Real-Time Detection of GWs from Binary Coalescence and EM Follow Up

Linqing Wen

School of Physics

University of Western Australia

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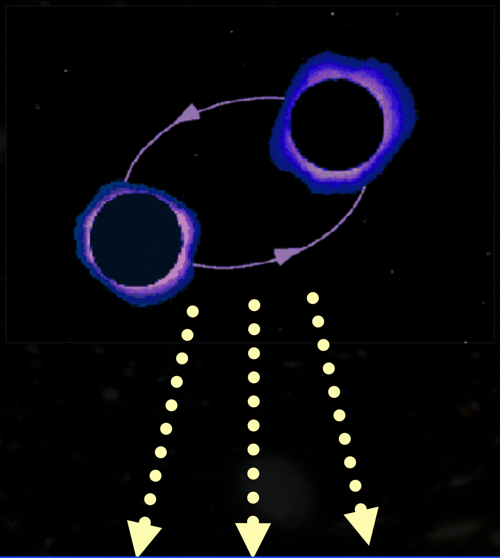
(Graphic source: NASA)

Outline

- Overview
- Multi-Messenger Prospects of Binary Merger
- Real-Time Low-Latency GW Search
- Conclusion

Gravitational Wave



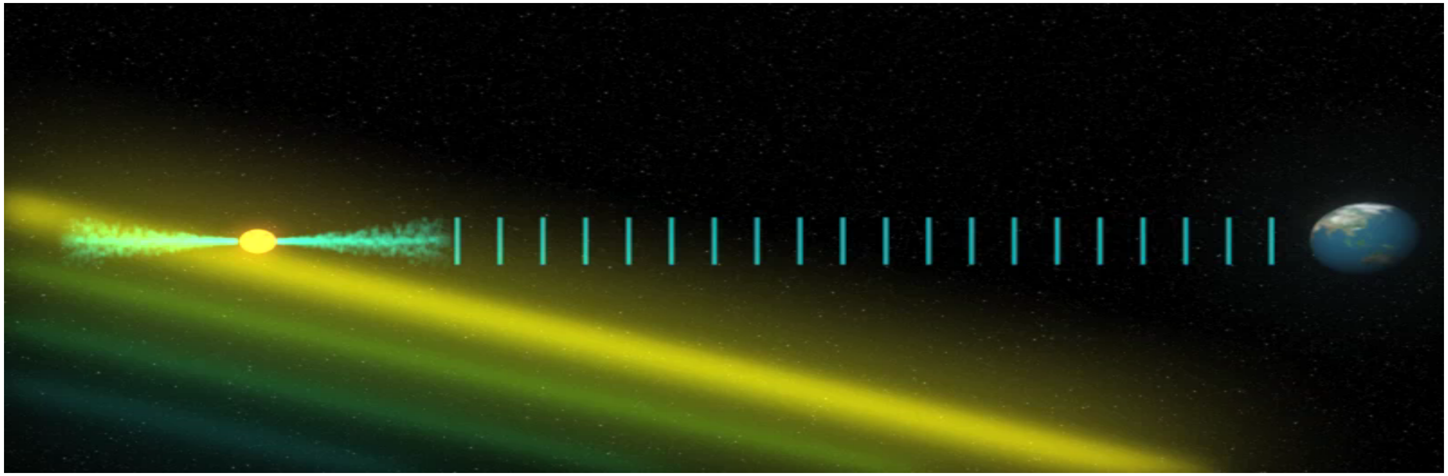
- GWs are ripples of curvature of space-time propagating at v=c
- Caused by acceleration of mass quadruple moment
  - Inspiraling binaries, core-collapse SN, fast spinning NS w/ mountain, stochastic backgrounc
- Measurable: strain $h=\delta L/L$
- The detector:

  ~ Michelson interferometer with km-long arm length

  - Sensitive in audio band of 10-1500 Hz

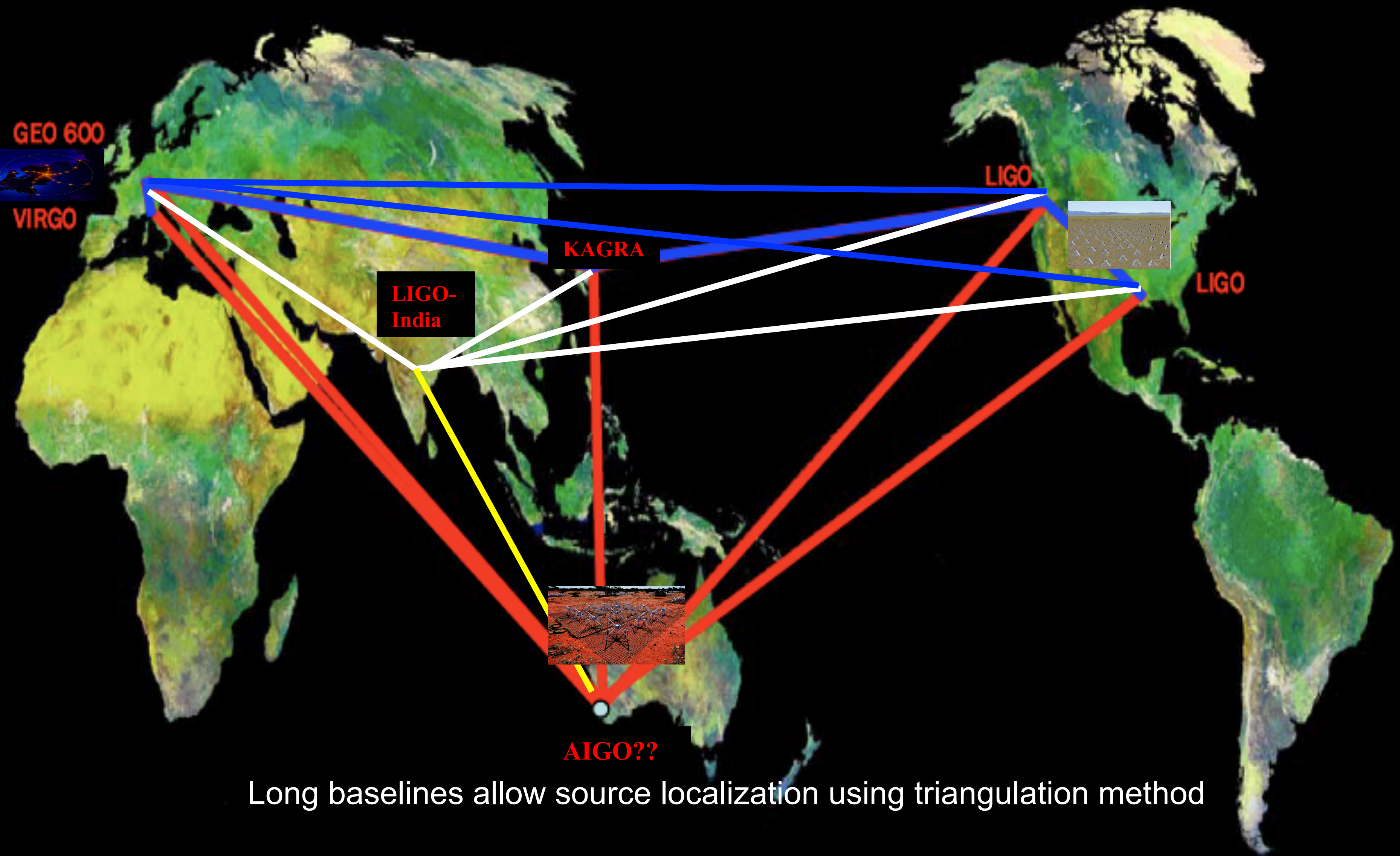
Detecting Nanohertz GWs using Millisecond Pulsars

- GW changes travel time of radio pulses
- Measuring timing residual induced by a GW
- Sensitivity
  - $f \sim 10^{-10} - 10^{-6}$ Hz
  - $\lambda_{GW} << L$
  - Typical $\Delta\tau \sim \lambda_{GW}\, h / c$ (~ 100 ns @ h~1e-15, $\lambda \sim$ pc)



Movie credit: http://www.gwastro.org/for%20scientists/visualization-pulsar-timing-and-gravitational-wave-detection

The Global Interferometric Audio-band GW Detector Network

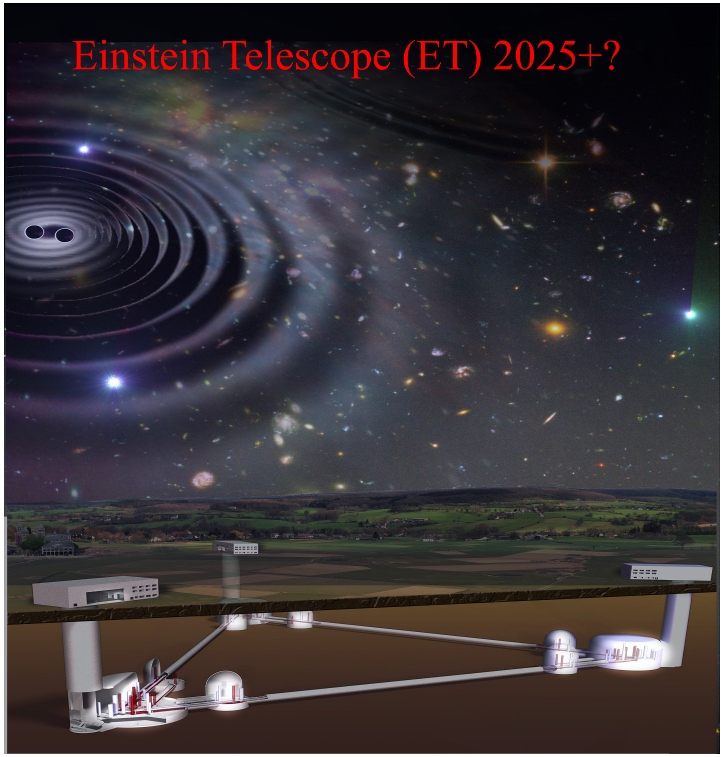


Long baselines allow source localization using triangulation method

Ground-based Interferometric GW Detector

- Initial GW detectors are successful
  - Operational at design sensitivity
  - 40 – 2000 Hz
  - Three-detector coincident observation for 1 yr
- Advanced LIGO/VIRGO detectors under construction
  - Operational around 2015
  - 10 – 2000 Hz
  - x 10 improvement in sensitivity, x 1000 in detection volume
  - Tens of detections per year expected

3^{rd} Generation GW Detector Planned



- 10 km long arm
- >150 m underground
- Cryogenic
- Start only after 1^{st} GW detection
  - SKA time scale?
- x 10 better sensitivity than aLIGO
- Low frequency reaching a few Hz

ACIGA

Australian
Consortium for
Interferometric
Gravitational
Astronomy

Australian National University

The University of Western Australia

The University of Melbourne

The University of Adelaide

MONASH

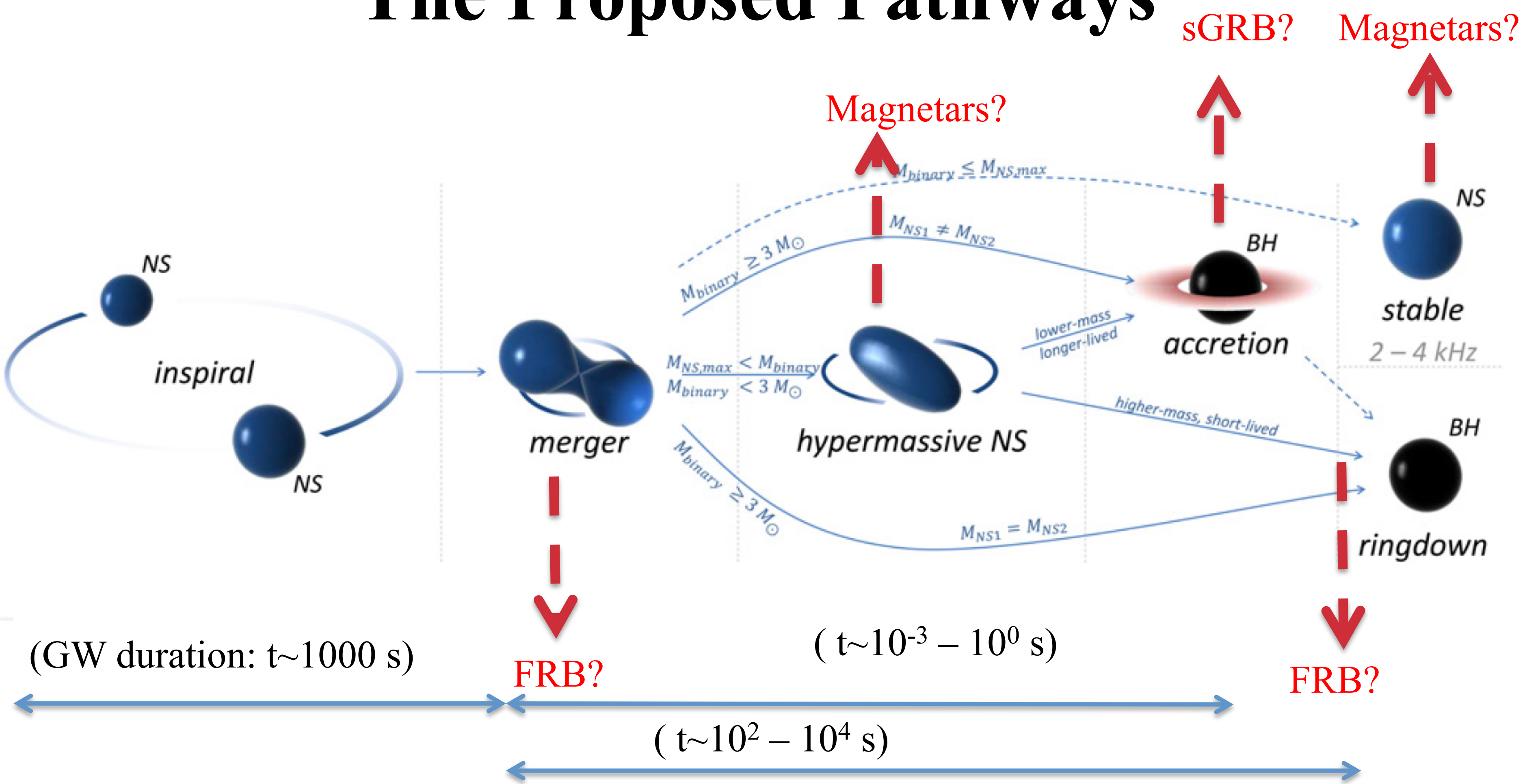
Australian Centre for Precision Optics

Gravitational Wave Astronomy @ UWA

- Observational/theory
  - Real-time low-latency detection of GWs
    - To detect binary coalescence signals as soon as there is enough SNR
      - Possibly at or before binary merger
      - To enable prompt EM follow up
  - Supercomputing with GPUs
  - GW-EM astrophysics

NS-NS Binary Merger: What is the Known Unknown?

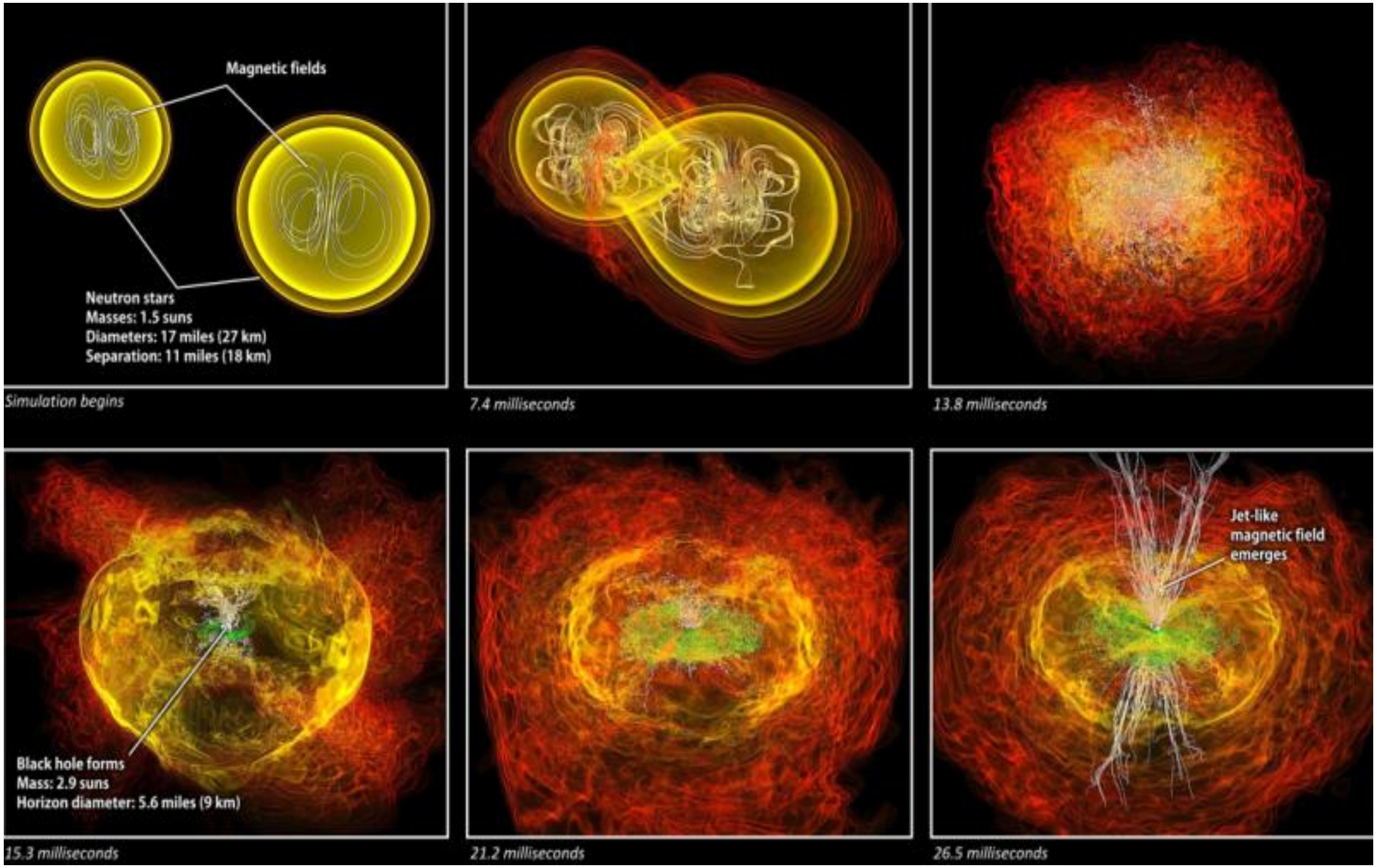
The Proposed Pathways



Modified from Bartos, I., Brady P. & Marka, Z. 2013
sGRBs: Fox et al 2010, Rezzola et al 2011
Magnetars: Giacomazzo & Perna 2013; Falcke & Rezzolla 2013; Zhang et al 2013; Gao et al 2013
FRBs: Zhang 2013, Totani 2013, Trott, Tingay & Wayth 2013

Pathway to sGRBs?

NS-NS merger and sGRB emissions connected within milliseconds!

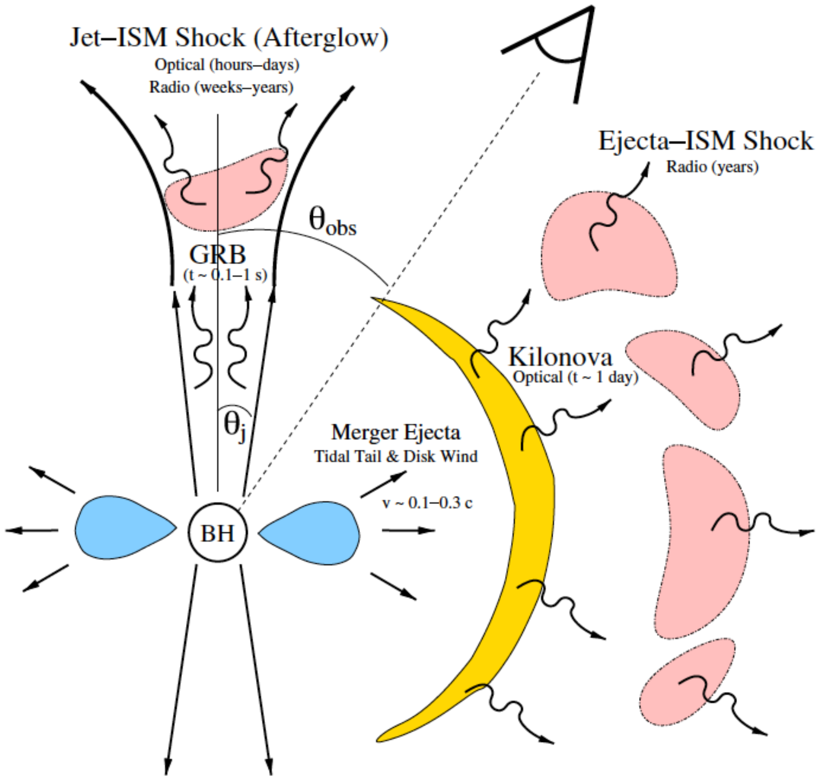


Baiotti, L. et al, PRD, 2011
Rezzolla, L. et al, ApJ 2011
Bruno, G. Luciano, R. and Baiotti, L. et al. 2011
Baiotti, L. et al. PRL, 2010

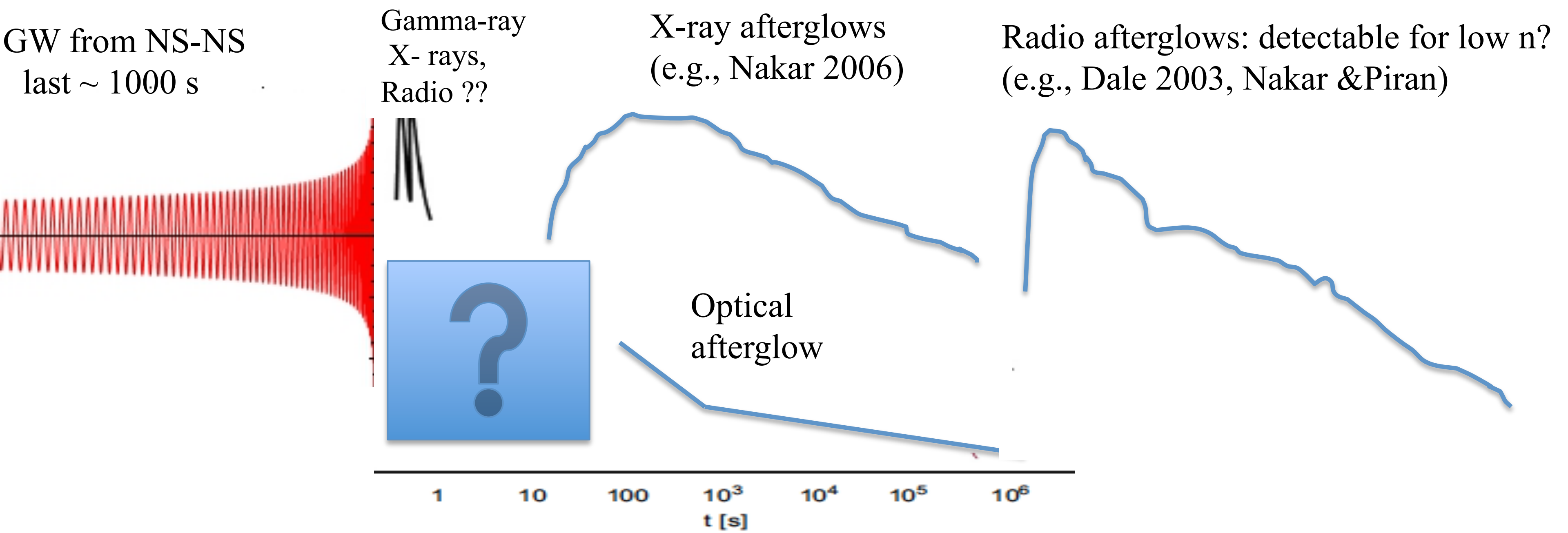
(Credit: NASA/AEI/ZIB/M. Koppitz and L. Rezzolla)

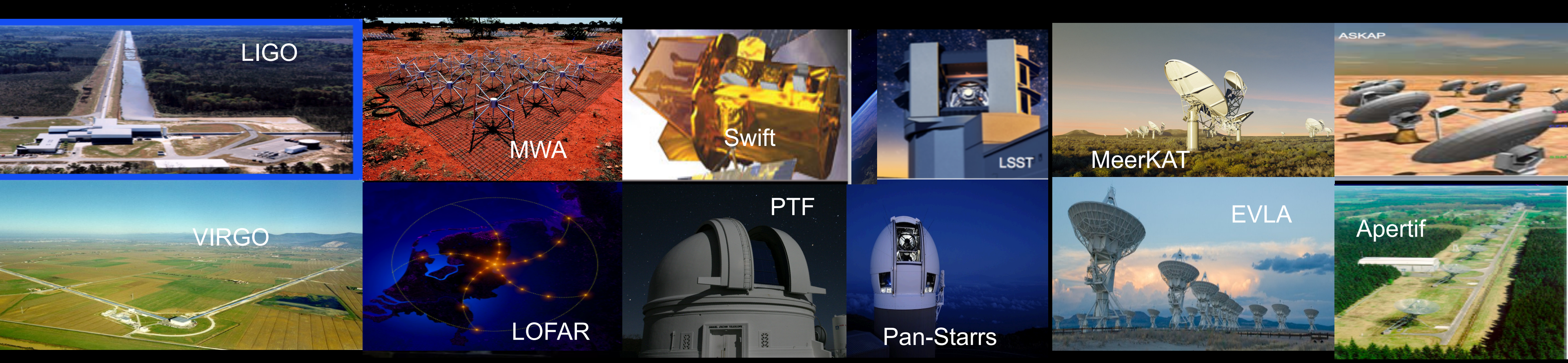
Binary Merger-sGRBs

- Prompt emissions (< 2s)
  - Highly collimated
  - ϒ-rays , X-ray
  - Optical ?
  - Low-f prompt radio emission ??
    - 12.5 kJy @ 100 MHz @200 Mpc (Postnov & Pshirkov 09)
- Afterglows (10s' of s -- years)
  - ϒ-rays , X-ray, Optical -beamed
  - Radio
    - isotropic
    - weeks –months
    - 10's mJy @ 1-10 GHz & 200 Mpc
  - X-ray plateau powered by Magnetars? (e.g. Rowlingson 2013)
  - Isotropic optical from Klonova ?



Metzger & Berger (2012)


GW from NS-NS
last ~ 1000 s
Gamma-ray
X- rays,
Radio ??
X-ray afterglows
(e.g., Nakar 2006)
Radio afterglows: detectable for low n?
(e.g., Dale 2003, Nakar &Piran)
Optical
afterglow
1
10
100
10³
10⁴
10⁵
10⁶
t [s]


LIGO
MWA
Swift
LSST
MeerKAT
ASKAP
VIRGO
LOFAR
PTF
Pan-Starrs
EVLA
Apertif

Pathways to Magnetars and FRBs ?

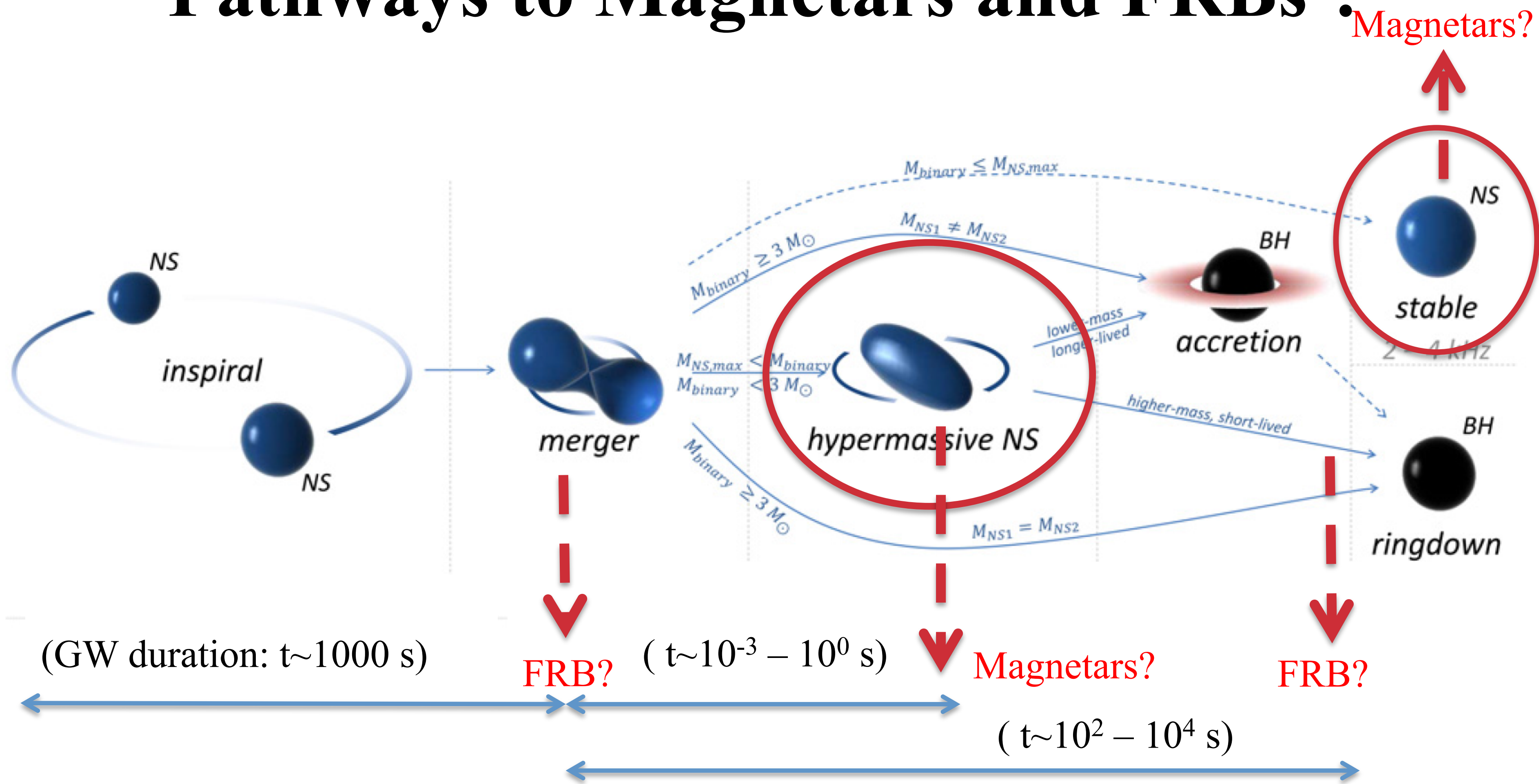


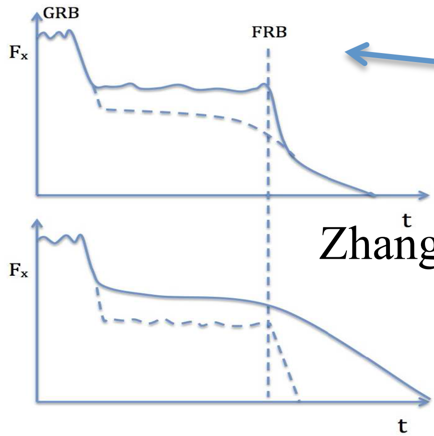
Figure modified from Bartos, I., Brady P. & Marka, Z. 2013

Magnetars: Giacomazzo & Perna 2013; Falcke & Rezzolla 2013; Zhang et al 2013; Gao et al 2013

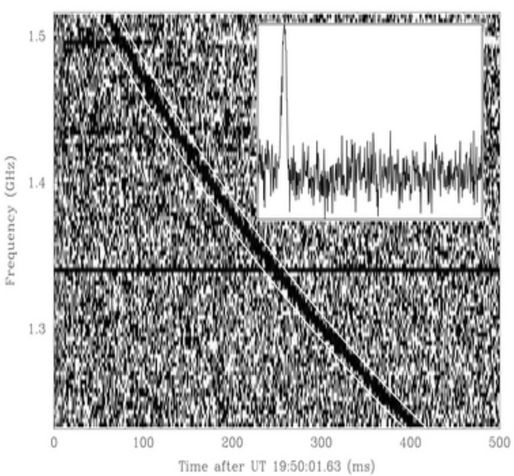
FRBs: Zhang 2013, Totani 2013, Trott, Tingay & Wayth 2013

Possible GW/sGRB/Magnetar/FRB System ?

(t~10^2 – 10^4 s)



Zhang 2013 arxiv



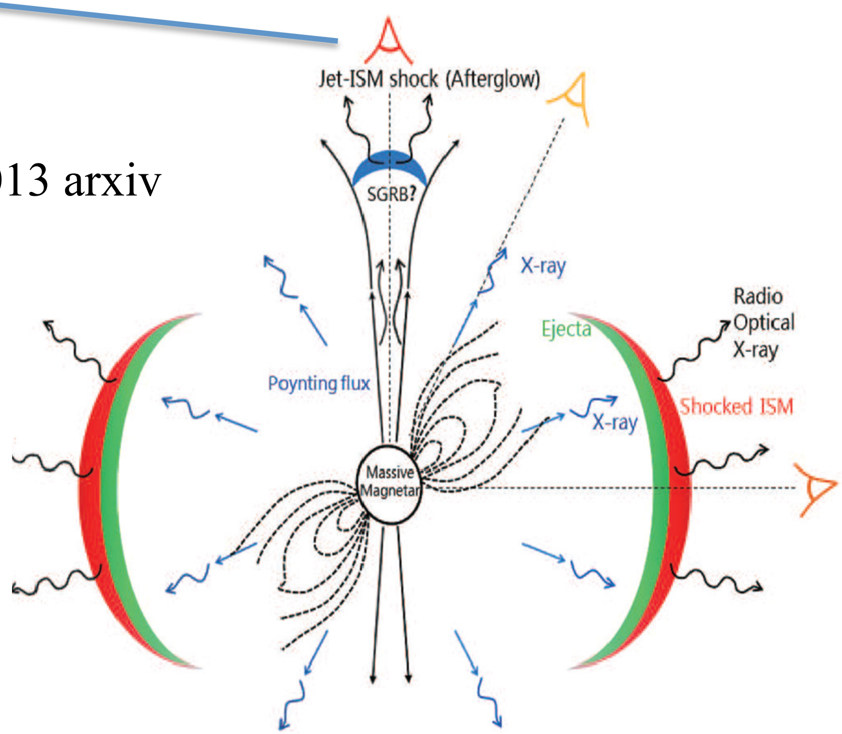


Figure from Gao et al 2013

All Paths → Multi-Messenger Astronomy

Time Scales

- Binary merger (GW) – sGRB prompt emission
  - ms – 1s
- Binary merger (GW) – Magnetar
- Binary merger (GW) – FRBs
  - 10^2- 10^4 s
- Binary Merger (GW)- sGRB/Magnetar Afterglows
  - Hours-weeks-years

Option I: EM triggered Search for GWs

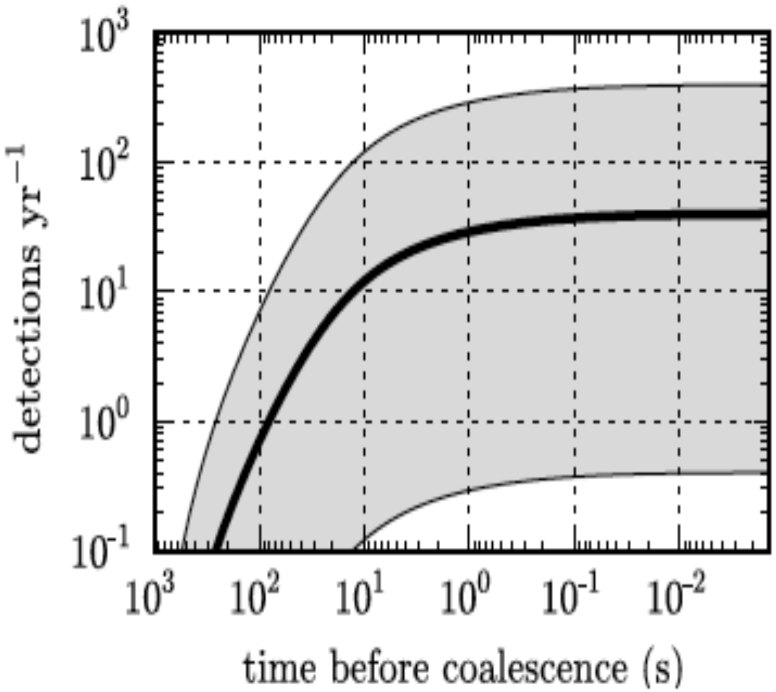
- Search for archival GW data for signals with given sky direction and time window
  - On-going effort at LVC
  - Challenges:
    - Swift/Fermi gives gamma-ray burst event triggers
      - No Swift/Fermi triggers of sGRBs within aLIGO horizon within last 9 years
        - Beaming of gamma-rays?
        - Low event rate for the next 10 years?

    - Radio transient triggers
      - Uncertain in event time ?

Option II
GW triggered Search for EM Counterparts

- Detecting GWs with extremely low latency
- Prompt EM follow up with, e.g., robotic optical telescopes
    - Tarot telescope has 6 s response time
- Wide-field telescopes desirable!
    - MWA/LOFAR -radio
    - GWAC - optical

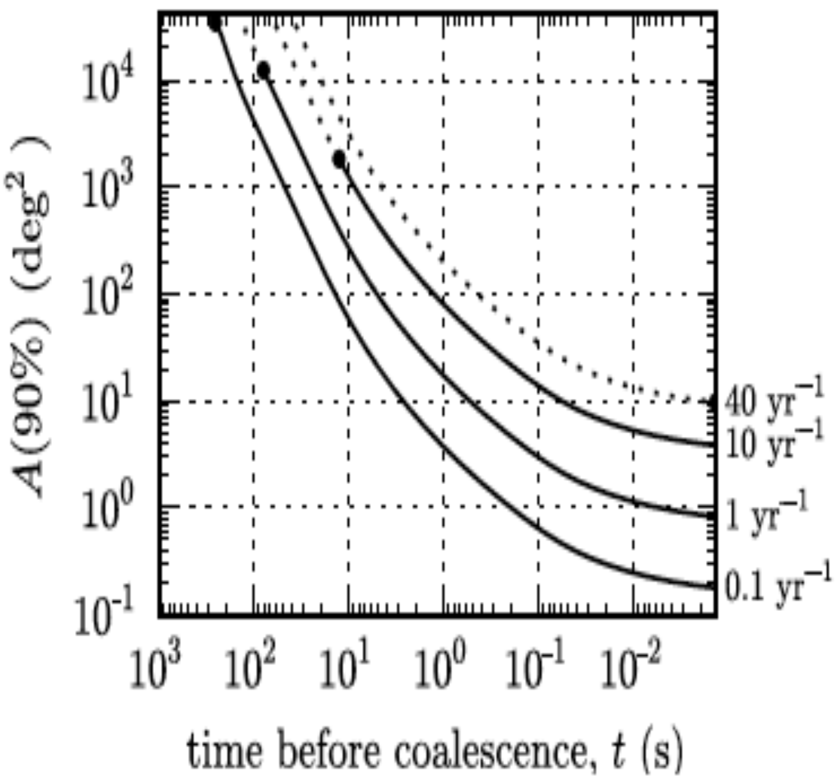
Sufficient Event Rate for Early Detection



Cannon, K. et al ApJ 2012

- 1 event/ yr can be detected 100 s before merger
- 10 events/yr can be detected 10 s before merger

Challenges: Source Localization



- 40/yr rate: ~10 sq-deg at merger
- 10/yr rate: 4 sq-deg at merger
  - But 100 sq-deg at 1 s before
- 1/yr rate
  - 100 sq-deg 5 s before merger
  - <~1 sq-degs at merger
  - Larger detector network helps
    - 50 sq-deg LHVK 10 s before
    - 10 sq-deg LHVIK 10 s before

(Chu, Q. et al 2012)

Cannon, K. et al ApJ 2012

On-going Low-latency CBC Search Pipelines

- Frequency domain method
  - Two existing pipelines:
    - MBTA
    - LLOID
  - Technique
    - (Overlapping) FFT method
      - Matched filtering: correlate data with known signal
    - Multi-band multi-rate approach to process less data
    - Template interpolation to reduce number of templates

SPIIR Concept
Summed Parallel Infinite Impulse Response Filters

$$y_k = a_k y_{k-1} + b_k x_k$$

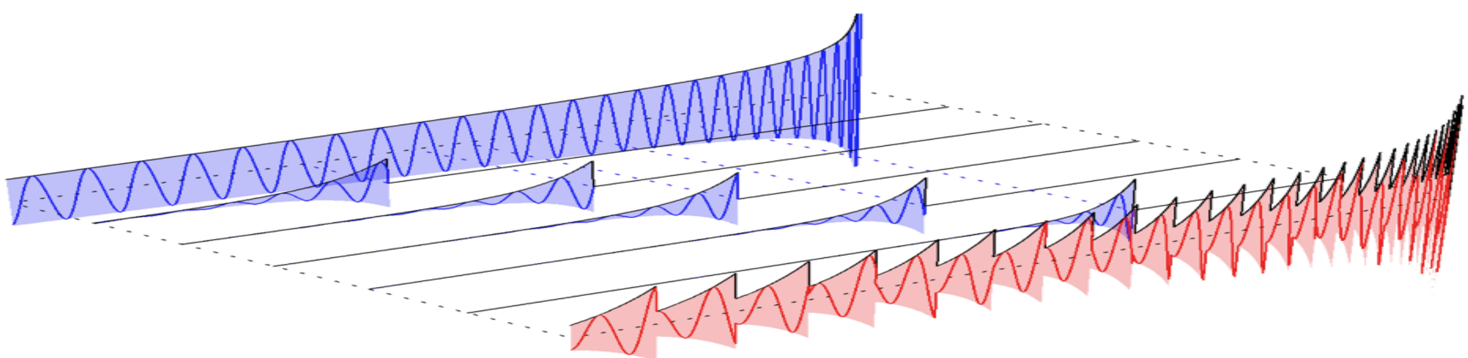
SNR at k-th time step

k-th GW data

SNR at (k-1)-th step

Coefficients calculated for each template at each segment

- Equivalent to matched filter data with a constant-f sinusoid of exponentially rising amplitude (+cutoff)



Luan, J. et al 2012 PRD, Hooper, S. et al 2012 PRD, Hooper, S. 2013 PhD thesis

GPU Accelerated Low-Latency Search (in Collaboration with Tsinghua U.)

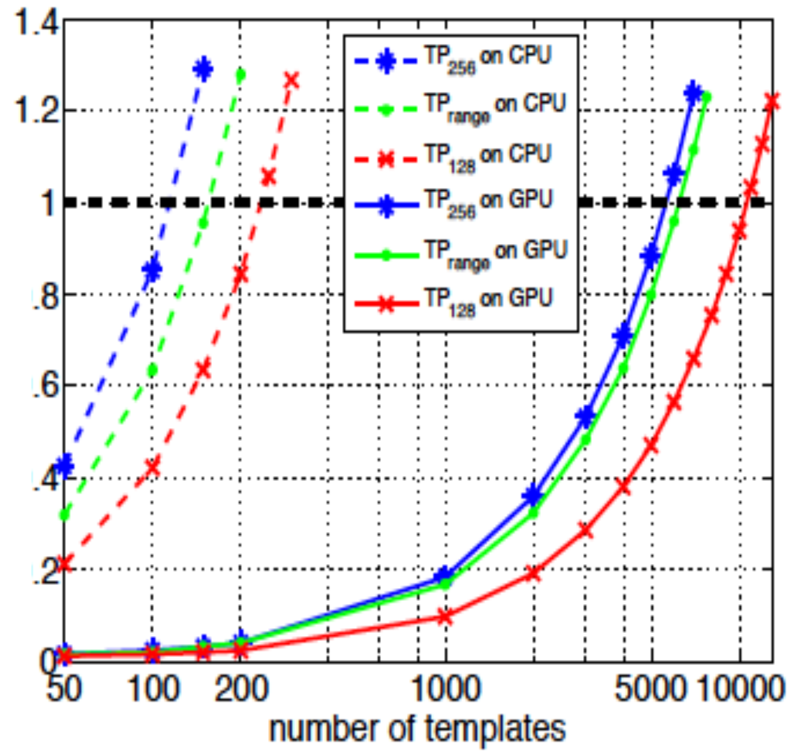
– Tflop supercomputing at desktop !

AUD $400/each

- First application to GW pipeline: x 16 (Chung et al. 2010)
- A community has formed
  - Tools, interface, libraries, template generation
  - Caltech, AEI et al installed the GPU cluster for LIGO data analysis
  - 96 –node GPU cluster @ UWA

C-GPU hybrid pipeline developed and tested on “online” data

Method	Overall Speedup
Straightforward	5.7
Parallel Sum Reduction	14
Reducing Block Level Synchronization	21
Avoid Bank Conflicts	24
Texture Memory	38
Tuning Resource Usage	47



- Used all possible GPU technique one can think of
- x 50 speed-up achieved for search engine compared to single-core CPU
    - Liu Y. BS thesis 2011
    - Liu, Y. MS thesis 2013
    - Liu, Y. et al 2012 CQG
- Other bottleneck in the pipeline to be solved

Conclusion

- Low latency detection will help establish binary merger/sGRB/magnetar/FRB association
  - Every second of latency (from data transfer, pipeline component, etc) counts!
- We have developed an online time-domain search pipeline with <1s latency for the search engine
  - Tested on S5 data with detection efficiency similar to optimal search
  - Successfully run on aLIGO's Engineering Runs
    - latency of 30-40s limited by other part of the pipeline
- Hybrid GPU-accelerated pipeline working
  - Working on the bottleneck with GPUs
- New template interpolation method (Luan J. et al 2012)