# Joint Gravitational Wave and Electromagnetic Observation of Neutron Star- Black Hole Coalescing Binaries: A New Method to Constrain Neutron Star Radius

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EWASS 27-06-2017

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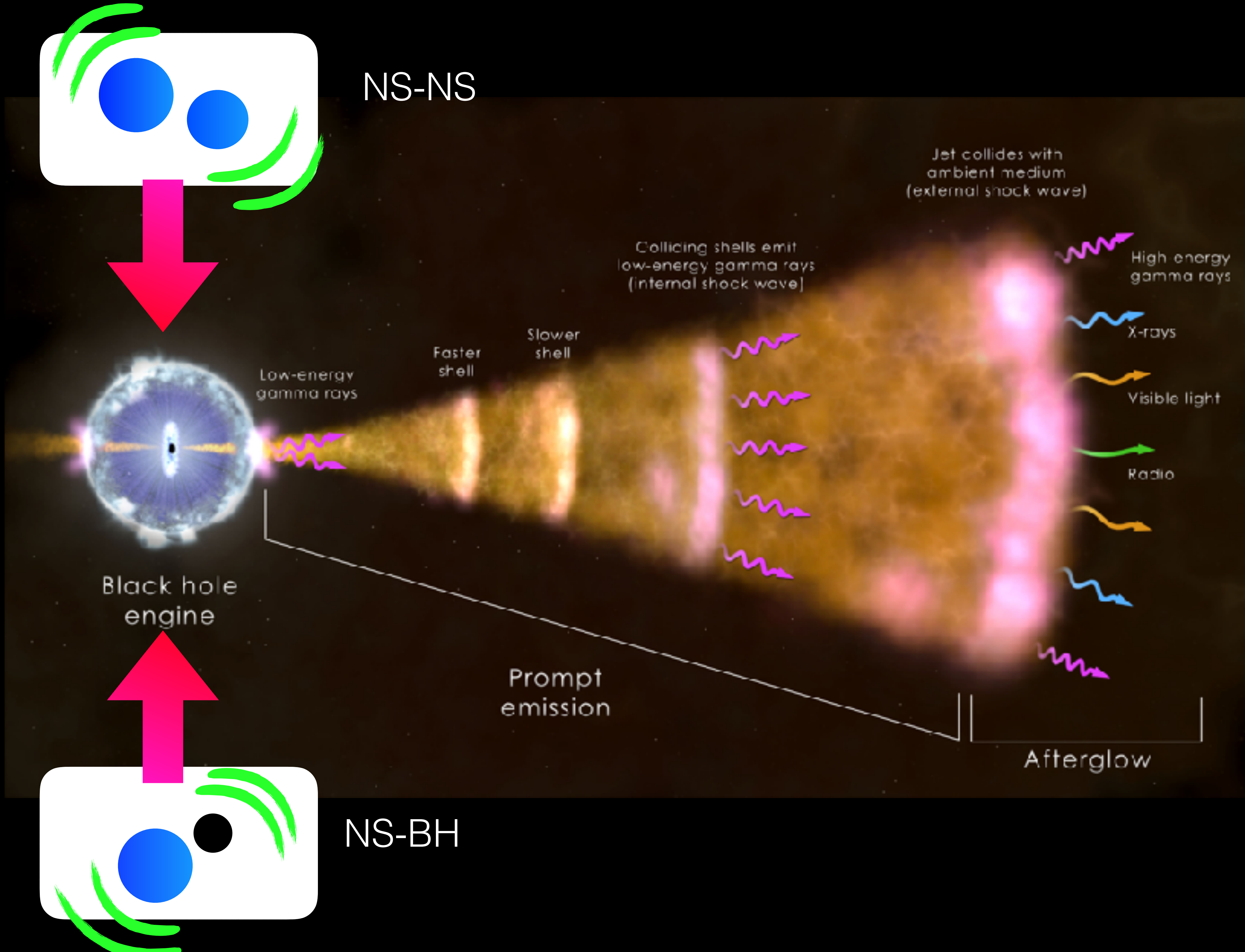
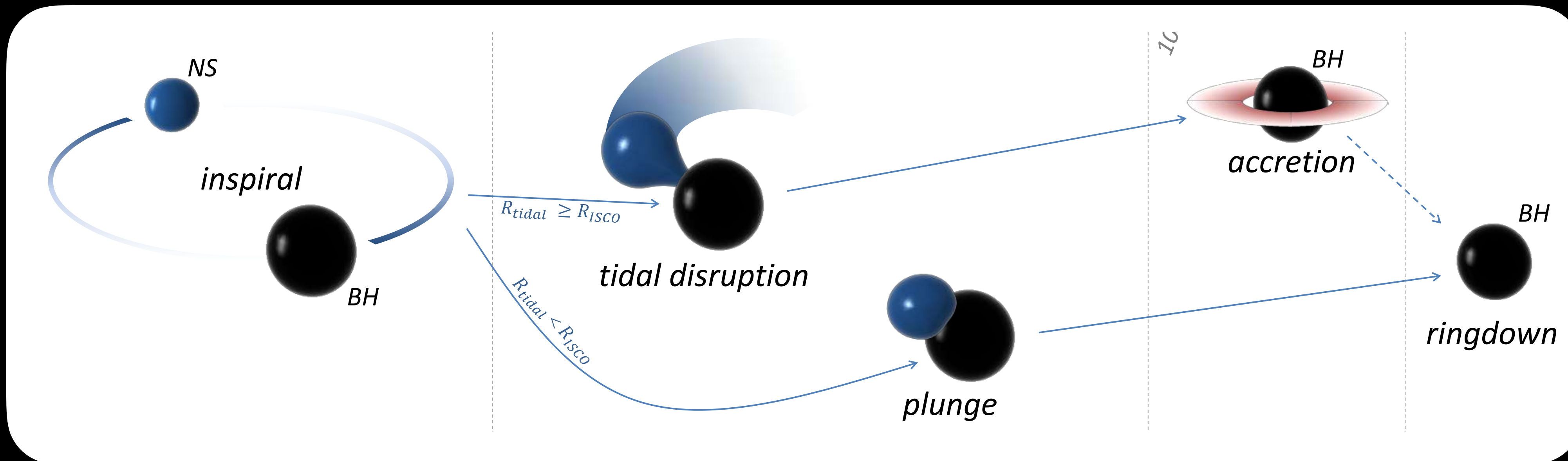
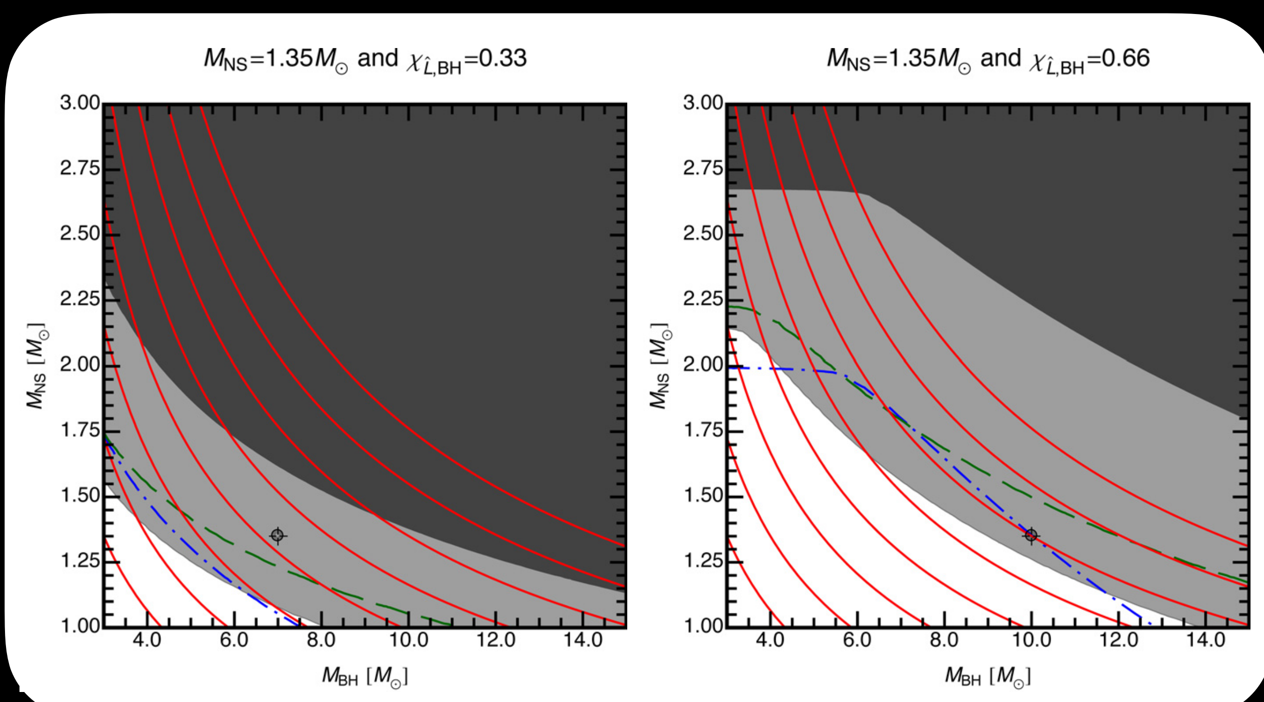
# Short Gamma Ray Burst



# NS-BH Merger




(Bartos 2012)



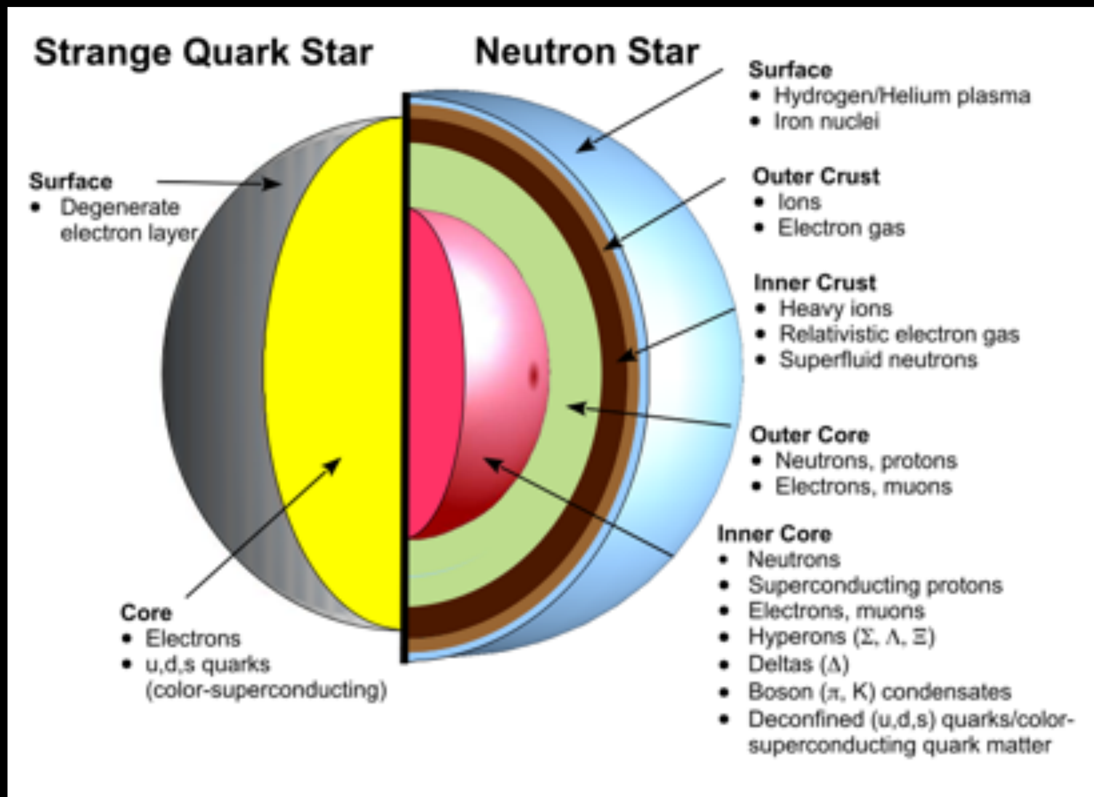

No Remnant EoS dipendent Remnant for all EoS

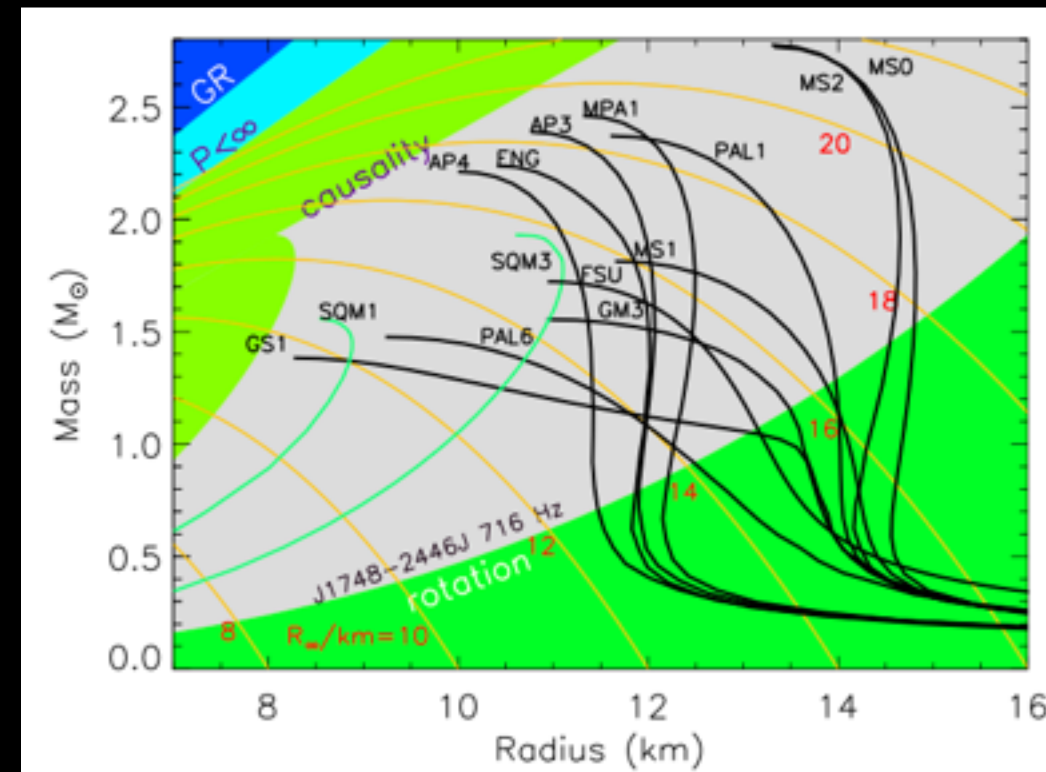
(Pannarale & Ohme 2014)

**Optimal scenario for EM counterpart**

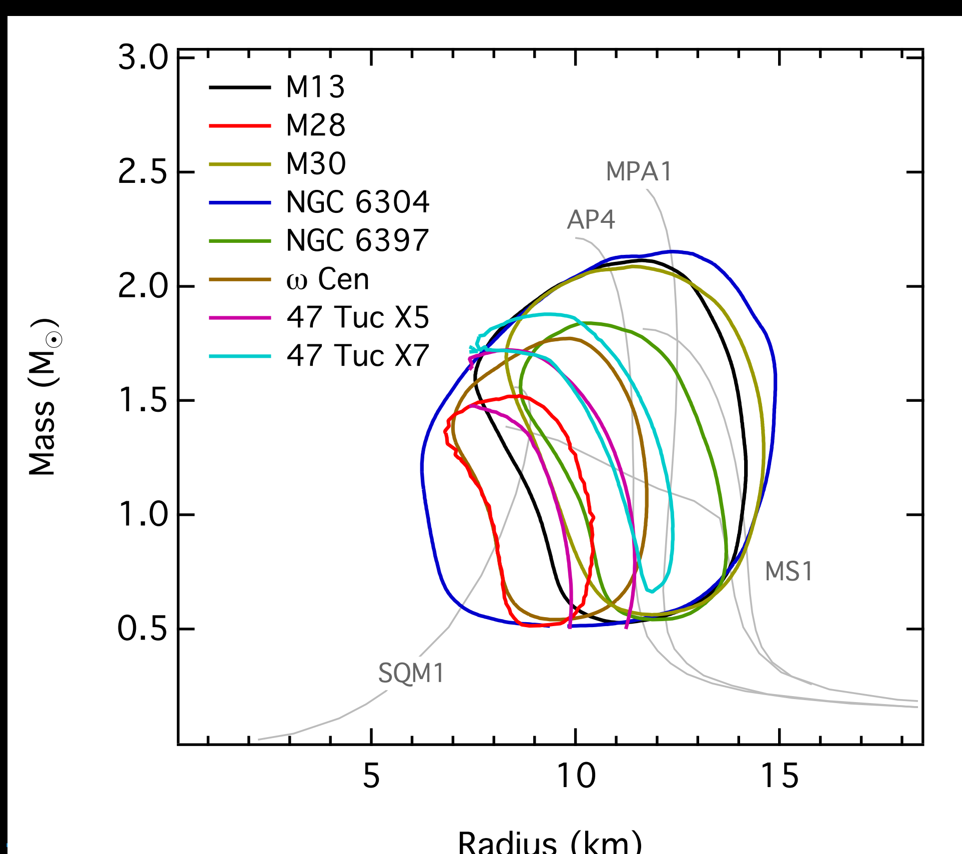
- **Low mass, highly spinning BH**
- **Large NS radius (stiff EoS)**

# NS Radii and EoS




(Lattimer & Prakash 2015)

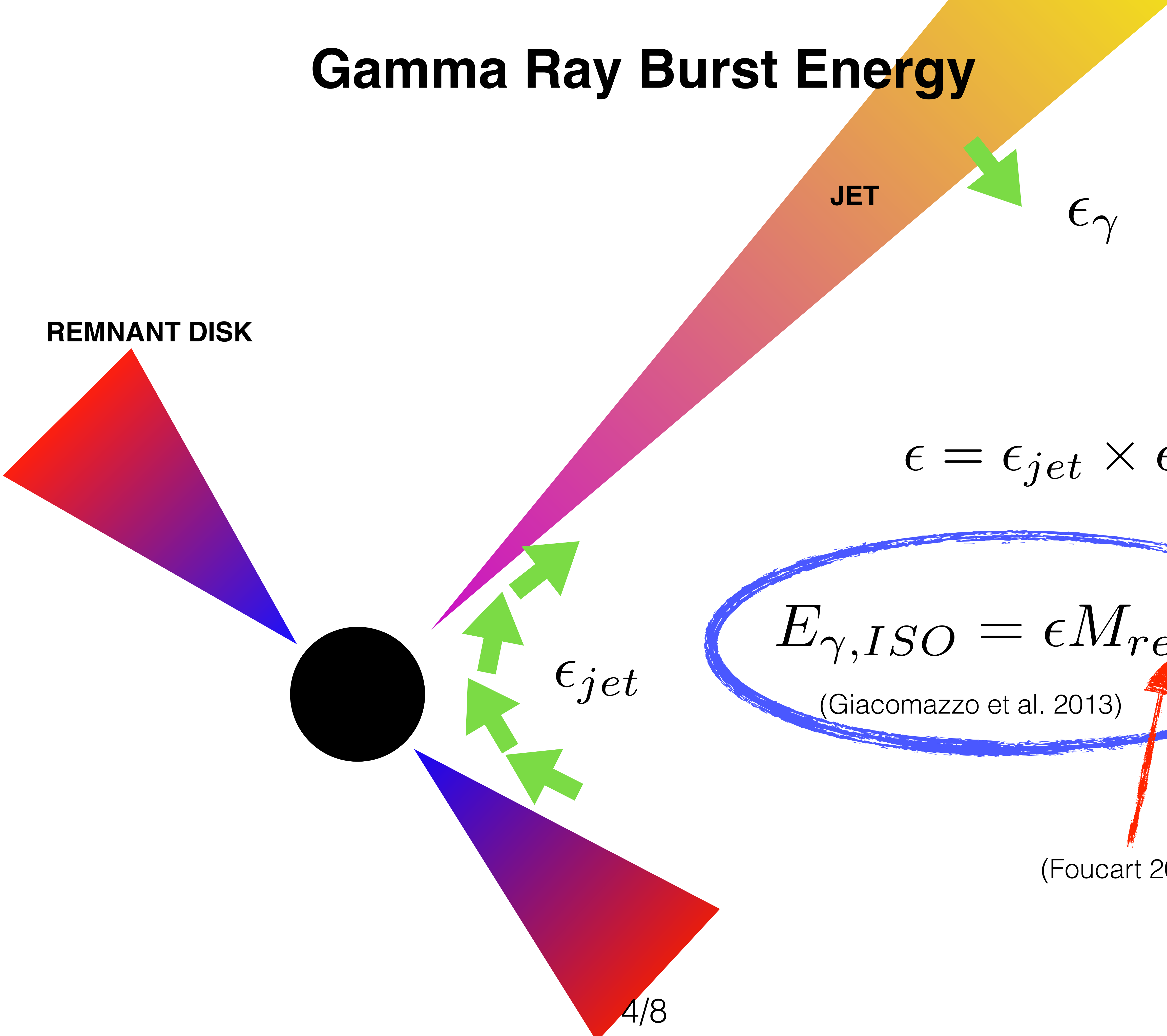



(Ozel & Freire 2016)

NS Radii are poorly constrained!

Constraints on NS EoS due to mass and radii measurements of quiescent LMXB

# Gamma Ray Burst Energy



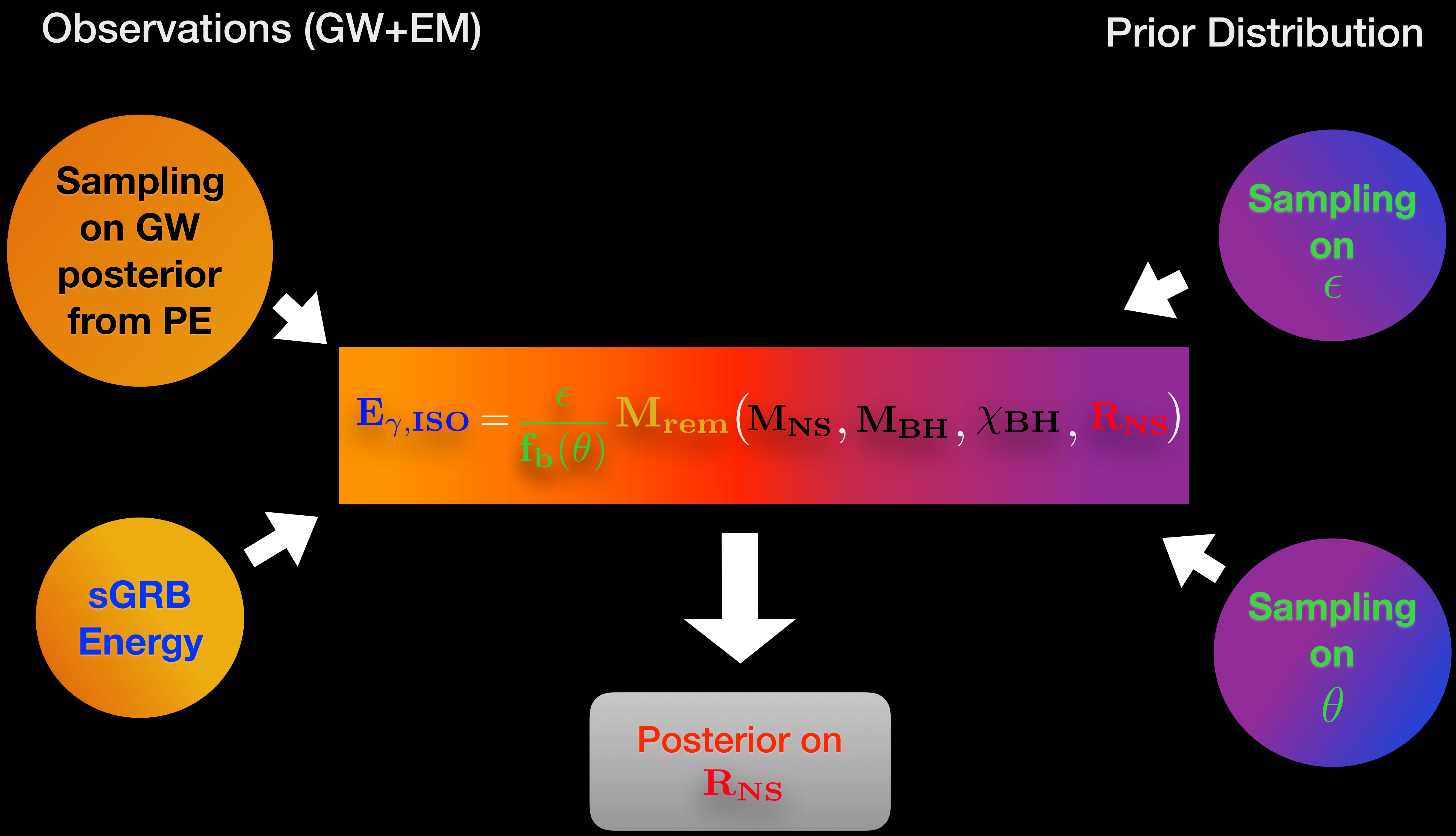

$$\epsilon = \epsilon_{jet} \times \epsilon_\gamma$$

$$E_{\gamma,ISO} = \epsilon M_{rem} c^2$$

(Giacomazzo et al. 2013)

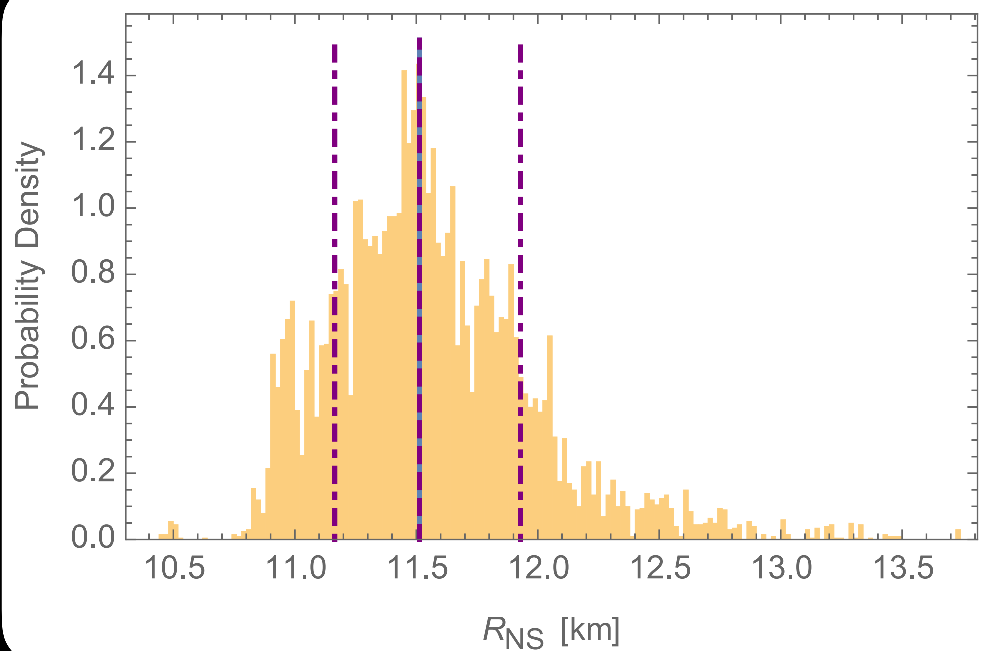
(Foucart 2012)

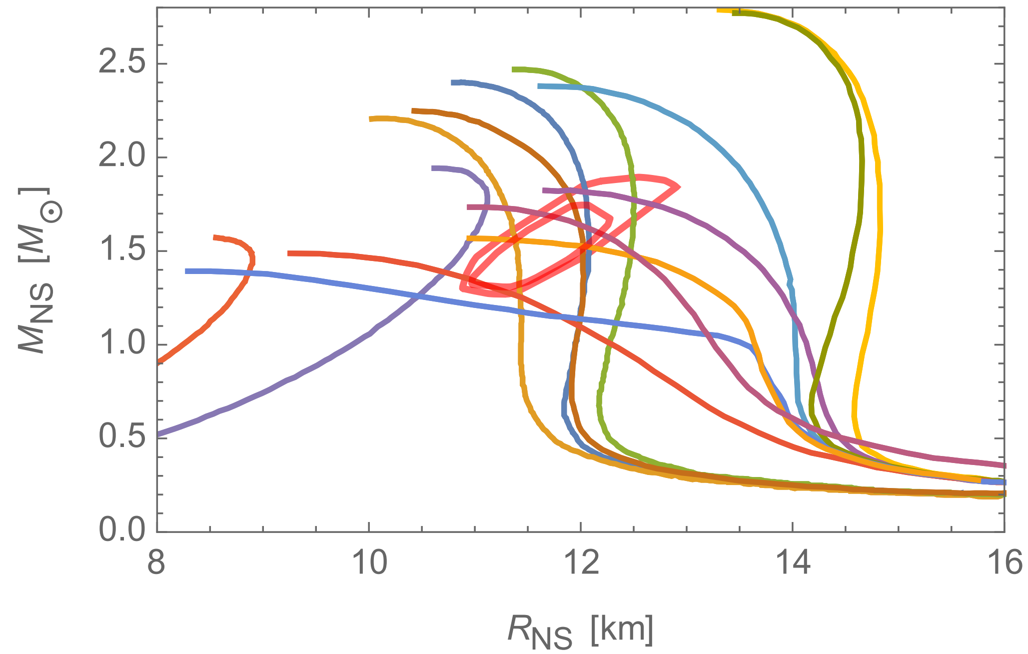
# Method


Observations (GW+EM)
Prior Distribution
Sampling on GW posterior from PE
sGRB Energy
$\mathbf{E}_{\gamma,\mathrm{ISO}} = \frac{\epsilon}{\mathrm{f_b}(\theta)} \mathrm{M_{rem}}(\mathrm{M_{NS}}, \mathrm{M_{BH}}, \chi_{\mathrm{BH}}, \mathrm{R_{NS}})$
Sampling on $\epsilon$
Sampling on $\theta$
Posterior on $\mathrm{R_{NS}}$

# Results

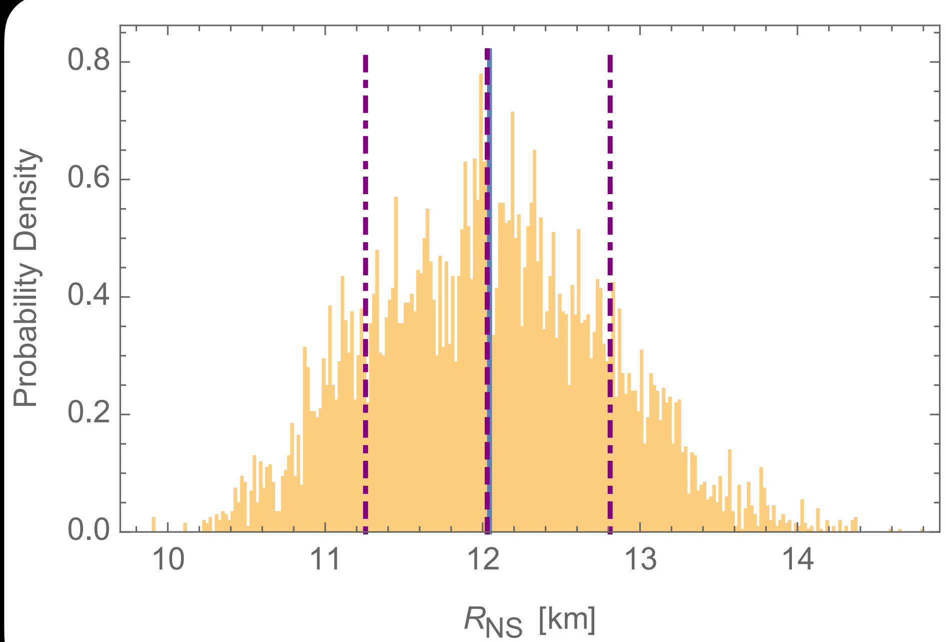
Parameters of Injection: $M_{BH} = 4.84\, M_{\odot}$ $M_{NS} = 1.35\, M_{\odot}$ $\chi_{BH} = 0.48$ $E_{\gamma,ISO} = 10^{50}\, erg$

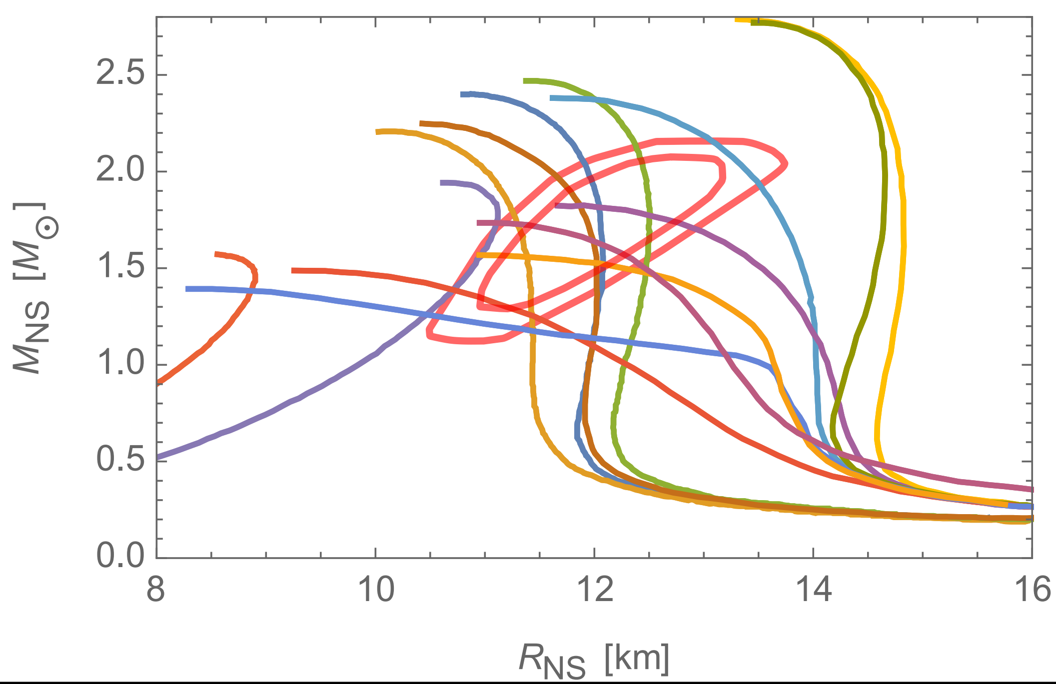



SNR =30

Efficiency peak at 1%, flat beaming angle in [1°-20°]

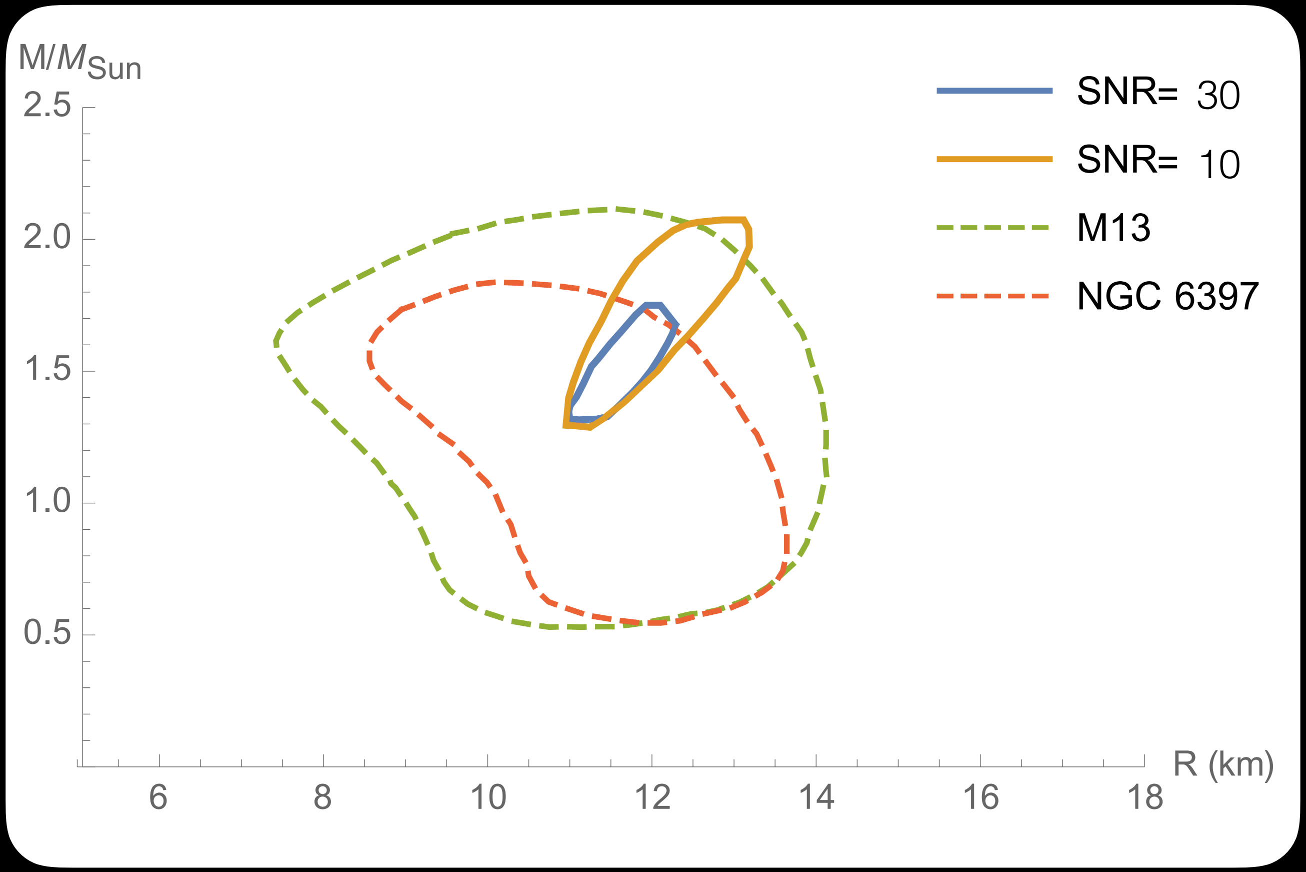



SNR =10

# Comparison with other methods

Comparison between our results (those in previous slides) and results from observation of two qLMXBs



# Conclusions

Summary

- Coalescing NS-BH binaries are promising LIGO-Virgo sources
- They are also possible progenitors of sGRB
- We developed a method to measure NS radii using a sGRB-GW joint detection.

Cons

- **Model dependent** method (but this is a common drawback)
- **Low rate of joint detection** with present facilities (but **NOT with third generation interferometers!**)

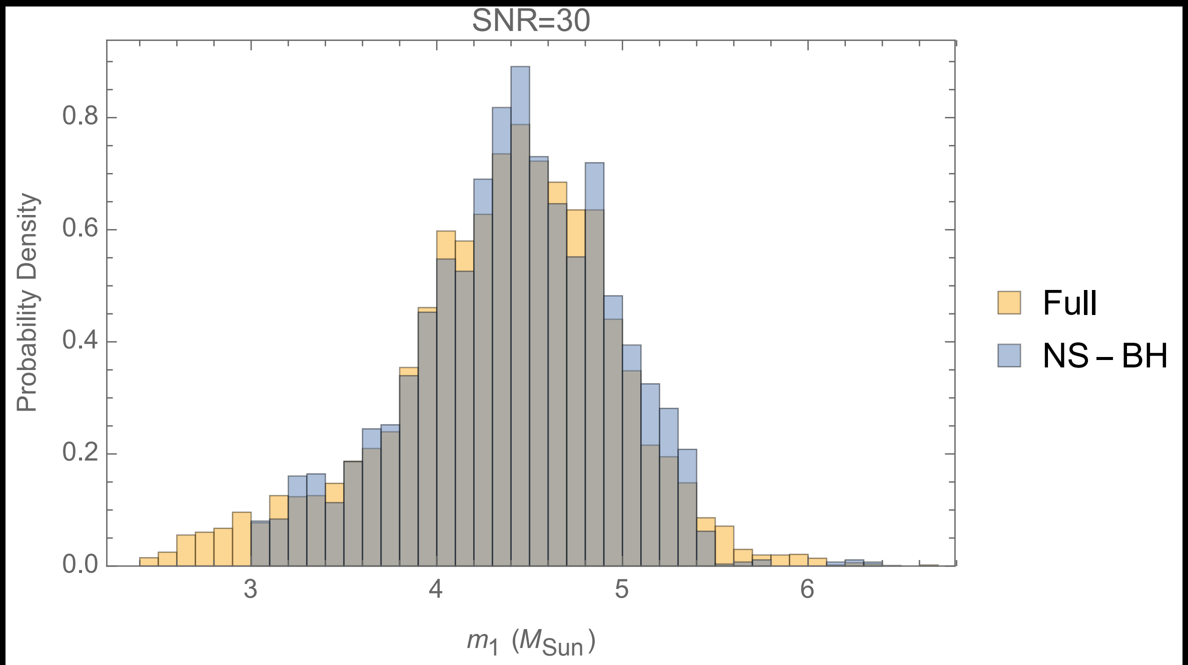
Pro

- **Radically different** from other methods, **enables cross-checks** with other methods.
- For realistic SNR we are below to **7% of accuracy**

# Thank you for your attention!

# Prior/Posterior Distribution from GW Parameter estimation

$m_1$



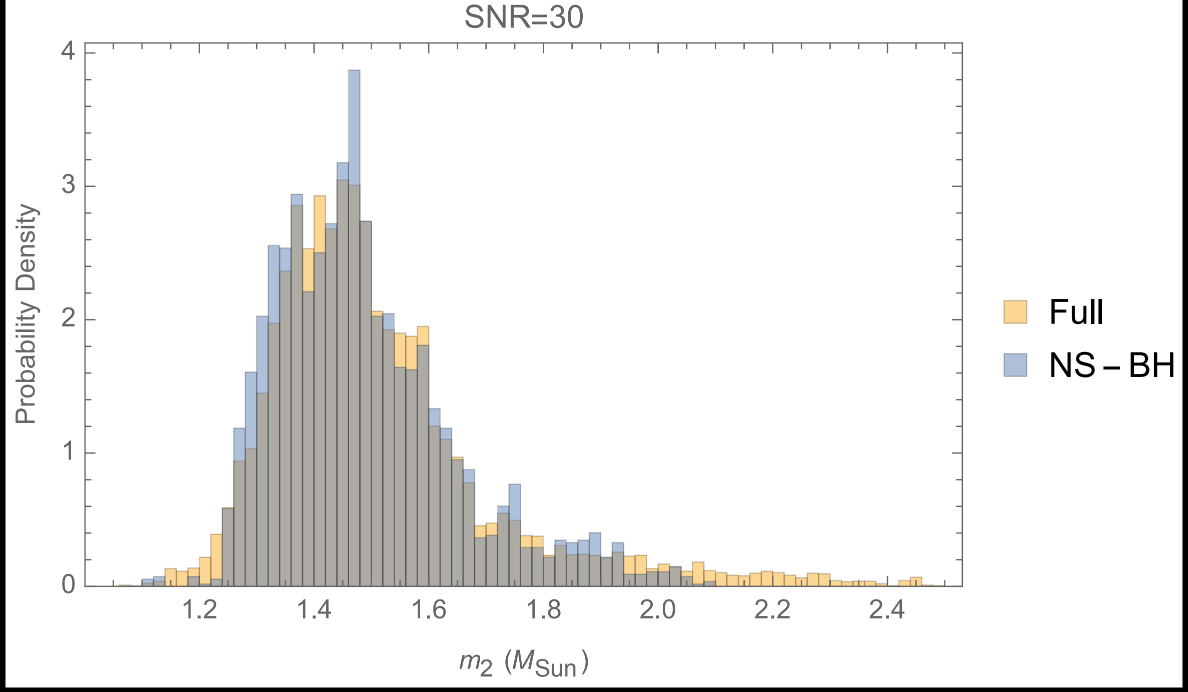

$m_1 = 4.84\, M_\odot$

$m_2 = 1.35\, M_\odot$

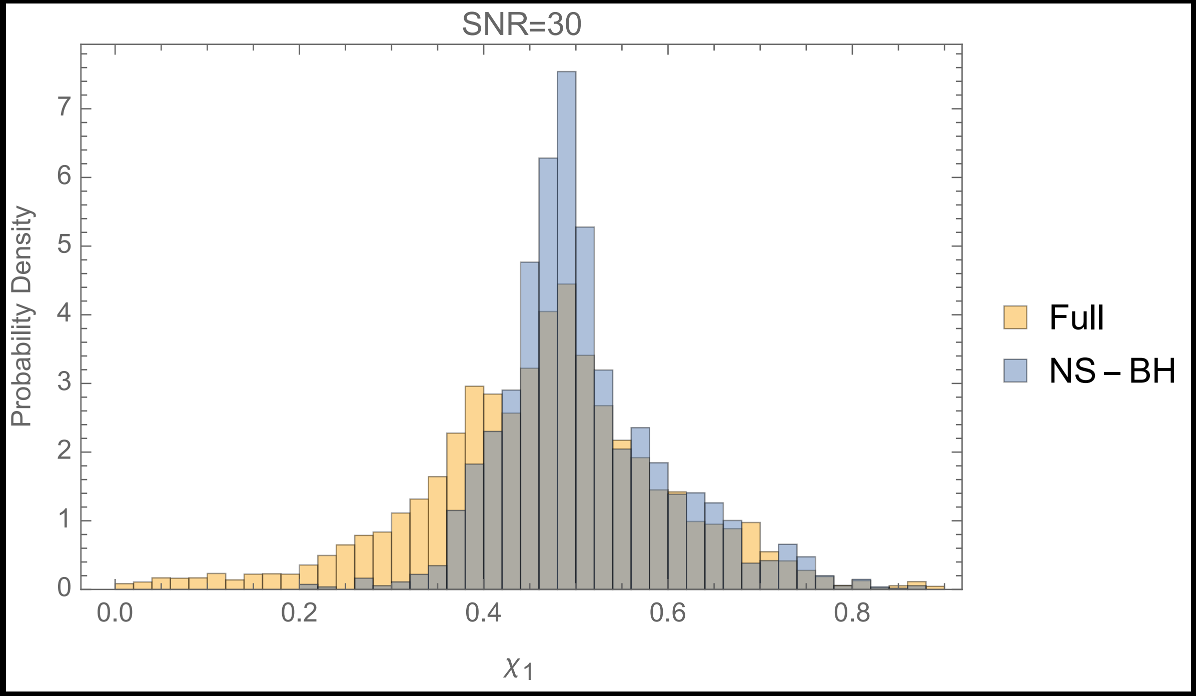
$\chi_1 = 0.48$

SNR = 30

$m_2$



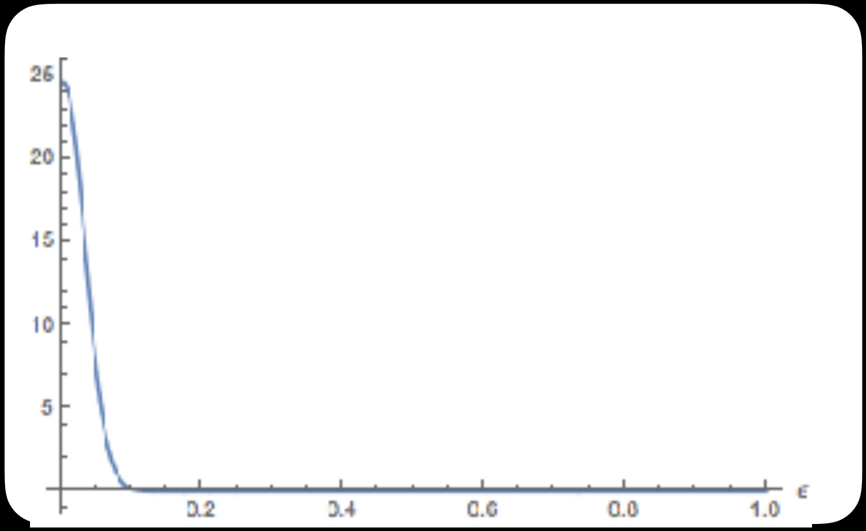

$\chi_1$



# Prior Distribution for the free parameters

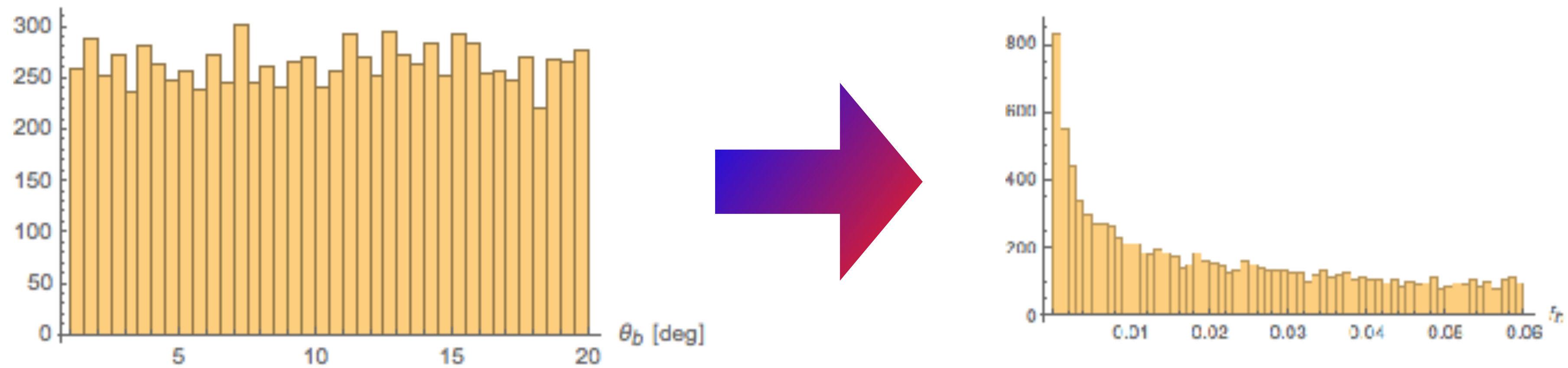
$\epsilon$

$$p(\epsilon) = N \times \exp\Big[-\frac{(\epsilon-\mu)^2}{2\sigma^2}\Big]\Theta(\epsilon)$$

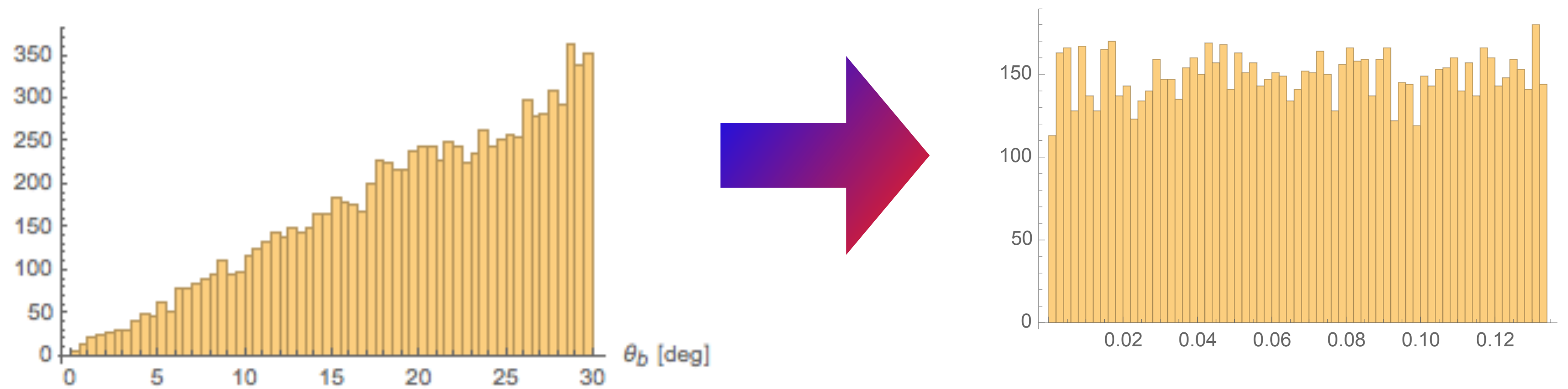


$\theta_b$

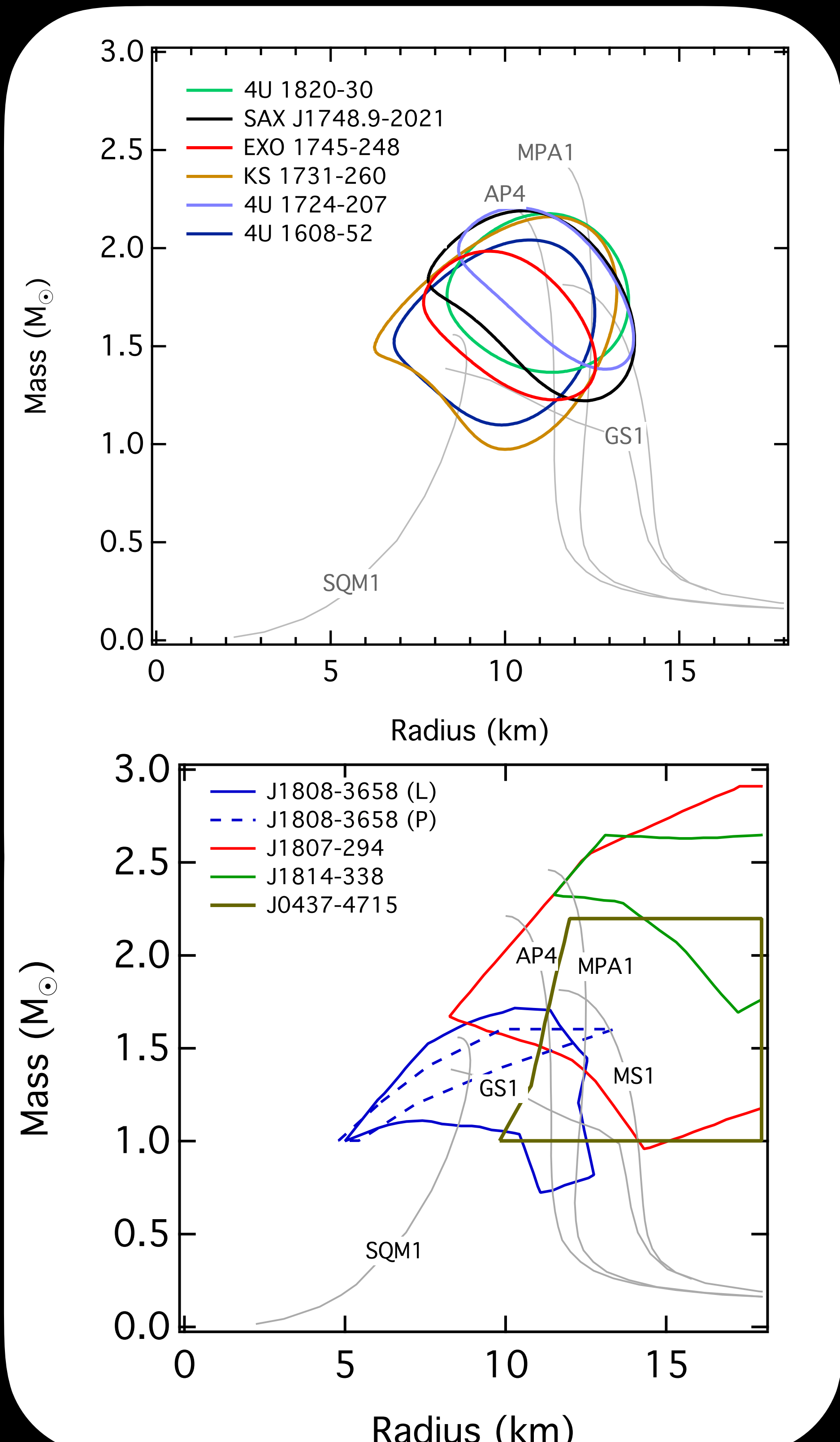
**Flat beaming angle in [1°-20°]**



**Flat cos beaming angle in [cos(30°)-cos(1°)]**



# Measuring NS Radii




(Ozel & Freire 2016)

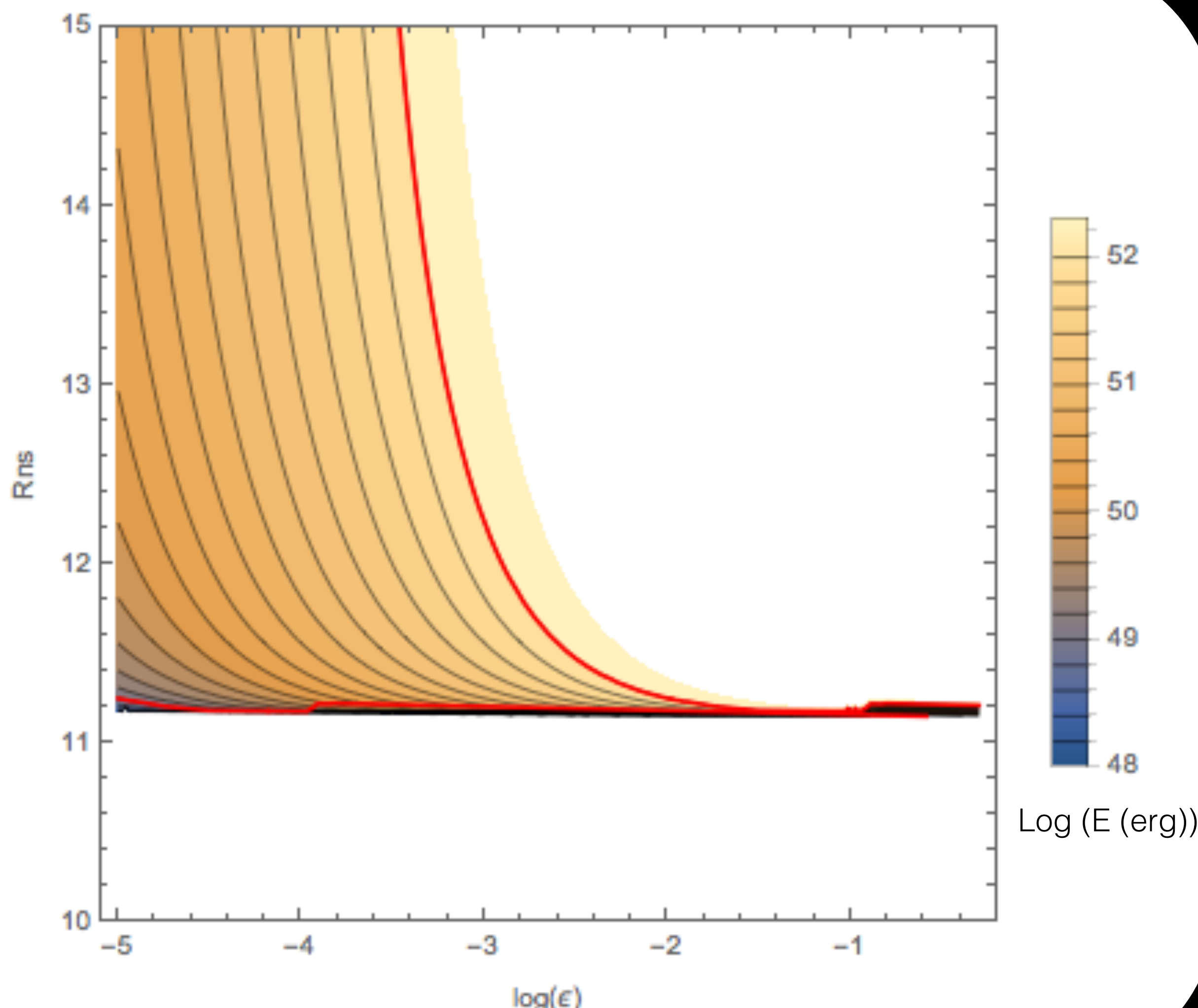
NS with thermonuclear bursts

Accreting Pulsars

**Common Drawbacks**

- Source distance required
- ISM absorption required
- Low (multipolar) source magnetic field required
- Model dependency (spacetime geometry, stellar atmosphere, hot spots geometry)
- Absolute X-ray flux calibration

# Efficiency-Radius degeneracy




There is a degeneracy between the radii and the efficiency, but for "sufficiently low" energy this degeneracy in mitigated

$$R_{NS} = \frac{2\alpha(3q)^{1/3} M_{NS} + \beta R_{ISCO}}{\alpha(3q)^{1/3} - \frac{E_\gamma}{\epsilon M_{NS}^b}}$$

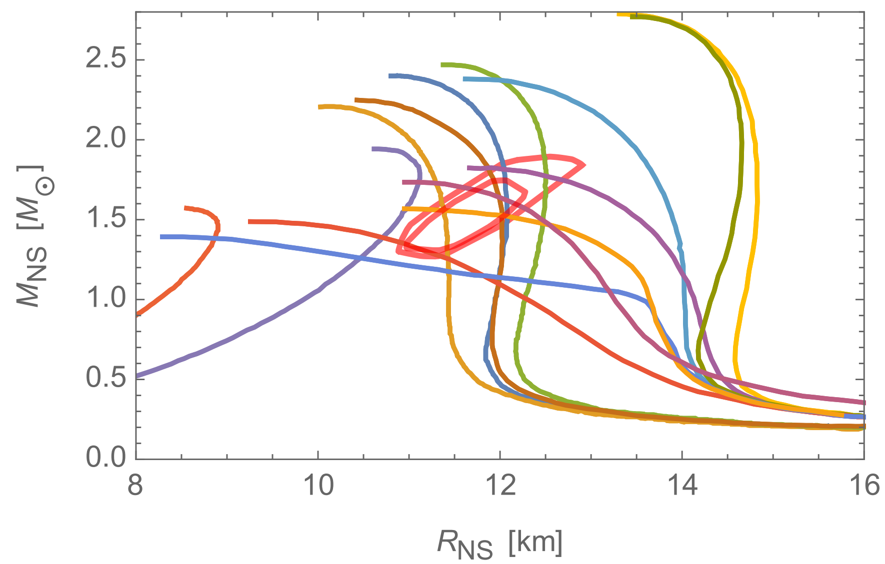
"Sufficiently low" means that this ratio has to be negligible

$$E_\gamma = 10^{50}\, erg$$

$$\epsilon \gg 10^{-3}$$

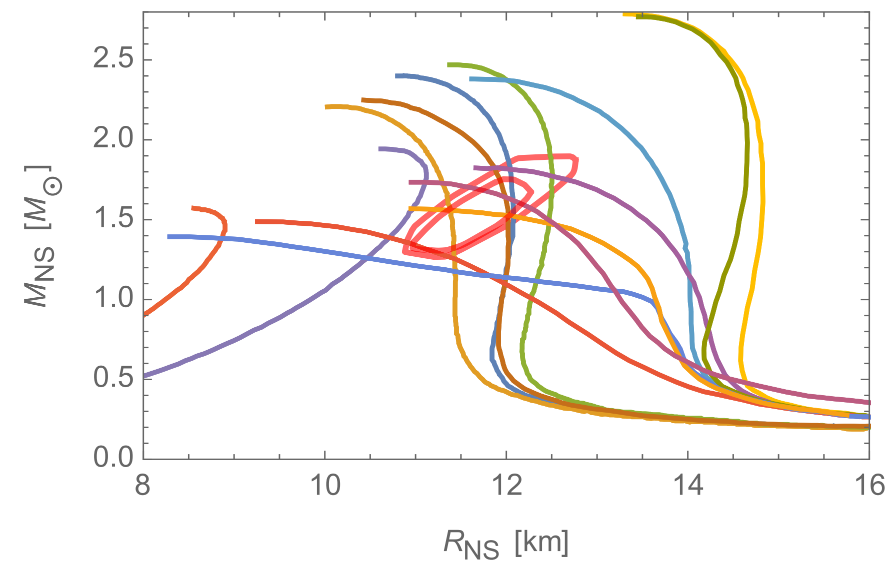
# More Results…

SNR =30



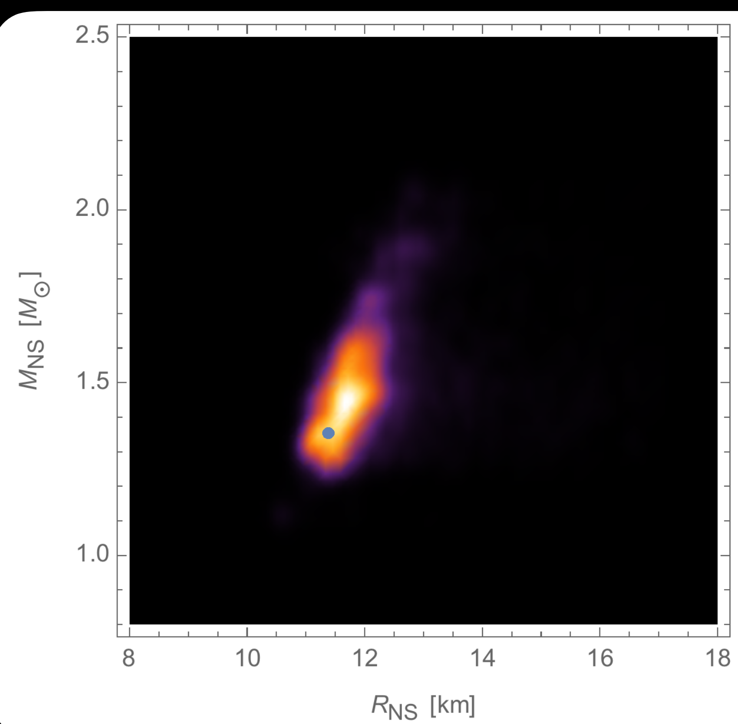

Flat beaming angle in [1°-20°]

$$E_{\gamma,ISO} = 10^{50}\, erg$$

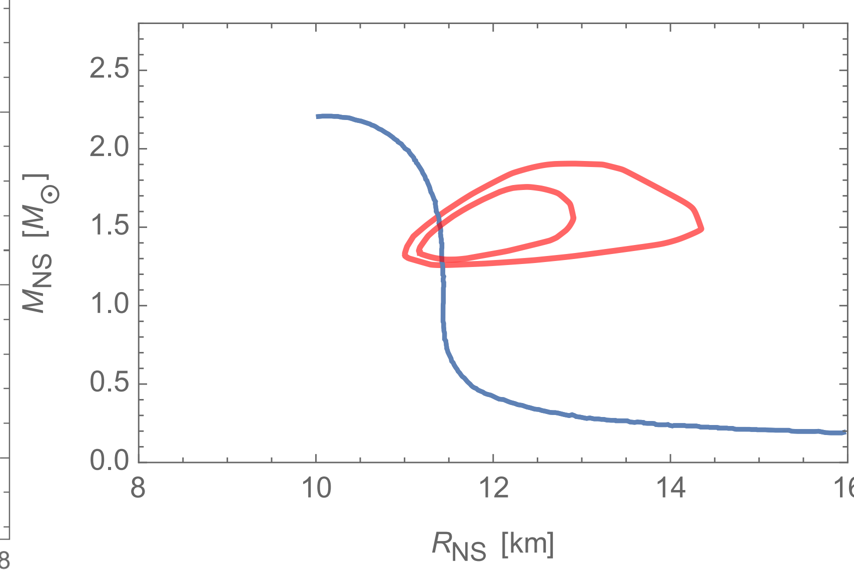


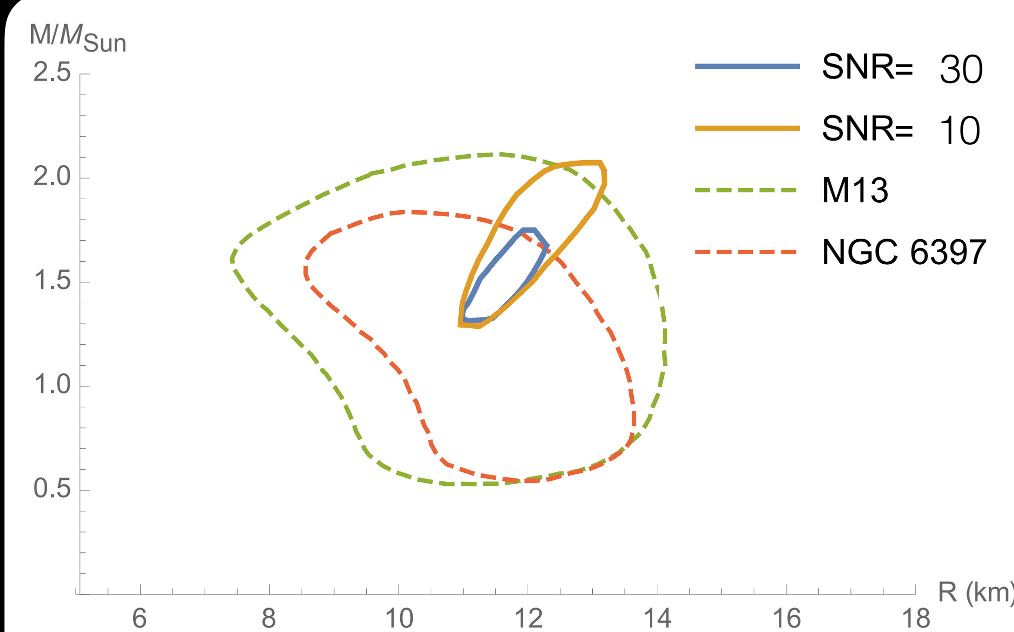

Flat cos beaming angle in [cos(30°)-cos(1°)]

$$E_{\gamma,ISO} = 10^{50}\, erg$$




Injected EOS = APR4

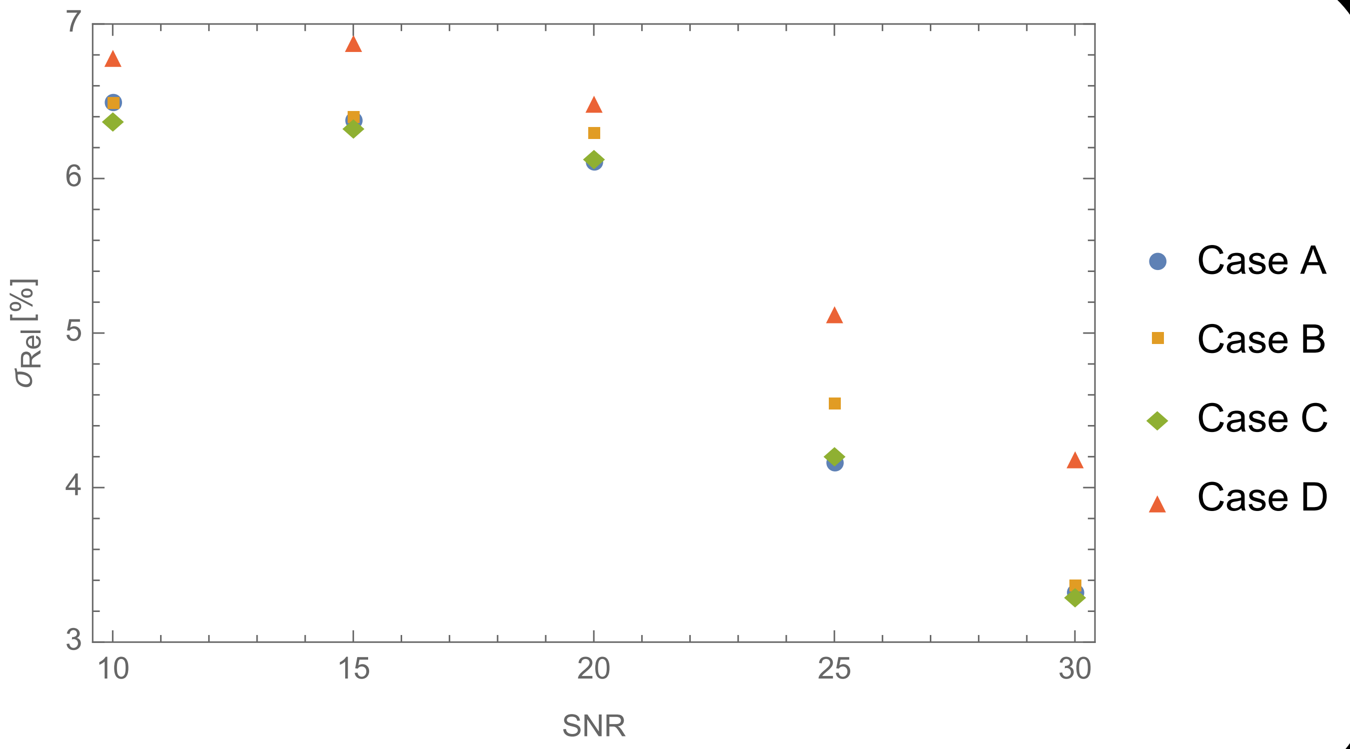



Predictivity Test: We are able to reconstruct an injected NS

Comparison between our results (those in previous slides) and results from observation of two qLMXBs

# More Results…




**Accuracy as a function of SNR for different choice of parameters**

- Cases A and B have $E_{\gamma,ISO} = 10^{50}\, erg$
- Cases C and D have $E_{\gamma,ISO} = 5 \times 10^{51}\, erg$
- Cases A and C have a flat prior in the beaming angle in the range [1°, 20°]
- Cases B and D have a flat prior in the cos of beaming angle in the range [cos(30°), cos(1°)]

Higher energy translates in higher degeneracy between parameters

# Rates

| Epoch | Run Duration | BNS Range (Mpc) | | Number of NSBH Detections | Number of GW–GRB Detections | | |
|---|---|---|---|---|---|---|---|
| | | LIGO | Virgo | | All Sky | *Fermi* GBM | *Swift* BAT |
| 2015 | 3 months | 70–130 | ⋯ | 0.0001–1 | $3 \times 10^{-4}$–0.06 | $2 \times 10^{-4}$–0.03 | $4 \times 10^{-5}$–0.007 |
| 2016–17 | 6 months | 130–200 | 30–100 | 0.002–10 | 0.005–0.5 | 0.003–0.3 | $7 \times 10^{-4}$–0.07 |
| 2017–18 | 9 months | 200–280 | 100–140 | 0.01–40 | 0.03–2 | 0.02–1 | 0.004–0.3 |
| 2019+ | (per year) | 330 | 110–220 | 0.05–100 | 0.2–6 | 0.1–2 | 0.02–0.5 |
| 2022+ | (per year) | 330 | 220 | 0.1–200 | 0.4–10 | 0.2–3 | 0.03–0.7 |

**ET**

$z_{max,NSBH} \simeq 4$ (ET design study http://www.et-gw.eu/etdsdocument )

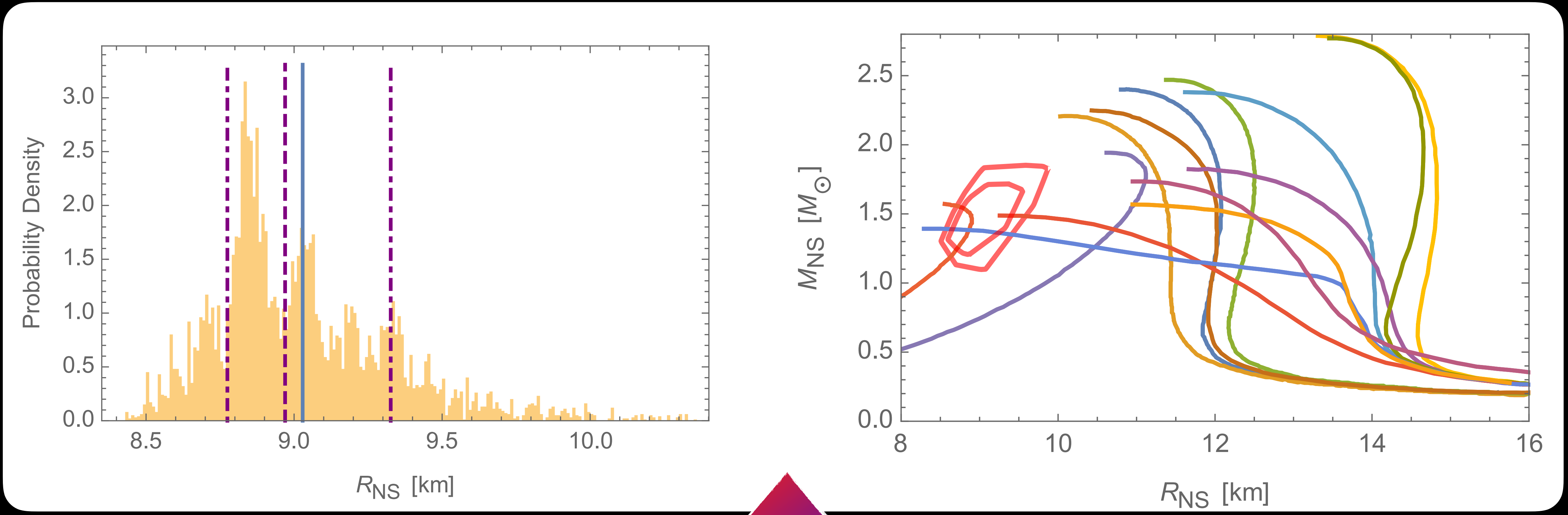
| Source | BNS | NS-BH | BBH |
|---|---|---|---|
| Rate (Mpc$^{-1}$ Myr$^{-1}$) | 0.1–6 | 0.01–0.3 | $2 \times 10^{-3}$–0.04 |
| Event Rate (yr$^{-1}$) in aLIGO | 0.4–400 | 0.2–300 | 2–4000 |
| Event Rate (yr$^{-1}$) in ET | $\mathcal{O}(10^3$–$10^7)$ | $\mathcal{O}(10^3$–$10^7)$ | $\mathcal{O}(10^4$–$10^8)$ |

# More Results…

A case with higher BH spin…

$m_1 = 4.84\, M_\odot \quad \chi_1 = 0.80$

$m_2 = 1.35\, M_\odot \quad z = 0.03$




Different GW parameters allows to probe different regions in the mass-radius plane !