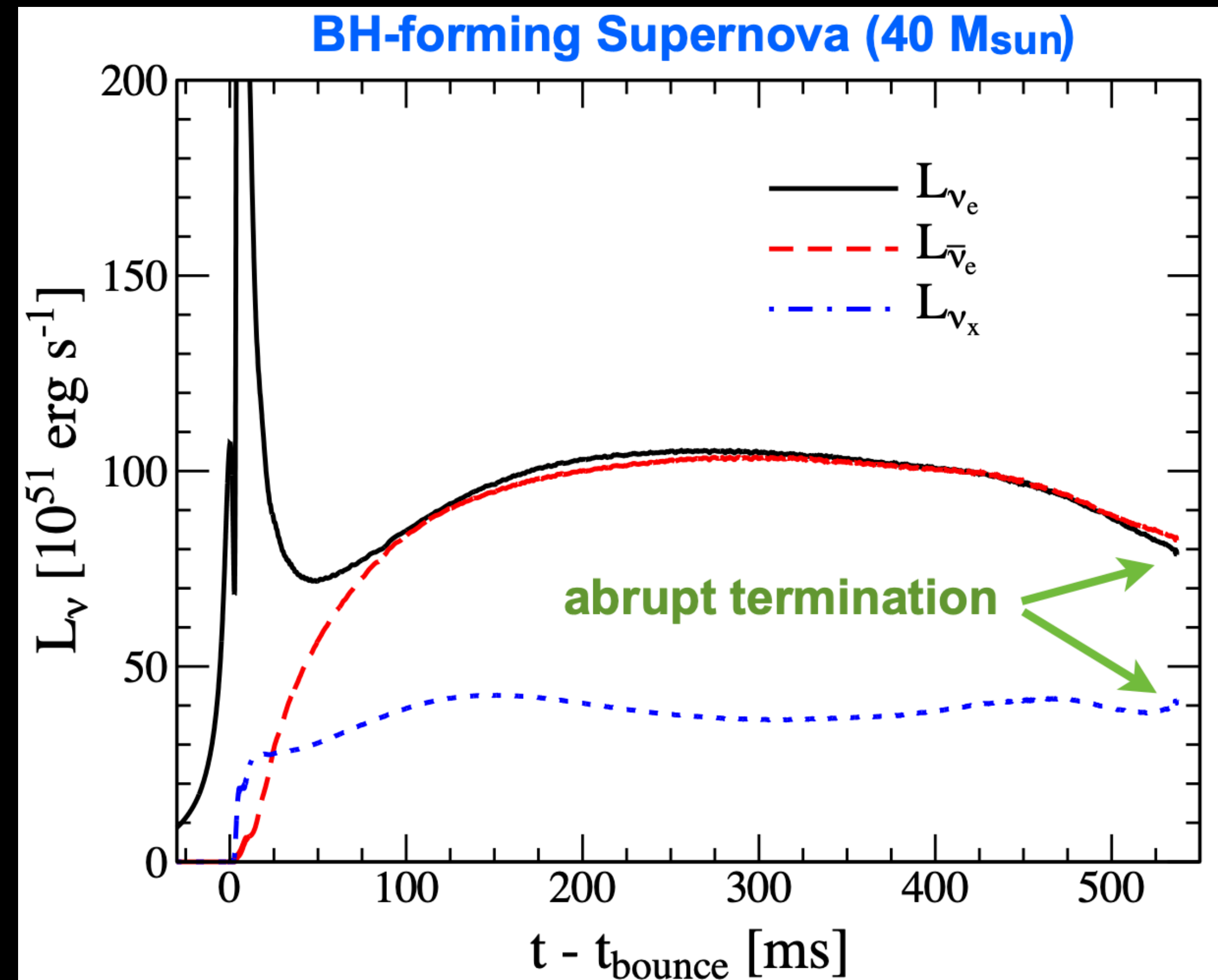
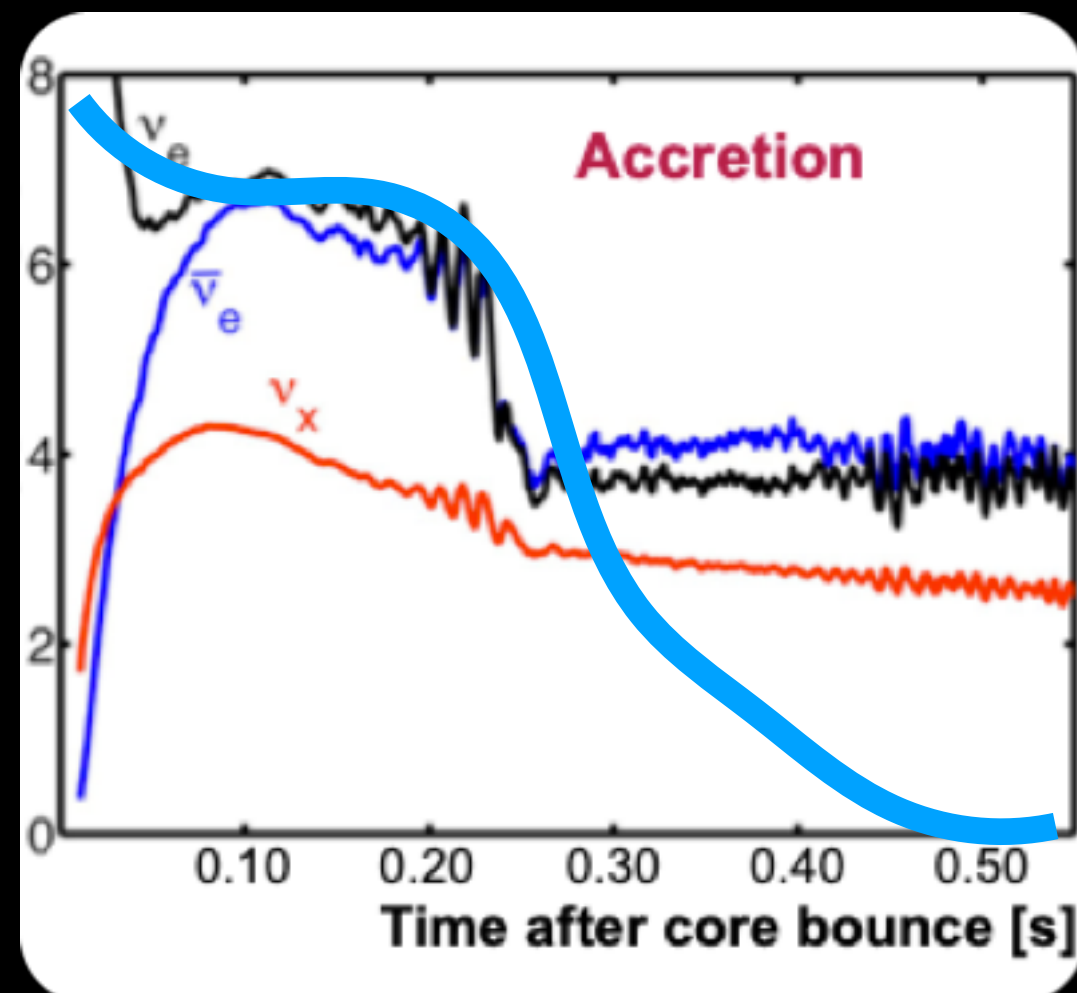
[I. Tamborra et. Al., PRL 111:121104 \(2013\)](#)

WHAT CAN WE PROBE WITH NEUTRINOS

Failed CCSNe
fraction: 4-43%

BLACK HOLE FORMATION

Stage II: Accretion

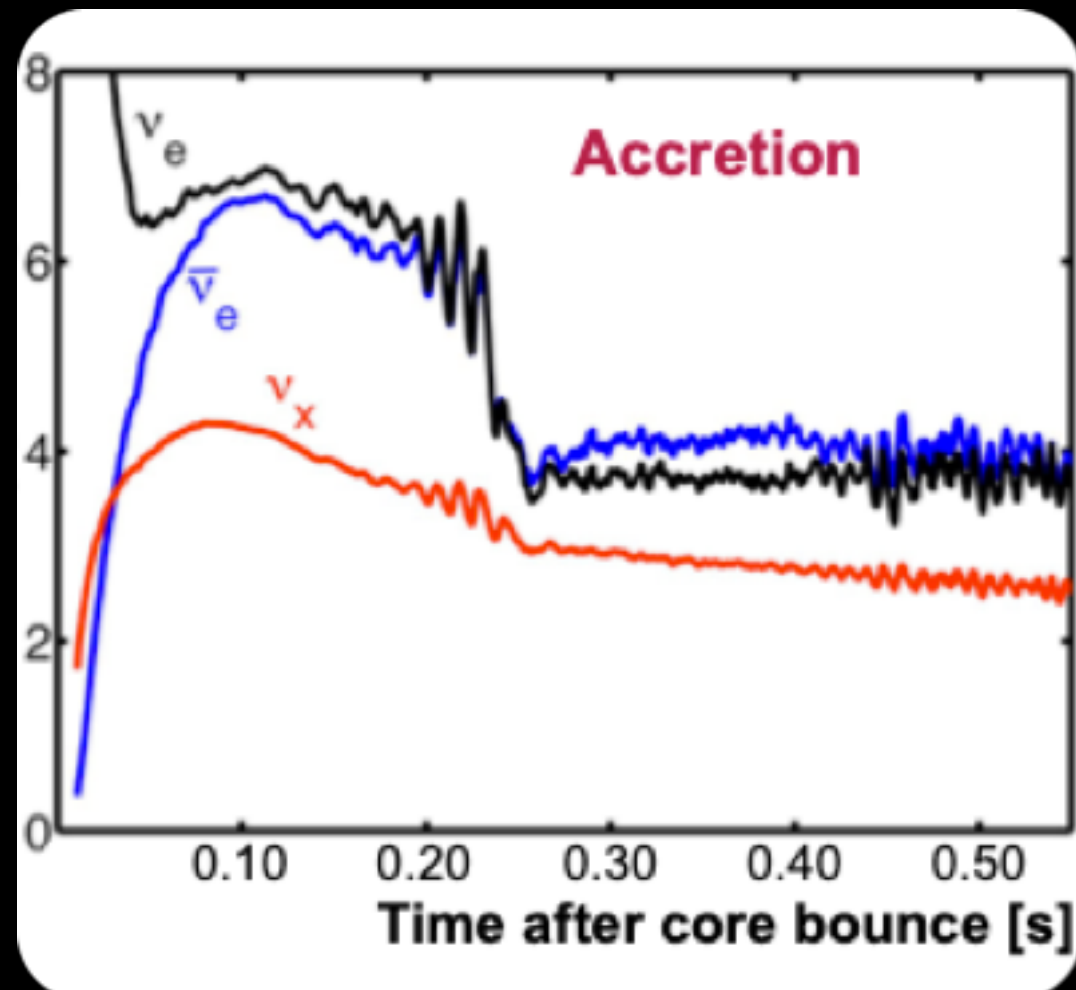


WHAT CAN WE PROBE WITH NEUTRINOS

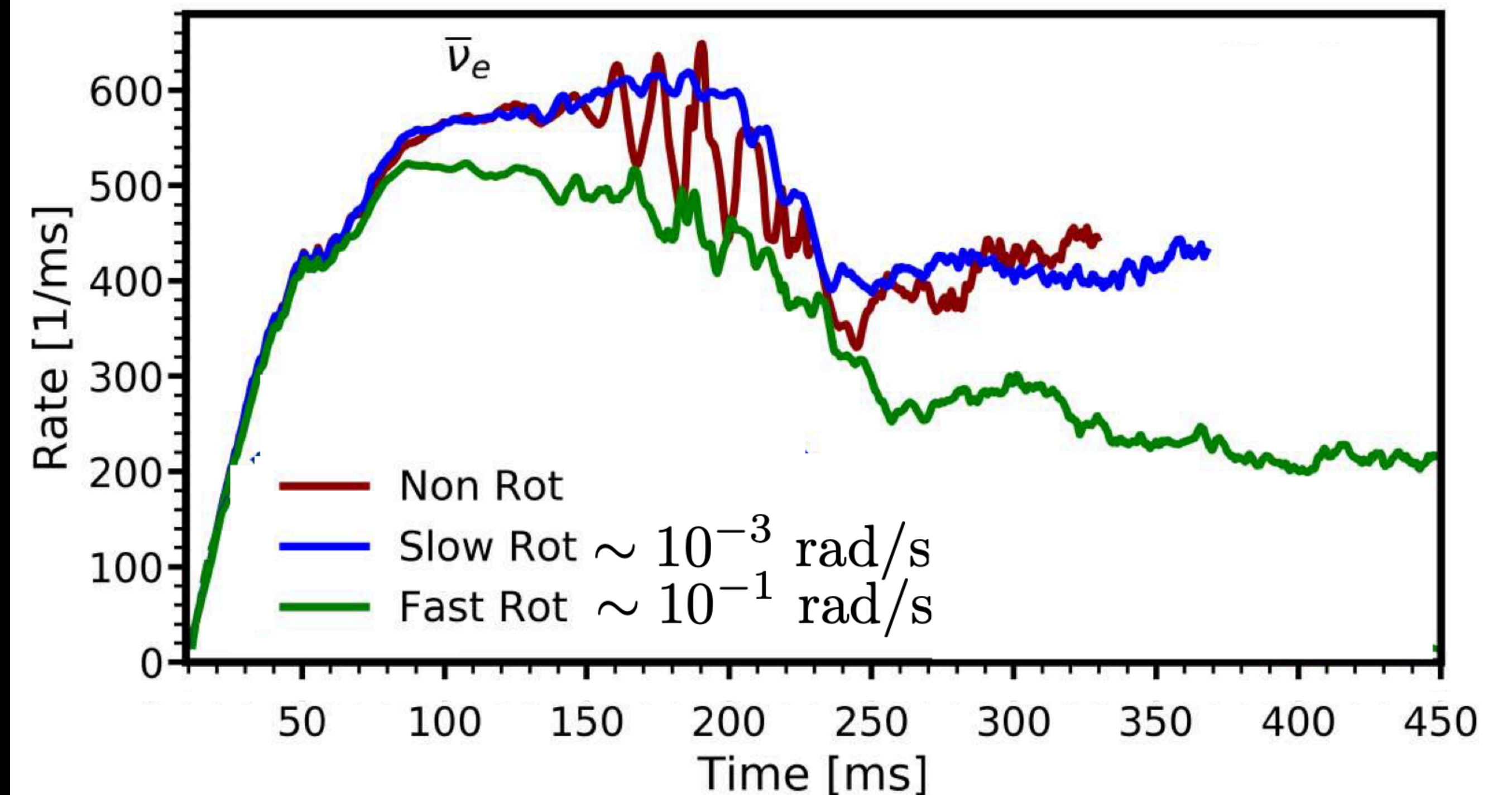
EXPLOSION MECHANISM

SUPERNOVA ROTATION

Stage II: Accretion



Depending on rotation, it would smear out the SASI



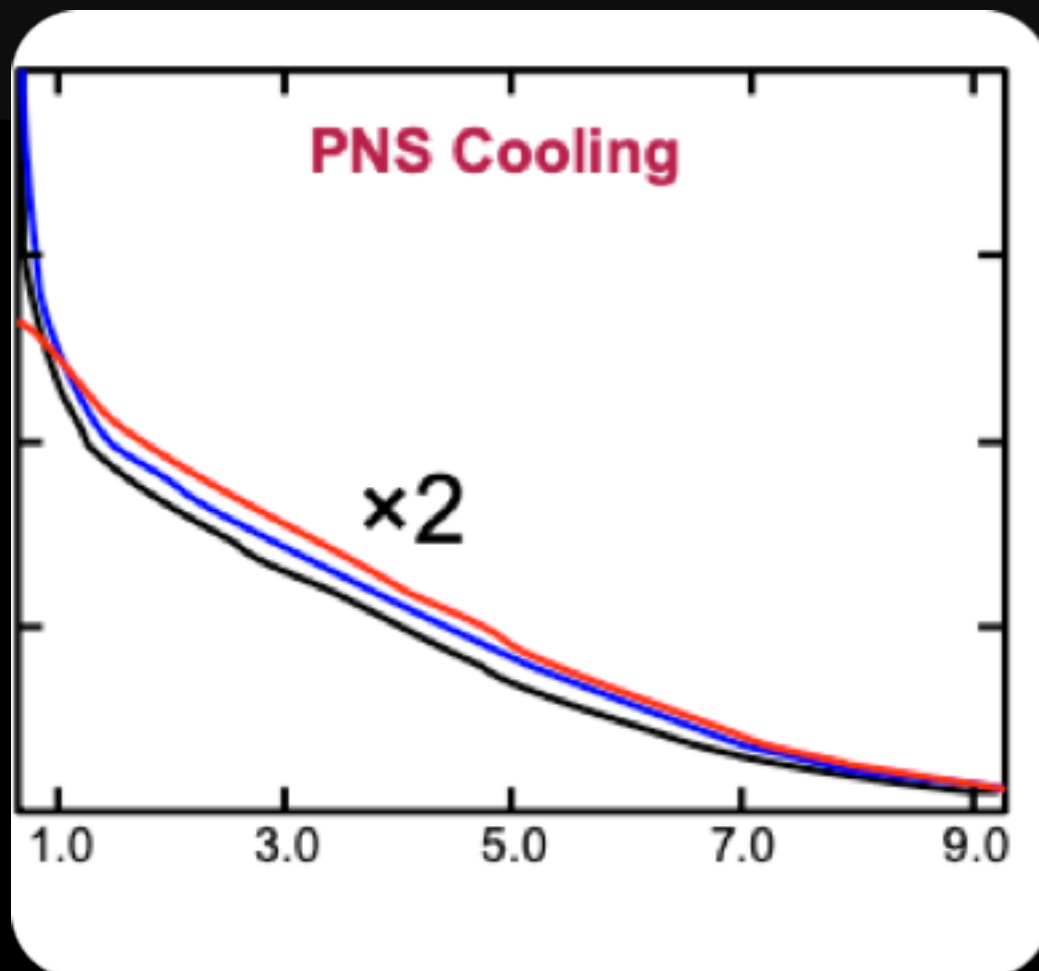
$15M_{\odot}$

WHAT CAN WE PROBE WITH NEUTRINOS

EXPLOSION MECHANISM

NUCLEOSYNTHESIS

Stage III: Cooling



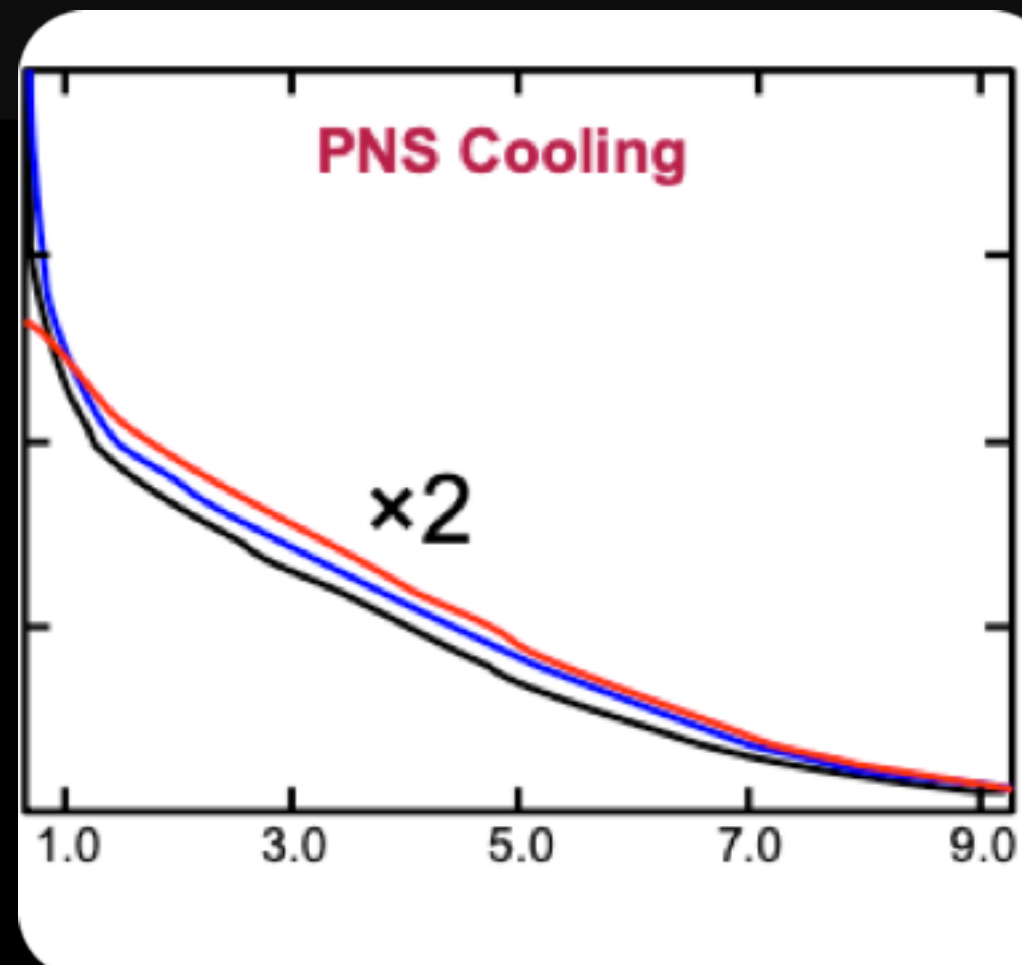
- Nucleosynthesis of new elements cannot happen without neutrinos —> They set the electron fraction Y_e
 - $\nu_e + n \rightarrow p + e^-$
 - $\bar{\nu}_e + p \rightarrow n + e^+$
- Neutron/proton ratio in the ejecta
- Neutrinos drive something called the ‘neutrino wind’ (an outflow) —> The **neutrino flavor**, luminosity and energy can decide which nuclei form

WHAT CAN WE PROBE WITH NEUTRINOS

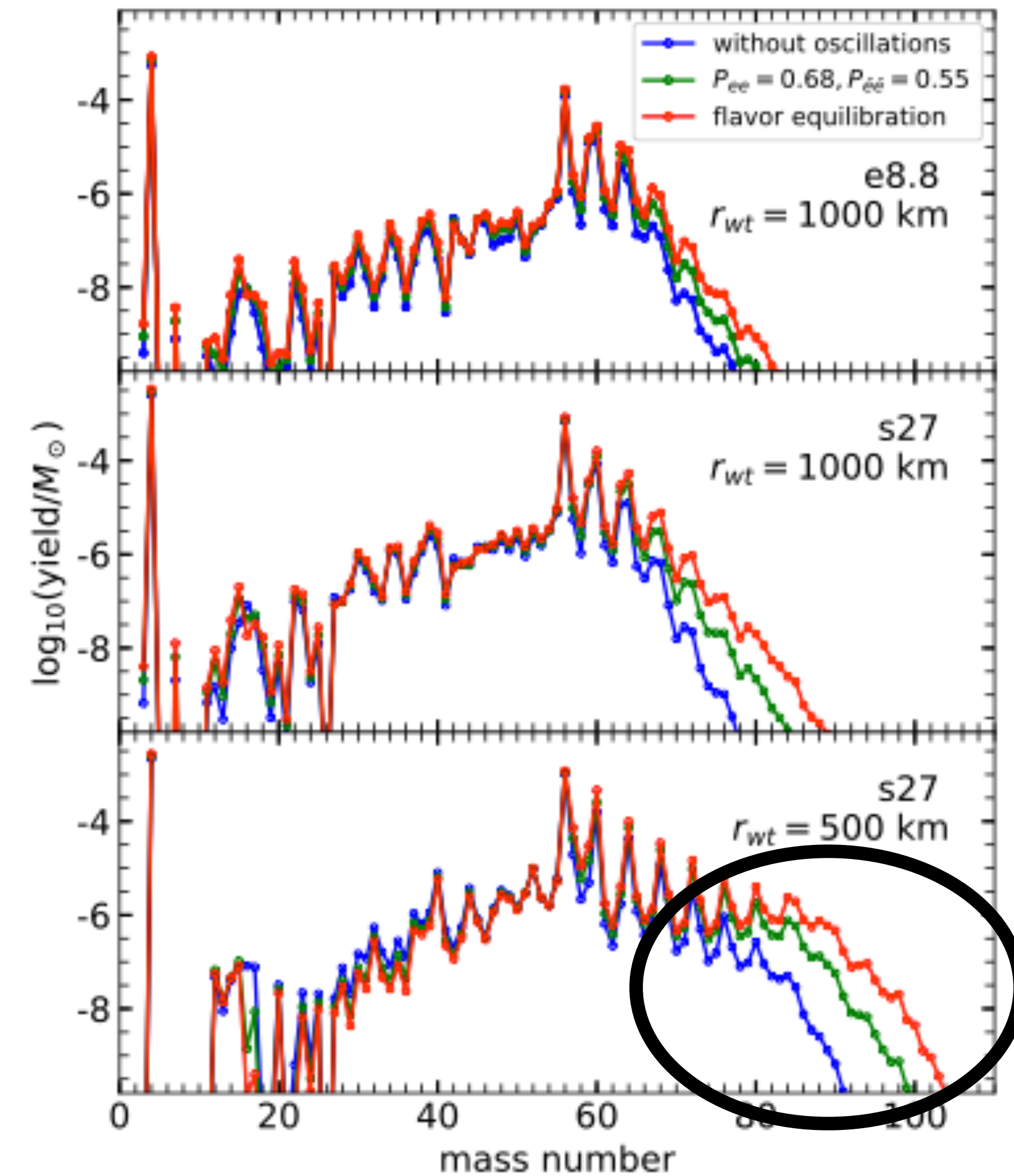
EXPLOSION MECHANISM

NUCLEOSYNTHESIS

Stage III: Cooling



Fast flavor oscillation:
More proton-rich, heavier nuclei ($A > 60$) can be produced via νp -process

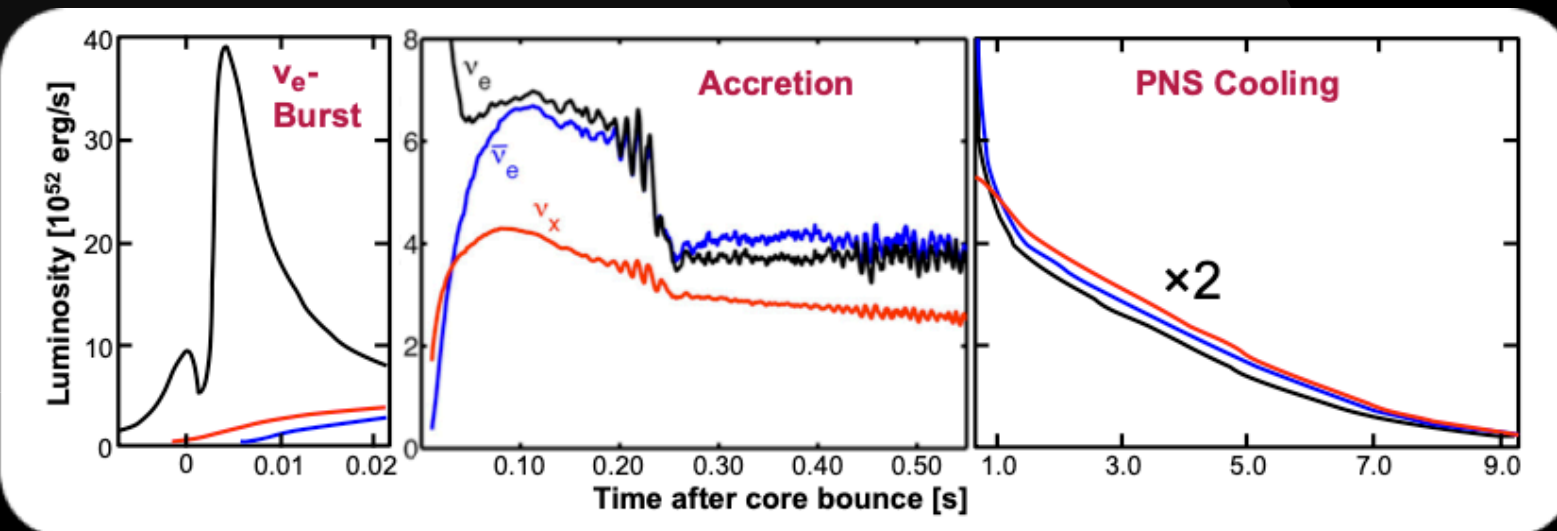


WHAT CAN WE PROBE WITH NEUTRINOS

EXPLOSION MECHANISM

NEUTRINO PHYSICS / PARTICLE PHYSICS

Stage I to III

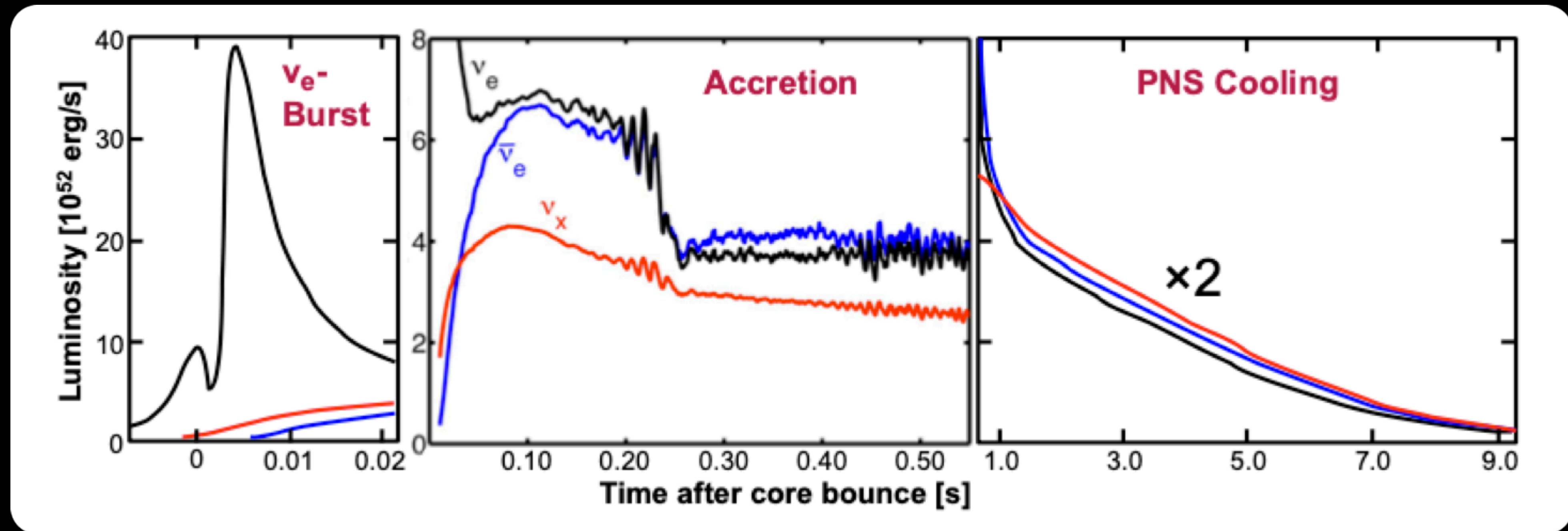


The next Galactic SN will be the ultimate neutrino experiment

- Neutrino mass ordering
- Time-of-flight limits on absolute neutrino mass
- Neutrino self-interactions
- MSW effects in the stellar envelope
- Non-standard interactions
- Sterile neutrinos
- Exotics —> Will touch on this

RECAP

Throughout: BSM, oscillation



Signal independent on the SN mass and EoS:

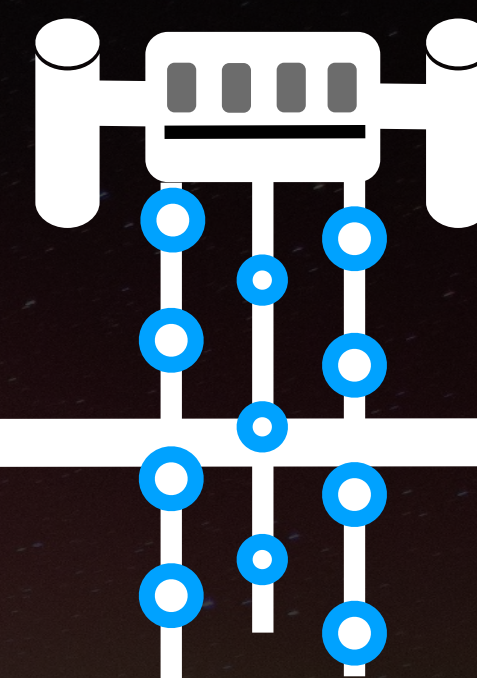
- SN distance (pseudo-standard candle)

Signal dependent on mass, EoS and 3D effects:

- Core collapse astrophysics (convection, BH formation)

Dependent on EoS and mass:

- Nuclear physics: Nucleosynthesis. Fast flavor oscillation can affect how heavier nuclei are formed

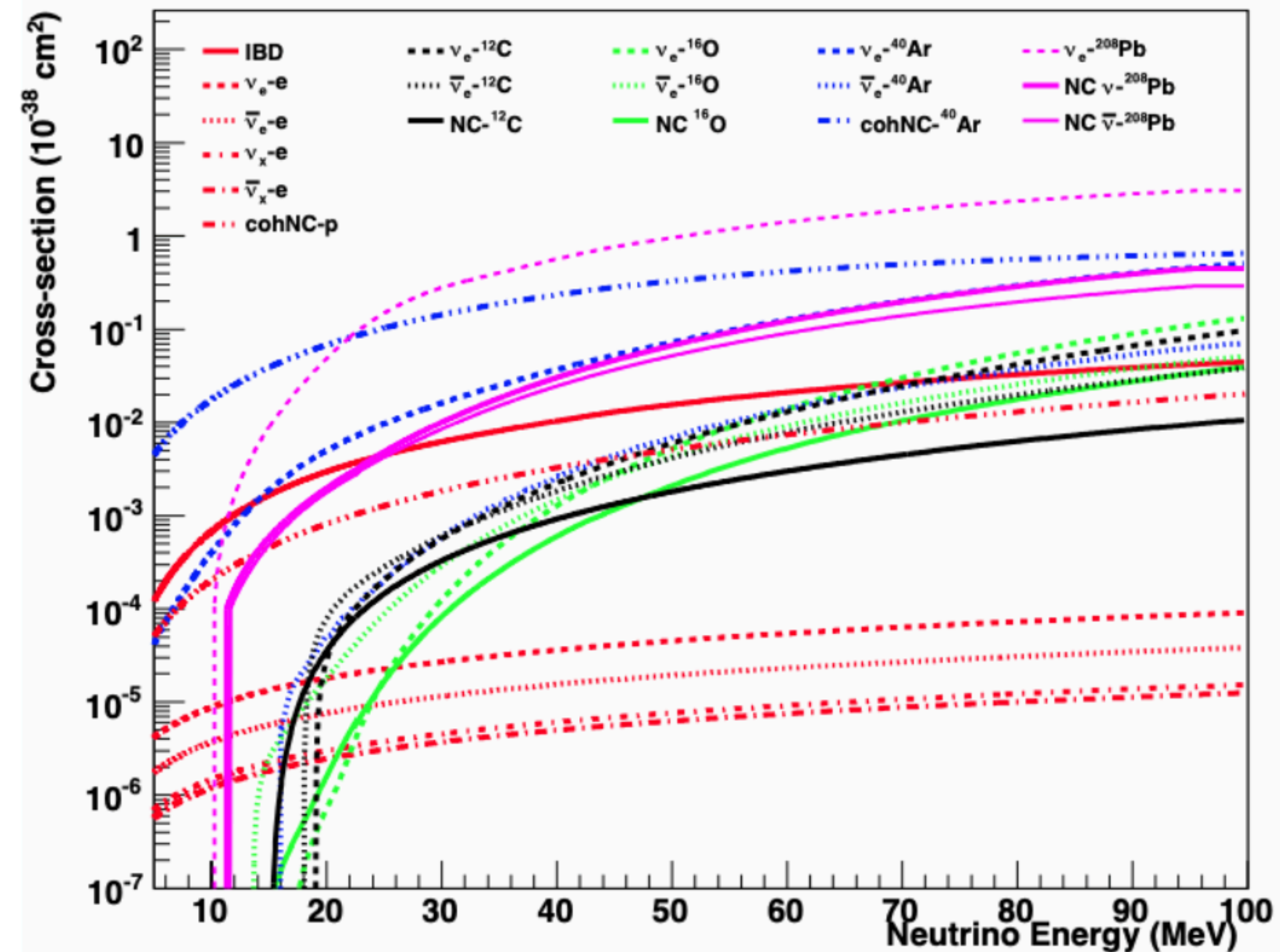
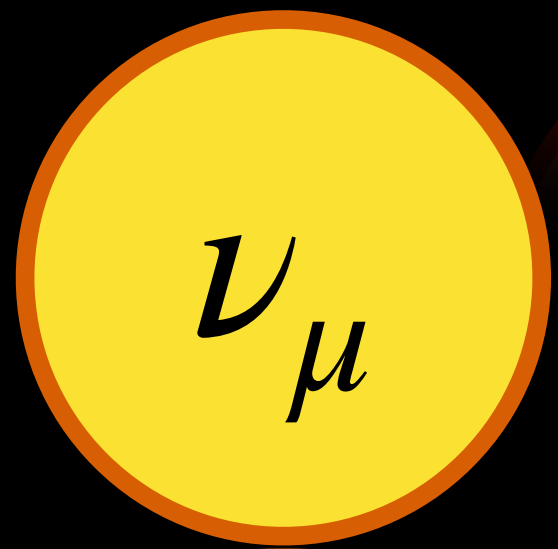
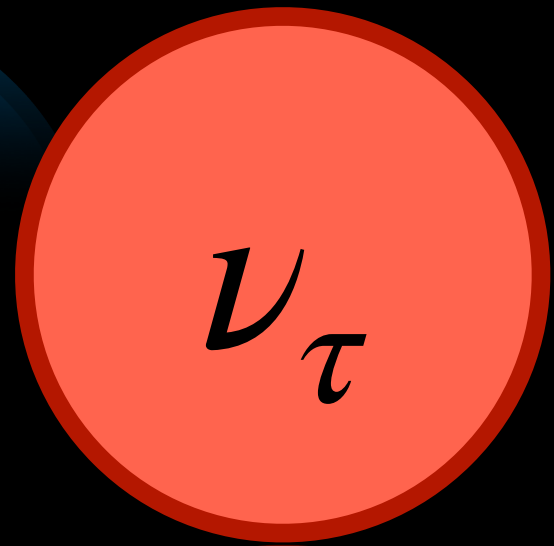
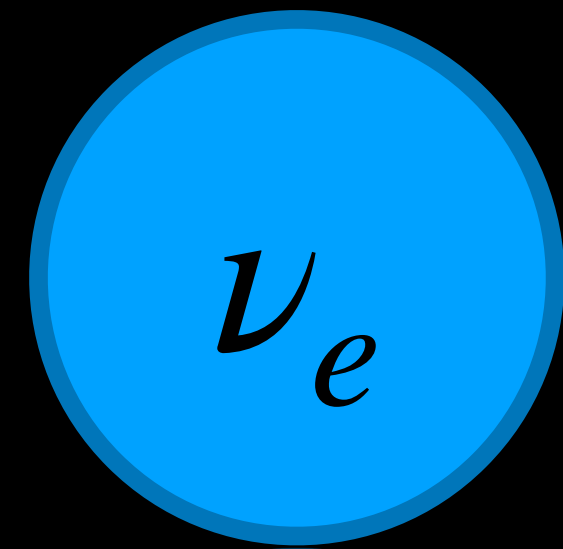


I come from a particle
physics background

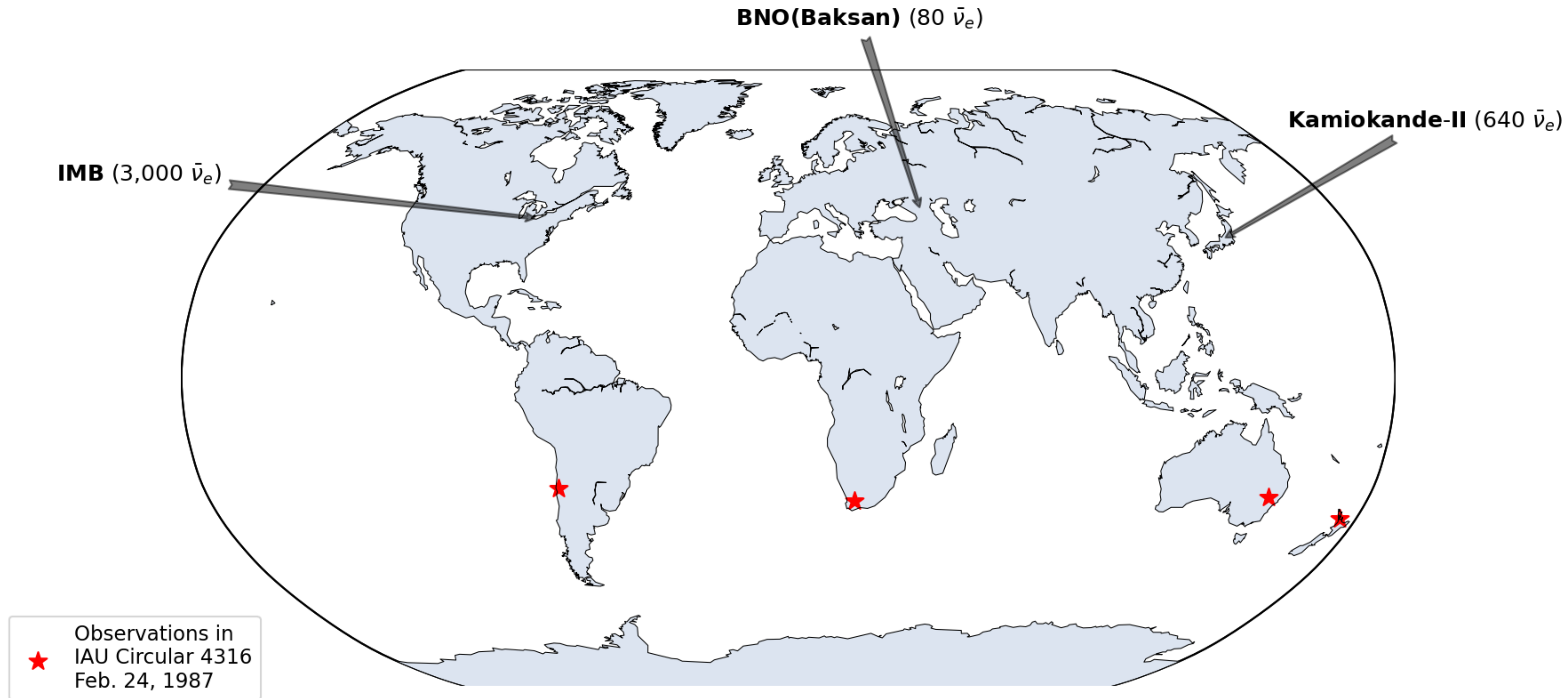
HOW DO WE OBSERVE THESE NEUTRINOS

FLAVOR SENSITIVITY

- Different luminosities expected for each flavor
 - Different detector technologies required to observe different flavors
- We want large detector volumes to increase our chances of observing neutrinos

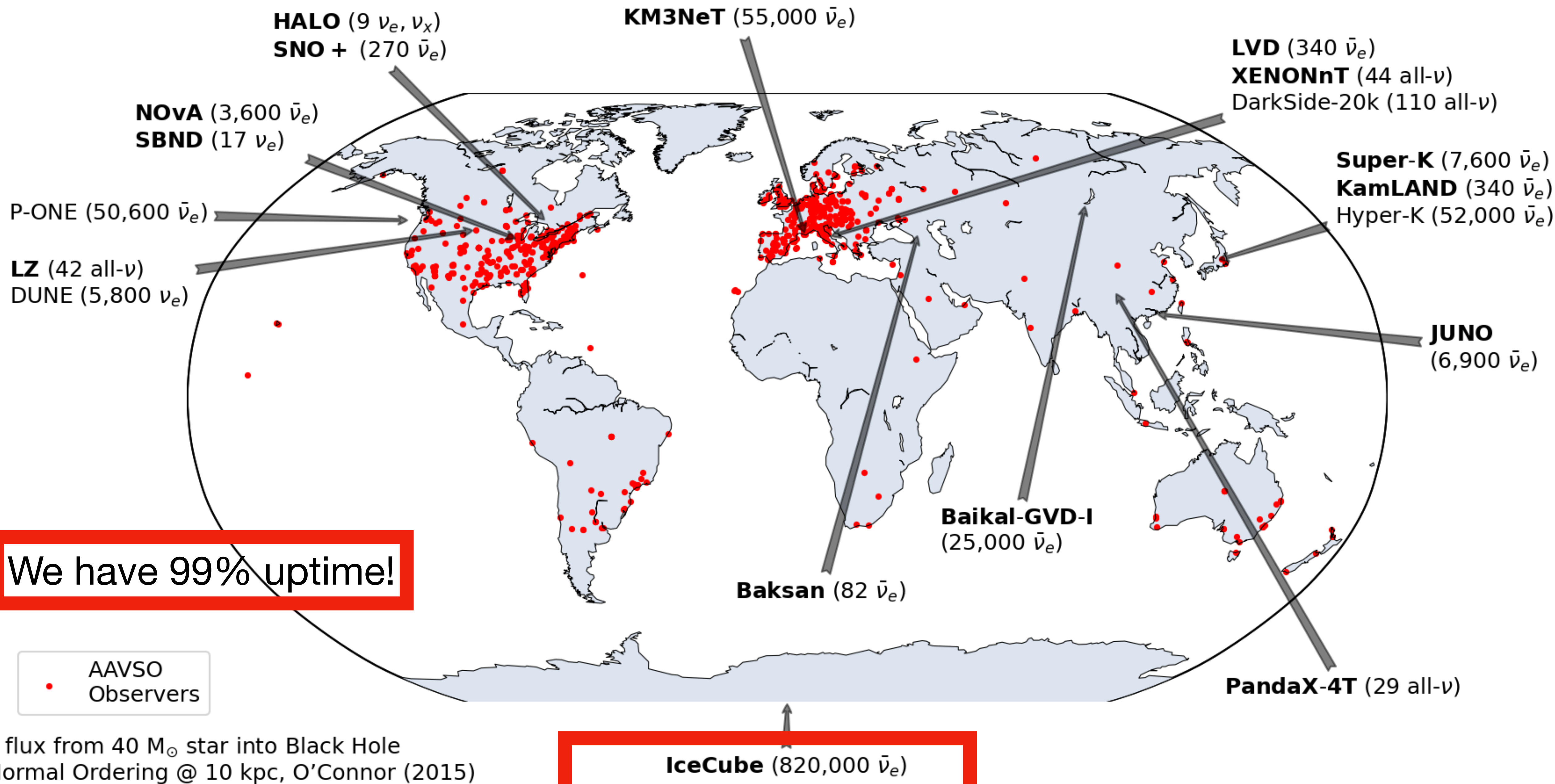


GC SENSITIVITY IN 1987



ν flux from 40 $M_{\odot}$ star into Black Hole
Normal Ordering @ 10 kpc, O'Connor (2015)

GC SENSITIVITY NOW



We have 99% uptime!

MeV to PeV sensitivity!

Astrophysical ν ($\sim 10^2 \text{yr}^{-1}$)

Atmospheric ν ($\sim 10^5 \text{yr}^{-1}$)

Atmospheric μ ($\sim 10^{11} \text{yr}^{-1}$)

Potential 'exotics' (Unknown)

ICECUBE

Astrophysics

Neutrino
Physics

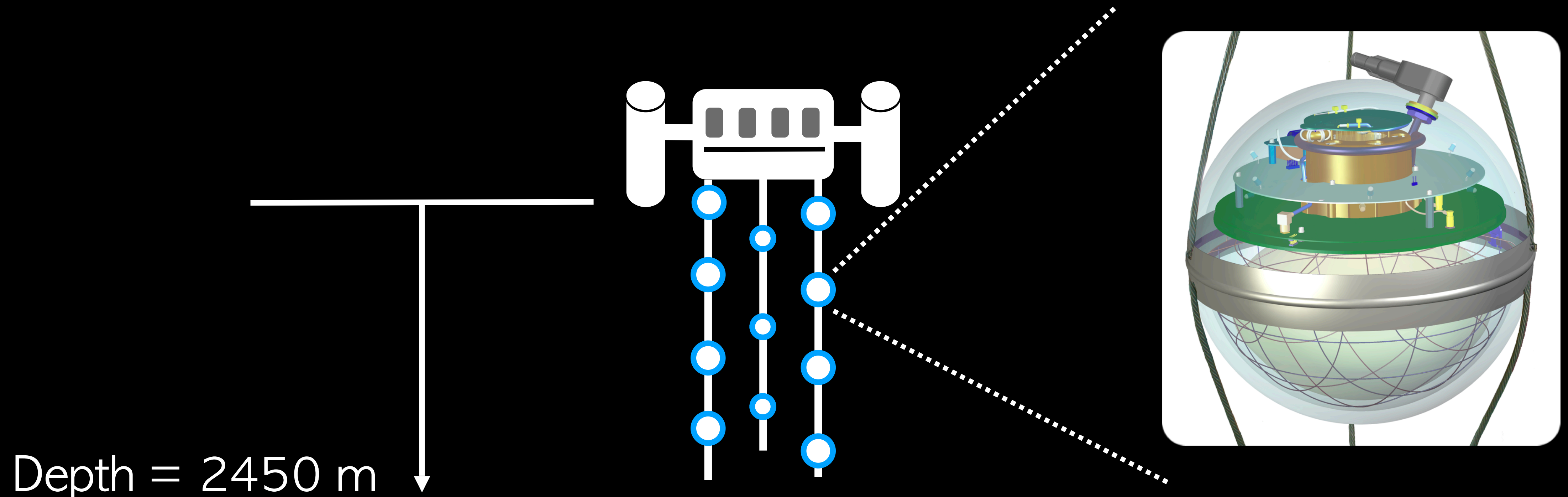
BSM

And much more!

ICECUBE

Located at the South Pole

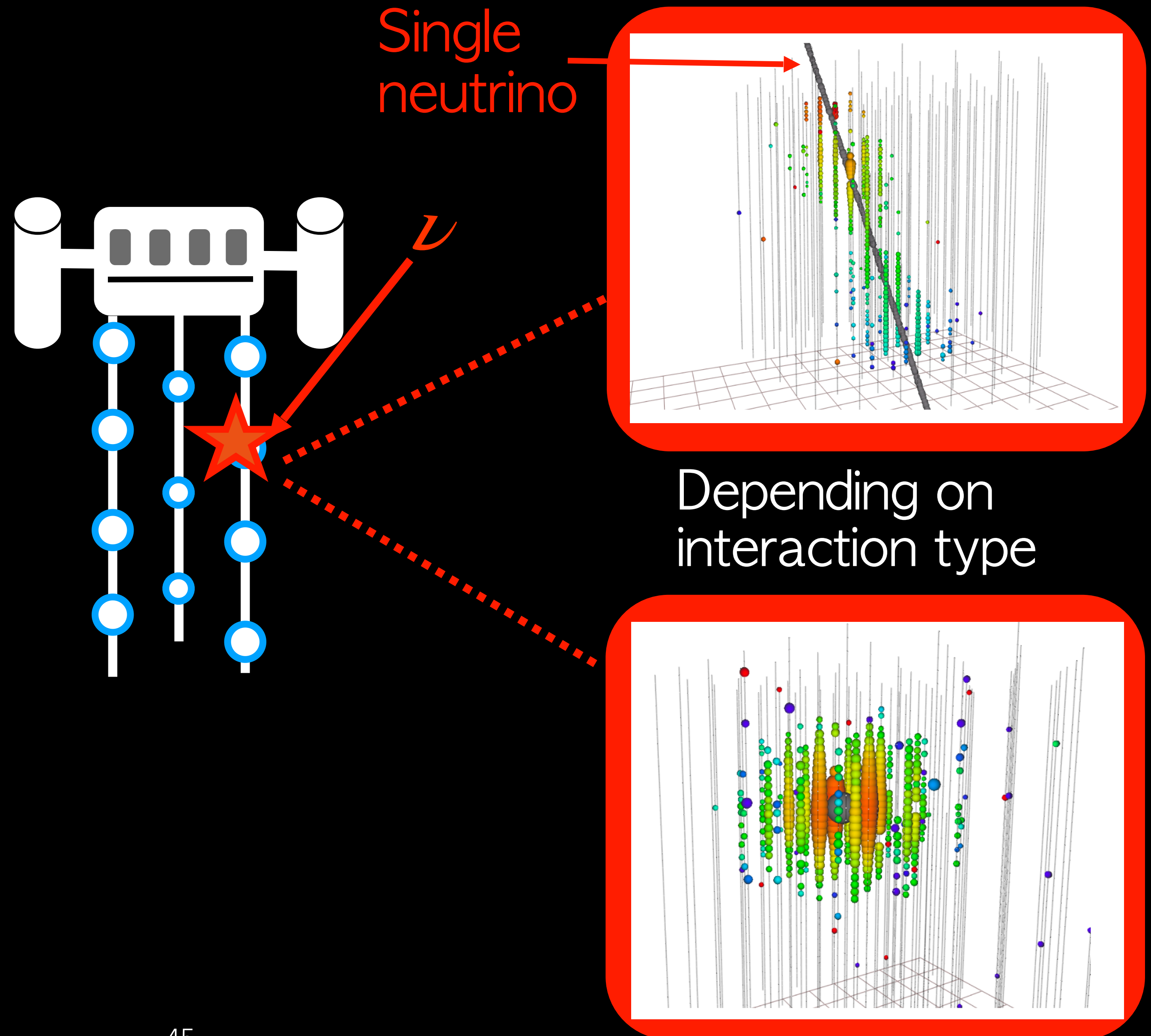
5160 sensors buried in 1km^3 of ice



We detect Cherenkov light produced when charged particles pass through ice

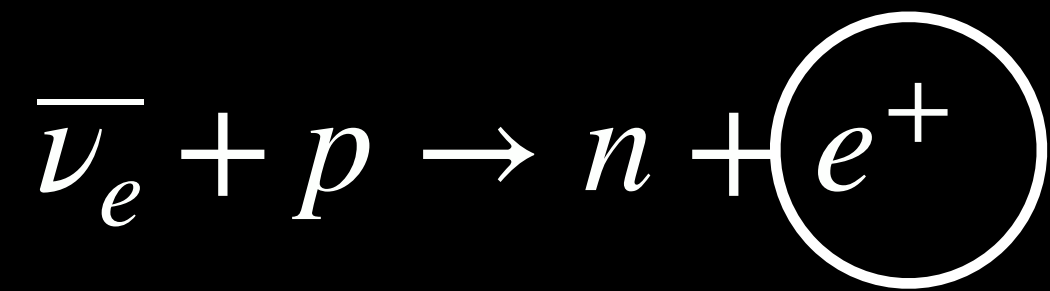
MeV ν

$>\text{GeV} - \text{PeV } \nu$



MeV ν

$>\text{GeV} - \text{PeV } \nu$

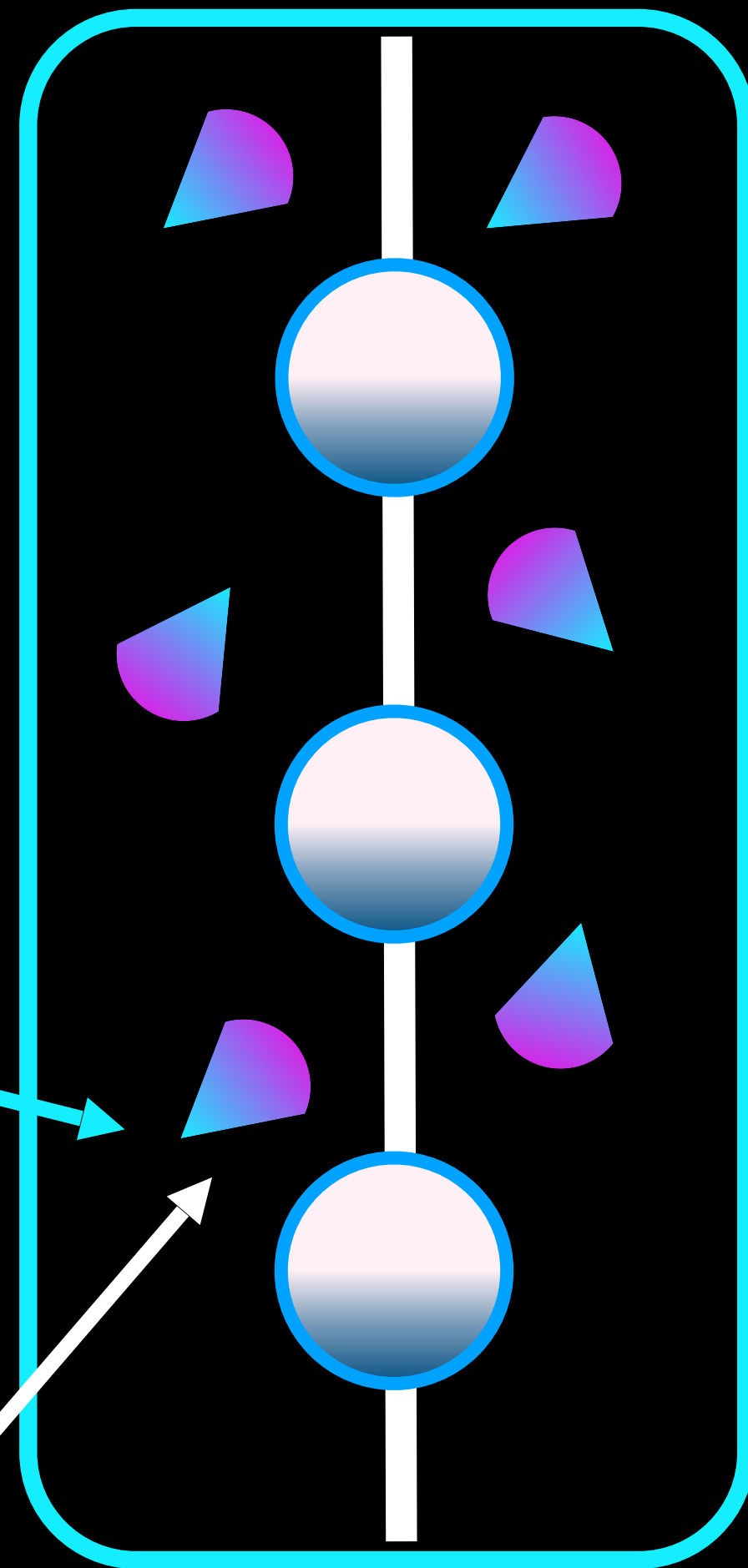


IBD is $\sim 94\%$ of interactions

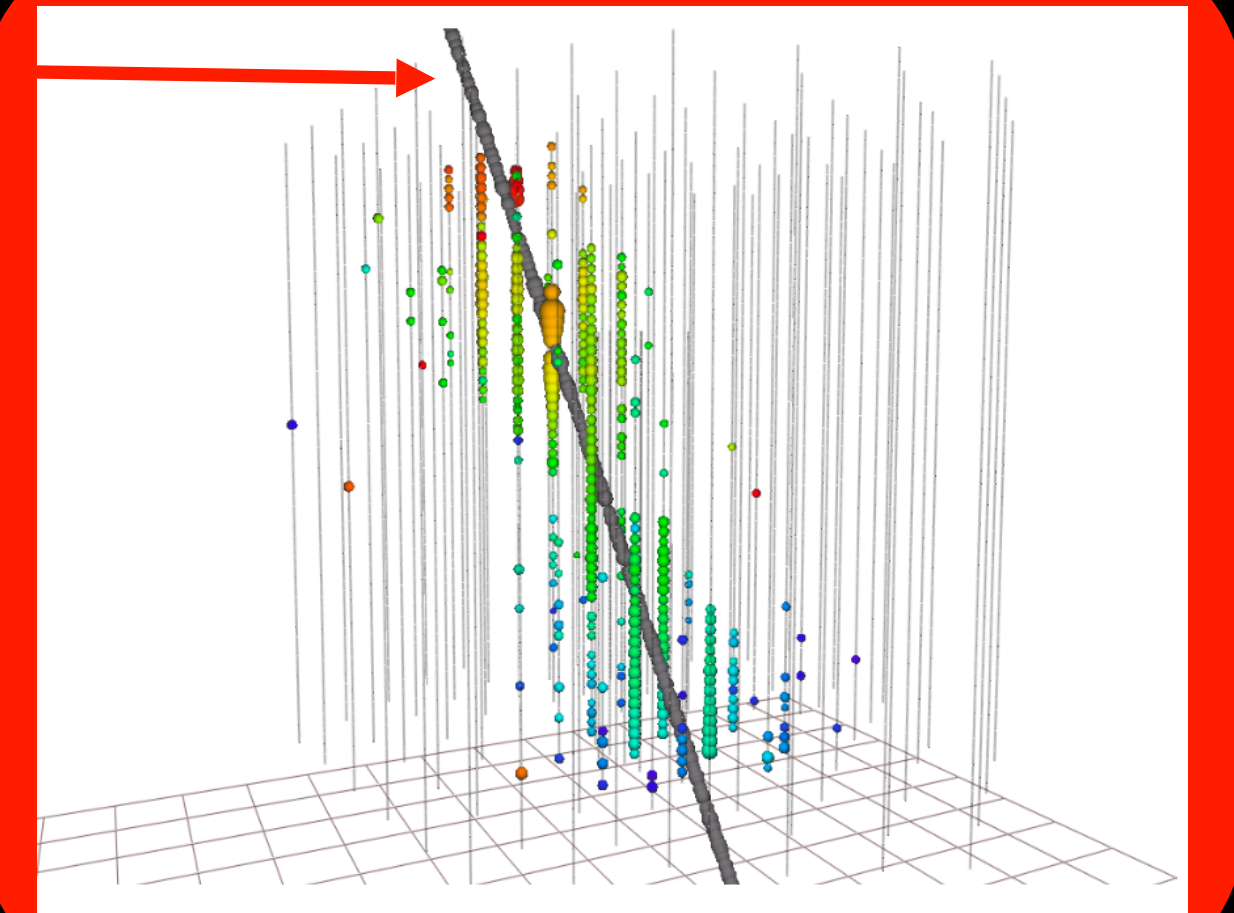
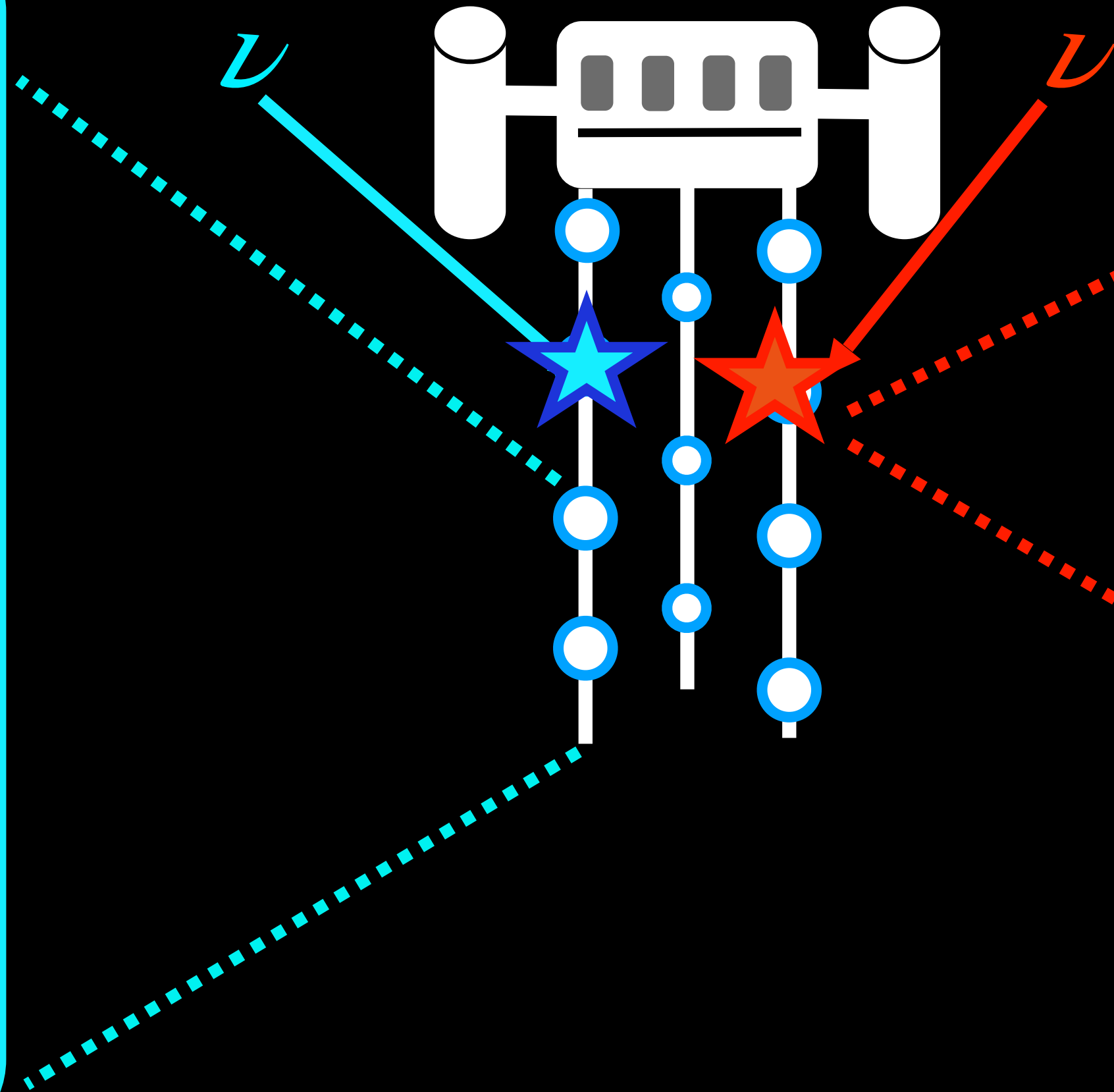
Single
neutrino

Single
neutrino
interaction

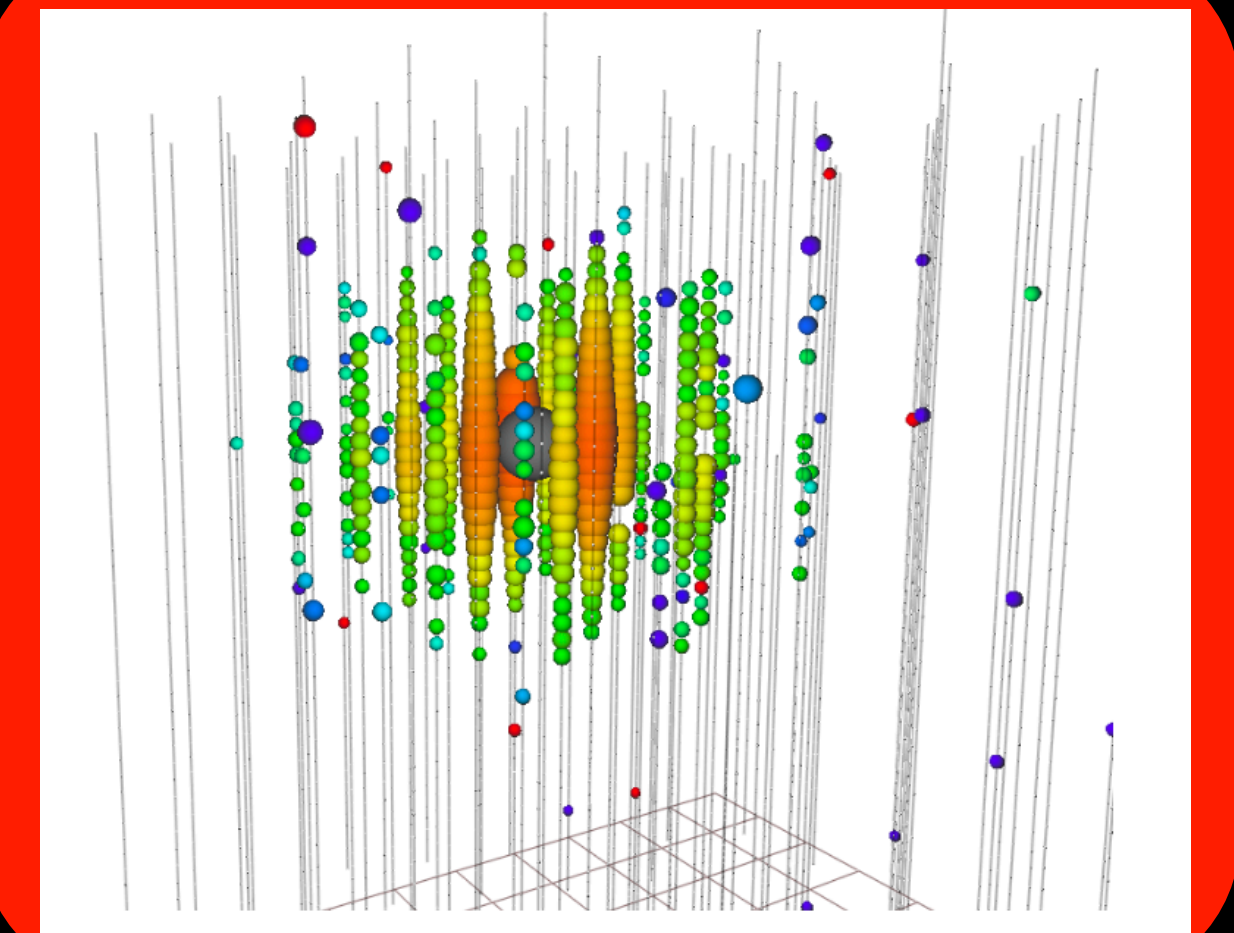
Cherenkov
light



Positron track length: $0.56 \text{ cm } (E_{e^+}/\text{MeV})$

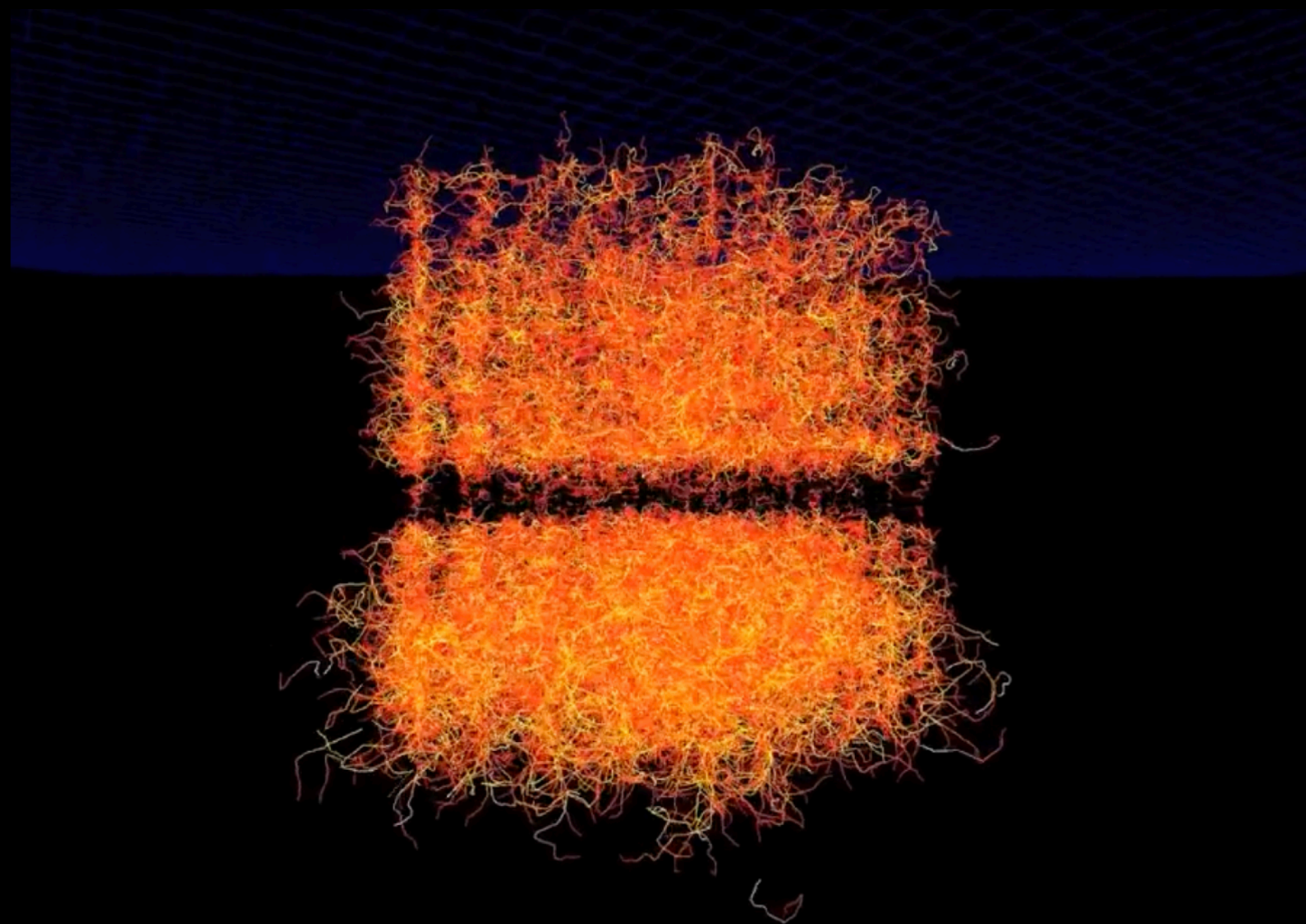


Depending on
interaction type

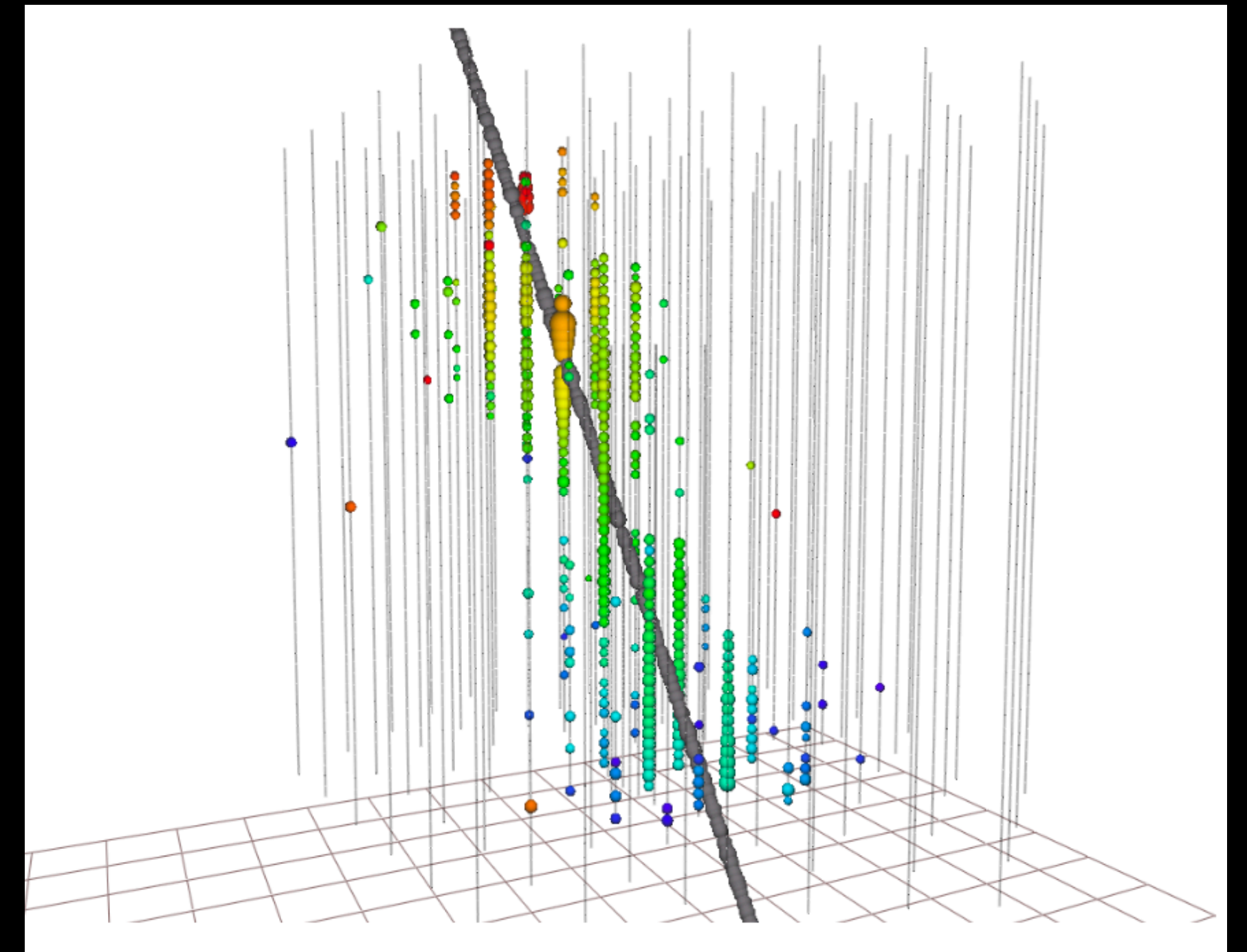
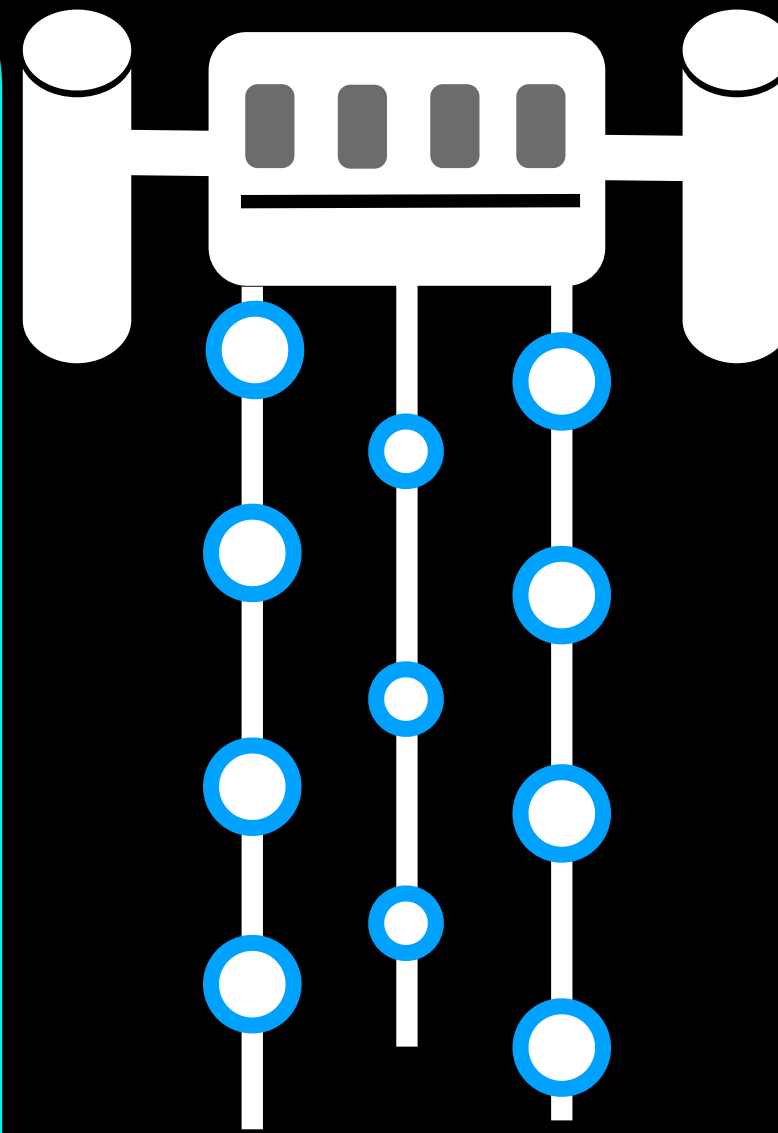


In-Ice MeV Interactions

Cannot extract directionality



But great statistics!



HOW WE SEARCH FOR MEV NEUTRINOS

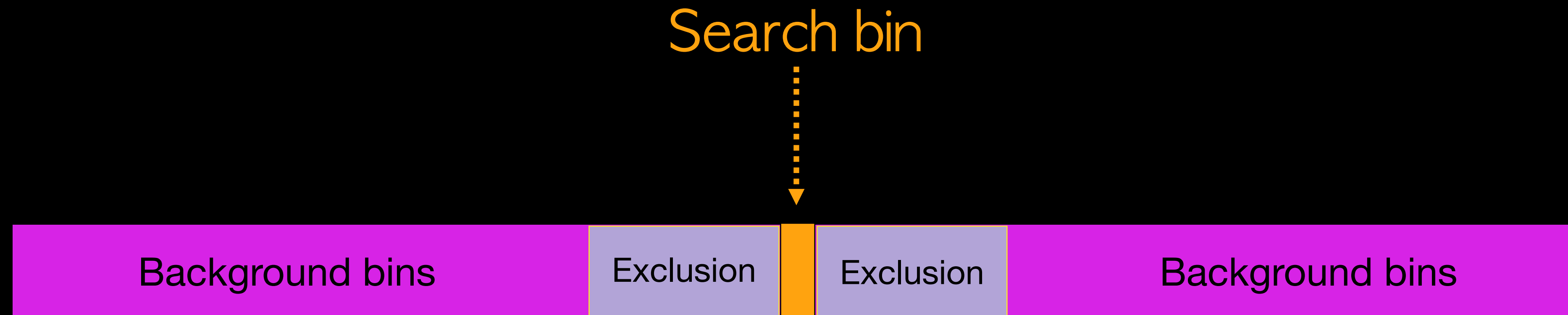
We look for a collective increase in detector rate

How significant is the deviation in the bin of interest compared to an average?

HOW WE SEARCH FOR MEV NEUTRINOS

We look for a collective increase in detector rate

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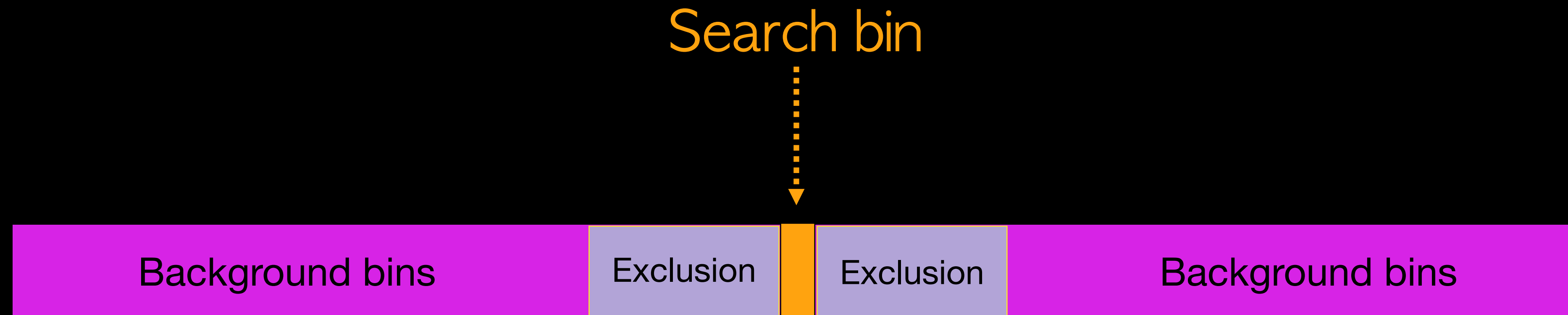


We compare the rate in the **search bin** to the average in the **background bins**.

HOW WE SEARCH FOR MEV NEUTRINOS

We look for a collective increase in detector rate

How significant is the deviation in the bin of interest compared to an average?

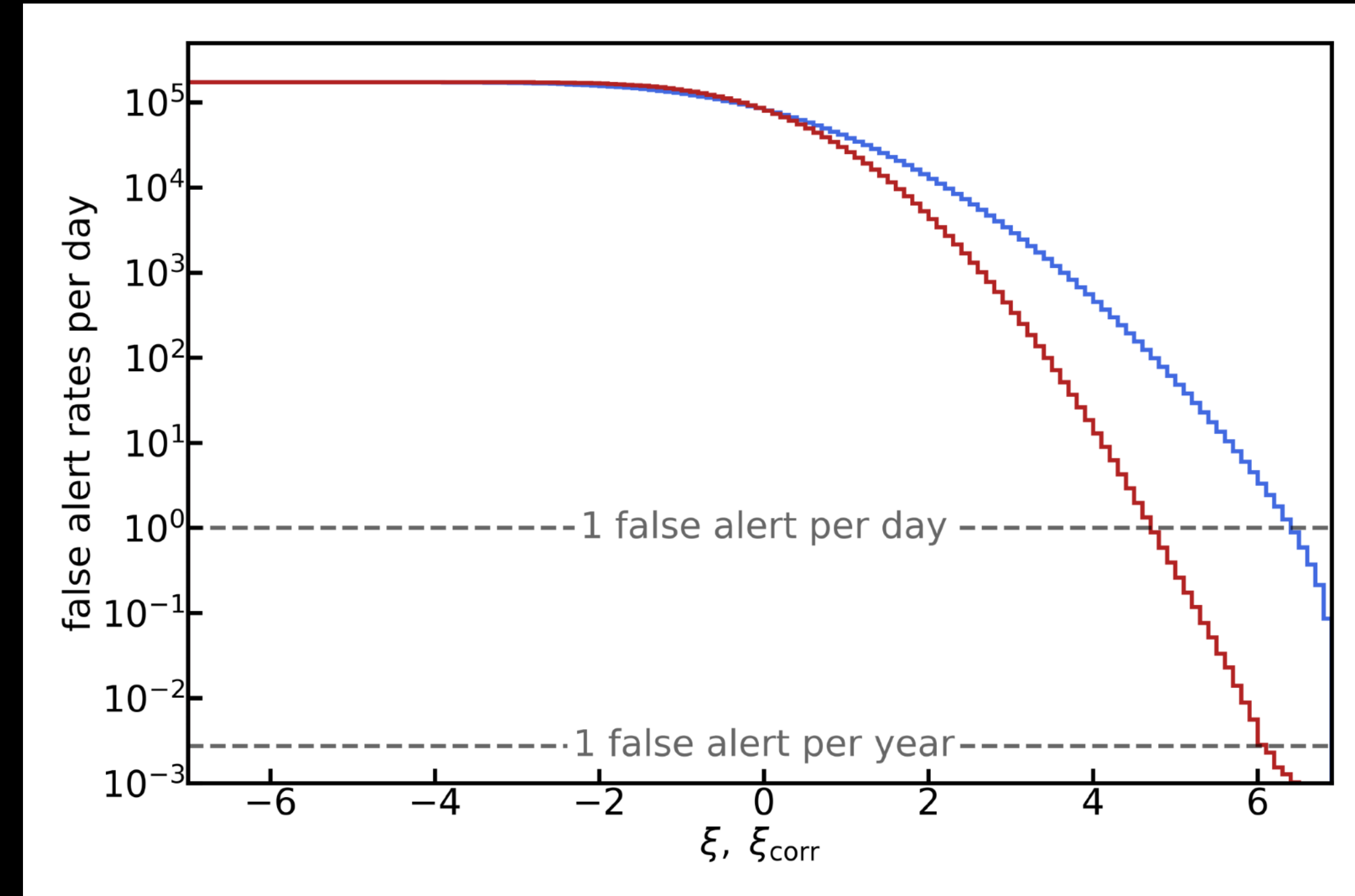


We compare the rate in the **search bin** to the average in the **background bins**.

This results in a test statistic $\xi = \frac{\Delta\mu}{\sigma_{\Delta\mu}} = \frac{\text{deviation from sliding average}}{\text{uncertainty of deviation}}$

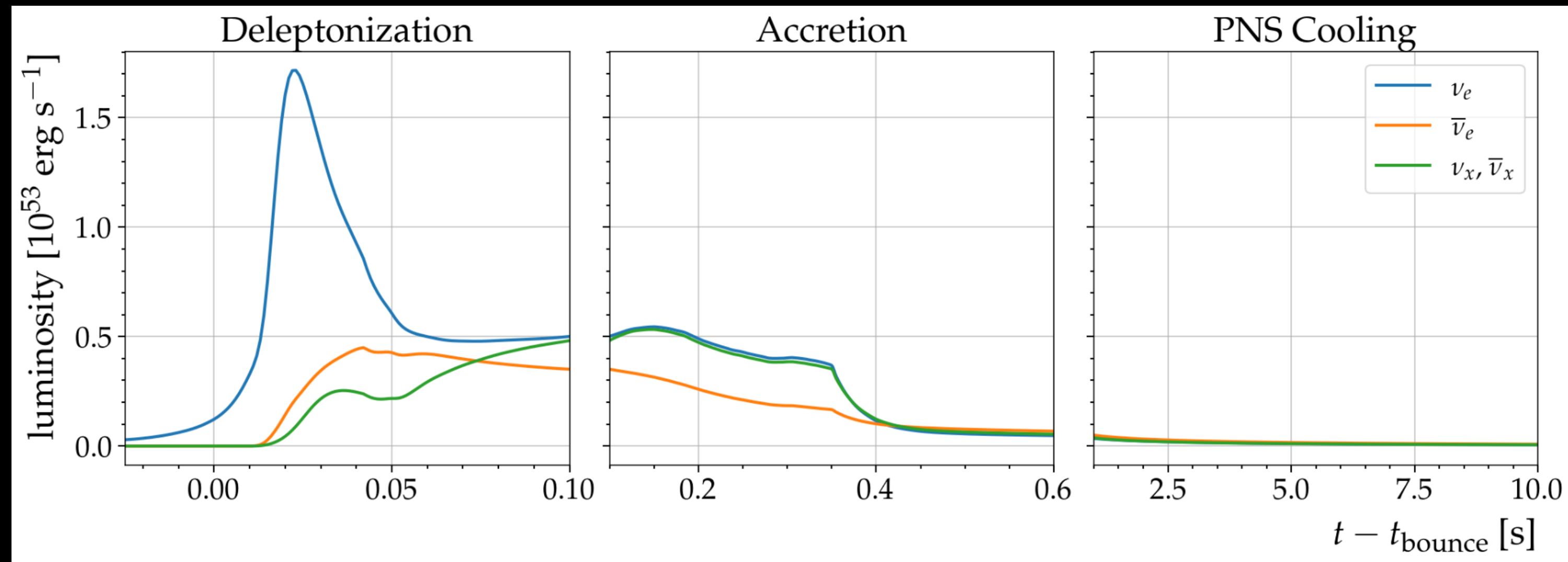
SUPERNOVA DATA ACQUISITION SYSTEM (SNDAQ)

- SNDAQ monitors the detector in realtime for an excess in detector hits
 - The test statistic ξ is used to form triggers in realtime
 - The aim is to have high-uptime $\rightarrow$ we are at $>99\%$!
 - Low-latency $\rightarrow$ few minutes
 - Low-FAR trigger $\rightarrow$ we have tiers that inform what is sent out (e.g., SNEWS)

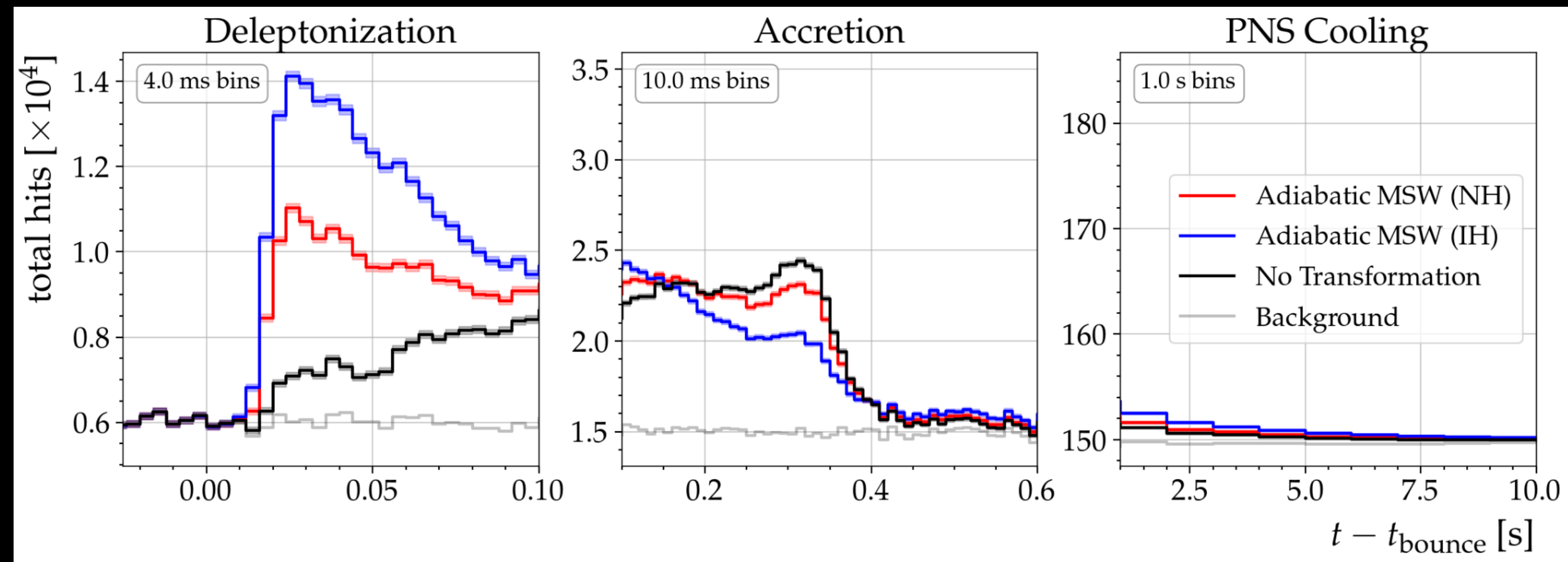


[Credit: R. Abbasi et al., IceCube Collaboration, 2024, ApJ 961, 84](#)

EXPECTED SIGNATURE IN ICECUBE



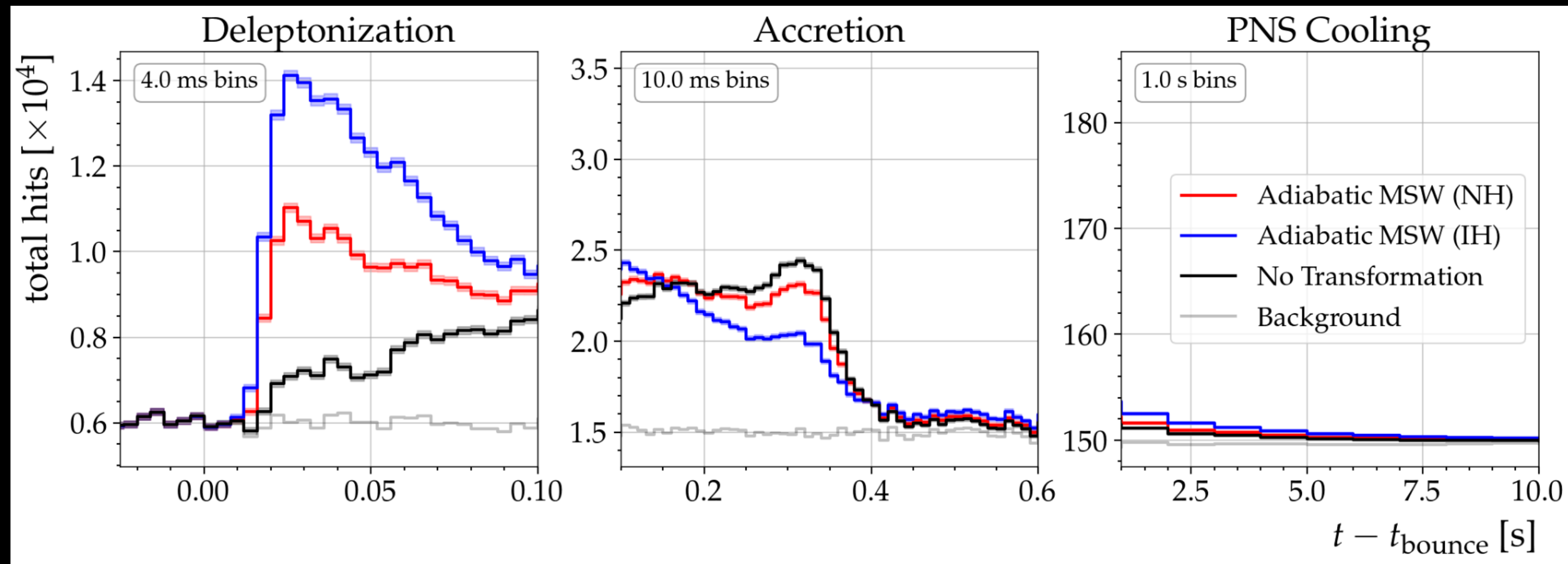
CCSN simulation of neutrino luminosity for a progenitor ending in a neutron star @ 10 kpc



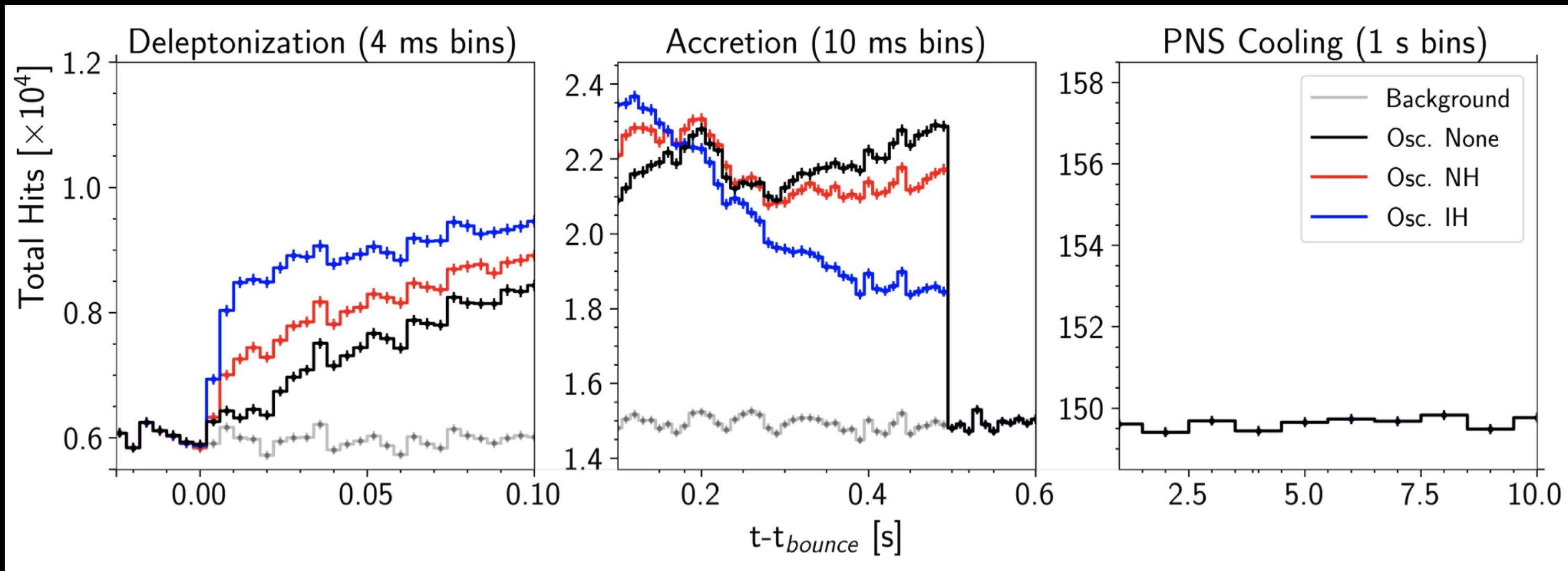
Detector hits

Signal: $O(10^6)$ Hz
Background: $O(10^5)$ Hz

EXPECTED SIGNATURE IN ICECUBE



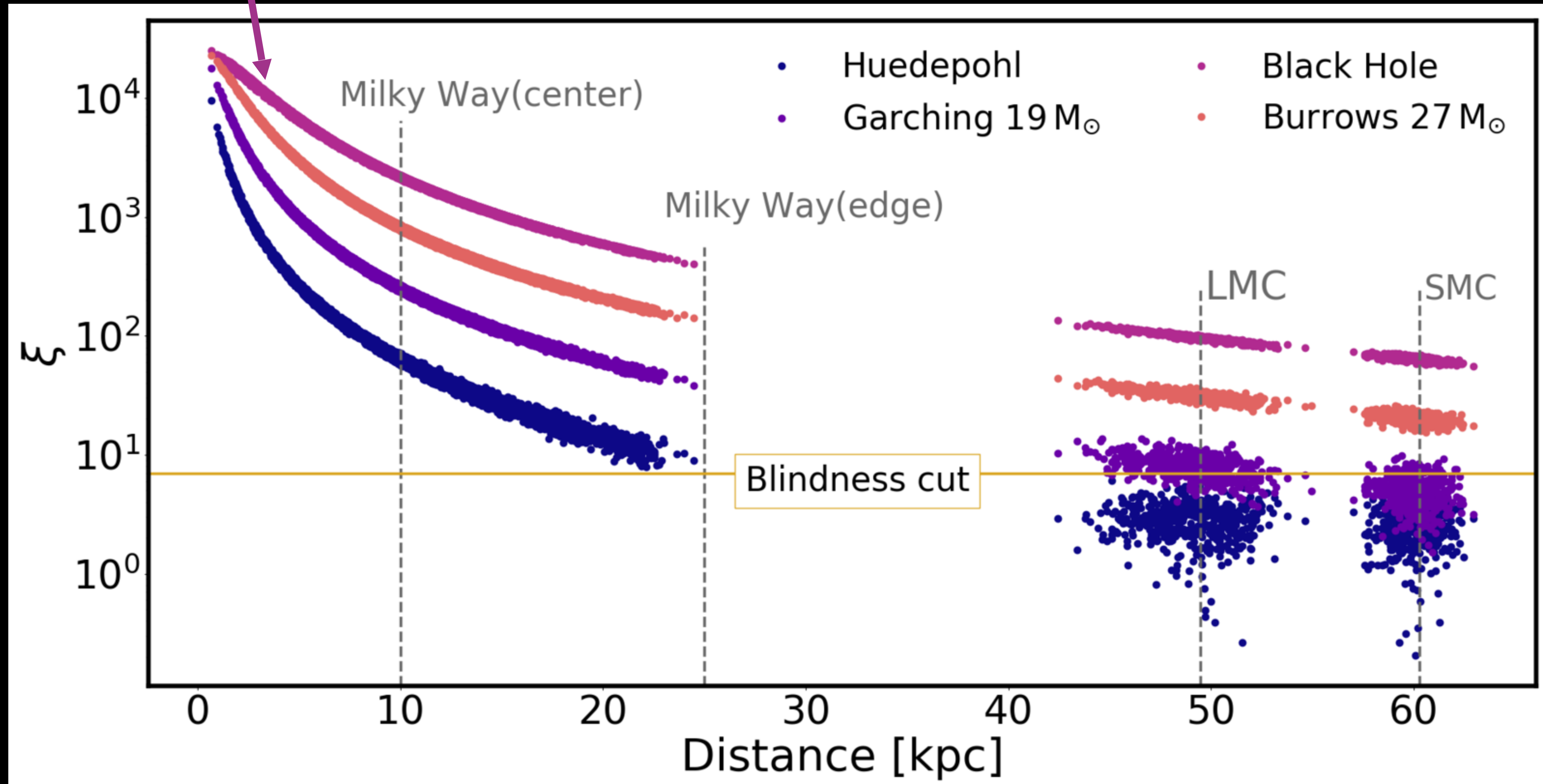
NEUTRON STAR



BLACK HOLE

ICECUBE SENSITIVITY TO SUPERNOVA NEUTRINOS

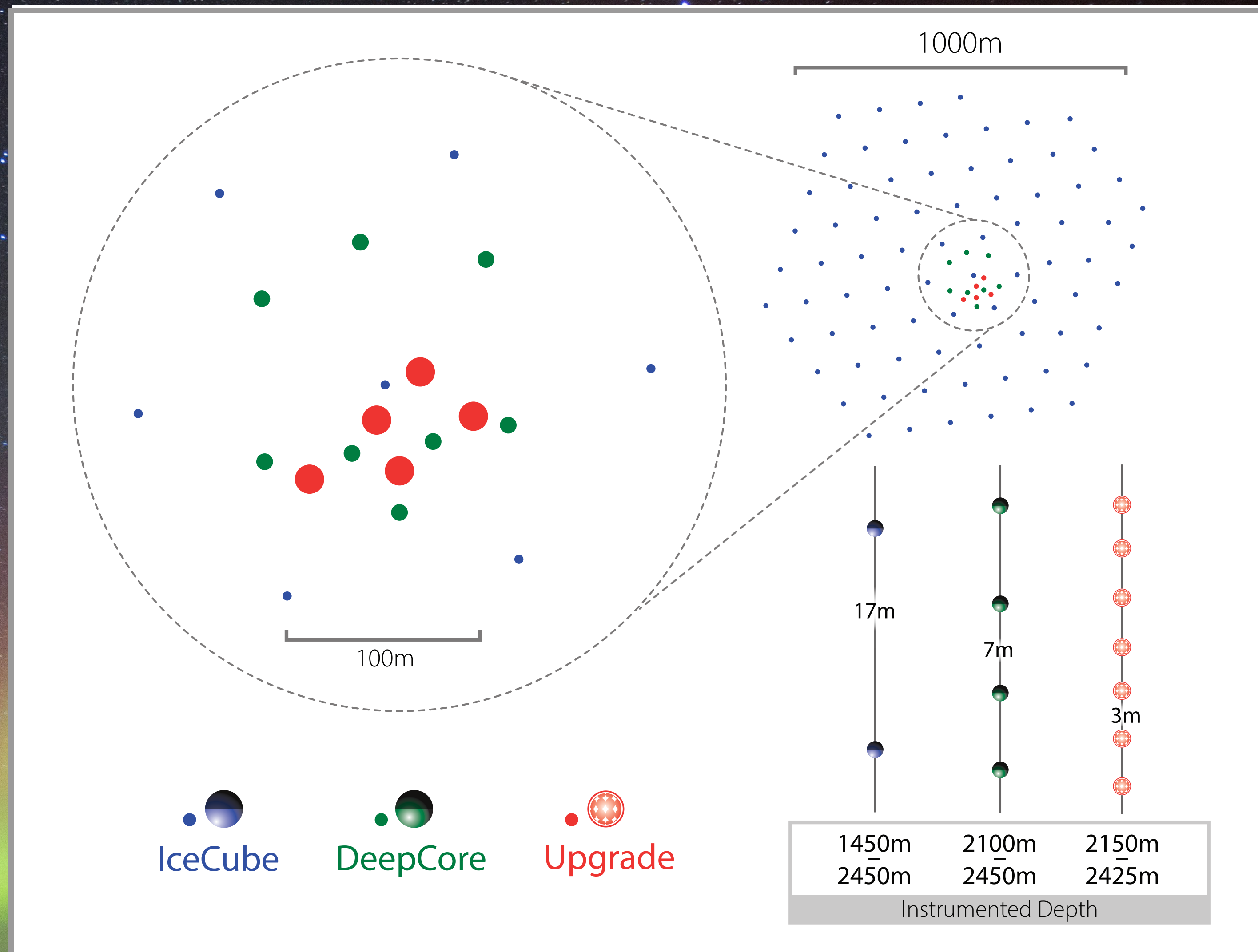
Failed CCSN (Black Hole)



FUTURE OF ICECUBE DETECTOR

NEAR FUTURE: ICECUBE UPGRADE

- 5 new 'strings' with ~ 700 new sensors.
- Smaller string spacing improves:
 - Systematic calibration of ice optical properties
 - Improved angular/energy resolution

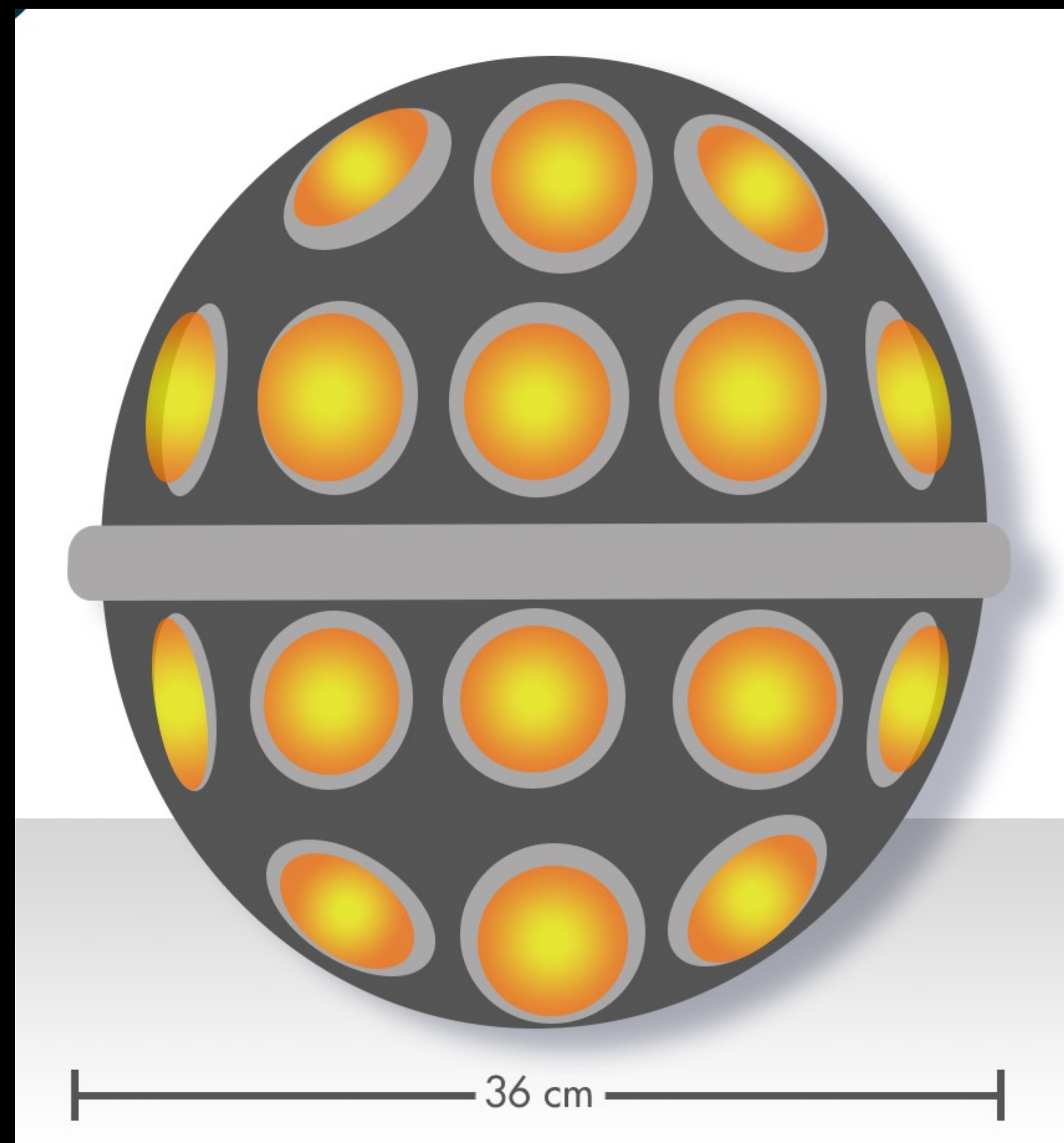


NEW OPTICAL SENSORS: D-EGG AND MDOM

D-Egg



mDOM



New modules provide with 4π coverage (improves effective volume and event resolution)

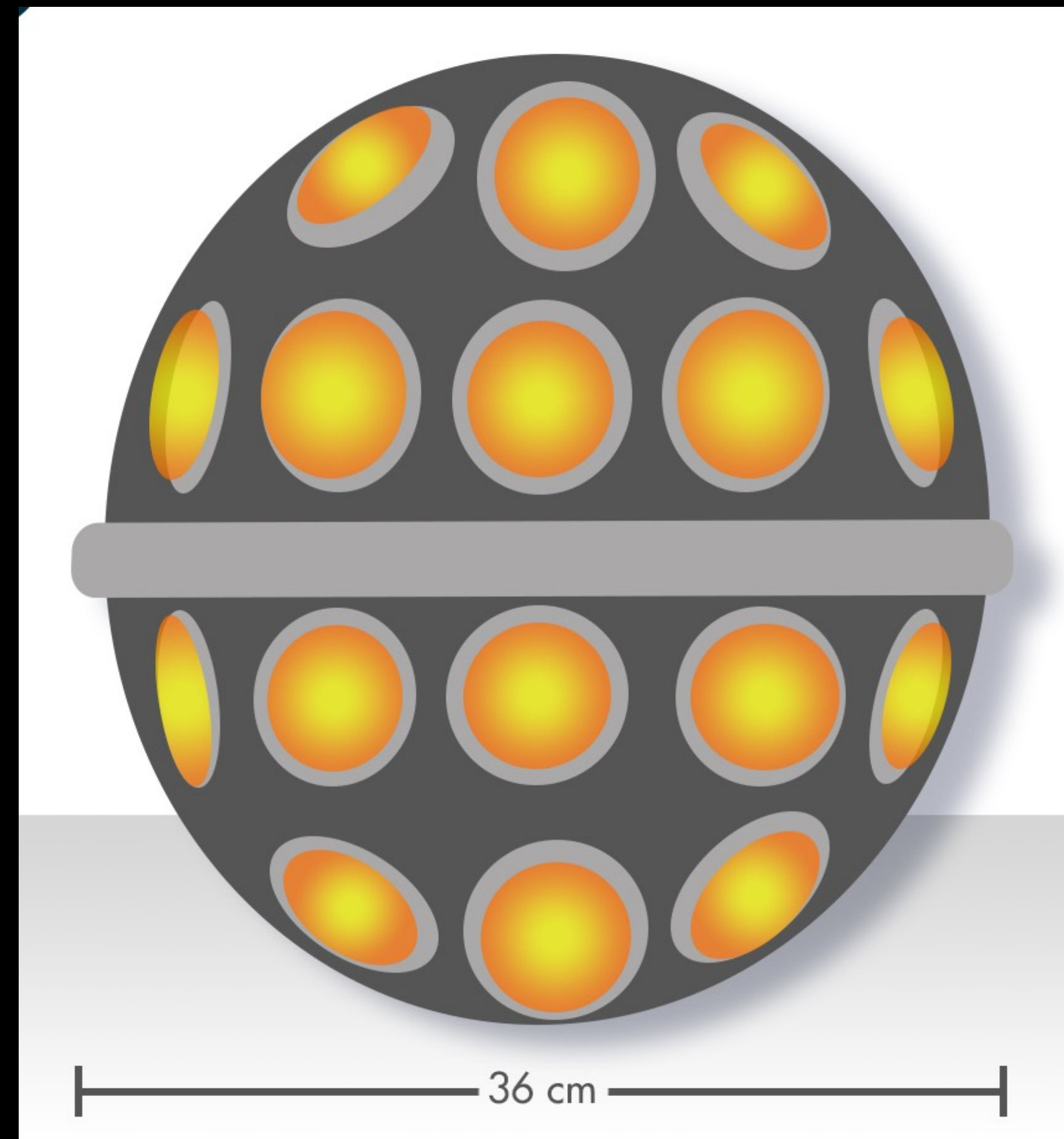
-LED flashers and cameras for improved ice calibration

NEW OPTICAL SENSORS: D-EGG AND MDOM

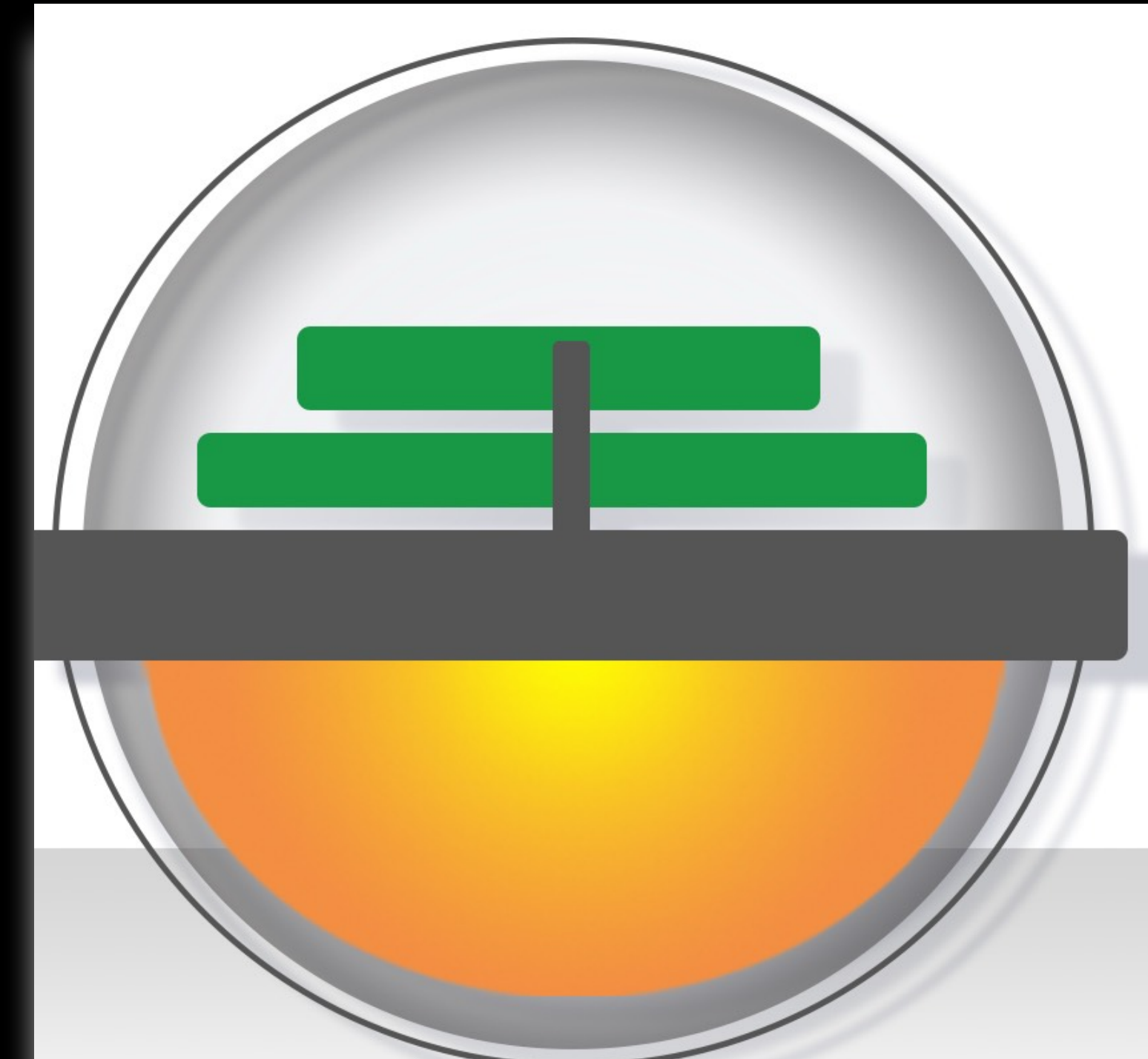
D-Egg



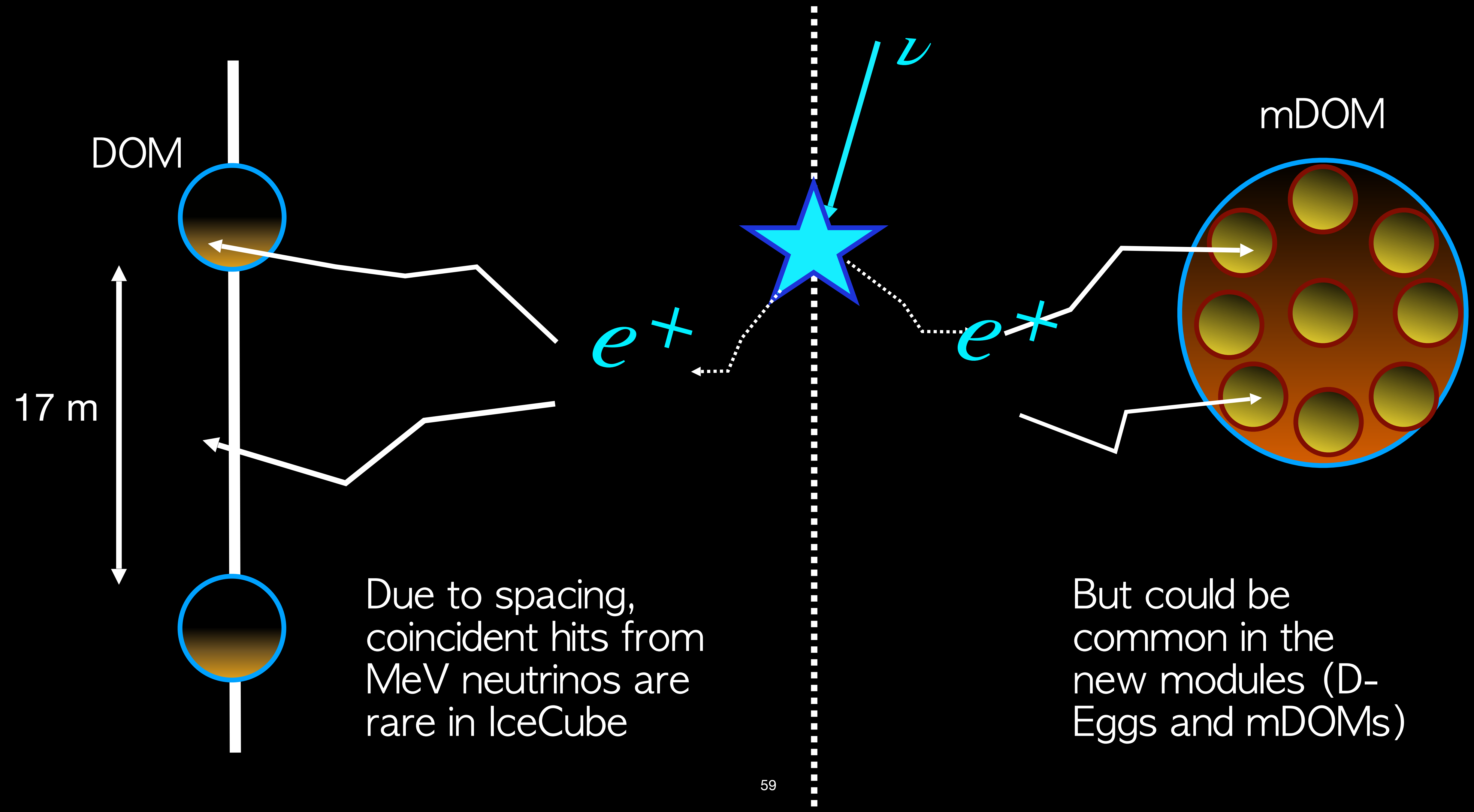
mDOM



What we had before

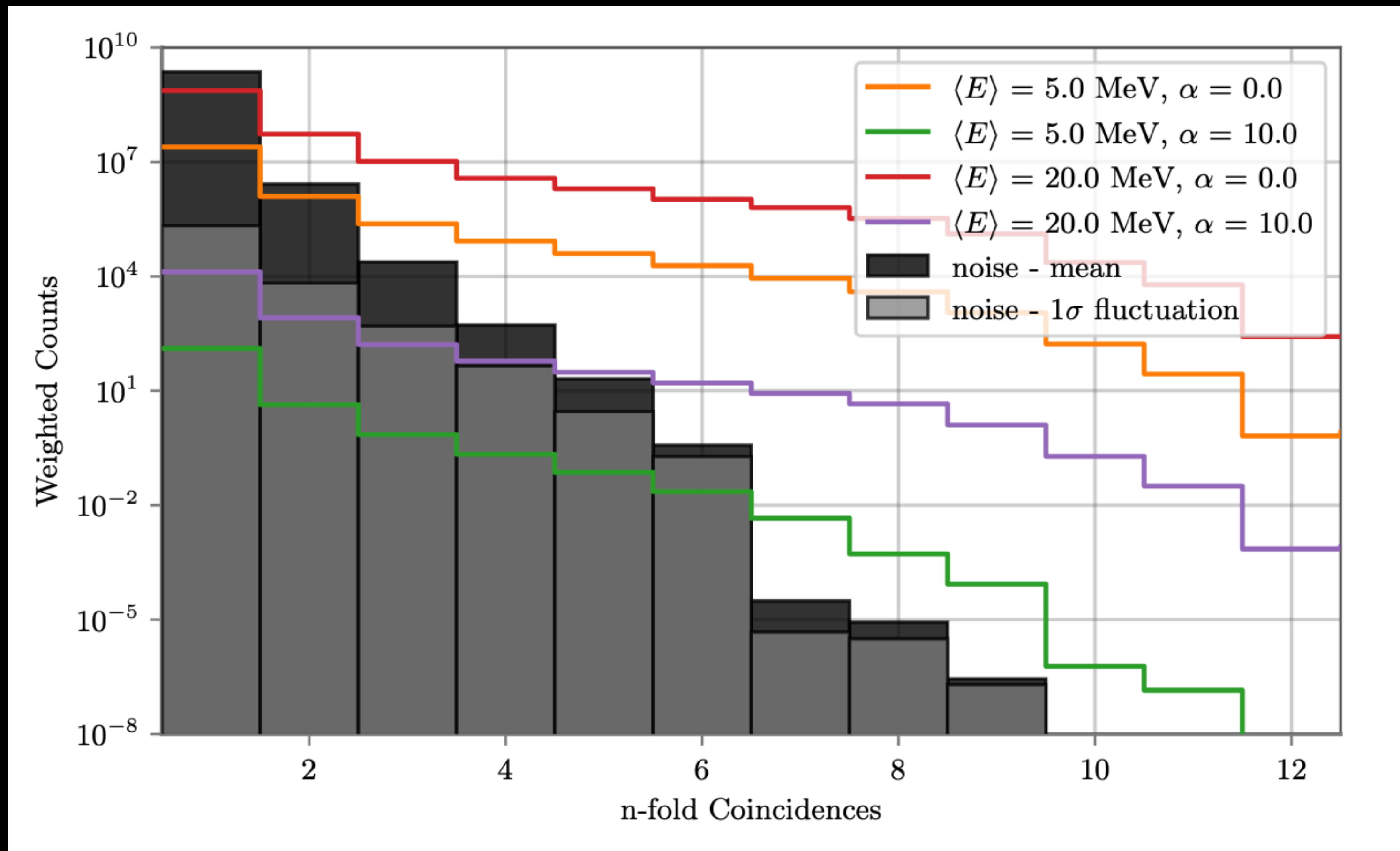


WHAT CAN WE DO WITH UPGRADE?



NEW OPTICAL SENSORS: D-EGG AND MDOM

Background / signal coincidences in 20 ns



N-fold hit coincidence could help us drive our background down

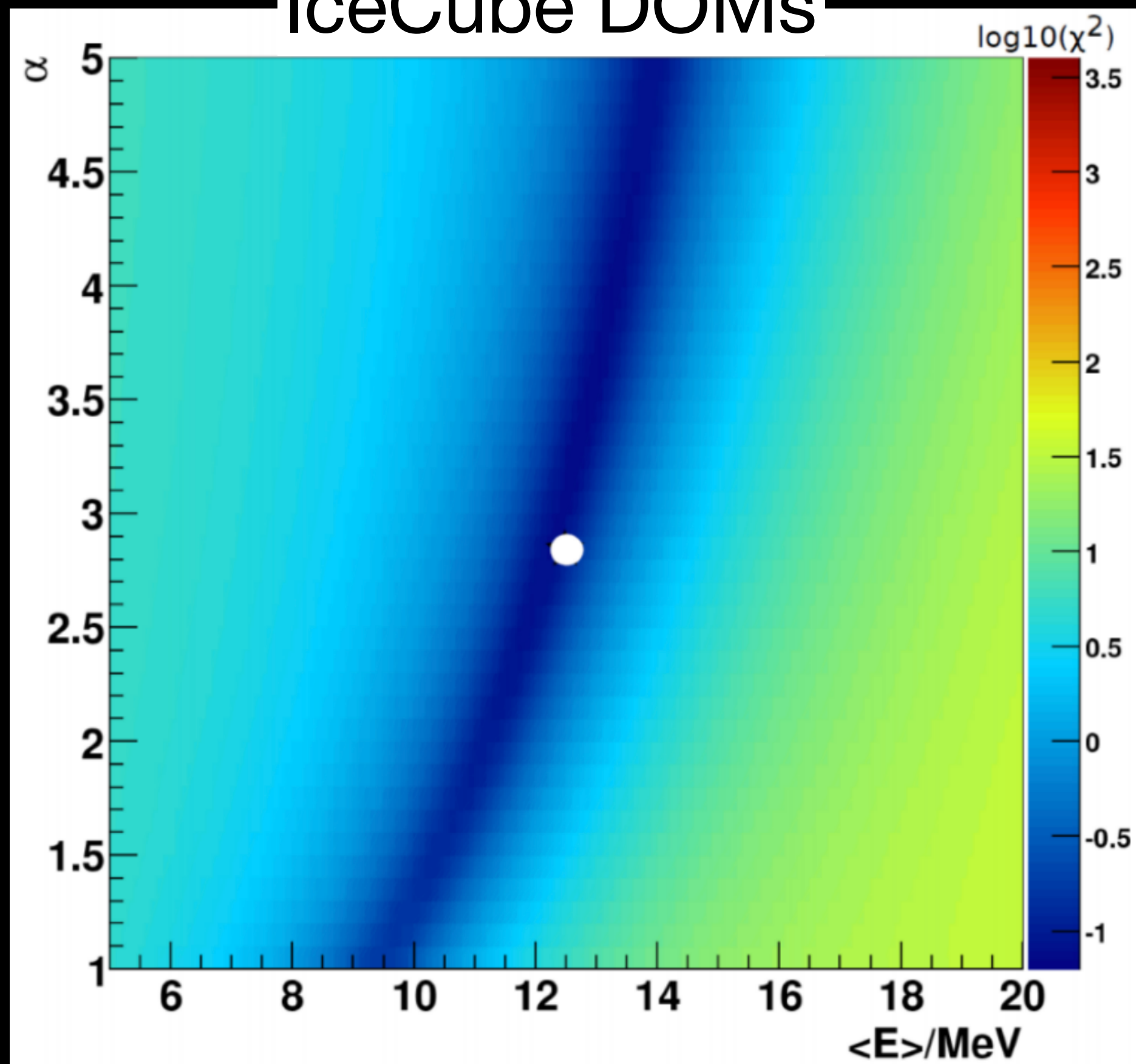
WHAT CAN WE DO WITH UPGRADE?

CCSN spectral shape is well approximated by: $f(E_\nu) \sim E_\nu^\alpha e^{-(\alpha+1)E_\nu/\langle E_\nu \rangle}$

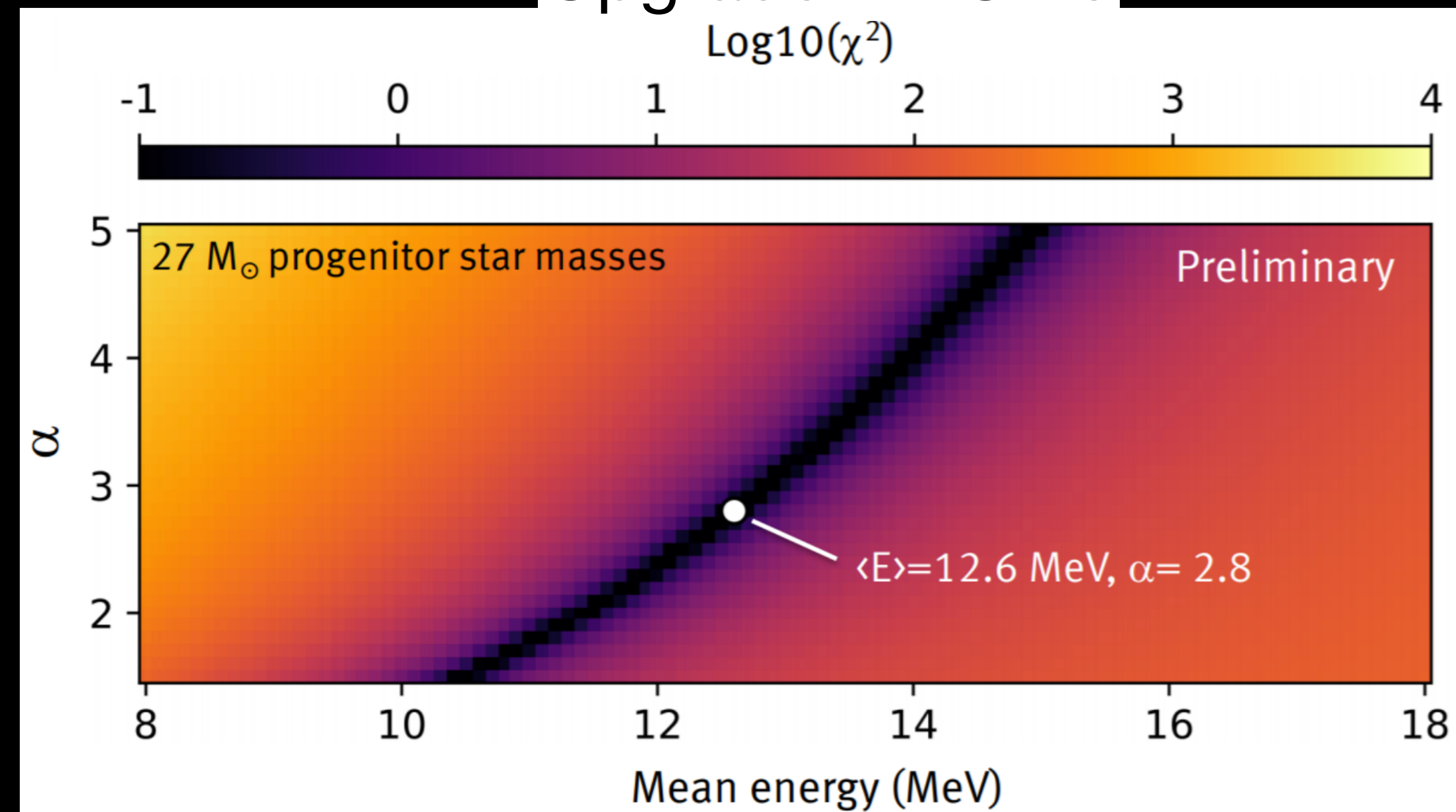
α and $\langle E_\nu \rangle$ dependent on neutrino flavor & time

$\langle E_\nu \rangle = 12.6\text{MeV}$ and $\alpha = 2.8$

IceCube DOMs

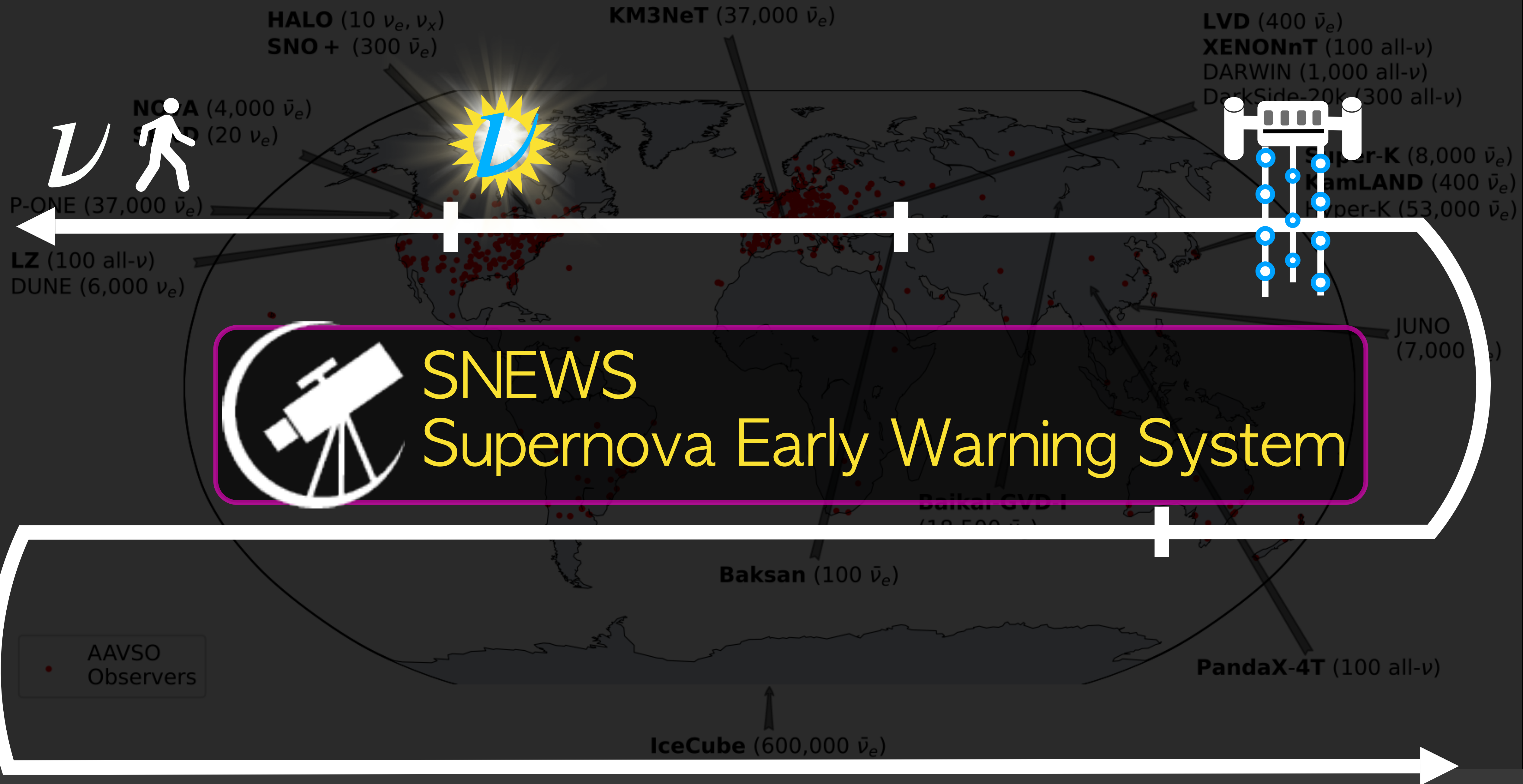


Upgrade mDOMs

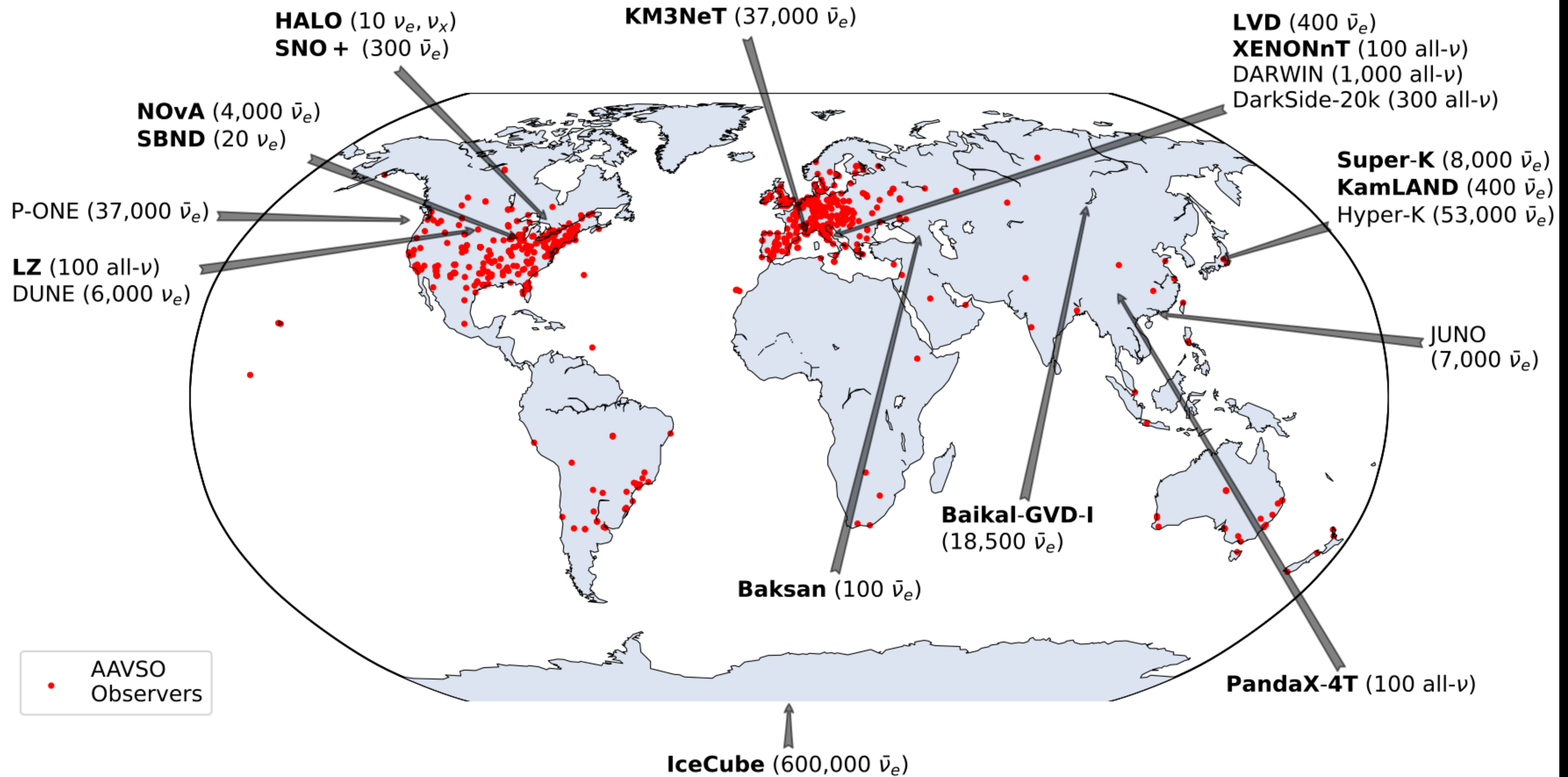


Credit: C. Lozano, Neutrino 2018

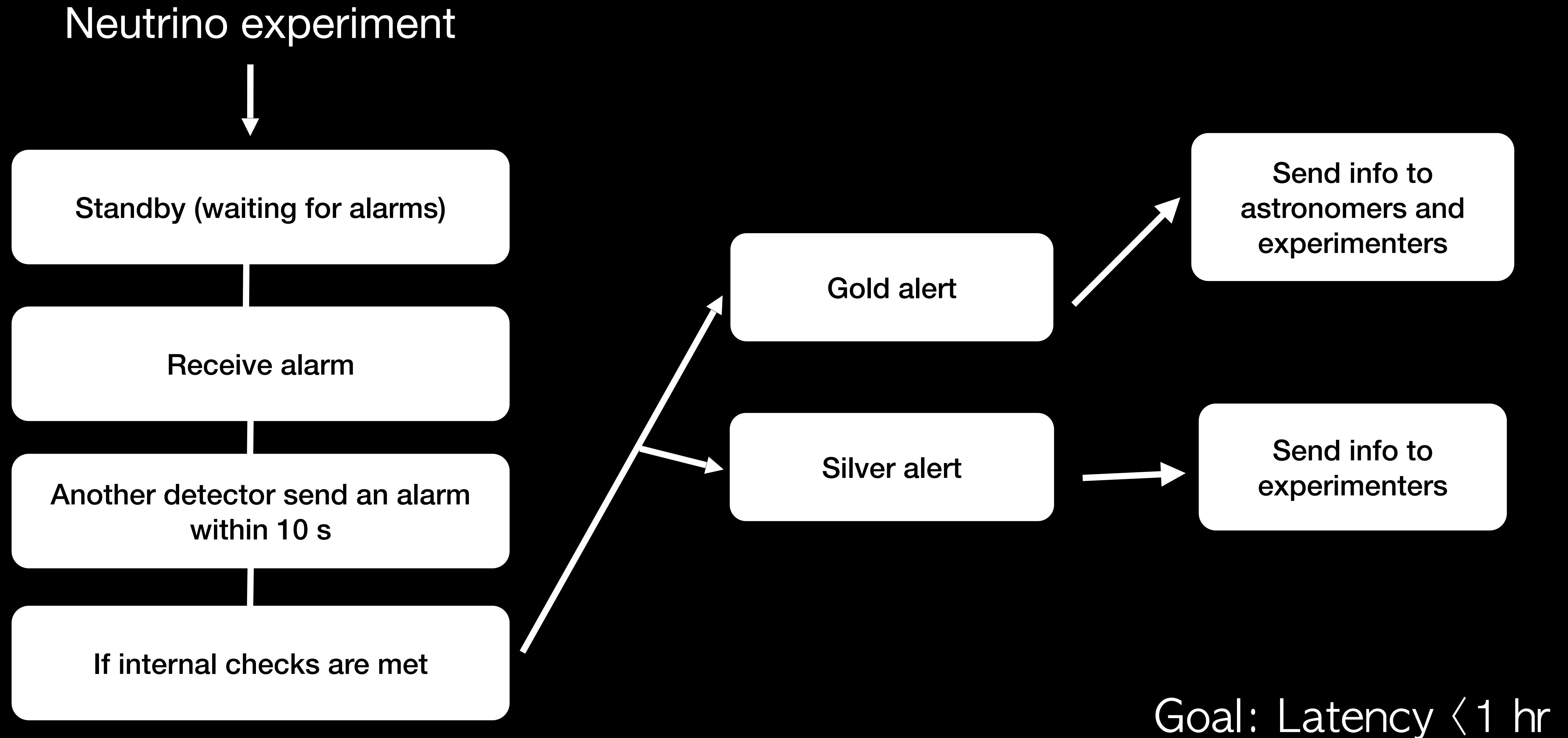
Resolution: $\sigma(E) / \langle E \rangle \leq 5\%$



SUPERNOVA EARLY WARNING SYSTEM (SNEWS)



SUPERNOVA EARLY WARNING SYSTEM (SNEWS)



SNEWS: NOW AND UPCOMING

Currently: SNEWS monitors for multi-detector coincidence

- There are 12 participating experiments including IceCube and Super-K

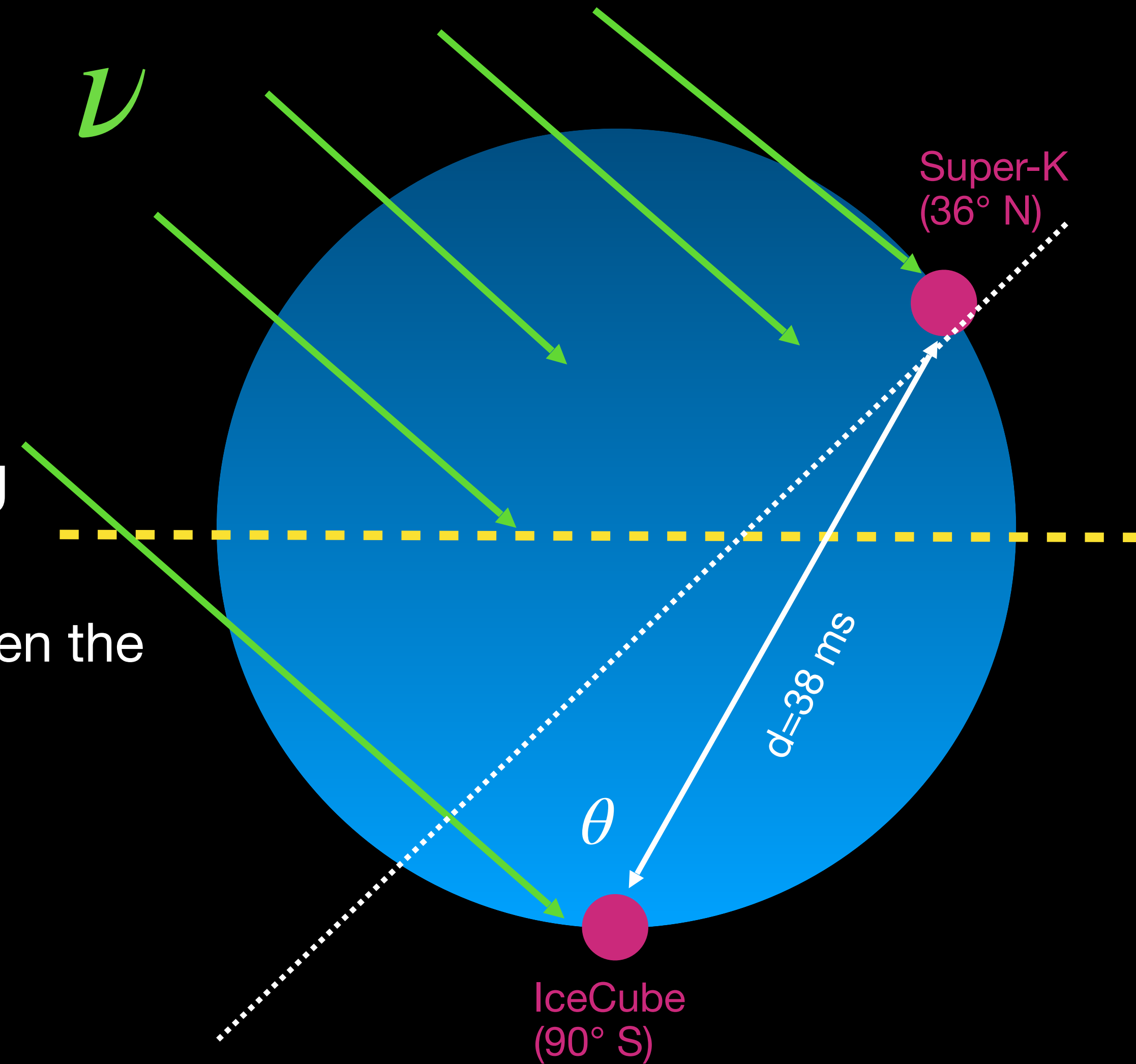
SNEWS: NOW AND UPCOMING

Currently: SNEWS monitors for multi-detector coincidence

- There are 10 participating experiments including IceCube.

Upcoming: SNEWS 2.0 will also provide pointing information!

- It will perform triangulation using the time delays between the detectors with low latency.

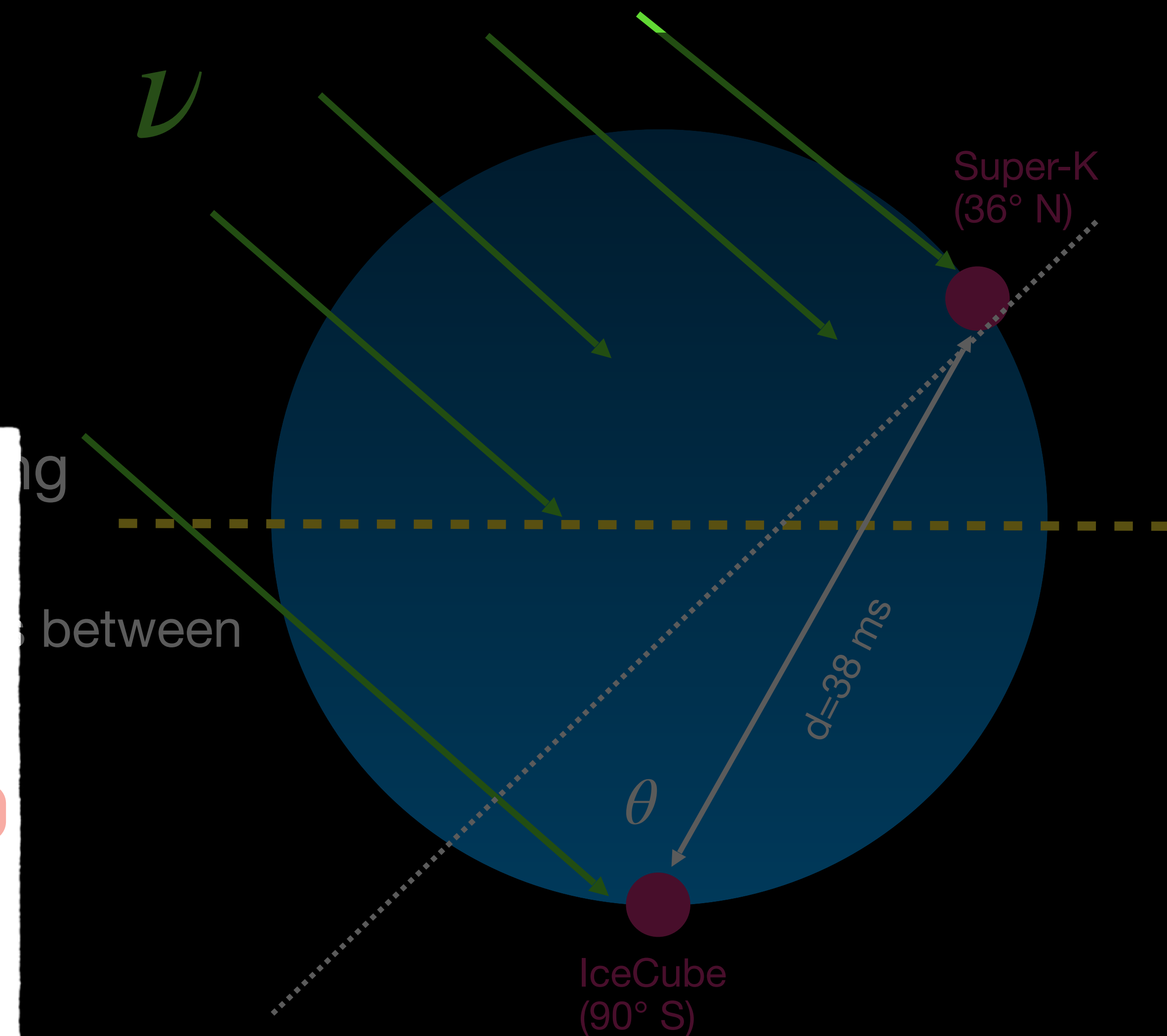


SNEWS: NOW AND UPCOMING

Currently: SNEWS monitors for multi-detector coincidence

- There are 10 participating experiments including IceCube.

Experiments	Major process	Target	δt (ms)	δt (BH)
Super-K	$\bar{\nu}_e + p \rightarrow e^+ + n$	32 kt H ₂ O	0.9	0.14 ms
JUNO	$\bar{\nu}_e + p \rightarrow e^+ + n$	20 kt C _n H _m	1.2	0.19 ms
DUNE	$\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$	40 kt LAr	1.5	0.18 ms
NO ν A	$\bar{\nu}_e + p \rightarrow e^+ + n$	14 kt C _n H _m	1.4	0.24 ms
CJPL	$\bar{\nu}_e + p \rightarrow e^+ + n$	3 kt H ₂ O	3.8	0.97 ms
IceCube	Noise excess	H₂O	1	0.16 ms
ANTARES	Noise excess	H ₂ O	100	32 ms
Borexino	$\bar{\nu}_e + p \rightarrow e^+ + n$	0.3 kt C _n H _m	16	5.5 ms
LVD	$\bar{\nu}_e + p \rightarrow e^+ + n$	1 kt C _n H _m	7.5	2.4 ms
XENON1T	Coherent scattering	2 t X _e	27	10 ms
DARWIN	Coherent scattering	40 t X _e	1.3	0.7 ms



SNEWS: NOW AND UPCOMING

Currently: SNEWS monitors for multi-detector coincidence

- There are 12 participating experiments including IceCube and Super-K

Upcoming: SNEWS 2.0 will also provide pointing information!

- It will perform triangulation using the time delays between the detectors
- Each pair of detectors produces a 'ring' shaped error band whose width depends on timing uncertainty

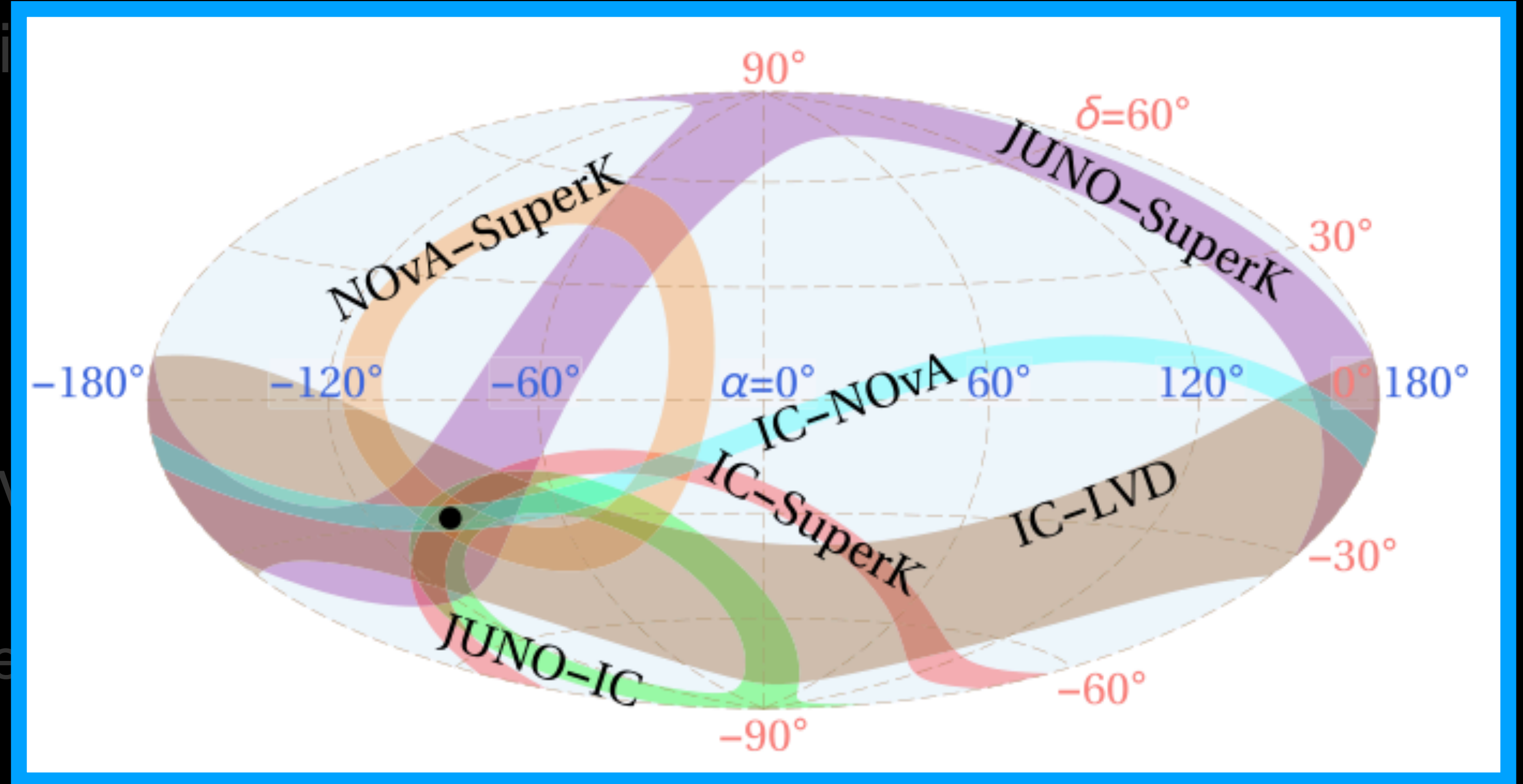
SNEWS: NOW AND UPCOMING

Currently: SNEWS monitors for multi coincidence

- There are 12 participating experiments including IceCube and Super-K

Upcoming: SNEWS 2.0 will also provide information!

- It will perform triangulation using the time of arrival of neutrinos at different detectors



- Each pair of detectors produces a 'ring' shaped error band whose width depends on timing uncertainty

<https://iopscience.iop.org/article/10.1088/1367-2630/abde33/pdf>

SNEWS: NOW AND UPCOMING

Currently: SNEWS monitors for multi-detector coincidence

- There are 12 participating experiments including IceCube and Super-K

Upcoming: SNEWS 2.0 will also provide pointing information!

- It will perform triangulation using the time delays between the detectors
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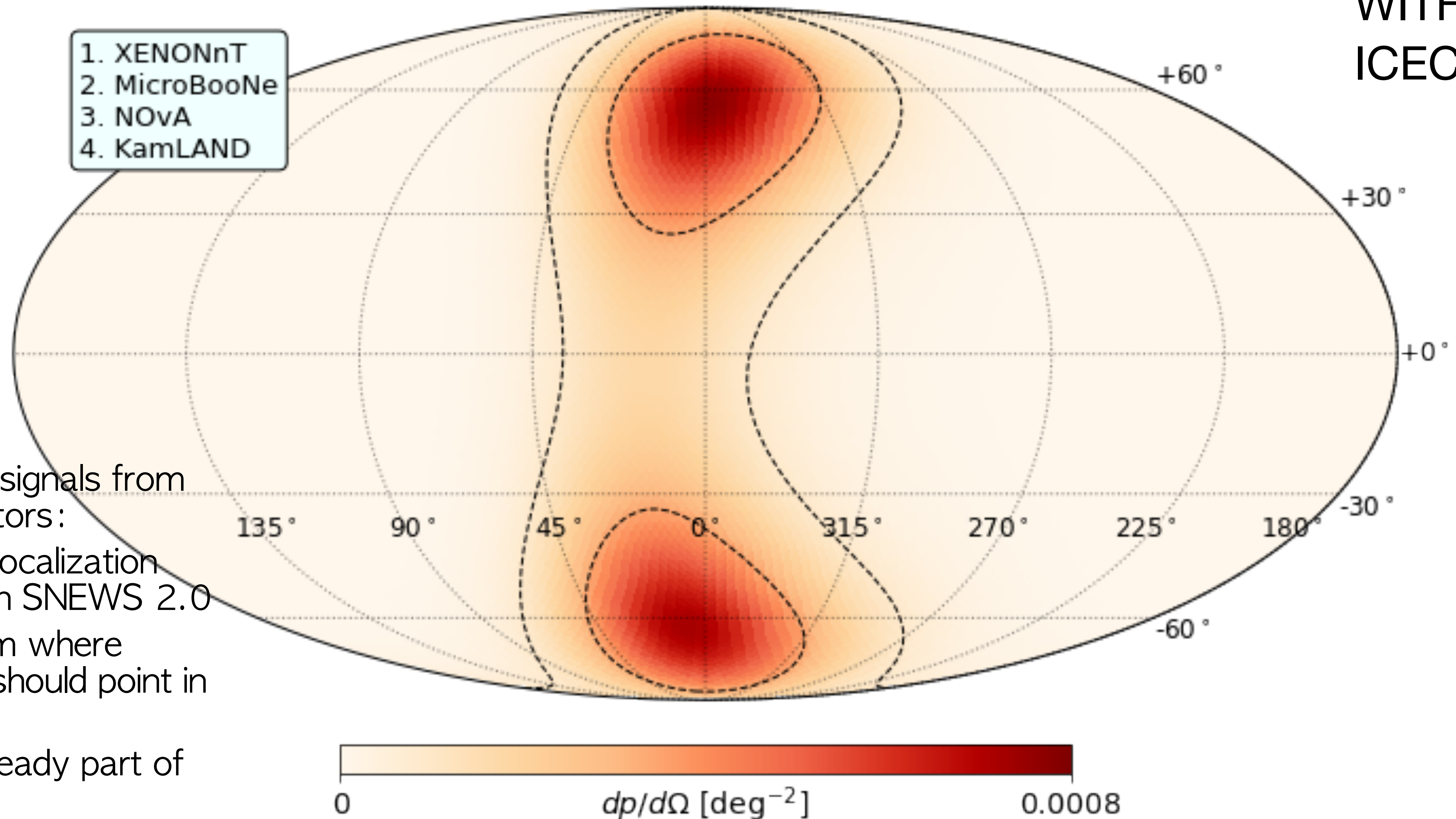
IceCube has a big role in SNEWS 2.0 alert formation!

- High uptime, full sky coverage, high statistics lightcurve
- Participates in triangulation drills!

SNEWS 2022-10-20T13:56:38.496255

WITHOUT
ICECUBE

1. XENONnT
2. MicroBooNe
3. NOvA
4. KamLAND



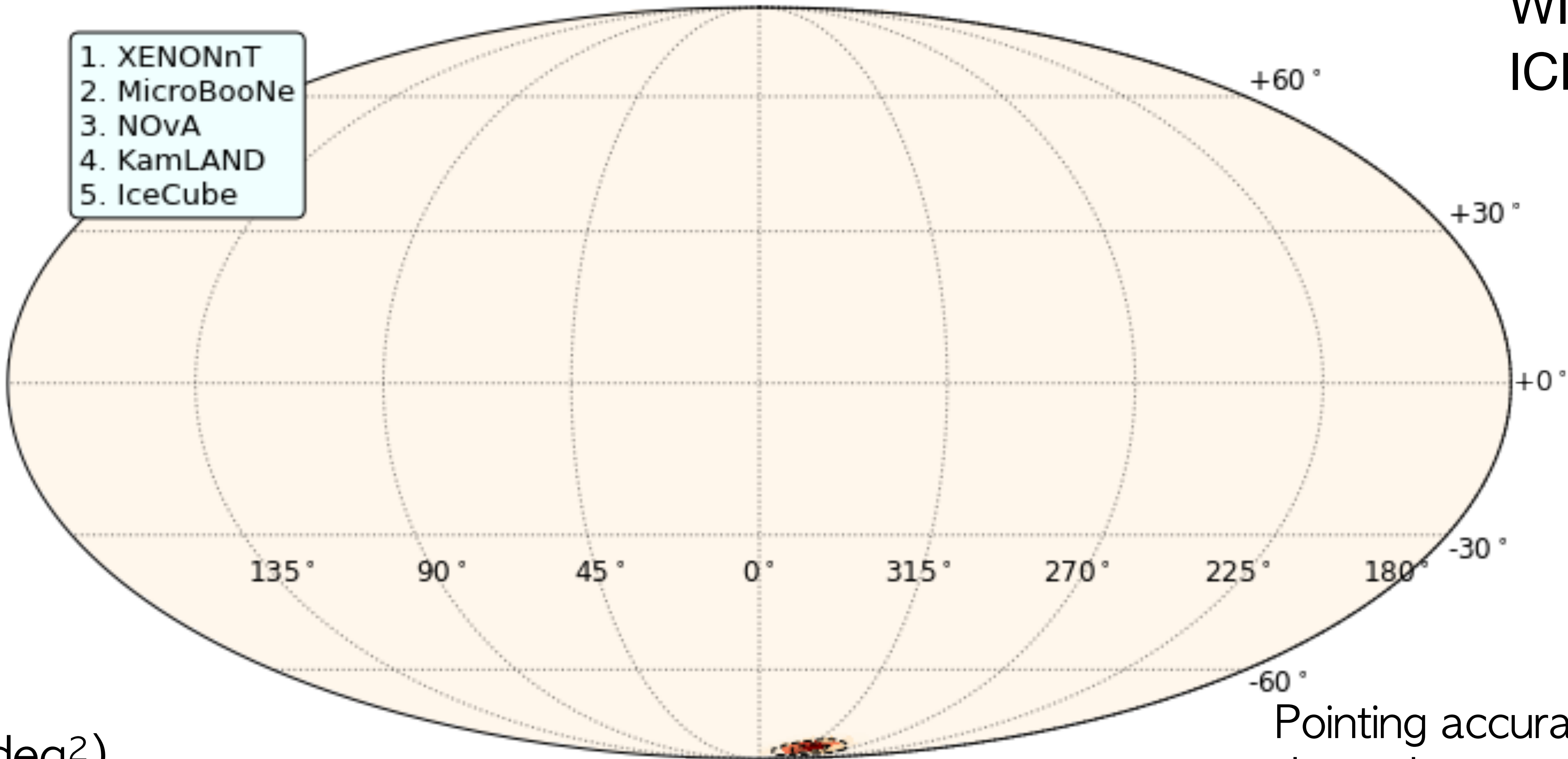
By combining signals from multiple detectors:

- Progenitor localization possible with SNEWS 2.0
- Helps inform where telescopes should point in the sky
- IceCube already part of firedrills!

SNEWS 2022-10-20T13:56:40.961208

WITH
ICECUBE

1. XENONnT
2. MicroBooNe
3. NOvA
4. KamLAND
5. IceCube

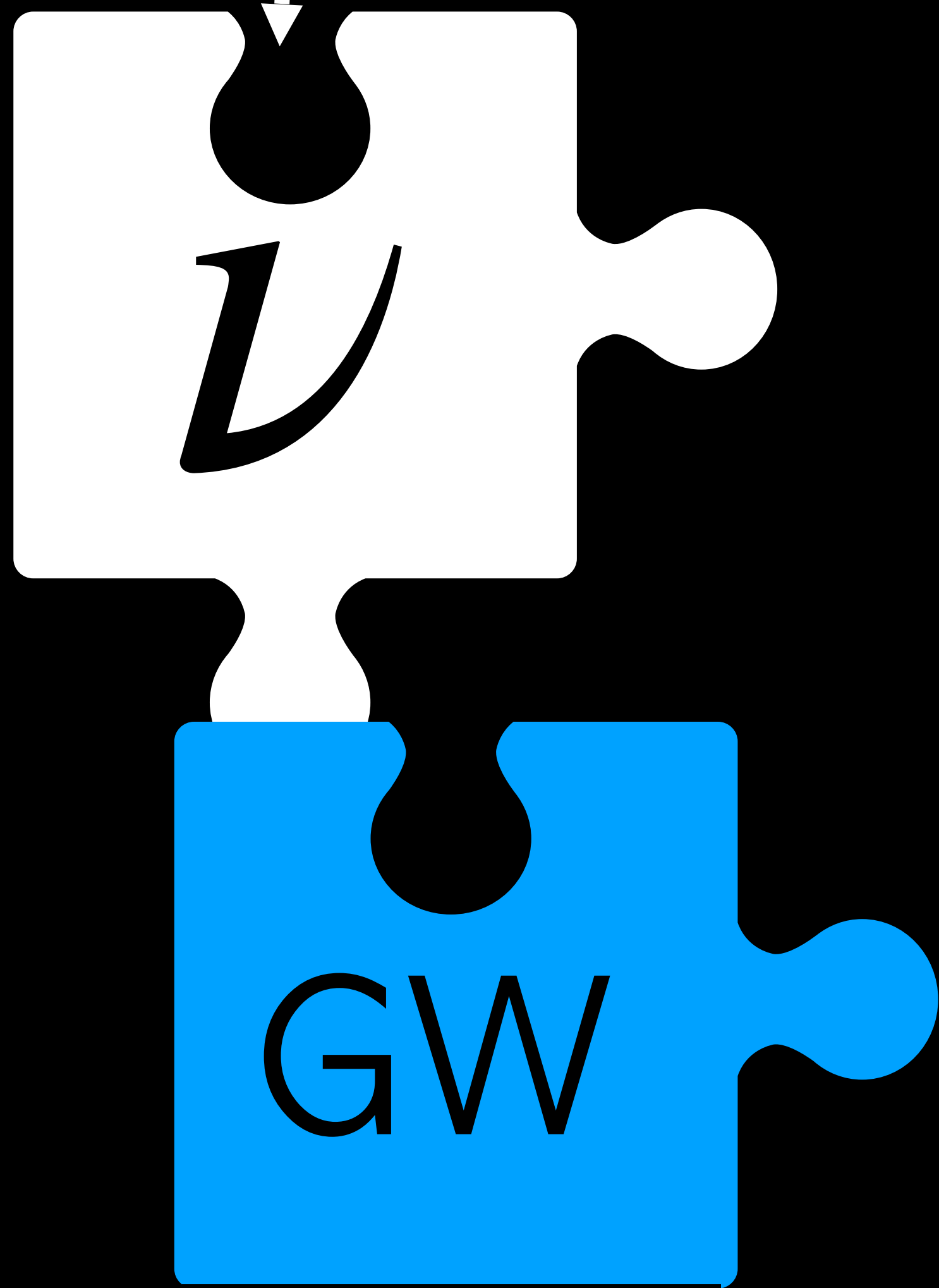


Average
pointing:
 $O(100 \text{ deg}^2)$

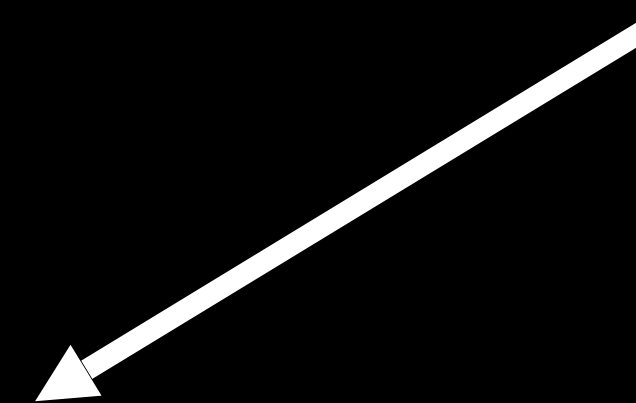
Pointing accuracy
dependent on true sky
position and participating
experiments

THE PICTURE

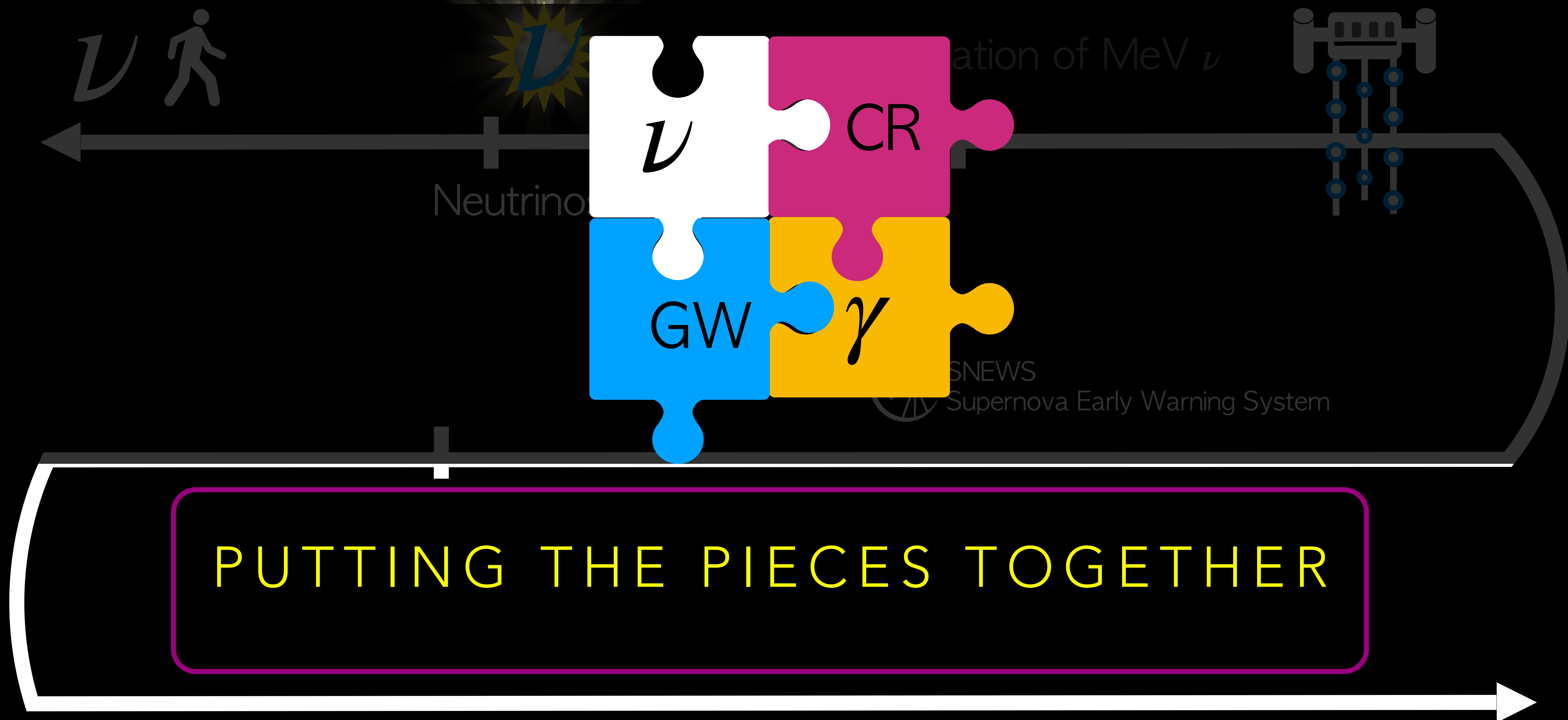
Exotics?



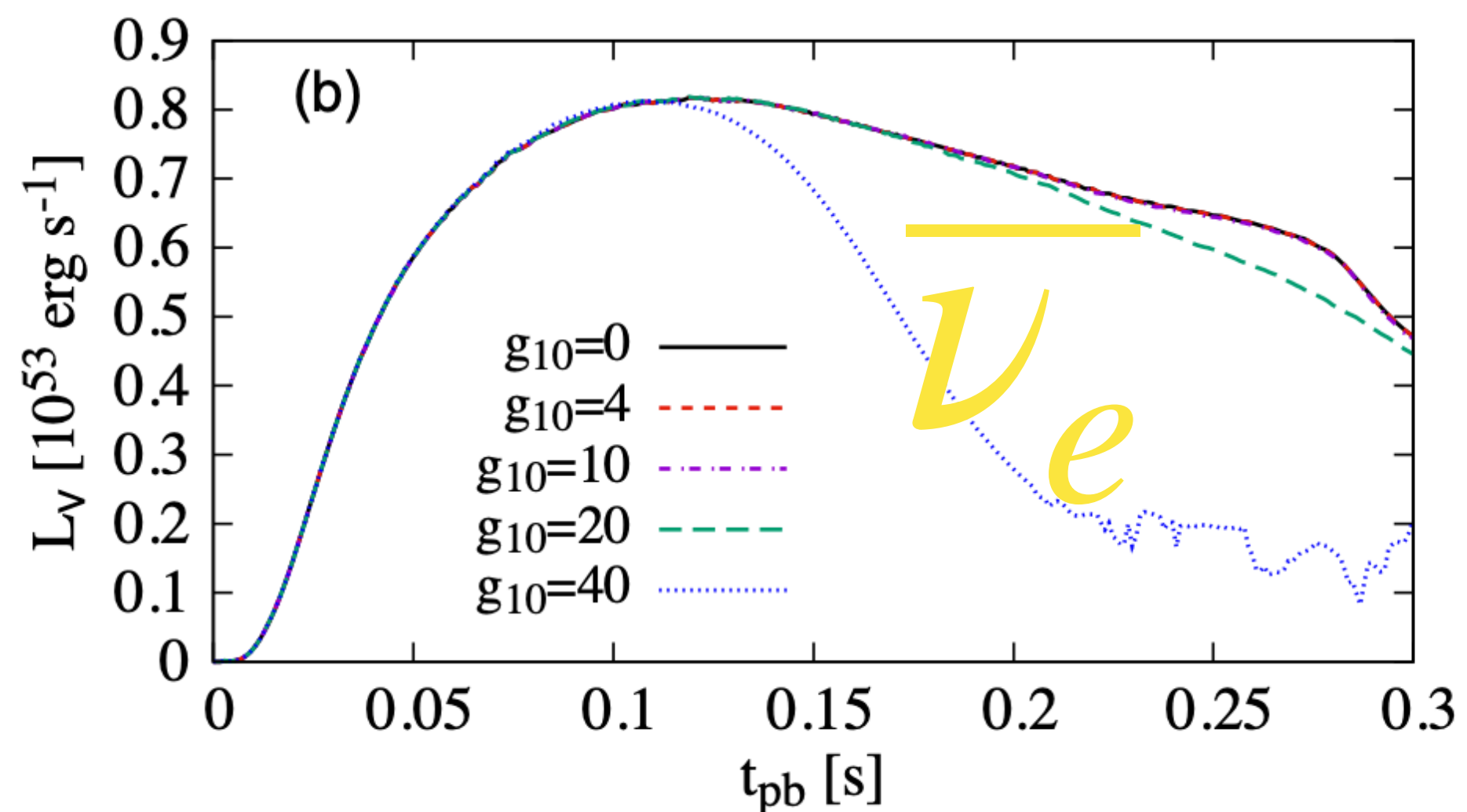
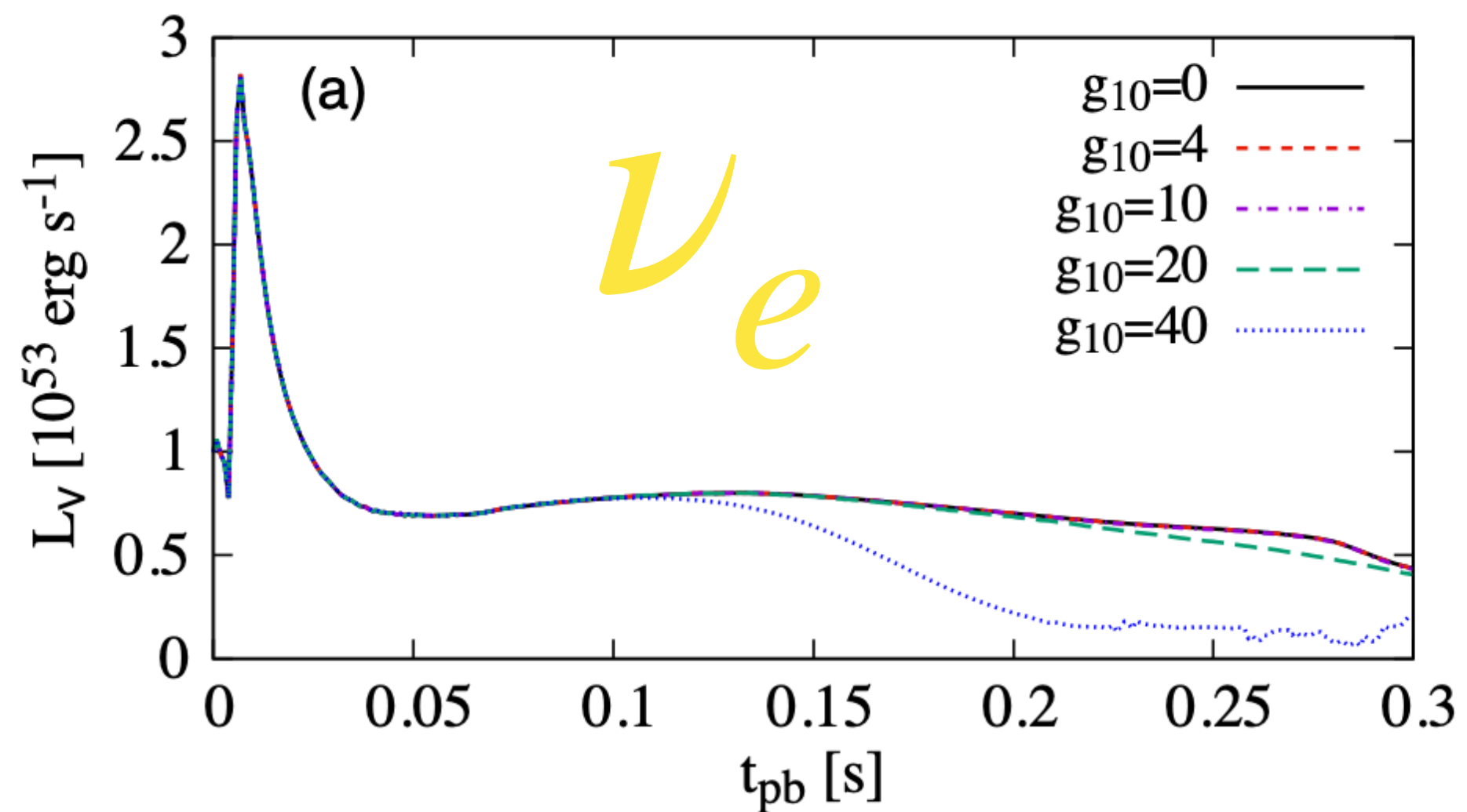
Not discussed



OUTLINE

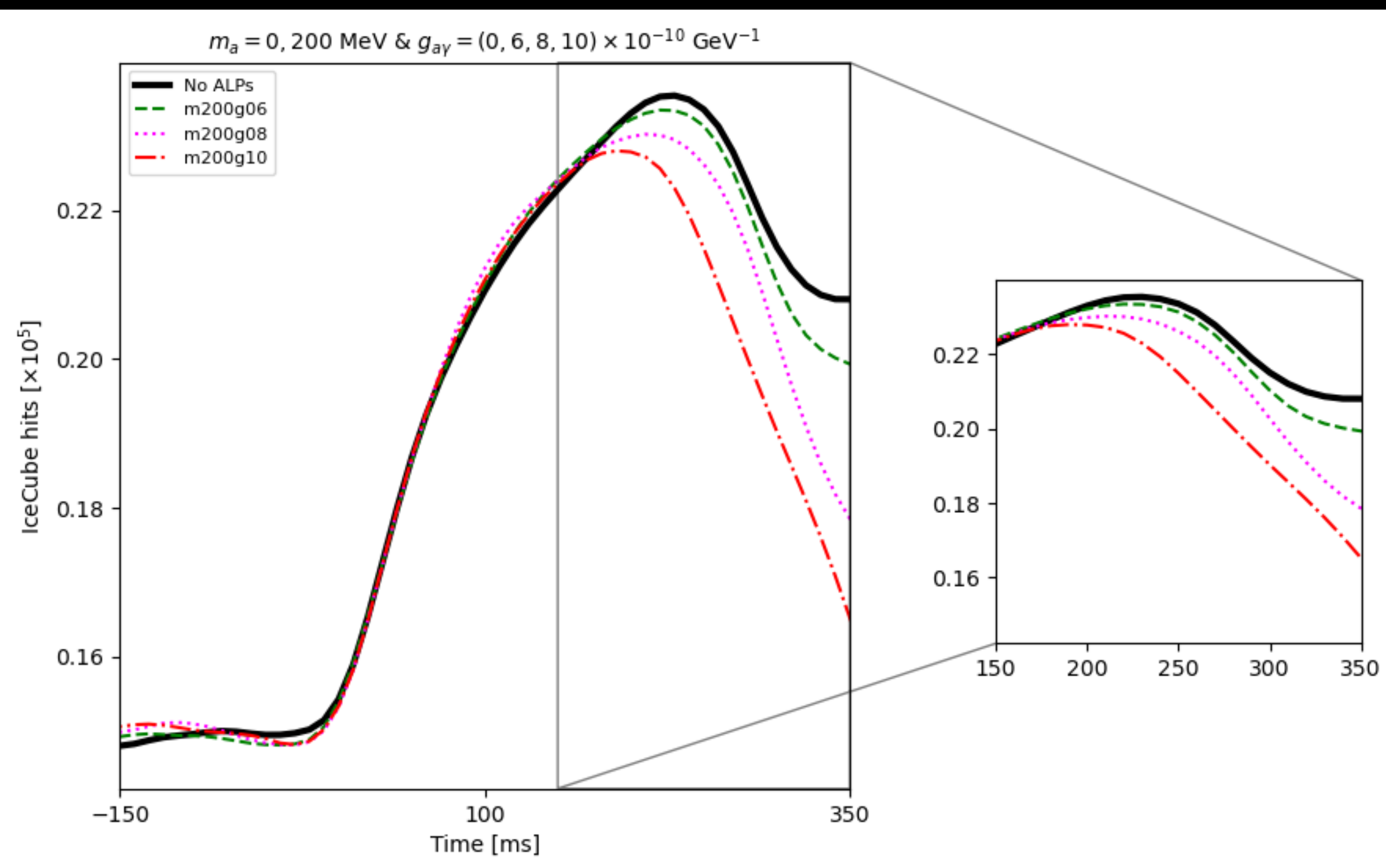


EXOTICS: INDIRECT OBSERVATION



- Axion-like particles (ALPs) are potential dark matter candidates
- If ALPs would be produced, they could take away energy that would otherwise go to neutrinos
- Deficit in the neutrino emission
- Some ongoing studies show promise for IceCube's ability to constrain this deficit

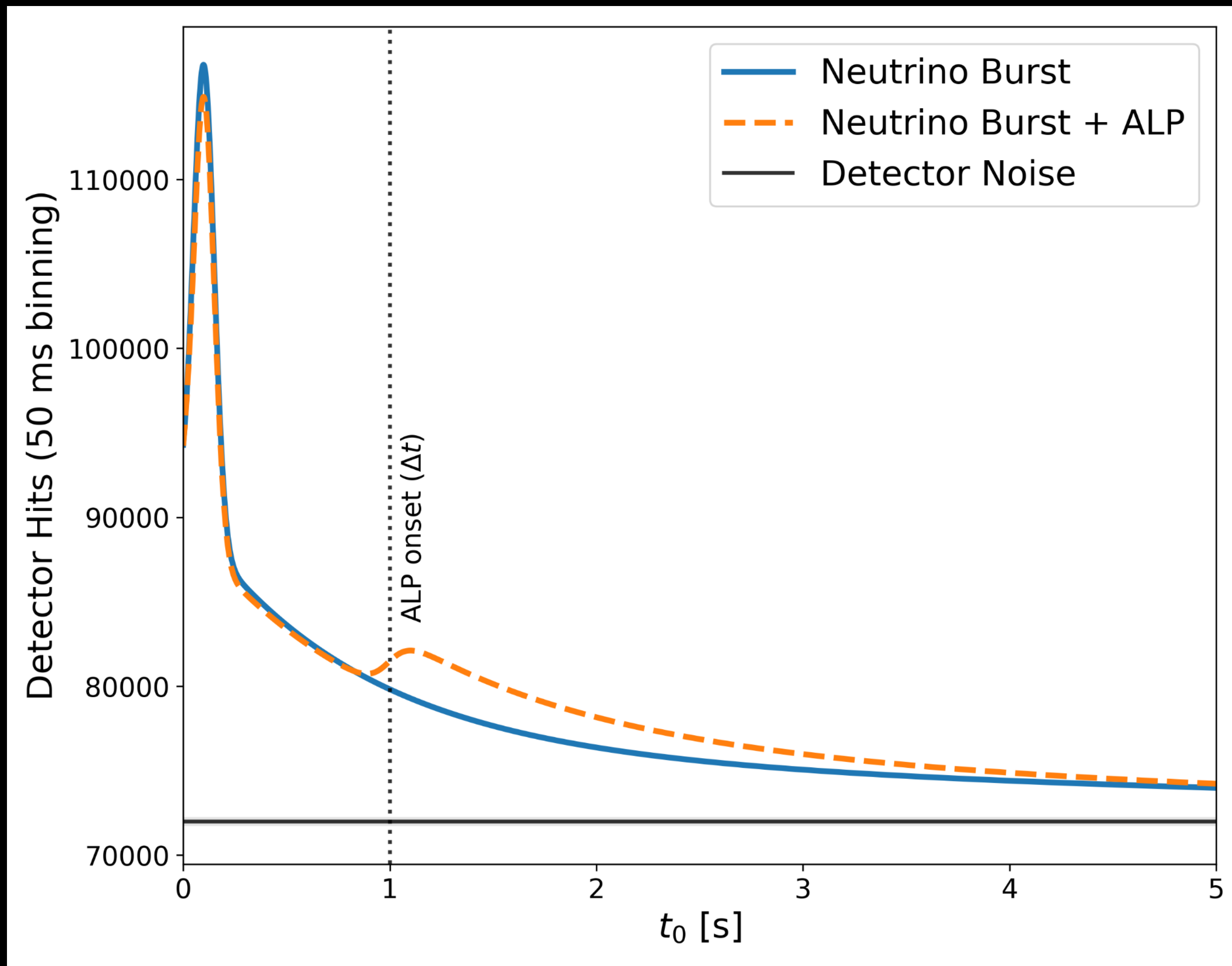
EXOTICS: INDIRECT OBSERVATION



- Axion-like particles (ALPs) are potential dark matter candidates
- If ALPs would be produced, they could take away energy that would otherwise go to neutrinos
 - Dampening the neutrino emission
 - Some ongoing studies show promise for IceCube's ability to constrain this deficit

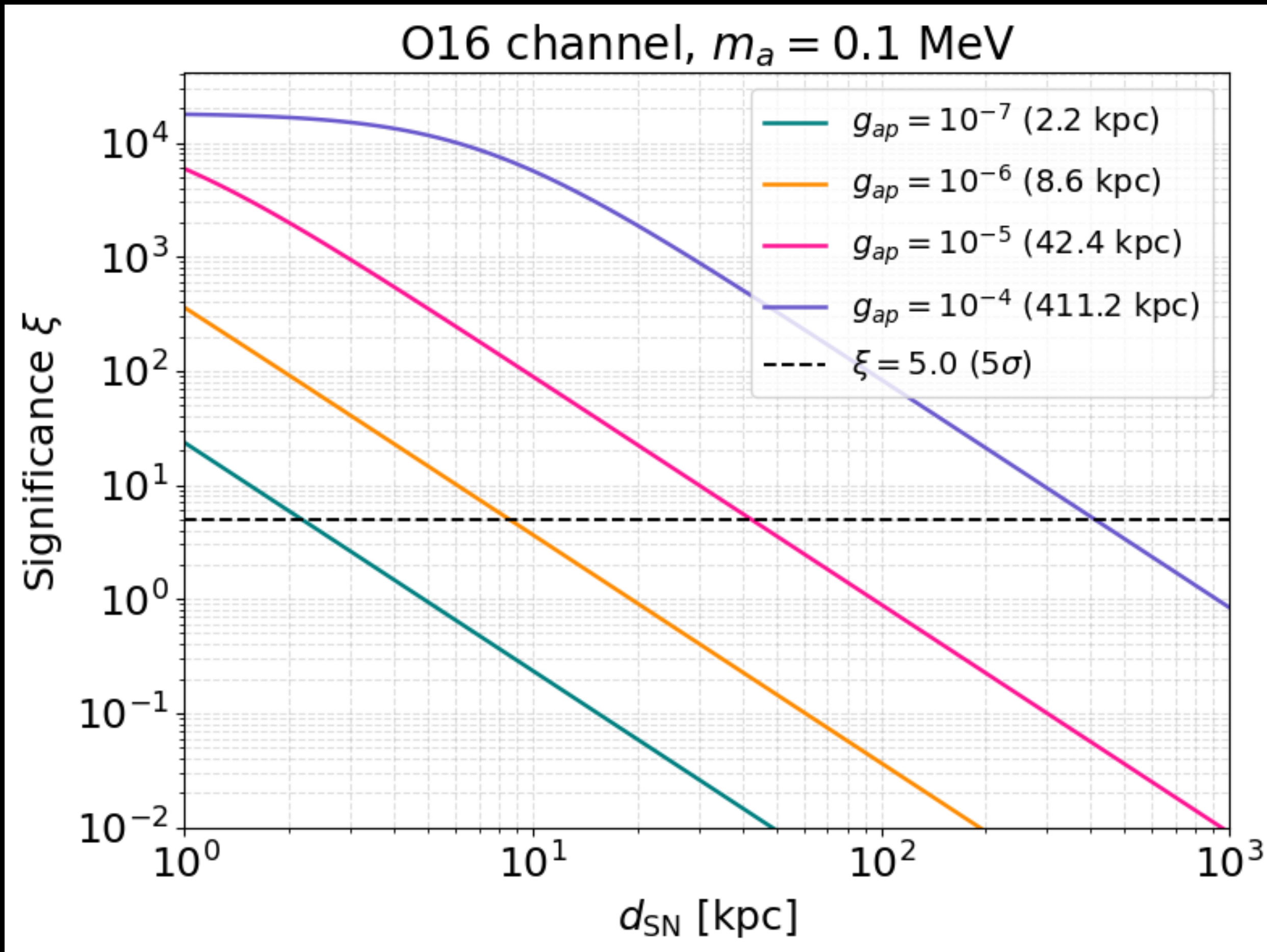
Credit: Shlok Shah, Rochester University

EXOTICS: DIRECT OBSERVATION



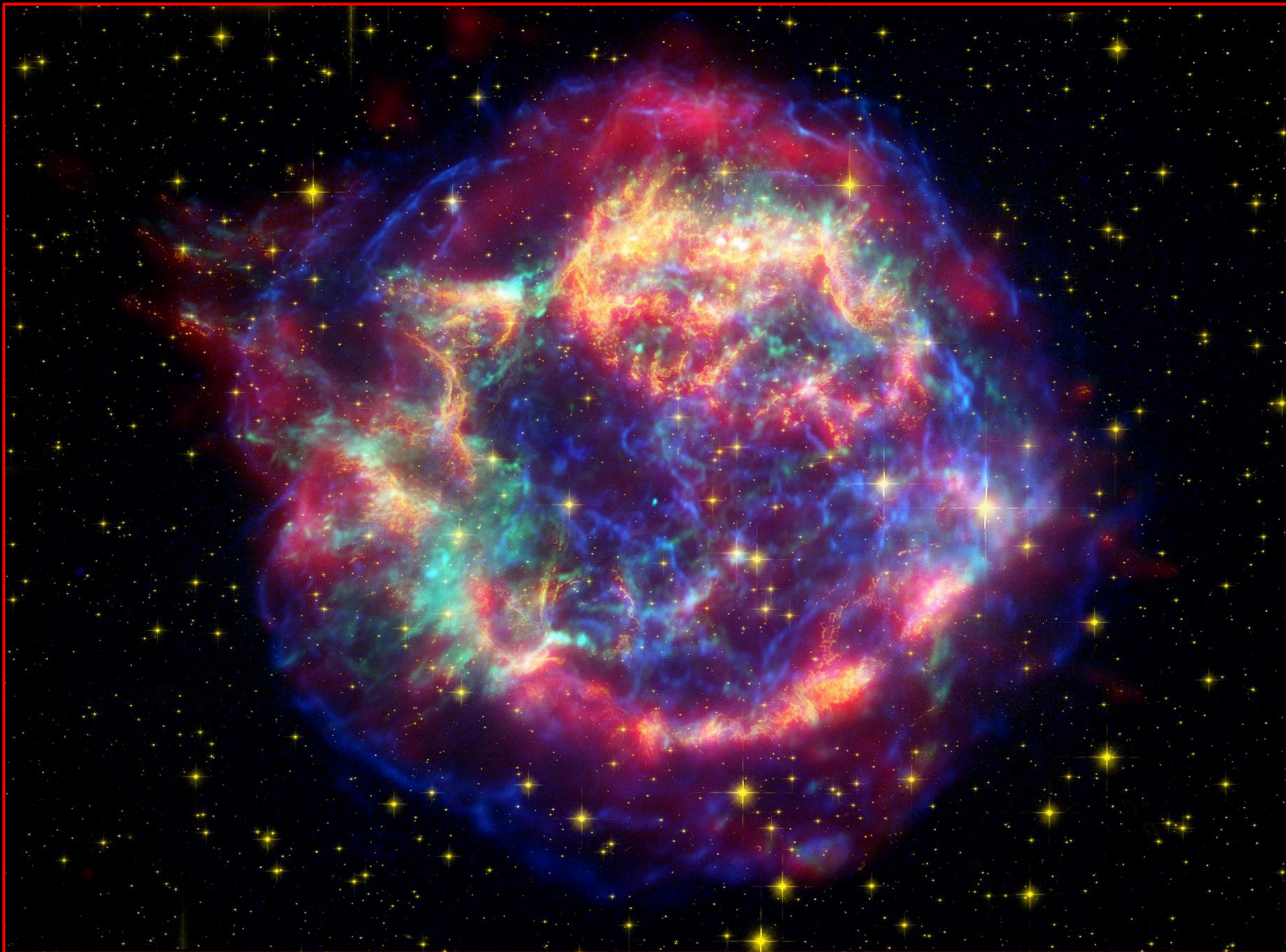
- We could also potentially directly observe these exotics in water/ice neutrino detectors
- ALP interactions with O16 or protons $\longrightarrow$ gamma rays $\longrightarrow$ electromagnetic cascades

EXOTICS: DIRECT OBSERVATION



- Depending on parameters and interaction channel, we could potentially see the ALP burst all the way to O(100's) kpc.

HIGH ENERGY NEUTRINOS



Cas A SNR. Credit: NASA/JPL-Caltech/O. Krause

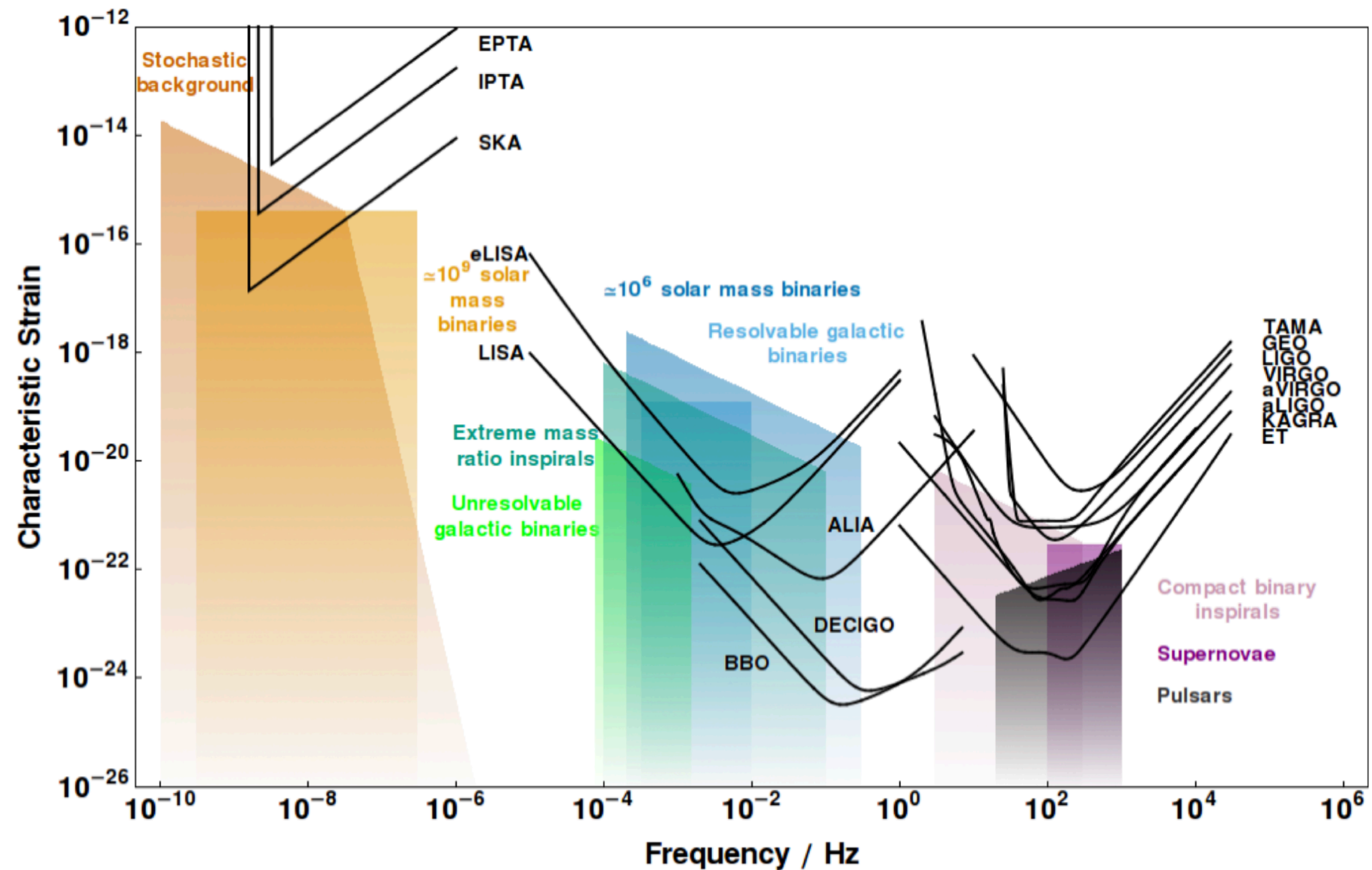
Core-collapse neutrinos (MeV) :

- 10 s burst, $\sim 10^{53}$ erg in neutrinos.
- GC: 10^5 to 10^6 events in IceCube, no MeV event reconstruction.

Post-explosion neutrinos (GeV-TeV) produced in shock acceleration (CSM, Jets) :

- > 1000 ν weeks to months after collapse; ν_μ localization to $< 1^\circ$ (Valtonen-Mattila + O'Sullivan 2023).
- These can also yield to cosmic rays and produce the shape of the Galactic Cosmic Ray $\rightarrow$ few percent of energy budget to CR x 2-3 CCSNe / century

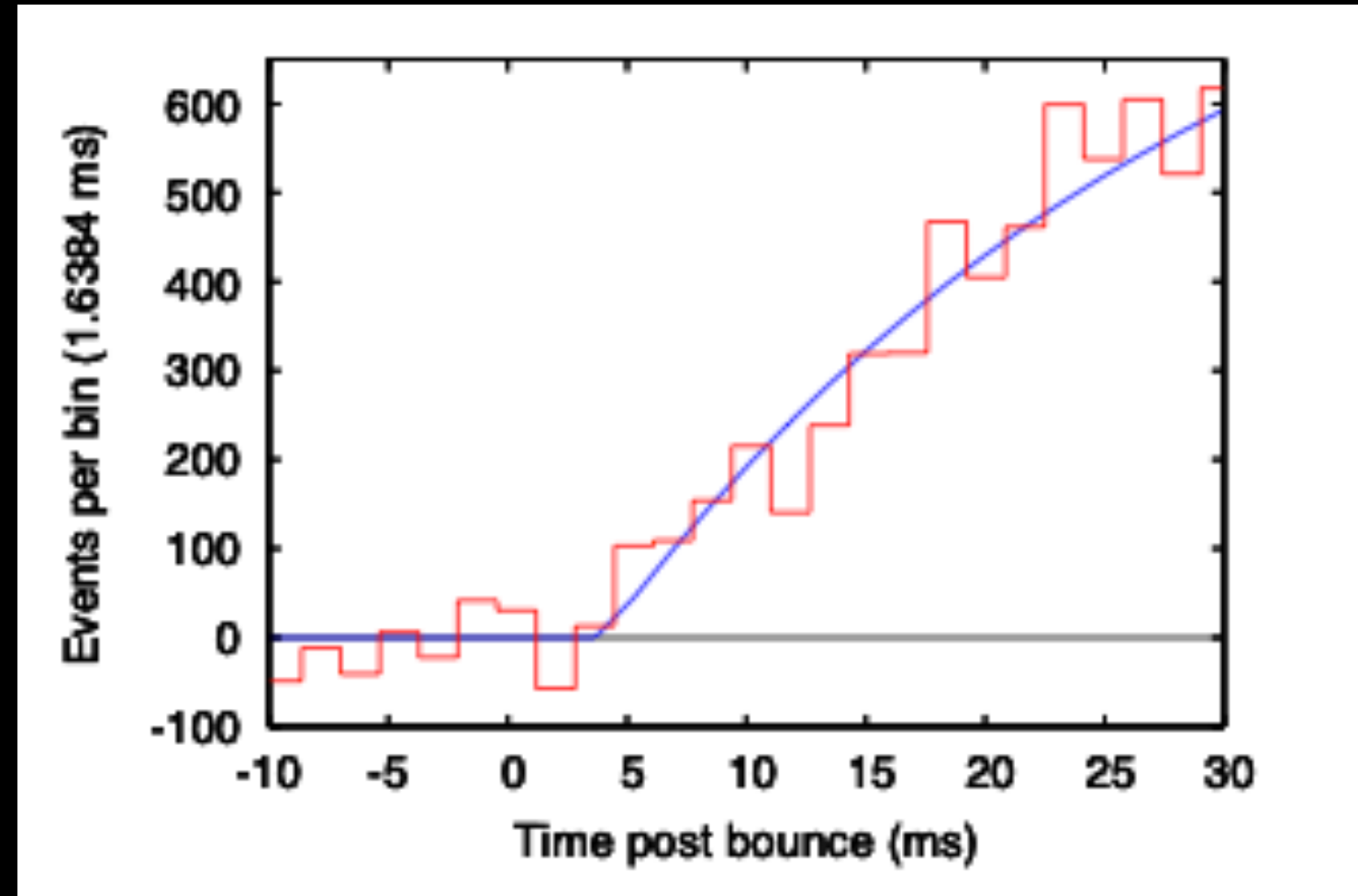
GRAVITATIONAL WAVES



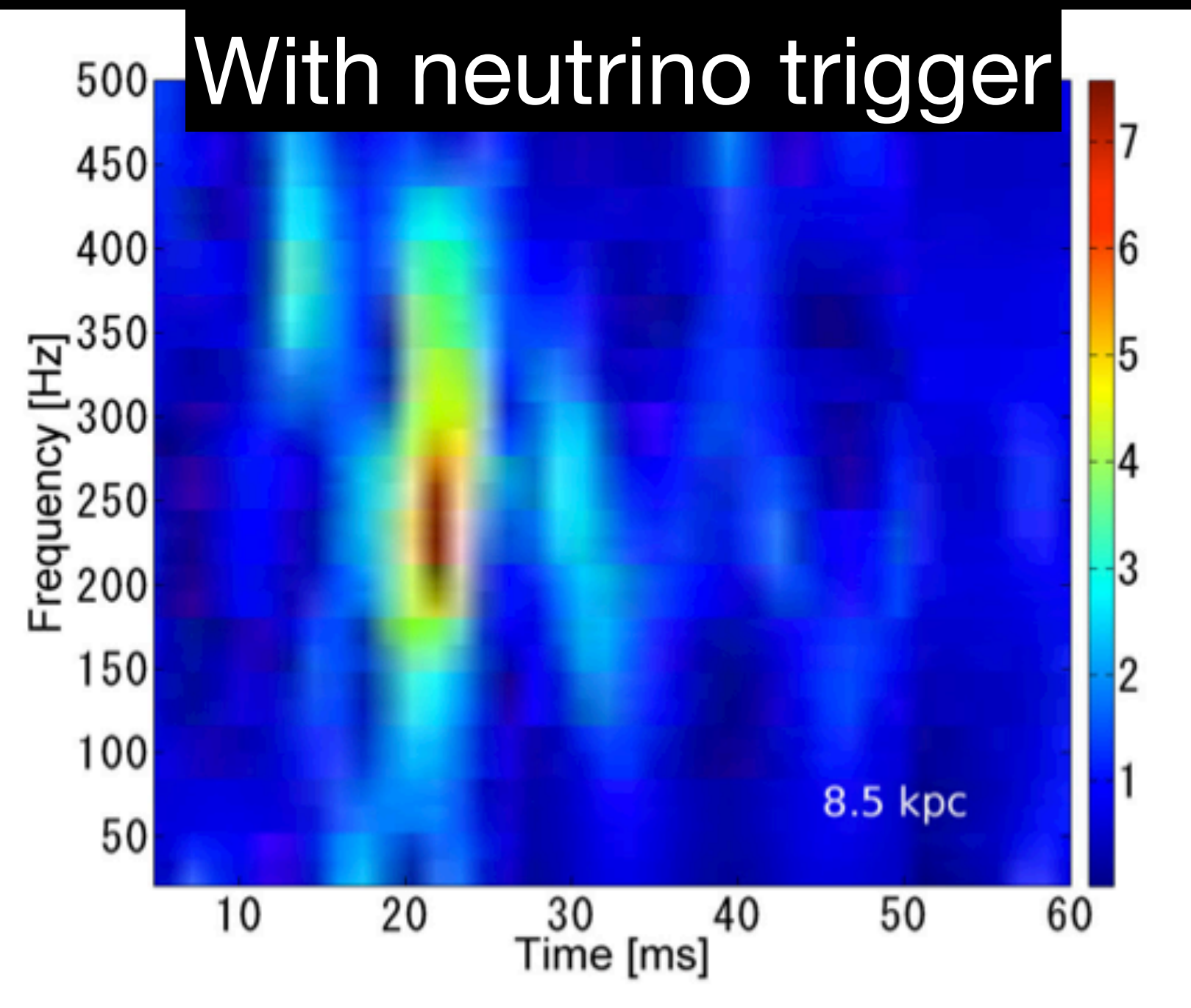
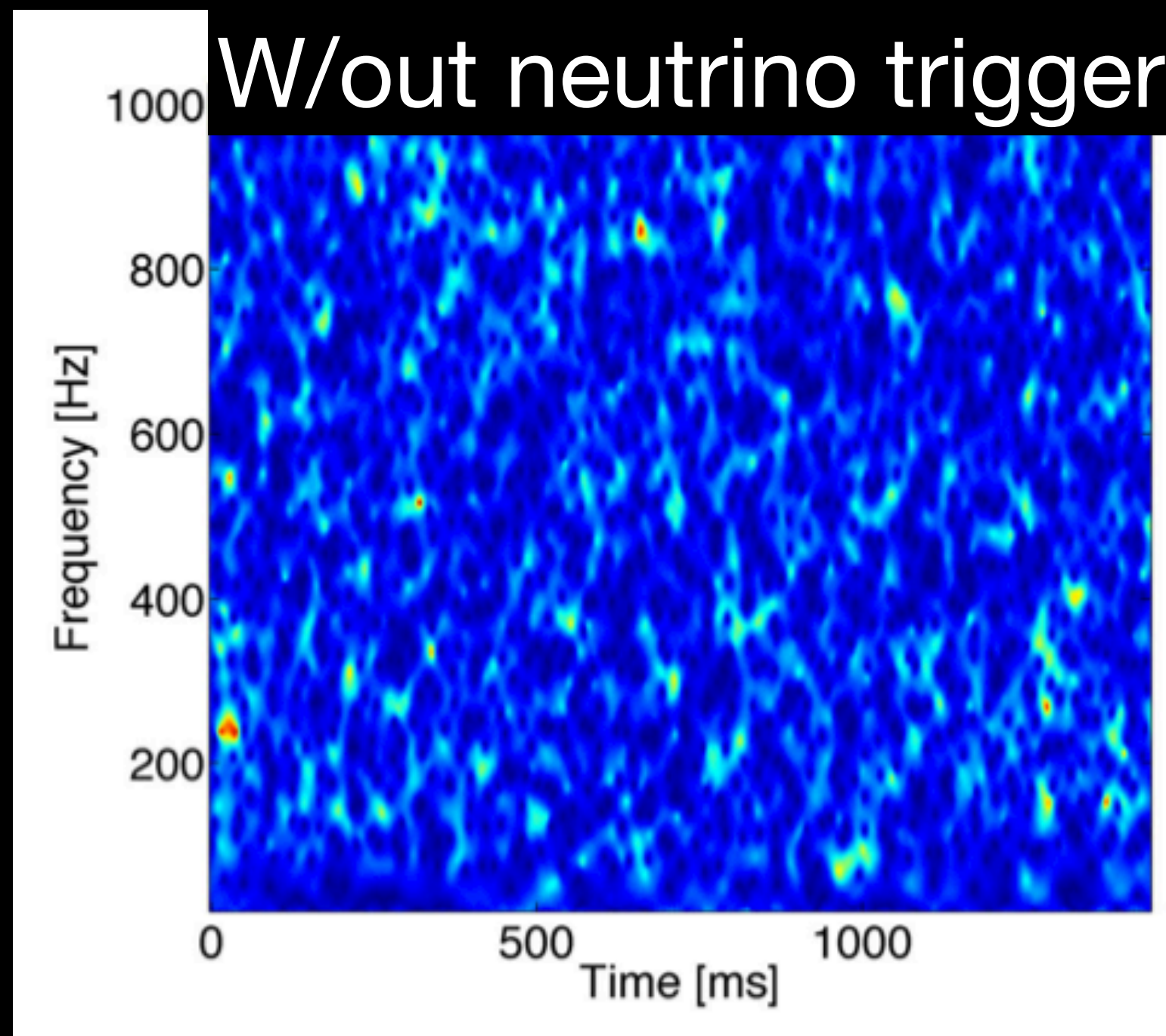
- GW could be produced in rotating stars or aspherical mass motions (convection, SASI)
- Challenging to detect due to long and complex signals, as well as low frequencies
 - CCSNe are one of the hardest astrophysical objects to model.
- However, sensitivity to Galactic CCSNe is expected to be reached by the fifth run of LIGO-Virgo-KAGRA
- Neutrinos could be used to search for this emission

https://dcc.ligo.org/public/0114/P1400129/003/noise_curve.pdf?utm_source=chatgpt.com

NEUTRINO TIMING FOR GW



Neutrino timing reconstruction of the core bounce can help with GW detection



Better
SNR

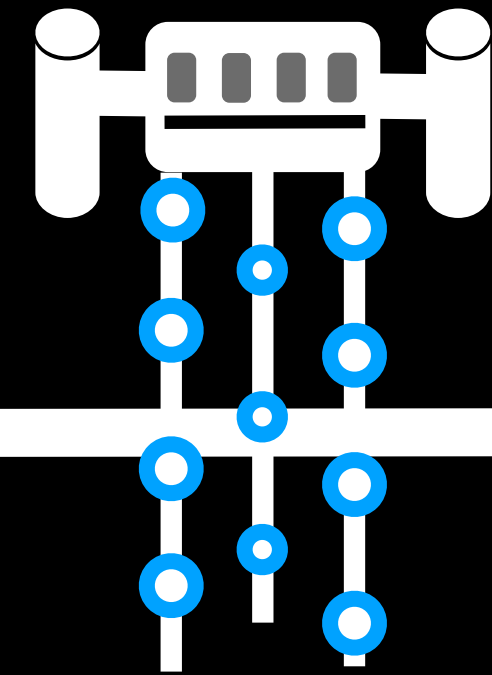
SUMMARY

- The next Galactic SN will be an incredible multi-messenger event and a **once-in-a-lifetime** opportunity to do study fundamental physics
- MeV neutrinos will play a key role not only in helping optical telescopes to catch the optical display, but also understand the physics in the deeper regions of the star
- Neutrino telescopes like IceCube are already having programs in place to monitor the sky for the next Supernova in realtime with 99% uptime and whole sky coverage.
- Programs like **SNEWS** will help to respond quickly to the astronomical community once a Galactic Supernova happens.
- We need to **improve our readiness** and work collaboratively across fields to make the most of this event!

OUTLINE



Observation of MeV ν



Neutrinos from CCSNe

Putting the pieces together



SNEWS
Supernova Early Warning System

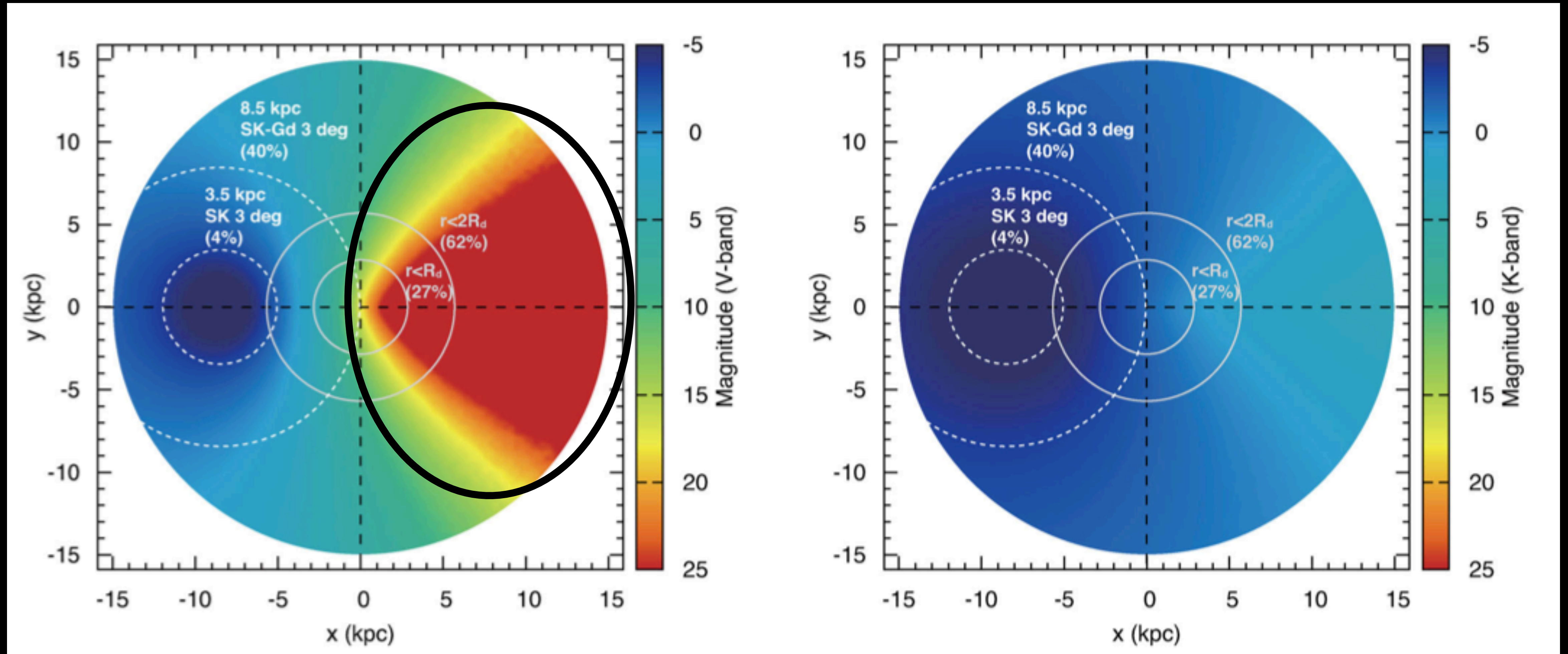
Why the next Galactic SN matters

Back up

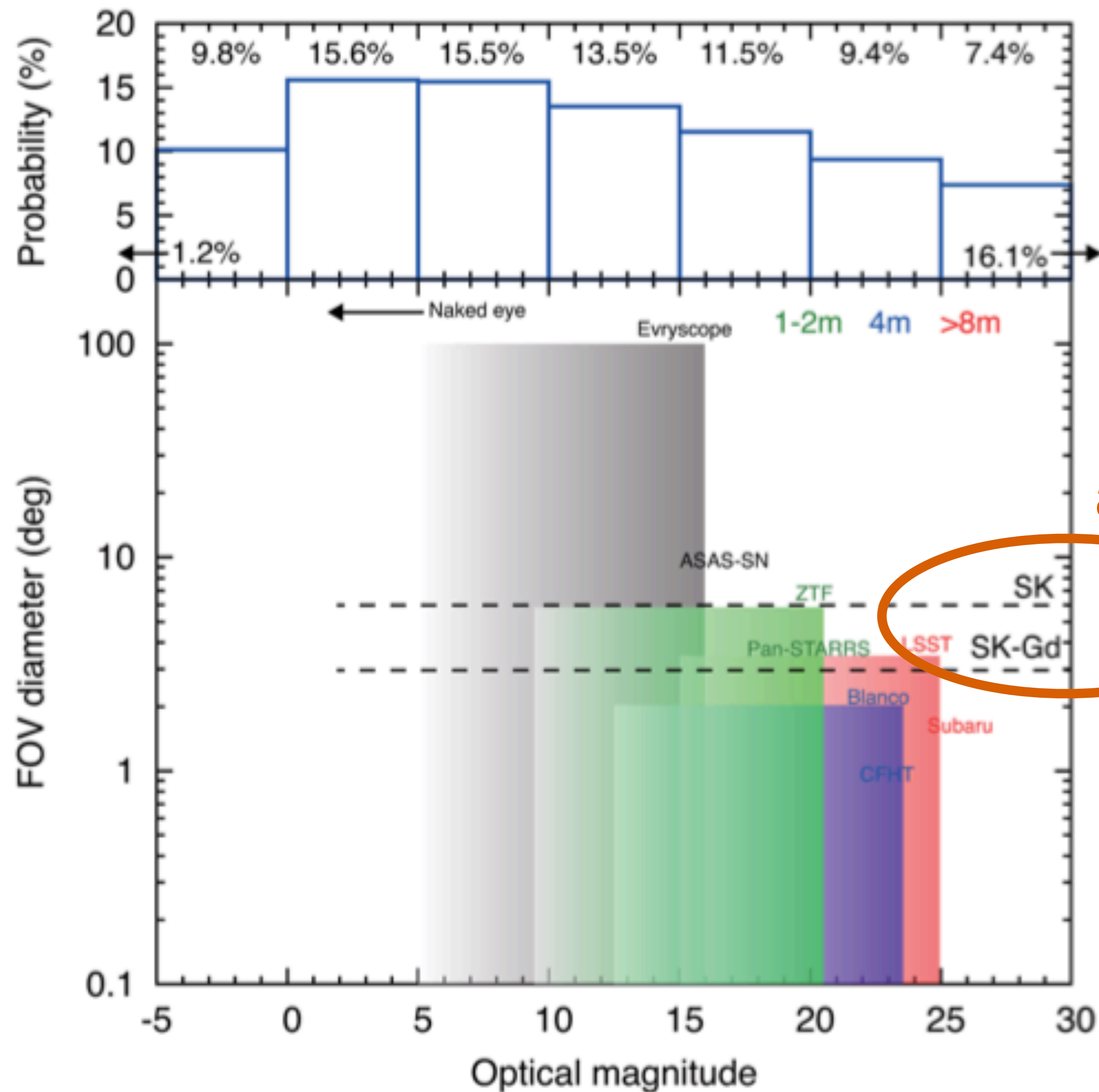
OPTICAL PLATEAU PHASE OBSERVATION

Optical

NIR



MULTI-MESSENGER SYNERGY: OPTICAL

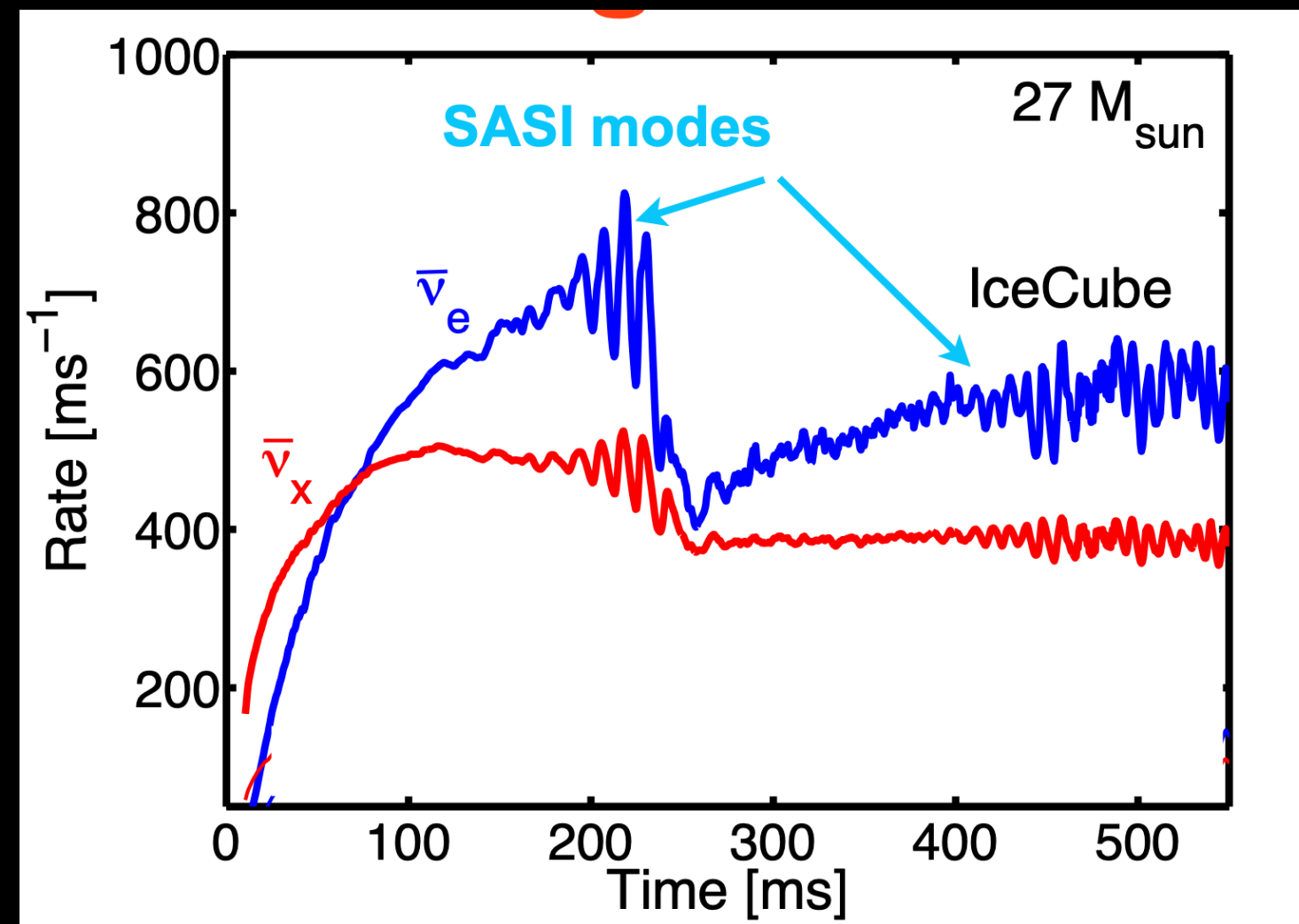


Fraction of all Galactic CCSNe

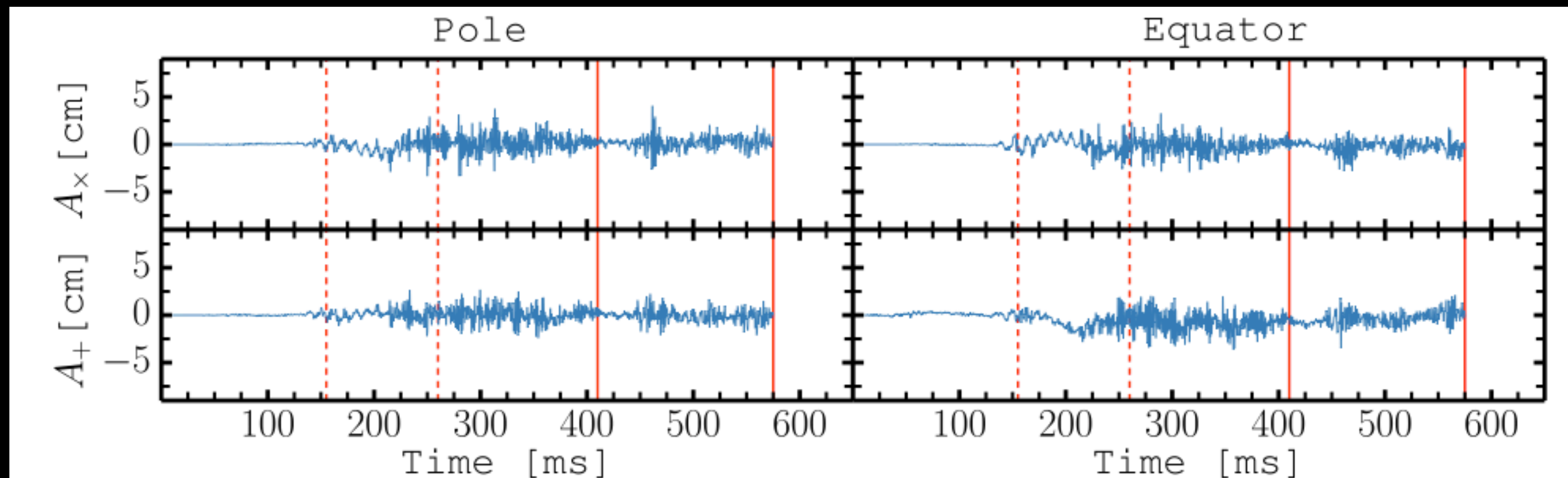
~25% of Galactic CCSNe will be fainter than 25 mag → inaccessible to even 8m telescopes

- SBO is expected to be similar in brightness
- Given how bright the SN is and how wide our FOV is, can we actually catch the SBO signal inside the neutrino error circle?
 - Small wide-field telescopes with large FOV can easily cover the entire neutrino error circle
- Hopefully with good triangulation from SNEWS 2.0 we can improve how fast telescopes can point

GRAVITATIONAL WAVES AND SASI



SASI can also be imprinted in GW,
and seeing this effect in two
messenger would help us
understand the convective
motions



SASI periods between
vertical lines

<https://academic.oup.com/mnras/article/468/2/2032/3070429>

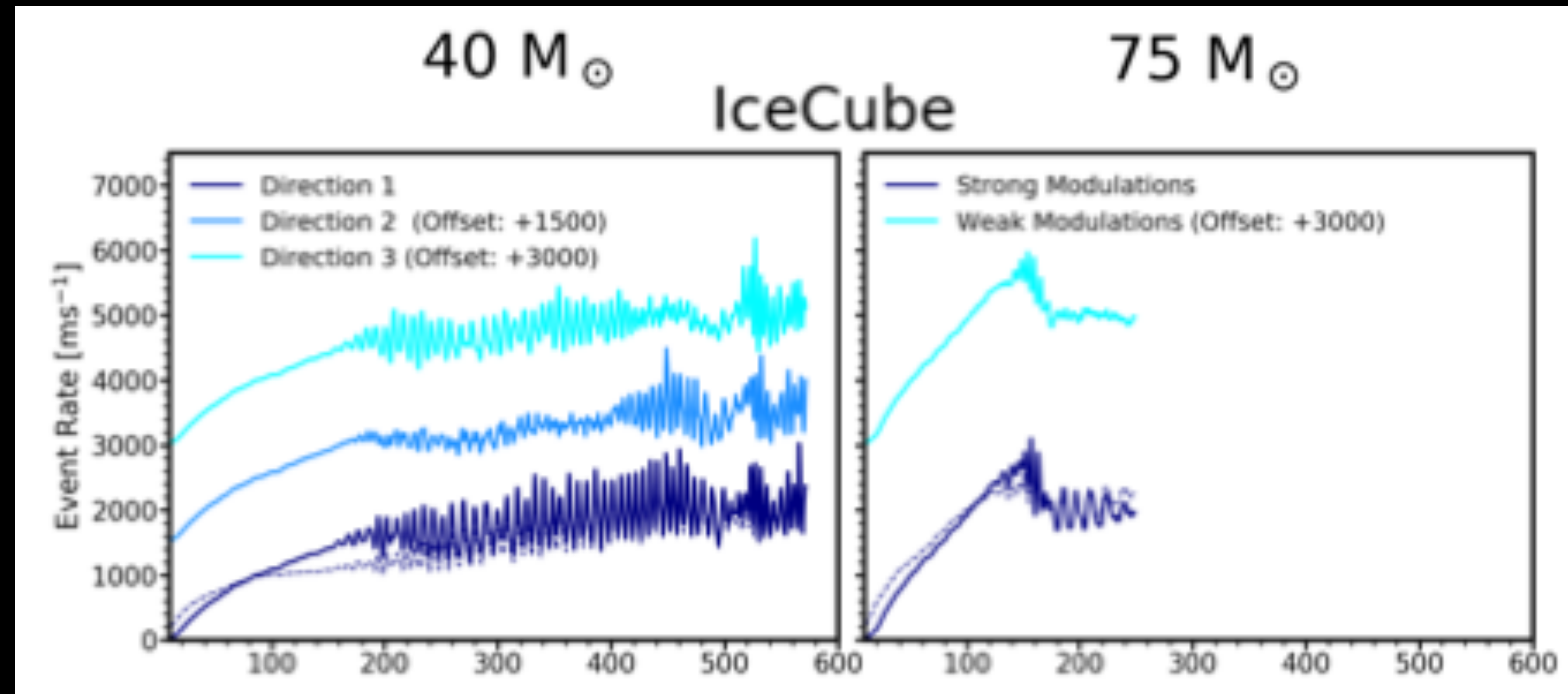
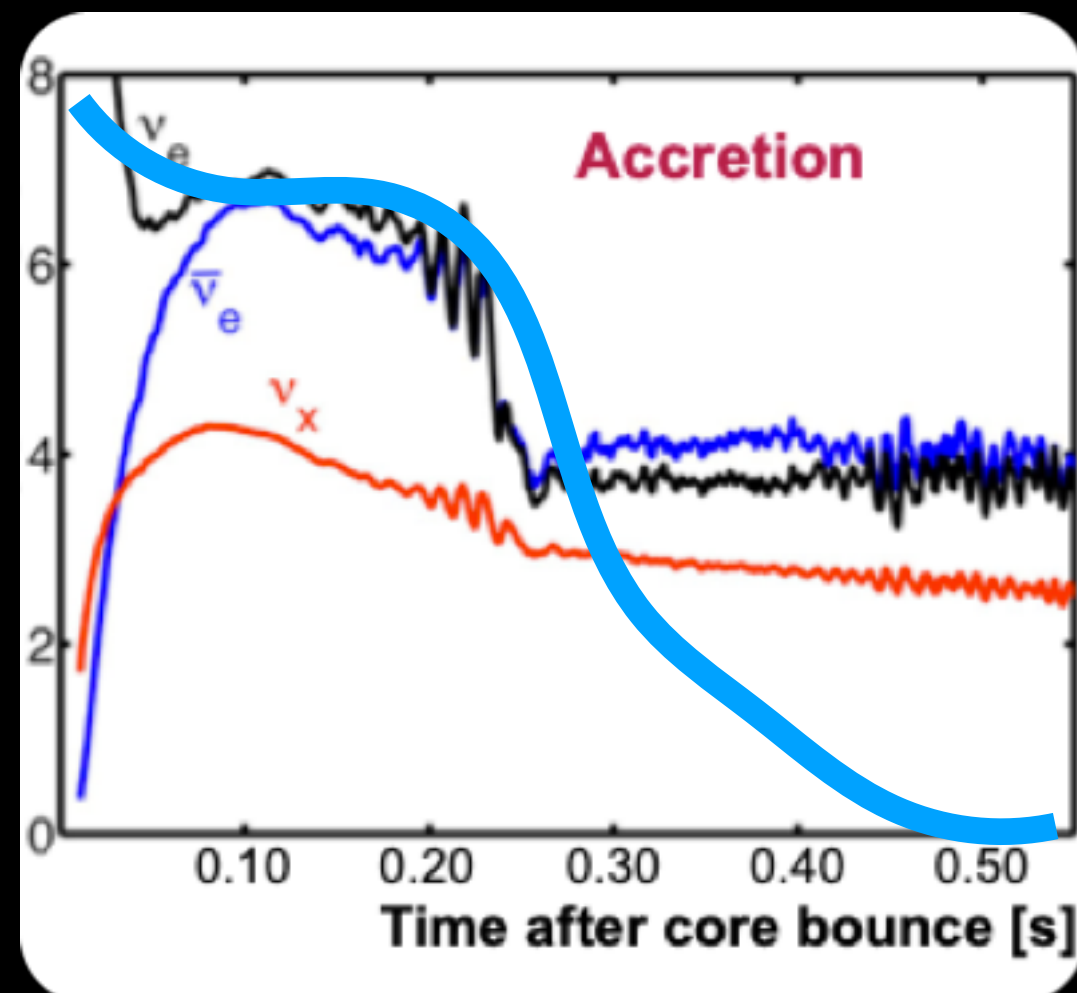
<https://arxiv.org/pdf/1307.7936>

WHAT CAN WE PROBE WITH NEUTRINOS

Failed CCSNe
fraction: 4-43%

BLACK HOLE FORMATION

Stage II: Accretion



Walk, Tamborra, Janka, Summa, Kresse, PRD (2020)

MULTI-MESSENGER SYNERGY: OPTICAL

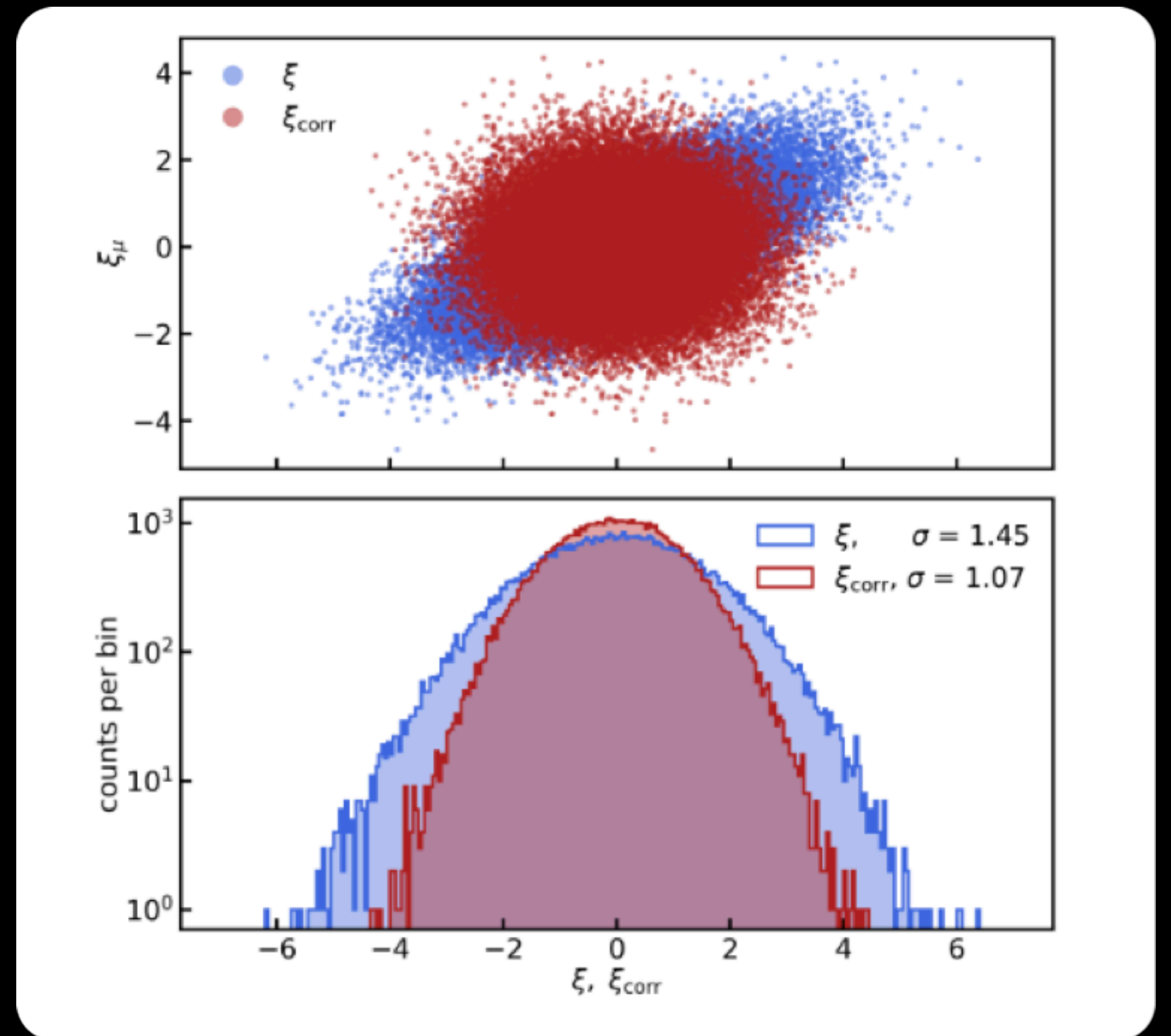
- Catching the SBO at all
- Answering the questions of when did it explode to how did the shock propagate
- Answering the question of energy budget and explosion physics (and potentially with optical polarization, understand explosion asymmetry better!)
- Answering the question on progenitor and environment

BACKGROUND SOURCES

Background sources: Thermal noise, radioactive decay, atmospheric muons

- Single DOM correlations: Noise $\approx$ Poissonian distribution. We apply a deadtime at the DAQ stage. Reduces rate from 540 Hz to 286 Hz.
- DOM-to-DOM correlations: Atmospheric μ produce correlated hits when passing through the detector. To remove them, we apply a linear correction to ξ using muon rates at the time of trigger.

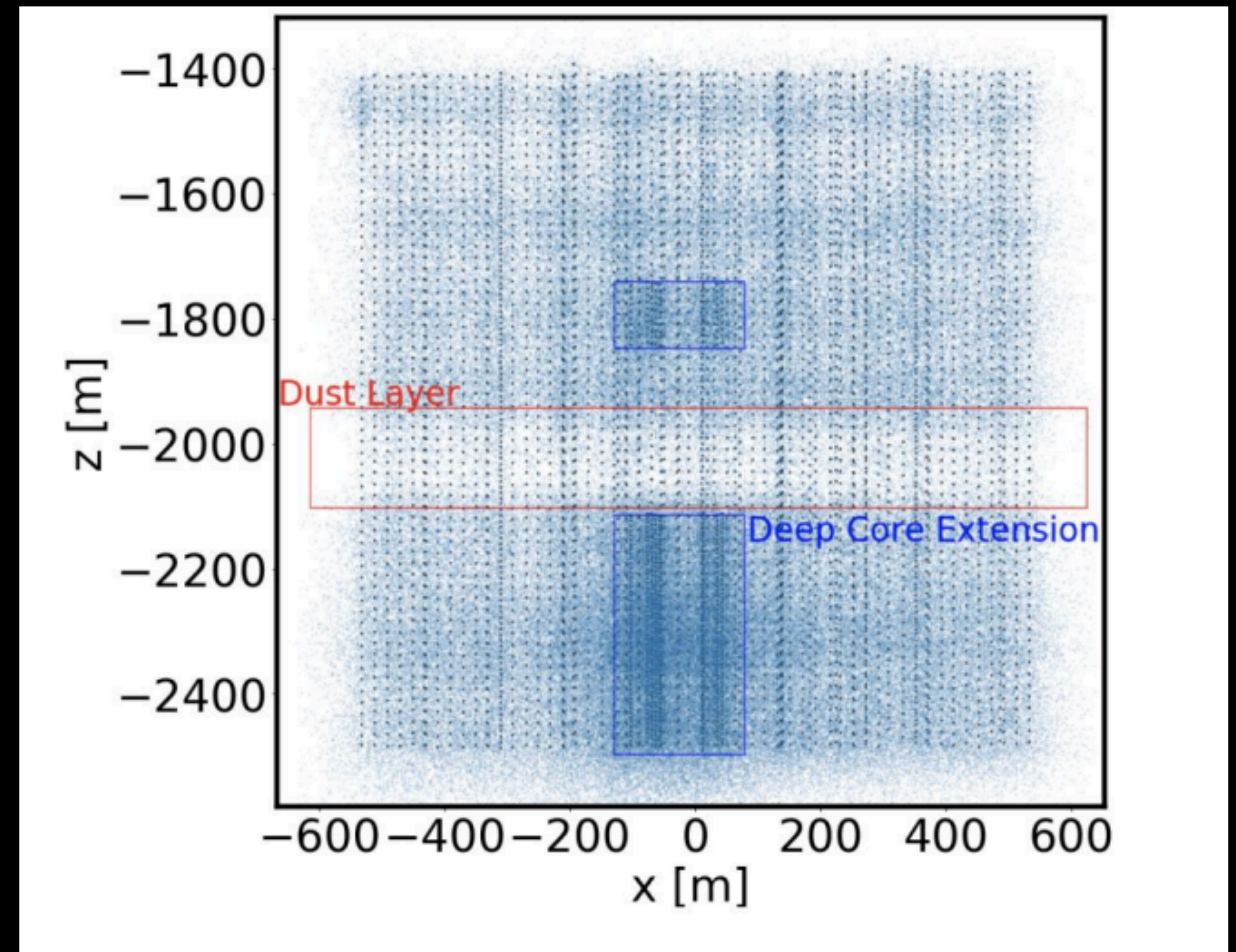
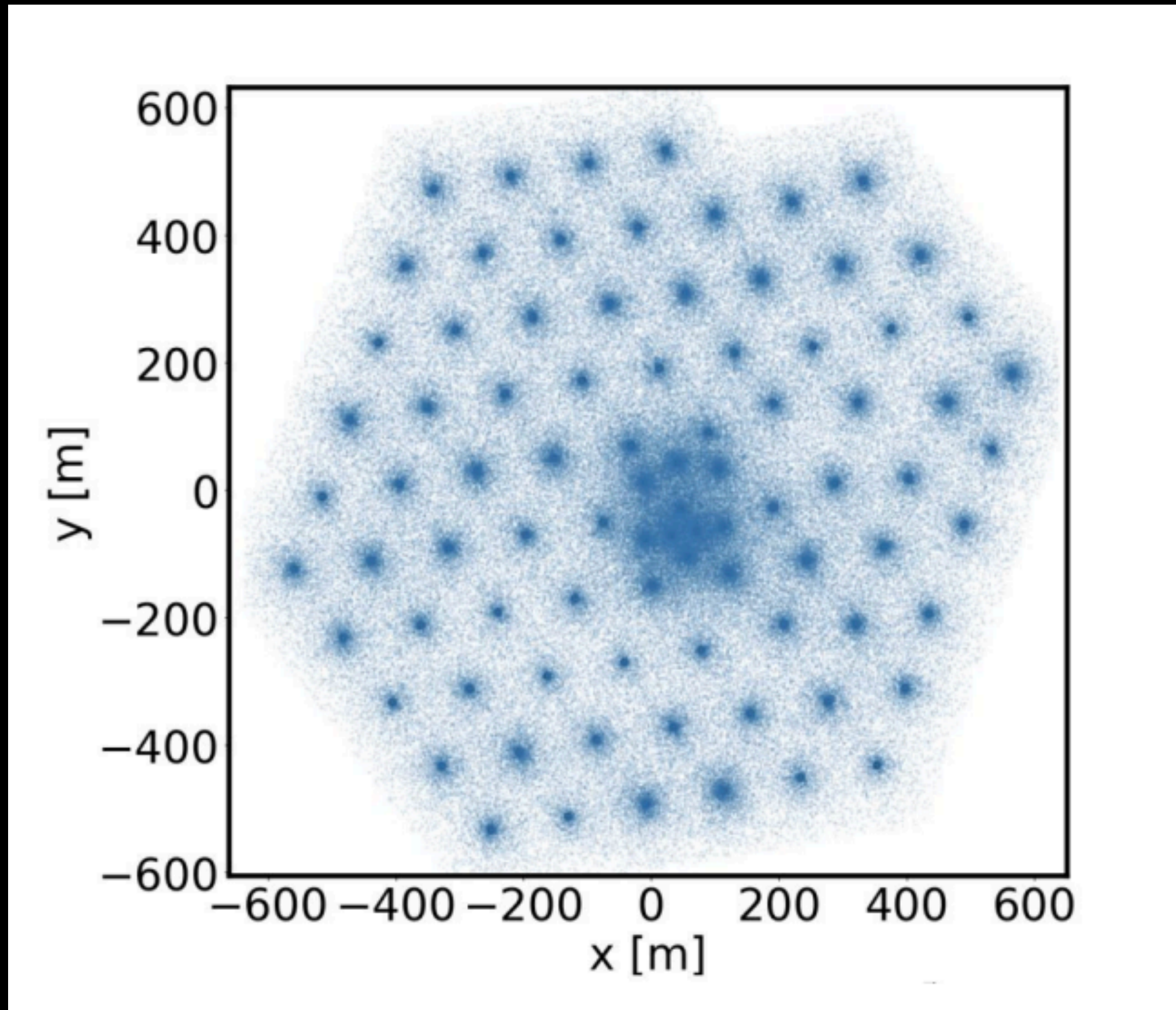
ξ' : Test statistic with the atmospheric μ contribution removed



Credit: R. Abbasi et al., IceCube Collaboration, 2024, ApJ 961, 84

INTERACTIONS IN ICE

Simulated MeV IBD vertices

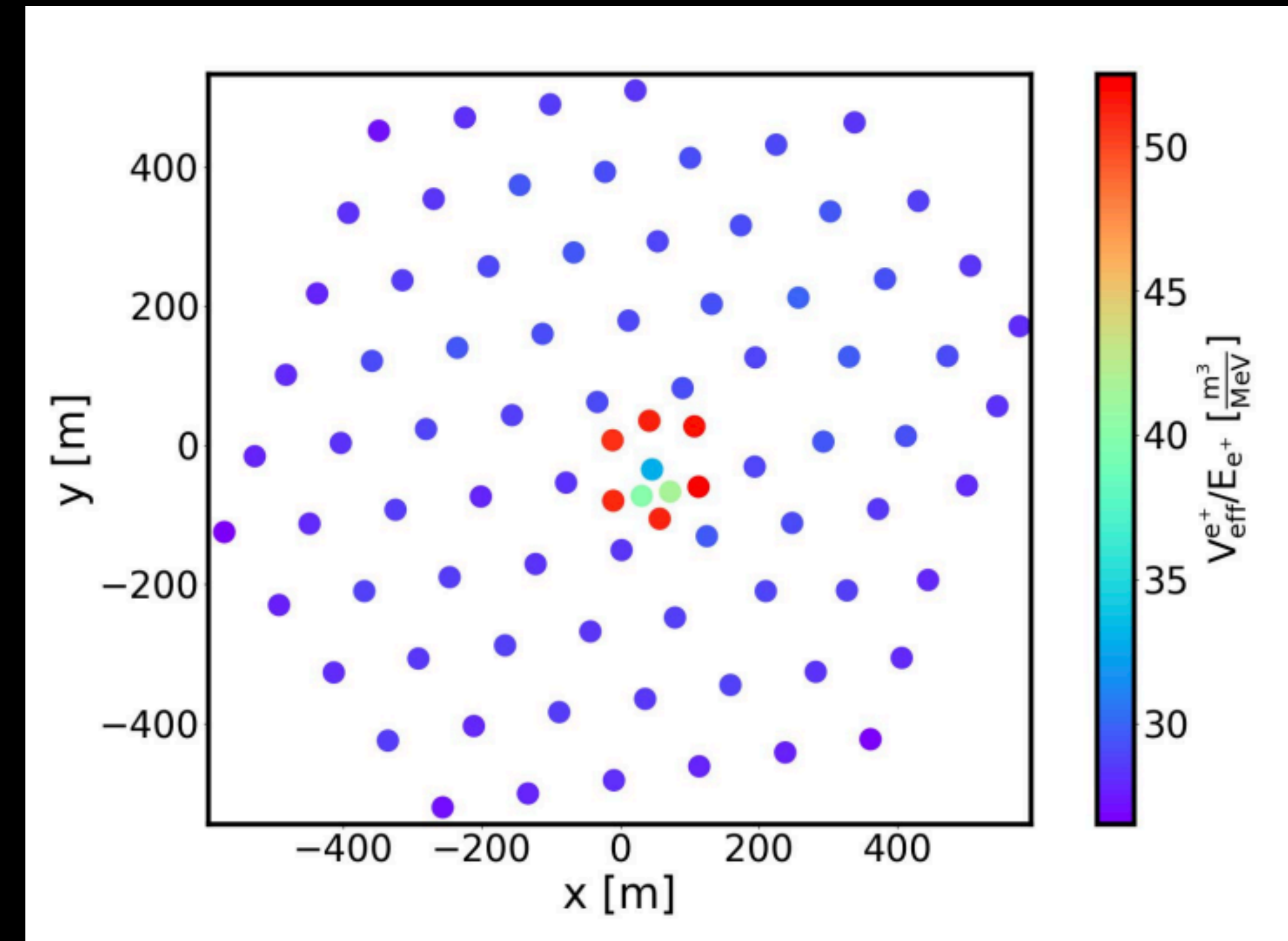
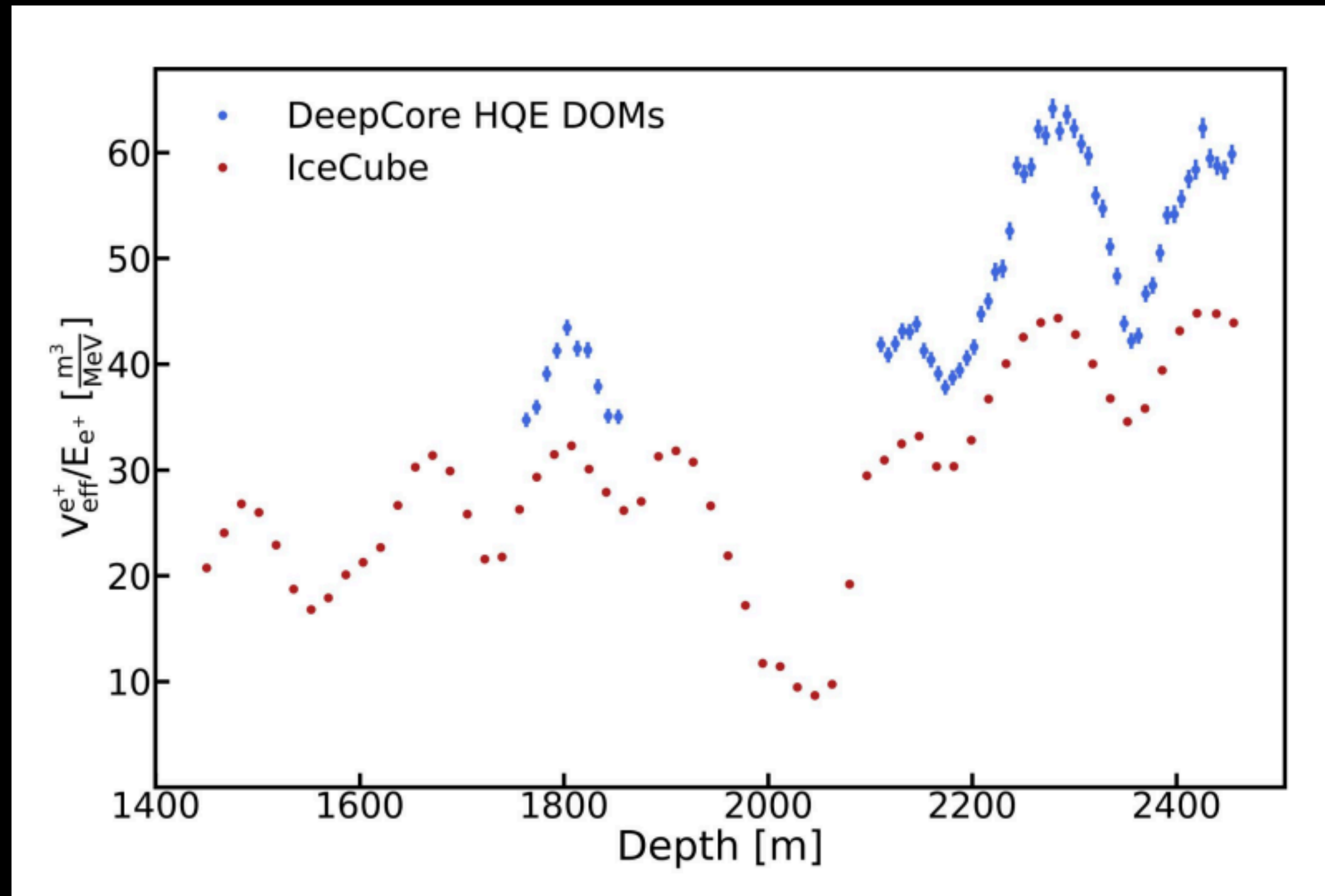


Credit: R. Cross, A. Fritz, S. Griswold, PoS(ICRC19)

EFFECTIVE VOLUME

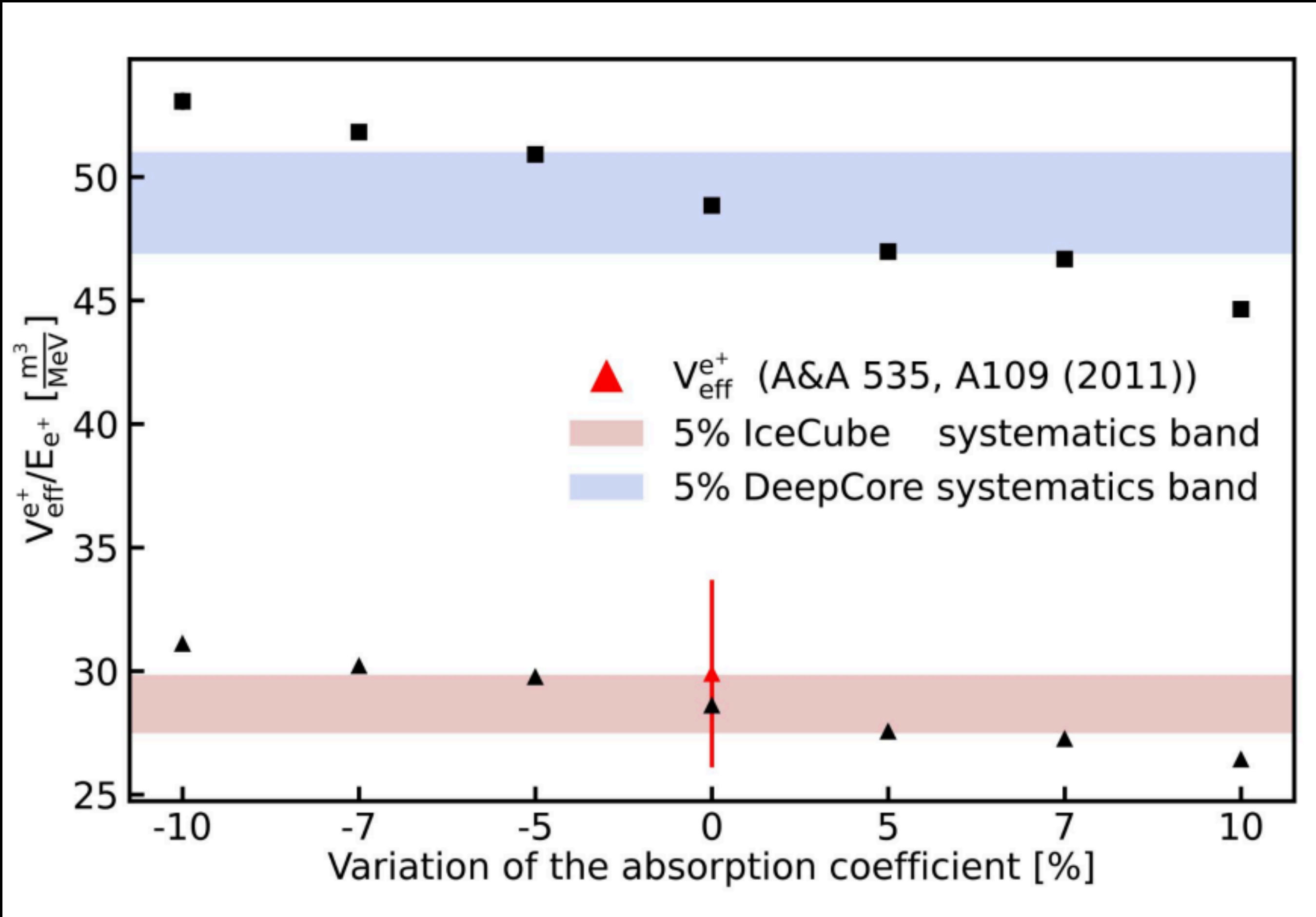
Per DOM effective volume

$\text{m}^3 \text{MeV}^{-1}$



Credit: A. Fritz (IceCube Collaboration), 2024

SYSTEMATIC UNCERTAINTIES



Systematic Uncertainty	Relative Size [%]
Rate deviation in sliding average window	± 1.6
Ice density vs. depth	± 0.2
Mean $e^\pm$ track length in ice	± 5.0
Ice optical properties	$[-3.6, +4.1]$
DOM efficiency	± 10.0
Artificial deadtime	± 3.0
Cross Sections (e^+p , e^-p , e^-O)	$< \pm 1, < \pm 1, \pm 0.2$
zenith-dependent neutrino oscillation in Earth	$[-0.2, +4.9]$
Total	$[-15.0, +16.2]$

Credit: A. Fritz (IceCube Collaboration), 2024

NEUTRINO PROCESSES: ENERGY REGIMES FOR ν OBSERVATION

Threshold-less processes		
Coherent scattering	$\nu + A_N^Z \rightarrow \nu + A_N^{*Z}$	NC
Low-energy processes ($\sim 1 - 100$ MeV)		
Inverse beta decay	$(\bar{\nu}_e, \nu_e) + (p, n) \rightarrow e^\pm + (n, p)$	CC
Intermediate energy processes ($\sim 0.1 - 100$ GeV)		
Elastic scattering off electrons	$(\bar{\nu}, \nu) + e^- \rightarrow (\bar{\nu}, \nu) + e^-$	NC
Elastic scattering off electrons	$(\bar{\nu}, \nu) + e^\pm \rightarrow (\bar{\nu}, \nu) + l^\pm$	CC
Quasi-elastic scattering off nucleon	$(\bar{\nu}, \nu) + N \rightarrow N + l^\pm$	CC
Elastic scattering off nucleon	$(\bar{\nu}, \nu) + N \rightarrow (\bar{\nu}, \nu) + N$	NC
Deep inelastic scattering (≥ 100 GeV)		
Charged current DIP	$(\bar{\nu}, \nu) + N \rightarrow l^\pm + X$	CC
Neutral current DIP	$(\bar{\nu}, \nu) + N \rightarrow (\bar{\nu}, \nu) + X$	NC

Table 3.2. *Important neutrino interactions for the observation of CCSNe neutrinos [62, 149]. $N = n, p$, $X =$ any final set of hadrons, and $l =$ lepton*

Credit: Valtonen-Mattila. 2022 Thesis: [Expanding the observational reach of core-collapse supernovae for IceCube using high-energy neutrinos.](#)

NEUTRINO PRODUCTION REGIME

MeV Domain

Beta processes	
e^- and ν_e capture by nucleons	$e^- + p \leftrightarrow n + \nu_e$
e^+ and $\bar{\nu}_e$ capture by nucleons	$e^+ + n \leftrightarrow p + \bar{\nu}_e$
e^- and ν_e absorption by nuclei	$e^- + (A, Z) \leftrightarrow (A, Z-1) + \nu_e$
Thermal pair production and annihilation processes	
Nucleon-nucleon Bremsstrahlung	$N + N \leftrightarrow N + N + \nu + \bar{\nu}$
Electron-positron pair process	$e^+ + e^- \leftrightarrow \nu + \bar{\nu}$
Neutrino scattering	
Neutrino scattering with nuclei	$\nu + (A, Z) \leftrightarrow \nu + (A, Z)$
Neutrino scattering with nucleons	$\nu + N \leftrightarrow \nu + N$
Neutrino scattering with $e^\pm$	$\nu + e^\pm \leftrightarrow \nu + e^\pm$
Neutrino-neutrino reactions	
Neutrino pair annihilation	$\nu_e + \bar{\nu}_e \leftrightarrow \nu_x + \bar{\nu}_x$
Neutrino scattering	$\nu_x + (\nu_e, \bar{\nu}_e) \leftrightarrow \nu_x + (\nu_e, \bar{\nu}_e)$

GeV-TeV Domain

Photohadronic

$$p + p \left\{ \begin{array}{l} \rightarrow X + \pi^\pm \rightarrow X + \mu^\pm + \nu_\mu(\bar{\nu}_\mu) \rightarrow X + e^\pm + \nu_e(\bar{\nu}_e) + \nu_\mu(\bar{\nu}_\mu) \\ \rightarrow X + \pi^0 \rightarrow X + 2\gamma \end{array} \right. + \text{also pn interaction!}$$

Hadronuclear

$$p + \gamma \rightarrow \Delta^+ \left\{ \begin{array}{l} \rightarrow n + \pi^+ \rightarrow n + \mu^+ + \nu_\mu \rightarrow n + e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu \\ \rightarrow p + \pi^0 \rightarrow p + 2\gamma \end{array} \right.$$
$$n + \gamma \rightarrow \Delta^0 \left\{ \begin{array}{l} \rightarrow n + \pi^0 \rightarrow n + 2\gamma \\ \rightarrow p + \pi^- \rightarrow p + \mu^- + \bar{\nu}_\mu \rightarrow p + e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu \end{array} \right.$$

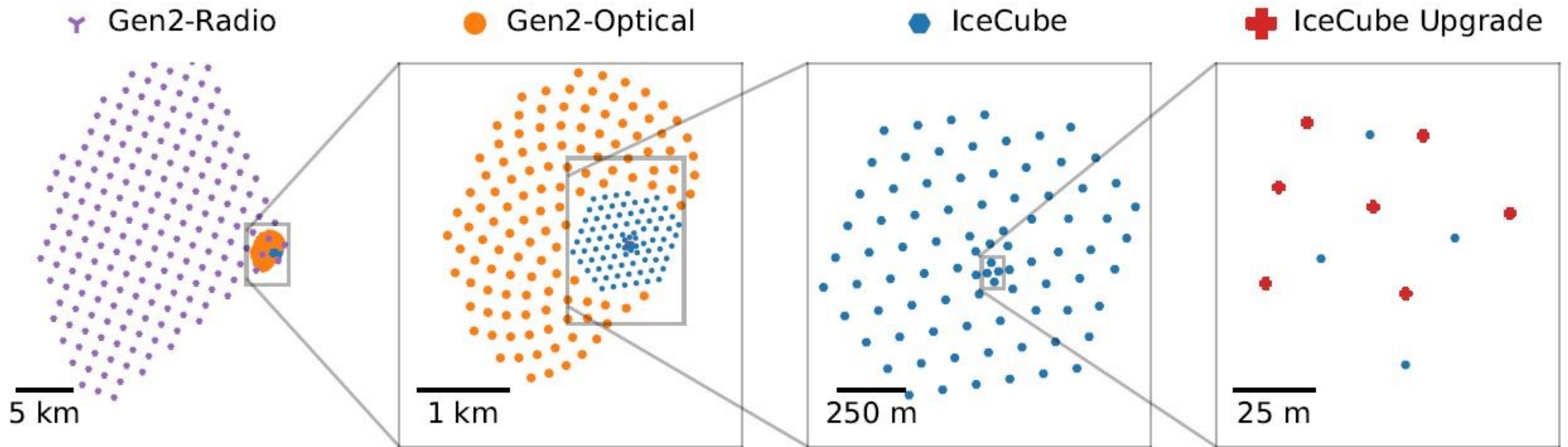
MEV NEUTRINO OBSERVATORIES

Table 1. A summary of supernova neutrino arrival time uncertainties (δt) estimated in reference (Brdar *et al* 2018). In the second and third columns, the main detection channel as well as the target are shown for each of the experiments listed in the first column. The next (last) two columns show the δt values for the galactic supernova core-collapse into a neutron star (black hole).

Experiments	Major process	Target	δt (ms)	δt (BH)
Super-K	$\bar{\nu}_e + p \rightarrow e^+ + n$	32 kt H ₂ O	0.9	0.14 ms
JUNO	$\bar{\nu}_e + p \rightarrow e^+ + n$	20 kt C _n H _m	1.2	0.19 ms
DUNE	$\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$	40 kt LAr	1.5	0.18 ms
NO ν A	$\bar{\nu}_e + p \rightarrow e^+ + n$	14 kt C _n H _m	1.4	0.24 ms
CJPL	$\bar{\nu}_e + p \rightarrow e^+ + n$	3 kt H ₂ O	3.8	0.97 ms
IceCube	Noise excess	H ₂ O	1	0.16 ms
ANTARES	Noise excess	H ₂ O	100	32 ms
Borexino	$\bar{\nu}_e + p \rightarrow e^+ + n$	0.3 kt C _n H _m	16	5.5 ms
LVD	$\bar{\nu}_e + p \rightarrow e^+ + n$	1 kt C _n H _m	7.5	2.4 ms
XENON1T	Coherent scattering	2 t X _e	27	10 ms
DARWIN	Coherent scattering	40 t X _e	1.3	0.7 ms

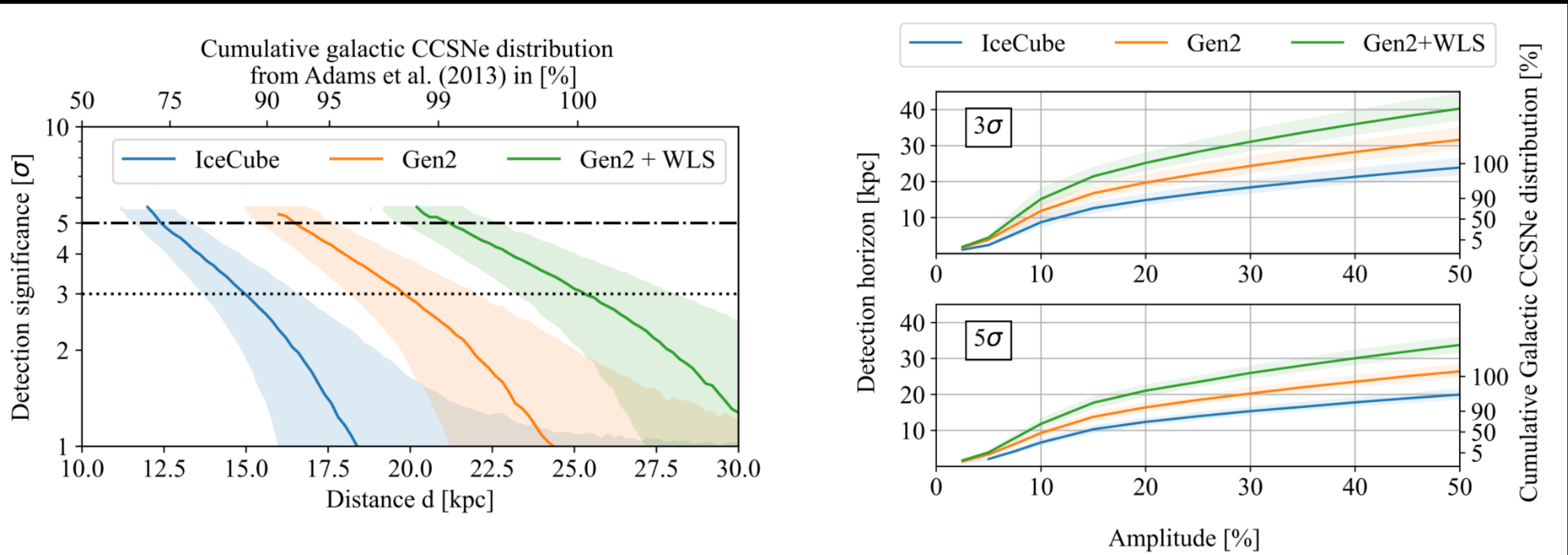
ICECUBE GEN2

GEN2 ARRAY



FAST TRANSIENT FEATURES FROM CCSN

CCSNe could have fast time features in the neutrino luminosity
With IceCube Gen2 we could potentially reach our entire Milky Way



[Credit: Beise J., BenZvi S., Griswold S., Valtonen-Mattila N. & O'Sullivan E. \(2025\)](#)