Probing Core-Collapse Supernovae Events through Gravitational Waves and Gamma-Ray Bursts

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Based on recent publications:

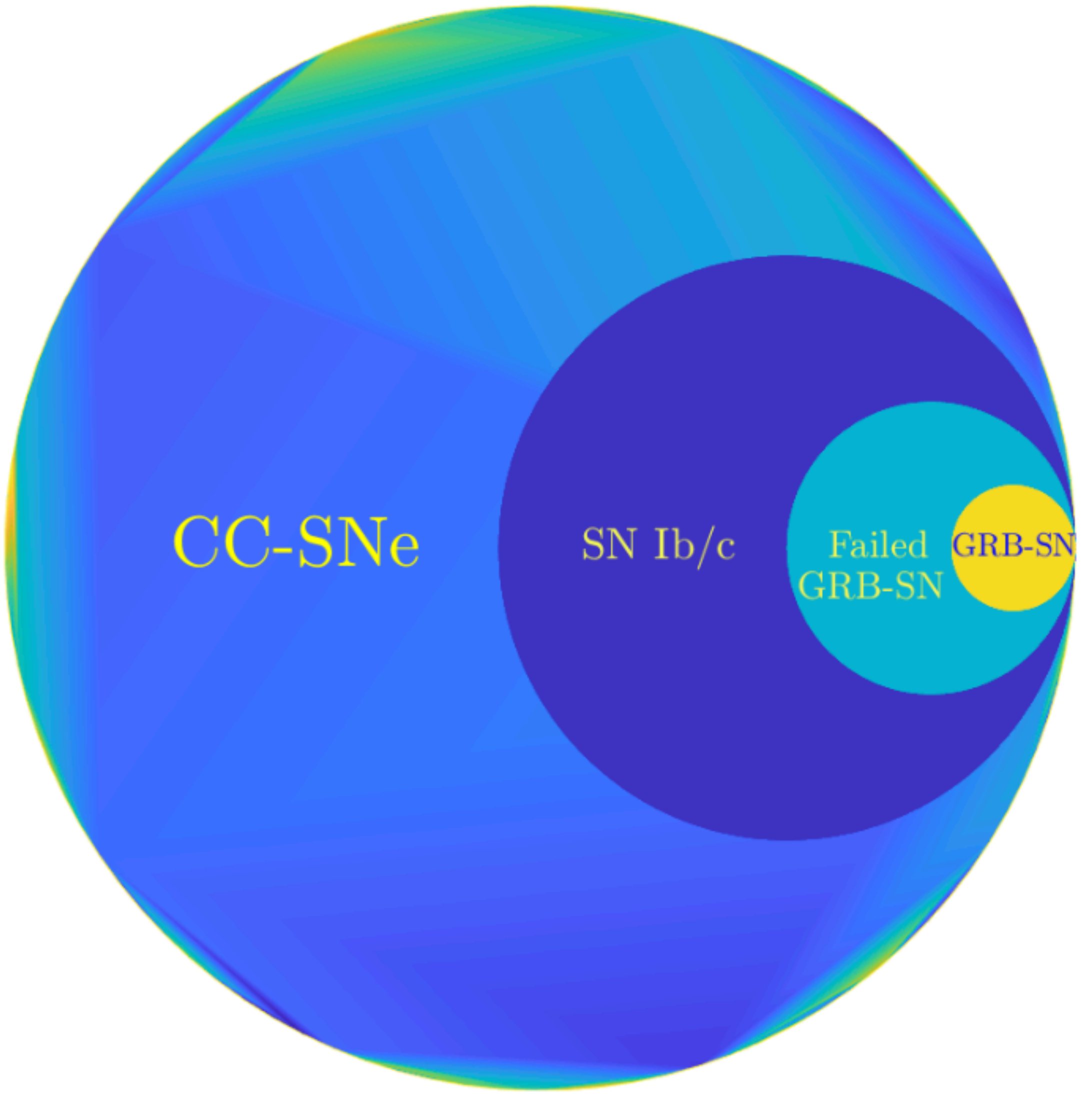
van Putten, Abchouyeh & Della Valle, ApJL (2024), van Putten & Della Valle A&A (2023), Abchouyeh, van Putten & Amati, ApJ (2023), van Putten, Universe (2024), van Putten, Della Valle & Levinson, ApJL (2019), van Putten & Della Valle, MNRASL (2019)

Apr 1-4, 2025, Padova, Italy.

April 4 2025 11:55-12:10 ET

INAF - Osservatorio Astronomico di Padova

Core-collapse supernovae: A family

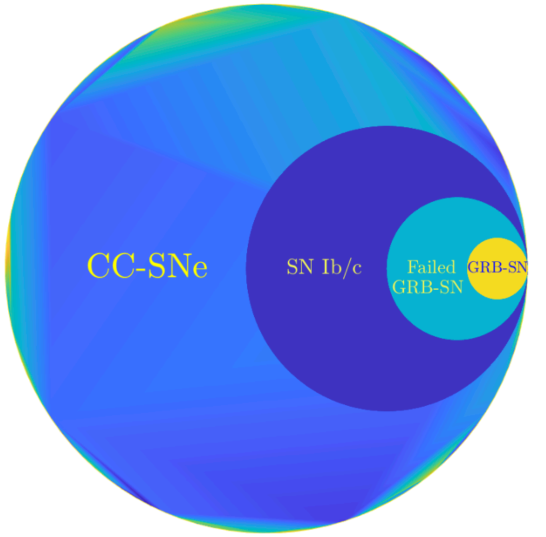


Core-collapse supernovae,

are explosively diverse…

van Putten, Abchouyeh & Della Valle ApJL (2024)

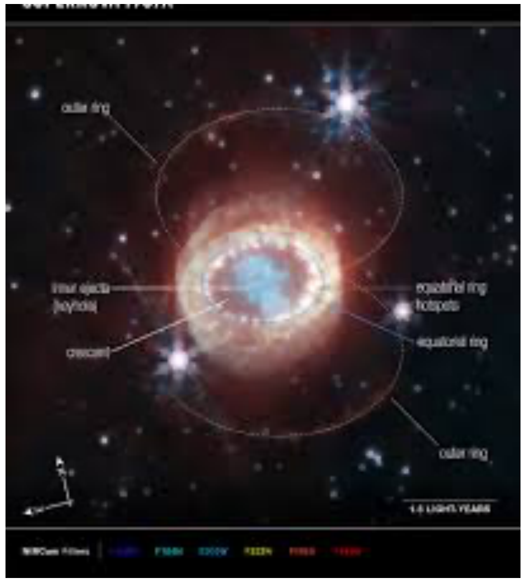
Core-collapse supernovae: A family



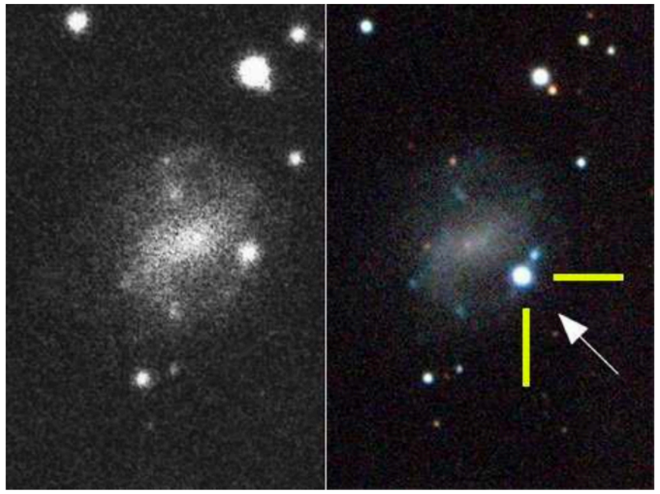
Without and with gamma-ray bursts,

Mildly to highly energetic…

SN 1987A: **Type II**

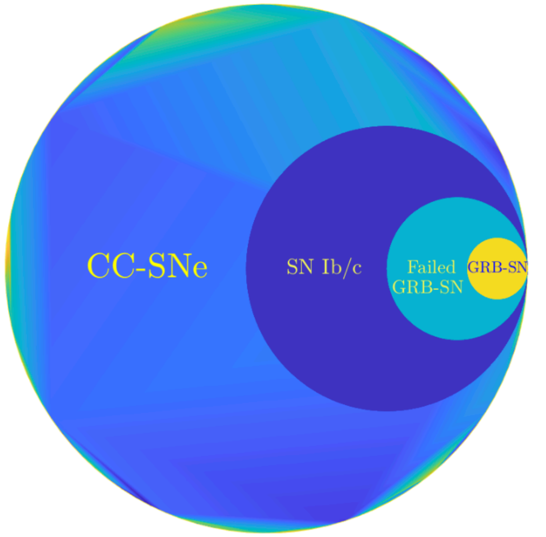


SN 1998bw (Gallama et al. 1998): **Type Ic**



van Putten, Abchouyeh & Della Valle ApJL (2024)

Core-collapse supernovae: Diversity



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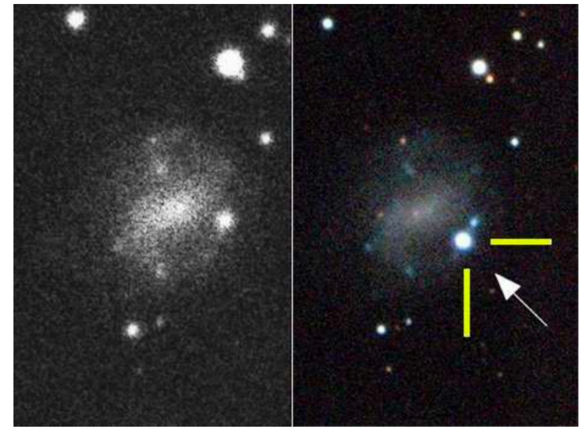
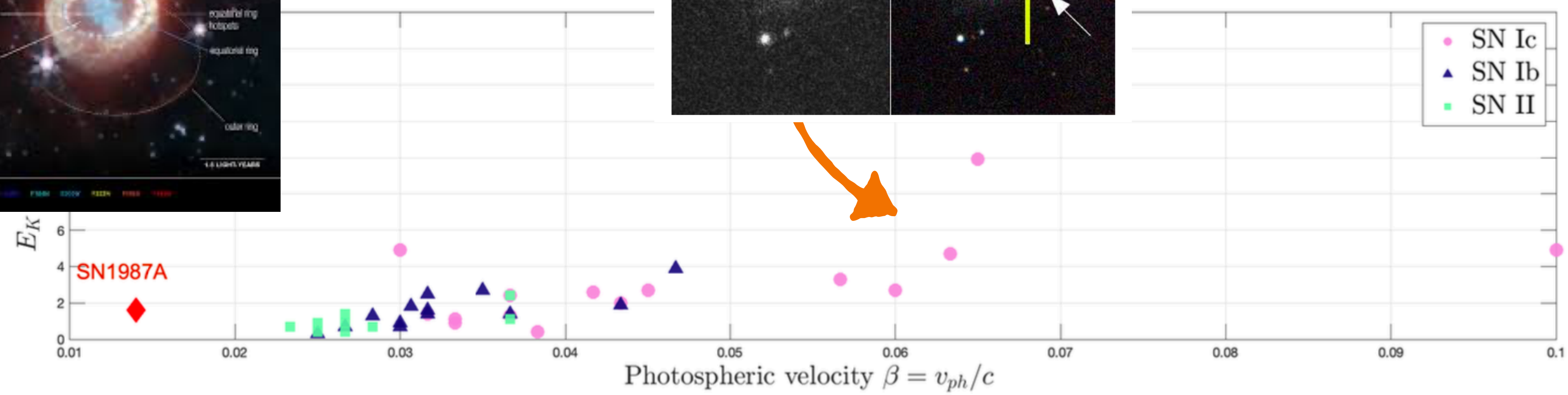
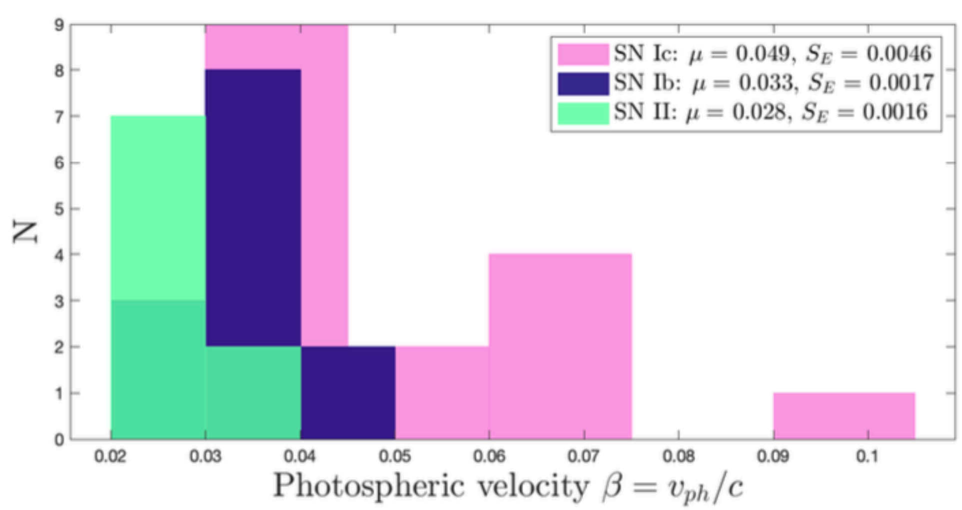
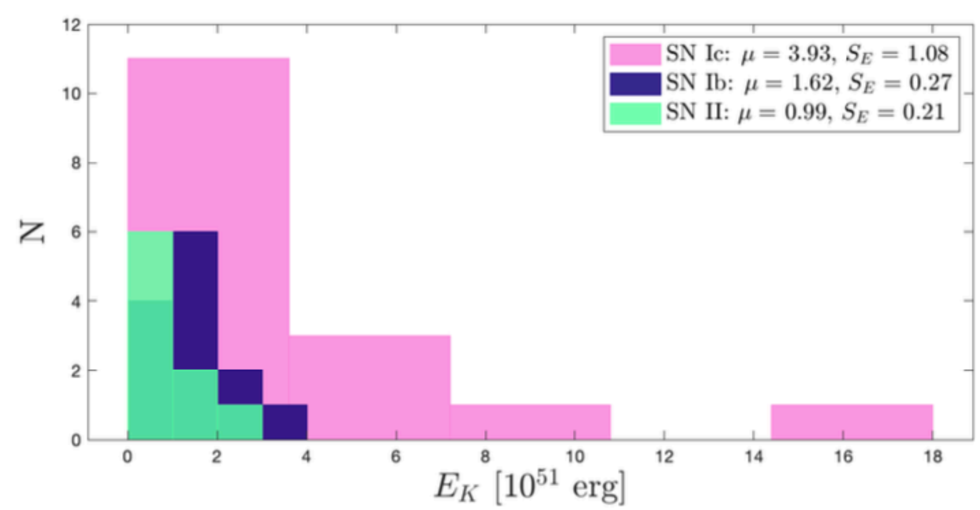


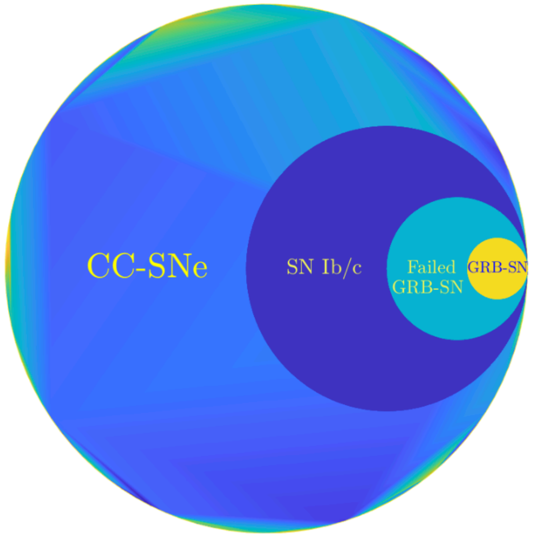






van Putten, Abchouyeh & Della Valle ApJL (2024)

Why so diverse?



Energetic diversity from different central engines?

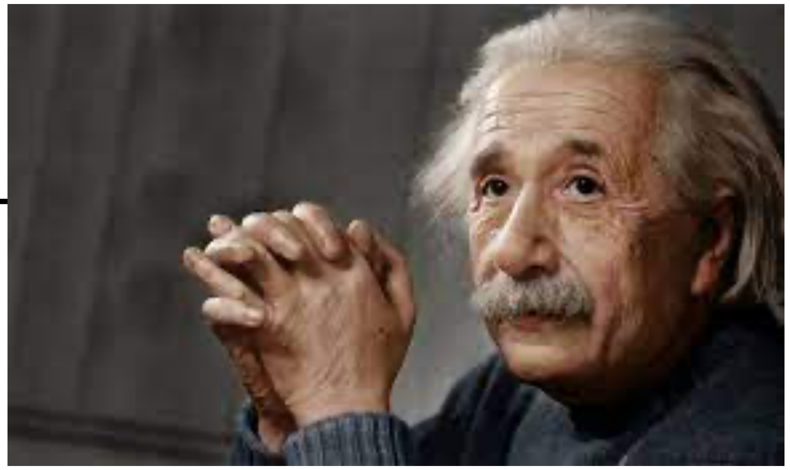
Neutron star (NS) or black hole (BH)

EM-neutrino observations tend to be inconclusive ....

$$\boxed{E_j < E_k < E_w < E_\nu < \ldots}$$

van Putten, Abchouyeh & Della Valle ApJL (2024)

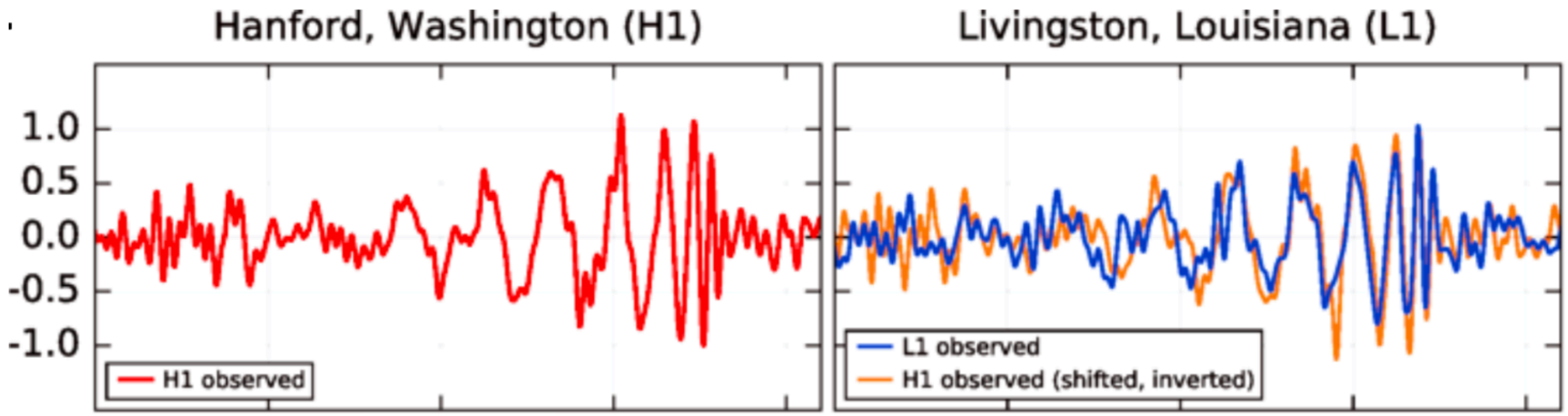
Quadrupole GW-emission



Unit of GW-luminosity

$$L_0 = \frac{c^5}{G} = 2 \times 10^5 M_\odot c^2$$

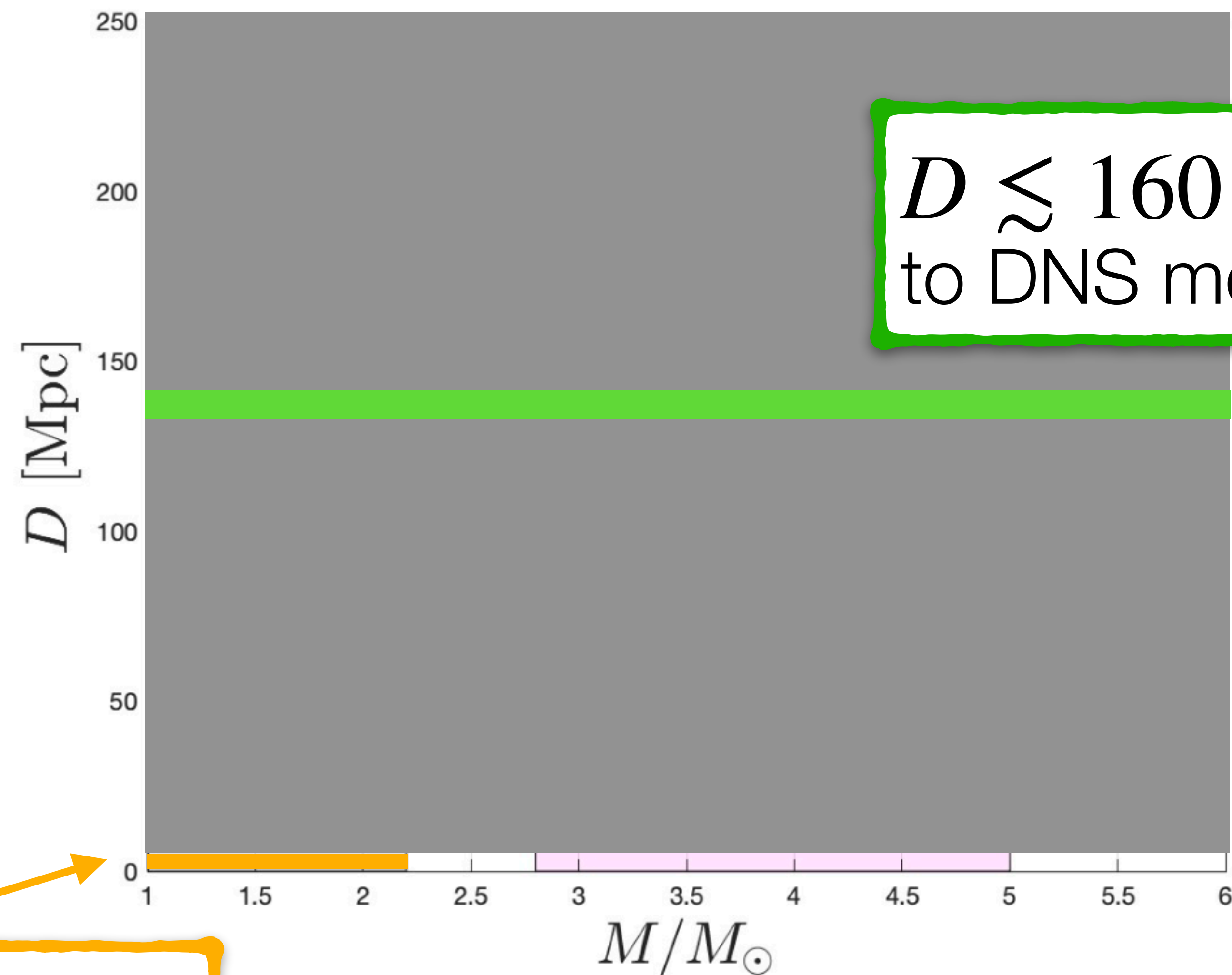
BBH merger GW150914



Abbott et al. 2016

$$\hat{L}_{GW} \simeq 0.1\,\%\,L_0$$

LIGO-Virgo horizon distance to NS-powered CC-SNe



$D \lesssim 160\,\mathrm{Mpc}$
to DNS mergers

$D \lesssim 1\,\mathrm{Mpc}$ from
NS spin-down

Kerr black holes: Energy reservoir in spin

Kerr black hole (1963)

Geometry of spacetime with J

$$\sin\lambda = a/M:$$

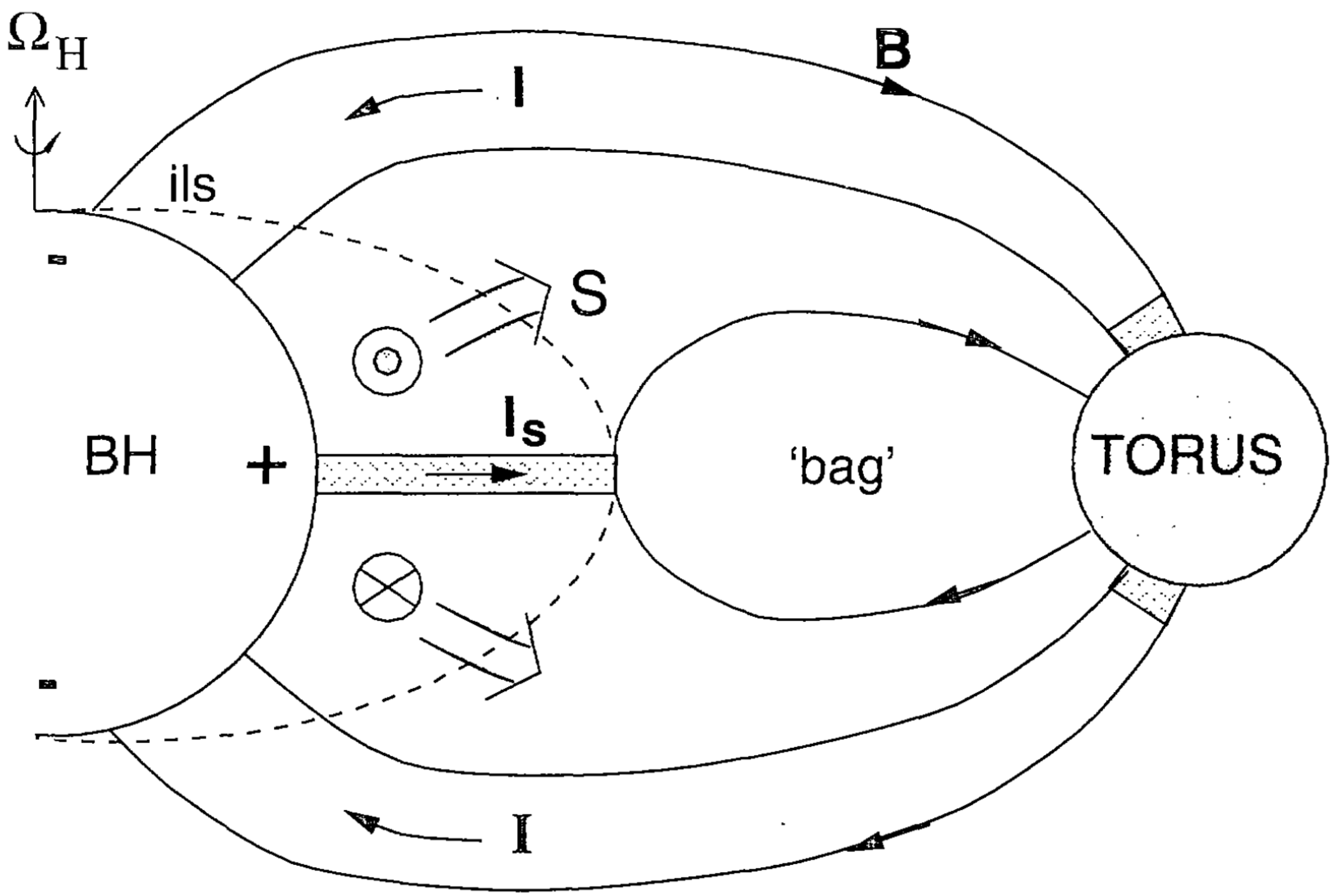
$$E_J = 2Mc^2\sin^2(\lambda/4)$$

Ample energy reservoir:

$$E_J \leq 29\,\%\,Mc^2$$

$$E_J^{BH} \gtrsim 10\text{X of } E_J^{NS} \lesssim few \times 10^{52}\text{erg}$$

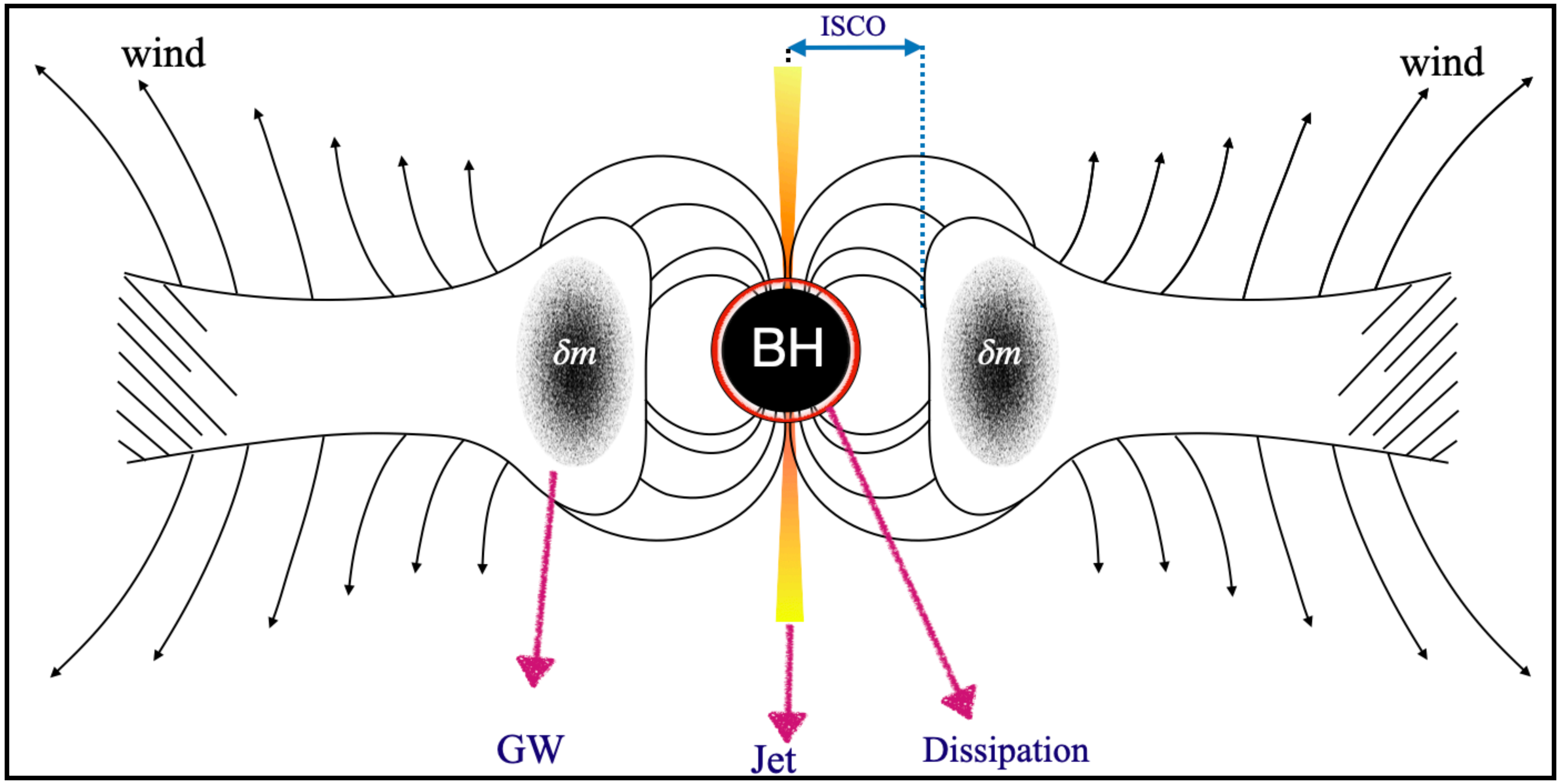
… can couple to matter



Dominant coupling over an inner torus magnetosphere

(van Putten, Science 1999, van Putten & Levinson Science 2002)

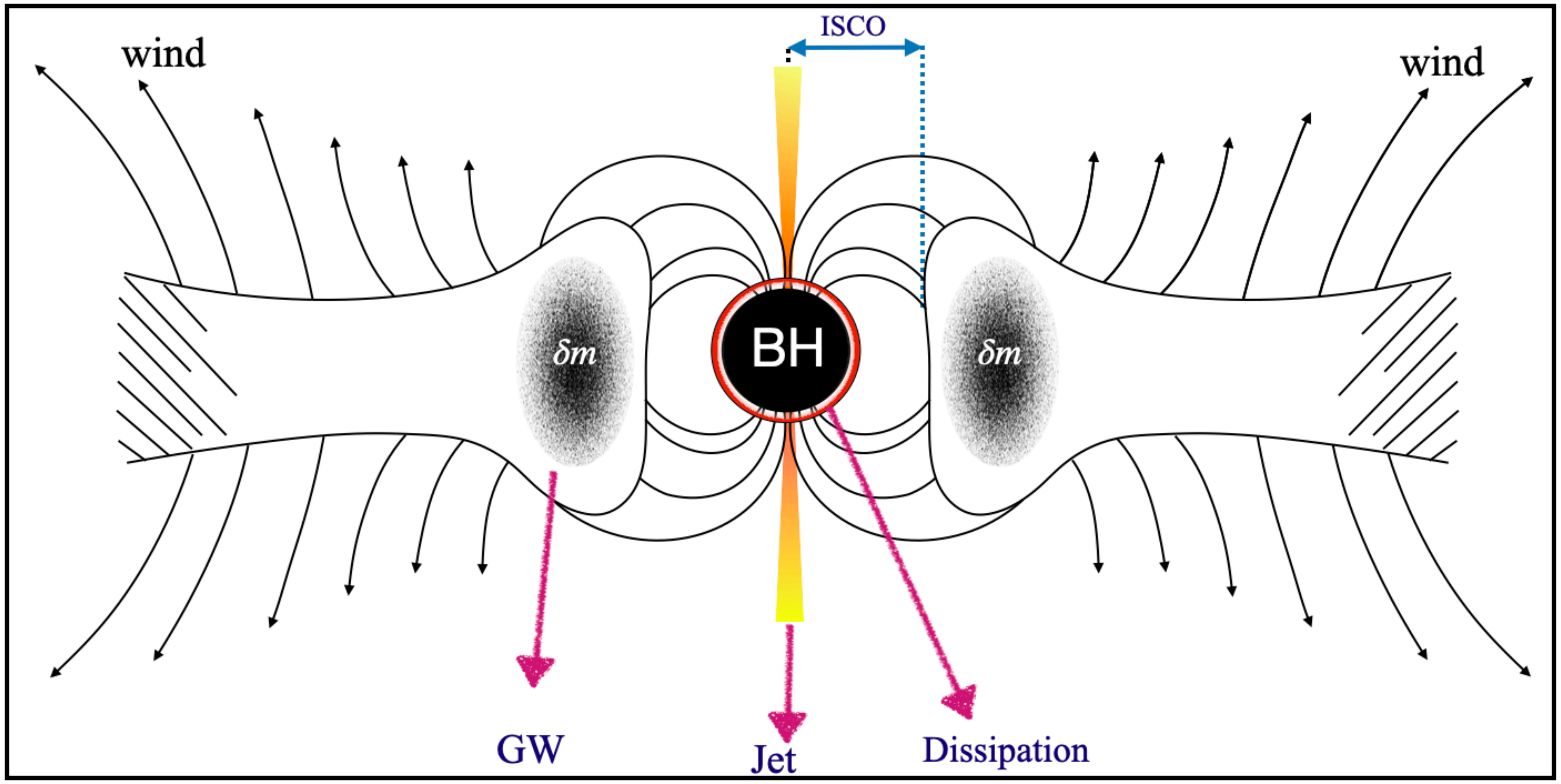
… providing multiple channels of radiation



van Putten, Abchouyeh, Della Valle, ApJL (2024)

$$\boxed{E_j < \underbrace{E_w < E_\nu < E_{GW}}_{\text{from torus}} < E^H_{diss}}$$

… including gravitational-wave emission

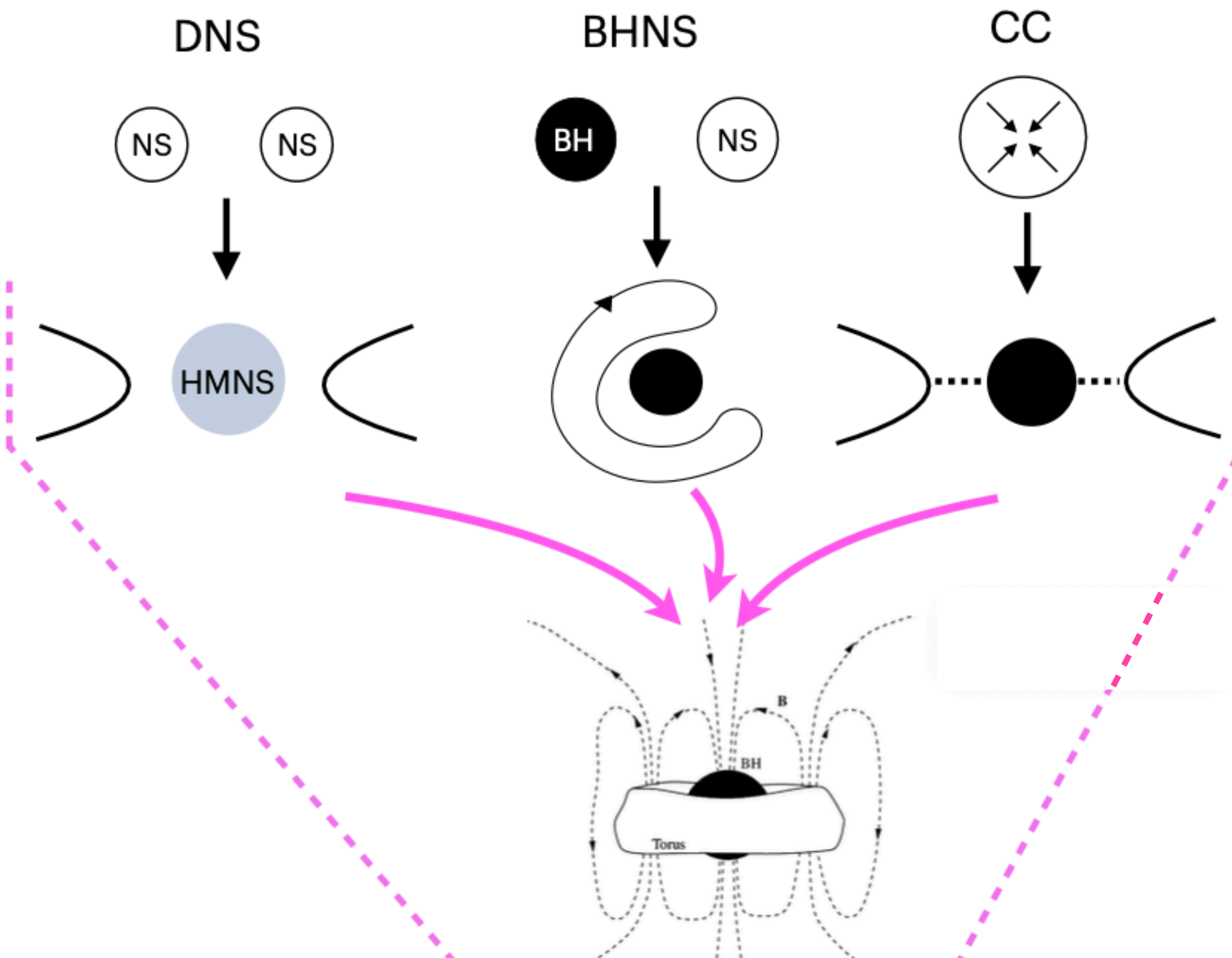


van Putten, Abchouyeh, Della Valle, ApJL (2024)

Over lifetime of black hole spin

$$L_{GW} = \frac{32}{5}\left(\frac{\delta m}{M}\right)^2\left(\frac{M}{a}\right)^2 L_0 \sim 10^{51}\mathrm{erg\ s^{-1}}$$

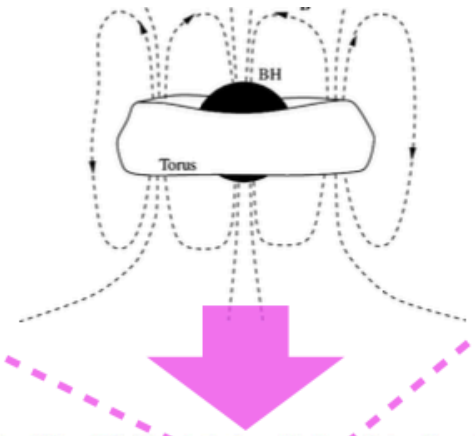
Unification scheme

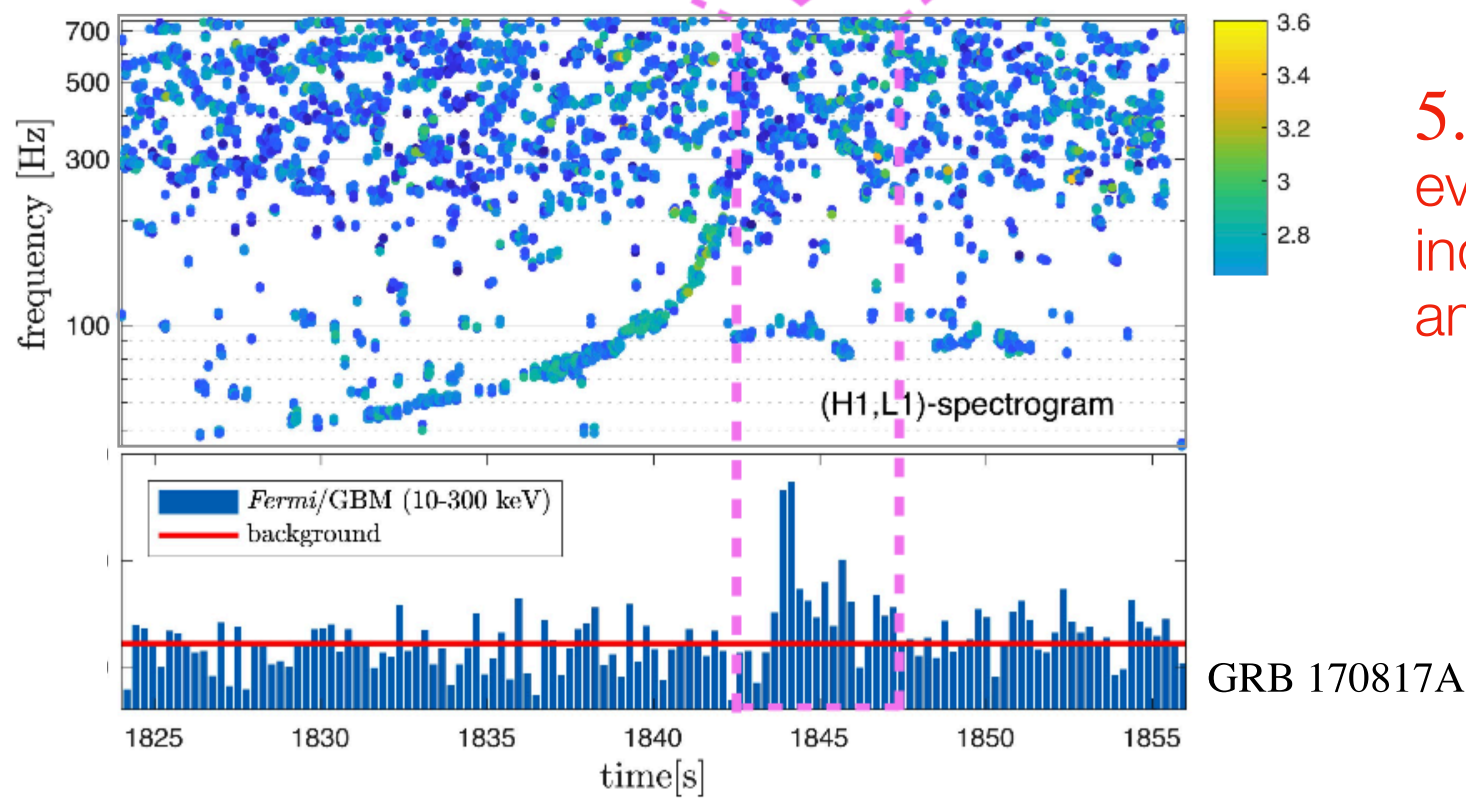


Universal up to scaling in total mass

Ascending-descending chirp GW170817/B during O2

$D_{0817} = 40$ Mpc





$5.5\,\sigma$ significance by event timing and independent H1-L1 analysis

$E_{GW} \simeq 2.25\,\%\,M_\odot c^2$

$M \simeq 2.8 M_\odot$

Abbott et al. 2017

$E_{GW} \simeq 3.5\,\%\,M_\odot c^2$

$M \simeq 2.8 M_\odot$

(van Putten & Della Valle 2023 A&A)

$\gtrsim$ 3X $\max E_J^{NS}$

$\sim 10X\ \mathscr{E}_{EM}$

Prospects: O4 gains by scaling

☑ k_D: O4/O2 detector sensitivity

$$D_{O4} \simeq 160\,\text{Mpc} \quad \textit{vs.} \quad D_{O2} \simeq 100\,\text{Mpc}$$

☑ k_M: More power from more massive BH in SN Ic

☑ k_n: f_{GW} closer to “sweet spot” of detector sensitivity from more massive BH

Prospects: O4 gains by scaling

☑ k_D: O4/O2 detector sensitivity

☑ k_M: More power from more massive BH in SN Ic

$$E_j \lesssim 0.29\,Mc^2, \quad M_{CC-SNe} \simeq 5\,M_\odot \;\; \textit{vs.} \;\; M_{0817} \simeq 2.8\,M_\odot$$

☑ k_n: f_{GW} closer to “sweet spot” of detector sensitivity from more massive BH

Prospects: O4 gains by scaling

- ☑ k_D: O4/O2 detector sensitivity
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- ☑ k_n: f_{GW} closer to "sweet spot" of detector sensitivity from more massive BH

$$\Delta F \simeq (700 - 200)\left(\frac{2.8}{M}\right) \text{ Hz}$$

Prospects: O4 gains by scaling

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$$\text{Total gain: } k_D \times k_M \times k_n \sim 4$$

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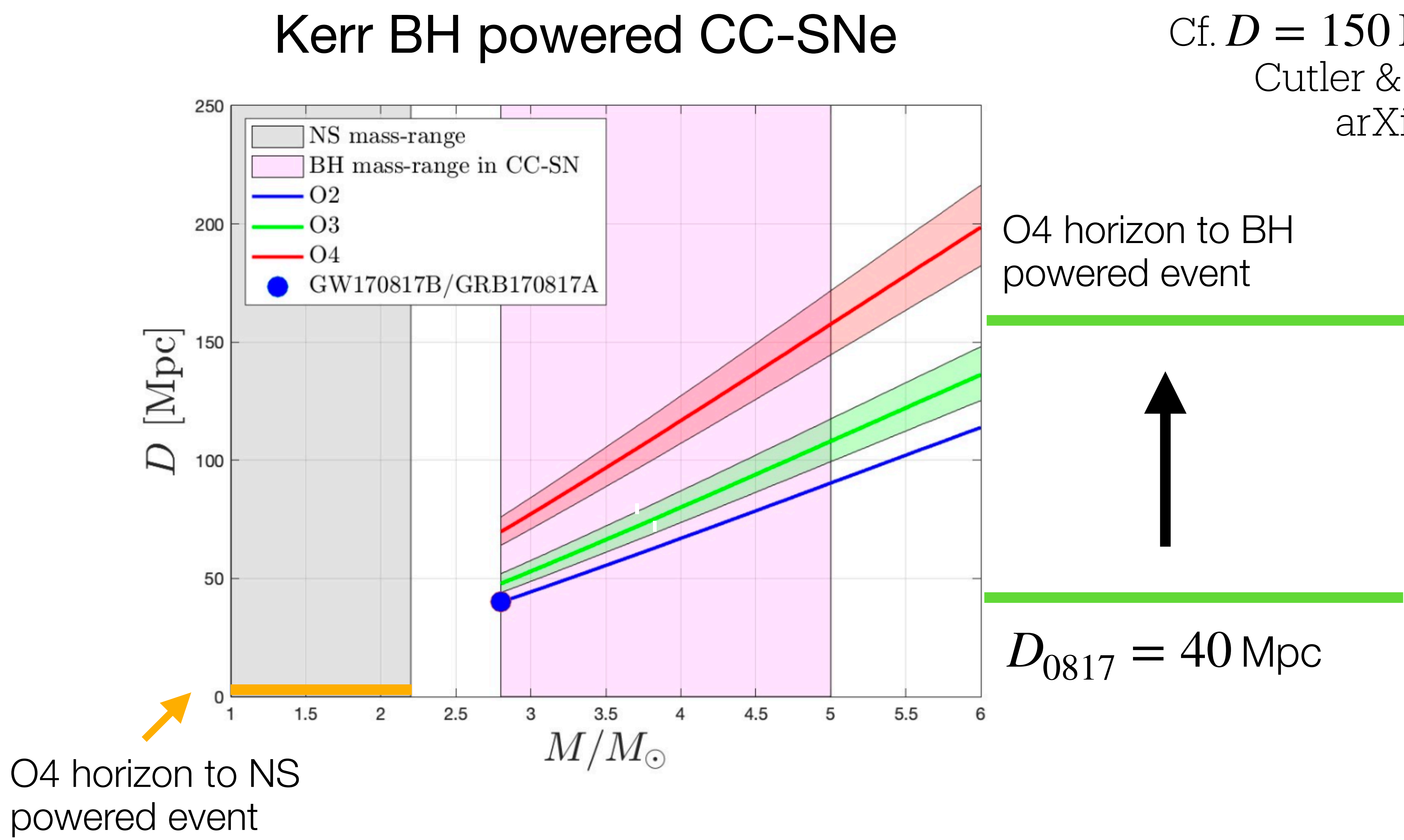
Total gain: $k_D \times k_M \times k_n \sim 4$

Today's horizon distance to BH powered CC-SNe:

$$\boxed{70\,\mathrm{Mpc} \lesssim D \lesssim 160\,\mathrm{Mpc}}$$

LIGO-Virgo O4 horizon distance to CC-SNe



Cf. $D = 150$ Mpc (LIGO II)
Cutler & Thorne 2002
arXiv:0204090v1

A CC-event may be observed tomorrow!

Extra slides

BMF versus time-slider FFT

Time-sliced FFT has sensitivity limited by time-frequency uncertainty relation $\tau\delta f = 1$, $\tau \simeq 1/\sqrt{\dot{f}}$:

Sensitivity scales with $\sqrt{N} \lesssim f^{\frac{1}{2}} \left|\dot{f}\right|^{-1/4}$

Butterfly MF over bank of time-symmetric chirp-like templates:

van Putten, Guidorzi & Frontera, 2014, ApJ, 786, 146

- Time-symmetric sensitivity to un-modeled signals on par with CBC.
- gain = $\sqrt{\frac{N_n}{N_{FFT}}} \simeq \left(\frac{(n+2)!}{2}\Delta N^{\frac{n}{2}}\right)^{\frac{1}{2(n+2)}} \simeq 2.2\ (n=1)$
- Gain $= \sqrt{2}$ gain $\simeq 3.11$ for merged (H1,L1)-spectrograms

x2 is equivalent to a decade of improvement in detector sensitivity.

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