Vietnam School on Neutrinos

Supernova Neutrinos

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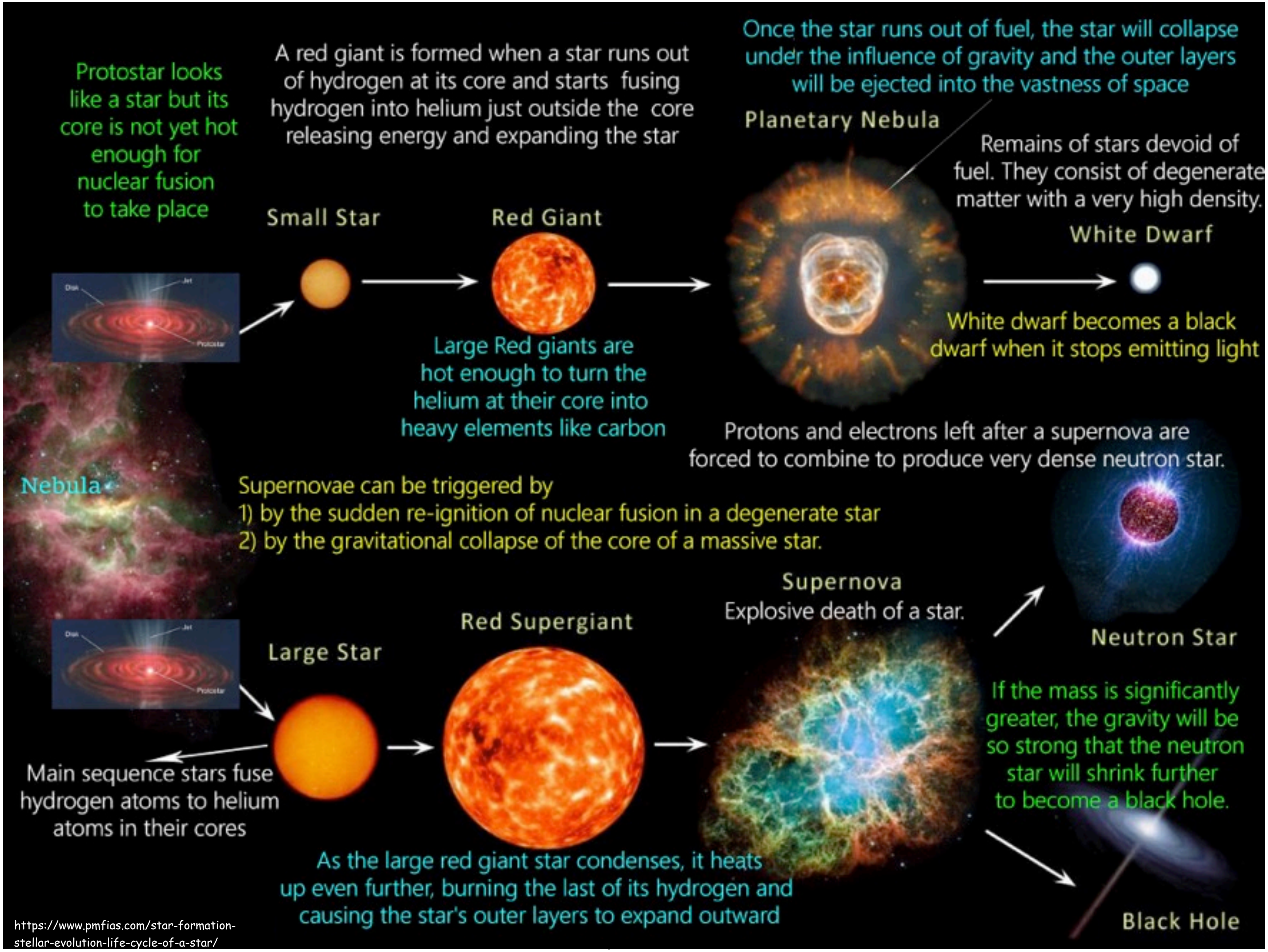
Life-cycle of stars



Protostar looks like a star but its core is not yet hot enough for nuclear fusion to take place

A red giant is formed when a star runs out of hydrogen at its core and starts fusing hydrogen into helium just outside the core releasing energy and expanding the star

Once the star runs out of fuel, the star will collapse under the influence of gravity and the outer layers will be ejected into the vastness of space

Remains of stars devoid of fuel. They consist of degenerate matter with a very high density.

Large Red giants are hot enough to turn the helium at their core into heavy elements like carbon

White dwarf becomes a black dwarf when it stops emitting light

Protons and electrons left after a supernova are forced to combine to produce very dense neutron star.

Supernovae can be triggered by
1) by the sudden re-ignition of nuclear fusion in a degenerate star
2) by the gravitational collapse of the core of a massive star.

Explosive death of a star.

If the mass is significantly greater, the gravity will be so strong that the neutron star will shrink further to become a black hole.

Main sequence stars fuse hydrogen atoms to helium atoms in their cores

As the large red giant star condenses, it heats up even further, burning the last of its hydrogen and causing the star's outer layers to expand outward

https://www.pmfias.com/star-formation-stellar-evolution-life-cycle-of-a-star/

Supernova neutrino astroparticle physics

snap.lbl.gov

Stars must die --- we just do not know how

SN 1987A

For massive stars ($> 8\,M_\odot$), most of the energy (~ 99%) is dissipated in neutrinos --- detecting them might solve the puzzle

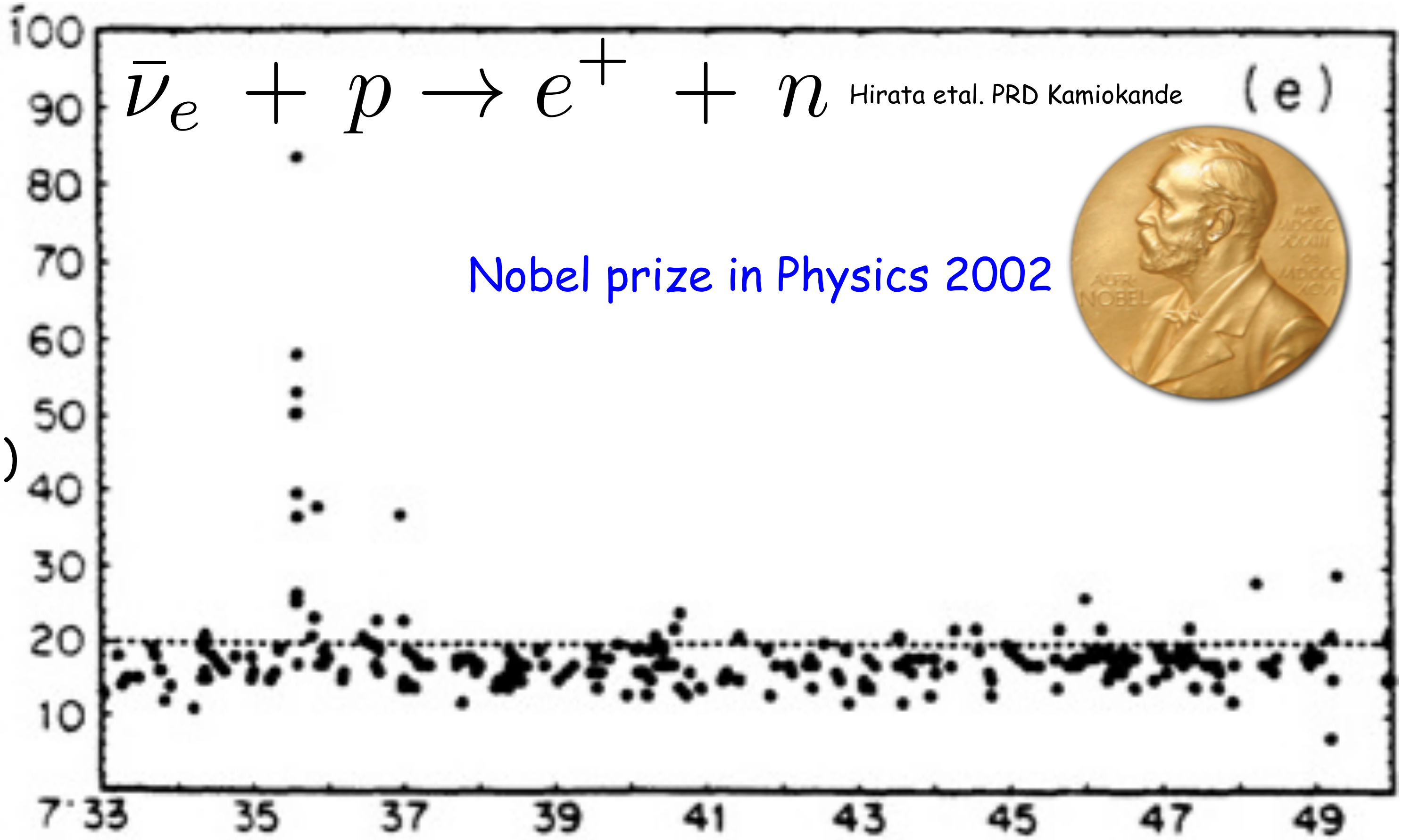
SN 1987A in LMC

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

Hirata etal. PRD Kamiokande

Nobel prize in Physics 2002

Nhit
(no. of
hit PMTs)



Time (min)

Nhit = 26 => 10 MeV total energy
Nhit = 73 => 30 MeV total energy

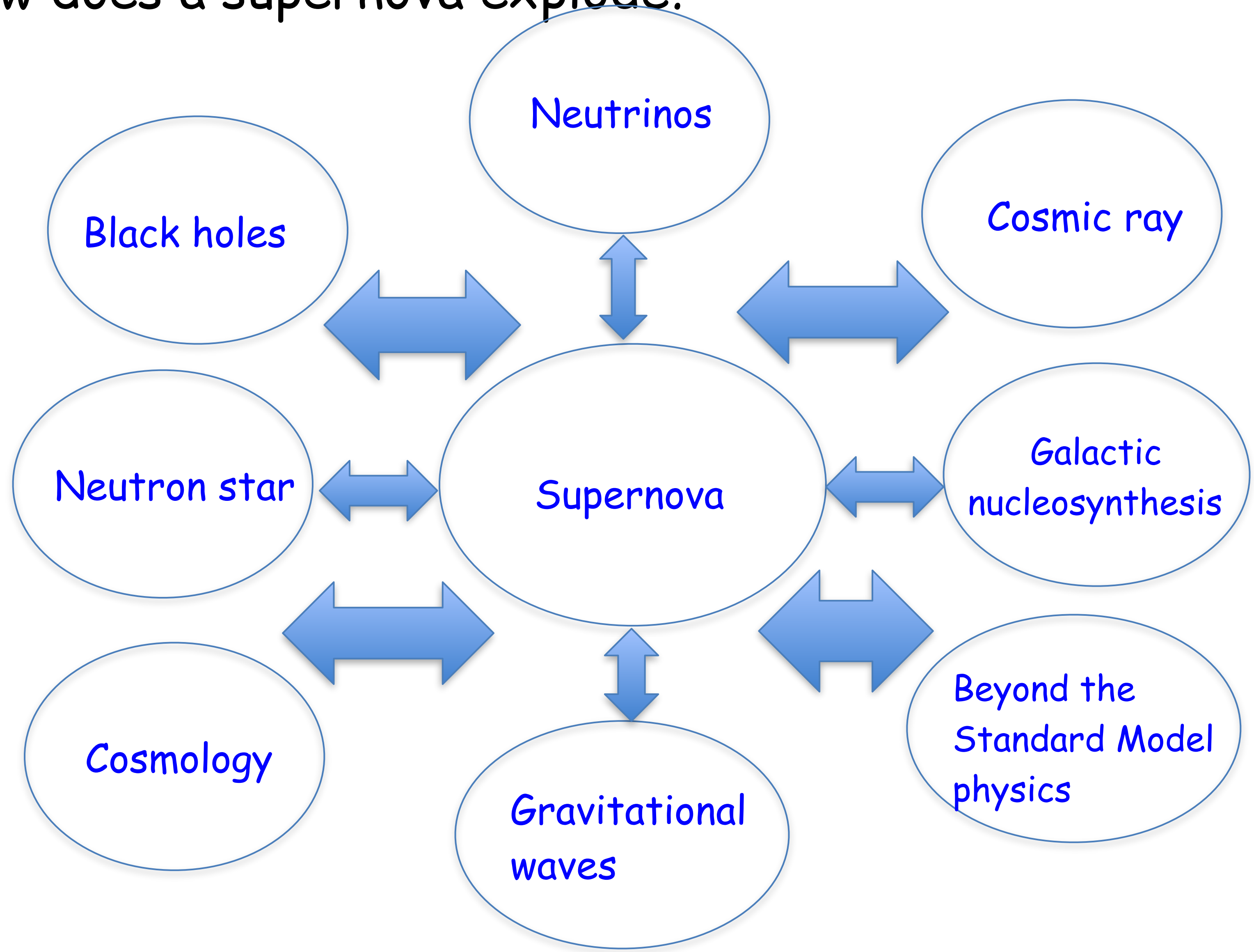
Simultaneous observation by IMB, Baksan

In broad agreement with the theoretical expectations

Many analyses to understand these events

Why study supernovae?

- What happens to a star after it dies?
- How does a supernova explode?



Supernova

Neutrinos

Cosmic ray

Galactic nucleosynthesis

Beyond the Standard Model physics

Gravitational waves

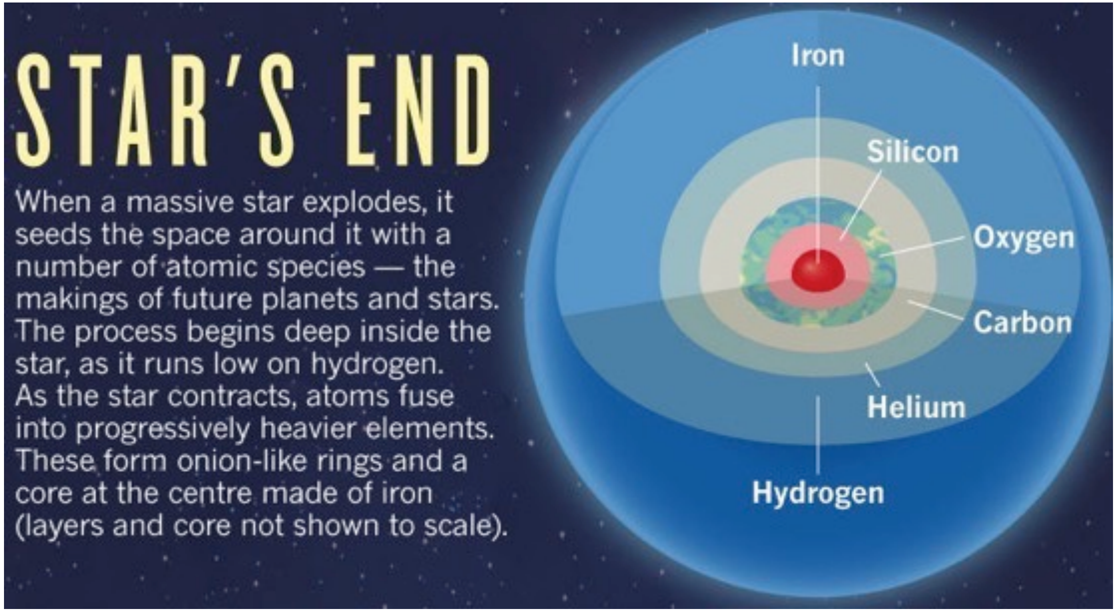
Cosmology

Neutron star

Black holes

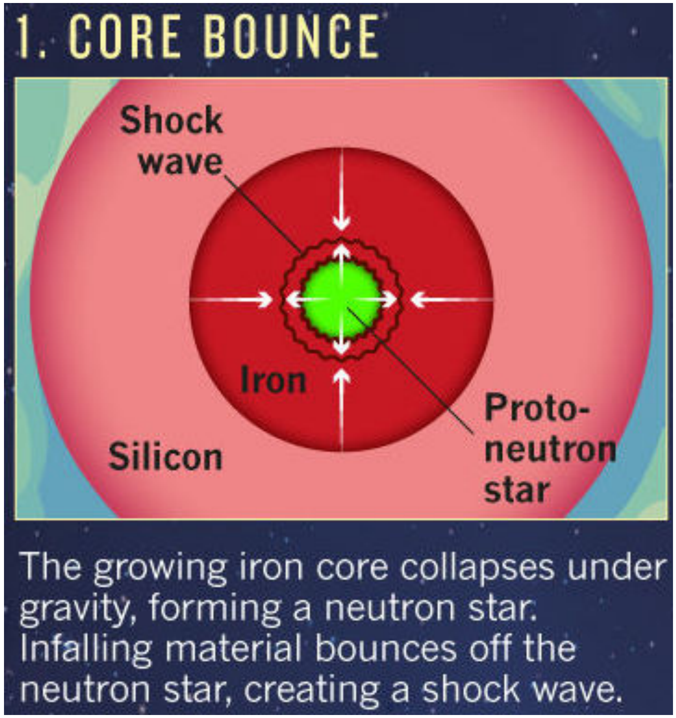
Supernova explosion mechanism and supernova neutrino emission

Core-collapse supernova explosion



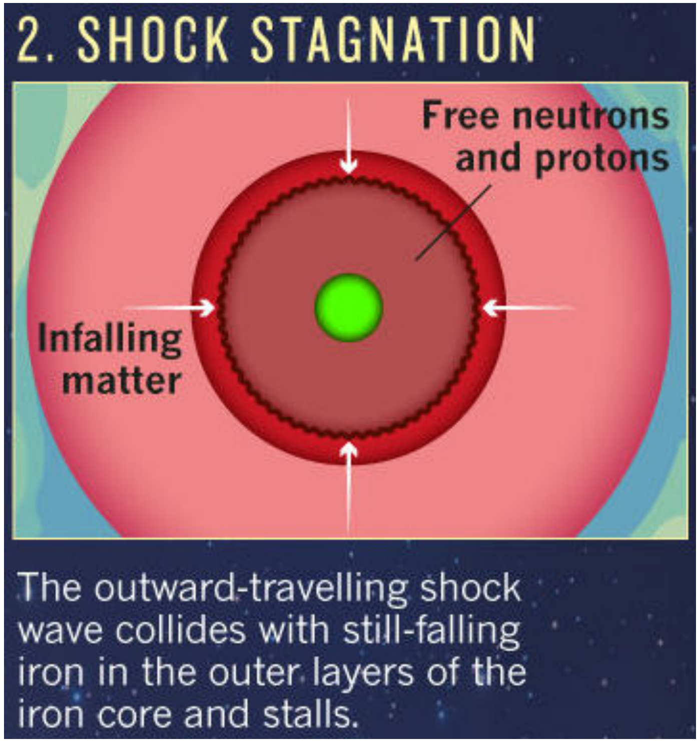
STAR'S END

When a massive star explodes, it seeds the space around it with a number of atomic species — the makings of future planets and stars. The process begins deep inside the star, as it runs low on hydrogen. As the star contracts, atoms fuse into progressively heavier elements. These form onion-like rings and a core at the centre made of iron (layers and core not shown to scale).



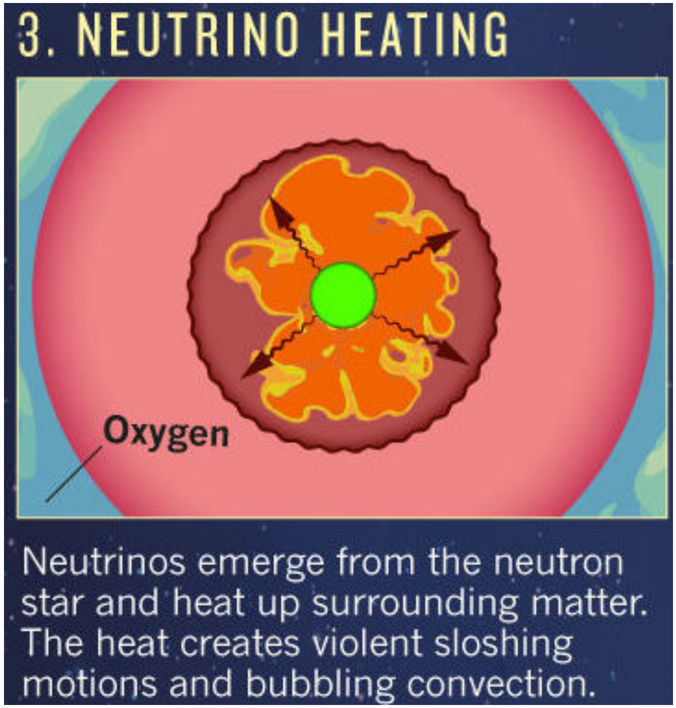
1. CORE BOUNCE

The growing iron core collapses under gravity, forming a neutron star. Infalling material bounces off the neutron star, creating a shock wave.



2. SHOCK STAGNATION

The outward-travelling shock wave collides with still-falling iron in the outer layers of the iron core and stalls.



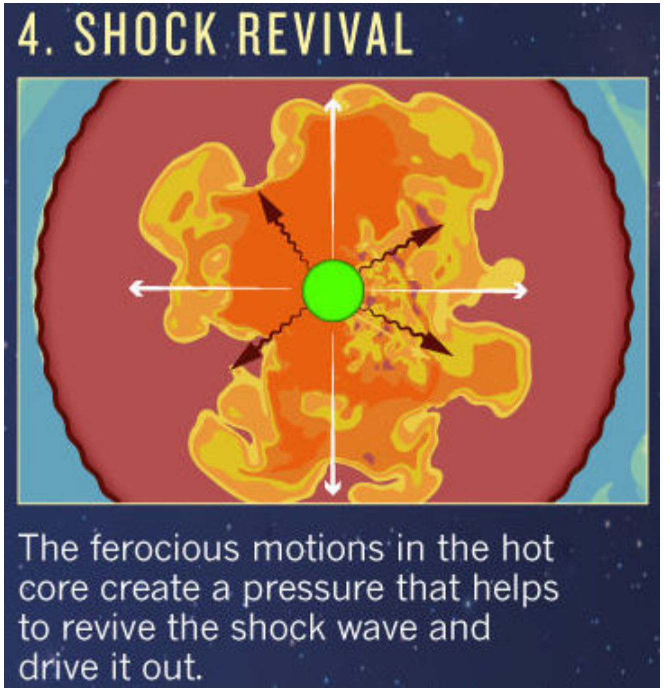
3. NEUTRINO HEATING

Neutrinos emerge from the neutron star and heat up surrounding matter. The heat creates violent sloshing motions and bubbling convection.

https://www.nature.com/articles/d41586-018-04601-7

Janka 1702.08825

Core-collapse supernova explosion

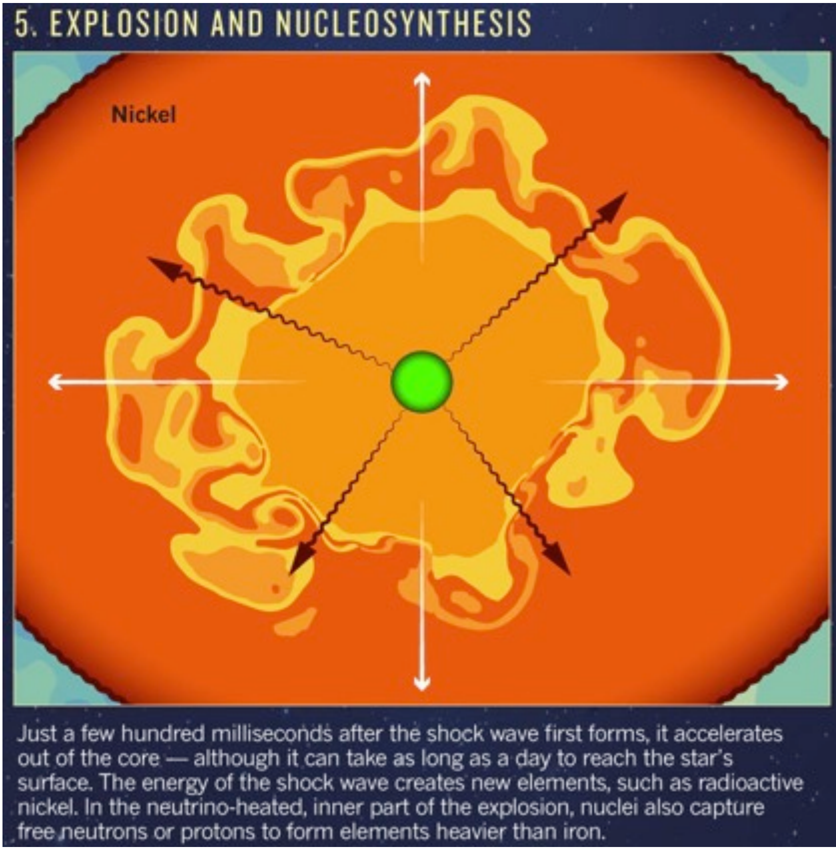


4. SHOCK REVIVAL

The ferocious motions in the hot core create a pressure that helps to revive the shock wave and drive it out.

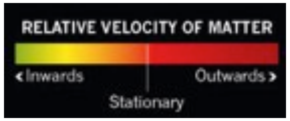
https://www.nature.com/articles/d41586-018-04601-7

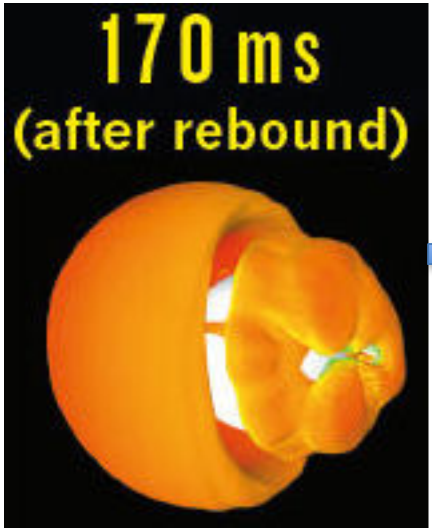
Janka 1702.08825

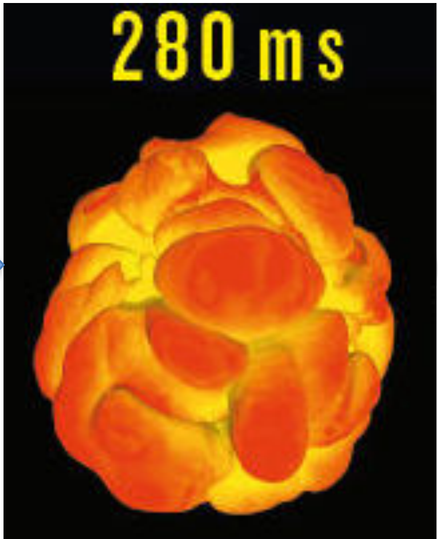


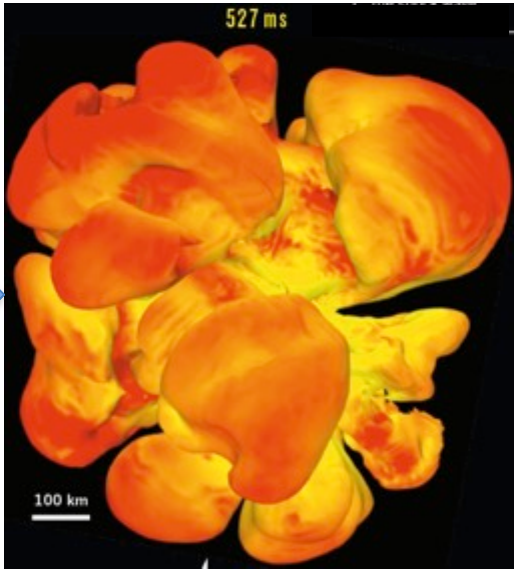
5. EXPLOSION AND NUCLEOSYNTHESIS

Just a few hundred milliseconds after the shock wave first forms, it accelerates out of the core — although it can take as long as a day to reach the star's surface. The energy of the shock wave creates new elements, such as radioactive nickel. In the neutrino-heated, inner part of the explosion, nuclei also capture free neutrons or protons to form elements heavier than iron.

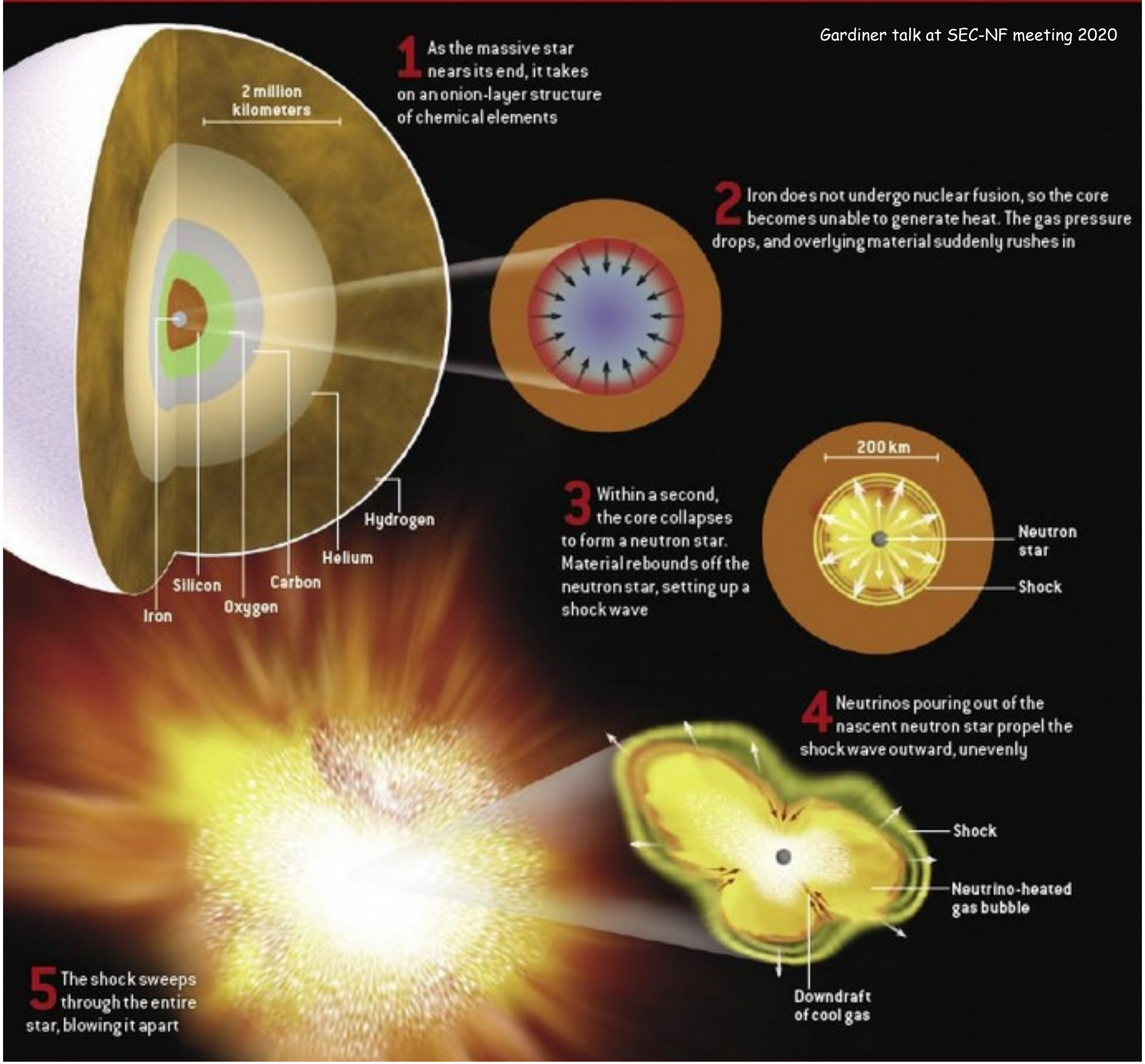








CORE-COLLAPSE SUPERNOVA



Gardiner talk at SEC-NF meeting 2020

1 As the massive star nears its end, it takes on an onion-layer structure of chemical elements

2 Iron does not undergo nuclear fusion, so the core becomes unable to generate heat. The gas pressure drops, and overlying material suddenly rushes in

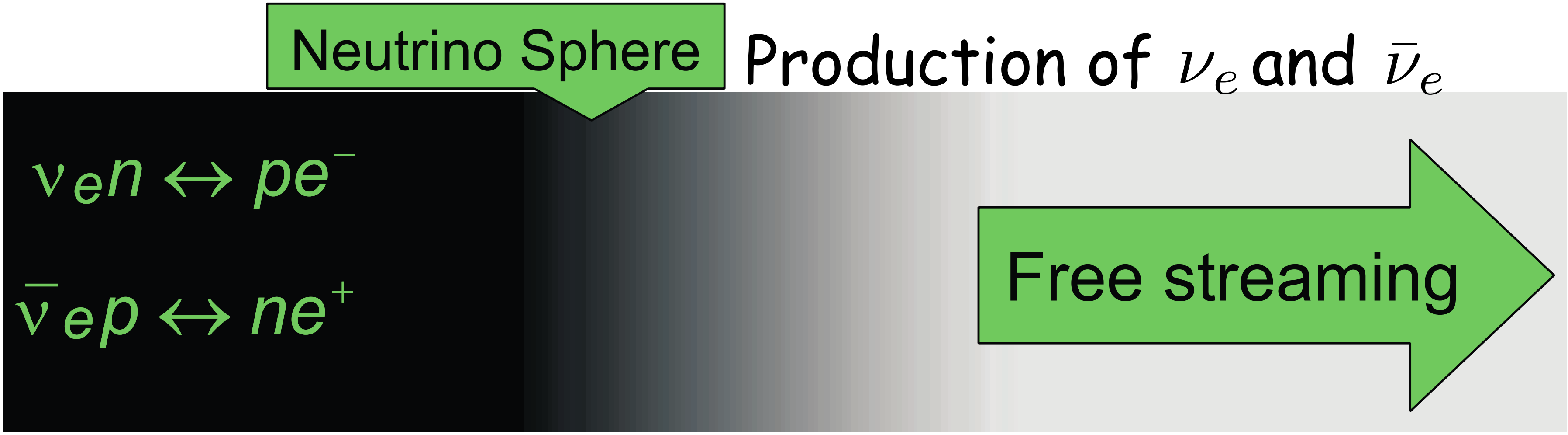
3 Within a second, the core collapses to form a neutron star. Material rebounds off the neutron star, setting up a shock wave

4 Neutrinos pouring out of the nascent neutron star propel the shock wave outward, unevenly

5 The shock sweeps through the entire star, blowing it apart

Neutrino generation inside supernova

Production of ν_e and $\bar{\nu}_e$



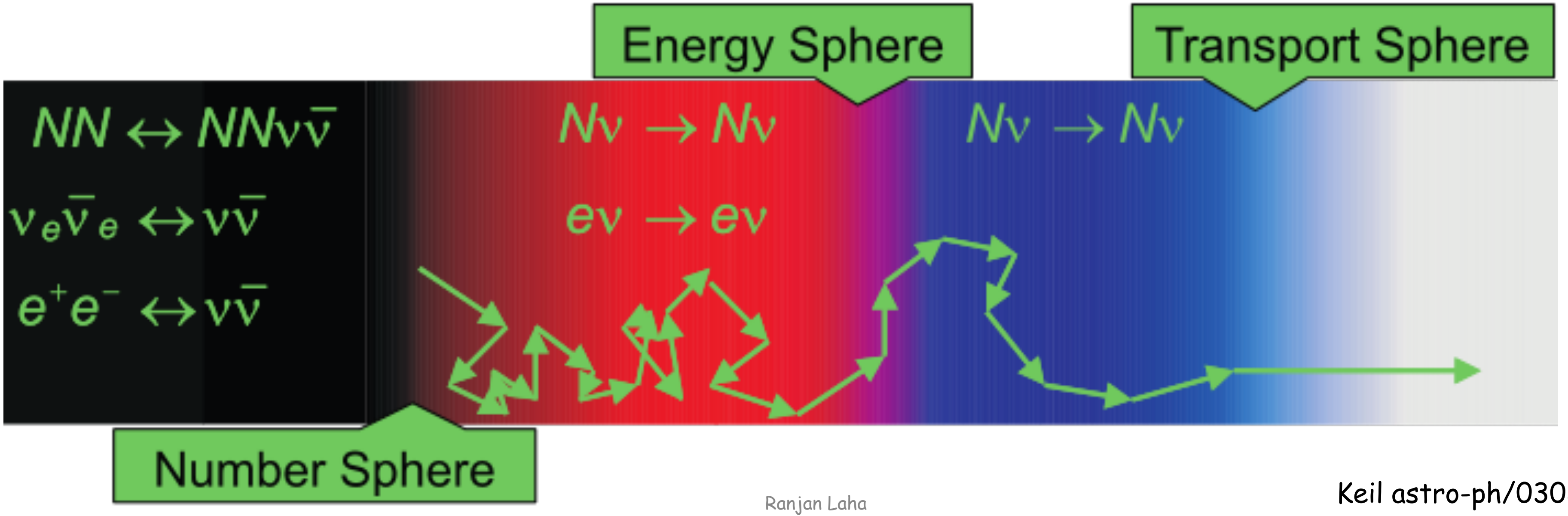
Neutrino Sphere

$\nu_e n \leftrightarrow p e^-$

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

Free streaming

Production of ν_μ, $\bar{\nu}_\mu$, ν_τ, and $\bar{\nu}_\tau$



Energy Sphere

Transport Sphere

$NN \leftrightarrow NN\nu\bar{\nu}$

$\nu_e\bar{\nu}_e \leftrightarrow \nu\bar{\nu}$

$e^+e^- \leftrightarrow \nu\bar{\nu}$

$N\nu \rightarrow N\nu$

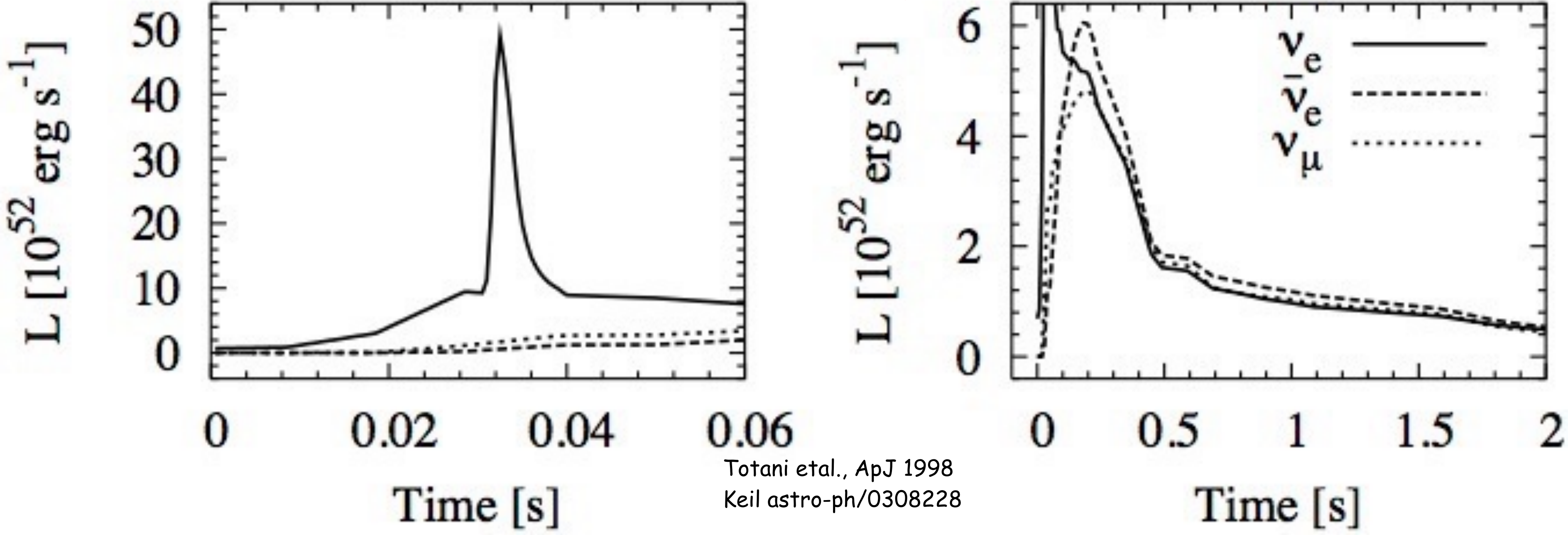
$e\nu \rightarrow e\nu$

$N\nu \rightarrow N\nu$

Number Sphere

Keil astro-ph/0308228

Theoretical expectations



Totani etal., ApJ 1998
Keil astro-ph/0308228

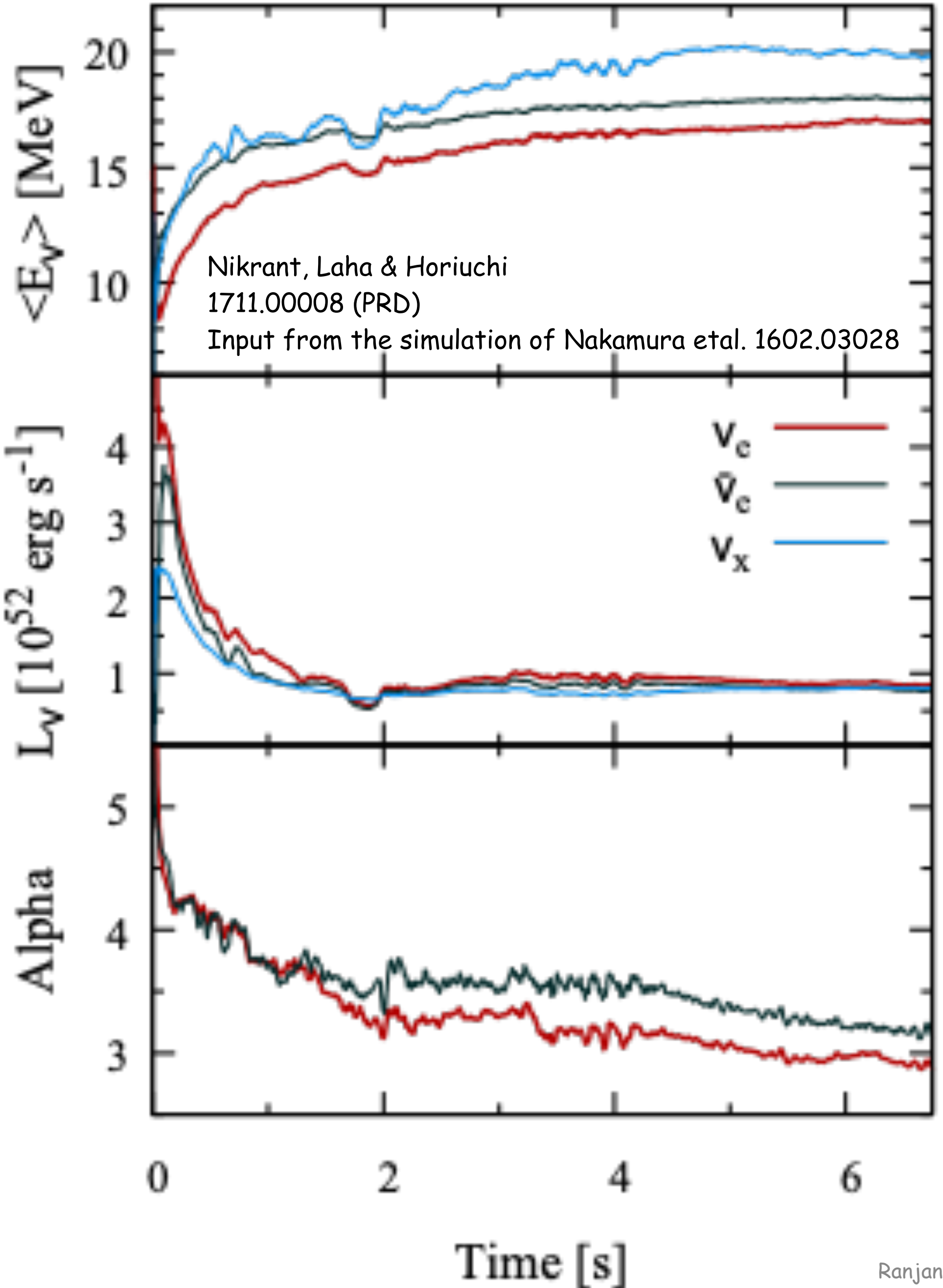
Neutrino burst of all flavors --- lasting for ~ 10 seconds

Neutrino energies up to ~ 50 MeV

Total energy carried by the neutrinos is approximately the full binding energy of the star ≈ 3×10^{53} erg --- must detect ALL the neutrinos

Neutrinos can be detected from Galactic supernova (happens approximately once in a century in the Milky Way) in large numbers

From numerical simulations



Nikrant, Laha & Horiuchi
1711.00008 (PRD)
Input from the simulation of Nakamura etal. 1602.03028

$$\nu_x = \nu_\mu + \nu_\tau + \mathrm{anti-particles}$$

$$\frac{dN_\nu}{dE_\nu}(E_\nu) = \frac{(\alpha+1)^{\alpha+1}}{\langle E_\nu\rangle \Gamma(\alpha+1)} \left(\frac{E_\nu}{\langle E_\nu\rangle}\right)^{\alpha} \times \exp\left[-(\alpha+1)\frac{E_\nu}{\langle E_\nu\rangle}\right]$$

E_ν = neutrino energy

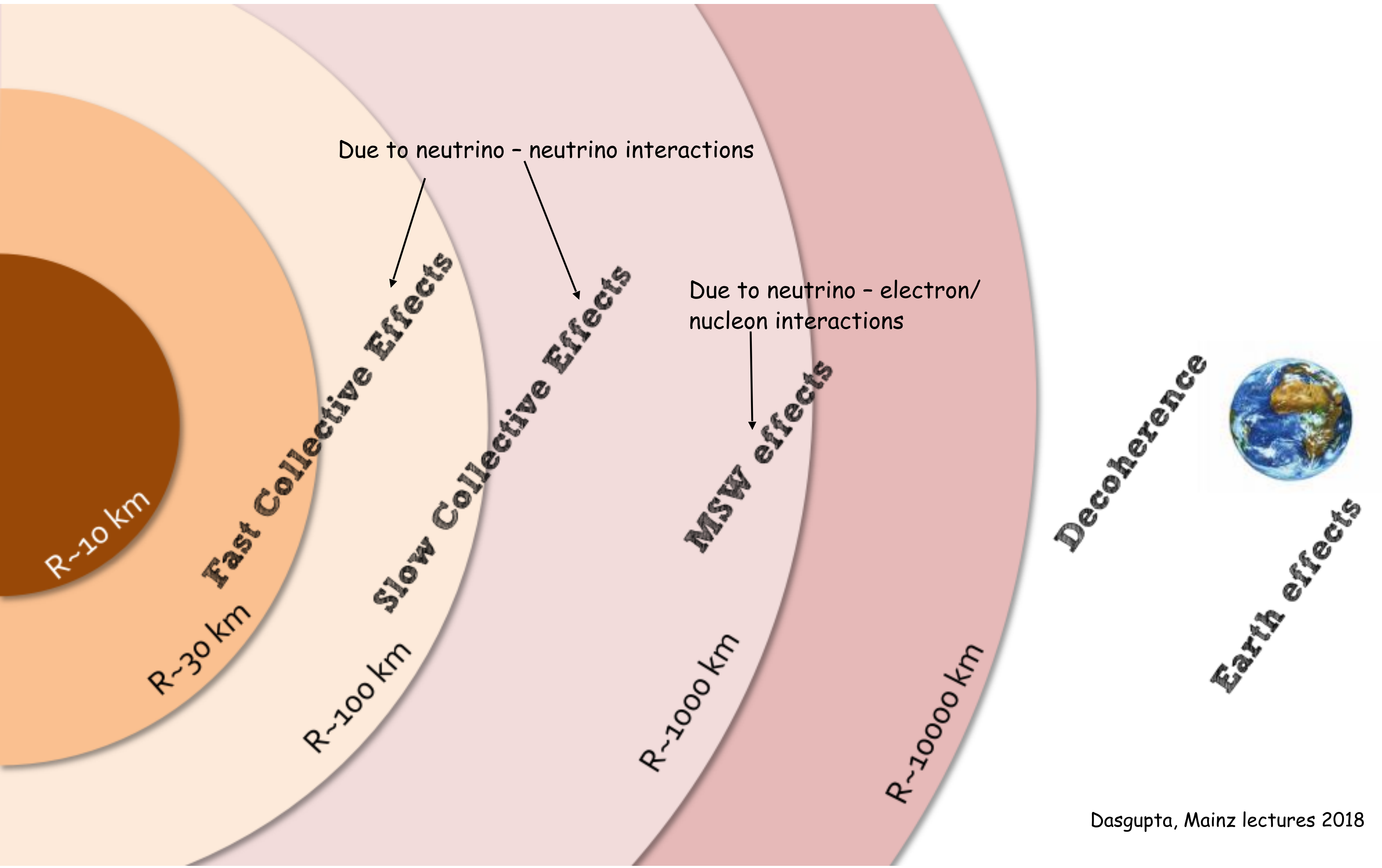
$\langle E_\nu \rangle$ = average neutrino energy of the spectrum

$$\Phi(E_\nu) = \frac{1}{4\pi d^2}\frac{E_\nu^{\mathrm{tot}}}{\langle E_\nu\rangle}\frac{dN_\nu}{dE_\nu}$$

Neutrino fluence

Distance from the supernova to the Earth = 10 kpc

Oscillation physics



Due to neutrino – neutrino interactions

Due to neutrino – electron/ nucleon interactions

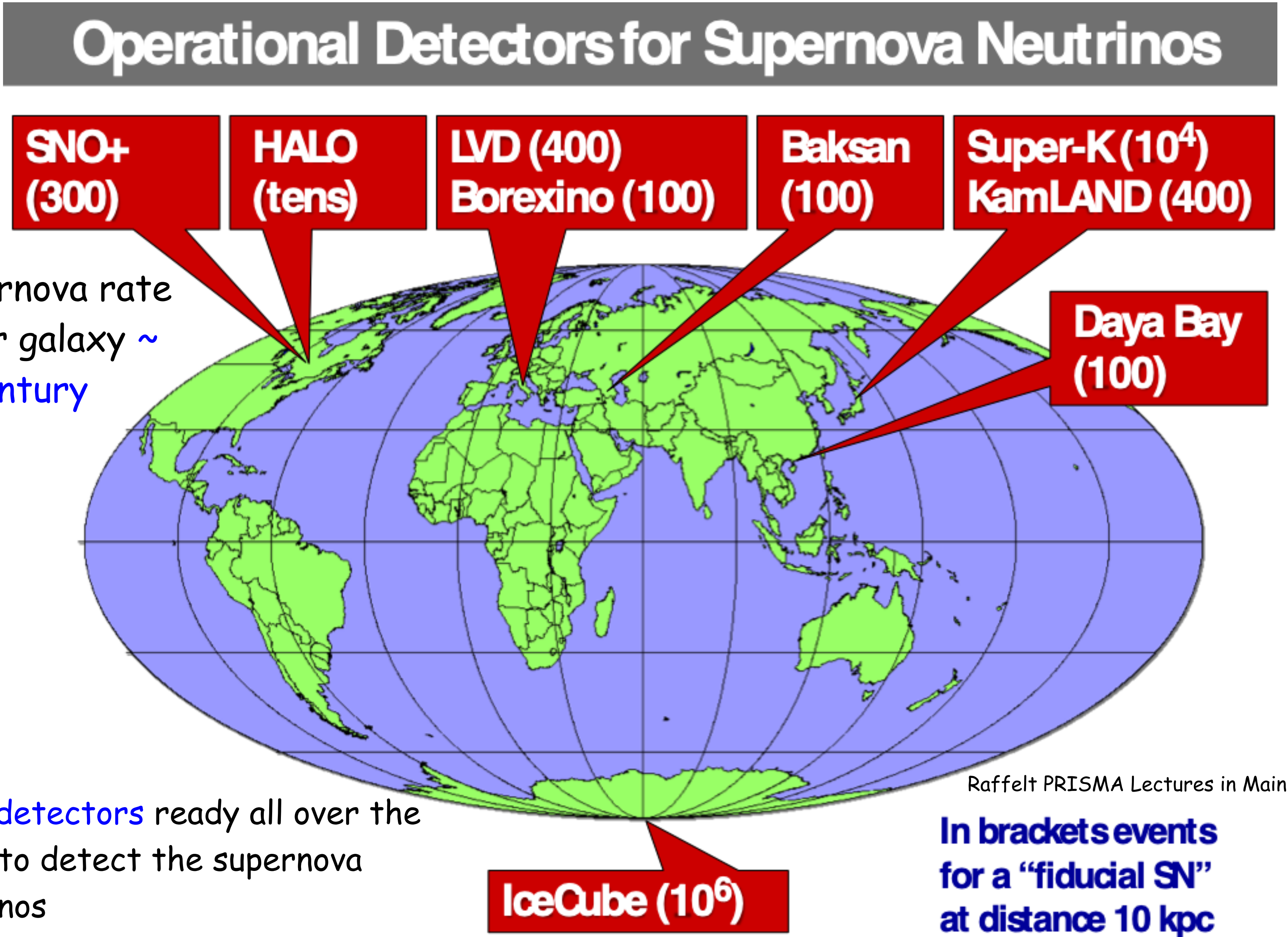
Dasgupta, Mainz lectures 2018

Extremely rich phenomenology --- turbulence and unknown matter density inside supernova adds to the richness of the problem

Mirizzzi et al., 1508.00785

Supernova neutrino detectors and supernova neutrino detection

Supernova neutrino detectors all around the World



Supernova rate in our galaxy ~ 1/ century

Raffelt PRISMA Lectures in Mainz 2015

In brackets events for a “fiducial SN” at distance 10 kpc

Many detectors ready all over the world to detect the supernova neutrinos

Summary of supernova neutrino detectors

Detector	**Type**	**Location**	**Mass (kton)**	**Events @ 10 kpc**	**Status**
Super-K	Water	Japan	32	8000	Running (SK IV)
LVD	Scintillator	Italy	1	300	Running
KamLAND	Scintillator	Japan	1	300	Running
Borexino	Scintillator	Italy	0.3	100	Running
IceCube	Long string	South Pole	(600)	(10^6)	Running
Baksan	Scintillator	Russia	0.33	50	Running
Mini-BooNE	Scintillator	USA	0.7	200	(Running)
HALO	Lead	Canada	0.079	20	Running
Daya Bay	Scintillator	China	0.33	100	Running
NOvA	Scintillator	USA	15	3000	Running
SNO+	Scintillator	Canada	1	300	(Running)
MicroBooNE	Liquid argon	USA	0.17	17	Running
DUNE	Liquid argon	USA	40	3000	Future
Hyper-K	Water	Japan	540	110,000	Future
JUNO	Scintillator	China	20	6000	Future
IceCube Gen-2	Long string	South pole	(600)	(10^6)	Future

plus reactor experiments, DM experiments...

Scholberg 1205.6003
Scholberg Trento 2019 talk

Supernova neutrino detection

$\bar{\nu}_e$

Supernova neutrino detection: $\bar{\nu}_{\mathrm{e}}$

$\bar{\nu}_e + p \rightarrow e^+ + n$: Inverse beta (IB) interaction

water Cherenkov / liquid scintillator detector

e^+: Detected by Cherenkov radiation/ scintillation

n : Can be detected via proton capture; near future addition of Gadolinium (Gd) in water Cherenkov detectors will improve detection prospects

$$\sigma(\bar{\nu}_e p) \approx 10^{-43}\,\mathrm{cm}^2\, p_e E_e E_\nu^{-0.07056+0.02018\,\ln E_\nu - 0.001953\,\ln^3 E_\nu}$$

Strumia & Vissani 2003

Threshold of interaction $E_\nu > 1.8\,\mathrm{MeV}$

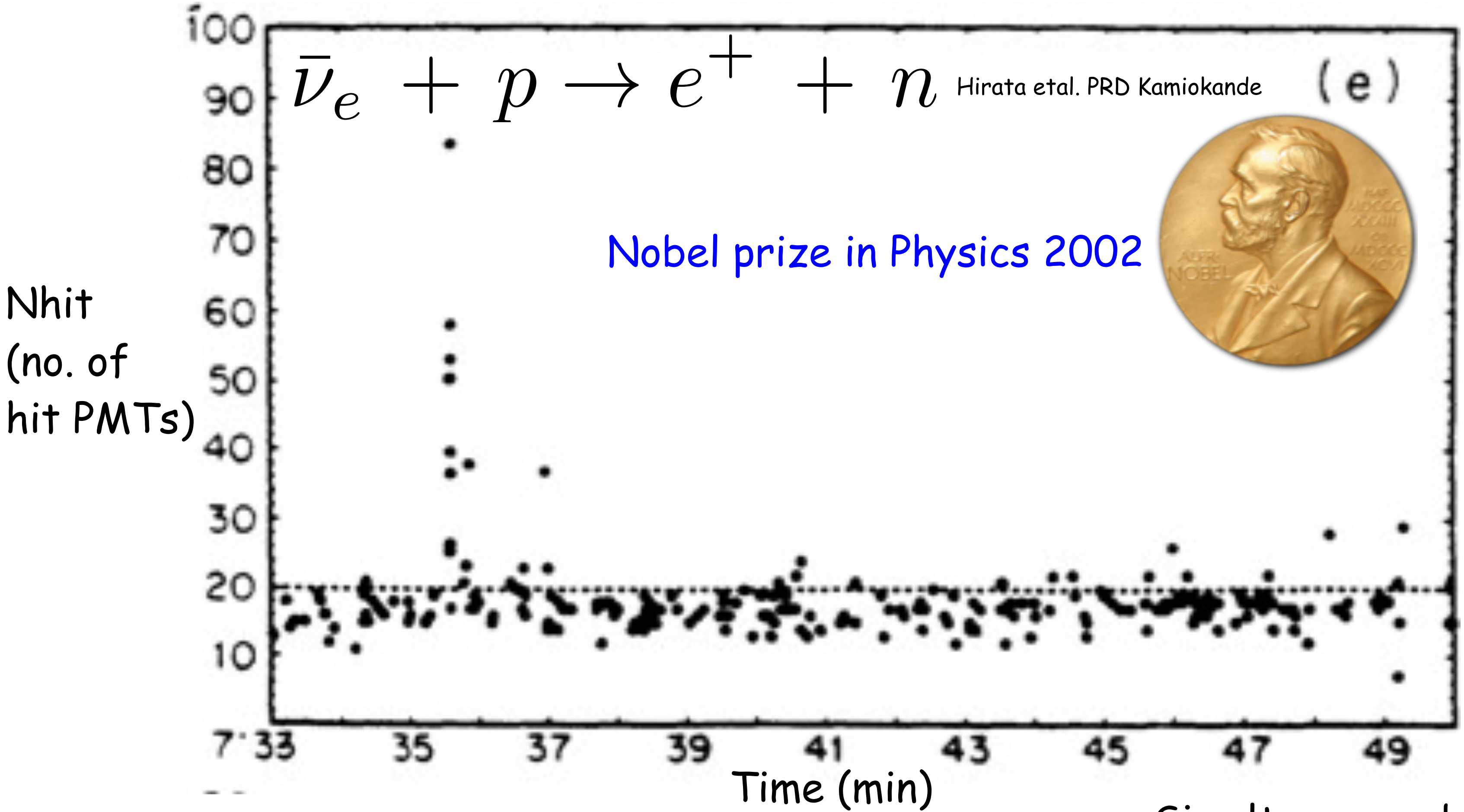
Vogel & Beacom 1999

$$T_e \approx E_\nu - 1.8\,\mathrm{MeV}$$

T_e: kinetic energy of the positron

Largest cross section at the relevant energies (~ MeV --- 50 MeV)

SN 1987A in LMC



$\bar{\nu}_e + p \rightarrow e^+ + n$ Hirata etal. PRD Kamiokande

Nobel prize in Physics 2002

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In broad agreement with the theoretical expectations

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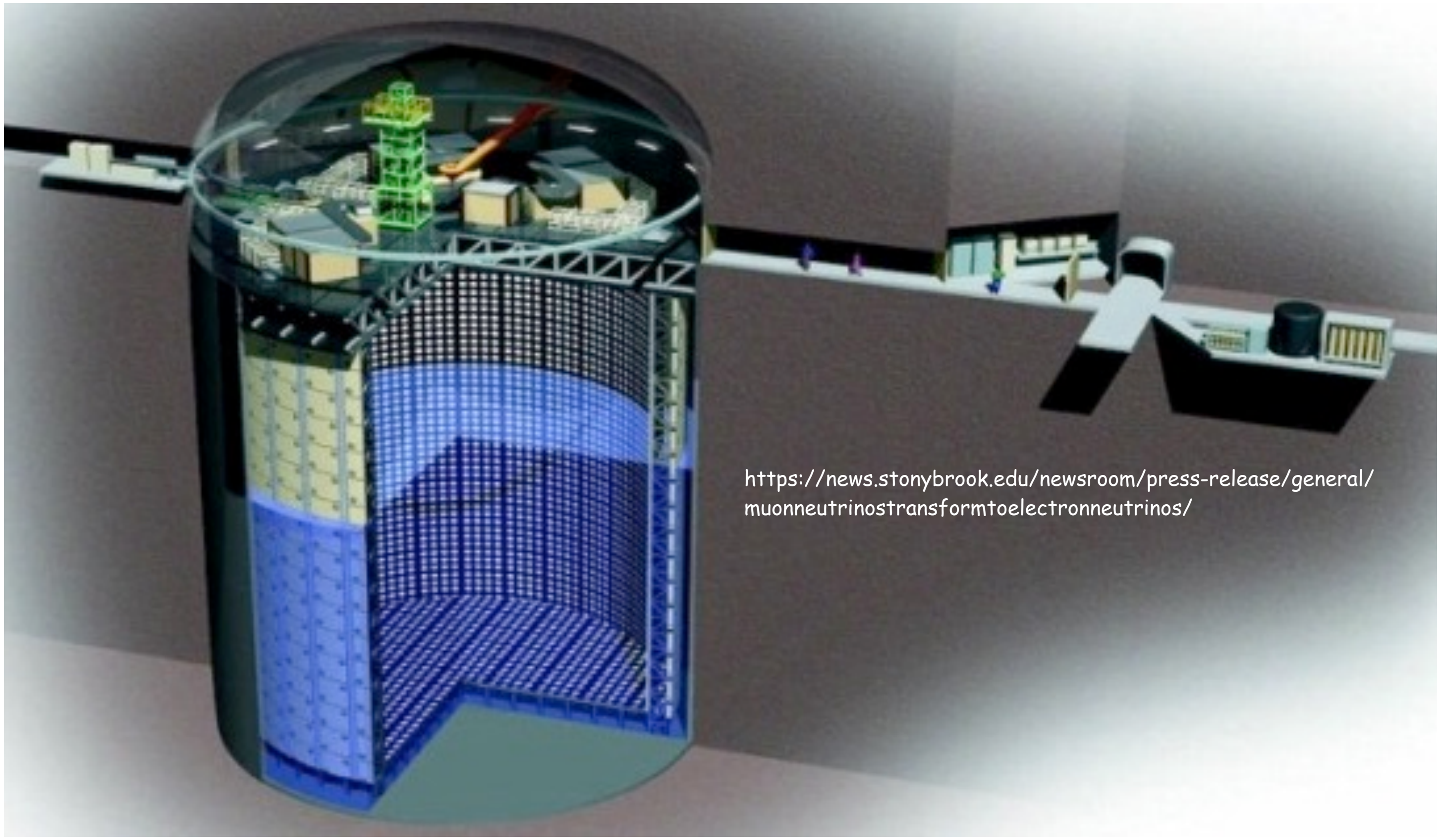
Super-Kamiokande


https://news.stonybrook.edu/newsroom/press-release/general/muonneutrinostransformtoelectronneutrinos/

Water Cherenkov detector

Total volume of water = 50 kton

Fiducial volume for supernova neutrino detection = 32 kton

Energy threshold ≈ 5 MeV

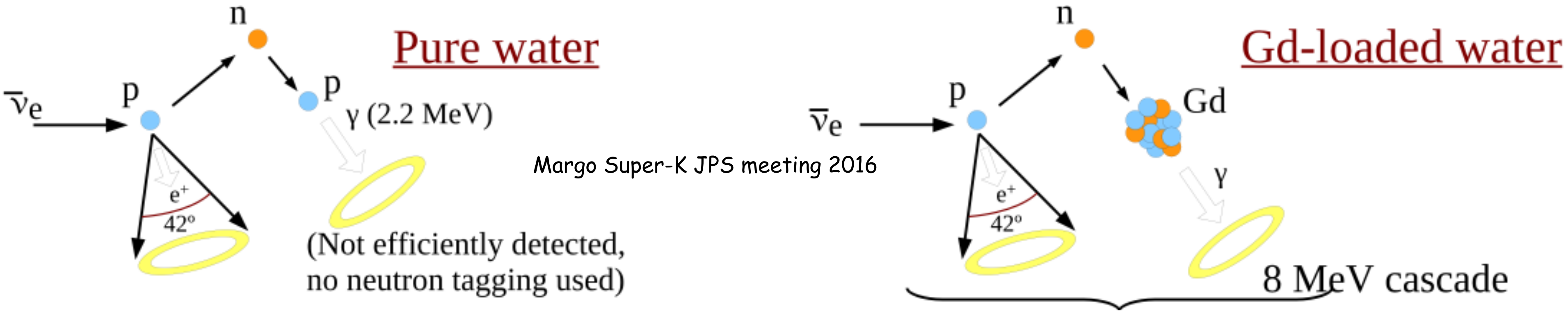
Charged particles and photons can be detected via Cherenkov radiation

Addition of Gadolinium in Super-Kamiokande will help in multiple physics cases

Hyper-Kamiokande (roughly 20 times larger than Super-Kamiokande) approved

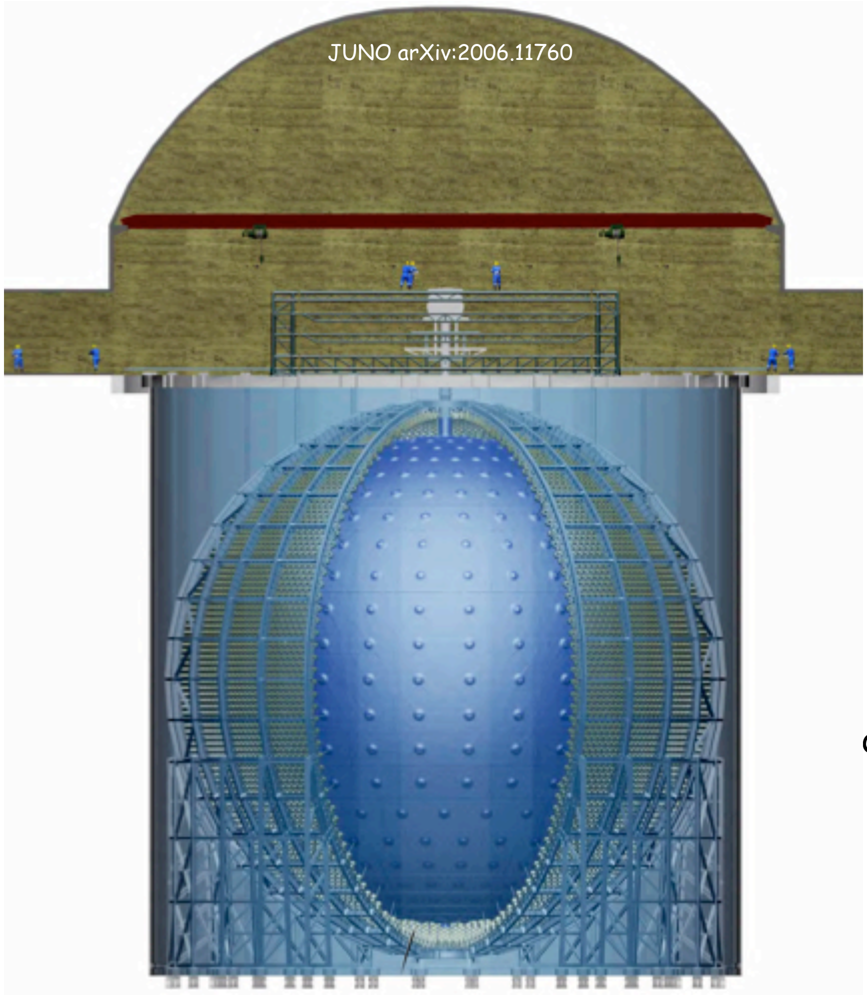
Supernova neutrino detection: $\bar{\nu}_e$

- Neutron capture on free proton produces 2.2 MeV photon --- delay time ~ 200 μsec --- capture cross section 0.3 barns
  $$n + p \rightarrow d + \gamma$$
- Neutron capture on Gd produces ~ 8 MeV photons --- delay time ~ 20 μsec --- capture cross section 49000 barns
- Typical number of events in SuperKamiokande detector (inner volume 32 kton) ~ 10^4 (from a SN at 10 kpc)
- Detecting both the final products uniquely identifies this reaction
- Determine $\bar{\nu}_e$ properties to ~ 1%



Margo Super-K JPS meeting 2016

JUNO



Liquid scintillator detector

Total volume of detector = 20 kton

Detection of charged particles and photons via scintillation

Energy threshold ≈ 0.2 MeV

$$\bar{\nu}_e + \underset{\text{detected via scintillation}}{p \to e^+} + \underset{\text{detected via proton capture}}{n}$$

detected via scintillation

detected via proton capture

$$n + p \to d + \gamma$$

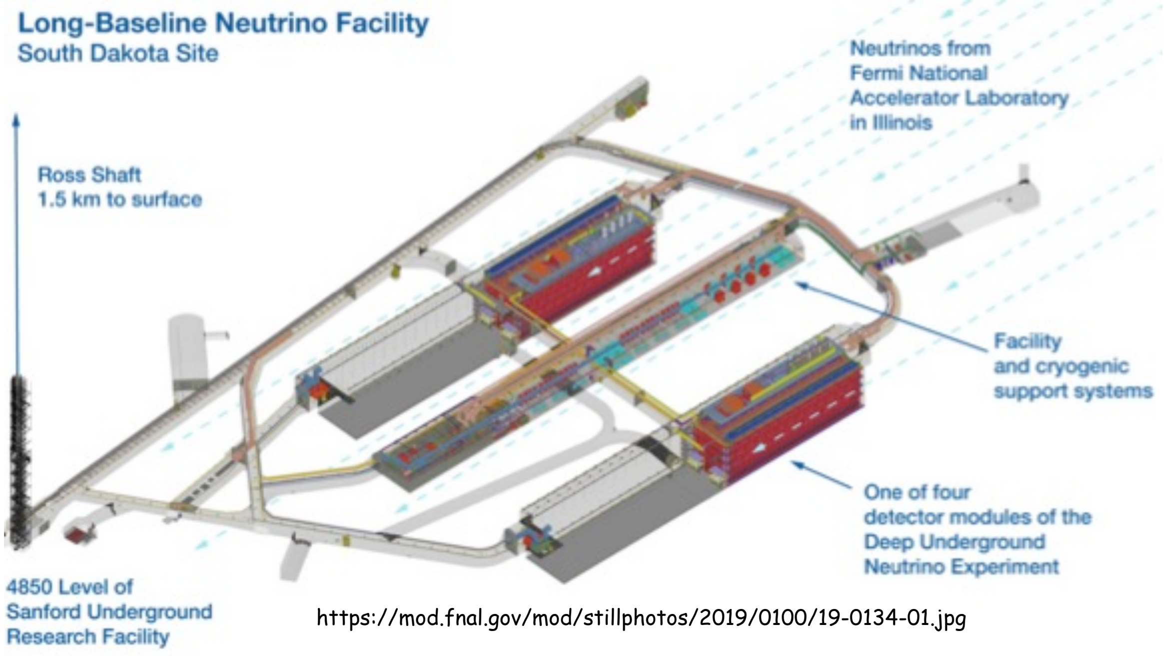
Typical number of events in JUNO ≈ 5000 (from a SN at 10 kpc)

Due to the expected energy resolution of JUNO (~ 3% at 1 MeV), it is expected that the incident neutrino energy spectrum will be well measured

Supernova neutrino detection

ν_e

DUNE



https://mod.fnal.gov/mod/stillphotos/2019/0100/19-0134-01.jpg

Liquid argon time-projection chamber

Total detector volume = 40 kton

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

observable

detectable via de-excitation products

Threshold ≈ 1.5 MeV

Uncertainty in the theoretical calculations of the cross-sections (Gardiner 2010.02393, Gardiner thesis, and Gardiner talk at SEC-NF meeting 2020)

Typical number of events in DUNE from ν_e CC interaction ≈ 3000 (from a SN at 10 kpc)

See Snowmass LOI (https://tinyurl.com/lowE-inelastic-nu-xsec) for experimental measurement prospects

Supernova neutrino detection: ν_e

$$\nu_e + e^- \rightarrow \nu_e + e^-$$

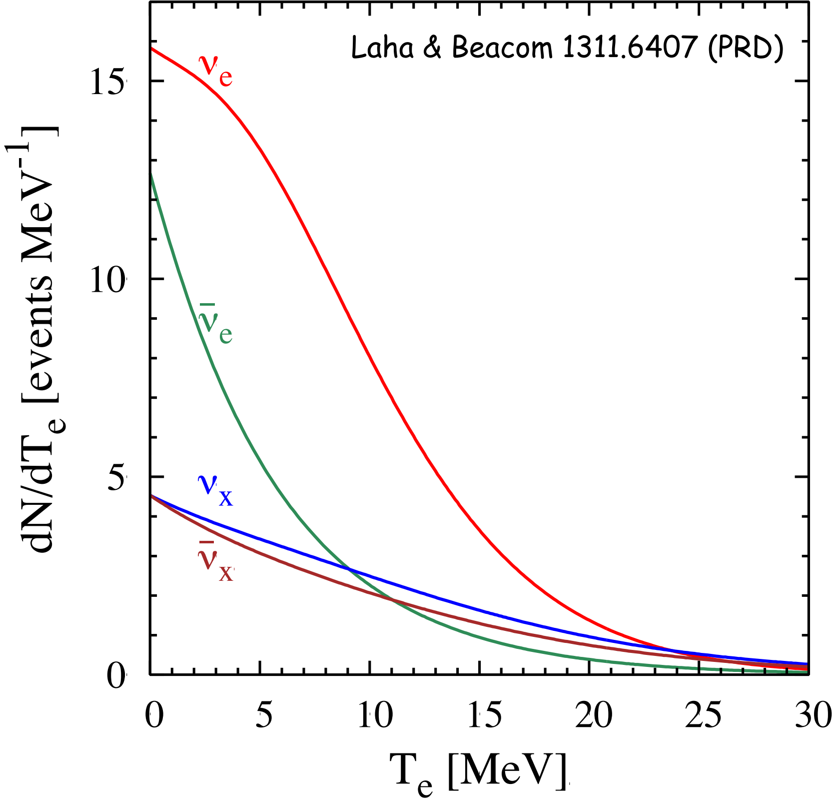
Sensitive to all neutrino species; ν_e produces largest number of events

Maximum number of events in water Cherenkov detectors

The electrons are forward scattered

$$\sigma(E_\nu) \propto G_F^2 \, m_e E_\nu$$

Neutrino energy E_ν ➔ recoil electron energy $\epsilon \left[0, \frac{2E_\nu^2}{m_e + 2E_\nu}\right]$



Electron spectra for $\nu + e^- \rightarrow \nu + e^-$ detection channels for a Galactic supernova in Super-K

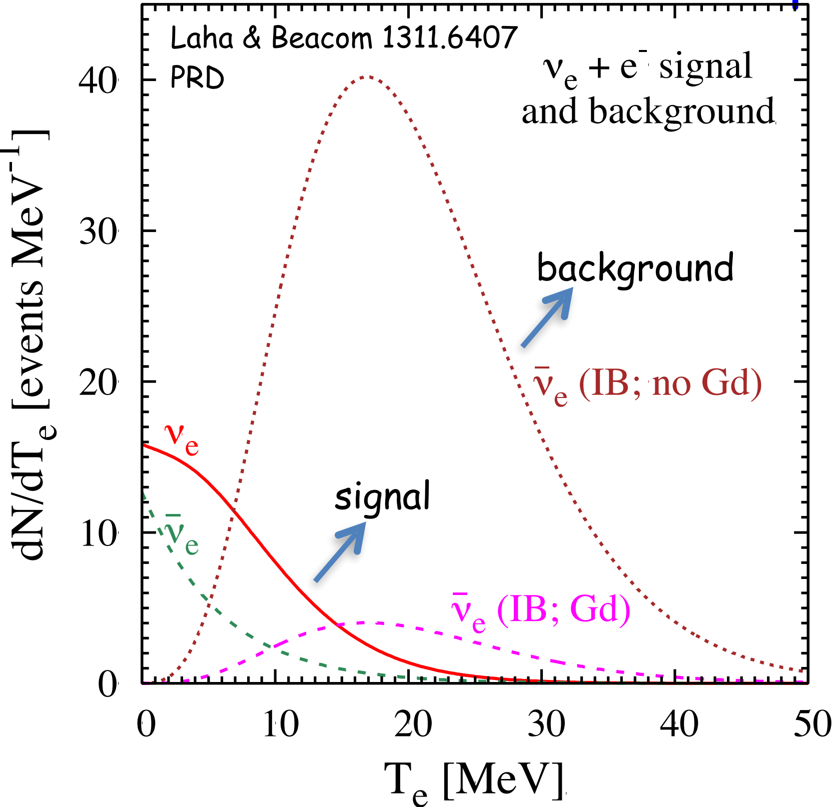
These are events in the forward 40° cone (~ 68% of the total). We take

$\langle E_{\nu_e} \rangle = 12\,\mathrm{MeV}$, $\langle E_{\bar{\nu}_e} \rangle = 15\,\mathrm{MeV}$, and $\langle E_{\nu_x} \rangle = 18\,\mathrm{MeV}$

Number of events in a Super-K ~ 200

$\nu_e + e^- \rightarrow \nu_e + e^-$

- Use angular cut: 128 signal events v/s 827 background events (mostly from inverse beta interactions)
- Difficult to distinguish these in the present configuration of Super-K
- How do we utilize this important neutrino detection channel?



- In the present configuration of Super-K, the signal is dwarfed by the background

- Important to extract this signal to improve reliability of the signal and search for various physics effects

A new way to detect supernova ν_e in water-Cherenkov detectors

Galactic Supernova happens

- Implement angular cut: forward cone contains most of the electron elastic scattering events; inverse beta is quasi-isotropic

- Gd can individually detect and remove the inverse beta reactions in the forward cone

- Remaining inverse beta backgrounds can be statistically subtracted

- Use the information about $\bar{\nu}_e$ and ν_x to statistically subtract the electron scattering events due to these flavors

- Addition of Gd also helps in identifying $\nu_e \ {}^{16}\mathrm{O}$ events

Supernova neutrino detection

ν_x

Supernova neutrino detection: ν_x

$$\nu_x + p \rightarrow \nu_x + p$$

Detectable part of the interaction mainly provided by ν_x

Liquid scintillator detector

Recoil protons detected by scintillation light

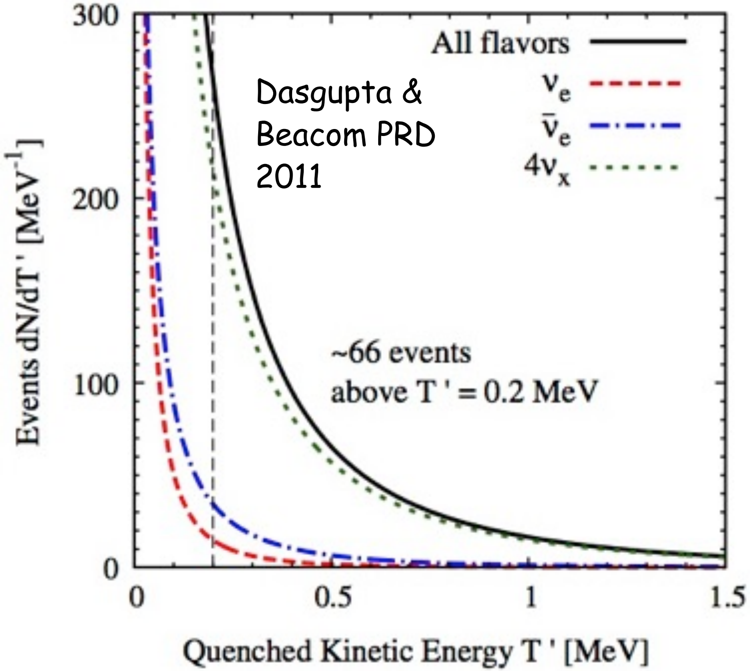
Neutral current interaction ➔ sensitive to all flavors

$$\frac{d\sigma}{dT} = \frac{4.83 \times 10^{-42}\,\mathrm{cm}^2}{\mathrm{MeV}} \left(1 + 466 \frac{T}{E^2}\right)$$

T Recoil proton energy

E Incoming neutrino energy

Neutrino of energy E ➔ proton recoil energy $\epsilon \left[0, \frac{2\,E^2}{m_p}\right]$



Dasgupta & Beacom PRD 2011

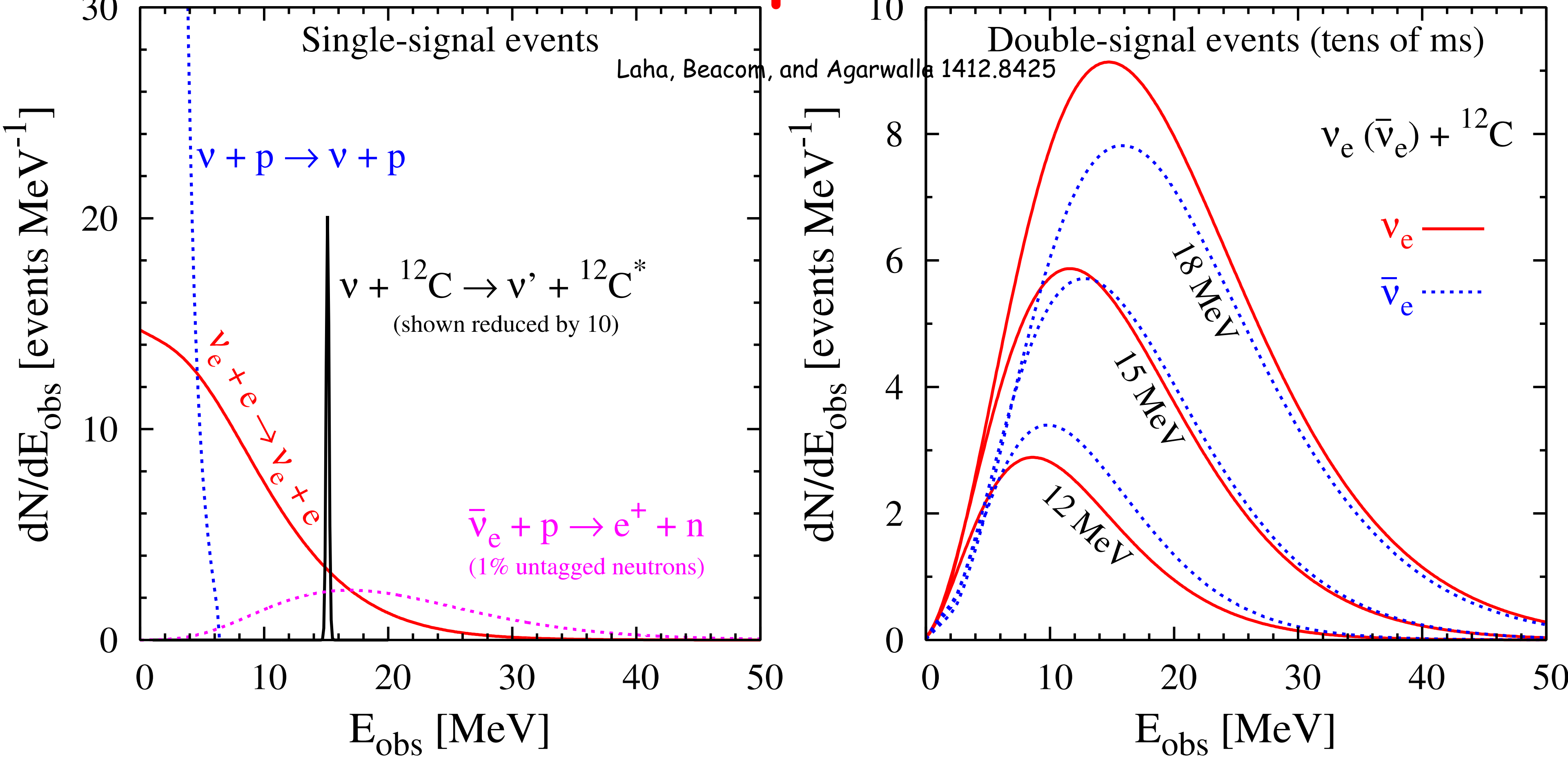
Detectable recoil proton spectrum in KamLAND

Smaller number of events in Borexino

JUNO will detect ~ 1000 events via this interaction

Beacom, Farr and Vogel hep-ph/0205220
Lujan-Peschard, Pagliaroli and Vissani 1402.6953
Laha, Beacom and Agarwalla 1412.8425
Li et al., 1903.04781

Event spectrum



Laha, Beacom, and Agarwalla 1412.8425

JUNO can detect supernova neutrinos of all flavors

Large number of events in distinct channels imply strong constraints on supernova neutrino spectral parameters

$$\nu_e + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{N}_{\mathrm{g.s.}} + e^-$$

$$\bar{\nu}_e + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{B}_{\mathrm{g.s.}} + e^+$$

Conclusions

Detection of a large number of neutrinos from a Galactic core-collapse supernova will be a landmark discovery of physics

It is important to detect all flavours of neutrinos in substantial numbers in order to extract the maximum amount of Standard Model particle physics, astrophysics, and beyond the Standard Model physics information from this event

This will be once-in-a-lifetime event --- we cannot miss it

Questions and comments: ranjanlaha@iisc.ac.in

Production of neutrinos and their average energies

$$\nu_e + n \leftrightarrow p + e^- \qquad \bar{\nu}_e + p \leftrightarrow n + e^+$$

$$N + N \leftrightarrow N + N + \nu + \bar{\nu} \quad \nu_e + \bar{\nu}_e \leftrightarrow \nu + \bar{\nu}$$

$$e^+ + e^- \leftrightarrow \nu + \bar{\nu}$$

Lowest cross section of ν_x ➔ decouples from matter earliest ➔ highest average energy

Larger number of neutrons than protons ➔ ν_e decouples last ➔ lowest average energy

$\bar{\nu}_e$ has an average energy in between these two extremes