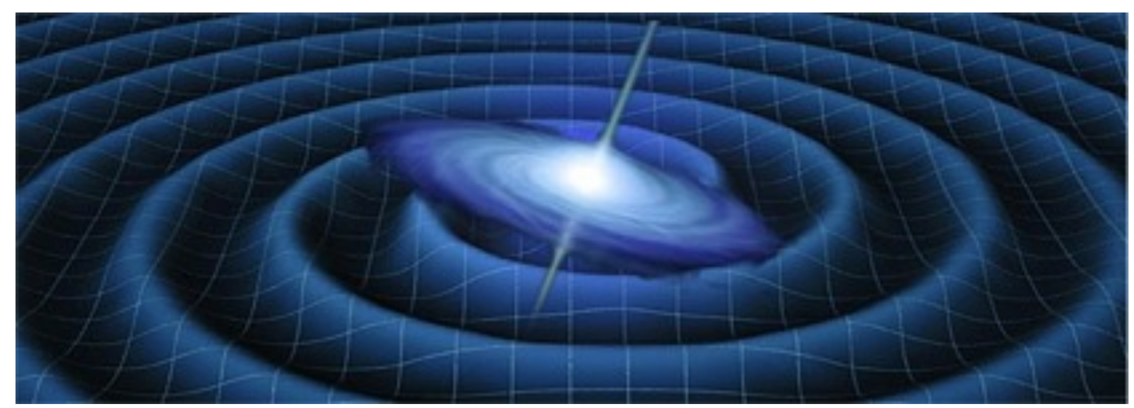
MoCA
Monash Centre for Astrophysics

Detecting gravitational waves from, and with, neutron stars

Paul Lasky



LSC LIGO Scientific Collaboration

PPTA

Contents:

LIGO Scientific Collaboration

- Overview & update
- Gravitational waves from neutron stars

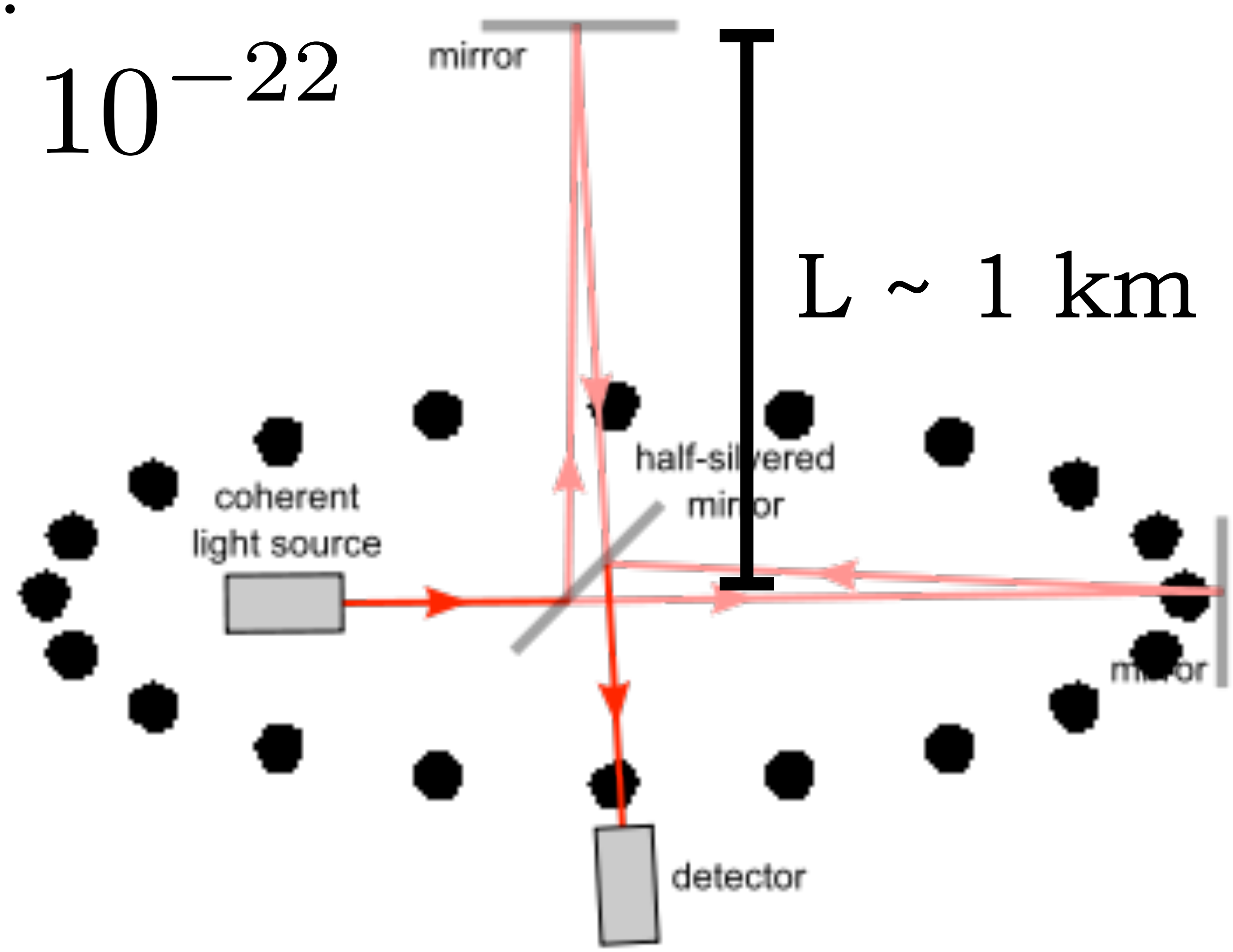
PPTA

- Overview & update
- Cosmology with current gravitational wave limits

Consider 2 merging black holes

Typical signal:

$$h = \Delta L / L \sim 10^{-22}$$



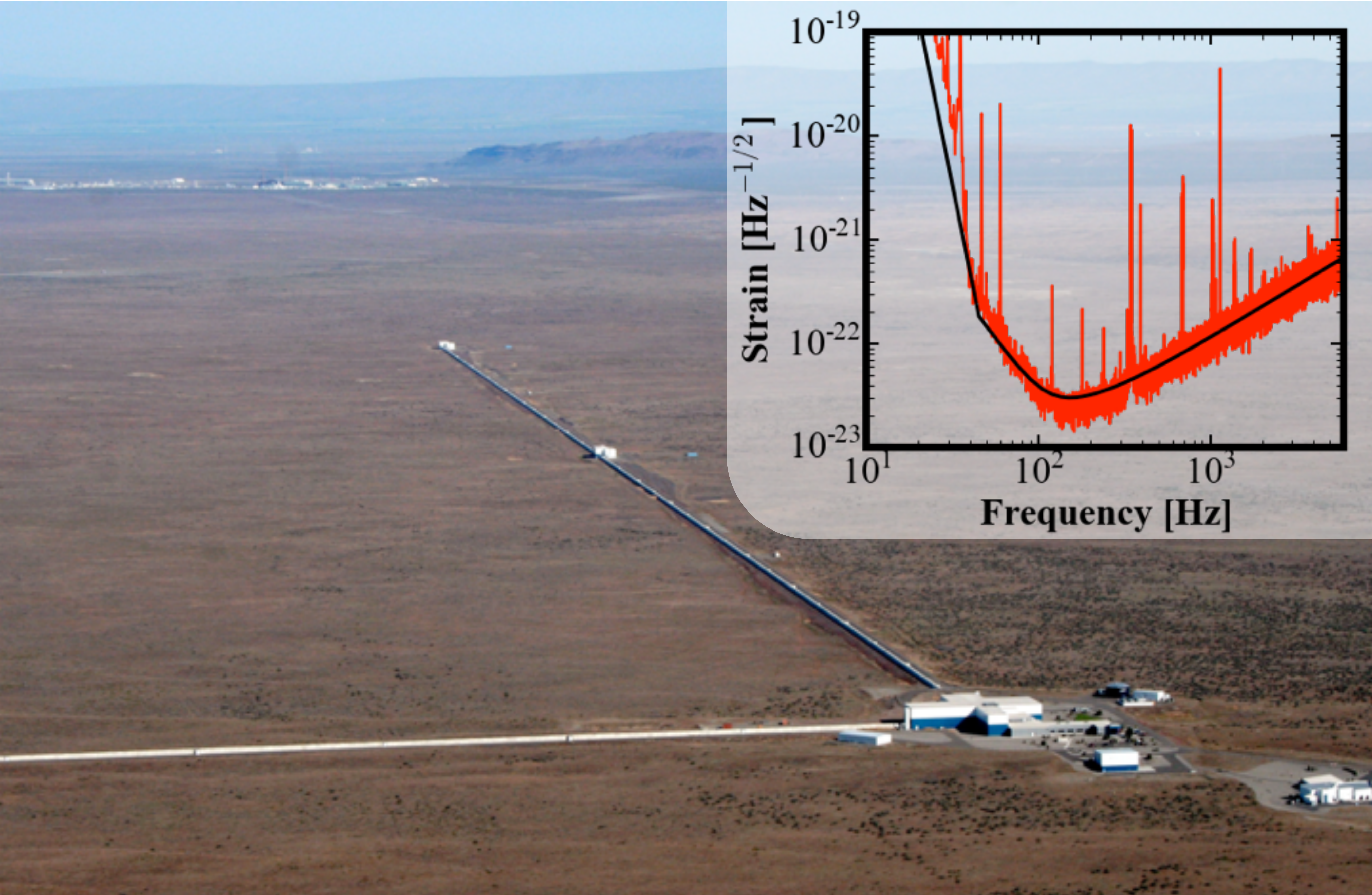
NOT TO SCALE!

$$\rightarrow \Delta L \sim 10^{-19}\ \mathrm{m}$$

cf. radius of proton

$\sim 10^{-15}$ m

LIGO Livingston



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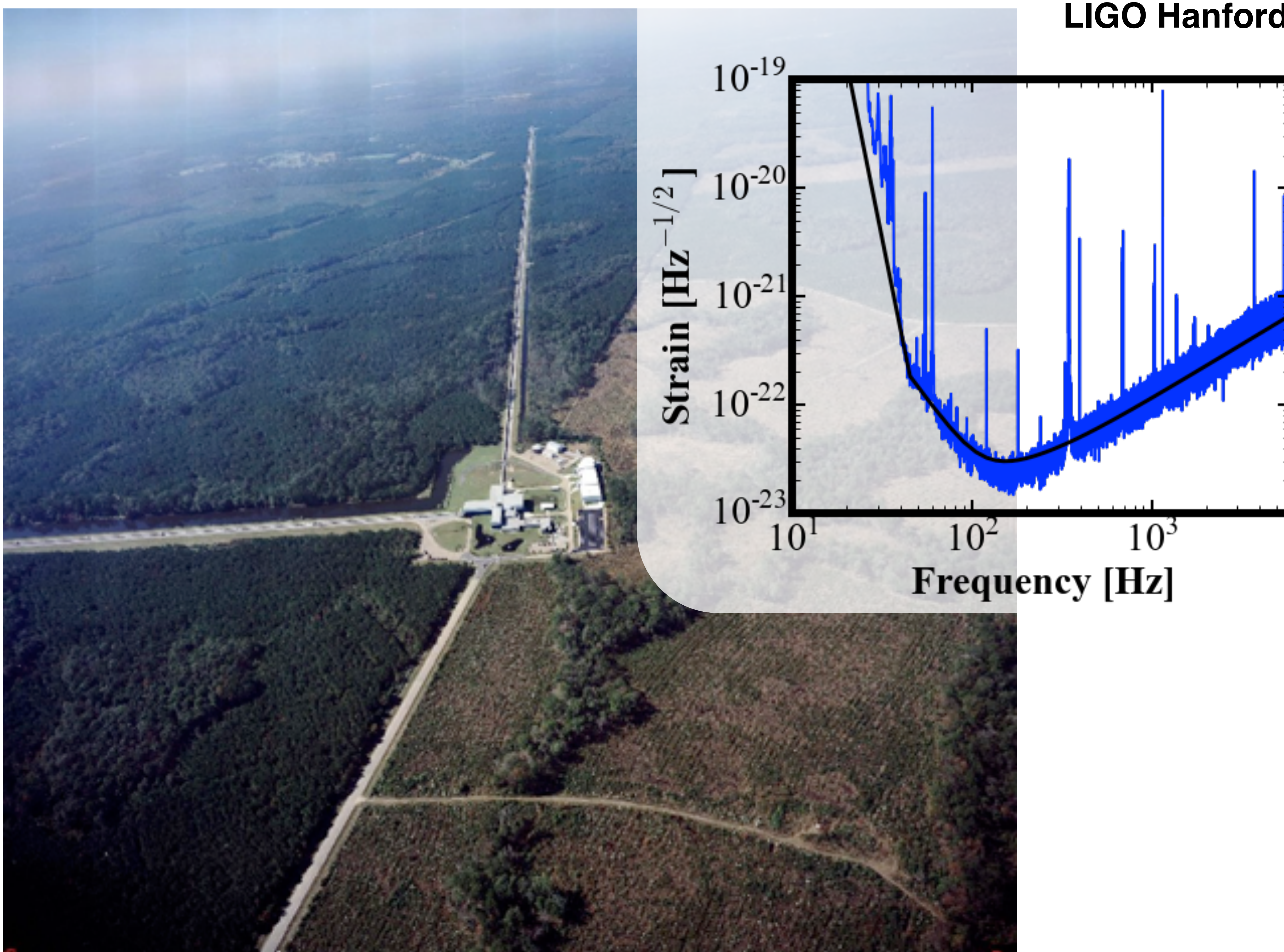
LIGO Hanford



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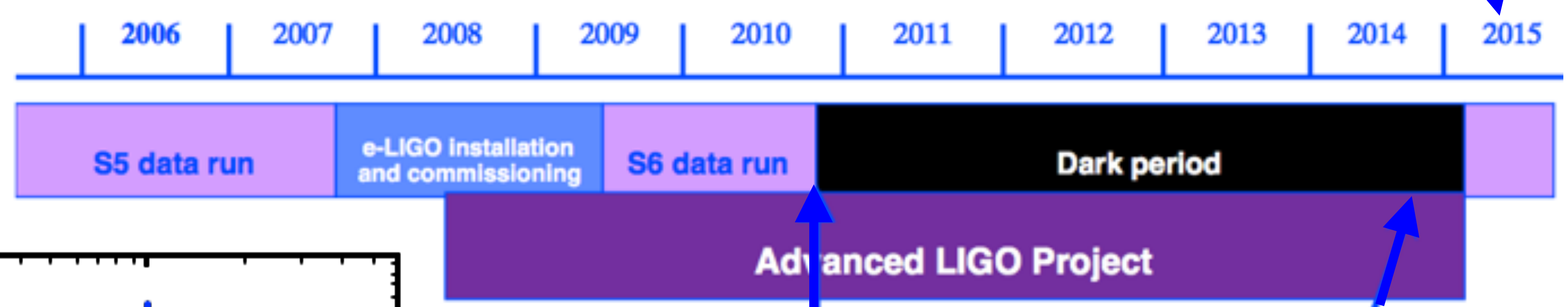
Laser Interferometer Gravitational wave Observatory

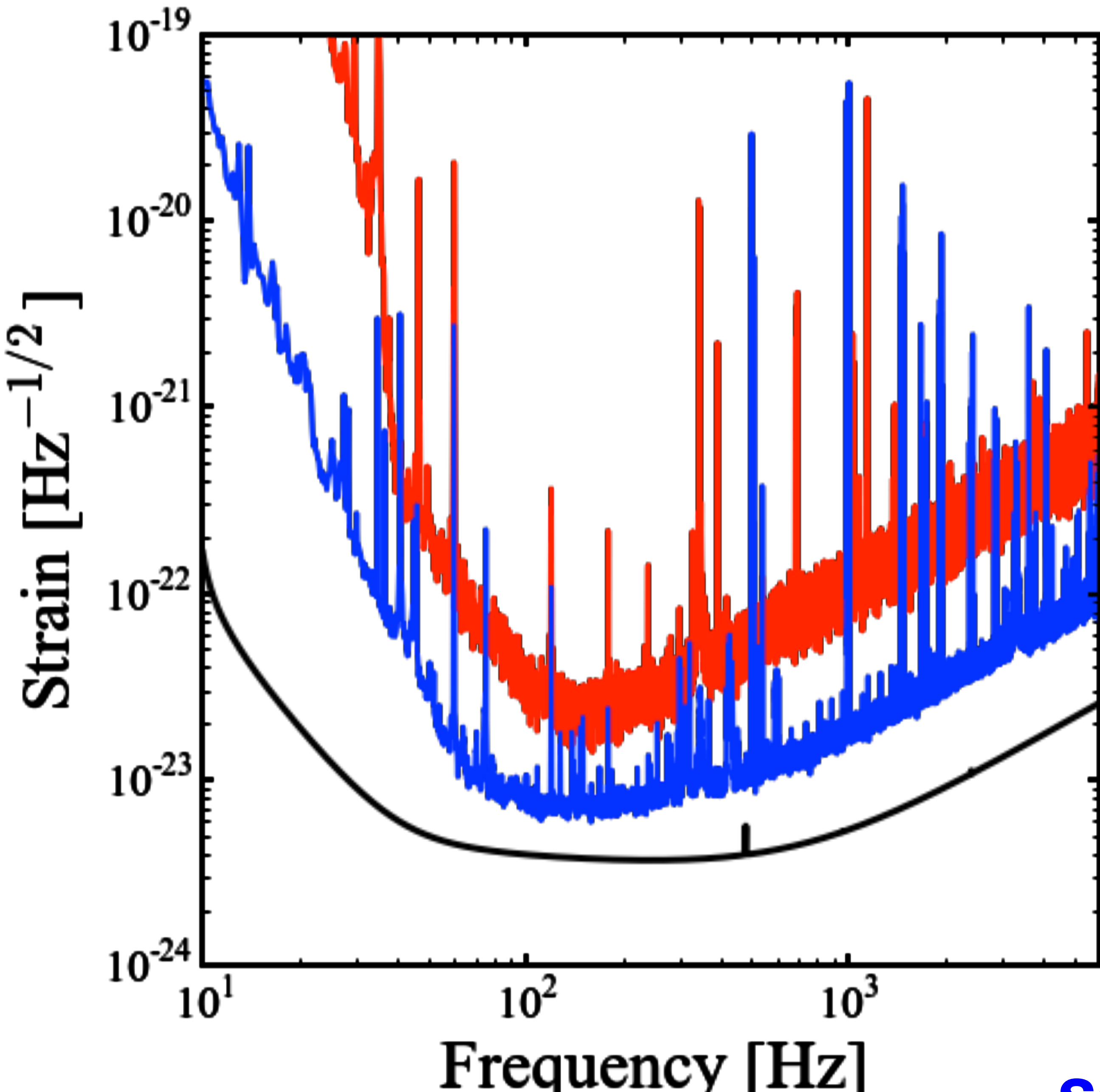
LIGO

you are here



AdvLIGO installation began

commissioning & initial data



horizon distance

iLIGO S6 (2010) — 16 Mpc

ER7 (June 2015) — 75 Mpc

aLIGO (~2019) — 200 Mpc

see talks by David McClelland & Eric Howell: 4pm Tuesday!

Isolated Neutron Stars

$$h \propto \frac{\epsilon f^2}{D}$$

ϵ due to magnetic or thermoelastic deformations:

Magnetic

e.g., Cutler (2002)
Haskell et al. (2008), PL & Melatos (2013),
Mastrano, PL & Melatos (2014)

$$\epsilon \sim 10^{-6} \left(\frac{\langle B_{\rm int} \rangle}{10^{15}\,{\rm G}} \right)$$

Thermoelastic

e.g. Ushomirsky, Cutler & Bildsten (2000)

5% temperature gradient → $\epsilon \sim 10^{-7}$

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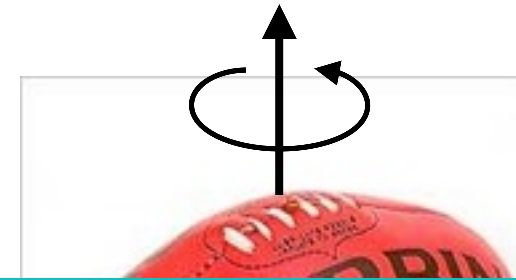
Isolated Neutron Stars



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ϵ due to magnetic

Magnetic

e.g., Cutler (2002)
Haskell et al. (2008), PL & Melatos (2013),
Mastrano, PL & Melatos (2014)

$$\epsilon \sim 10^{-6} \left(\frac{\langle B_{\rm int} \rangle}{10^{15}\,{\rm G}} \right)$$

A nuclear physics experiment!

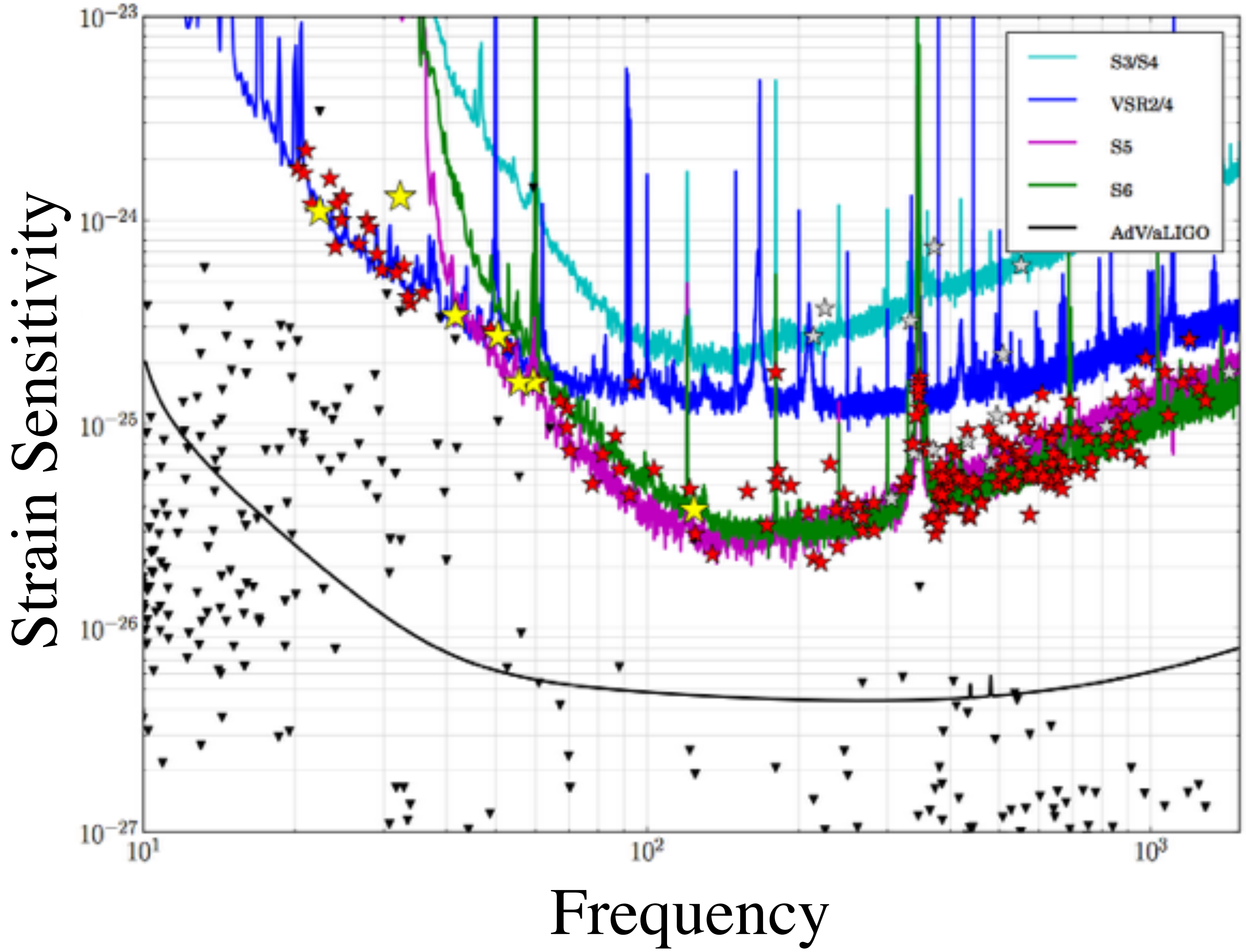
$$\epsilon^{2SC} \sim 8.0 \times 10^{-5} \left(\frac{\langle B_{\rm int} \rangle}{10^{15}\,{\rm G}} \right)$$

$$\epsilon^{CFL} \sim 2.5 \times 10^{-4} \left(\frac{\langle B_{\rm int} \rangle}{10^{15}\,{\rm G}} \right)$$

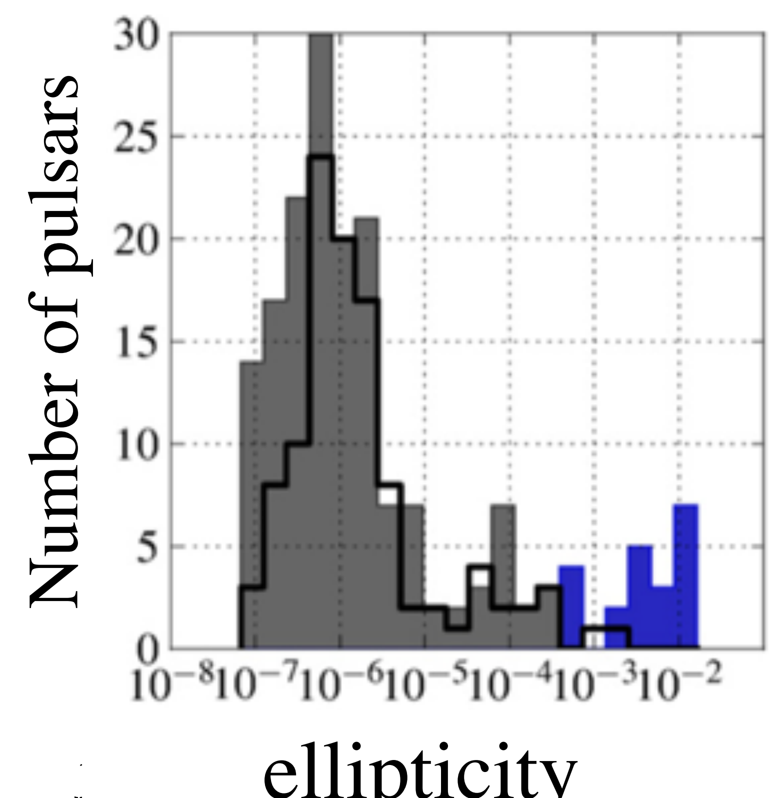
Owen (2004), Glampedakis et al. (2012)

Known Radio Pulsars

Aasi et al. (2014)



Crab Nebula



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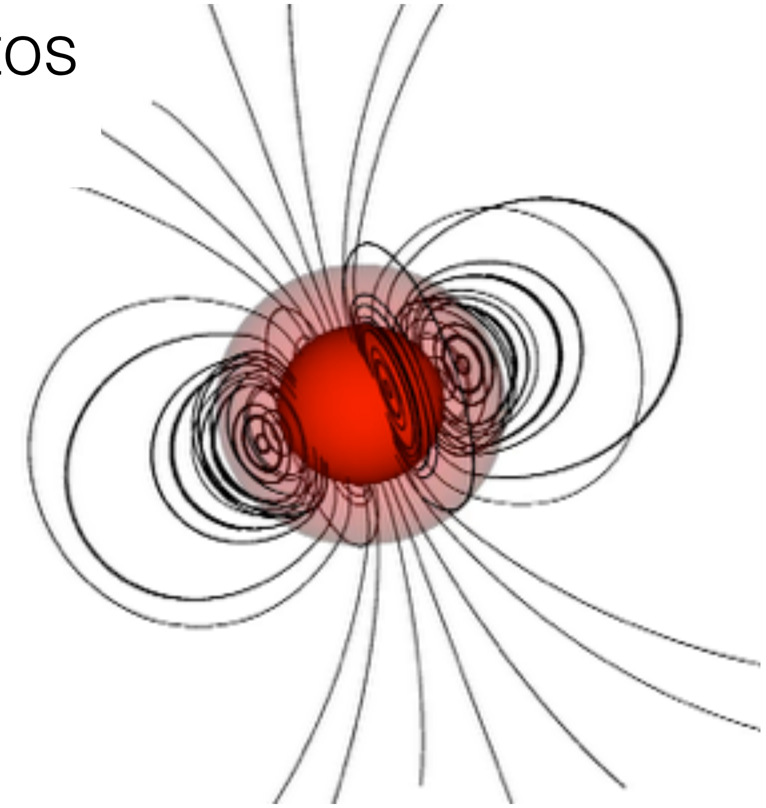
Young Neutron Stars — SN remnants

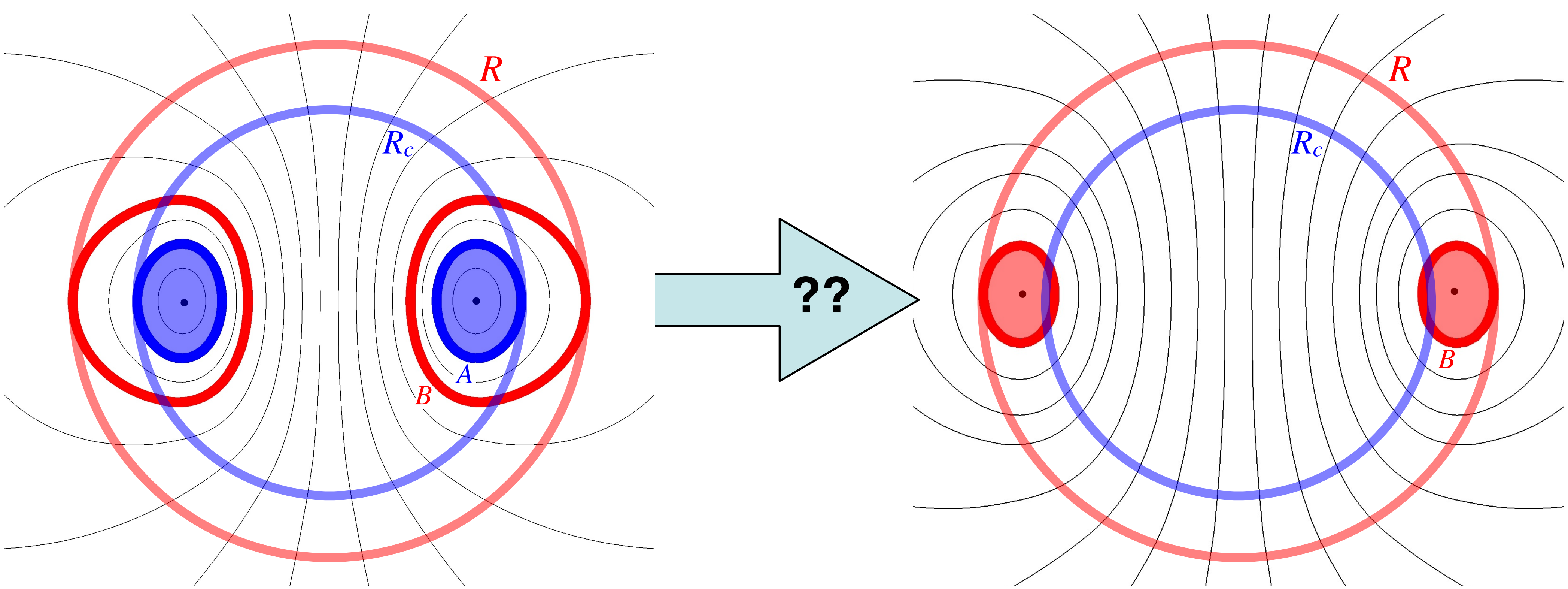
Characterised by complex, dynamic magnetic field evolution

PL & Melatos (2013)



Magnetic dynamo grows B field to ~ 10^{15} — 10^{16} G

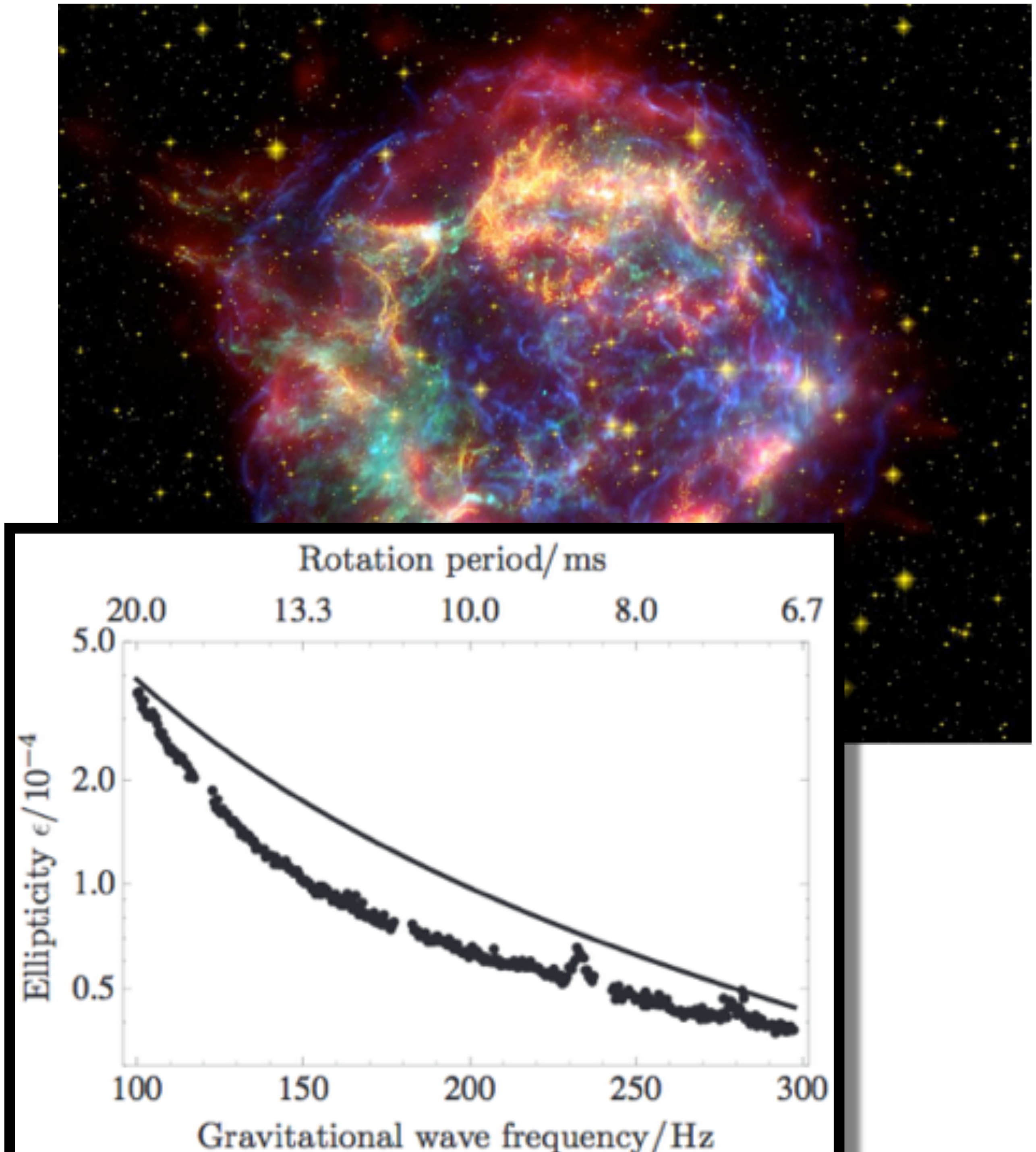
e.g., Thompson & Duncan (1995)



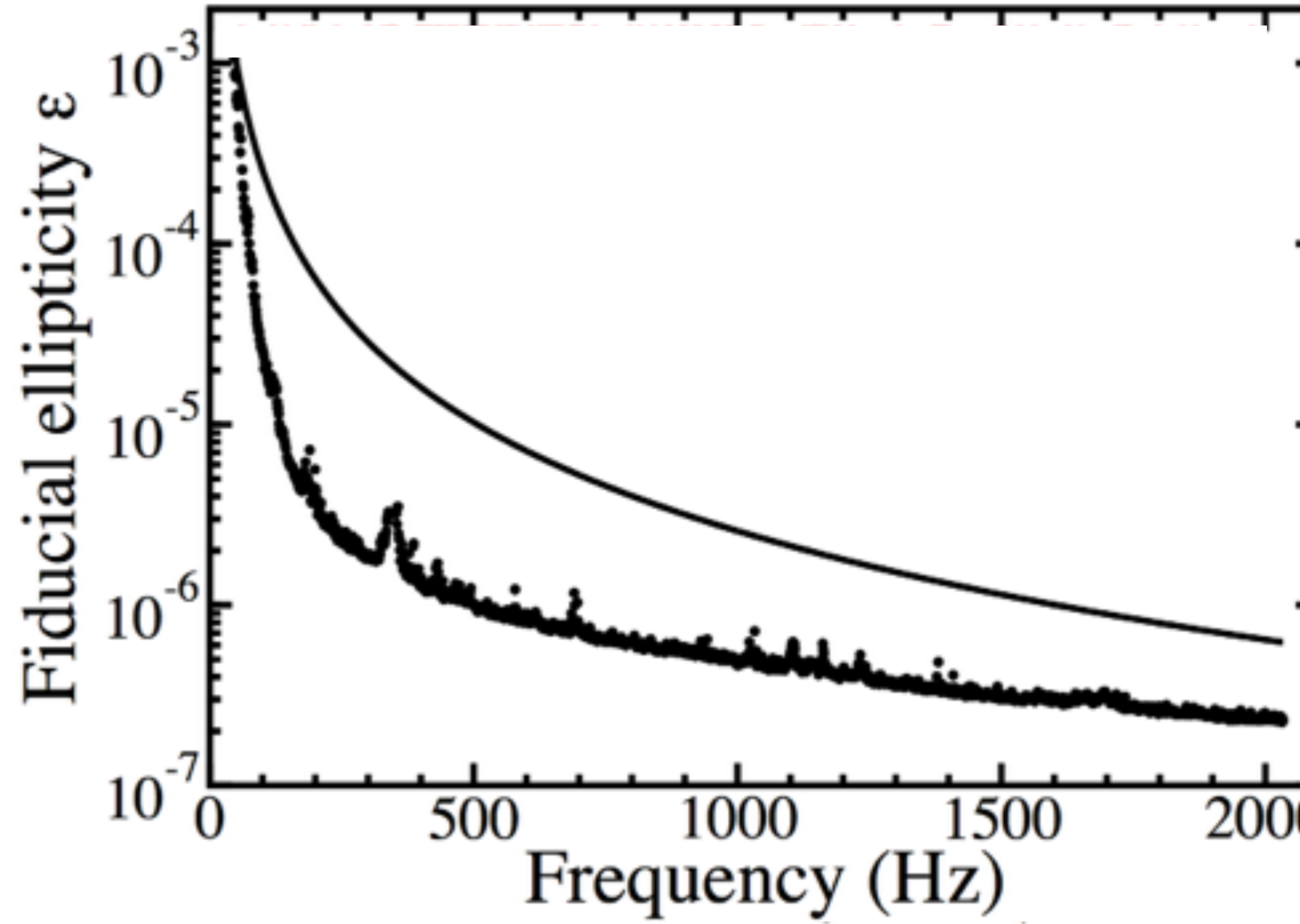
Glampedakis & PL (2015)

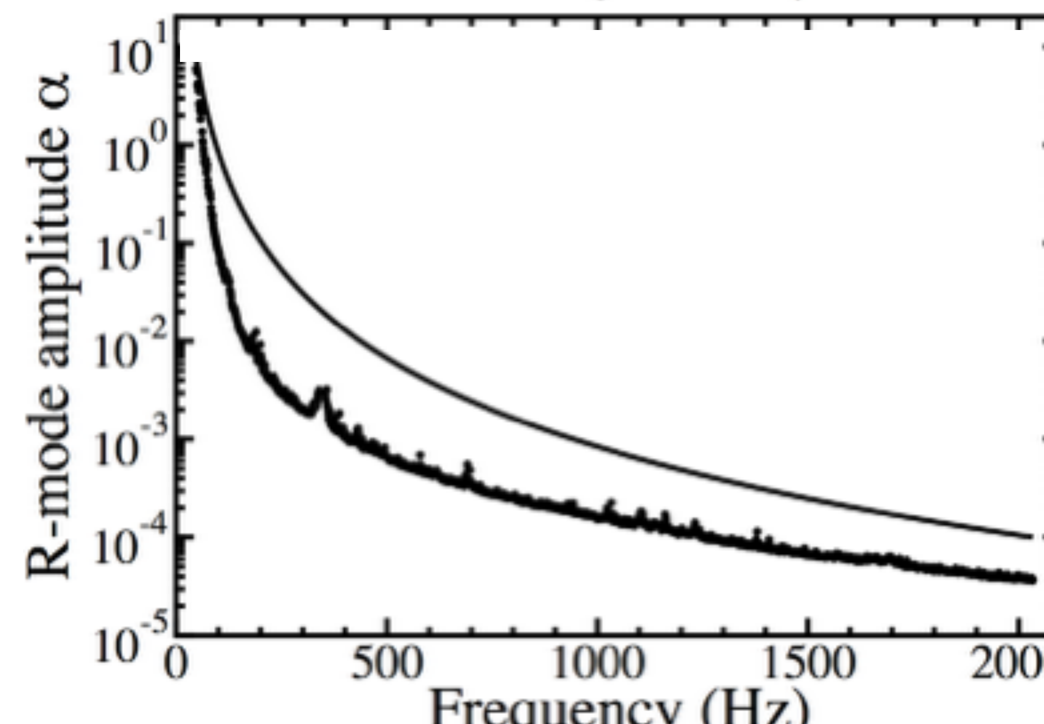
Young Neutron Stars — SN remnants

Cassiopeia A
Wette et al. (2008); Abadie et al. (2010)



Vela Jr.
Aasi et al. (2014)





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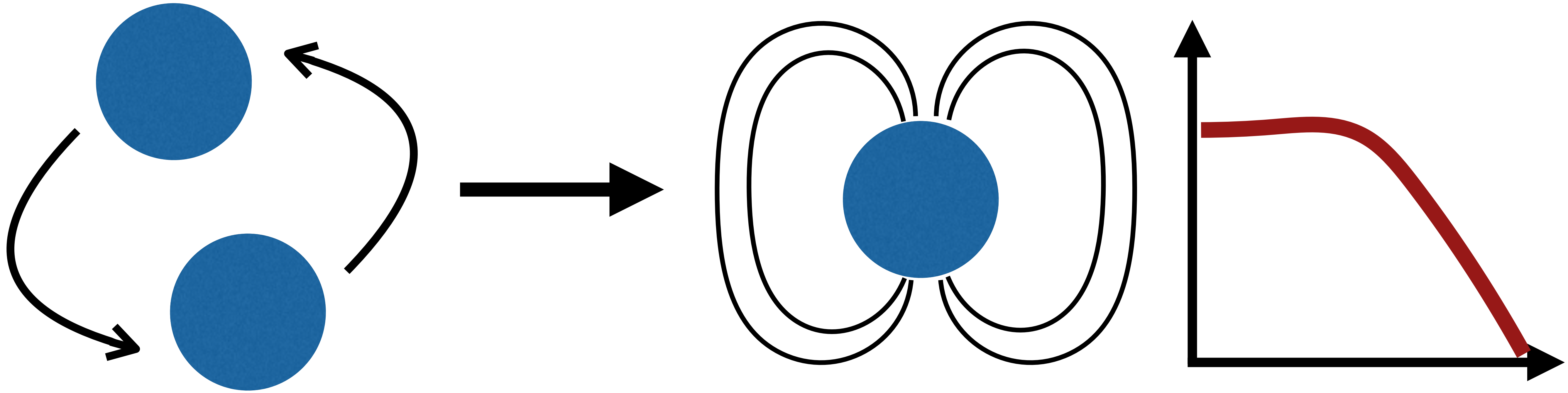
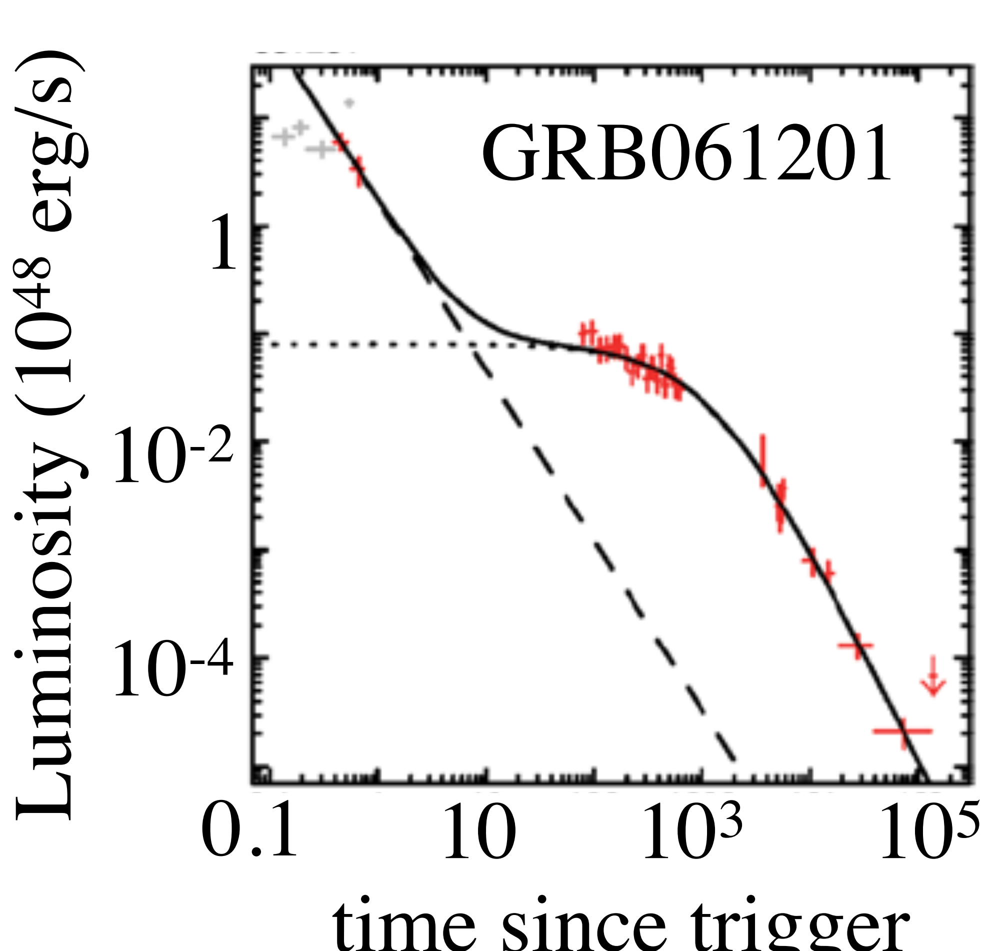
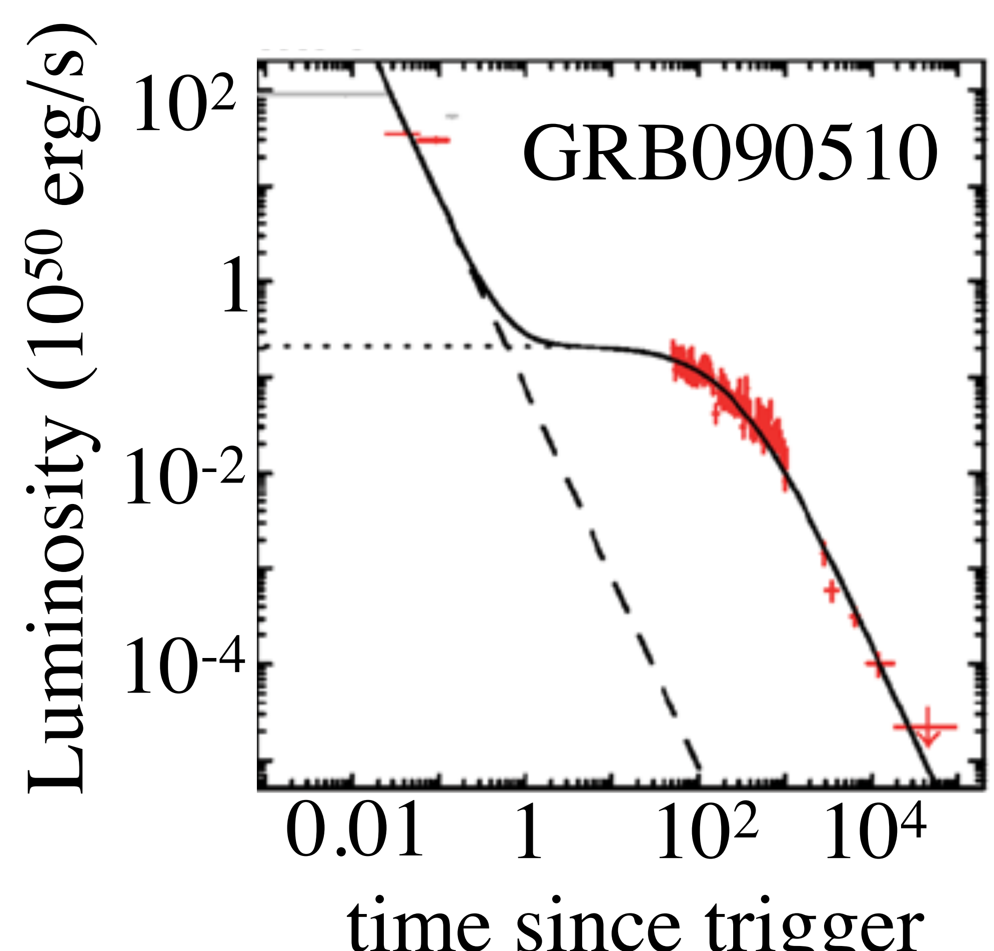
Very young neutron stars — short GRBs



Rowlinson et al. (2013), Lü, Zhang, Lei, Li & PL (2015)





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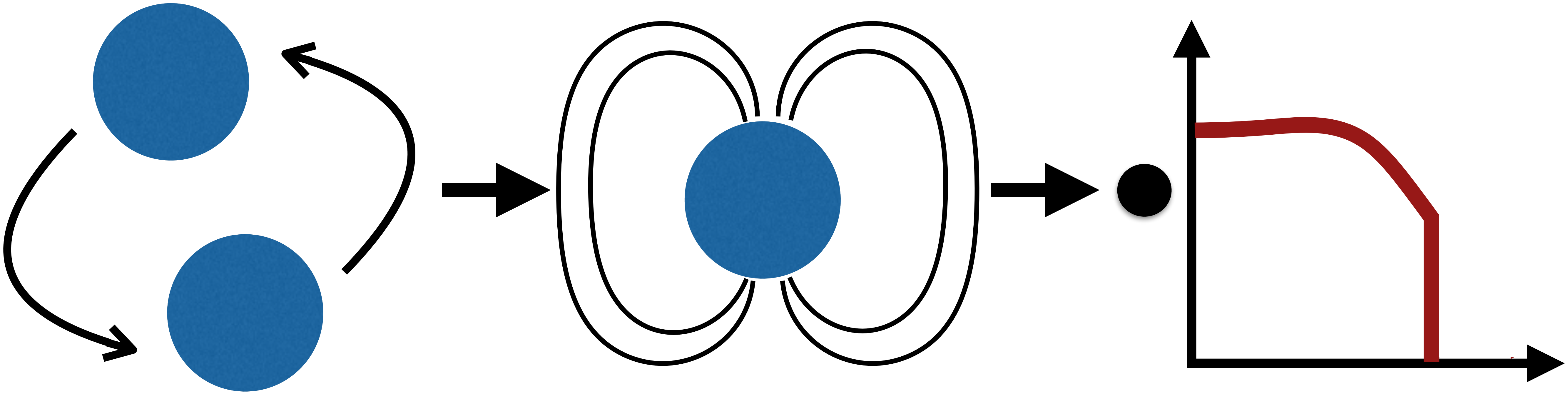
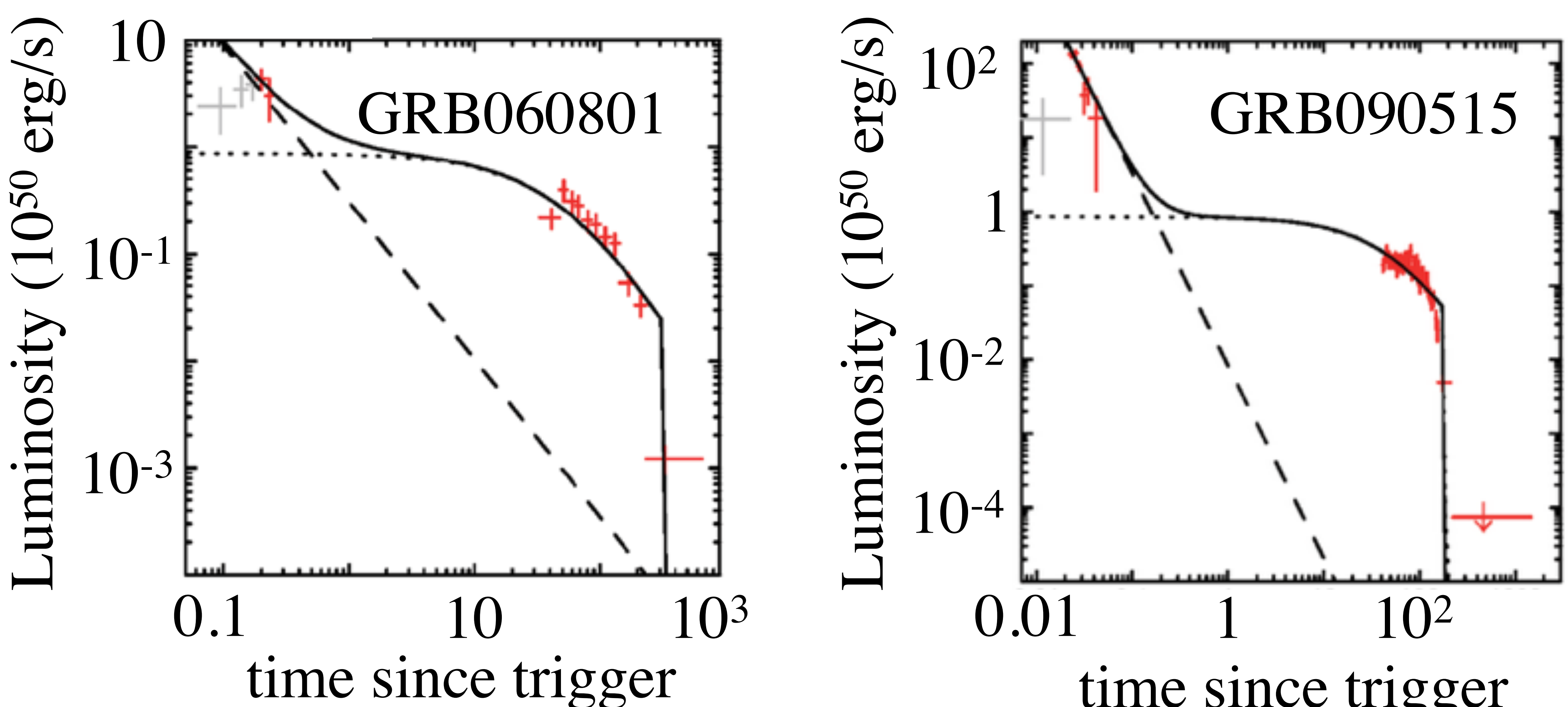
Very young neutron stars — short GRBs



Rowlinson et al. (2013), Lü, Zhang, Lei, Li & PL (2015)



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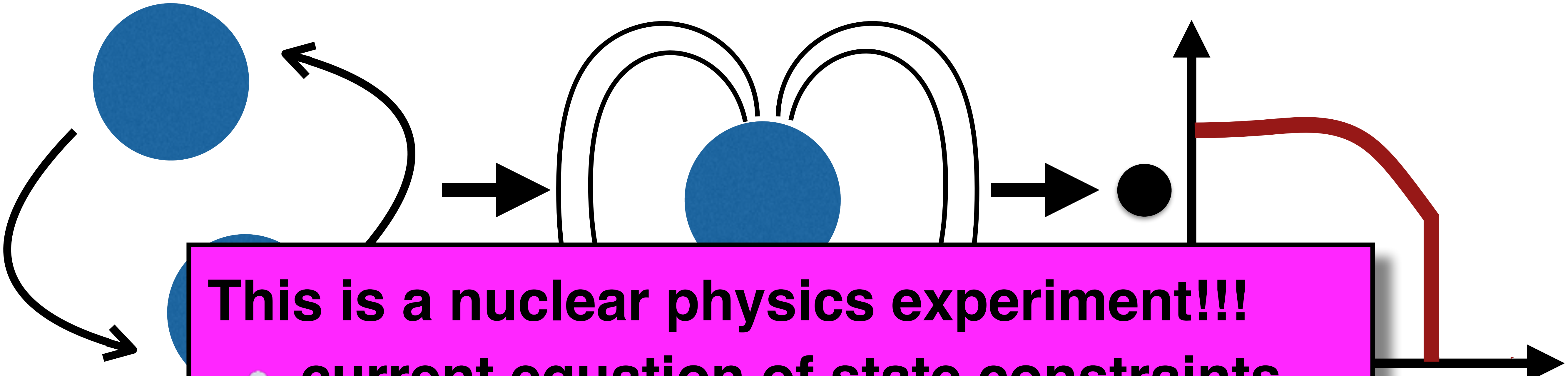
Very young neutron stars — short GRBs



PL (2015)

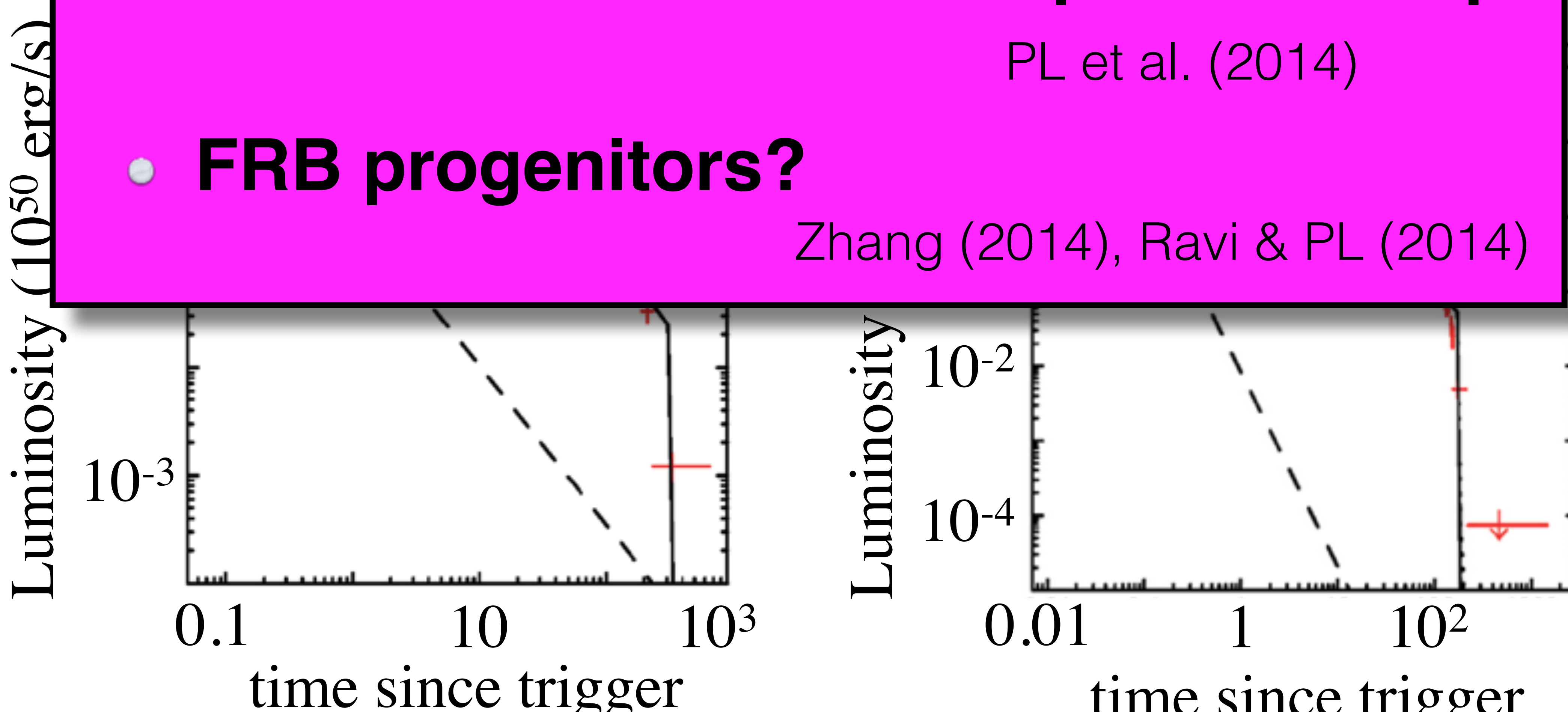
This is a nuclear physics experiment!!!

- **current equation of state constraints**
- **LIGO observations of inspiral *will* help!**

PL et al. (2014)

- **FRB progenitors?**

Zhang (2014), Ravi & PL (2014)



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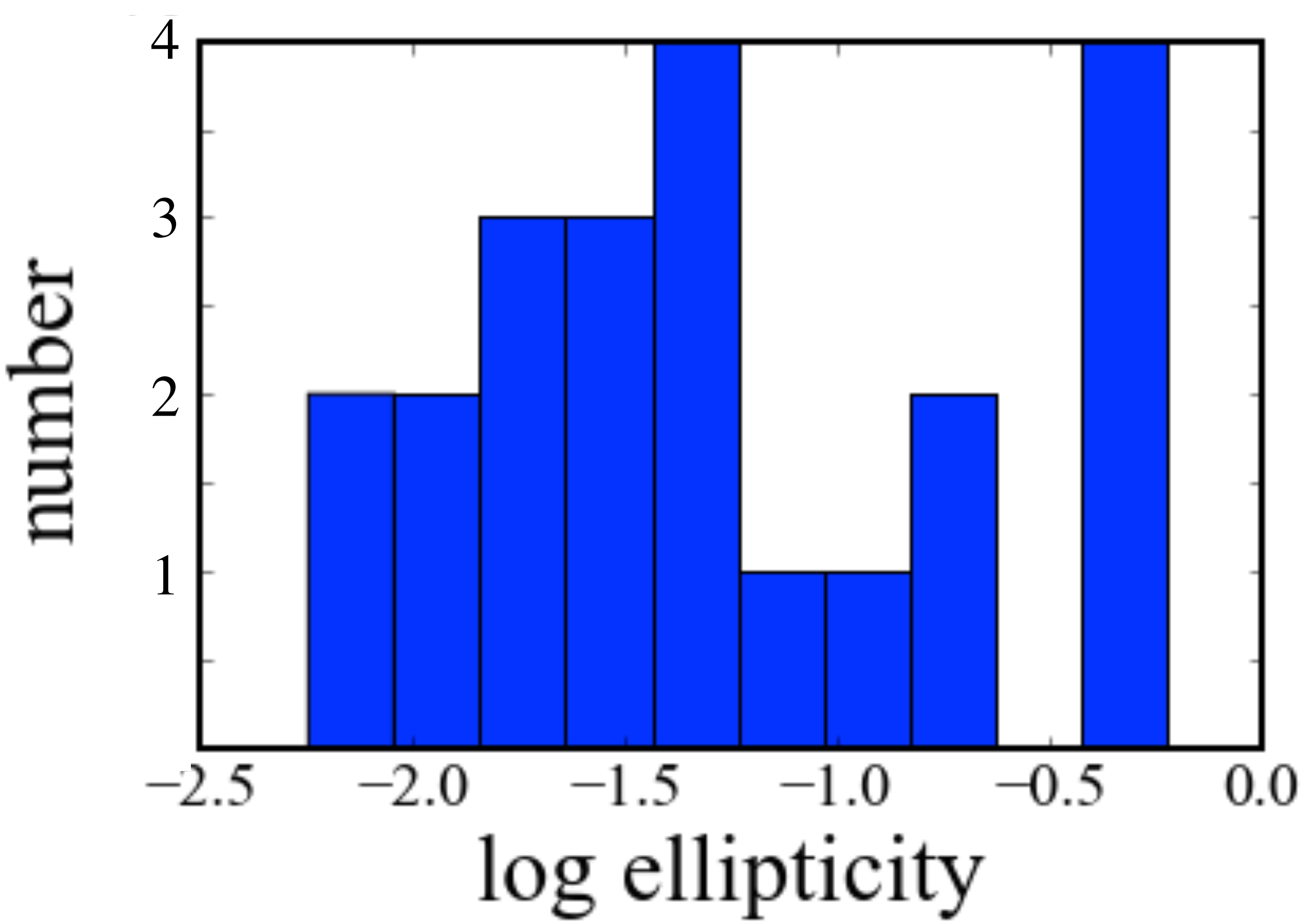
Very young neutron stars — short GRBs

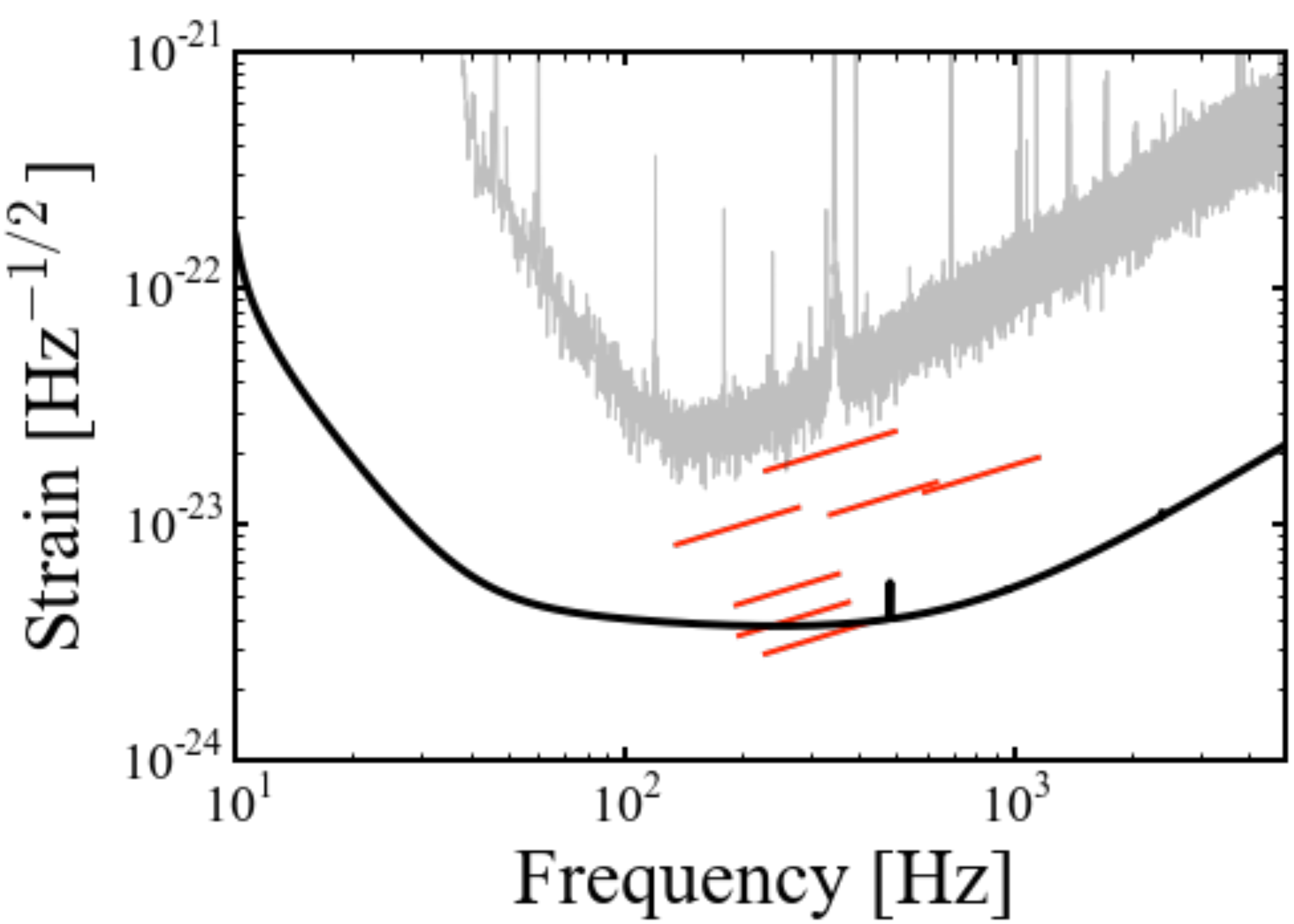
protoneutron stars radiate through:

- magnetic field-induced ellipticity (e.g., Fan et al. 2013, Dall'Osso et al. 2015)
- secular bar modes (e.g., Corsi & Meszaros 2009)

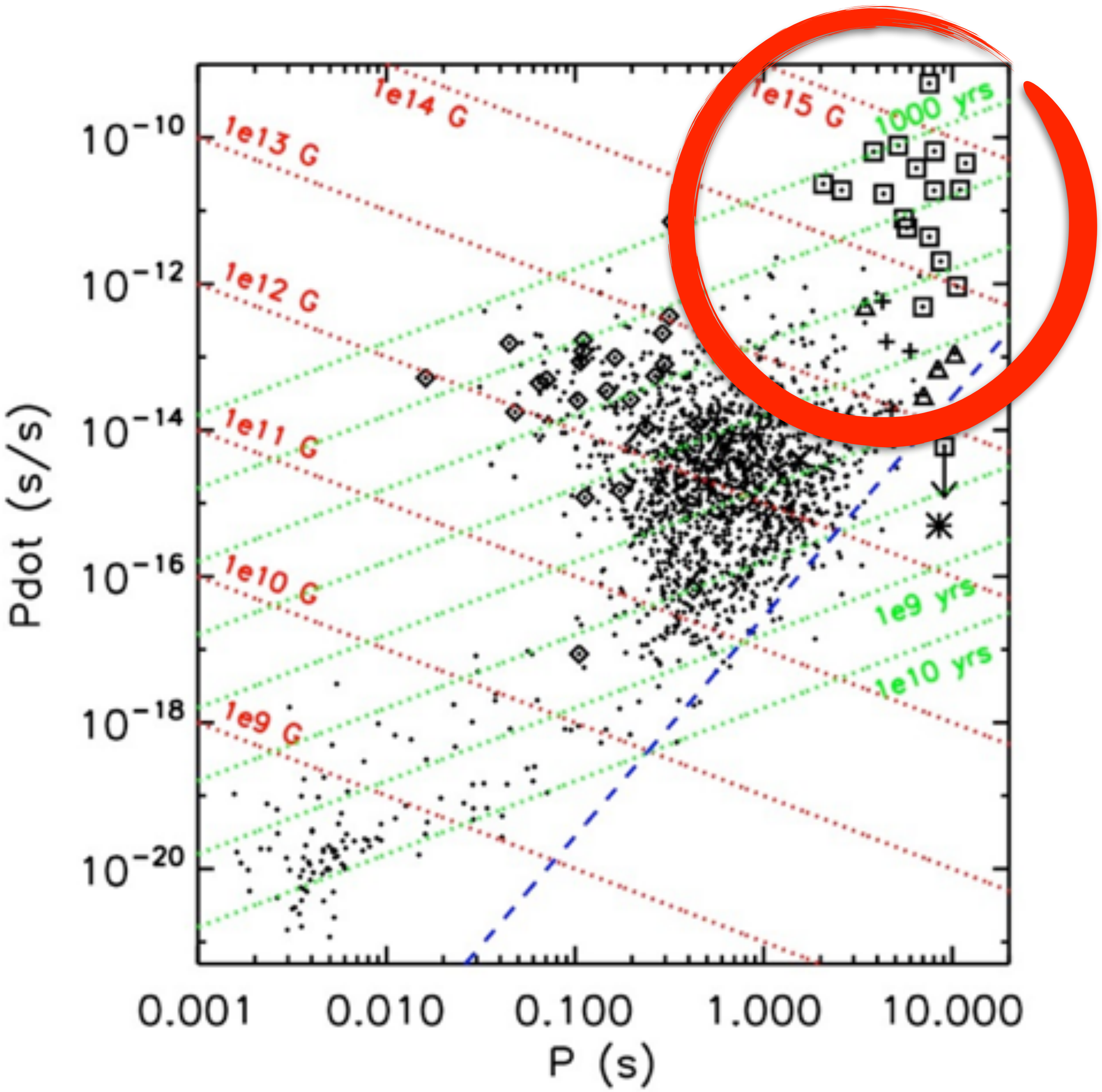
Can constrain neutron star physics and GW emission from light curve only!

(PL 2015; in prep)

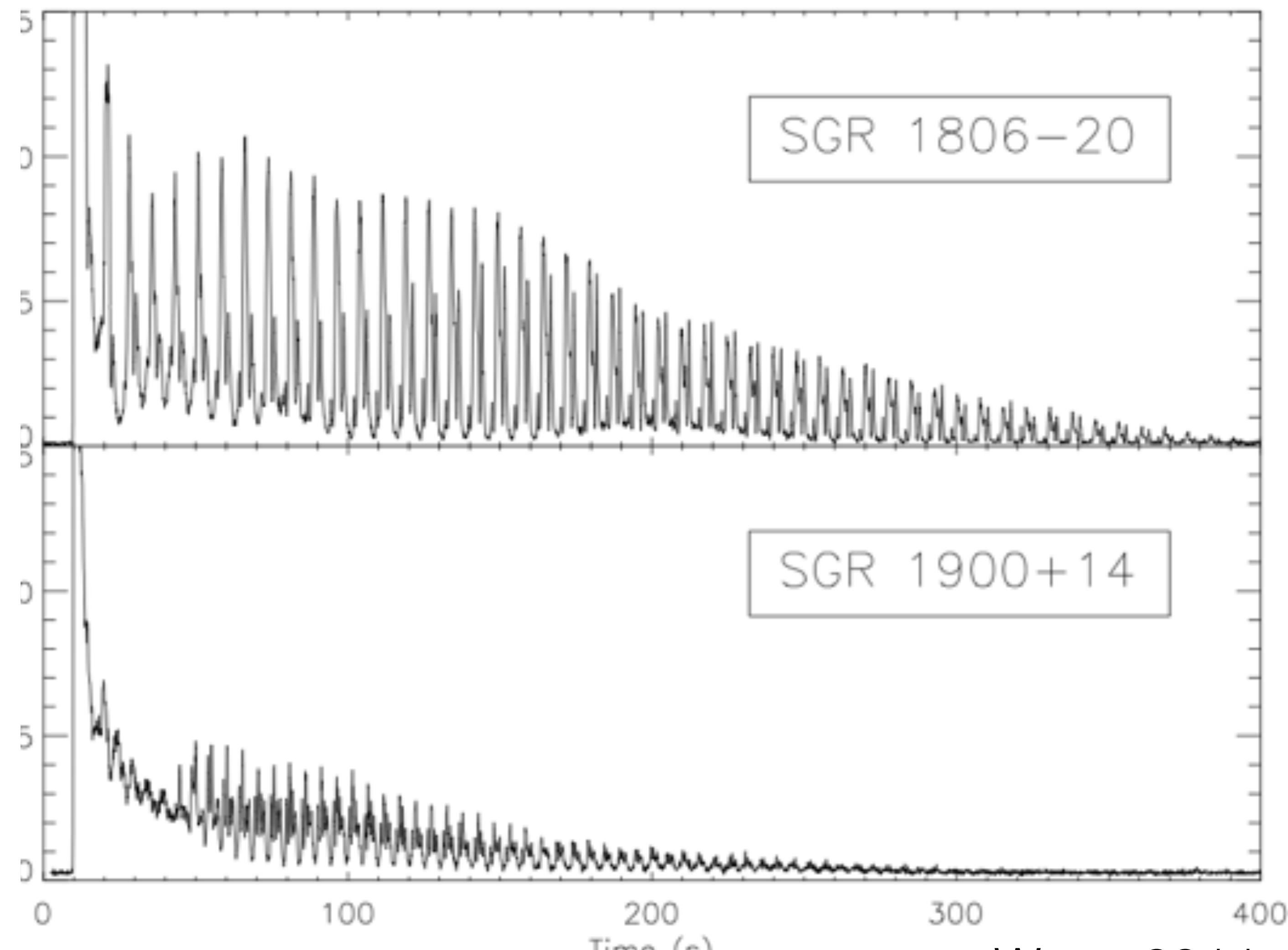




Magnetar *Giant* Flares



3 Giant Flares observed with peak luminosities ~ 10^{47} erg s^{-1}



Watts 2011

"The PCA is completely saturated in the peak of the flares, despite the fact that neither event is on-axis for the telescope"

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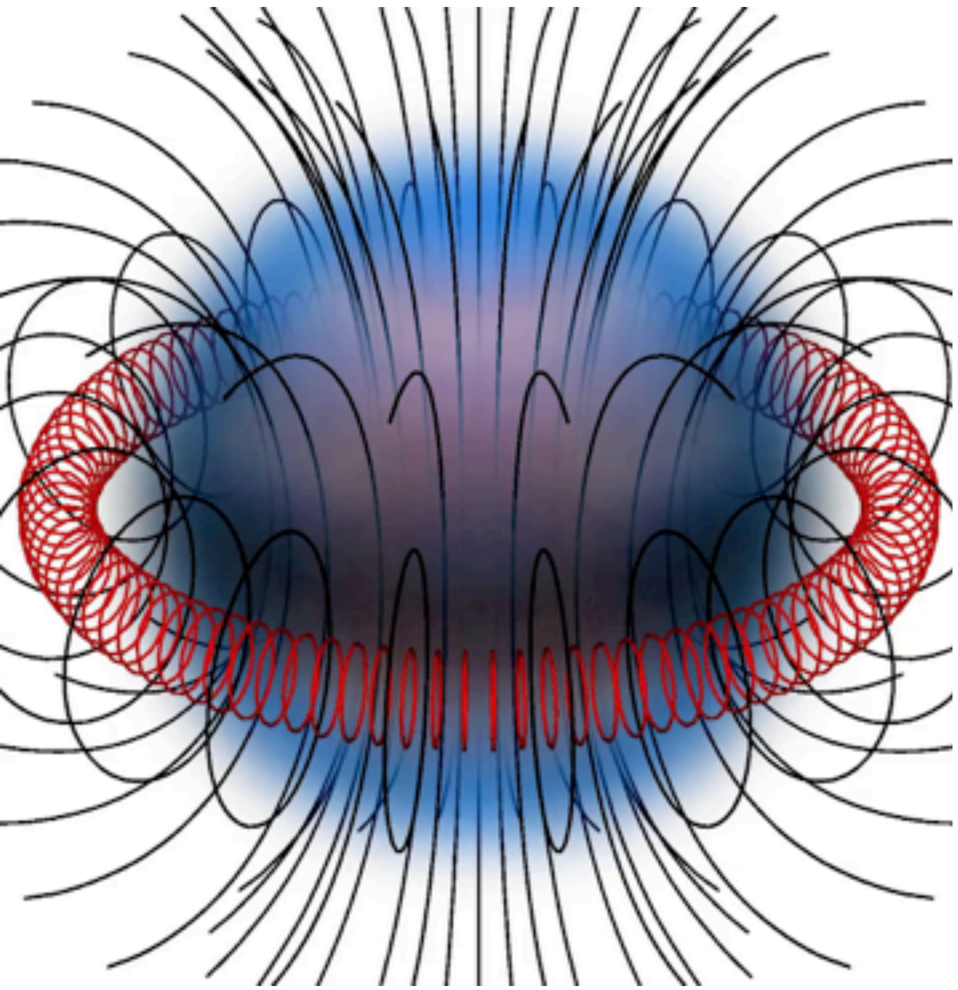
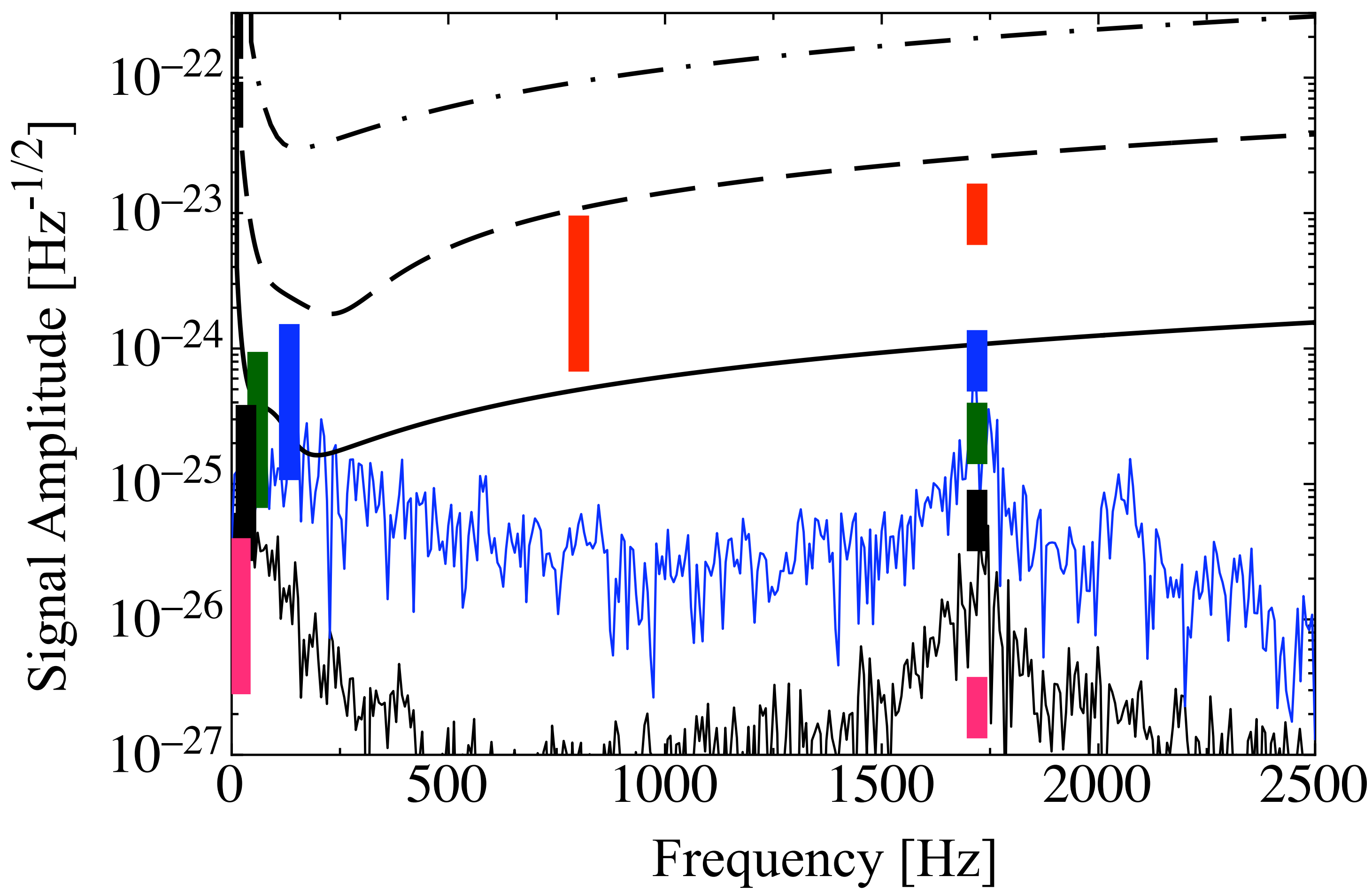
Magnetar *Giant* Flares



PL et al. (2011, 2012)
Zink, PL & Kokkotas (2012)
Levin & van Hoven (2011)



$$E_{\rm gw} \sim 10^{36} \left(\frac{B}{10^{15}\,{\rm G}}\right)^{5.8} {\rm erg}$$

$$E_{\rm gw}^{\rm obs} \lesssim 3 \times 10^{44}\,{\rm erg}$$

(Abadie et al., 2010)

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Conclusions

- **Advanced LIGO coming online in 2015**
- First detections likely from compact binary inspirals
- Many possible gravitational wave sources from isolated neutron stars
    - (many not covered here)

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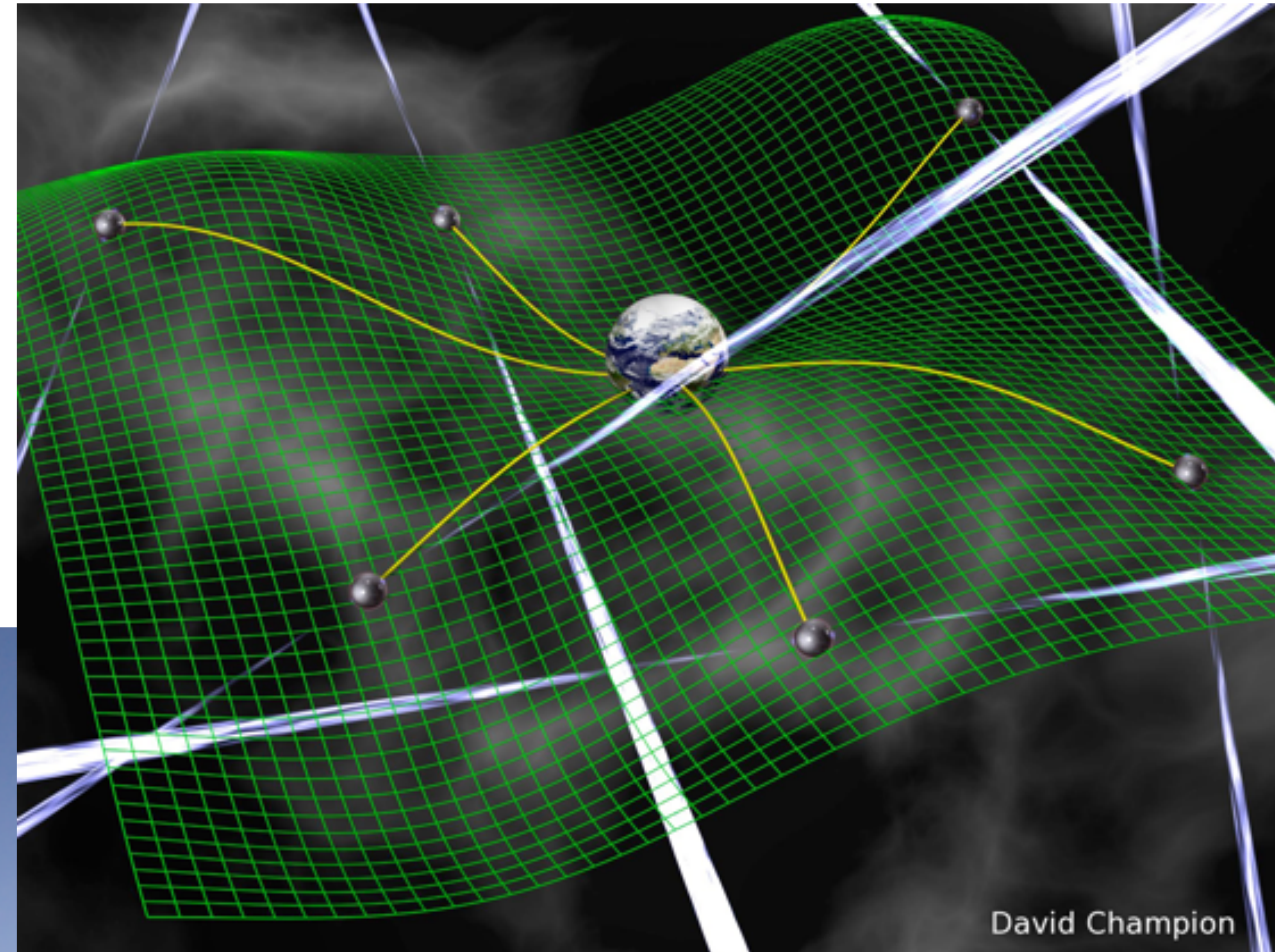
MONASH University

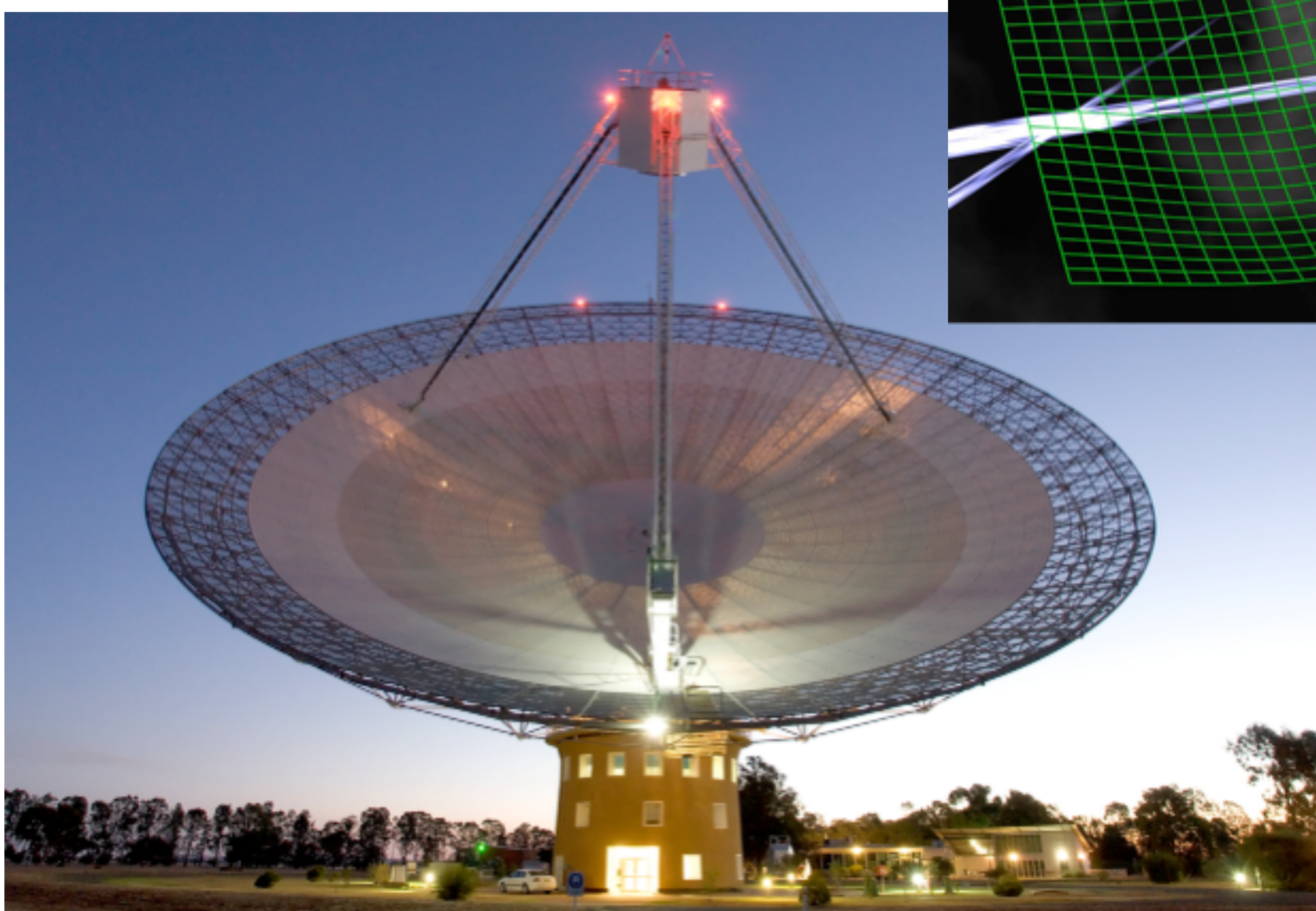
Paul Lasky

MoCA
Monash Centre for Astrophysics

Paul Lasky

PPTA





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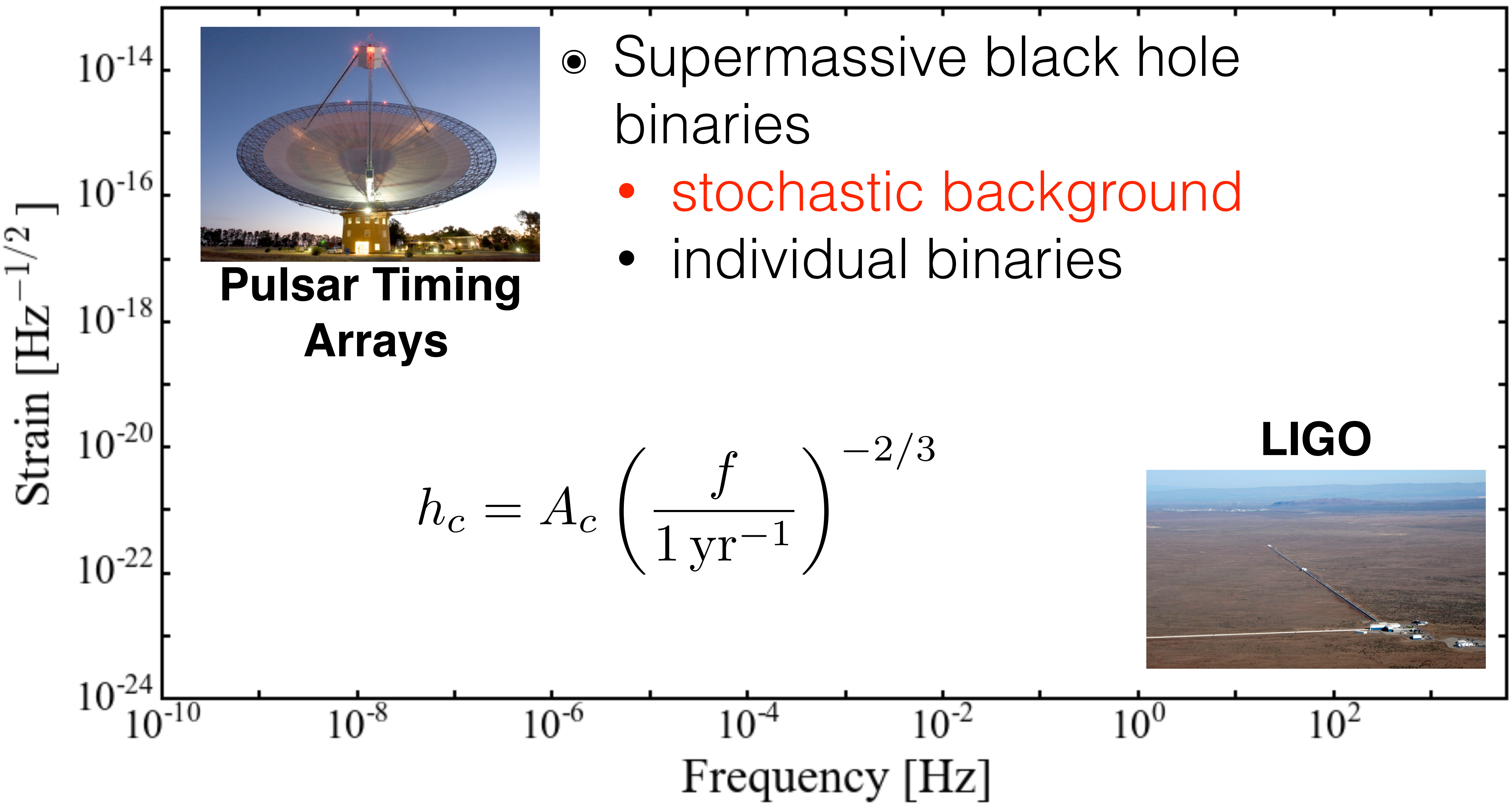
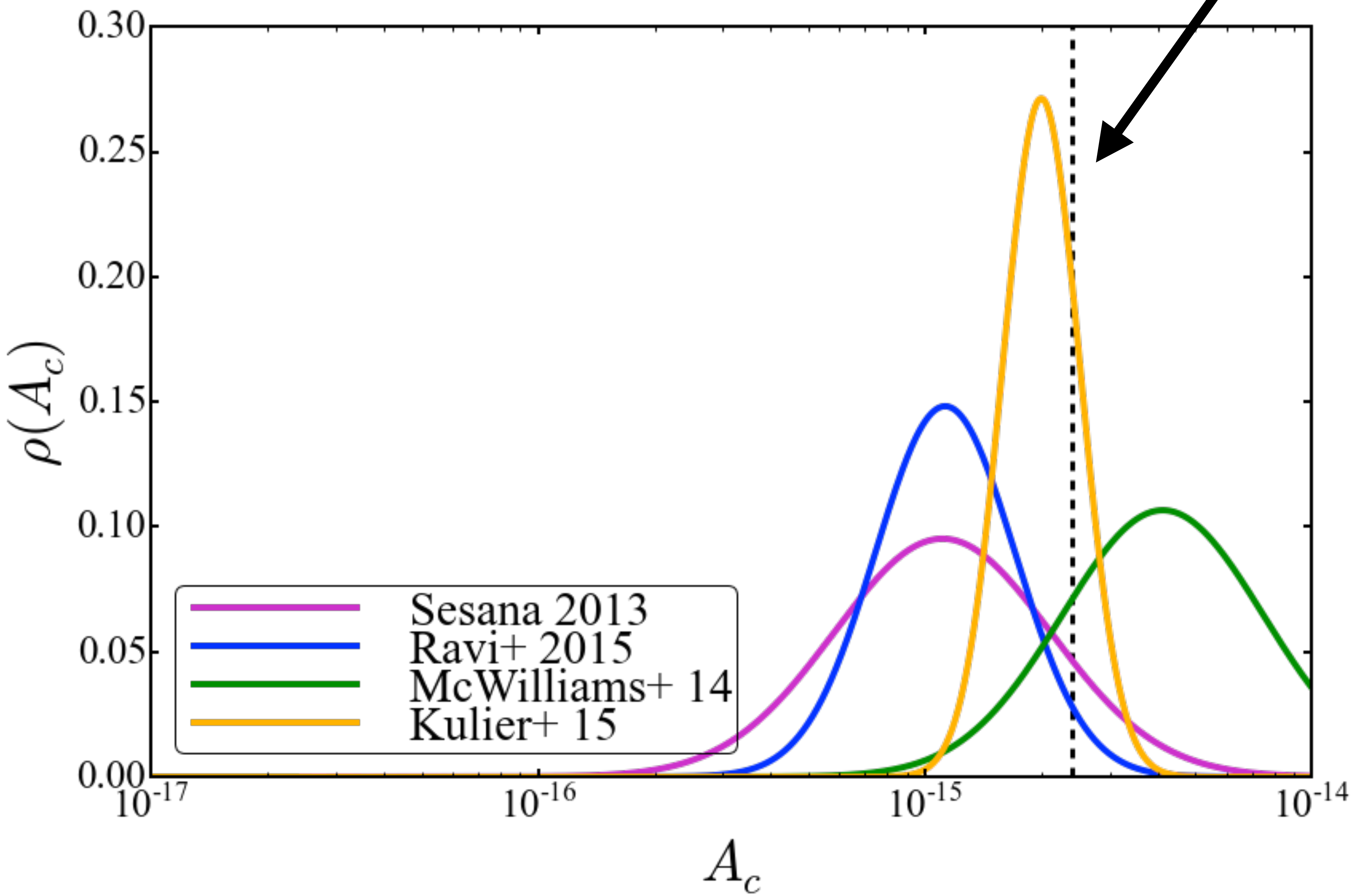
- Supermassive black hole binaries
  - stochastic background
  - individual binaries

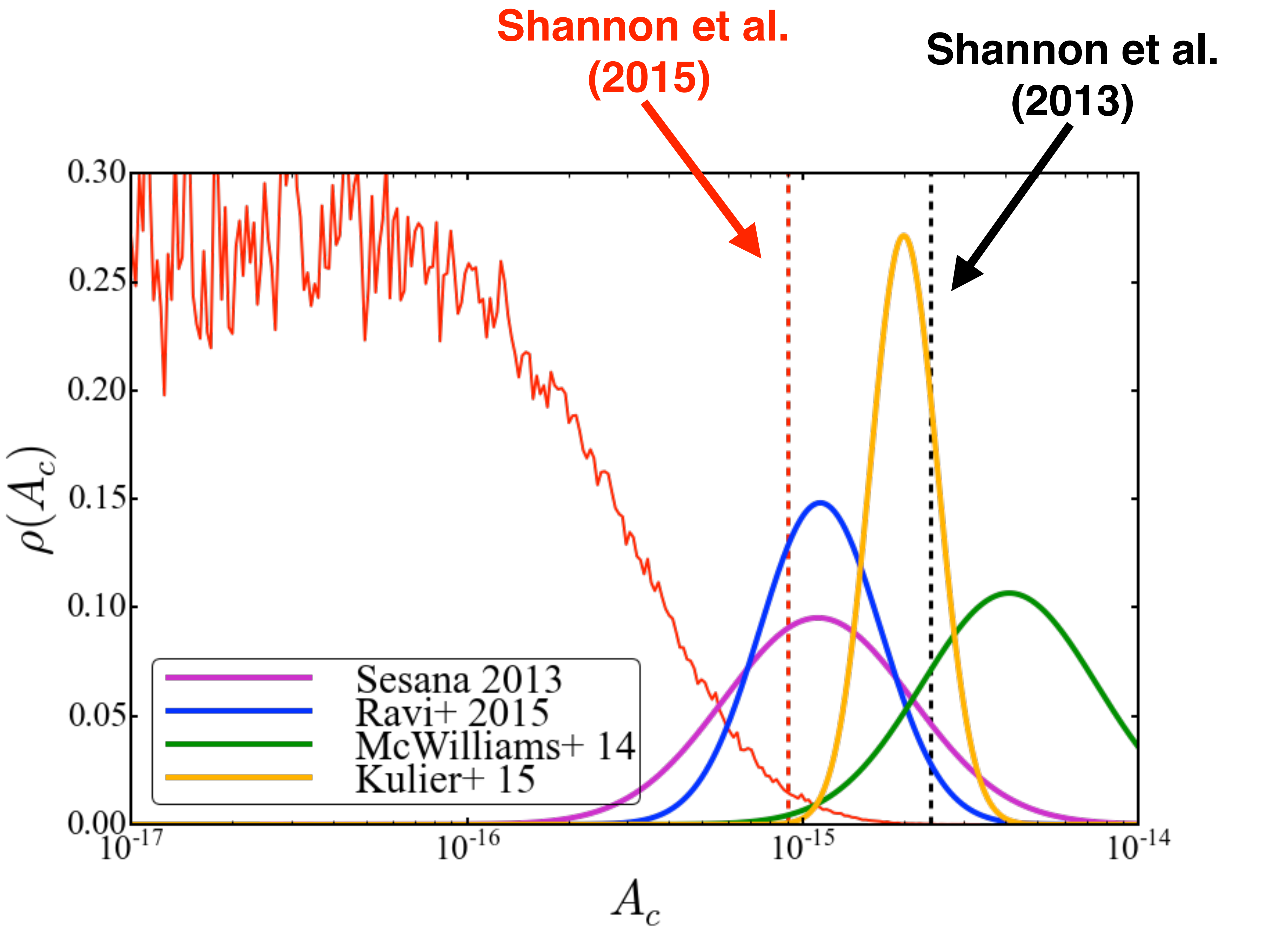
$$h_c = A_c \left(\frac{f}{1\,\mathrm{yr}^{-1}} \right)^{-2/3}$$



Shannon et al. (2013)

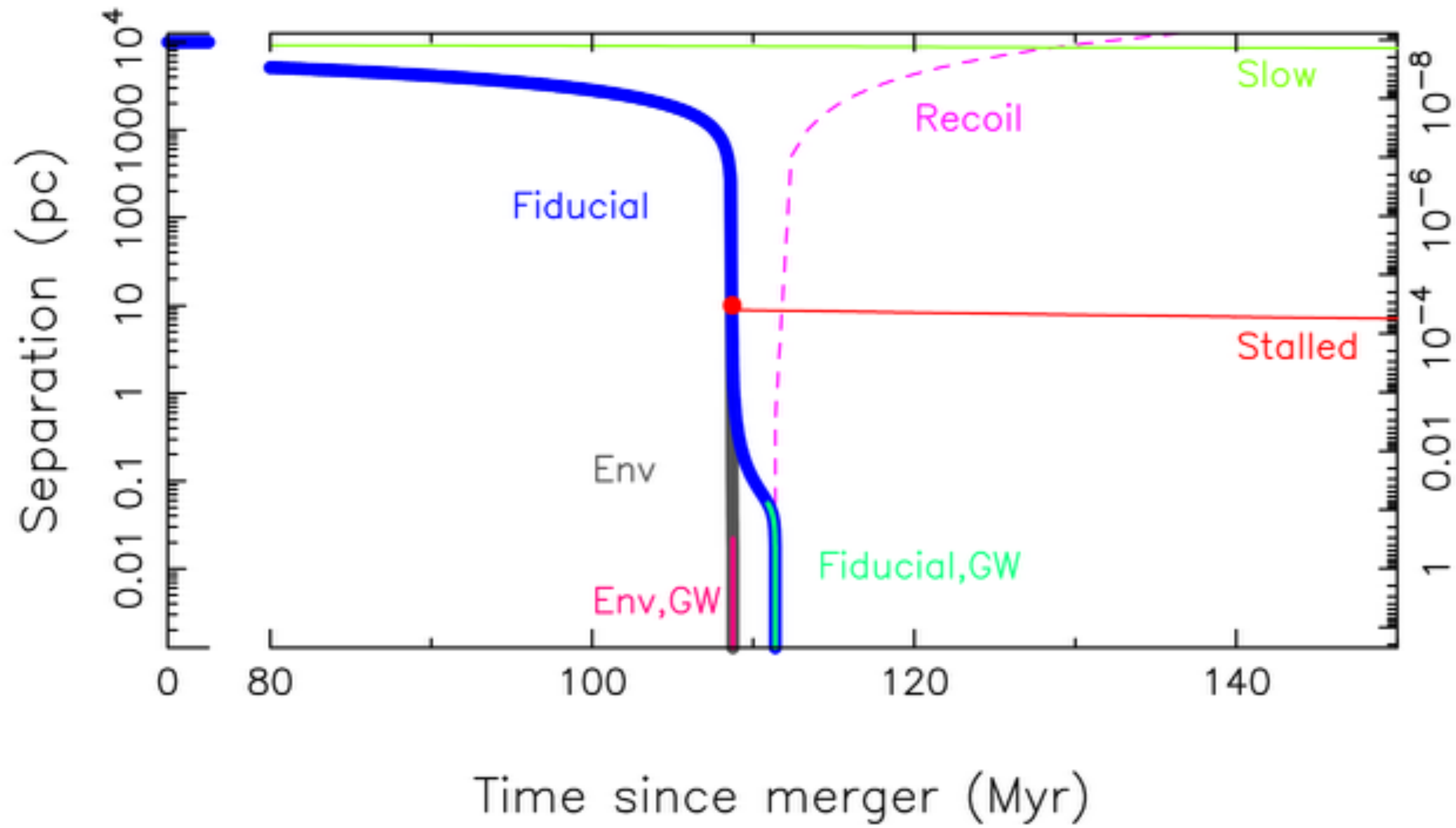


Shannon, Ravi, Lentati, PL, et al., 2015 (submitted)



Shannon, Ravi, Lentati, PL, et al., 2015 (submitted)

Astrophysical Inference



- Black hole mass function at z ~ 2?
- Galaxy merger rate?
- Environmental factors: stars, gas, …

see Ryan Shannon's talk, 2:15 Tuesday & PPTA poster

Shannon, Ravi, Lentati, PL, et al., 2015 (submitted)

Conclusions

- **Advanced LIGO coming online ~Q4 2015**
  - Binary inspirals likely first detection
  - detection of isolated neutron stars has huge pay-off.
- **PPTA currently doing cosmology with non-detections!**
- **<u>Exciting times for gravitational wave science!!</u>**

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Extra Slides

Laser Interferometer
Gravitational wave Observatory

LIGO

Epoch	Estimated run duration	No. of BNS Detections
2015	3 months	0.0004 — 3
2016 – 17	6 months	0.006 — 20
2017 — 18	9 months	0.04 — 100
2019 +	(per year)	0.2 — 200
2022 + (India)	(per year)	0.4 — 400

Abadie et al. (2010; arXiv:1003.2480)

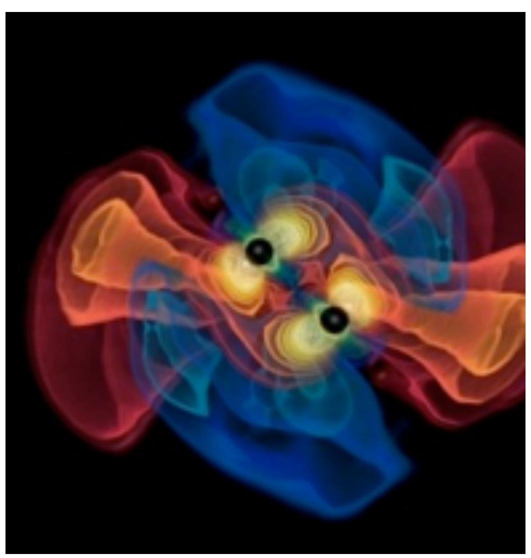
see David McClelland's talk, 4pm Tuesday!

Laser Interferometer Gravitational wave Observatory LIGO

900+ members, 80+ institutions, 17 countries

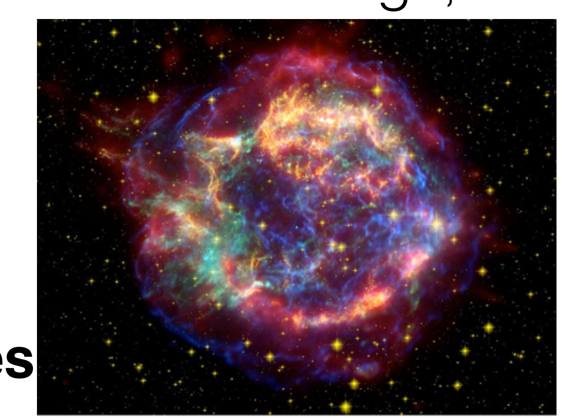
LIGO Hanford

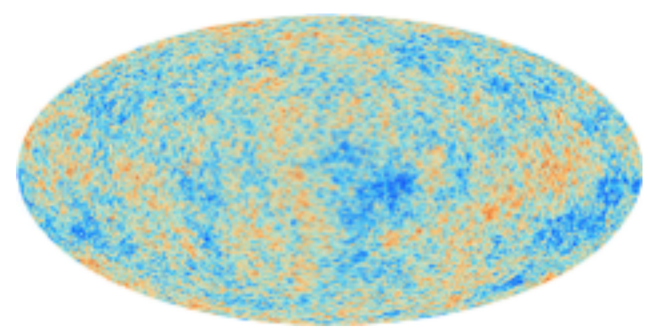
LIGO Livingston



Coalescing compact binaries
NS-NS, NS-BH, BH-BH

Bursts
core-collapse SN, pulsar glitches, magnetar flares, cosmic strings, …





stochastic background
Astrophysical & cosmological

continuous wave
rotating neutron stars

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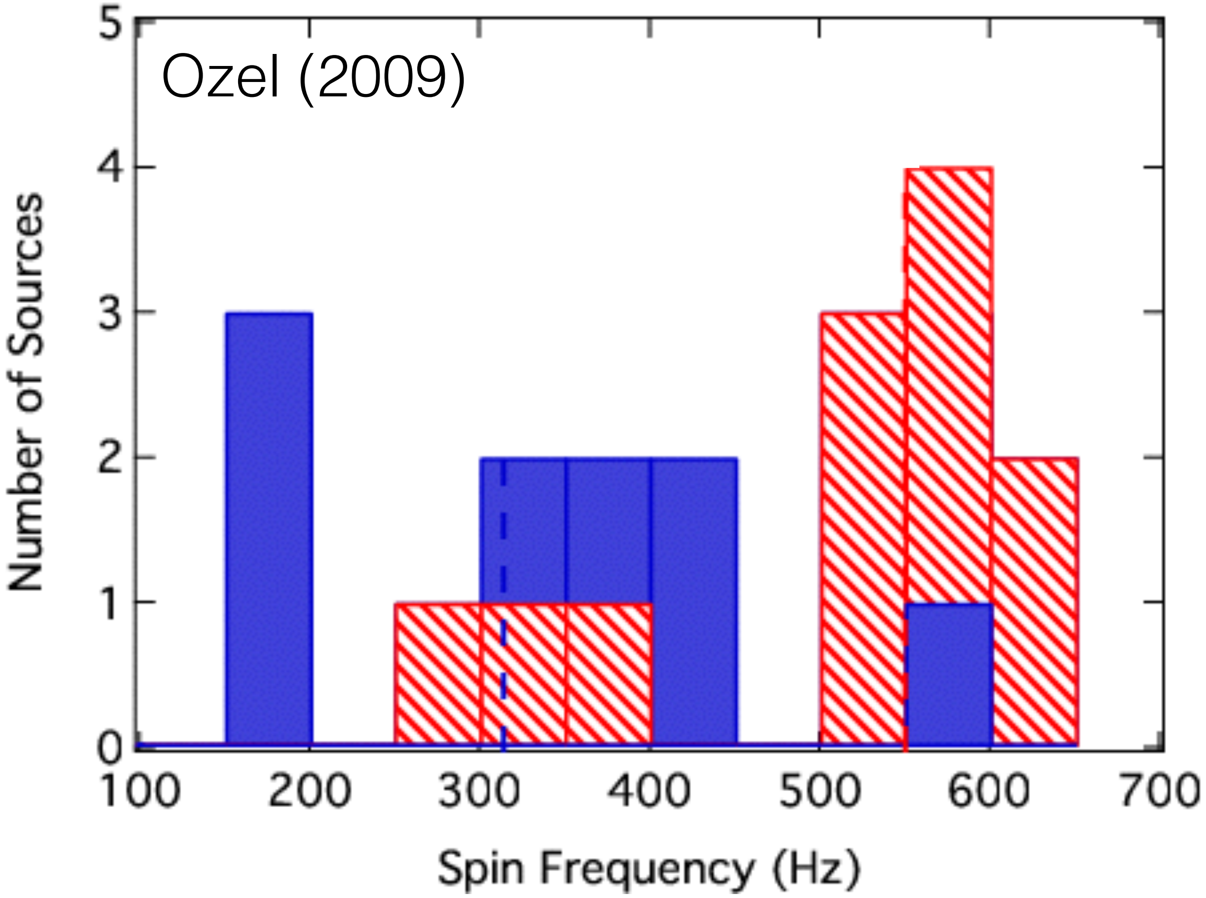
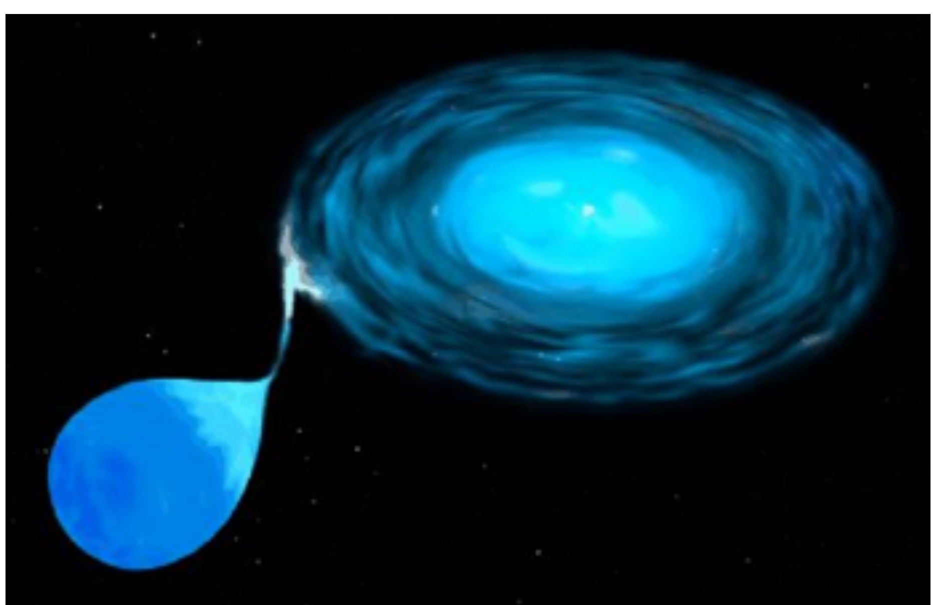
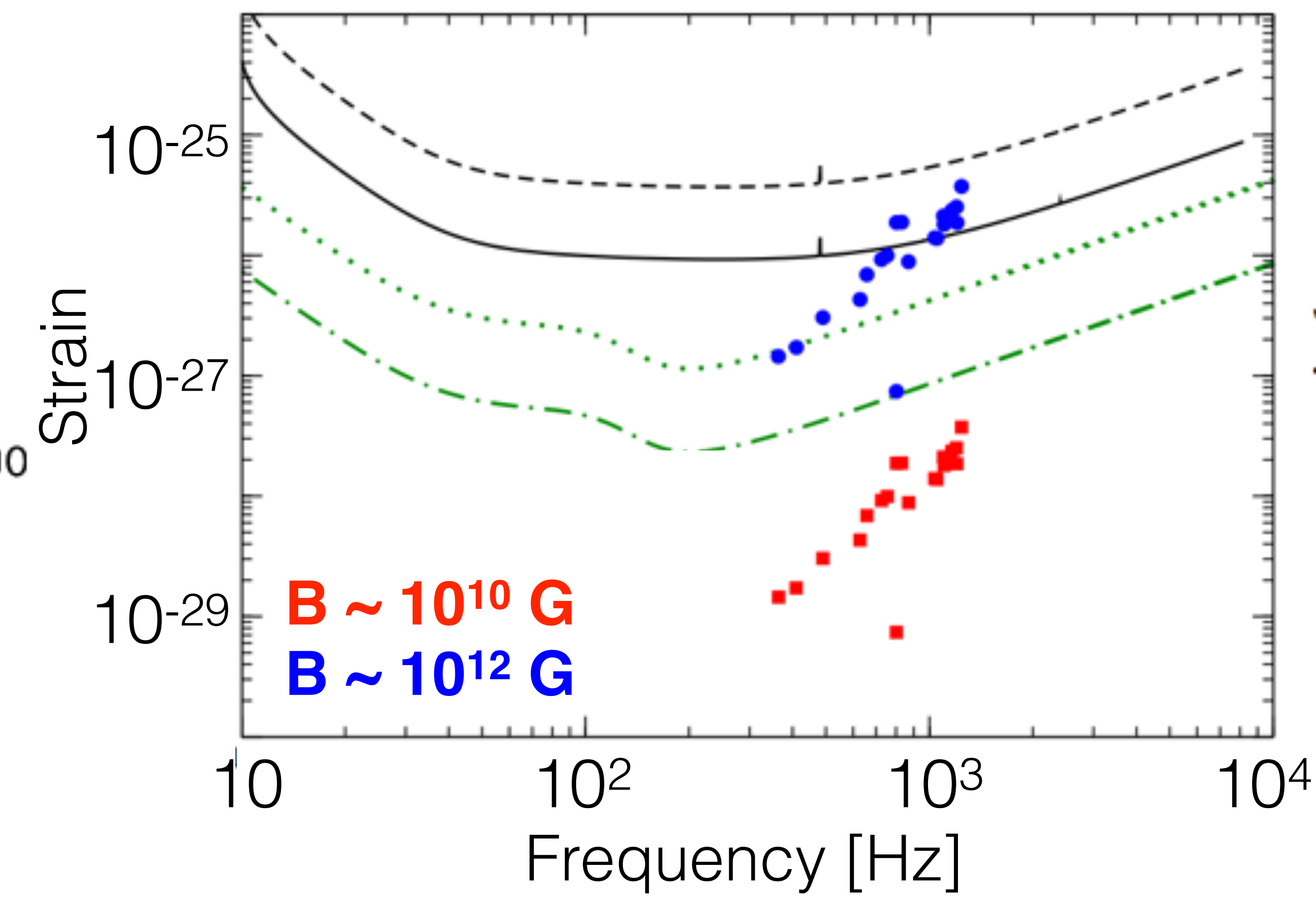
Accreting X-ray Binaries





Haskell, … PL (2015)



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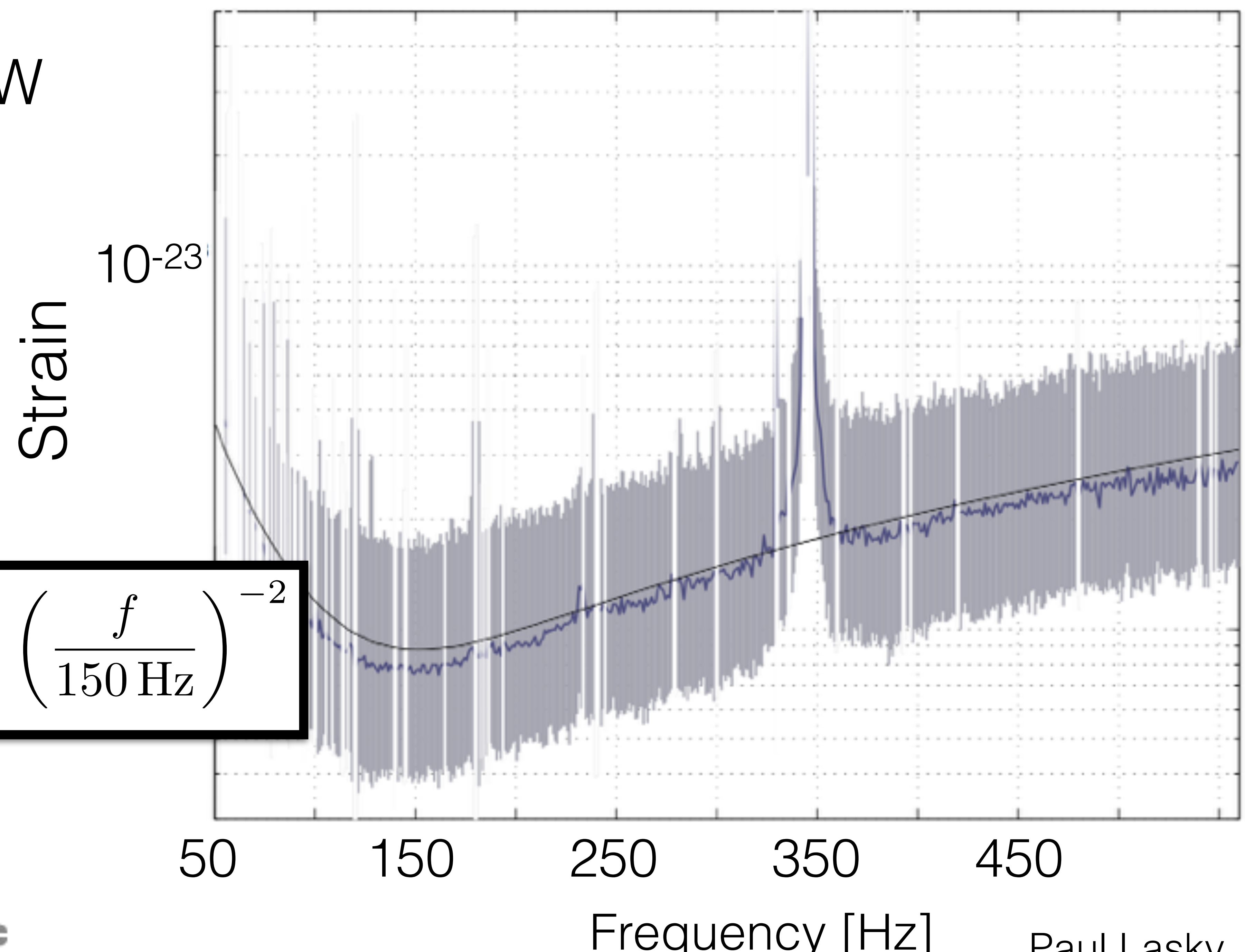
Low Mass X-ray Binary: Sco X1

- Brightest extrasolar X-ray source
  - torque balance
  - loudest binary GW

Sammut et al. (2014); Aasi et al. (2015)
Messenger, … PL, … (2015)



$$\epsilon \leq 5 \times 10^{-4} \left(\frac{h}{4 \times 10^{-25}} \right) \left(\frac{f}{150\,\mathrm{Hz}} \right)^{-2}$$

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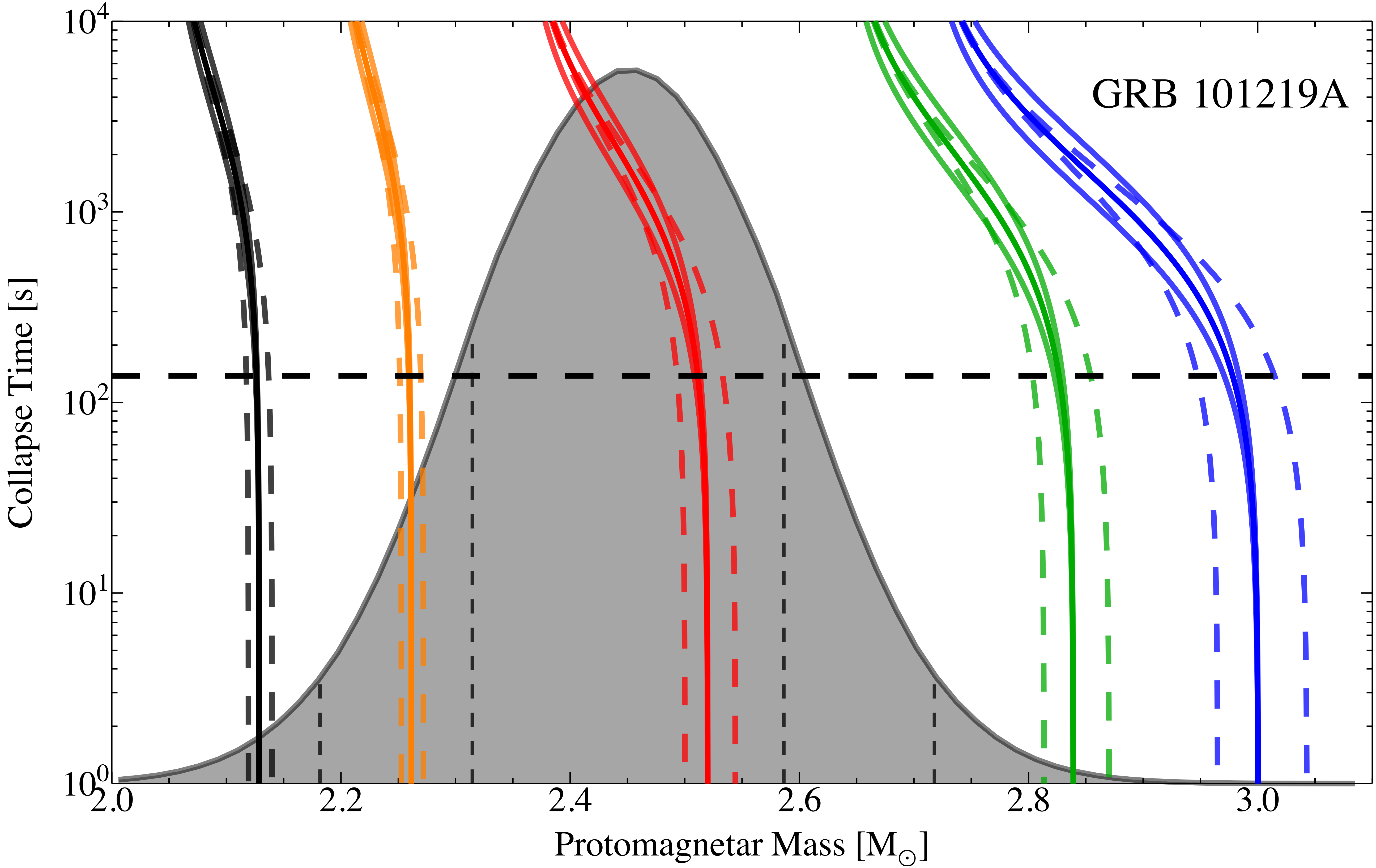
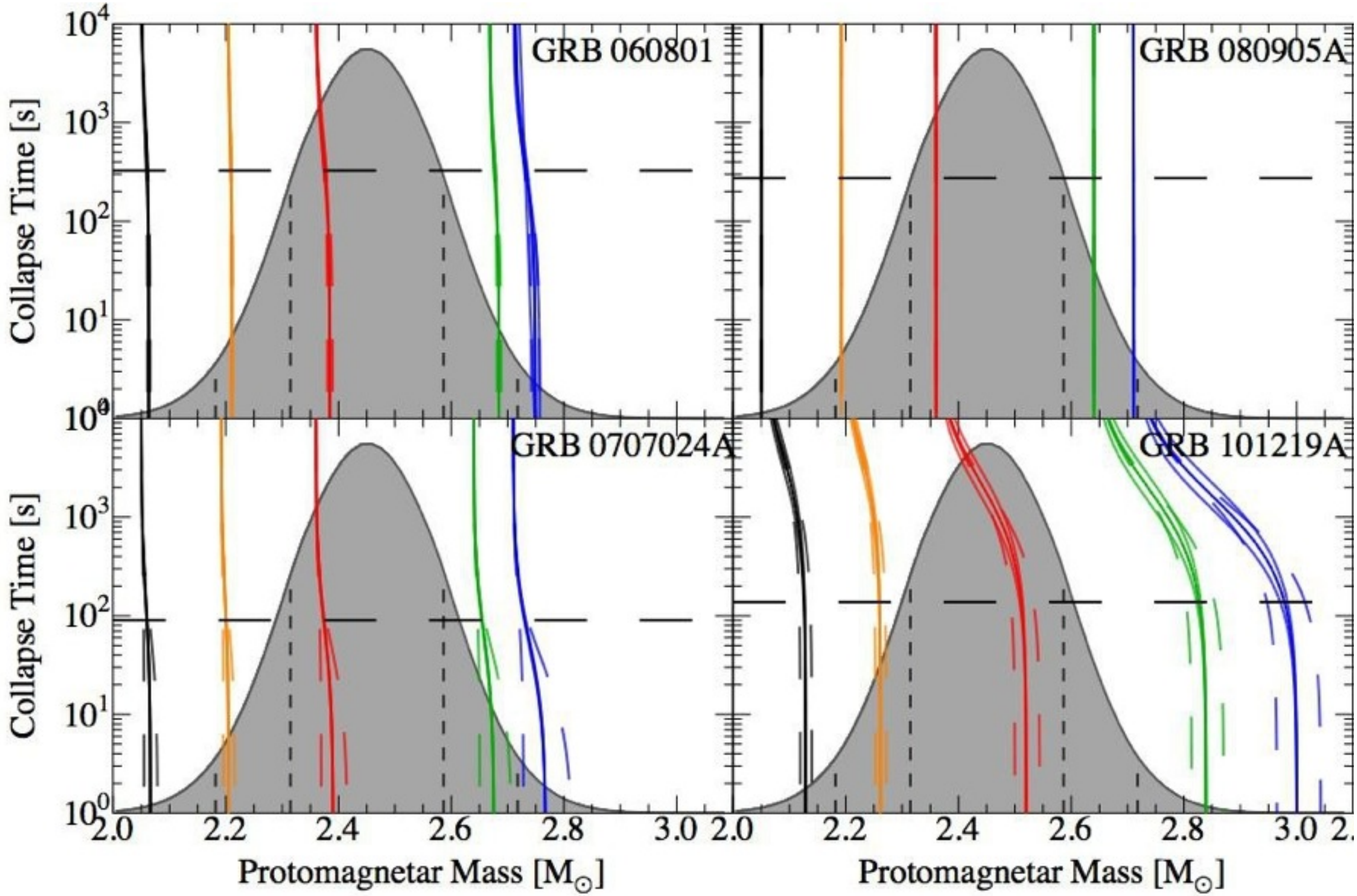


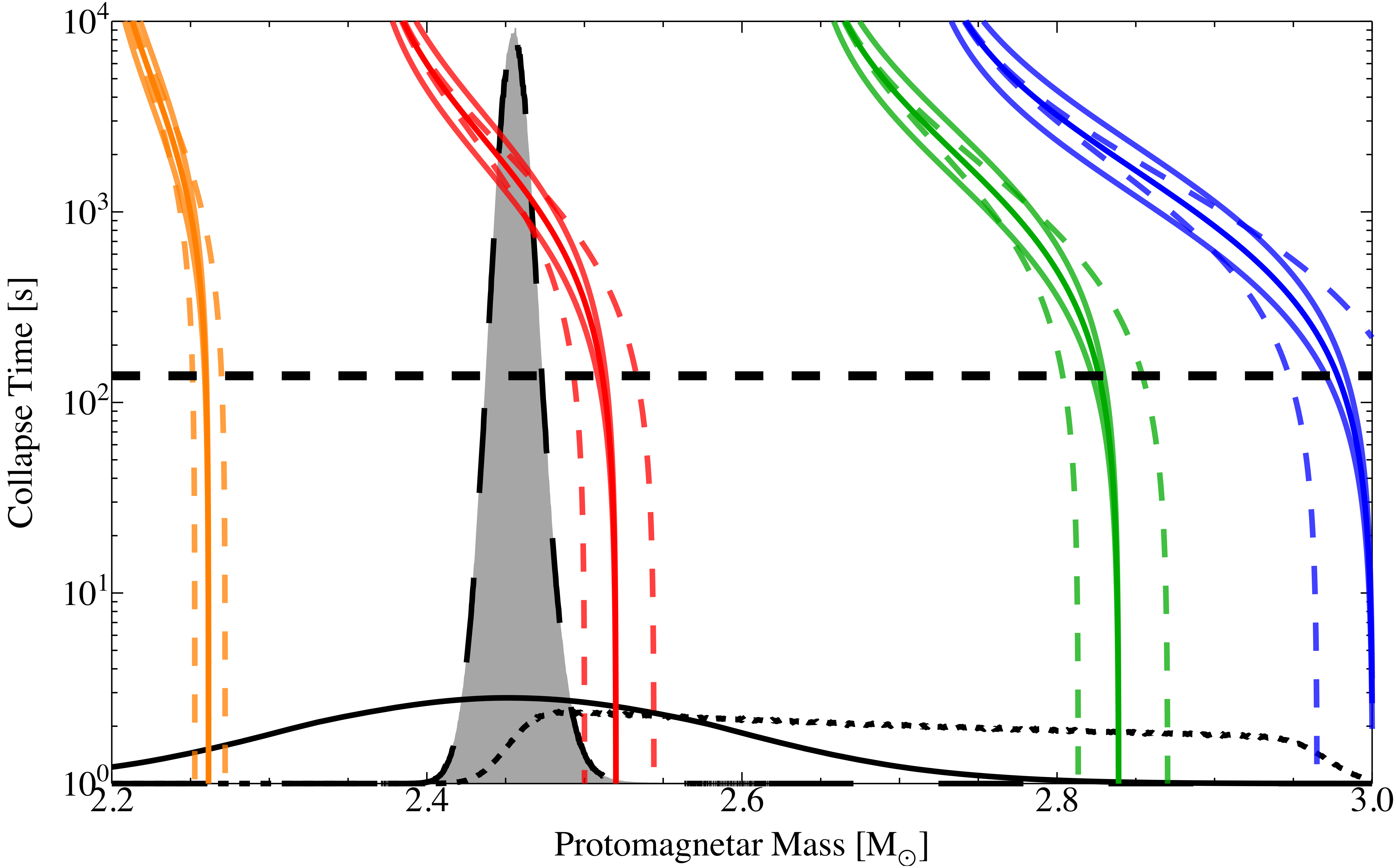
GRB 101219A
Collapse Time [s]
10^4
10^3
10^2
10^1
10^0
2.0
2.2
2.4
2.6
2.8
3.0
Protomagnetar Mass [$M_\odot$]

PL et al. (2014)



GRB 060801
GRB 080905A
GRB 0707024A
GRB 101219A
Collapse Time [s]
Collapse Time [s]
Protomagnetar Mass [M$_\odot$]
Protomagnetar Mass [M$_\odot$]

PL et al. (2014)



Collapse Time [s]
10^4
10^3
10^2
10^1
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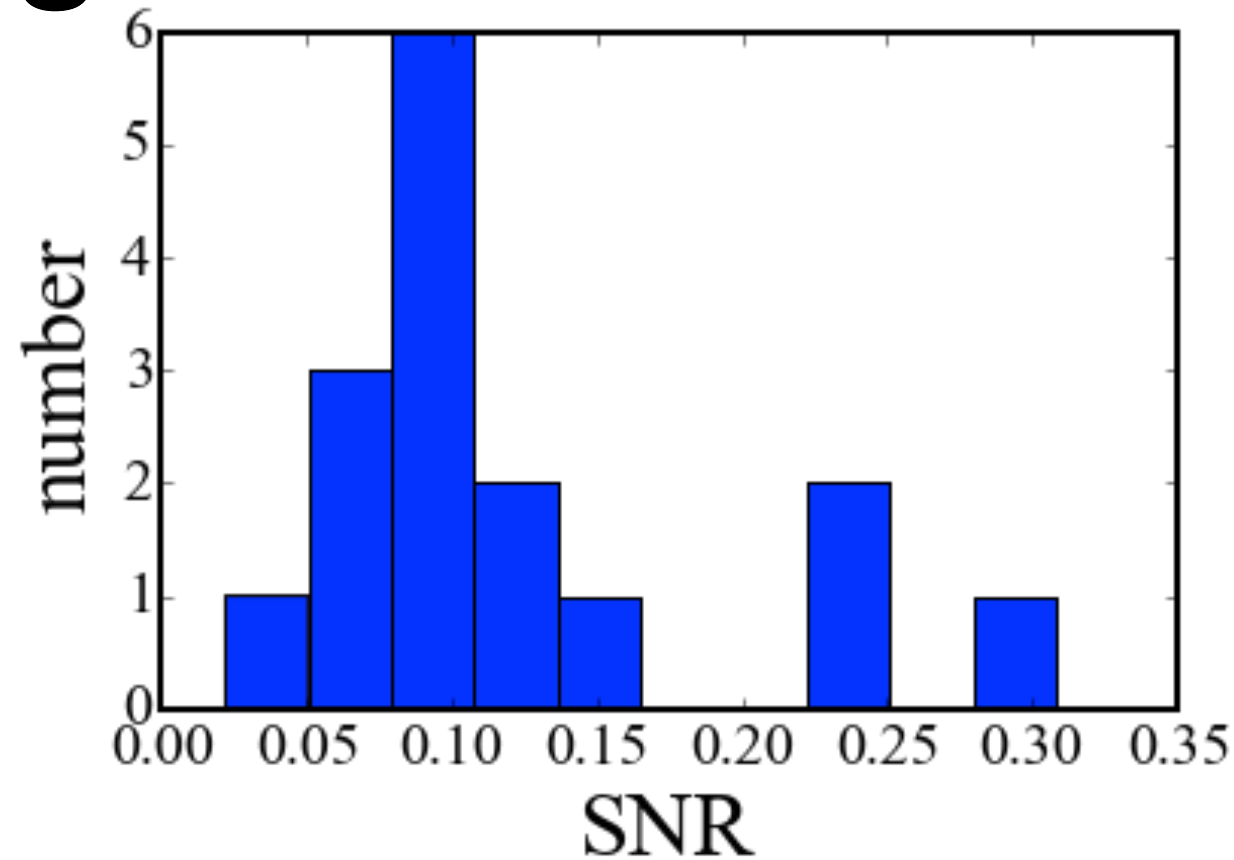
Protomagnetar Mass [$M_\odot$]

PL et al. (2014)

Very young neutron stars — short GRBs



upper limit SNR for
full aLIGO sensitivity

(PL 2015; in prep)