Electromagnetic follow-up of gravitational-wave candidate events

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EM follow-up will likely be a **key ingredient** during the **advanced detector era**

Why? – Motivations

What? – EM signals from GW transient sources

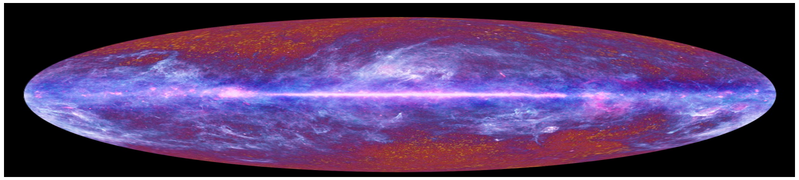
- EM emission mechanism for **binary mergers**
- Gamma-ray bursts and their afterglows
- Other scenarios

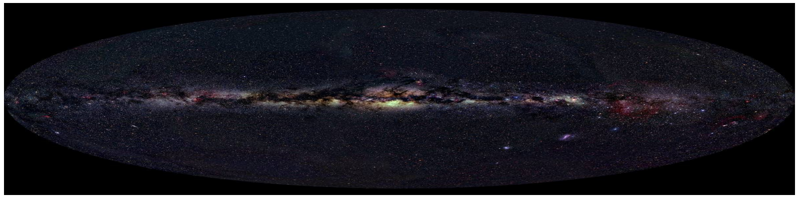
How? – EM follow-up of GW events

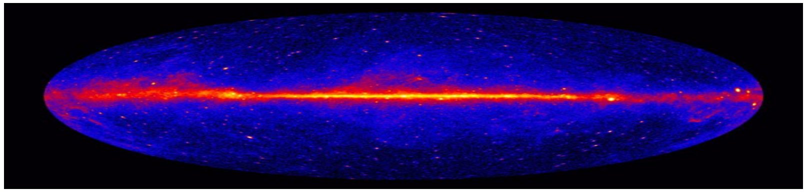
- First EM follow-up program and lessons learned
- Source position reconstruction
- Pointing and observational strategy
- EM transient search (methods, background, ...)

Short history of photon-based astronomy

Multiwavelength

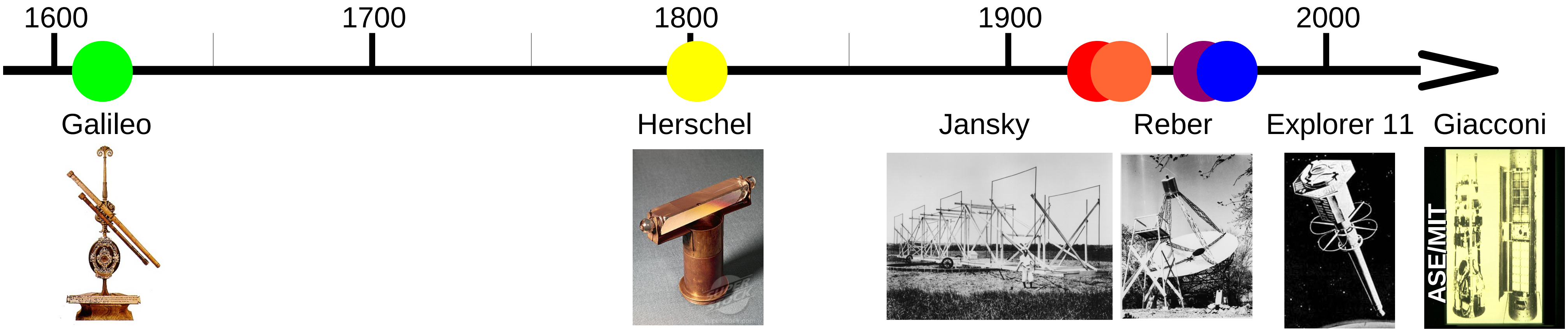






Photon

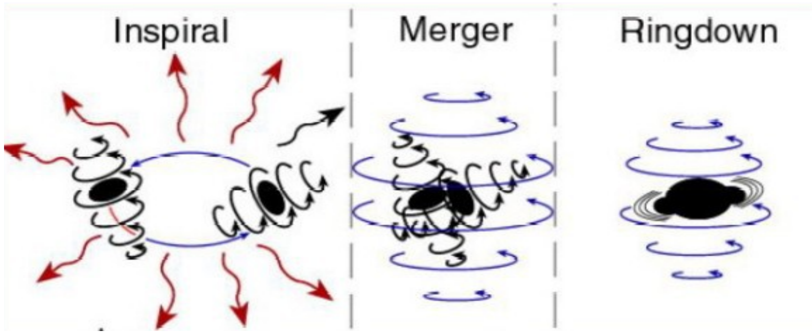
Radio
Micro-wave
Infra-red
Visible
X-rays
Gamma-rays

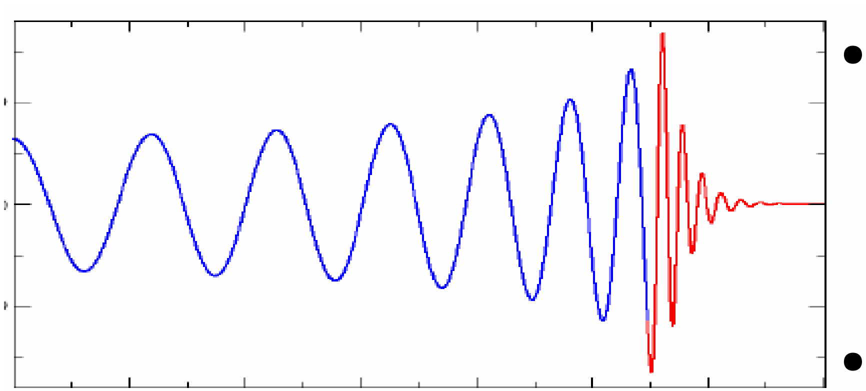


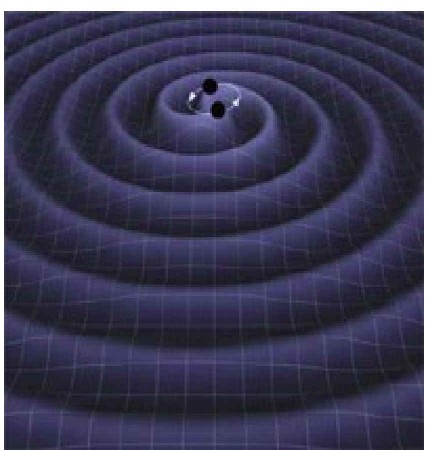
Rationale for multimessenger astronomy

- EM observatories have long history
  - Many orders of magnitude more sensitive than GW detectors
- If we assume that the GW flux fixes the size of the energy reservoir, a **tiny fraction** of this reservoir converted into EM radiation suffices to produce a **detectable signal**
  - Which conversion mechanism?
  - Caveat: source compactness may be an obstacle
- **Motivation for EM follow-up**
  - Pointing telescopes in response to GW observations

GW transients (1)

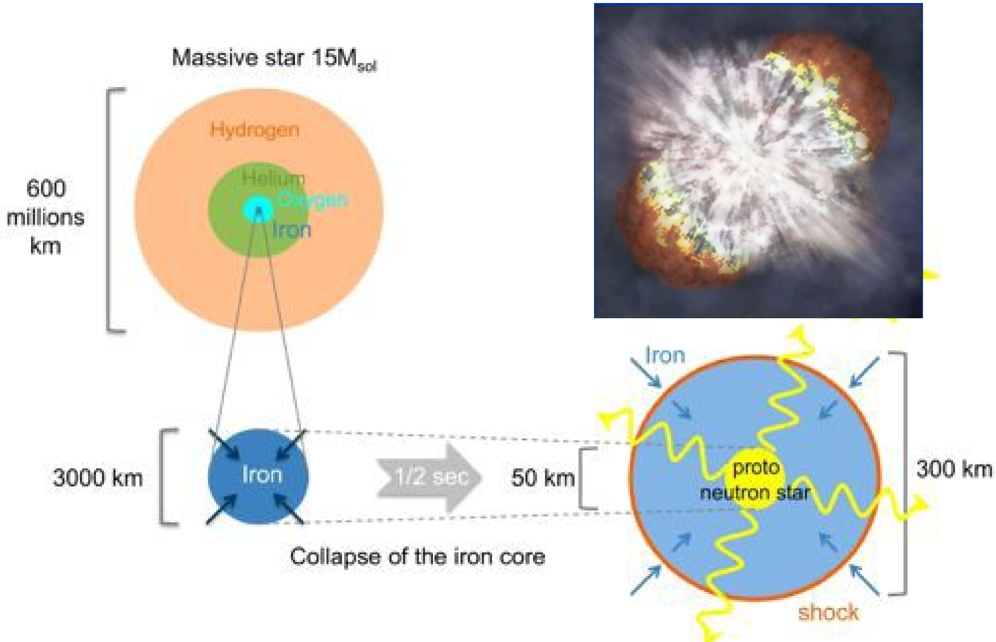


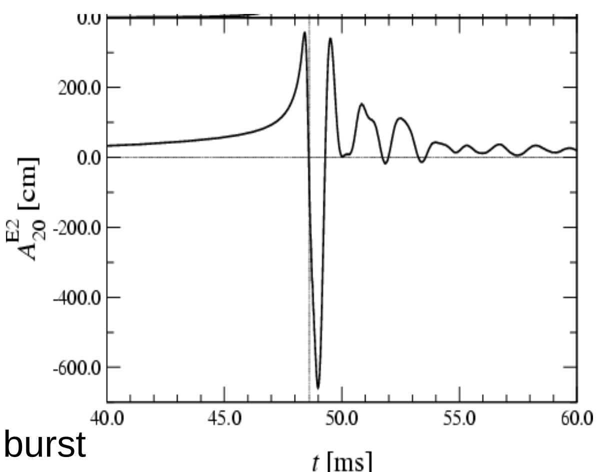




- Coalescing binary mergers
  - ✓ Neutron stars and/or black holes
  - ✓ Three main dynamic regimes of the coalescence
- GW signal from binaries
  - ✓ Frequency modulated signal, “chirp”
  - ✓ SNR is concentrated at ~ few 100 Hz
- Observ. horizon and event rate
  - ✓ NS–NS initial: 20 Mpc, advanced: ~200 Mpc
    < 1/yr 40/yr
  - ✓ NS–BH initial: 50 Mpc, advanced: ~400 Mpc
    < 1/yr 10/yr

GW transients (2)





For monochromatic burst

$$E_{GW} \approx 2\pi^2 \frac{c^3}{G} D_L^2 \, f_0^2 S(f_0) \rho^2$$

- Supernova core collapses
  - ✓ Collapse of the iron stellar core into proto-NS
  - ✓ Infalling material → core bounce → post-bounce shock → explosion
- GW signal from SN CC and rate
  - ✓ GW emission uncertain
  - ✓ Different scenarios

    Core bounce: f_0= 1 kHz, $E_{GW}=10^{-8}$ M$_{sun}$

    → D_L~ 100 kpc, galactic SNCC

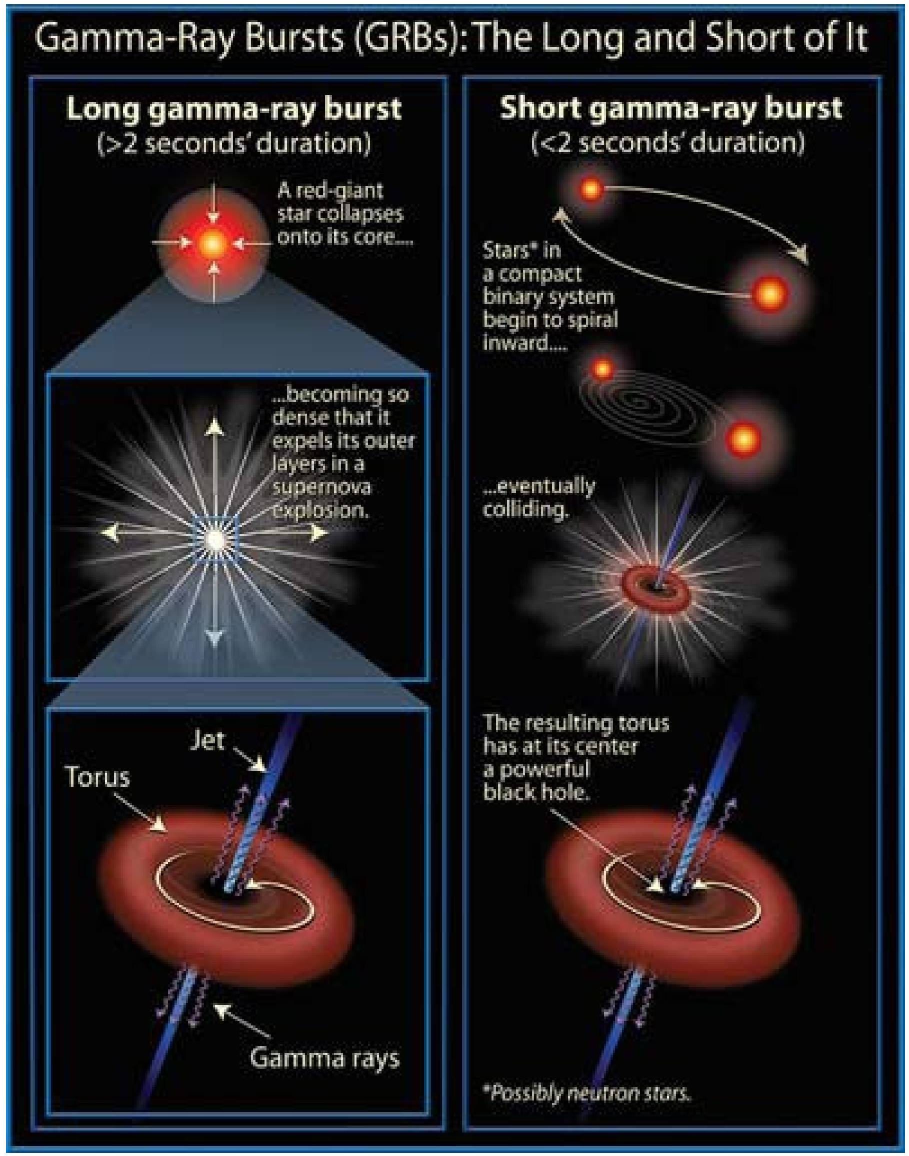
    Fragmentation: f_0= 100 Hz, $E_{GW}=10^{-2}$ M$_{sun}$

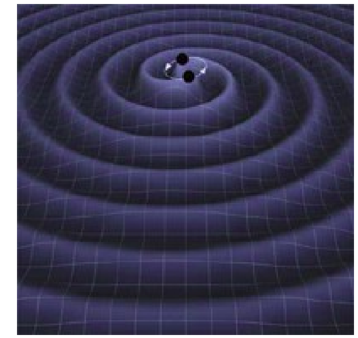
    → D_L~ 200 Mpc
  - ✓ 1/100 yr/galaxy & 1/yr at 10 Mpc

Connection to gamma-ray bursts

LGRB **SHB**

Core collapse of massive stars

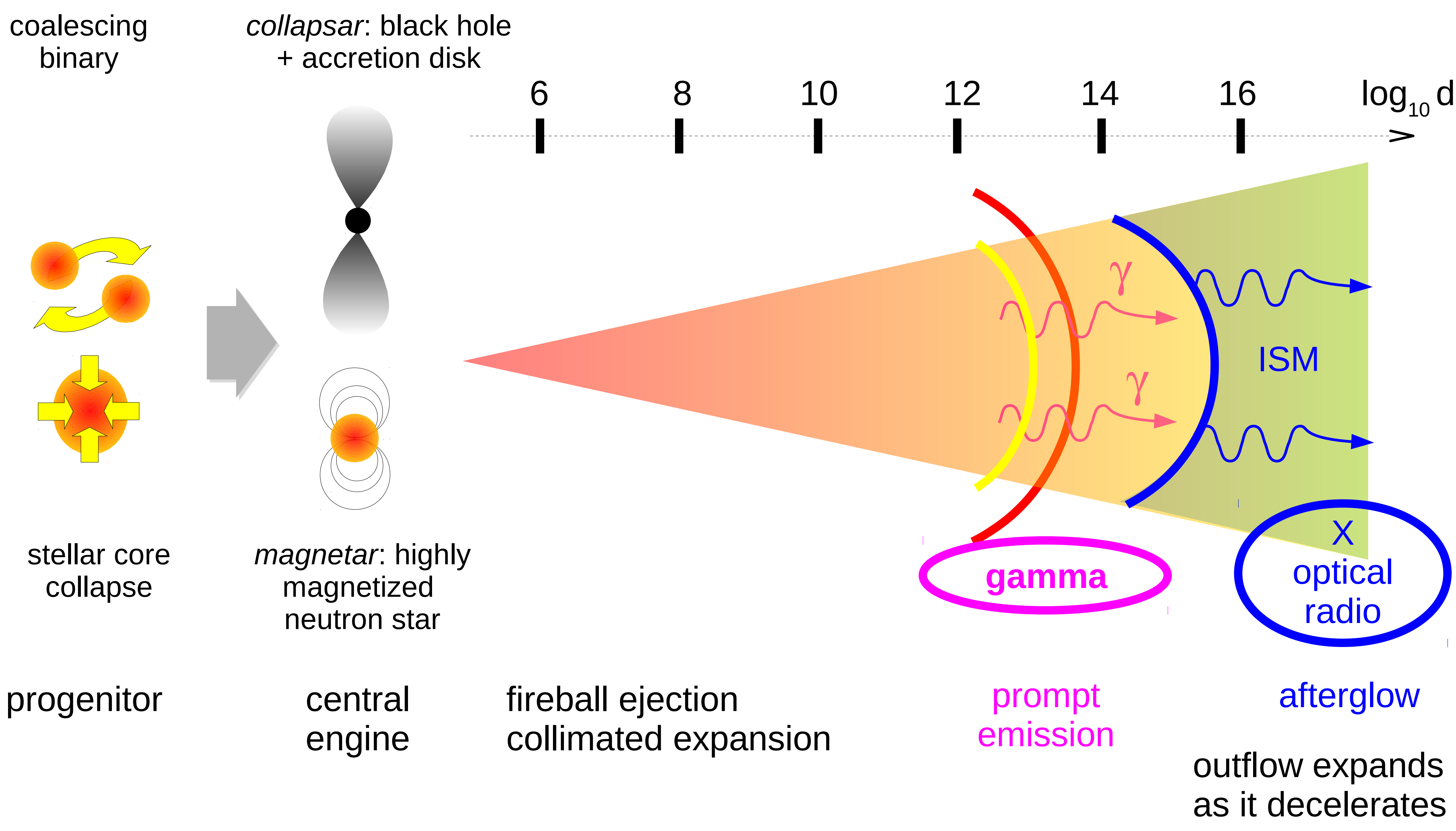




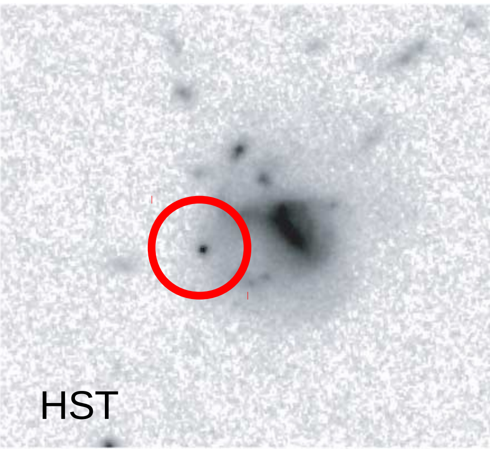
Coalescing binary mergers

Three closest SHBs
GRB 080905, z=0.122 560 Mpc
GRB 050709, z=0.161 760 Mpc
GRB 050724, z=0.257 1.28 Gpc

Gamma-ray bursts

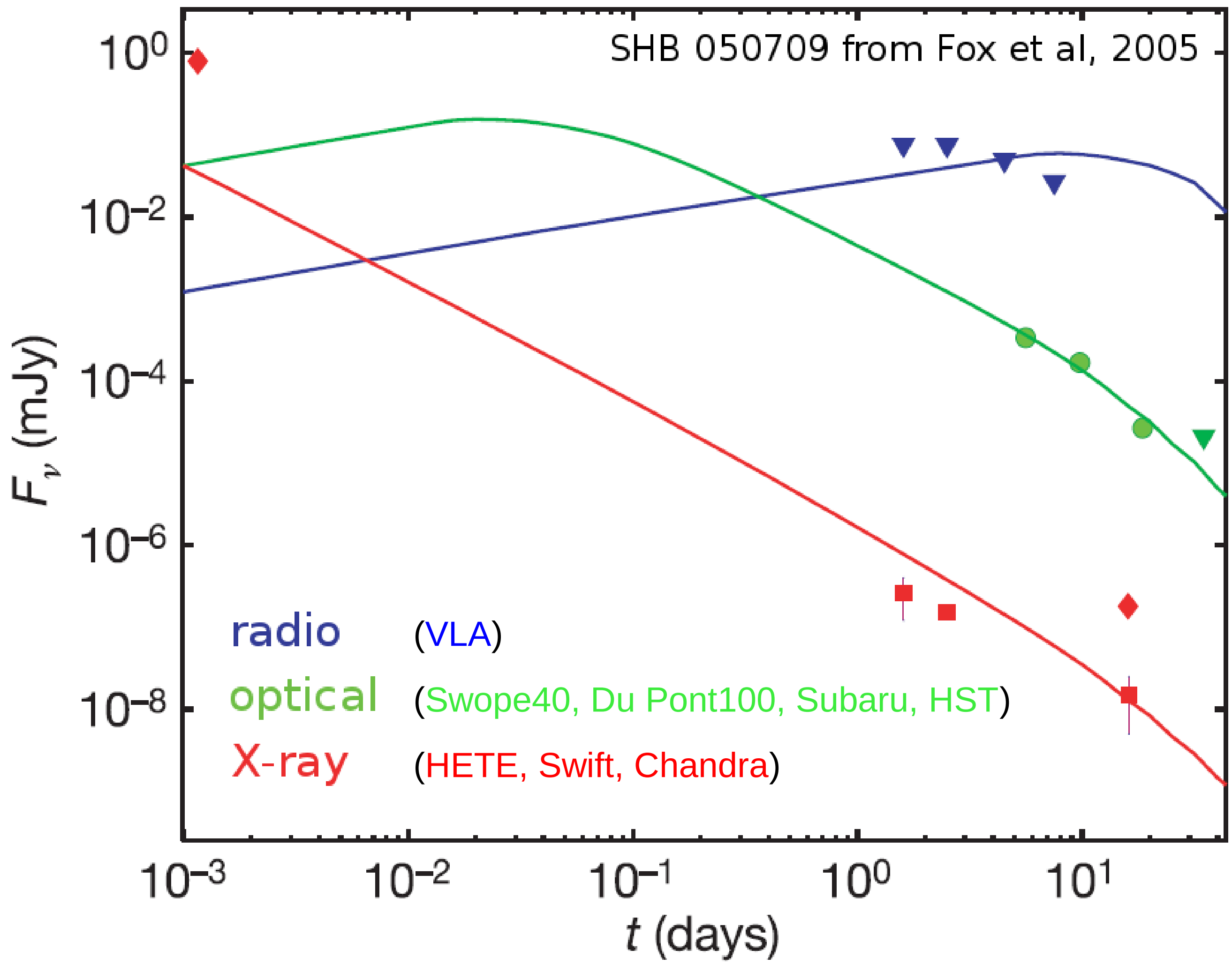


An example :SHB 050709



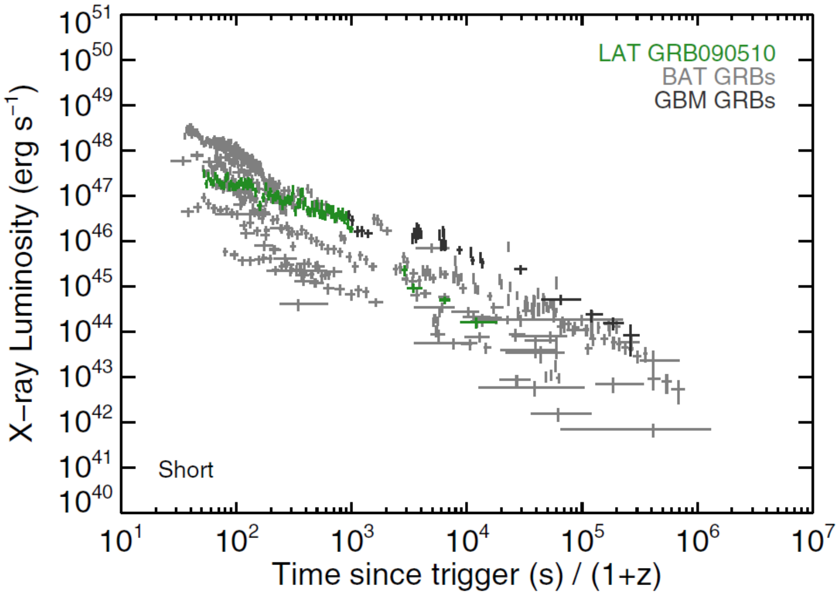
Offset location (typ. 2 kpc) wrt center of host galaxy due to kick at the NS formation

Prompt emission within seconds of the central engine activity

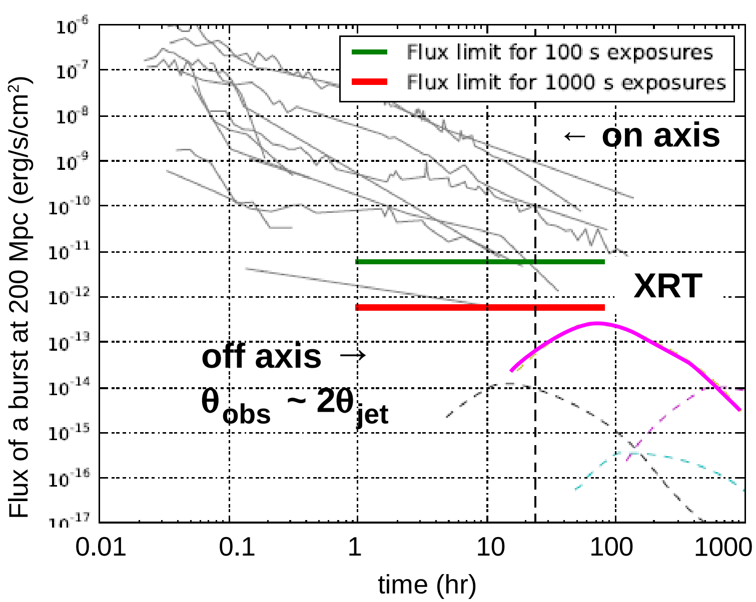


minutes **days** **months**

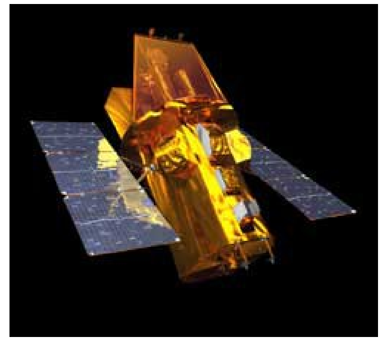
SHB afterglows in the X-rays



Racusin et al. ApJ 738:138, 2011

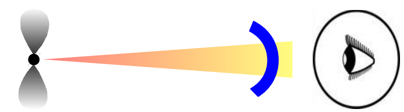


Kanner et al. arXiv:1209.2342



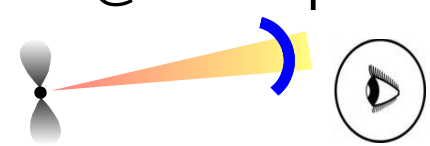
Swift XRT
0.3 keV – 10 keV

- “On-axis”



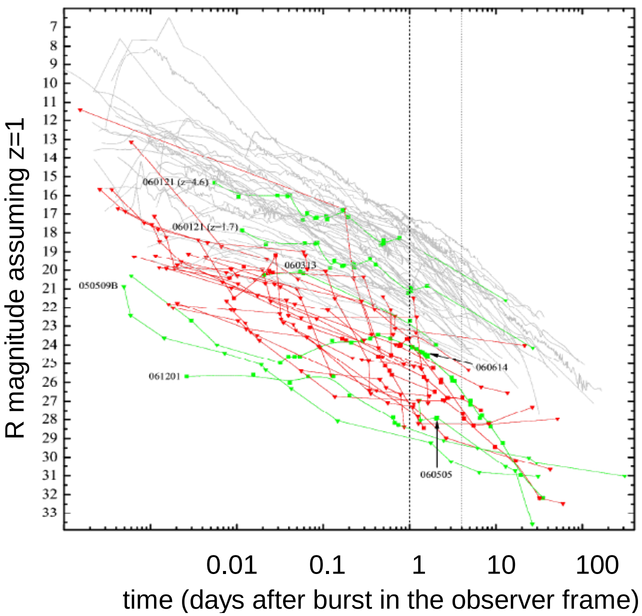
  - ✓ Swift XRT finds the afterglows of 80% of the observed SHBs
  - ✓ decays with $t^{-\alpha}$ with α~1.5 (minutes)
  - ✓ < 10^{45} erg/s after a day
    → 10^{-9} erg/s/cm^2 @ 200 Mpc

- “Off-axis”

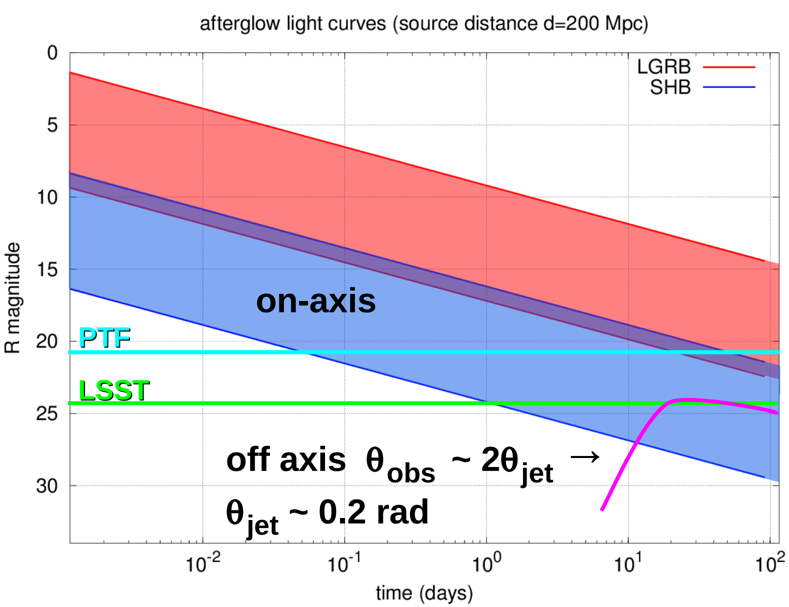


  - ✓ Longer brightnening time (> 1 day to 20 days)
  - ✓ Much fainter: observable with the XRT for close source with long (>10 ks) exposure

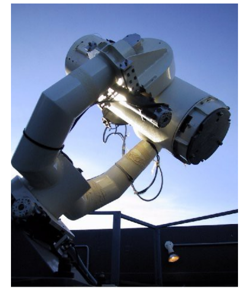
SHB afterglows in the optical & near IR

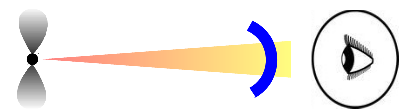
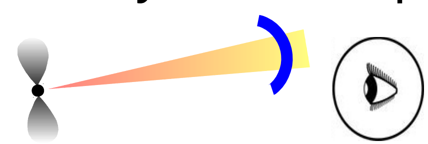


Kann et al, arXiv:0854.1959



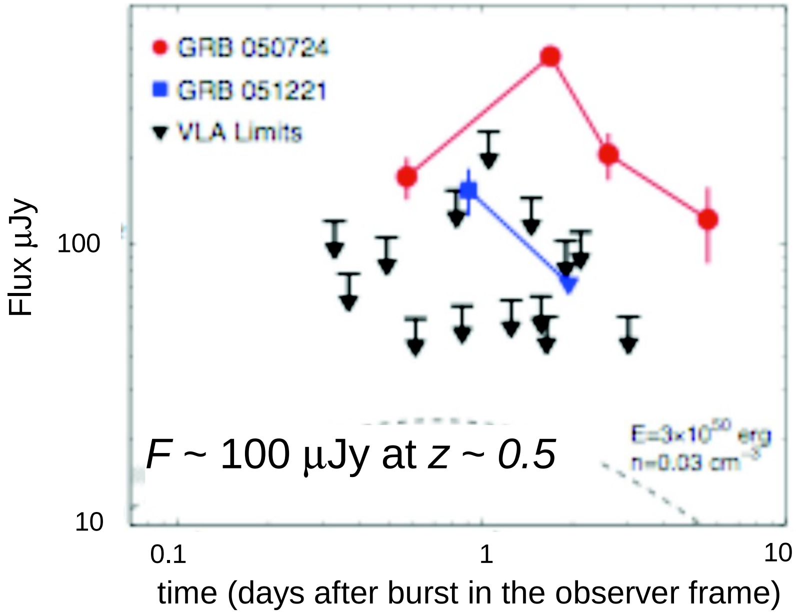
Van Eerten et al., ApJ, 733 L37



- “On-axis” 
  - ~30% of the detected SHB afterglows are observed
  - decays as $L \sim t^{\alpha}$ with $\alpha \sim 1 - 1.5$ (hours)
  - m_R~16-24 after a day @ 200 Mpc
- “Off-axis” 
  - Longer brightening time (> 10 days)
  - Much fainter: R > 20 @ 100 Mpc, close source and large aperture telescopes

apparent magnitude: $m = -2.5 \log_{10} \mathcal{F}_{obs} + C$

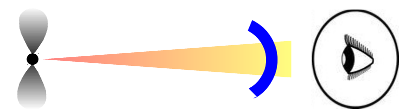
SHB afterglows in the radio band



Courtesy D. Frail

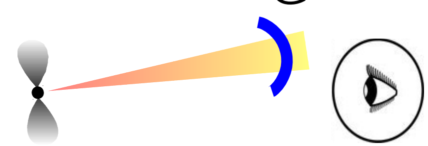
VLA
GHz

- "On-axis"

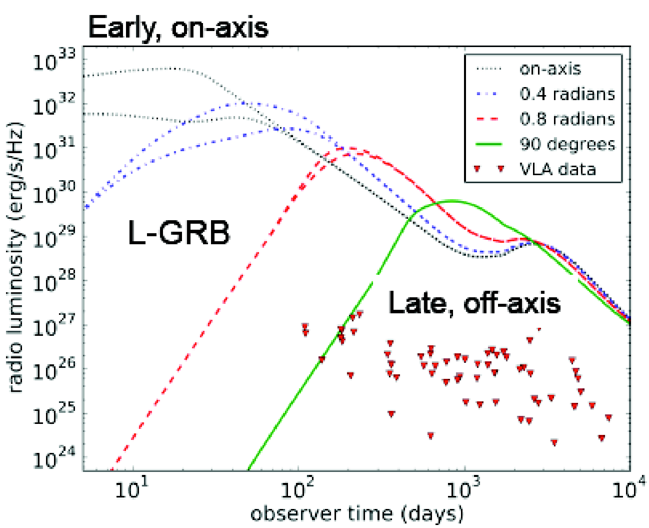


  - ✓ 2 (3?) SHB afterglows detected in the radio band: GRB 050724, 051221, 121226A?

    many more radio afterglows of LGRB observed
  - ✓ Typical decay time ~ weeks
  - ✓ *F* ~O(10) mJy at 1-10 GHz @ 200 Mpc
- "Off-axis"

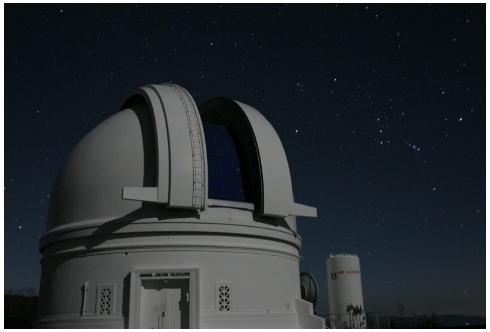


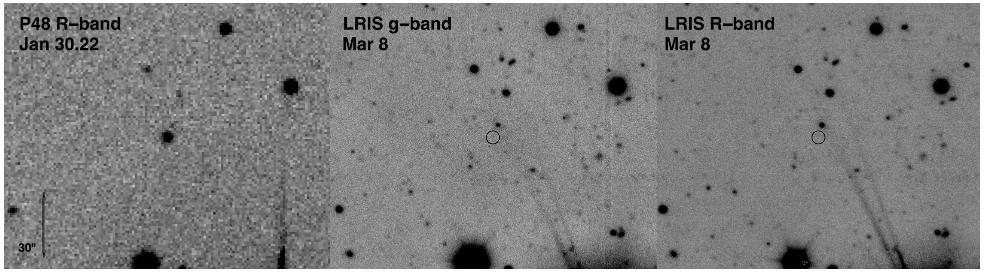
  - ✓ Longer brightnening time (months to year!)
  - Much fainter but still detectable: t=30 days, F=0.3 mJy at 1 GHz @ 300 Mpc

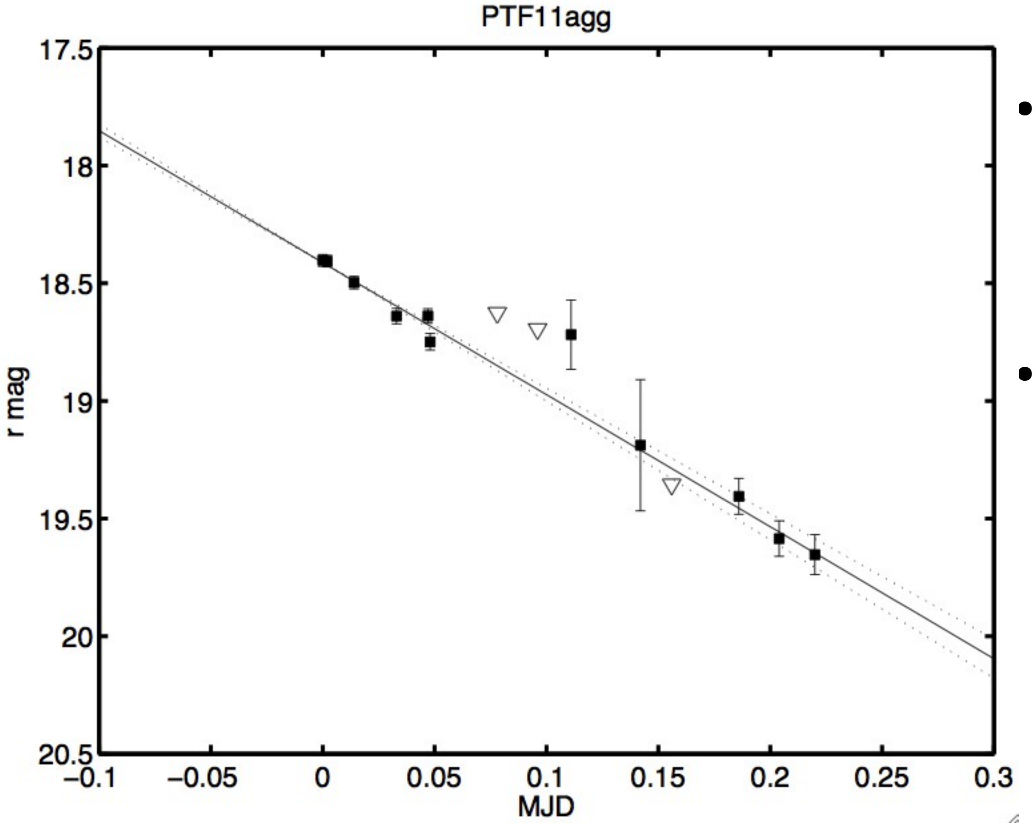


Van Eerten et al., ApJ, 733 L37

“Orphan” afterglow





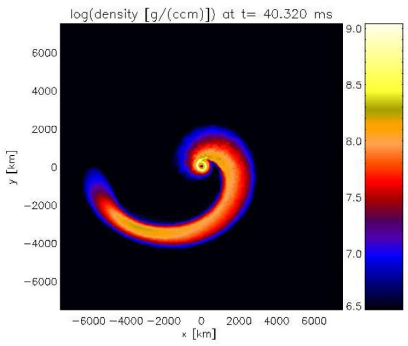


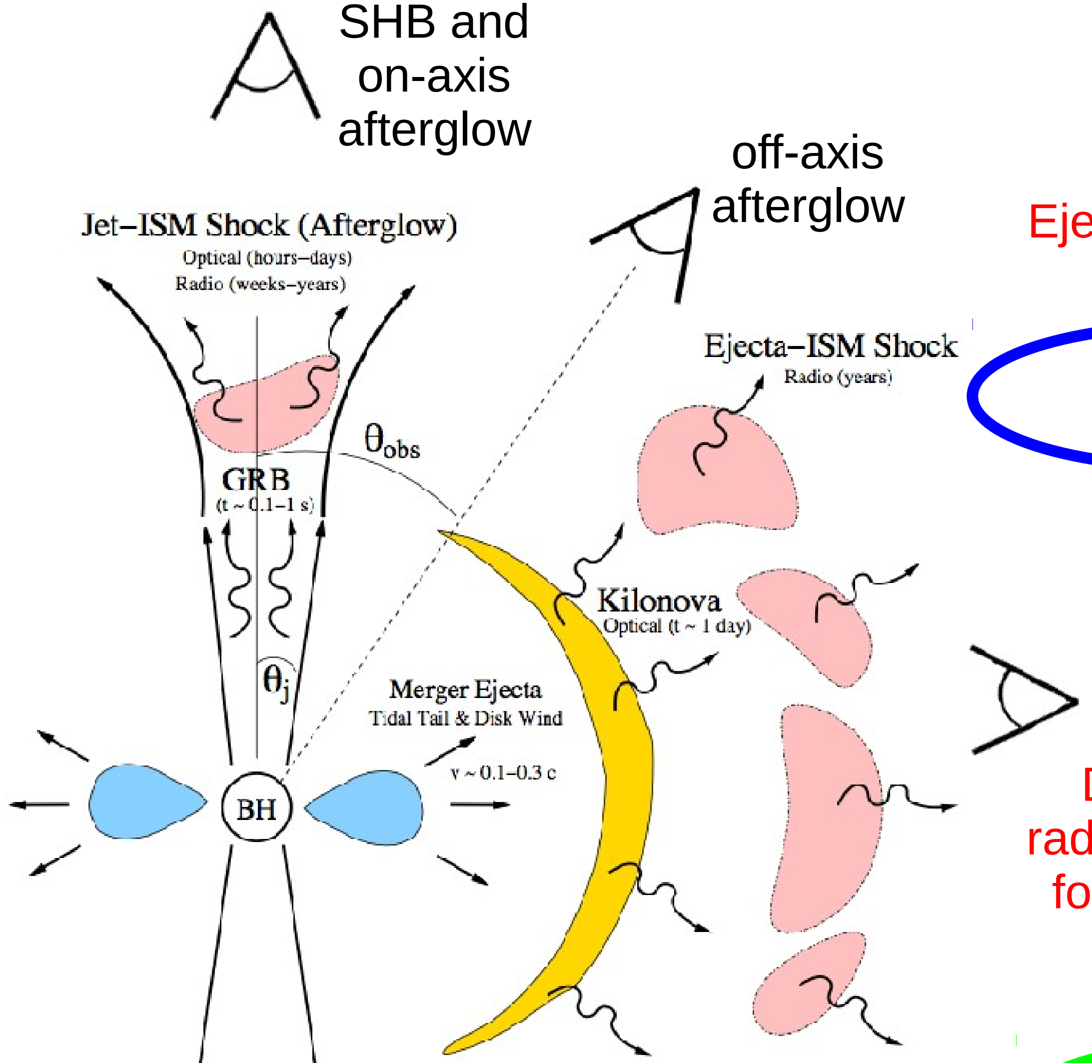
Bradley Cenko et al. arXiv:1304.4236

- PTF11agg, 2011 Jan 30 detected by the Palomar 48 inch telescope
  - Bright (R~18.5 mag) rapidly fading (+4 mag in 2 days) optical transient
  - No connection to HE trigger
- Galactic origin is excluded
  - Blue quiescent
  - Year-long, scintillating radio transient
- LGRB as an extragalactic source?
  - "Untriggered", lack of satellite coverage simplest explanation but unlikely (~2.6 %)
  - "Orphan" afterglow: viewing-angle effects but obs inconsistent with off-axis afterglow
  - "Dirty fireball": suppressed HE emission in that case: pop. > 4 x larger than LGRB

Other (unobserved) scenario

Tidal tails form an accretion disk





Ejecta-ISM shock

radio transient

Decay of heavy radioactive elements formed by neutron capture

thermal optical transient

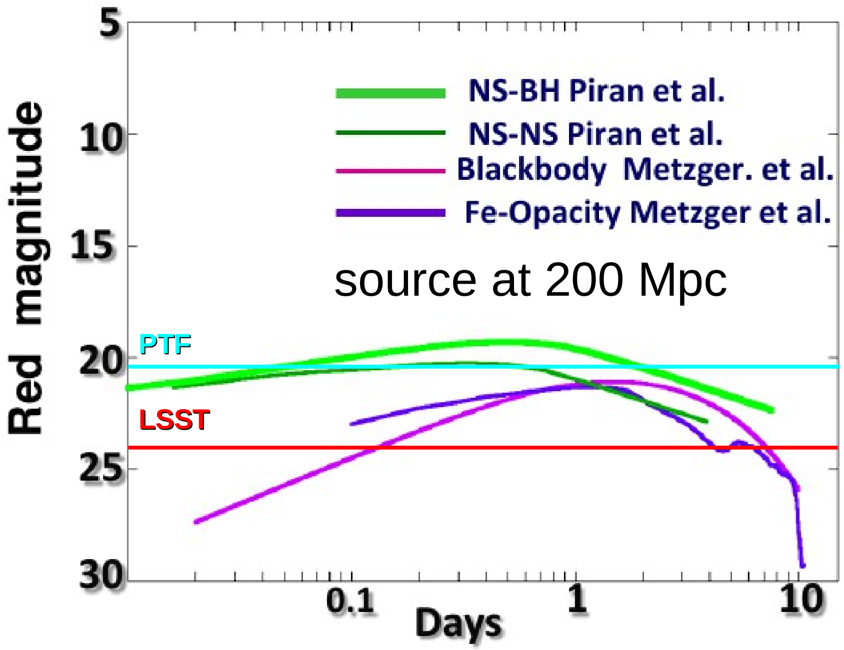
Disk wind: neutrino cooling & nuclear recombination

.1 M_{sun} ejected at v~.1c

Courtesy of B. Metzger
See Piran et al MNRAS 2013 and ref. therein

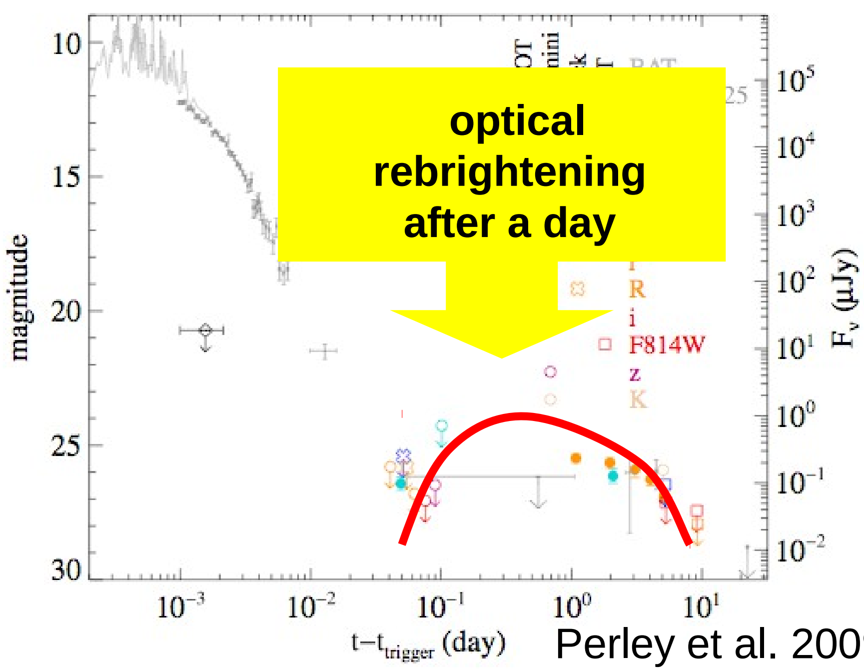
Macronova
Kilonova

Macro/kilonova optical transients



Courtesy of M Branchesi

GRB 080503: Candidate Kilonova



Perley et al. 2009

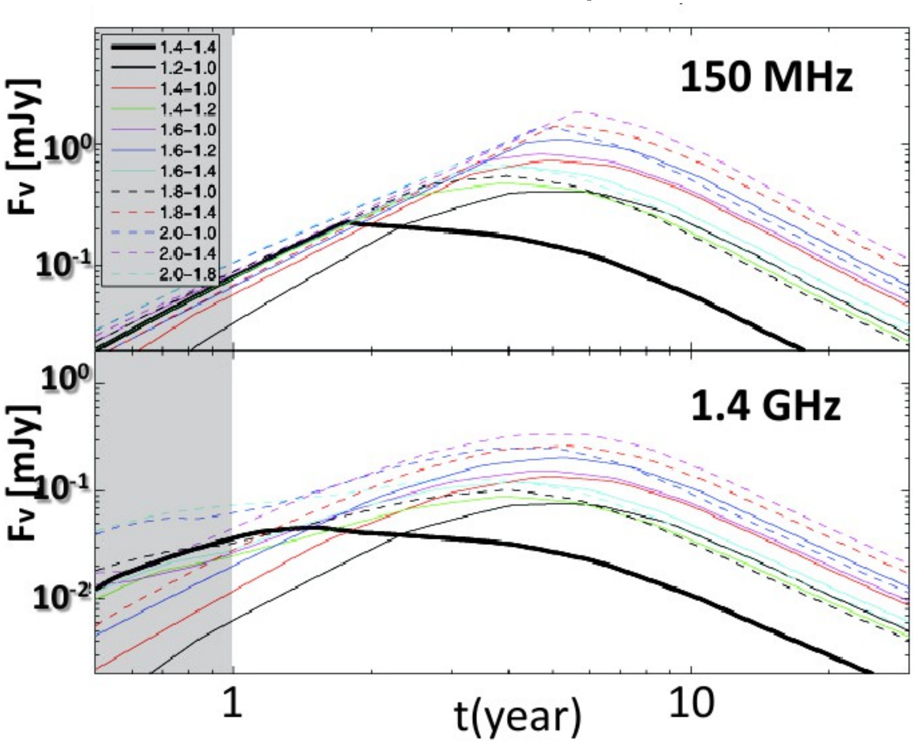
- EM transient similar to supernova
  - Isotropic
  - Luminosity peak about a day after merger
  - R > 20 mag @ 200 Mpc

    Requires large telescopes
  - Uncertainty due to unknown opacity of heavy r-process elements

- GRB080503: potential candidate?

Macro/kilonova radio transients

source at 300 Mpc



ISM density: n~1/cm^3

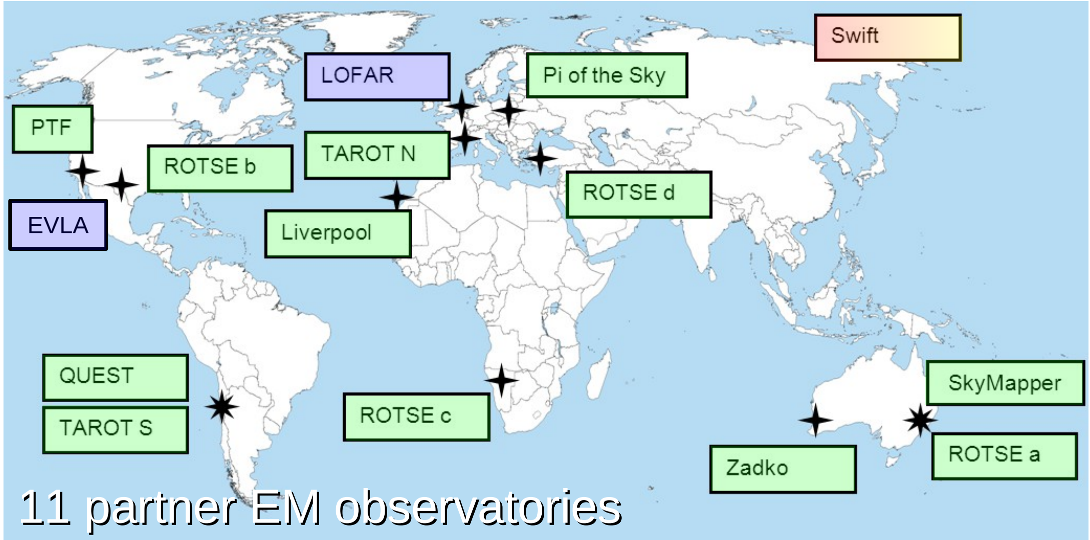
- Year-long radio flare
  - ✓ Peaks 1 – 5 years after merger
  - ✓ Larger signal < 1 mJy in the low-frequency band (100 MHz)

    Target for LOFAR
  - ✓ Depends on ambient density!

Courtesy of M Branchesi
Piran et al MNRAS 2013

First EM follow-up program

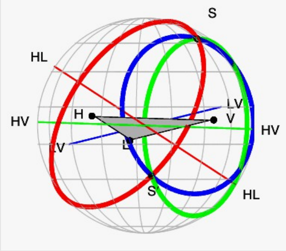
- Dec 2009-Oct 2010, S6/VSR2/3
  - ✔ Initial detectors, horizon < 50 Mpc
  - ✔ Three operating GW detectors required for source direction rec
  - ✔ 14 GW alerts, 9 followed-up by at least 1 partner



GW data from HLV

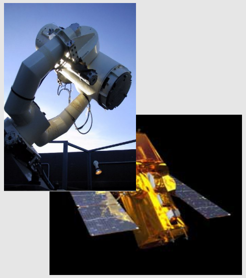
Low-latency analysis GW trigger selection

Source direction reconstruction



Alert validation

Partner EM observatories



CBC & bursts

10 mins

30 mins

Lessons learned

- Source position reconstruction
  - ✓ Characterization of the GW error box
- Pointing strategy
  - ✓ Field of View (FoV) of EM obs. << GW angular error

    Techniques to increase probability of correct pointing

    (e.g., catalog of local galaxies, …)
- Searches for EM transients
  - ✓ Observational strategy (cadence)
  - ✓ Methods for detecting EM transients
  - ✓ Characterization of background

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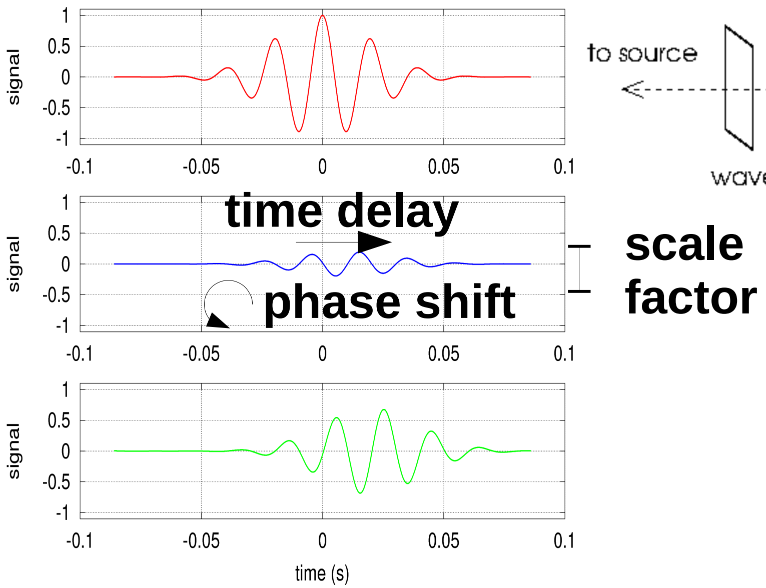
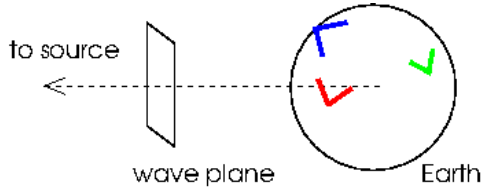
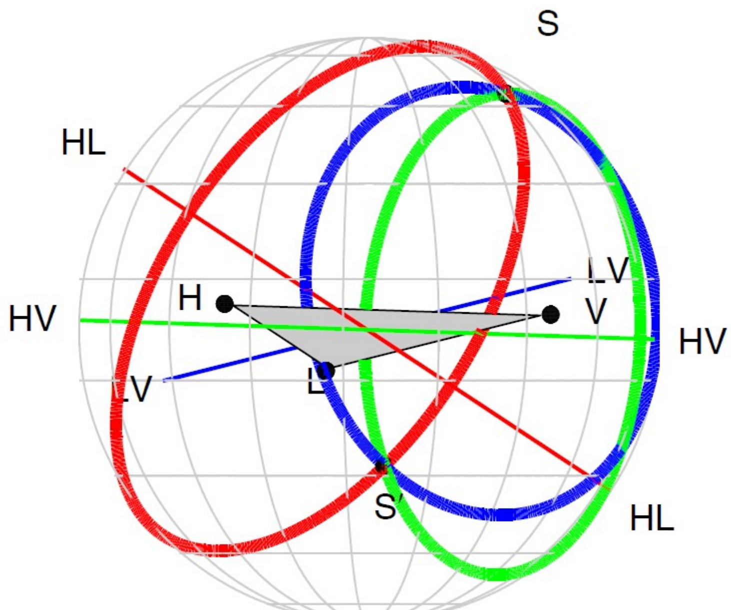
Source position reconstruction (1)







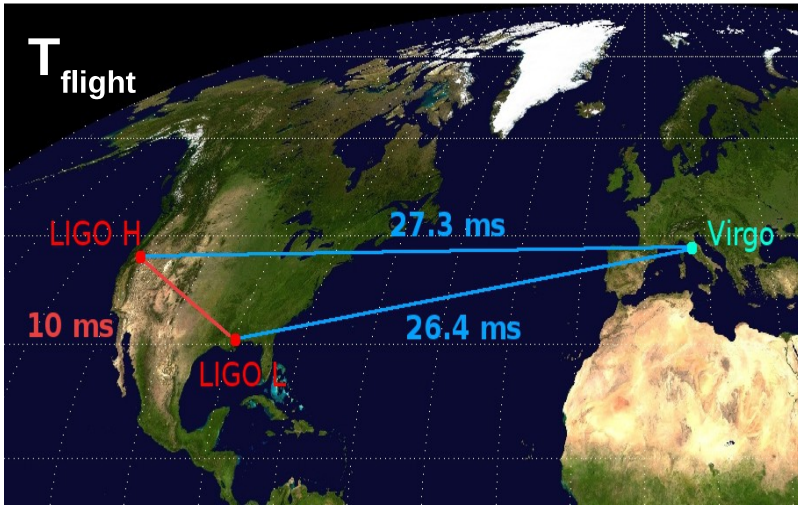
- Response of detector network
  - Detectors receive the same wave...
  - … but the wave couples differently

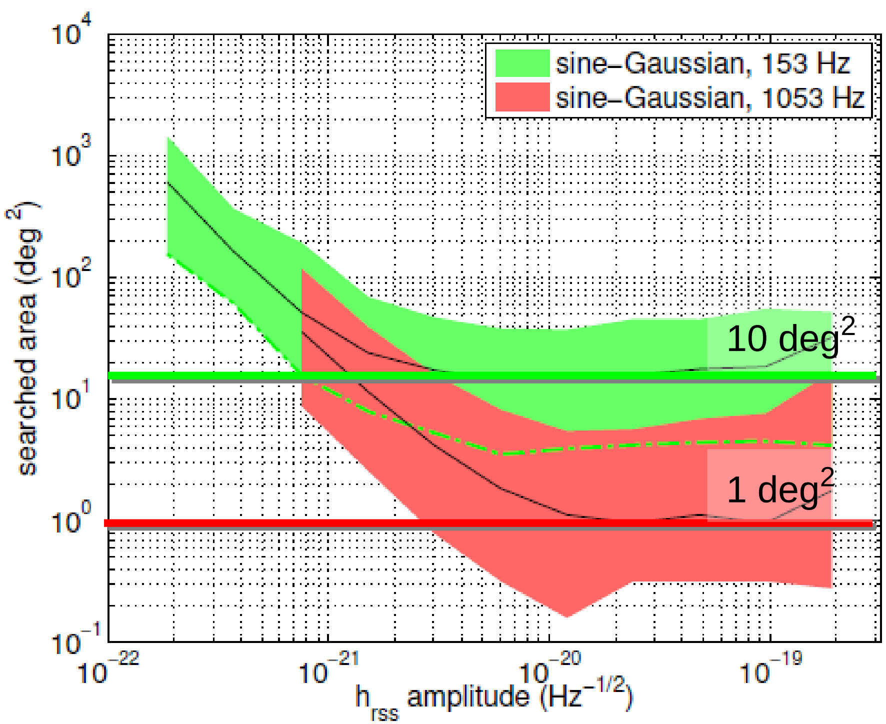
$$s(t) = F_+ h_+(t-\tau) + F_\times h_\times(t-\tau)$$

- Use of multi-detector data
  - Sensitivity improvement
  - **Source direction reconstruction**

If using timing information only → **triangulation** (leading order approximation)

Source position reconstruction (2)





Aasi et al, arXiv:1304.0670

- Triangulation angular error
  - Timing uncertainty $\sigma_t \approx (2\pi\rho\sigma_f)^{-1}$

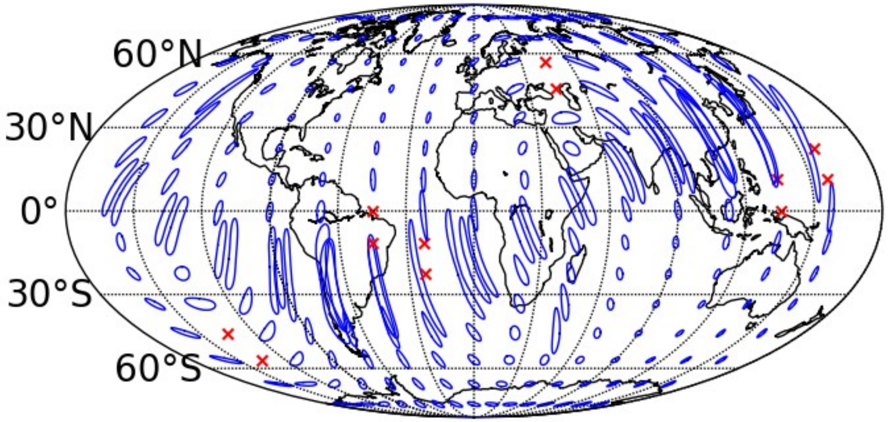
    SNR ρ =10, in the bucket, σ_t ~ 0.1 ms
  - Diffraction limit estimate

    σ_t / T_{flight} ~ 4 degrees

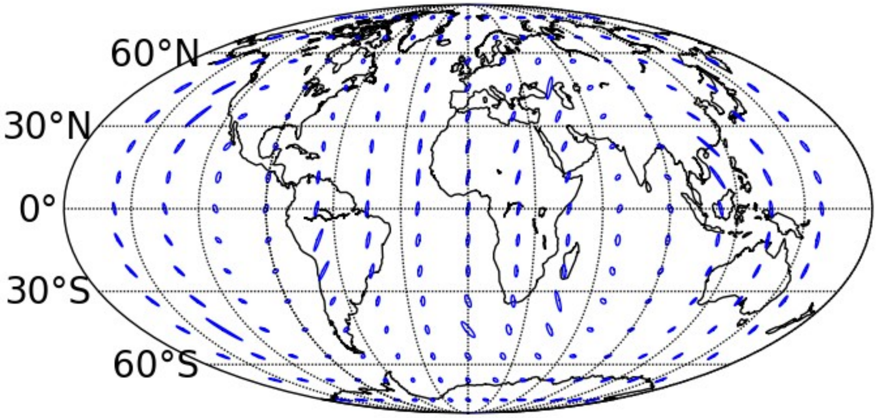
    → tens of square degrees
  - Better resolution for burst at higher frequencies

Source position reconstruction (3)

BNS 160 Mpc HLV 2019+
~30 % contained in 20 deg^2



BNS 160 Mpc HILV 2022+
~50 % contained in 20 deg^2



- Localization of binary systems
  - Non-trivial interplay between sensitivity and angular error

    Better sensitivity → larger SNR ρ and larger bandwidth σ_t
- More detectors around the globe
  - Long baseline between detectors leads to large improvements in the angular resolution
  - LCGT (Japan), LIGO India
  - Ultimate subdegree resolution with five detectors

Aasi et al, arXiv:1304.0670

Lessons learned

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    (e.g., catalog of local galaxies, …)
- Searches for EM transients
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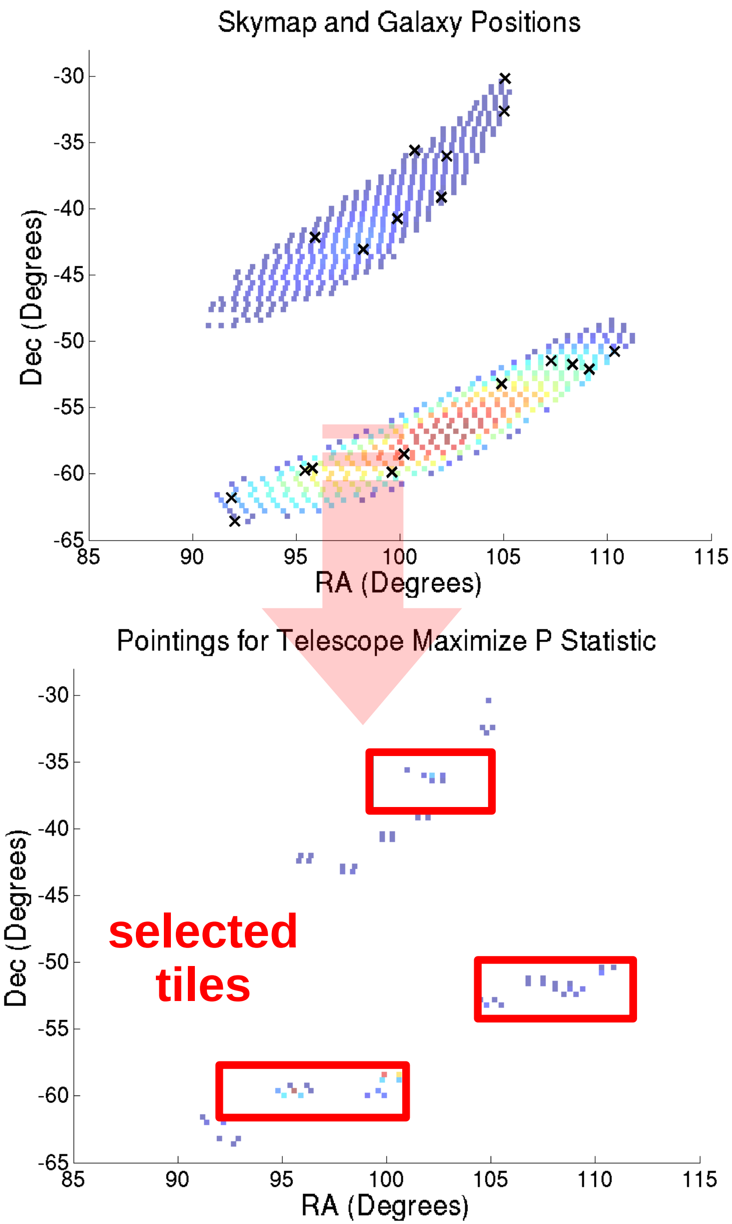
Pointing strategy (1)

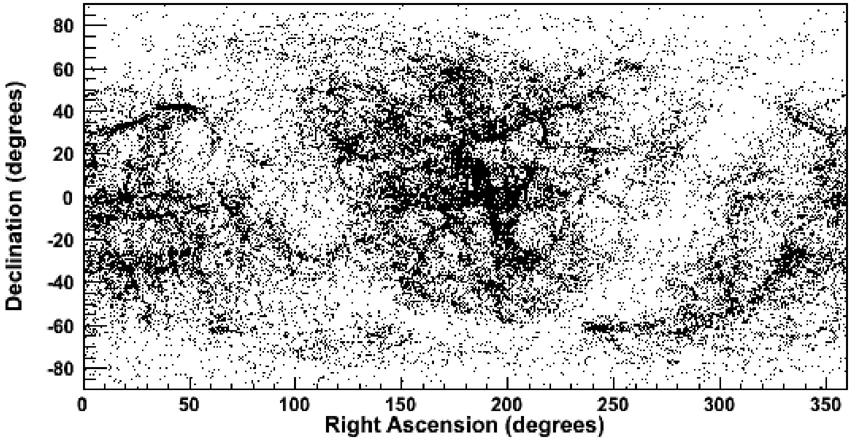


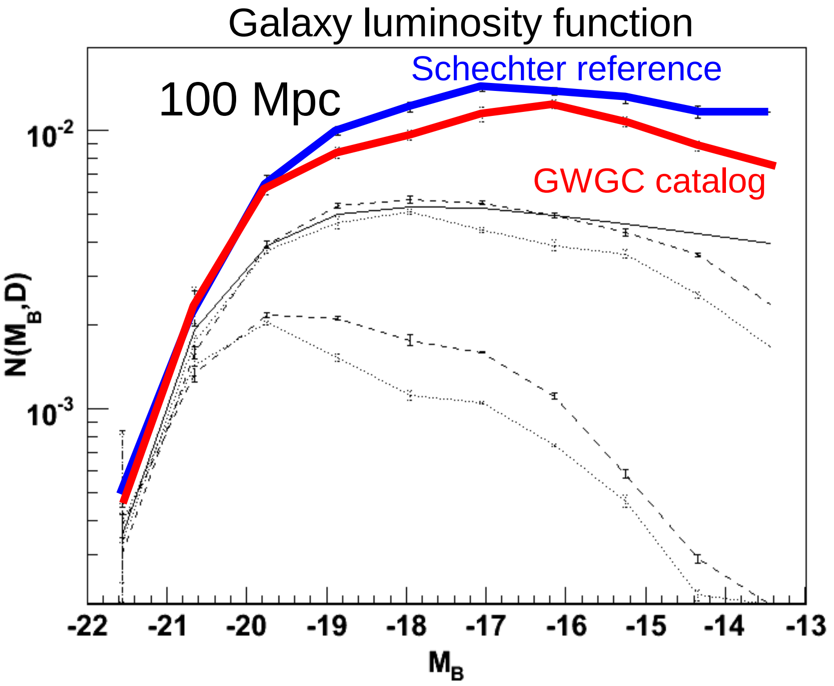
- Posterior sky map
  - Composed of disconnected islands
- Galaxy weighing
  - Local distrib. of mass is heterogeneous at small distances
  - **Observe close and massive galaxies first**
  - Ad-hoc ranking statistic

$$P = \sum_{\text{gal} \in \text{pixel}} \frac{\text{mass(gal) likelihood (pixel)}}{\text{distance(gal)}}$$

  - Used catalog of close galaxies: GWGC
  - Factor of 2 improvement in the probability of a correct pointing for initial detectors (50 Mpc)

Pointing strategy (2)





- Galaxy catalogs incomplete from 100 Mpc
  - Surveys of local galaxies (WALLABY and Hα) are upcoming.
- Galaxy distribution to 400 Mpc is isotropic
  - No significant gain in galaxy weighting
- Other ideas?
  - Select hosts that are consistent to binary distance estimate
  - Select potential hosts based on their type

Lessons learned

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- Searches for EM transients
  - Observational strategy (cadence)
  - Methods for detecting EM transients
  - Characterization of background

Lessons learned

- Source position reconstruction
  - Characterization of the GW error box
- Pointing strategy
  - Field of View (FoV) of EM obs. << GW angular error

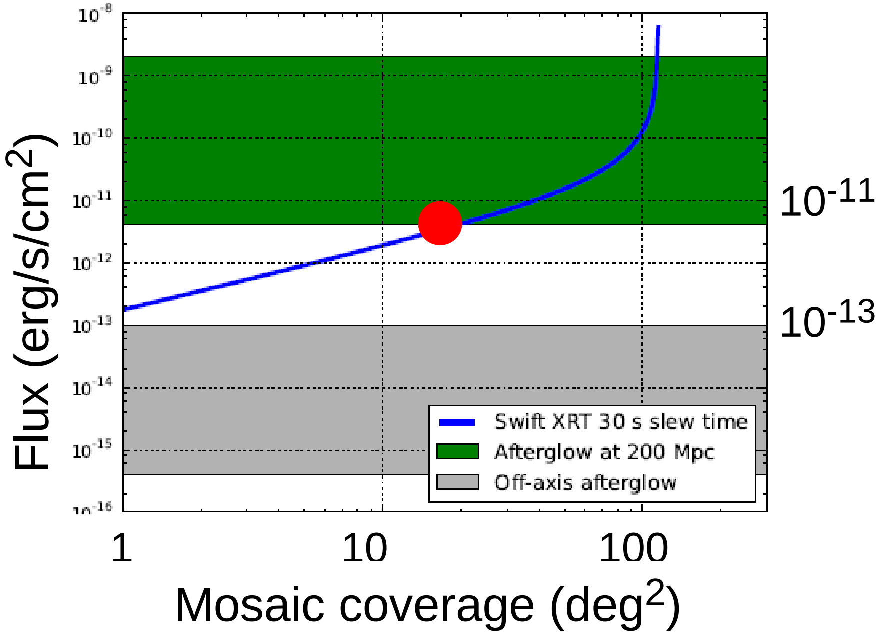
    Techniques to increase probability of correct pointing

    (e.g., catalog of local galaxies, …)
- Searches for EM transients
  - Observational strategy (cadence)
  - Methods for detecting EM transients
  - Characterization of background

X-ray **optical** ~~**radio**~~

Observational strategy
X-rays

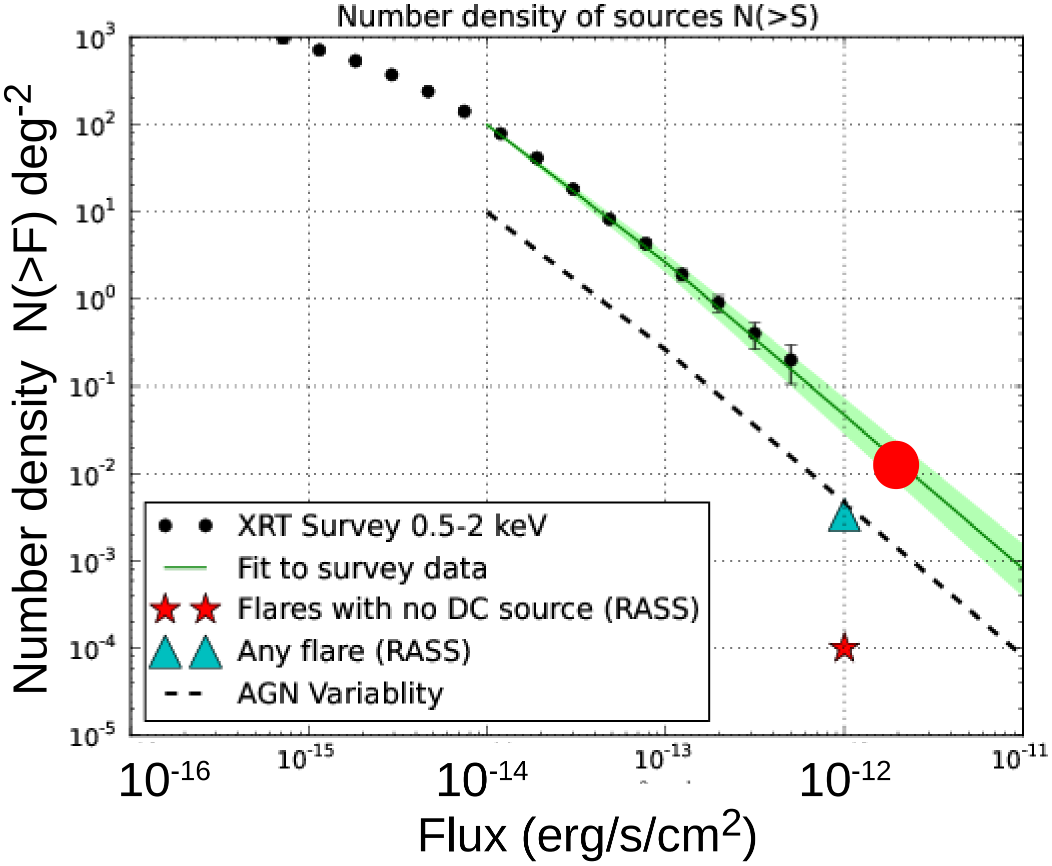
Swift XRT FoV=0.16 deg^2, 24 hr total



- Depth/cadence/area trade-off
  - ✓ Fix amount of total observation time Short exposures → large mosaic *but* bad sensitivity and vice versa
  - ✓ ~300 exposures of 100 sec → 35 deg^2 in 1 orbit at 6 x 10^{-12} erg/s/cm^2

Kanner et al. arXiv:1209.2342

Search for EM transients (1)
X-rays

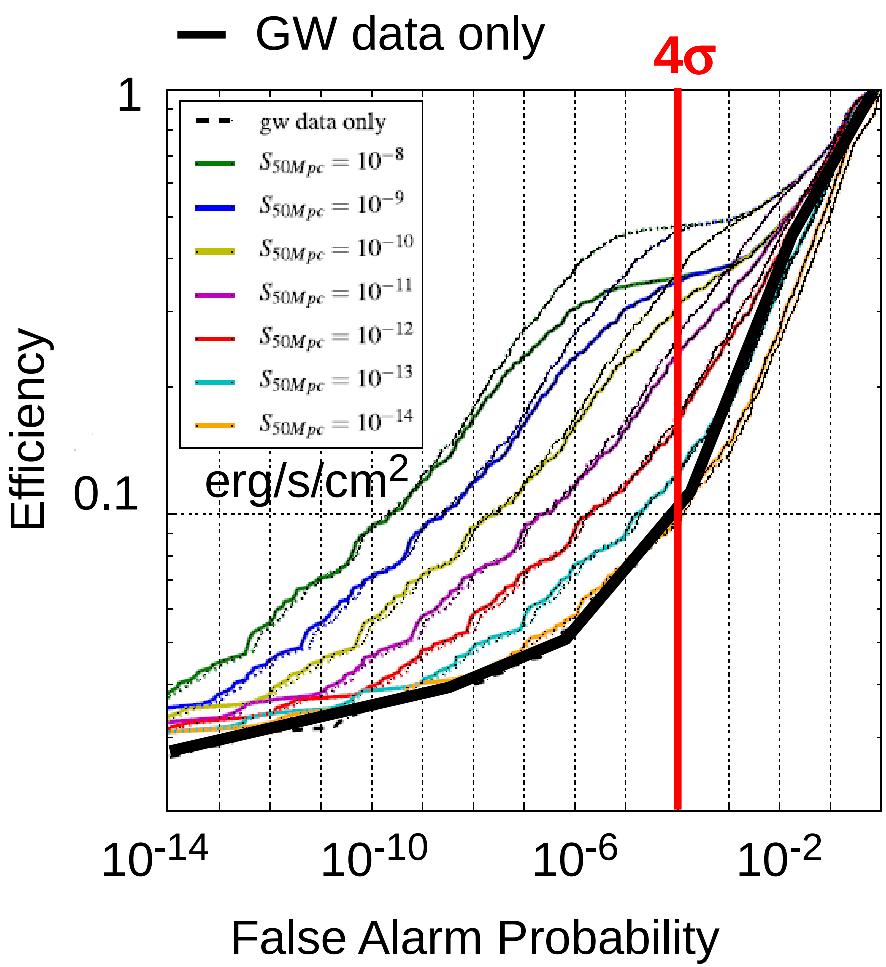


- X-ray sky is quiet
  - O(1) extragalactic sources of flux > 2 x 10^{-12} erg/s/cm^2 in 100 deg^2
  - Impose variability leads to a lower background

    variable AGN, limit on variable sources ROSAT all-sky survey

    1% sources of flux > 2 x 10^{-12} erg/s/cm^2 in 100 deg^2

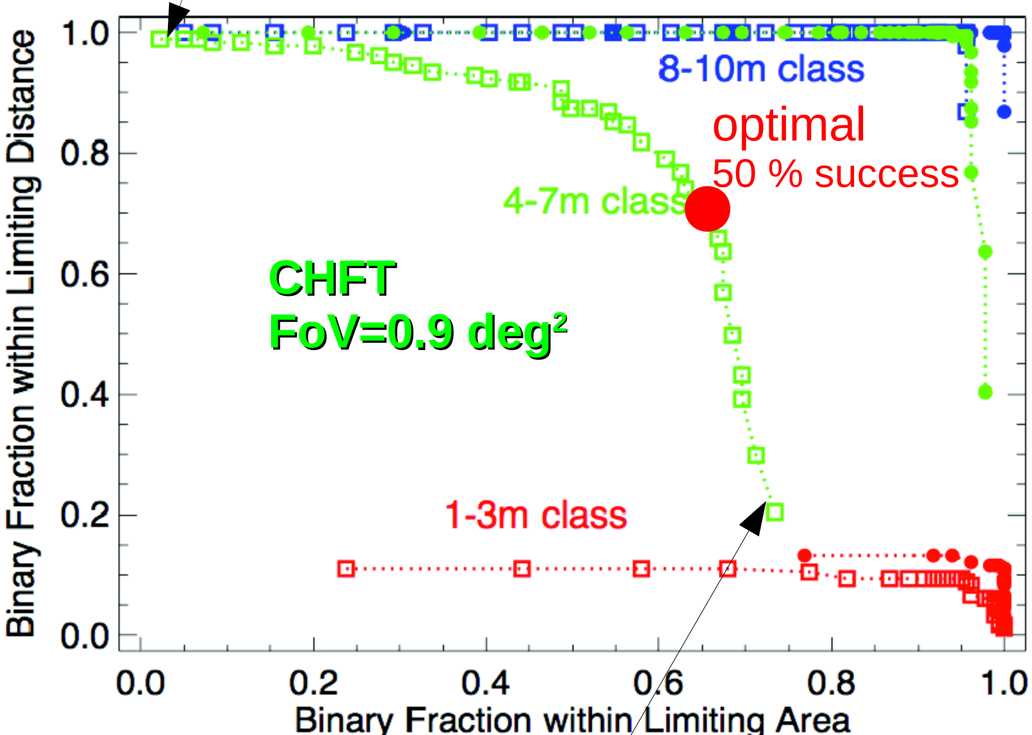
Search for EM transients (2)
X-rays



- Sensitivity of a combined search
  - Require X-ray counterpart → reject background → relax cuts → increase sensitivity
  - x ~2 improvement for an X-ray flux of 10^{-12} erg/s/cm^2 at FAP=4σ
  - Saturation at large fluxes: sources missed because not targetted (not in the selected tiles)

Observational strategy
Optical/NIR

Single long exposure
m_R= 25 (650 Mpc)



Many short exposures
m_R= 23 (250 Mpc)

- Depth/cadence/area trade-off
  - ✓ Assume population of BNS search for kilonova-like transient: isotropic, M_R=-14 for 2 hrs

$$m = -2.5 \log_{10} \mathcal{F}_{obs} + C$$
$$= M - 5 \log_{10} D_L / 10 \,\text{parsec}$$

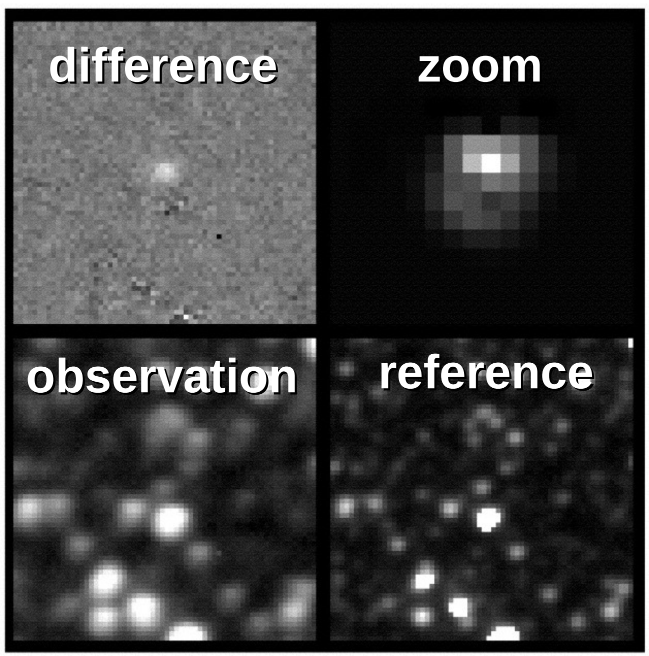
  - ✓ Budget: 3 x 1 hour
  - ✓ Detection in 3 images

Conclusion: large telescopes required but meter-class telescopes may contribute

Nissanke et al, arXiv:1210.6362

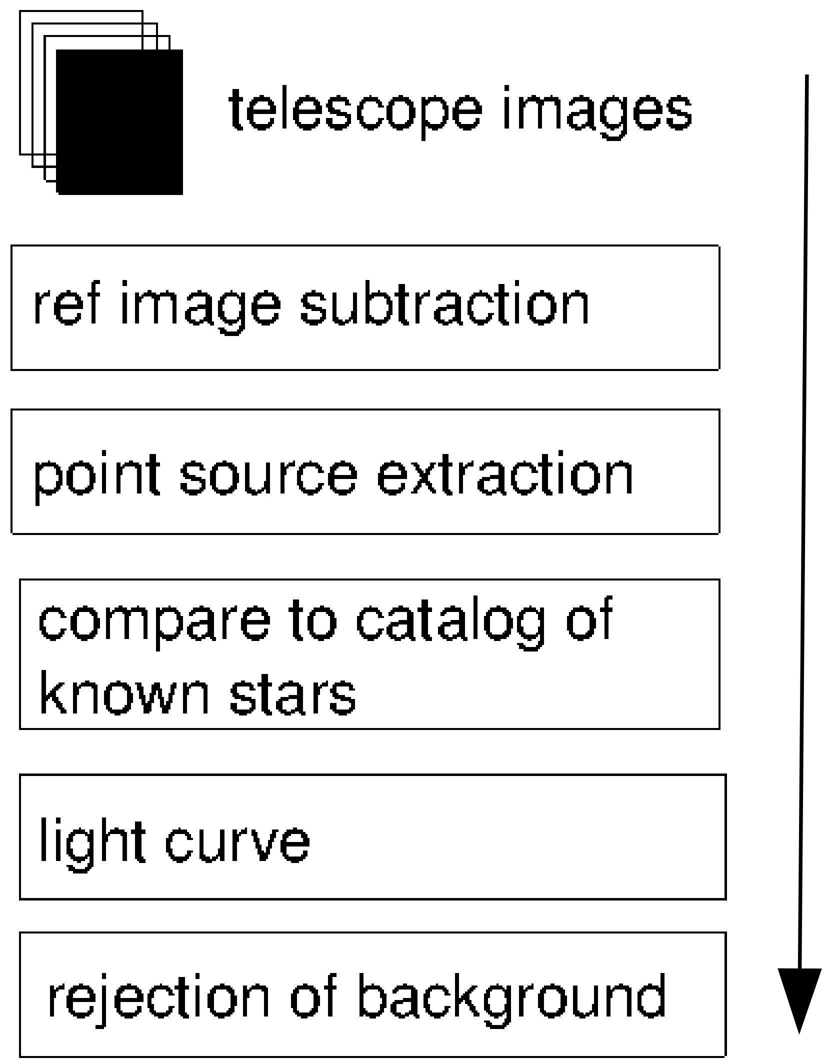
Search for EM transients (1)
Optical/NIR

Search for fading point source in a series of images

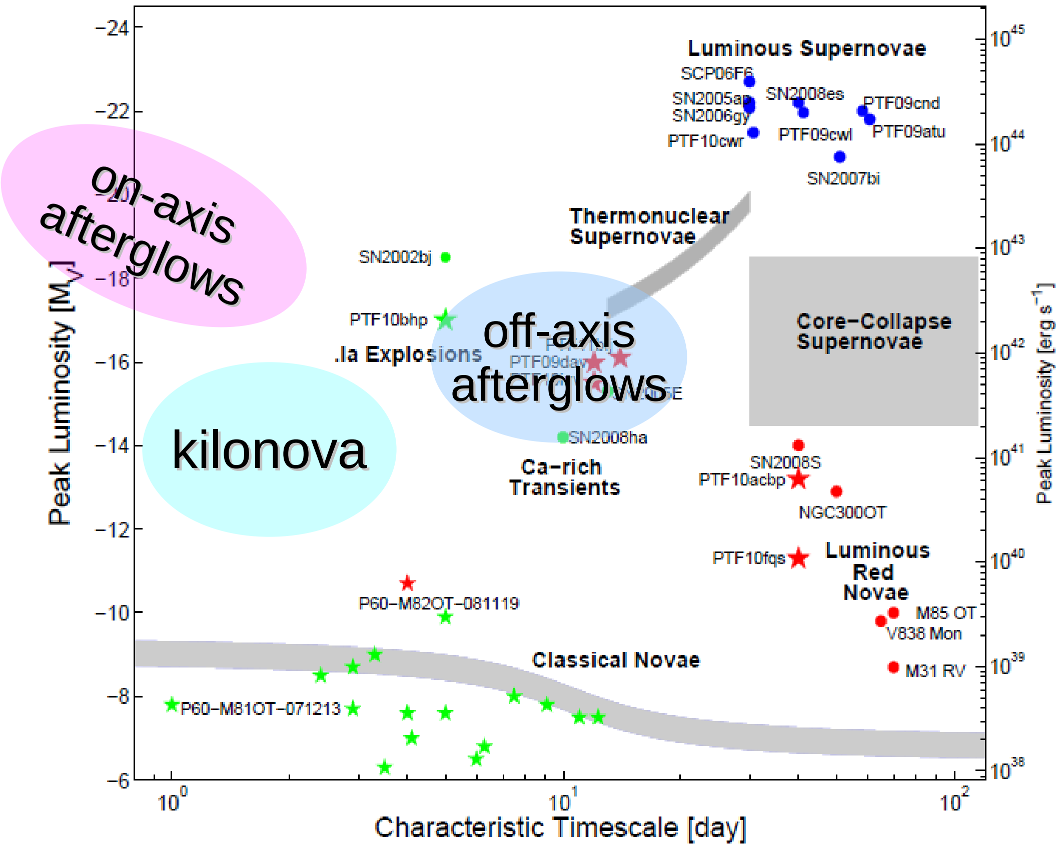


Selection cuts (decay evolution, consistent observation in multiple images)

Transient classification (e.g., machine learning)



Search for EM transients (2)
Optical/NIR



- Astrophysical background of optical transients
  - Much less known – Lack of large surveys
  - Rate are poorly known – Larger than X-rays

Kasliwal, BASI, 2011

Golden channel for EM follow-up?

EM band	Pros	Cons
Radio waves	Isotropic emission Quiet background sky	Long-duration signals and long delays
(Sub-) mm waves	Isotropic emission Immune of extinction+scintillation	Rather unexplored Missing wide-field instrument
Near-IR optical (kilonova)	Isotropic emission Up-coming surveys	Weak and uncertain signal
X-rays	Quiet and well-understood background sky	Beamed emission (3% association) Missing wide-field instruments

Source models

van Eerten et al, Off-axis GRB afterglow […], *ApJ* 722 (2010) 235, arXiv:1006.5125

Metzger and Berger, Electromagnetic counterpart of a neutron star binary merger, *ApJ* 746 (2012) 48, arXiv:1108.6056

Piran et al, Electromagnetic signals from compact binary mergers, *MNRAS* 430 (2013) 2121, arXiv:1204.6242

Rosswog et al, Multimessenger picture of compact object encounters […], *MNRAS* 430 (2013) 2585, arXiv:1204.6240

Observations

Kann et al, The Afterglows of Swift-era GRBs. I. […], *ApJ* 720 (2010) 1513, arXiv:0712.2186

Kann et al, The Afterglows of Swift-era GRBs II. […], *ApJ* 734 (2011) 96, arXiv:0804.1959

Rau et al, Exploring the optical transient sky […], *PASP* 121 (2009) 1334, arXiv:0906.5355

Bradley Cenko et al, Discovery of [PTF11agg], arXiv:1304.4236

Source identification

Nissanke et al, Localizing compact binary inspirals […], *ApJ* 739 (2011) 99, arXiv:1105.3184

Nissanke et al, Identifying EM counterparts to gravitational wave mergers, *ApJ* 767 (2013) 2, arXiv:1210.6362

Singer et al, Optimizing optical follow-up of gravitational-wave candidates, arXiv:1204.4510

Searches

Abadie et al, Implementation and testing of the 1st prompt search […] *A & A* 539 (2012) A124, arXiv:1109.3498

Abadie et al, First low-latency search for binary inspirals […] *A & A* 541 (2012) A155, arXiv:1112.6005

Evans et al, Swift follow-up […] 2012 *ApJS* 203 28, arXiv:1205.1124

Advanced detector era

Aasi et al, Prospects for localization [...] for Advanced LIGO and Advanced Virgo, arXiv:1304.0670

Kanner et al, Seeking counterparts […] with Swift, *ApJ* 759 (2012) 22, arXiv:1209.2342

Branchesi, Presentation at VESF School on GW and multiwavelength astronomy, Rome 2013

Motivation for multimessenger astronomy with GW

EM observatories have a much longer history !
Sensitivity is better by orders-of-magnitude

Approximation here! Noise property affect similarly the detection of short and long signals

Radio

1 mJy (for LOFAR) $\mathcal{F}_{radio} \sim$ **10^{-22} erg/m^2**

Optical [*limit magnitude*]

25 cm aperture $\mathcal{F}_{V} \sim$ **5×10^{-7} erg/m^2**

X and gamma-ray

1 photon/cm^2/s,100keV $\mathcal{F}_{\gamma} \sim$ **10^{-3} erg/m^2**

Initial GW detectors [*f=200 Hz*]

$h_{rss} \sim 2.5 \times 10^{-21}\ \mathrm{Hz}^{-1/2}$ $\mathcal{F}_{GW}$ **= 10^{3} erg/m^2**

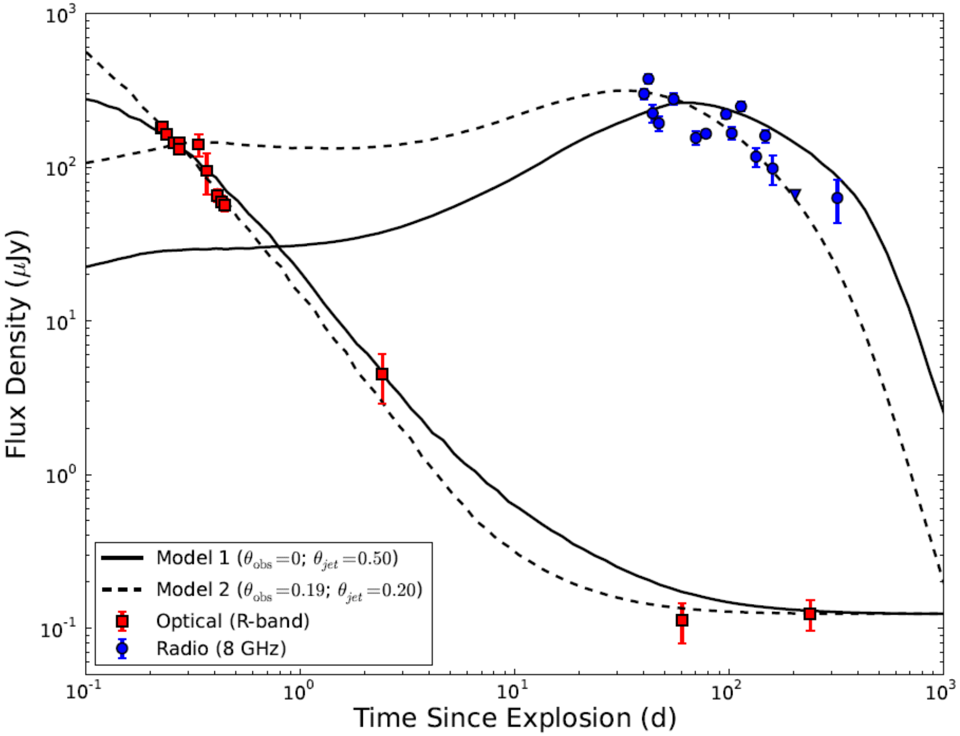
Advanced GW detectors

$h_{rss} \sim 2.5 \times 10^{-22}\ \mathrm{Hz}^{-1/2}$ $\mathcal{F}_{GW}$ **= 10 erg/m^2**

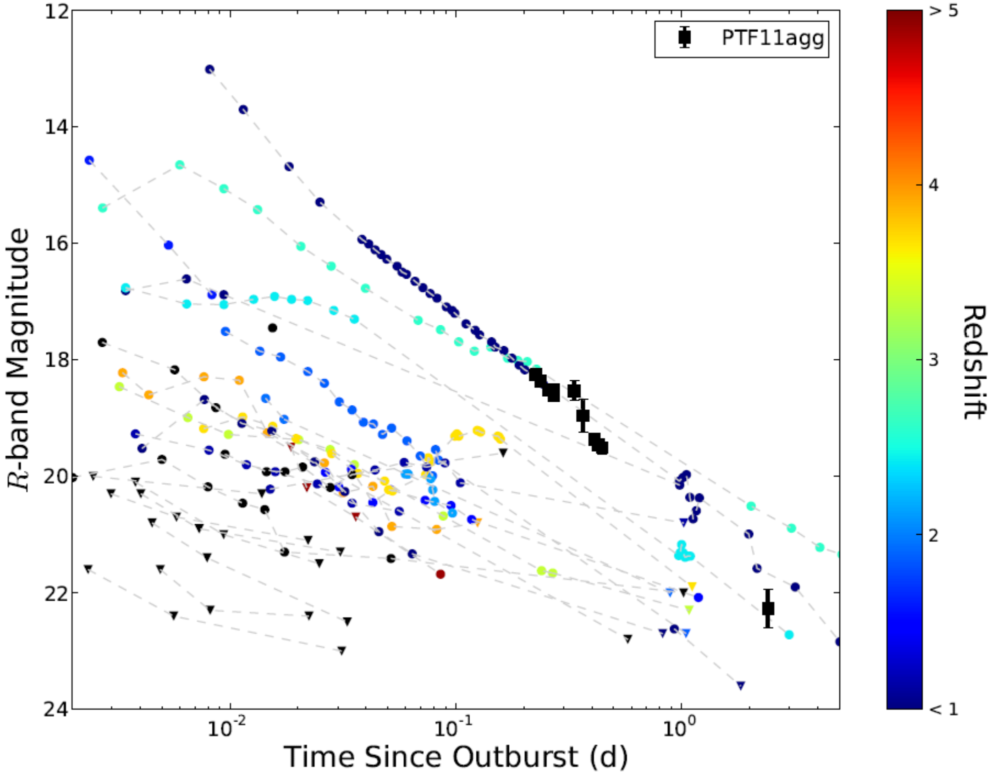
3rd generation detectors

$h_{rss} \sim 10^{-23}\ \mathrm{Hz}^{-1/2}$ $\mathcal{F}_{GW}$ **= $1.5\ 10^{-2}$ erg/m^2**

PTF11agg

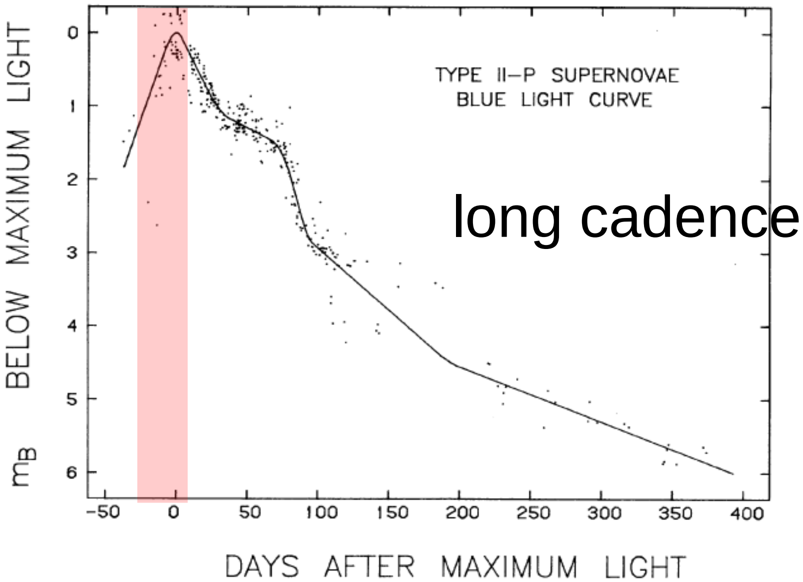


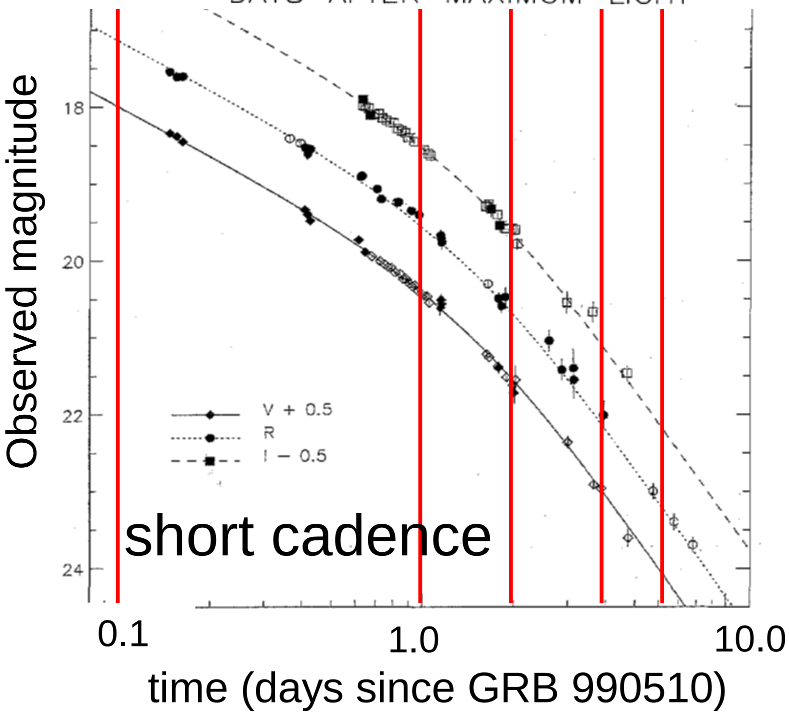
Flux Density (μJy)
Time Since Explosion (d)
Model 1 (θobs=0; θjet=0.50)
Model 2 (θobs=0.19; θjet=0.20)
Optical (R-band)
Radio (8 GHz)



R-band Magnitude
Time Since Outburst (d)
PTF11agg
Redshift
> 5
< 1

Observational strategy (2) Optical/NIR





- Cadence

Proper sampling of the expected light curve

“long” schedule for SN-like event

example: [D+0 +6 +7 +9 +16 +27 +28]

“short” schedule for GRB afterglow-like event

example: [D+0 +1 +2 +4 +6]

- Exposure

Defines limiting magnitude for a given aperture

Short exposure < 60 s (→ ~15 mag)

Long exposure > 120 – 180 s (→ ~17 mag)

[more at the hand-on session tomorrow]

- No filtering