

# Multi-messenger constraints on core-collapse supernovae in the Local Universe (Part I)

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*Based on*

van Putten, Abchouyeh & Della Valle, *ApJ* **972** (2024) L23

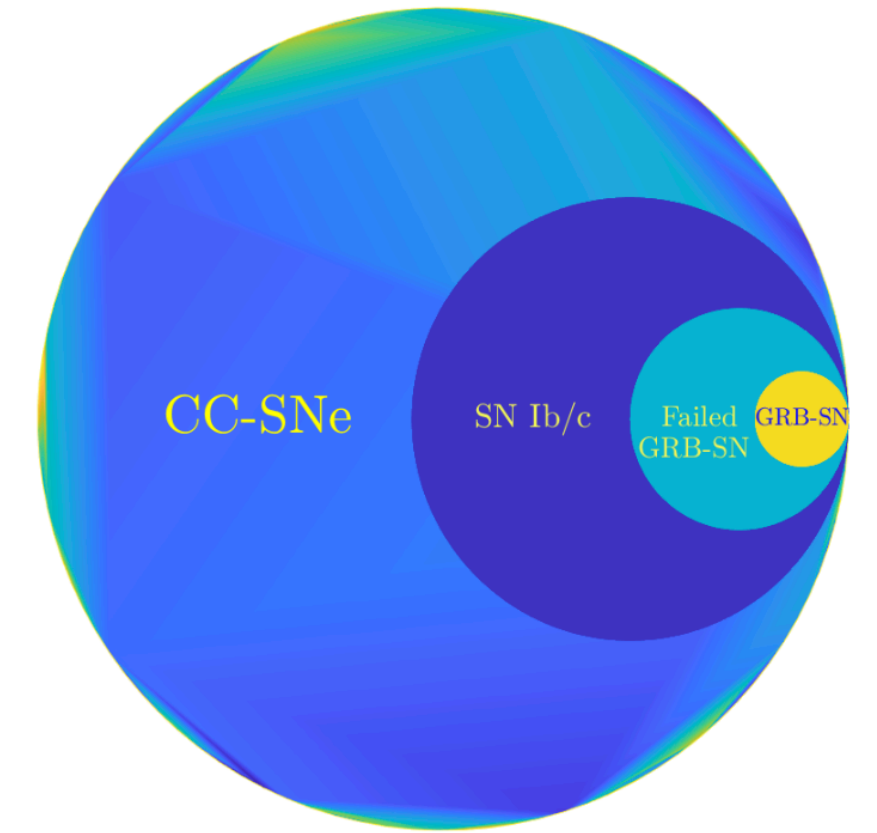
Abchouyeh, van Putten, & Della Valle, under review

**June 18, 2025**

Yerevan, Armenia

*High Energy Astrophysics and Cosmology in the era of all-sky surveys*

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Diversity of core-collapse SNe

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Conclusions

# Supernovae from optical surveys

## SN Ia and core-collapse SNe

- SN Ia are remarkably standard (Phillips 1993)
- CC-SN are remarkable diverse:

NL, minor fraction BL

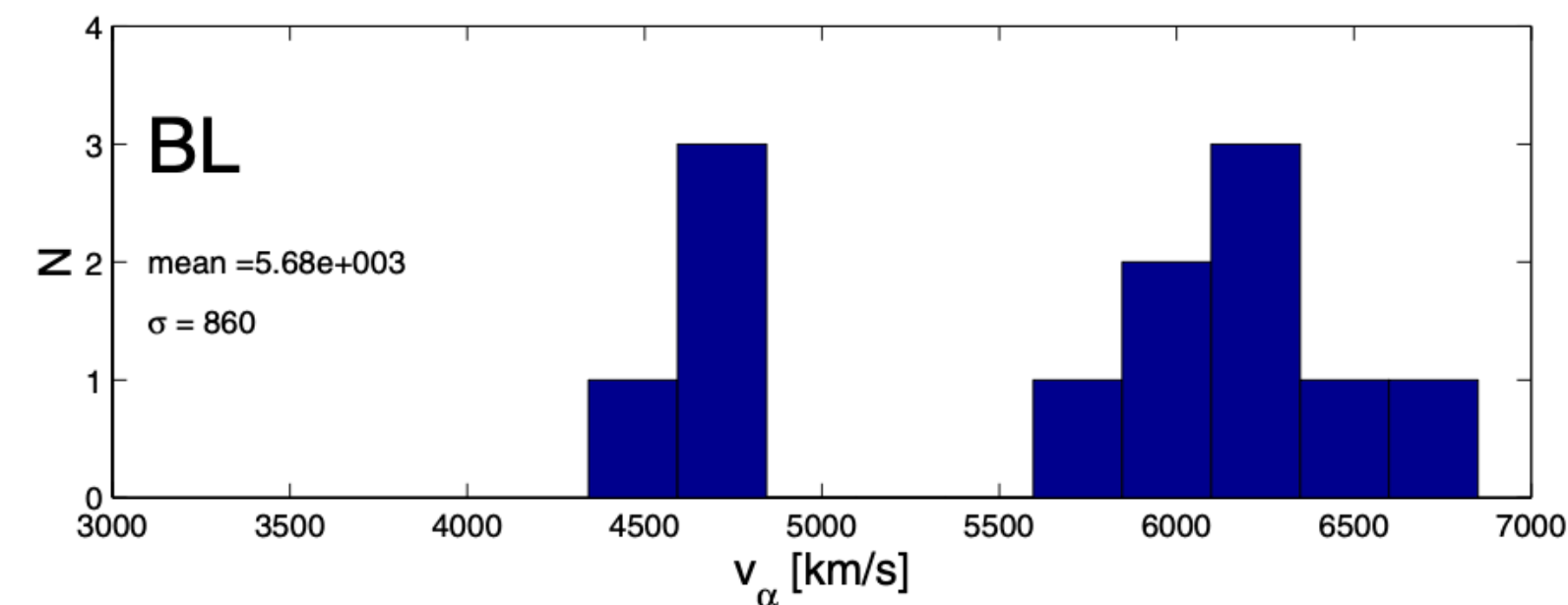
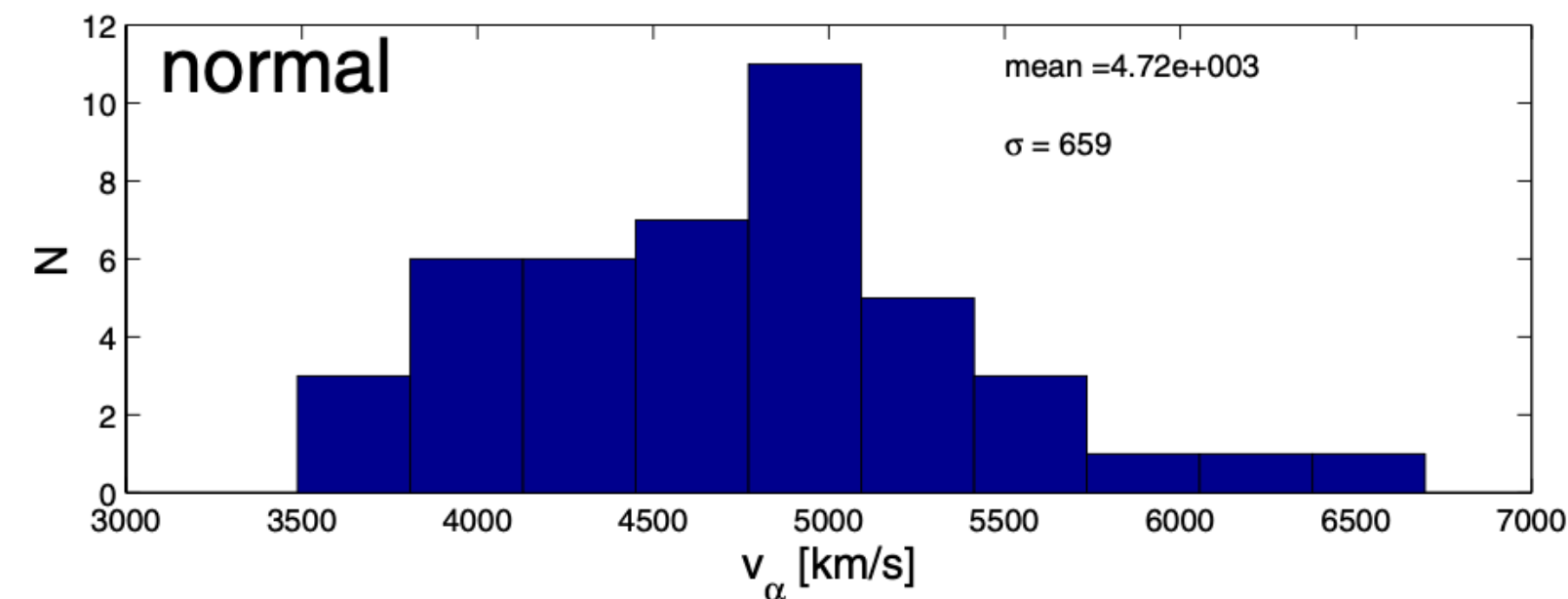
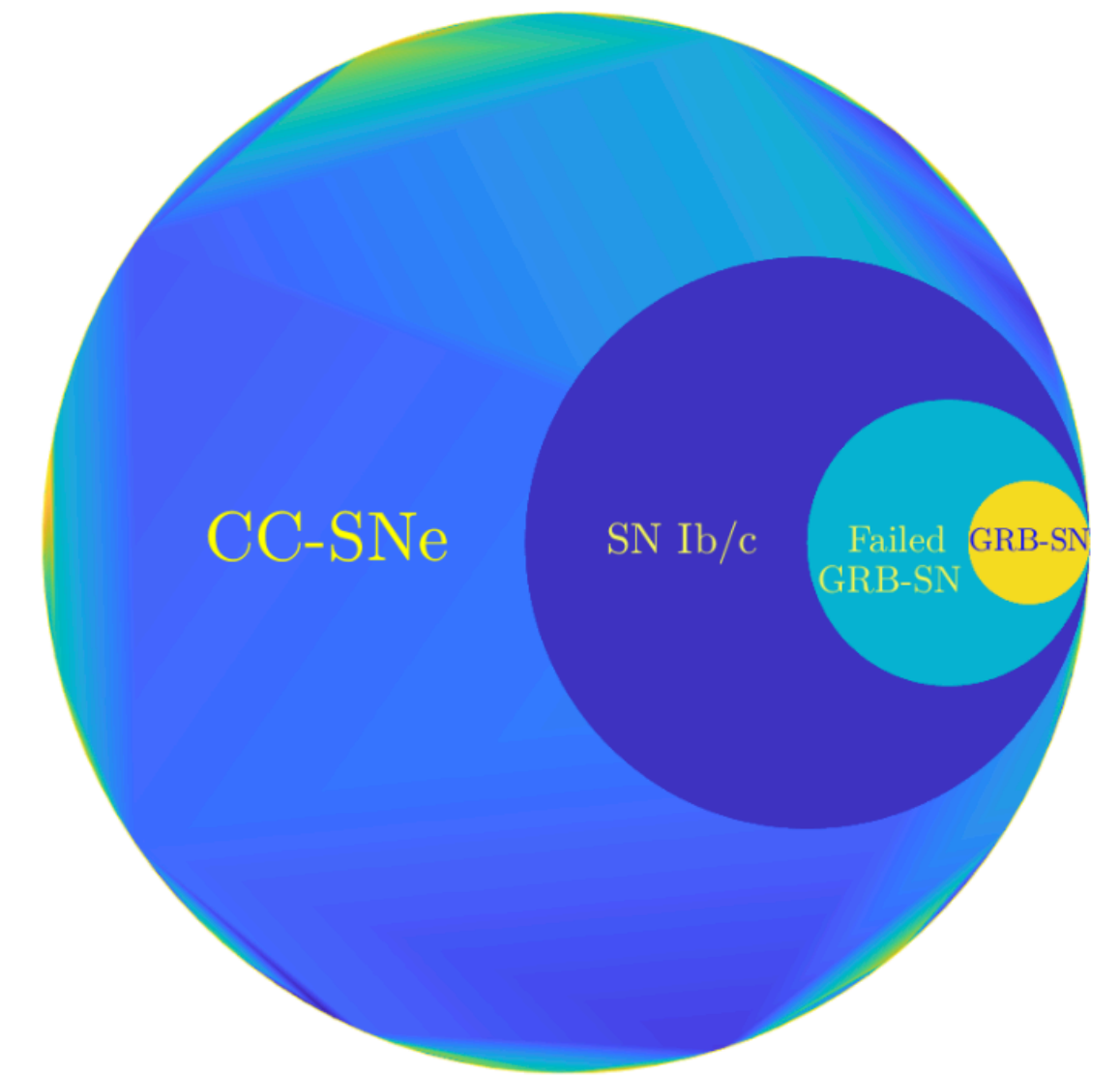
II-P (plateau), II-L (linear)

$^{56}\text{Ni}$ : few % to tens of %  $M_{\odot}$

Progenitor mass  $< 25 M_{\odot}$ ?

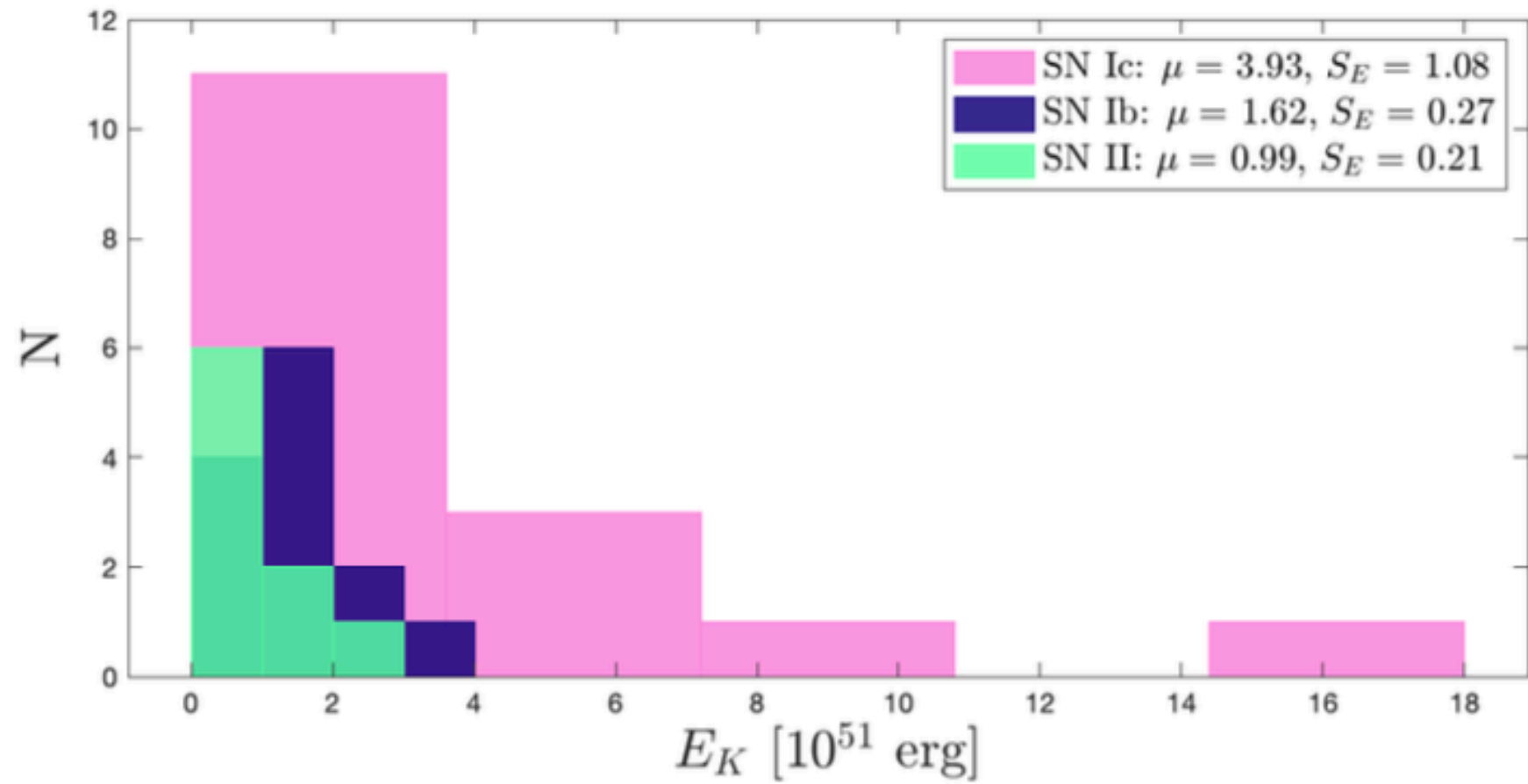
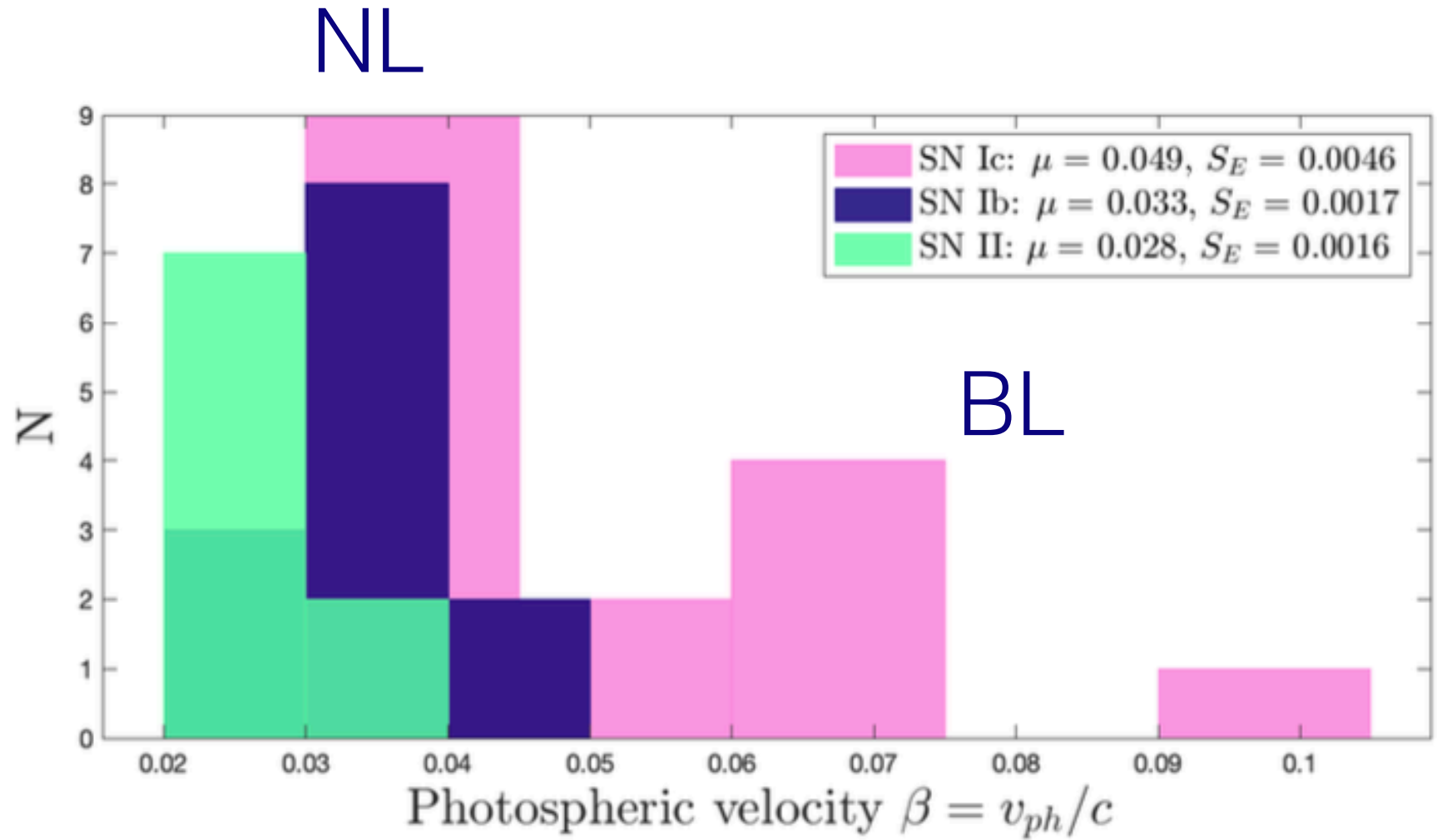
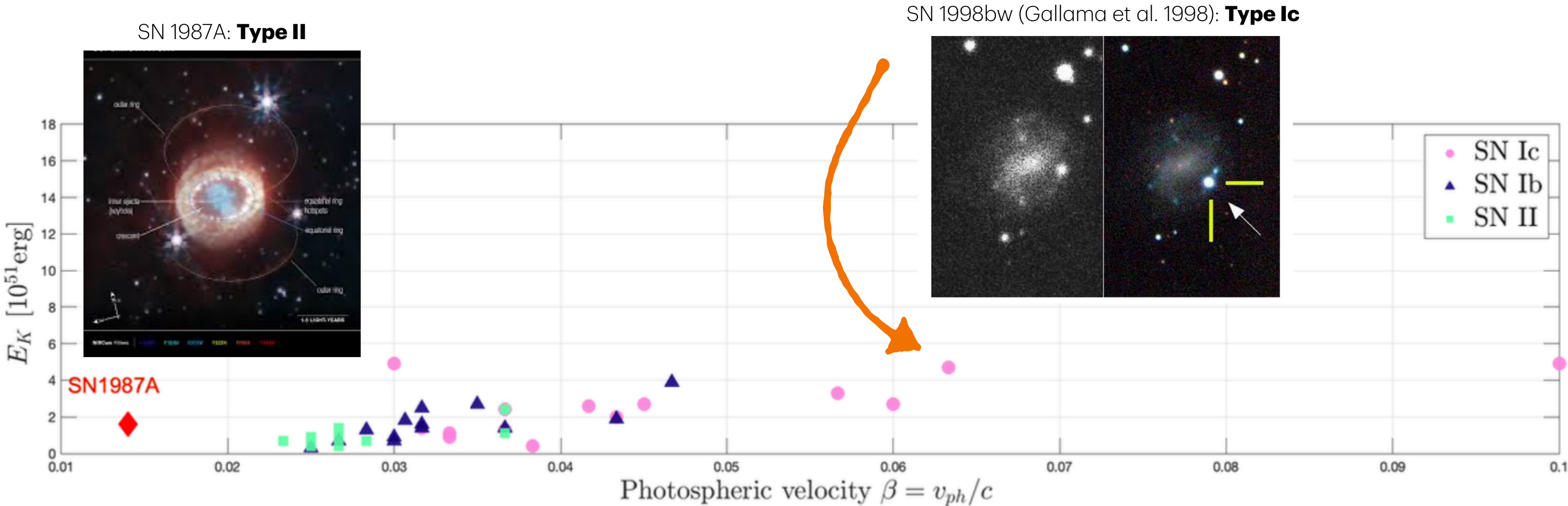
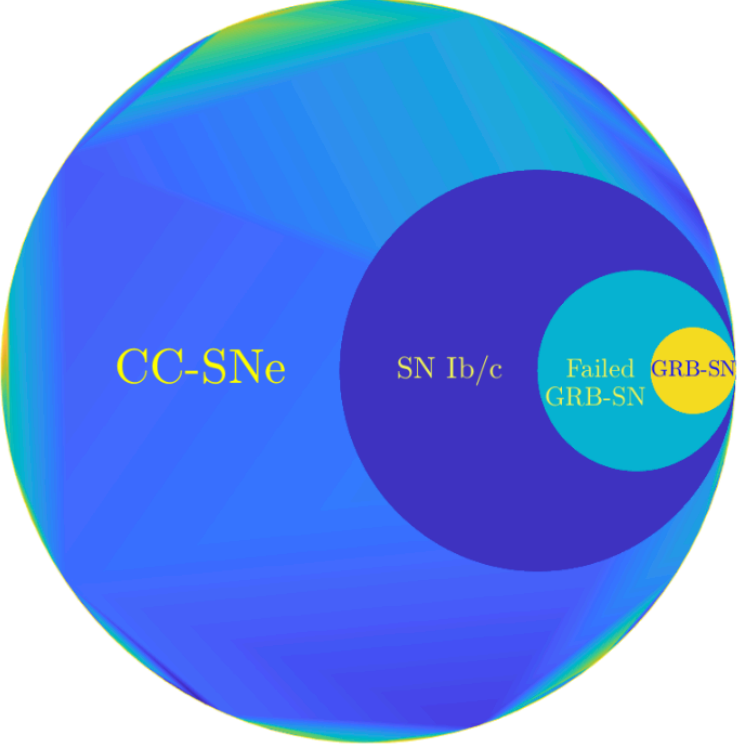
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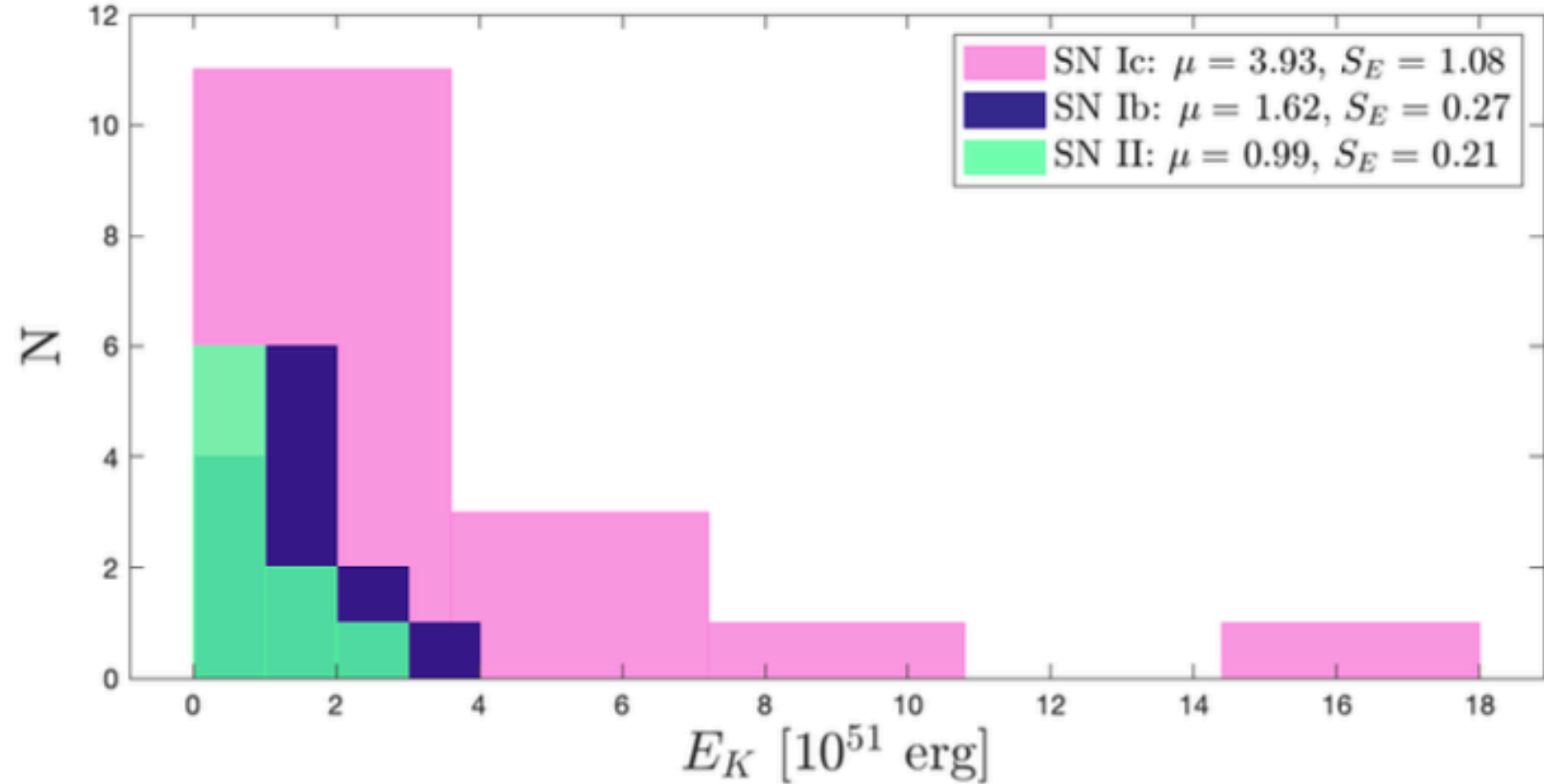
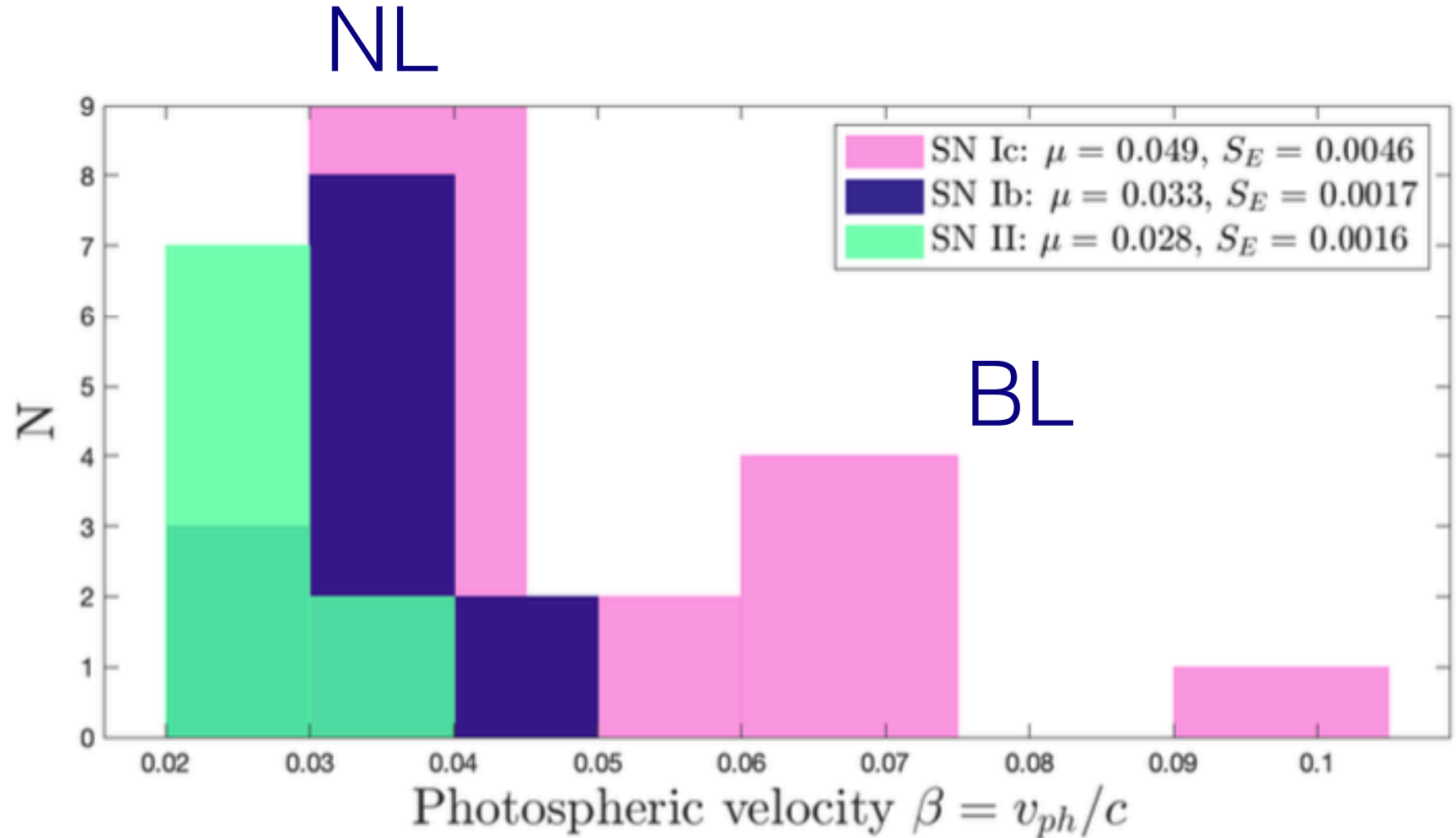
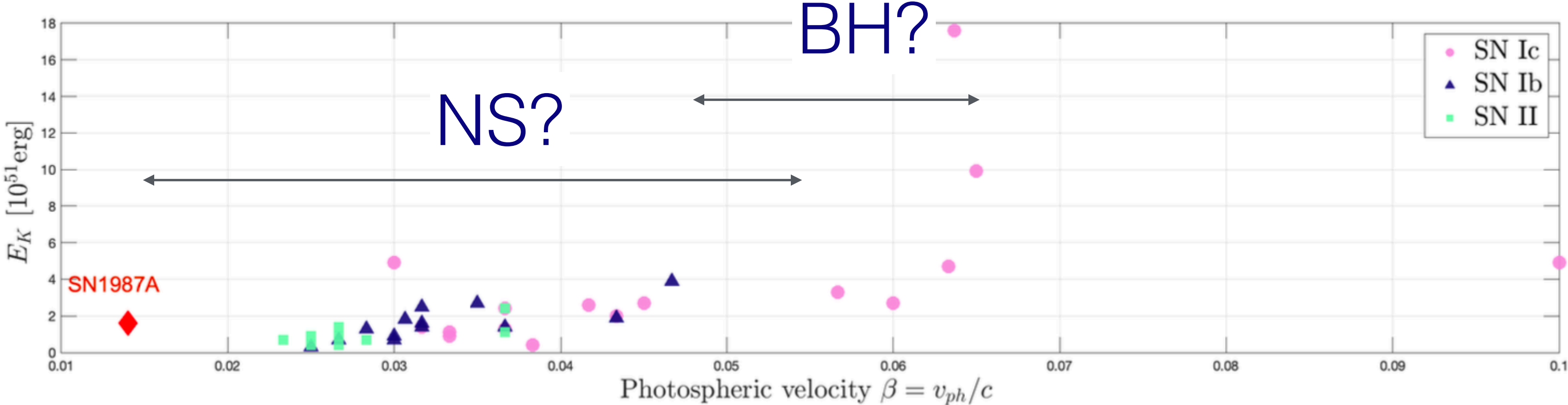
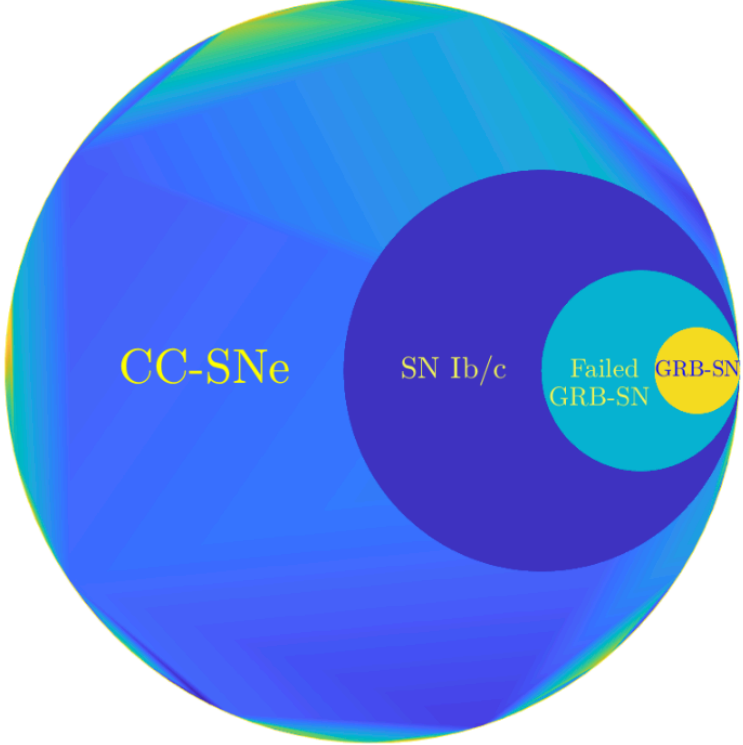
Phillips ApJL 1993  
 Maurer et al. MNRAS 2010  
 van Putten & Della Valle A&A Lett (2011)  
 Smartt 2015  
 Beasor et al. ApJ 2025

# Diversity in core-collapse supernovae



van Putten, Abchouyeh & Della Valle ApJL (2024)

# Diversity in core-collapse supernovae

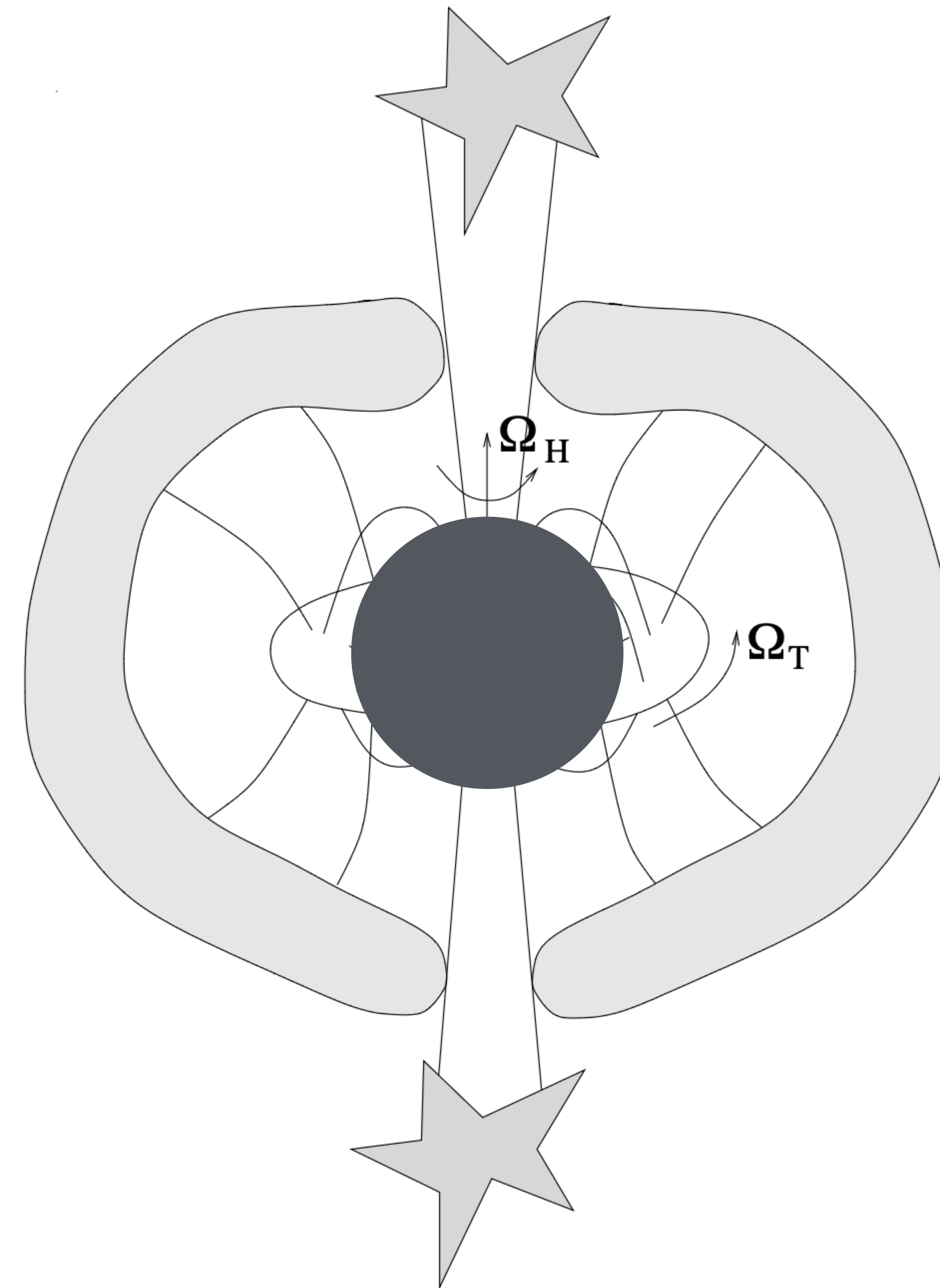


van Putten, Abchouyeh & Della Valle ApJL (2024)

# Angular momentum powered supernovae?

Bisnovatyi-Kogan, Sov. Ast. (1971):

$E_k$  from  $E_J$ -rich central engine:



... by NS or BH?

(HM)NS:

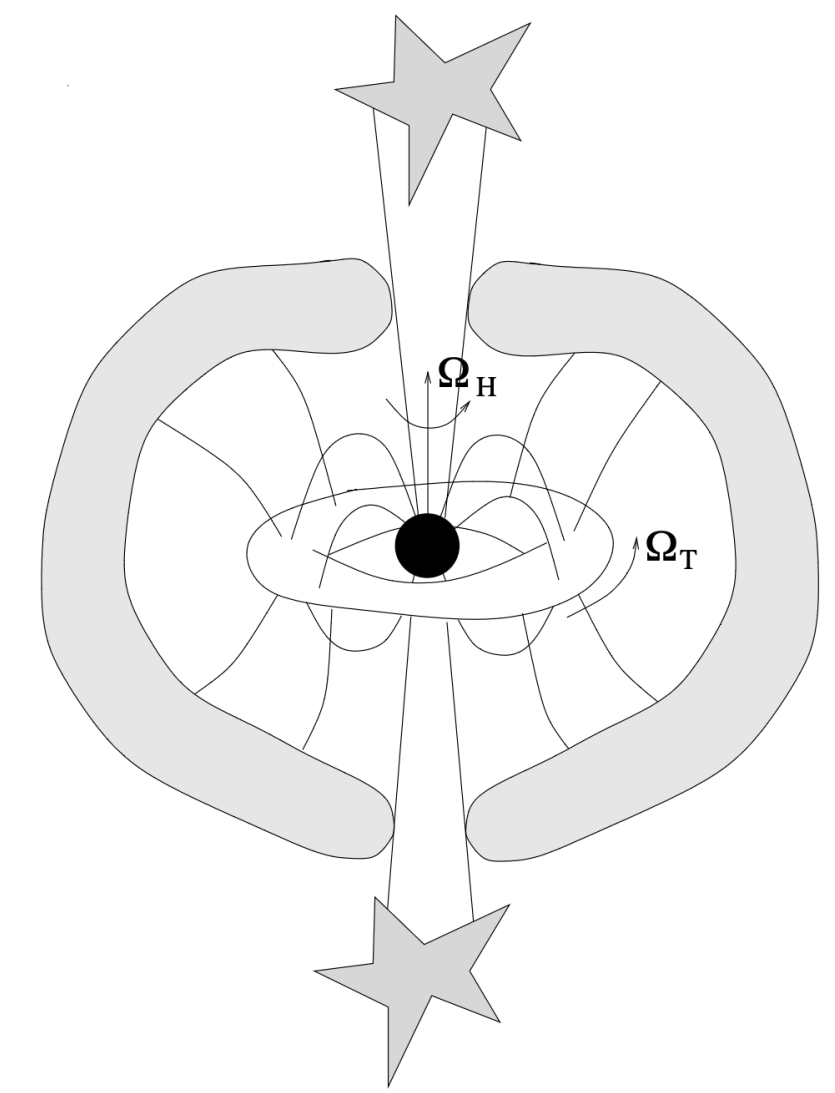
$$E_J^{NS} = \frac{\pi^2}{5} f_{gw}^2 MR^2 \simeq 0.07 Mc^2 \left( \frac{f}{2\text{KHz}} \right)^2 \left( \frac{R}{15\text{ km}} \right)^2$$

Kerr BH:

$$E_J^{BH} = 2Mc^2 \sin^2(\lambda/4) \simeq 0.29Mc^2 \left( \frac{\sin(\lambda/4)}{\sin(\pi/8)} \right)^2; \quad \sin \lambda = a/M$$

Readily feasible  $E_J^{BH} \gg \hat{E}_J^{NS}$  by choice of **spin rapidity**  $\lambda$  and mass  $M$

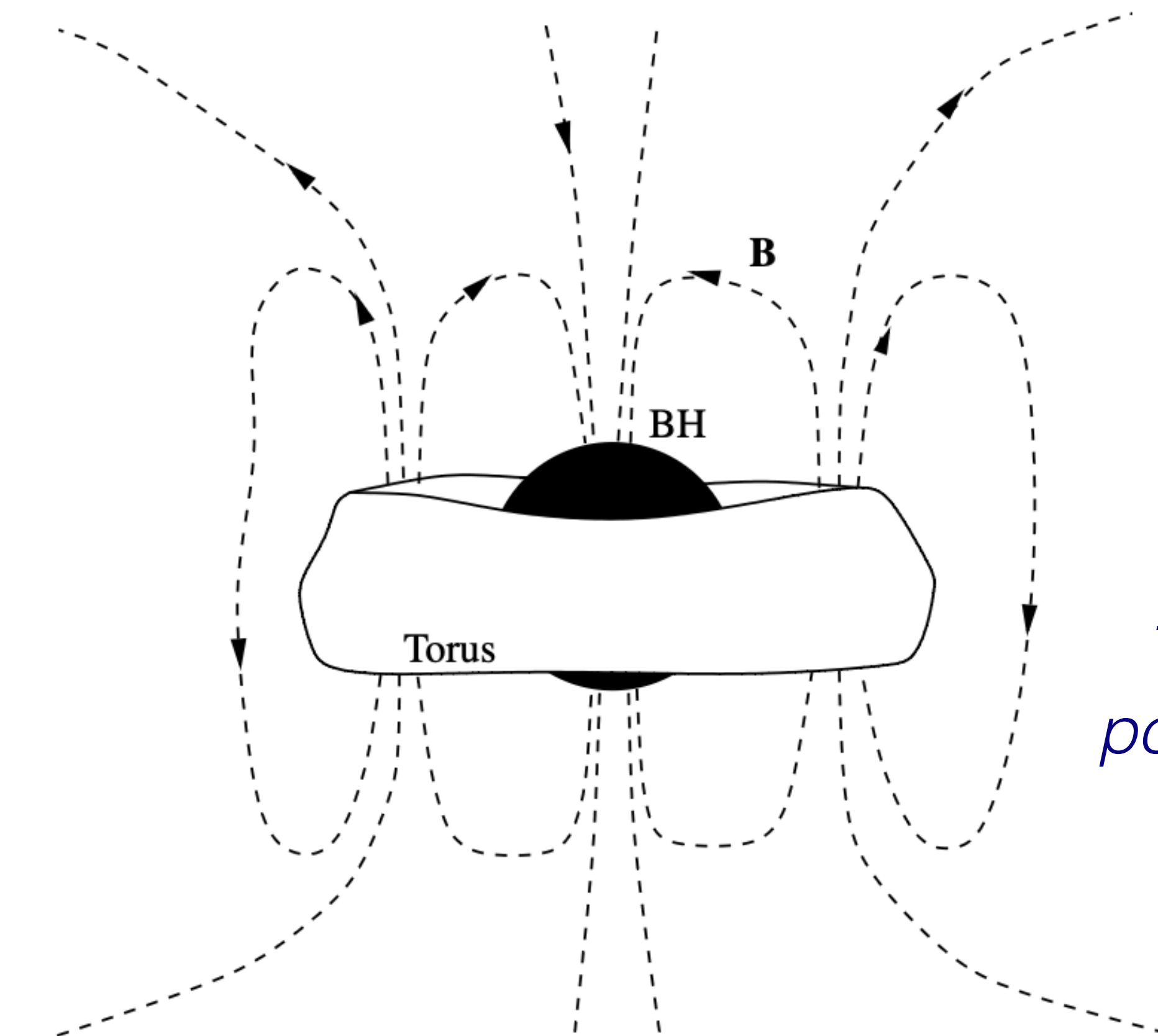
↳ Observable radiation channels?



van Putten, Levinson, Lee, Regimbau,  
Punturo & Harry, PRD 2004

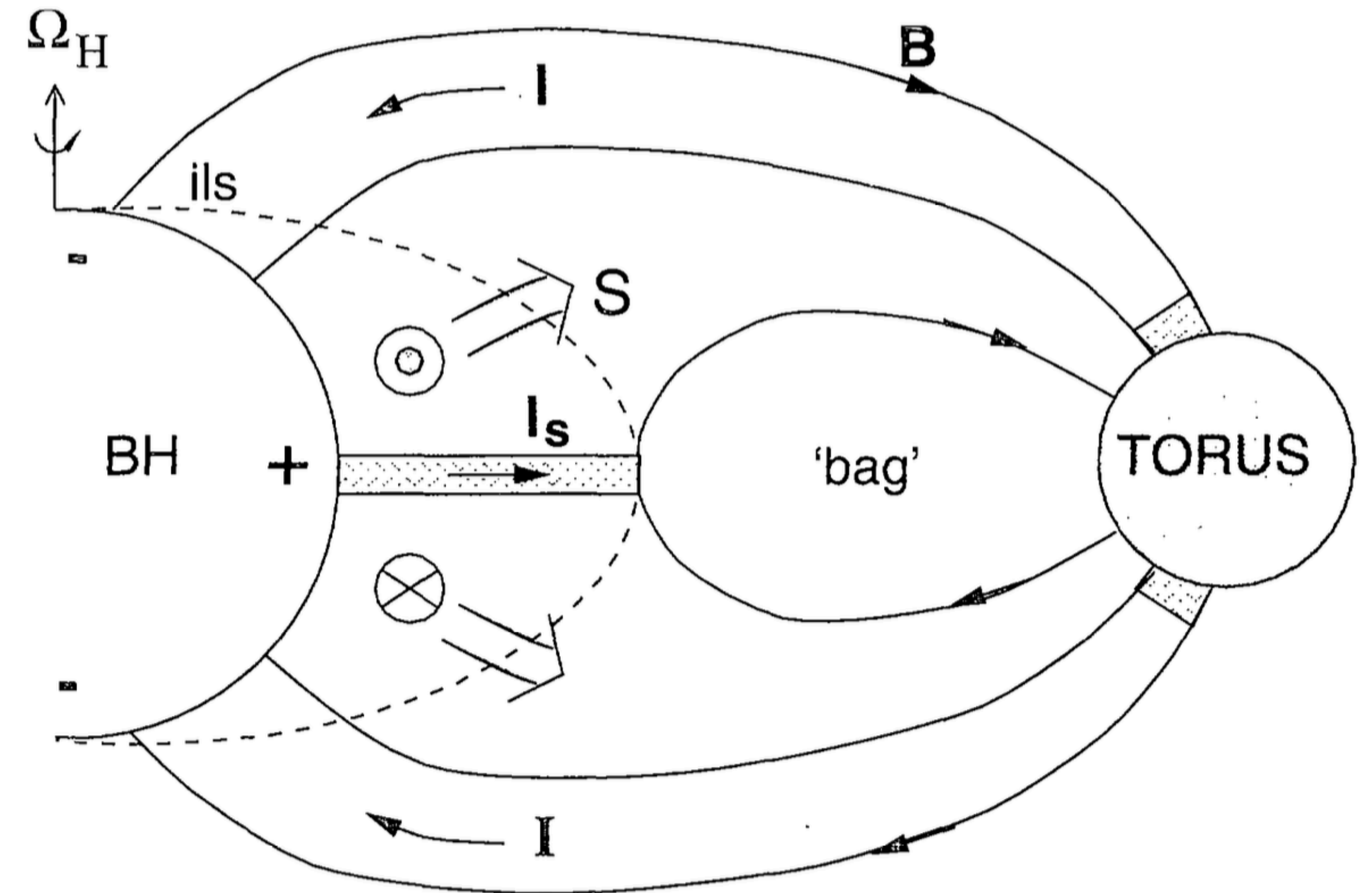
van Putten, Della Valle & Levinson ApJL 2019; A&A 2023

# Catalytic Energy Extraction Process (CEEP)



PRL 84 091101 (2001)

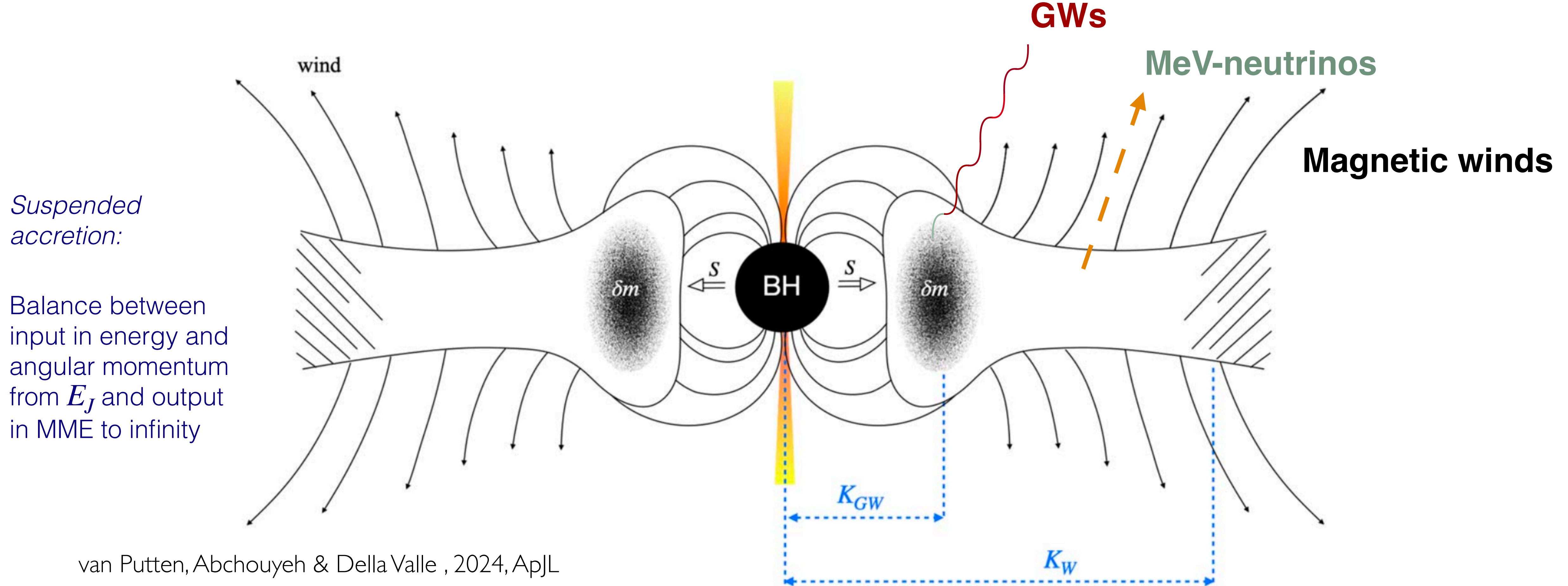
→  
*Topology in  
poloidal cross-  
section*



Science 284 115 (1999)

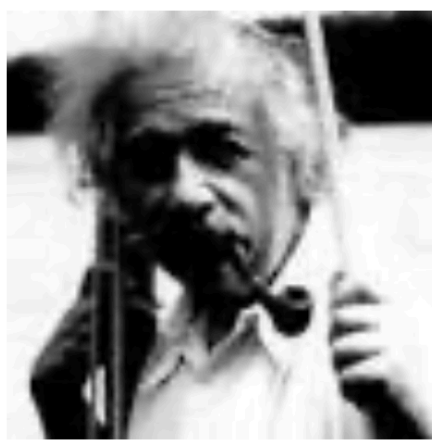
BH luminosity mostly incident onto the inner face of the torus

# Multi-Messenger Emission in suspended accretion

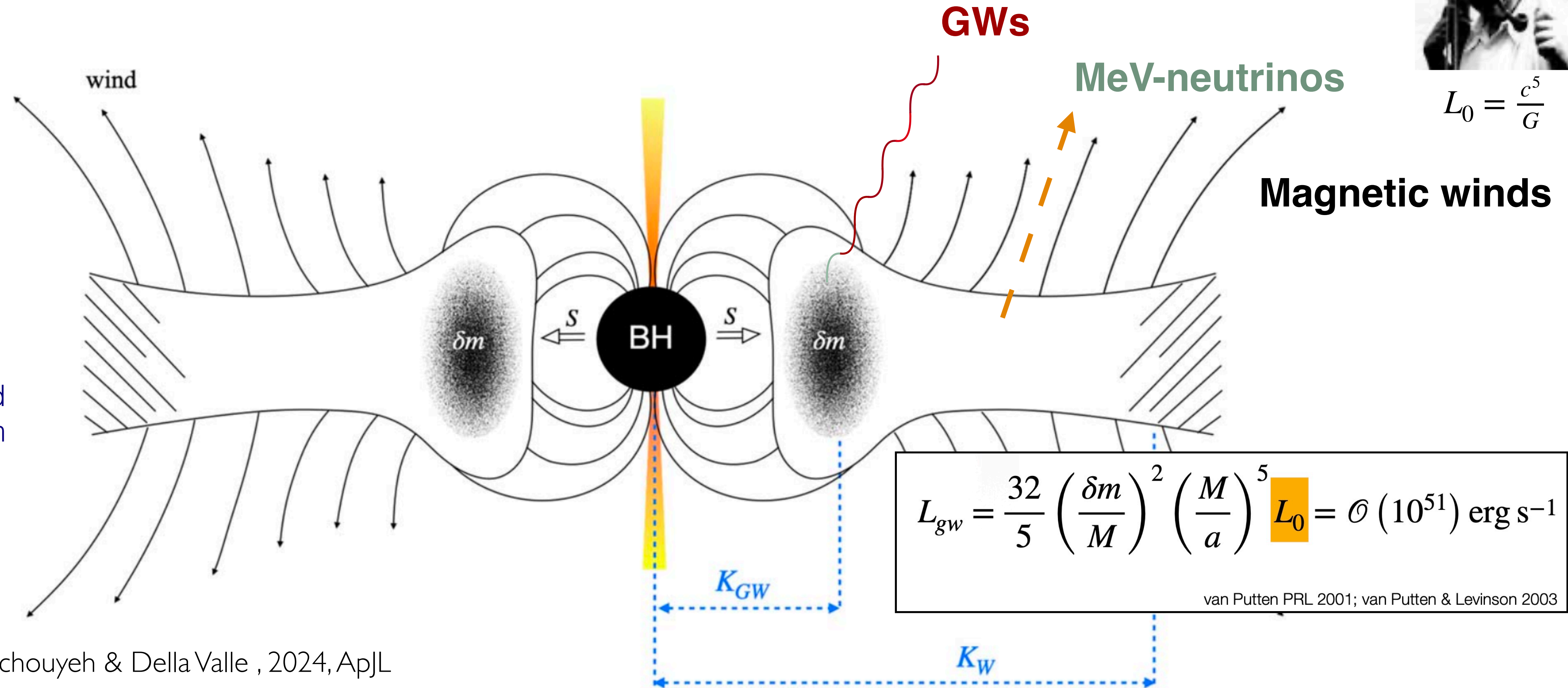


van Putten, Abchouyeh & Della Valle , 2024, ApJL

# Multi-Messenger Emission in suspended accretion



$$L_0 = \frac{c^5}{G}$$



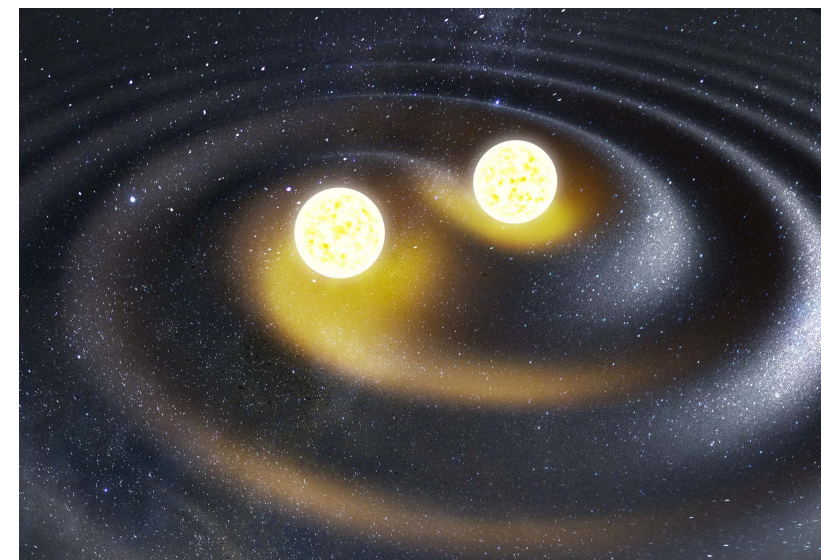
van Putten, Abchouyeh & Della Valle, 2024, ApJL

**GW-dominated** output when BH spins rapidly, faster than surrounding high-density matter

# GW170817/B-GRB170817A

van Putten, Della valle, Levinson, ApJL, 2019  
 van Putten & Della Valle A&A 2023  
 van Putten, Abchouyeh & Della Valle, ApJL, 2024

GW170817

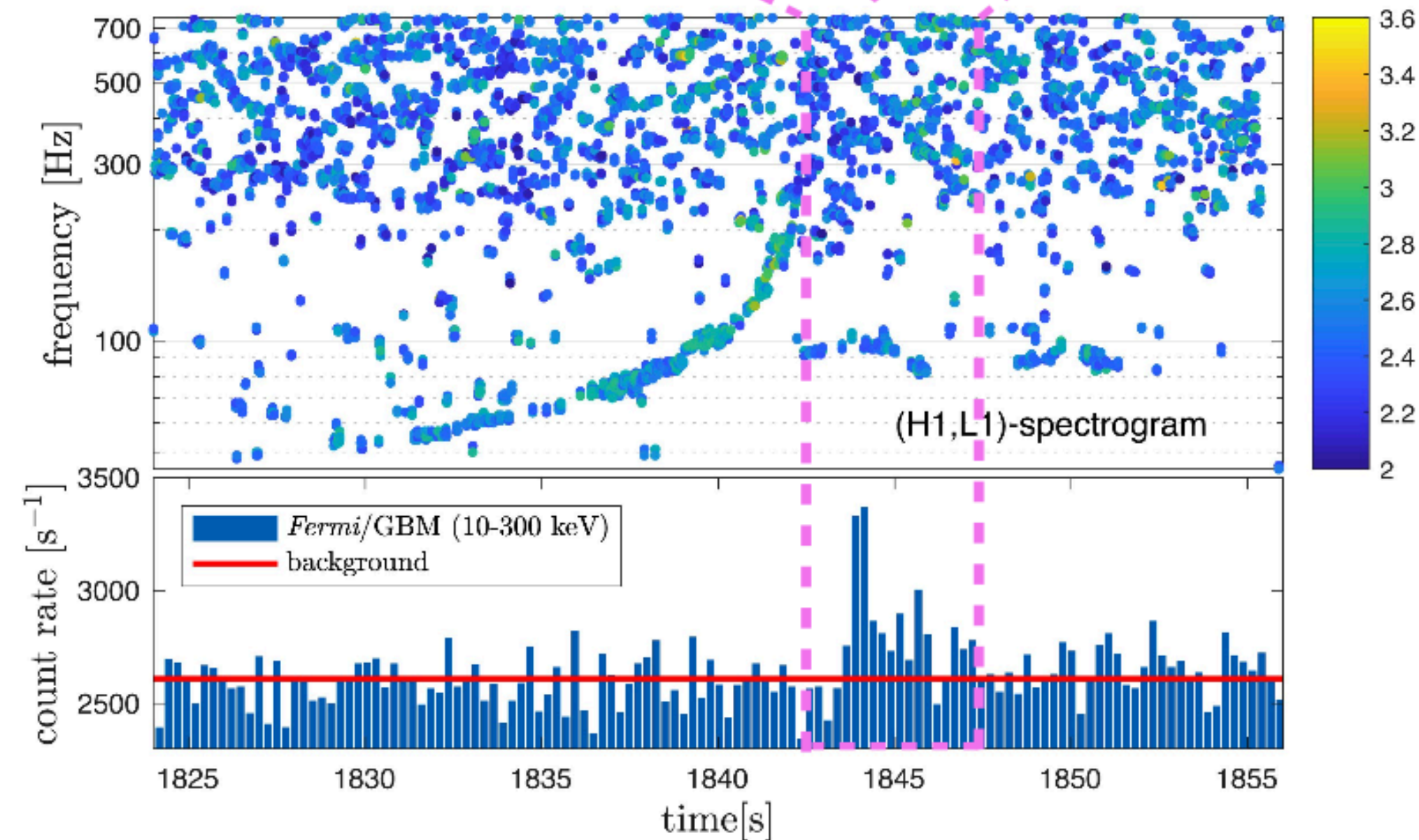
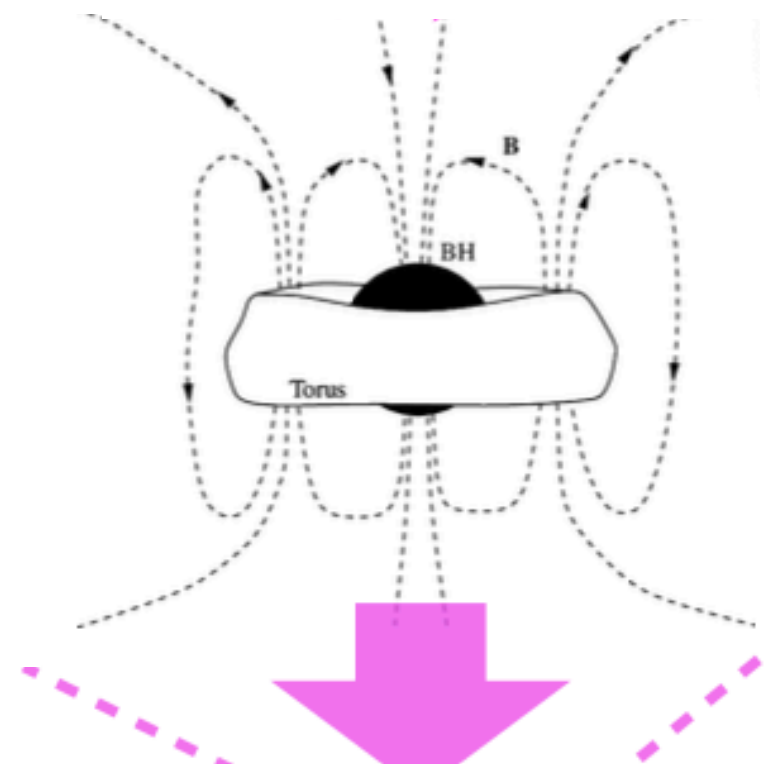


Ascending chirp  
 from a merger:

$$\text{♩} G_1 - C_4^\#$$

$$D = 40\text{Mpc}$$

Abbott et al. 2017



GW170817B



Descending chirp  
 from spin-down:

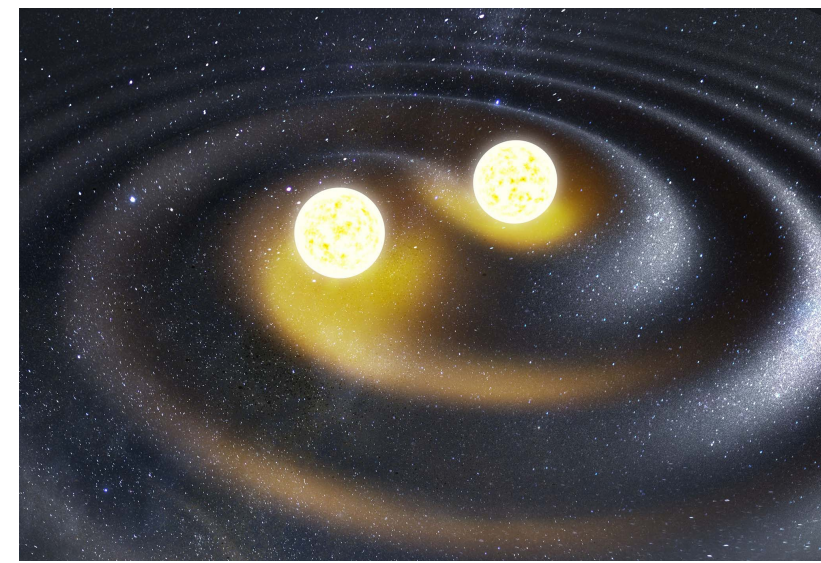
$$\text{♩} F_5 - G_3^\#$$

Un-modeled observation at  $5.5\sigma$  using BMF

# GW170817/B-GRB170817A

van Putten, Della valle, Levinson, ApJL, 2019  
 van Putten & Della Valle A&A 2023  
 van Putten, Abchouyeh & Della Valle, ApJL, 2024

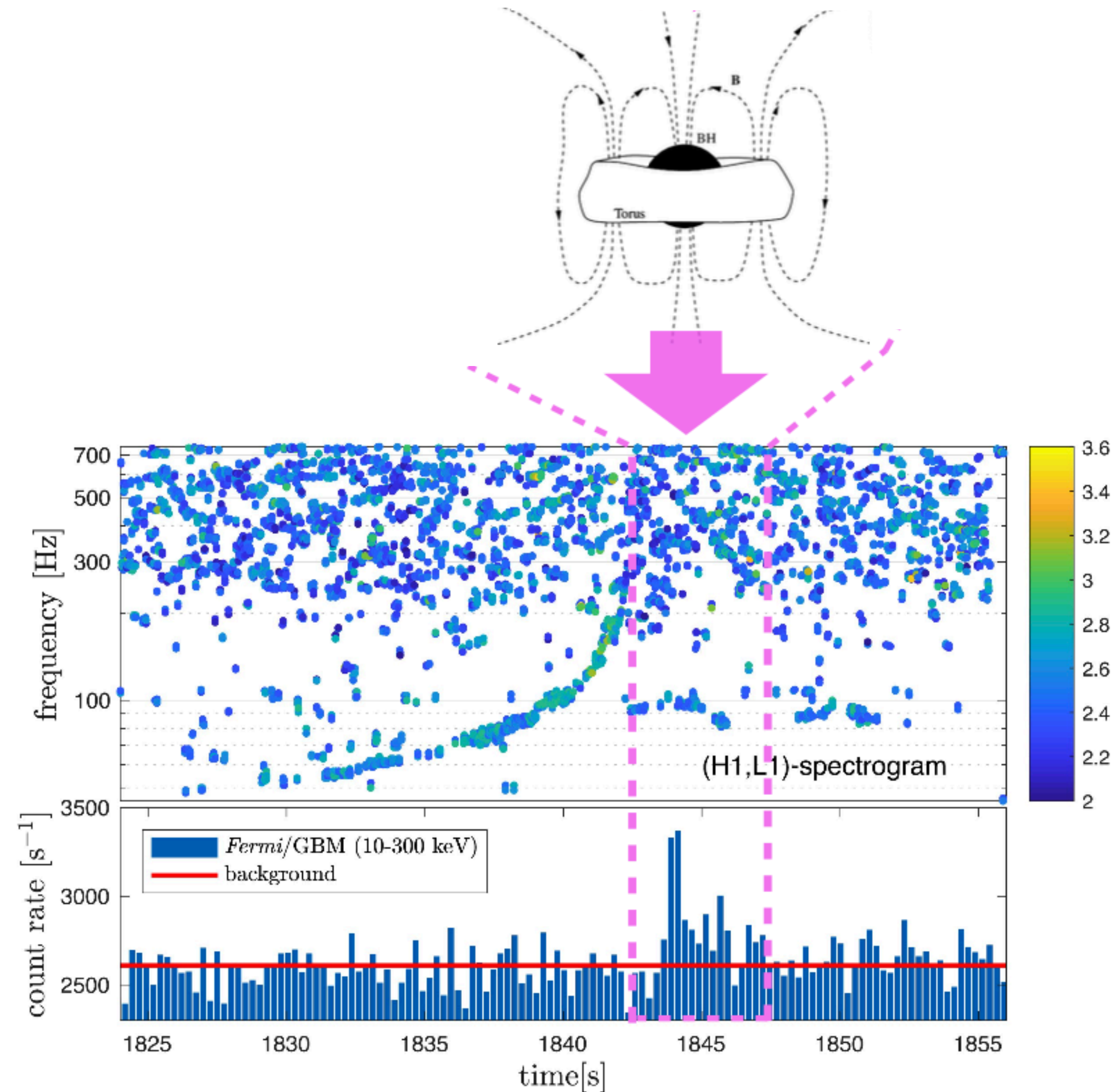
GW170817



$$E_{GW} \simeq 2.5 \% M_{\odot}$$

$$M_0 \simeq (2.74 \pm 0.04) M_{\odot}$$

Abbott et al. 2017



GW170817B



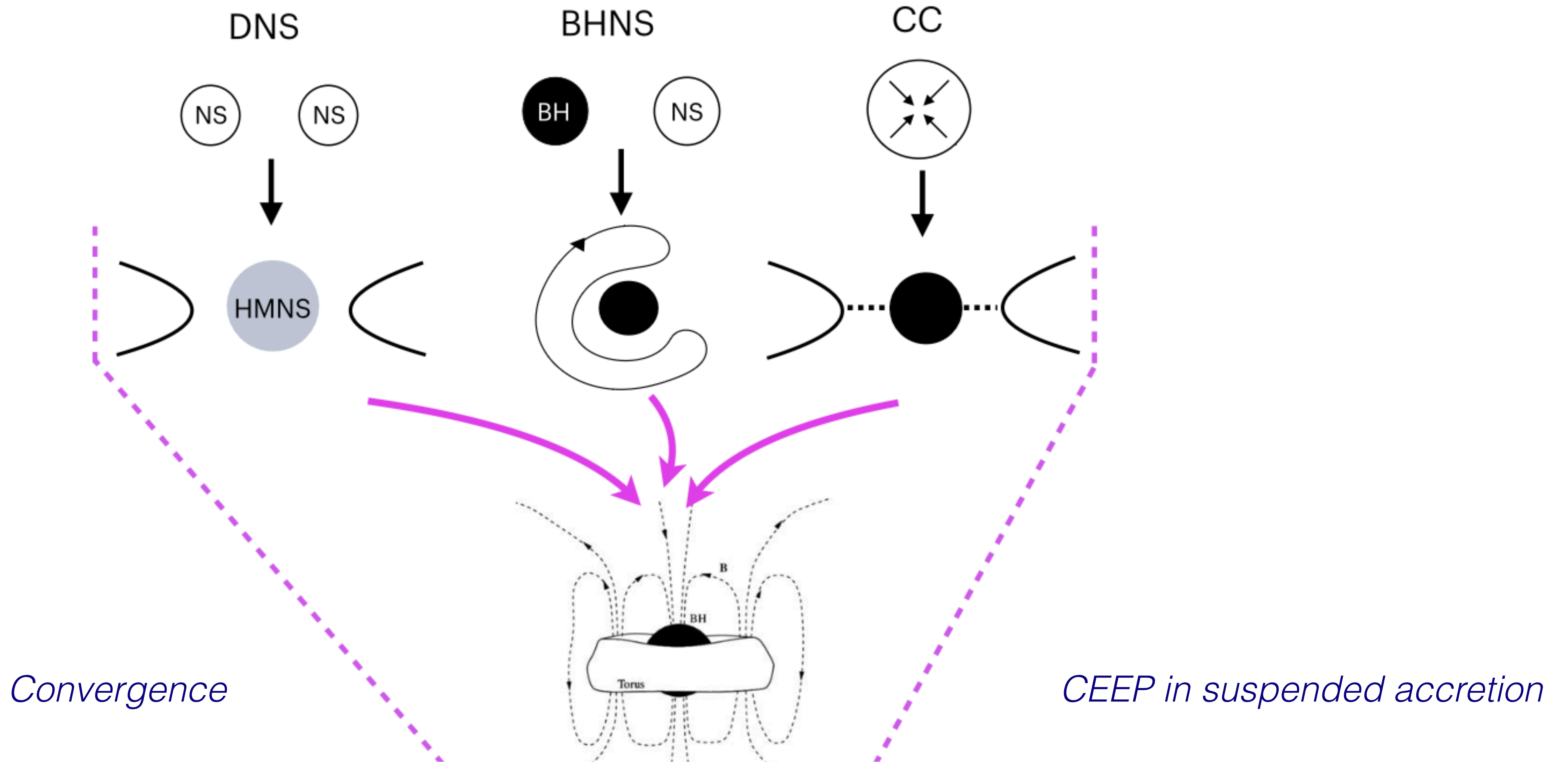
$$E_{GW} \simeq 3.5 \% M_{\odot}$$

$$M \simeq (2.8 \pm 0.3) M_{\odot}$$

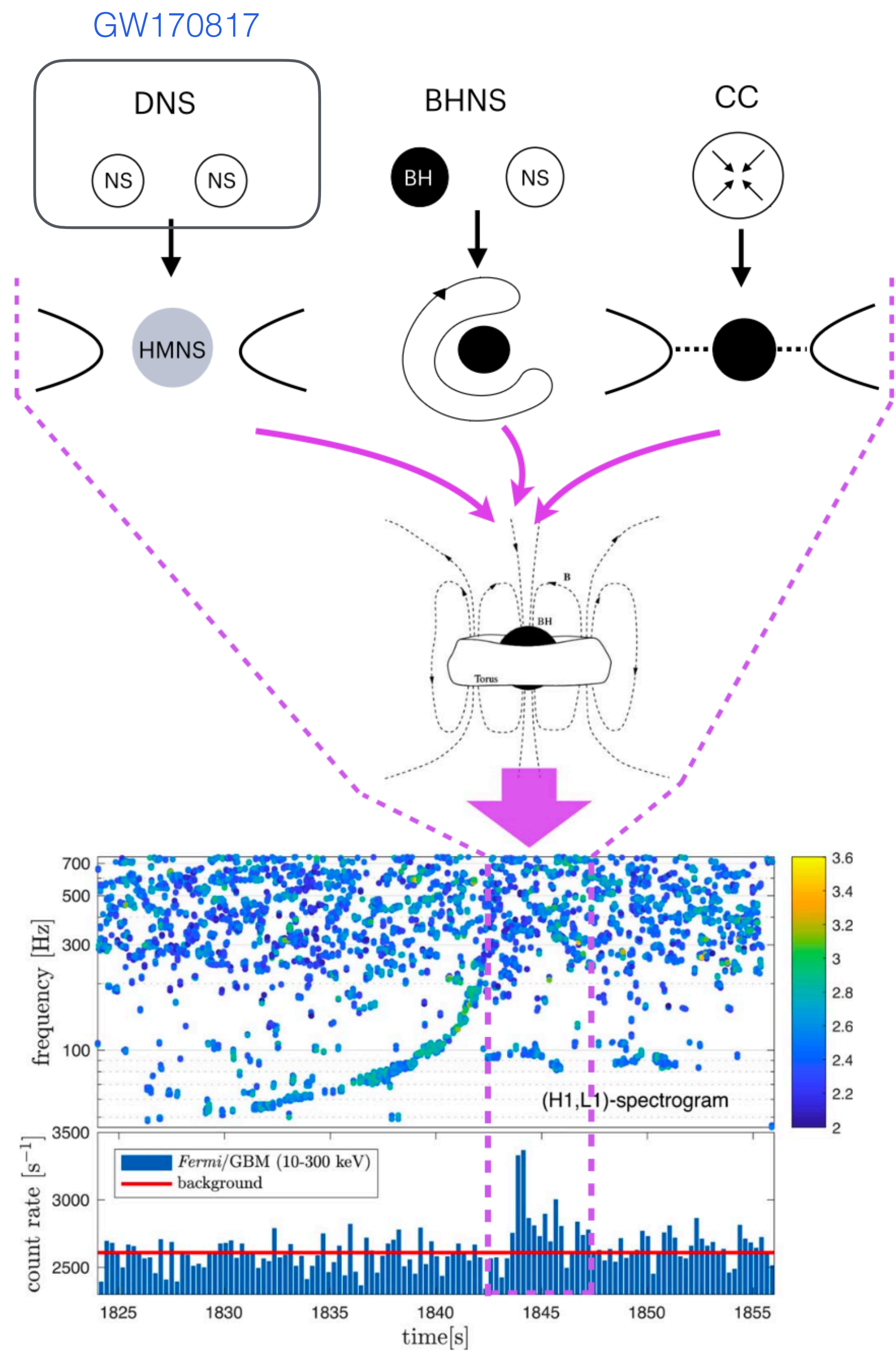
$$E_{GW} > 2 \times \hat{E}_J^{NS}$$

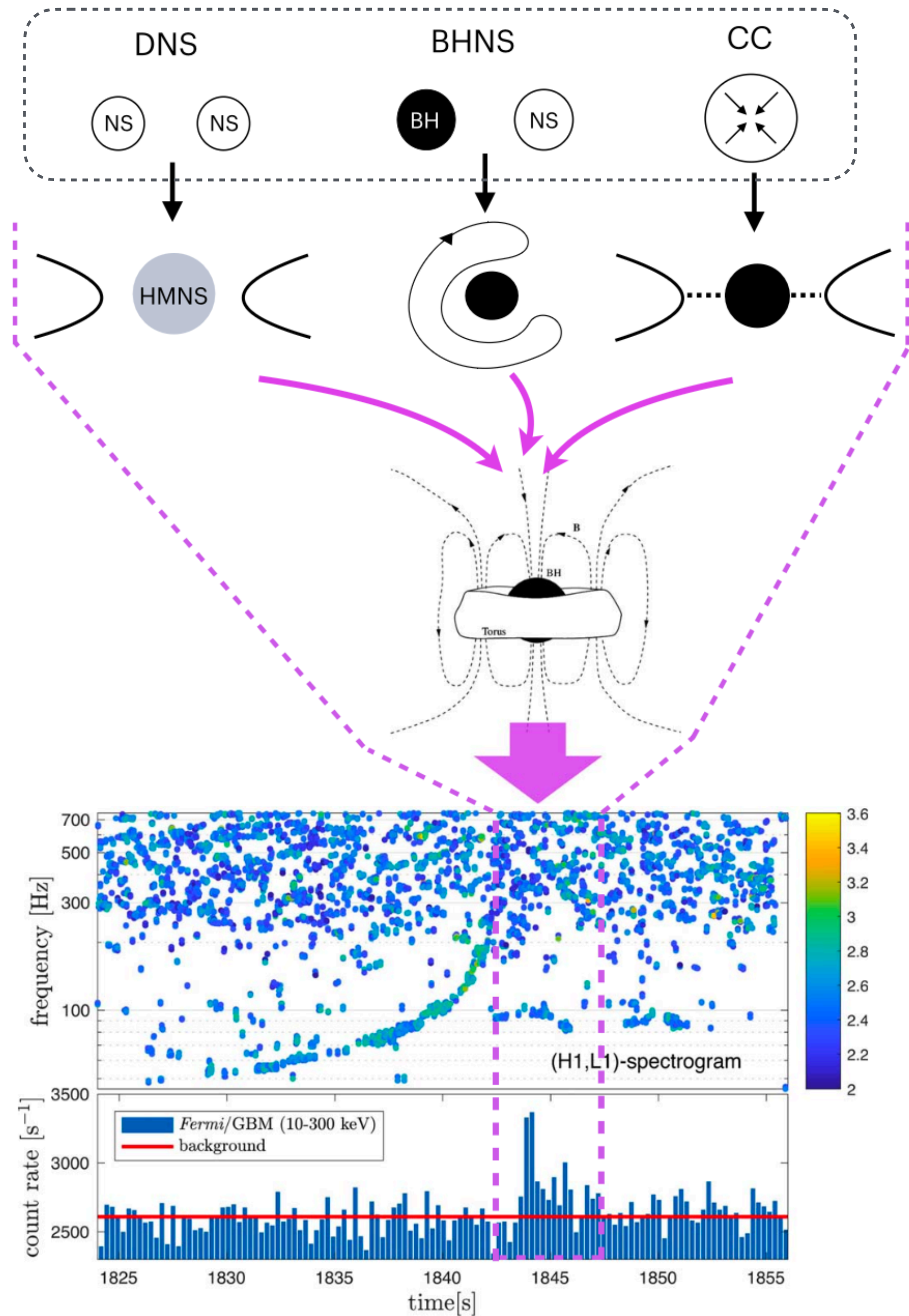
$$E_{EM} \lesssim 0.5 \% M_{\odot} c^2$$

CBC transitions to BH spin-down following delayed gravitational collapse:  $\Delta m_{GW} \sim 1$



# Black hole universality





Mass-scaling law for descending branch  $(E, f)$ :

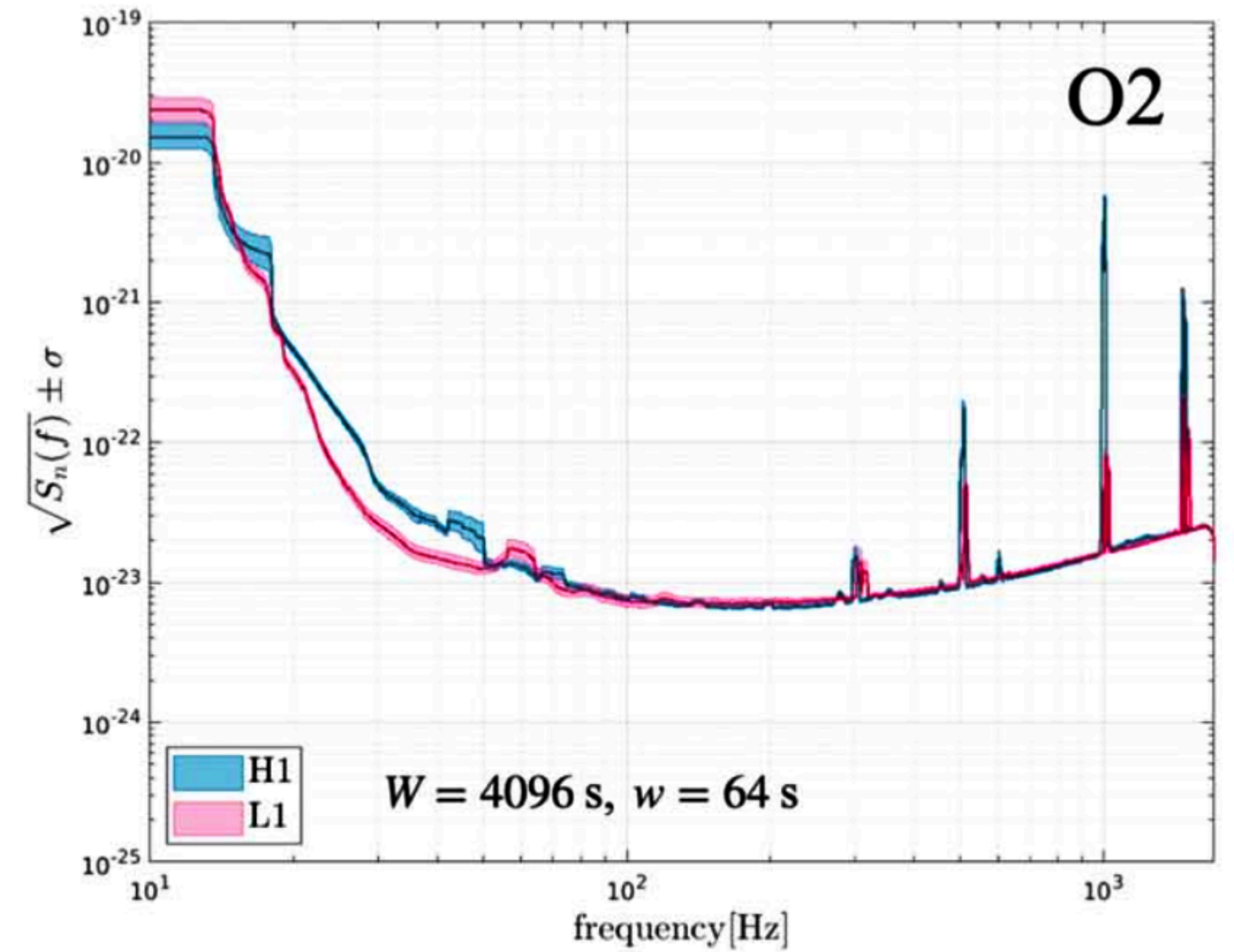
$$E_{GW} \simeq 3.5 \% \left( \frac{M}{M_0} \right) M_{\odot} c^2$$

$$f_{GW} \simeq (700 - 200) \left( \frac{M_0}{M} \right) \text{ Hz}$$

# Prospect to probe for BH central engines

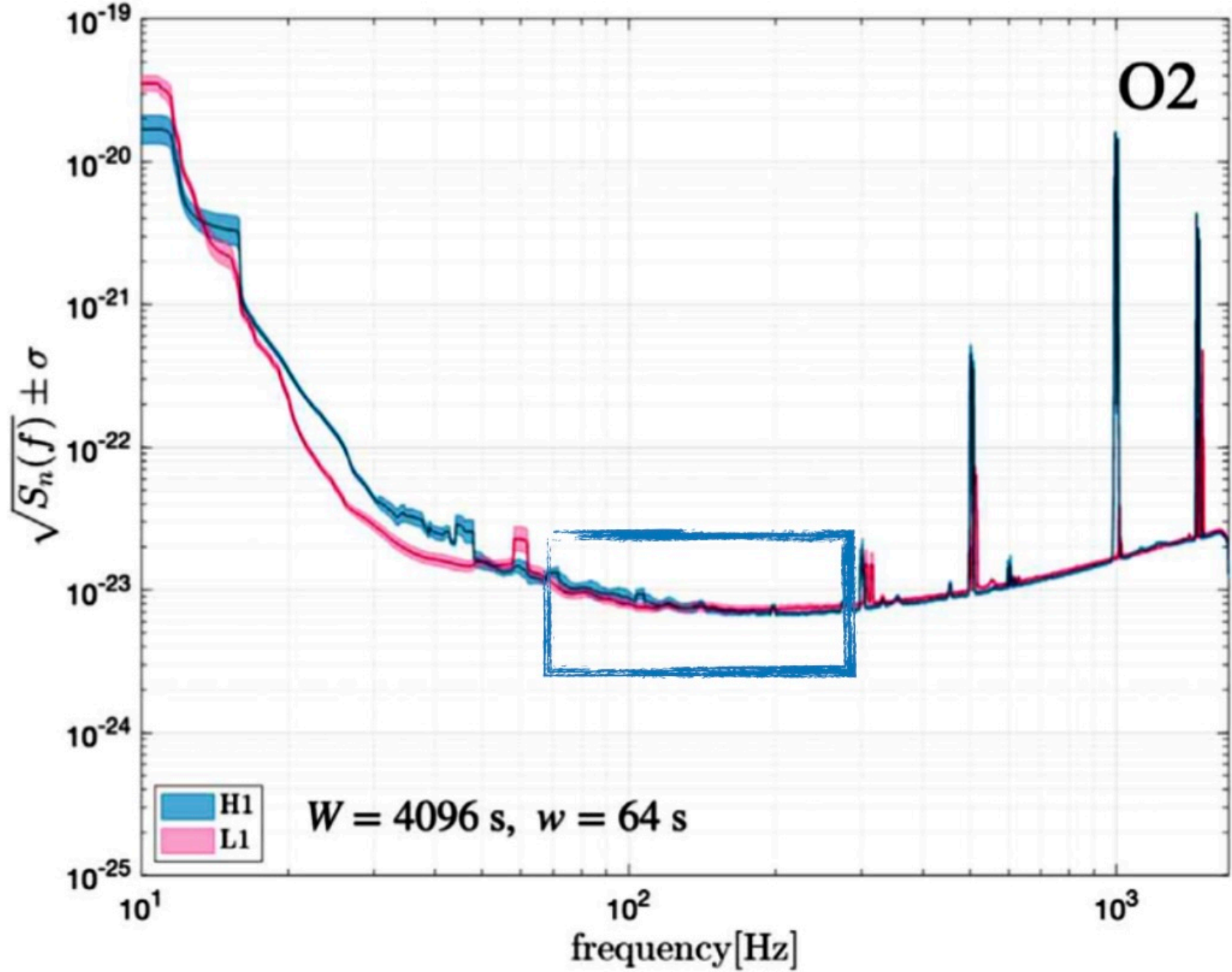
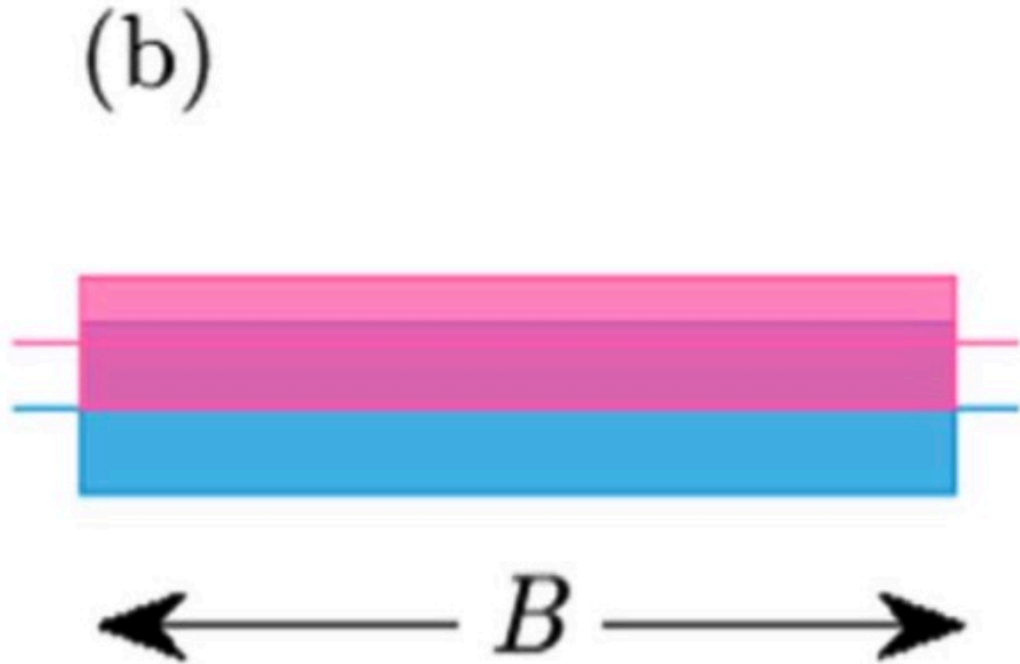
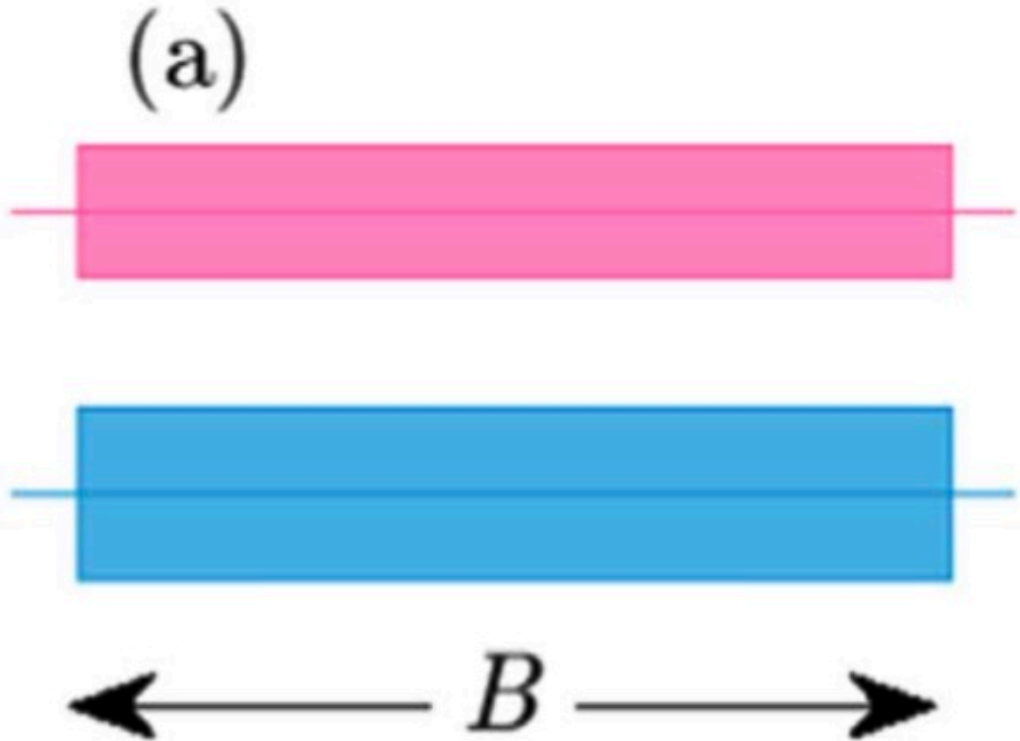
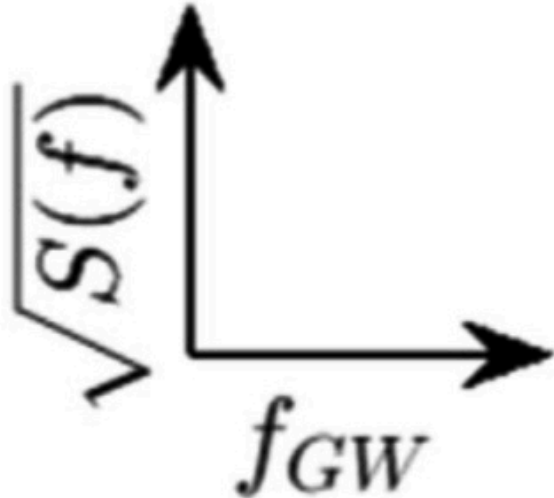
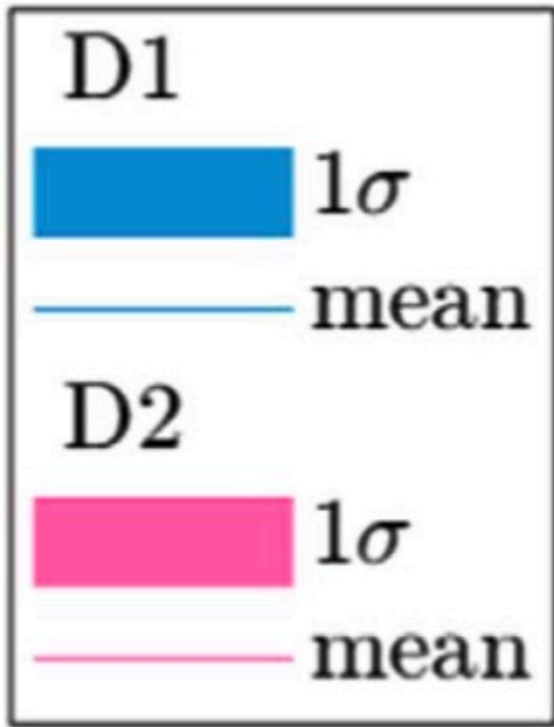
**Mass-scaling of descending branch**  $(E, f)_{\text{GW170817B}}$

$k_M \gtrsim 2$ : Energy output from a more massive BH ( $M \gtrsim 5 M_\odot$ )



# Sweet spot in sensitivity...

Detector pair at nominal performance over  $B = 100 - 250$  Hz

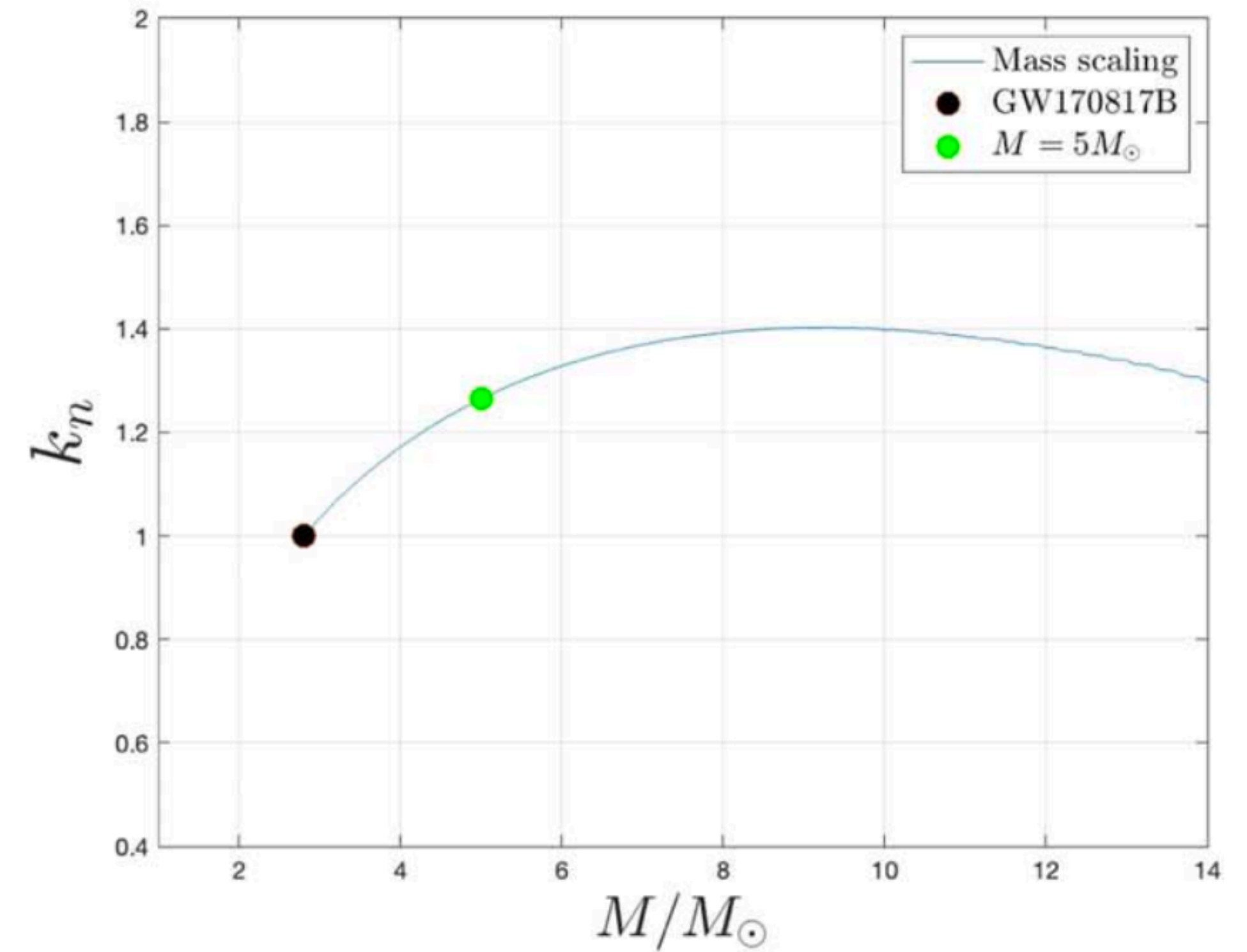


# Prospects to probe for BH central engines

## Mass-scaling of descending branch $(E, f)_{\text{GW170817B}}$

$k_M \gtrsim 2$ : Energy output from a more massive BH ( $M \gtrsim 5 M_\odot$ )

$k_n \simeq 1.3$ : Frequency from more massive BH is closer to “sweet spot”



# Prospects to probe for BH central engines

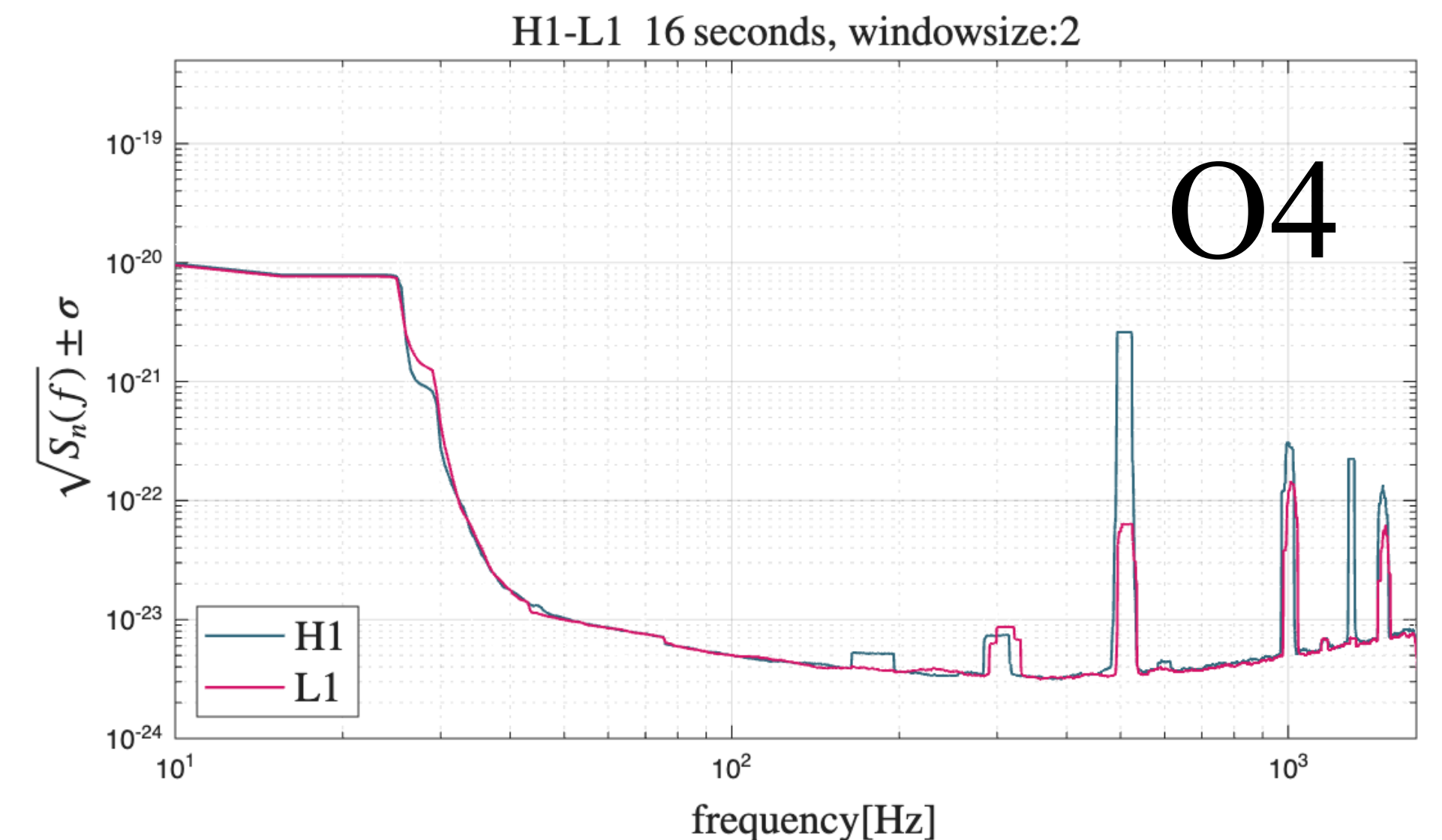
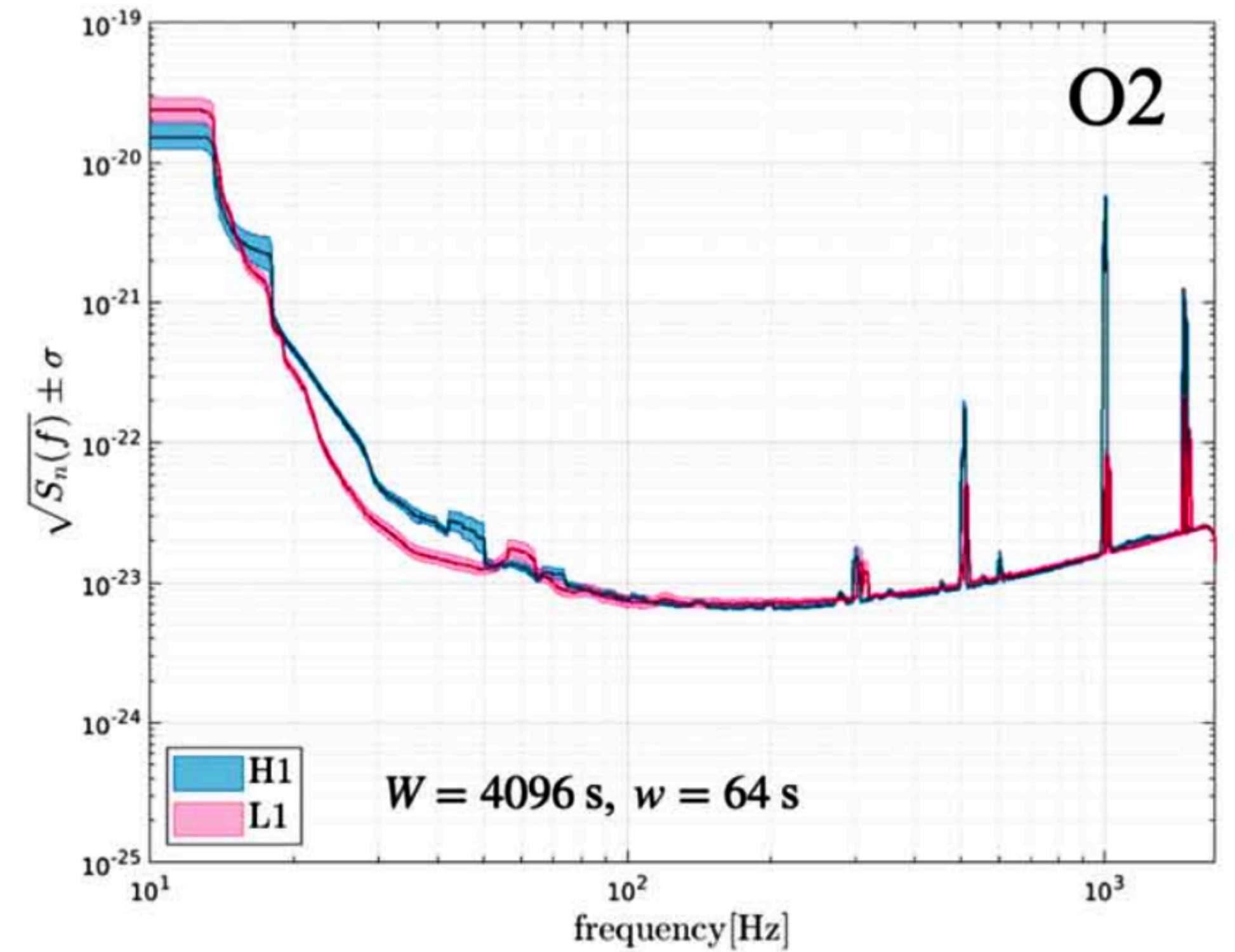
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## Improvement in detector sensitivity O4/O2

$$k_D = 1.8$$



# Prospects to probe for BH central engines

## Mass-scaling of descending branch $(E, f)_{\text{GW170817B}}$

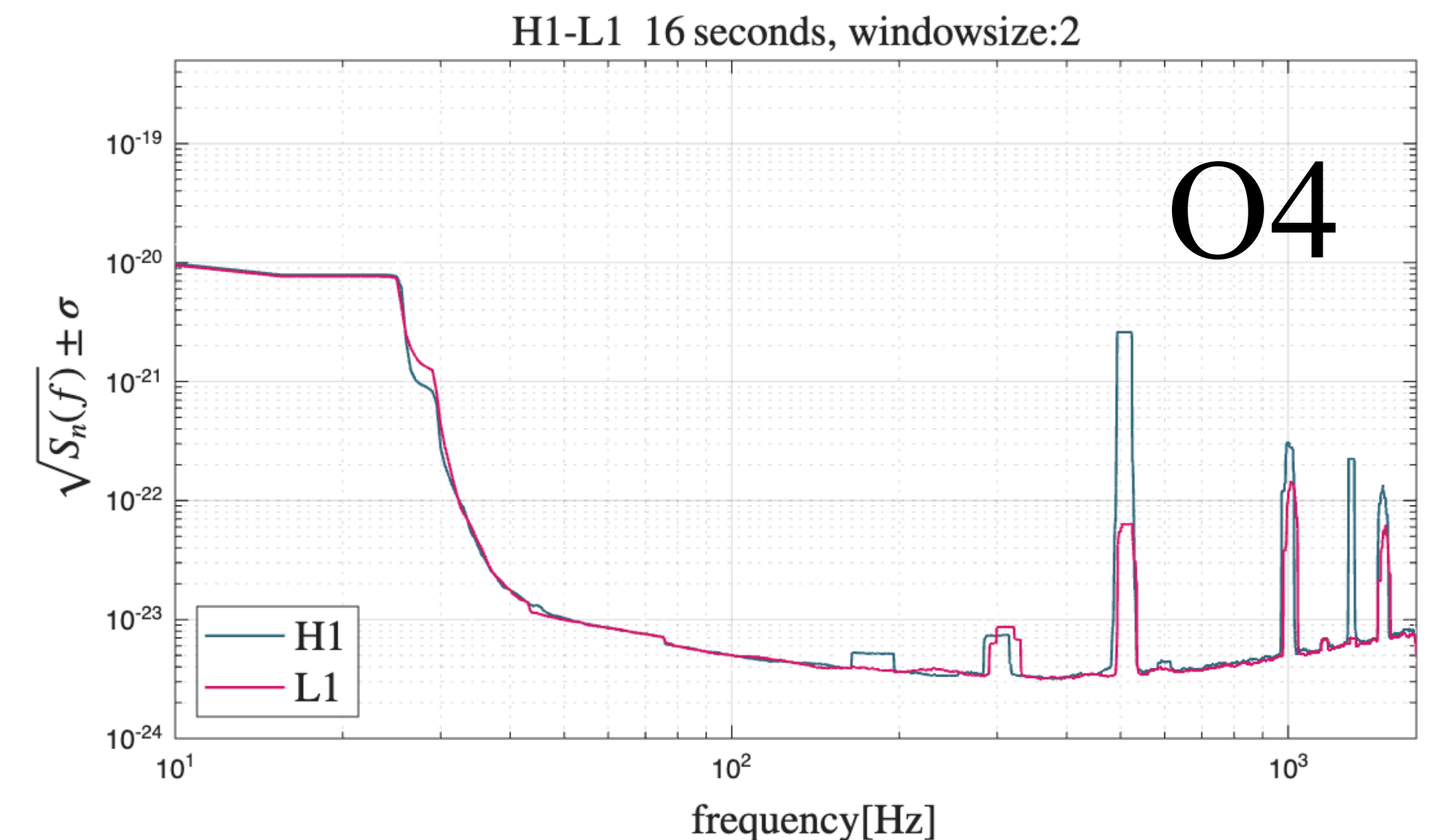
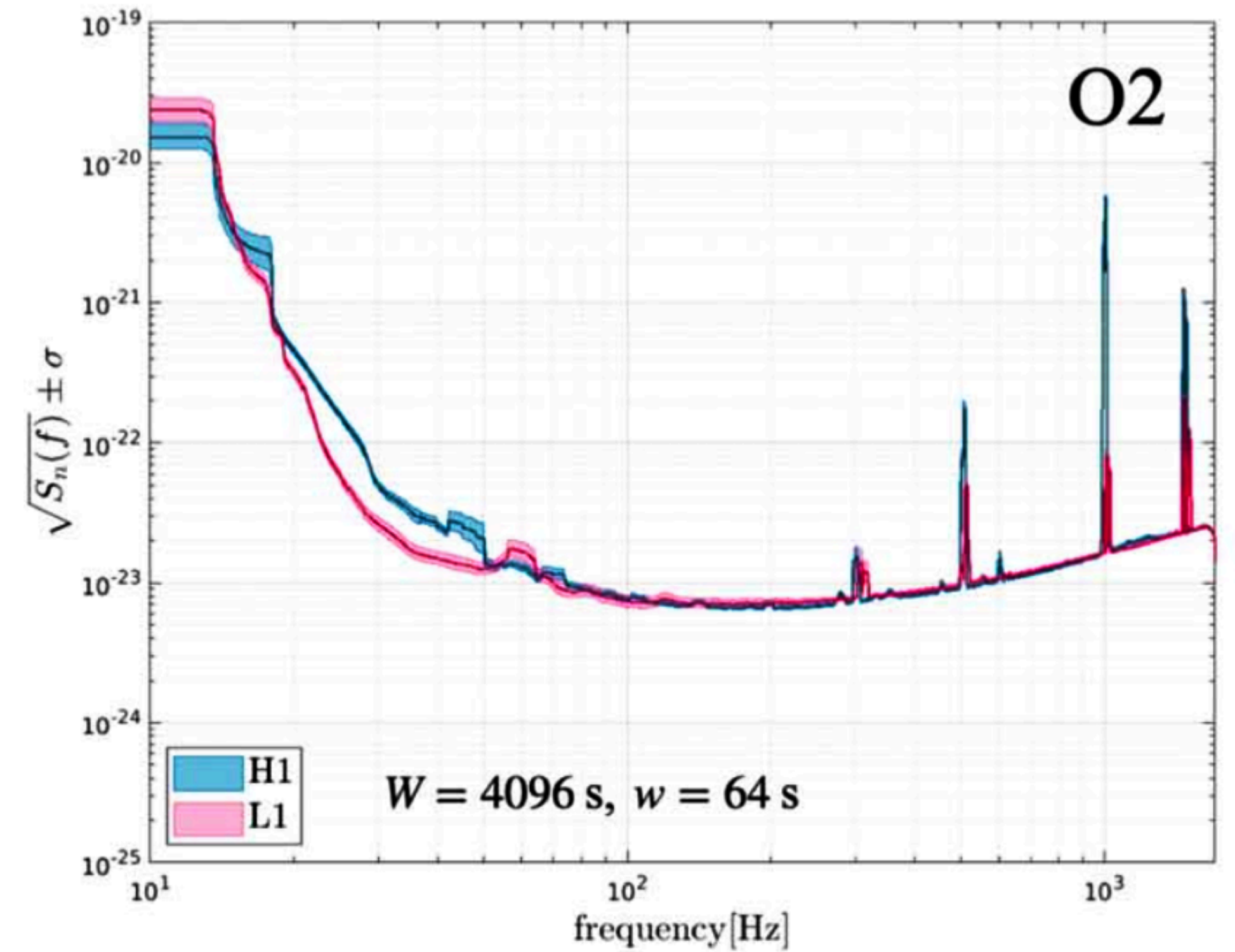
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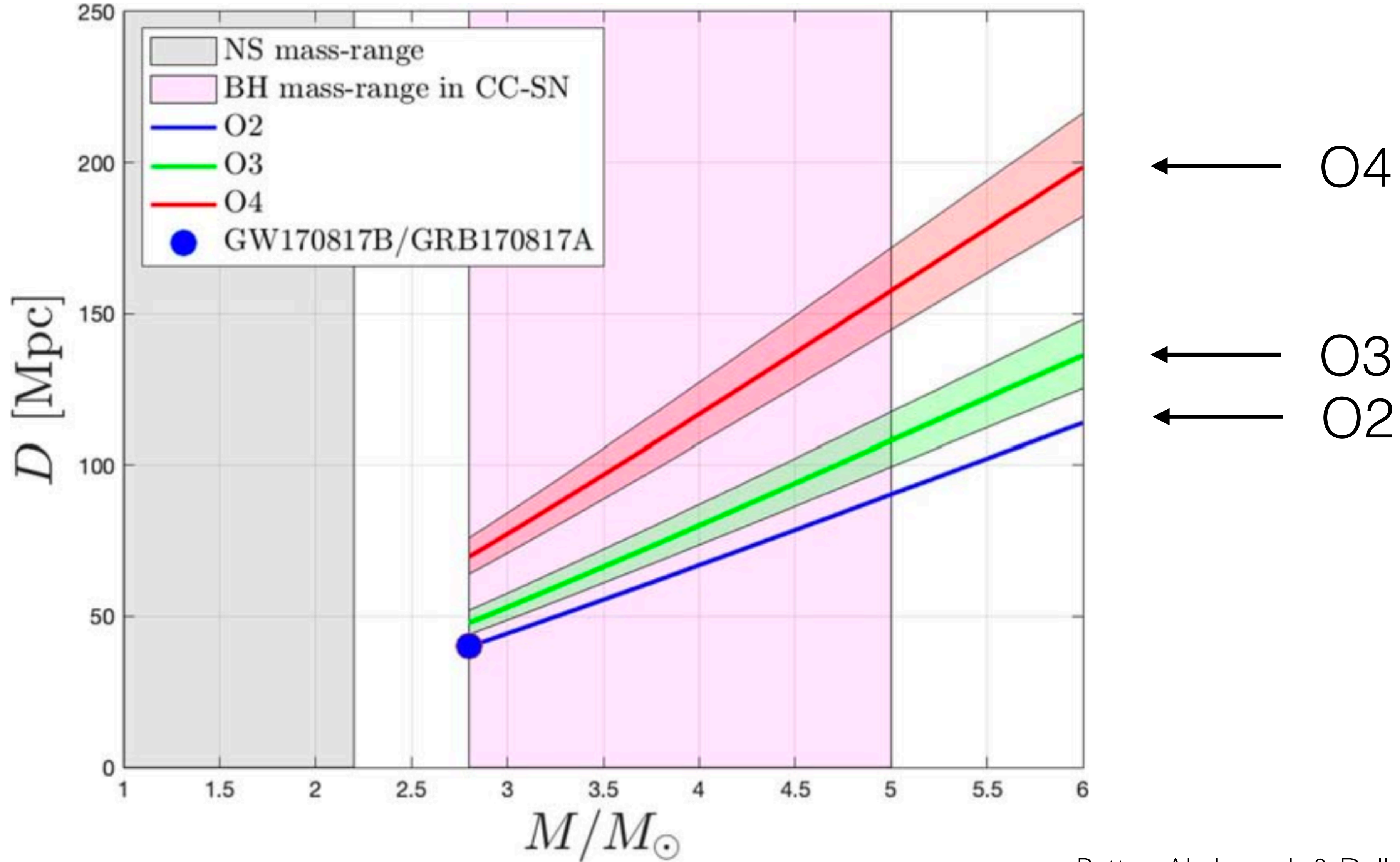
## Improvement in detector sensitivity O4/O2

$$k_D = 1.8$$

$$\text{Net gain: } g = k_D \times k_M \times k_n \sim 4$$

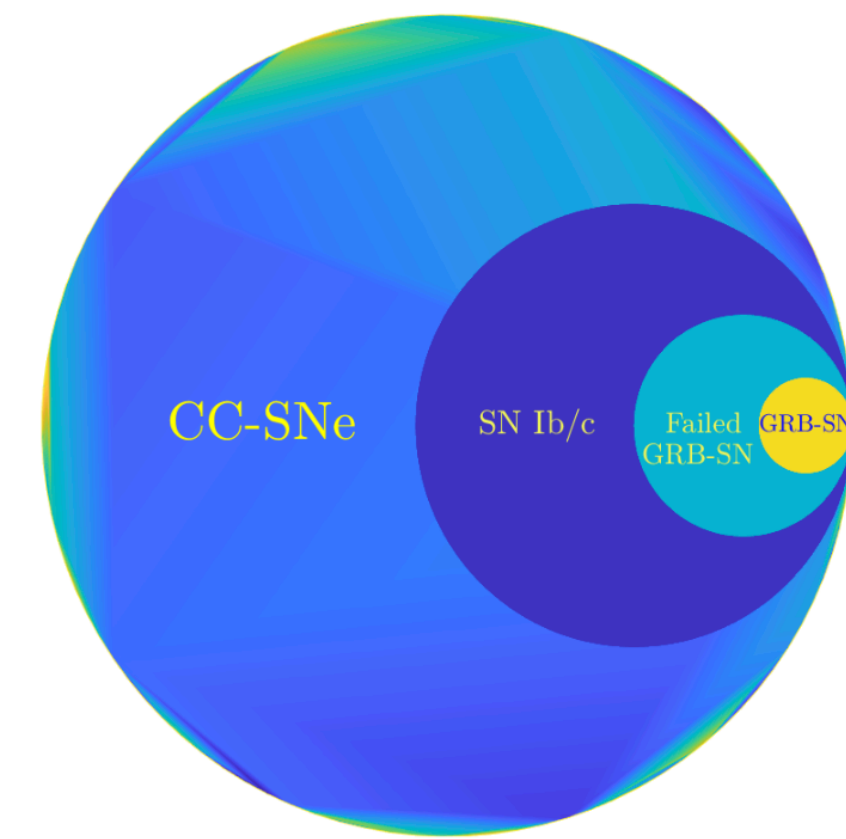


# Horizon distance to BH central engines



van Putten, Abchouyeh & Della Valle, ApJL, 2024

# Observational opportunities in the Local Universe



- Existing LIGO-Virgo searches specialize to GW-probes of proto-neutron stars (PNS):  
horizon distance  $D \sim \text{few Mpc}$

Abac et al 2025 ApJ 985 183

- GW-probes of BH central engines with BMF: horizon distance  $D \gtrsim 100 \text{ Mpc}$

New opportunities beyond DNS mergers are energetic CC-SNe

Event rate SN Ic is about  $100 \text{ yr}^{-1}$  within 100Mpc

van Putten, Abchouyeh & Della Valle, ApJL, 2024

# EM-triggered Image-based searches

Over search window, generate (H1,L1,V1)-spectrograms  $< 1\text{kHz}$  by BMF for available data:

- Matched filtering over large bank of time-symmetrized chirps of intermediate duration
- Circumvents sensitivity limitation of FFT by the time-frequency uncertainty relation
- Realizes near detector-limited sensitivity to transient signals (ascending, descending, ...)

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

van Putten, 2024, Universe, 9,, 279

## CC-supernovae:

- The *most energetic* events may be triggered by collapse to a rapidly spinning **Kerr BH**, converting  $E_J \rightarrow E_k$  by a catalytic energy extraction process rather than producing 'failed supernovae'.
- $E_J \rightarrow E_k$  is signaled by a *dominant output in GW-emission* ( $E_\gamma \ll E_k \ll E_\nu \lesssim E_{GW}$ )
- May be probed out to a horizon distance of about **160Mpc**
- TOOs of interest are specifically **SN Ib/c**

## Unveiling the central engine: NS or BH?

- *Case A: Confident null-detection of a long-duration descending branch.*

Supports the absence of BH spin-down. If  $^{56}\text{Ni}$  output is also modest, a BH central engine is effectively ruled out.

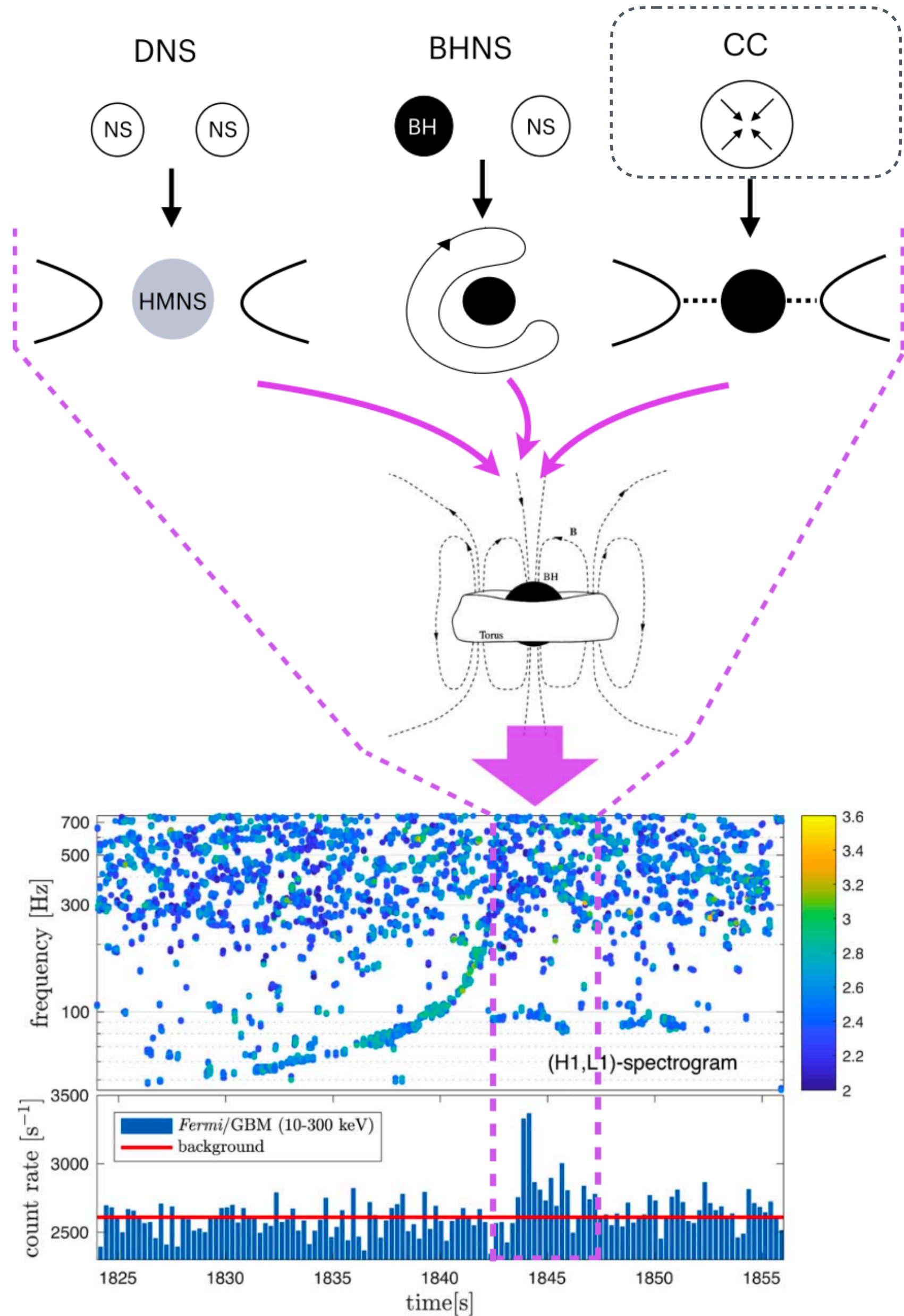
- *Case B: An anomalously faint signal.*

If real — supported by two or more detectors — this may be a chance coincidence (given relatively weak constraints on  $t_0$ ) or indicate a NS, subject to detailed consistency conditions.

- *Case C: Confident positive detection.*

Support the presence of a BH rather than a NS by GW-calorimetry:  $E_{GW} > \hat{E}_J^{NS}$  at observed  $f_{GW}$ .

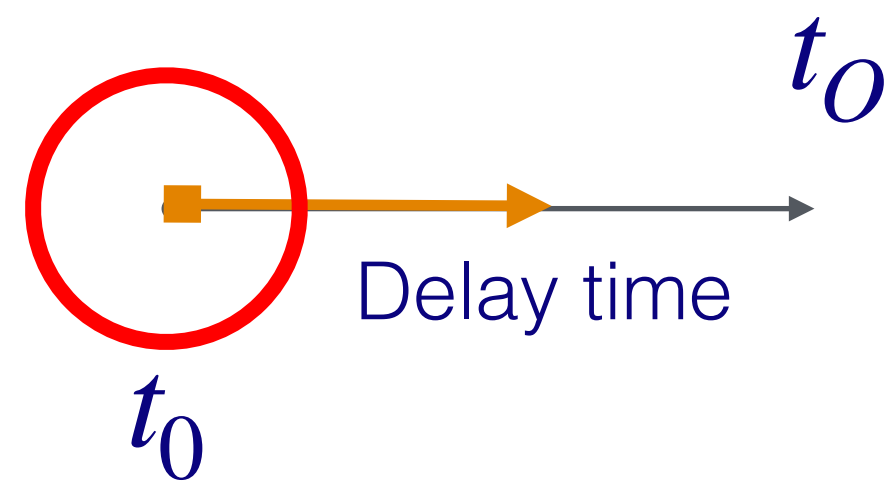
# Extra slides



Time of observation  $t_O$  constrains time-of-onset  $t_0$  (“explosion time”):

- Delay due to shock break-out:  $\Delta_0 = t_b - t_0$
- Delay to shock break-out time:  $\Delta_1 = t_O - t_b$
- Delay to time-of-onset  $t_0$ :  $\Delta_2 = \Delta_0 + \Delta_1 = t_O - t_0$

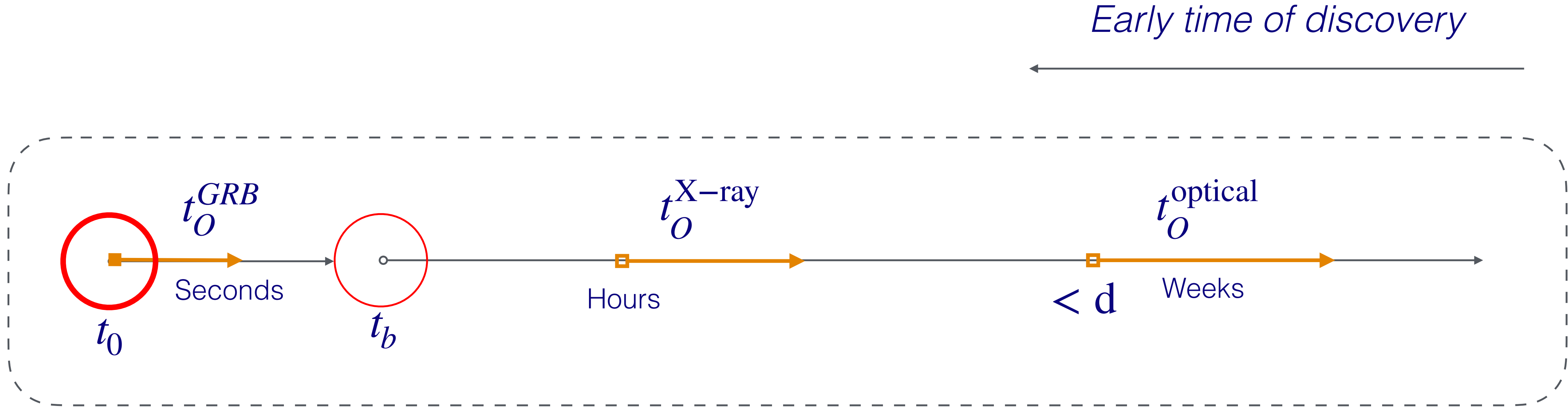
# EM-triggered GW-probes of CC-SNe



Narrow the GW-search window about the time-of-onset  $t_0$  by an EM-trigger time  $t_O$



# EM-triggered GW-probes of CC-SNe



Eg.: Einstein Probe EP260321a:  
 SN Ic BL (GCN 44068; O’Conner  
 et al. 2026, arXiv:2606.09992v1)

Continuous wide-field observatories  
 (Della Valle et al. 2025,  
 arXiv:2512.18157)