Future Science from Gamma-ray Observations of Neutron Star Mergers

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and

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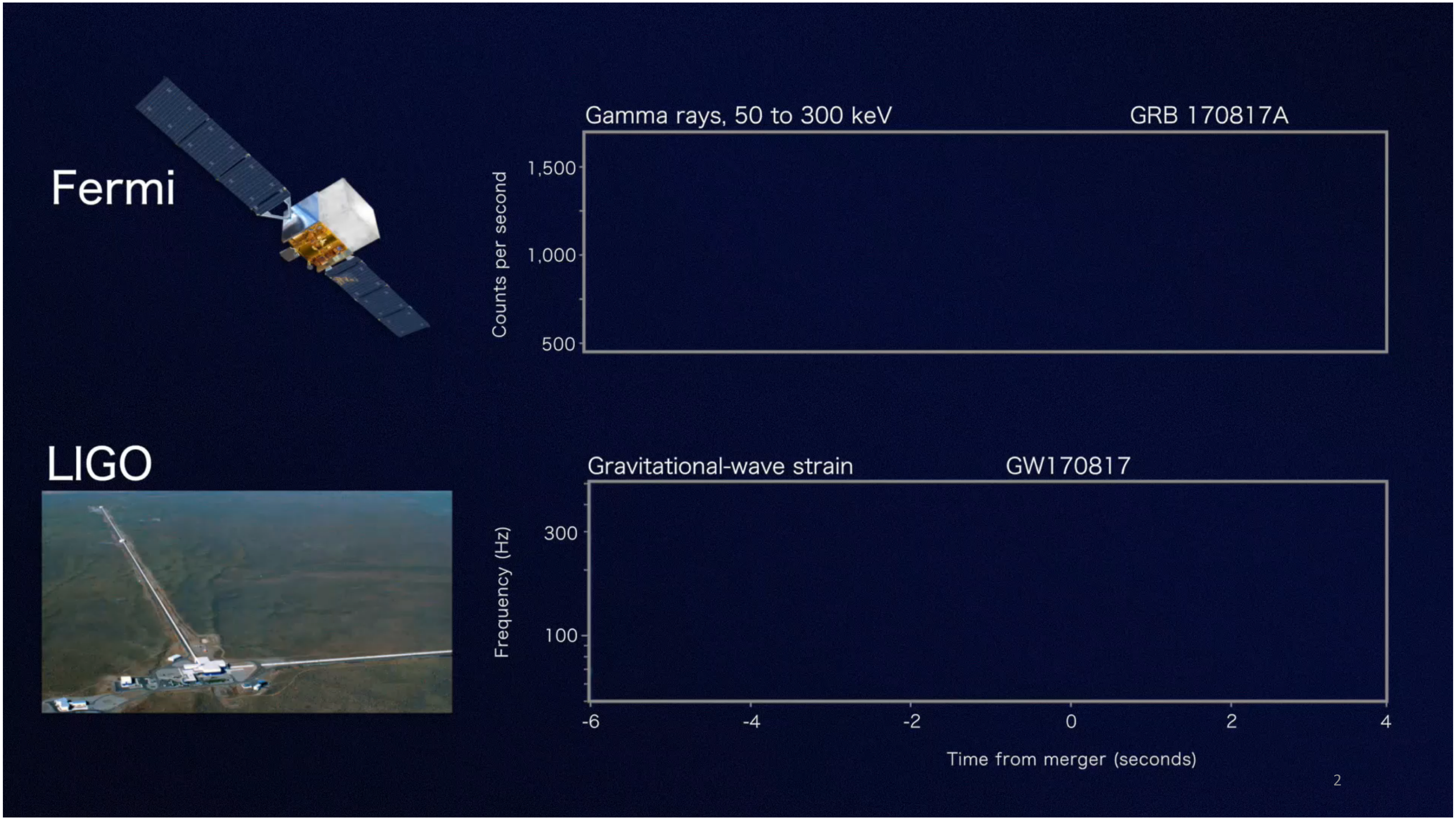
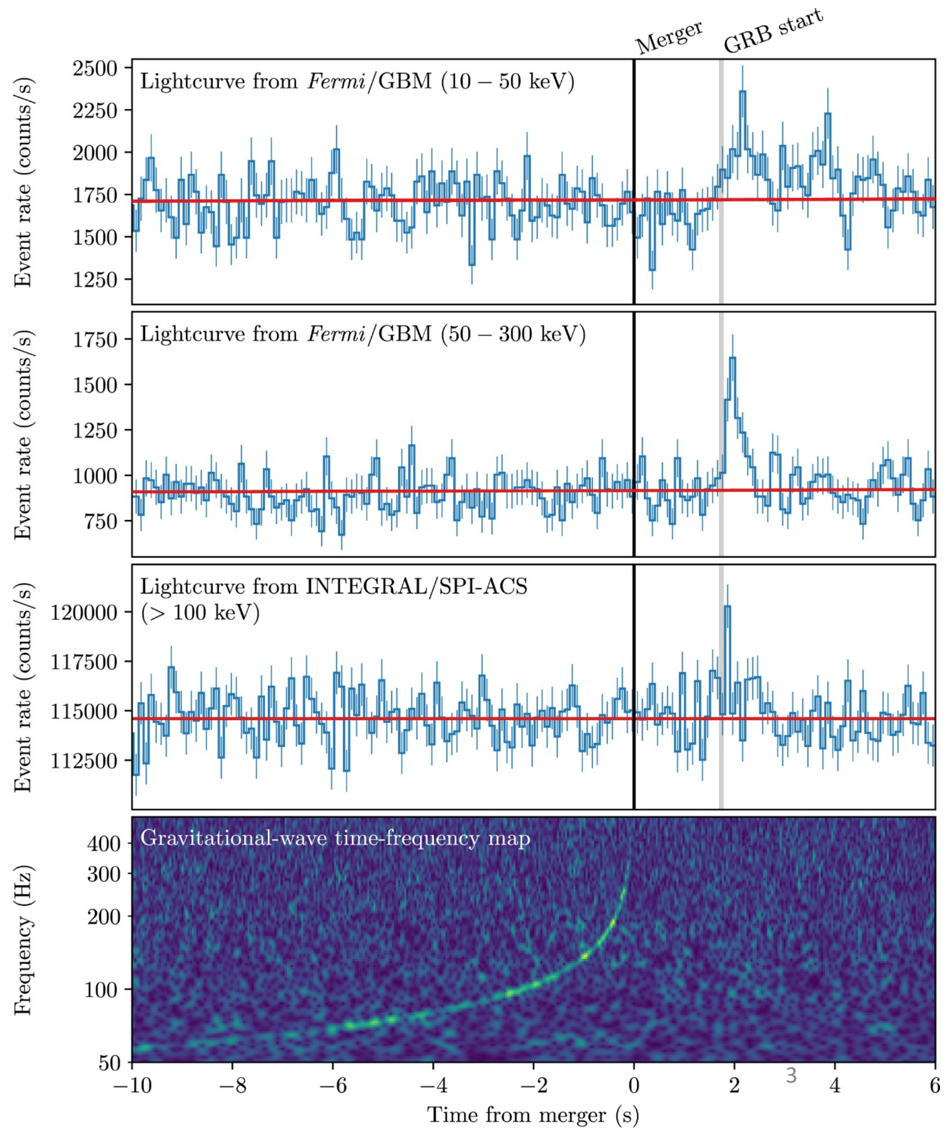

Fermi
Gamma rays, 50 to 300 keV
GRB 170817A
Counts per second
1,500
1,000
500
LIGO
Gravitational-wave strain
GW170817
Frequency (Hz)
300
100
-6
-4
-2
0
2
4
Time from merger (seconds)

1.7 Seconds

$\Delta t \equiv \Delta t_{EM} - \Delta t_{GW}$



$\Delta t_{total} =$

$$\Delta t_{\text{total}} = \Delta t_{\text{collapse}} + \ldots$$

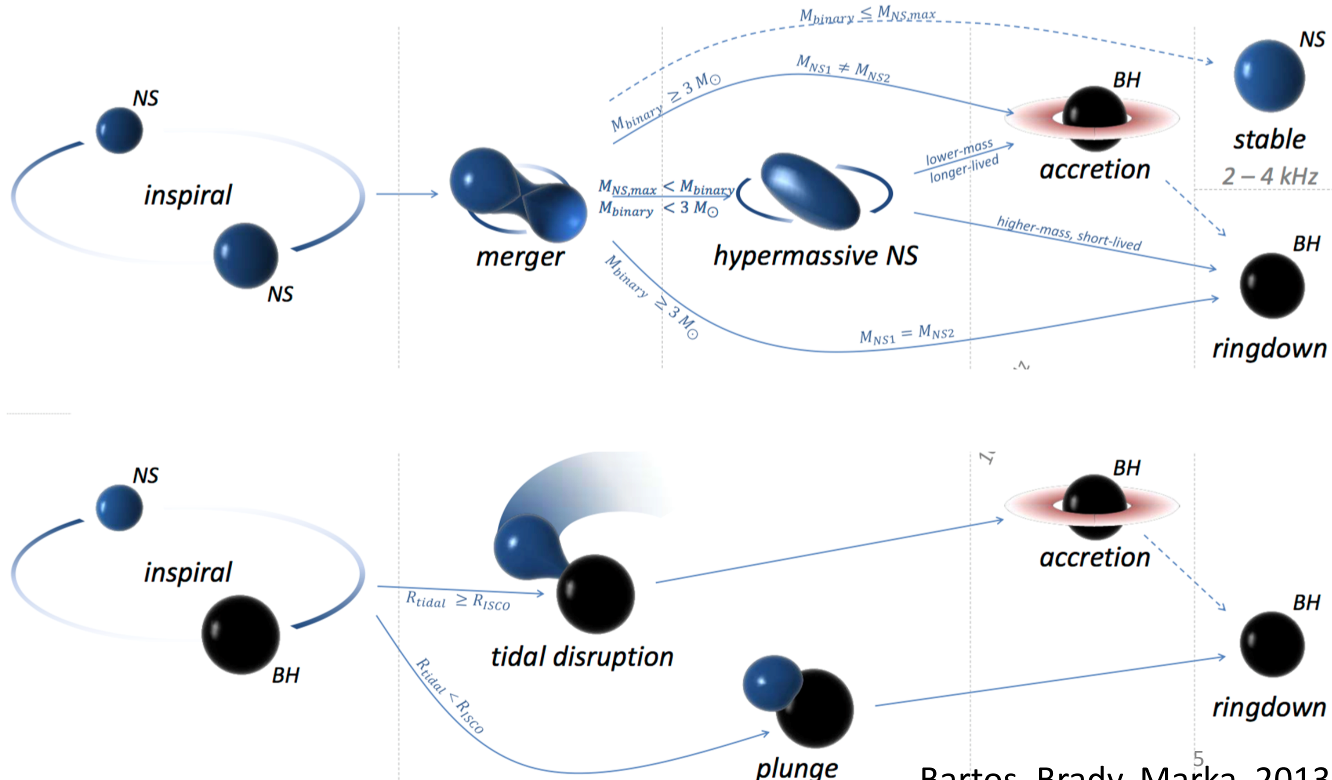
$\Delta t_{\text{collapse}} \equiv$ Time for the merging objects to collapse to a black hole

$$\Delta t^{prompt}_{\text{collapse}} = 0$$

$$\Delta t^{HMNS}_{\text{collapse}} \lesssim 1\ \text{s}$$

$$\Delta t^{SMNS}_{\text{collapse}} \lesssim 100\ \text{s}$$

$$\Delta t^{NS}_{\text{collapse}} = \infty$$



Bartos, Brady, Marka 2013

$$\Delta t_{total} = \Delta t_{collapse} + \Delta t_{jet\ formation} + \ldots$$

$\Delta t_{jet\ formation}$ ≡ Time for jet to form at the poles of the central engine

$$\Delta t_{total} = \Delta t_{collapse} + \Delta t_{jet\ formation} + \Delta t_{breakout} + \ldots$$

$\Delta t_{breakout}$ ≡ Time for the jet to break out of the previously ejected material

Inferred from Stefan–Boltzmann law

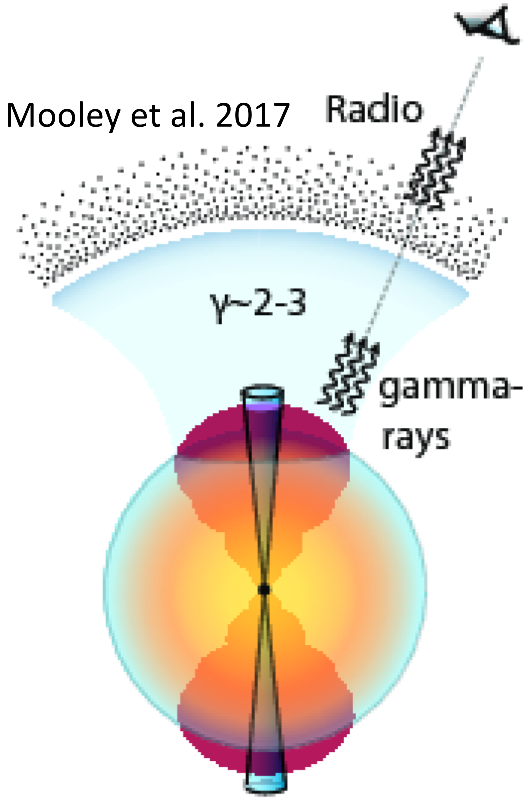
Nakar and Sari (2012)

$$\Delta t_{breakout} = \left(\frac{R}{1.4x109cm}\right)\left(\frac{10\ keV}{T}\right)^{2}$$

GRB Observable

If the prompt gamma-rays originate from cocoon emission, we can constrain the fraction of $\Delta t_{EM\text{-}GW}$ due to $\Delta t_{breakout}$

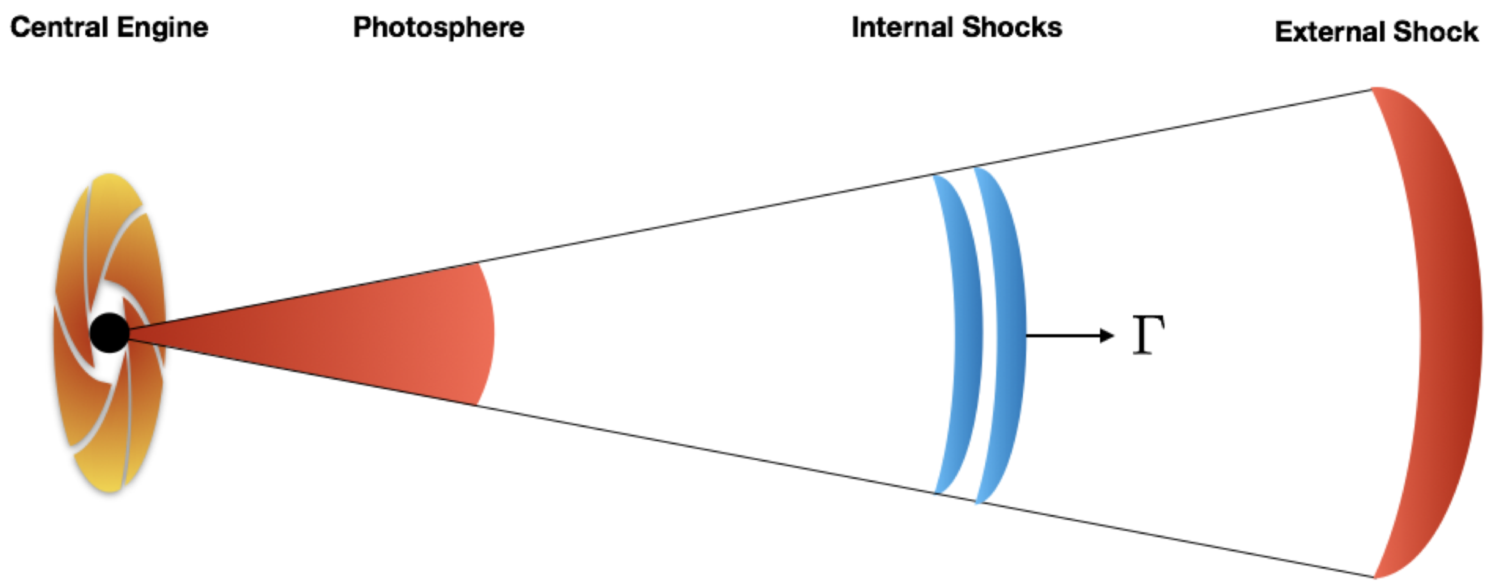
Mooley et al. 2017



E. Successful hidden Jet
Cocoon gamma-rays
and afterglow

$$\Delta t_{total} = \Delta t_{collapse} + \Delta t_{jet\ formation} + \Delta t_{breakout} + \Delta t_{\Gamma}$$

$\Delta t_{\Gamma} \equiv$ Time for jet propagation before the prompt gamma-ray emission and escape (regardless of mechanism)



$$\Delta t_{total} = (\Delta t_{collapse} + \Delta t_{jet\ formation} + \Delta t_{breakout} + \Delta t_{\Gamma}) + \ldots$$

Negligible for high Γ SGRBs

Negligible for NSBH Mergers

Infer from GW-GRB observables

Infer from GRB and kilonovae observables; eventually direct measurement from GW

Constrain from face-on NSBH Merger

Unique GW-GRB Observations, with partners, will enable us to delineate the time delay due to each of these components

$$\Delta t_{total} = \Delta t_{intrinsic} * (1+z) + \Delta t_{massive} + \ldots$$

$\Delta t_{massive} \equiv$ Propagation delay due to massive photon/graviton

$$= \frac{D}{c}\frac{(mc^2)^2}{2E^2} = 0$$

$m_g \leq 7.7 \times 10^{-23}\ \mathrm{eV/c^2}$

LIGO/Virgo Observations of GW170104

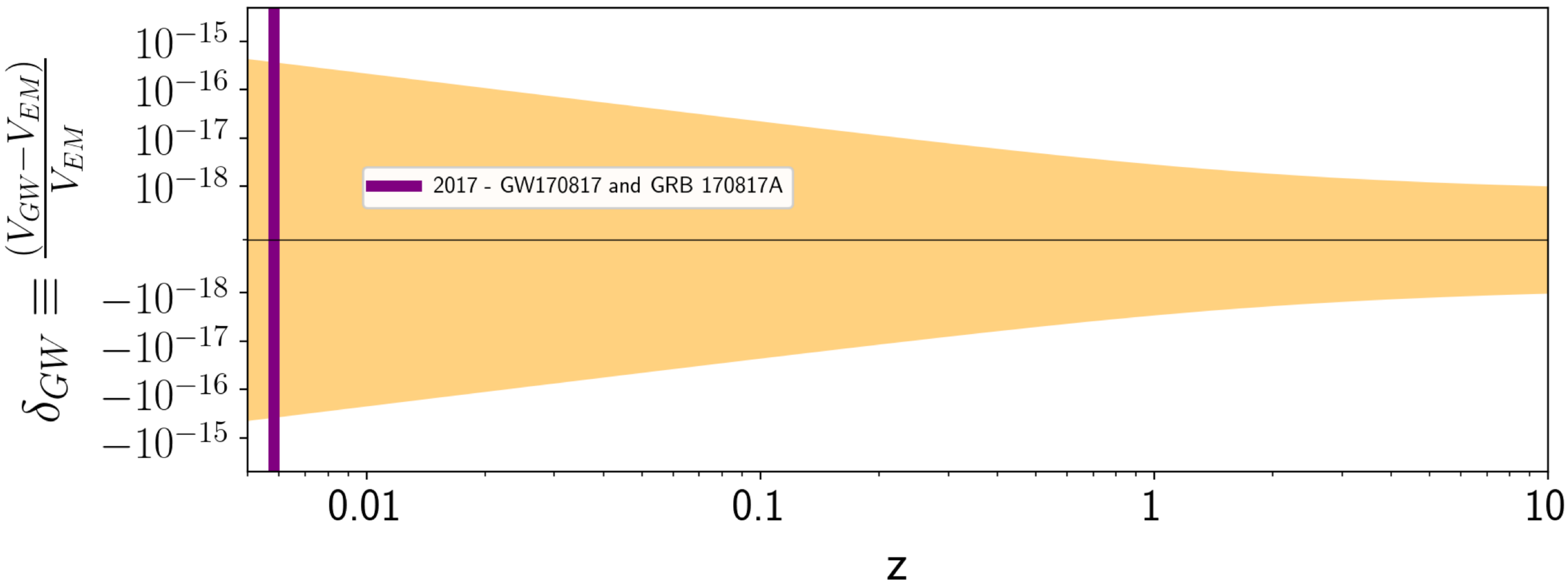
$m_\gamma \leq 10^{-18}\ \mathrm{eV/c^2}$

Particle Data Group

$\Delta t_{total} = \Delta t_{intrinsic} * (1+z)$
$+ \Delta t_{massive} + \Delta t_{VGW} + \ldots$

$\delta_{GW} \approx c \frac{\Delta t}{D}$

$\Delta t_{VGW} \equiv$ Relative propagation delay if $V_{GW} \neq V_{EM}$



Current: $|\delta_{GW}| \leq 10^{-15}$

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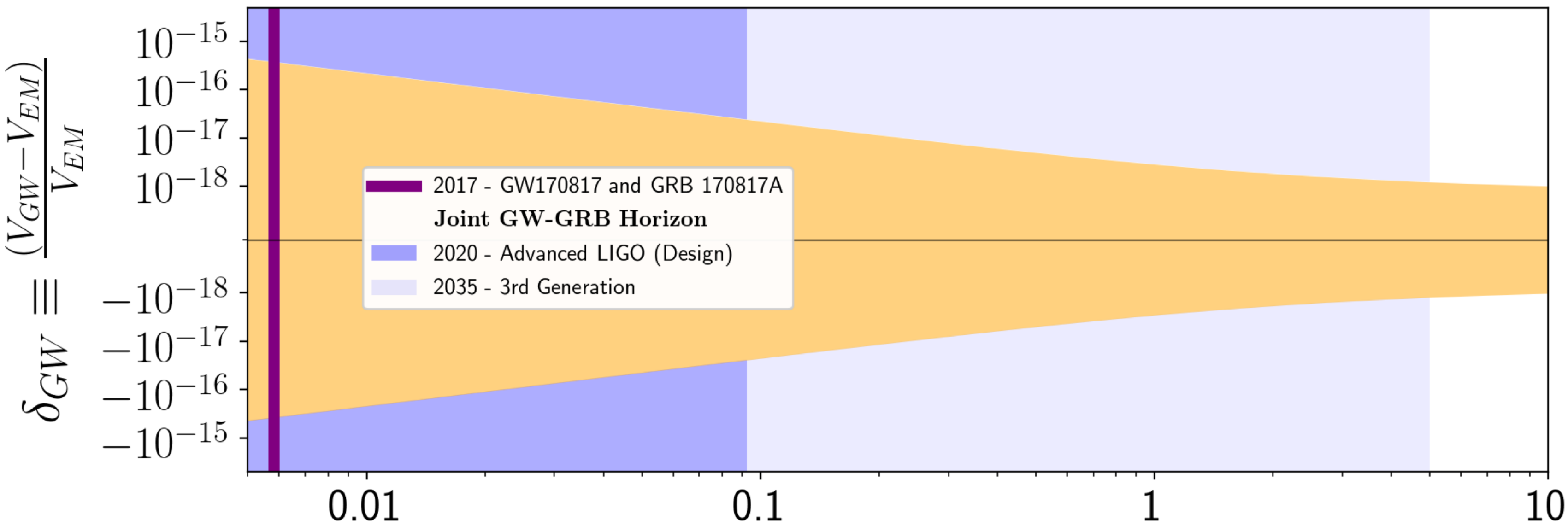


Current: $|\delta_{GW}| \leq 10^{-15}$
Advanced LIGO Design: $|\delta_{GW}| \leq 10^{-16}$

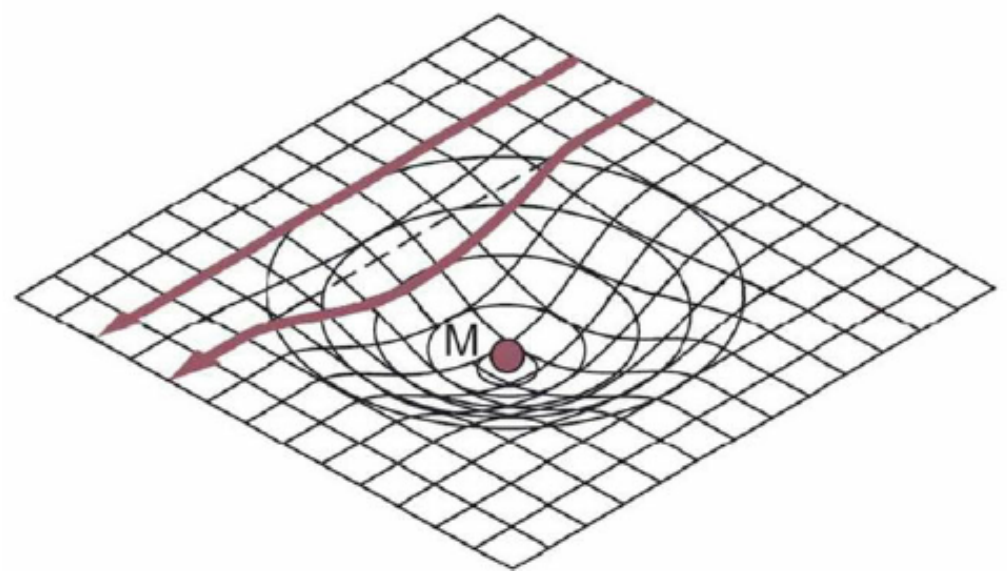
Ultimate: $|\delta_{GW}| \leq 10^{-18}$

$\Delta t_{total} = \Delta t_{intrinsic} * (1+z)$
$+ \Delta t_{massive} + \Delta t_{VGW} + \Delta t_{Shapiro} + \ldots$

$\Delta t_{Shapiro}$ ≡Relative propagation delay due to gravitational potentials

$$\delta t_S = -\frac{1+\gamma}{c^3}\int_{\mathbf{r}_e}^{\mathbf{r}_o} U(\mathbf{r}(l))dl$$

δt_S = Shapiro delay using the same time bounds
$\mathbf{r}_o$ = observation positon, $\mathbf{r}_e$ = emission position
$U(\mathbf{r})$ = gravitational potential (here the Milky Way's)
= wave path
γ = deviation from Einstein-Maxwell theory
(where γ_{EM} and γ_{GW} are both equal to 1)



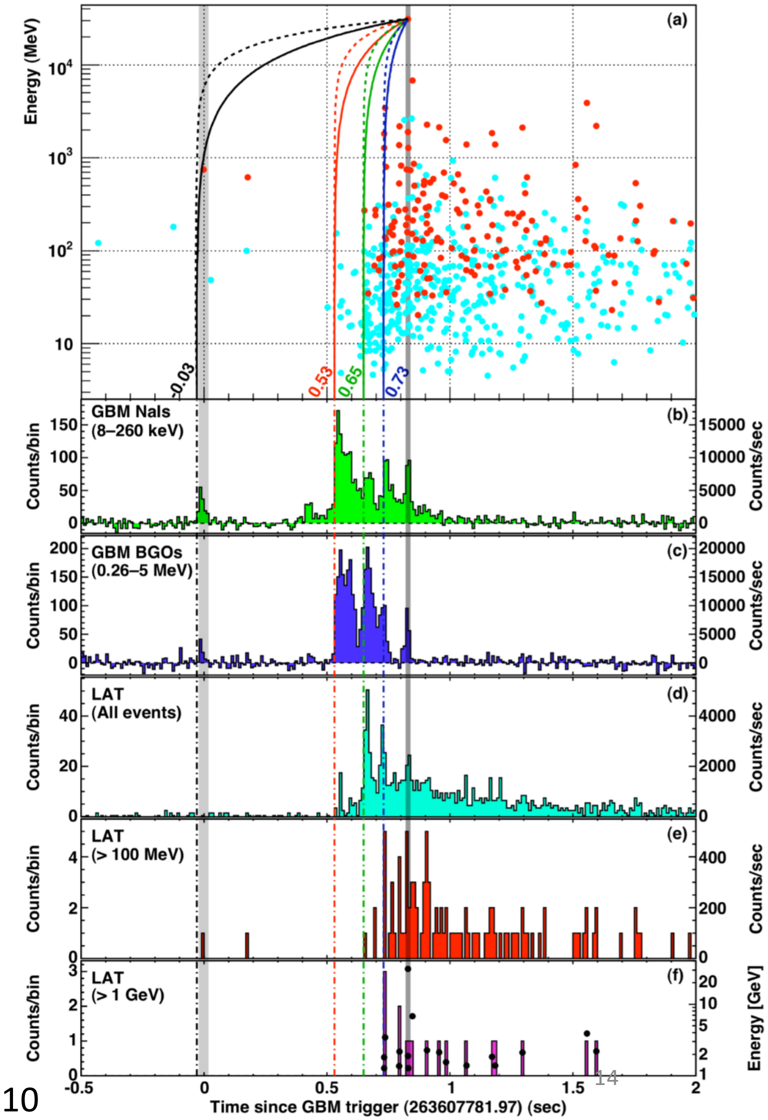
If gravity and light couple to different metrics they will have relative Shapiro delays.

$$\Delta t_{total} = \Delta t_{intrinsic} * (1+z) + \Delta t_{massive} + \Delta t_{VGW} + \Delta t_{Shapiro} + \Delta t_{LIV}$$

$\Delta t_{LIV} \equiv$ Relative propagation delay due to violation of Lorentz Invariance

- The best limits on Lorentz Invariance Violation come from Fermi (GBM+LAT) observations of the short GRB 090510

- This was likely from a neutron star merger



Fermi LIV paper on 090510

$$\Delta t_{total} = \Delta t_{intrinsic} * (1+z) + \Delta t_{massive} + \Delta t_{VGW} + \Delta t_{Shapiro} + \Delta t_{LIV}$$

$\Delta t_{massive}$: Goes as the distance; preexisting constraints

Δt_{VGW}: Goes as the distance

$\Delta t_{Shapiro}$: Goes with total intervening gravitational potential

Δt_{LIV}: Goes as distance and photon energy; preexisting constraints (from NS mergers)

We can disentangle intrinsic and relative propagation delays as $\Delta t_{intrinsic} * (1+z)$ will go as the redshift and relative propagation delays should not ($\propto$ distance, gravitational potential, photon energy)

$$\Delta t_{total} = (\Delta t_{collapse} + \Delta t_{jet\ formation} + \Delta t_{breakout} + \Delta t_{\Gamma}) * (1+z)$$

Equation of State of Supranuclear matter

How jets form

NS Merger Ejecta

Emission mechanism of GRBs

$$+ \Delta t_{massive} + \Delta t_{VGW} + \Delta t_{Shapiro} + \Delta t_{LIV}$$

Beyond GR, SM

Beyond GR

Beyond SR; Quantum Gravity

Fundamental Physics **Nuclear Physics** **Astroparticle Physics**

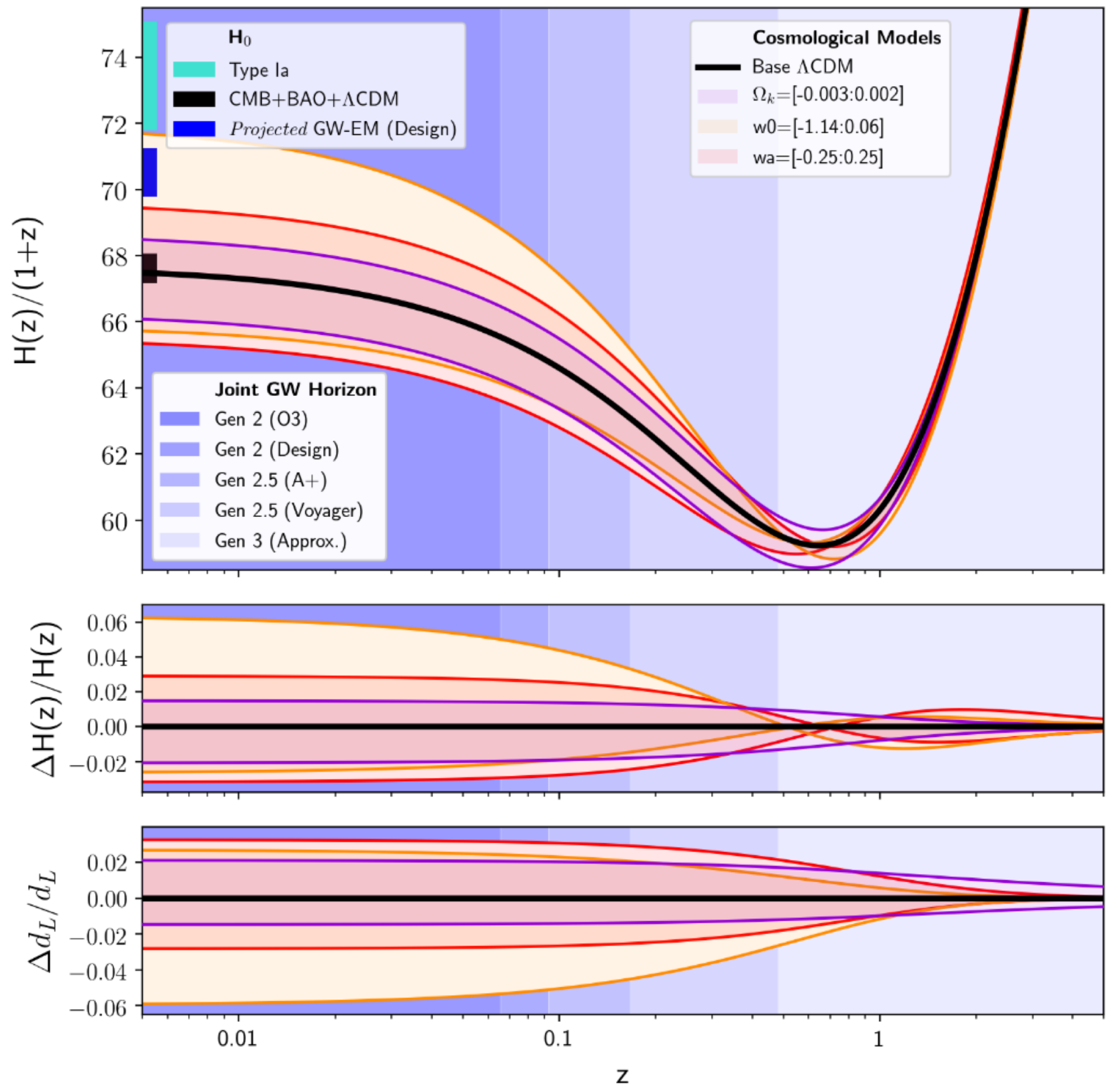
NS mergers involve the most extreme timescales, densities, and energetics in the universe.

Other Future NS Merger Science with Gamma-rays

- Cosmology - the best luminosity distance vs redshift measure possible
- The heavy element enrichment history of the universe
- The existence of NSBH mergers – a new stellar system type
- Ultrarelativistic jet composition
- The best understood astrophysical transient
- Kilonova remnants in the Milky Way

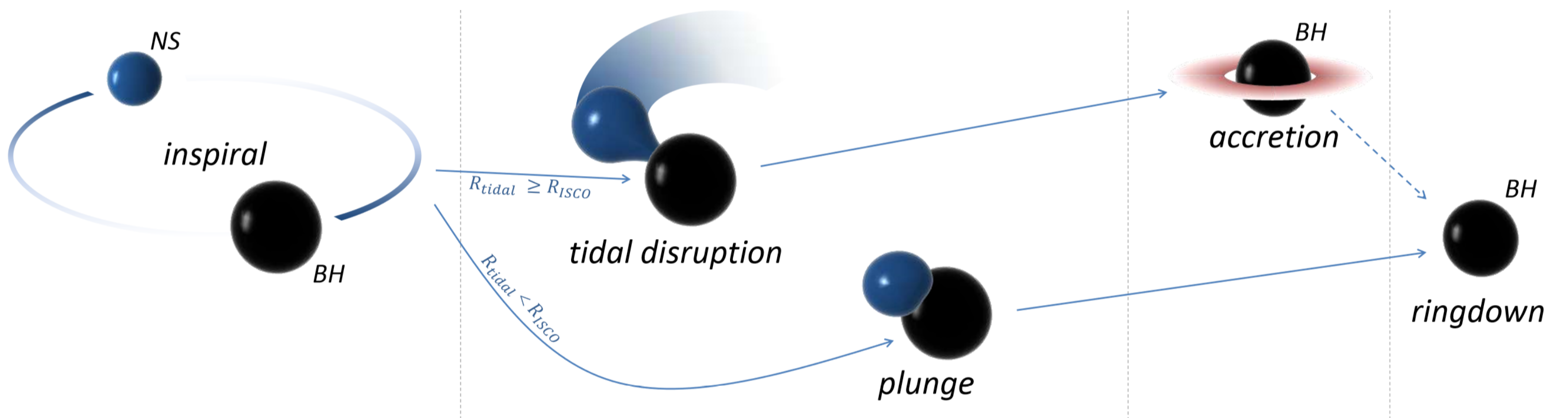
Extra Slides

Cosmology



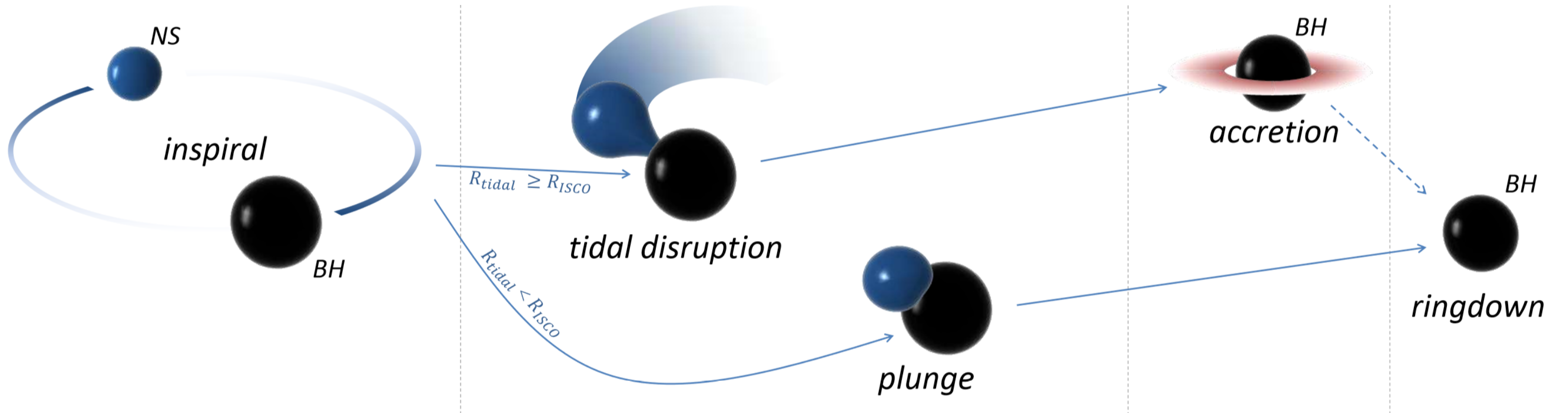
H$_0$
Type Ia
CMB+BAO+ΛCDM
Projected GW-EM (Design)
Cosmological Models
Base ΛCDM
Ω_k=[-0.003:0.002]
w0=[-1.14:0.06]
wa=[-0.25:0.25]
Joint GW Horizon
Gen 2 (O3)
Gen 2 (Design)
Gen 2.5 (A+)
Gen 2.5 (Voyager)
Gen 3 (Approx.)
H(z)/(1+z)
74
72
70
68
66
64
62
60
ΔH(z)/H(z)
0.06
0.04
0.02
0.00
−0.02
$\Delta d_L/d_L$
0.02
0.00
−0.02
−0.04
−0.06
0.01
0.1
1
z

The Existence of NSBH Systems



- NSBH Mergers have predicted observables
  - GW detections can constrain the mass and spin components
  - SGRB quasi-periodic oscillations
  - Only red kilonova with larger ejecta mass (~0.1 $M_{\odot}$)

The Existence of NSBH Systems



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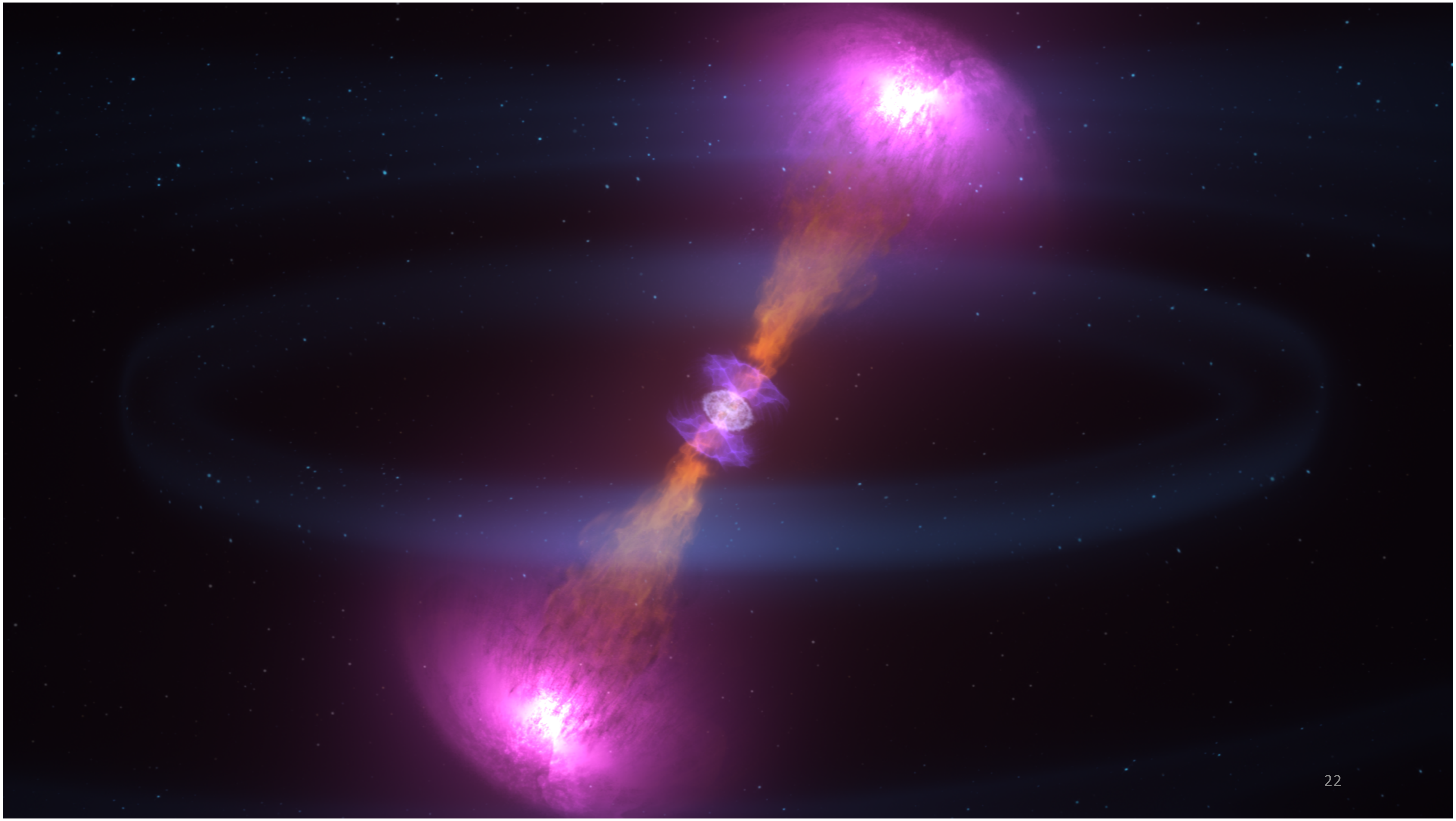
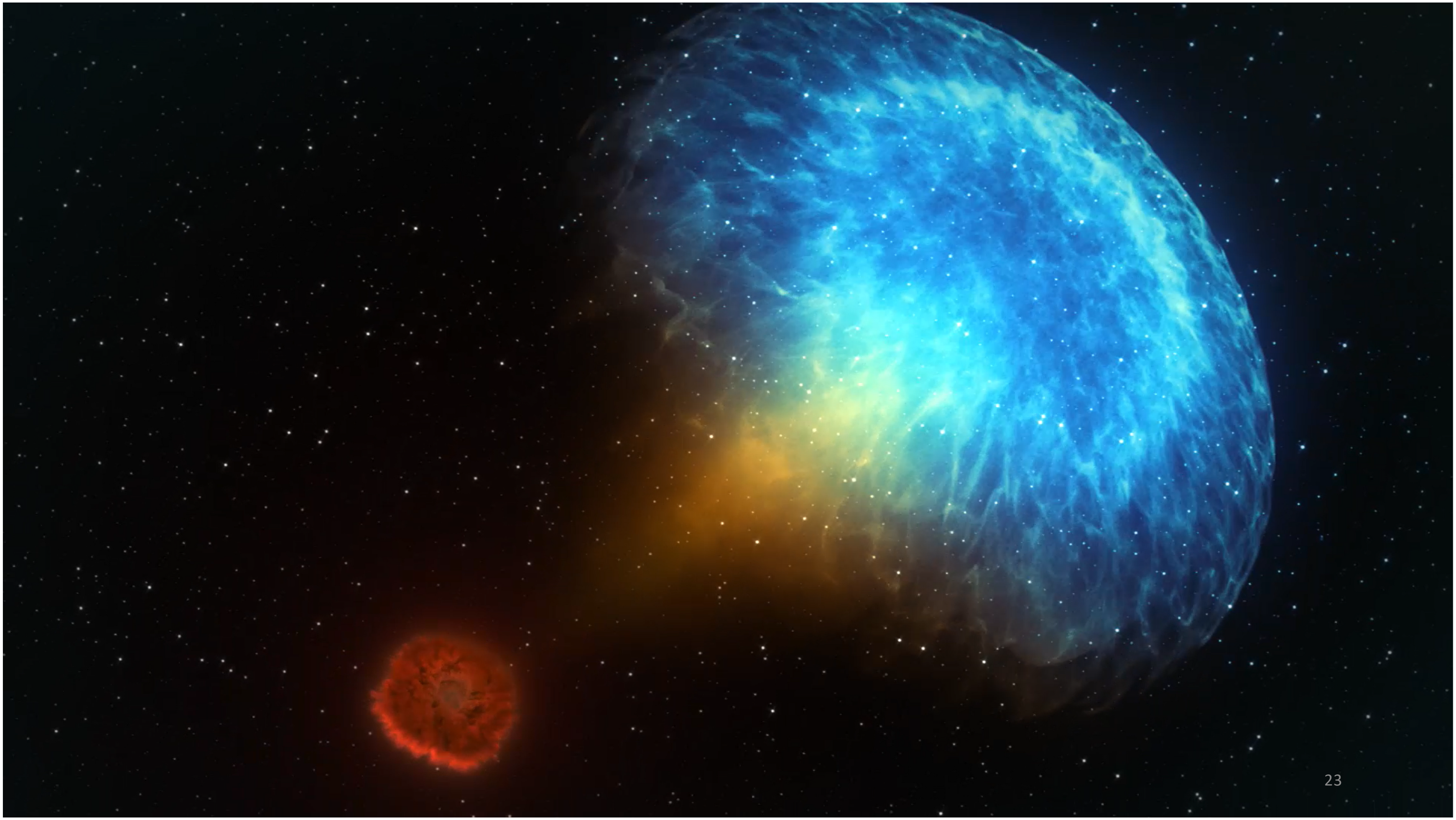
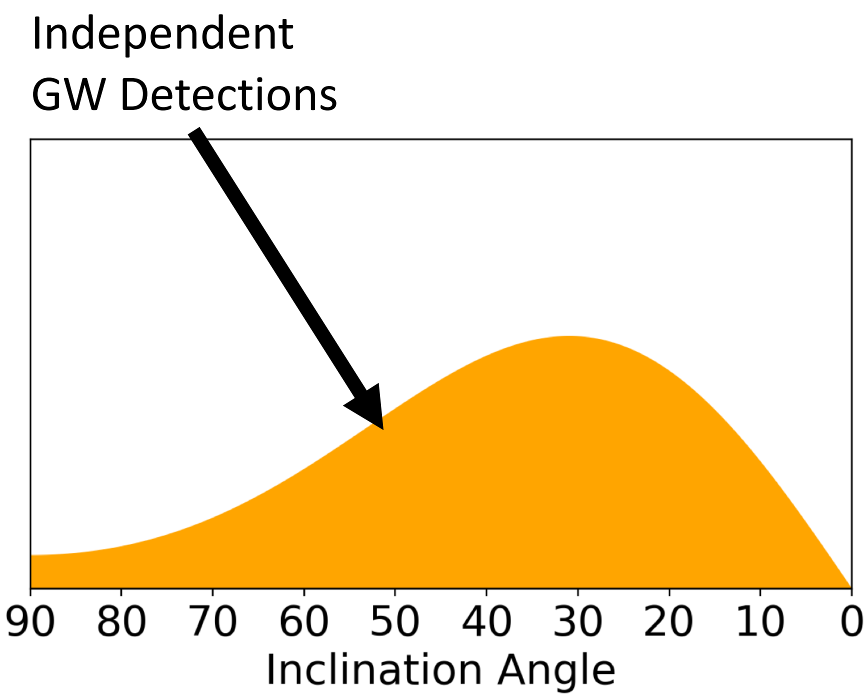
GW-EM observations can discover a new stellar systems



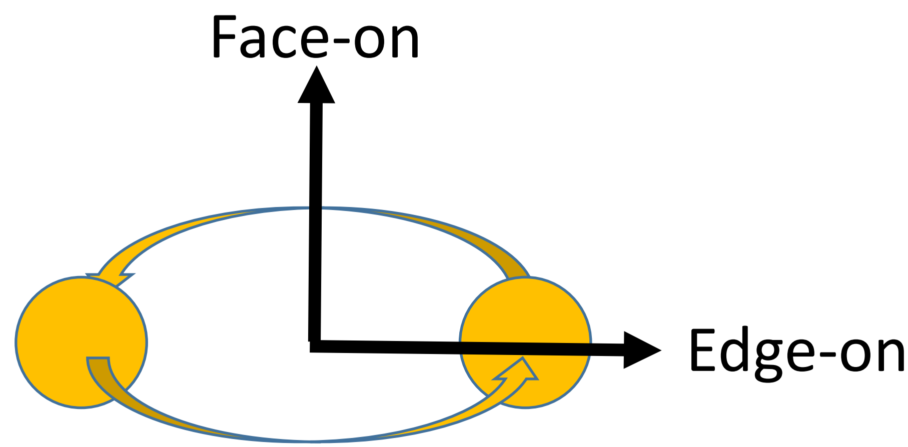


GW Detections

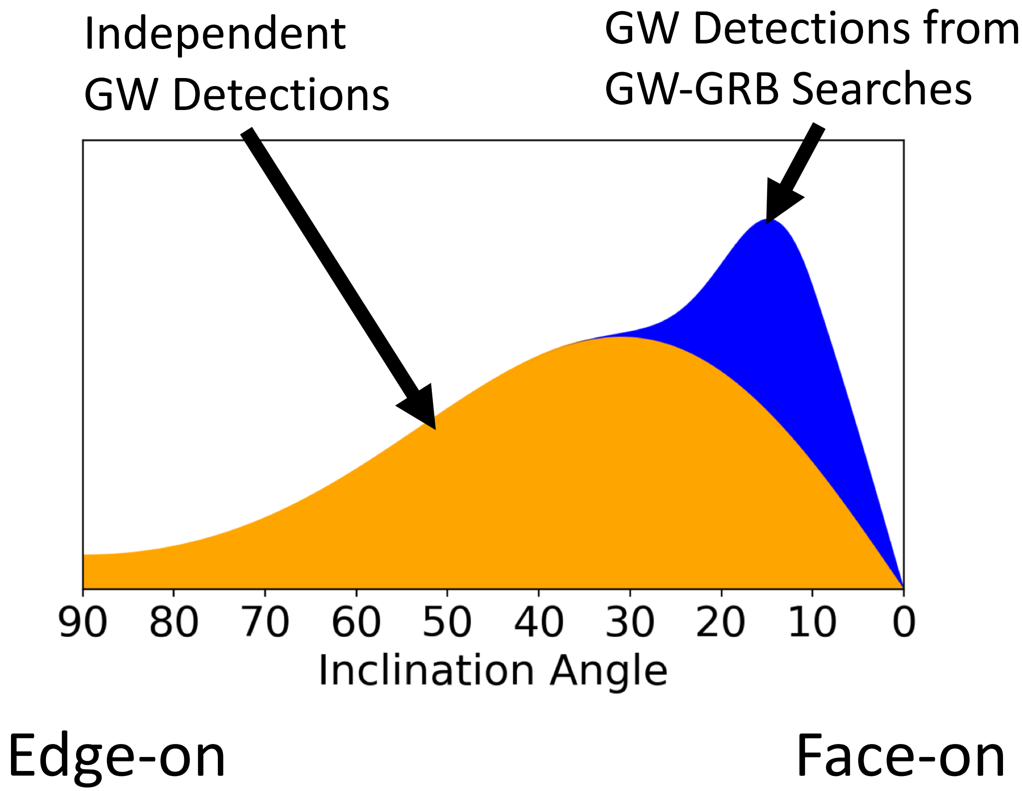


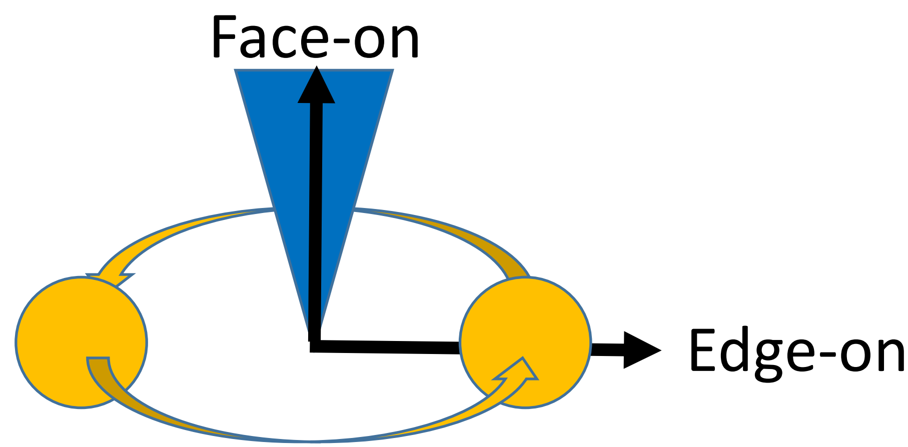
Edge-on

Face-on

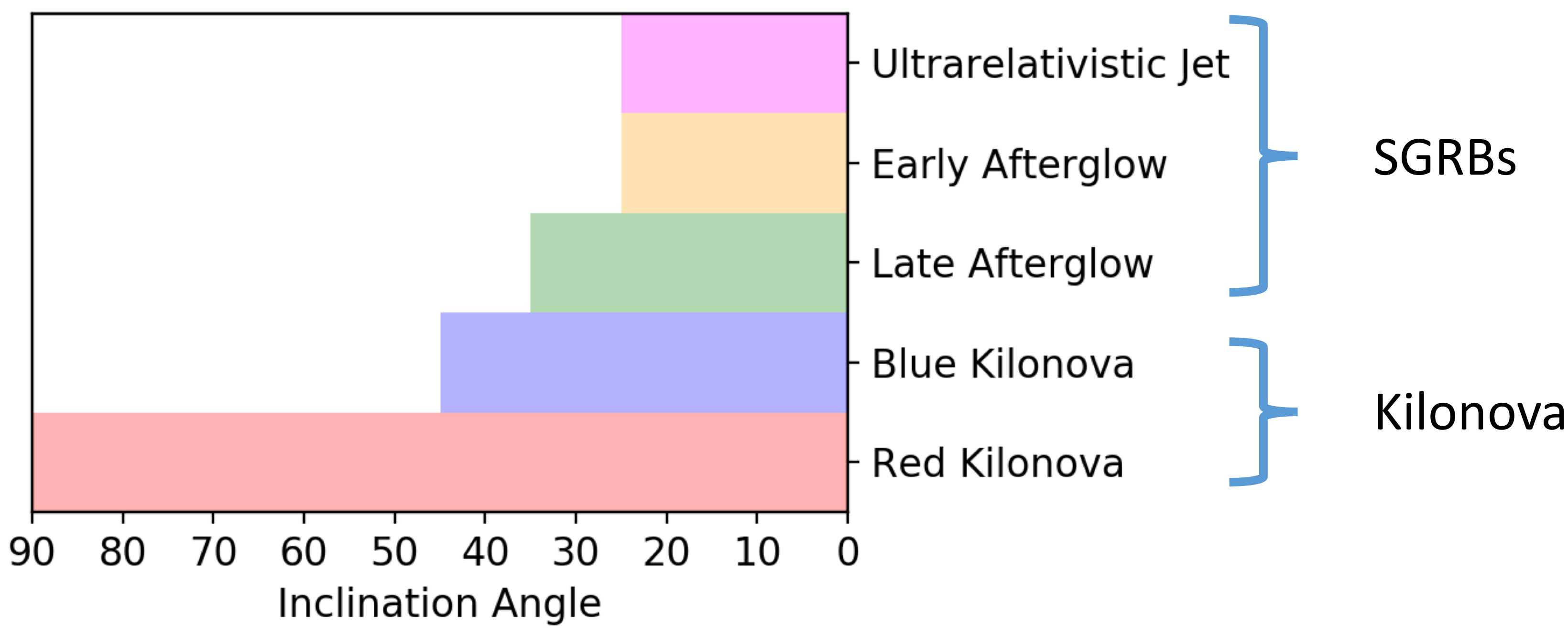


Additional GWs from Joint GW-GRB Searches





Electromagnetic Signals of NS Mergers



Electromagnetic Signals of NS Mergers