The 'kinesthetic' Universe

What can we learn?

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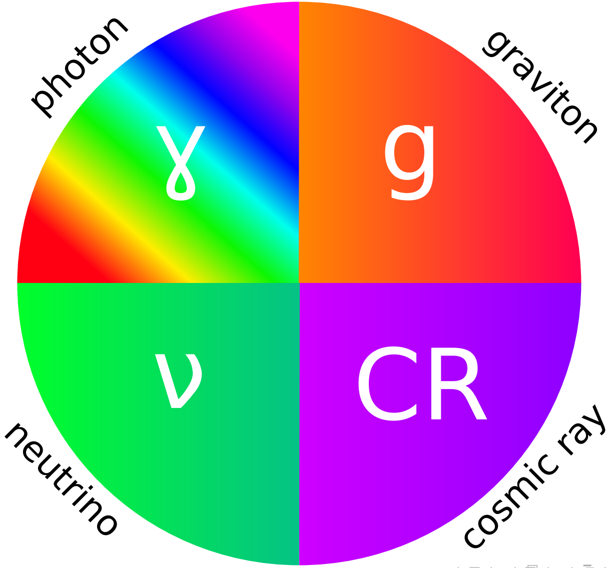
Cosmic messengers



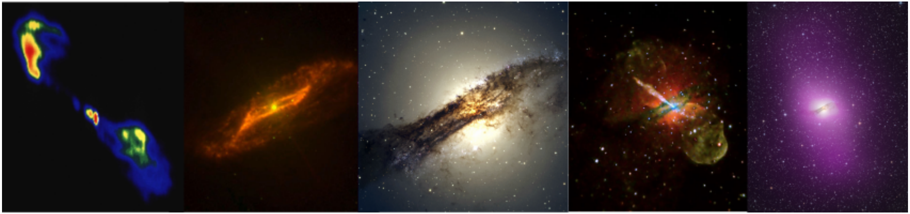
Kinesthesia

Body position and movement awareness $\leftarrow$ integrated info from senses

Contact Improvisation dancers at Nancy Stark Smith's workshop in Florence, January 2017

XX Century: multi-wavelength view of the Universe

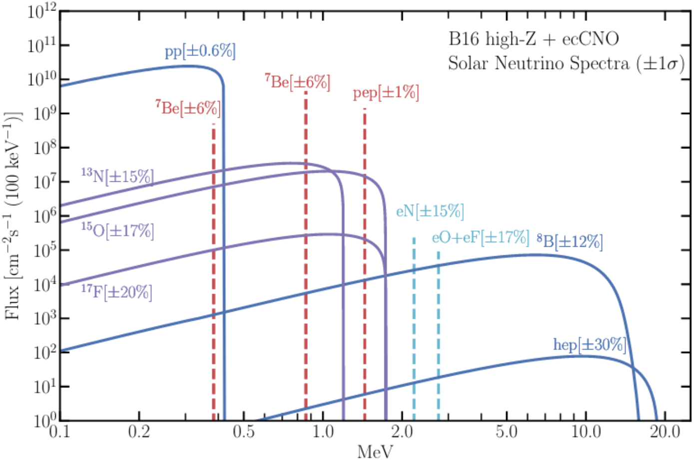
Radio VLA	Infrared Spitzer	Optical WFI	X-rays Chandra	ɣ-rays Fermi



NRAO/AUI	NASA/JPL-Caltech/SST	ESO	NASA/CXC/CfA/Kraft	NASA/DOE/Fermi LAT

Multi-wavelength view of the Centaurus A galaxy

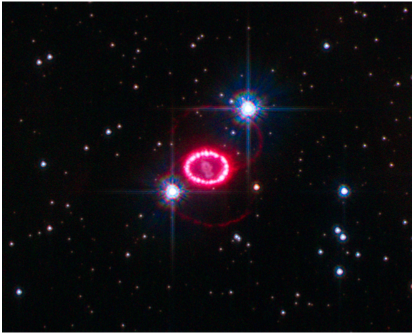
The Sun: the first multi-messenger source (1960s+)



Orebi Gann et al. 2021

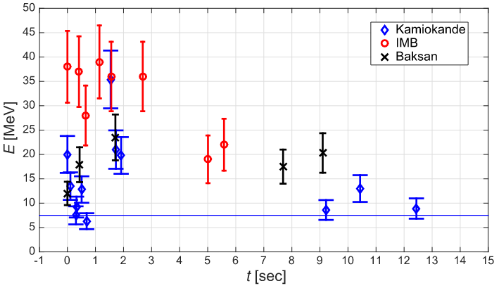
SN1987A: the first multi-messenger extra-solar event

Optical



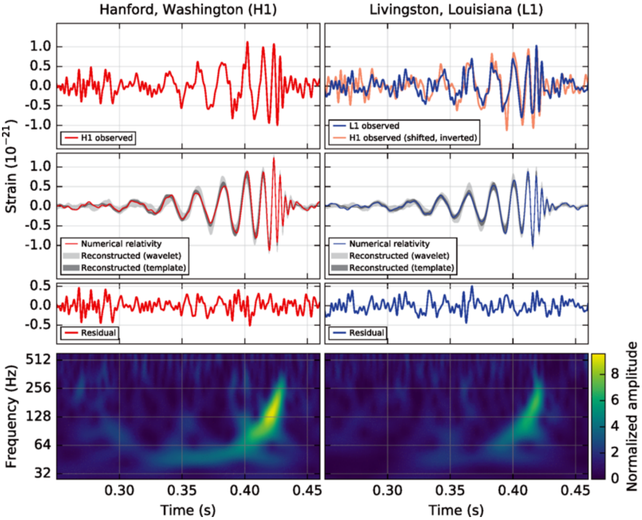
NASA, ESA, K. France (Boulder), P. Challis & R. Kirshner (HSC)

Neutrinos



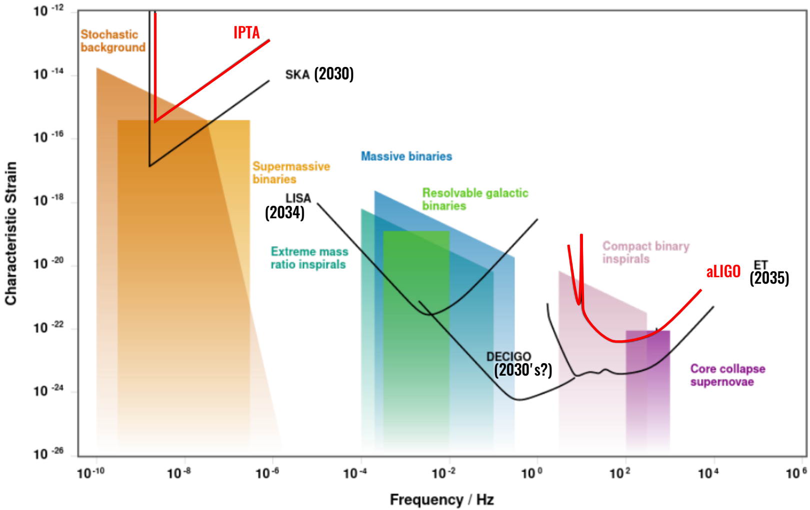
Blum & Kushnir 2016

XXI Century: enter gravitational waves



GW150914, Abbott et al. 2016

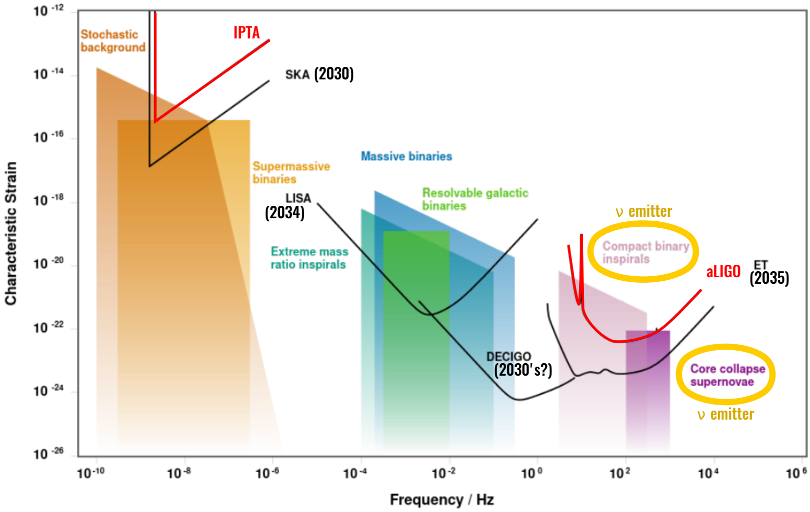
Gravitational wave sources and detectors



Made using GWPLOTTER – Moore, Cole & Berry 2014

(see also Bersanetti's, Greco's & Vetrugno's talks)

Gravitational wave sources and detectors



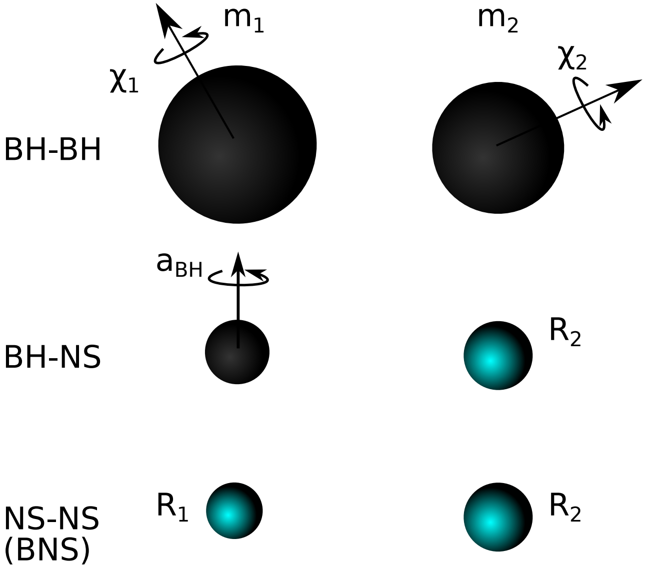
Made using GWPLOTTER – Moore, Cole & Berry 2014

(see also Bersanetti's, Greco's & Vetrugno's talks)

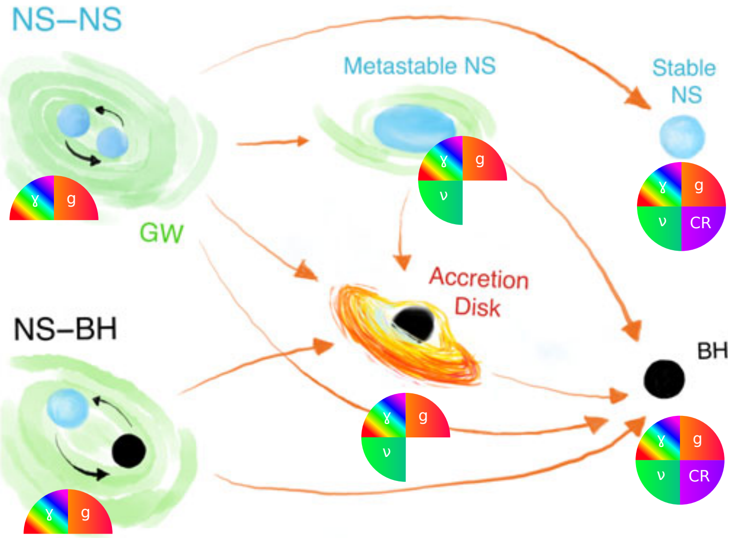
Extreme physical conditions

Compact binary mergers & supernovae: strong gravity, supra-nuclear densities, large magnetic fields, relativistic motion $\rightarrow$ extreme physics laboratories

Compact binary mergers



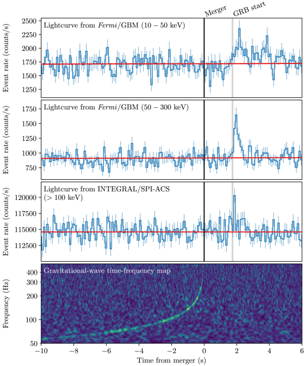
NS-NS & BH-NS merger outcomes



(Adapted from Ascenzi et al. 2021)

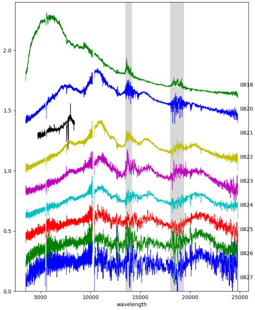
GW170817: the first GW+EM astrophysical event

GW & γ-rays



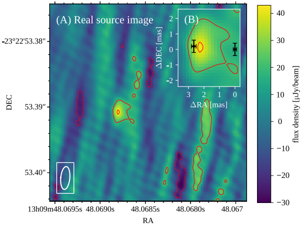
Abbott et al. 2017

Kilonova



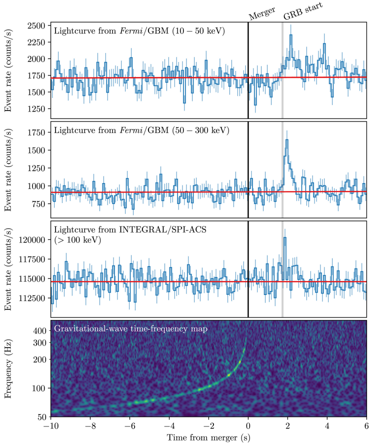
Pian, ..., **OS**, et al. 2017

Relativistic jet



Ghirlanda, **OS**, et al. 2019

GW+γ-rays: constraints on gravity/dark energy



Abbott et al. 2017

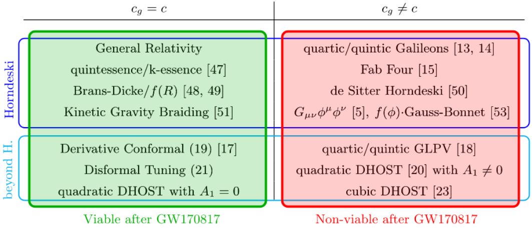
Arrival time diff. + Distance

$t_\gamma - t_{\rm GW} \sim 2\,{\rm s}$ $\quad d_{\rm L} \sim 40\,{\rm Mpc}$

→ GW propagation speed constraint

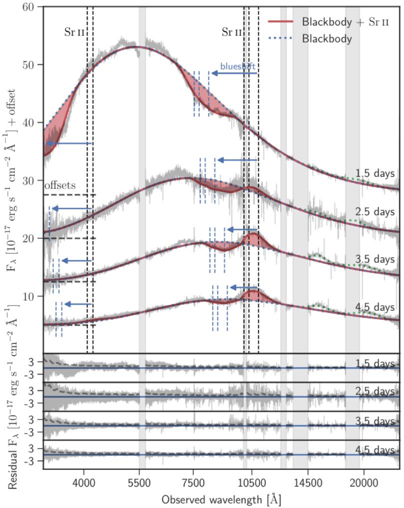
$$\frac{v_{\rm GW} - c}{c} \lesssim 10^{-15}$$

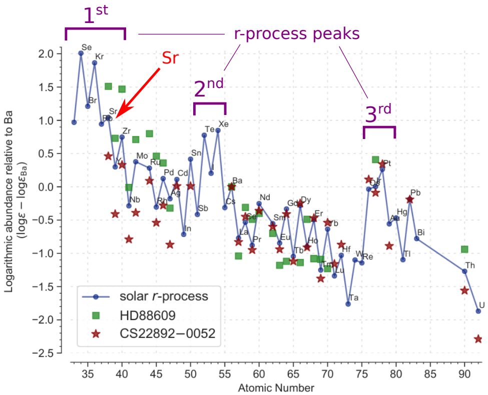
(e.g. Baker et al. 2017)



Ezquiaga & Zumalacarregui 2017

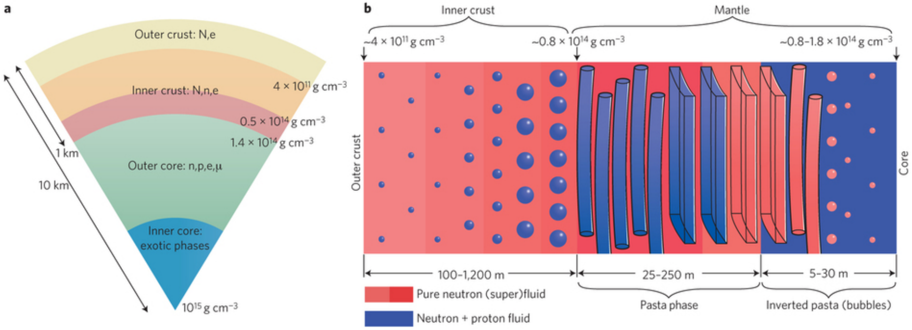
Kilonova: r-process nucleosynthesis





Sr in AT2017gfo/GW170817 (Watson et al. 2019)

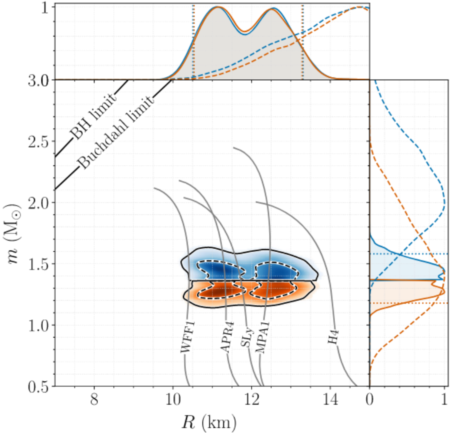
Neutron star structure

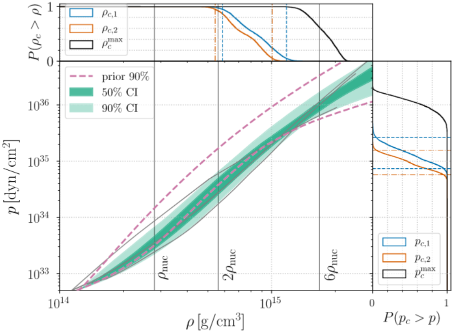


(W.G. Newton)

GW170817 equation of state constraints (GW only)

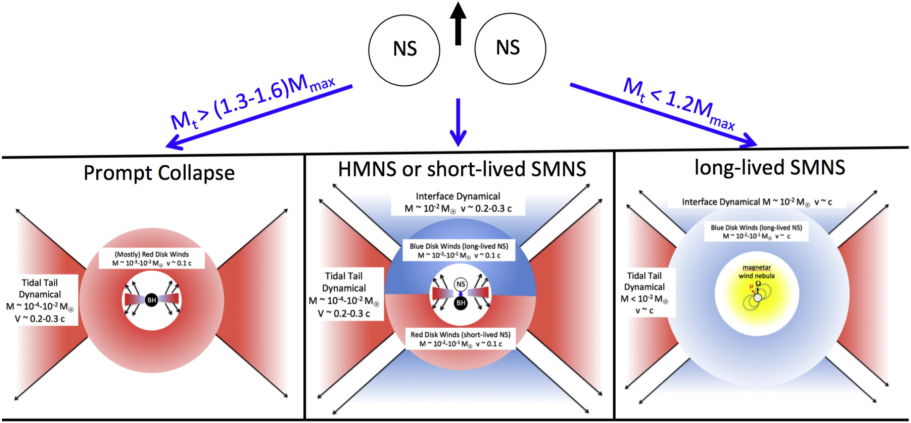
"Tidal deformability" $\Lambda \propto R^5/M^5 \rightarrow$ GW obs. constrain radius





(Abbott et al. 2018)

GW170817: 'kinesthetic' EoS constraint

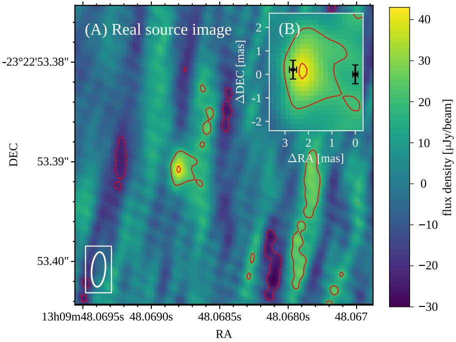


(Margalit & Metzger 2017, see also e.g. Radice et al. 2018, Shibata et al. 2019)

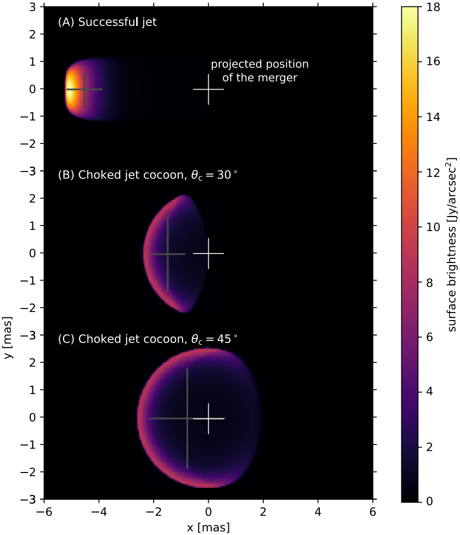
Luminosities & colours of red & blue kilonova + expected merger dynamics $\rightarrow M_{\rm max} \lesssim 2.2\,{\rm M}_\odot$

GW170817: relativistic jet

VLBI observations

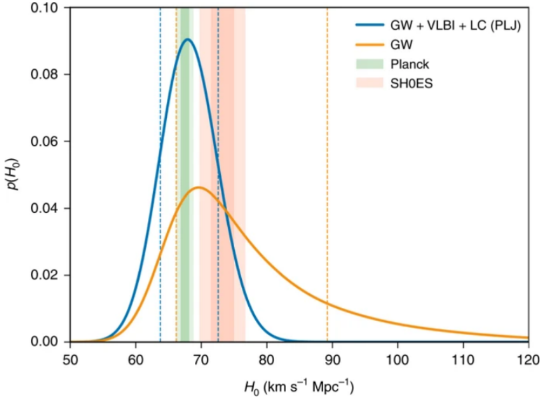


(Ghirlanda, **OS**, et al. 2019; see also Mooley et al. 2018)

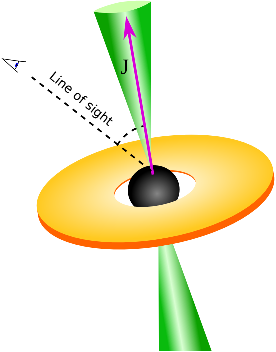


‘Kinesthetic’ standard siren H_0 measurement

Fig. 2: Posterior distributions for H_0.

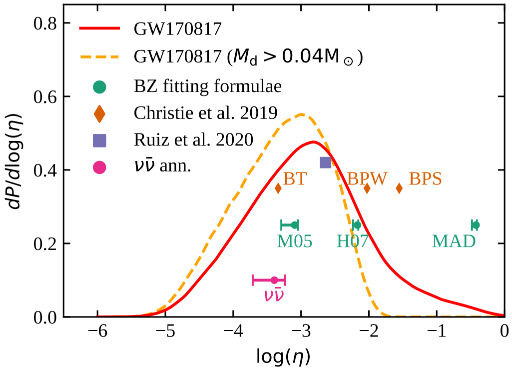


(Hotokezaka et al. 2019)

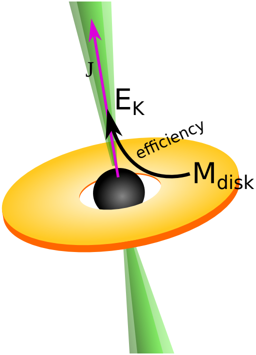


‘Kinesthetic’ accretion-to-jet efficiency measurement

$$\eta \sim E_{\rm jet}/M_{\rm disk}c^2$$



(**Salafia** & Giacomazzo 2020)



ν from neutron star mergers: mechanisms

Relativistic jet

Main ``photomeson'' route to neutrino emission:

$$p + \gamma \longrightarrow \Delta^+ \rightarrow n + \pi^+ \rightarrow n + \mu^+ + \nu_\mu \longrightarrow n + e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

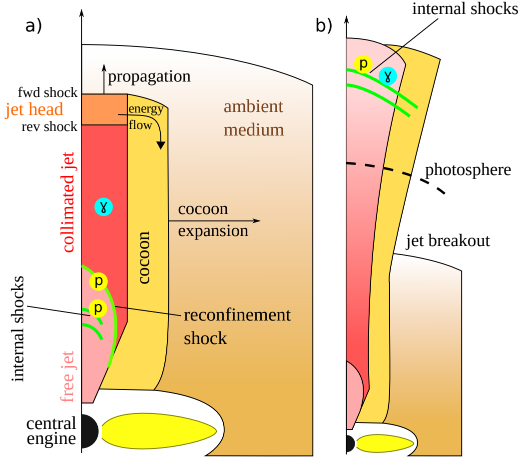


Illustration adapted from Salafia et al. 2020, with input from Paczynski & Xu 1994, Waxman & Bachall 1997, Murase & Ioka 2013, Kimura+2018

Proto-magnetar

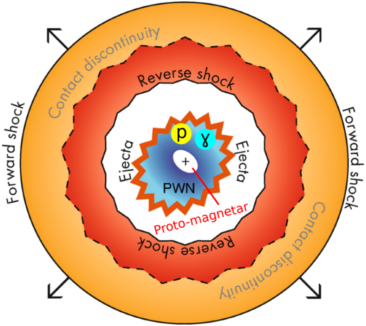
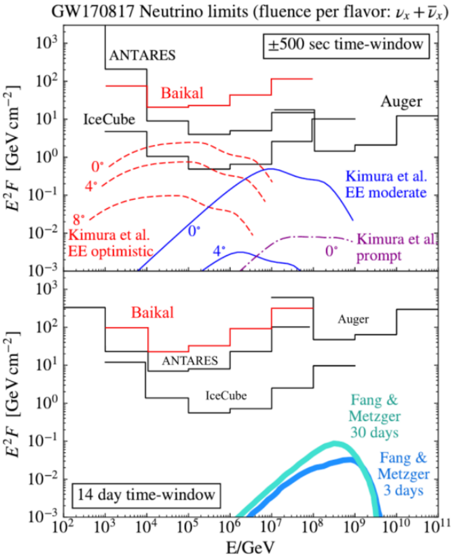


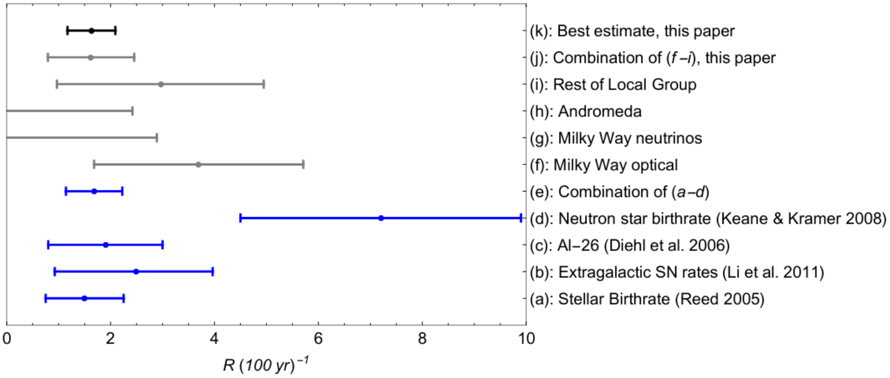
Illustration adapted from Vink 2020; emission scenario from Fang & Metzger 2017

ν from neutron star mergers: limits for GW170817



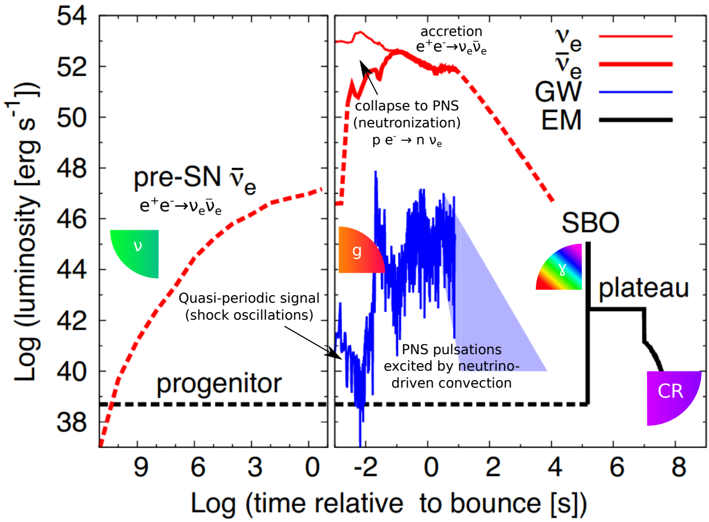
(Avrorin et al. 2018, Albert et al. 2017)

A core-collapse supernova in the Milky Way?



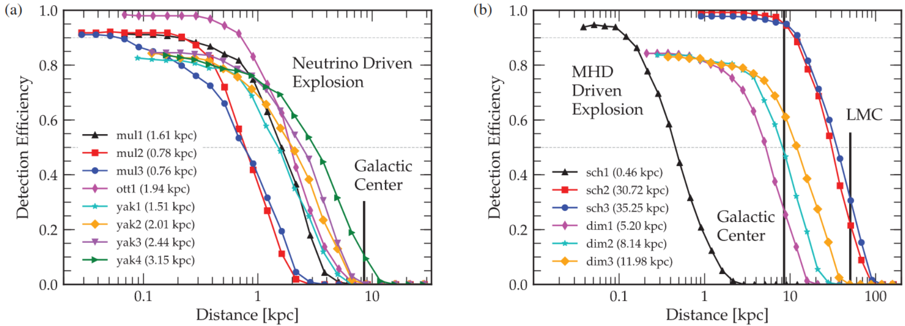
Rozwadowska, Vissani & Cappellaro 2020

Kinesthetic view of a core-collapse supernova



Nakamura et al. 2016

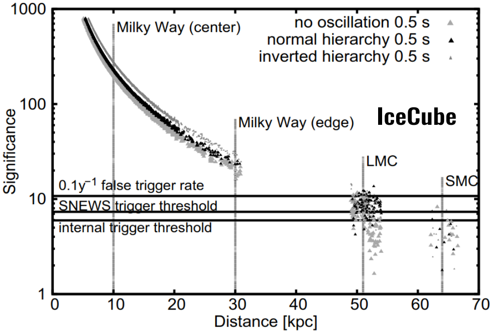
Current & future GW detector reach to supernovae



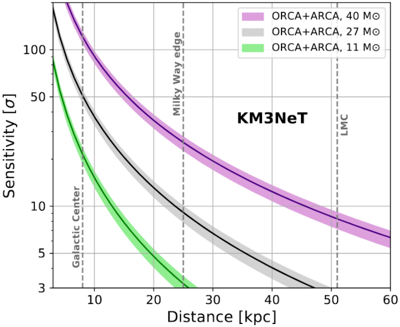
LIGO & Virgo (Abbott et al. 2020)

3G detectors: $\sim 10\times$ anticipated improvement (see G. Greco's talk)

Current & future ν detector reach to supernovae



Abbasi et al. 2011



Aiello et al. 2021

What can we learn?

Astrophysics

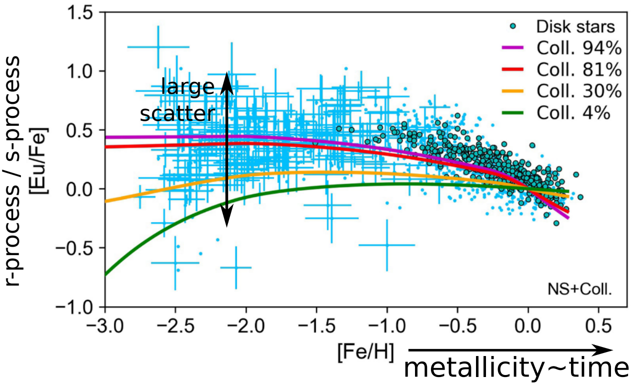
- merger remnants
- origin of elements and their cosmic abundances
- relativistic jets
- supernova explosion mechanisms
- cosmological parameters
- compact binary population properties (masses, spins, etc)
- formation channels $\leftrightarrow$ binary stellar evolution

Fundamental physics

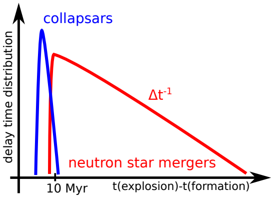
- constraints on theories of gravity (see W. Del Pozzo's talk)
- equation of state of matter at supra-nuclear densities
- tests of the Standard Model

Backup slides

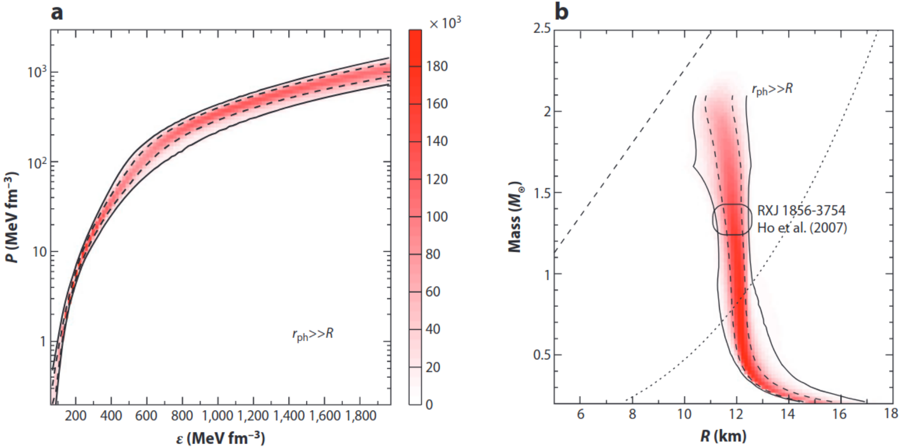
Issues with r-process enrichment from mergers alone



(Siegel et al. 2019)

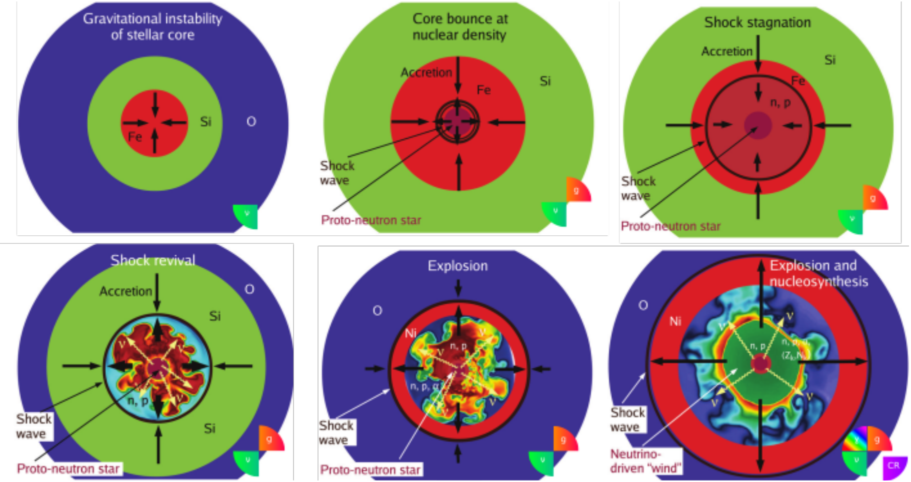


Equation of state → macroscopic properties



(Lattimer 2012)

Core-collapse supernova



(Adapted from Janka et al. 2012)