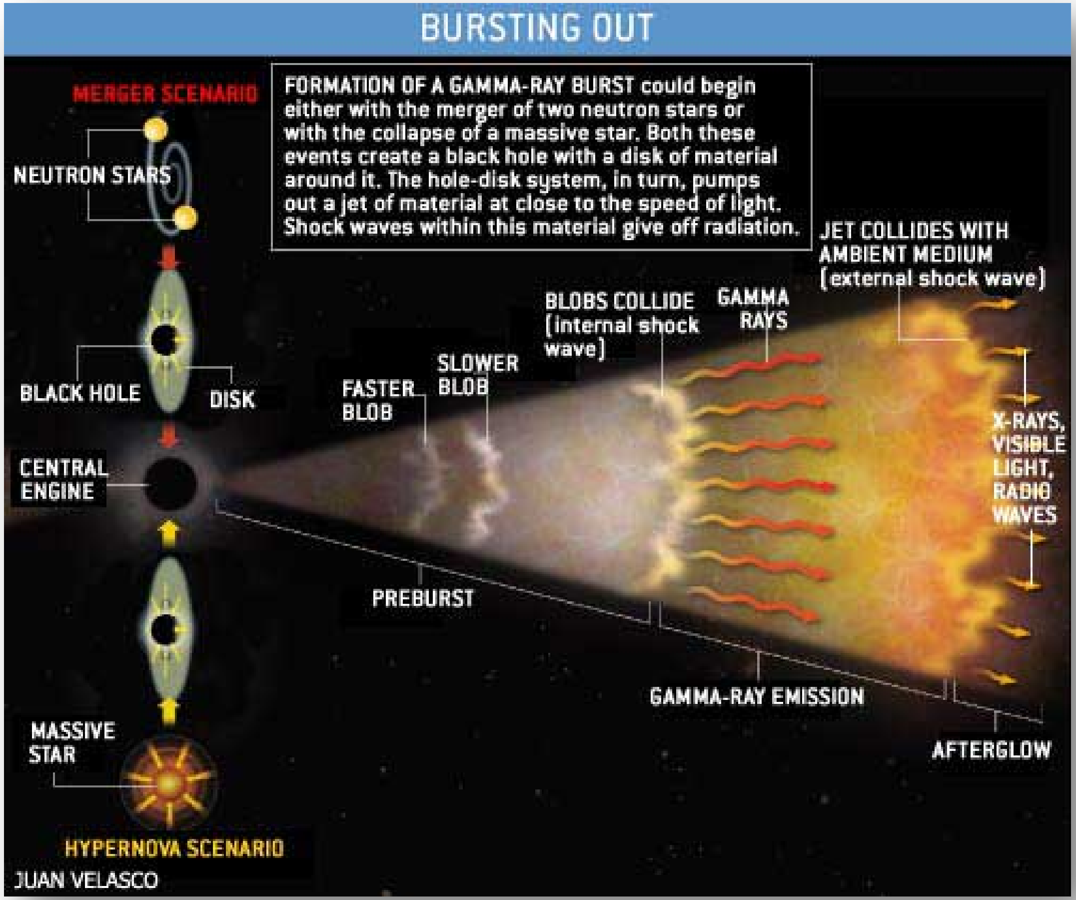
Gamma-ray bursts in the multimessenger era

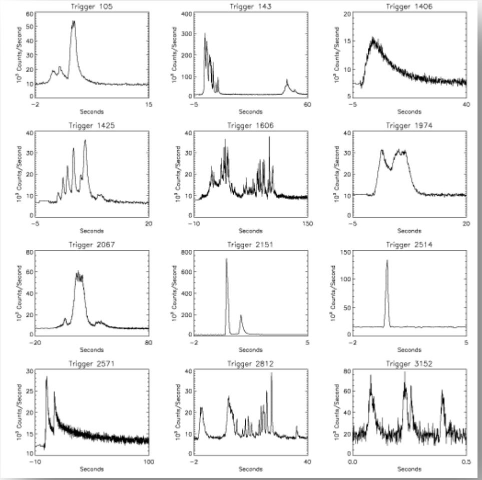
Eric Howell

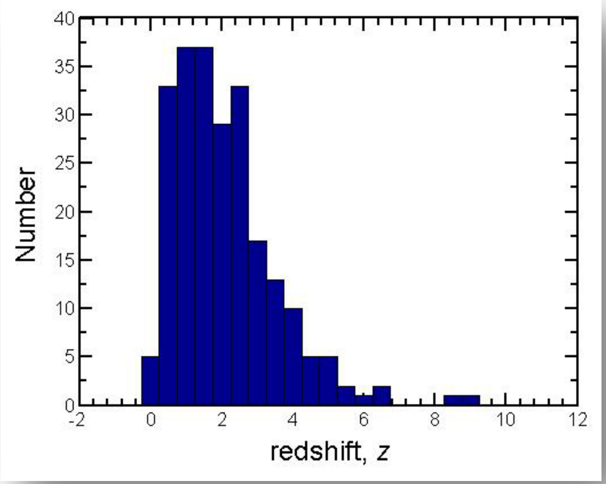
The University of Western Australia

1. GRB overview
2. GRB topics @ UWA
3. GRBs: Fermi & CTA
4. GWs & Multimessenger era
5. Low Latency EM follow-up of GW triggers

Gamma-ray bursts

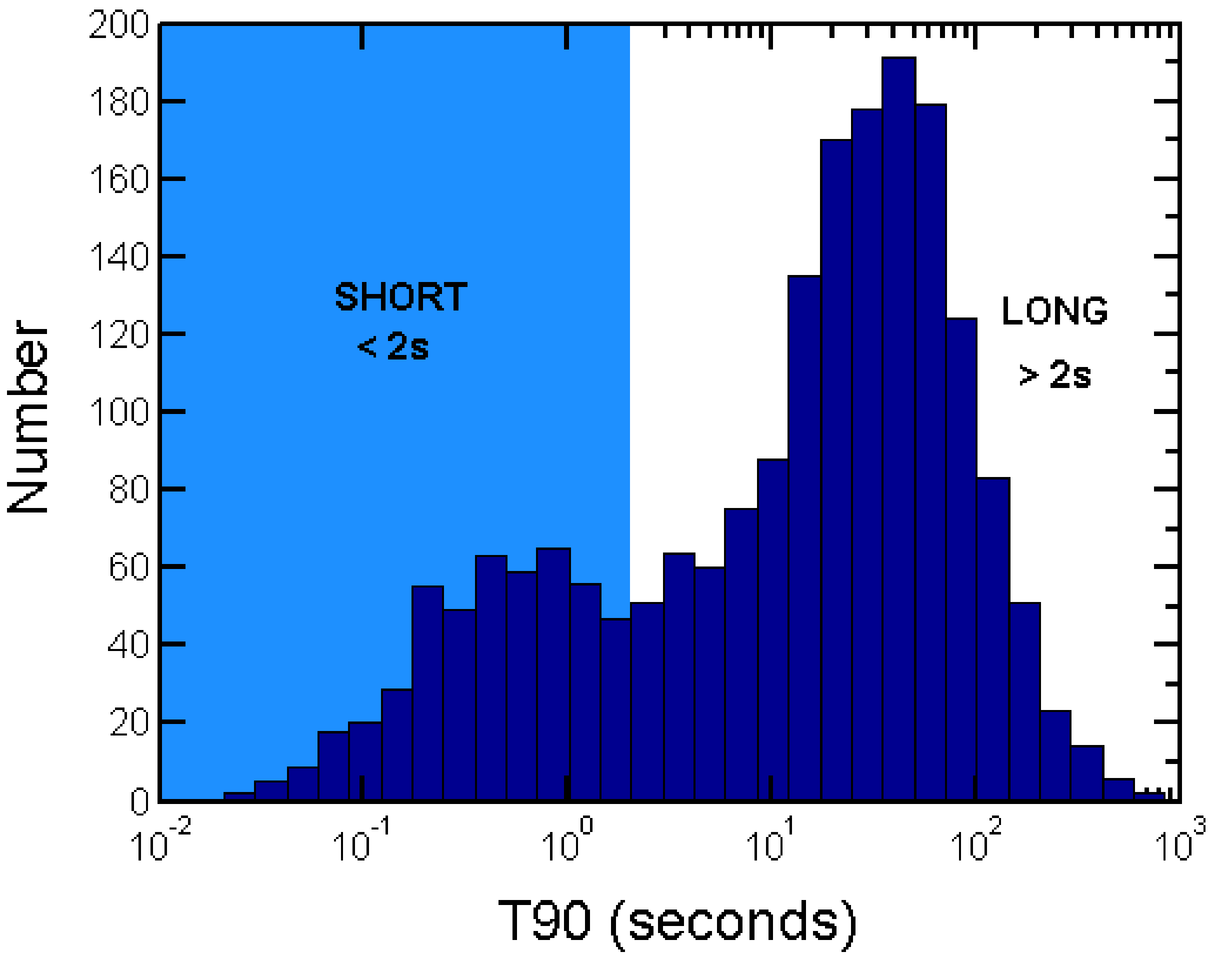






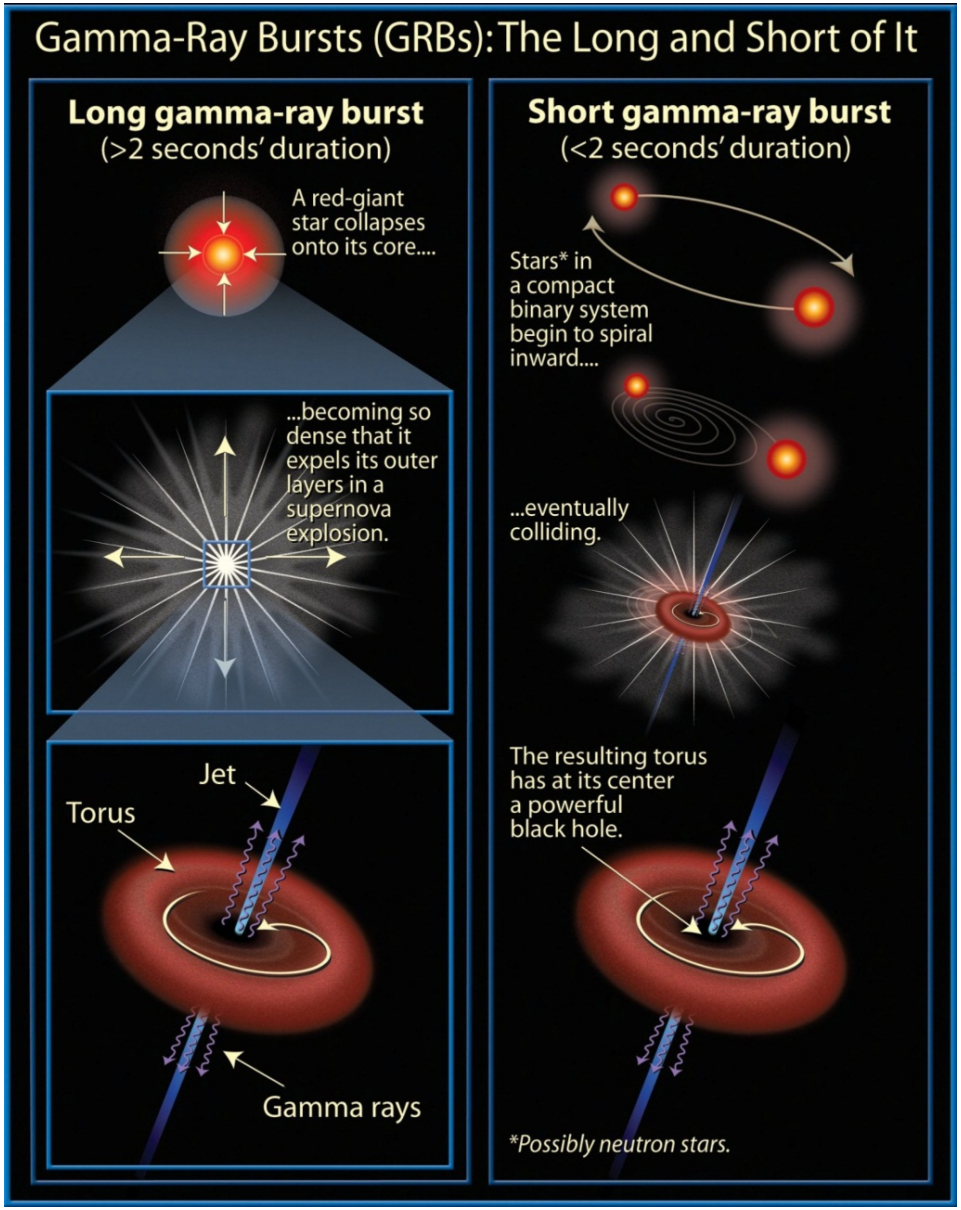
- 10keV-GeV photons
- 10^{51}-10^{54} ergs in few seconds
- γ-rays - ultra-relativistic energy flow converted to radiation

BATSE – duration distribution

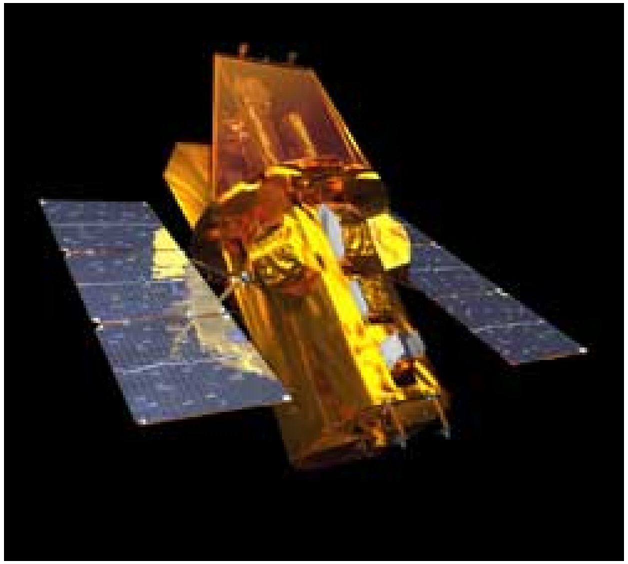


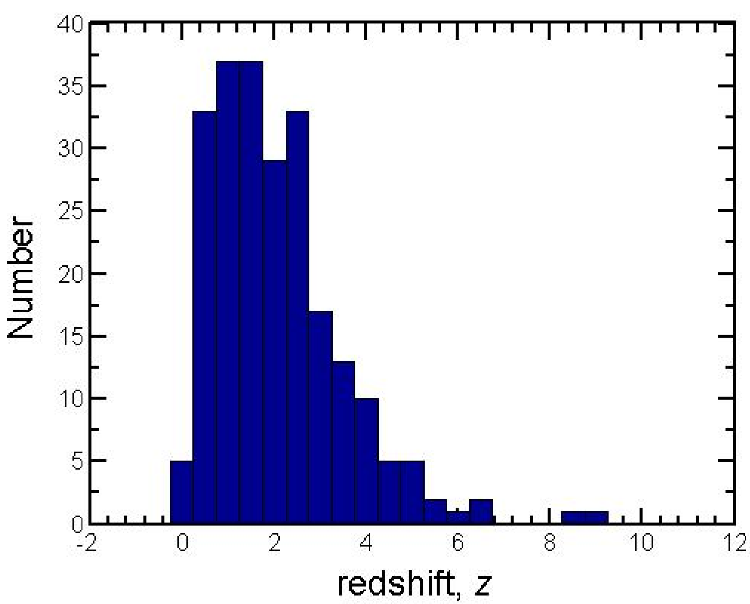
BATSE (1991- 2000) >2000 GRBs detected

GRB categories – the popular picture



Swift : 2004 – 2019 + ?





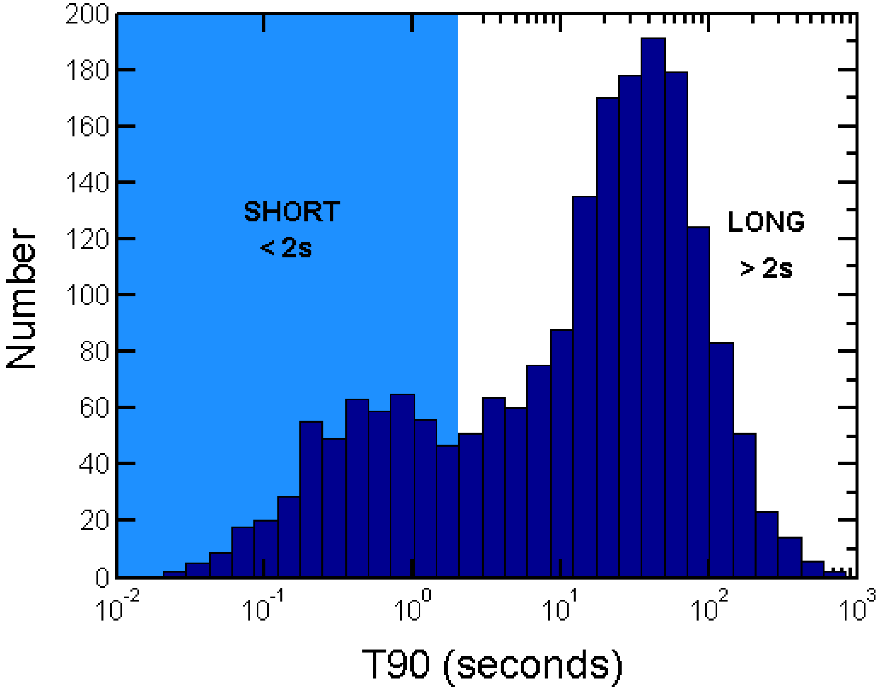
- **(15–150) keV**
- **Over 700 bursts recorded**
- **10% are SGRBs**
- **2% are SGRB-EEs**
- **Over 200 redshifts**
- **Triggering – complex**

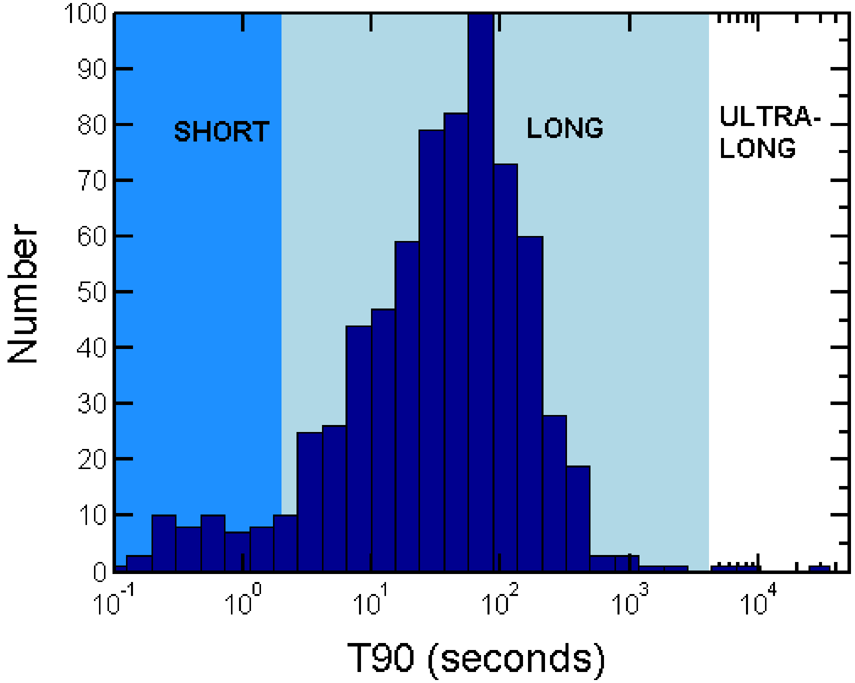
<u>UNITS</u>

Flux: ph s^{-1} cm^{-2} ; erg s^{-1} cm^{-2}

Luminosity: ph s^{-1} ; erg s^{-1}

GRB populations – 2 detectors





BATSE (1991- 2000)
>2000 GRBs detected

Swift (late 2004-2019)
>700 GRBs detected

GRB populations in the Swift era

T90>2s (?)

L-GRBs (Type II) – soft spectra; hosts – irregular galaxies with star formation (?); progenitors – SNe (?); 200 with *z*

SL-GRBs – lower luminosities than L-GRBs; lower *z*

UL-GRBs – T90>10,000s

T90<2s (?)

S-GRBs (Type I) - harder spectra; hosts – elliptical/early type galaxies – little star formation (?); progenitors – compact binary mergers (?); ~10 with *z*

S-GRB-EE – pulse + extended emission ~100s

? = anomalous observations have provided exceptions to this framework

1. GRB overview
2. GRB topics @ UWA
3. GRBs: Fermi & CTA
4. GWs & Multimessenger era
5. Low Latency EM follow-up of GW triggers

GRB Research at UWA

- Detector selection bias (Goddard, correlations)

Swift bias-Goddard, effect on high energy correlations

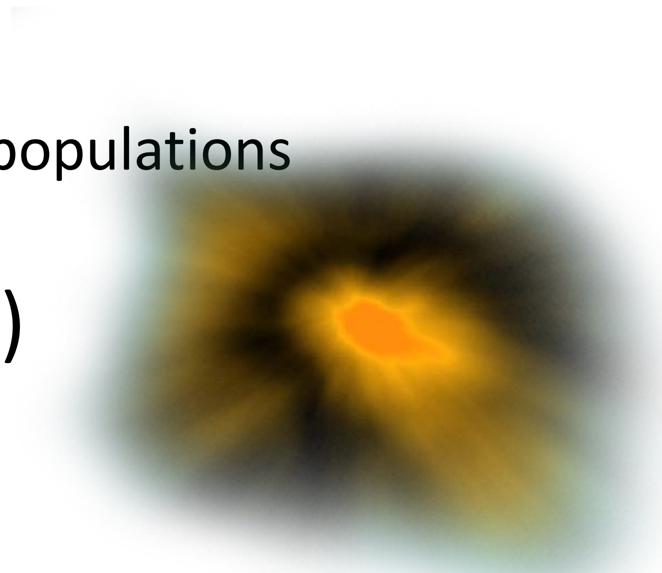
- Event rate estimation (GRB and GWs)

- Population studies

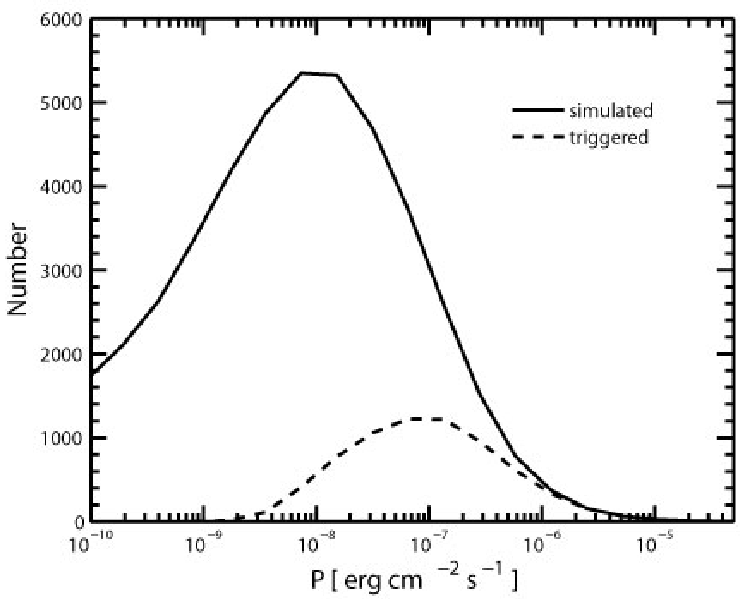
Estimating global parameters, Untangling populations

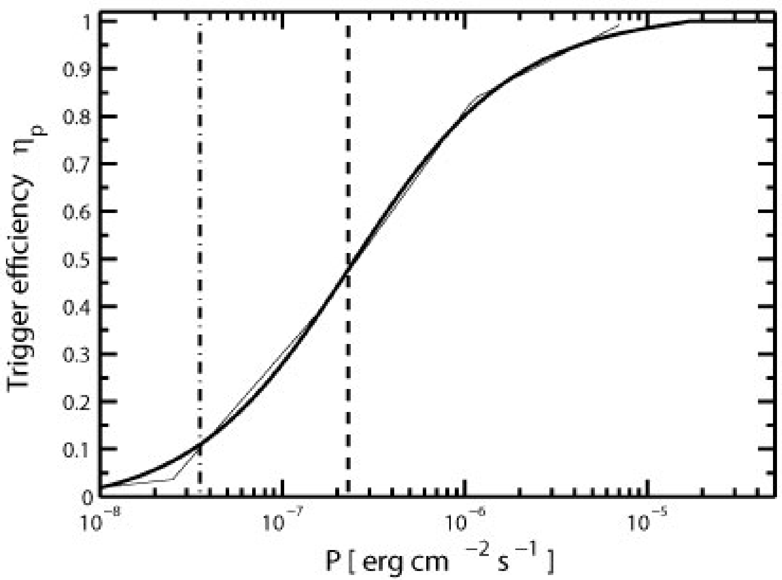
- GRB Follow-ups (Zadko, TAROT)

- Multimessenger studies



Estimating Swift triggering efficiency





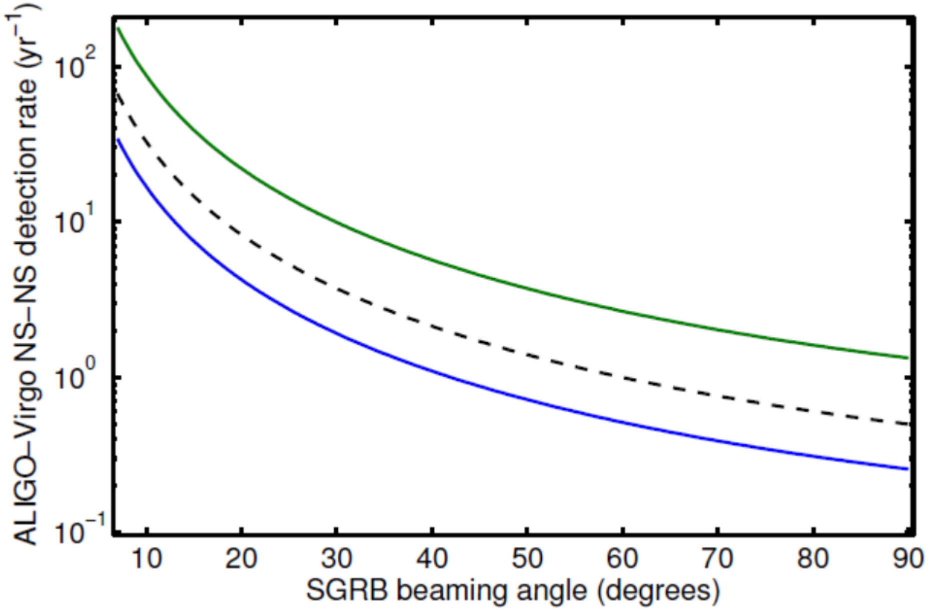
- **Swift - over 500 (650) triggering criteria – complex**
- **Working with Goddard Space Flight Centre to estimate the Swift Efficiency function***

*** See Lien et al. (2014), ApJ, 783, 24 & Howell et al. (2014), MNRAS 444, 25**

The Swift/aLIGO SGRB rate

- Start with observed Swift SBRB rate from a strict sample
- Factor out detector selection bias to obtain true rate

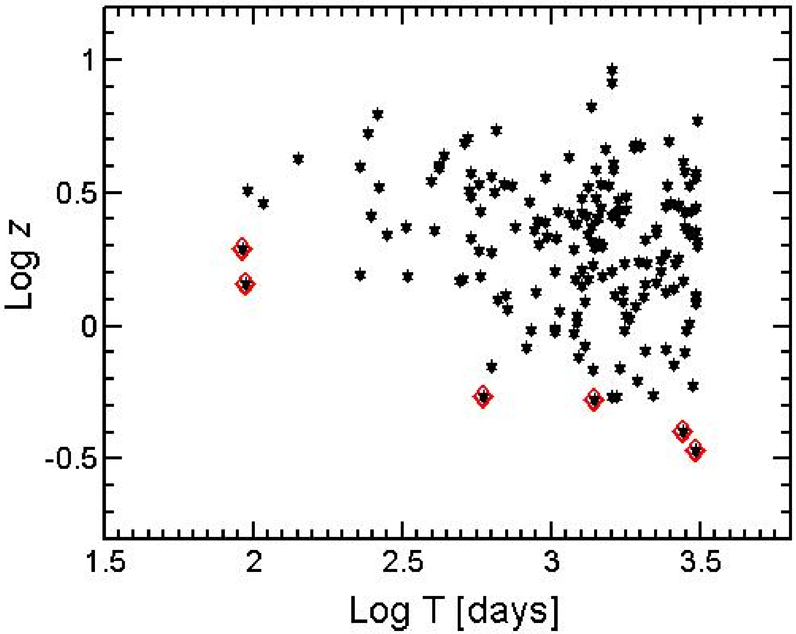
$$R_{\mathrm{SGRB}} = \sum_{i}^{n} \frac{1}{V_{\mathrm{i(max)}}} \frac{1}{F_r} \frac{1}{T} \frac{1}{\Omega} R_{B/S} B_i(\theta_{\mathrm{j}}) \mathrm{P}_{i(T_{90};\mathrm{P_L})}.$$

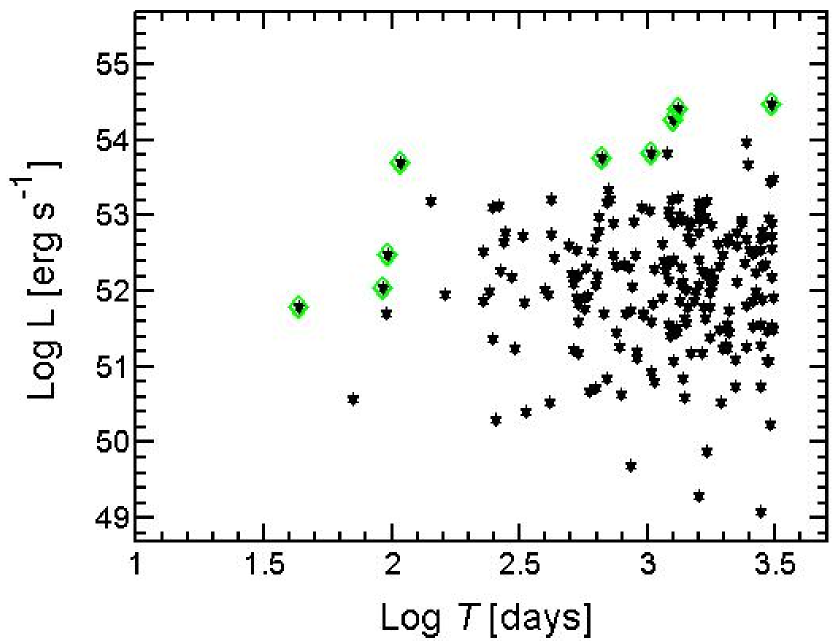


Coward, Howell, Piran et al. (2012), MNRAS 425, 2668

The observation time dependence of Swift L-GRBs

Observation-time: waiting time to detection – taken from when a detector is switched on





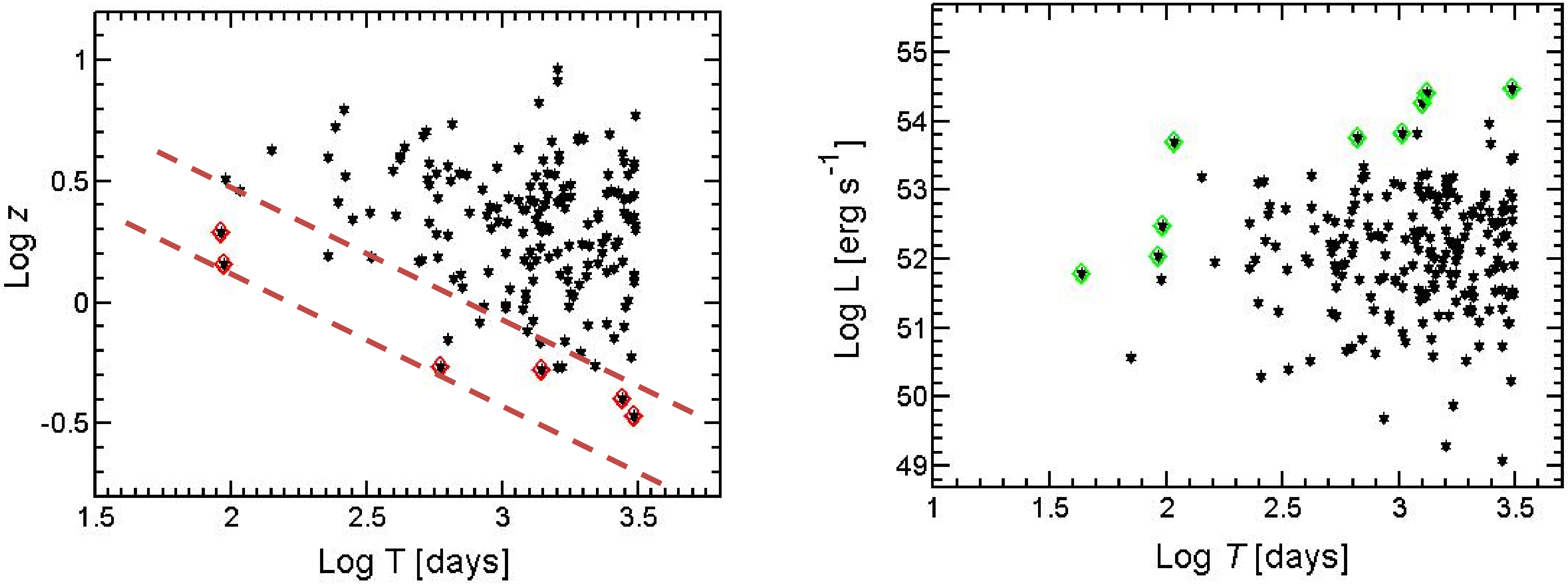
Successively rarer events as a function of time – PEH data

- **Can the PEH sample provide insight ?**
- **How can you model this sample ?**

PEH - Coward & Burman, (2005) MNRAS , 361, 362

The observation time dependence of Swift L-GRBs

Observation-time: waiting time to detection – taken from when a detector is switched on



Successively rarer events as a function of time – PEH data ◇ ◇

- ➢ **Model the PEH sample to provide insight**

Howell & Coward, MNRAS, 428, 167, 2013

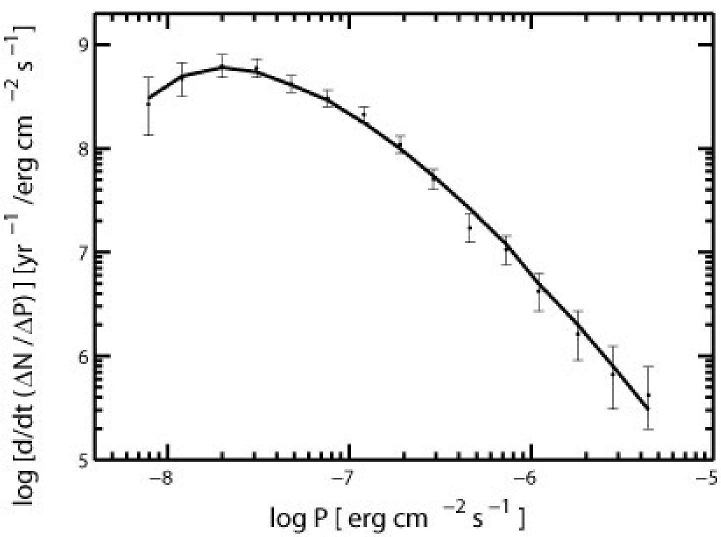
PEH - Coward & Burman, (2005) MNRAS , 361, 362

The Log z – Log T relation

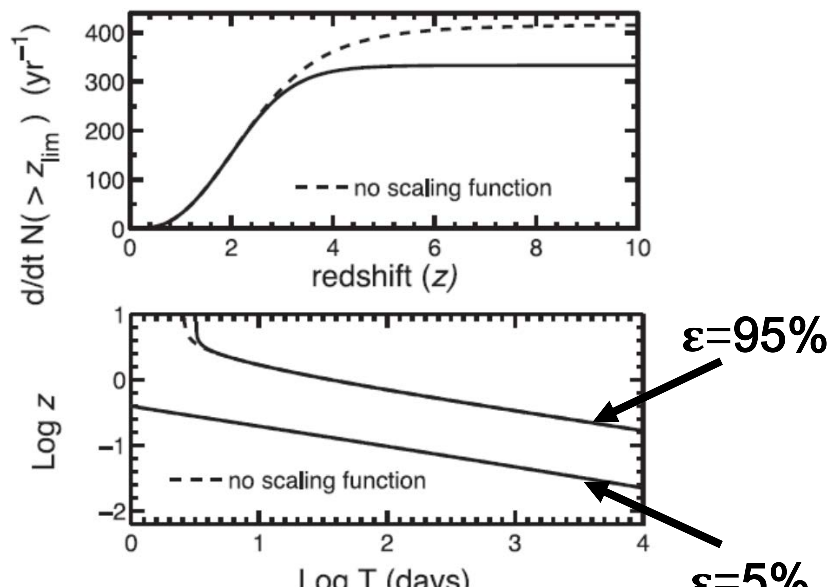
Introduce an observation time dependence to a number count distribution through Poisson statistics

$$\dot{N}(<Z_{\rm L}) = \frac{\Omega\,\eta_z}{4\pi}\int_{L_{\rm min}(P_{\rm L},Z_{\rm L})}^{L_{\rm max}}\Phi(L)\,{\rm d}L\int_0^{Z_{\rm L}}\frac{{\rm d}V(z)}{{\rm d}z}\frac{R_{\rm GRB}(z)}{(1+z)}\,{\rm d}z\,,$$

$$\dot{N}(<Z_{\rm L})T = |\ln(1-\epsilon)|.$$



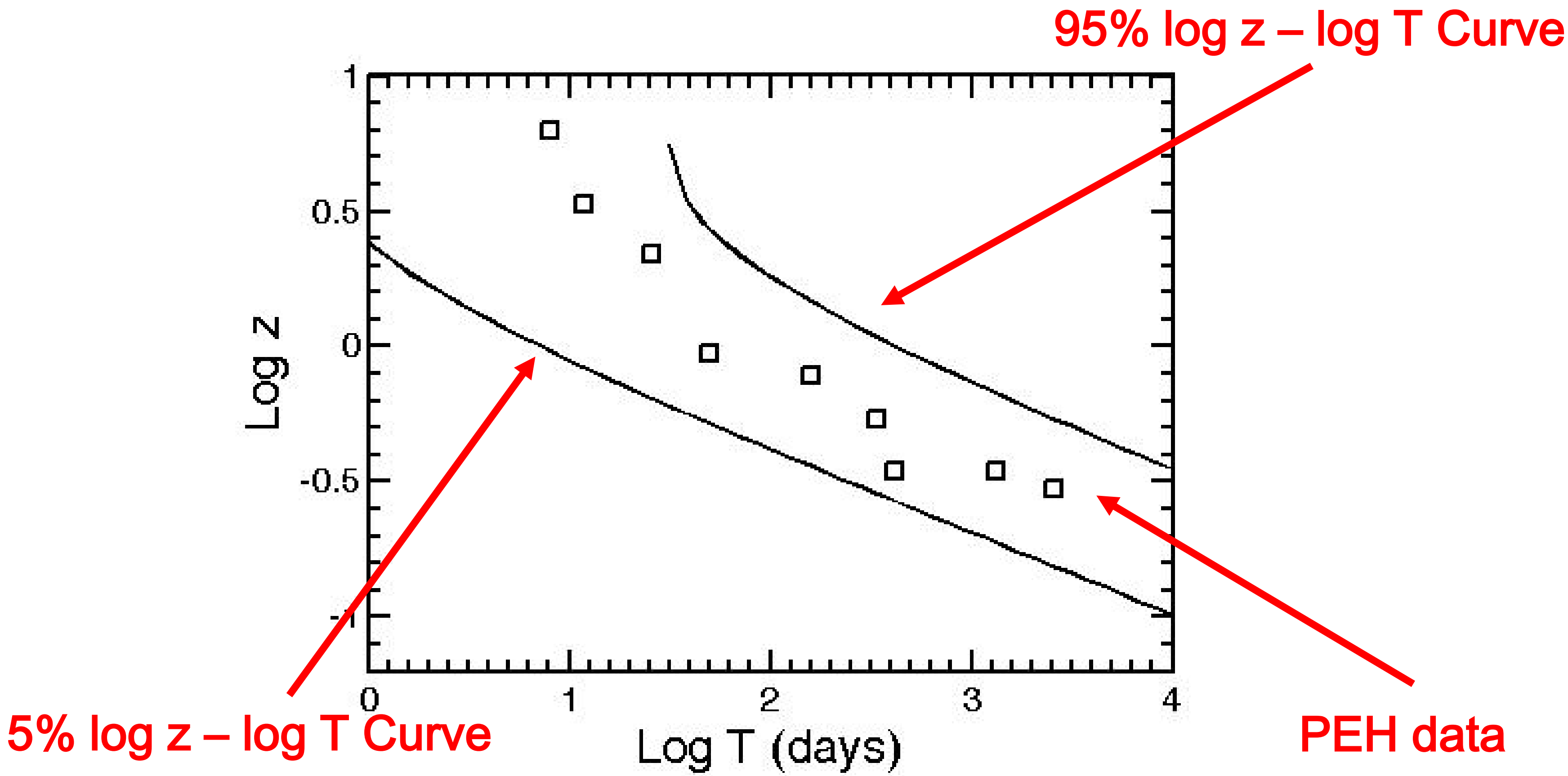
differential distribution



Integral distribution

Howell & Coward, MNRAS, 428, 167, 2013

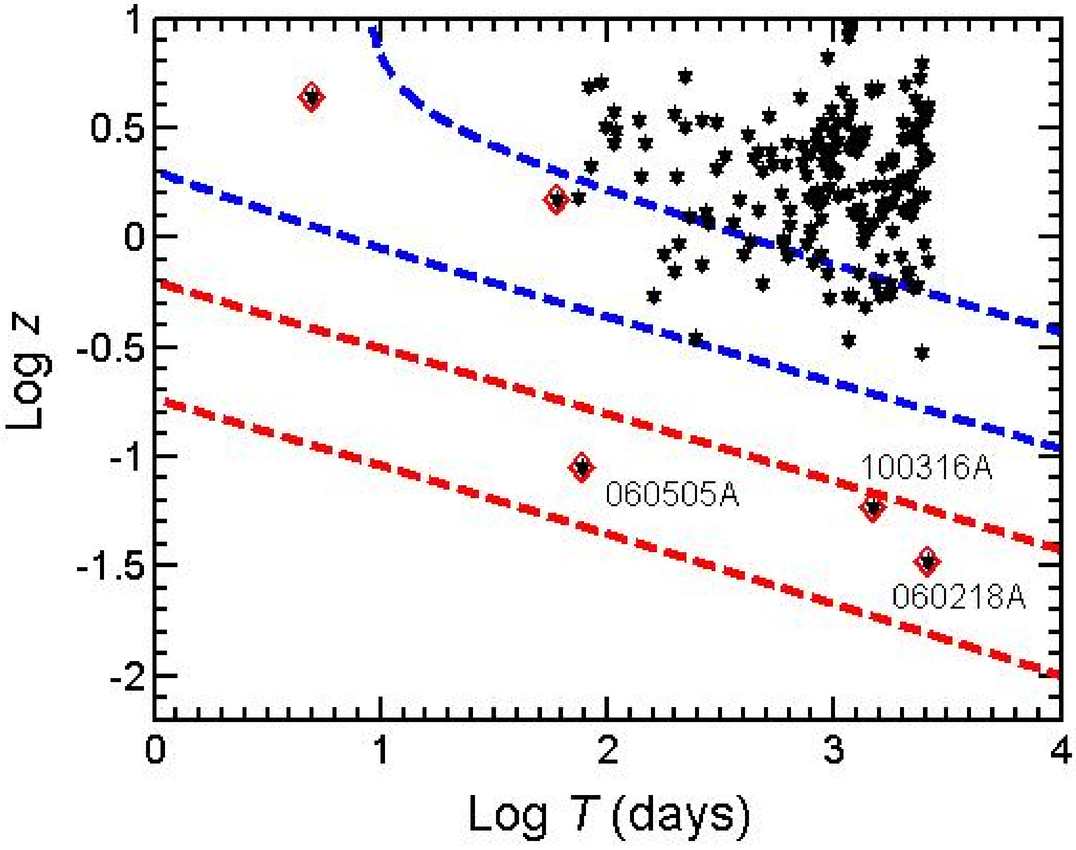
Swift: Log Z – Log T



Log z – Log T for Swift L-GRBs based on parameters determined from a Log N-Log P distribution

Howell et al.(2013), MNRAS, 428, 167

Log Z – Log T to separate different GRB populations L-GRBs + SL-GRBs



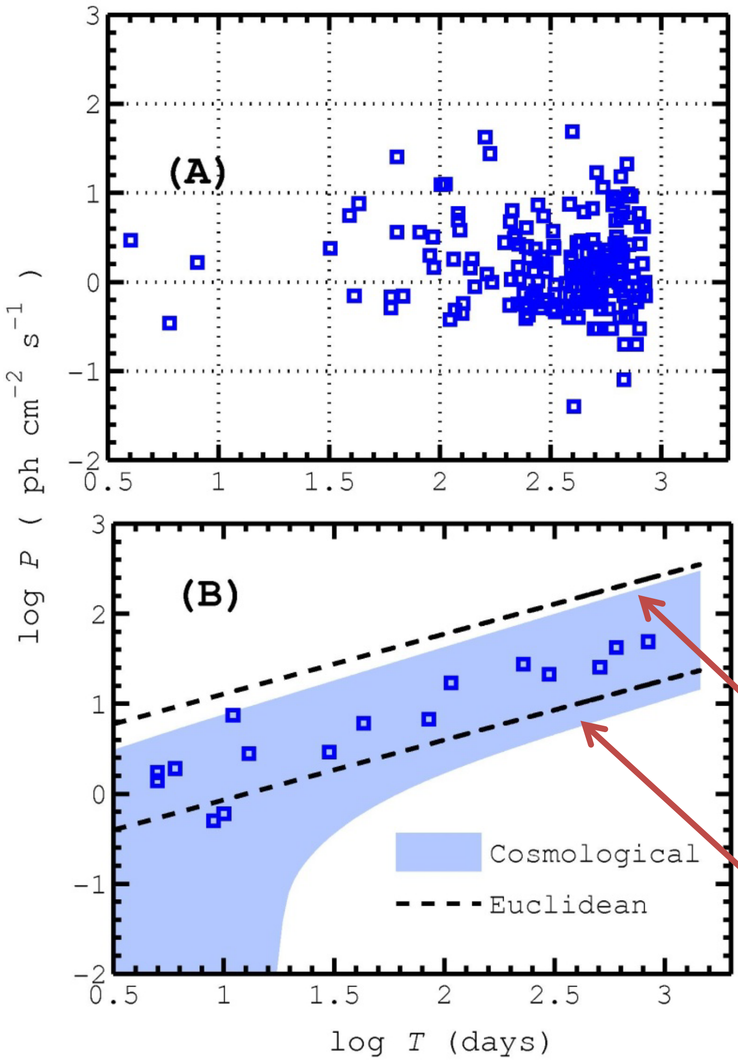
L-GRBs

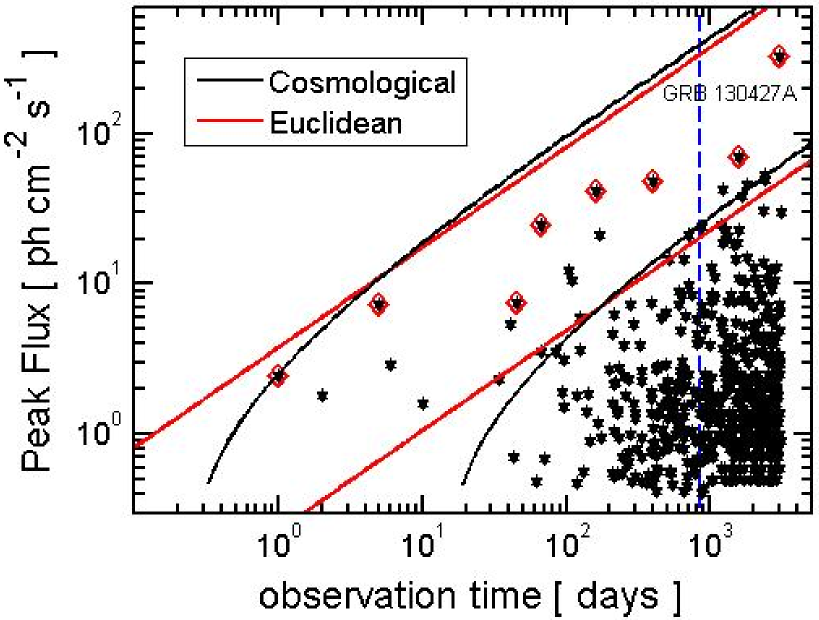
+

SL-GRBs

Howell & Coward, MNRAS, 428, 167, 2013

Log P – Log T as a predictive tool - application to Swift Peak Flux data



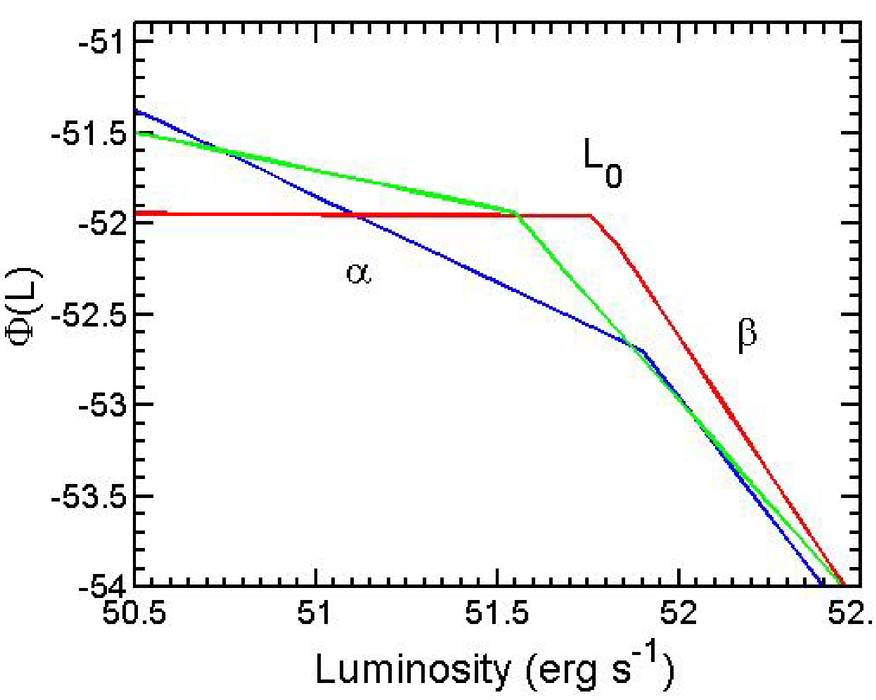


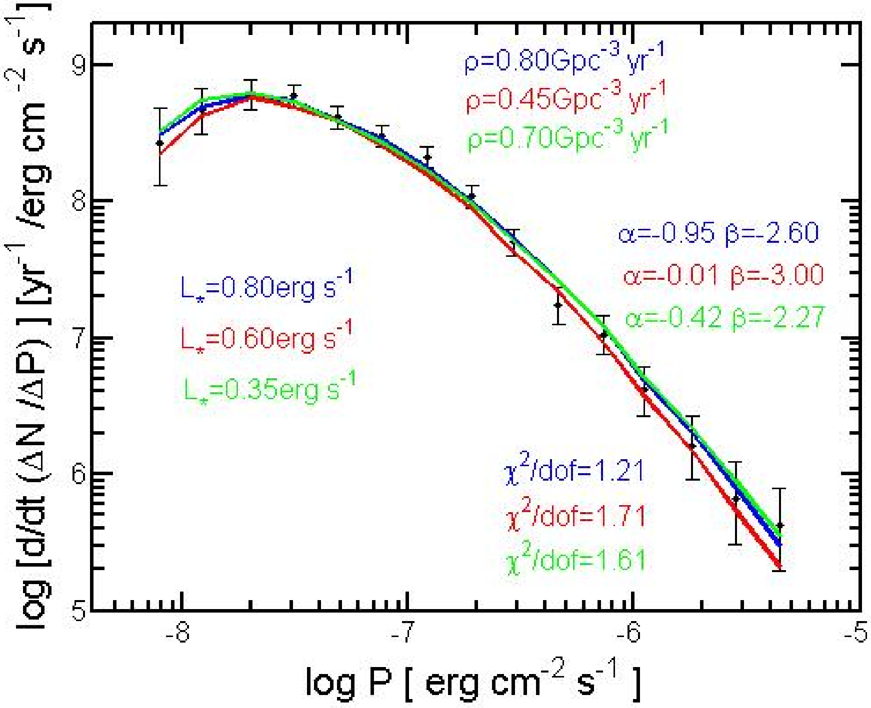
Howell et al. (2014), MNRAS 444, 25

5% CL
95% CL
} 90% PEH Bands

Howell et al.(2007), ApJ L666, L65

Constraining the GRB LF – degeneracy

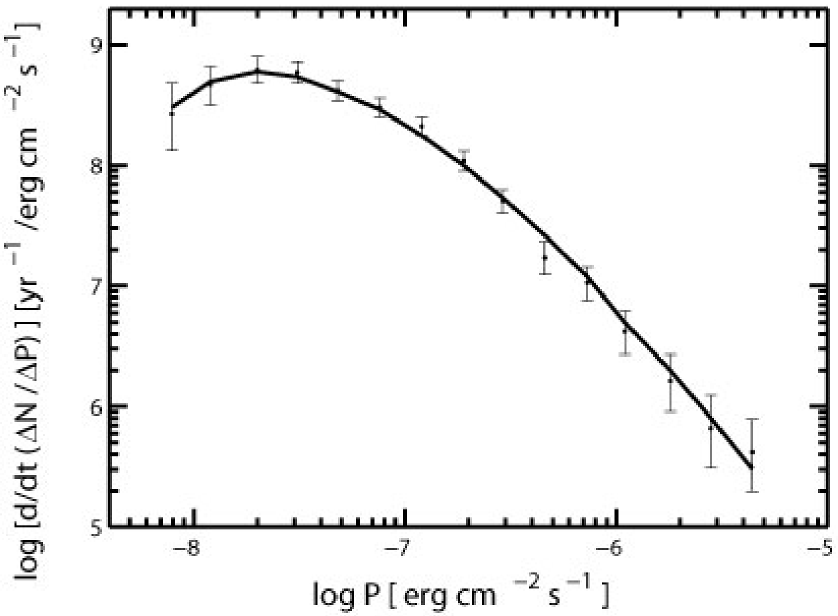


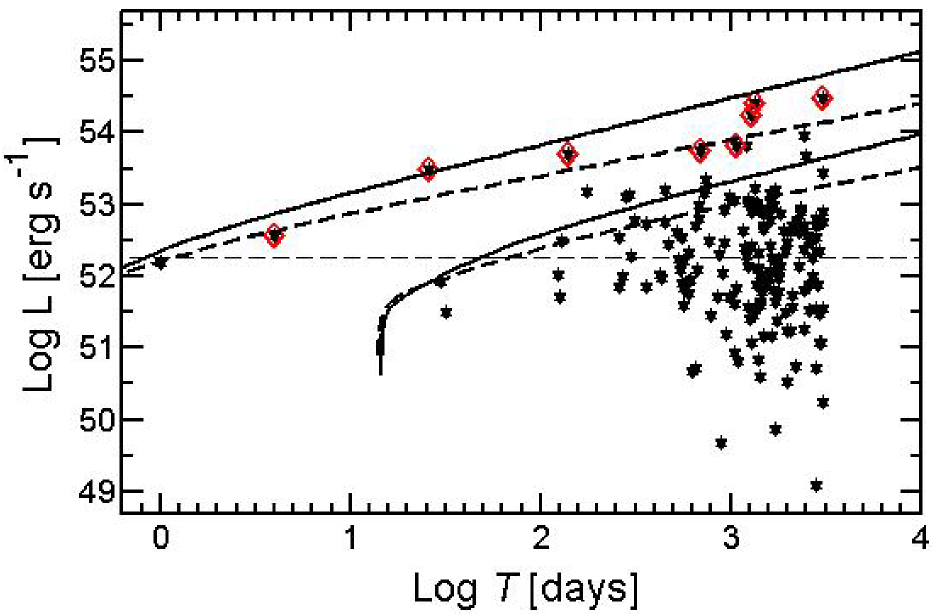


Degeneracy between the LF and source rate evolution

Require an independent test

The Swift rate and LF





- ➢ **Iterative procedure using log N-log P and Log L-log T**
- ➢ **Best results support a rate 0.8 Gpc^{-3} yr^{-1} with a steep high end slope (this is supported by other recent studies)**

Howell et al. (2014), MNRAS 444, 25

1. GRB overview
2. GRB topics @ UWA
3. **GRBs: Fermi & CTA**
4. GWs & Multimessenger obsservations
5. Low Latency EM follow-up of GW triggers

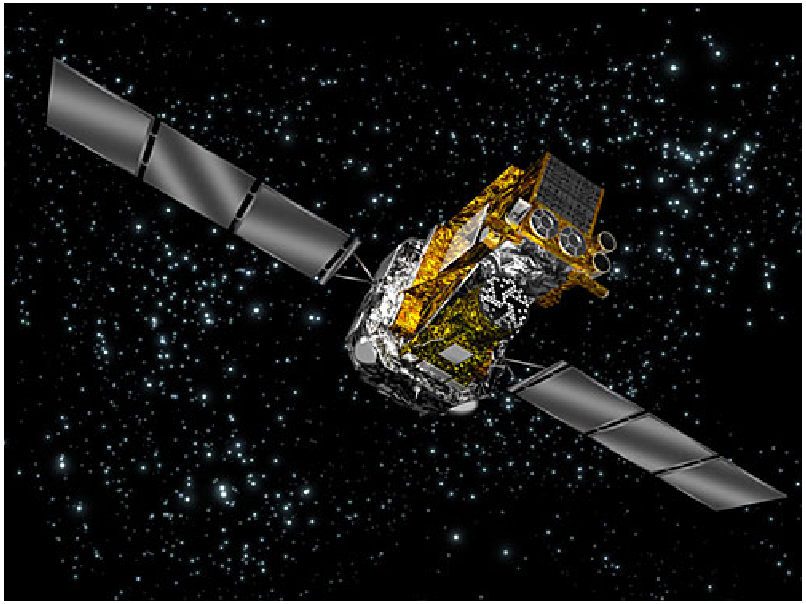
Fermi GRBs

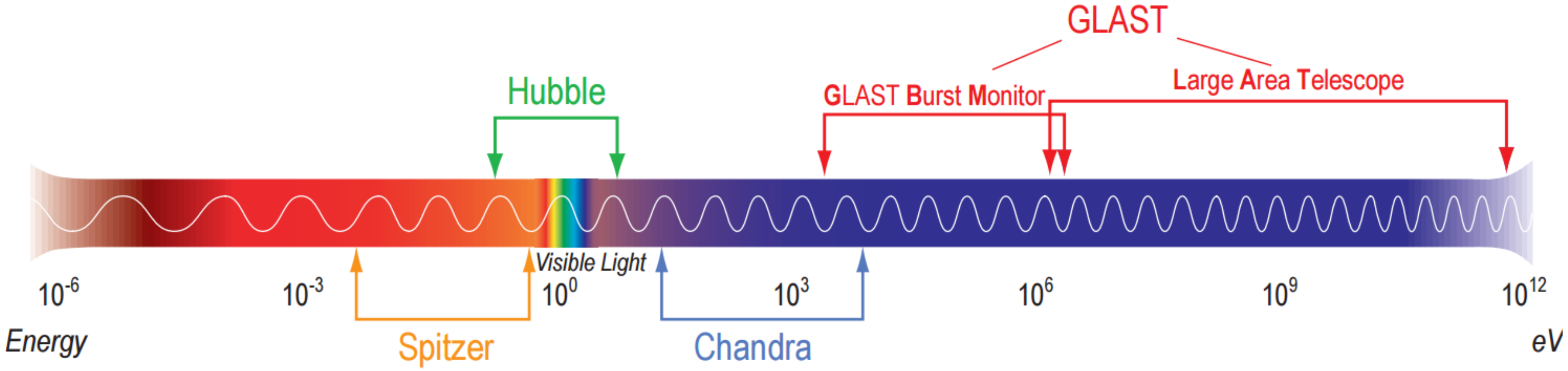
Fermi GBM – 8-30 MeV
- $4x10^{-8}$ erg $s^{-1}cm^{-2}$
- almost all sky

Fermi LAT – 0.02-300 GeV
$6x10^{-9}$ erg $s^{-1}cm^{-2}$
2.4pi sr

~250 GRBs/yr detected by GBM
> 40 GRBs detected by LAT in first 4 yrs

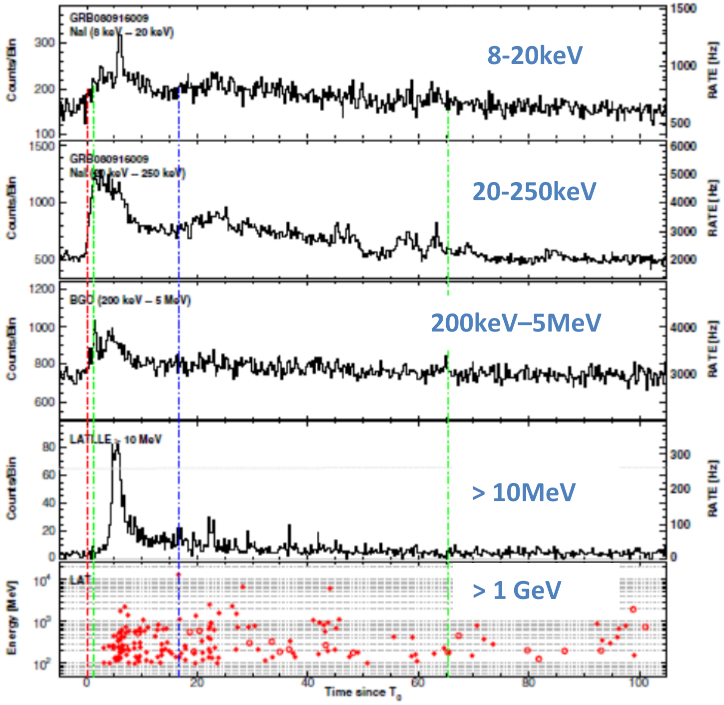
> 10GeV photons detected
(EGRET detected > 100MeV photons)



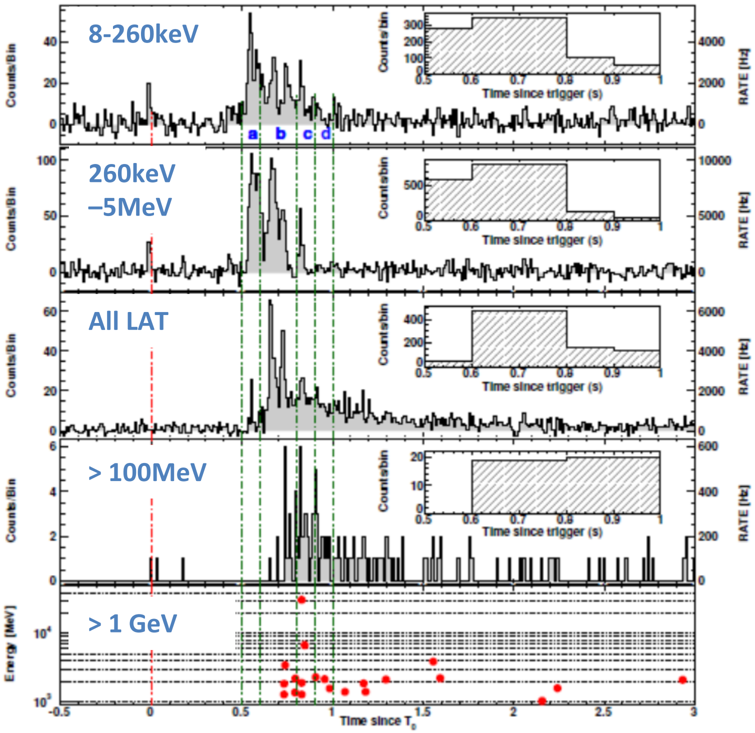


Fermi High and Low Energy Emissions

Long GRB 080916C



Short GRB 090510

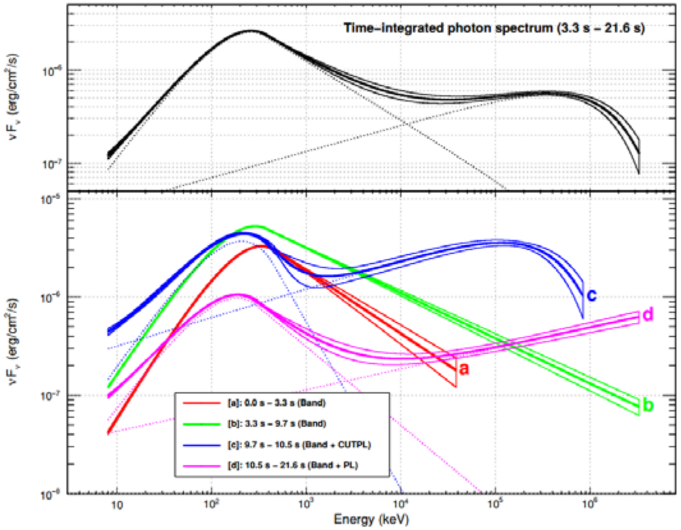


GeV emission:

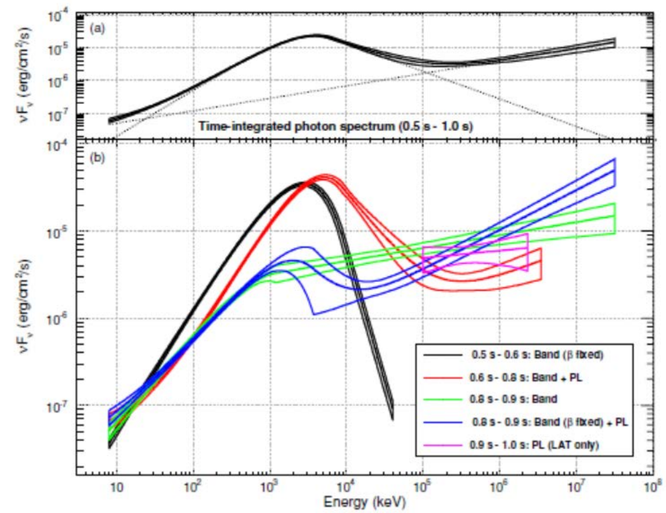
- delayed onset GeV wrt MeV emission
- GeV longer lived than MeV emission
- evident in both long and short duration Fermi GRBs

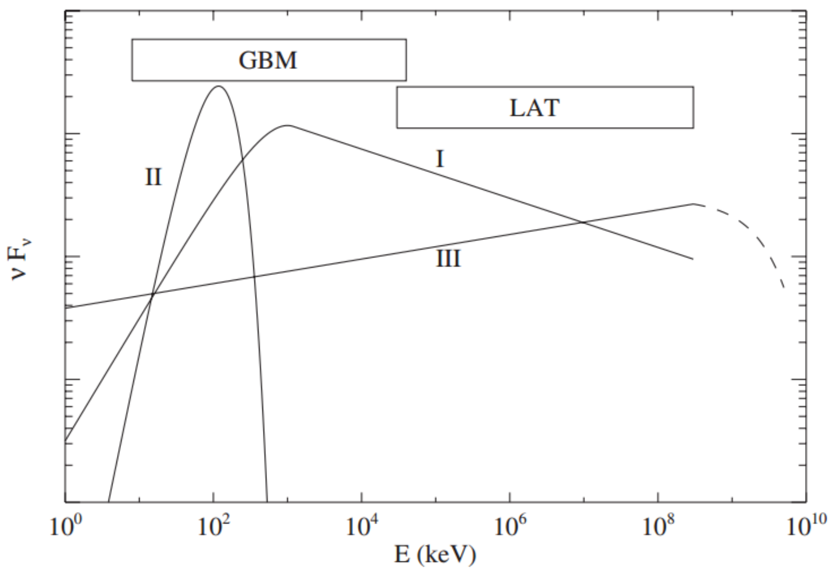
Extra components observed in both long and short GRBs

Long GRB 090926A



Short GRB 090510

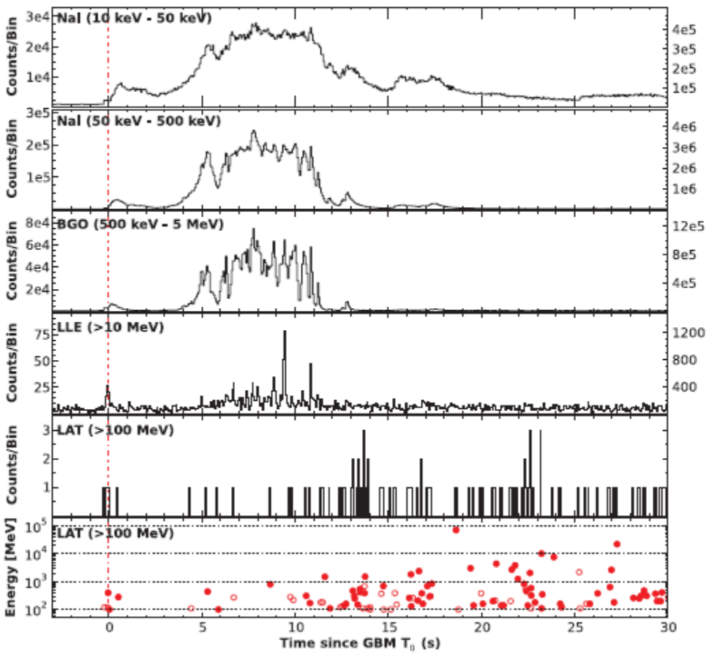


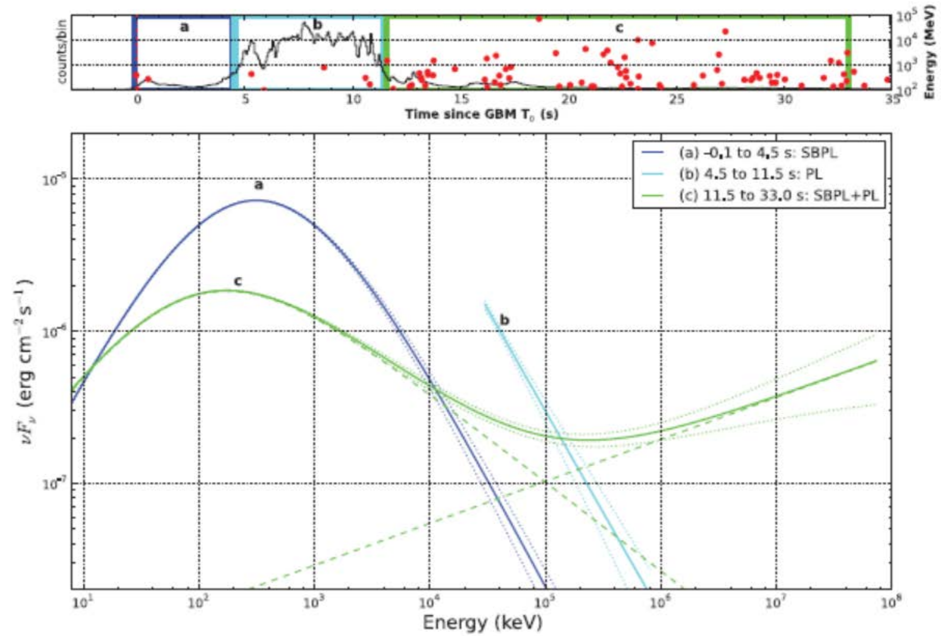


I) Band function
II) Pseudo-Thermal
III) Hard power law component

MeV – synchrotron
GeV - ?

Fermi GRBs – GRB 130427A





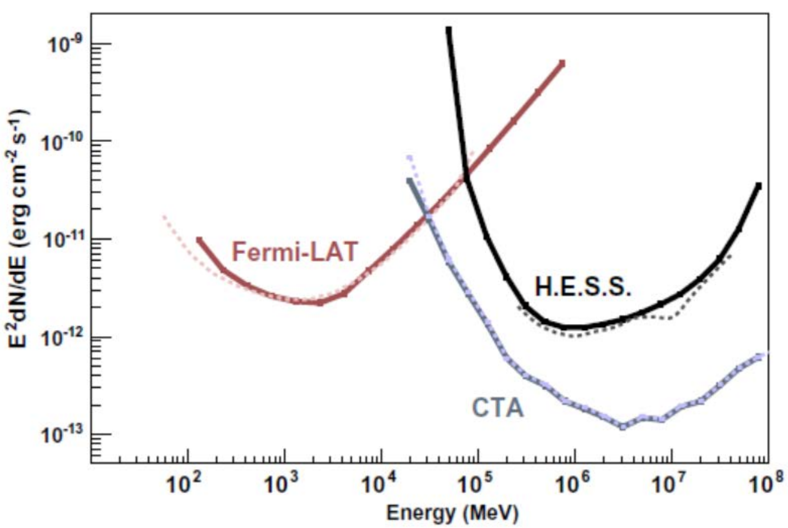
- z=0.34 (average Luminosity burst but very close)
- Highest recorded fluence $>10^{-3}$ erg cm^{-2}
- Highest observed photon energy – 95 GeV (128 GeV in rest frame)
- Longest lasting GeV emission – 19 hours
- LAT spectrum becomes harder after GBM spectrum has faded

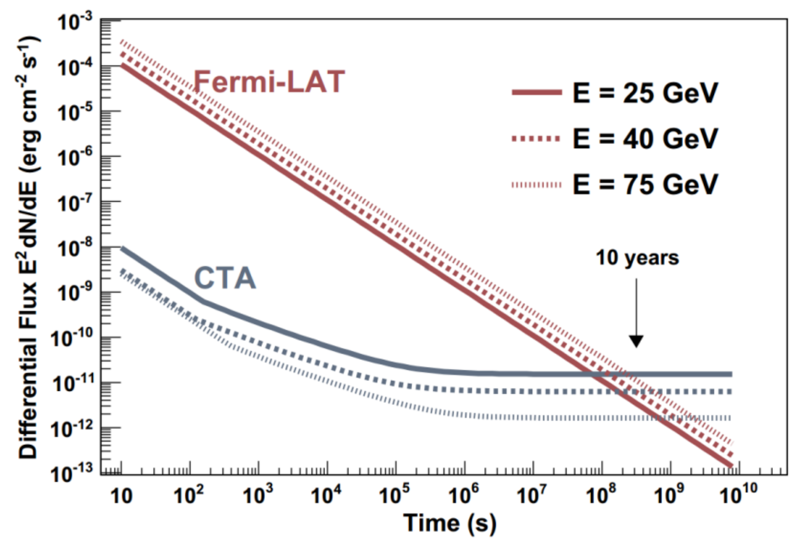
GRBs with CTA

Fermi Observations

- Delayed onset & distinct GeV spectral component
- Long lived GeV emission

Fermi LAT	CTA
$0.6m^2$ @ 10 GeV – limited statistics	Large eff area (~ 10^4 greater @ 30GeV)
GRB photon flux falls with E	LSTs – less effected by EBL
Better FoV and duty cycle	Fast response (180 deg slew in 20-30s)
	1-2 GRBs/yr (BUT photon rich)





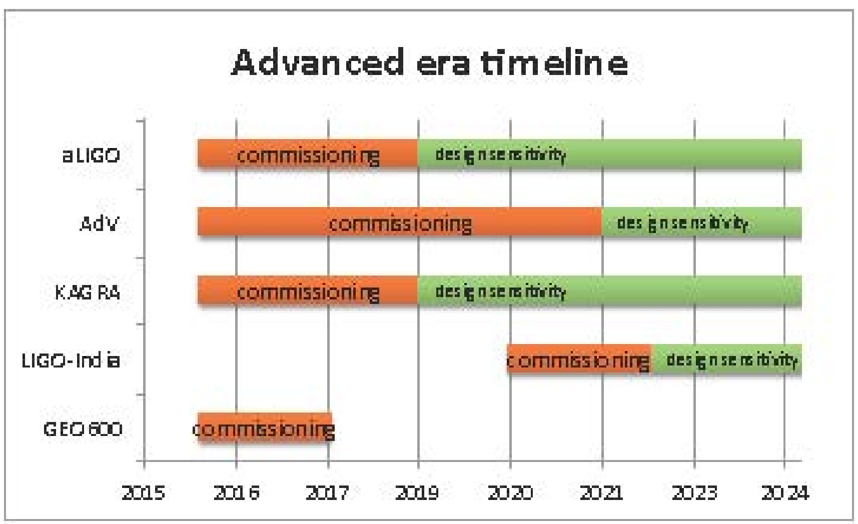
Funk, Hinton for CTA Consortium, 2013, Astro. Phys, 43, 348

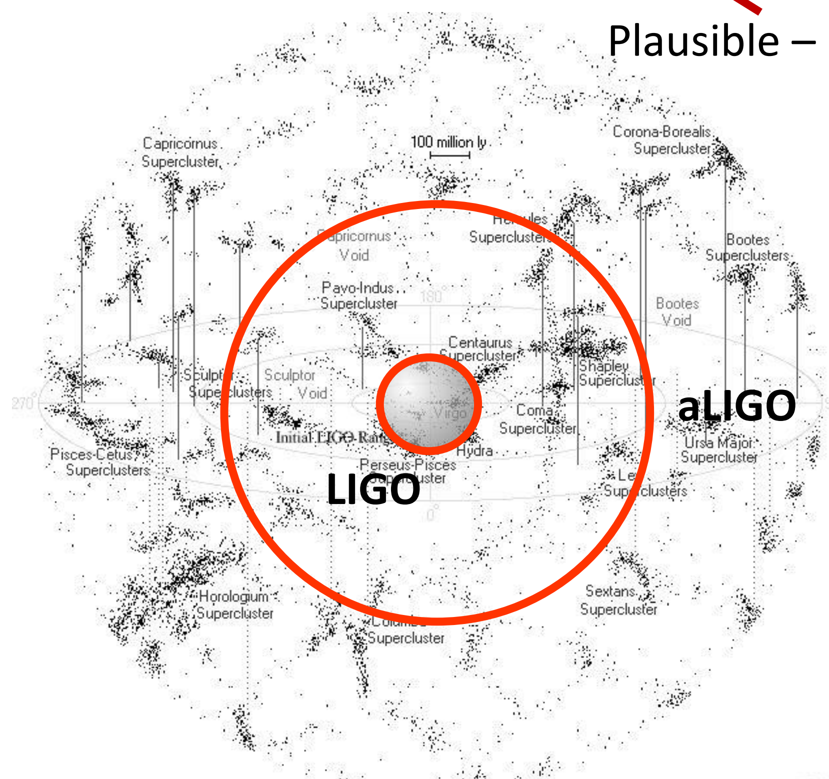
1. GRB overview
2. GRB topics @ UWA
3. GRBs: Fermi & CTA
4. GWs & Multimessenger era
5. Low Latency EM follow-up of GW triggers

Expected Detection Rates

Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 70	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

Plausible – 20/yr





LIGO Scientific Collaboration

>900 members, >80 institutions, 17 countries

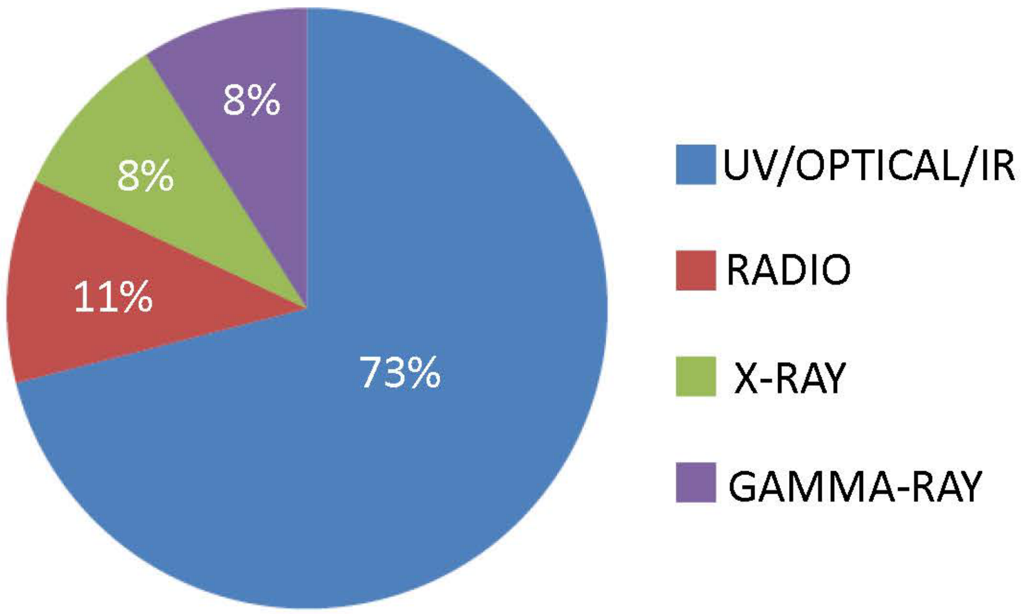
GW-EM Follow-up program

LVC/partner astronomers MoU STATUS

63 eligible applications

↓

51 signed MoU

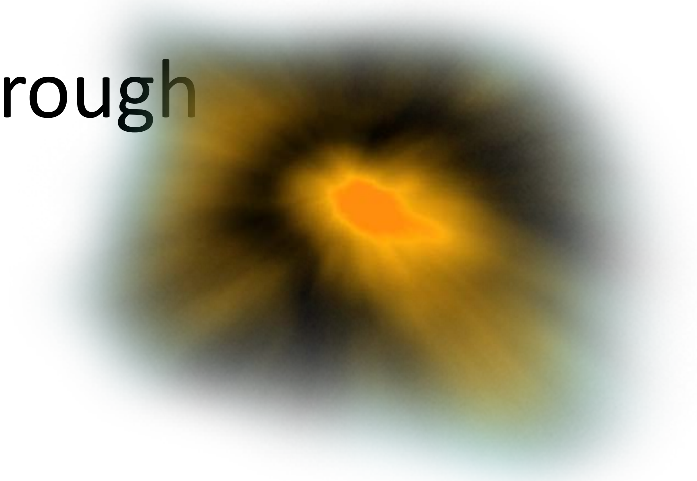


Australian Involvement: CTA, MWA, ASKAP (VAST), AAT, Skymapper, Zadko, GOTO, Zadko

Multimessenger astrophysics with GWs

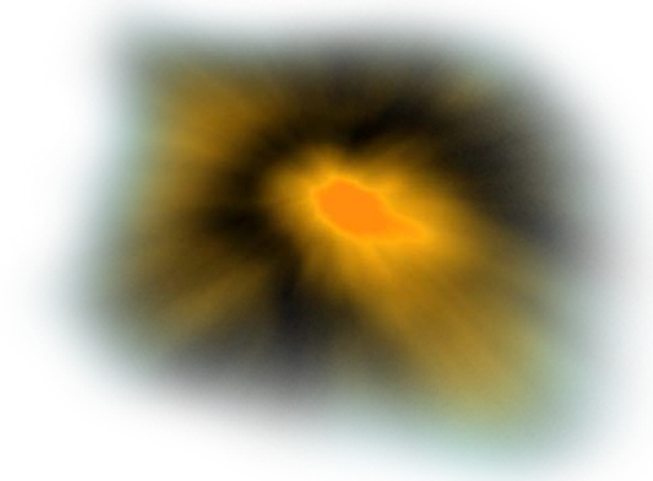
Three main strategies for coordinated GW/EM observations:

- EM follow-up of GW Triggers
- EM Triggered archival GW searches
- GW parameter refinement through EM observations



GW detection pipeline

- Low-latency data analysis
- Position reconstruction
- Host Galaxy Identification
- False Alarm Rate estimation (significance)
- Communication of Triggers



1. GRB overview
2. GRB topics @ UWA
3. GRBs: Fermi & CTA
4. GWs & Multimessenger era
5. Low Latency EM follow-up of GW triggers

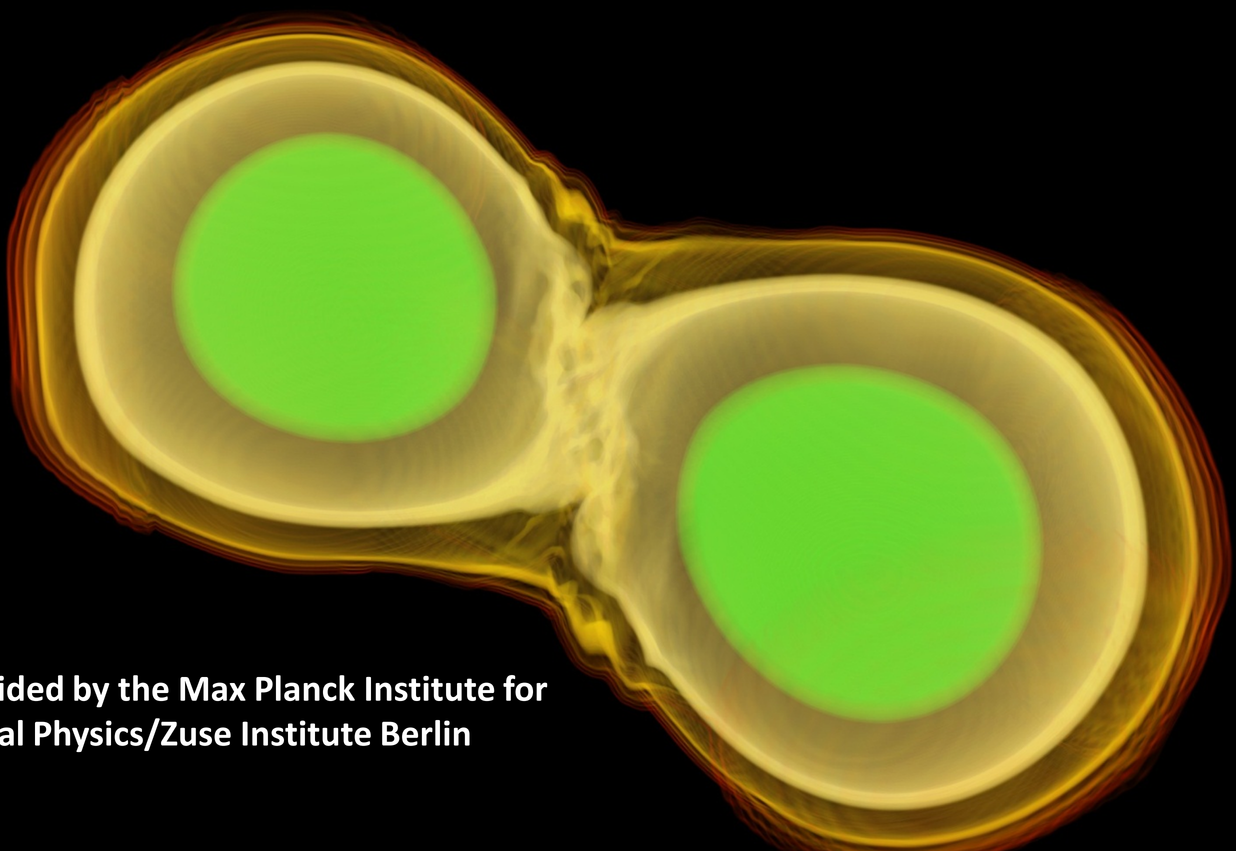
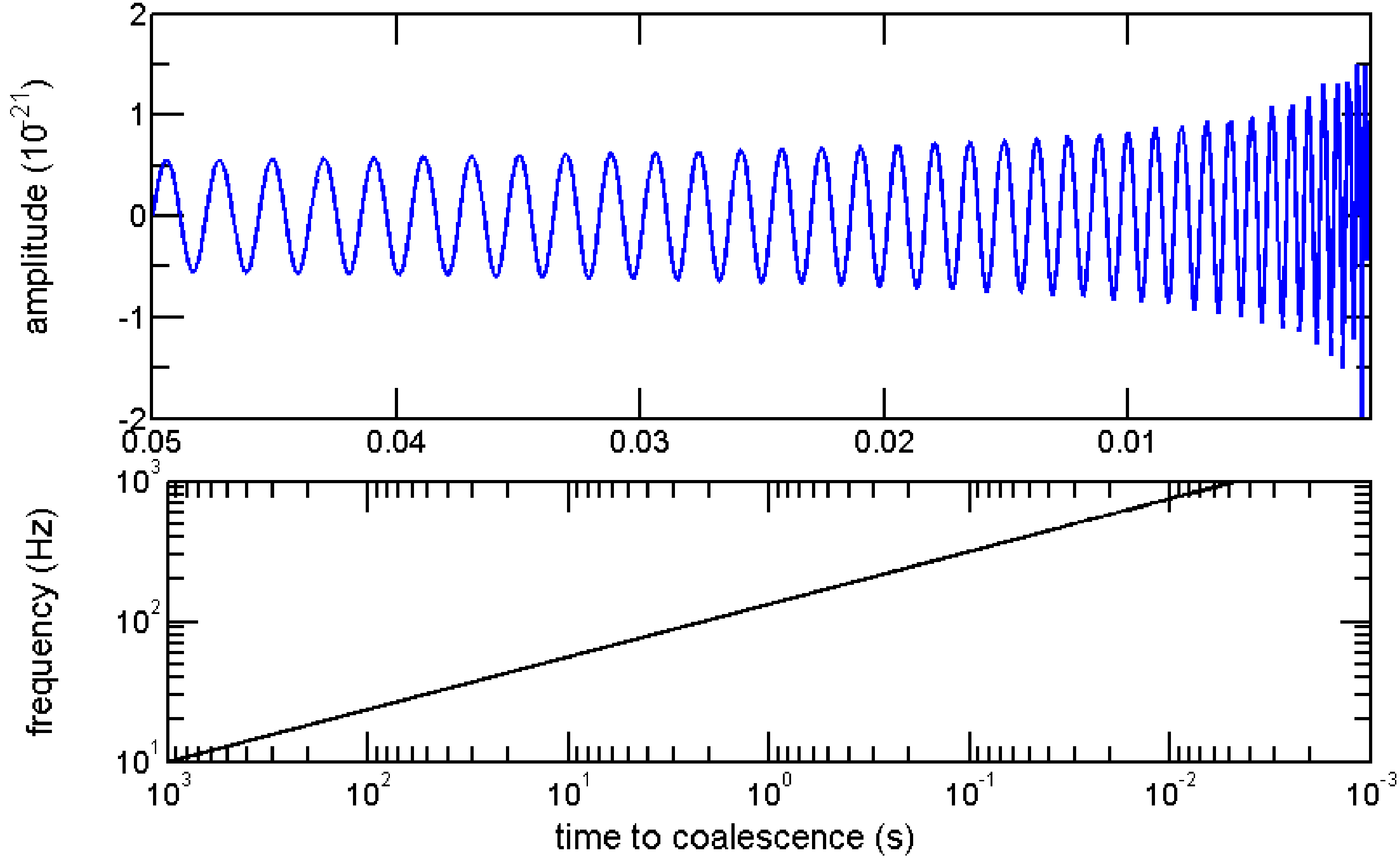


Image provided by the Max Planck Institute for Gravitational Physics/Zuse Institute Berlin

Compact binary coalescence – chirping waveform

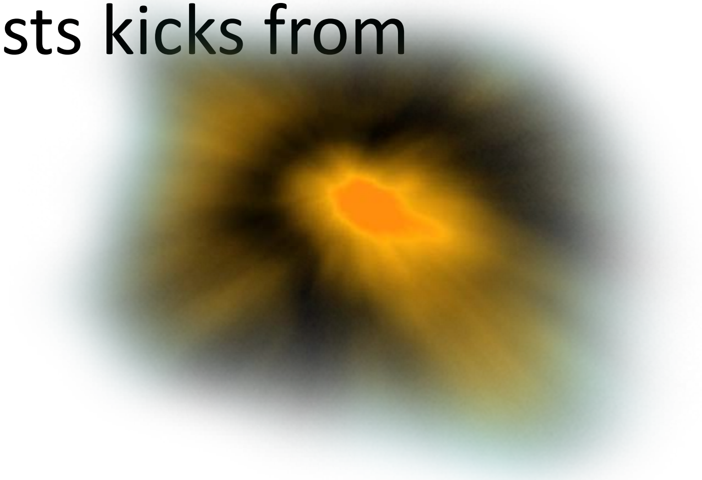


Short hard GRBs (SGRBs)

SGRBs strongly linked to compact binary NS/NS and/or NS/BH mergers

Evidence includes:

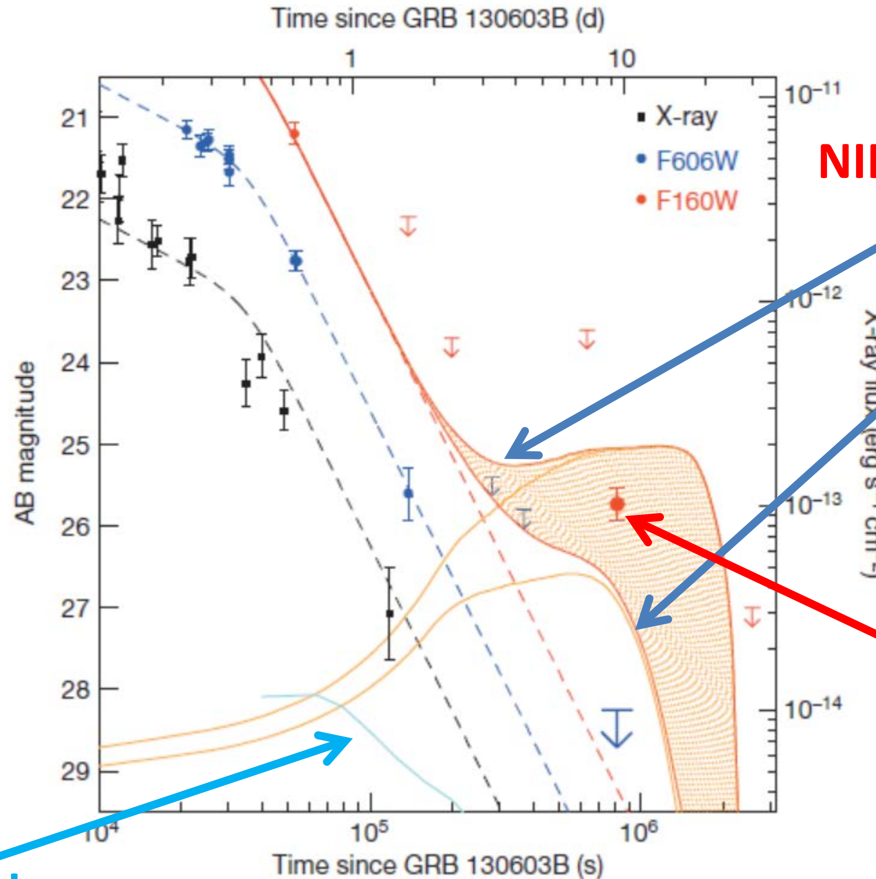
- Dynamical timescale of disks consistent with duration of GRB
- Lack of association with star formation and SNe
- Distance from host (few kpc) suggests kicks from NS/NS, NS/BH mergers
- Kilonova



Kilonova - observations

- NS/NS mergers create significant quantities of neutron-rich radioactive species
- Radioactive decay produces a fain transient - ***kilonova***

Light curves:
X-ray --
Optical --
NIR --

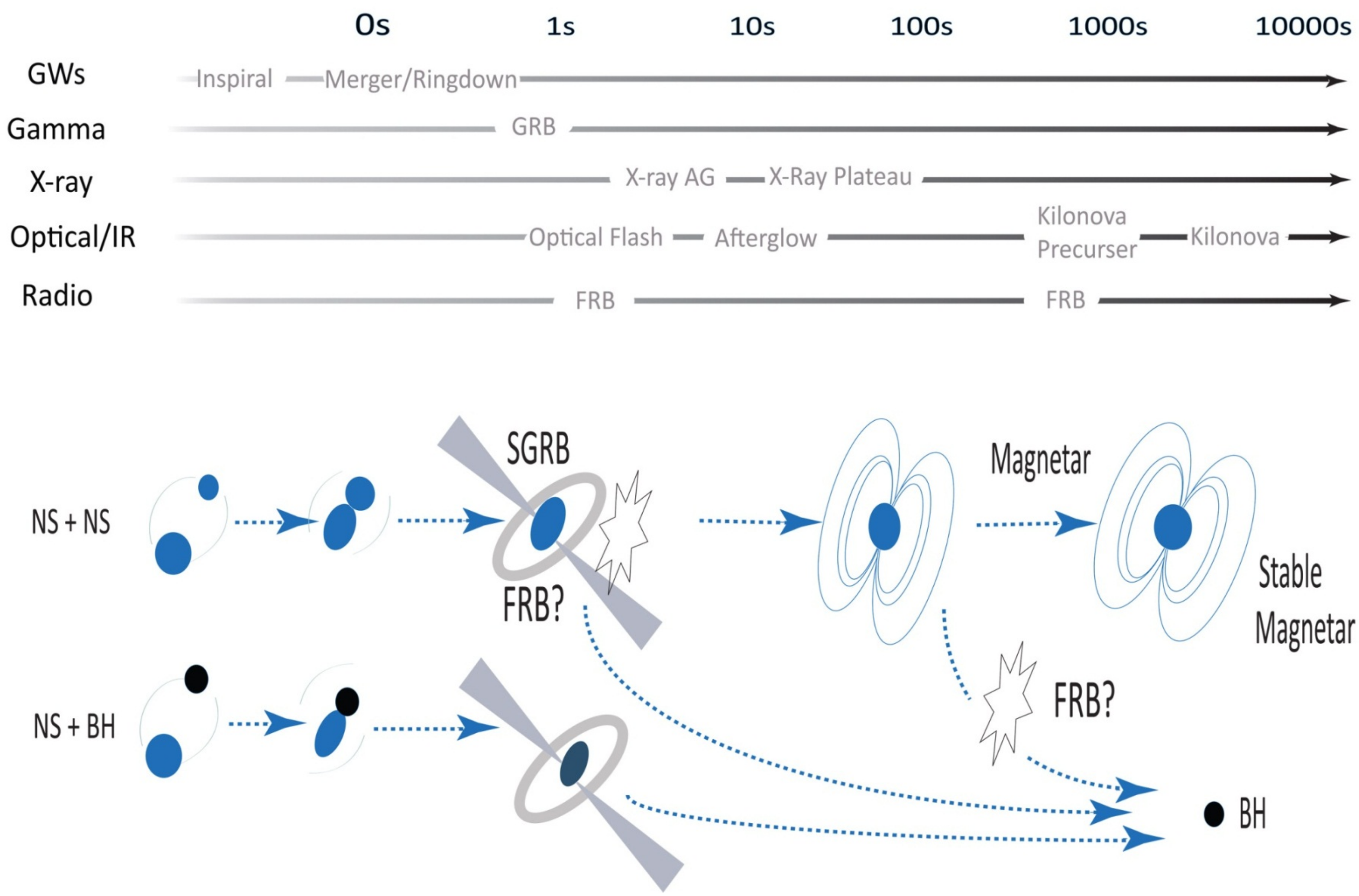


NIR kilonova models

HST observation

Optical kilonova model

Low-latency follow-ups

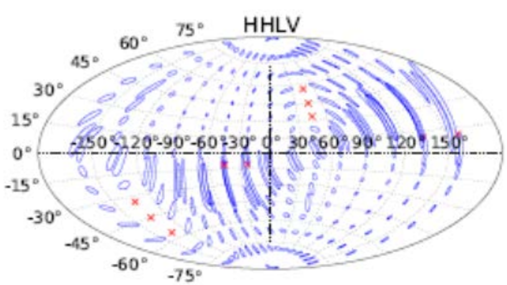


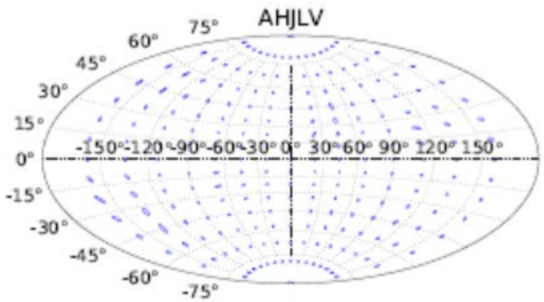
Chu,Howell,Rowlinson,Zhang,Gao & Wen, MNRAS in prep, 2015

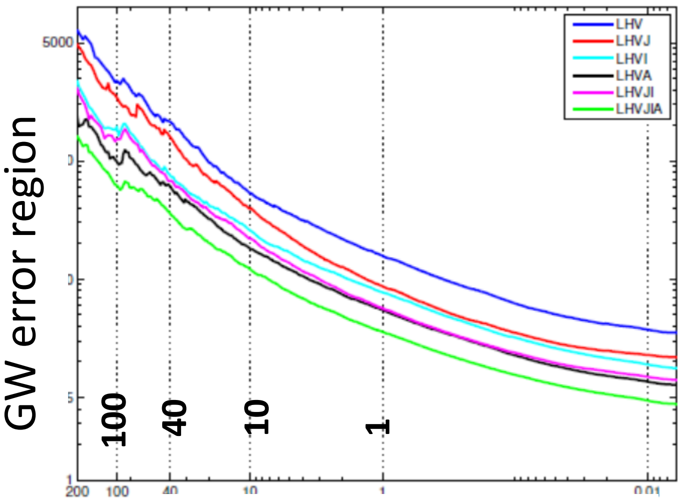
Low latency performance

Table 2. The percentage of detected sources within the aLIGO/AdV horizon and localisation error regions determined at different times prior to merger for different detector networks.

Detector network		Time before merger 40s	10s	1s	0s
LHV	Percentage detected	9%	35%	76%	100%
	Error region of [10%/50%/90%] of detections [deg^2]	302/1000/2163	73/269/782	23/79/240	5.4/18/54
LHVJ	Percentage detected	8%	32%	76%	100%
	Error region of [10%/50%/90%] of detections [deg^2]	240/815/1595	48/198/471	12/44/121	3/11/30
LHVI	Percentage detected	9%	33%	75%	100%
	Error region of [10%/50%/90%] of detections [deg^2]	119/383/914	39/130/349	12/39/105	2.7/8.8/ 24
LHVA	Percentage detected	9%	35%	76%	100%
	Error region of [10%/50%/90%] of detections [deg^2]	76/312/850	26/91/248	8.6/27/76	1.9/6.3/17
LHVJI	Percentage detected	8%	32%	75%	100%
	Error region of [10%/50%/90%] of detections [deg^2]	95/339/833	33/111/296	9/28/78	2.2/7.0/18
LHVJIA	Percentage detected	9%	33%	75%	100%
	Error region of [10%/50%/90%] of detections [deg^2]	60/183/402	21/61/135	5.9/18/42	1.4/4.3/9.7







Time before coalescence

Chu, Howell, Rowlinson, Zhang, Gao & Wen, MNRAS in prep, 2015

EM follow-up prospects - LHV

TARGET	TIME RANGE (s)	Gamma		X-ray	Optical/IR	Radio	
		High (> 10 MeV)	Low (< 10 MeV)			High (> 1 GHz)	Low (< 1 GHz)
FRB (early)	-5-10					?	?
SGRB Prompt	0-5	✓	✓	✓	✓	?	?
Early engine	0-1000	?	✓	✓	✓	?	?
FRB (late)	10-10000					?	?
Reverse shock	60-10000	?		✓	✓	✓	✓
Afterglow	100s->	✓		✓	✓	✓	✓

	Response fast enough FoV within range
	Fast response FoV too small
	Response too slow FoV within range
	Response too slow + FoV too small
✓	Observed
?	Predicted

- Detection 40s pre-merger
- **LHV network**

- **40s reaction latency** (to send out trigger)
- 1000 deg^2 error region (50% case)

Radio	Large FoV and fast response (~mins) potential
Optical	Potential for fast responses
Low gamma and X-ray	Confident science return – response ToO very slow at present
High gamma – CTA	Large FoV and fast response (< min)

Chu, Howell, Rowlinson, Zhang, Gao & Wen, MNRAS in prep, 2015

EM follow-up prospects-LHVJIA

TARGET	TIME RANGE (s)	Gamma		X-ray	Optical/IR	Radio	
		High (> 10 MeV)	Low (< 10 MeV)			High (> 1 GHz)	Low (< 1 GHz)
FRB (early)	-5-10					?	?
SGRB Prompt	0-5	✓	✓	✓	✓	?	?
Early engine	0-1000	?	✓	✓	✓	?	?
FRB (late)	10-10000					?	?
Reverse shock	60-10000	?		✓	✓	✓	✓
Afterglow	100s->	✓		✓	✓	✓	✓

	Response fast enough FoV within range
	Fast response FoV too small
	Response too slow FoV within range
	Response too slow + FoV too small
✓	Observed
?	Predicted

- Detection 40s pre-merger
- **LHVJIA network**

- **1s reaction latency** (to send out trigger)
- 182 deg^2 error region (50% case)

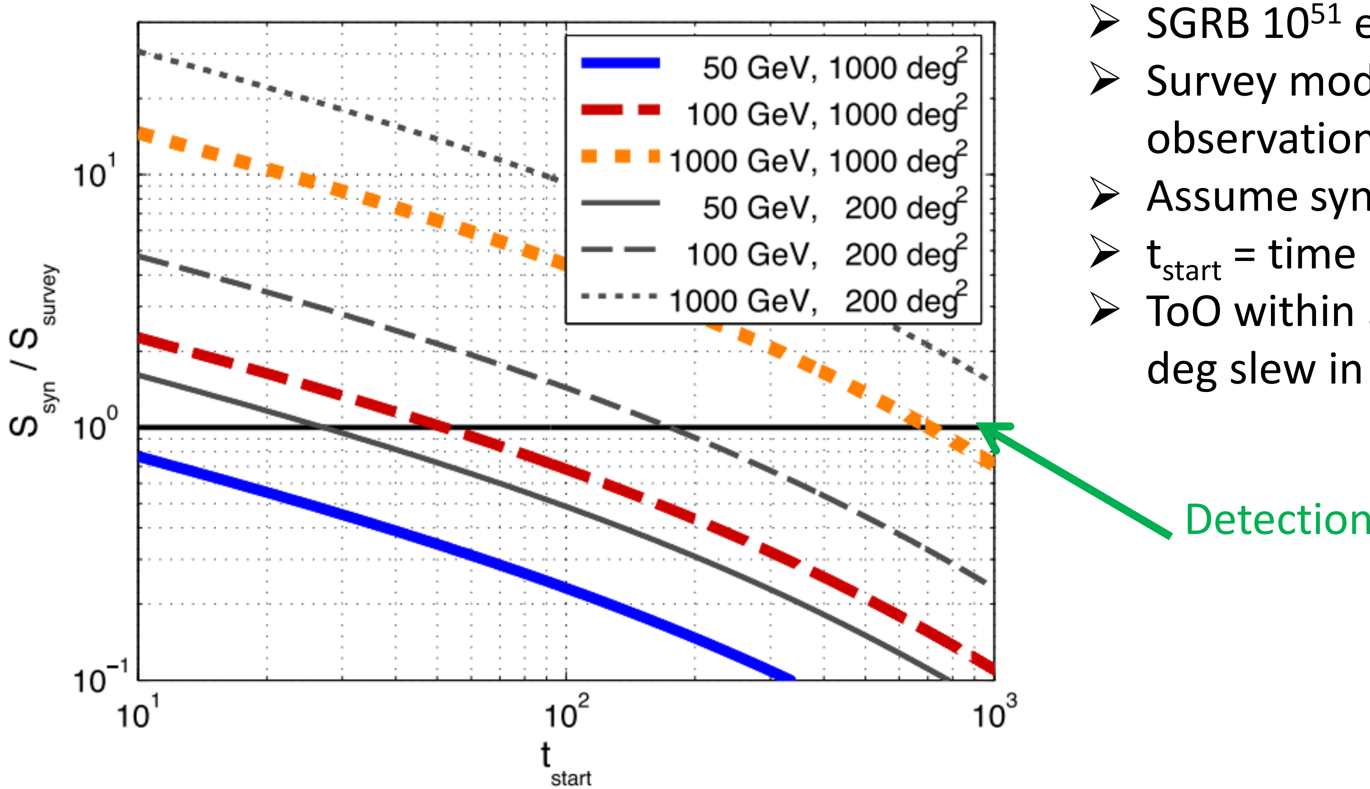
➢ Both the improved error region and reaction latency provides greater opportunities for breakthrough science

➢ It could be argued that most of the breakthrough science requires a fast response

➢ Clear motivation for Swift/Fermi to employ some sort of fast triggering pipeline

Chu, Howell, Rowlinson, Zhang, Gao & Wen, MNRAS in prep, 2015

GWs and CTA



- SGRB 10^{51} erg @ 300 Mpc
- Survey mode (~1000deg^2) observation of 1000 s
- Assume synchrotron emission
- t_{start} = time after merger
- ToO within 30s (LSTs fastest – 180 deg slew in ~20s)

- 100 GeV – require t_{start} <50s for 1000 deg^2 error region
- 100 GeV – require t_{start} <200s for 200 deg^2 error region
- Sub TeV photons @ aLIGO/AdV range not effected by EBL

(EBL models : Stecker, Malkan & Scully 2006; Dominguez et al. 2011)

Bartos, I. et al., MNRAS, (2014), 443, 738-749

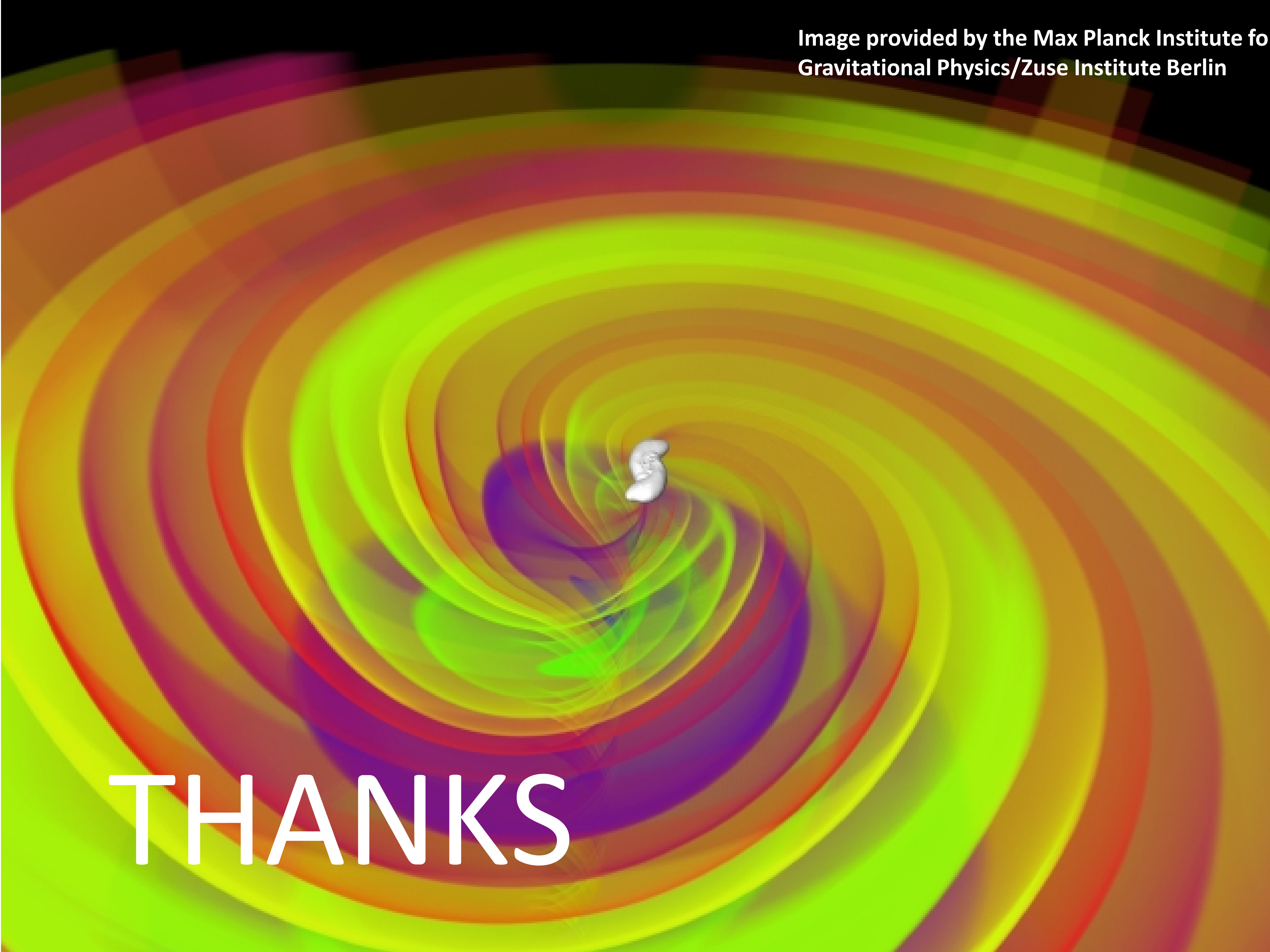


Image provided by the Max Planck Institute fo
Gravitational Physics/Zuse Institute Berlin
THANKS