Some New Results on Stellar Neutrinos

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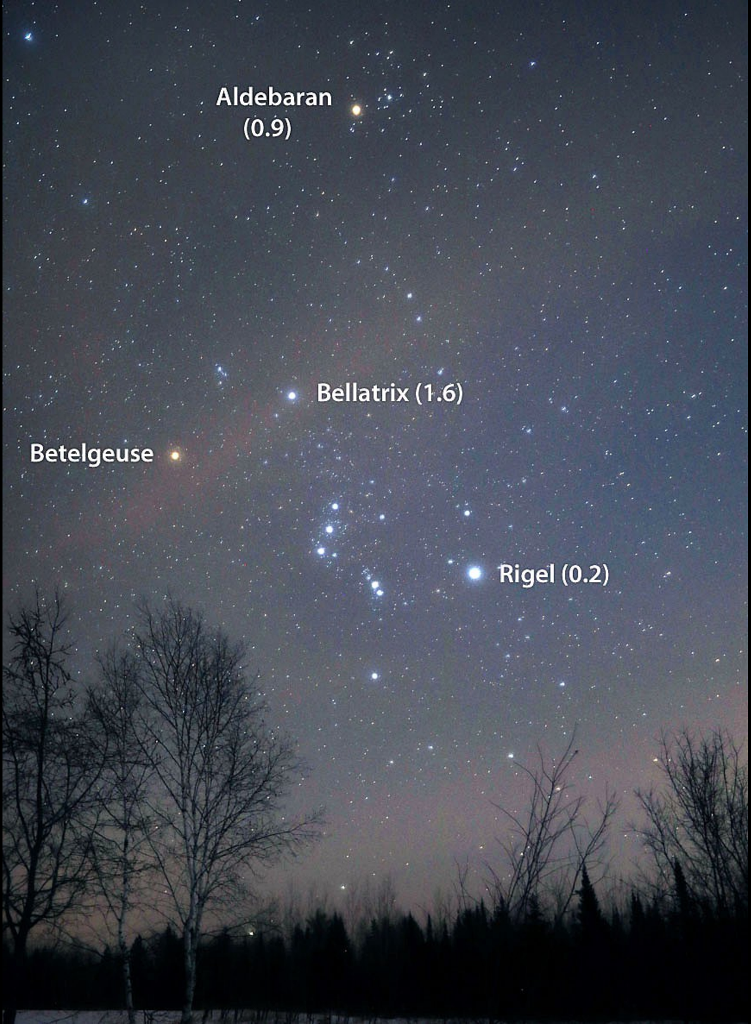
Roadmap

38 slides on

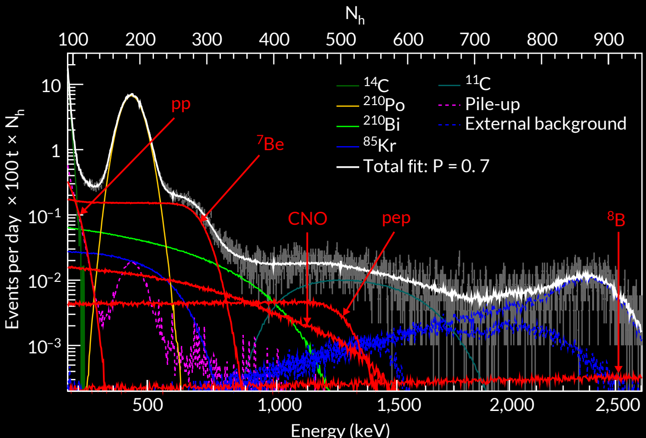
1) Neutrino astronomy
2) Neutrino production in stars
3) MESA
4) Neutrino Hertzsprung-Russell Diagram
5) Probing the presupernova isotopic evolution
6) Identifying the presupernova progenitor
7) Low mass stars count too



Bob King,
Sky & Telescope,
22Dec2019

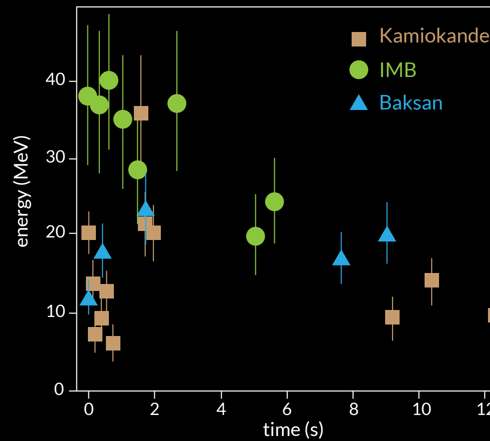
Over the next decade, neutrino astronomy will probe the rich astrophysics of neutrino production in the sky.

The Sun

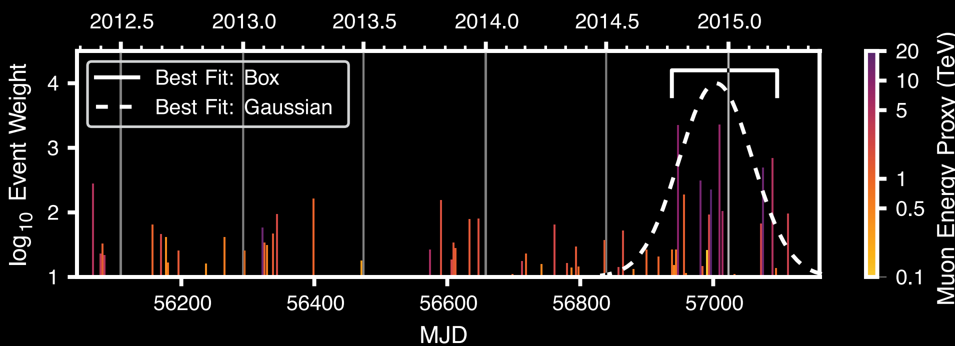


Borexino Collaboration 2018, 2020

supernova 1987A



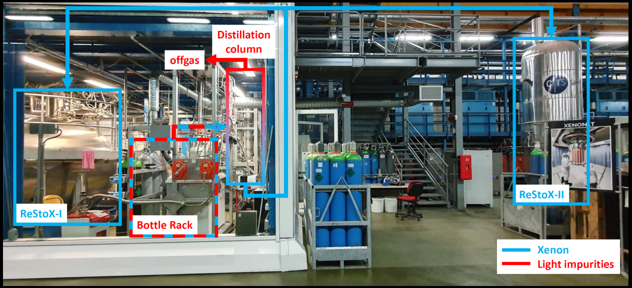
blazar TXS 0506+056



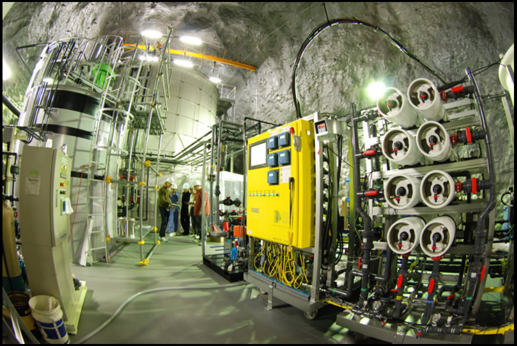
IceCube Collaboration 2018

Super-Kamiokande with Gadolinium, Jiangmen Underground Neutrino Observatory, XENON and other experiments usher in a new generation of detectors designed to open new avenues for potentially observing currently undetected neutrinos.

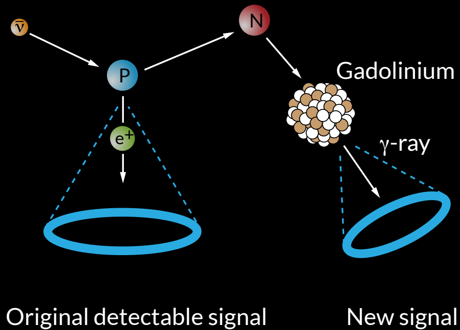
JUNO aims to begin taking data in 2021



XENON dark matter project



Super-K with Gadolinium Test Facility



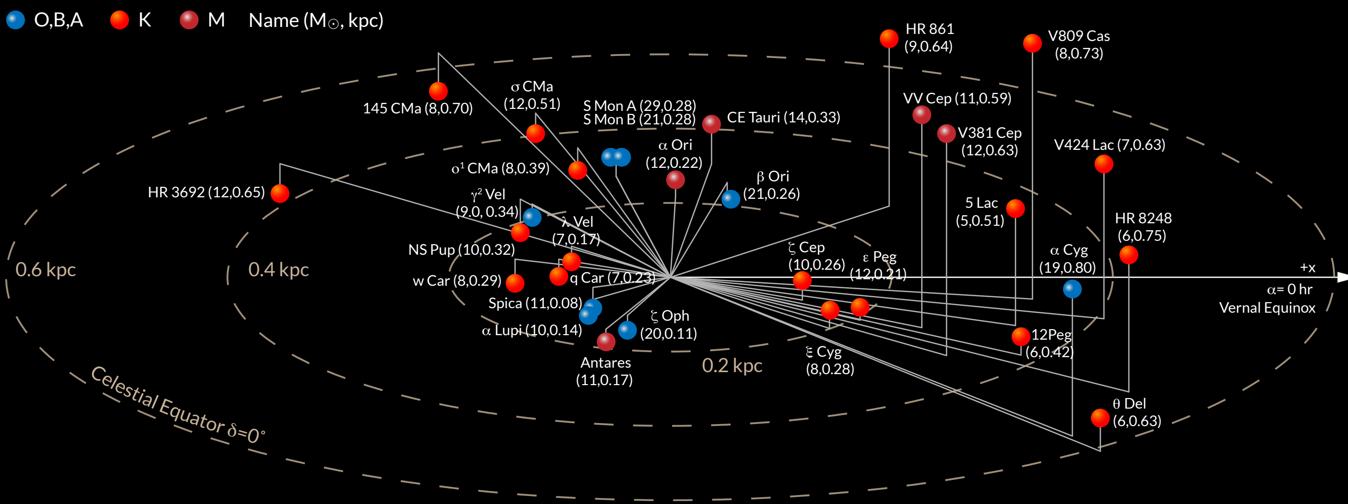
ApJ, Nov 2019

Sensitivity of Super-Kamiokande with Gadolinium to Low Energy Anti-neutrinos from Pre-supernova Emission

C. Simpson et al, The Super-Kamiokande Collaboration

ABSTRACT

Supernova detection is a major objective of the Super-Kamiokande (SK) experiment. In the next stage of SK (SK-Gd), gadolinium (Gd) sulfate will be added to the detector, which will improve the ability of the detector to identify neutrons. A core-collapse supernova will be preceded by an increasing flux of neutrinos and anti-neutrinos, from thermal and weak nuclear processes in the star, over a timescale of hours; some of which may be detected at SK-Gd. This could provide an early warning of an imminent core-collapse supernova, hours earlier than the detection of the neutrinos from core collapse. Electron anti-neutrino detection will rely on inverse beta decay events below the usual analysis energy threshold of SK, so Gd loading is vital to reduce backgrounds while maximising detection efficiency. Assuming normal neutrino mass ordering, more than 200 events could be detected in the final 12 hours before core collapse for a 15-25 solar mass star at around 200 pc, which is representative of the nearest red supergiant to Earth, α-Ori (Betelgeuse). At a statistical false alarm rate of 1 per century, detection could be up to 10 hours before core collapse, and a pre-supernova star could be detected by SK-Gd up to 600 pc away. A pre-supernova alert could be provided to the astrophysics community following gadolinium loading.



Mukhopadhyay et al 2020

Let’s explore recent theoretical results that can provide

New targets for current and future neutrino detectors.

New estimates of the stellar neutrino background signal.

New opportunities for nuclear physics.

Neutrino Production in Stars

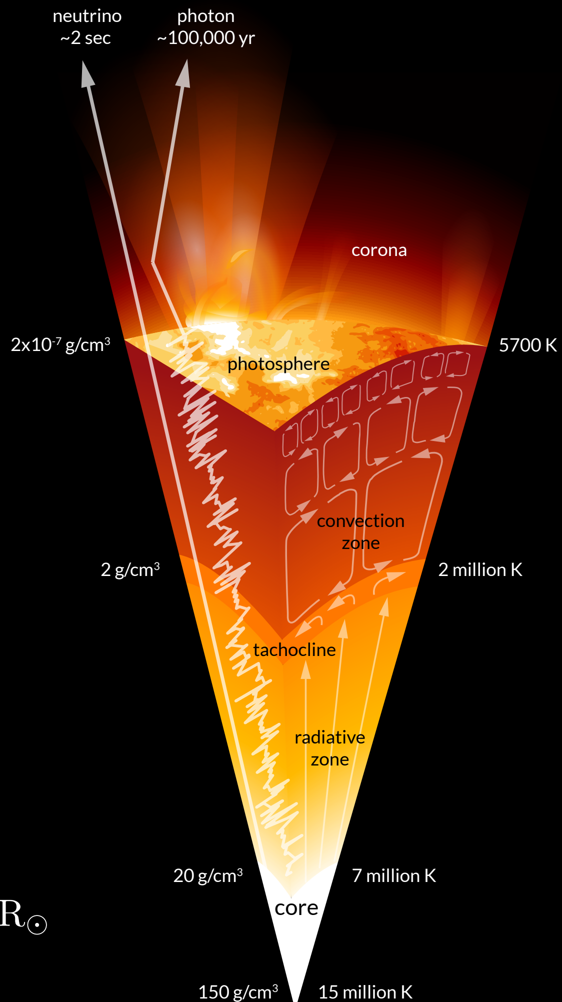
Stars radiate energy by releasing photons from the stellar surface and neutrinos from the stellar interior.

$$\sigma_\gamma \simeq \frac{8\pi}{3}\left(\frac{e^2}{m_e c^2}\right)^2 \simeq 10^{-24}\ \mathrm{cm}^2$$

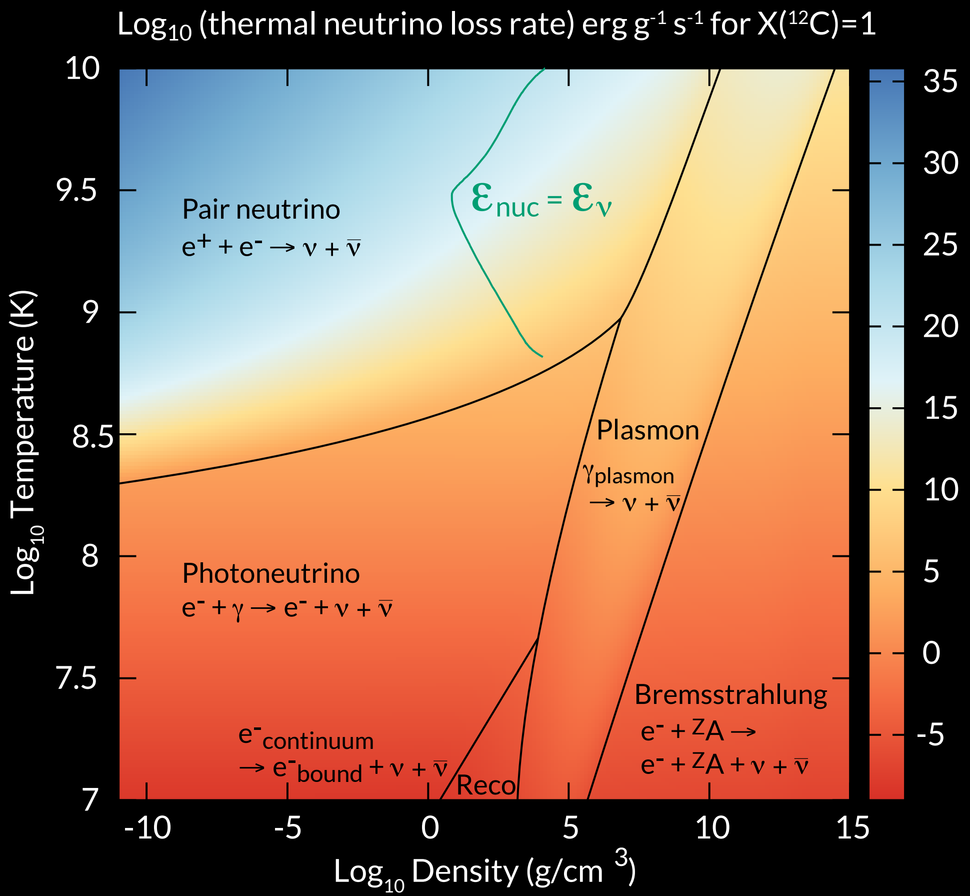
$$\sigma_\nu \simeq (E_\nu / m_e c^2)^2 \cdot 10^{-44}\ \mathrm{cm}^2$$

$$\lambda_\gamma = \left.\frac{\mathrm{m_u}}{\rho \cdot \sigma_\gamma}\right|_\odot \simeq 0.3\ \mathrm{cm}$$

$$\lambda_\nu = \left.\frac{\mathrm{m_u}}{\rho \cdot \sigma_\nu}\right|_\odot \simeq 3 \cdot 10^{19}\mathrm{cm} \simeq 10\ \mathrm{pc} \simeq 4 \cdot 10^9\ \mathrm{R}_\odot$$



Weak reactions produce neutrinos by thermal processes



Weak reactions produce neutrinos from β-processes

Electron captures:

$$^{A}Z + e^- \xrightarrow{W^\pm} {}^{A}(Z-1) + \nu_e$$
$$p + e^- \xrightarrow{W^\pm} n + \nu_e$$

Positron captures:

$$^{A}Z + e^+ \xrightarrow{W^\pm} {}^{A}(Z+1) + \bar{\nu}_e$$
$$n + e^+ \xrightarrow{W^\pm} p + \bar{\nu}_e$$

Electron emission (β^- decay):

$$^{A}Z \xrightarrow{W^\pm} {}^{A}(Z+1) + e^- + \bar{\nu}_e$$
$$n \xrightarrow{W^\pm} p + e^- + \bar{\nu}_e$$

Positron emission (β^+ decay):

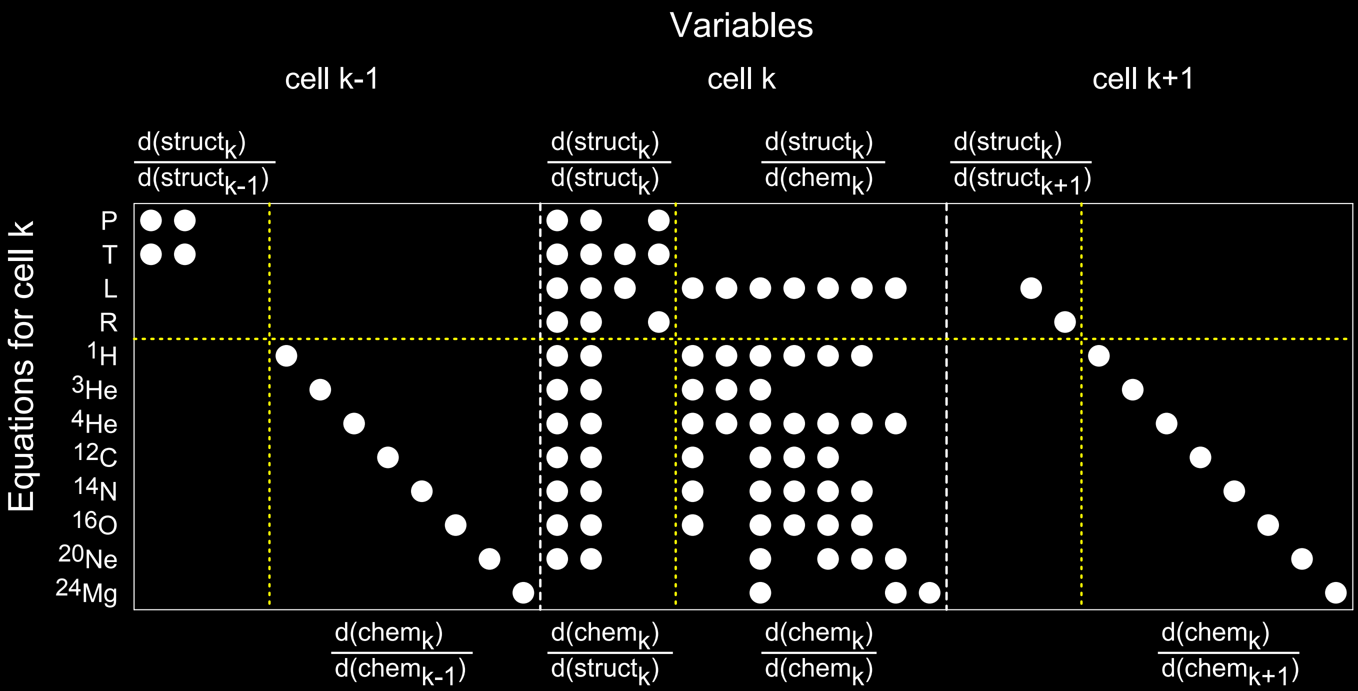
$$^{A}Z \xrightarrow{W^\pm} {}^{A}(Z-1) + e^+ + \nu_e$$
$$p \xrightarrow{W^\pm} n + e^+ + \nu_e$$

De-excitation:

$$^{A}Z \xrightarrow{Z^0} {}^{A}Z + \nu + \bar{\nu}_e$$

A Stellar Evolution Instrument

The MESA source code is a set of software modules for stellar astrophysics that can be used on their own, or combined to solve the coupled equations governing 1D stellar evolution with an implicit finite volume scheme.



Josiah Schwab

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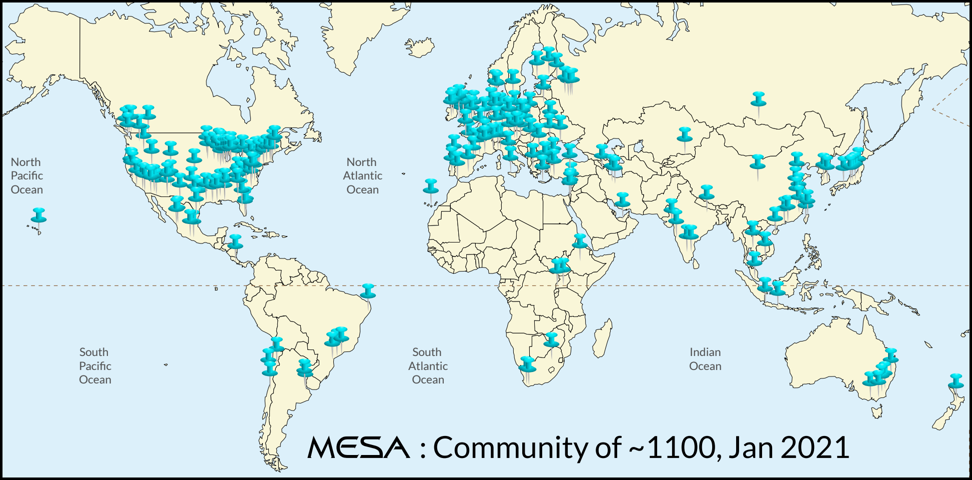
Radek Smolec



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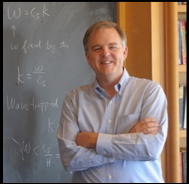

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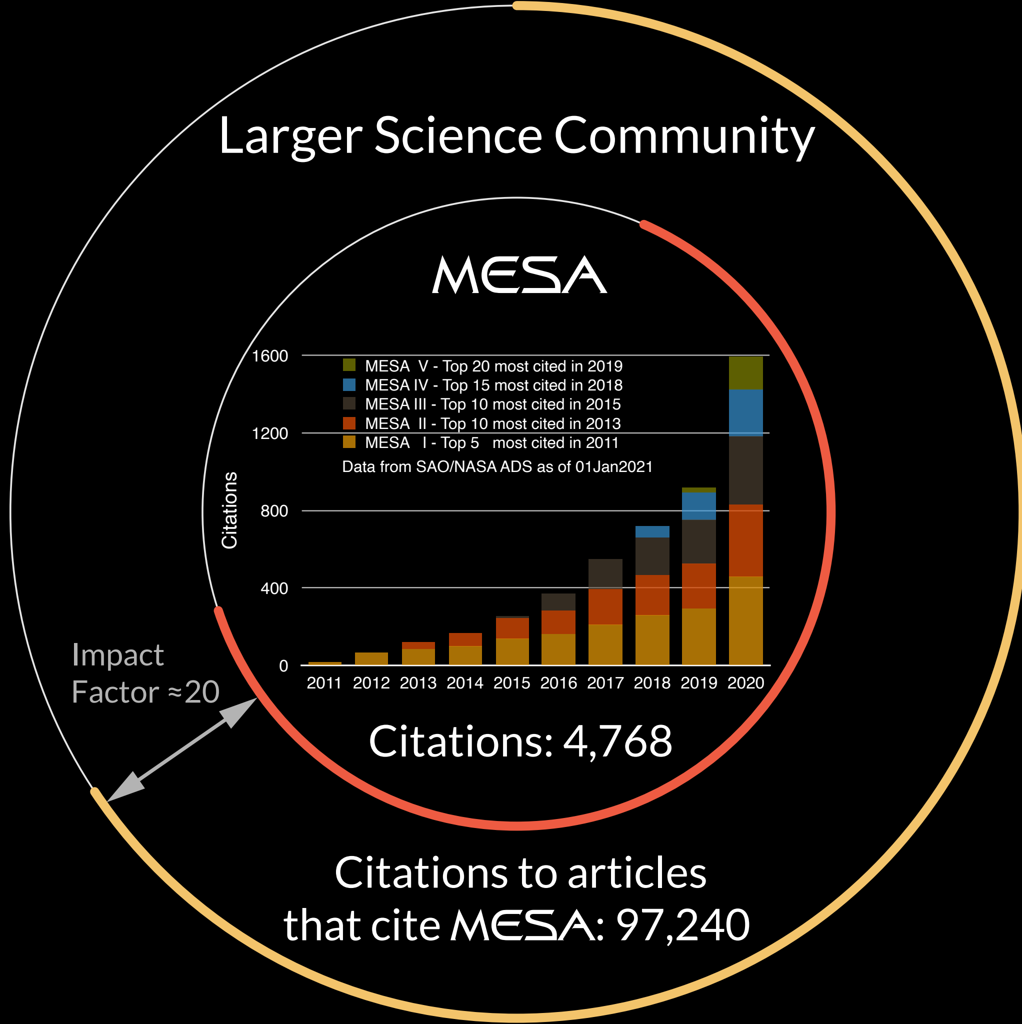
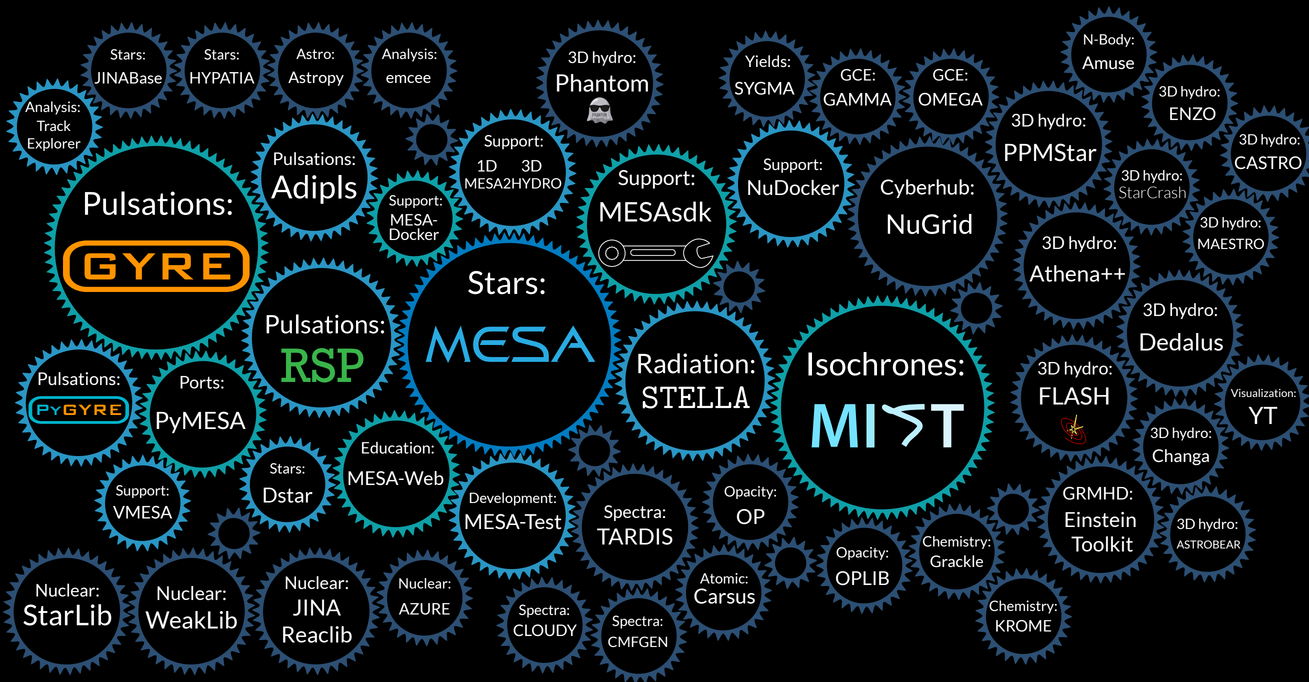


Larger Science Community
MESA
1600
1200
800
400
0
Citations
MESA V - Top 20 most cited in 2019
MESA IV - Top 15 most cited in 2018
MESA III - Top 10 most cited in 2015
MESA II - Top 10 most cited in 2013
MESA I - Top 5 most cited in 2011
Data from SAO/NASA ADS as of 01Jan2021
2011 2012 2013 2014 2015 2016 2017 2018 2019 2020
Citations: 4,768
Impact Factor ≈20
Citations to articles that cite MESA: 97,240

Telescopes

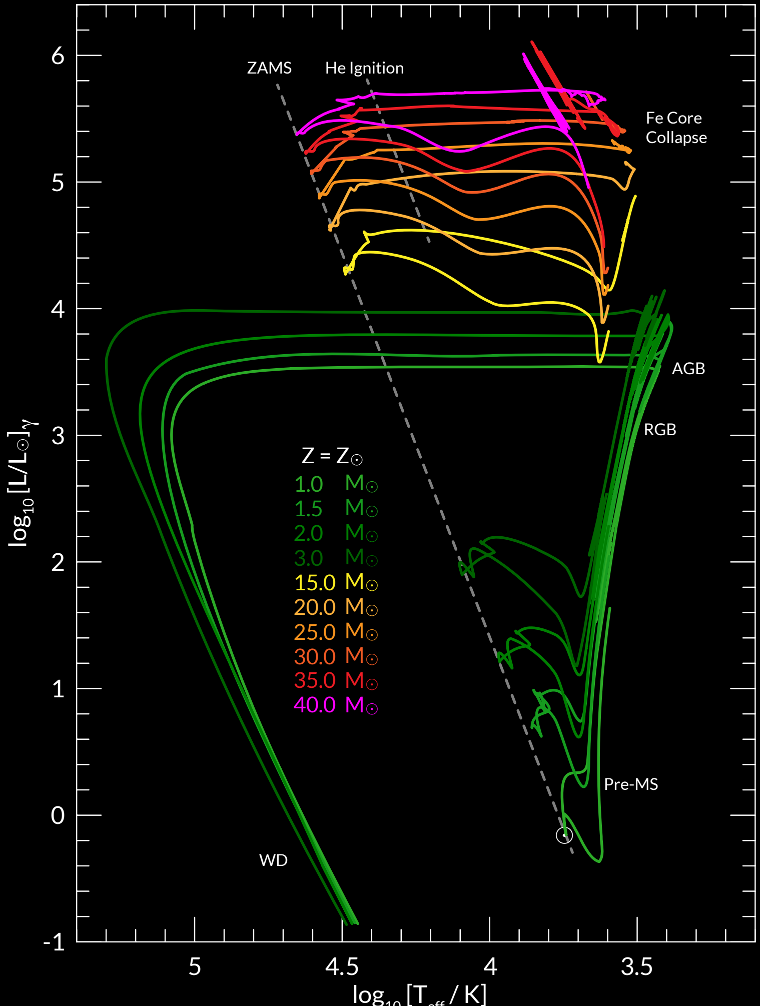
Gaia LIGO SDSS Hubble JWST VRO ASAS-SN TESS ZTF LCO NuSTAR SK-Gd



NSCL FRIB CASPAR SECAR St. George Z-Pinch Diamond Anvil

Laboratory Astrophysics

Neutrino Hertzsprung-Russell Diagram



The ~110 year old classic HR Diagram.

One doesn't mess with a classic …

… but what if the y-axis showed the neutrino luminosity?

Farag et al 2020

A MESA standard solar model

$p(p, e^+\nu_e)^2H$
$p(e^-p, \nu_e)^2H$
$^3He(p, e^+\nu_e)^4He$ → Φ_{pp}
$^7Be(e^-, \nu_e)^7Li$ → Φ_{Be}
$^8B(,e^+\nu_e)^8Be$ → Φ_B
$^{13}N(,e^+\nu_e)^{13}C$ → Φ_N
$^{13}N(e^-, \nu_e)^{13}C$
$^{15}O(,e^+\nu_e)^{15}N$ → Φ_O
$^{15}O(e^-, \nu_e)^{15}N$

Solar Neutrino Fluxes

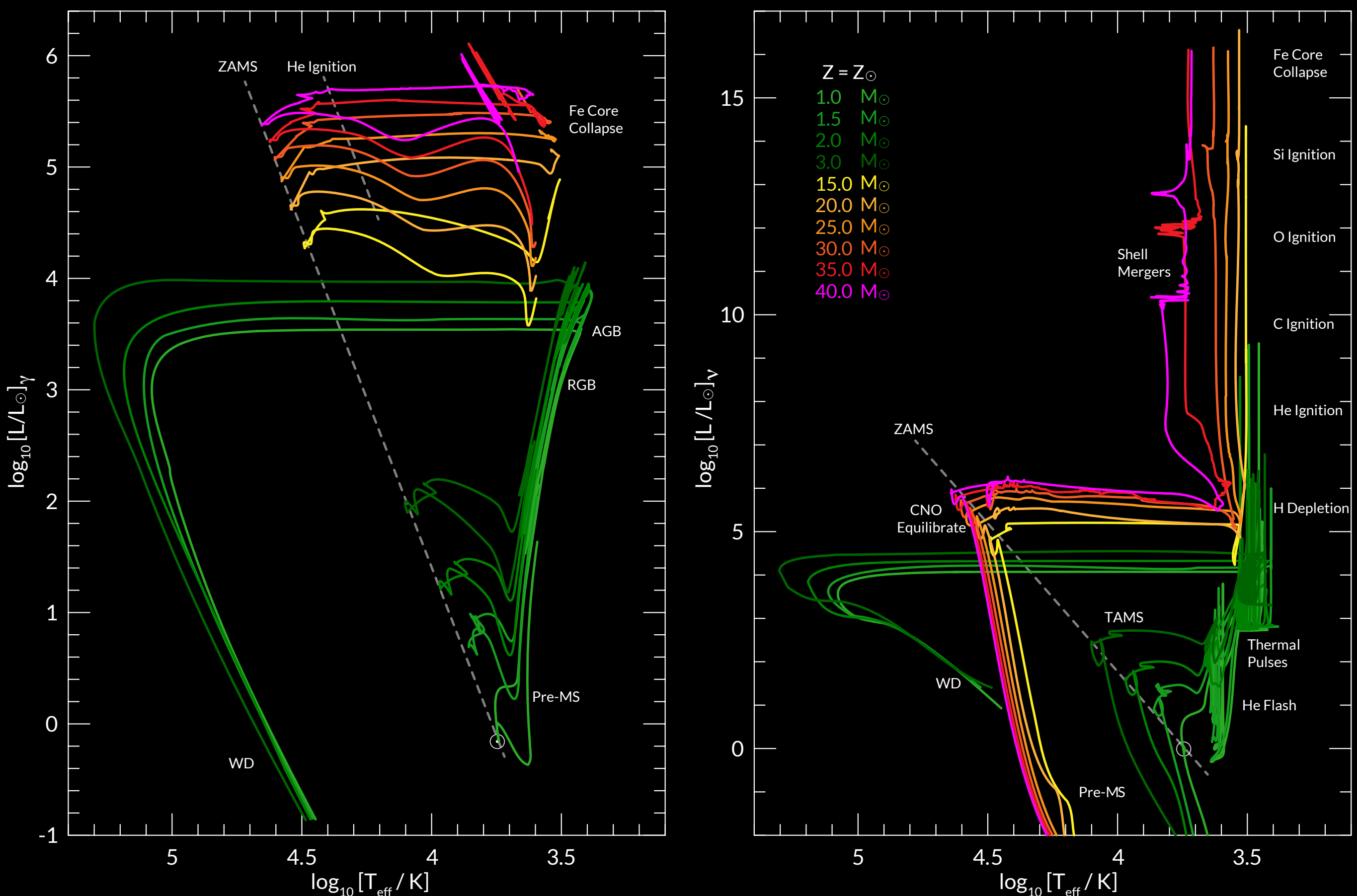
Component	AGSS09	GS98	Observed[a]
Φ_{pp}	6.01	5.98	$6.05(1^{+0.003}_{-0.011})$
Φ_{Be}	4.71	4.95	$4.82(1^{+0.05}_{-0.04})$
Φ_B	4.62	5.09	$5.00(1 \pm 0.03)$
Φ_N	2.25	2.91	≤ 6.7
Φ_O	1.67	2.21	≤ 3.2

[a] Neutrino observations from the Borexino Collaboration (Bellini et al. 2011) as presented in Haxton et al. (2013) and Villante et al. (2014). The scales for neutrino fluxes Φ (in cm^{-2} s^{-1}) are: 10^{10} (pp); 10^9 (Be); 10^6 (B); 10^8 (N); and 10^8 (O).

$$L_{\nu,\odot} = 0.024 \cdot L_{\gamma,\odot}$$
$$= 9.18 \times 10^{31} \text{ erg/s}$$

Farag et al 2020

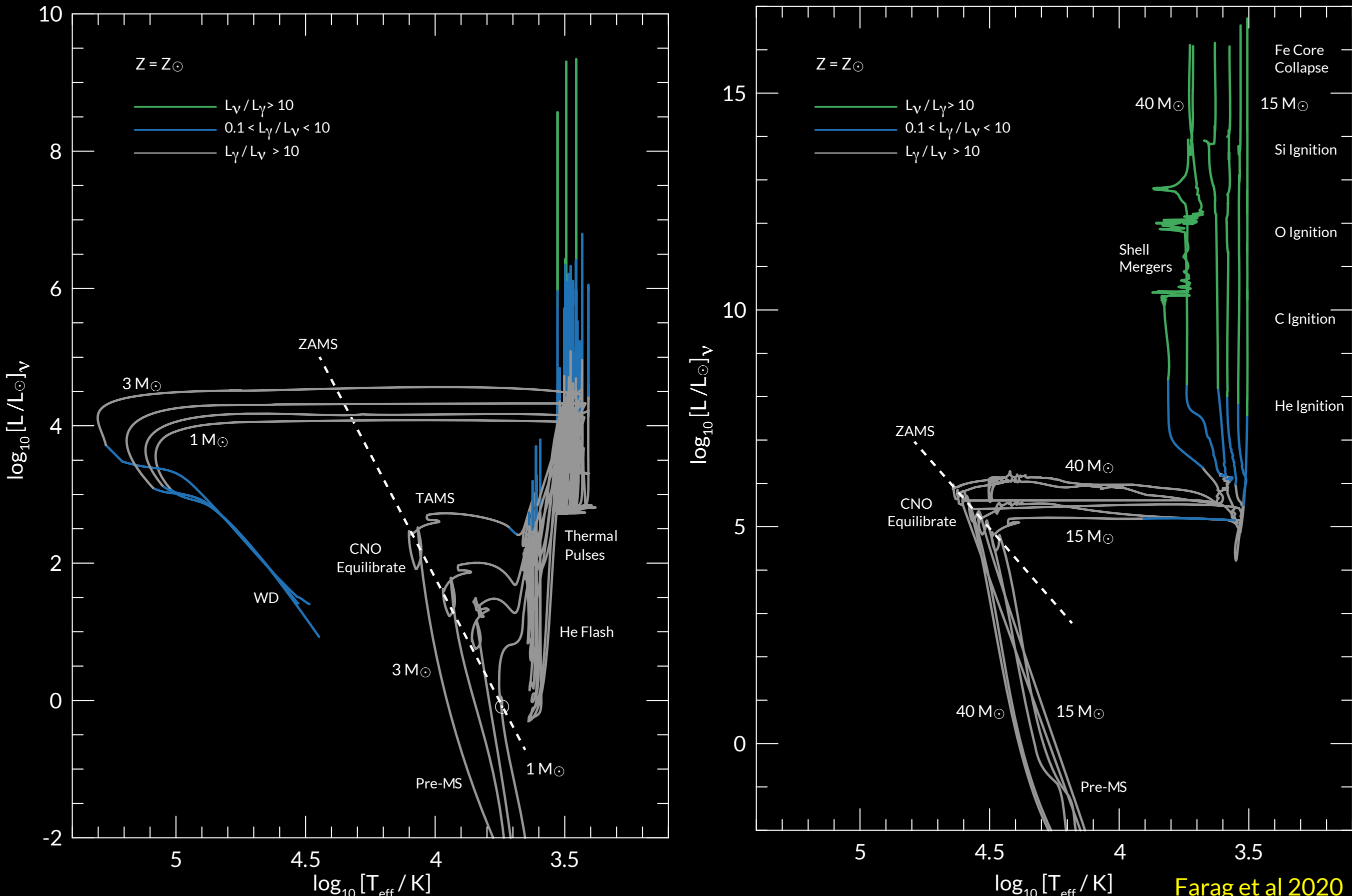
A neutrino HR Diagram!



Farag et al 2020

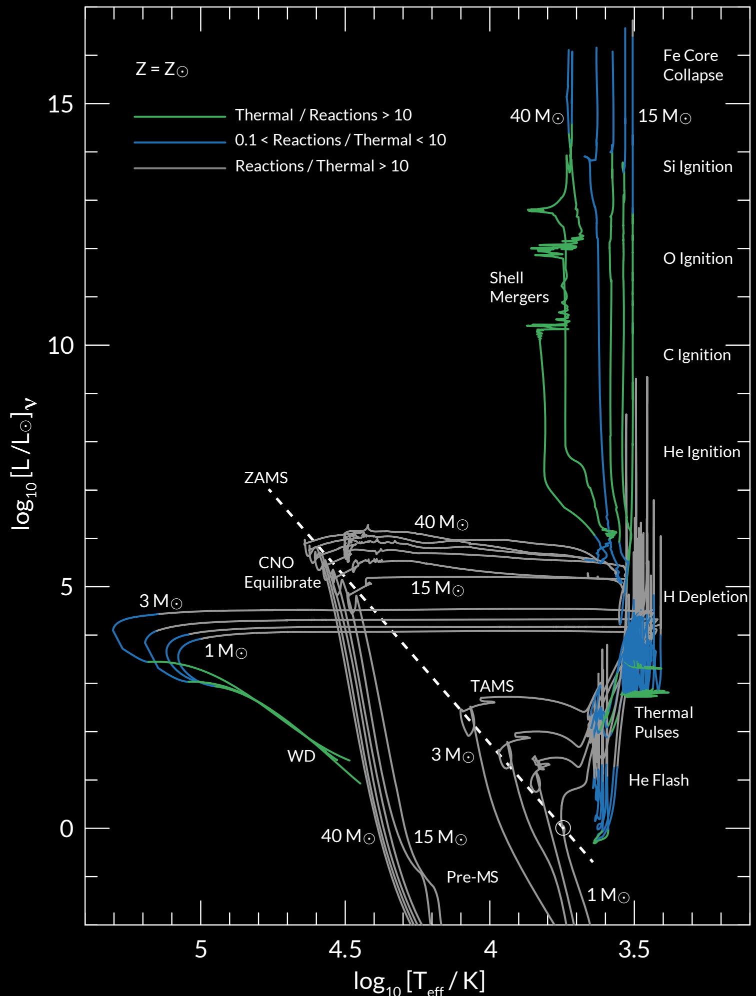
When do photons or neutrinos dominate?

Neutrinos tend to dominate at flashes and at the end of star's life.

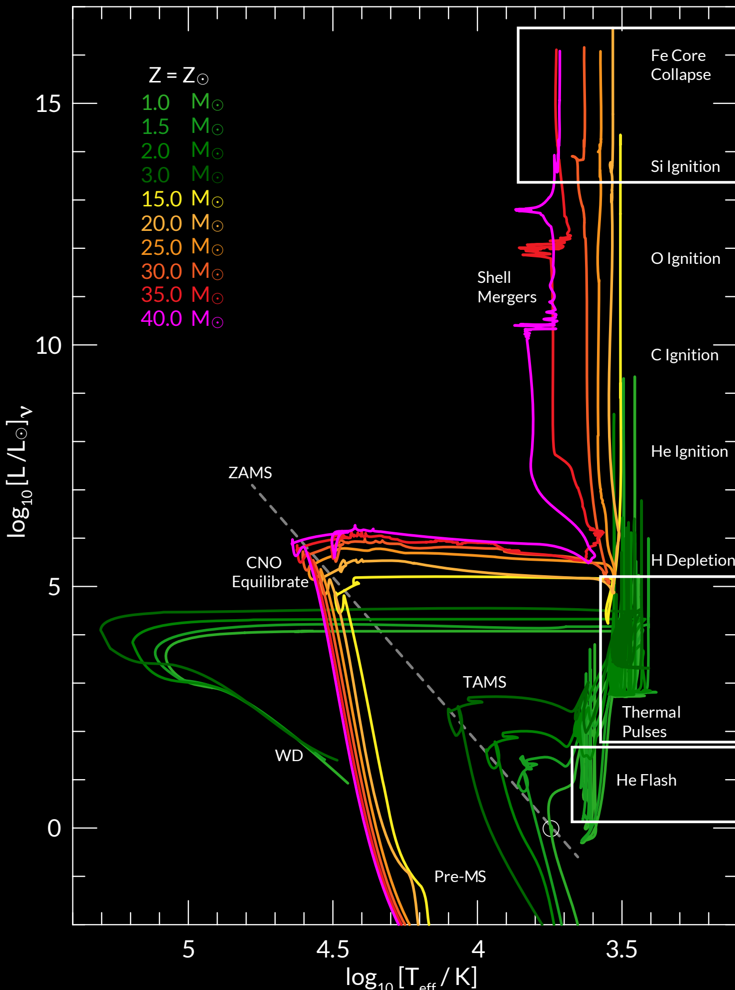


When do thermal neutrino or β-processes dominate?

β-processes tend to dominate whenever H or He burns.



Farag et al 2020



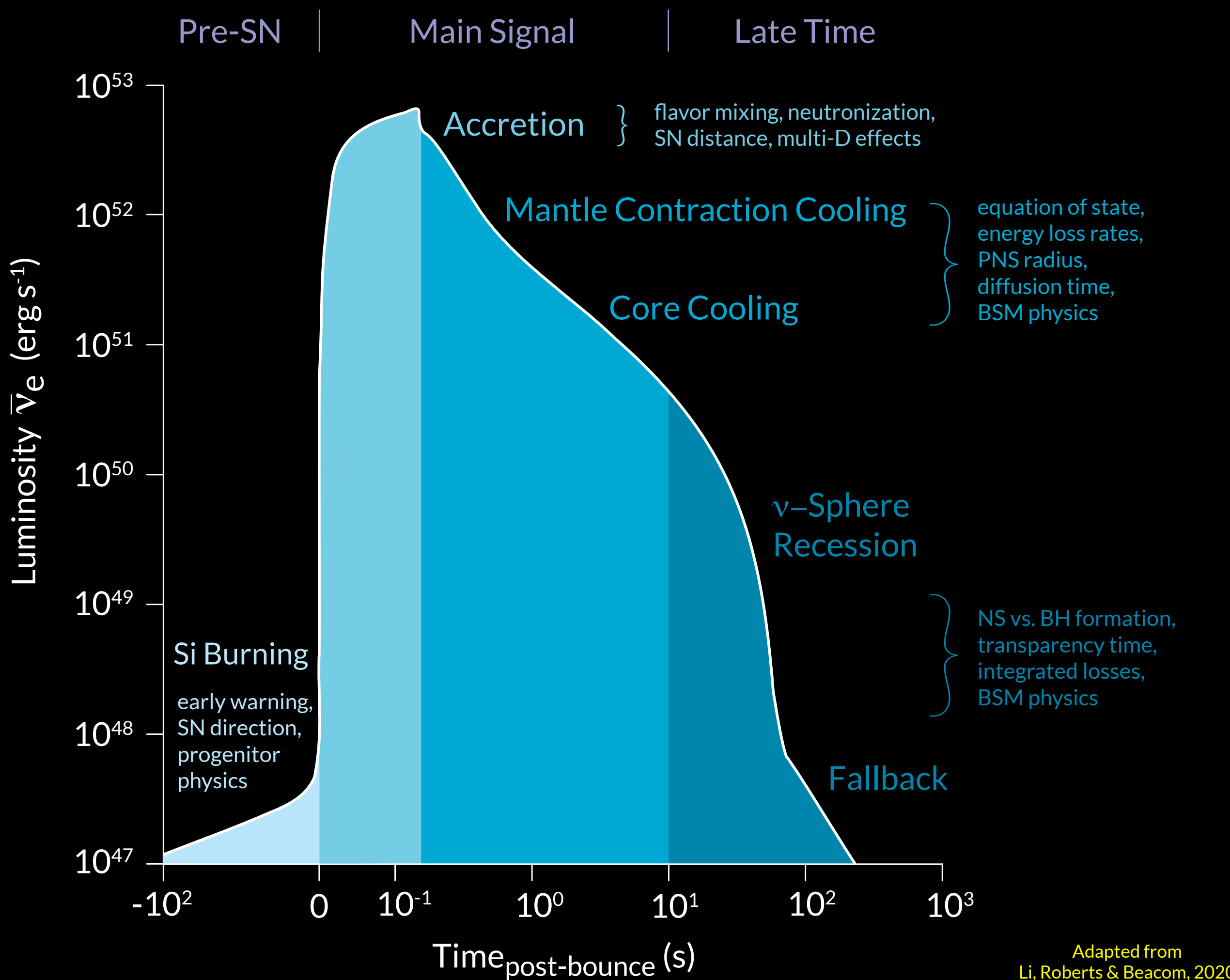
Observable now with SK-Gd, JUNO, etc

flux ~ 1.7×10^6 (d / 10 pc) $cm^{-2}\,s^{-1}$

flux ~170 (d / 10 pc) $cm^{-2}\,s^{-1}$

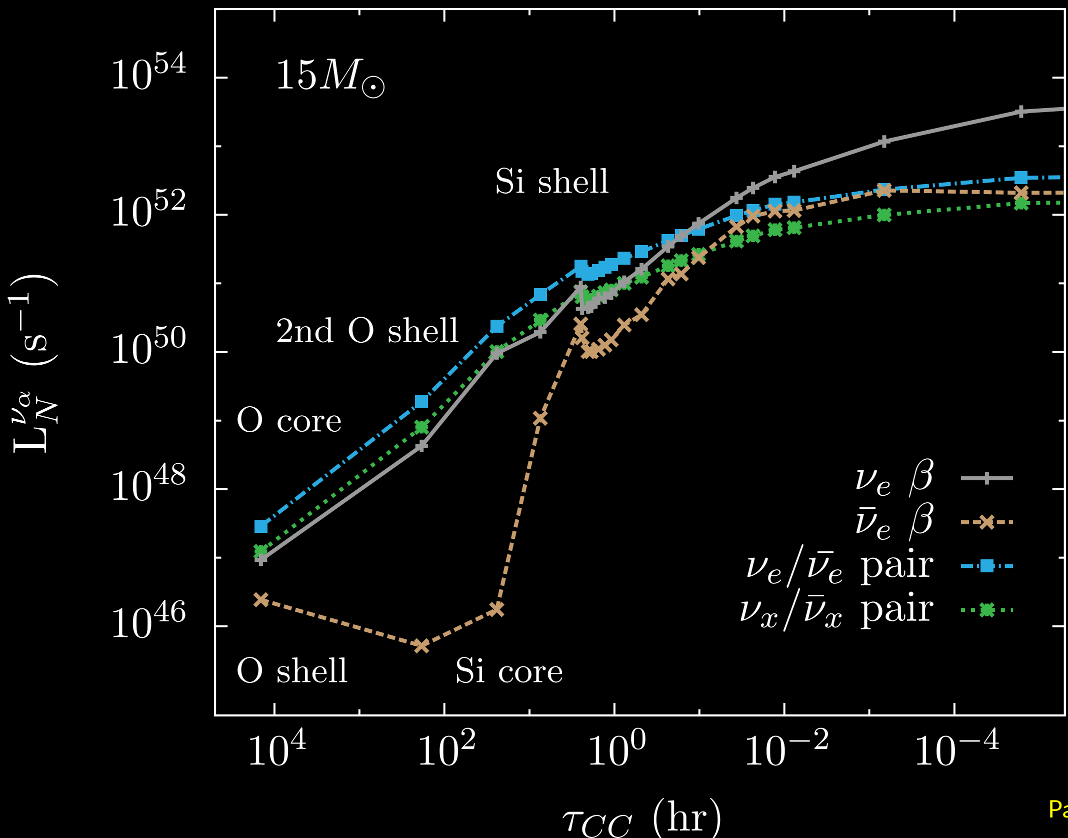
Farag et al 2020

Probing the evolution of pre-supernova models



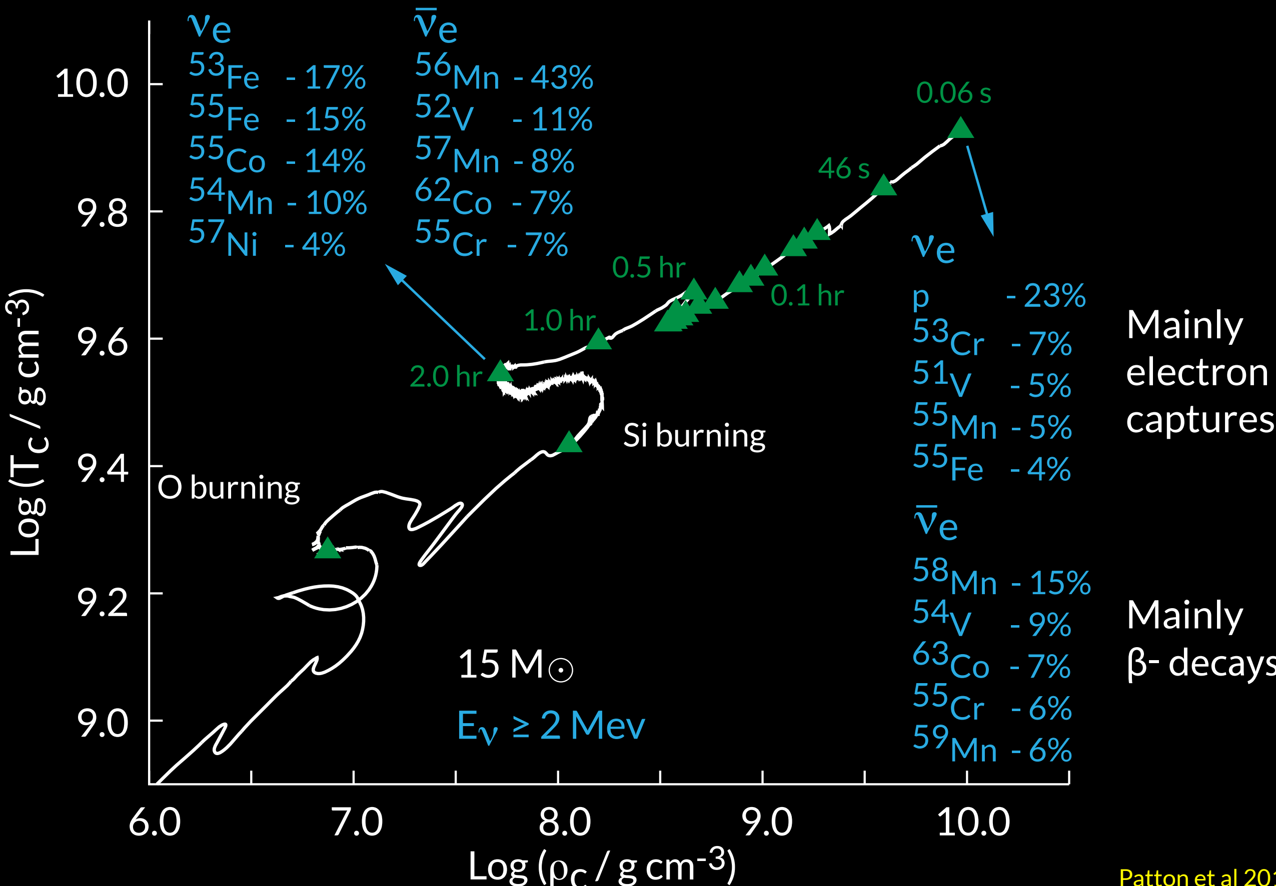
Pre-SN
Main Signal
Late Time
Accretion
flavor mixing, neutronization, SN distance, multi-D effects
Mantle Contraction Cooling
Core Cooling
equation of state, energy loss rates, PNS radius, diffusion time, BSM physics
ν–Sphere Recession
NS vs. BH formation, transparency time, integrated losses, BSM physics
Fallback
Si Burning
early warning, SN direction, progenitor physics
Luminosity $\bar{\nu}_e$ (erg s^{-1})
10^{53}
10^{52}
10^{51}
10^{50}
10^{49}
10^{48}
10^{47}
-10^{2}
0
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
Time$_{\text{post-bounce}}$ (s)
Adapted from Li, Roberts & Beacom, 2020

The march to core-collapse



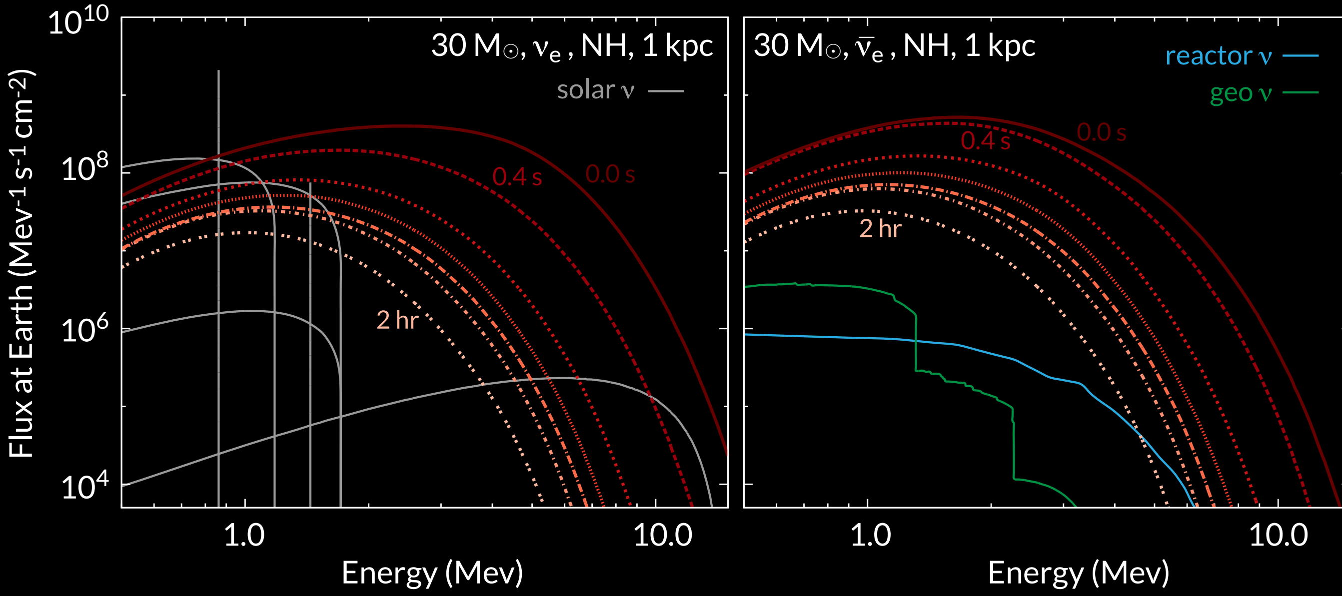
Patton et al 2017

β-process rates that matter



Patton et al 2017

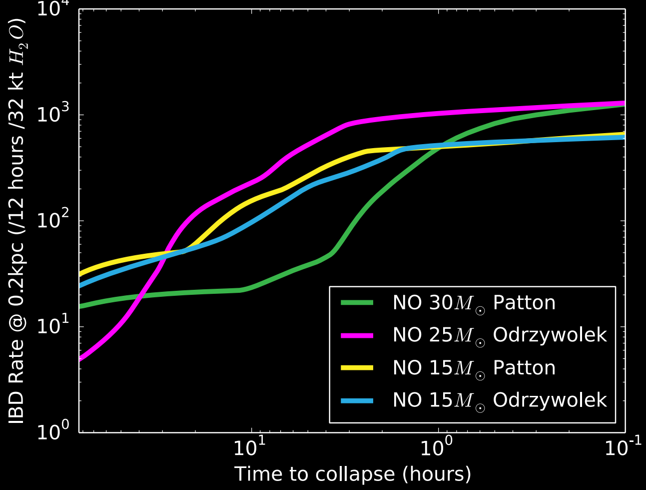
Pre-supernova fluxes at 1 kpc : as strong as solar neutrinos, larger than background geo or reactor neutrinos.



Patton et al 2017

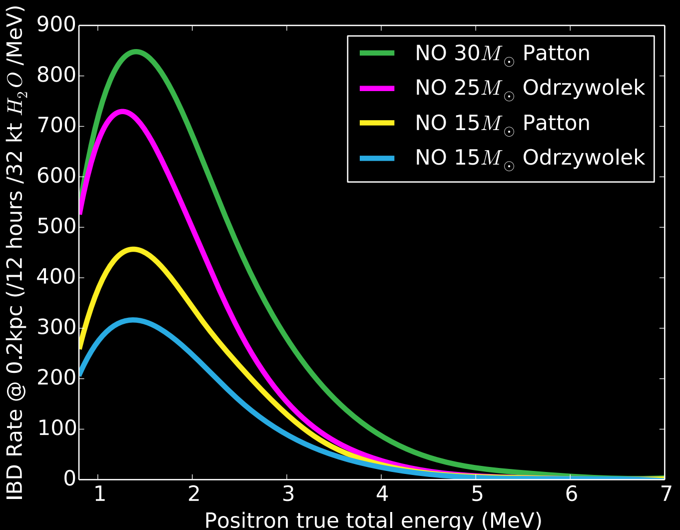
"A prime example is the red supergiant Betelgeuse (α Orionis) … we find that for D=200 pc, a presupernova neutrino signal would be practically background-free — in energy windows that are realistic for detection — for several hours, and the window of observability can extend up to ~10 hr."

Patton et al 2017



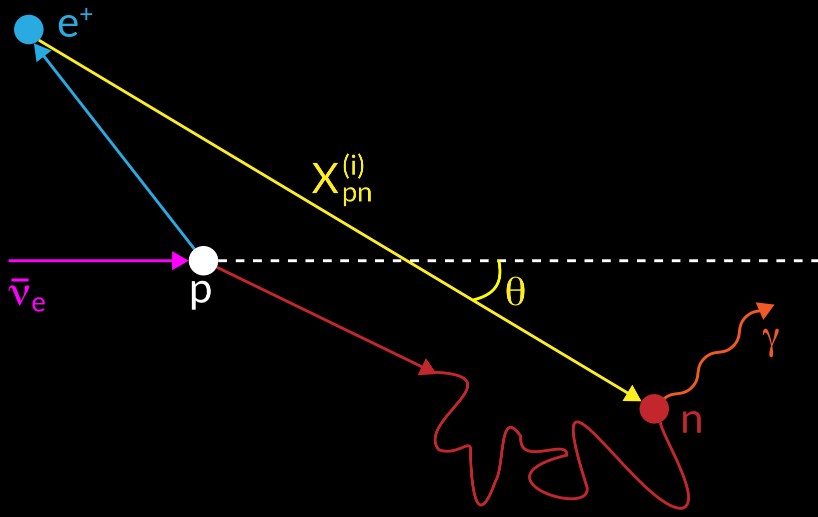
"A presupernova alert could be provided to the gravitational wave and electromagnetic communities …"

SK-Gd, Simpson et al 2019



Identifying the Progenitor

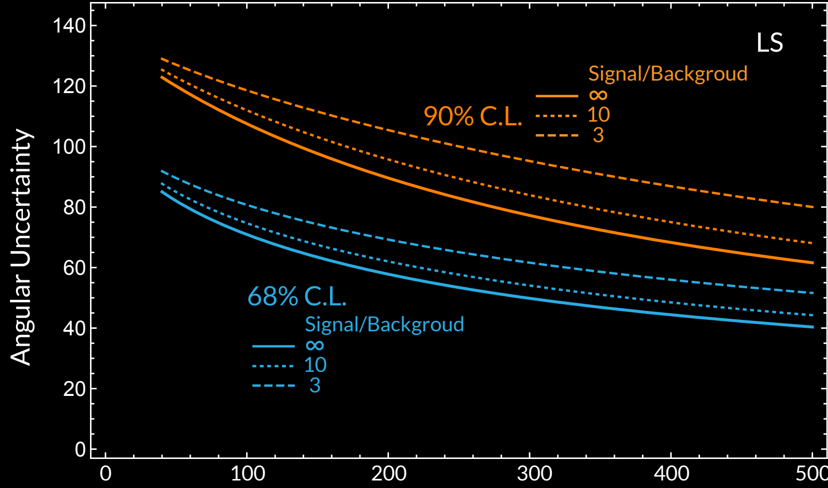
Geometry in a liquid scintillator detector:



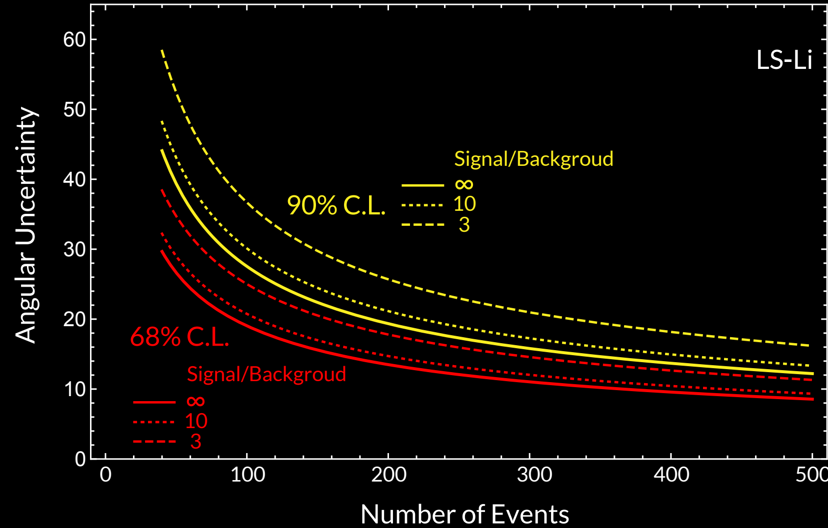
Mukhopadhyay et al 2020

θ gives information on the directionality on the sky.

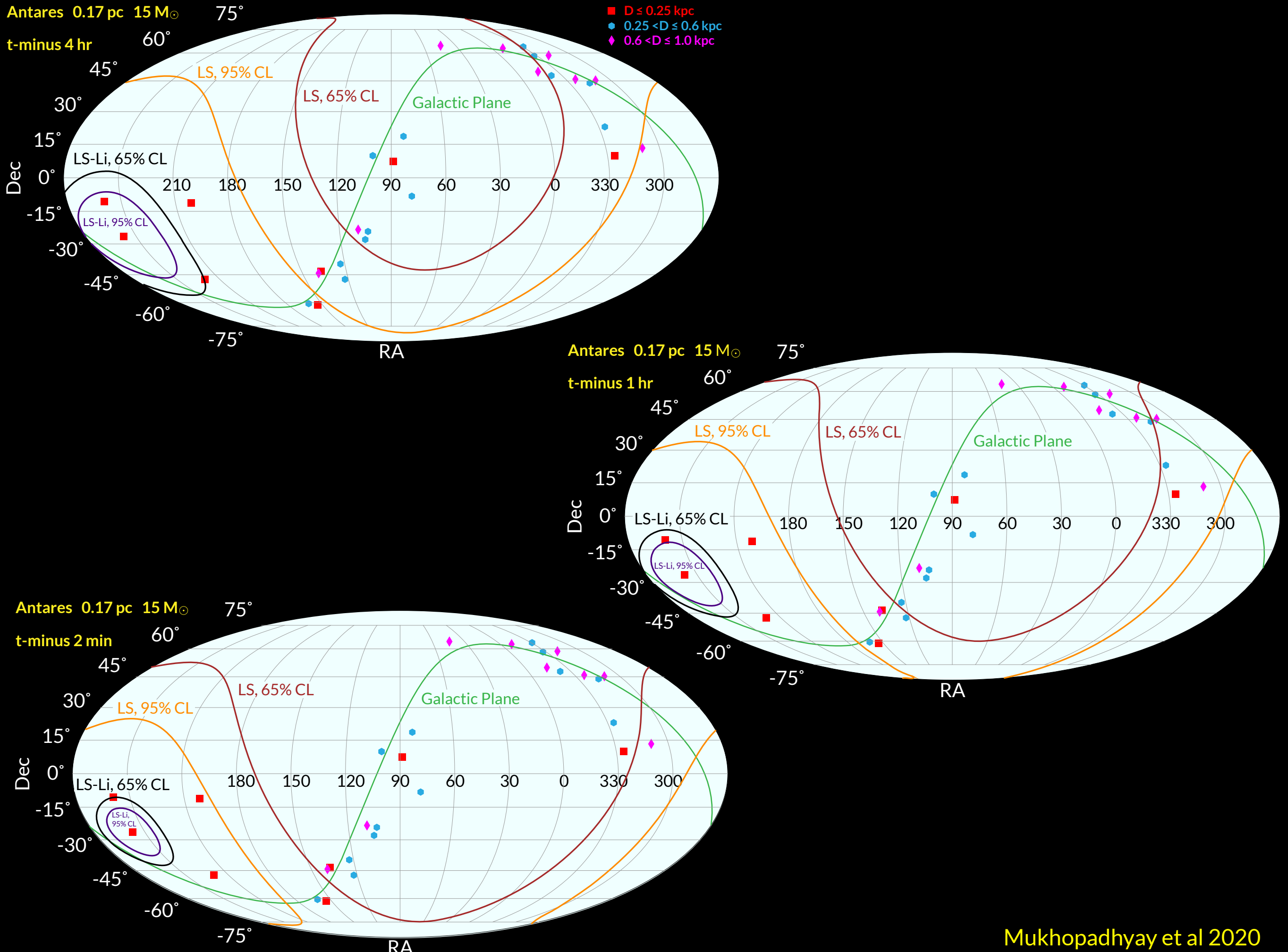
Standard liquid scintillators could localize a pre-supernova to ~70° at 90% confidence after~200 detections.



Enhanced liquid scintillators could localize a pre-supernova to ~15° at 90% confidence after ~200 detections.

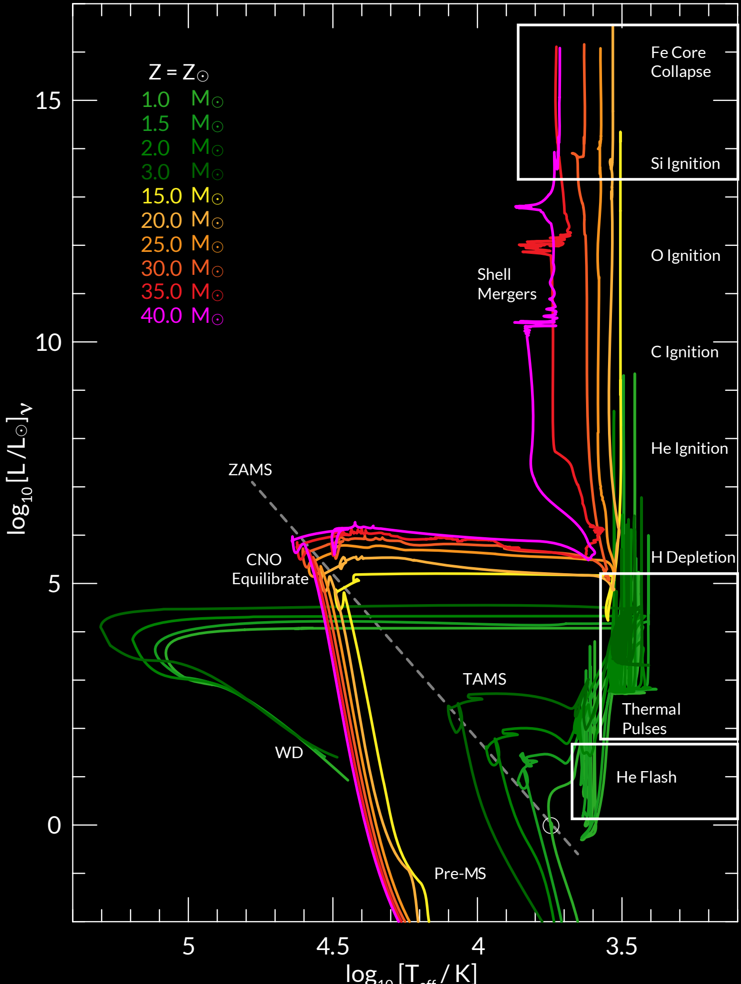


Mukhopadhyay et al 2020



D ≤ 0.25 kpc
0.25 <D ≤ 0.6 kpc
0.6 <D ≤ 1.0 kpc
Antares 0.17 pc 15 M☉
t-minus 4 hr
LS, 95% CL
LS, 65% CL
Galactic Plane
LS-Li, 65% CL
LS-Li, 95% CL
Dec
RA
75° 60° 45° 30° 15° 0° -15° -30° -45° -60° -75°
210 180 150 120 90 60 30 0 330 300
Antares 0.17 pc 15 M☉
t-minus 1 hr
LS, 95% CL
LS, 65% CL
Galactic Plane
LS-Li, 65% CL
LS-Li, 95% CL
Dec
RA
75° 60° 45° 30° 15° 0° -15° -30° -45° -60° -75°
180 150 120 90 60 30 0 330 300
Antares 0.17 pc 15 M☉
t-minus 2 min
LS, 95% CL
LS, 65% CL
Galactic Plane
LS-Li, 65% CL
LS-Li, 95% CL
Dec
RA
75° 60° 45° 30° 15° 0° -15° -30° -45° -60° -75°
180 150 120 90 60 30 0 330 300
Mukhopadhyay et al 2020

Probing the evolution of low mass models



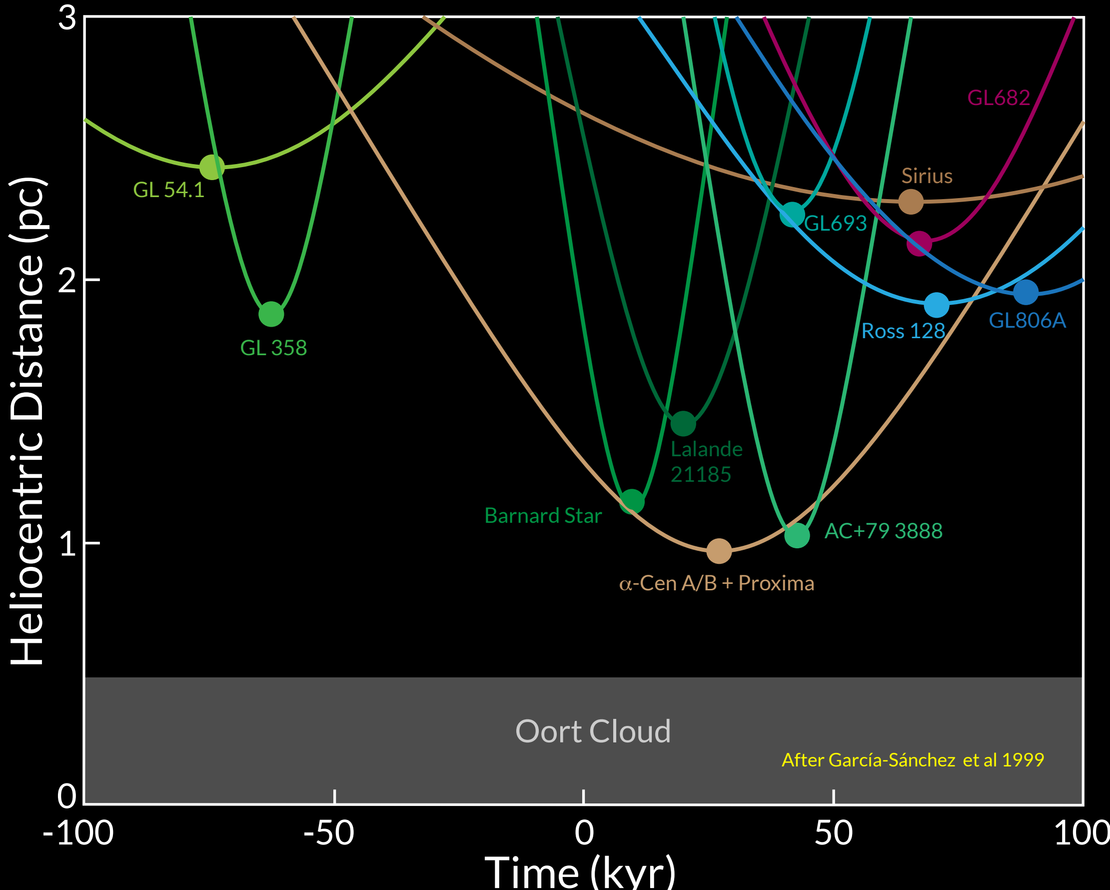
Observable now with SK-Gd, JUNO, etc

flux ~ 1.7×10^6 (d / 10 pc) $cm^{-2}\, s^{-1}$

flux ~170 (d / 10 pc) $cm^{-2}\, s^{-1}$

Farag et al 2020

No good nearby targets for detections of the He-flash or a thermal pulse.



Big Science Take-Home Message

Current generation underground neutrino detectors have sufficient sensitivity to detect pre-supernova neutrinos ~10 hours before the supernova explosion within ~1000 light-years. This allows

1) an early alert to the gravitational wave and electromagnetic communities that a supernova is coming.

2) a unique probe of weak interaction nuclear astrophysics in dense stellar core.

Time for a Neutrino Cocktail

2016, Jill Preston, Sandbox Studio, Chicago