Selected topics in nuclear and particle astrophysics

Meng-Ru Wu & Yen-Hsin Lin (Institute of Physics, Academia Sinica)

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中央研究院物理研究所
INSTITUTE OF PHYSICS, ACADEMIA SINICA

MOST 科技部
Ministry of Science and Technology

Outline

- overview of nuclear and particle astrophysics
- core-collapse supernova explosion & neutrinos
- binary neutron star mergers
- dark matter (by Yen-Hsun)

Overview

- What do we study in nuclear astrophysics and particle astrophysics?

  microphysics ⟷ macrophysics

  - How nuclear reactions / particle interactions affect the evolution of astrophysical systems
  - How known elements, nuclear isotopes, observable particles are produced in astrophysical environments

Overview

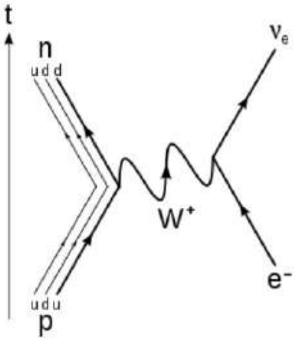
- What do we study in nuclear astrophysics and particle astrophysics?

microphysics ↔ macrophysics

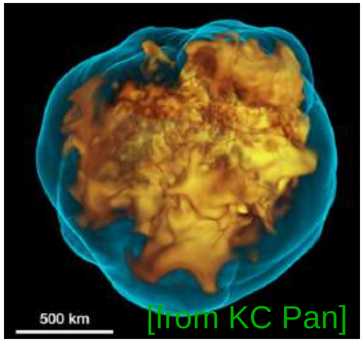
  - How nuclear reactions / particle interactions affect the evolution of astrophysical systems
  - How known elements, nuclear isotopes, observable particles are produced in astrophysical environments

- How do we study them?

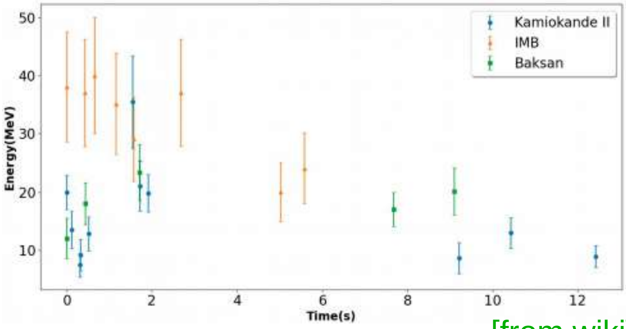
theory ↔ simulation ↔ observation



[from wiki]



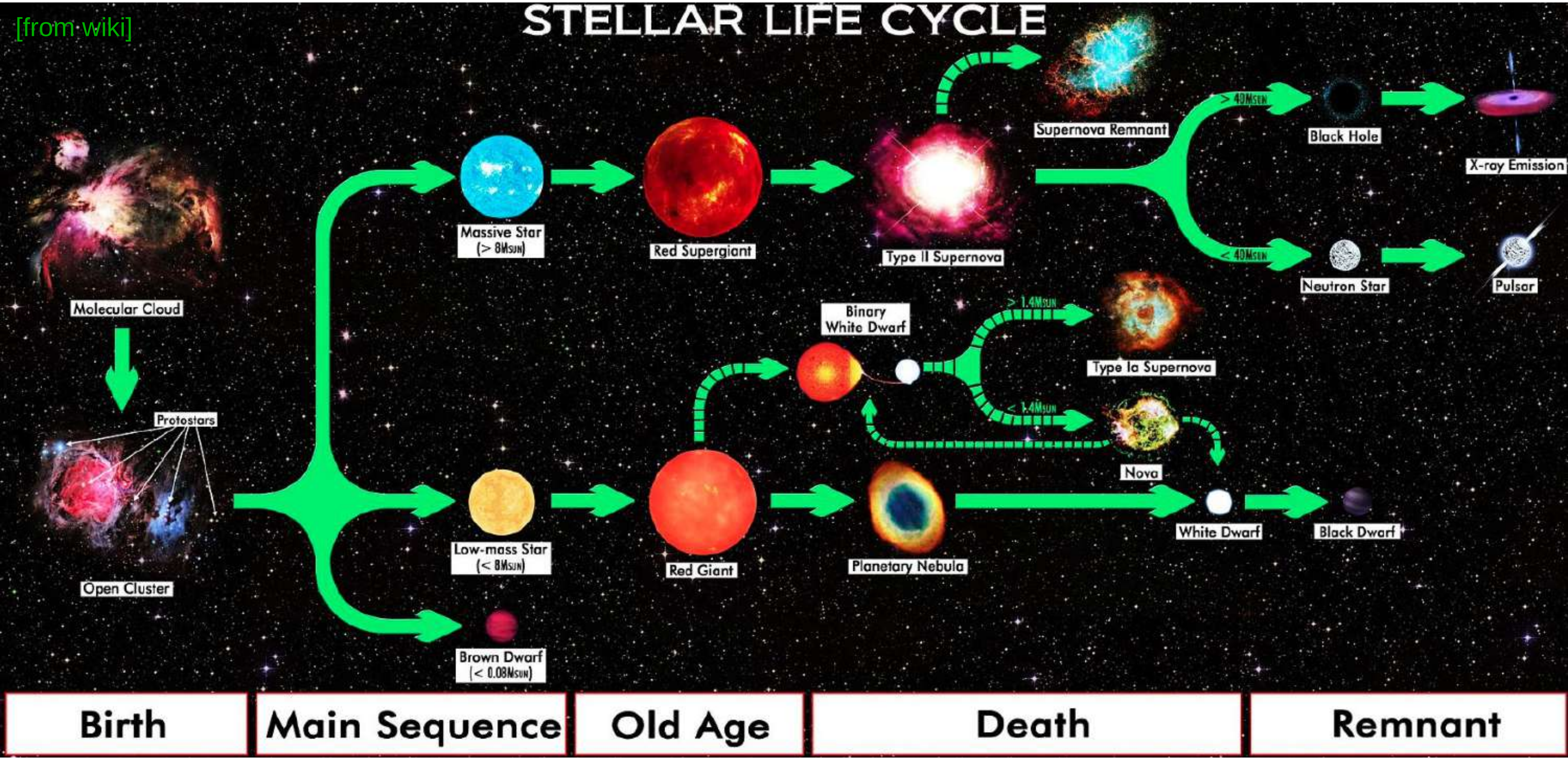
[from KC Pan]



[from wiki]

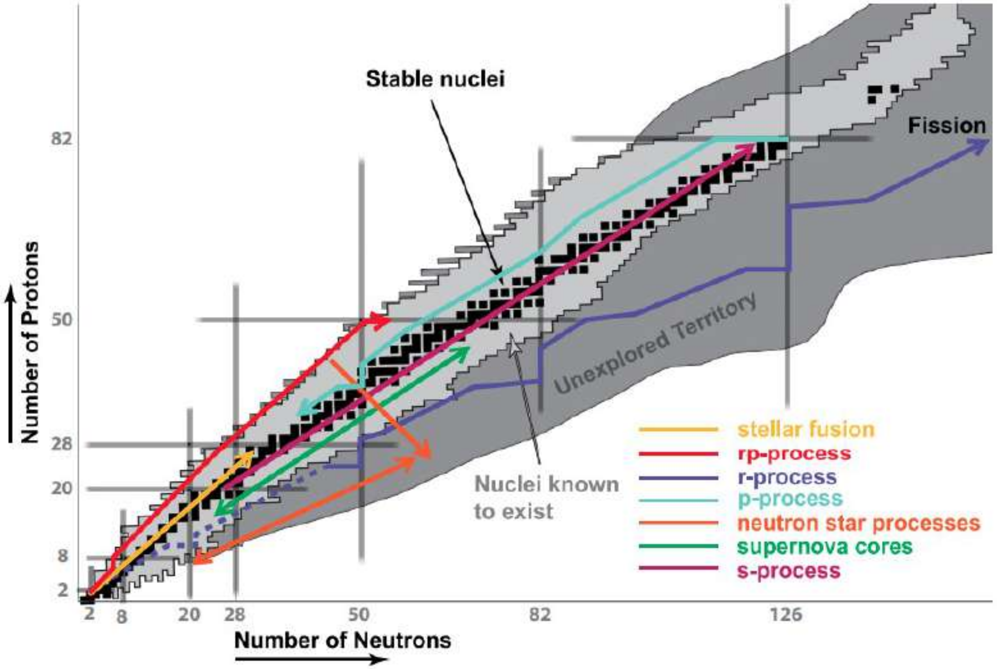
Scope of nuclear astrophysics

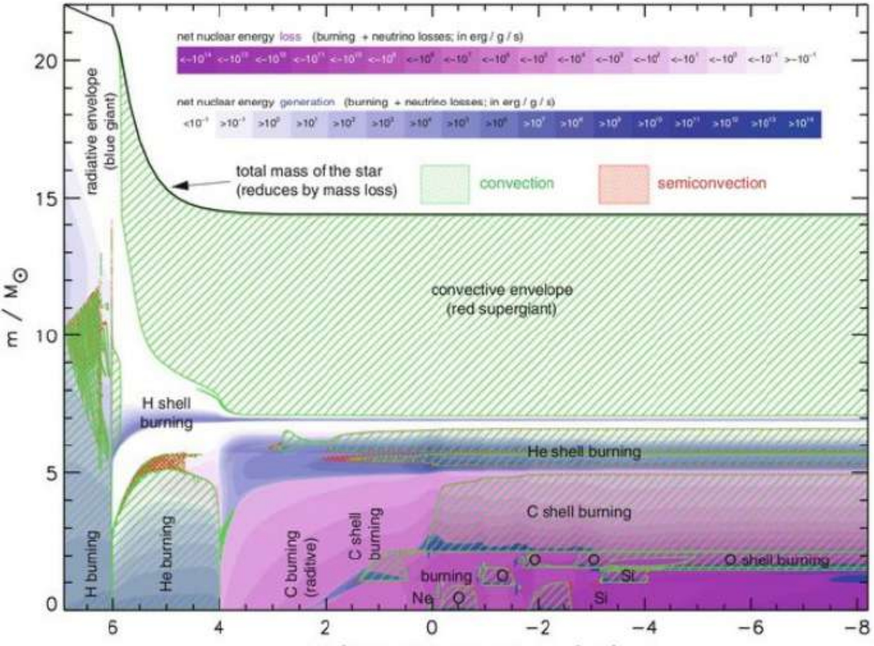
Nuclear burning & reactions play important roles in life cycle of stars:


[from wiki]

+ X-ray bursts, neutron star mergers (kilonovae) important to understand key nuclear reaction rates, e.g.,

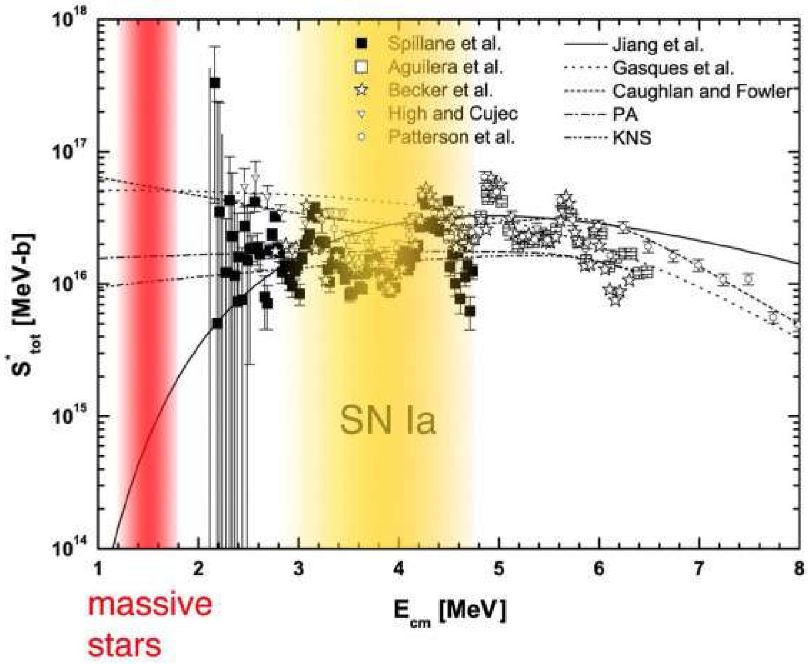
- C/O/Ne burning (massive stars)
- e^- capture (pre-SN)
- p capture (X-ray burst)
- n-capture, β-decay & fission (kilonova)





[from Heger]

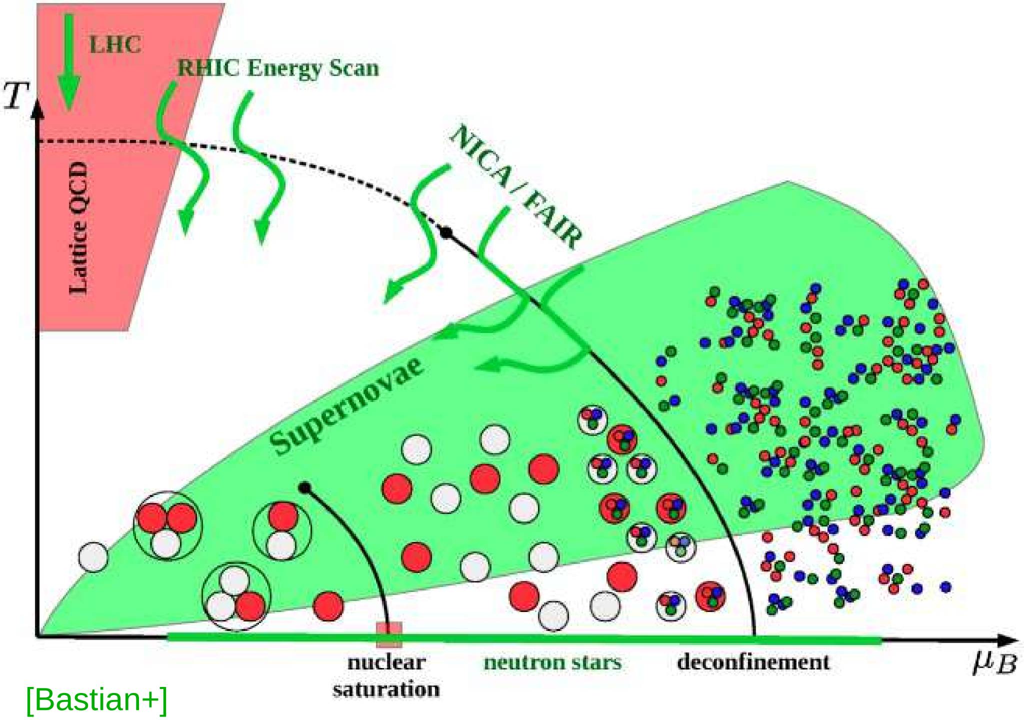
[from BNL white paper]



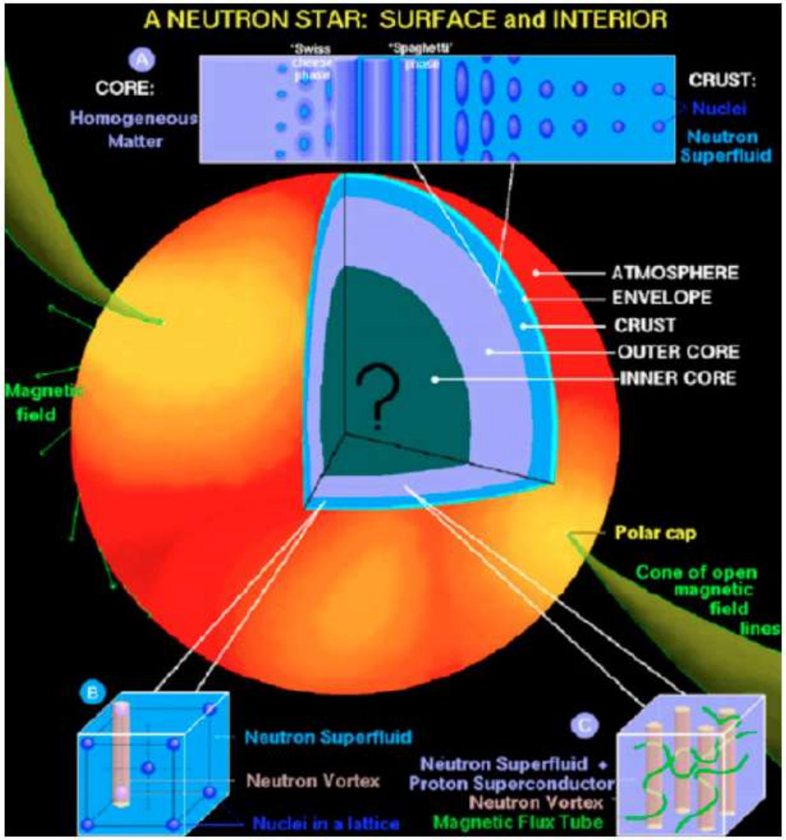
For objects/phenomena involving neutron stars, e.g., core-collapse supernovae, neutron star mergers, neutron star cooling:

– property of nuclear matter at supra nuclear density and high temperature

– neutrino interactions in dense media



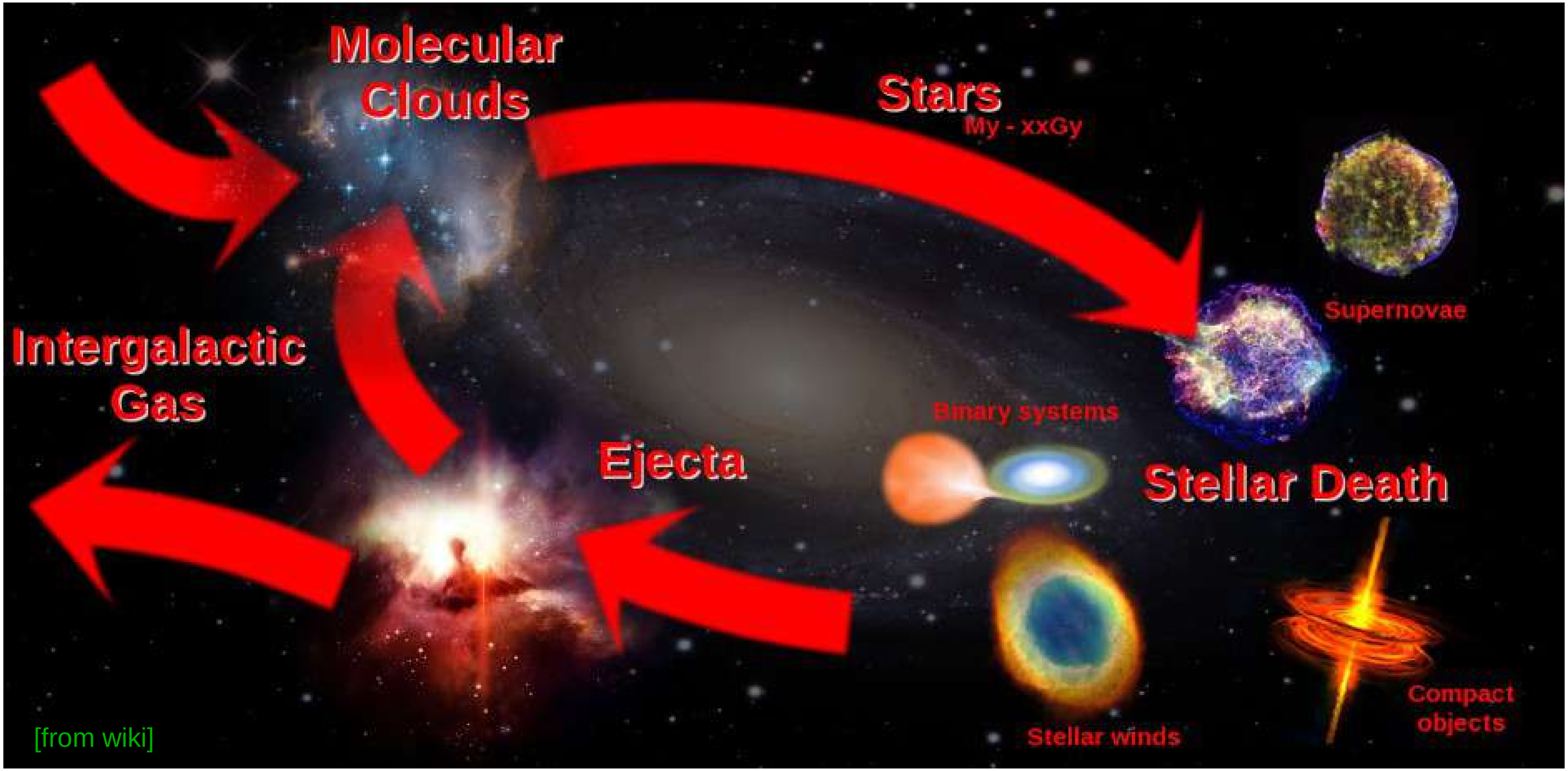
[Bastian+]



[from BNL white paper]

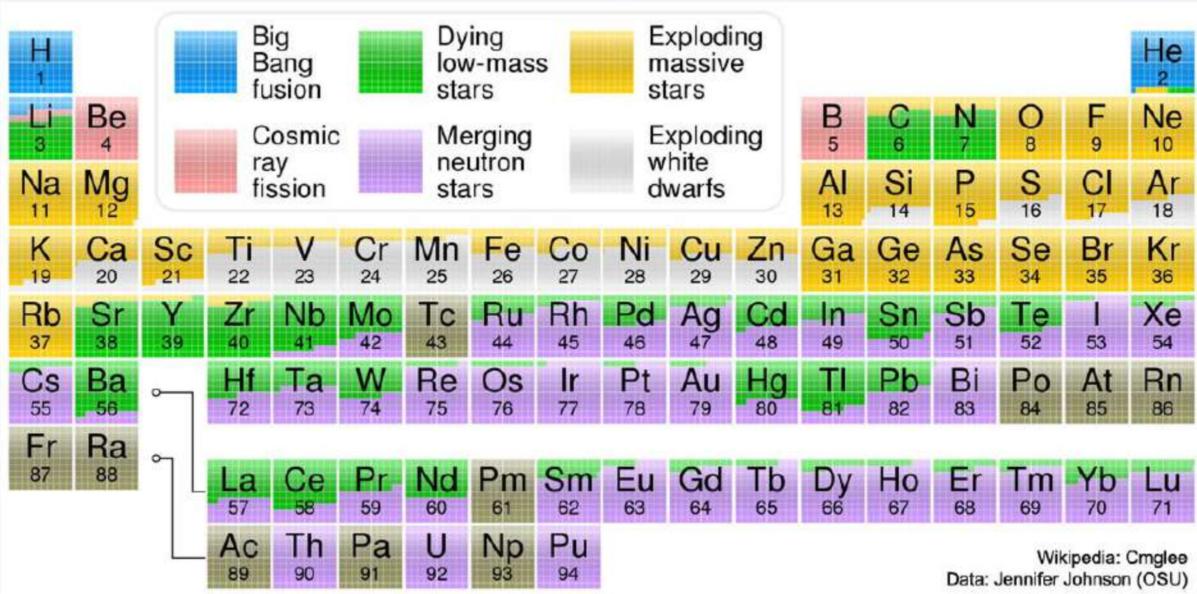
Scope of nuclear astrophysics

The “nuclear fingerprints (abundances)” from stars can affect how galaxy evolves:

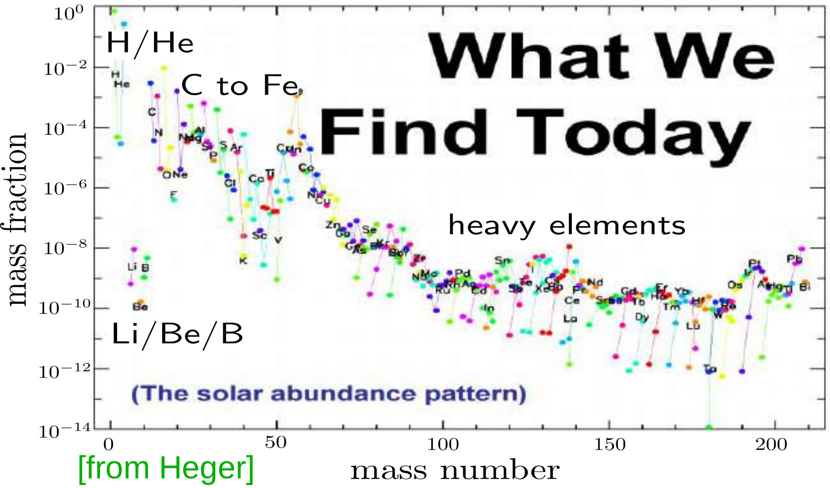


[from wiki]

need to combing yields
from individual sites and
the the evolution of galaxies
to pin-point the origin
of different elements



Wikipedia: Cmglee
Data: Jennifer Johnson (OSU)



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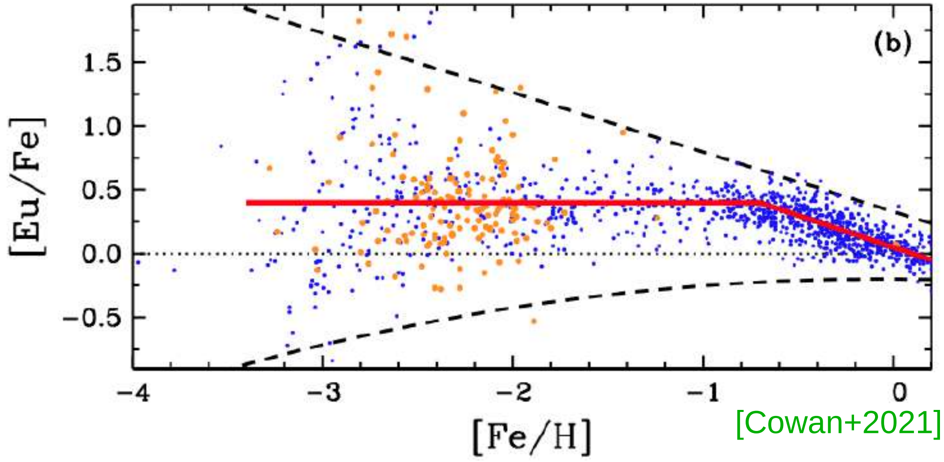
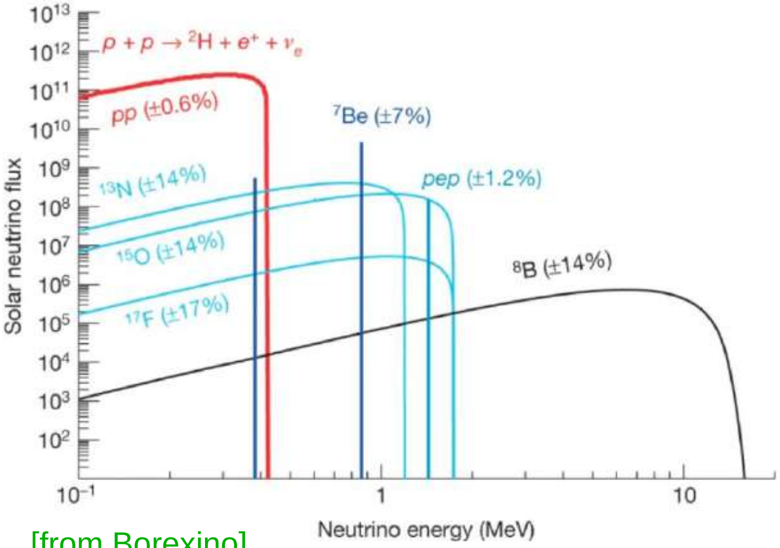


[Cowan+2021]

Scope of particle astrophysics

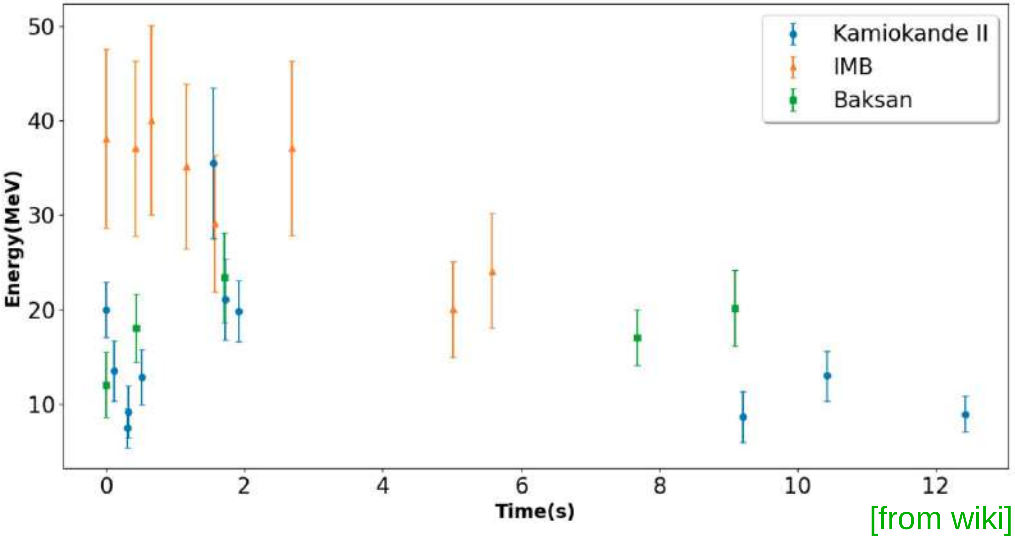
Low-energy (MeV) neutrinos

solar neutrinos



[from Borexino]

supernova neutrinos



[from wiki]

established neutrino oscillations

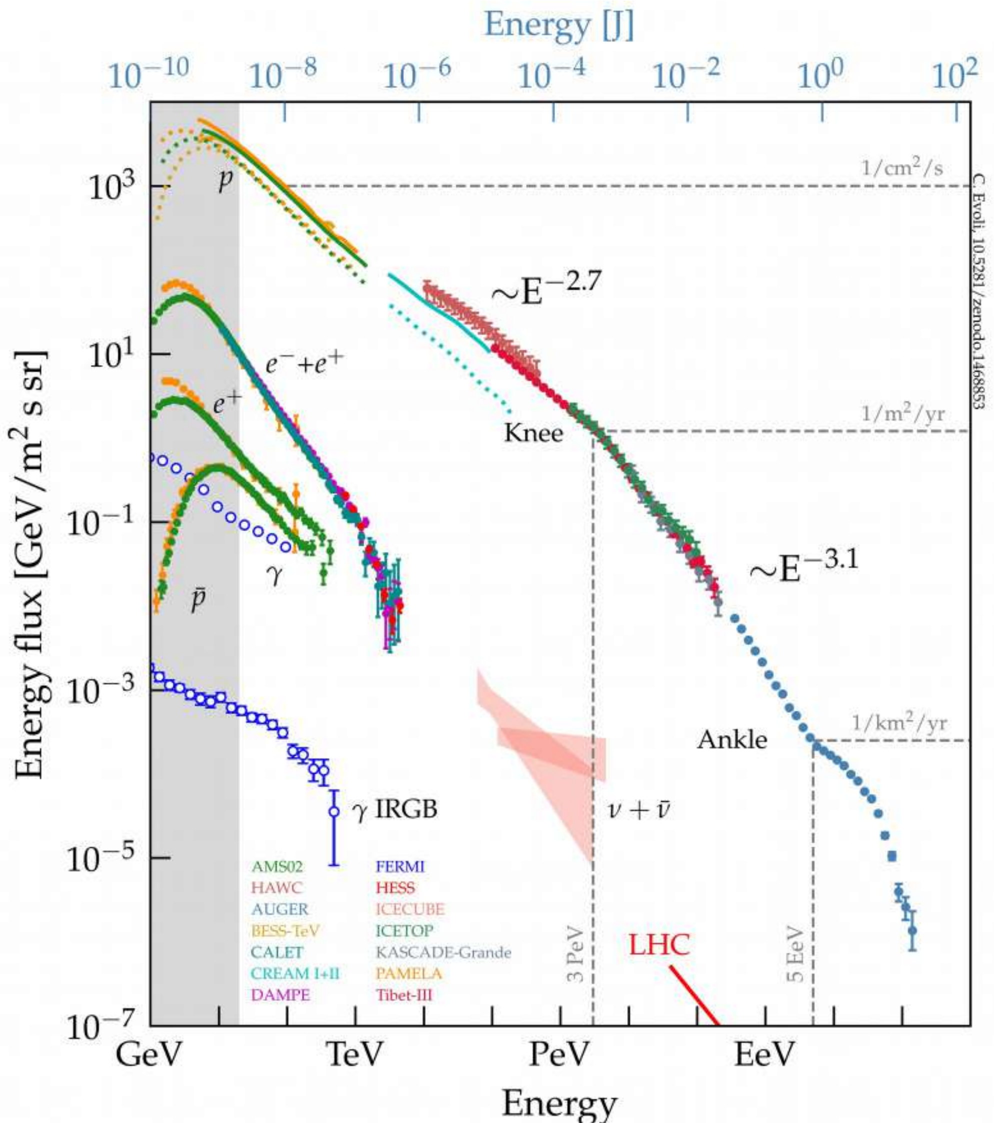
use neutrinos to probe solar physics

probe supernova interior?

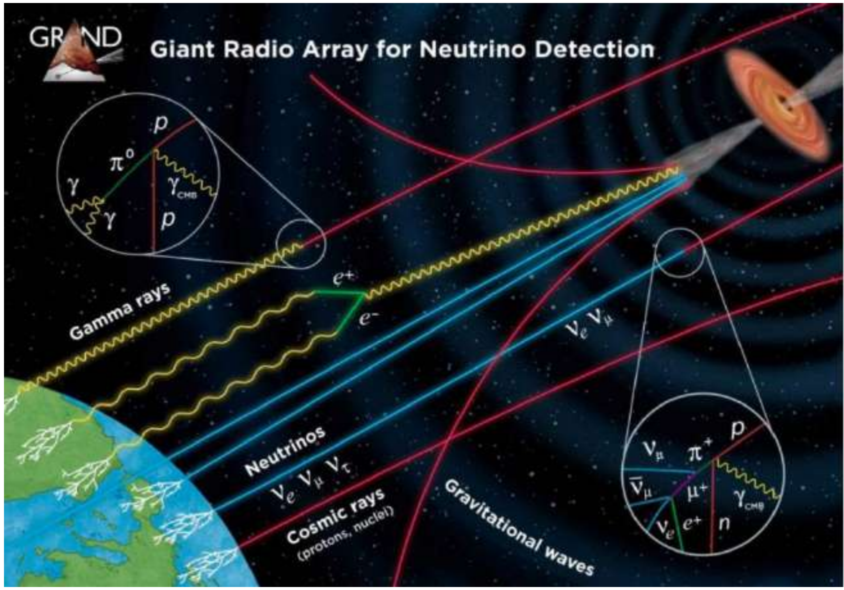
learn about neutrino themselves?

Scope of particle astrophysics

High-energy (∼GeV–EeV) astroparticles:



C. Evoli, 10.5281/zenodo.1468853

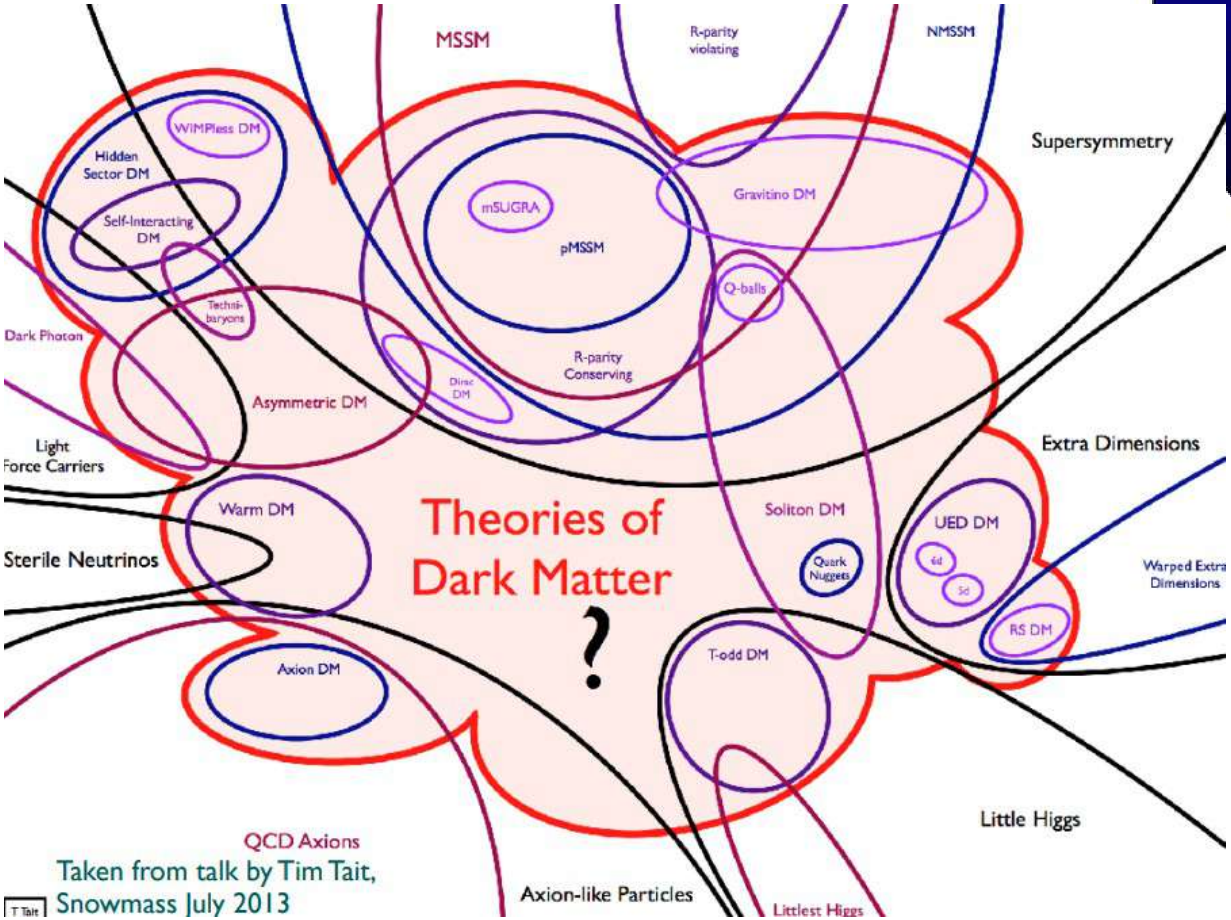


sources of ultra high-energy cosmic-rays & high-energy neutrinos?

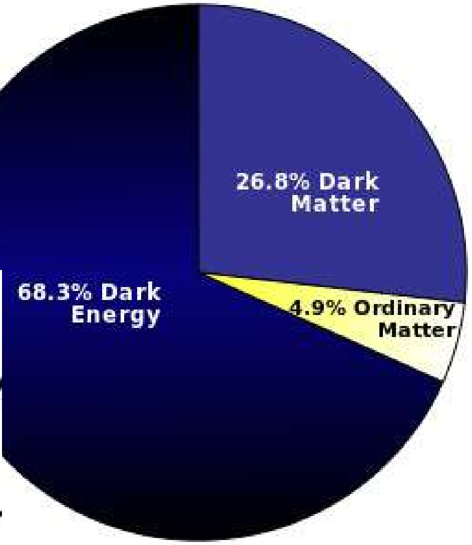
sources & propagation of galactic cosmic-rays?

Scope of particle astrophysics

physics beyond the Standard Model



Taken from talk by Tim Tait, Snowmass July 2013



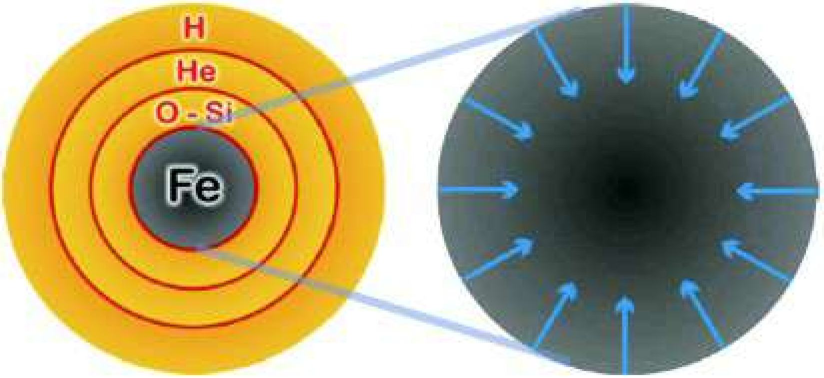
how to use astrophysical observations to probe these models?

Core-collapse supernova explosion and neutrinos

Core-collapse supernovae

progenitor star ($\sim 10 - 25\ M_\odot$)

[Figure adapted from G. Raffelt]



$$M_{\rm Fe,core} \approx 1.4 M_\odot$$

$$R_{\rm Fe,core} \approx 3000\ {\rm km}$$

$$\rho_c \approx 10^9\ {\rm g\ cm}^{-3}$$

$$T_c \approx 10^{10}\ {\rm K} \sim 1\ {\rm MeV}$$

– core pressure supported by relativistic electrons, $p \propto \rho^{4/3}$

– gravitational collapse happens when core size exceeds the Chandrasekhar mass limit ($M_{\rm Ch} \sim 1.4\ M_\odot$)

Implosion (Collapse)

↓

?

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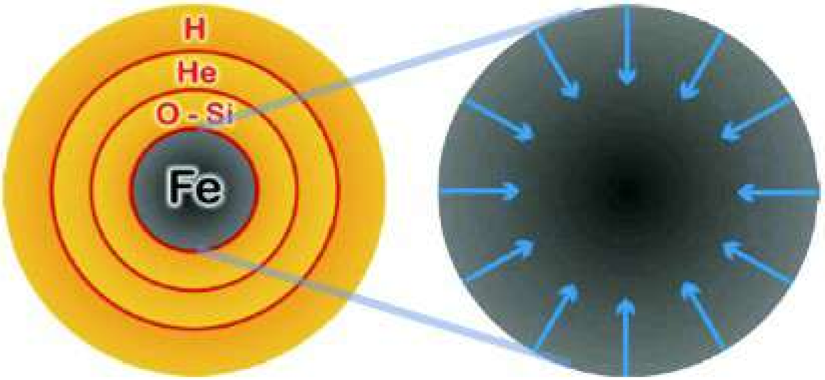
[Figure adapted from G. Raffelt]



Implosion (Collapse)

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$T_c \approx 10^{10}$ K~ 1 MeV

– core pressure supported by relativistic electrons, $p \propto \rho^{4/3}$

– gravitational collapse happens when core size exceeds the Chandrasekhar mass limit ($M_{\rm Ch} \sim 1.4\ M_\odot$)

– timescale of collapse $\sim \tau_{\rm dyn} \sim \sqrt{R^3/(GM)} \simeq \mathcal{O}(100)$ ms

– core temperature arises $\sim$ adiabatically with density increase

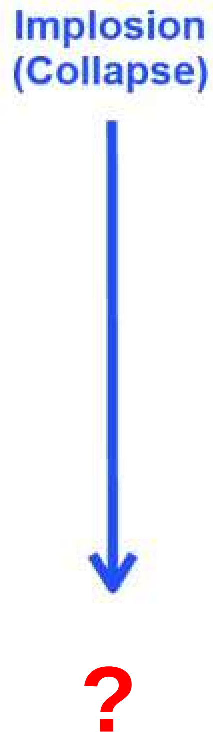
– neutrinos are produced via electron capture on nuclei, and pair processes

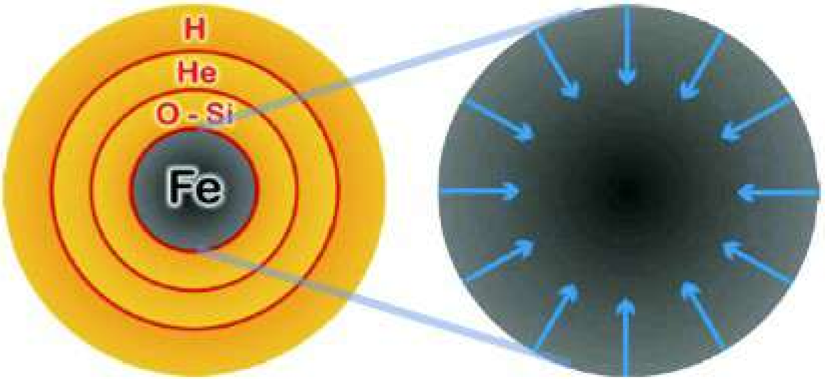
?

Core-collapse supernovae

progenitor star ($\sim 10 - 25\ M_\odot$)

[Figure adapted from G. Raffelt]





$$M_{\text{Fe,core}} \approx 1.4 M_\odot$$
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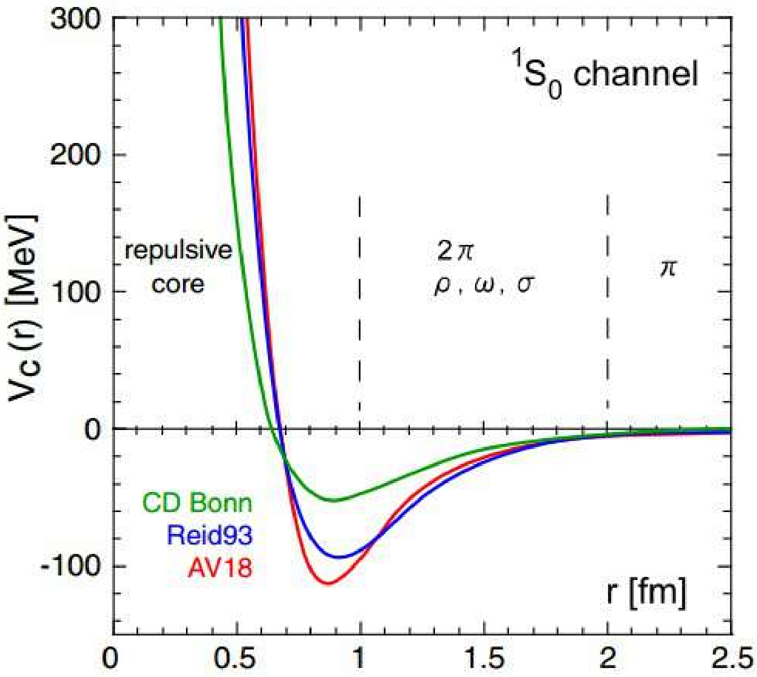
$$\rho_c \approx 10^9\ \text{g cm}^{-3}$$
$$T_c \approx 10^{10}\ \text{K} \sim 1\ \text{MeV}$$

– the collapse stops and the core bounces when nuclear force kicks in at supra-nuclear density

– neutrino diffusion timescale:

$$\tau_{\text{diff}} \sim R_{\text{PNS}}^2 \cdot (\lambda_{\text{mfp}} c)^{-1} \sim \mathcal{O}(1)\ \text{s}$$

→ even neutrinos are trapped!

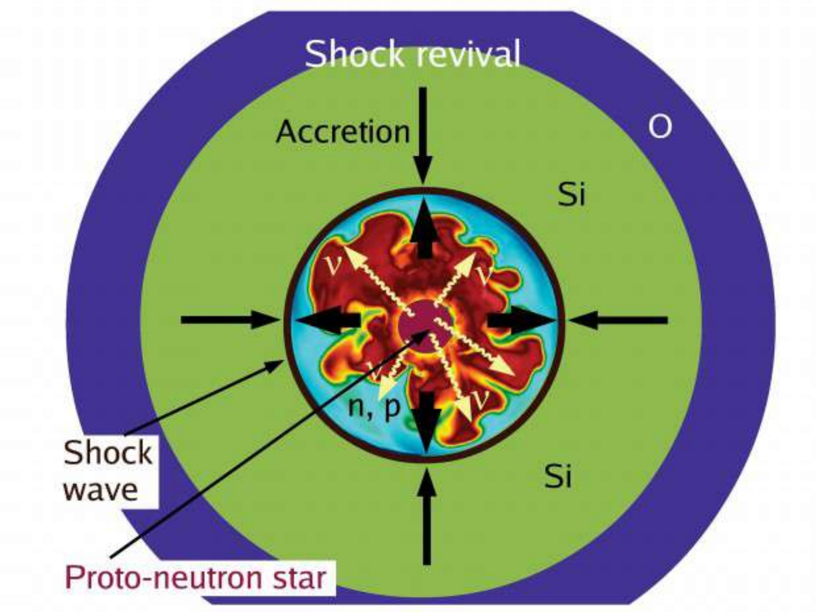


[Ishii, Aoki, Hatsuda, PRL 99 (2007) 022001]

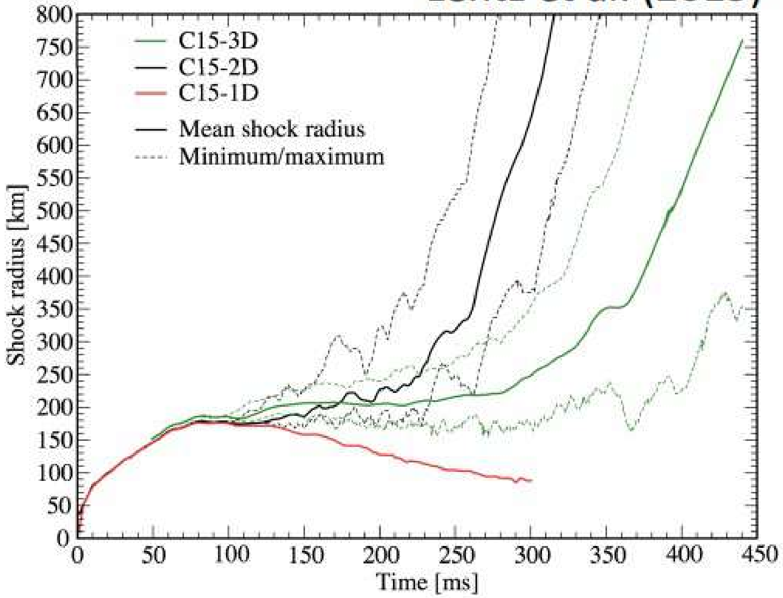
Core-collapse supernovae

The core-bounce generates an out-going shockwave, which, however, loses its energy and stalls at ~ 200 km

key question: how to transform the energy carried by neutrinos to revive the shock?



Lentz et al. (2015)

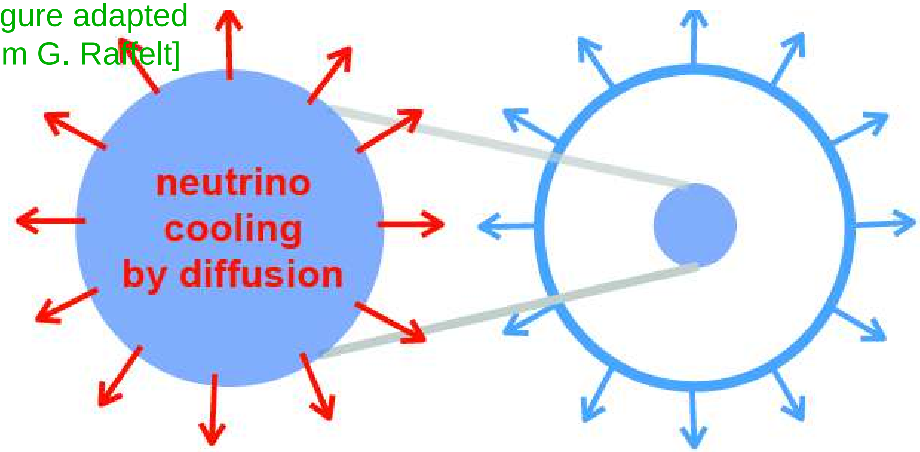


- – multidimensional fluid effect?
- – progenitor dependence?
- – neutrino – nuclear matter interaction?
- – collective neutrino flavor oscillations?

Needs millions of CPU hours, a big challenge to include all known forces!

Core-collapse supernovae

After shock revival, the proto-neutron star cools down by emitting neutrinos in all flavors



[Figure adapted from G. Raffelt]

$E_{\mathrm{grav}} \sim \frac{GM_{\mathrm{PNS}}^2}{R_{\mathrm{PNS}}} \sim 10^{53}$ erg,

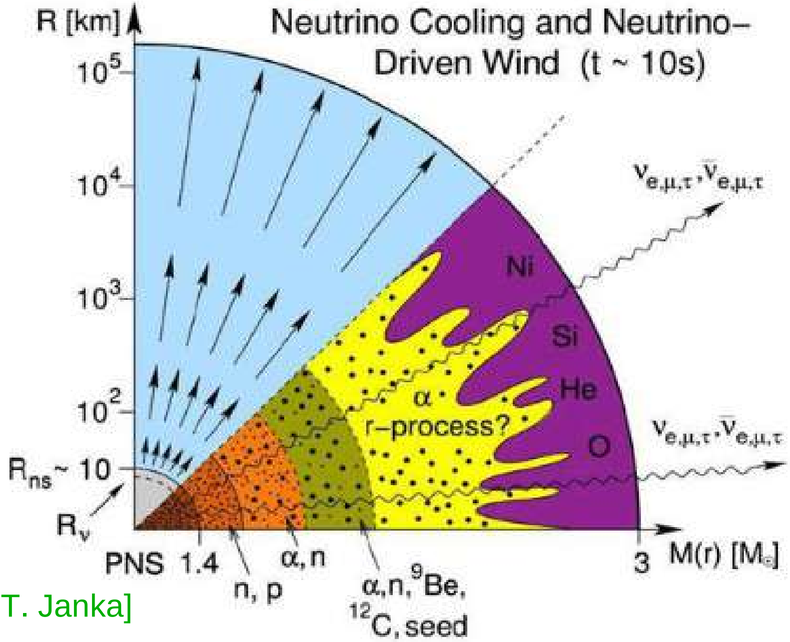
carried away by $\sim 10^{58}$ neutrinos in ~ 10 seconds

$M_{\mathrm{PNS}} \approx 1.4 M_\odot$

$R_{\mathrm{PNS}} \approx 15\text{–}50$ km

$\rho_c \approx 3 \times 10^{14}$ g cm^{-3}

$T_c \approx 30$ MeV



[from H.-T. Janka]

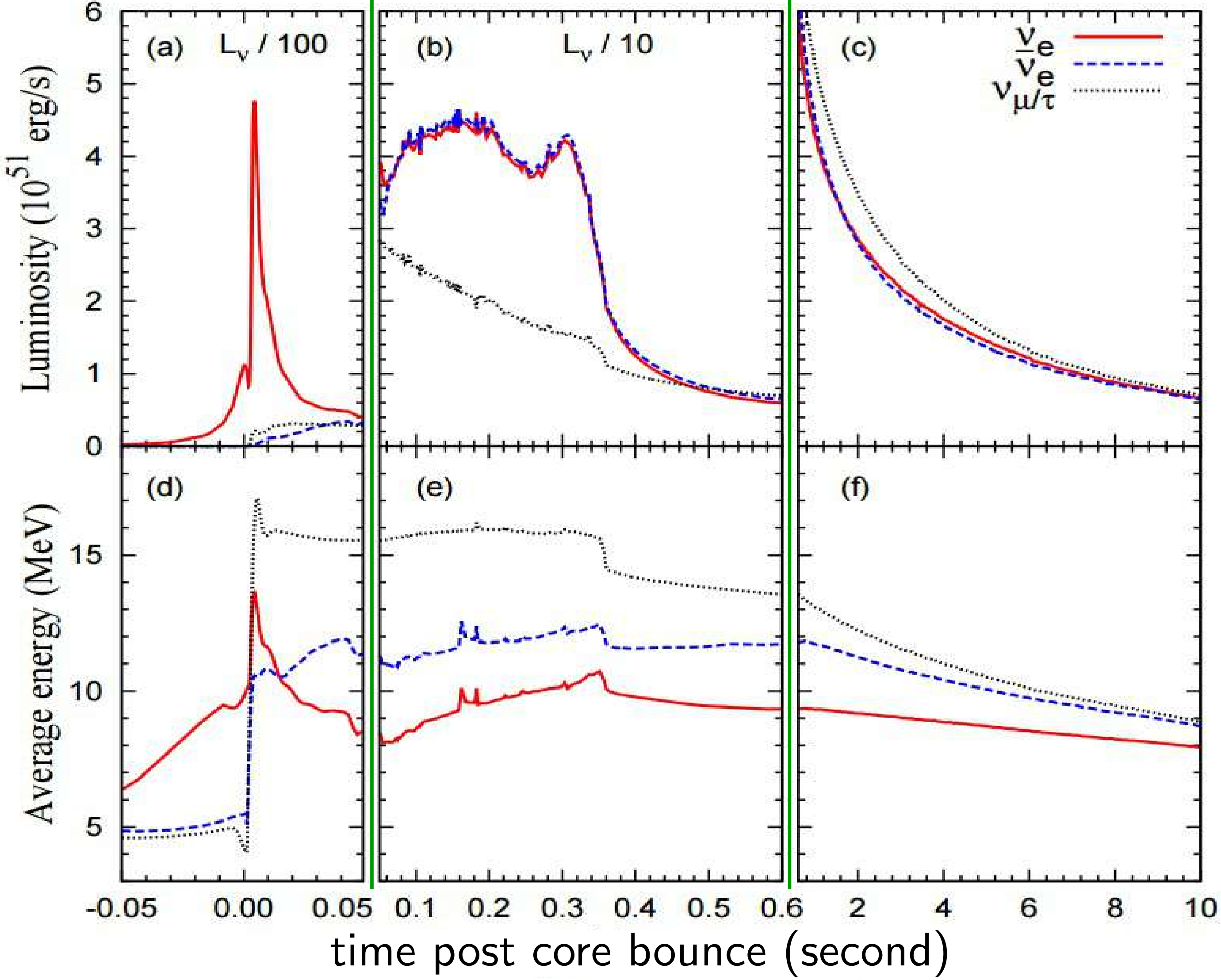
sites of heavy element production

Supernova neutrinos

neutronization burst
& early rise time

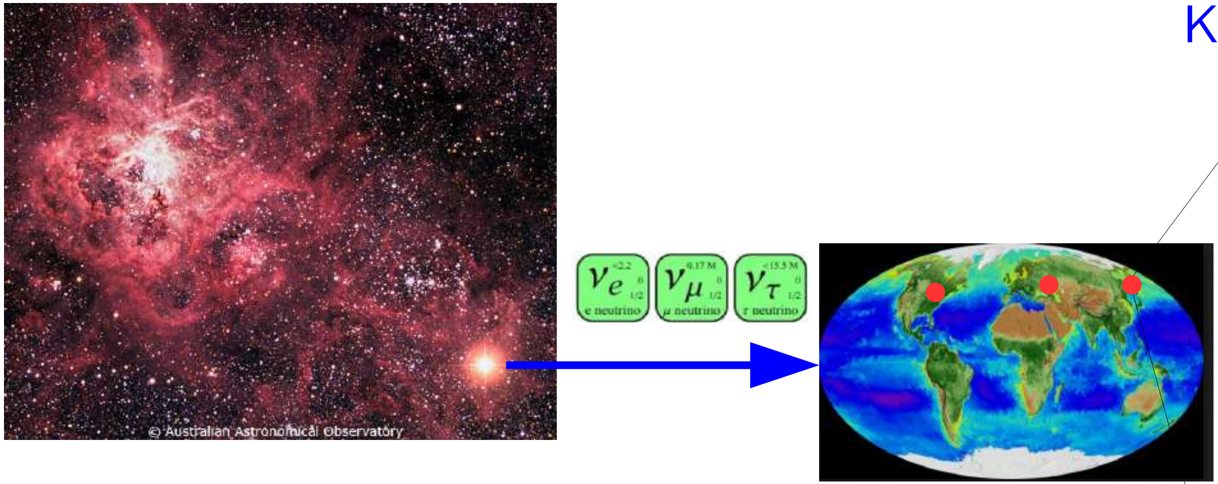
accretion phase

PNS cooling phase



[MRW+ 2015, from simulation of Fisher+ 2010]

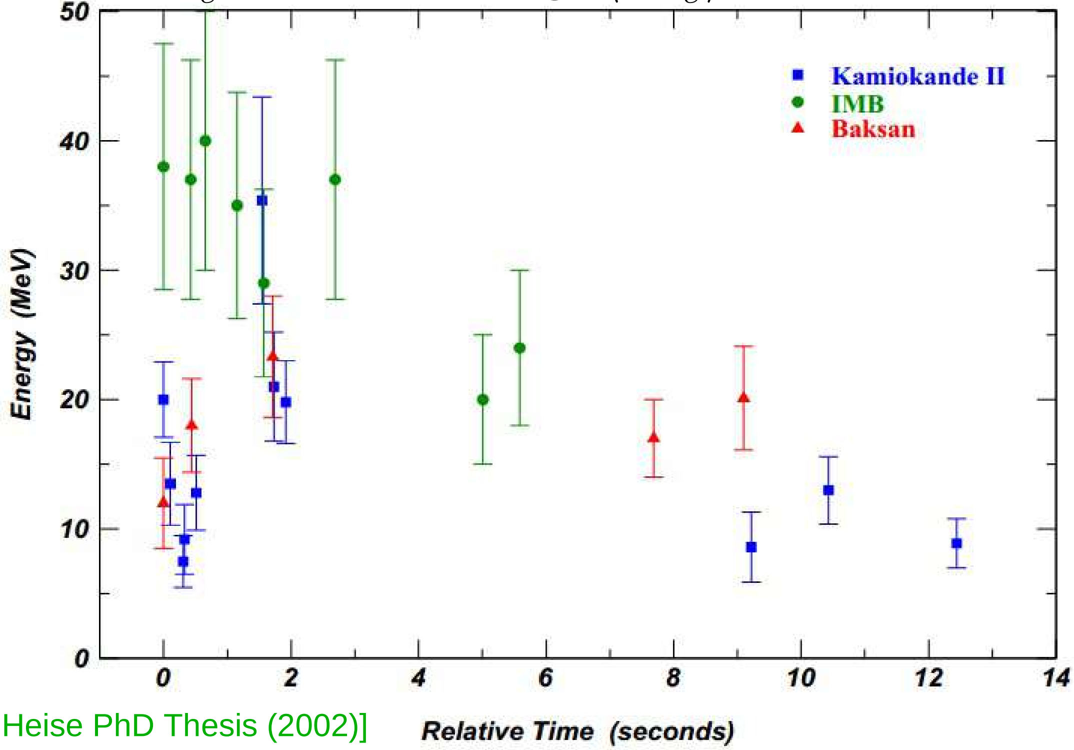
Kamiokande neutrino detector



[From wikipedia]

3000 tons of water
height: 16 m
radius: 15.6 m
~ 1 km underground

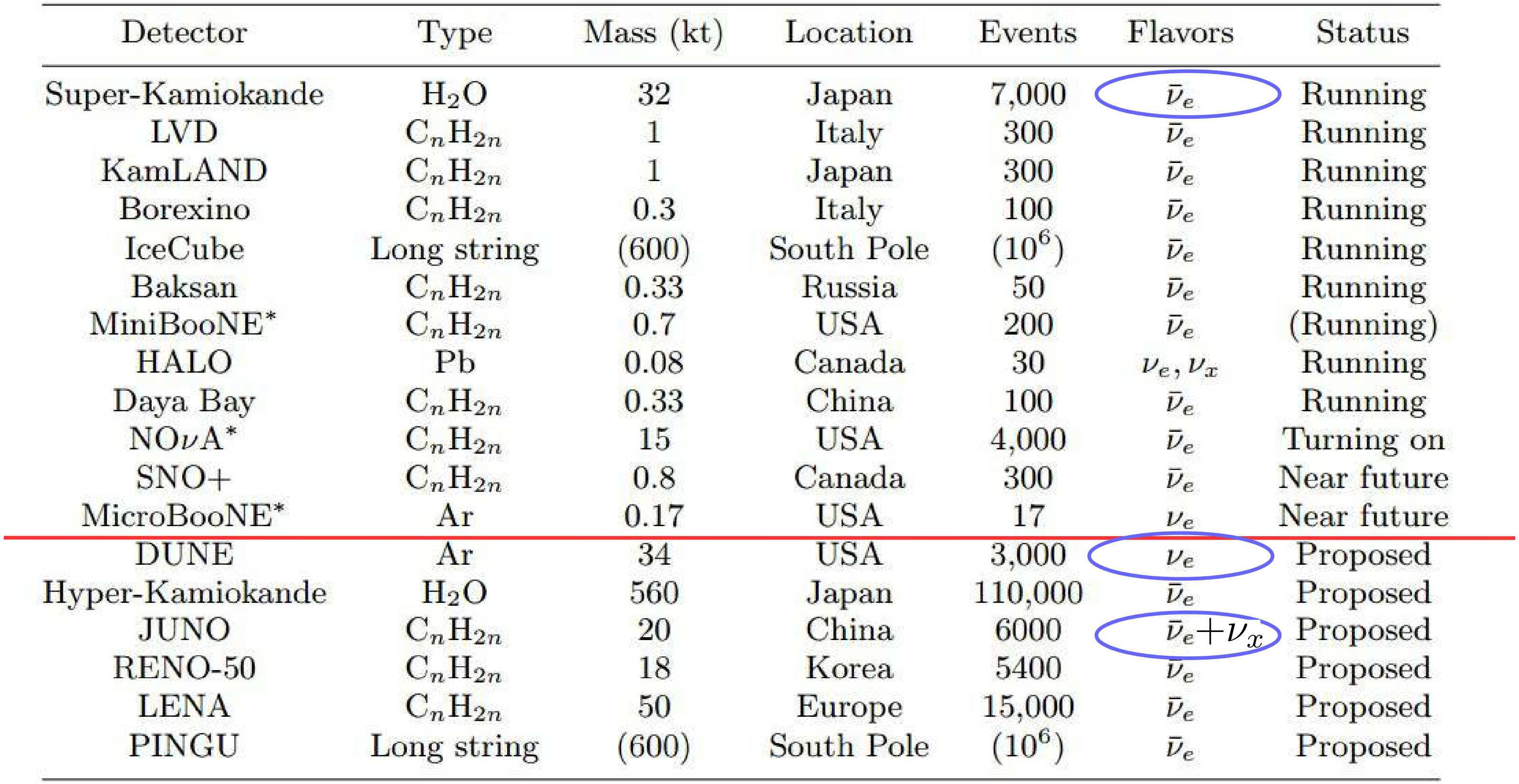
$$L_{\bar{\nu}_e} \sim 5 \times 10^{52} \text{ erg}, \ \langle E_{\bar{\nu}_e} \rangle \sim 15 \text{ MeV}$$



[J. Heise PhD Thesis (2002)]

Future Galactic supernovae

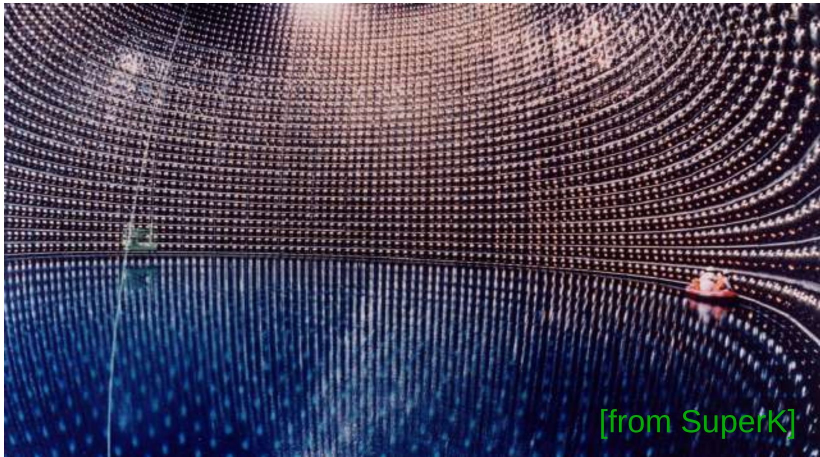
[Mirizzi+ Riv. Nuovo. Cim 39, 1 (2016)]



Detector	Type	Mass (kt)	Location	Events	Flavors	Status
Super-Kamiokande	H_2O	32	Japan	7,000	$\bar{\nu}_e$	Running
LVD	C_nH_{2n}	1	Italy	300	$\bar{\nu}_e$	Running
KamLAND	C_nH_{2n}	1	Japan	300	$\bar{\nu}_e$	Running
Borexino	C_nH_{2n}	0.3	Italy	100	$\bar{\nu}_e$	Running
IceCube	Long string	(600)	South Pole	(10^6)	$\bar{\nu}_e$	Running
Baksan	C_nH_{2n}	0.33	Russia	50	$\bar{\nu}_e$	Running
MiniBooNE*	C_nH_{2n}	0.7	USA	200	$\bar{\nu}_e$	(Running)
HALO	Pb	0.08	Canada	30	ν_e, ν_x	Running
Daya Bay	C_nH_{2n}	0.33	China	100	$\bar{\nu}_e$	Running
NOνA*	C_nH_{2n}	15	USA	4,000	$\bar{\nu}_e$	Turning on
SNO+	C_nH_{2n}	0.8	Canada	300	$\bar{\nu}_e$	Near future
MicroBooNE*	Ar	0.17	USA	17	ν_e	Near future
DUNE	Ar	34	USA	3,000	ν_e	Proposed
Hyper-Kamiokande	H_2O	560	Japan	110,000	$\bar{\nu}_e$	Proposed
JUNO	C_nH_{2n}	20	China	6000	$\bar{\nu}_e + \nu_x$	Proposed
RENO-50	C_nH_{2n}	18	Korea	5400	$\bar{\nu}_e$	Proposed
LENA	C_nH_{2n}	50	Europe	15,000	$\bar{\nu}_e$	Proposed
PINGU	Long string	(600)	South Pole	(10^6)	$\bar{\nu}_e$	Proposed

$\mathcal{O}(10^3 - 10^4)$ events in all flavors!

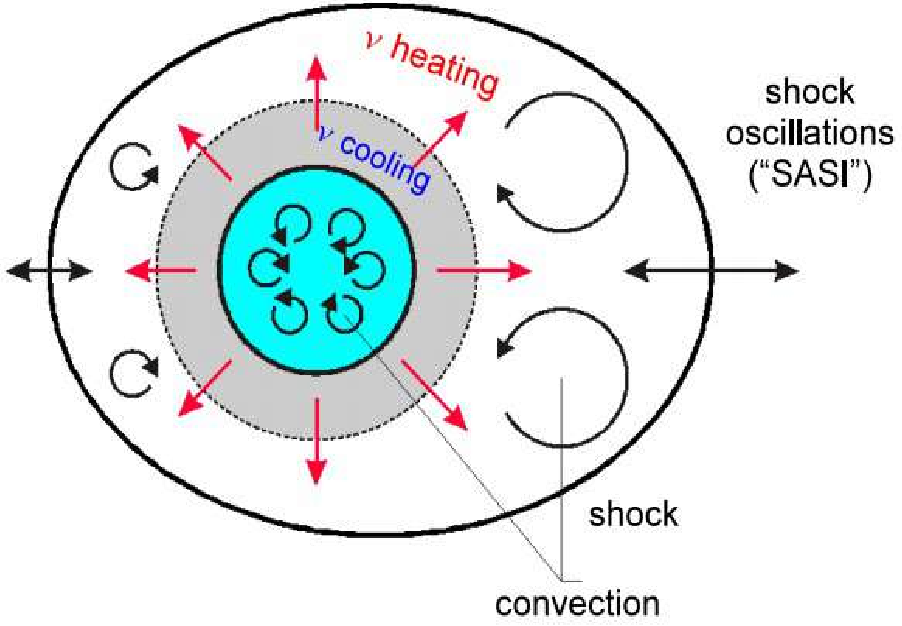
can offer tremendous insights to explosion mechanism, property of nuclear matter, and property of neutrinos



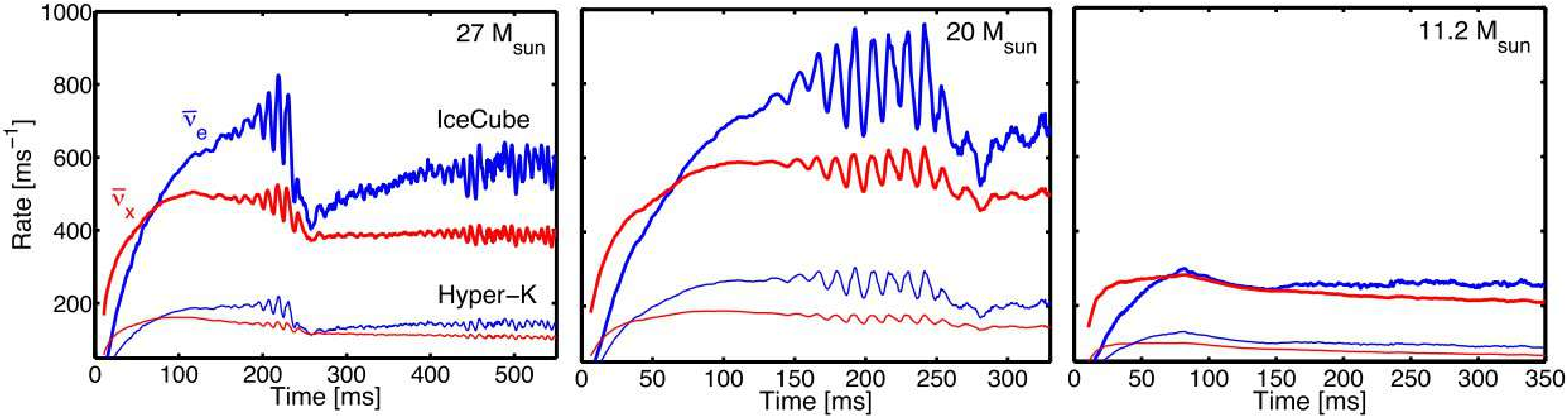
[from SuperK]

Neutrinos as diagnostics for explosion mechanism

Key-mechanism for SN explosion may leave imprints on the neutrino time profile that can be resolved in IceCube or Hyper-Kamiokande

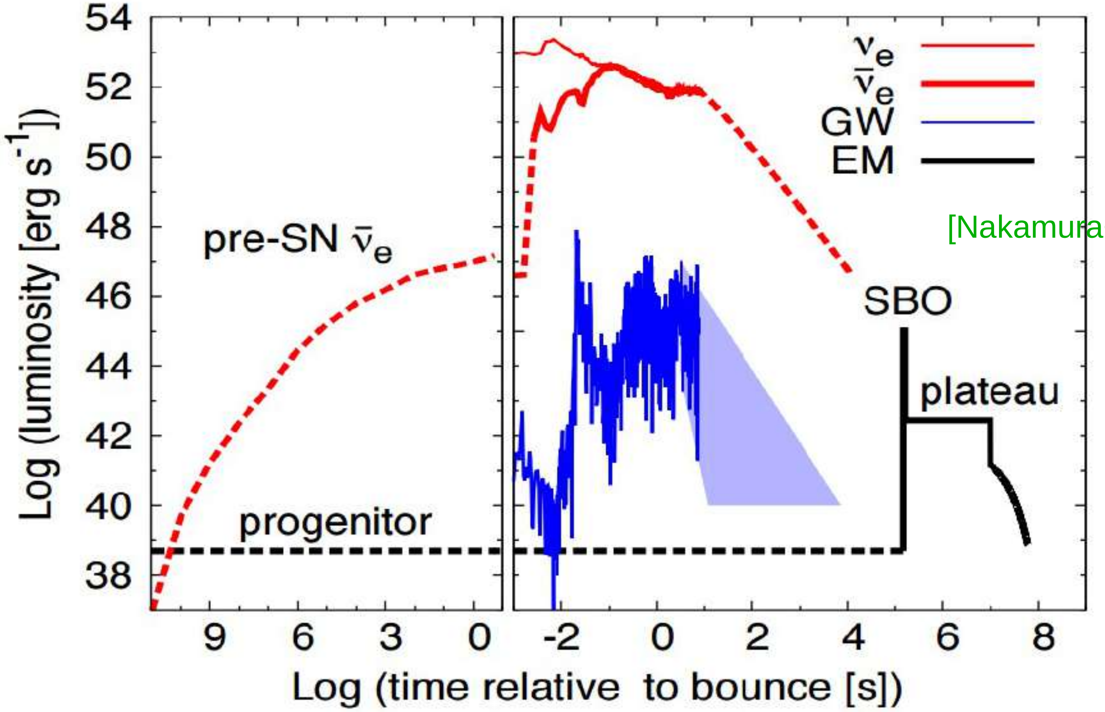

[Mueller+ 2017]

[Tamborra+ PRL 111, 121104 (2013)]



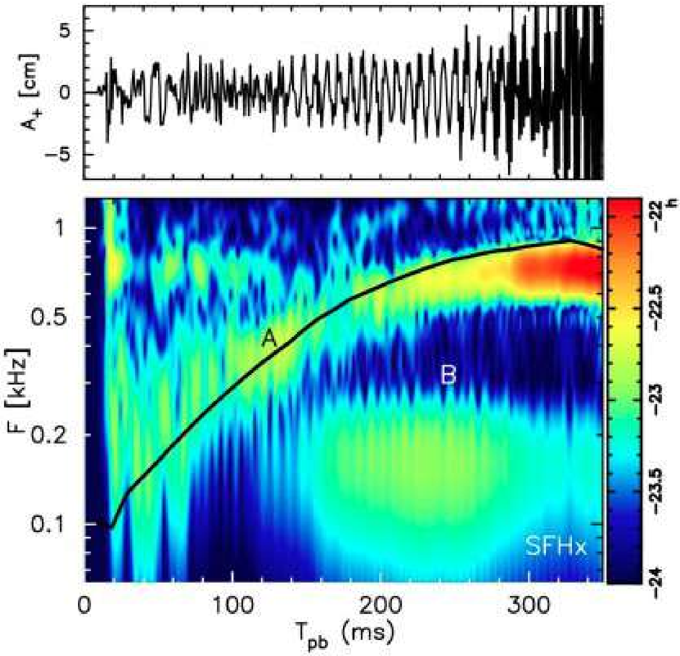
(see L. Walk+ 2018, 2019 for SASI in rotating SNe)

Multimessenger with core-collapse supernovae



[Nakamura+, MNRAS 461, 3 (2016)]

[Kuroda+ (2016)]



The GW signals can also help probe the interior of SN core, in addition to neutrinos

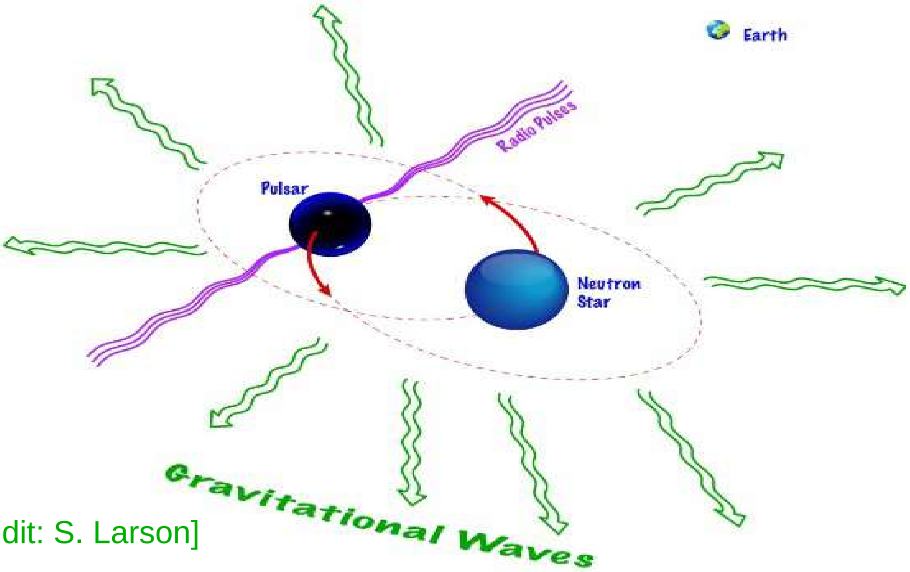
see also Kuo-Chuan Pan's work

Binary neutron star mergers, kilonova, and nuclear physics

Binary neutron star system

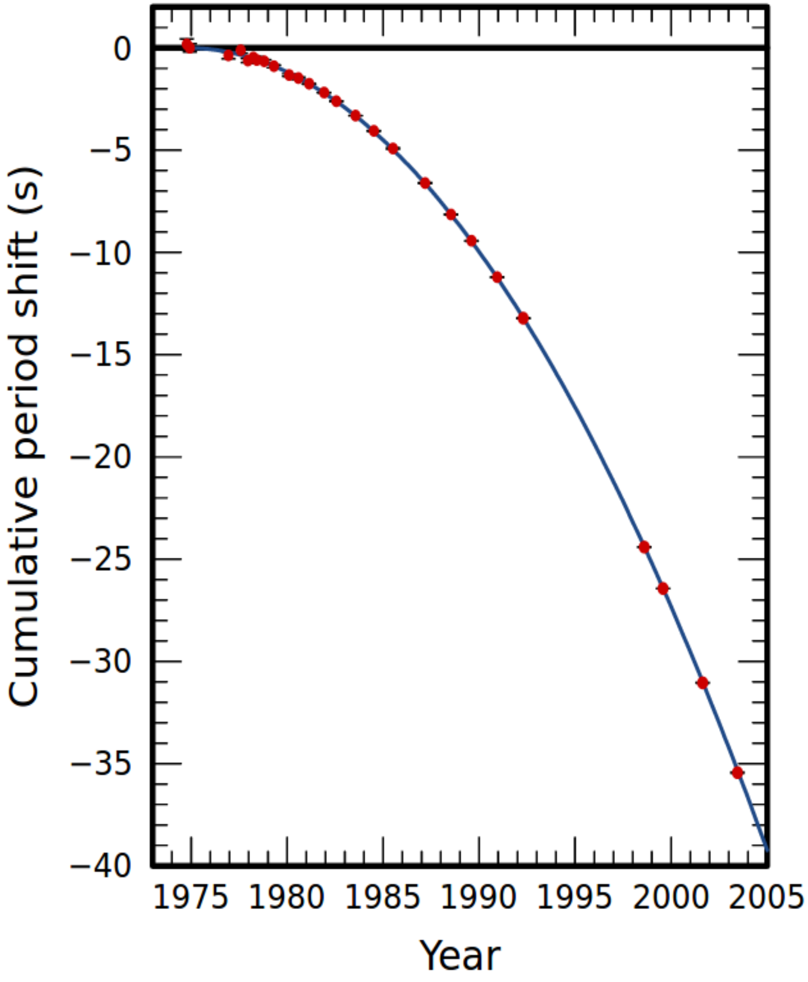
– ~ 20 known such systems that contain at least one pulsar

– The measurement of the famous Hulse–Taylor binary was the first indirect evidence of gravitational wave emission



[Credit: S. Larson]

[From wikipedia]



Binary neutron star system

– merger time scale governed by the GW emission time scale, e.g., for quasi-circular orbit (lowest post-Newtonian order):

$$\tau_{\mathrm{GW}} = \frac{5}{64}\frac{a^4}{\mu M^2} = \frac{5}{64}\frac{a^4}{q(1+q)M_1^3}$$

[From Faber & Rasio 2012]

$$= 2.2 \times 10^8 q^{-1}(1+q)^{-1}\left(\frac{a}{R_\odot}\right)^4\left(\frac{M_1}{1.4\,M_\odot}\right)^{-3}\ \mathrm{yr},$$

($M = M_1 + M_2$, $q = M_2/M_1$, a is the separation)

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[From Faber & Rasio 2012]

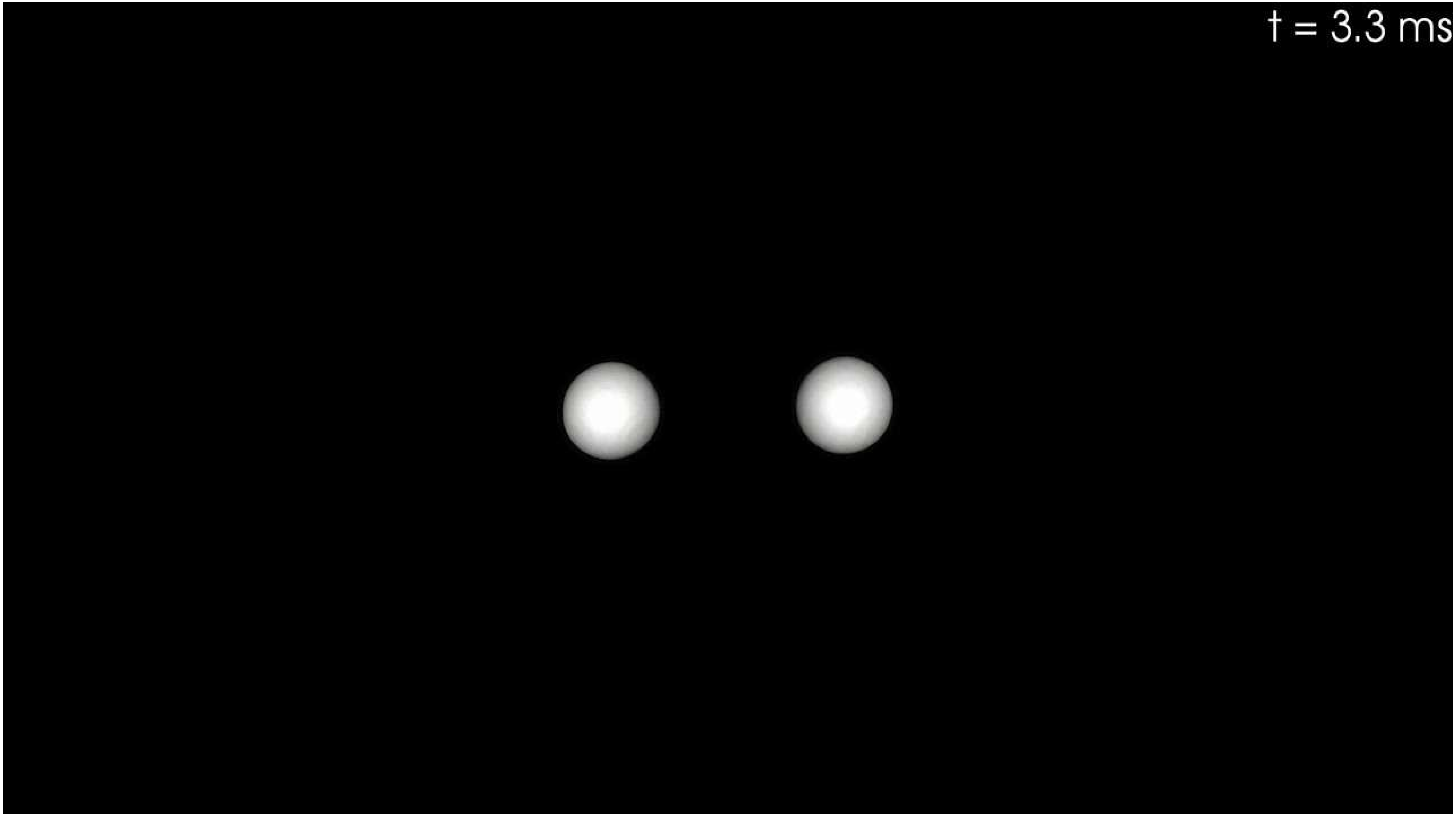
($M = M_1 + M_2$, $q = M_2/M_1$, a is the separation)

– the gravitational wave strength shortly before merger:

$$h = \frac{4M_1M_2}{aD} = 5.53 \times 10^{-23} q\left(\frac{M_1}{1.4\,M_\odot}\right)^2\left(\frac{a}{100\ \mathrm{km}}\right)^{-1}\left(\frac{D}{100\ \mathrm{Mpc}}\right)^{-1},$$

$$f_{GW} = 2f_{\rm orb} = \frac{1}{\pi}\sqrt{\frac{M}{a^3}} = 194\left(\frac{M}{2.8\,M_\odot}\right)^{1/2}\left(\frac{a}{100\ \mathrm{km}}\right)^{-3/2}\ \mathrm{Hz}.$$

When two neutron stars merge:

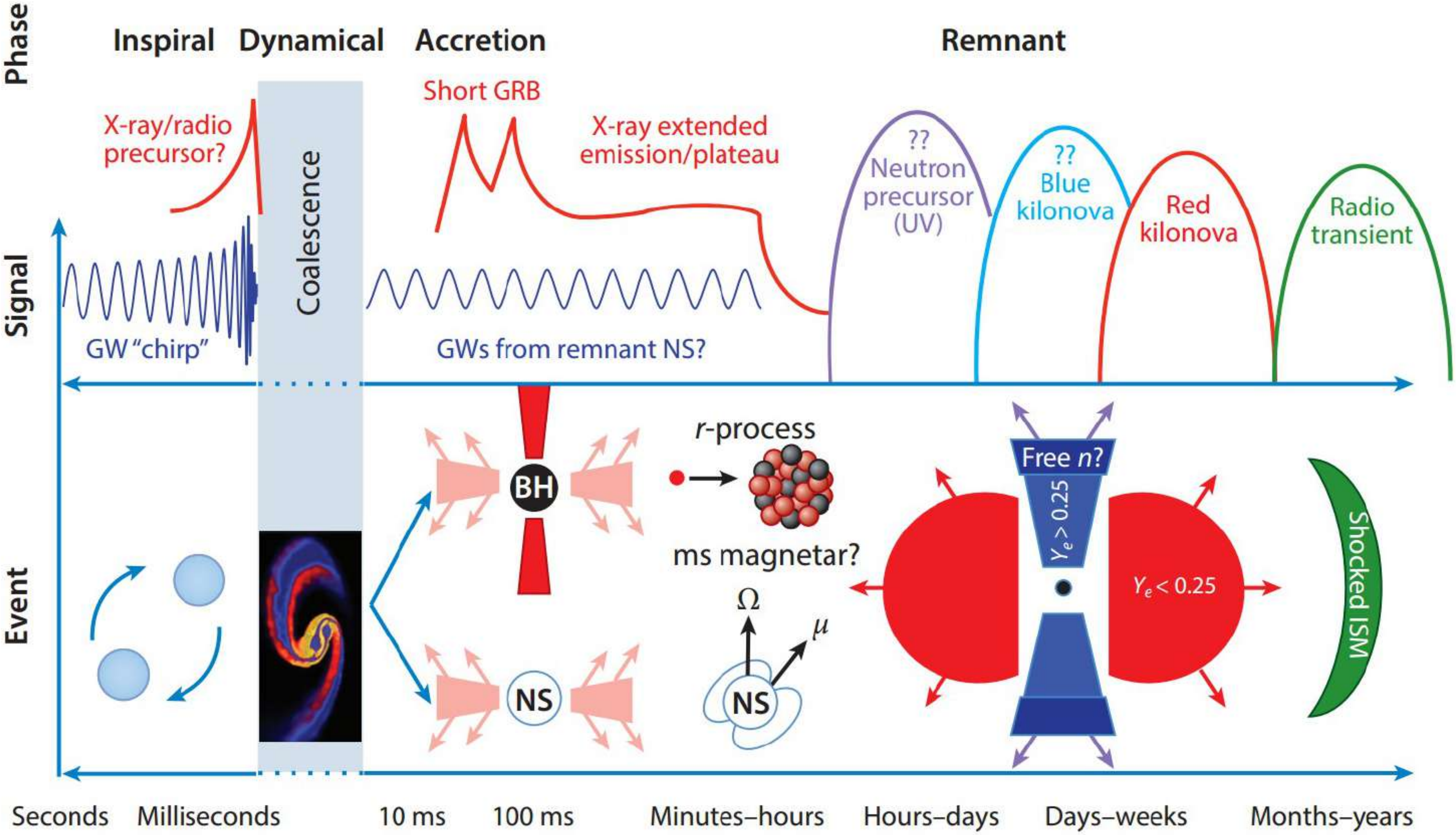


[From LIGO website; Endrizzi+]

The multi-messenger of binary neutron star mergers

Expected signals:

1. GW, 2. sGRB (gamma ray, x-ray...) 3. kilonovae/macronovae (optical, infrared)



[Fernandez & Metzger, ARNPS 66 (2016) 23]

Kilonova 101

When density is large, photons cannot escape the system, these injected energy gets entirely converted into the internal and kinetic energy of the system.

The observation of the EM signals becomes possible when most of the thermal photons can escape.

R: typical radius of the ejecta $\sim v_{\rm ej} t$

l: photon mean-free-path$\sim (\kappa\rho)^{-1}$

κ: photon opacity

ρ: mean mass density $\sim M_{\rm ej}(\pi R^3)^{-1}$

$M_{\rm ej}$, $v_{\rm ej}$: mass and velocity of the ejecta

$\dot{Q}$: nuclear energy release rate $\approx 10^{10} \times (t/1{\rm day})^{-1.3}$ erg/s

diffusion time scale:

$$\tau_{\rm diff} \sim \frac{R^2}{c \cdot l}$$

ejecta expansion time scale:

$$\tau_{\rm exp} \sim \frac{R}{v_{\rm ej}}$$

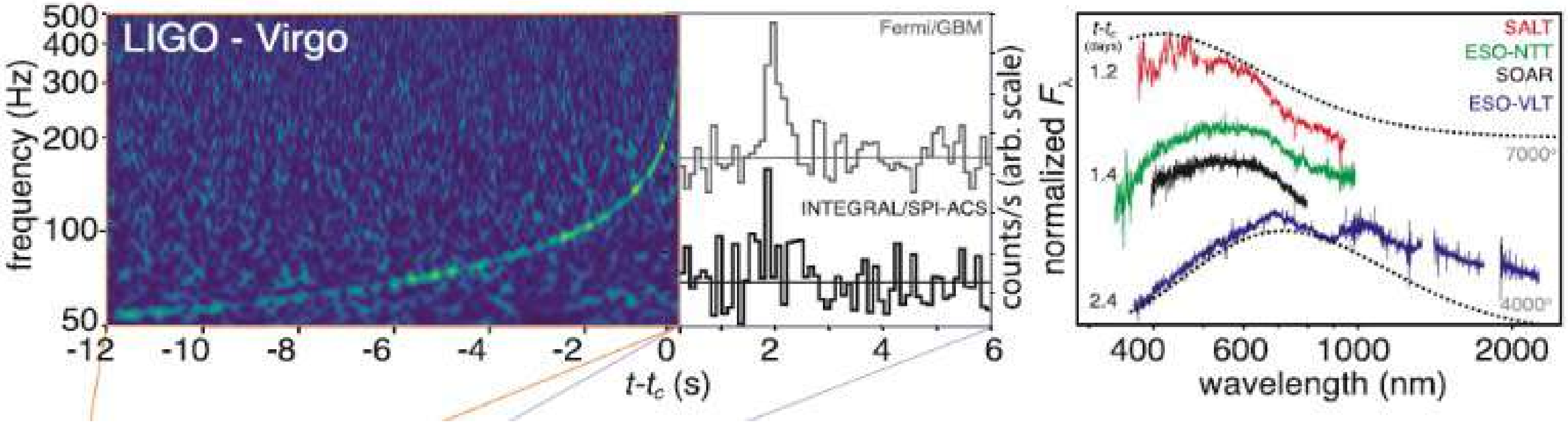
$$\rightarrow t_{\rm peak} \sim \left(\frac{\kappa M_{\rm ej}}{\pi c v_{\rm ej}}\right)^{1/2} \sim 3.8\ {\rm day} \left[\left(\frac{\kappa}{10{\rm cm}^2/{\rm g}}\right)\left(\frac{M_{\rm ej}}{0.01 M_\odot}\right)\left(\frac{0.1c}{v_{\rm ej}}\right)\right]^{1/2}$$

$$\rightarrow L(t_{\rm peak}) \sim \dot{\varepsilon}(t_{\rm peak}) \sim M\dot{Q}(t_{\rm peak}) \sim 2.0 \times 10^{41}{\rm erg/s} \times \left(\frac{M_{\rm ej}}{0.01 M_\odot}\right) \times \left(\frac{t_{\rm peak}}{1{\rm day}}\right)^{-1.3}$$

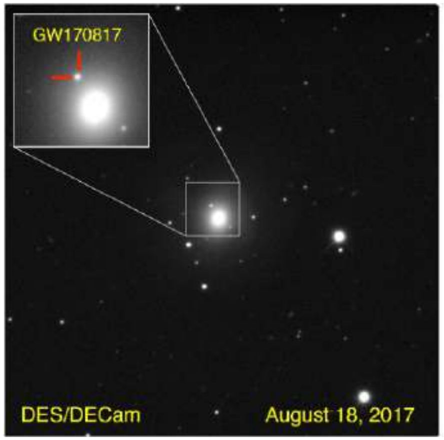
[Arnett's law]

First detected BNS merger: GW170817

[LIGO+2017]



- origin of short gamma-ray bursts
- origin of heavy elements (r-process material $\sim 0.05 M_\odot$)
- dawn of gravitational multimessenger astronomy

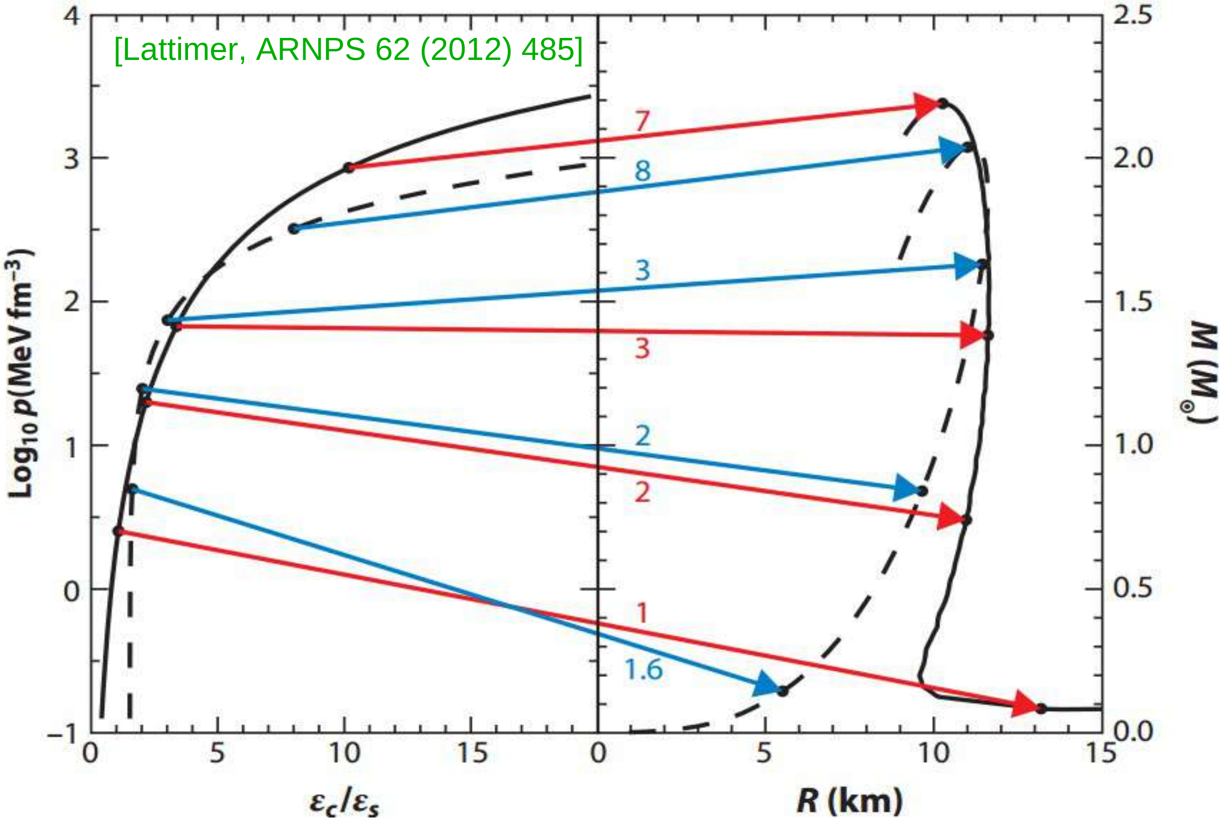


host galaxy:
NGC4993 ~ 40Mpc

Since GW170817, LIGO/Virgo detected (confirmed) another BNS merger and two other NS–BH mergers

Nuclear equation of state & neutron star radius

The nuclear EoS relates the energy density and pressure of the system $p(\epsilon)$ and determines the size of a neutron star



[Lattimer, ARNPS 62 (2012) 485]

hydrostatic equilibrium:

$$\frac{dp}{dr} = -\frac{G}{c^2}\frac{(p+\varepsilon)(m+4\pi r^3 p/c^2)}{r(r-2Gm/c^2)},$$

$$\frac{dm}{dr} = 4\pi r^2 \frac{\varepsilon}{c^2},$$

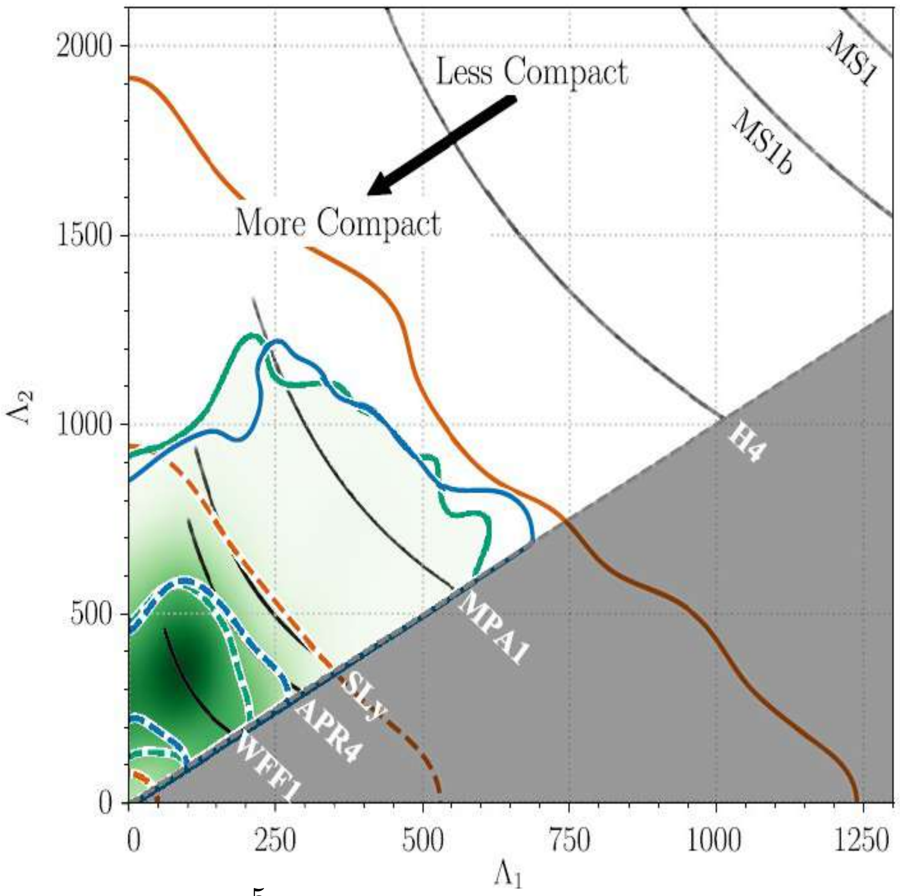
Roughly speaking, more stiff EoS → larger NS radius → earlier contact of merger → lower frequency & amplitude during the inspiral

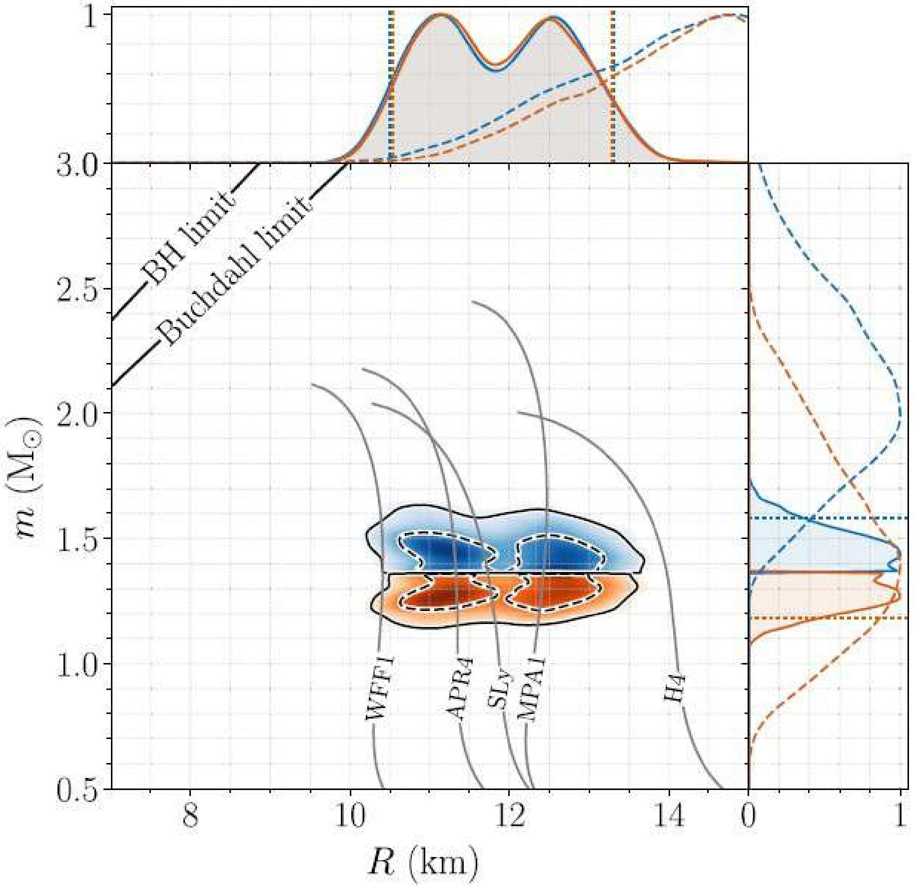
Gravitational waves from mergers can contain signature of nuclear EoS!

Gravitational waves and nuclear equation of state

very stiff EoS that produces $R_{1.4} \simeq 14$ km is ruled out by GW170817, consistent with other astrophysical measurements

[LIGO/Virgo, PRL 121 (2018) 161101]



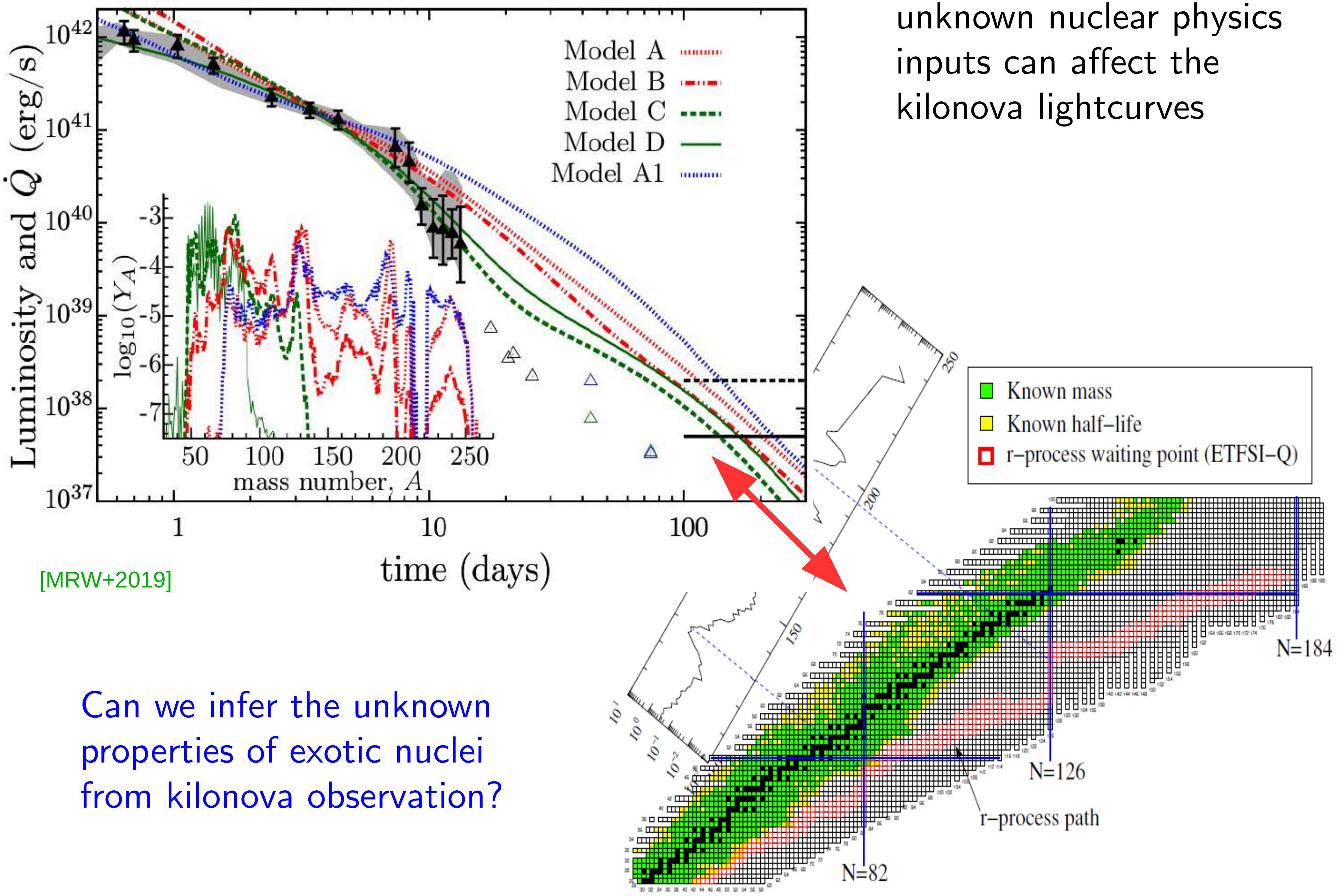


$\Lambda = \frac{2}{3}k_2\left(\frac{R}{M}\right)^5$: the quadrupolar dimensionless tidal deformability

Further efforts that combine GW & EM are on-going

Kilonova and exotic nuclei

unknown nuclear physics inputs can affect the kilonova lightcurves



[MRW+2019]

Can we infer the unknown properties of exotic nuclei from kilonova observation?

Take home messages for the first part

- Fundamental nuclear and particle interactions can affect how stars/stellar phenomena evolves ↔ How different nuclear isotopes and energetic particles are produced by stars/stellar phenomena?

- Core-collapse supernova explosions are ideal labs where yet-uncertain nuclear and particle physics play important roles. The multimessenger signals (neutrinos and gravitational waves) from the next galactic supernova can help answer a number of key issues.

- The detection of the first binary neutron star merger event GW170817 marked the openning of gravitational wave multimessegner astronomy. Future events can hopefully shed further lights on nuclear equation of state and/or the property of exotic nuclei.