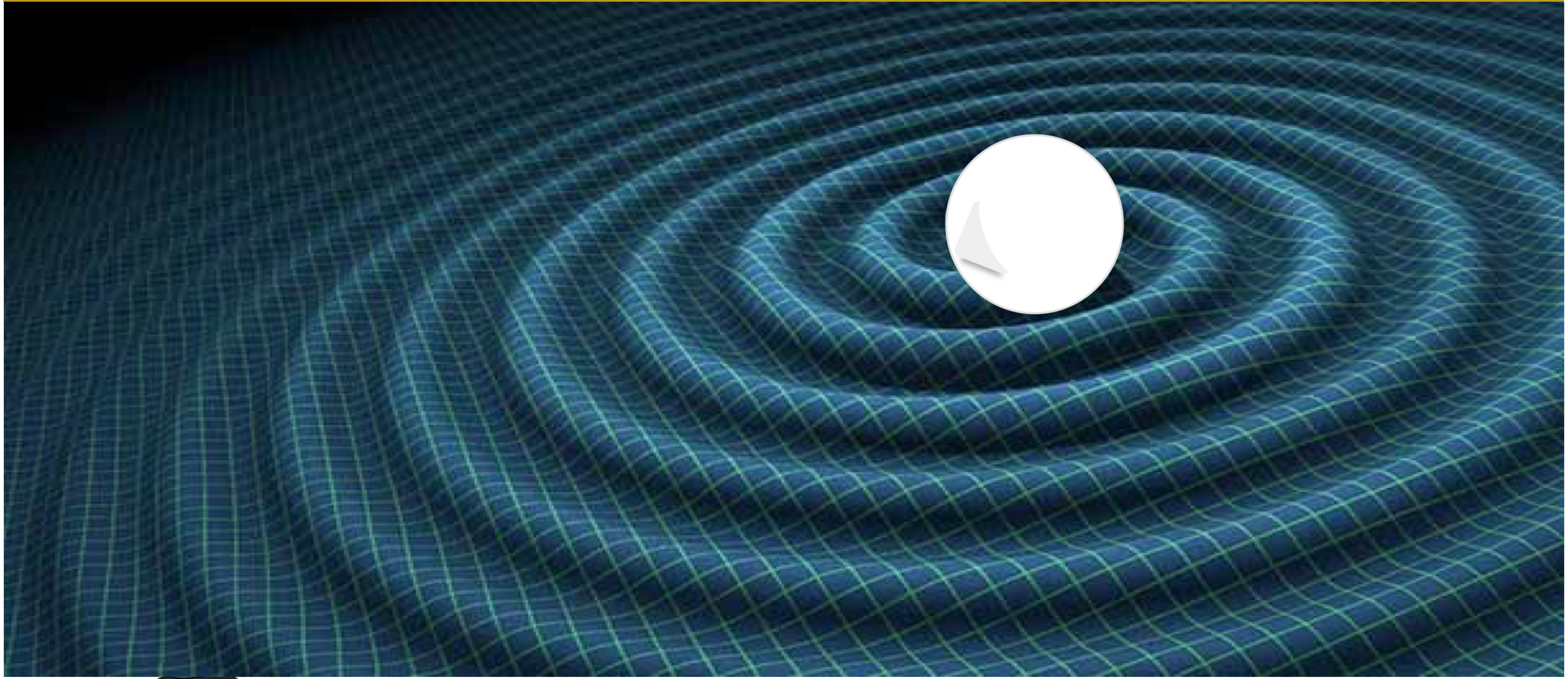
XVII Marcel Grossman Meeting

11/07/2024

Continuous and Long-transient GW signals from spinning NS

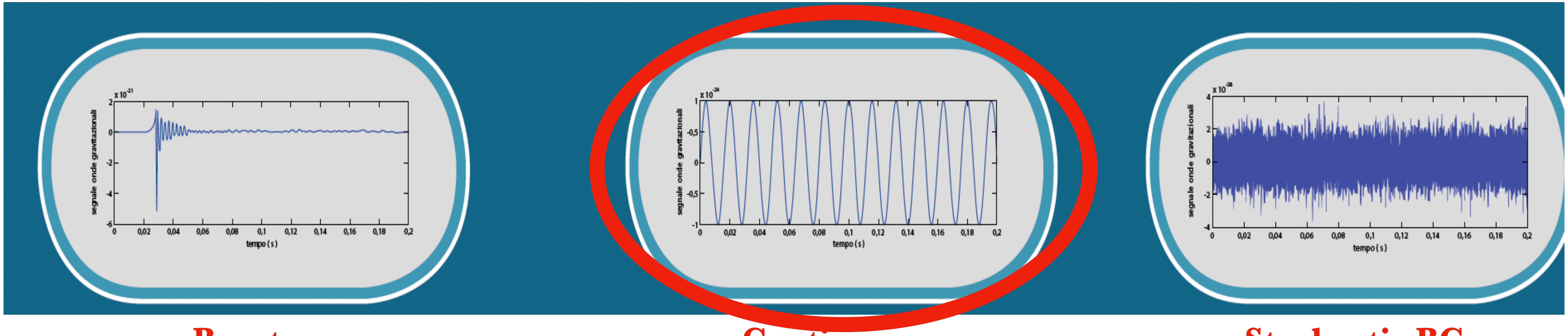


Fellowship for Innovation at INFN
H2020 MSCA COFUND
G.A. 754496

Simone Dall'Osso
"Sapienza" Università di Roma
Virgo-Roma

INFN
Istituto Nazionale di Fisica Nucleare

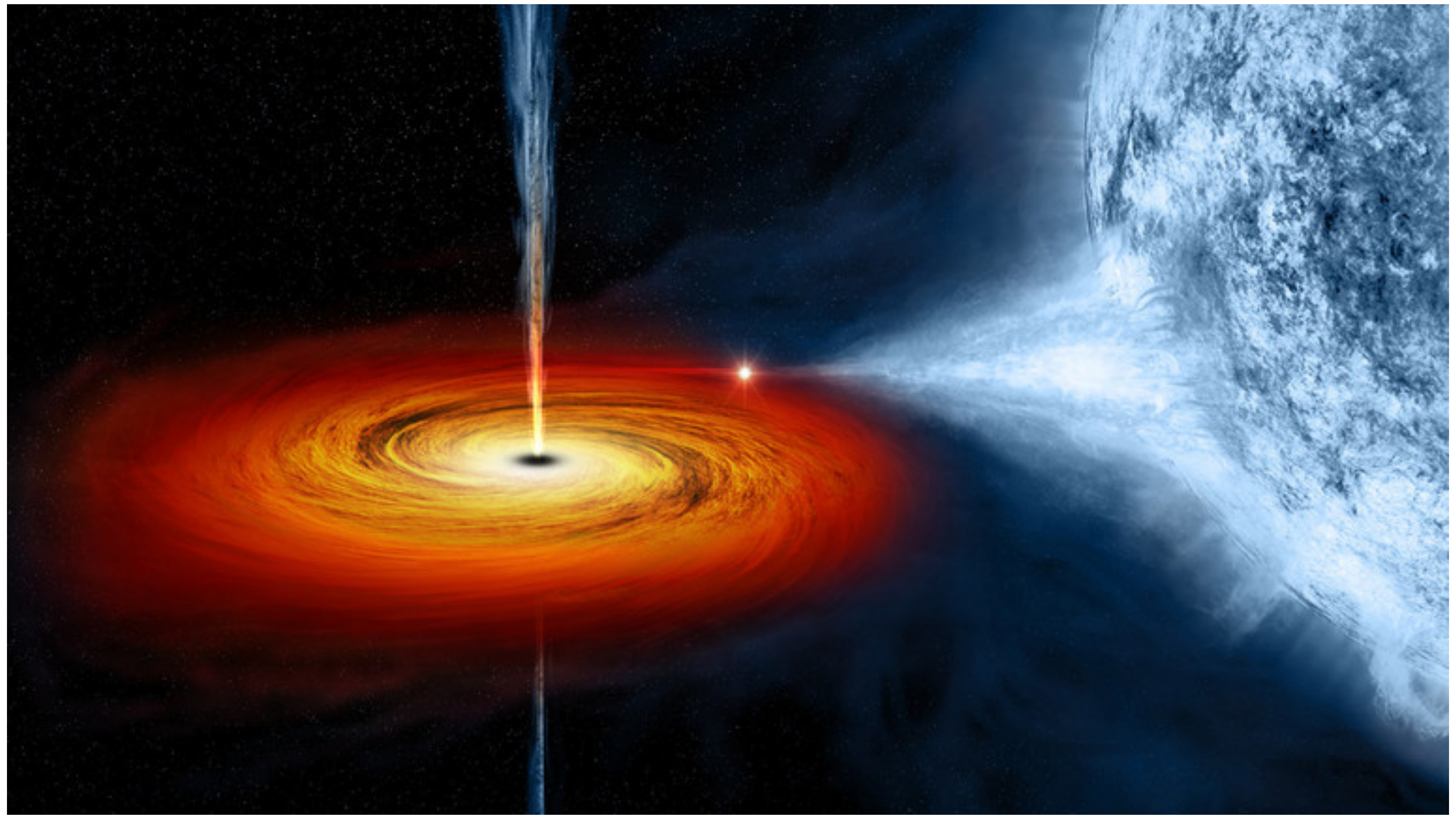
ZOOLOGY OF GW SIGNALS (besides CBCs)



Burst | **Continuous** | **Stochastic BG**

Isolated pulsars

Accreting NS



(some) DM candidates

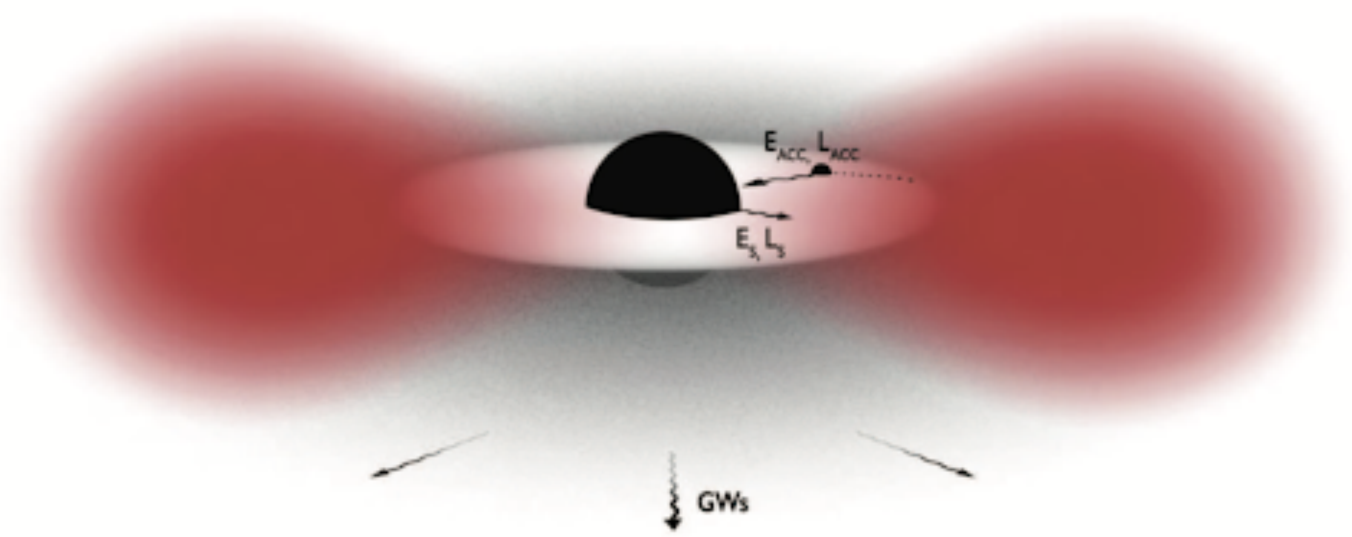


Figure Credit: [Brito, Cardoso, Pani]

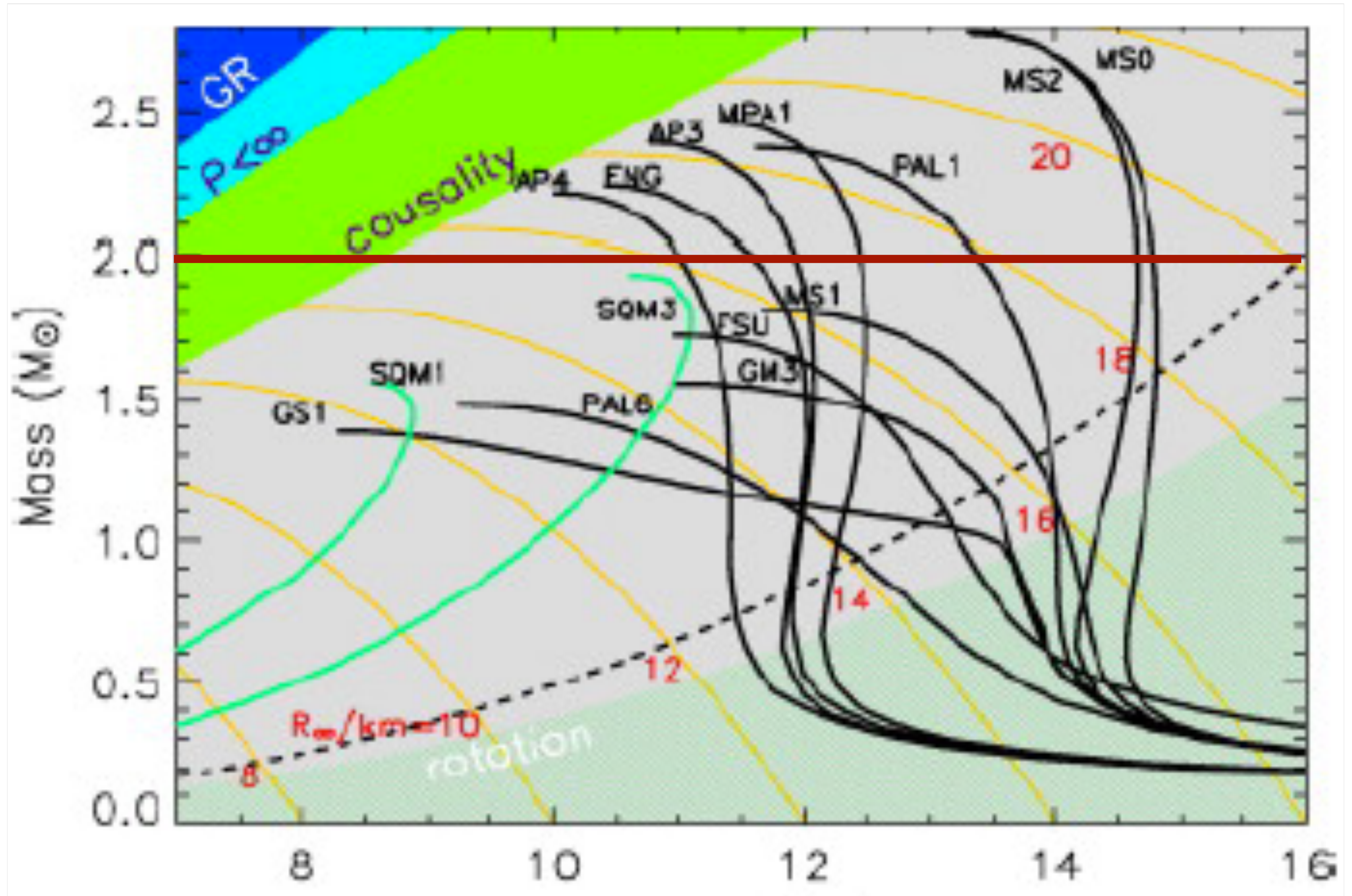
e.g. light boson clouds around stellar-mass BHs, inspiral of low-mass primordial BHs, dark photons, etc

NS AS SOURCES OF CONTINUOUS WAVES (CWs)

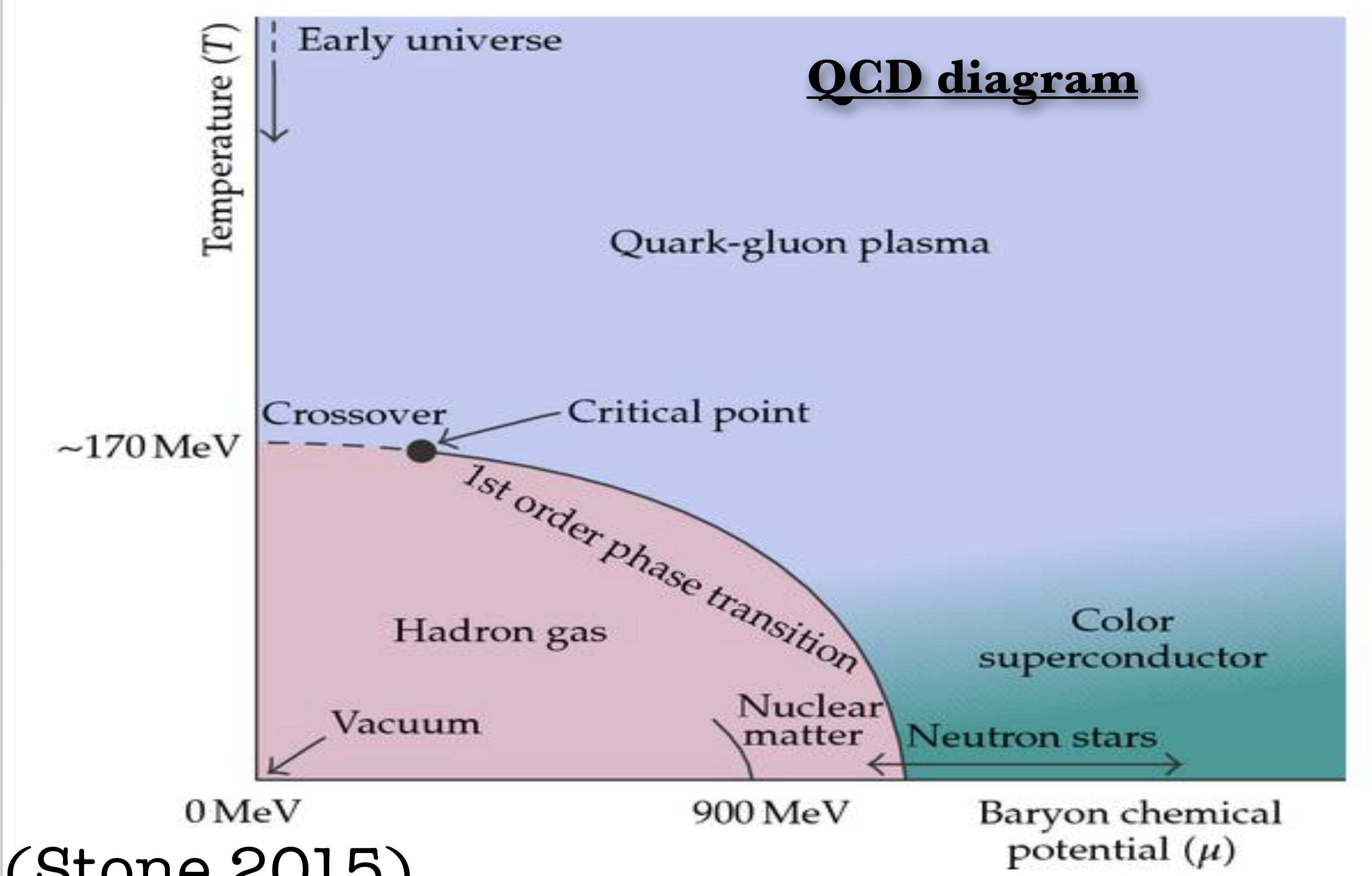
<u>**What CWs can tell us about NS**</u>

- NS internal structure (M, R, EOS)
- Maximum spin allowed for a NS
- Strength and arrangement of interior B-field
- new/complementary constraints on accretion processes
- NS demography

  (including a possible population of ``exotic" stars)
- Testing GR

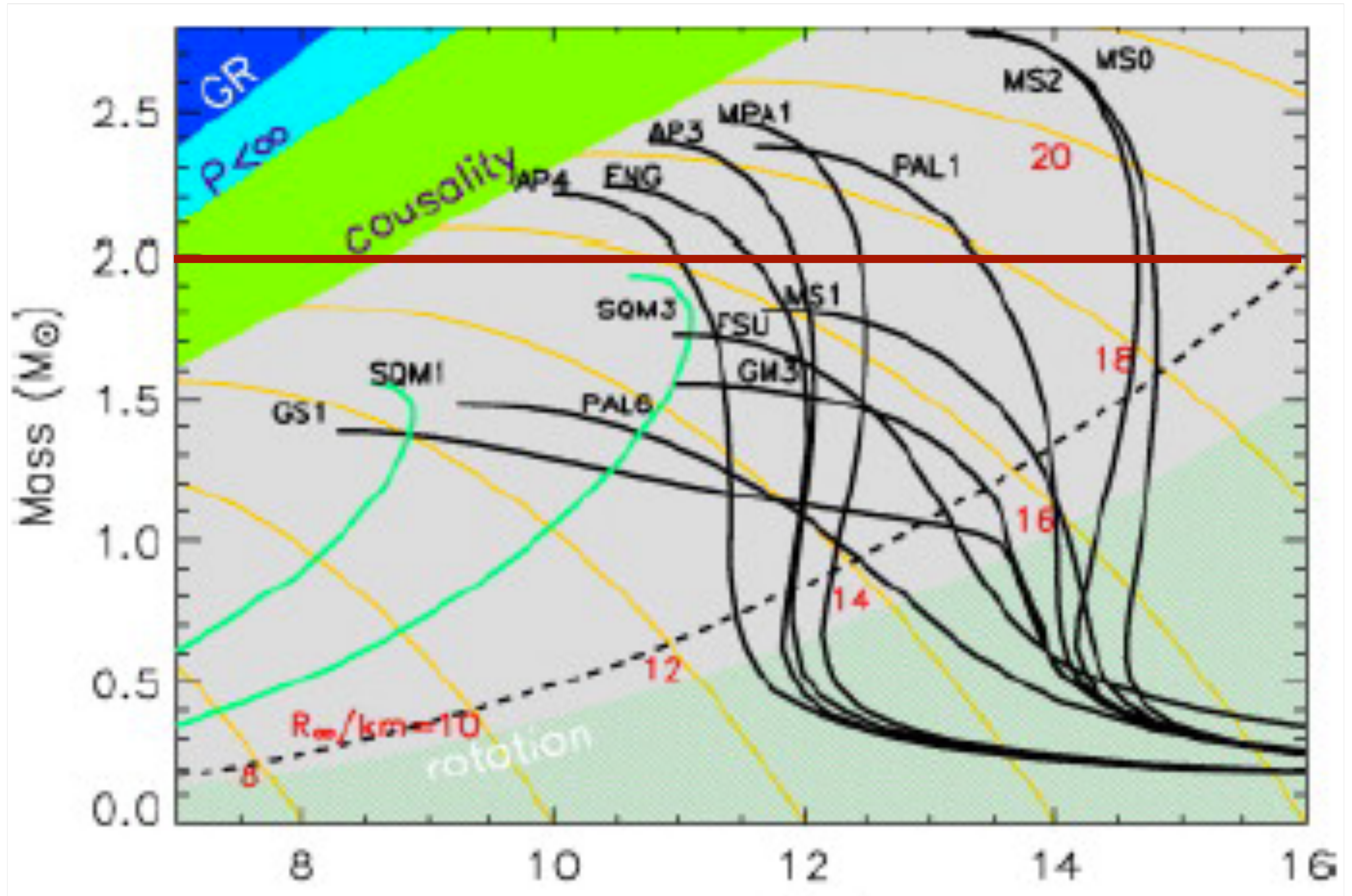


(Lattimer 2010)



(Stone 2015)

NS AS SOURCES OF CONTINUOUS WAVES (CWs)



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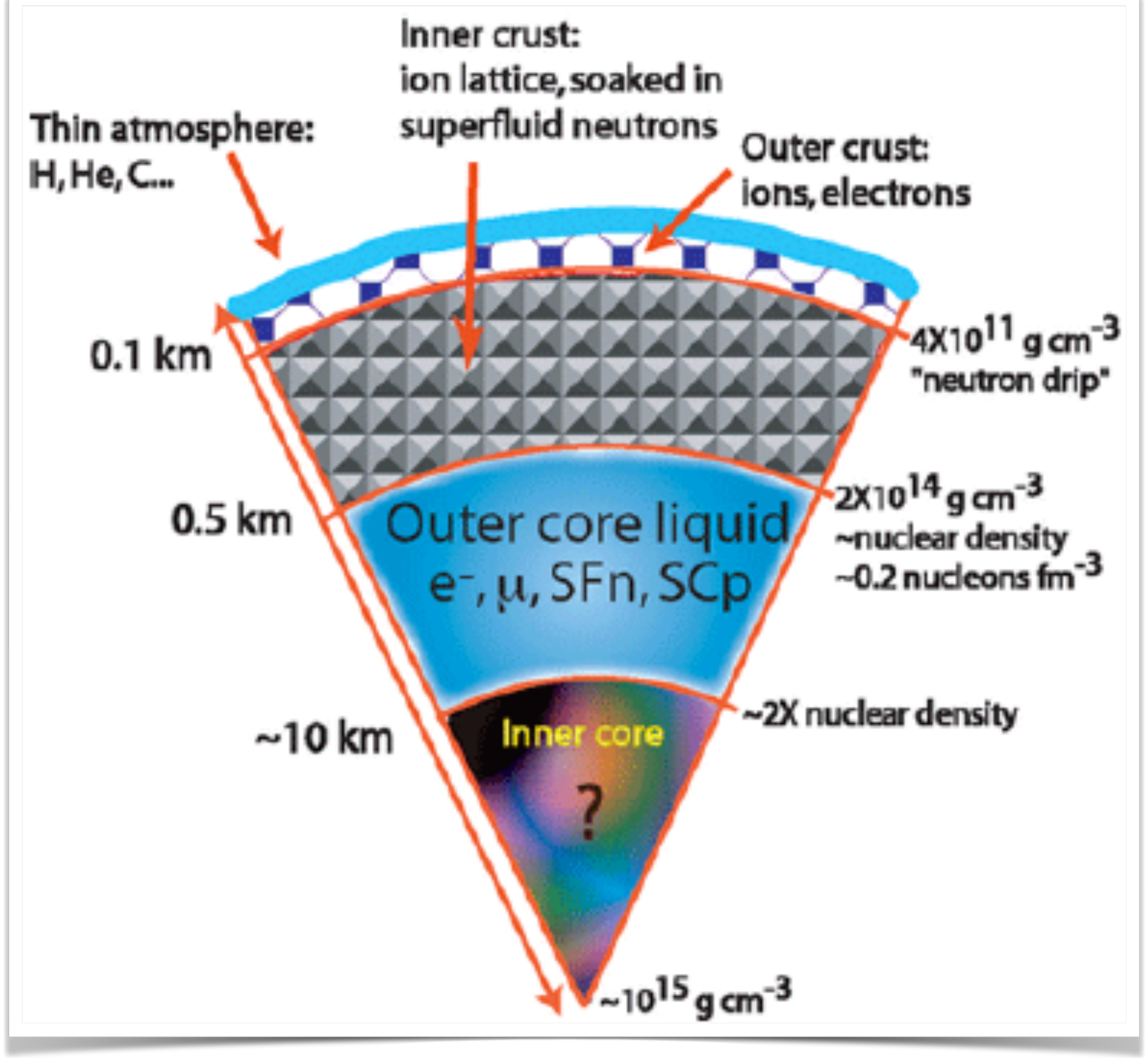


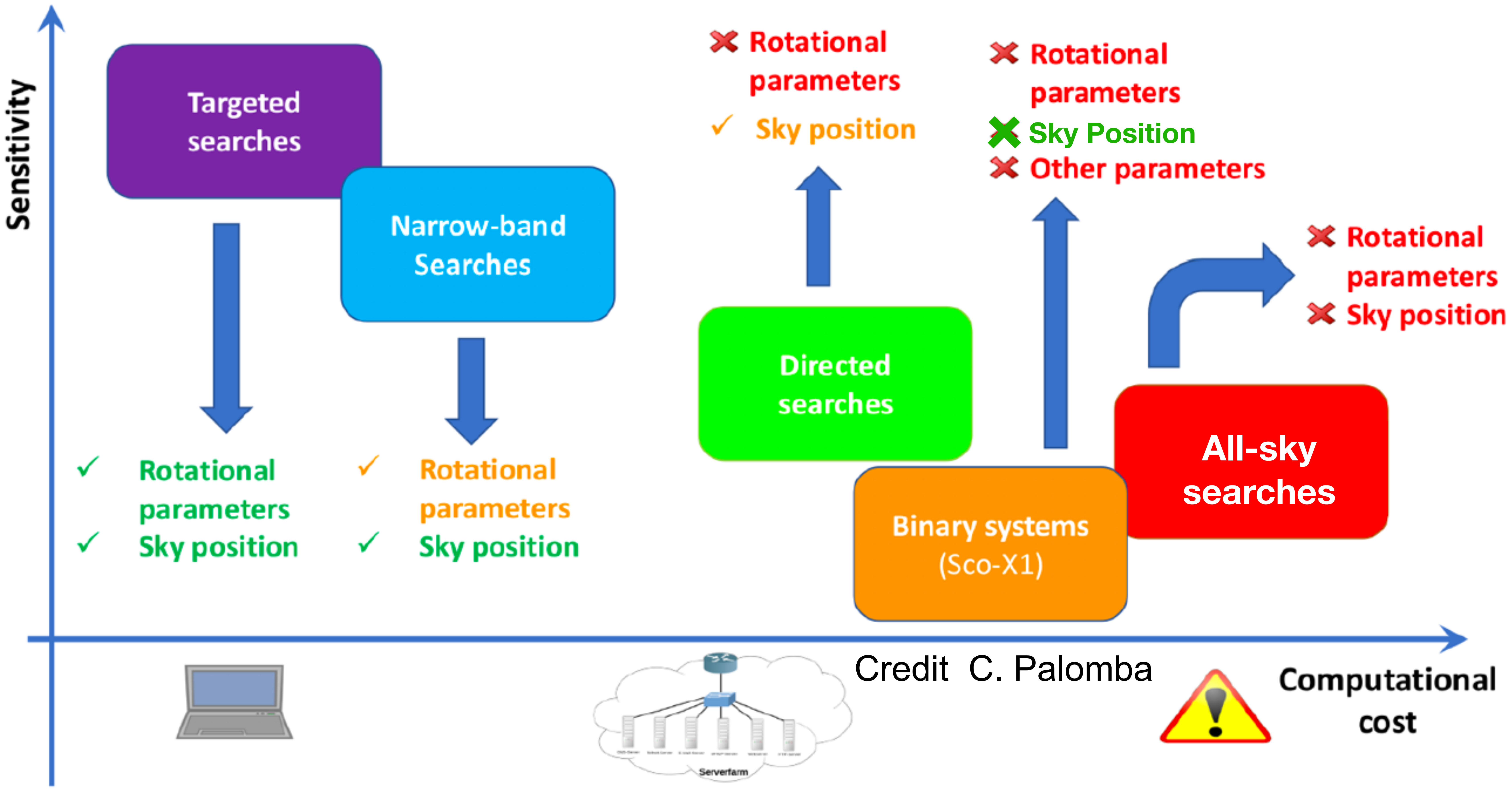
$$h_0 = \frac{16\pi^2 G}{c^4}\frac{I_{zz}\epsilon f_{\rm spin}^2}{D} \sim 3\times 10^{-26}\, f_{300\ \rm Hz}^2\, \epsilon_{-6}\, D_{10\ \rm kpc}^{-1}$$

$$\begin{cases} \epsilon \lesssim 10^{-6} & \text{for max crustal strain, normal NS matter} \\ \epsilon \lesssim 10^{-4} & \text{for hybrid stars (hadron – quark) core NS} \end{cases}$$

N. Jonhson-McDaniel, B. Owen
PRD 86 063600 , PRD 87 129903

Haskell B., Jones P.I., Andersson N., 2006
Horowitz et al. (2009)

NS AS SOURCES OF CONTINUOUS WAVES (CWs)



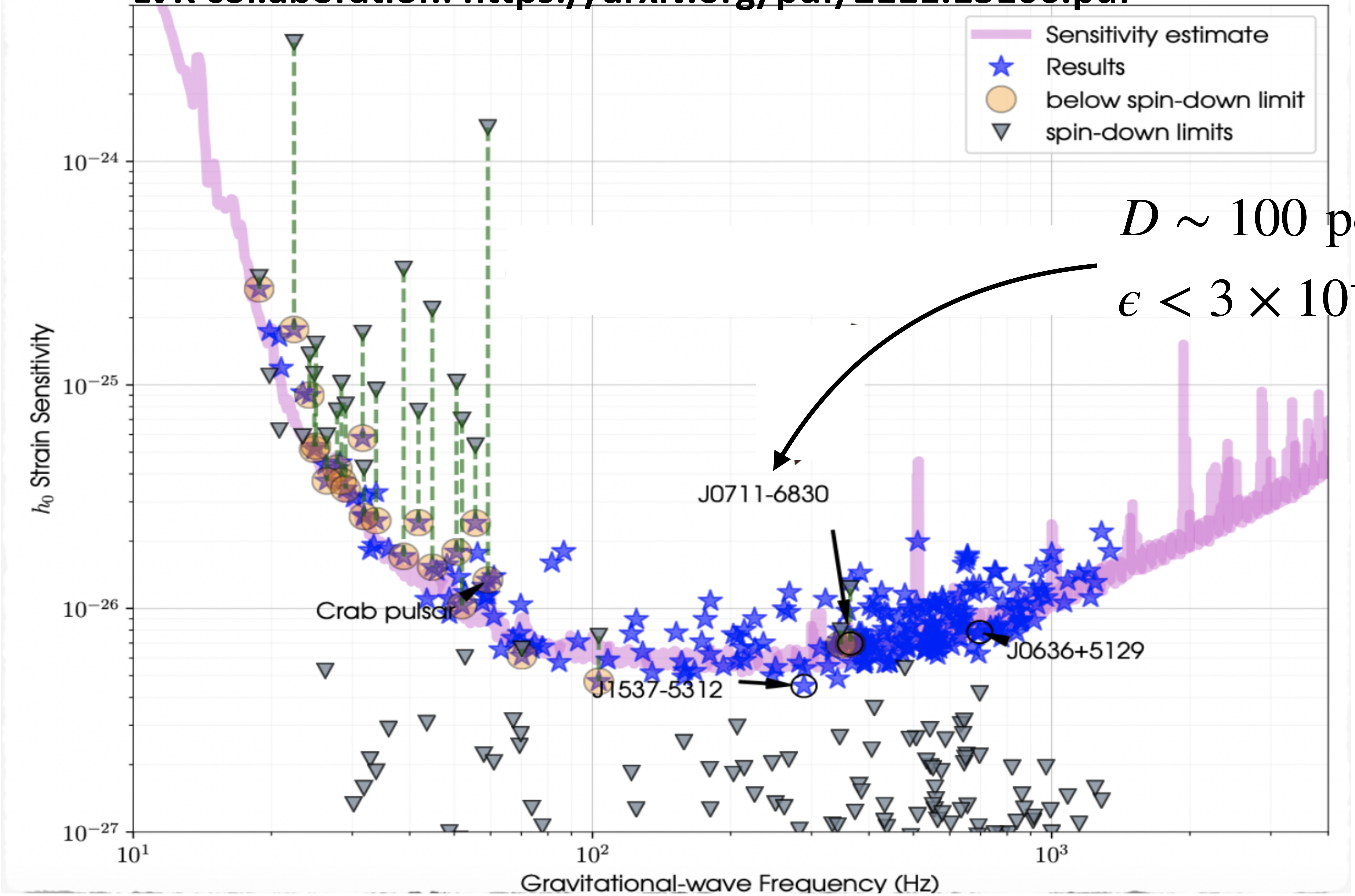
Order of magnitude estimate

Frequency Hough hierarchical All Sky search (isolated NS)

1 year - 3 detectors ~ 80 million core-hours

TARGETED CW SEARCHES FOR KNOWN GALACTIC PULSARS

LVK collaboration: https://arxiv.org/pdf/2111.13106.pdf



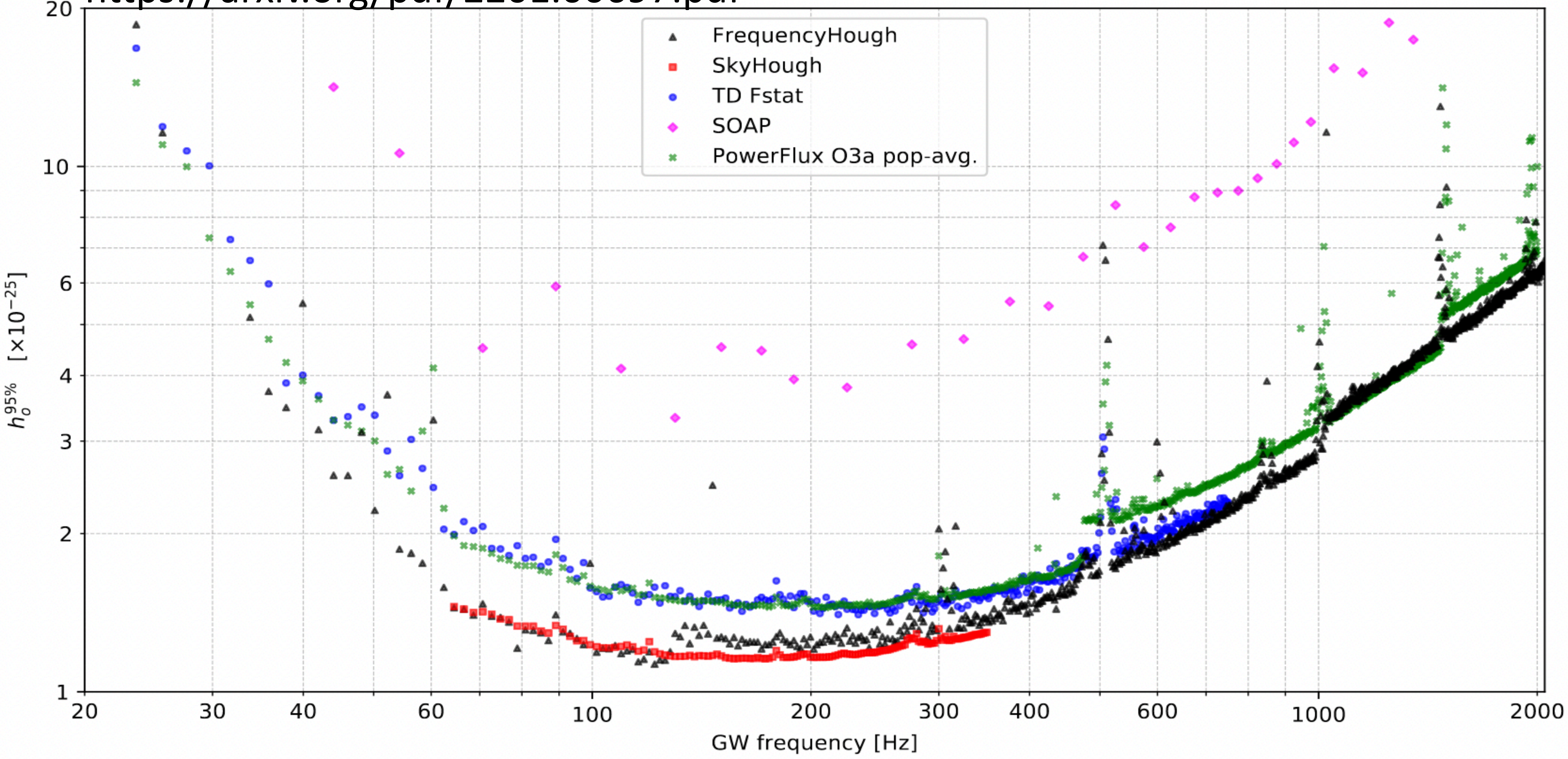
$D \sim 100$ pc

$\epsilon < 3 \times 10^{-9}$

$$h_0 = \frac{16\pi^2 G}{c^4} \frac{I_{zz} \epsilon f_{\rm spin}^2}{D} \sim 3 \times 10^{-26}\, f_{300\ \rm Hz}^2\, \epsilon_{-6}\, D_{10\ \rm kpc}^{-1}$$

ALL-SKY SEARCHES FOR UNKNOWN SOURCES

https://arxiv.org/pdf/2201.00697.pdf



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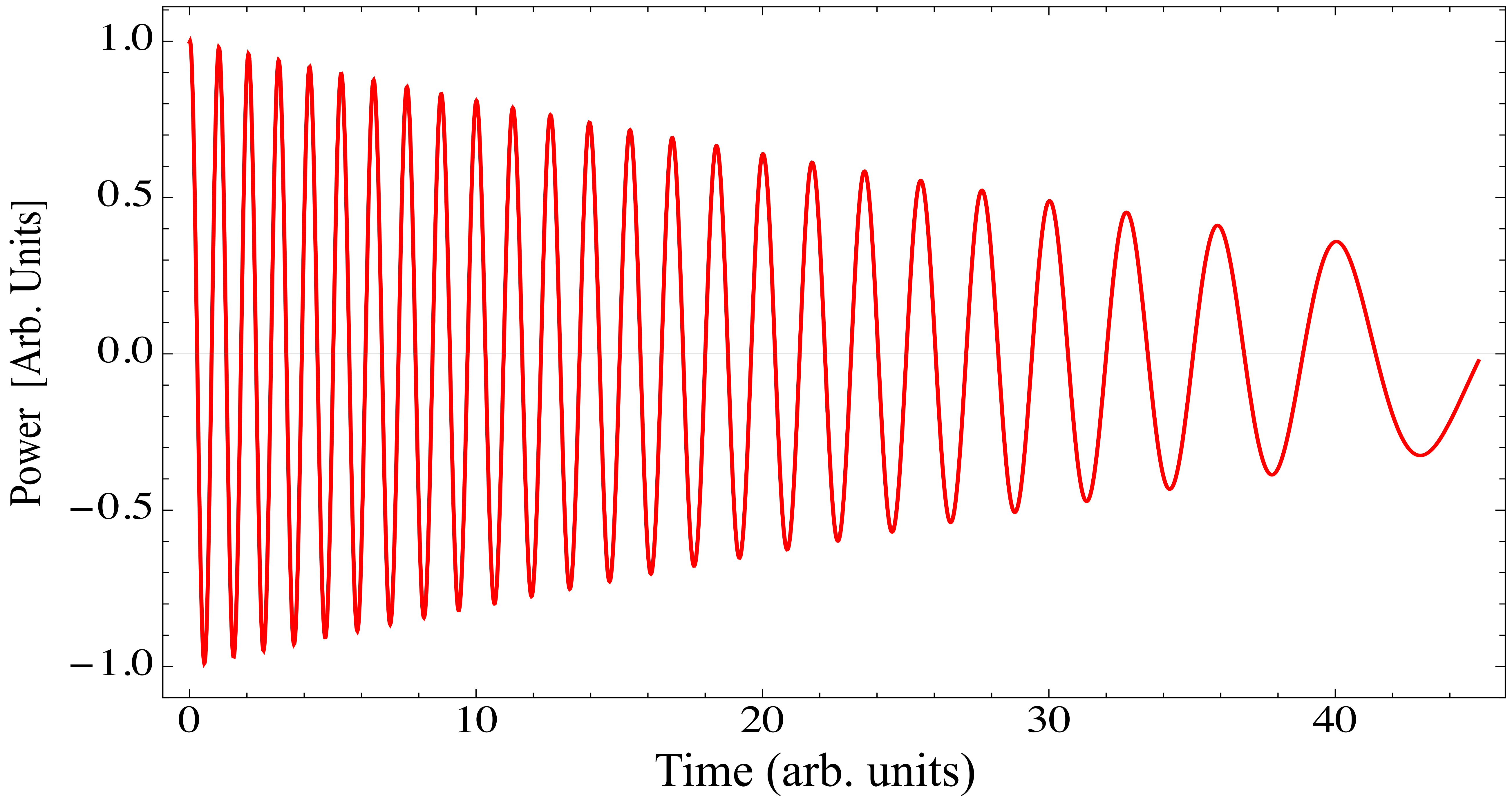
LONG-TRANSIENTS (quasi-CW) FROM NEWBORN MAGNETARS



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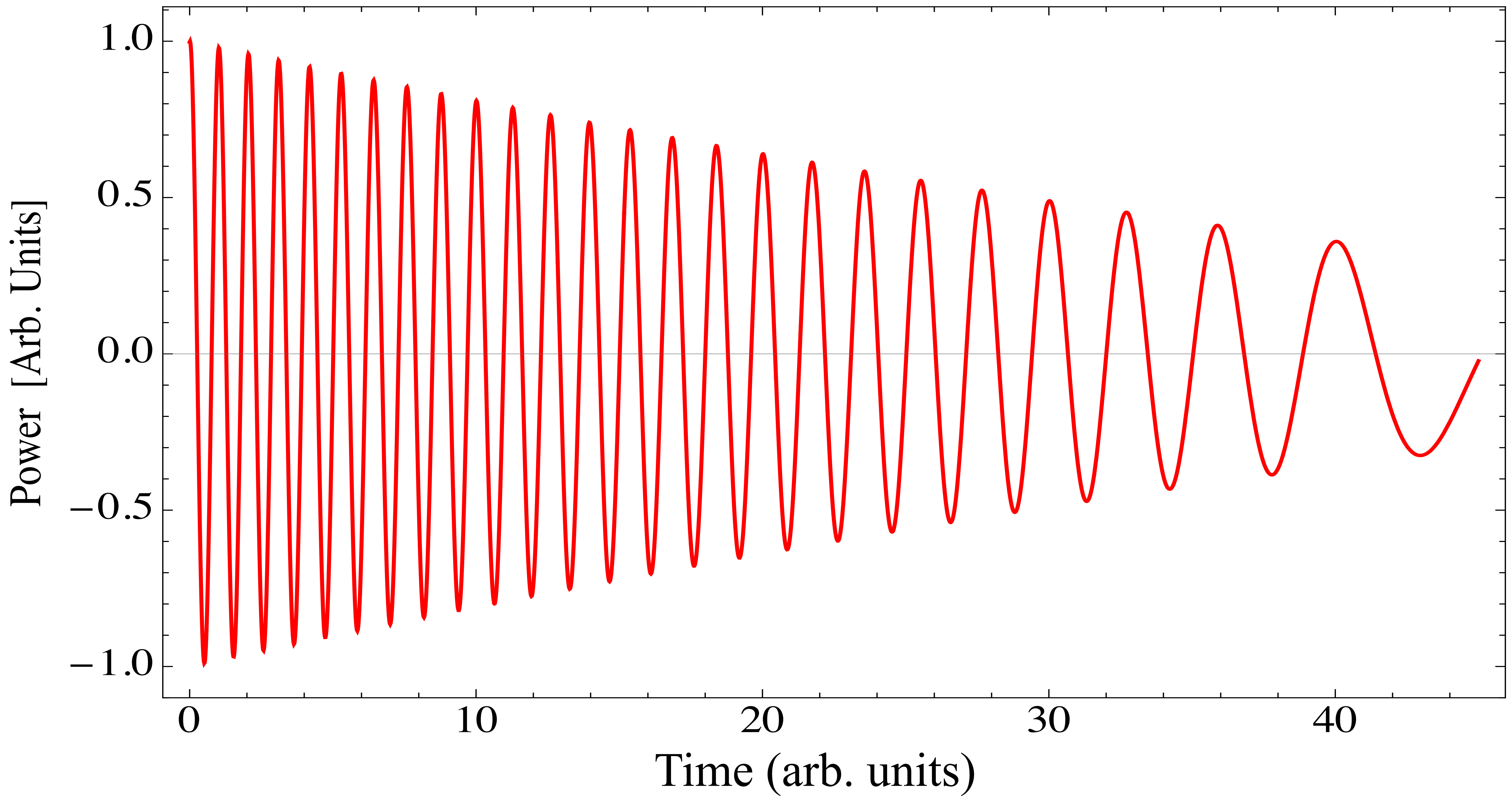
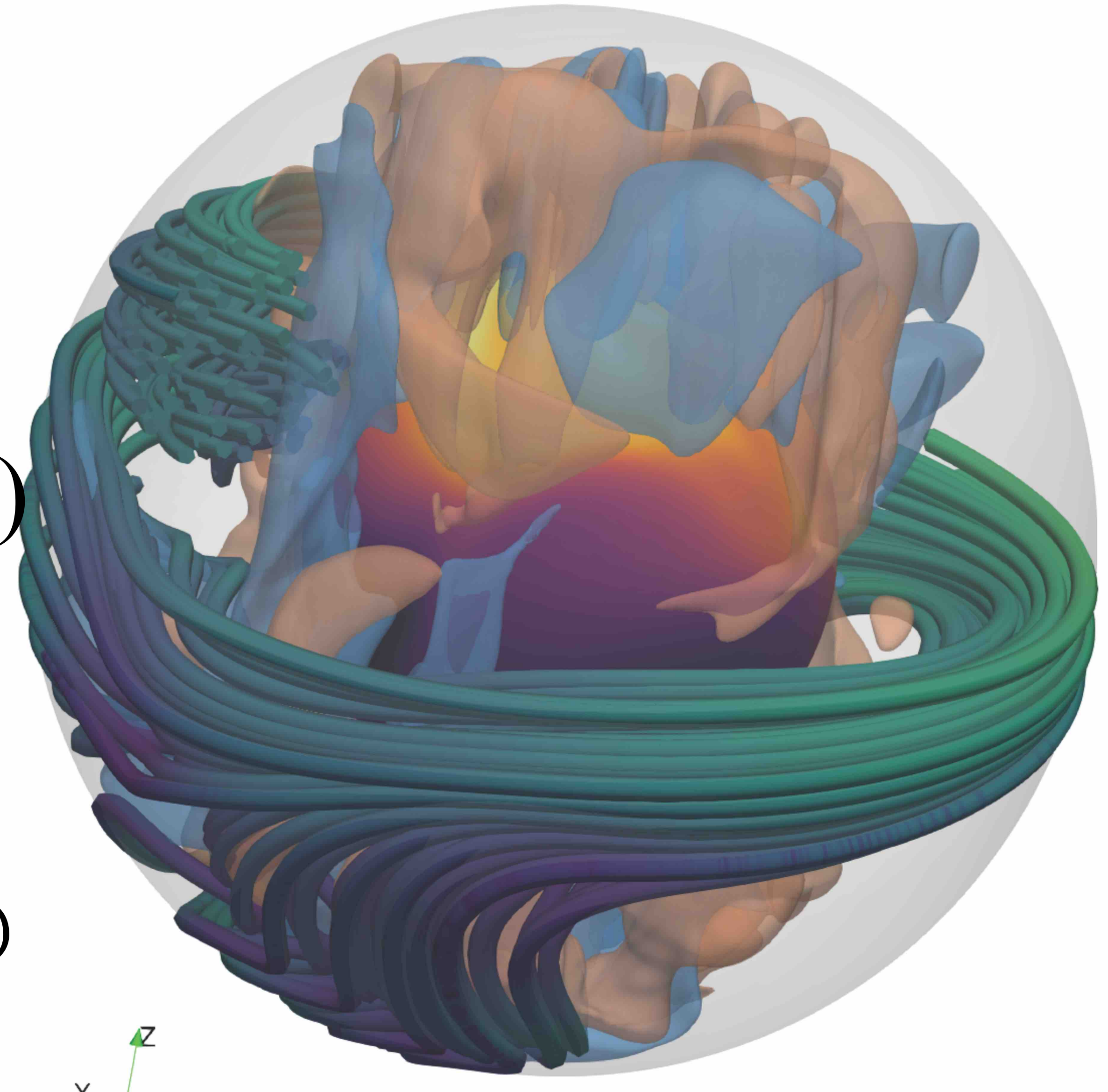


Magnetically-induced large ellipcicity (ms-spinning magnetars)

$\epsilon \sim 10^{-4} - 10^{-3}$

Cutler (2002)
Dall'Osso et al. (2005, 2007, 2009, 2015, 2018, 2022)
Ciolfi & Rezzolla (2013)
Frieden & Rezzolla (2015)
Lander & Jones (2020)



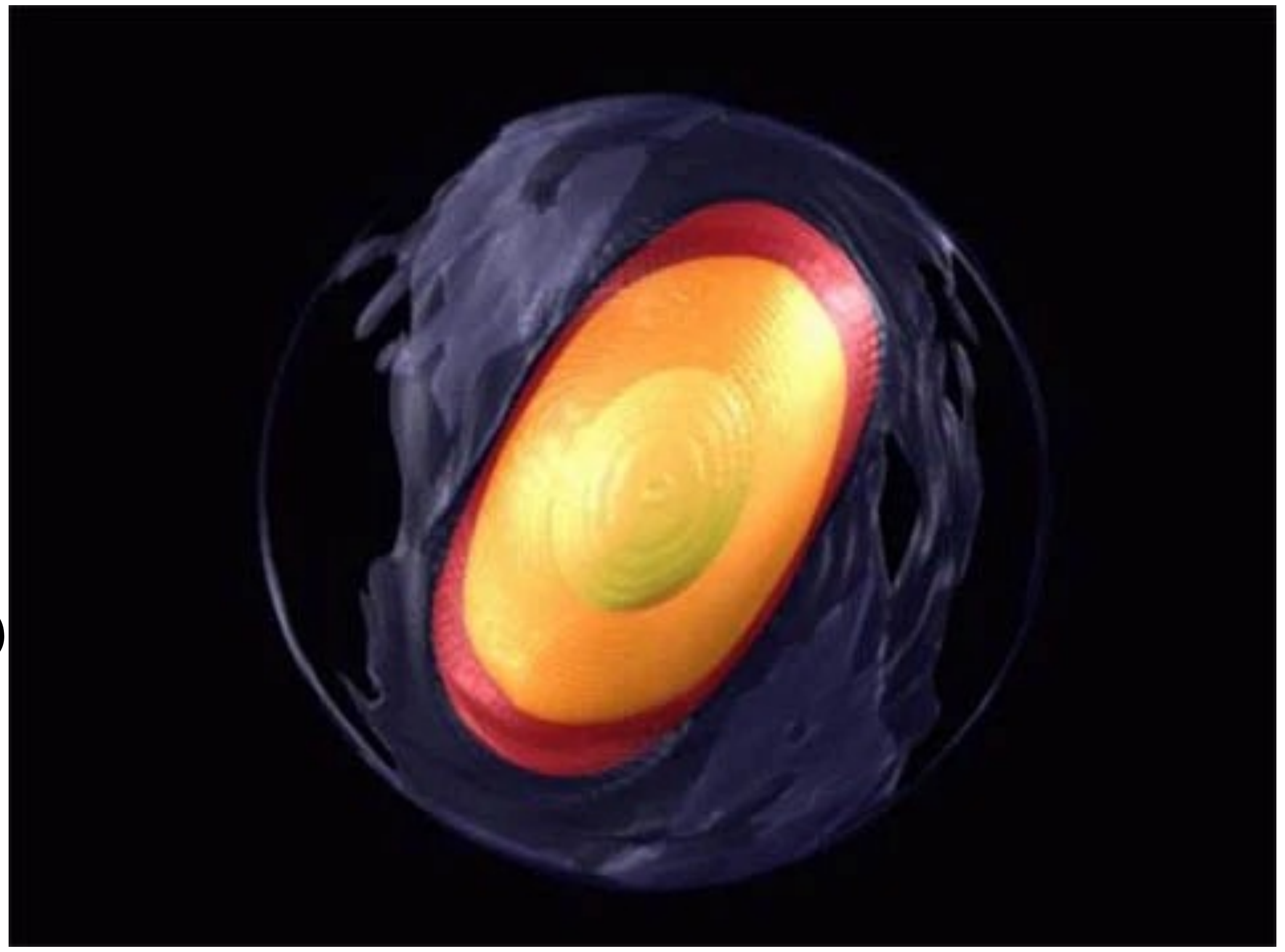
Raynaud et al. (2020)

$$h_0 = \frac{16\pi^2 G}{c^4}\frac{I_{zz}\epsilon f_{spin}^2}{D} \sim 3\times 10^{-26}\, f_{kHz}^2\, \epsilon_{-4}\, D_{10\,Mpc}^{-1}$$

Secular bar-mode instability (ms-spinning NS)

$\epsilon \sim 10^{-2} - 10^{-1}$

Lai & Shapiro (1995)
Corsi & Meszaros (2009)



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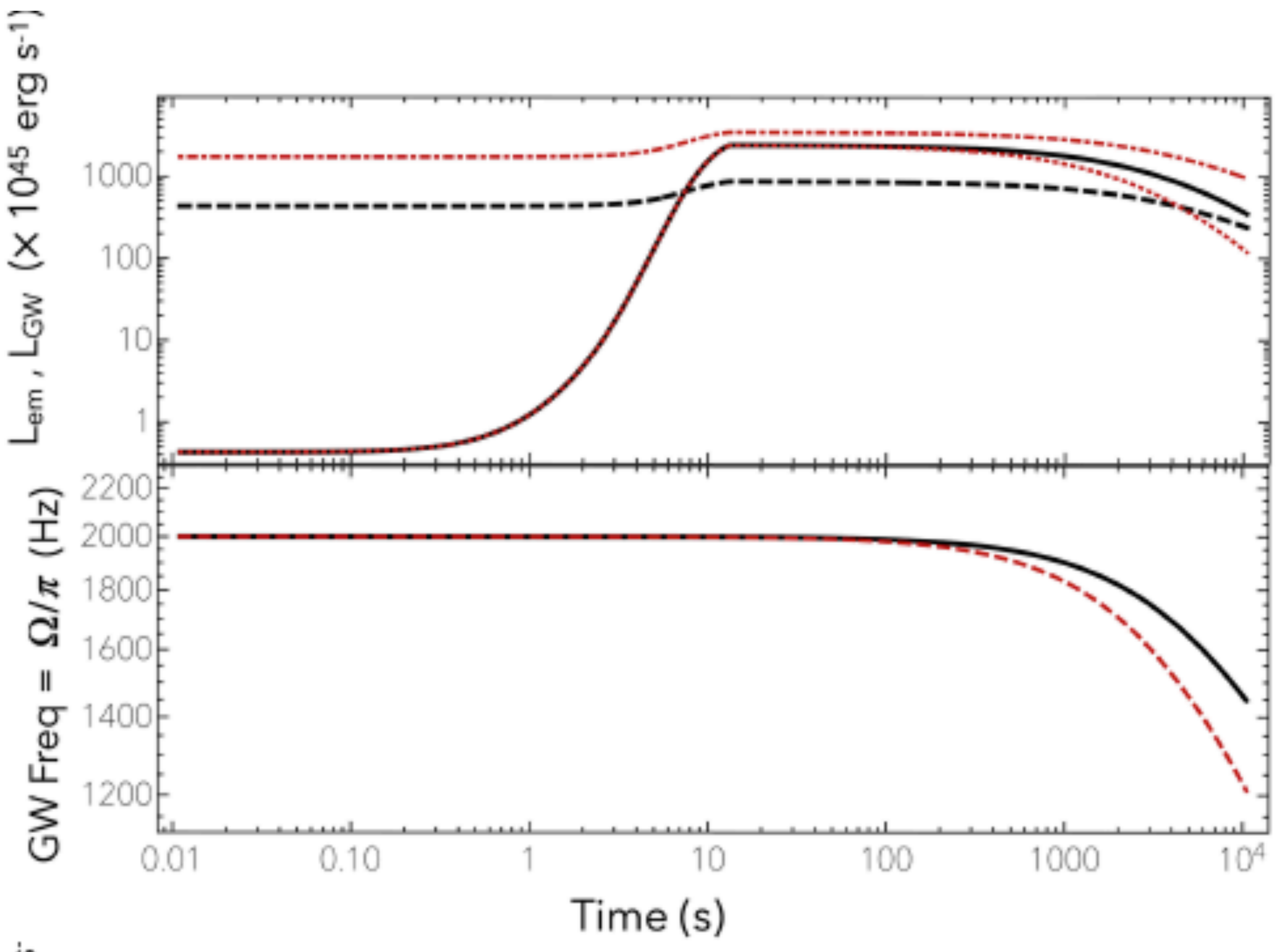
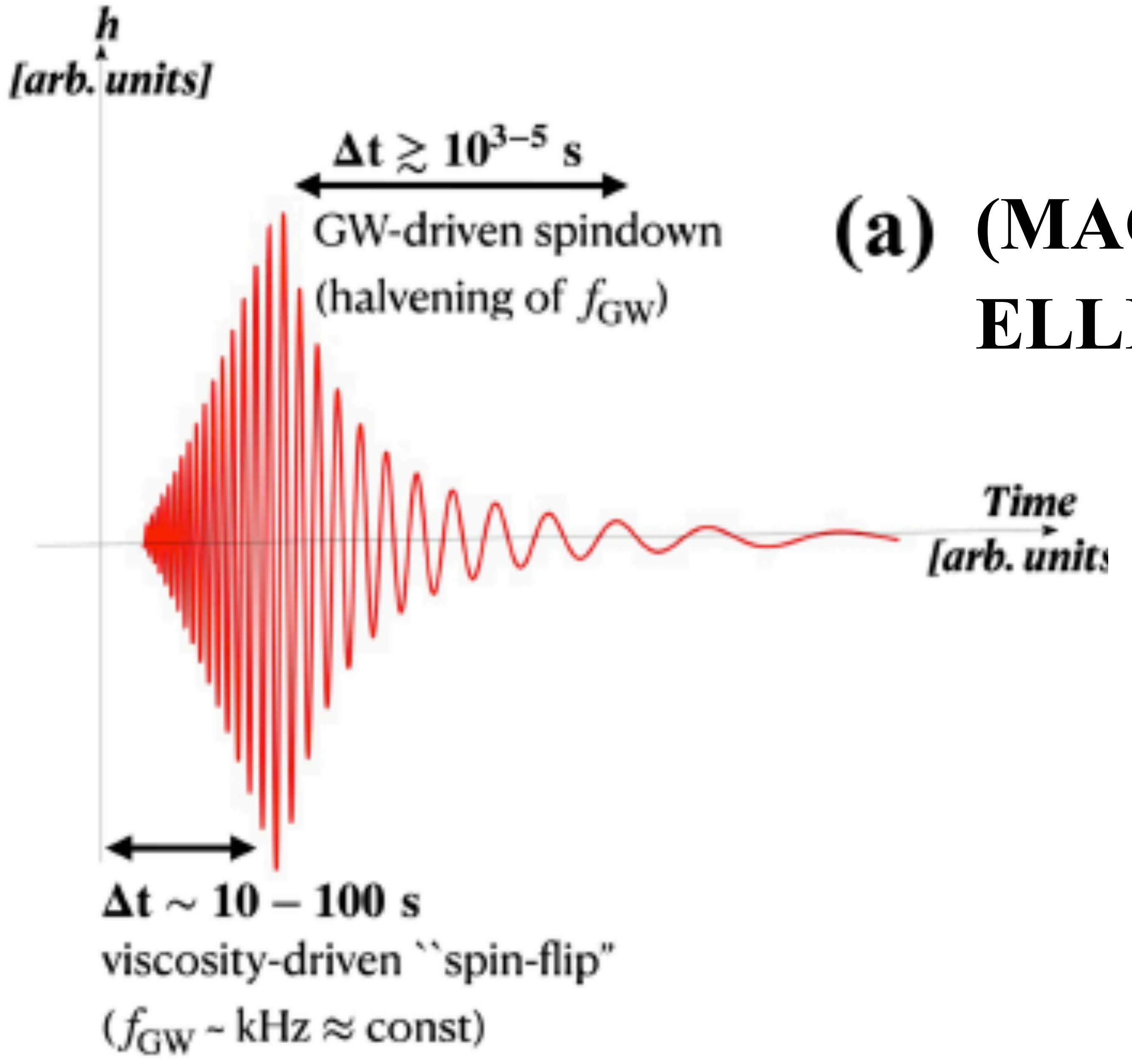
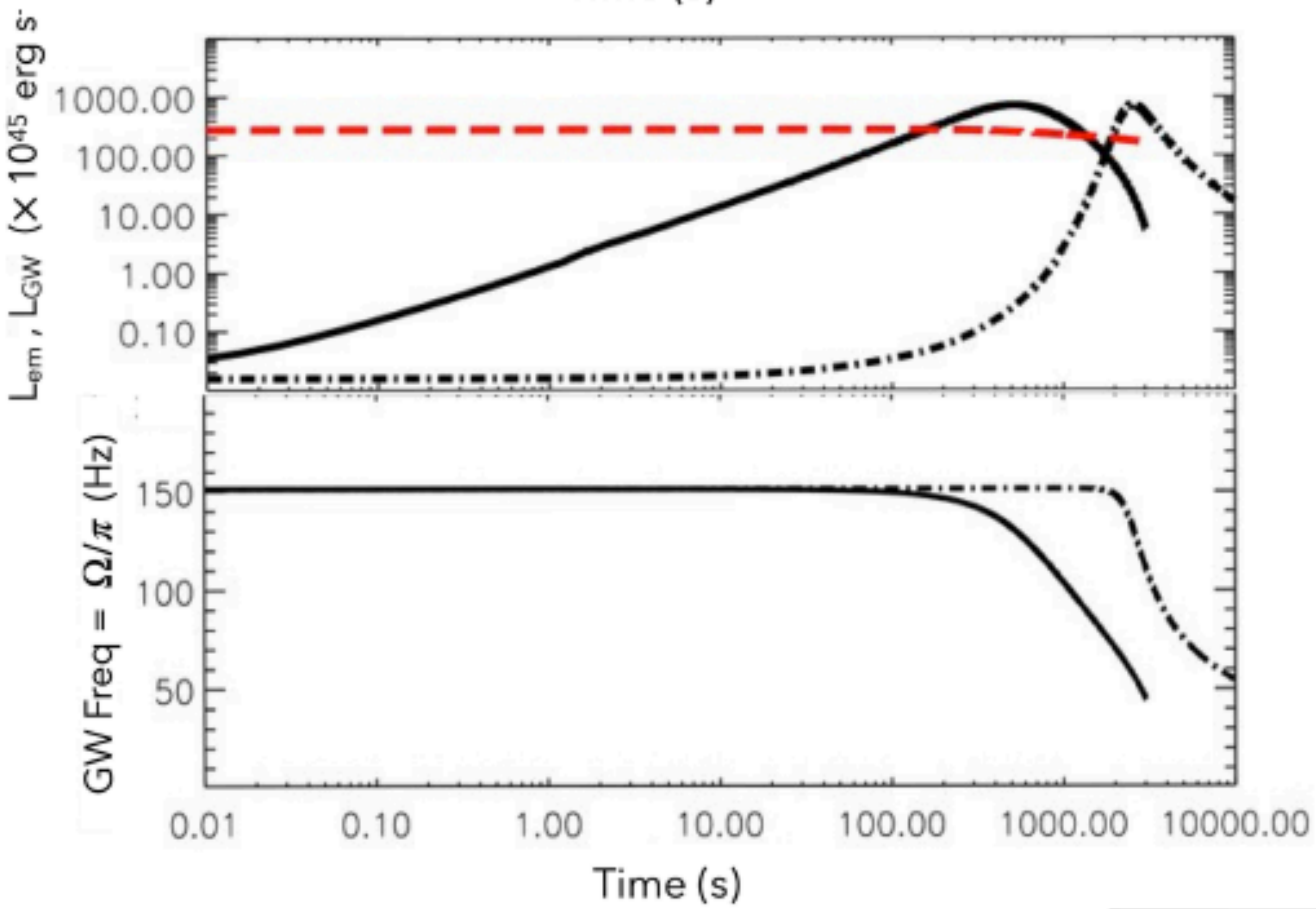
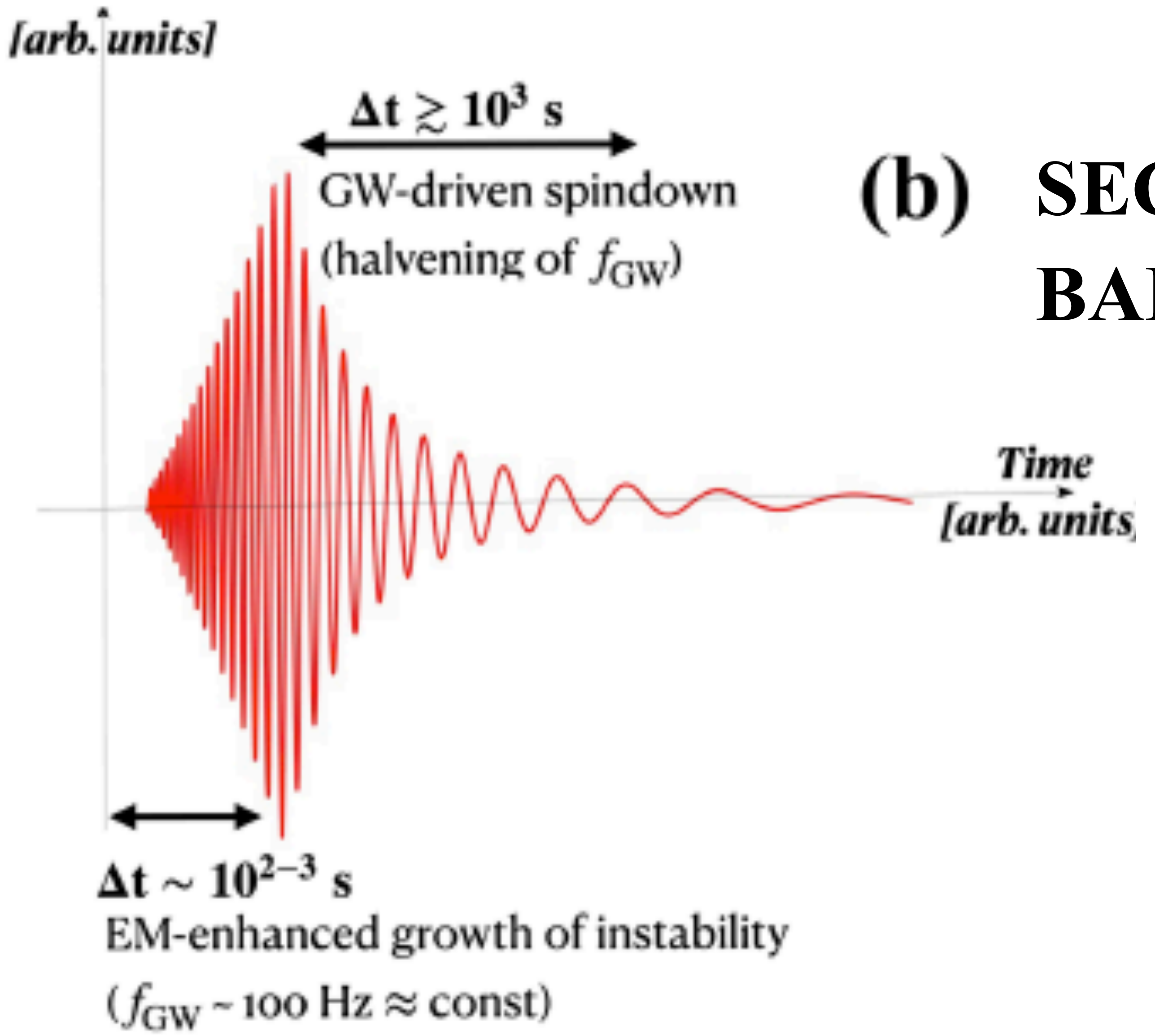




(a) (MAGNETIC) ELLIPTICITY

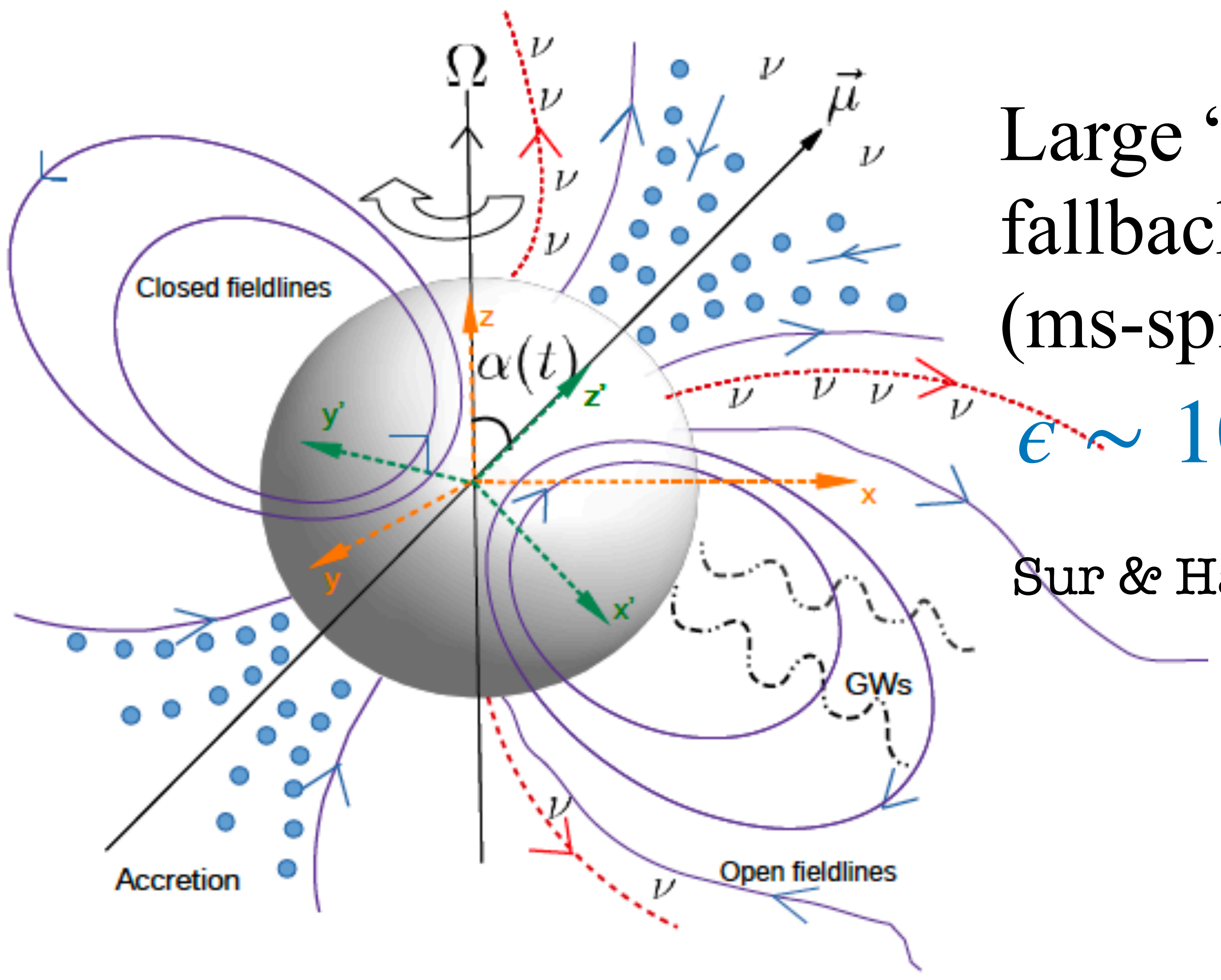




(b) SECULAR BAR-MODE

Dall'Osso and Stella (2022)

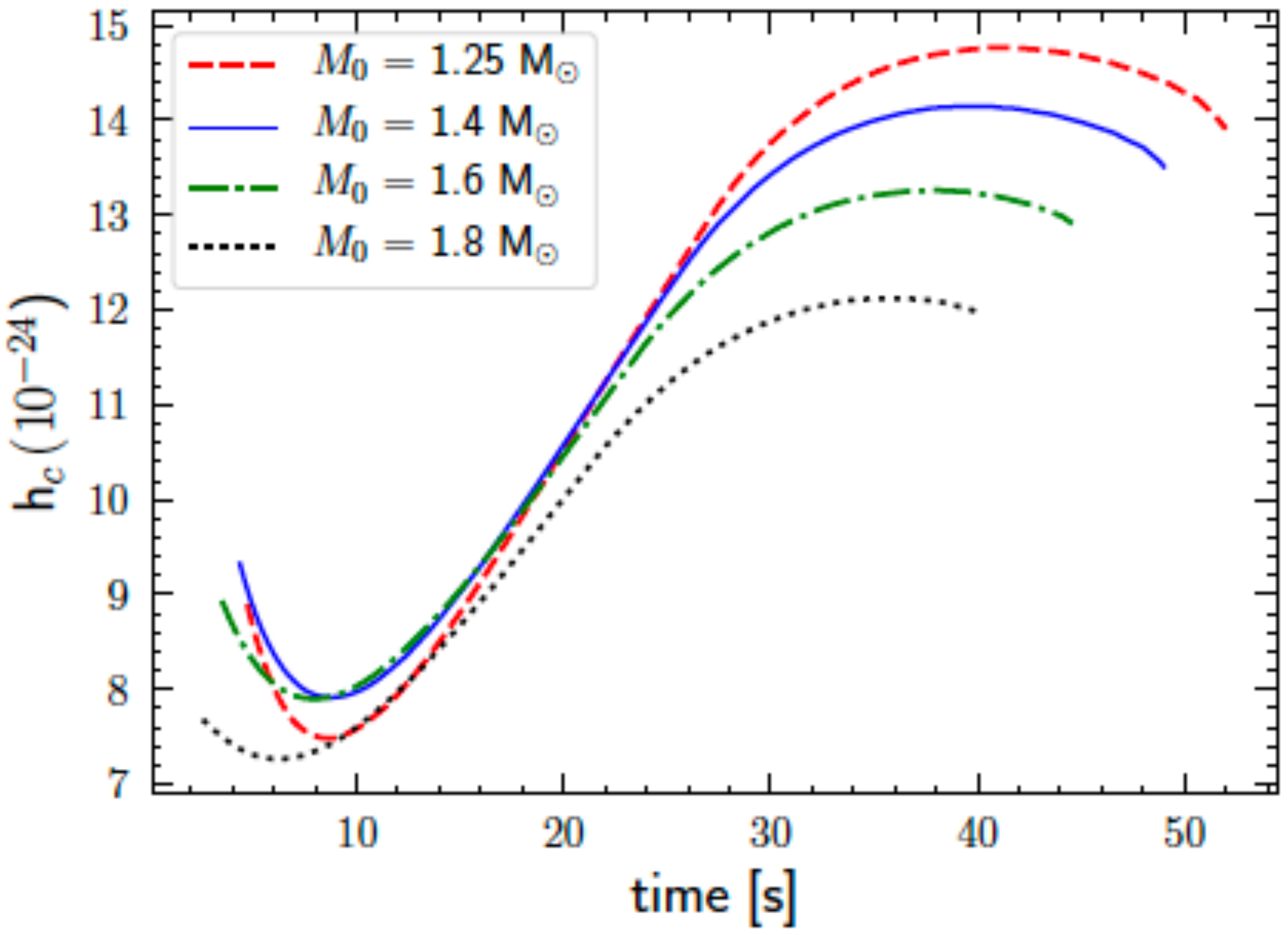
LONG-TRANSIENTS (quasi-CW) FROM NEWBORN MAGNETARS



Large "mountains" from fallback accretion (ms-spinning magnetar)

$\epsilon \sim 10^{-6} - 10^{-5}$

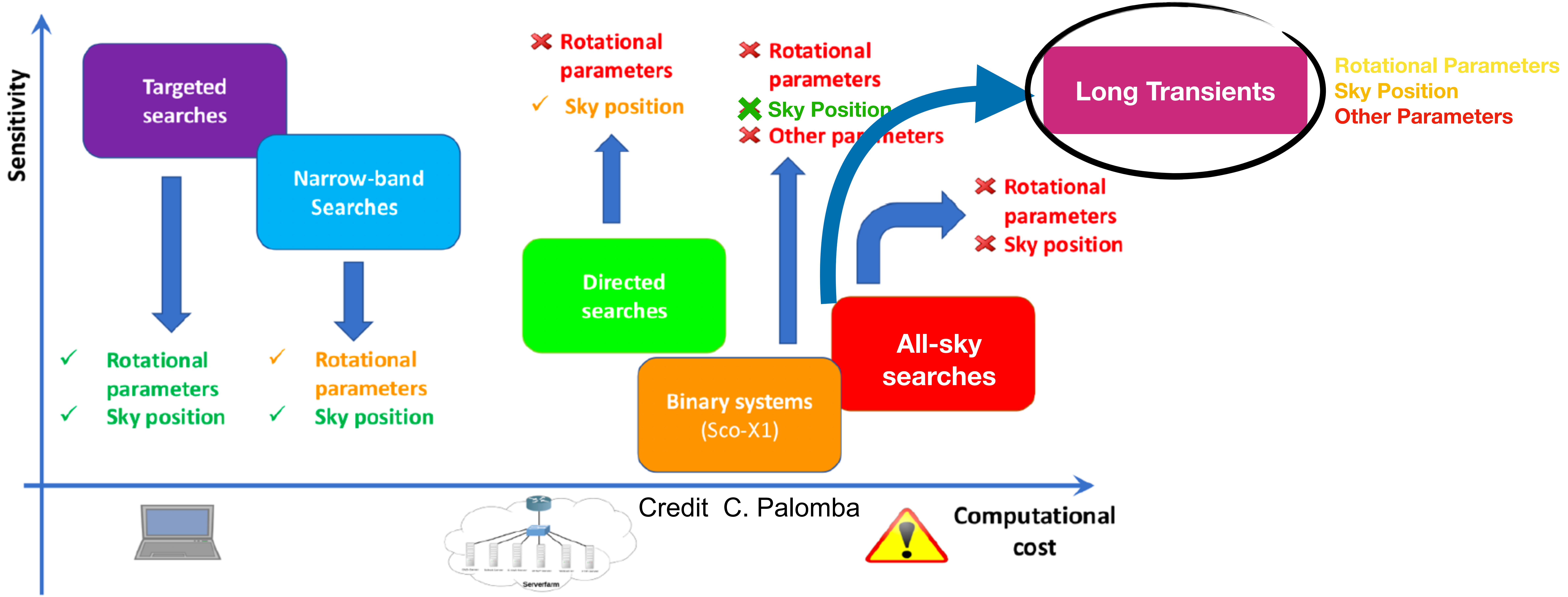
Sur & Haskell (2021)



$$h_0 = \frac{16\pi^2 G}{c^4}\frac{I_{zz}\epsilon f_{\rm spin}^2}{D} \sim 3 \times 10^{-26}\, f_{\rm kHz}^2\, \epsilon_{-4}\, D_{10\ \rm Mpc}^{-1}$$

But in this case the evolution of both $f_{\rm kHz}$ and ϵ are complex and depend particularly on the amount of fallback and on its interaction with the NS B-field

LONG-TRANSIENTS (quasi-CW) FROM NEWBORN MAGNETARS



Order of magnitude estimate

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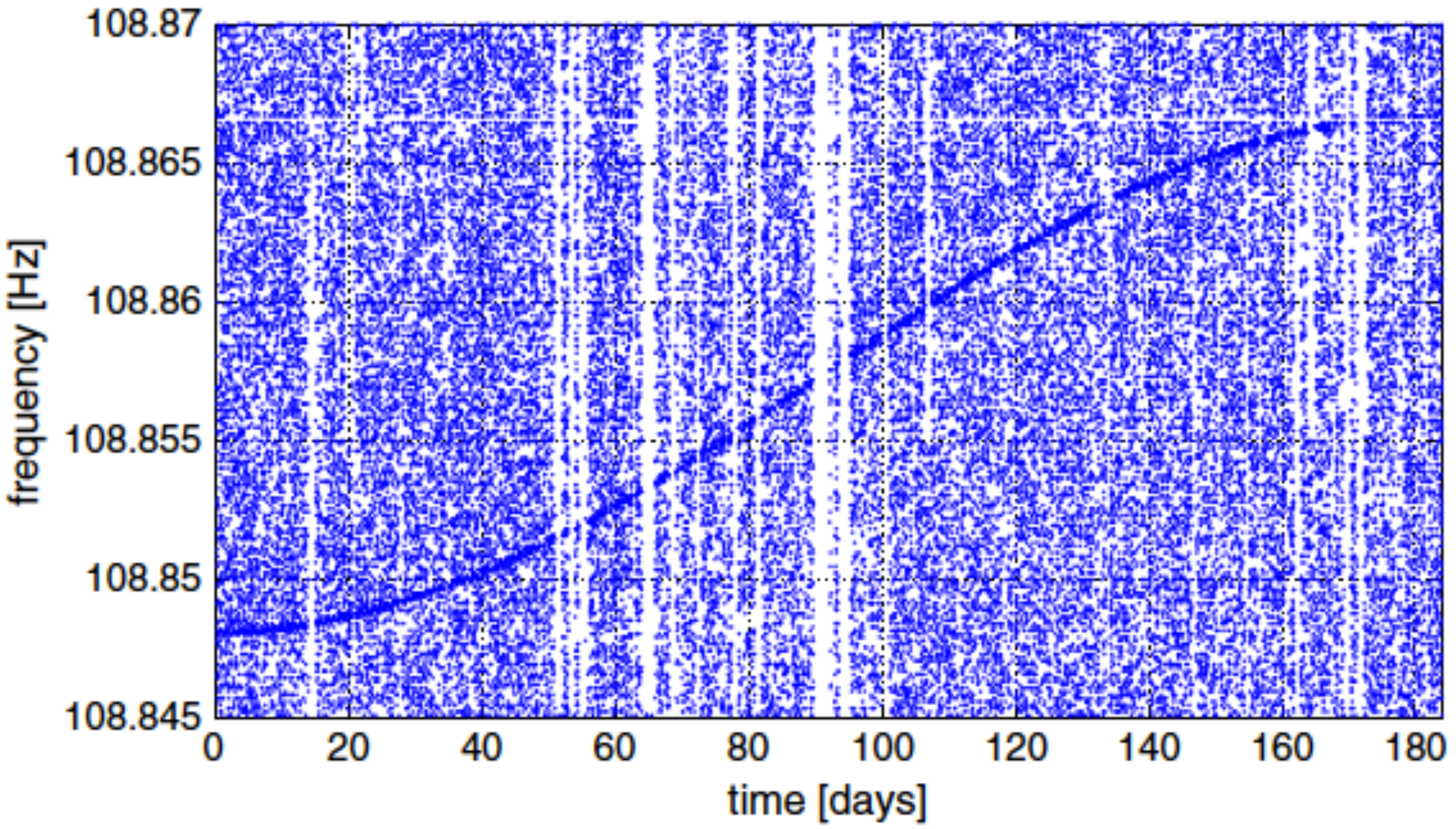
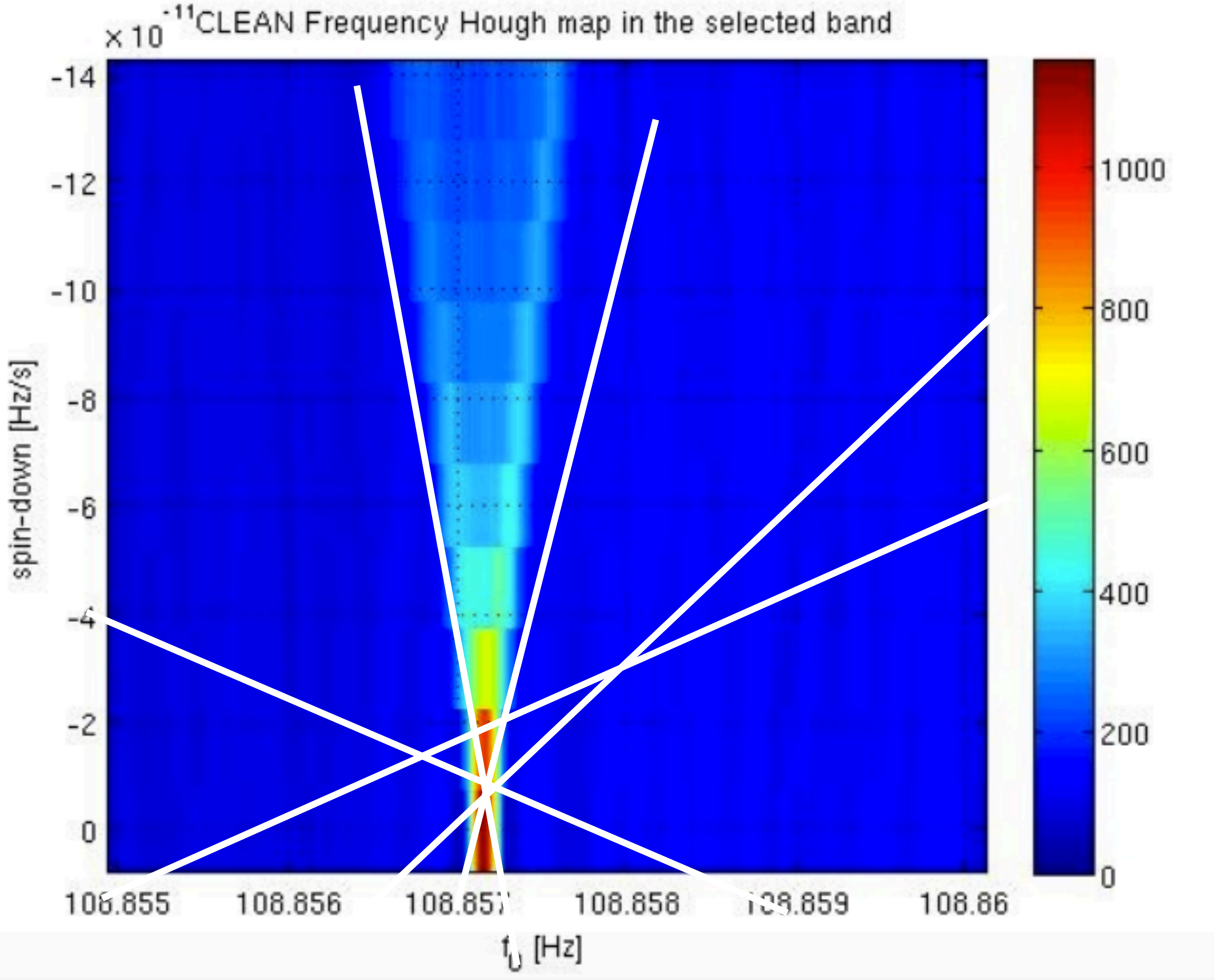
LONG-TRANSIENTS (quasi-CW) FROM NEWBORN MAGNETARS

Development and optimisation of a semi-coherent approach

Starting point: the Generalised FrequencyHough (GFH) pipeline, developed in the Roma 1 Virgo Group

Used in O2 search for merger remnant in GW 170817 (**horizon D $\lesssim$ 1 Mpc**)





Hough Transform

$$f = f_0 + \dot{f}_0(t - t_0) \quad \Rightarrow \quad \dot{f}_0 = -\frac{f_0}{t - t_0} + \frac{f}{t - t_0}$$

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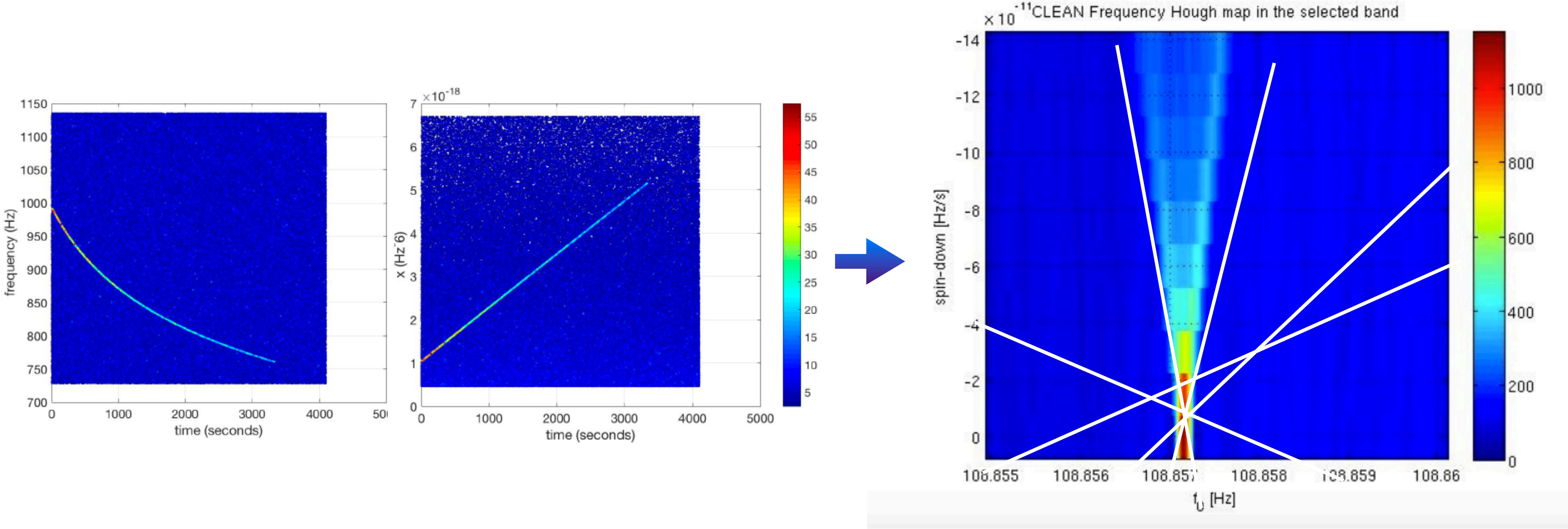

Hough Transform

$$\dot{f} = -kf^n \quad \rightarrow \quad \begin{cases} x = f^{-(n-1)} \\ x_0 = f_0^{-(n-1)} \end{cases} \quad \Rightarrow \quad x = x_0 + (n-1)k(t - t_0)$$

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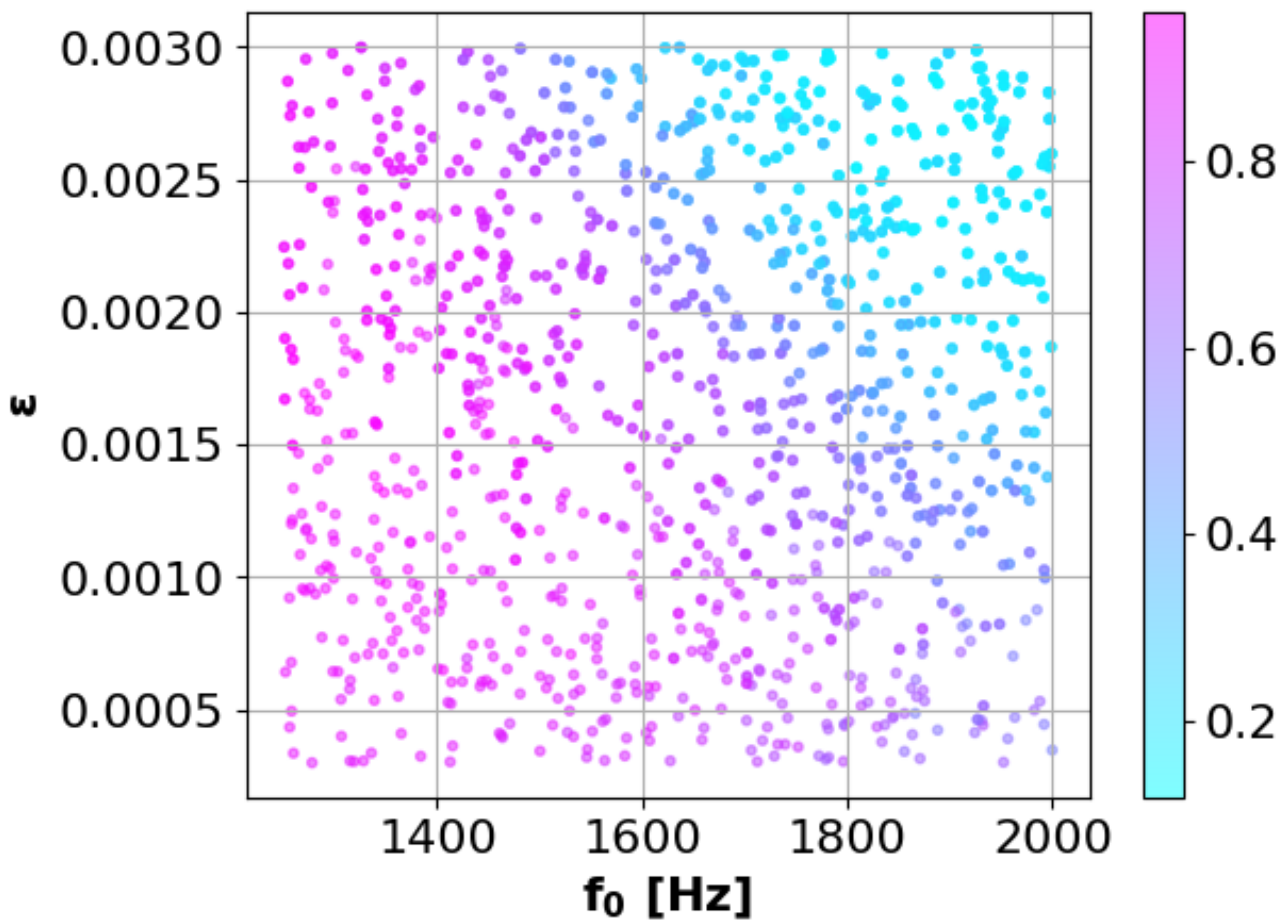
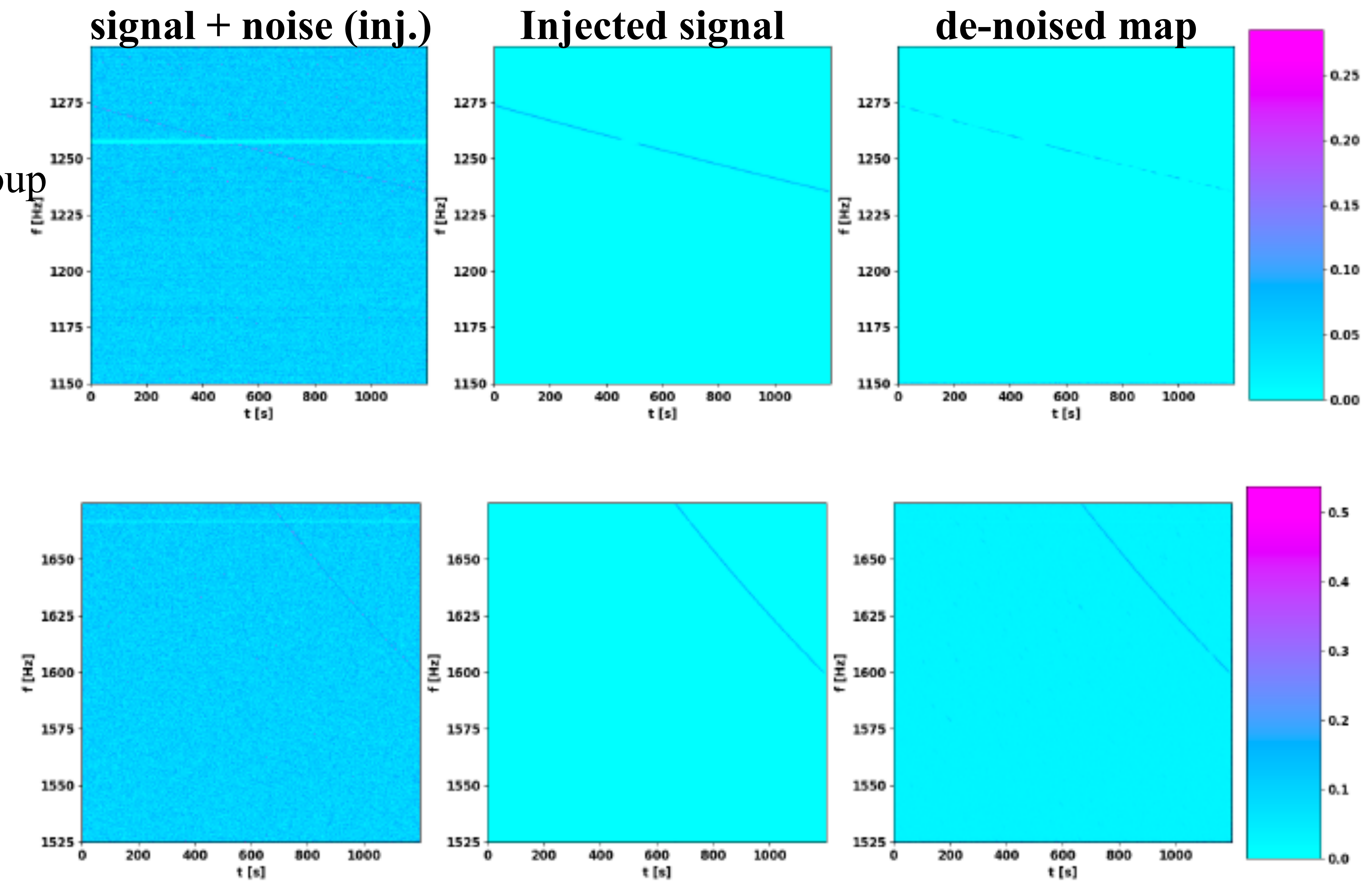
ML-based algorithm to look for candidates

Master Thesis by Francesca Attadio

Now PhD @Sapienza University/Roma1 Virgo Group

Check talk on Friday in the Magnetar session!





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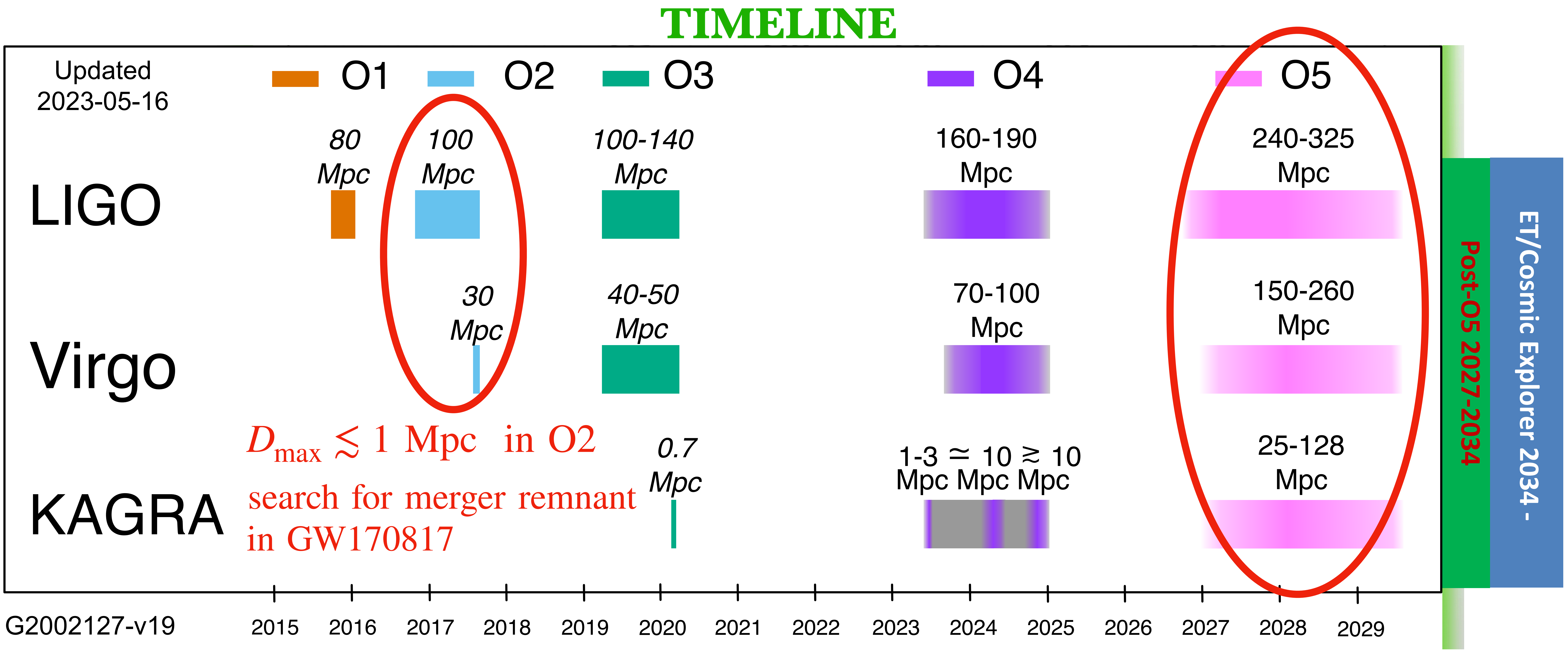
Check talk on Friday in the Magnetar session!

Improvement of GFH and `coupling' with ML-algorithm
PhD project of Sandhya S. Menon (ongoing)
(Sapienza University/Roma1 Virgo Group)

↓

Currently preparing the data for a search directed at the recent SN 2023ixf in the Pinwheel Galaxy (M101) at ~6 Mpc distance

LONG-TRANSIENTS (quasi-CW) FROM NEWBORN MAGNETARS



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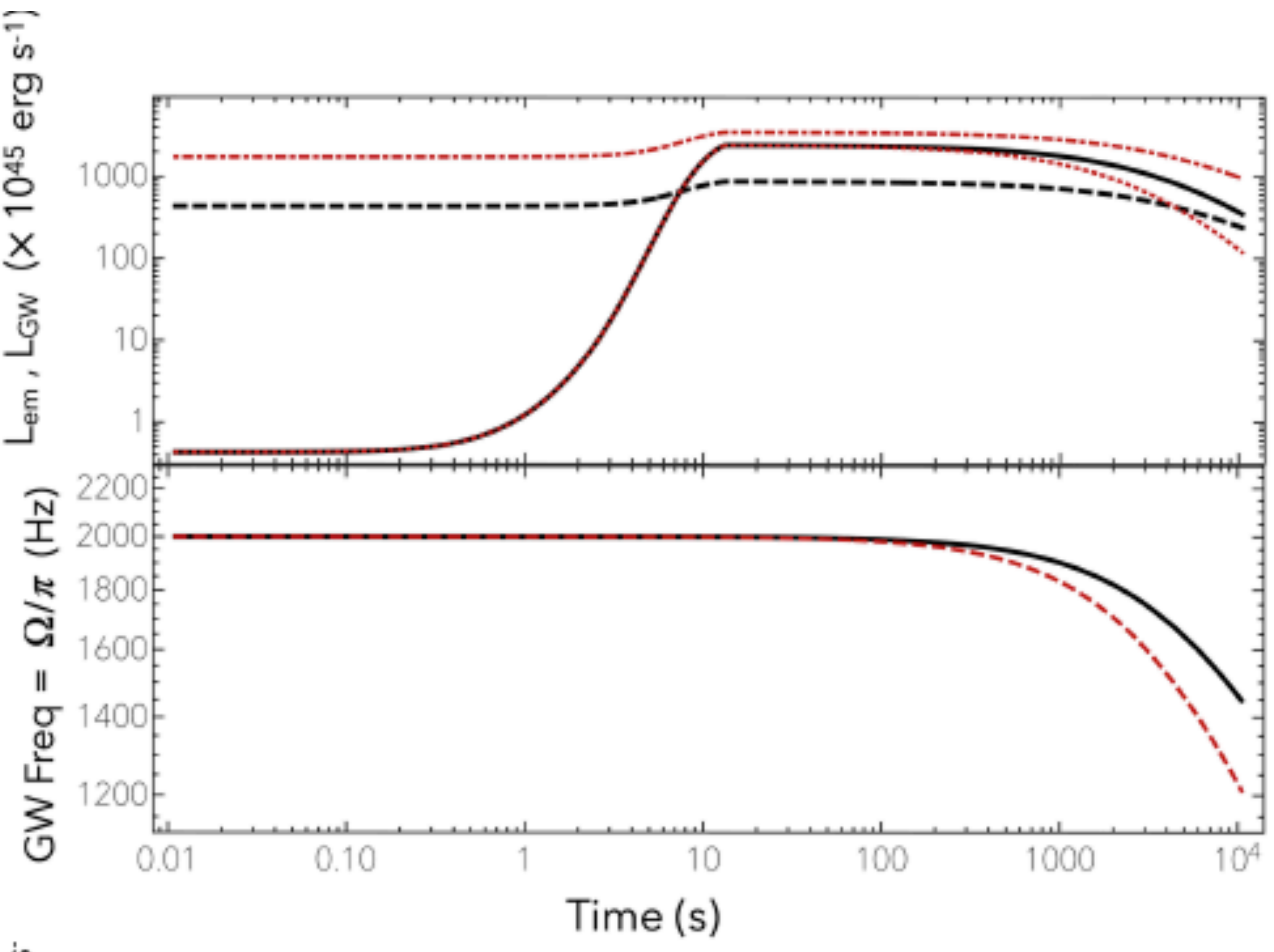

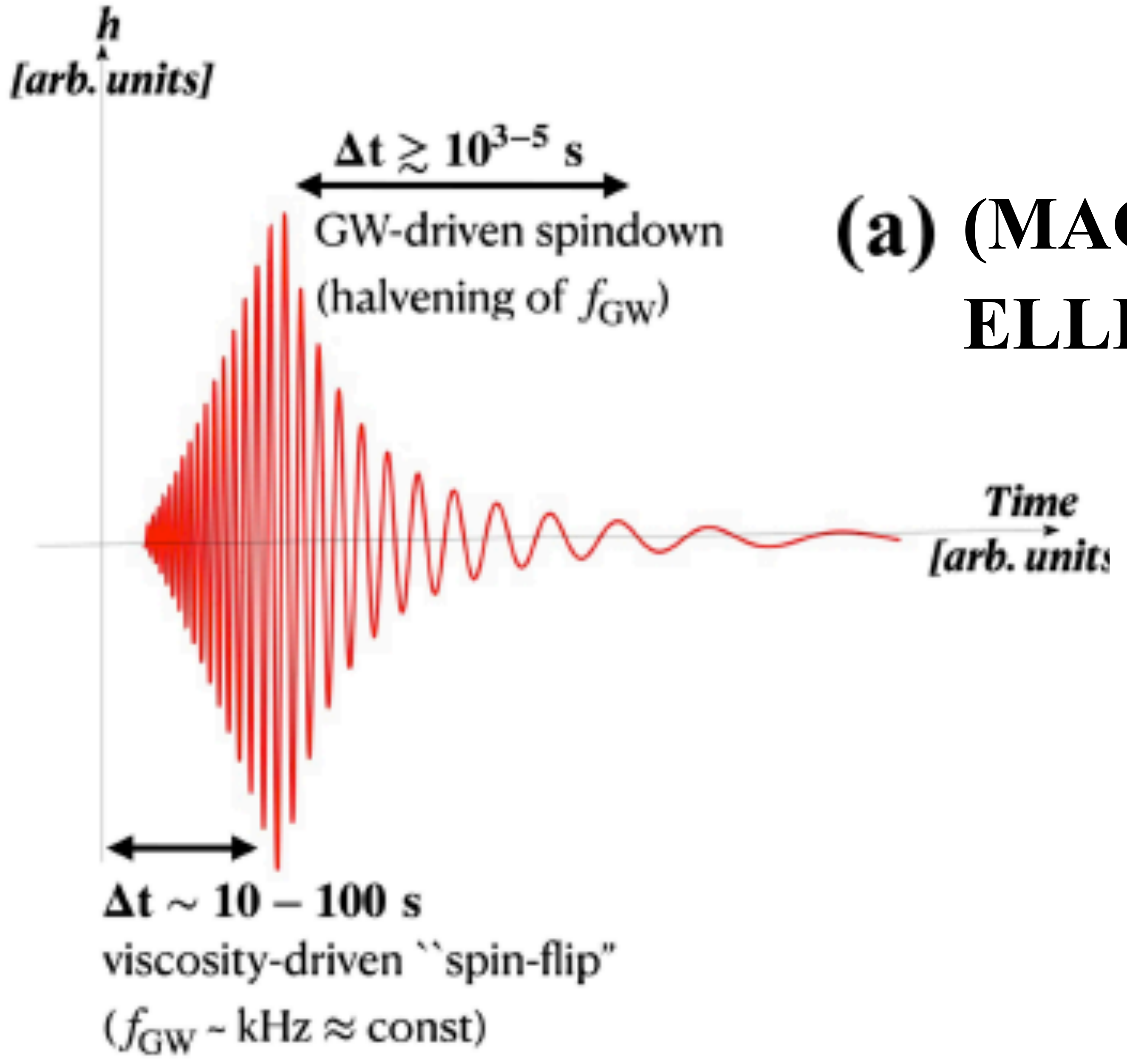

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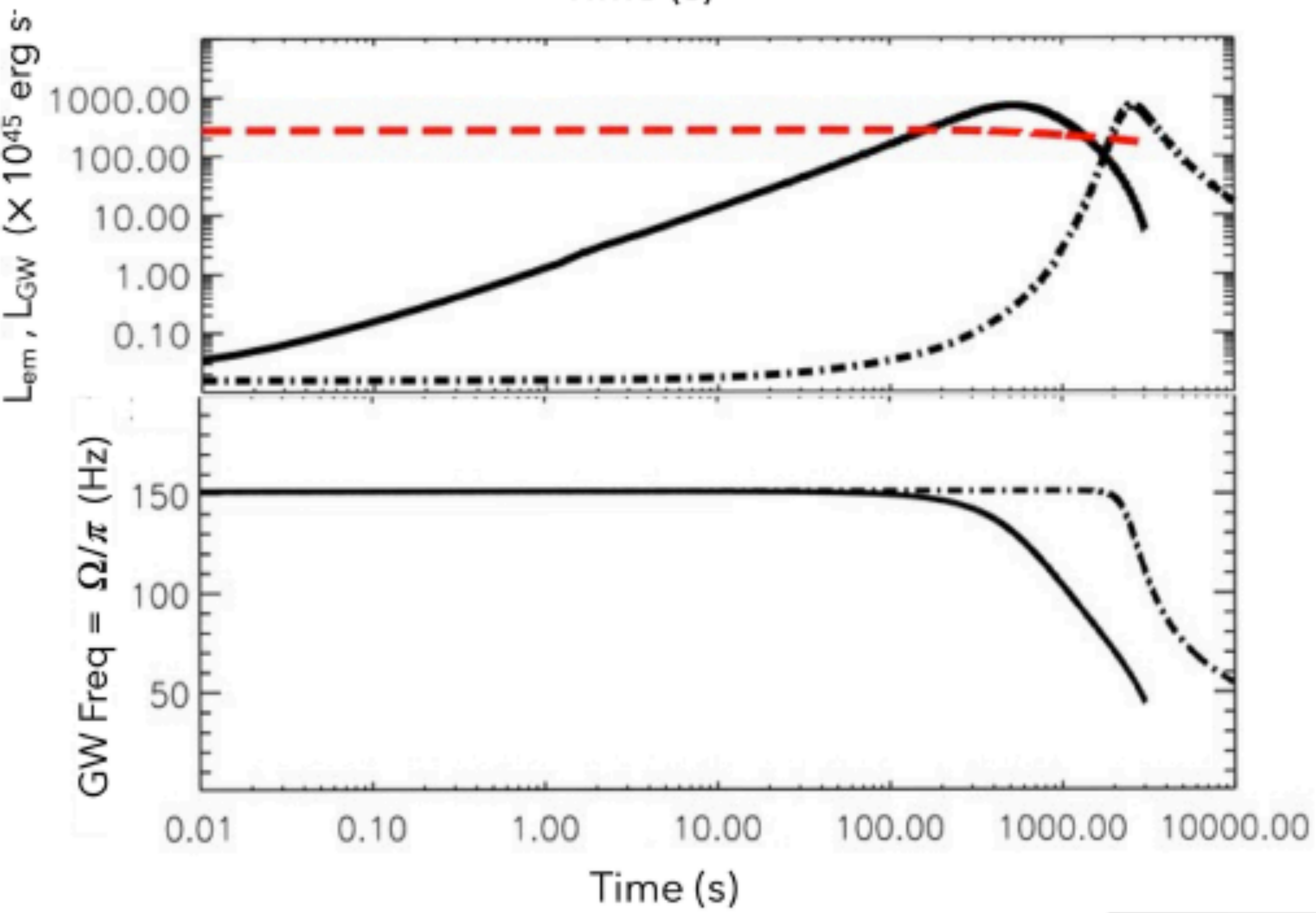
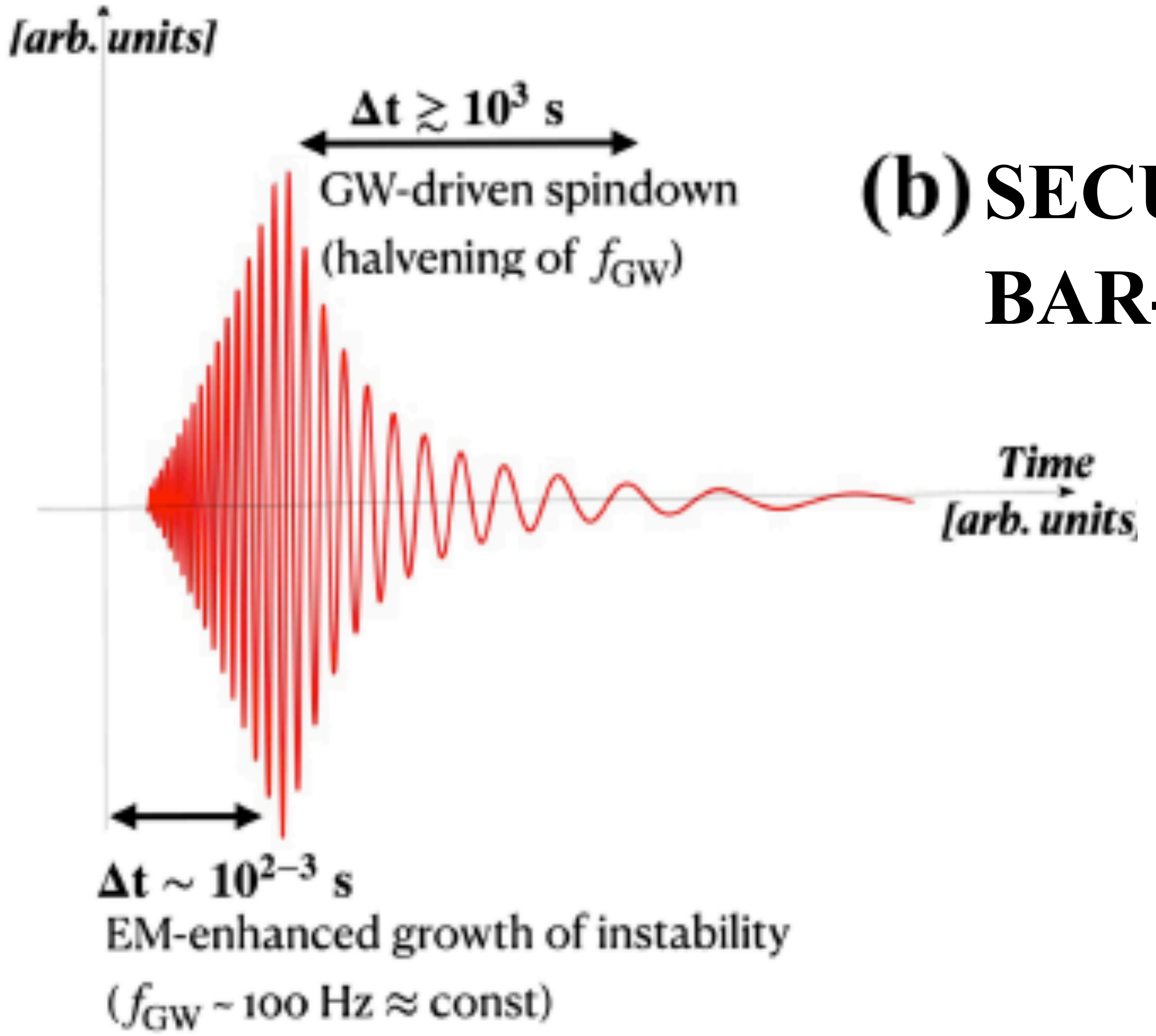




(b) SECULAR BAR-MODE

Dall'Osso and Stella (2022)

$D_{max} \lesssim 1$ Mpc in O2 search for merger remnant in GW170817

↓

$\lesssim 5$ Mpc in O5

Possible targets in O5 (rate ~ 0.1 yr^{-1})

(i) local SN (e.g. SN2023ixf)

(ii) improve the efficiency of search pipelines (under way)

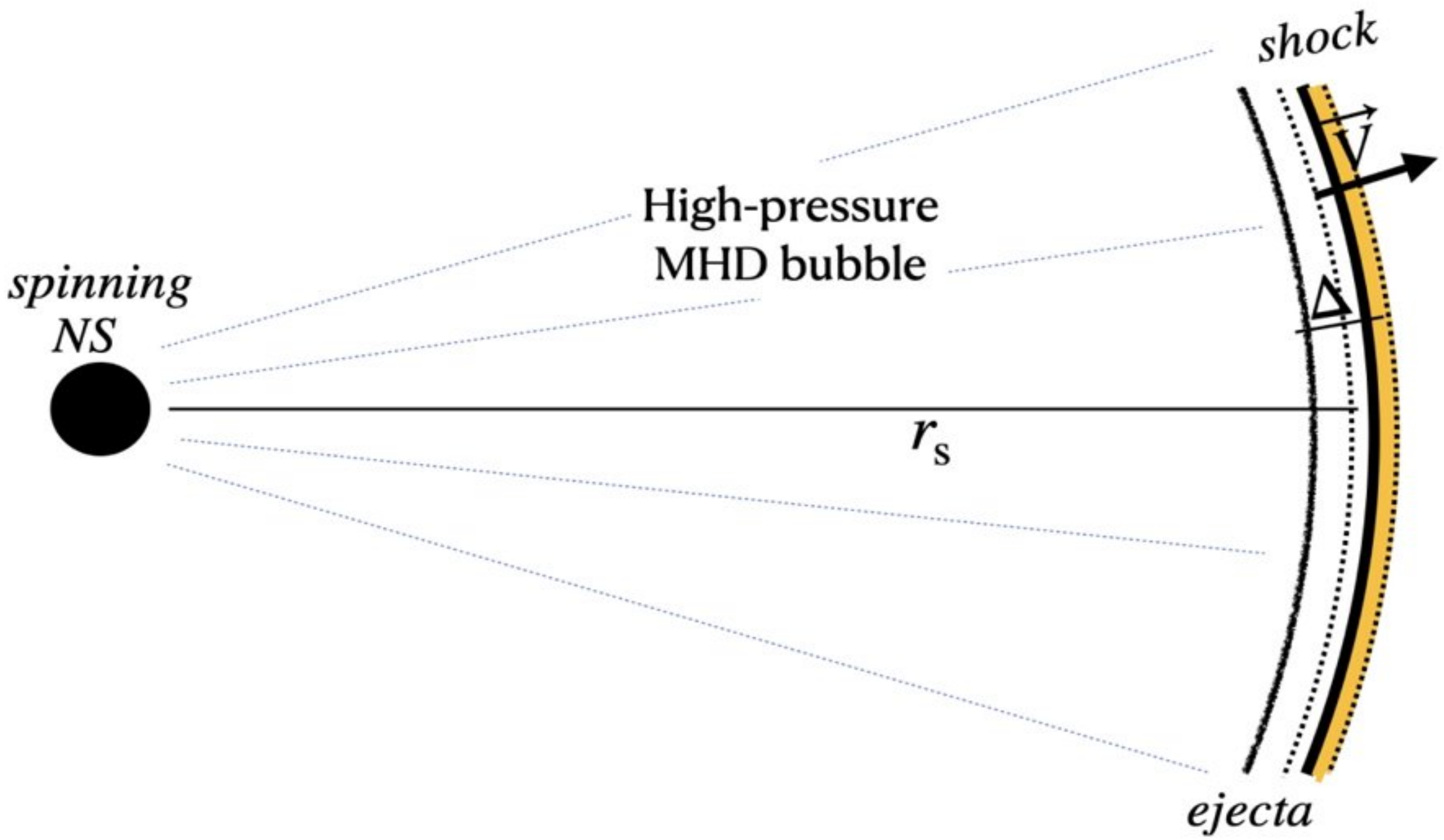
(iii) identify EM counterparts (under way)

↓

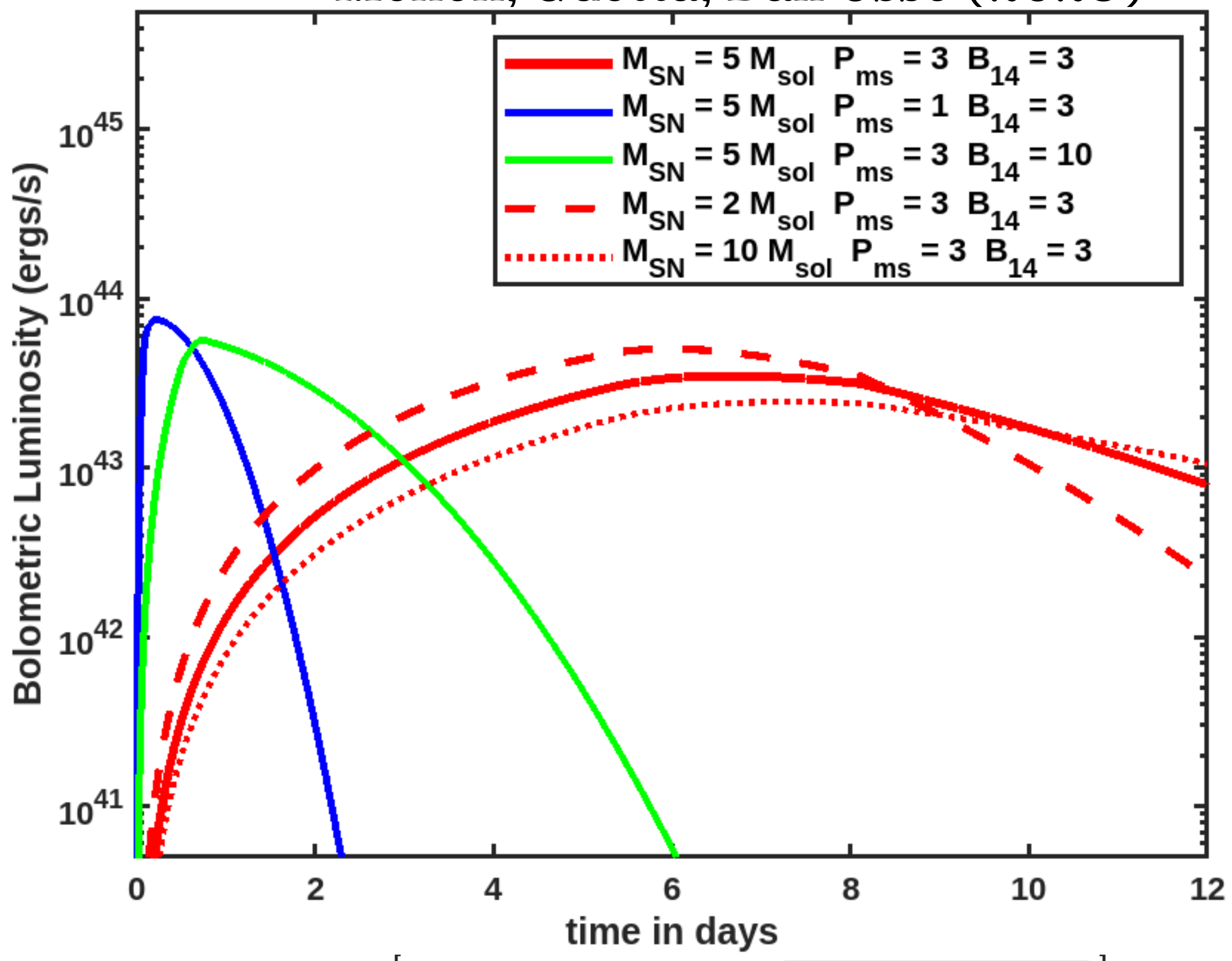
Interesting targets for post-O5 (≳1.5 increase in *h*, ~3 in rate)

Very interesting for ET with a ≳ 7-fold increase in *h*

EM TRIGGERS FOR GW SEARCHES OF LOCAL SOURCES

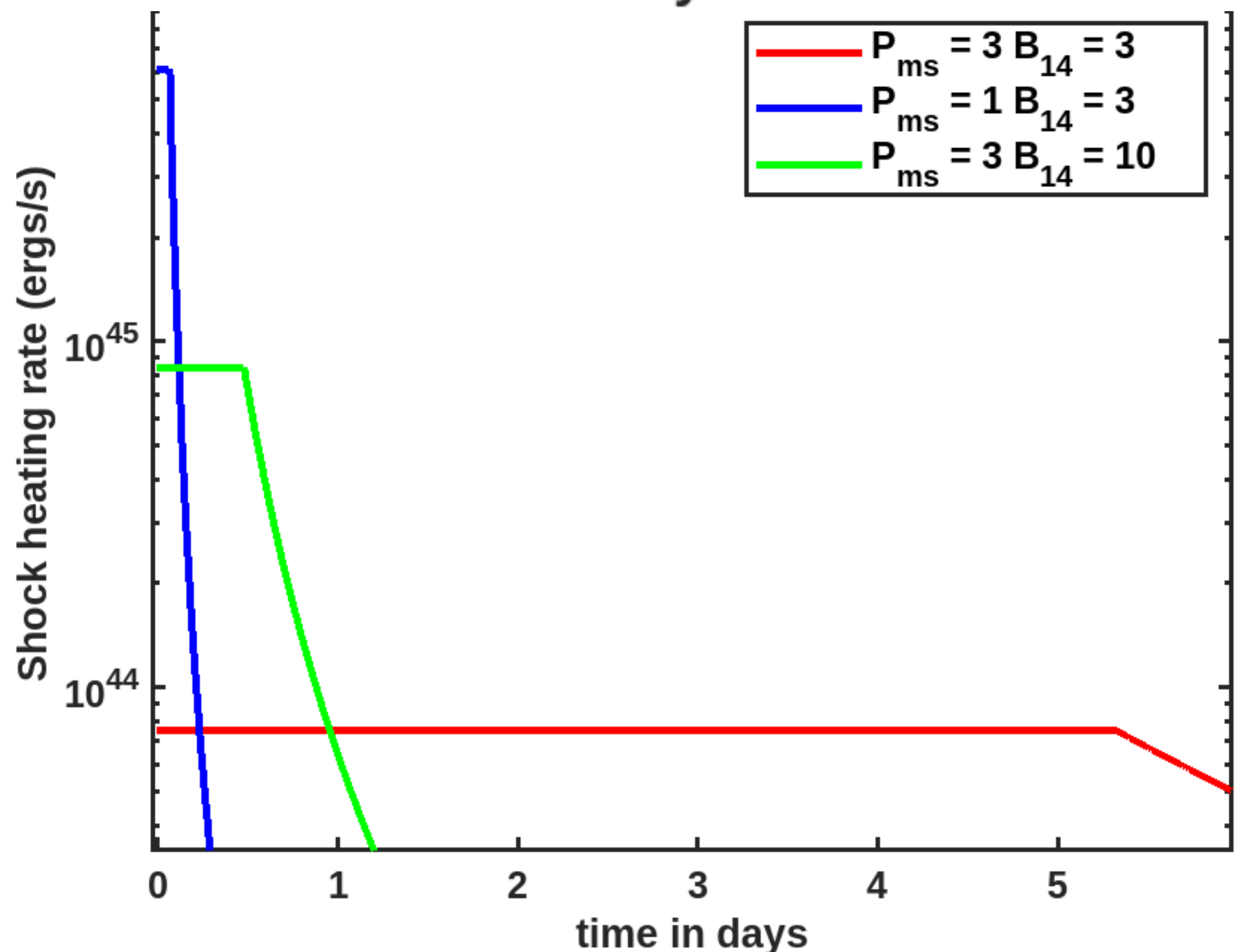


Menon, Guetta, Dall'Osso (2023)



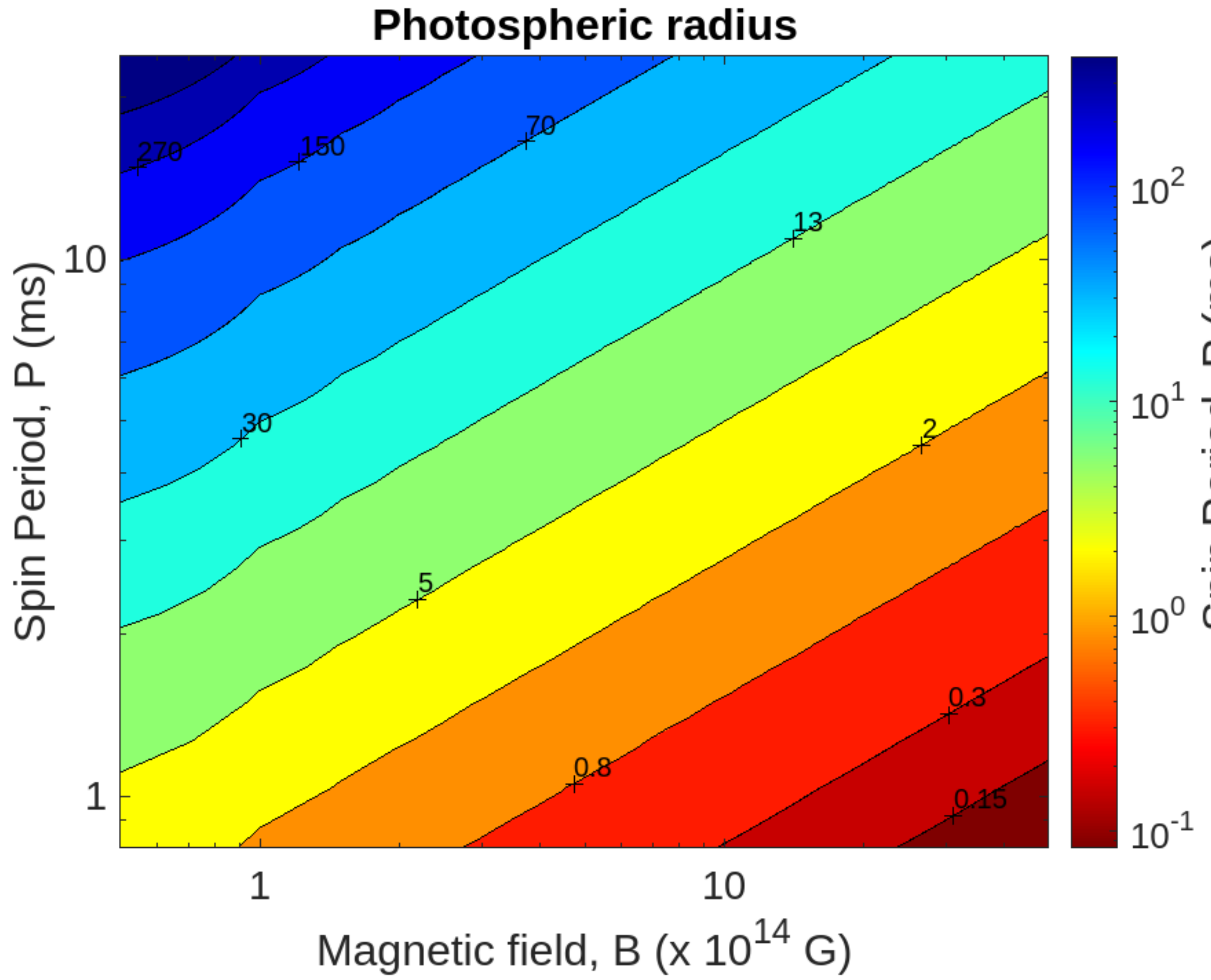
The released energy inflates a high-pressure bubble of relativistic particles and B-field, sweeping the SN ejecta into a thin shell and driving a shock through it. Shock energy is dissipated at the rate $\dot{\epsilon}_{sh} = 4\pi r_s^2 v_{ej}^3 (\rho/2)\eta^3$

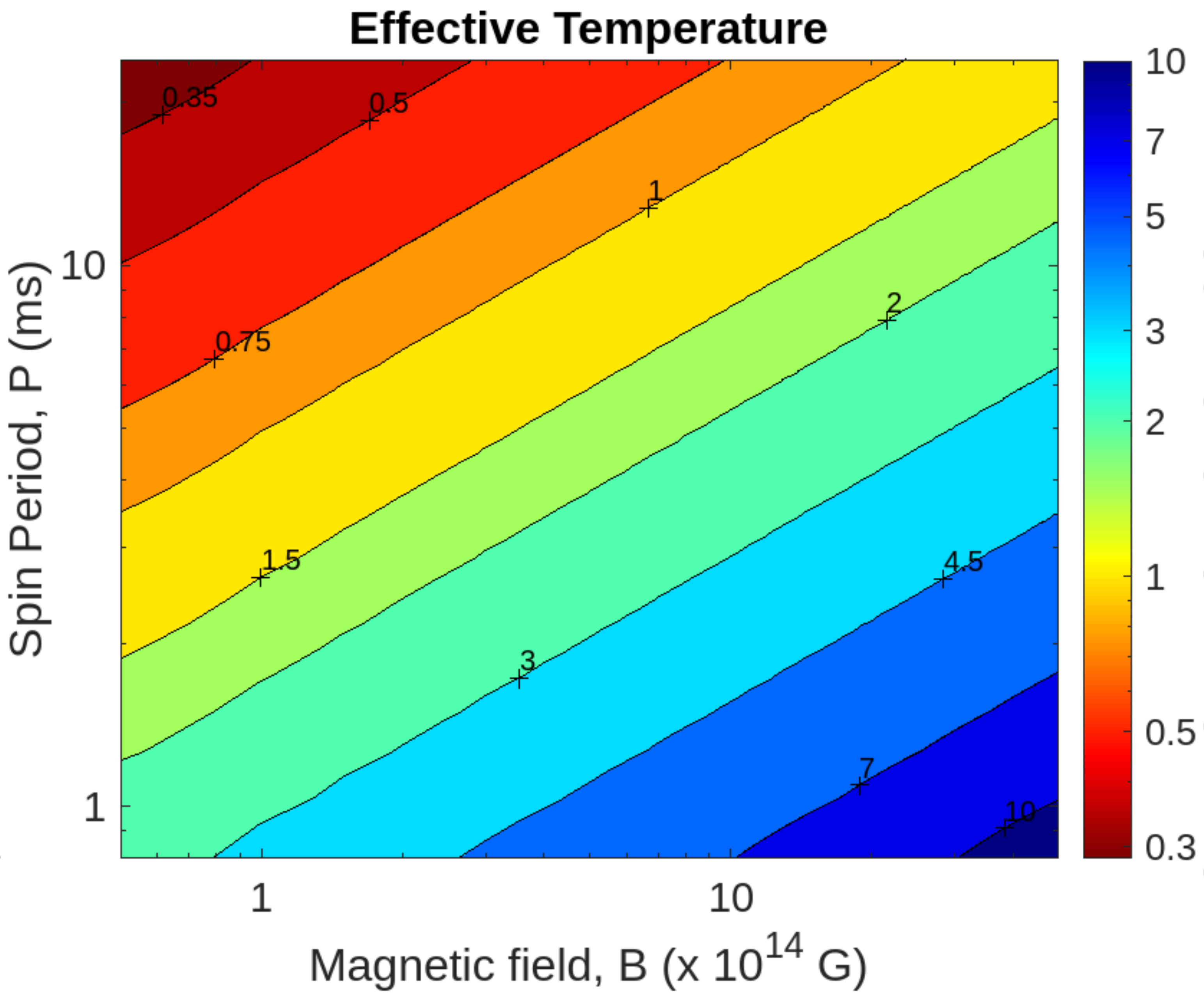
$$\eta = \frac{v_{sh} - v_{ej}}{v_{ej}}$$ shock strength parameter



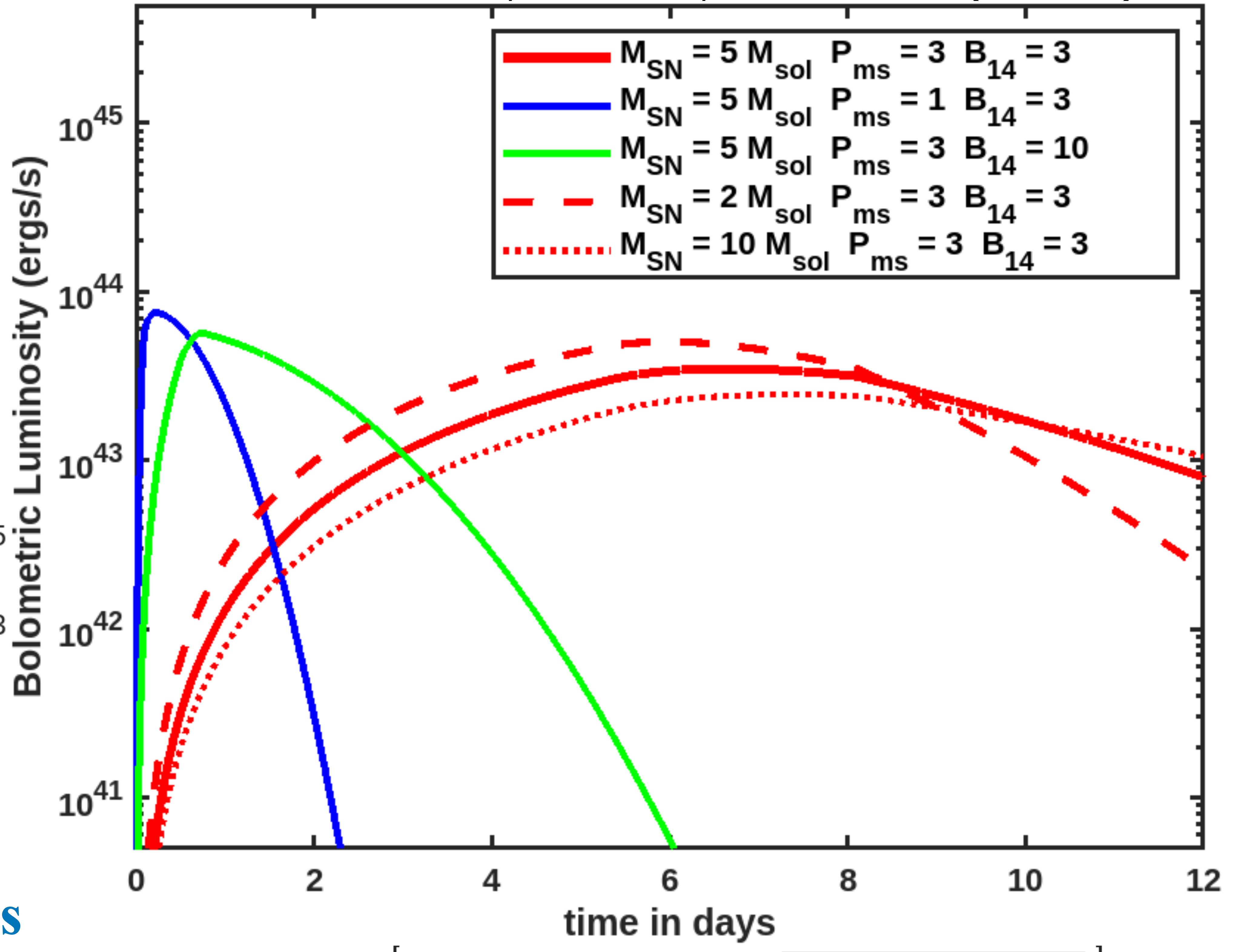
Kasen et al. (2016)

EM TRIGGERS FOR GW SEARCHES OF LOCAL SOURCES



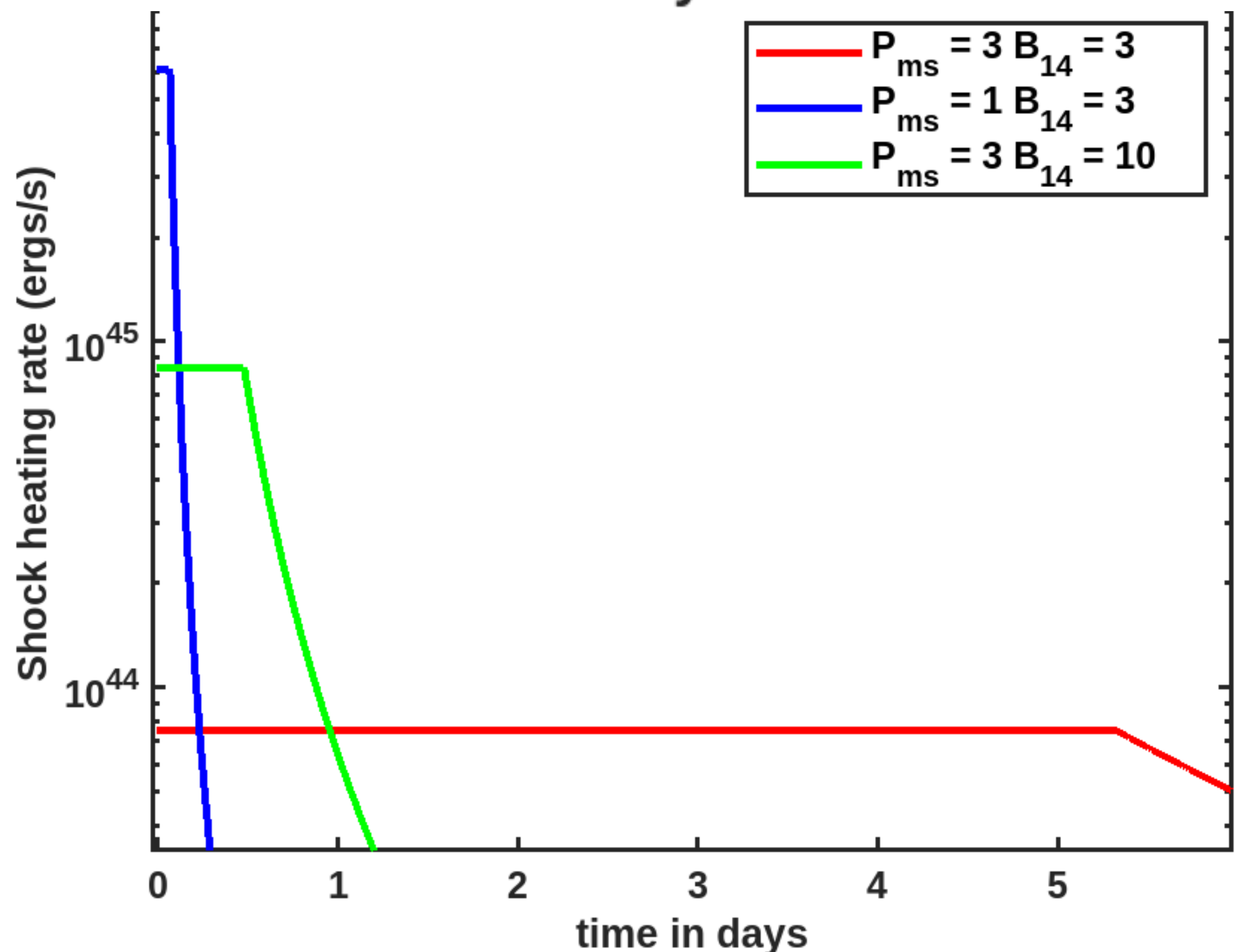


Menon, Guetta, Dall'Osso (2023)

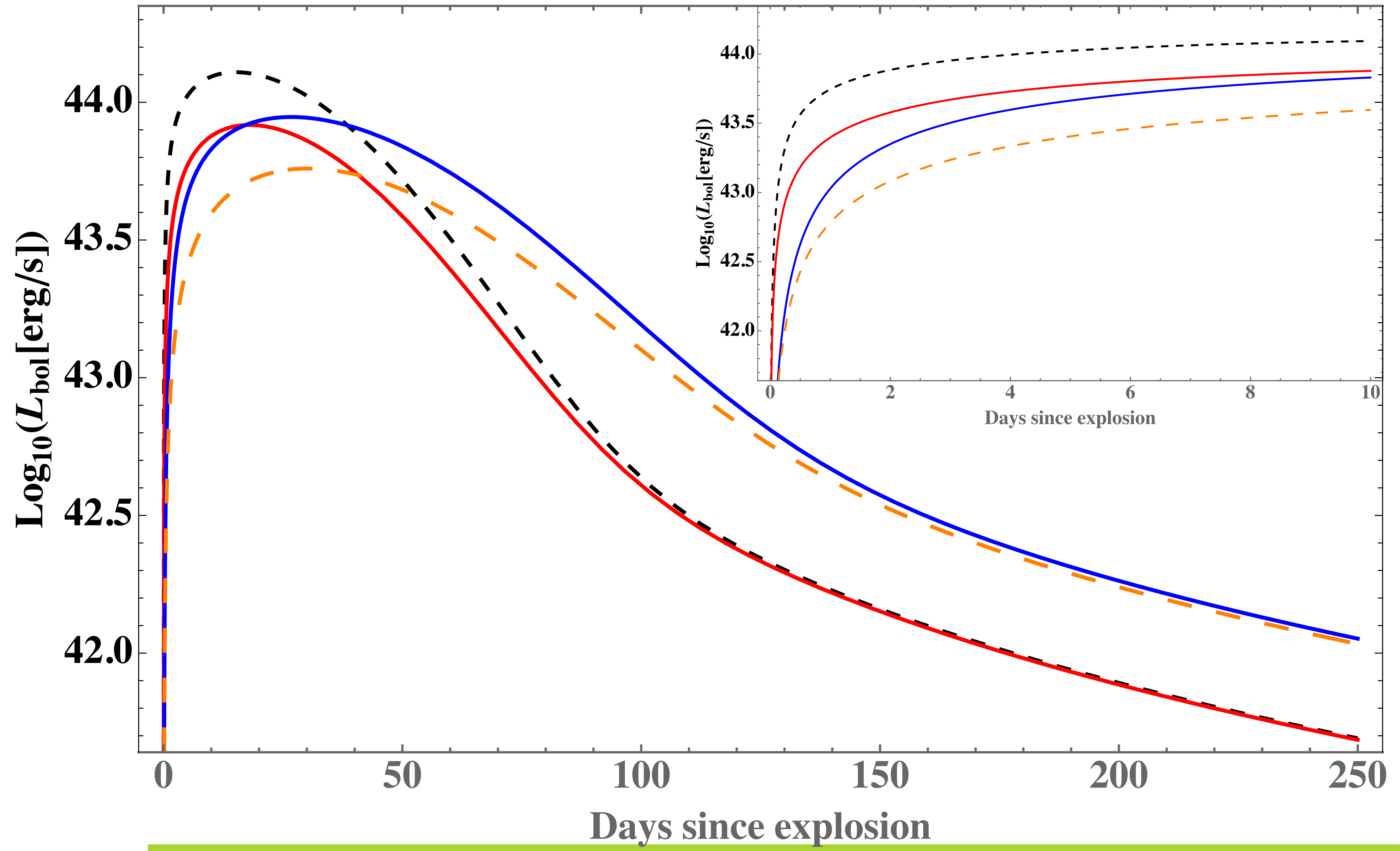


Expected UV (230-290 nm) event rate	
B-fields	$(0.5–50)\times10^{14}$G
Spin periods	0.8-15 ms
ULTRASAT fov	~ 204 deg^2
A_{NUV}	0 – 1.75 mag
M_{ej}	5 – 15 M⊙
Expected #events per year	≈ (3 – 30) yr^{-1}
	≈ (2 – 20) yr^{-1}

Expected UV events with the ULTRASAT satellite



EM TRIGGERS FOR GW SEARCHES OF LOCAL SOURCES



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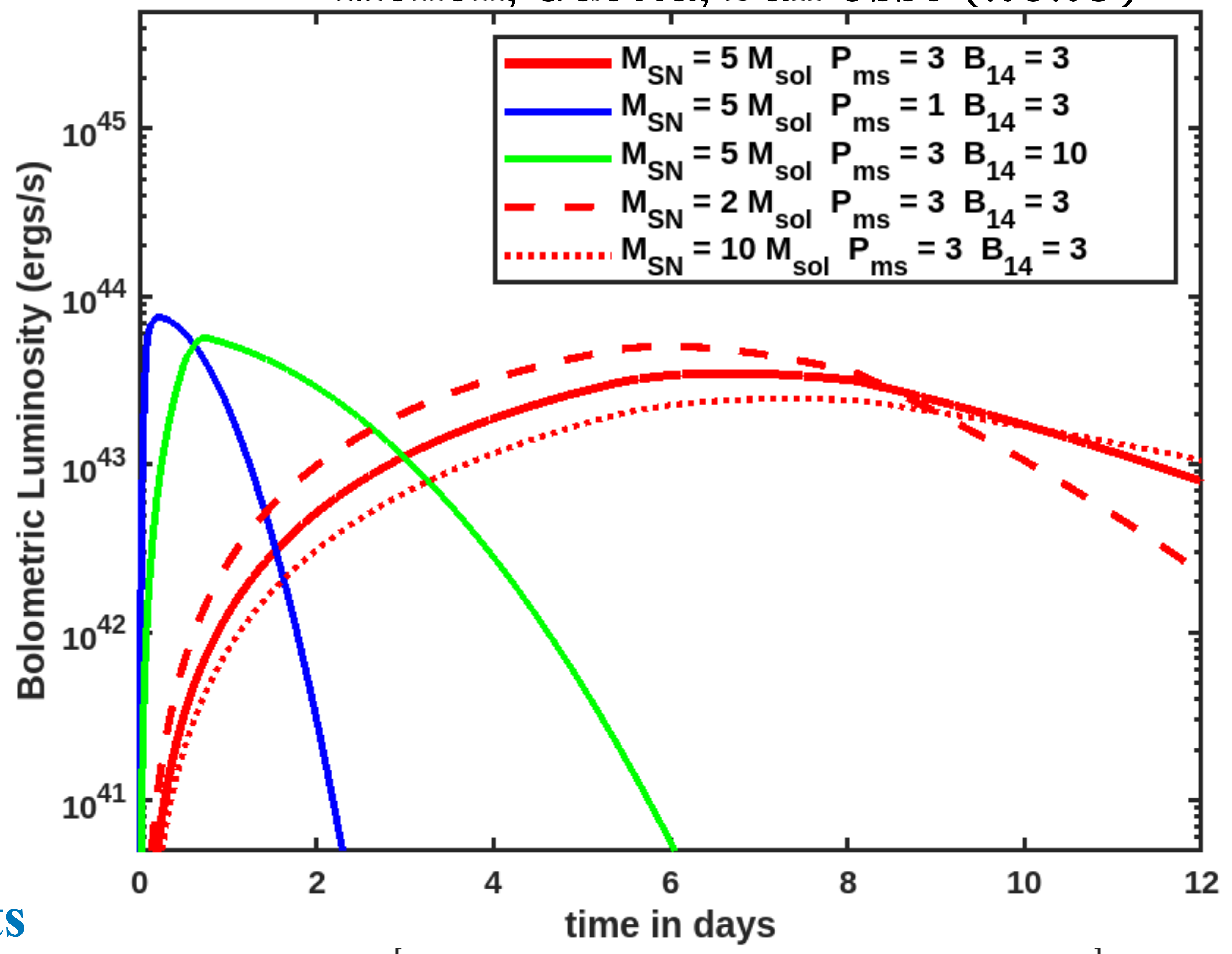
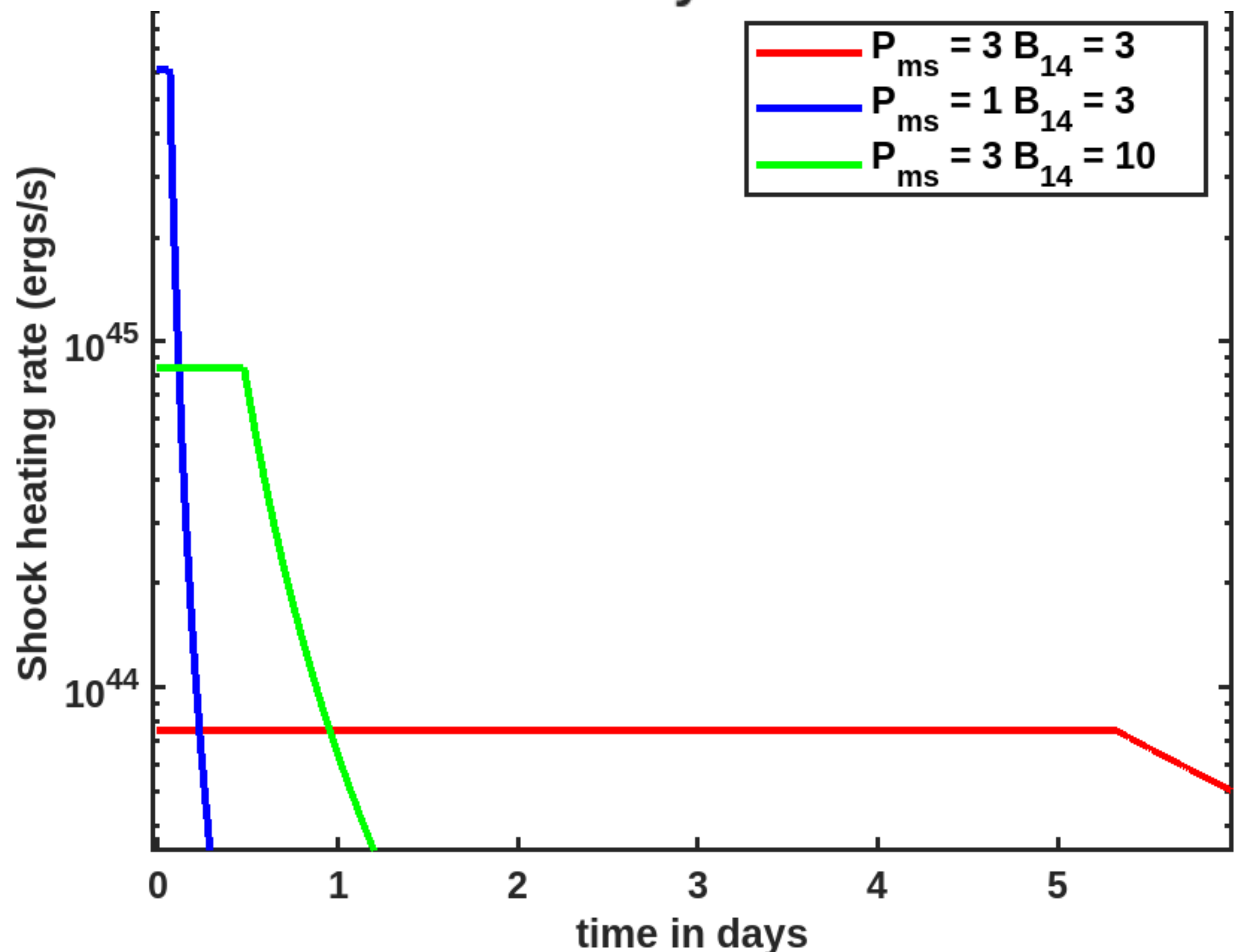
Menon, Guetta, Dall'Osso (2023)



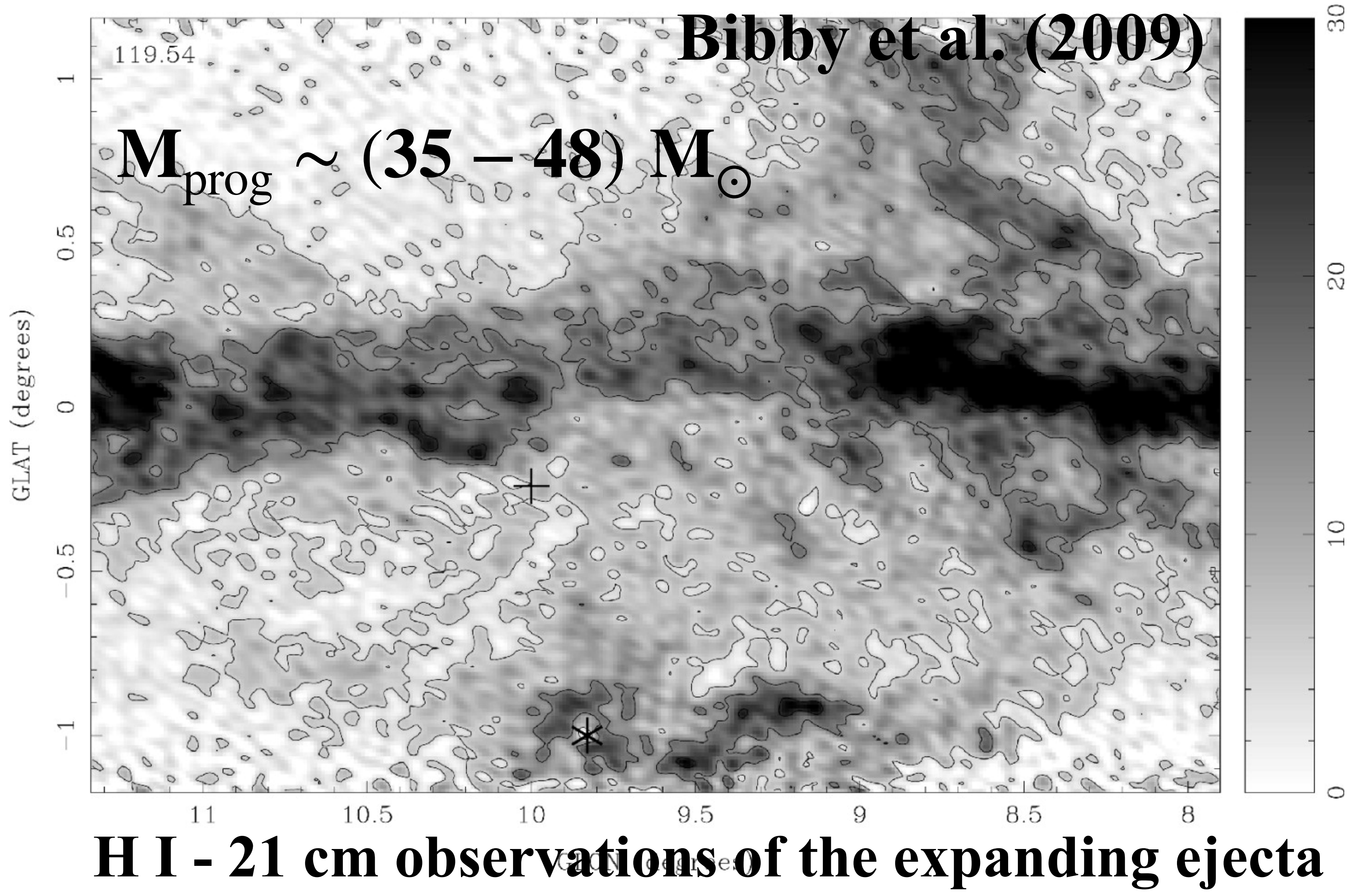


STELLAR PROGENITORS OF GALACTIC MAGNETARS

SGR 1806-20

Cameron et al. (2005)
McLure et al. (2005)
Bibby et al. (2009)

$M_{prog} \sim (35 - 48)\ M_\odot$

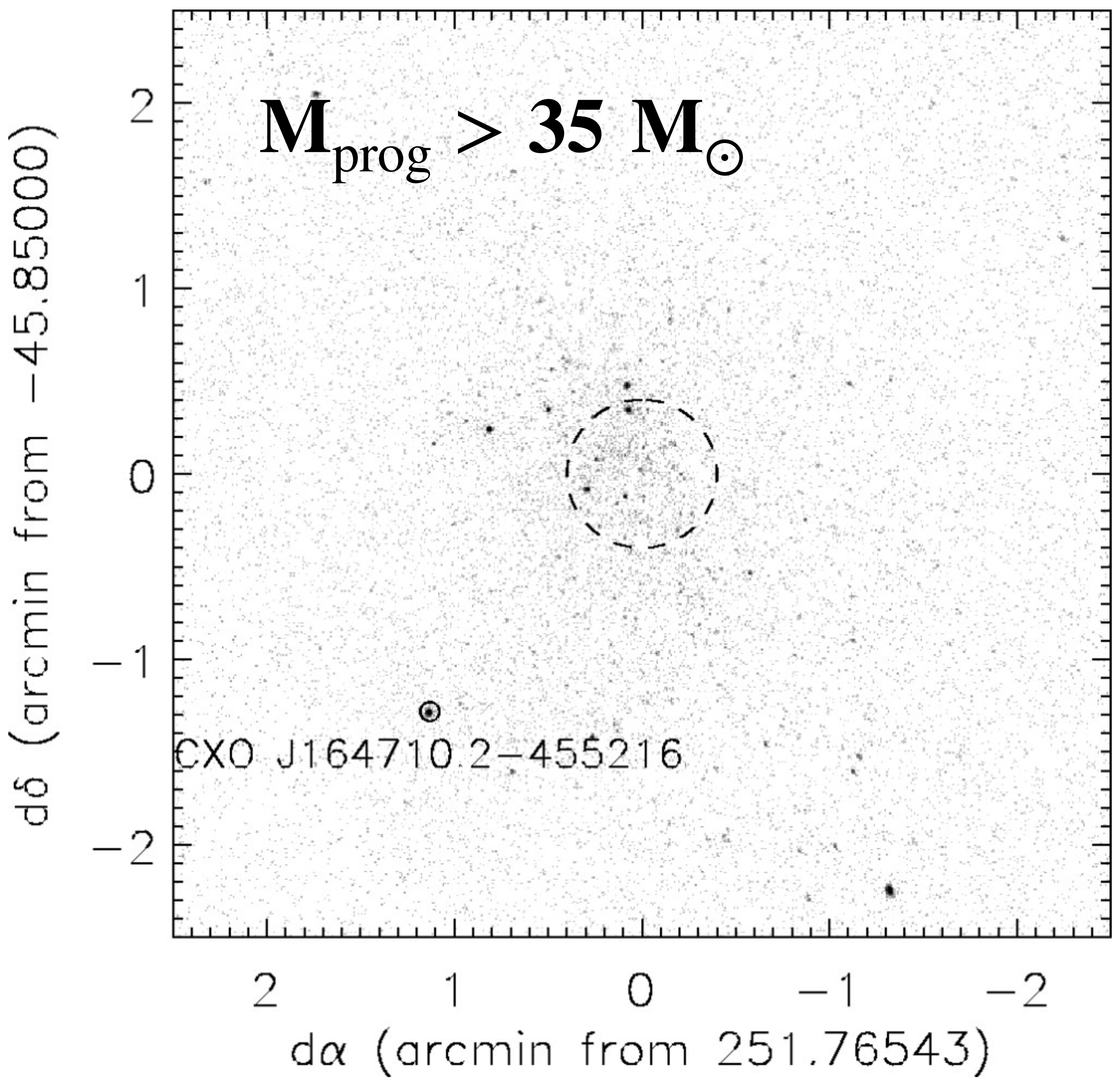


H I - 21 cm observations of the expanding ejecta following the 2004 Giant Flare

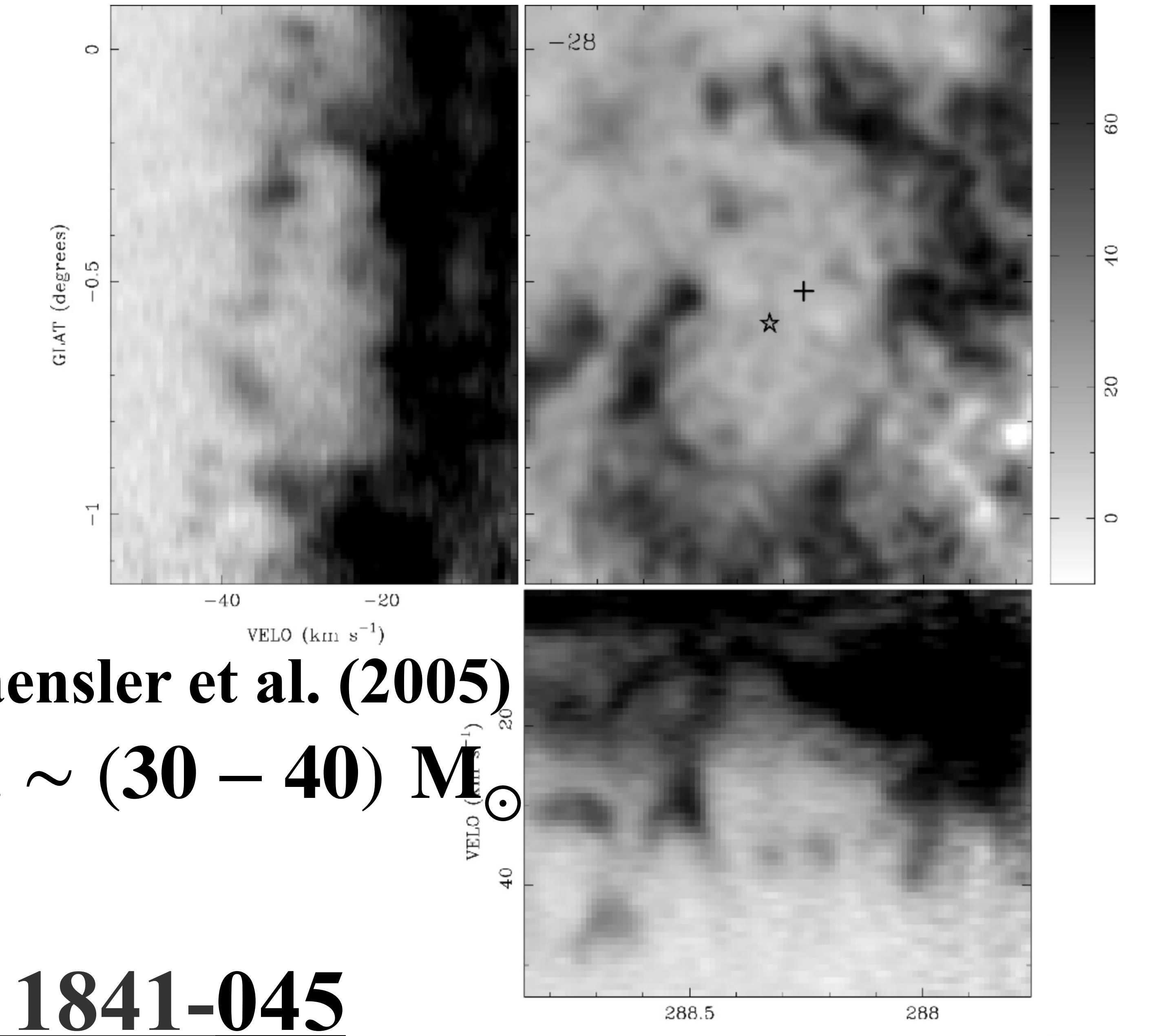
CXO J164710.2-455216

Muno et al. (2006)

$M_{prog} > 35\ M_\odot$



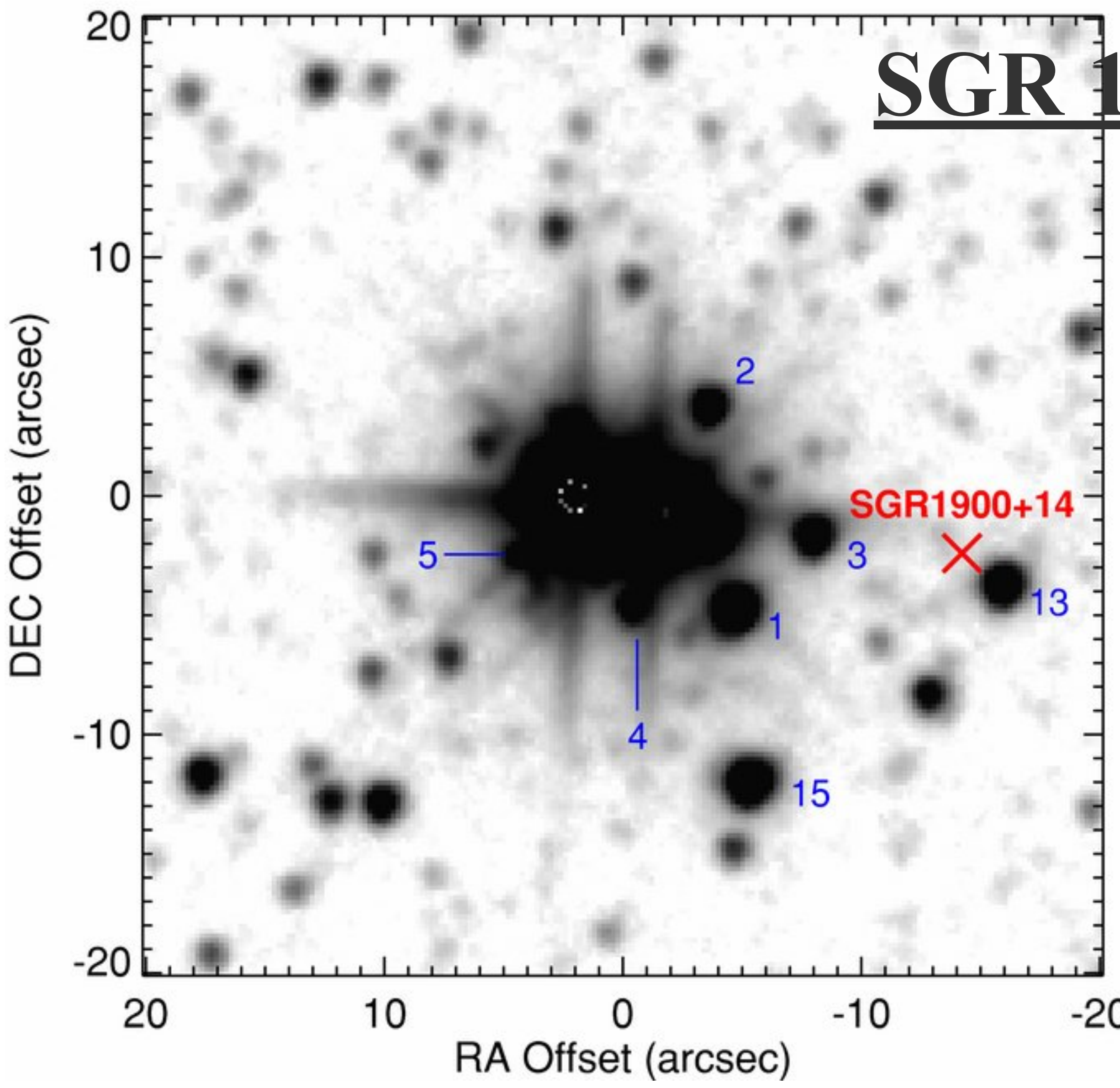
AXP - 1E 1048.1−5937

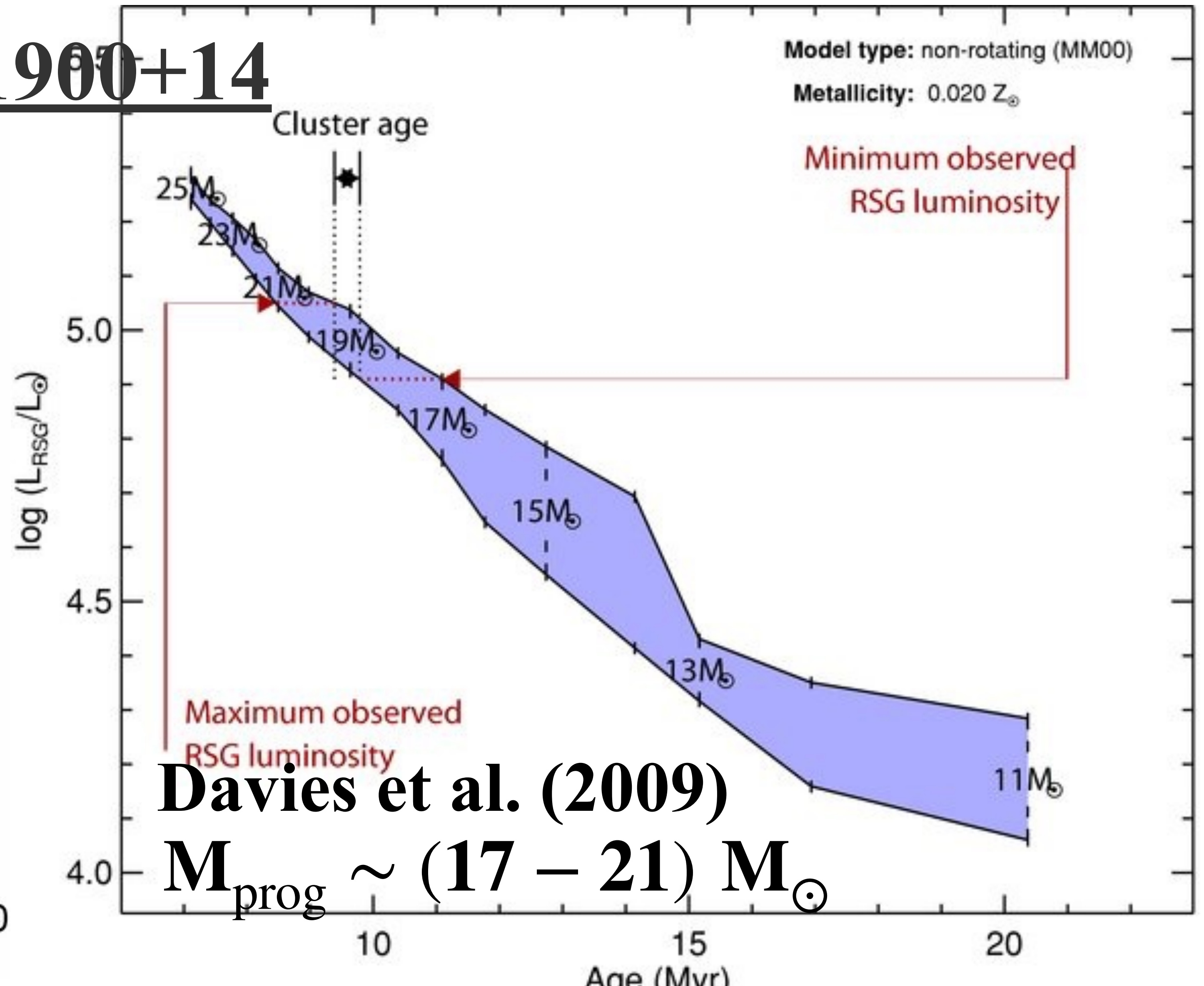


Gaensler et al. (2005)

$M_{prog} \sim (30 - 40)\ M_\odot$

SGR 1900+14





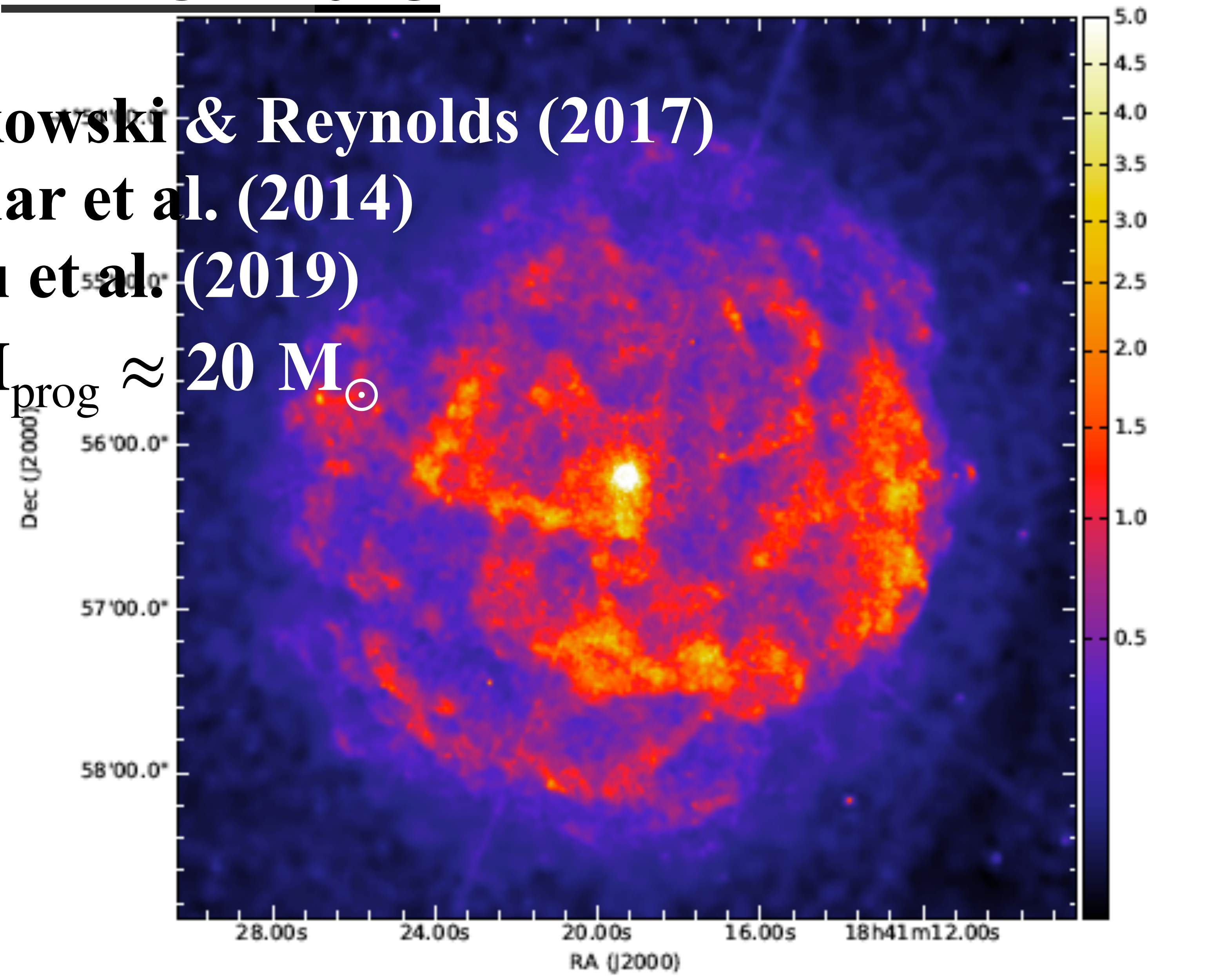
Davies et al. (2009)

$M_{prog} \sim (17 - 21)\ M_\odot$

1E 1841-045

Borkowski & Reynolds (2017)
Kumar et al. (2014)
Zhou et al. (2019)

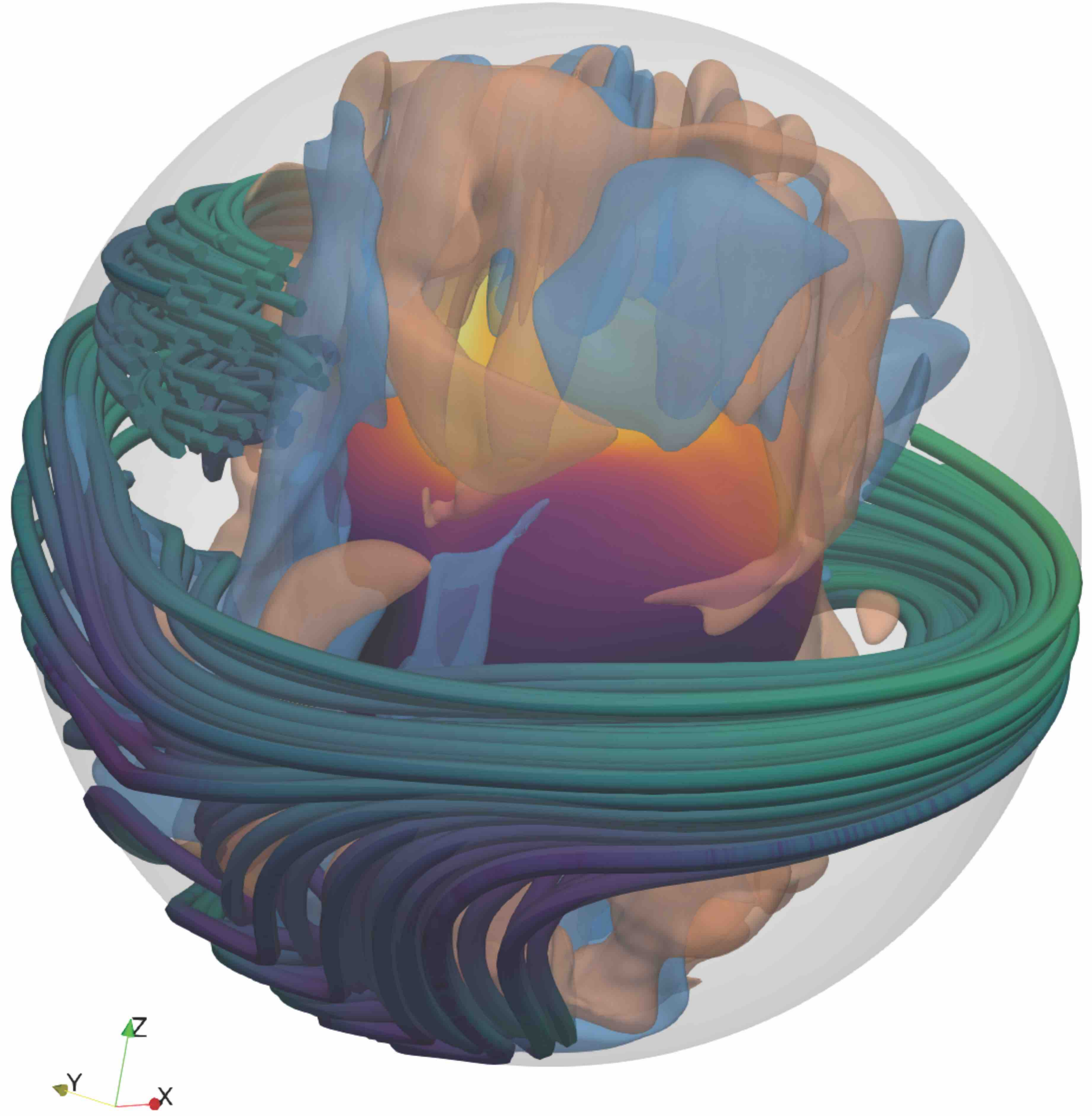
$M_{prog} \approx 20\ M_\odot$



WHAT MAKES THEM SO SPECIAL?

(a) How do magnetars acquire such strong B-fields?

(b) Which factors decide whether a nascent NS will become a magnetar?



Raynaud et al. 2020

(a) A ms-spin at birth was suggested as the key condition for a proto-NS to generate a super-strong B-field through an efficient dynamo.

$$E_{\rm rot} = \frac{1}{2} I\omega^2 \sim 3 \times 10^{52}\ {\rm erg}\ P_{\rm ms}^{-2}$$

$\Rightarrow B_{\rm int} \sim (1-3) \times 10^{16}$ G $\Rightarrow \sim (0.3-1) \times 10^{50}$ erg interior, toroidal B-field

Duncan & Thompson 1992
Thompson & Duncan 1993

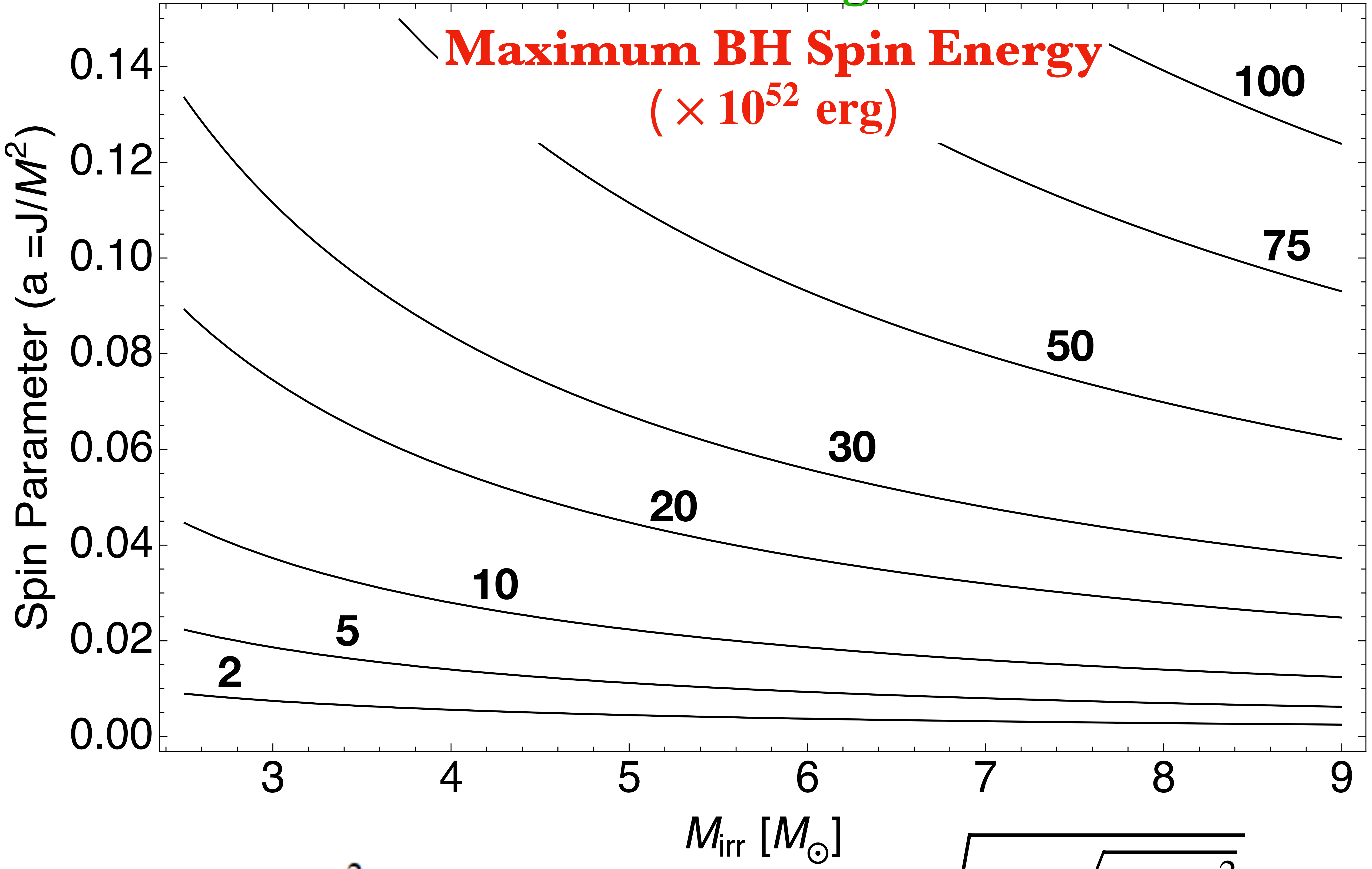
(b) We don't know yet. The mass of the progenitor star is one possibility…but more on this in next slide
In BNS mergers ms-spin is expected, yet a stable NS is not very likely: maximum NS mass plays a crucial role

Plenty of rotational energy at birth to power bright transients in the EM/GW window
(e.g. Cutler 2002, Dall'Osso et al. 2005-.....-2022, Metzger et al. 2006-.....-2018+)

SEARCHING MORE INFO FROM EM OBSERVATIONS: GRBs

GAMMA-RAY BURSTS CENTRAL ENGINES

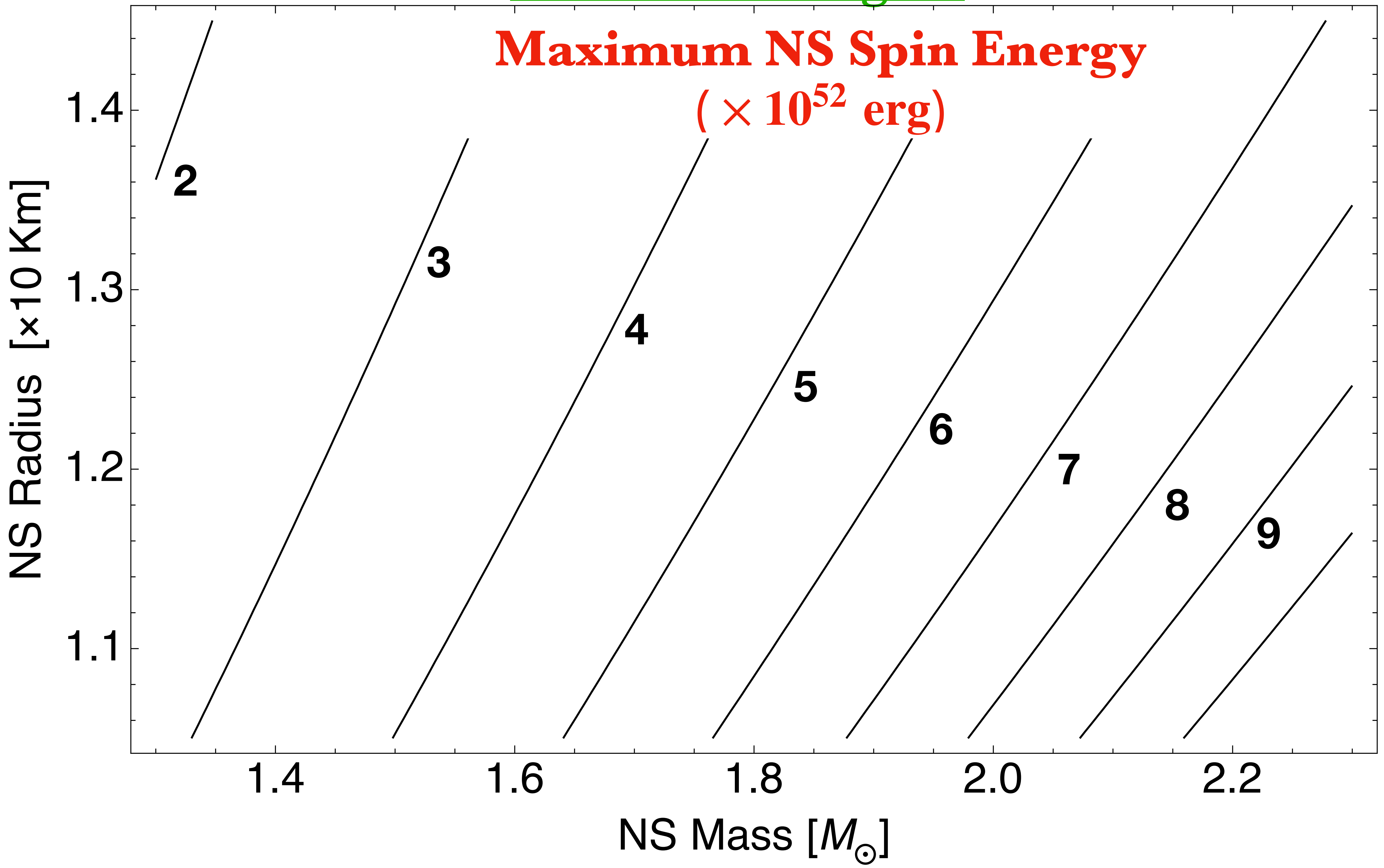
BH Central Engine



$$M^2 = \frac{J^2}{4M_{irr}^2} + M_{irr}^2 \Rightarrow E_{\rm spin} = Mc^2\sqrt{\frac{1-\sqrt{1-a^2}}{2}}$$

$$\ell = \frac{L}{m} > \sqrt{12}\frac{GM}{c} \approx 5\times 10^{16}\ {\rm cm^2/s}\ \left(\frac{M}{3\ M_\odot}\right)$$

NS Central Engine



$$\Omega_{\rm shed} = \left(\frac{2}{3}\right)^{3/2}\sqrt{\frac{GM}{R^3}} \Rightarrow E_{\rm shed} \propto \Omega_{\rm shed}^2 \approx \frac{1}{10}E_{\rm bind}$$

$$\ell = \frac{L}{m} > \frac{\sqrt{2I\ E_{\rm spin}}}{M} \approx 3\times 10^{15}\ {\rm cm^2/s}\ \frac{R_6^2}{P_{\rm ms}}$$