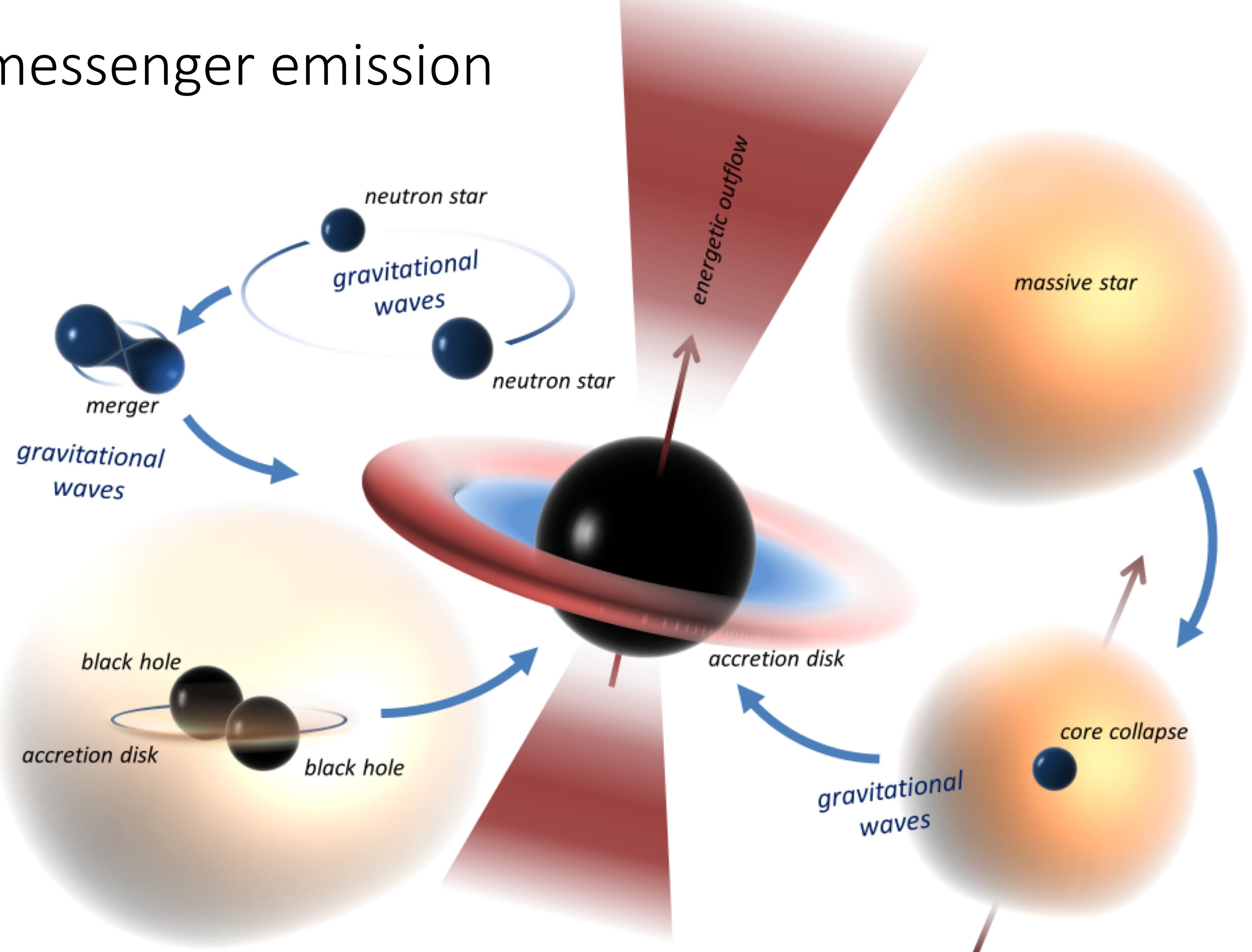
How can CTA Perform Best in the Changing Gravitational-Wave Follow-Up Landscape?

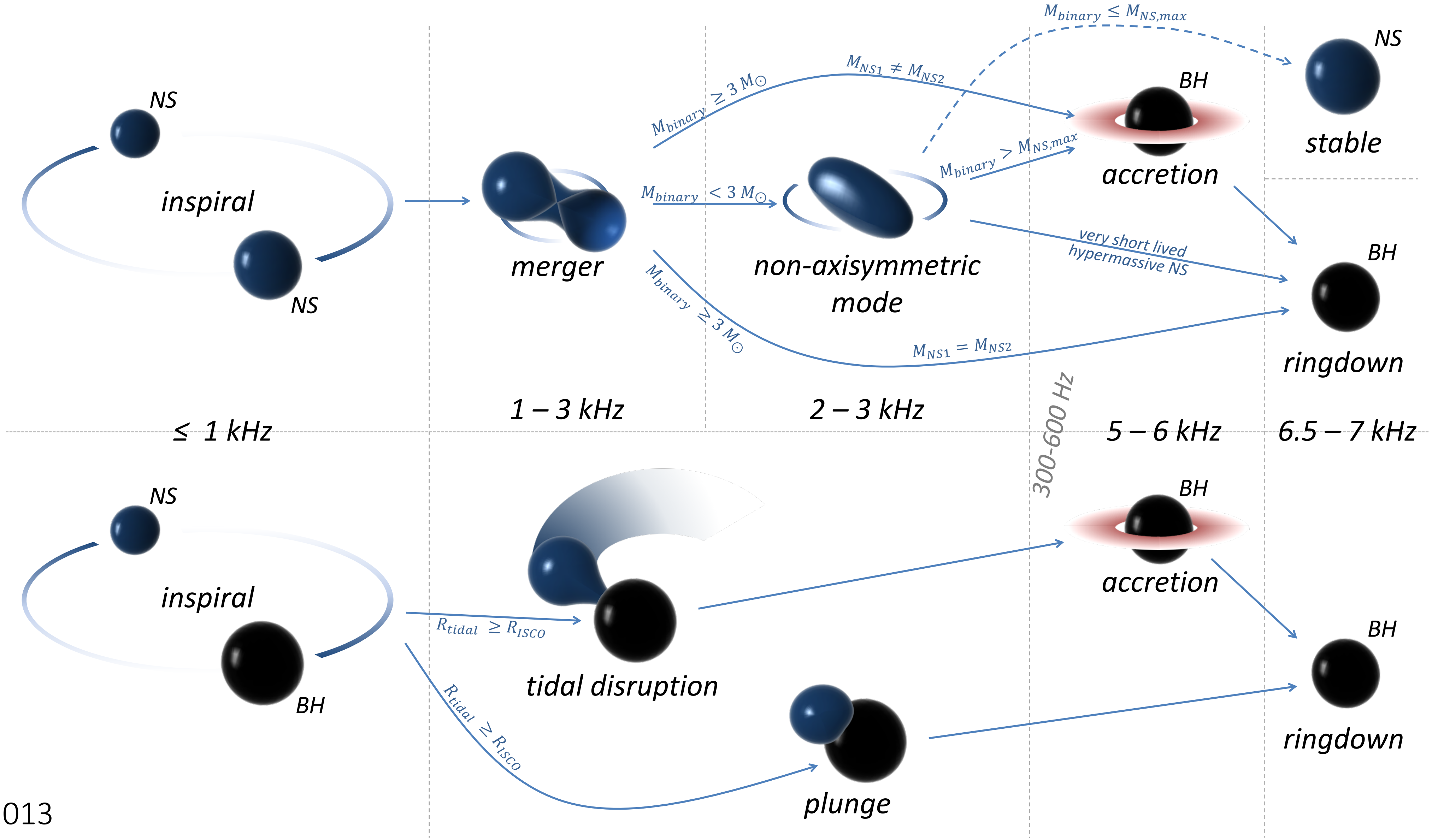
Imre Bartos
University of Florida

CTA Symposium | 05.09.2019 | Bologna

multi-messenger emission



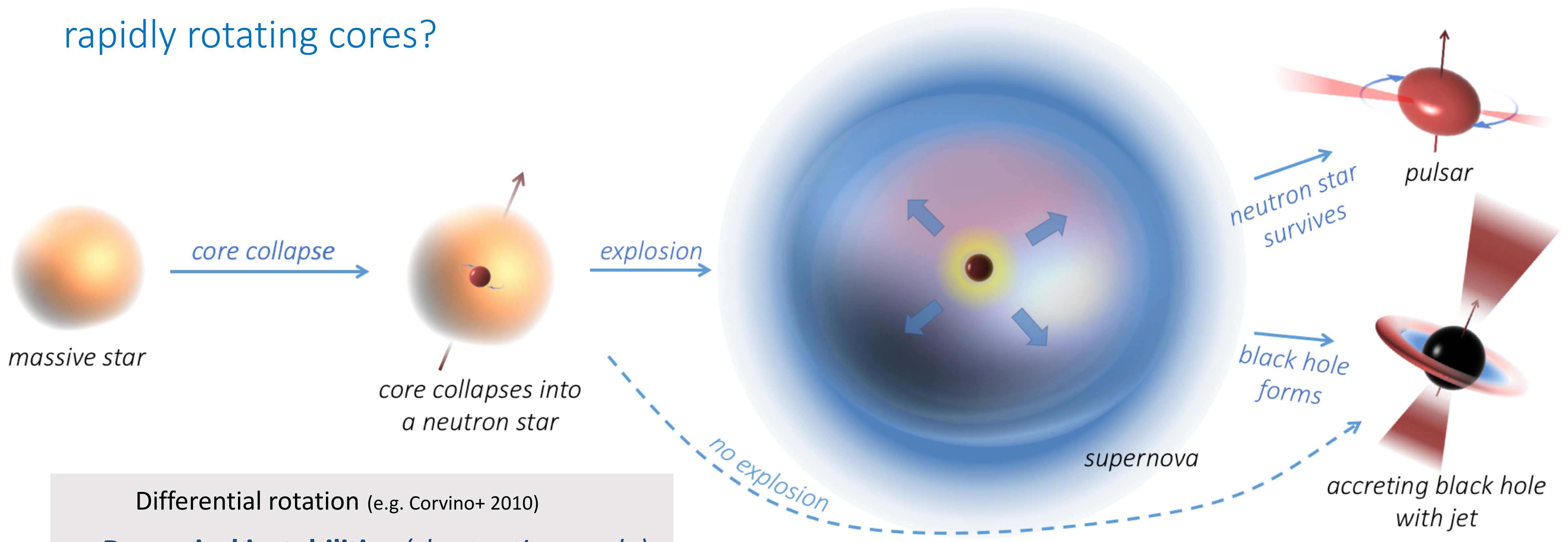
Compact binary mergers



Bartos+ 2013

Stellar core collapse

Gravitational waves from rapidly rotating cores?

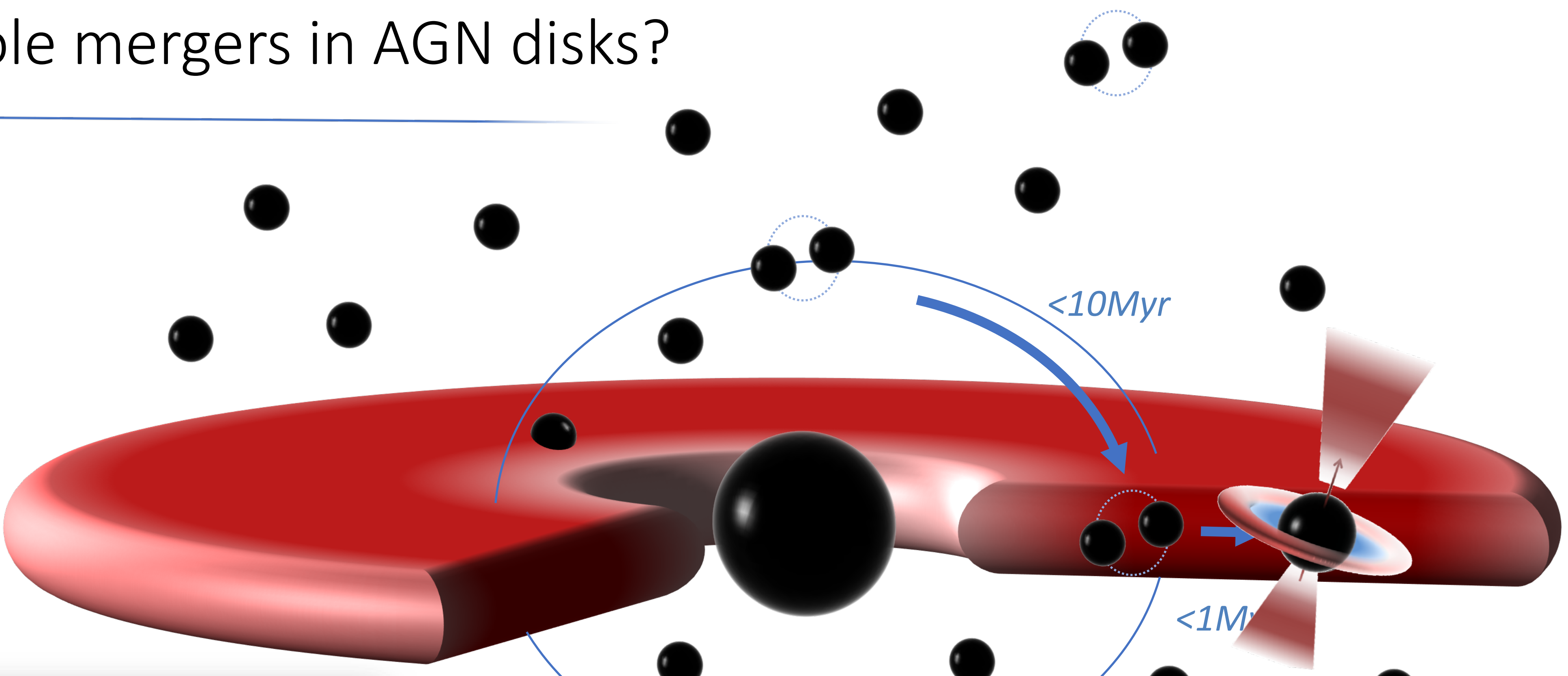


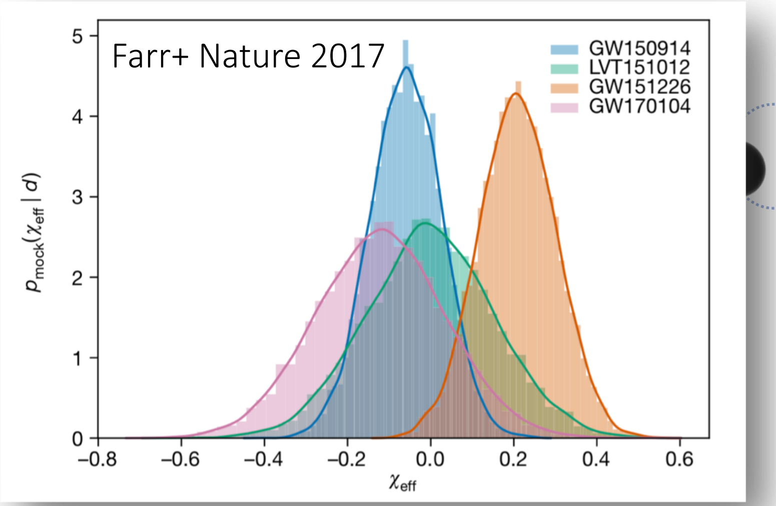
Differential rotation (e.g. Corvino+ 2010)

- **Dynamical instabilities** *(shorter time scale)*
- **Secular instabilities** *(longer time scale)*
- **Magnetic distortion**

Fallback accretion? *(Piro & Thrane, 2012)*

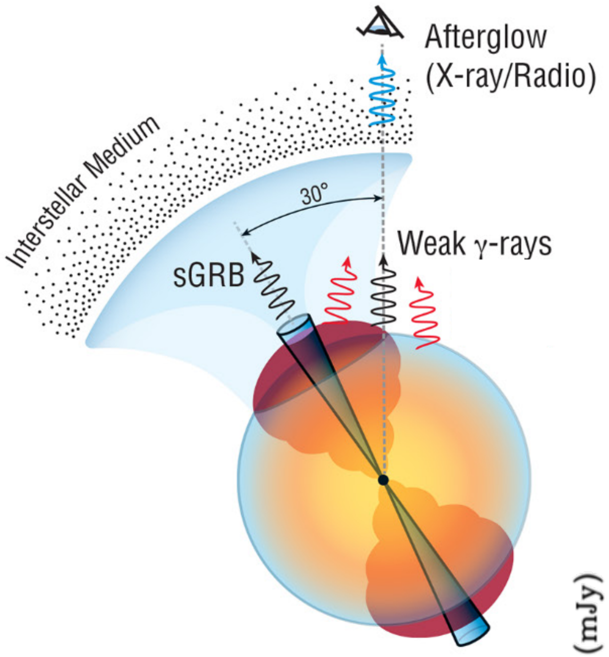
Black hole mergers in AGN disks?





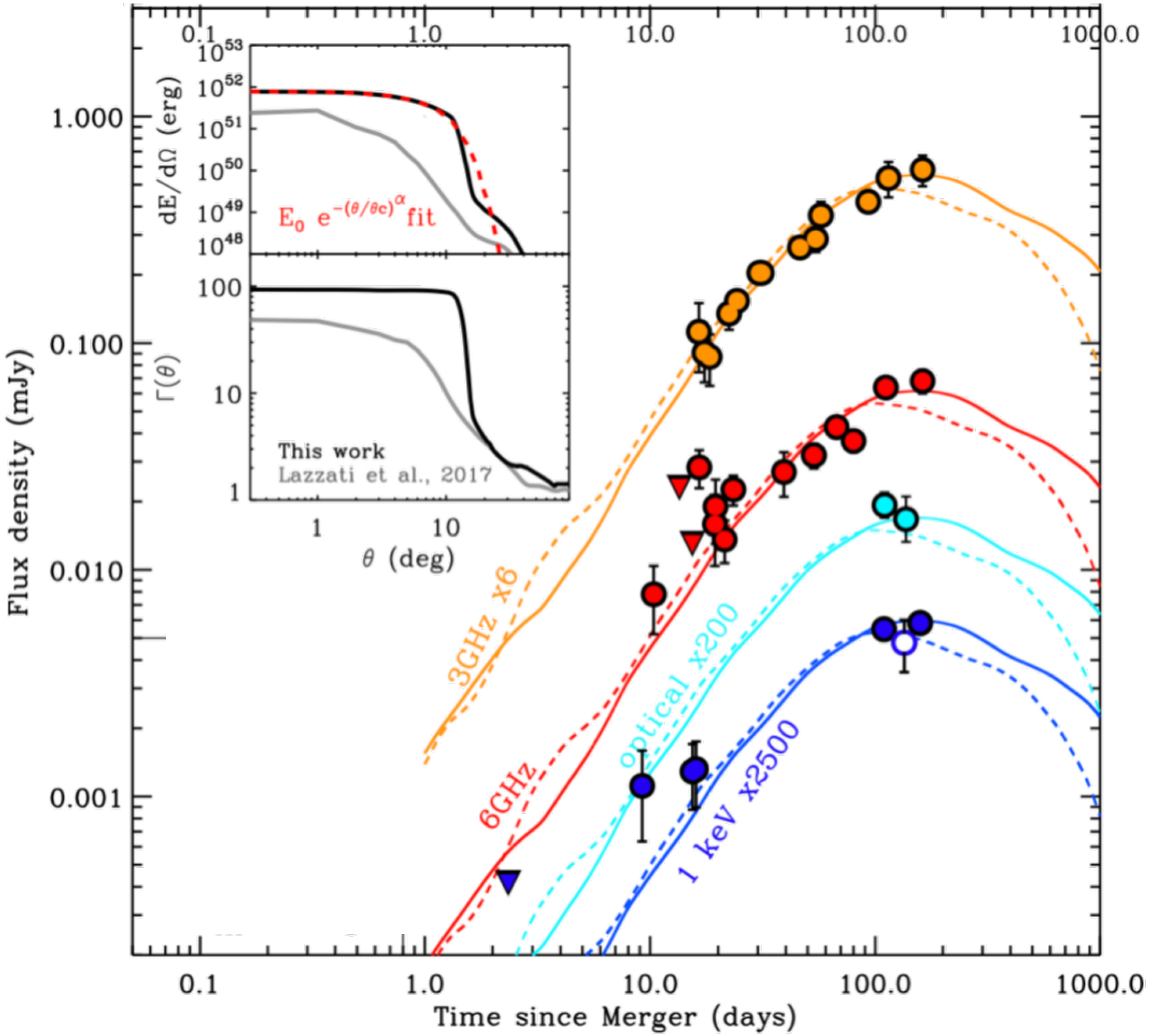
Bartos+ ApJ 2017
Stone+ MNRAS 2017
Bartos+ Nature Comm. 2017
Ford+ 2019

GW170817
an off-axis GRB



Kasliwal+ 2017

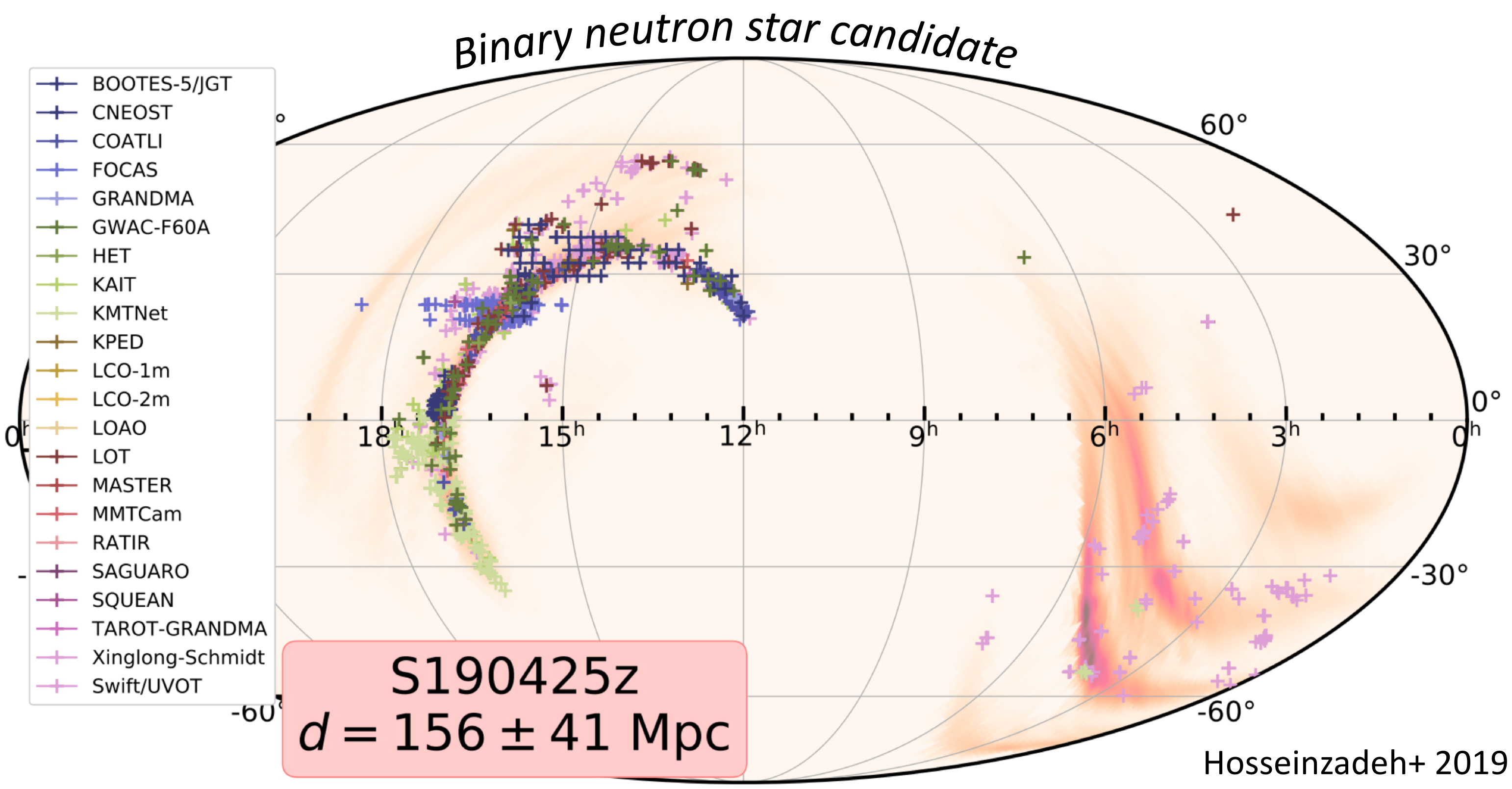
- First GW+high-energy discovery
  - Already very informative
- Afterglow observations point to structured jet.
(Margutti, Ghirlanda, Lazzati, Mooley, …)
  - ~30% of GWs from BNS will have GRB counterpart.
  - Significant fraction (10%) of GRBs should be nearby.
(Gupte & Bartos 2018)
- How does TeV emission look like at large viewing angles?
  - Fermi-LAT did not detect this event.
  - Can help differentiate between emission mechanisms.
  - This will be central to whether CTA will see LIGO/Virgo sources.



Margutti+ 2018

EM follow-up is difficult

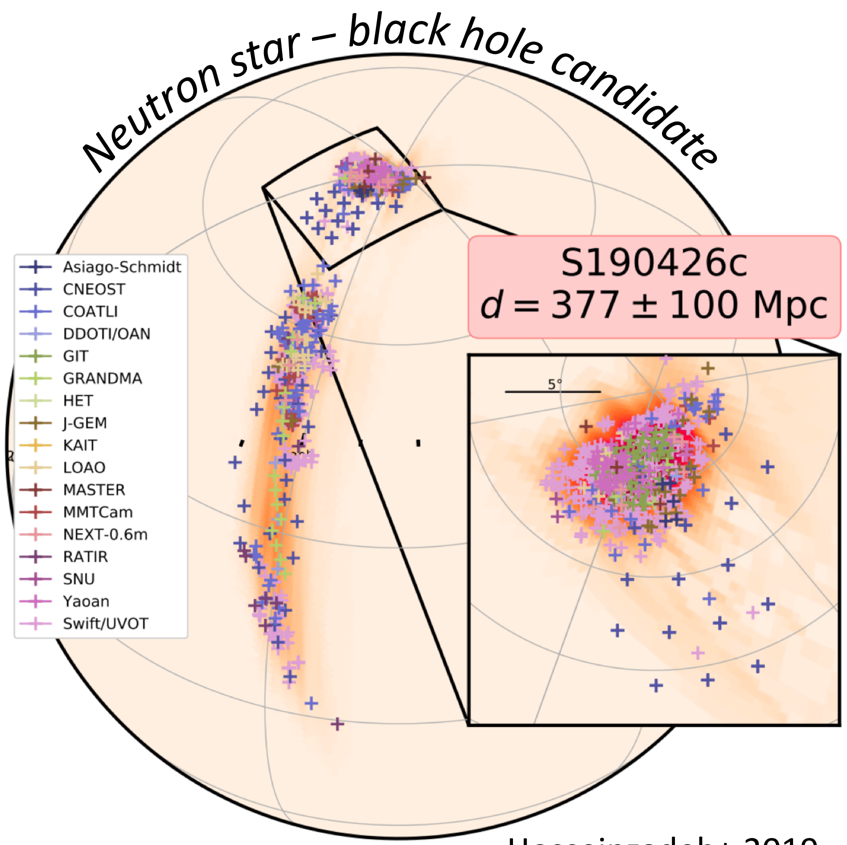
- First NS-NS candidate during O3 already detected.
- Poor localization – Hanford was off.
- No GRB / high-energy neutrino counterpart.
- Dozens of observatories, 100s of observations (>230 GCN circulars).
- Extensive observation campaign only covered ~50% of volume.
- Many false positives.
- Galaxy targeted searches --- < 1% covered.



Hosseinzadeh+ 2019

Other candidates

- Multiple black hole – black hole merger candidates.
- First neutron star – black hole merger candidate.
- Significant optical follow-up effort despite large distance.
- Expected NS-BH merger rate is highly uncertain.
- Threshold for announcement: few false alarms per year.

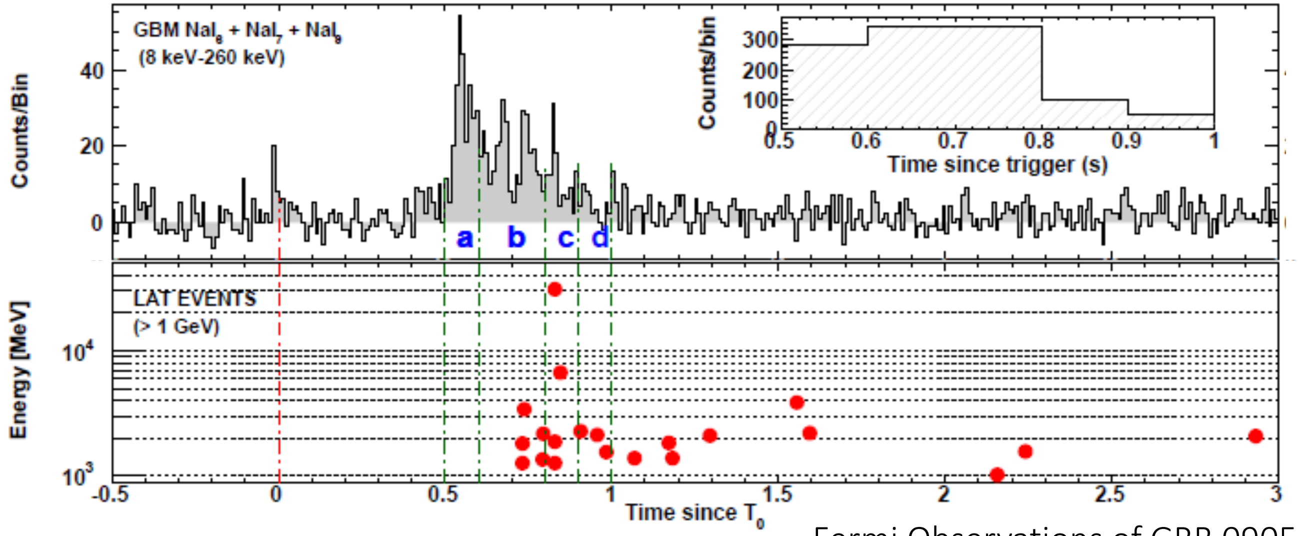


Hosseinzadeh+ 2019

Can CTA detect gravitational-wave sources?

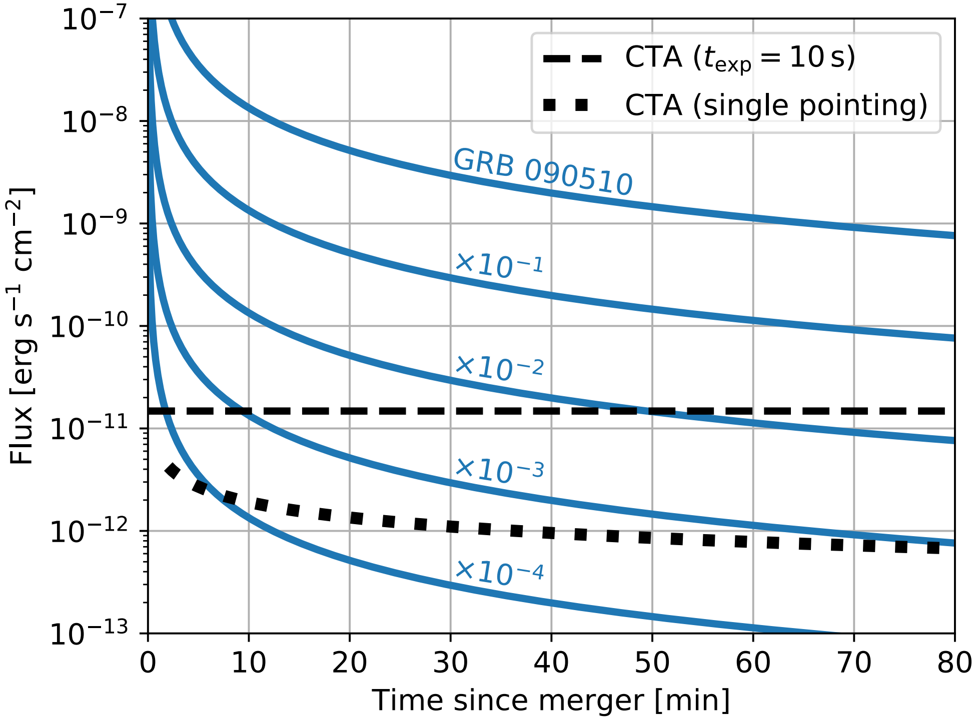
- ✓ At least some short GRBs emit >GeV photons (GRB 090510).
- ✓ Emission up to TeV (GRB 190114C; z=0.42).
- ✓ Cherenkov Telescope Array is sufficiently sensitive to quickly detect high-energy gamma-rays from short GRBs (Bartos+ 2014)
  - Relevant source distance: < 500 Mpc (average; 700 Mpc max)

Barsotti+ 2018



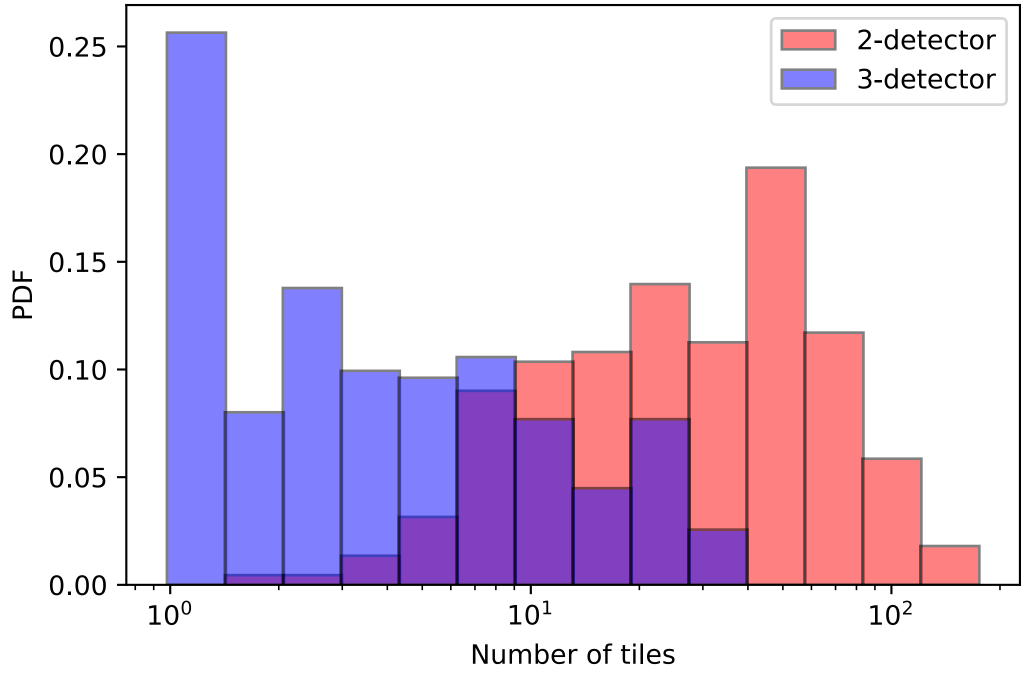
Fermi Observations of GRB 090510

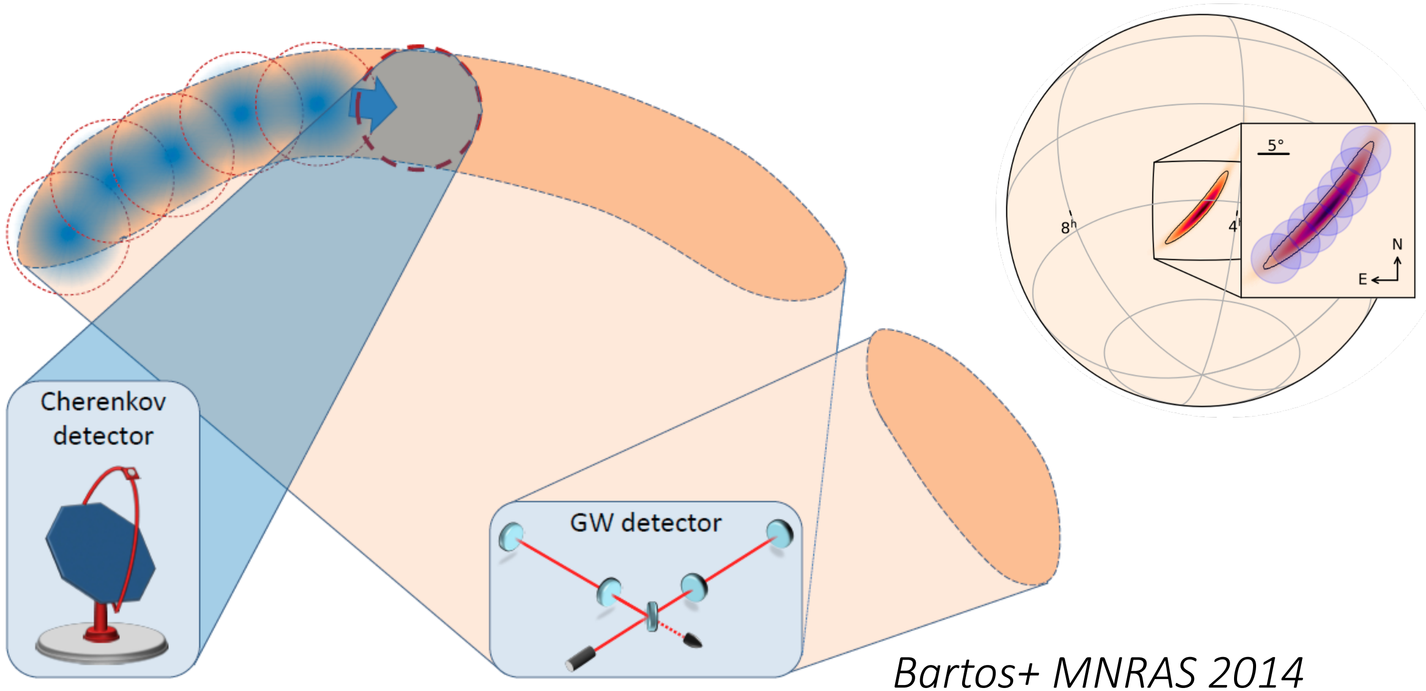
Take:
- ✓ GRB 090510
- ✓ 500 Mpc
- ✓ Flux $\propto t^{-1.38}$
- ✓ exposure time $t_{\rm exp} = 10$ s / continuous
- ✓ E^{-2} spectrum, $E_{\max} = 1$ TeV



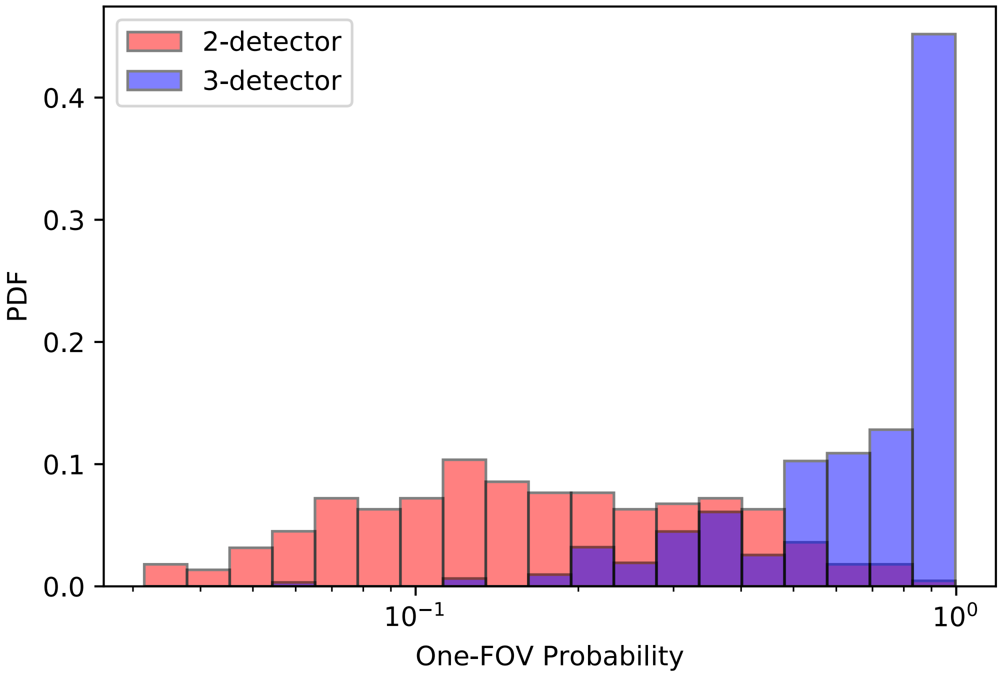
How many CTA pointing will be needed?

- LIGO/Virgo analysis delay: ~minute.
- We carried out NS-NS mergers simulations and localization.
  - ✓ LIGO+Virgo: 1-10 pointings. (easy)
  - ✓ LIGO-only: 10-100 pointings. (some will be constraining for GRB 190114 / 10^3)





Bartos+ MNRAS 2014



Expected number of LIGO+Virgo+CTA detections

LIGO A+ (325 Mpc range; Barsotti+ 2018), Virgo+

\+ neglect LIGO/Virgo duty cycle

\+ 100-4000 Gpc^{-3} yr^{-1} NS-NS detections (Abbott+ 2018)

10 – 600 NS-NS merger detections / year

→ for beaming with $\theta_{\mathrm{jet}} = 30^o$: 2 – 80 detections / year

→ for beaming with $\theta_{\mathrm{jet}} = 10^o$: 0.2 – 10 detections / year

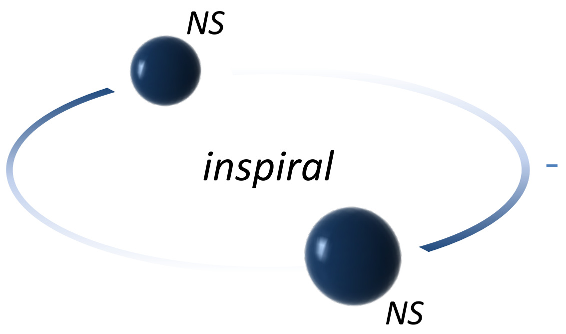
→ for beaming with $\theta_{\mathrm{jet}} = 5^o$: 0 – 2 detections / year

(NS merger rate estimate will quickly improve with O3)

CTA duty cycle will reduce these rates by a factor of $\sim 5 - 10$

Joint observations will probe off-axis TeV emission very quickly, with the potential for quick discovery.

How much CTA time will this take?



$t_{\text{exp}} = 10\text{s}$
$t_{\text{slew,initial}} \sim 20s$
$t_{\text{slew}} \sim 5s$

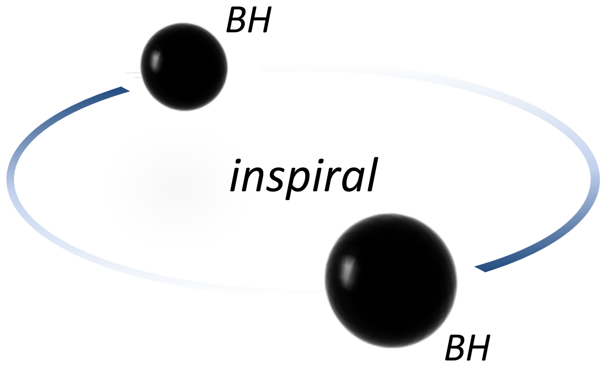
30s – 1500s for each event
(take 300s average)

15% CTA duty cycle

→ 10 minutes – 8 hours / year
of CTA time on NS-NS mergers

More time will be needed if observations start late

Other sources?



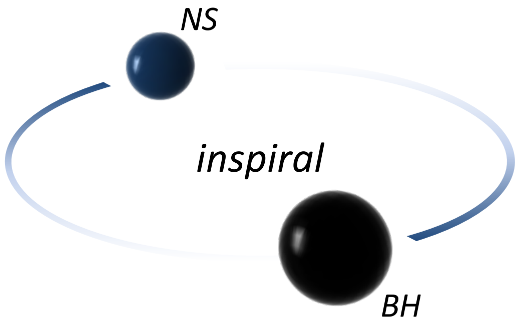
- Black hole – black hole
  - Range: ~2.5 Gpc with LIGO A+ (Barsotti+ 2018)
  - Rate: 10 – 100 $\text{Gpc}^{-3}\ \text{yr}^{-1}$ (Abbott+ 2018)

  → detection rate: 600 – 6000 / year.

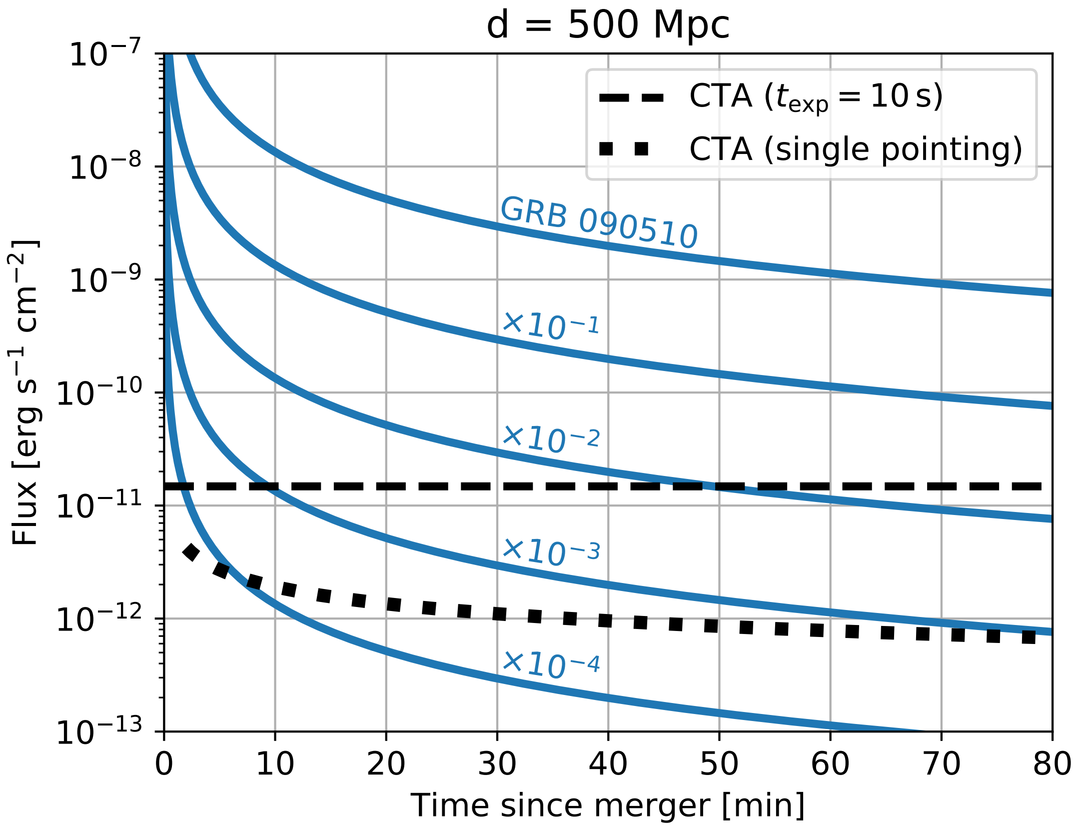
  → 10x more time would be needed than NS-NS…

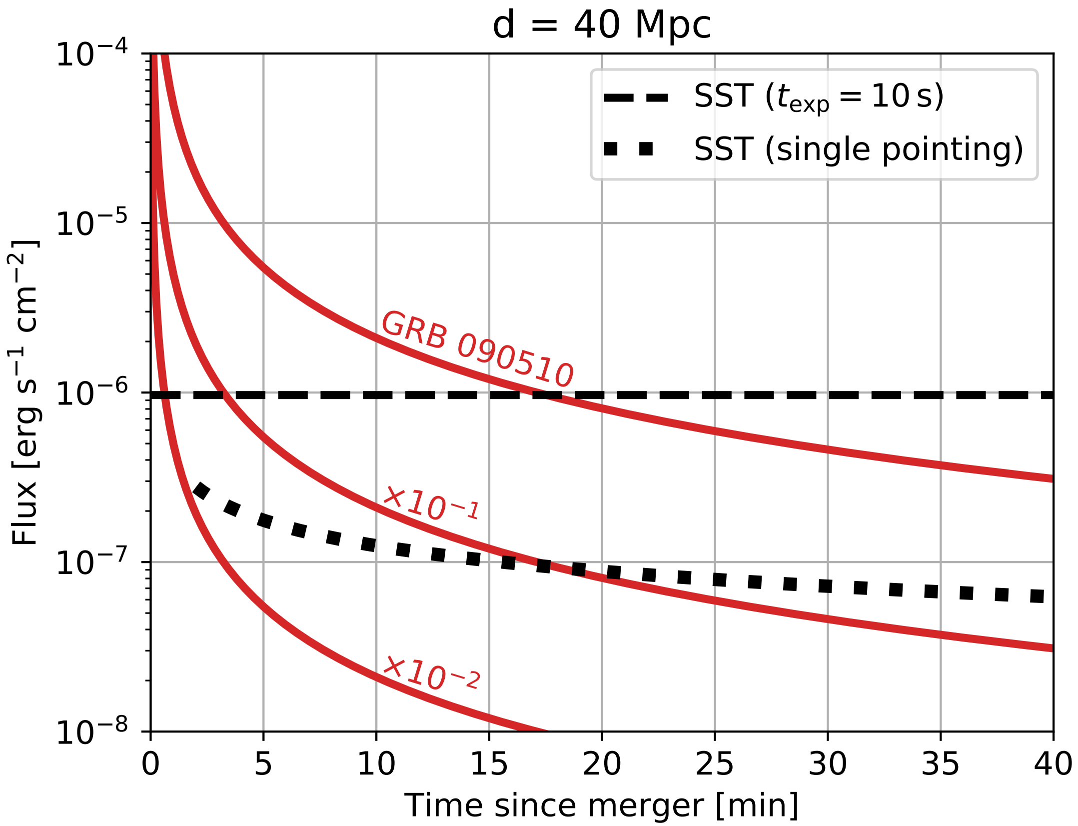
- Neutron star – black hole:
  - ?

- Sub-threshold events



Do we need to wait until the array is complete?





(Sensitivity: Noethe+ 2017)

- ✓ Partially completed array may be sufficient.
- ✓ Divergent observing mode is interesting.
- ✓ GWs tell us how far the event is --> we can choose observing modes based on this.

gravitational-wave follow-up strategies

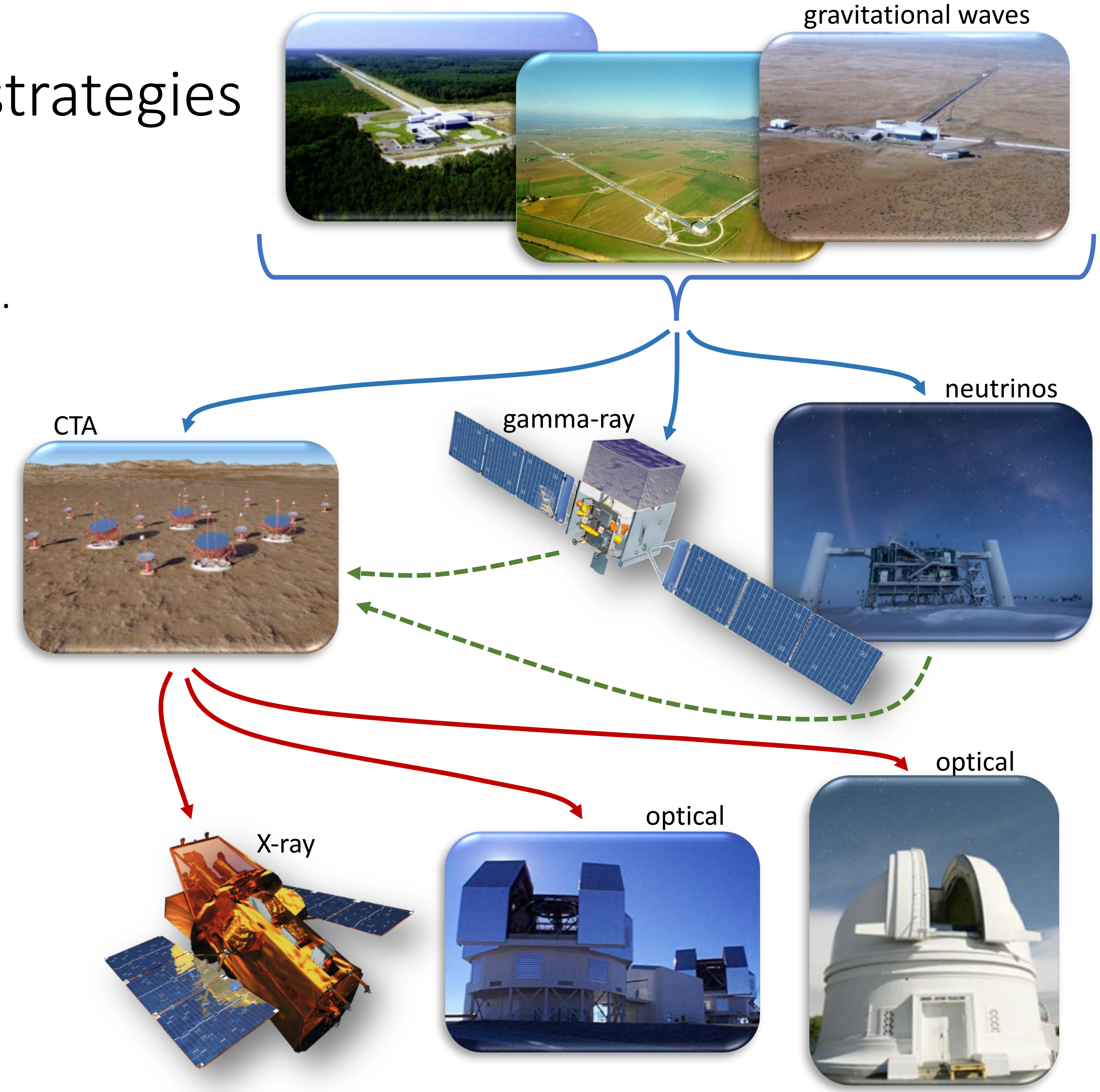
1. Every GRB / NS-NS merger can be followed up, even with partial CTA (it will not take much time). Special BH-BH + NS-BH + unmodeled events as well.

2. Receive GW trigger.

3. Narrow sky area given a coincident GRB / high-energy neutrino.

4. Power-law fading of emission --- optimize pointings to minimize slew time and cover GW skymap *(GW prob. density not useful)*

5. Counterpart found:
   a) Keep monitoring (rapid ID?)
   b) Alert optical/X-ray follow-up observatories.



Conclusion

- GW+CTA observations will connect high-energy emission with the formation/evolution of the central engine.
- Off-axis observations are critical to understand.
- CTA will be able to rapidly scan even large LIGO-Virgo sky areas.
- Rapid identification → alert/point optical follow-up observatories.
- All NS-NS mergers can be followed up without needing to prioritize.
- Other (BH-BH / BH-NS / subthreshold) sources will require prioritization.
- Even a partially completed array could be sufficient for detection.