Offline EM follow-up

Search high-energy offline EM data about GW candidate events

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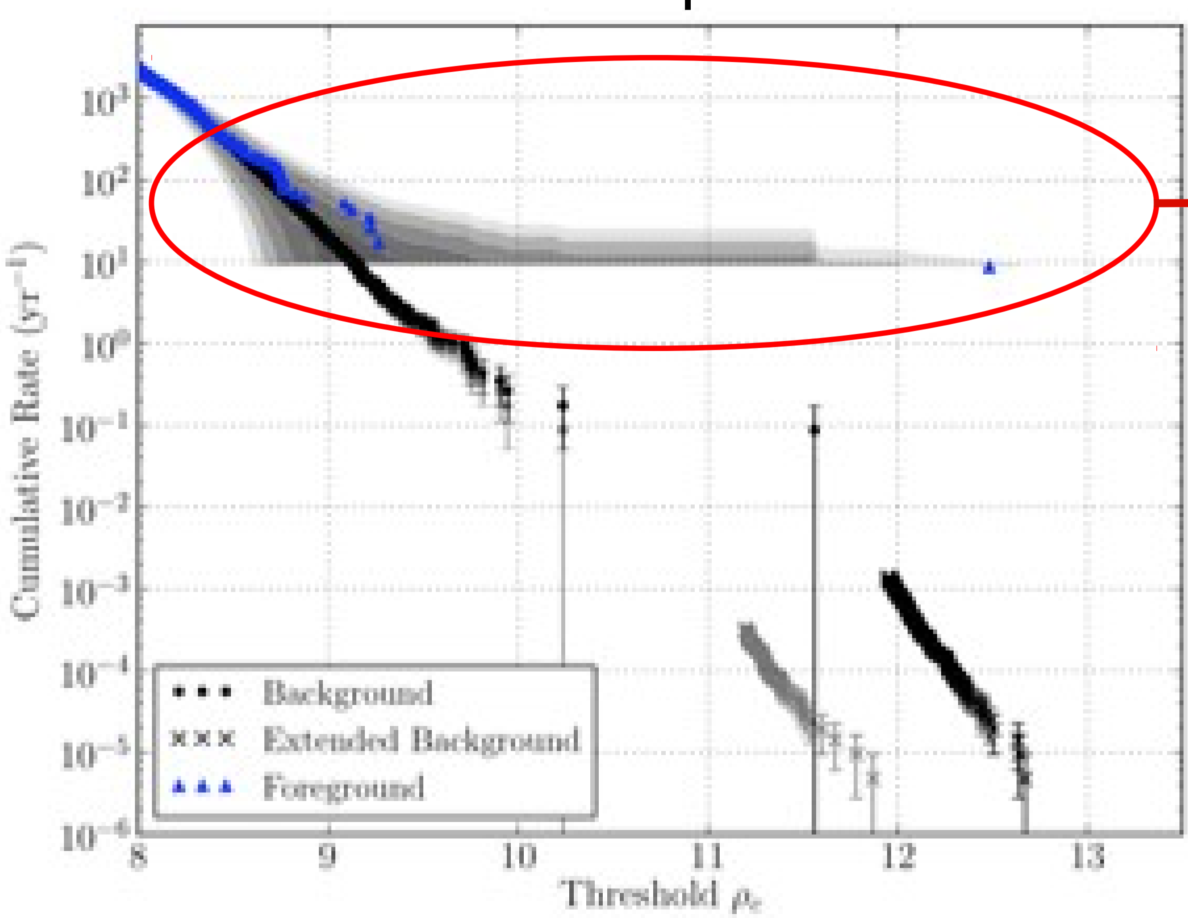
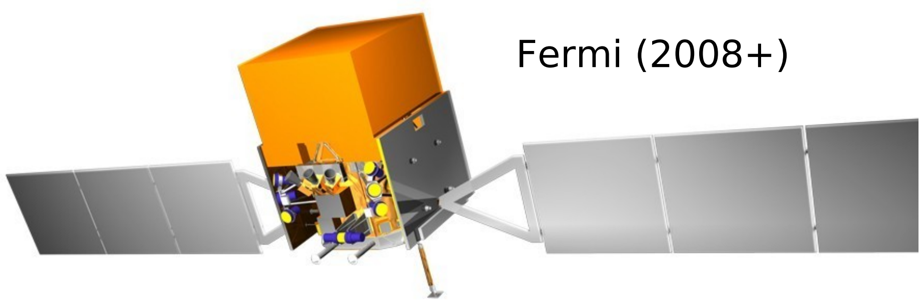
GBM: Michael Briggs, Valerie Connaughton, Pete Jenke (UAH)
ASM: Ron Remillard (MIT)

S6 ihope

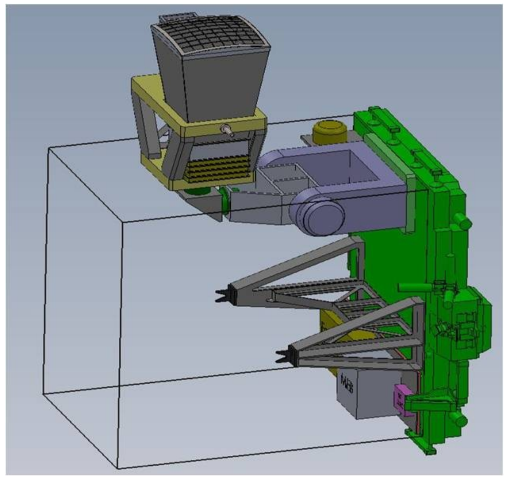




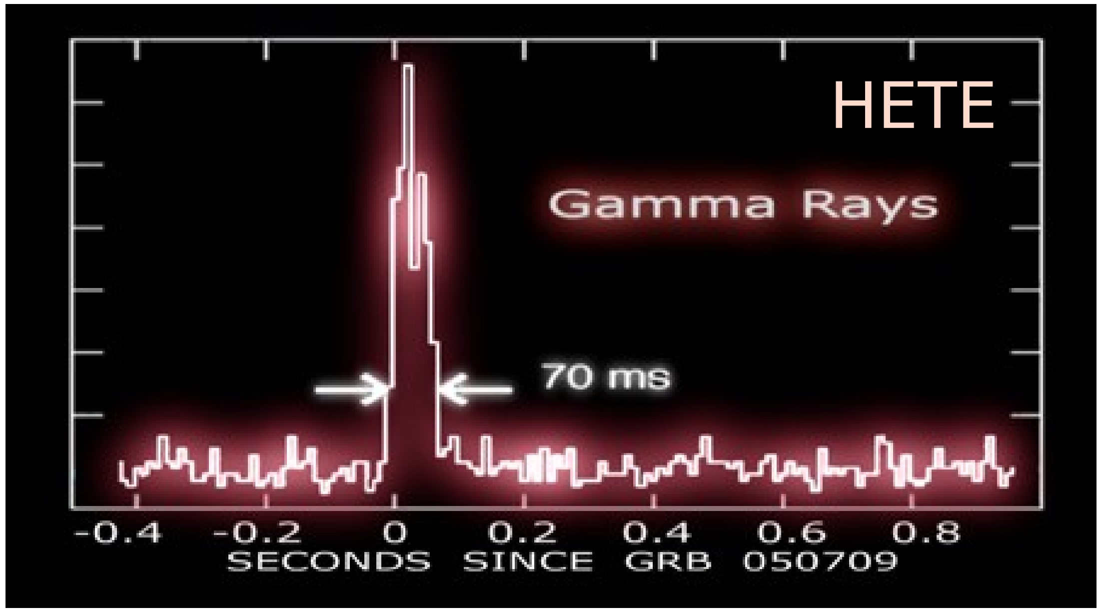
Fermi (2008+)

RXTE (1995-2012)

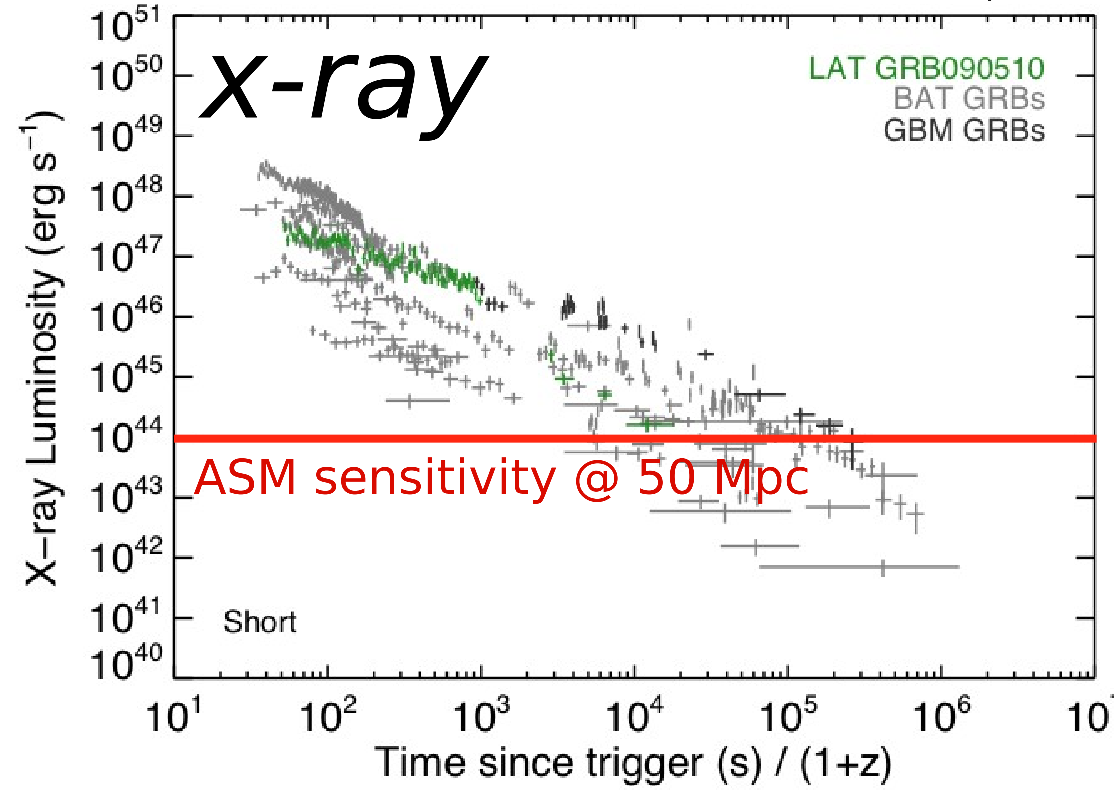
ISS-Lobster (proposed)

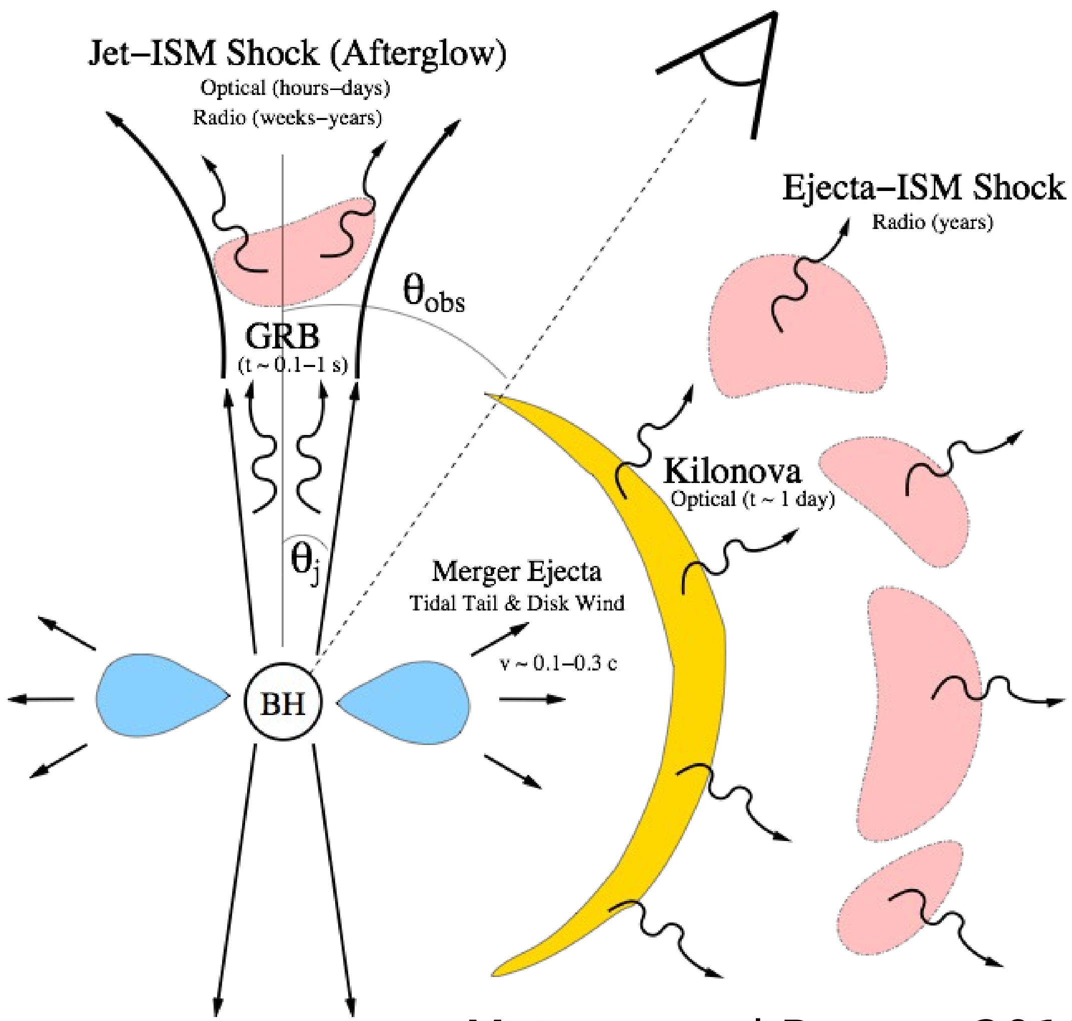


SGRB emission



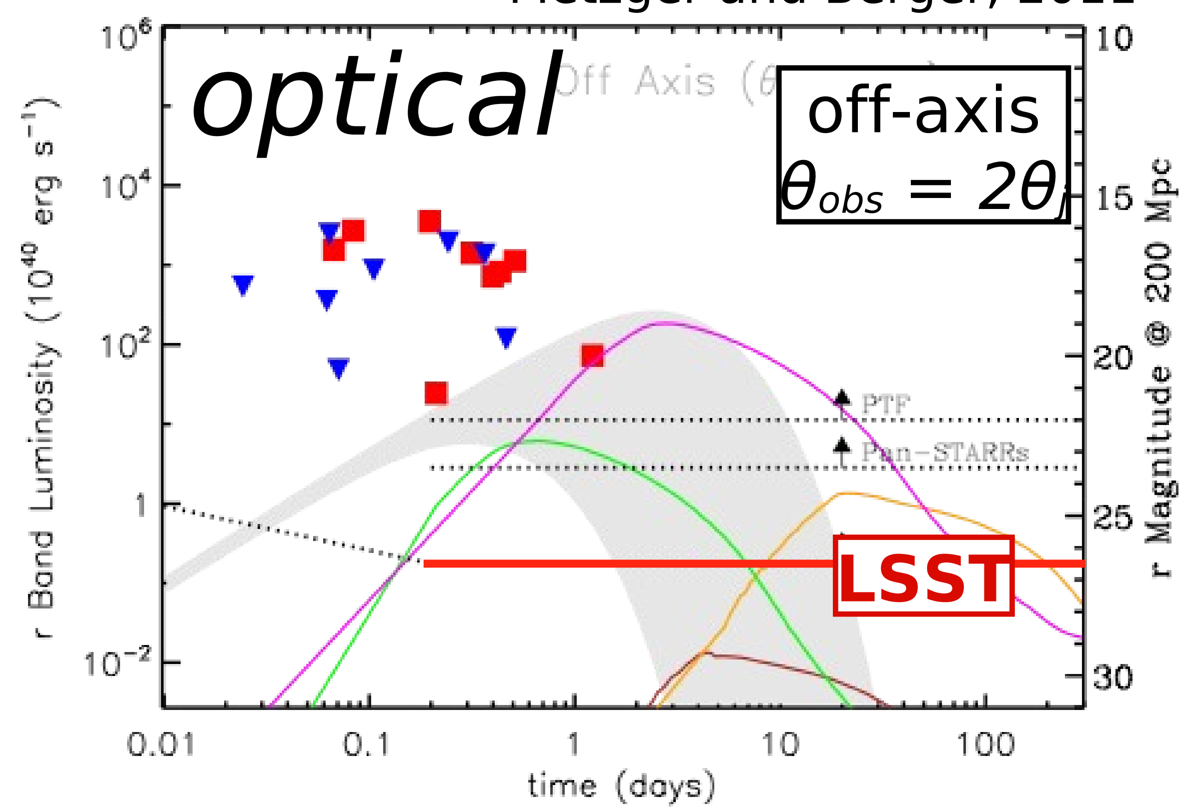
Racusin et al, 2011



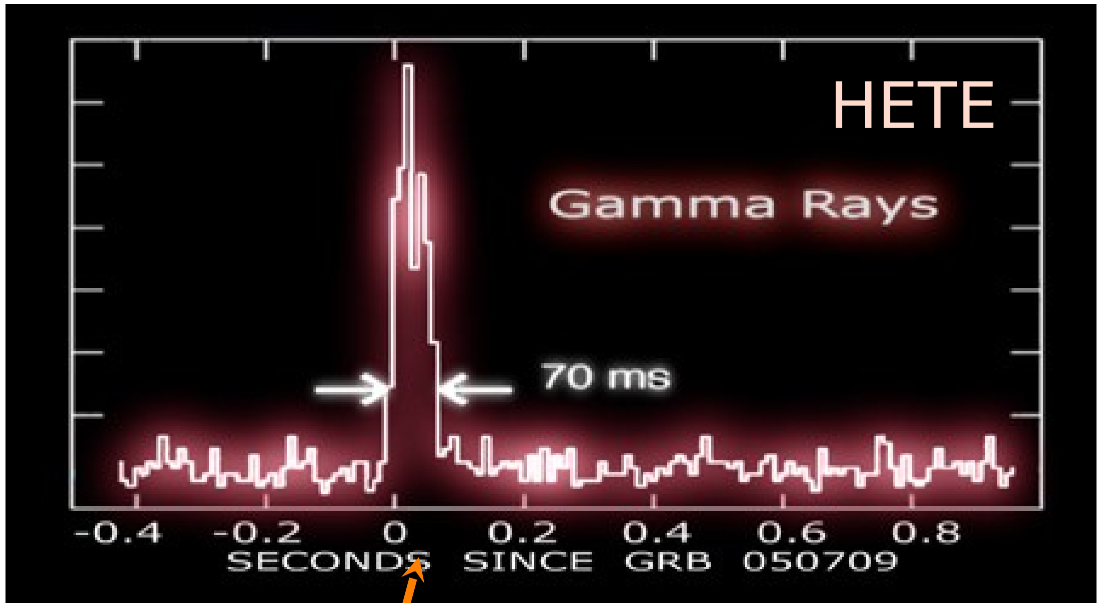


Metzger and Berger, 2011

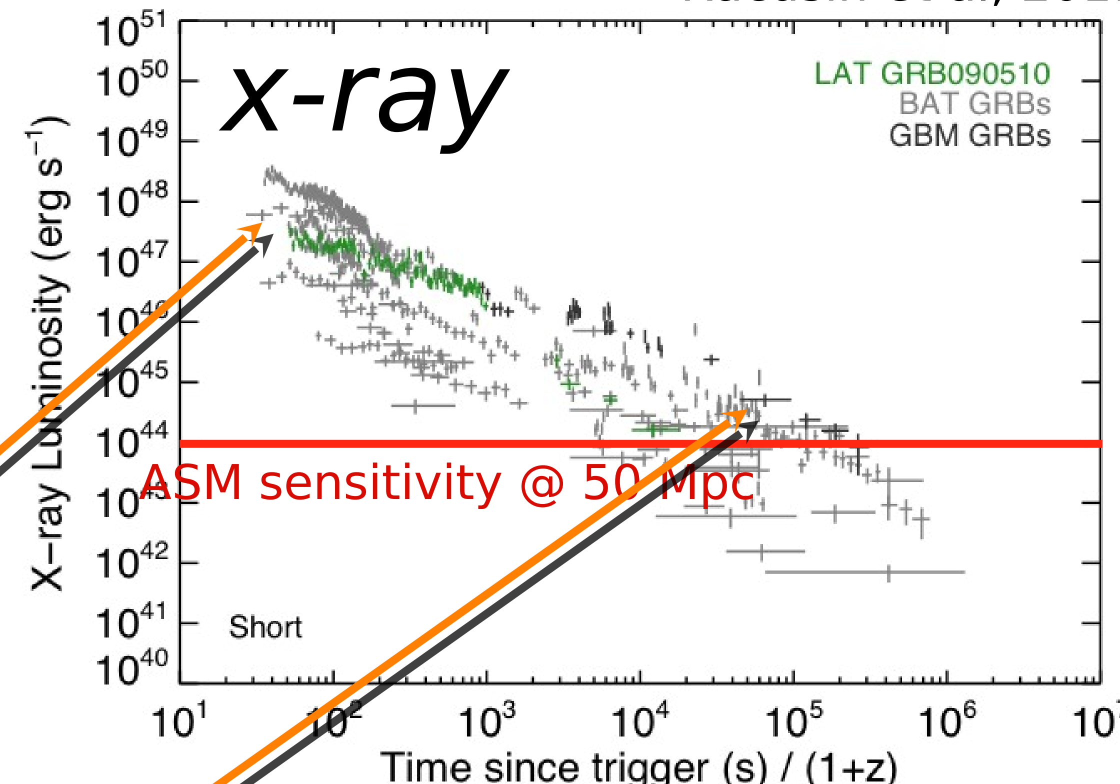
Metzger and Berger, 2011

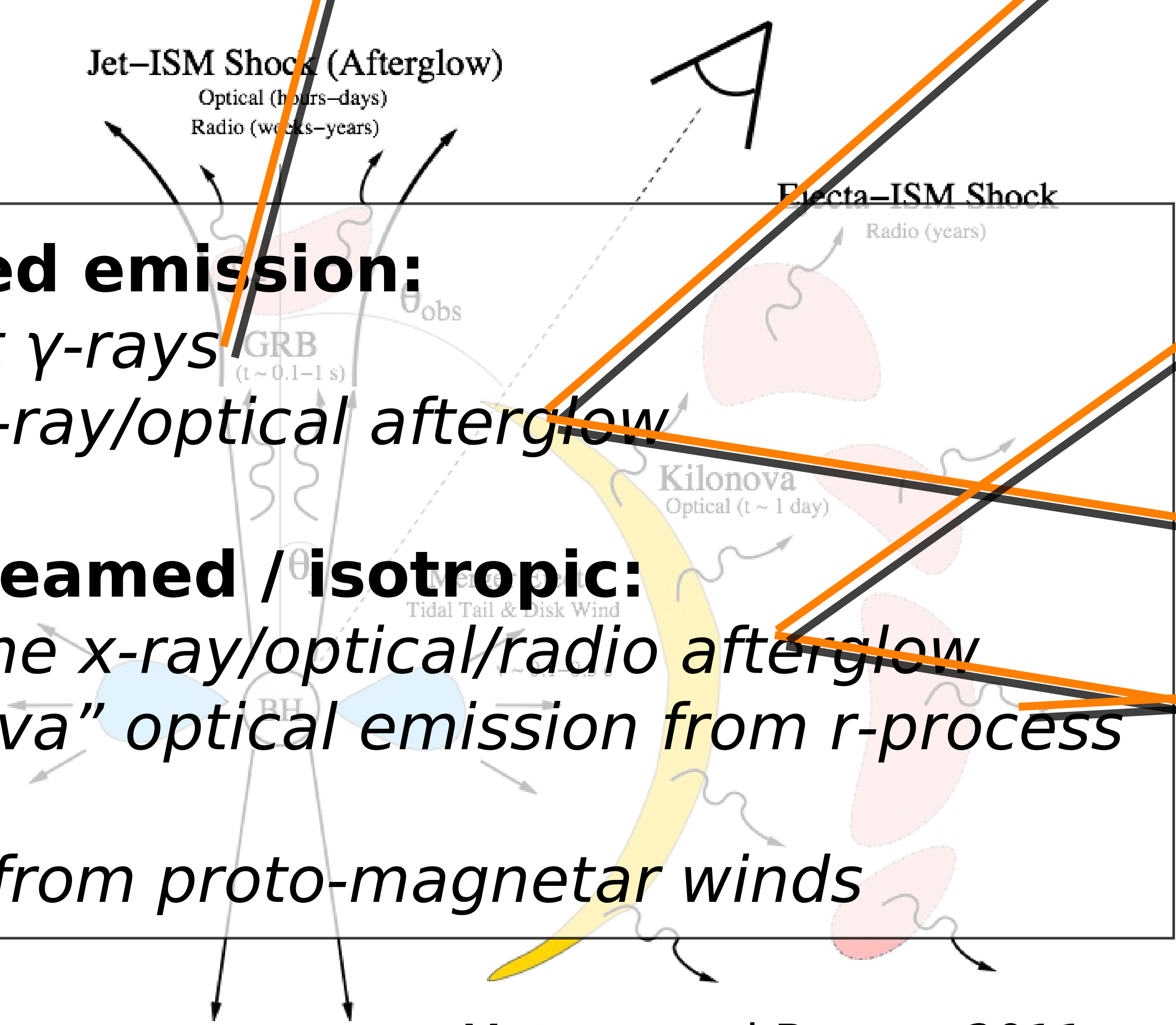


SGRB emission



Racusin et al, 2011



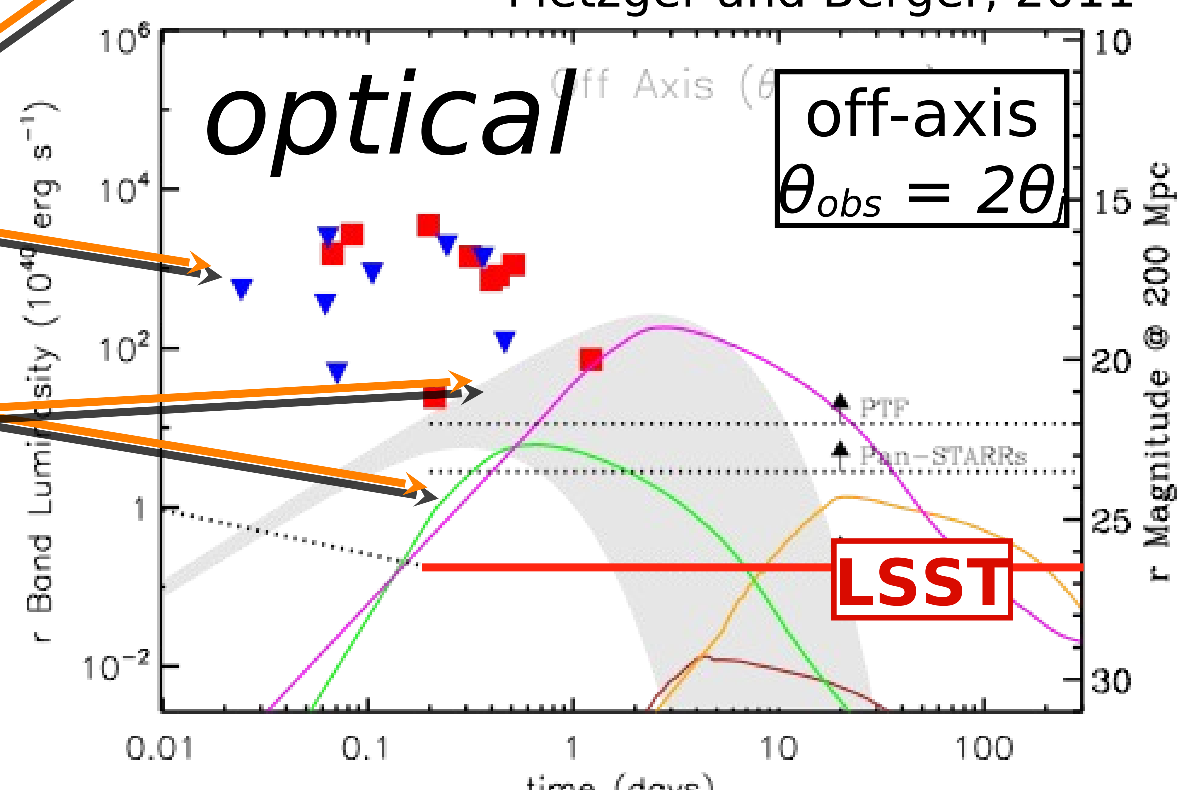


Beamed emission:
prompt γ-rays
early x-ray/optical afterglow

Less beamed / isotropic:
late-time x-ray/optical/radio afterglow
"kilonova" optical emission from r-process decay
x-rays from proto-magnetar winds

Metzger and Berger, 2011

Metzger and Berger, 2011



EM Followup with NASA missions

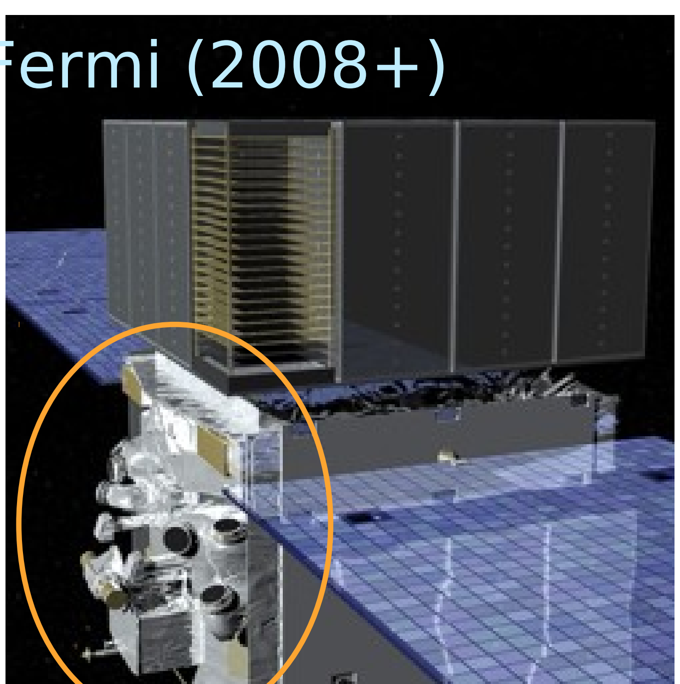
GW observation ➜ EM search

Targeted search for EM counterparts to LIGO-Virgo GW events in NASA archival satellite data

EM detectors:

Mission	Instrument	Energy	FOV *	Δθ	$T_{transit}$
FERMI	GBM	20 keV–40 MeV	65%	>5°	3 hr
RXTE	ASM	1–10 keV	3%	<1°	1.5 hr

* FOV: fraction of sky observed, Δθ: source localization resolution, $T_{transit}$: time required for full-sky coverage

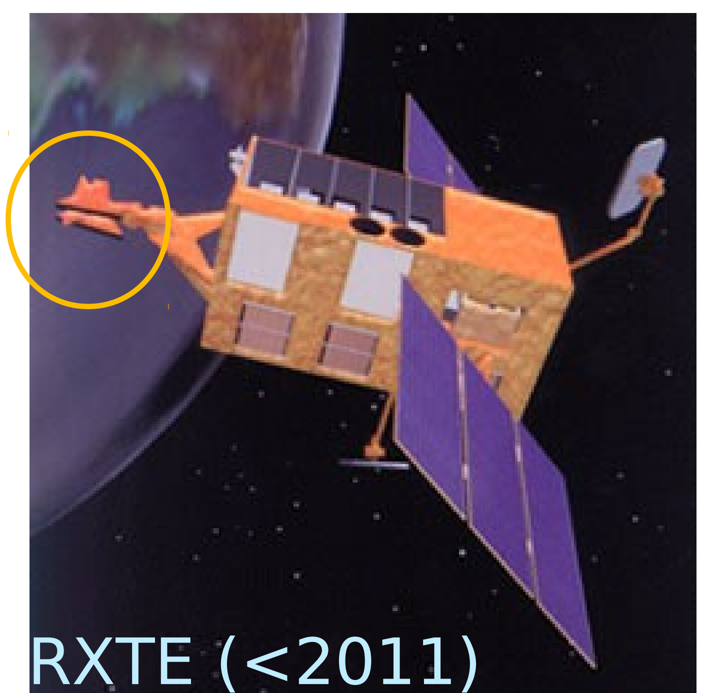


Missions selected for excellent sky coverage and availability of offline data

- *GBM gives 8-channel binned count data*
- *ASM has full coded mask data per 90s dwell*

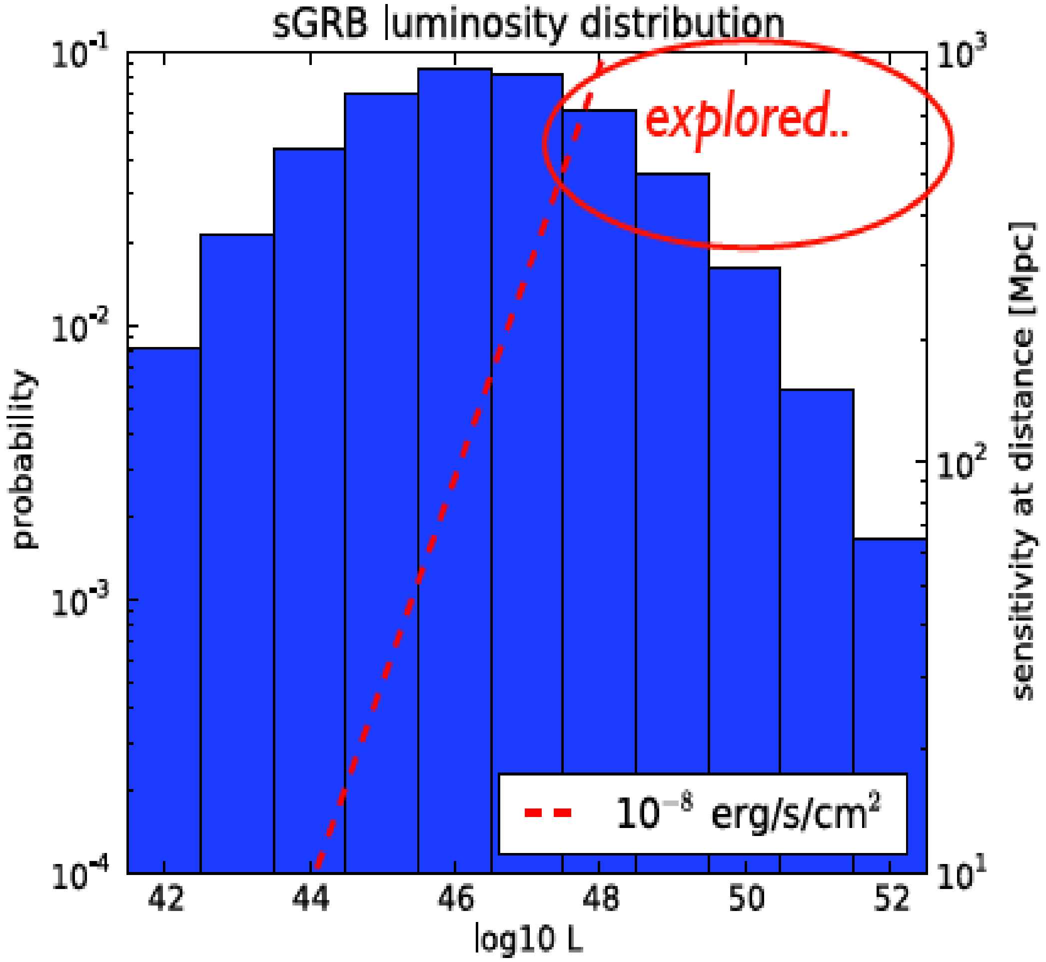
Need automated analysis for characterization of sensitivity and false-coincidence probability

Complements low-latency EM followup for x-ray and optical images, but done offline.



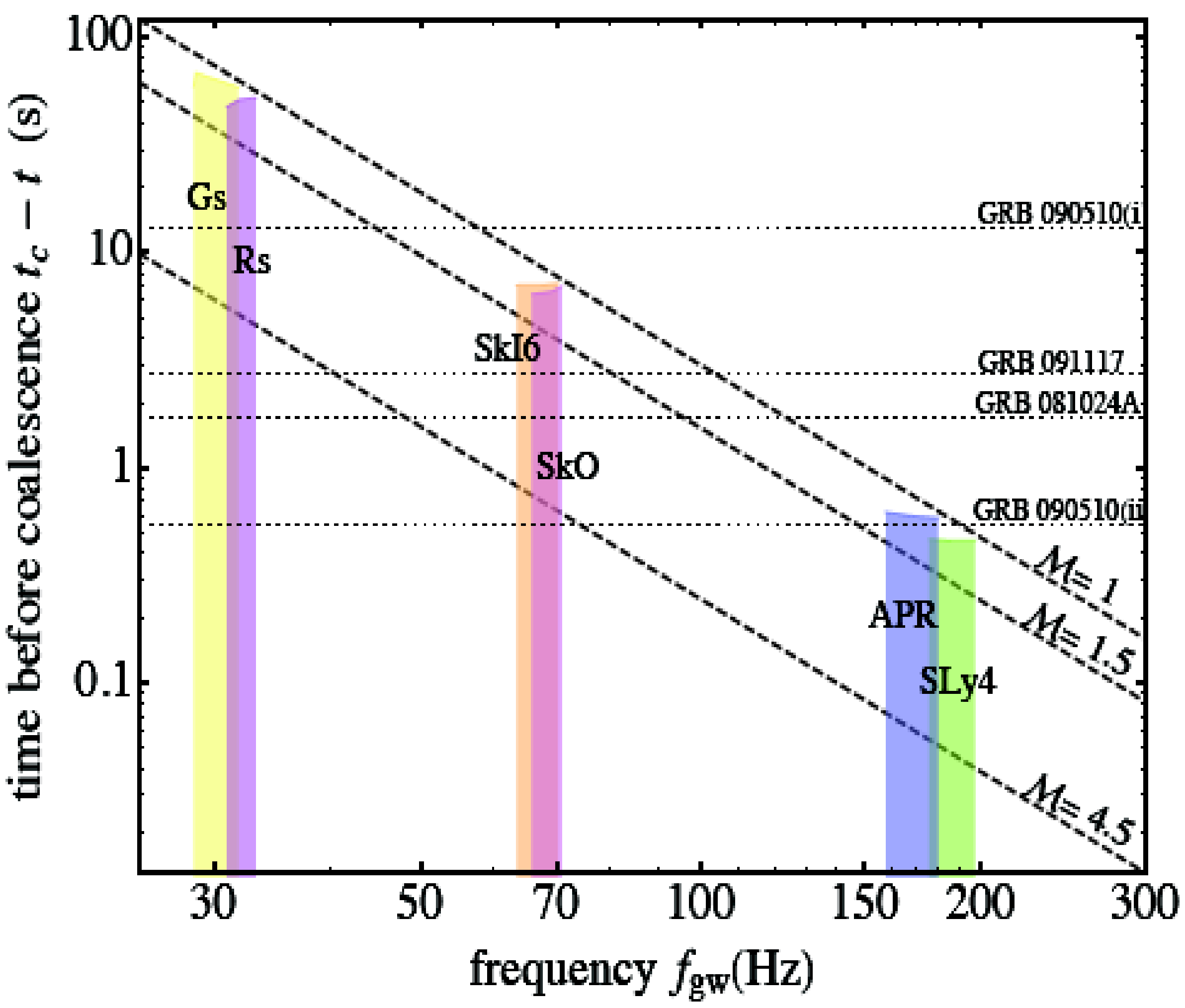
Example sources (γ-ray)

sub-threshold or missed sGRB [Kelly et al 2012]
also see [Yonetoku et al 2013]



unexplored territory of
low-luminosity short GRBs

NS crust shattering pre-merger [Tsang et al 2011]

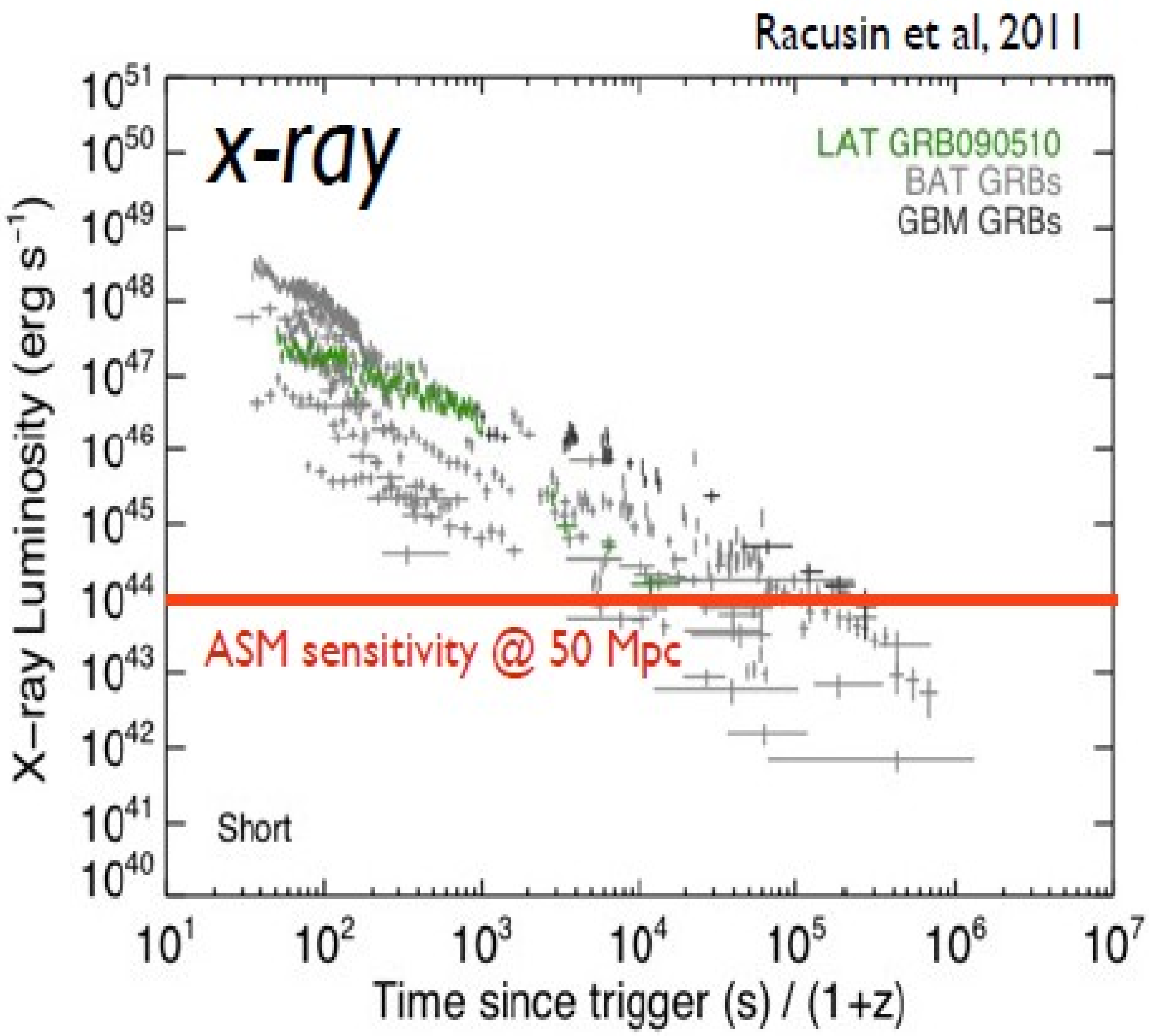


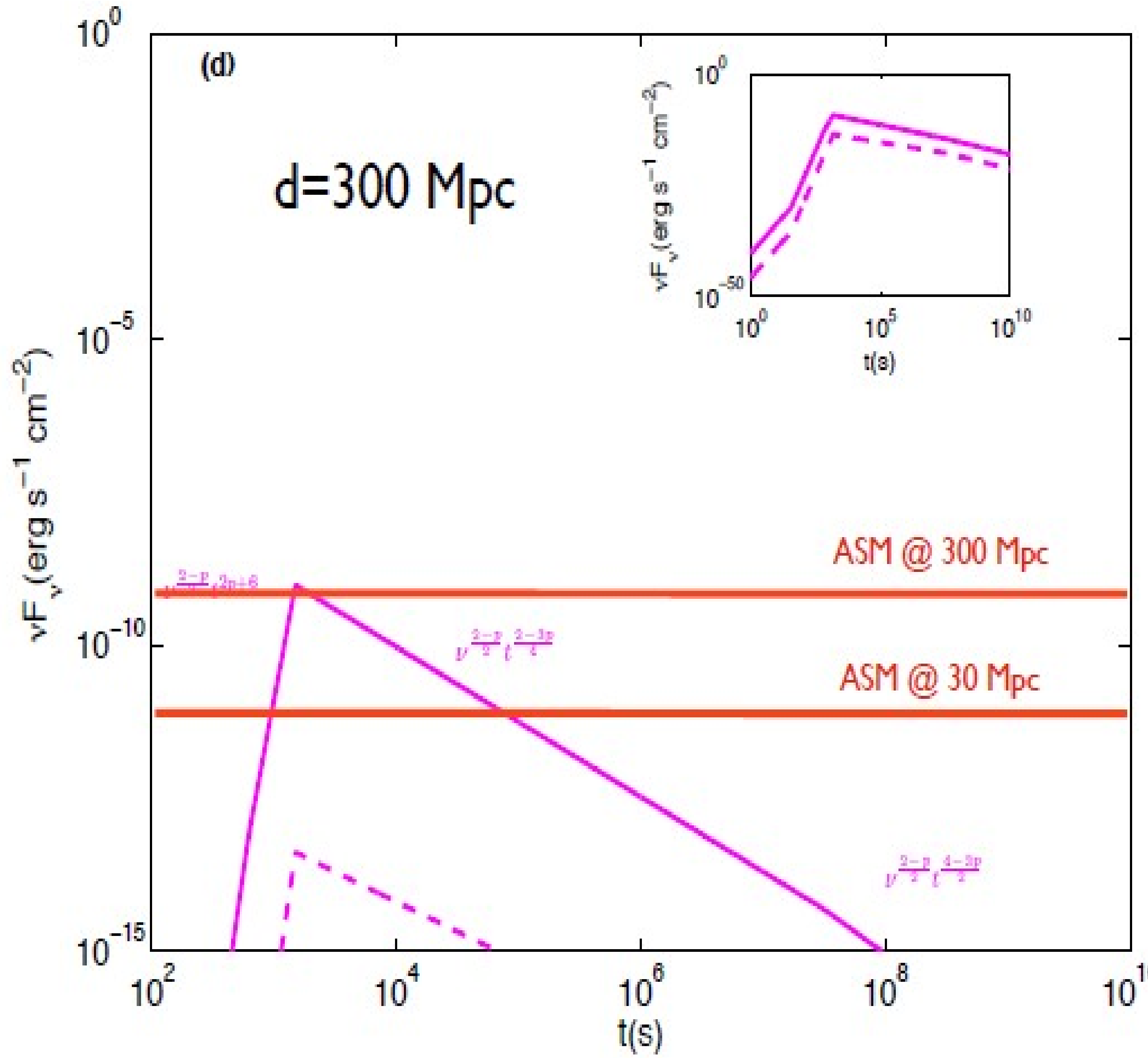
possible high-energy precursors to
NS/NS merger, with properties
depending on EOS

Example sources (x-ray)

sGRB x-ray afterglow

proto-magnetar wind-driven afterglow [Gao et al 2013]





orphan x-ray afterglows
to compact mergers

proto-magnetar wind-driven x-ray
afterglows indicating post-merger remnant

Pipeline

LV inspiral trigger:
GPS time,
chirpmass

→

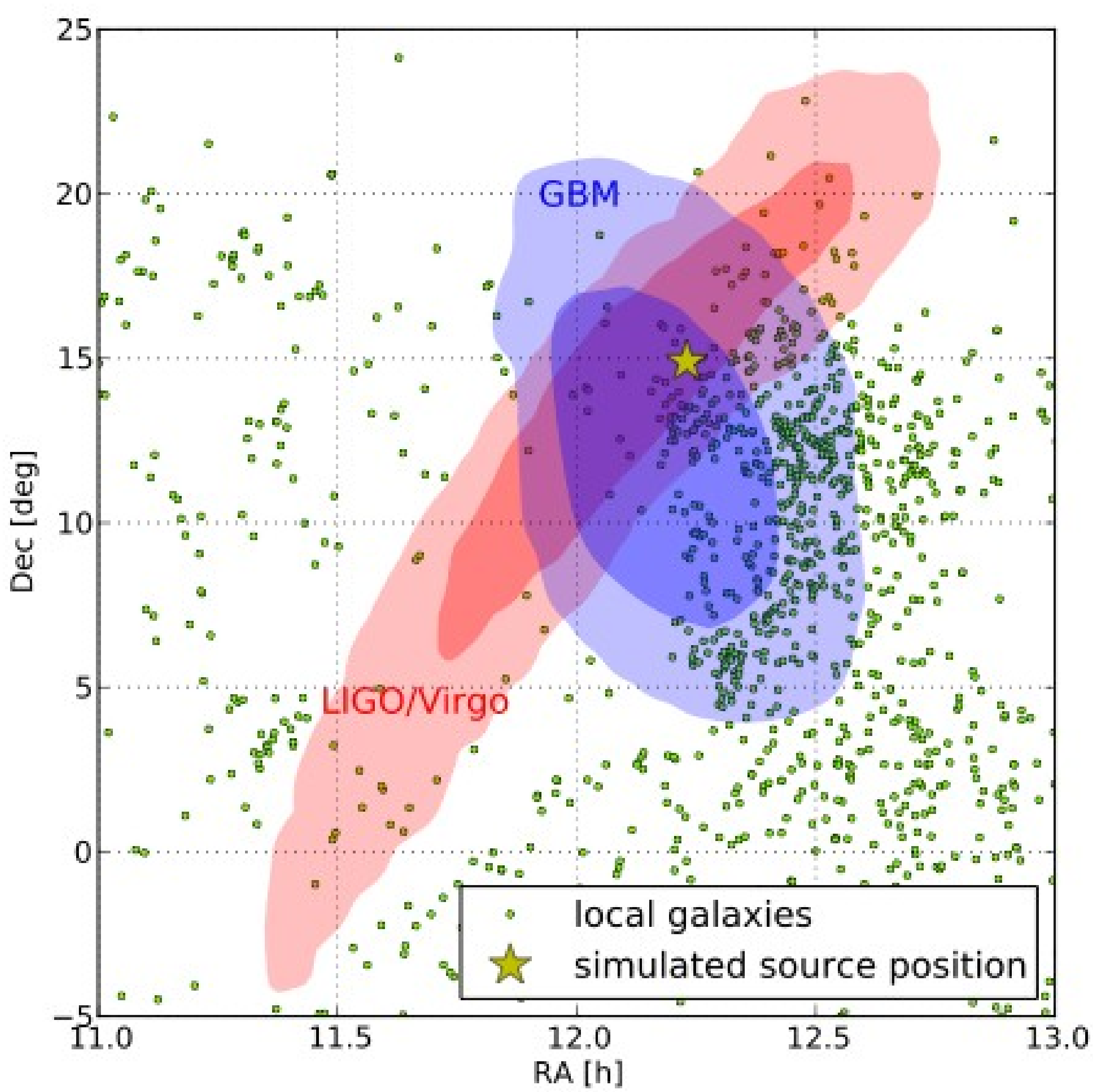
LALInference:
Sky location and
distance posteriors

Fermi GBM:
likelihood of prompt
gamma-ray flux
within
+/-30s of trigger and
consistent with GW
sky location

GWGC filter:
identify possible
host galaxies

RXTE ASM:
likelihood of x-ray
afterglow
signature from
host locations

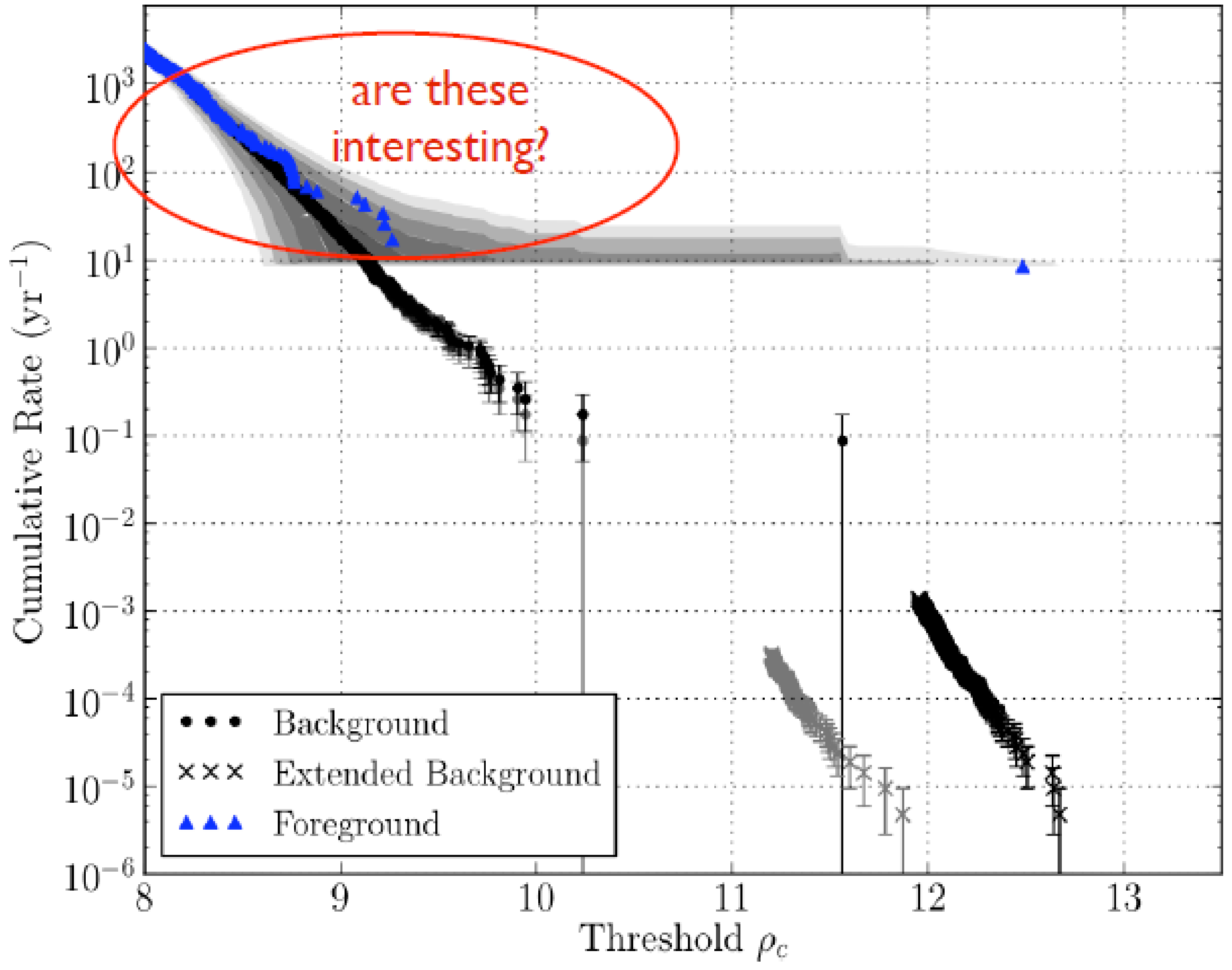
Final GW-EM coincident events



ihope triggers from S6d

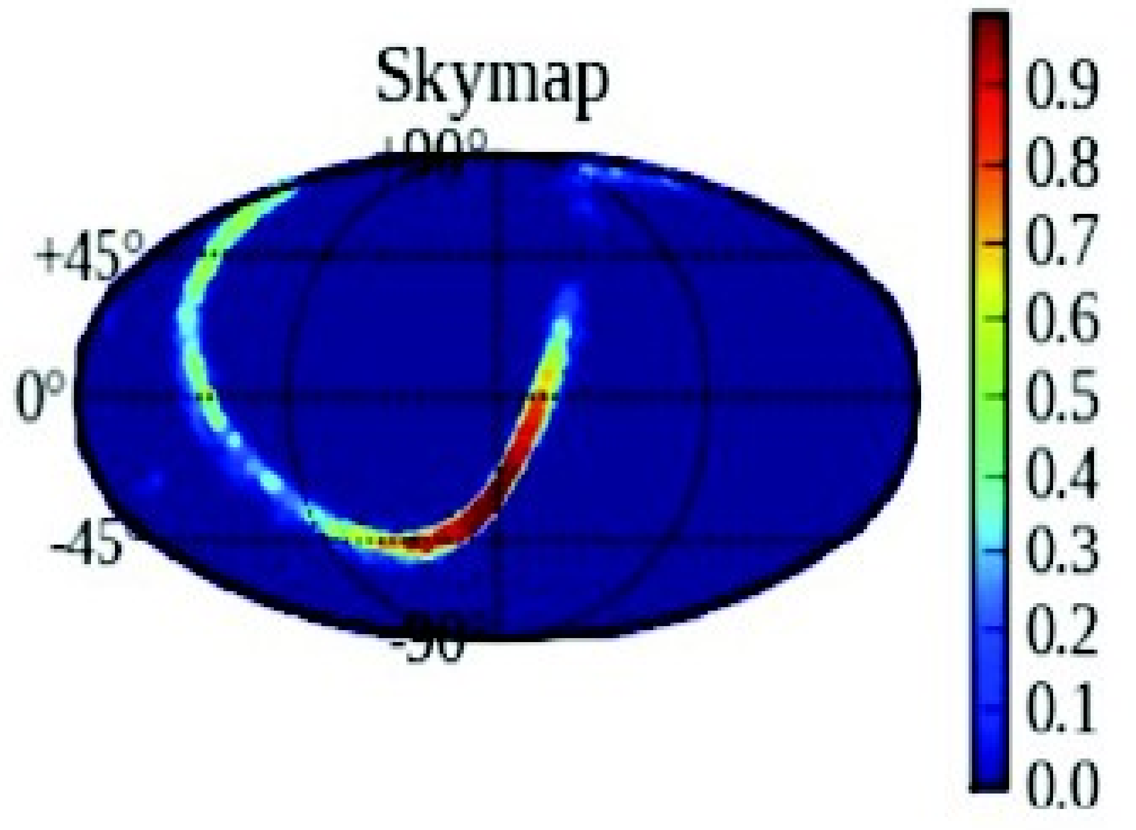
60d of S6D: 966383960-971614865 [Aug 20 2010 23:59:05 to Oct 20 2010 13:00:50]

- *Begin with low-mass ihope production*
- *100 time-shifts and non-spinning NS/NS injections used for testing method*
- *Probe tail of background distribution (~SNR 7.5)*



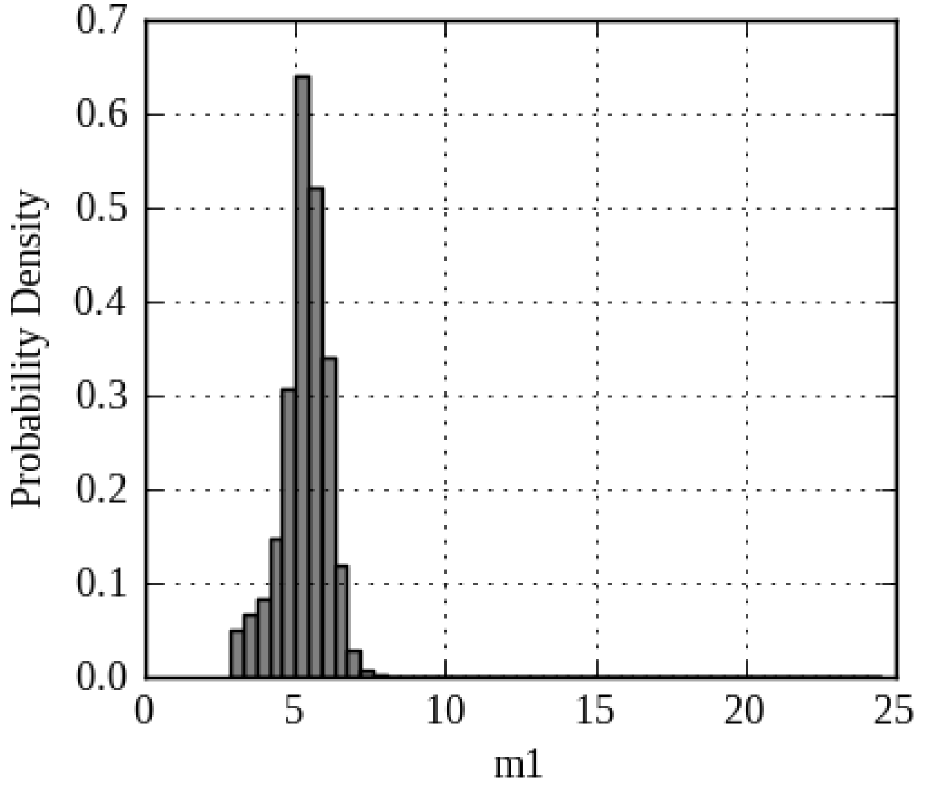
LALInference and Bayes Factors

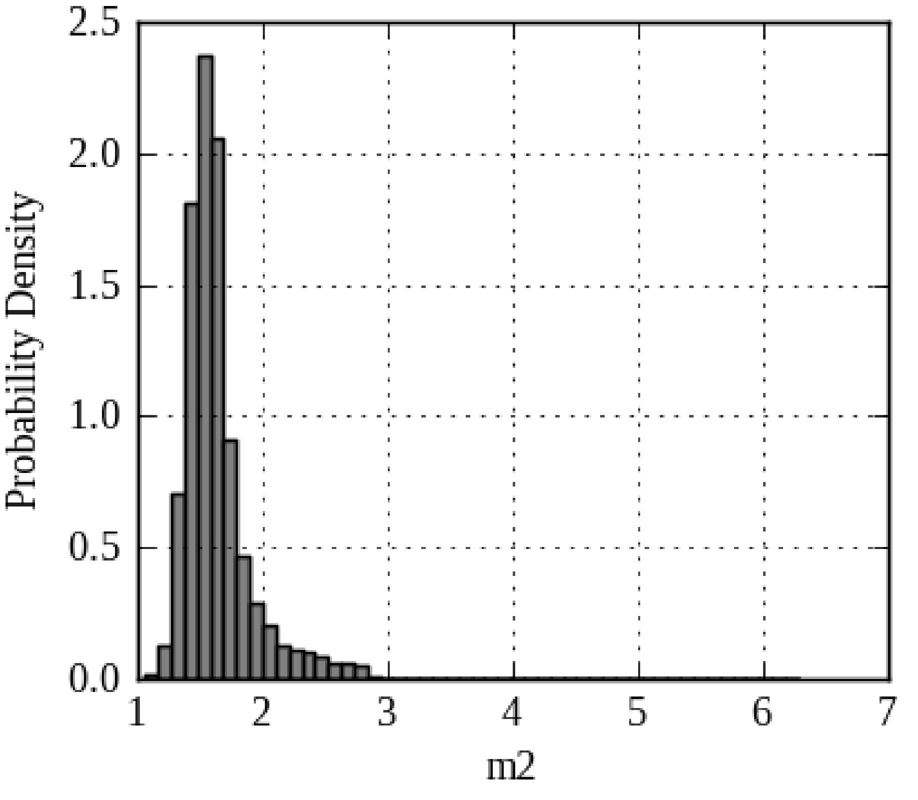
- For now just timeshift results
- Use timeshift triggers to develop and test the pipeline
- Calculate Bayes factors, physical parameter estimates
- Sky position estimates too
- Coherent Bayes Factor; coherent verses incoherent or noise
- Examining thousands of events with reasonable false alarm rates
- Testing on LIGO S6, Virgo VSR2,3



Example (time slide) event. Bayesian parameter estimation - sky position. Relatively large Bayes factor too.

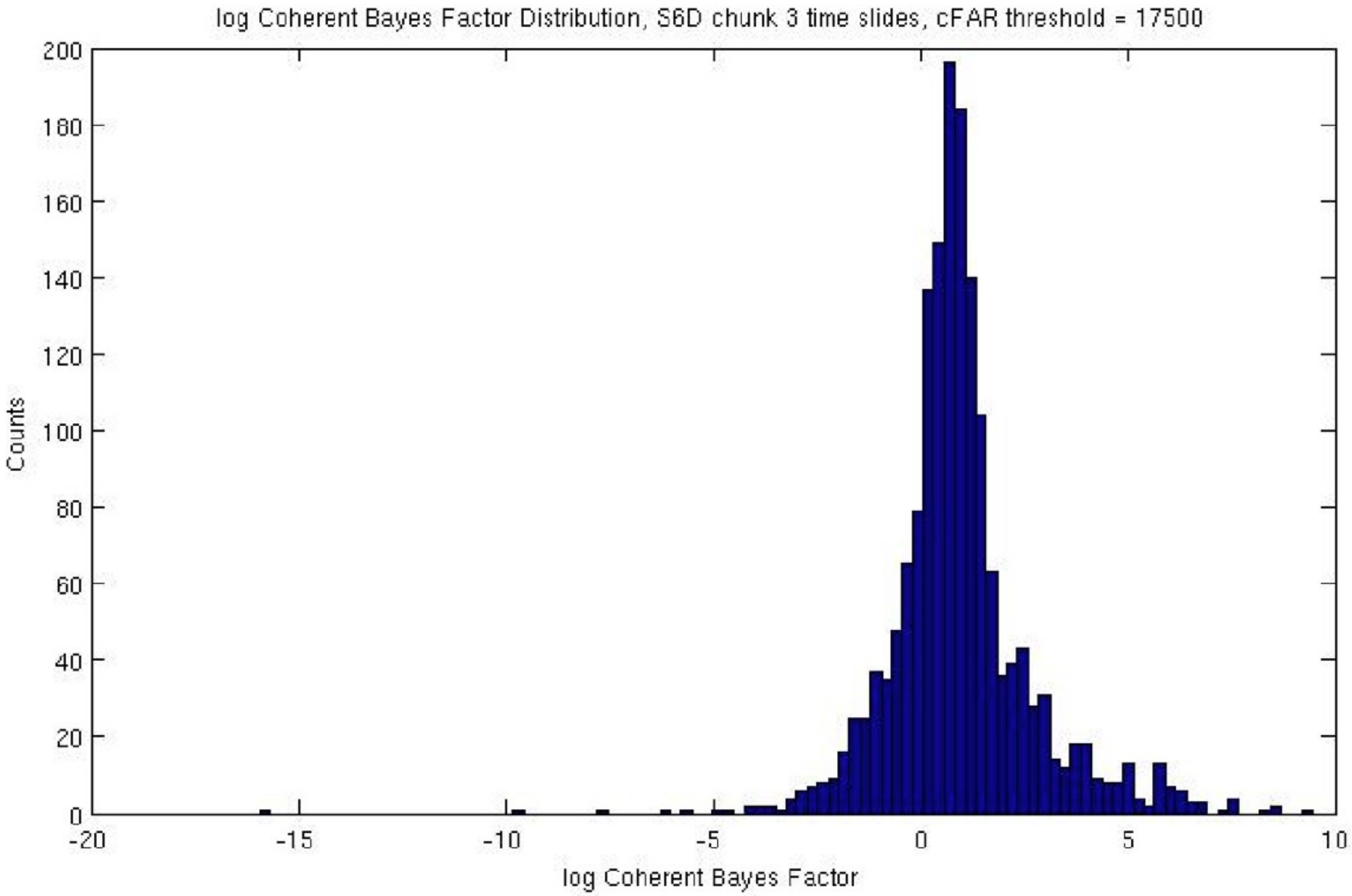
Parameter Estimation





CBC search trigger defines a time.
Run Bayesian parameter estimation code on all data for that time.
For low mass CBC, 9 physical parameters.
Example above of posterior probability for two masses.

How Much Does A Trigger Look Like A Real Binary Inspiral Event?



LALInference Bayes Factors

- *Coherent vs Incoherent signal model, provides complimentary information to SNR*
- *Time-shift events*
- *Bayes Factors not used in this analysis, but possibly a future addition.*

Thousands of S6 events processed:

- *Zero-lag results to come (not here)*
- *Time-shifts to develop and test the pipeline*
- *low-mass NS/NS injections*

Gravitational-Wave Galaxy Catalogue integration

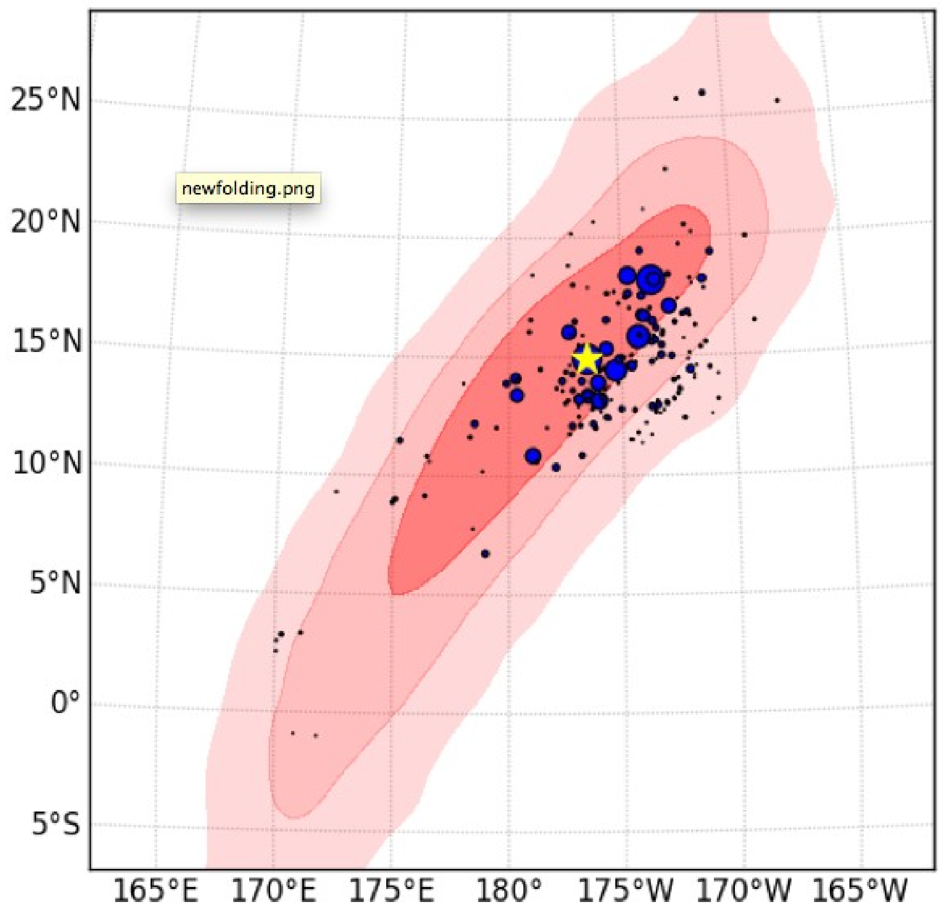
Follow up most probable galaxy hosts consistent with PE posterior

Galaxy catalog (~50k) up to 100 Mpc [D. White et al, 2011]

- *position, type, shape, blue-light luminosity, ...*

For each galaxy, we estimate density of posterior samples in distance and sky location

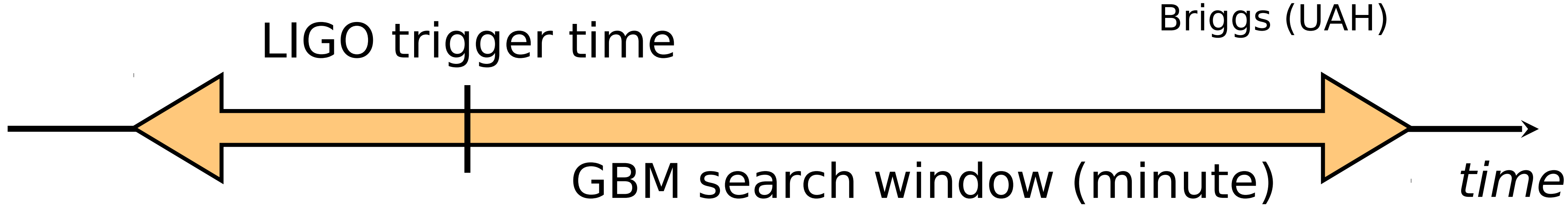
- *distance posterior, width determined by sampling and reported galaxy distance error (10-20% depending on galaxy)*
- *location posterior binned and smoothed to ~3°*
- *galaxies ranked by: mass × $f(d)/d^2$ × $f(\phi, \theta)$*
- *distance and sky-location calculated independently*

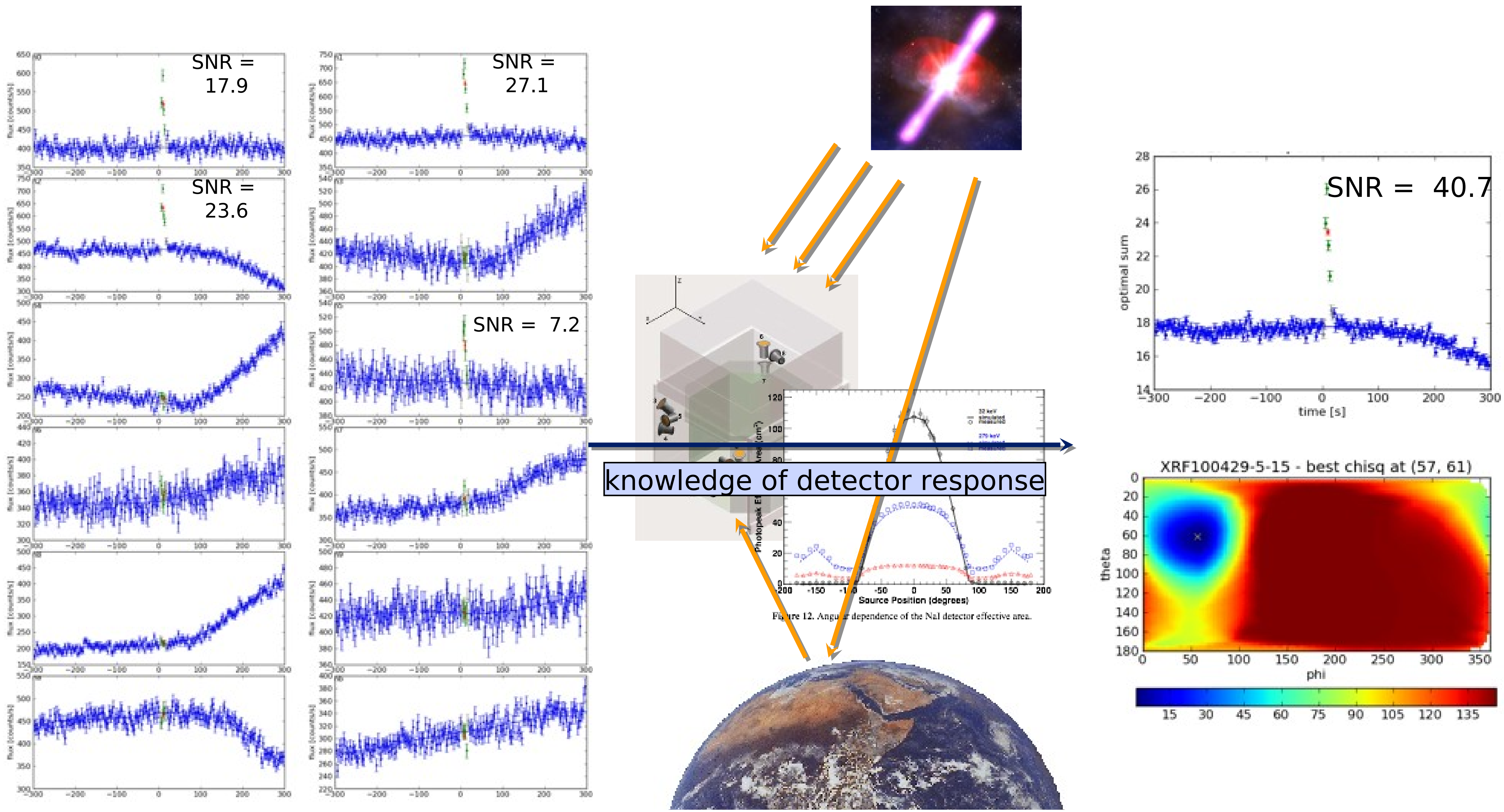


- *simulated HLV event from the Virgo cluster*
- *hosts from GWGC ranked by mass × overlap with LALInference posterior*
- *most probable galaxy is true host*
- *complications arise from: completeness, distance uncertainty (20%), blue-light luminosity prior*

Coherent search over GBM detectors

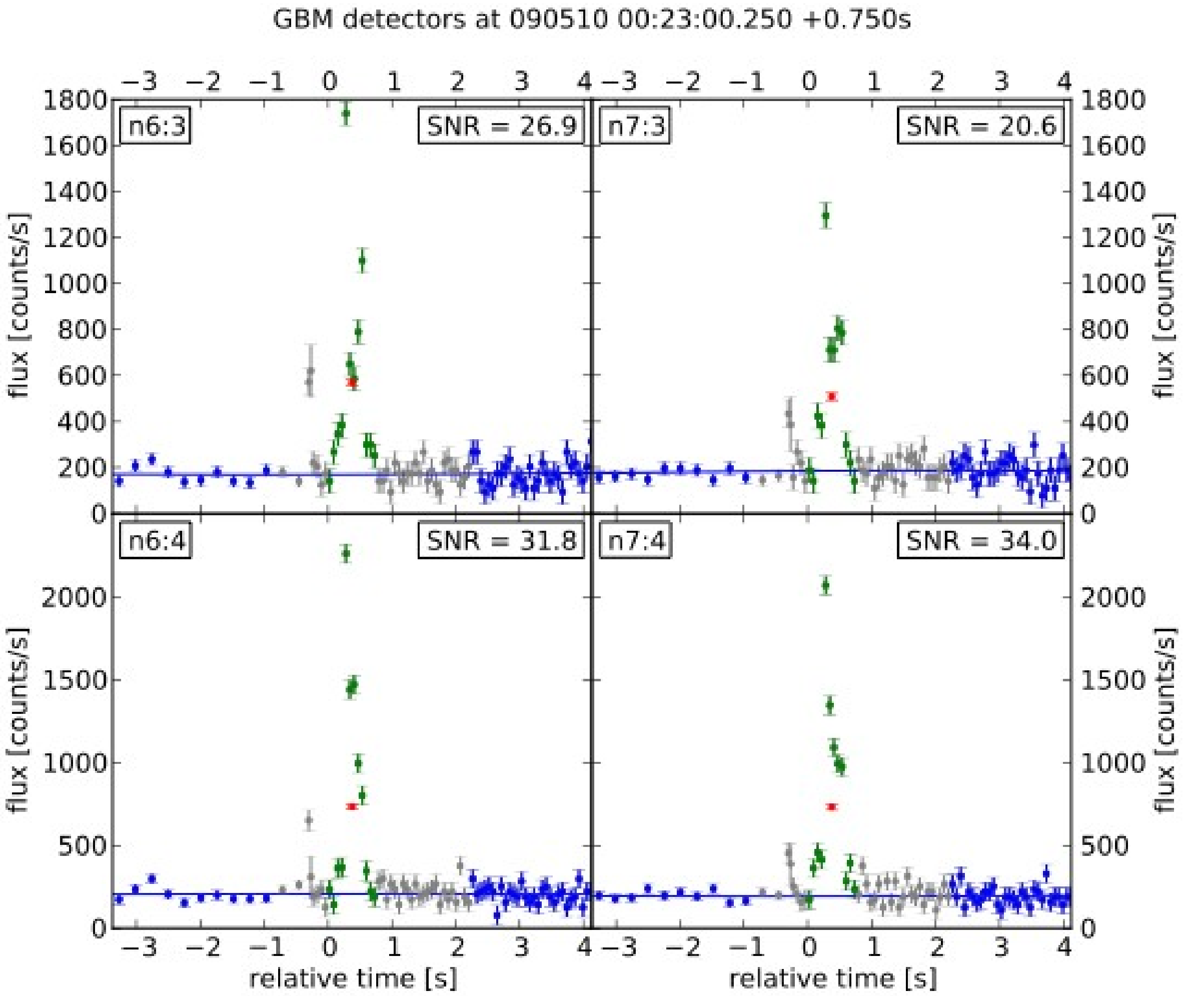
in collaboration with V. Connaughton and M. Briggs (UAH)





Coherent GBM statistic

fit local background to polynomial function



construct Gaussian log-likelihood statistic using response model for known source

background-subtracted counts

response

source amplitude

$$\mathcal{L} = \sum_i \left[\ln \frac{\sigma_{n_i}}{\sigma_{d_i}} + \frac{\tilde{d}_i^{\,2}}{2\sigma_{n_i}^2} - \frac{(\tilde{d}_i - r_i s)^2}{2\sigma_{d_i}^2} \right]$$

measurements

uncertainty in counts (background only, background+signal)

with systematic uncertainty in background fit, and response

$$\sigma_{n_i}^2 = \langle n_i \rangle + \sigma_{b_i}^2$$

$$\sigma_{d_i}^2 = \sigma_{n_i}^2 + r_i s + \sigma_{r_i}^2 s^2 \quad (s \geq 0)$$

semi-analytic marginalization over unknown source amplitude using power-law amplitude prior $P \sim s^\beta$

width of [clipped] Gaussian likelihood function on s

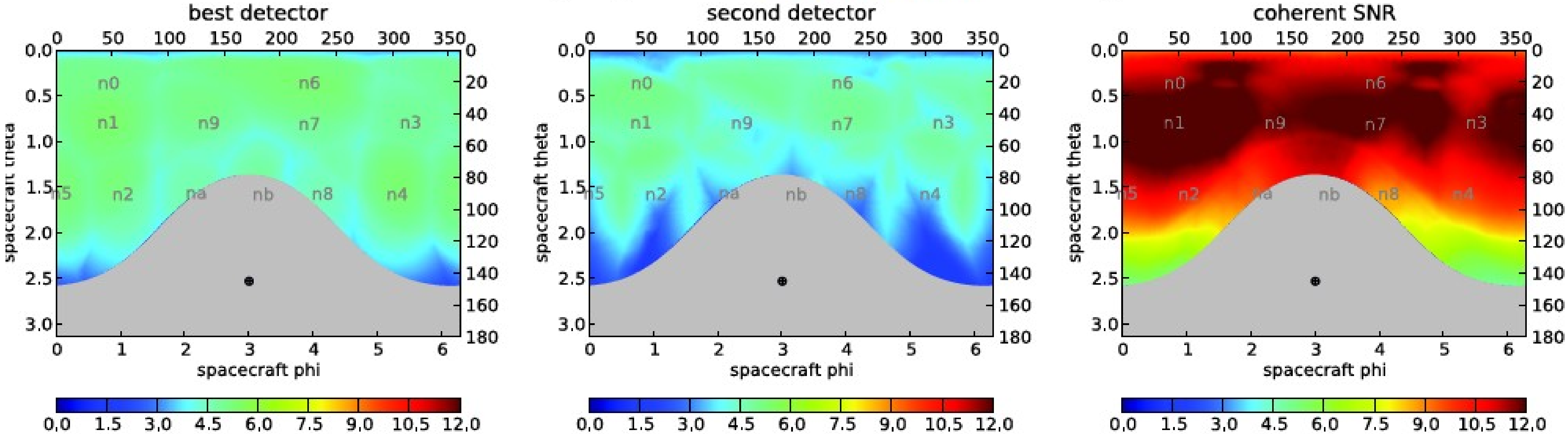
max likelihood

scale-free amplitude prior β=1, avoiding $s \to 0$ divergence

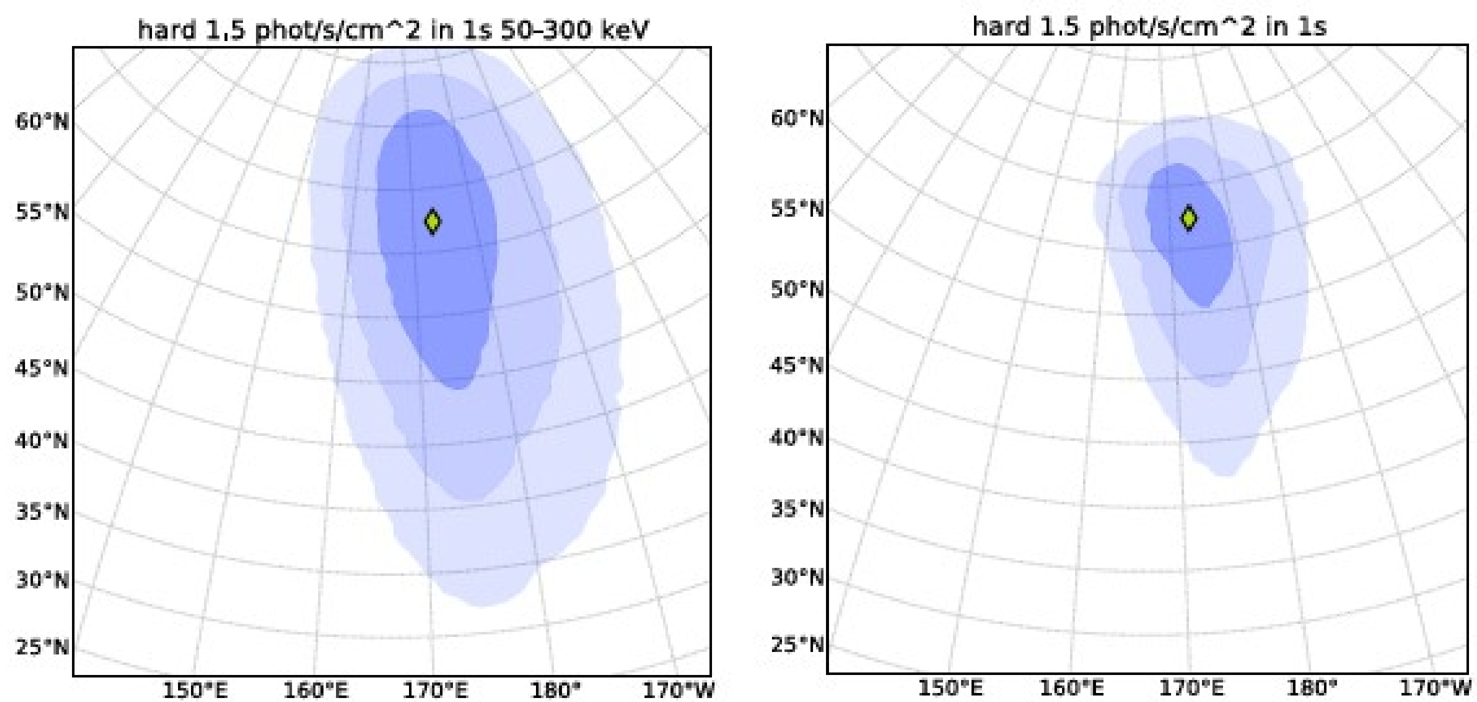
$$\mathcal{L}(d) = \ln \sigma_{\mathcal{L}} + \ln \left[1 + \mathrm{Erf}\left(\frac{s_{\mathrm{best}}}{\sqrt{2}\sigma_{\mathcal{L}}} \right) \right] + \mathcal{L}(d|s_{\mathrm{best}}) + \begin{cases} \ln \left[1 - e^{-(s_{\mathrm{best}}/\gamma\sigma_{\mathcal{L}})^\beta} \right] - \beta \ln s_{\mathrm{best}} & s_{\mathrm{best}} > 0 \\ -\beta \ln (\gamma \sigma_{\mathcal{L}}) & s_{\mathrm{best}} \leq 0 \end{cases}$$

Increase in statistics

- Multi-detector analysis provides increased SNR over single-detector



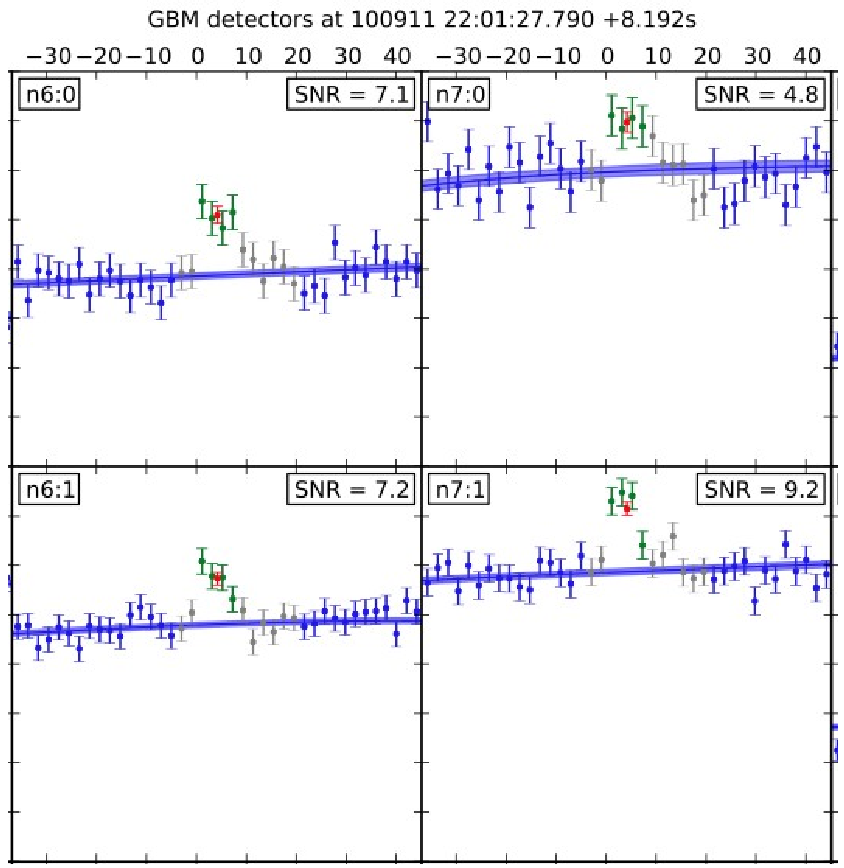
- Additional channels allow smaller statistical errors for sky reconstruction for weak signals



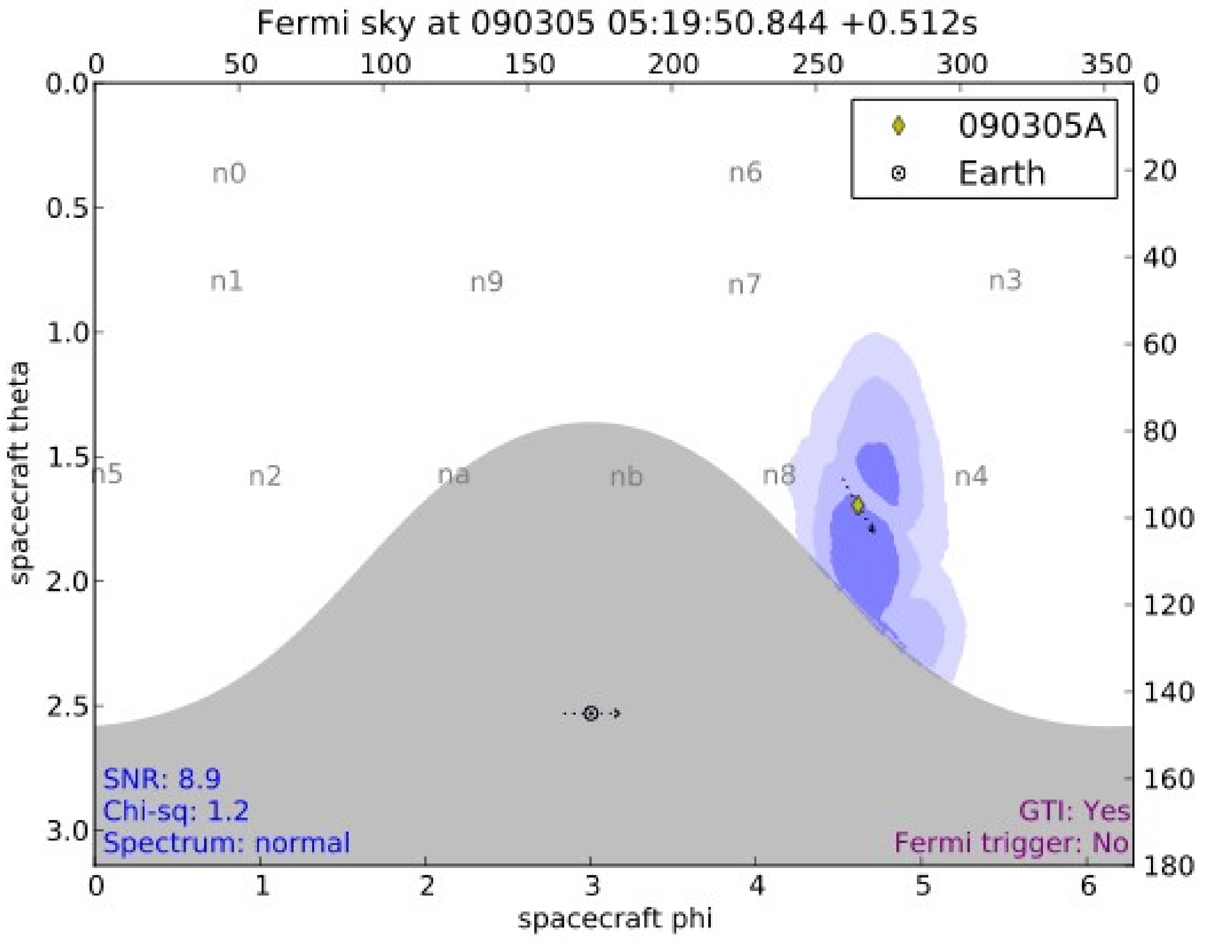
Background of GBM analysis

- Background of analysis from a variety of sources..

un-triggered x-ray burst



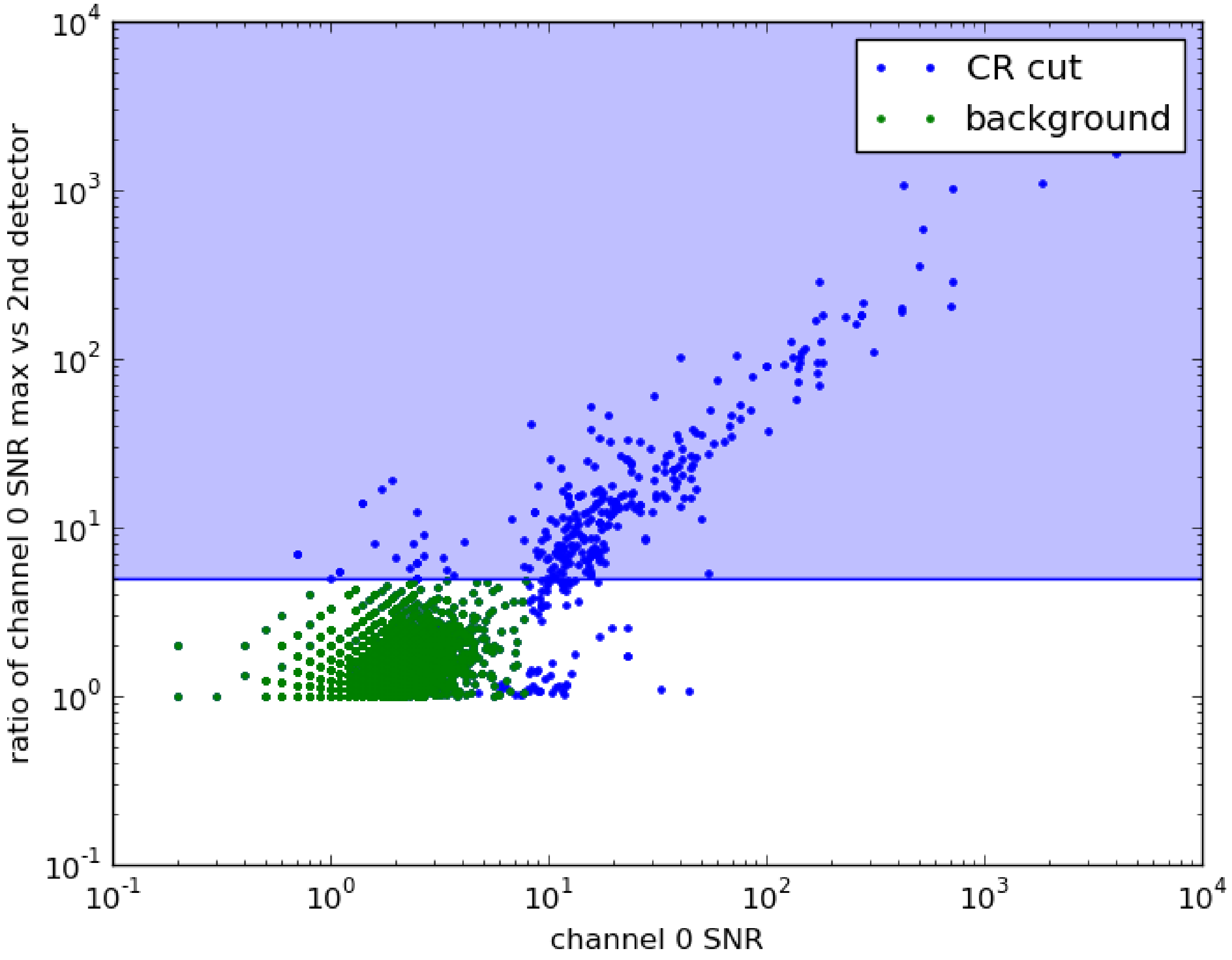
triggered and un-triggered GRBs



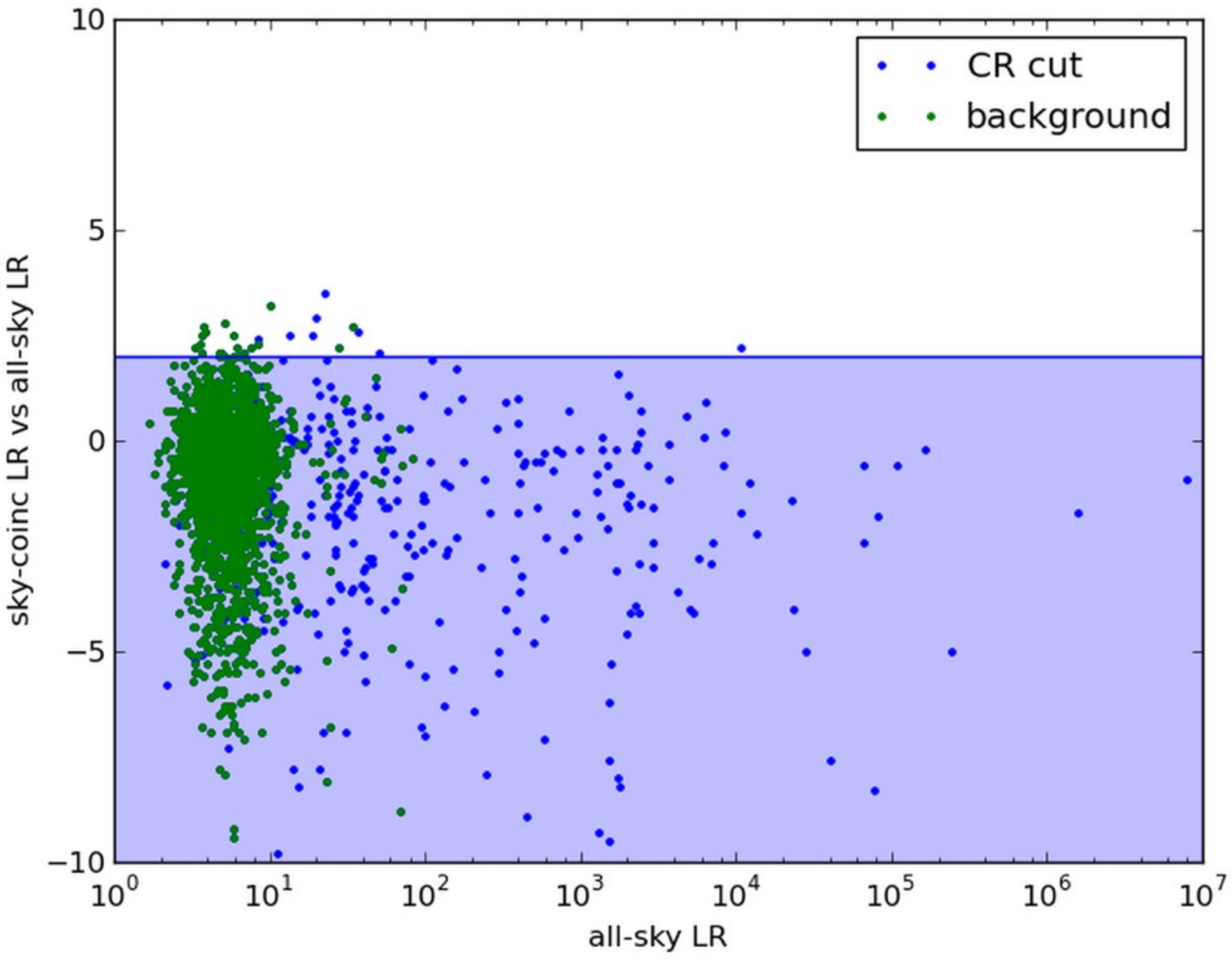
mundane sources: solar activity, occultation steps, particle events, ...

Main cuts for GBM

Particle events strike and single detector, and are very soft.



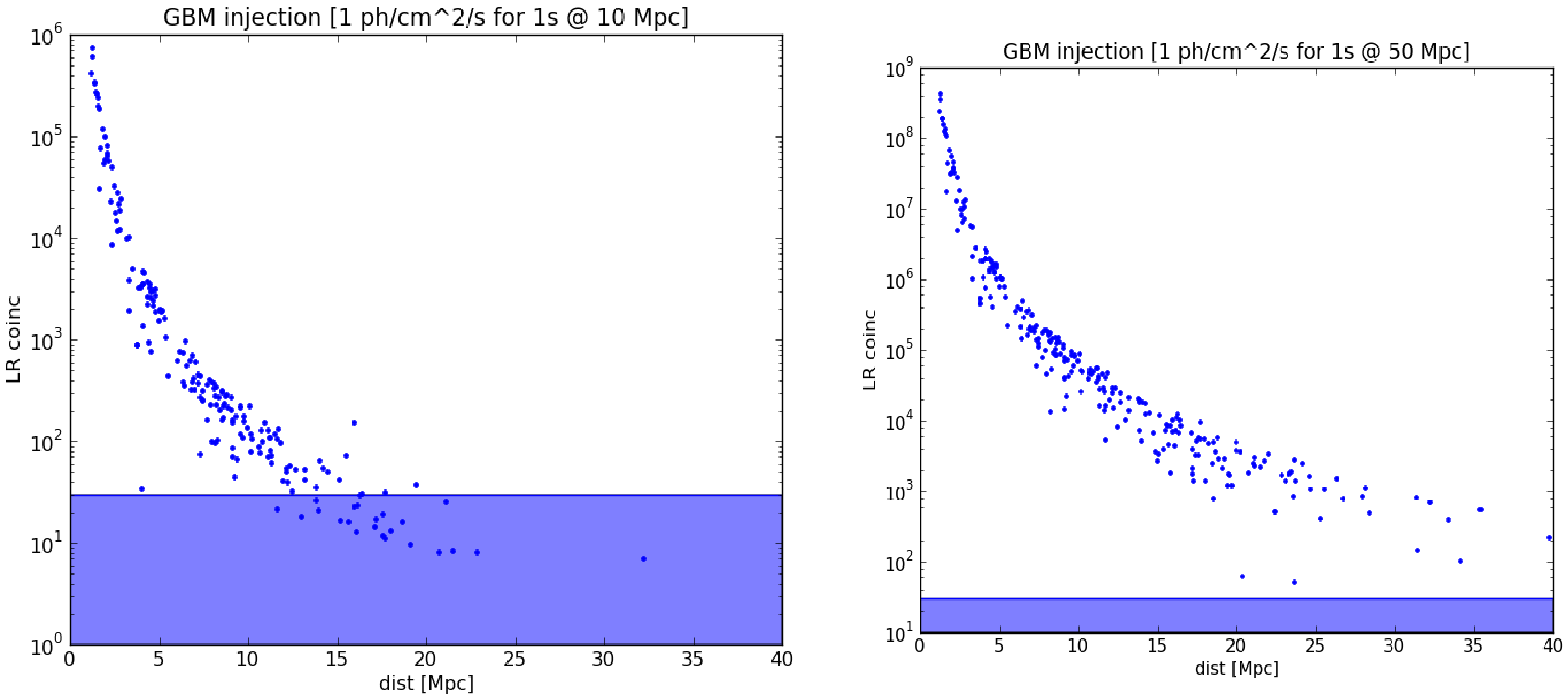
Consistency with LALInference sky posterior: GBM likelihood ratio with vs without sky prior information



Other sources filtered automatically as needed. After cuts, coincidence background is low, easy to reach target 1000x coincidence rejection factor.

Software sensitivity to weak GRBs

Inject signal into GBM data using known response of instrument
Inject at parameters (location, distance) of ihope injections

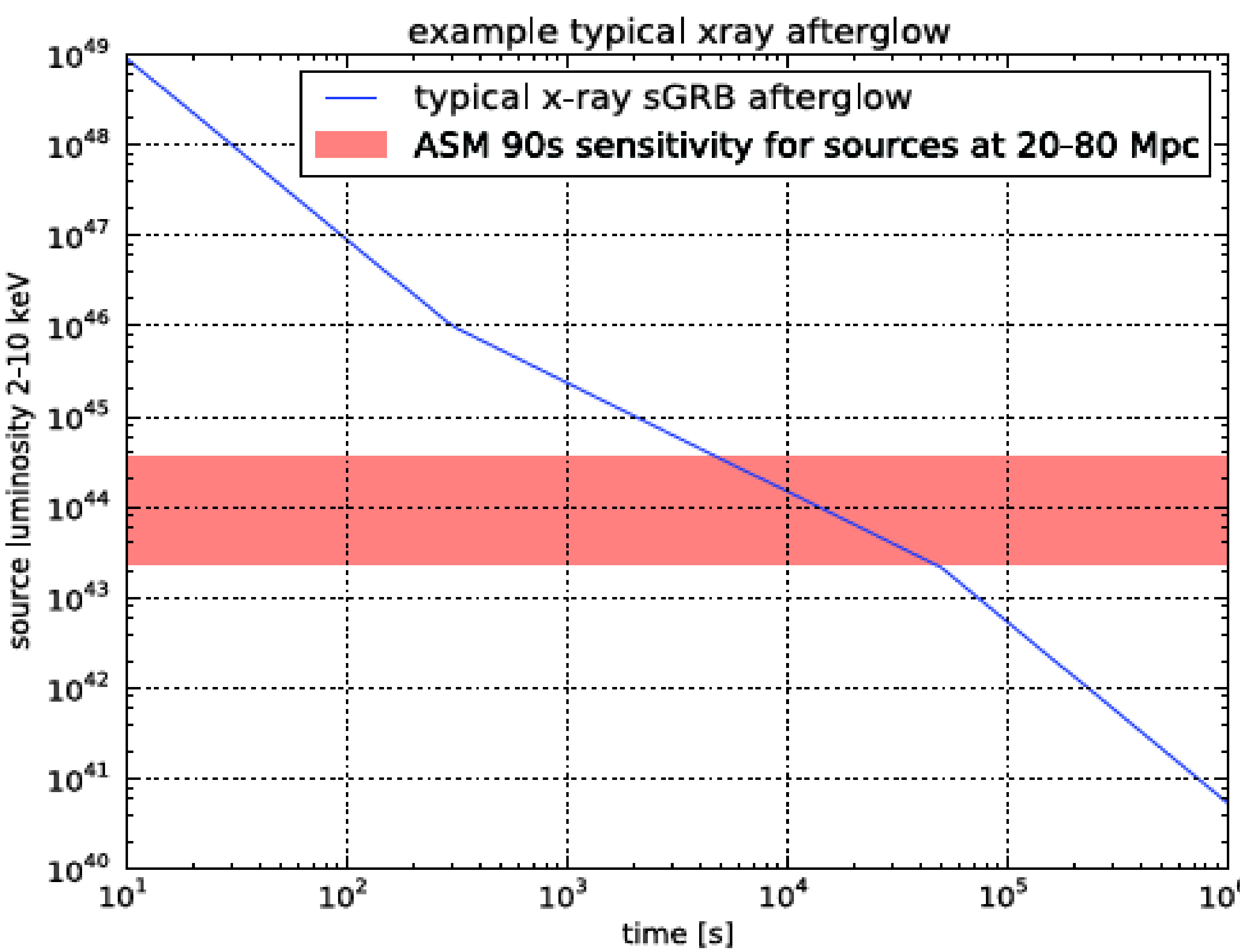


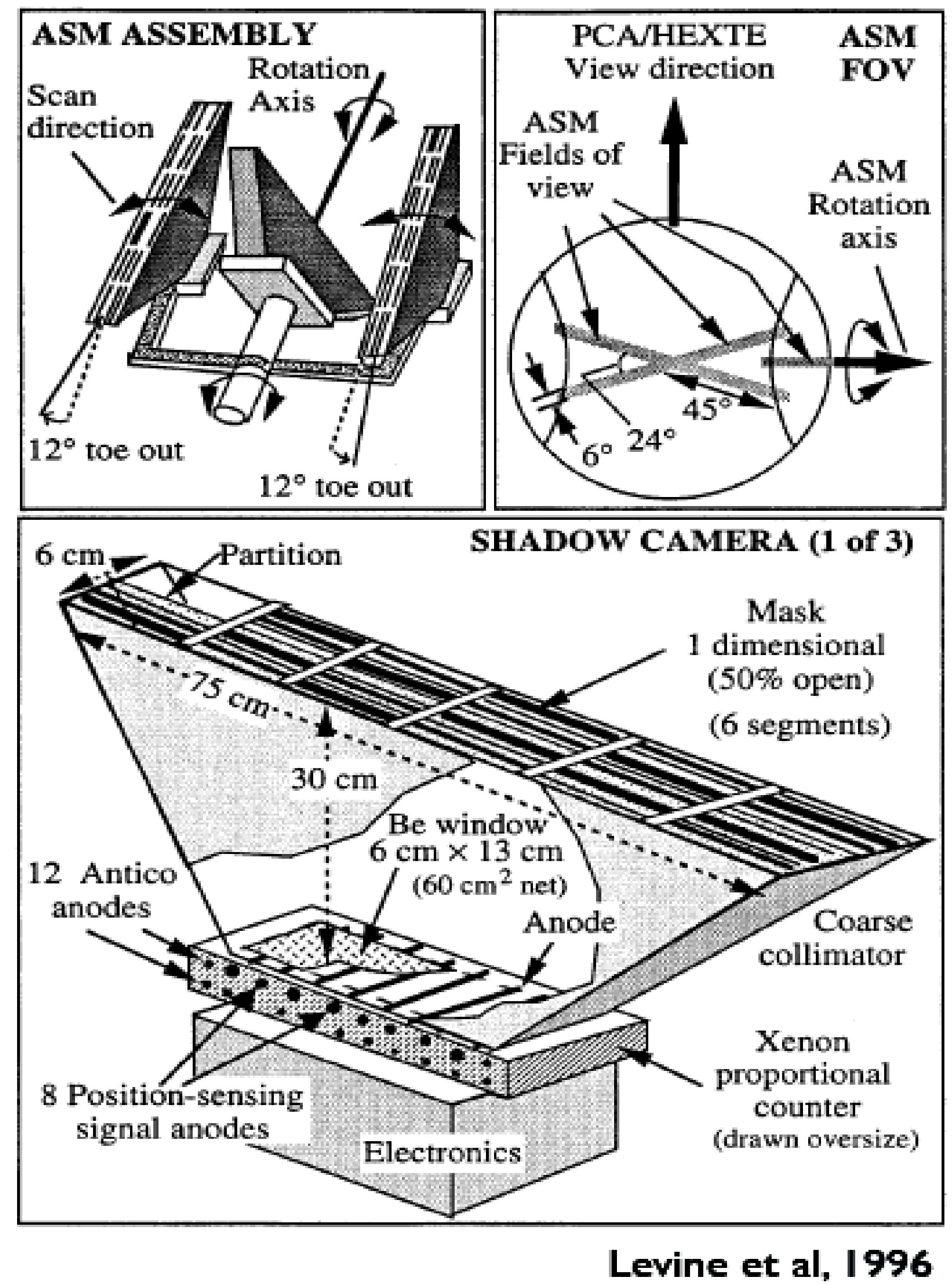
1 ph/cm^2/s is a moderate flux for a short signal
Need to do some stronger injections (standard candle at larger distance). 50-300 keV

X-ray flux measurements with ASM

- *ASM is a coded-mask x-ray detector that operated 1995-2011*
- *Flux from a single location is reconstructed from the observed shadow pattern*
- *90s observations with sensitivity ~20 mCrab every few hours*
- *Able to see typical on-axis x-ray afterglows at LIGO horizon for hours-days*

in collaboration with R. Remillard (MIT)

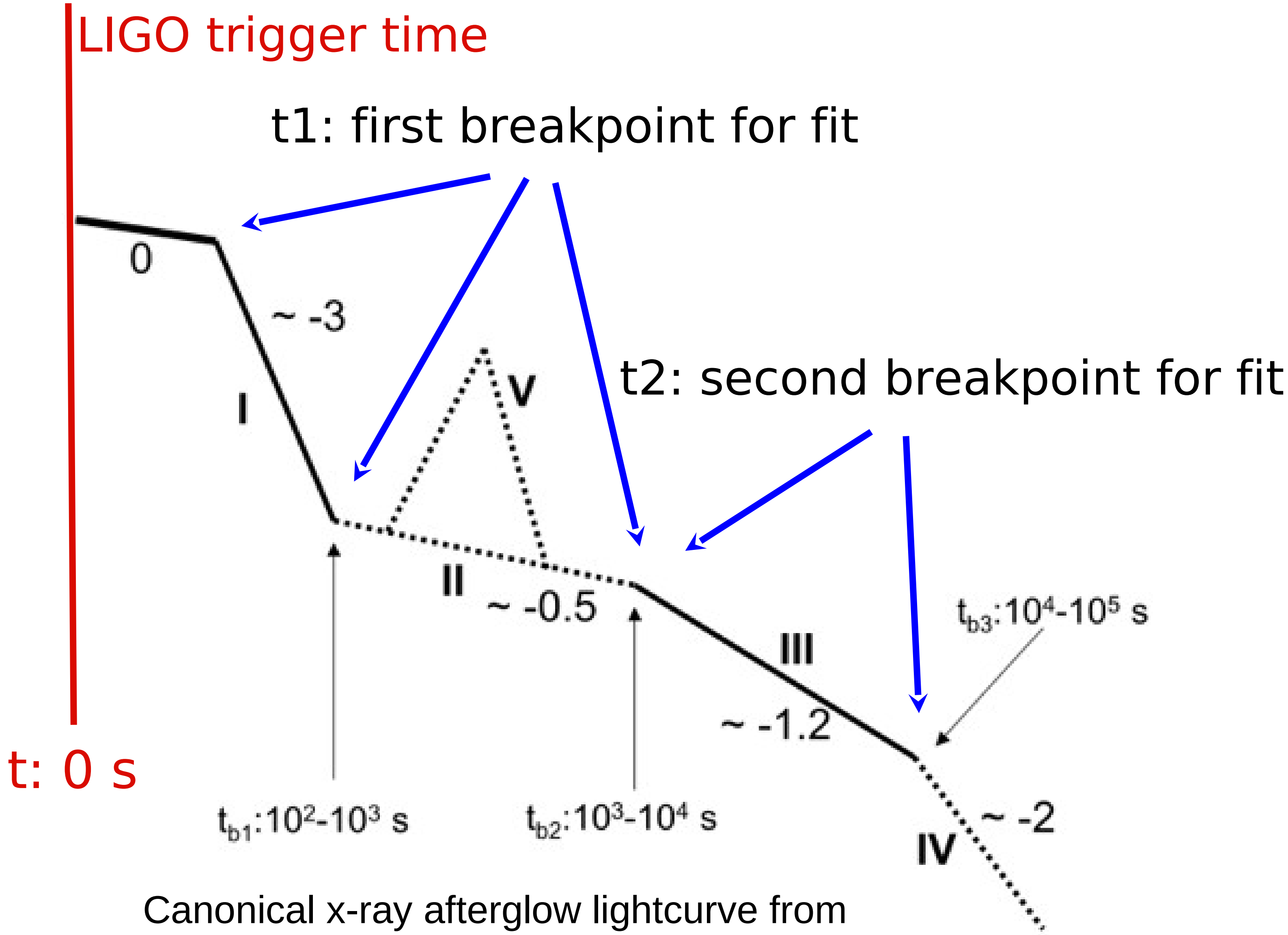




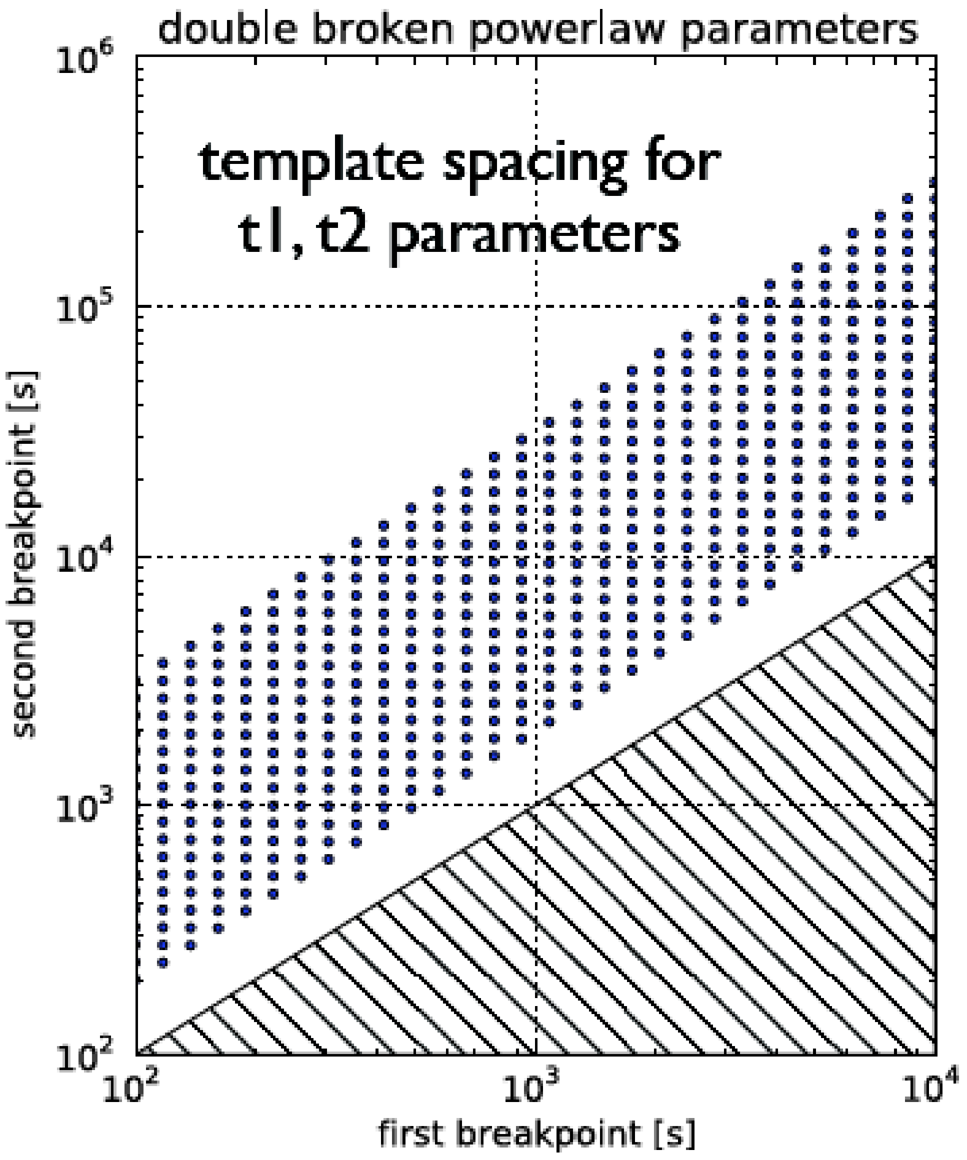
Levine et al, 1996

X-ray flux measurements with ASM

- *Template search over possible afterglow light-curves in sparse, non-uniform data*
- *Parametrize light-curve as a double-broken power-law*
- *try to capture various scenarios: measurements during standard decay (III), early measurement (I), extended emission (II), delayed onset due to off-axis observation (negative index for first segment)*
- *decay indexes vary freely, breakpoint times on fixed grid (difficult to fit due to sparse data)*

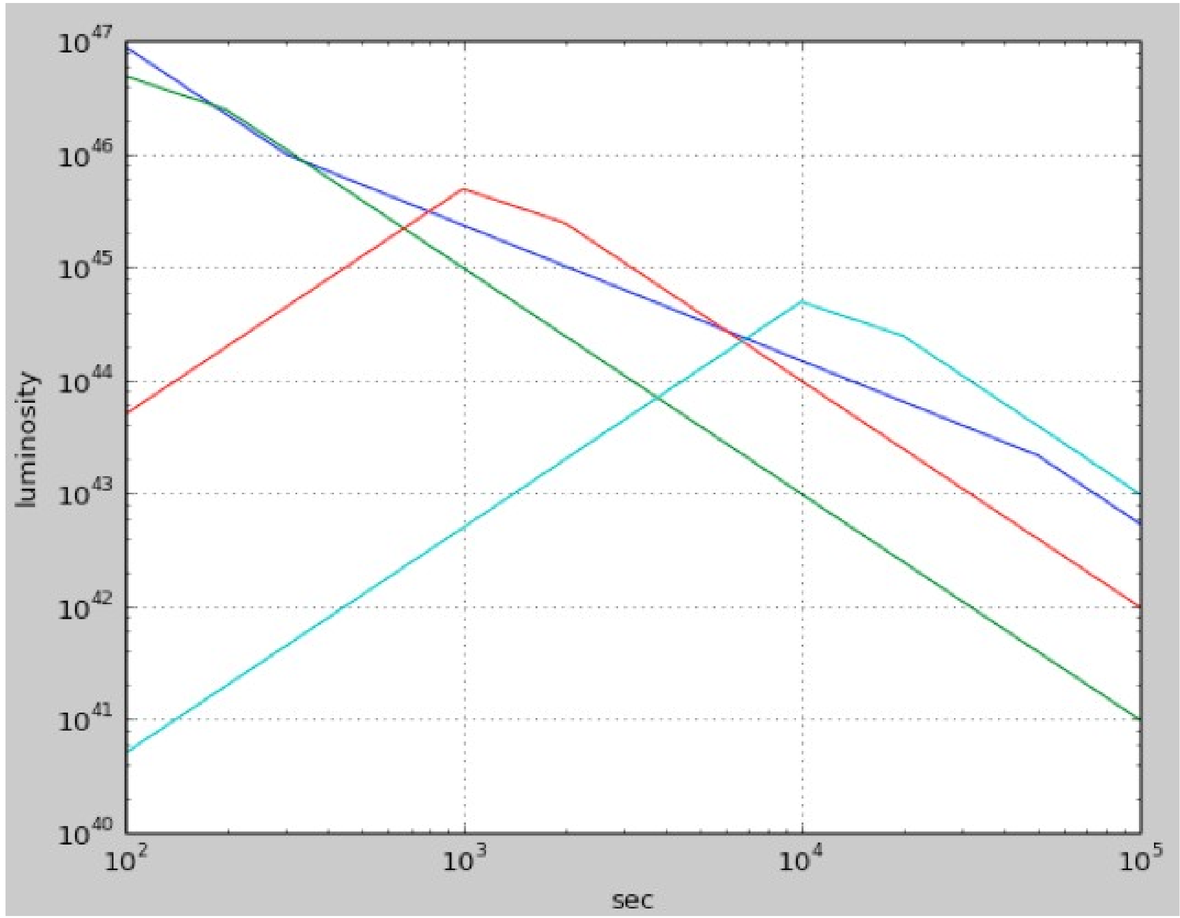


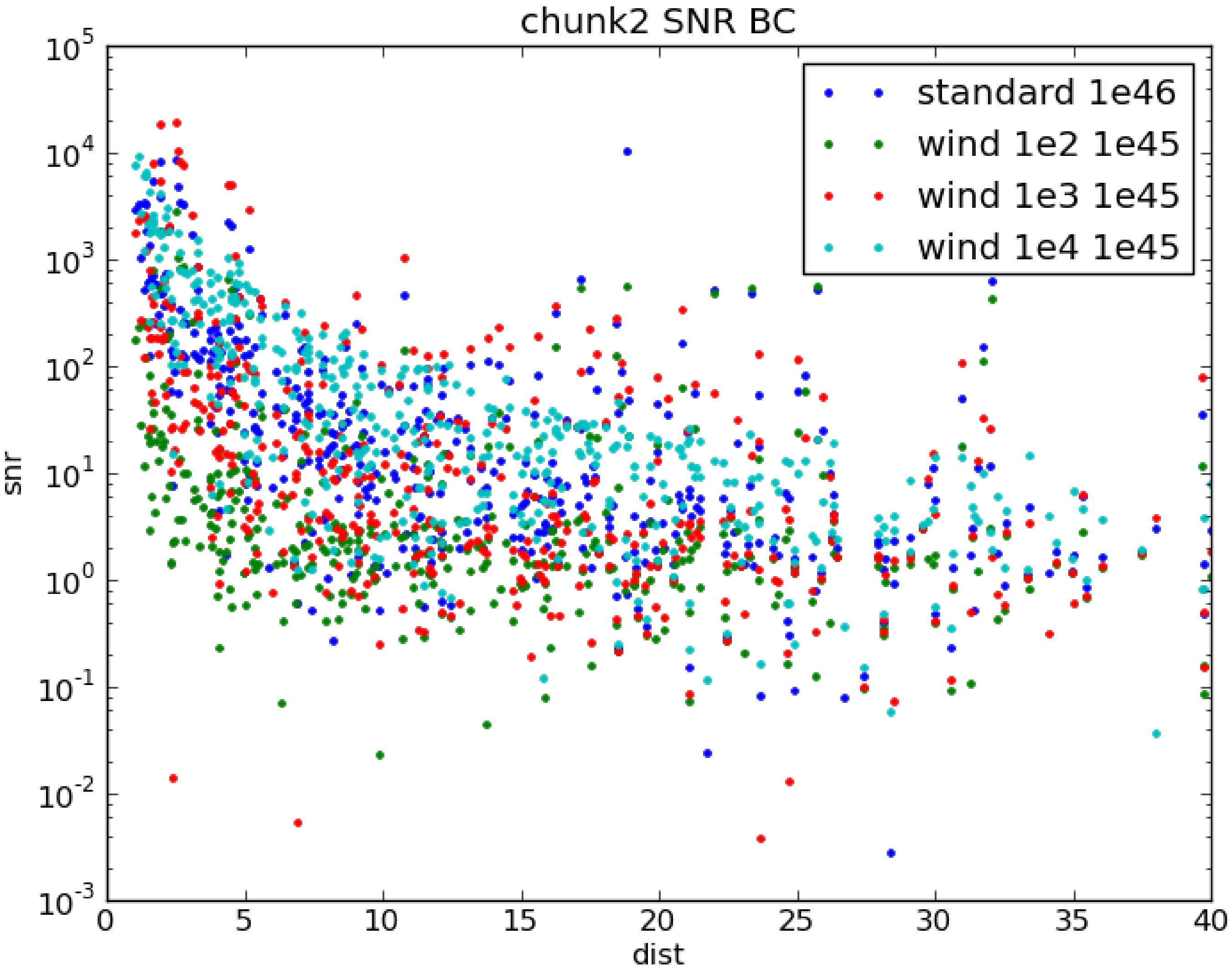
Canonical x-ray afterglow lightcurve from Zhang et al, 2006



Sensitivity to simulated afterglow signals

- We sample a family of "typical" sGRB afterglow signals, as well as burst-like signals on varying timescales in order to test isolated extended emission models.



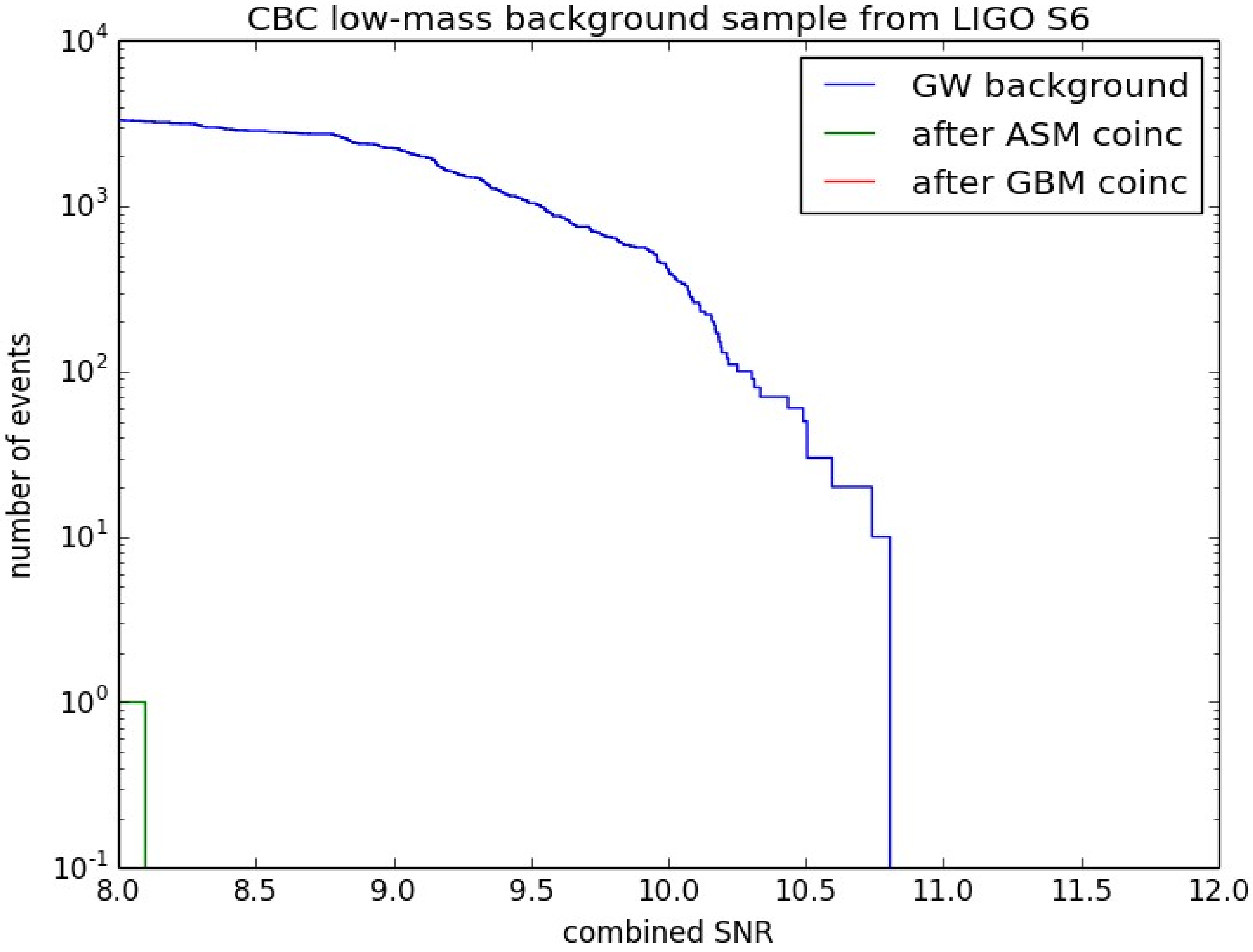


- There is a very large spread in observed signal-to-noise from ASM, due to the fact that the time-to-first-observation is highly variable and afterglows fade rapidly.

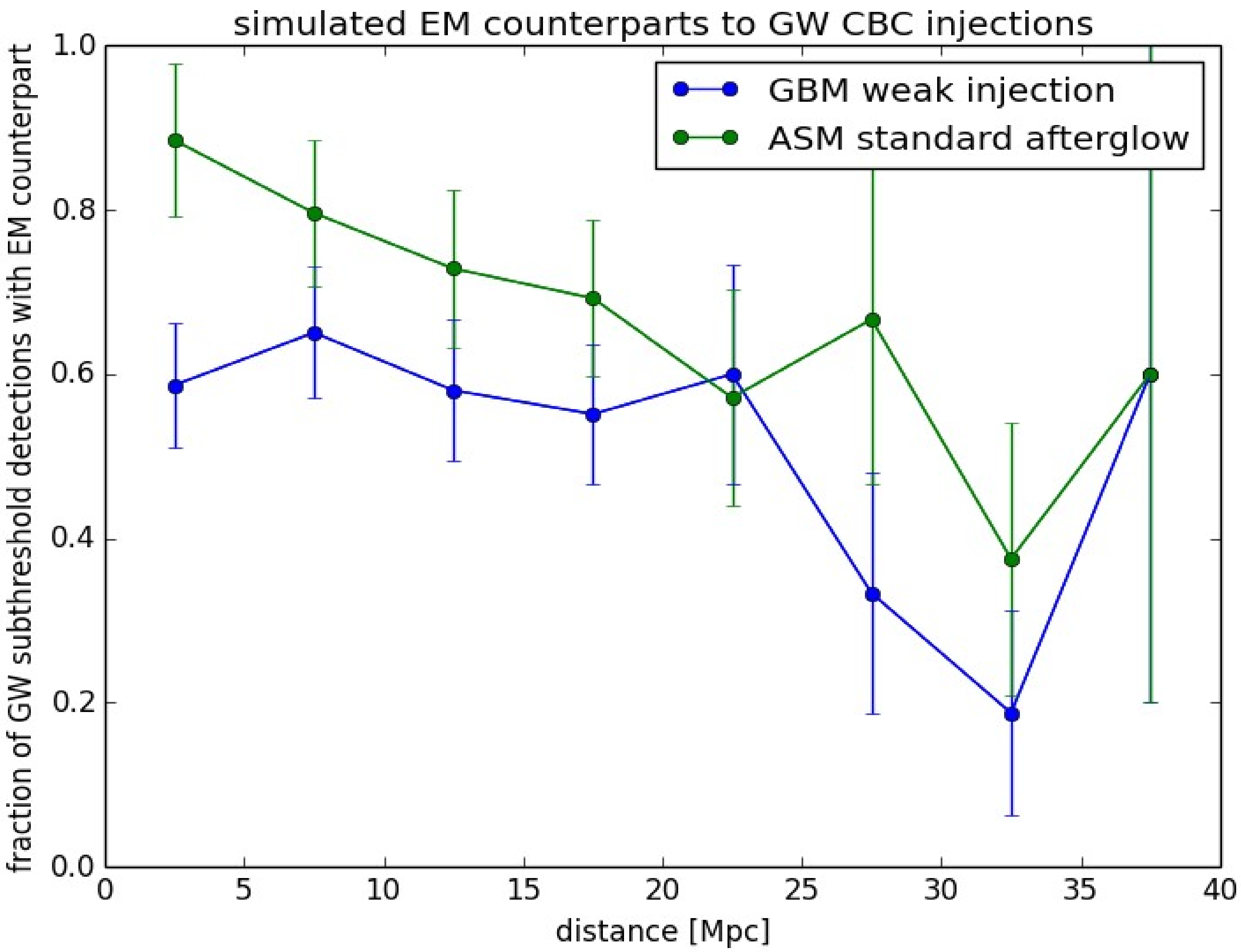
- As expected, longer signals are observed more consistently.

CBC Low Mass Background Sample (preliminary)

- The background is simply the GW background before and after EM coincidence.
- EM false-alarm rate is small enough to reject factor ~1000 of GW background.
- Small amount of x-ray coincident background. No GBM surviving coincident background after sky coincidence requirement.



Efficiency (preliminary)



- Efficiency of EM detection for sub-threshold GW event
  - Standard x-ray afterglow, and weak GRB prompt coincidence (1 phot/s/cm^2 in 50-300 keV at 50 Mpc)
  - Effects of duty-cycle, sky coverage, localization success, and signal strength

Toward Advanced LIGO-Virgo

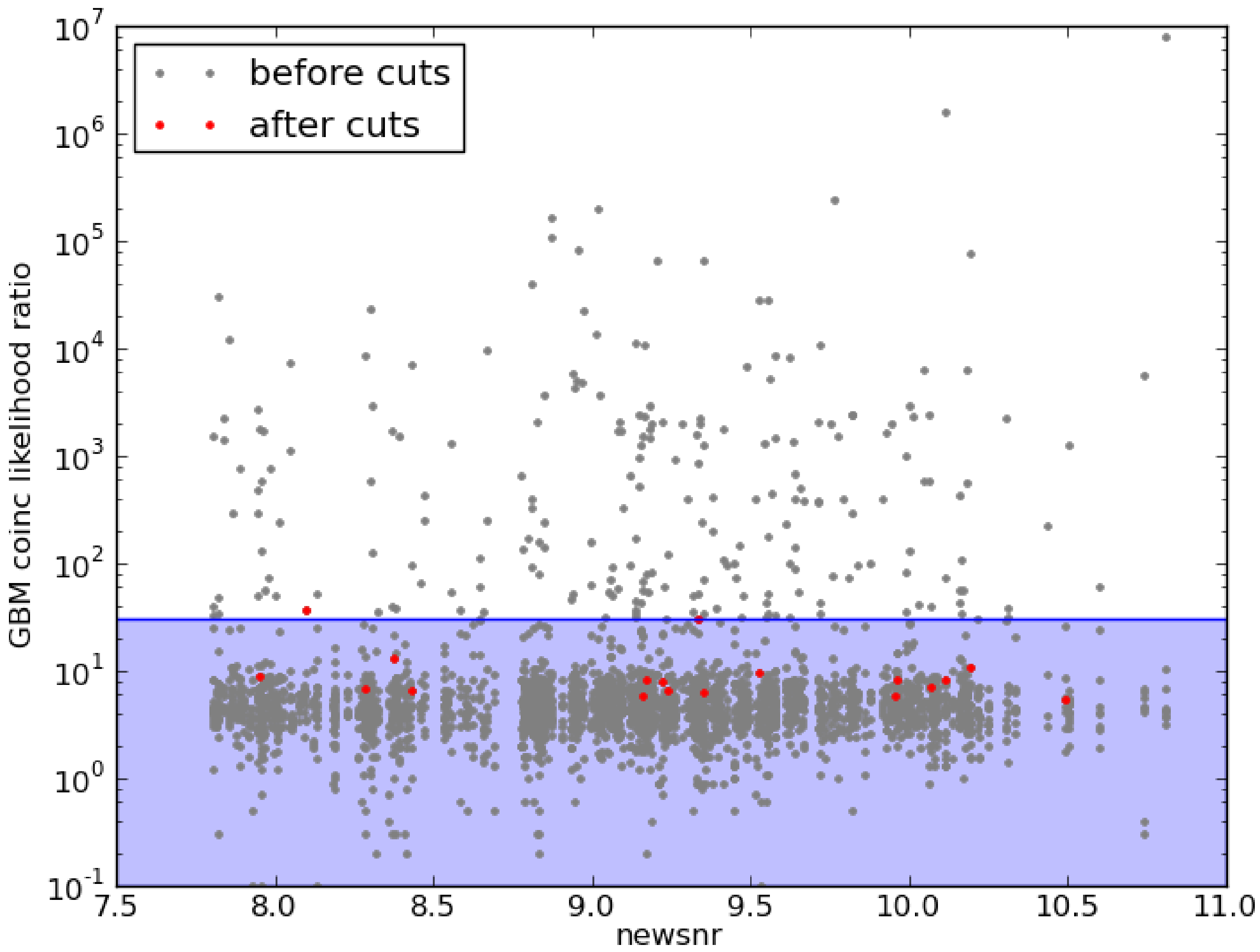
- *Advanced detectors should provide convincing GW candidates for follow-up*
- *EM coincidences through traditional channels expected to be rare*
- *GW-triggered targeted offline search can search for subthreshold or exotic emission scenarios*
- *Survey data not limited by observation time -- can follow-up thousands of events and fully leverage GW-EM coincidence background rejection*
- *Automated analysis will characterize EM data, and can place EM upper limits about a known merger event*

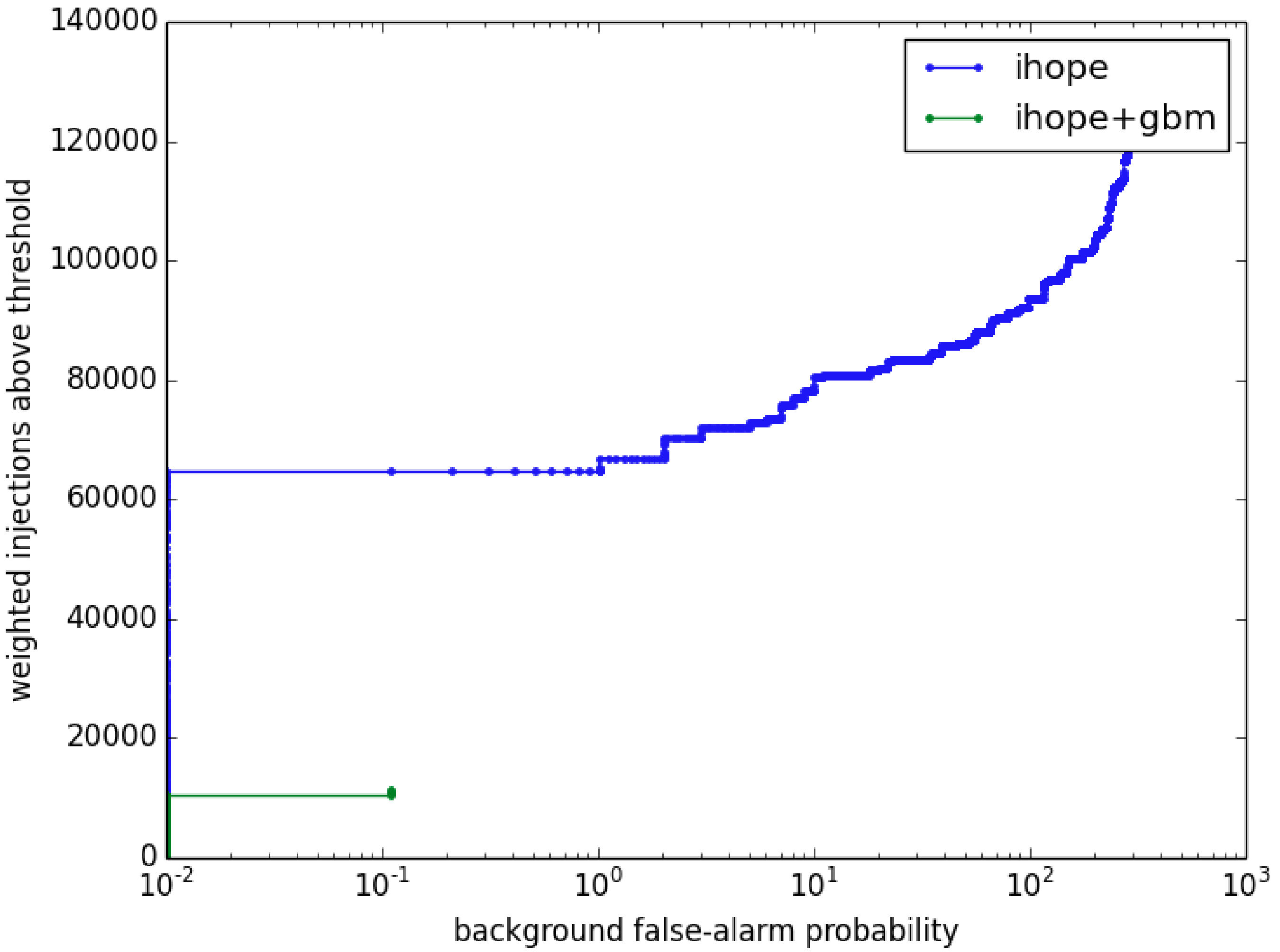
More information:

- *http://arxiv.org/abs/1303.2174*

Follow-up on time-shift events

GW time-shift events (100x livetime) searched using additional GW-EM time-shifts (10x)
Following plot represents about 1/3 of 60d S6D period, and about 2d of continuous GBM livetime

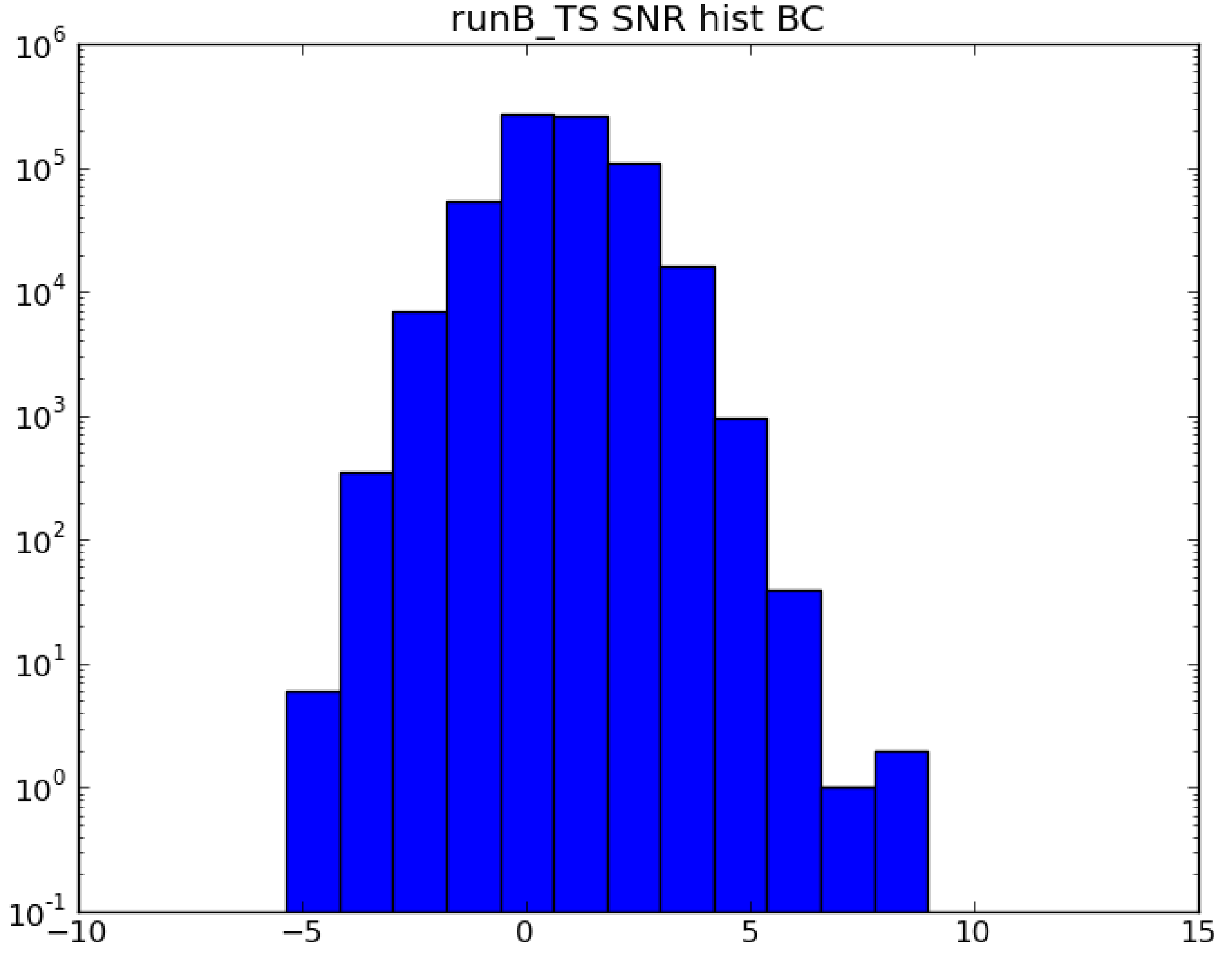


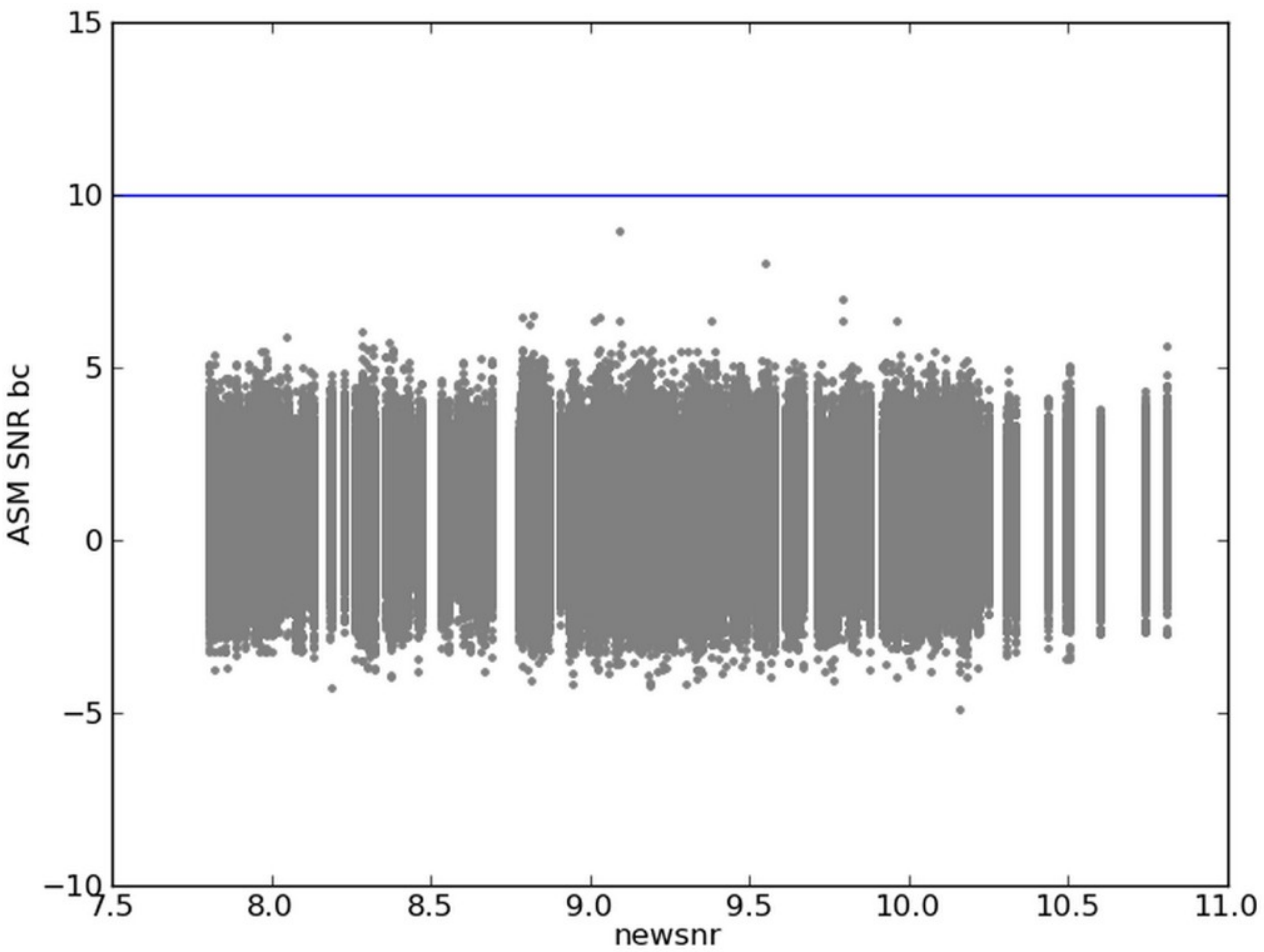


Only one event above thresholds in 1000x live-time.
Efficiency loss due to observational constraints, localization, but mostly because our test signal was too weak.

Follow-up of time-shift events

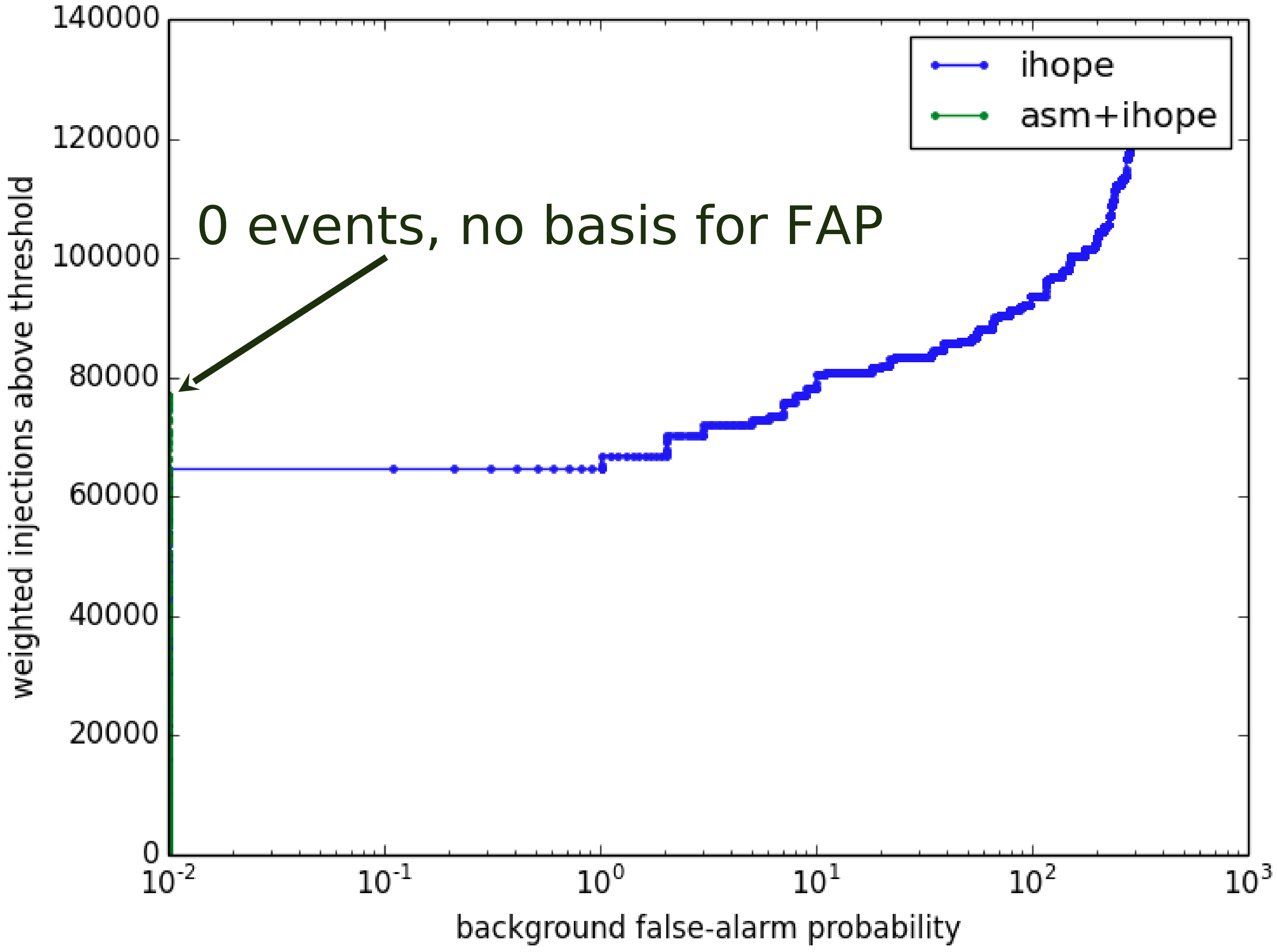
- Follow-up 200 most promising galaxy hosts per event (computational constraint). This covers most of the probability for a well-localized event.





- No ASM outliers in the preliminary S6d epoch (~1/3 of total time).
- 10x GW-EM timeshifts (in additional to 100 H1-L1 shifts) used.
- Small set of ASM cuts according to chi-sq against template, and a couple previously identified noisy locations (appear multiple times) vetoed.

Sensitivity to simulated afterglow signals



- ROC curve for a typical strong short-GRB afterglow.
- Since there are no coincidences in the preliminary background set, we take the ihope sensitivity at production thresholds.