Orbitally-modulated electromagnetic counterparts to neutron-star mergers

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Classical high-energy counterpart to NS mergers

NS disruption

↓

Accretion disk

↓

Jet - Prompt emission

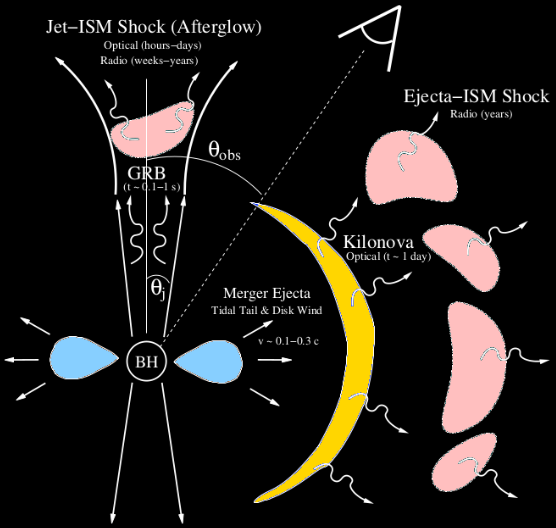
↓

Shock - Afterglow

Emission *at* or *after* the merger

↓

NS already gone



Metzger and Berger 2011

NS crust shattering model (Tsang et al 2012)

Periodic tidal stress during close inspiral

$\downarrow$

Resonance transfers orbital energy to NS crust-core mode

$\downarrow$

Mode energy builds up until the crust shatters

$\downarrow$

$\vec{B}$ lines are violently shaken

$\downarrow$

γ-ray emission *before* merger
(direct or via a pair-photon fireball)

Energy release: $[\sim 0.01, \sim 1] \times E_{\mathrm{SGRB}}$

Light curve? Spectrum? Time scale? ...

Negligible effect on GW phase

Resonance frequency depends strongly on NS EoS

"BH battery" model (D'Orazio et al 2016)

Highly-magnetized NS inspirals into $\sim 10 M_{\odot}$ BH

$\downarrow$

BH "short-circuits" $\vec{B}$ lines

$\downarrow$

Charge acceleration along $\vec{B}$

$\downarrow$

Emission of curvature radiation

$\downarrow$

$\gamma + \vec{B} \rightarrow$ Pair-photon fireball

Common features of precursor flares

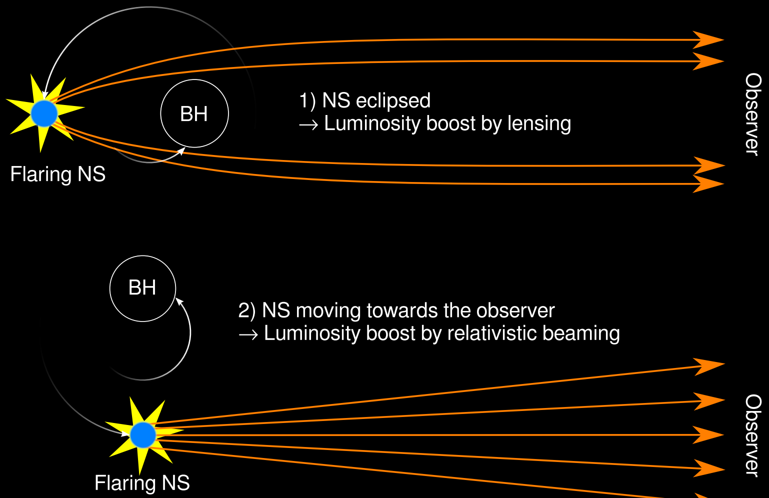
- Precede the merger by ~ 0.1 s to ~ 100 s
  - Complicates the EM-GW association
  - NS still intact and inspiraling
- *Not* beamed
- Emission may be close to the NS surface

Challenges

- Pair-photon fireball
- Modeling of time scales, light curve, spectra

How do we detect and recognize such flares as CBC counterparts?
How do the companion and/or orbital motion affect the signal?

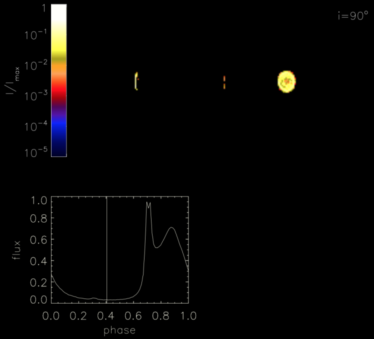
Flare modulation from orbital motion



Full raytracing simulation

Launch and track photons in an analytical two-puncture spacetime

$$m_1 = 10M_\odot,\ m_2 = 1.4M_\odot,\ \iota = 90\ \mathrm{deg}$$



Simulation by J Schnittman and B Kelly - arXiv:1704.07886

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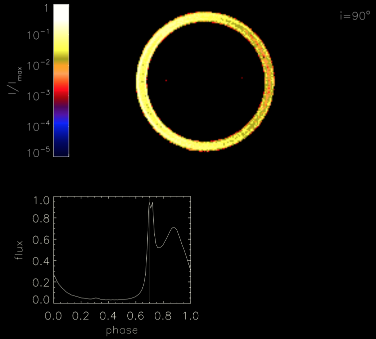

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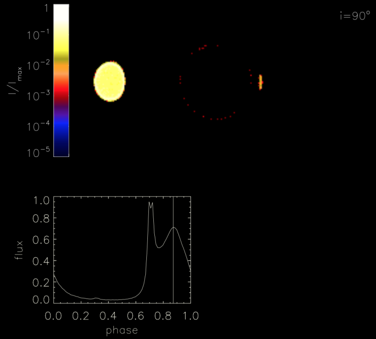

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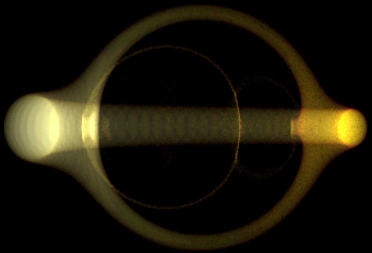

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Analytical model

1) Newtonian inspiral $\rightarrow$ Orbital position and velocity over time

2) Flux magnification due to relativistic beaming F_{beam}

3) Flux magnification due to gravitational lensing F_{lens}

4) Observed flux: lensing time scale is smaller, so let's just multiply

$$\mathcal{I}_{\mathrm{obs}} = F_{\mathrm{beam}} \, F_{\mathrm{lens}} \, \mathcal{I}_{\mathrm{emi}}$$

5) Emitted flux $\leftarrow$ Big assumptions!

Analytical model

Relativistic beaming:

- NS $\rightarrow$ point source in circular motion
- Emitted spectrum $\rightarrow$ power law $S(\nu) \sim \nu^{\alpha}$
- Time dilation, aberration, redshift $\rightarrow$ Doppler factor

$$F_{\mathrm{beam}} = \left[\left(1 - \frac{v^2}{c^2}\right)^{1/2} \left(1 - \frac{\vec{v} \cdot \vec{n}}{c}\right)^{-1} \right]^{3-\alpha}$$

$\vec{n}$: unit vector to observer, $\vec{v}$: NS velocity

Analytical model

Gravitational lensing:

- BH $\rightarrow$ point lens
- NS $\rightarrow$ point source
- Compute standard microlensing magnification

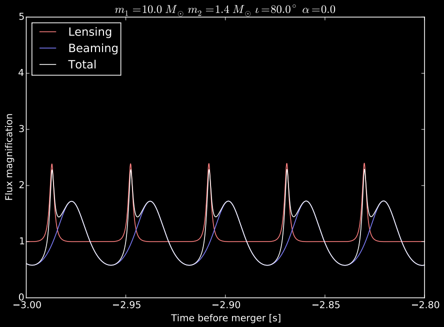
$$F_{\mathrm{lens}} = \frac{u^2+2}{u(u^2+4)^{1/2}}, \quad u = \frac{1}{2}\left(\frac{d}{r_1}\right)^{1/2} \frac{\sin\varphi}{(\cos\varphi)^{1/2}}$$

$\vec{d}$: orbital separation, r_1: BH gravitational radius, φ: $\vec{d}\angle\vec{n}$

Perfect alignment $\rightarrow$ Singularity!
$\rightarrow$ Assume Einstein ring is the upper limit

Analytical model

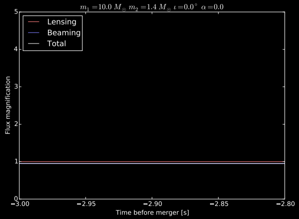
NSBH system with $m_1 = 10M_\odot$, $m_2 = 1.4M_\odot$



"Electromagnetic chirp"

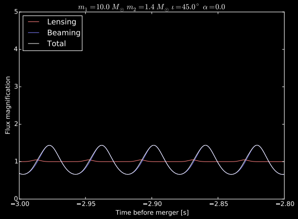
Analytical model: varying the inclination

Face-on



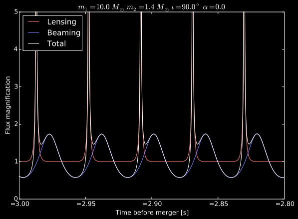
No modulation

45 deg



Beaming dominates

Edge-on

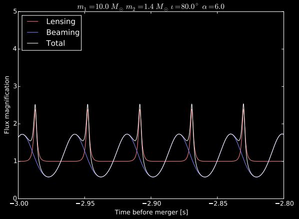


Max lensing

Analytical model: varying the spectral index

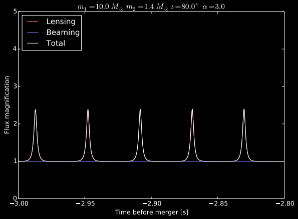
$$S(\nu) \sim \nu^{\alpha}$$

$\alpha > 3$



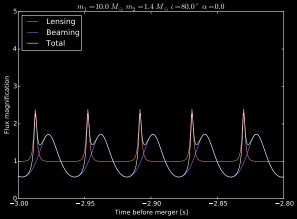
Beaming leads

$\alpha = 3$



No beaming

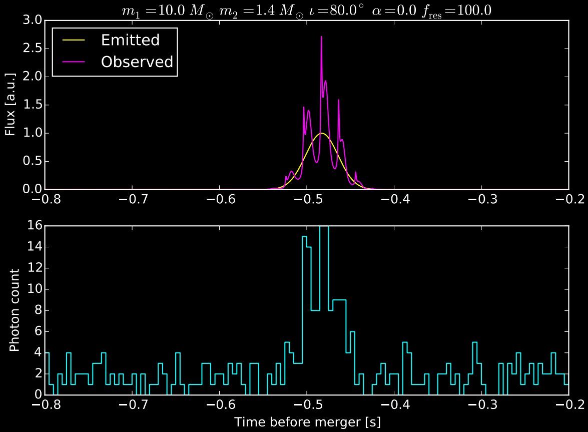
$\alpha < 3$



Beaming follows

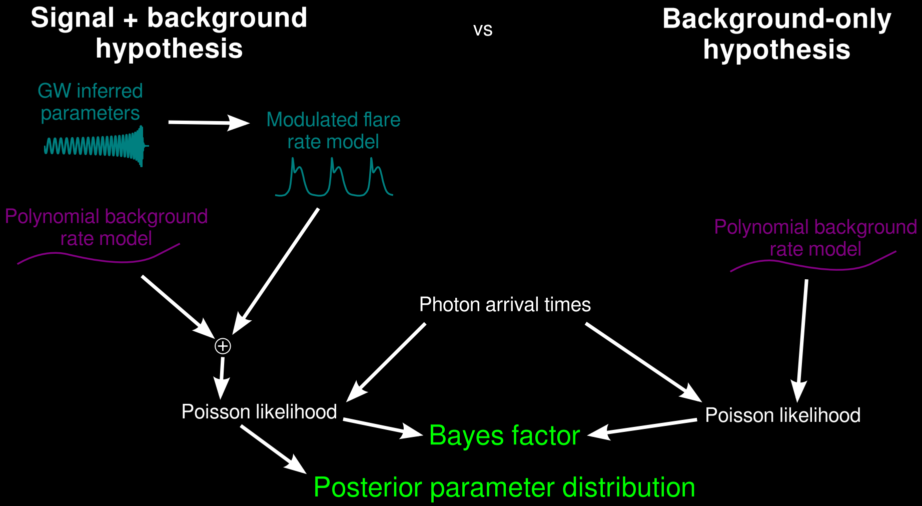
Analytical model: adding the flare

Flare parameters from Tsang et al 2012



Need detector with ~ 1 ms timing!

Analyzing simulated photon data



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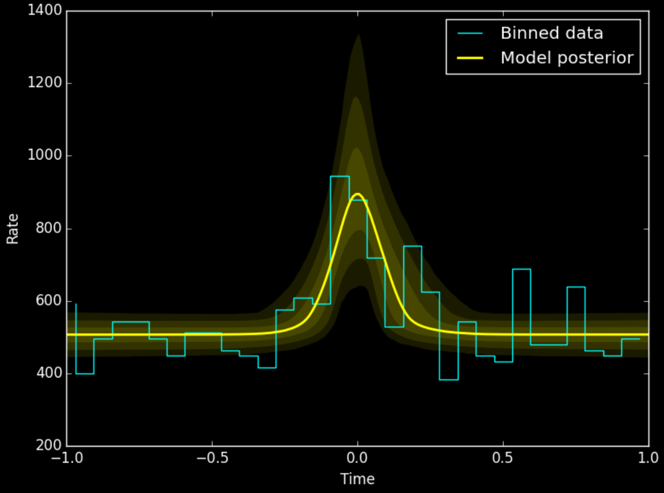

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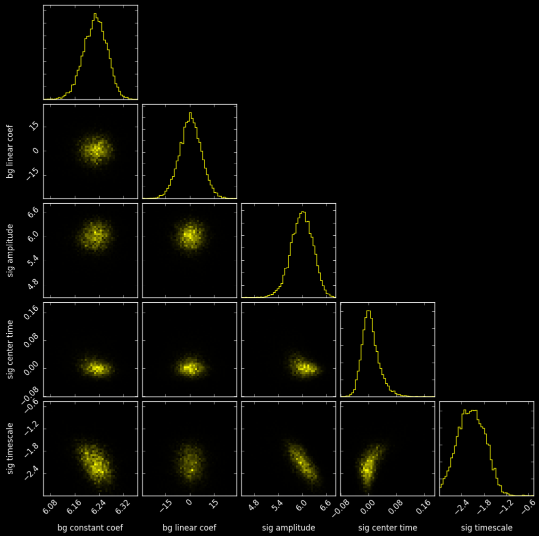


Suitable γ-ray telescope: Fermi/GBM

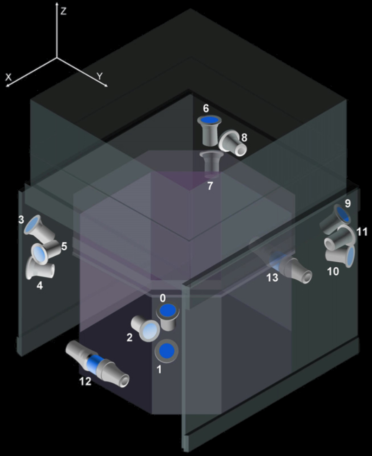
Timing sufficient to resolve the modulation (2 μs)

Wide FOV - 70% of the sky

Sky localization to several degrees for best cases

Complicated background from many sources

Already being used for GW followup



Meegan et al 2009

Targeted Fermi/GBM followup (Blackburn et al 2015)

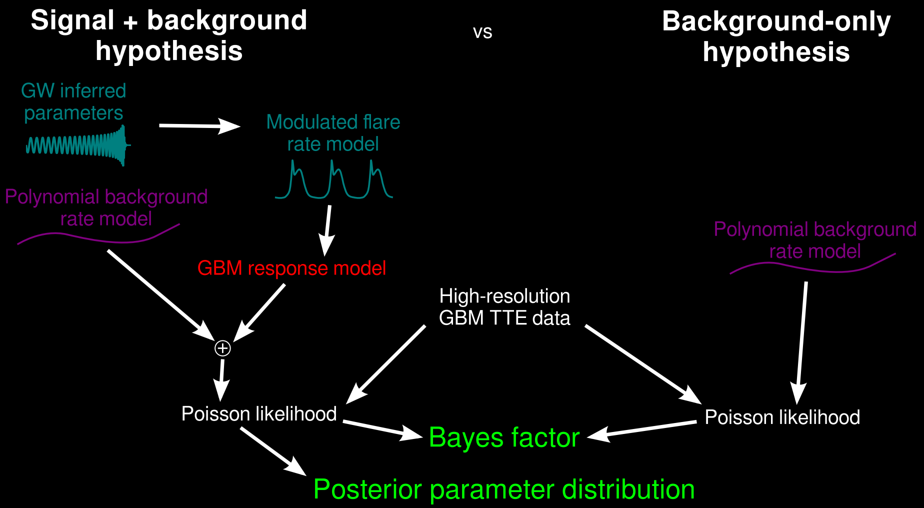
See talk by Adam Goldstein

- Following up GW triggers since 2015
- Detects γ bursts regardless of time structure
- Not designed for $\sim$ ms time resolution
- Significance of GW-γ association decreases with $|\Delta t|$

Want to further target orbitally-modulated precursors

- Use light curve model to increase sensitivity
- Reject transients with incompatible light curves
- Infer parameters of flare
- Big assumptions needed

Extending the Fermi/GBM followup: idea



Extending the Fermi/GBM followup: challenges

Computational cost

Large parameter space (~ 10)
Calculation of CBC GW waveform required
$\sim 10^4$ photons/s, each requiring several operations *per waveform*
Expected cost comparable to LIGO CBC parameter estimation

Model

Flare spectrum
Flare light curve in the NS frame
GBM response
More complicated inspiral dynamics, spins etc

Summary

Precursor counterparts to GW events could have a chirpy modulation

Unambiguous association to GW signal
Reduce degeneracies
NS structure
Constrain $\Delta\phi$ or Δt

Implementing Fermi/GBM followup of GW events

Deep search for weak flares
Characterization of strong (triggered) flares
Applicable to other light curve models (e.g. prompt emission)
Plan to follow up LIGO CBC triggers compatible with NSs

Thank you!