PHAROS – Jena

# Multi-wavelength EM observations of compact binary mergers

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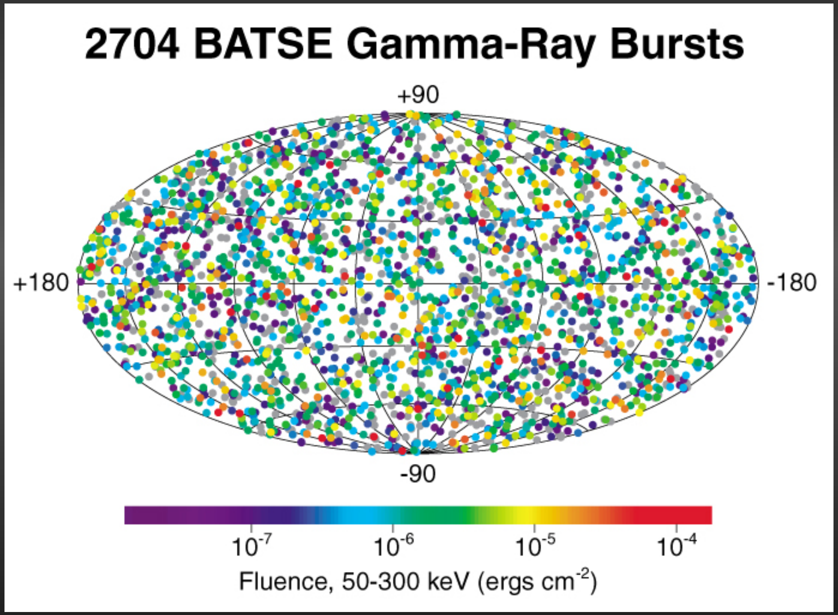
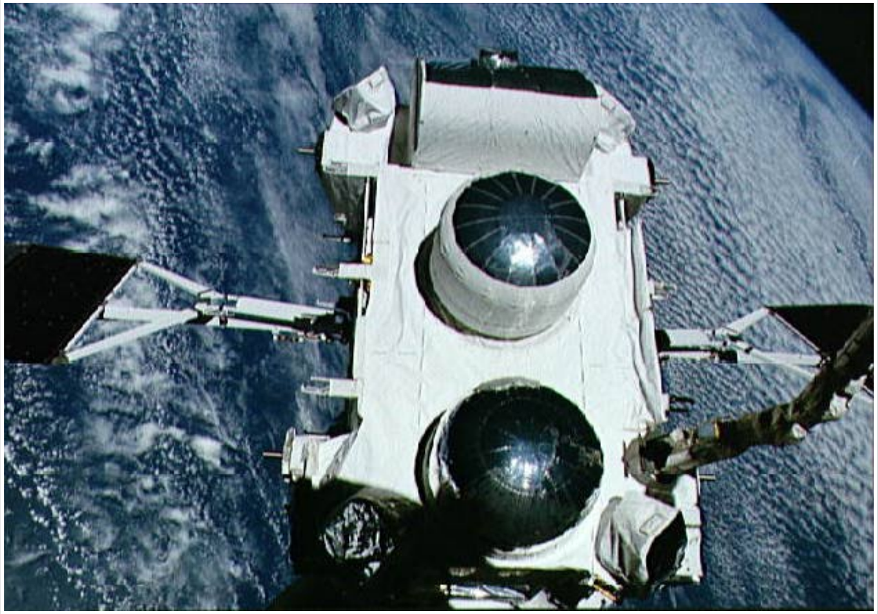
# The plan

- Gamma-ray bursts – lessons from history.
- Targets of interest, emission sources.  Why care?
- Setting the scene, and some generic issues
- GW170817 – searching for the counterpart
- Let’s hunt kilonovae
- Diversion: how common are SGRBs within LIGO/Virgo horizon?
- GW170817 – intensive studies
- Near future: prospects and strategies for O3
- Further future…

# Gamma-ray bursts- a history lesson

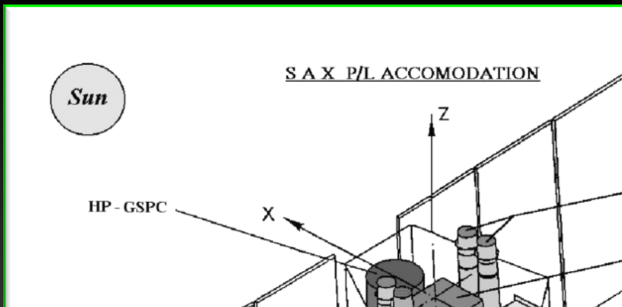
As of ~1990, most popular progenitor hypothesis: Milky Way neutron stars, but hard to confirm due to large gamma-ray error regions, and no counterparts at longer wavelengths.

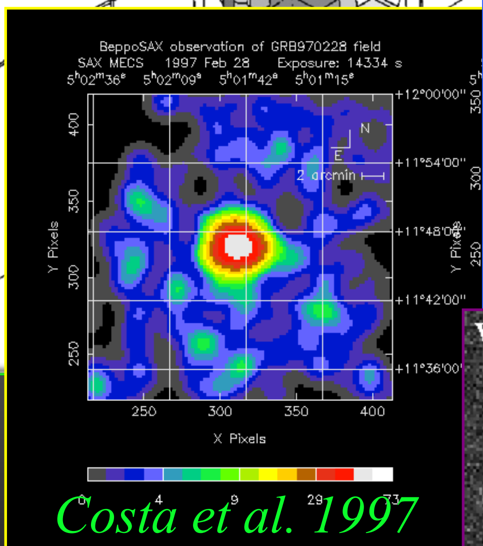


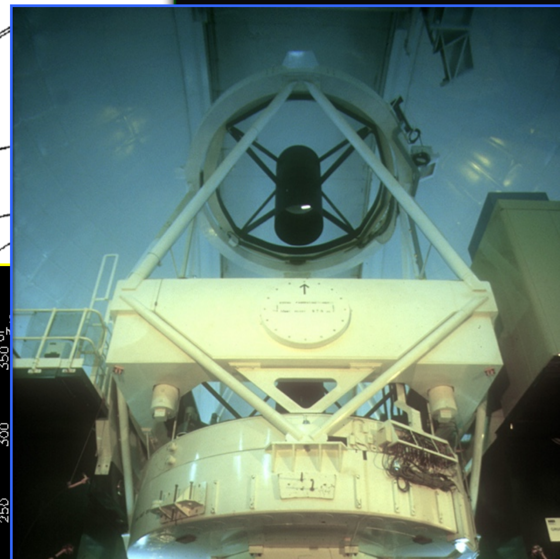
CGRO – better positions (few degree errors) and many bursts – isotropic distribution favours extragalactic origin.

# Gamma-ray bursts- a history lesson

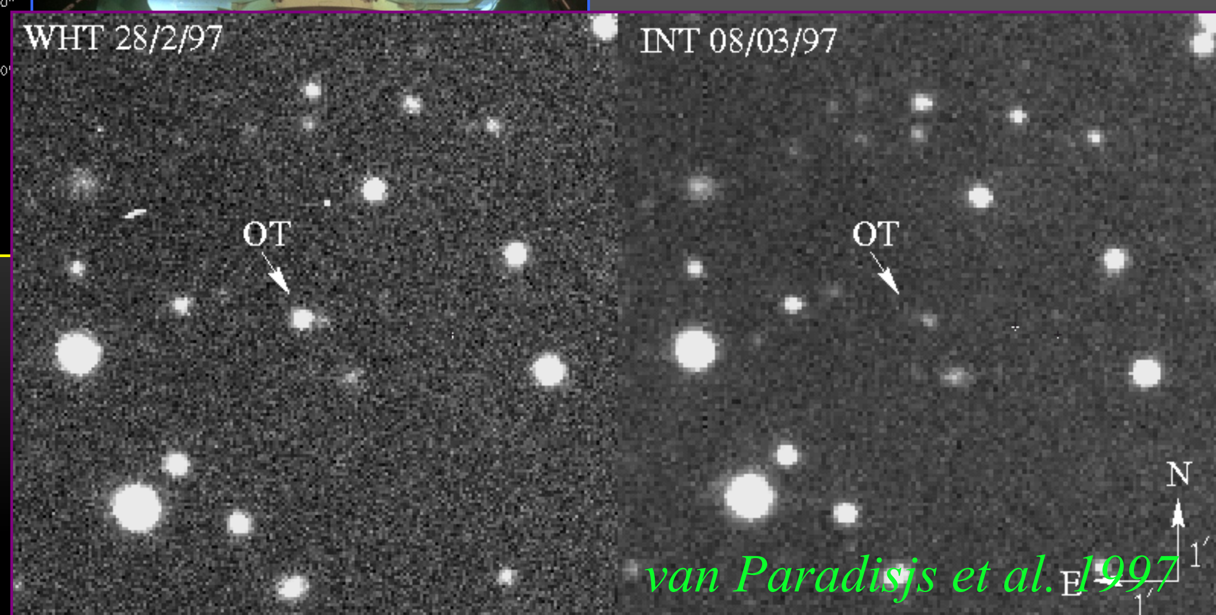



*Costa et al. 1997*



Beppo-SAX discovers slower fading X-ray “afterglows”, providing much better (few arcmin) localisation.



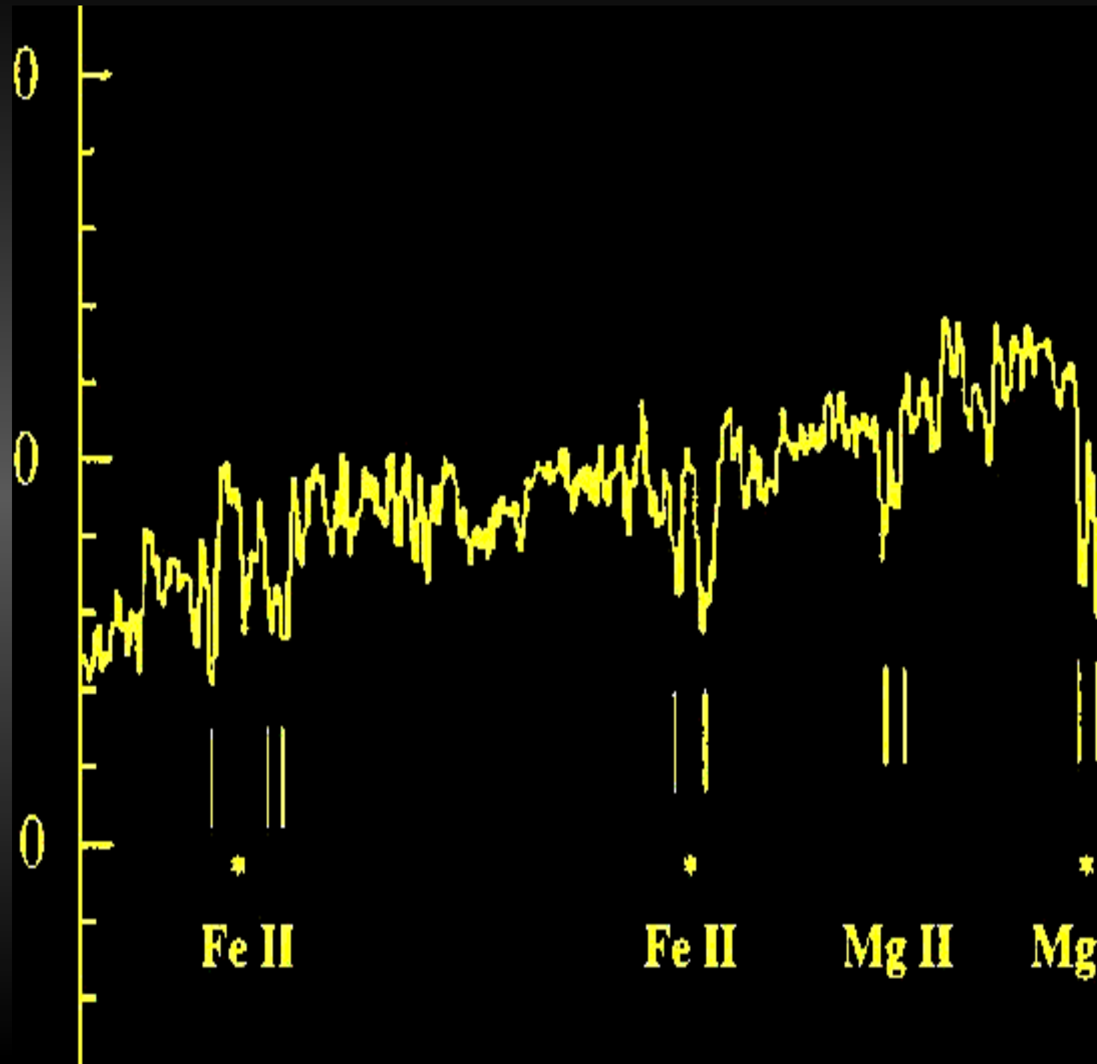

*van Paradisjs et al. 1997*

Ground follow-up leads to optical afterglows – arcsec localisation.

# Gamma-ray bursts- a history lesson

Hence spectroscopy and redshifts.

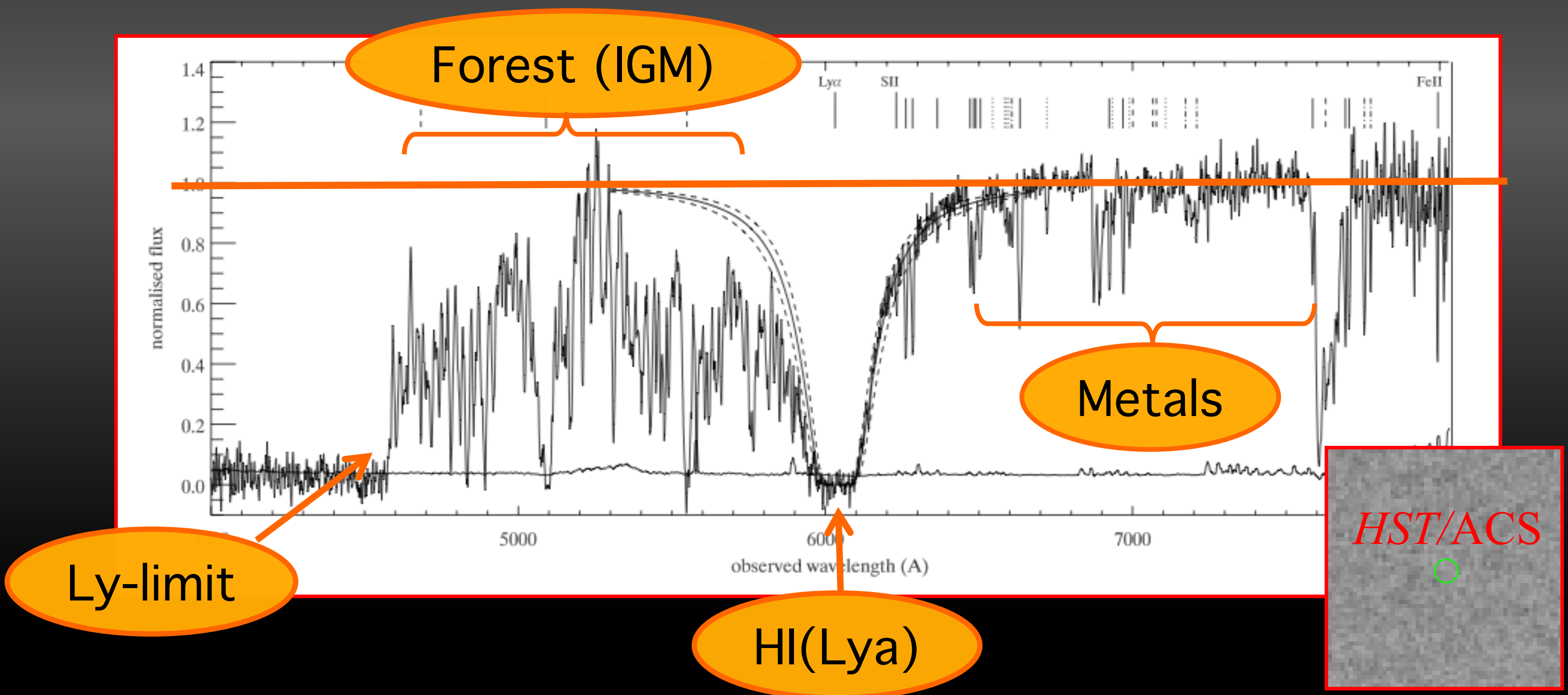
GRB 970508, at redshift z=0.84 (Metzger et al. 1997). Absorption lines due to gas in host interstellar medium, seen against power-law continuum of the afterglow.




*Metzger et al. 1997*

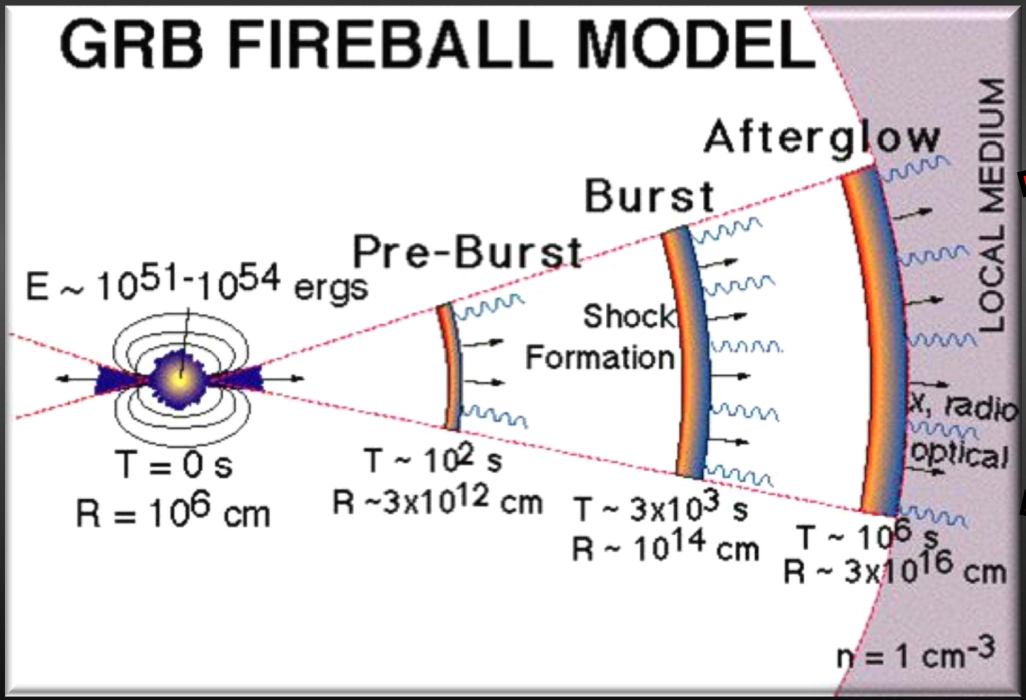
Detailed follow-up of large samples, including hosts and locations, provides insights into:

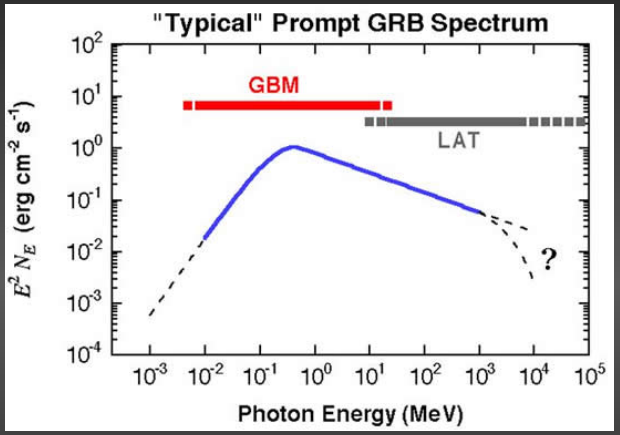
- progenitors and their evolutionary pathways
- explosion physics
- emission mechanisms
- abundances of chemical elements
- cosmological questions
- population diversity and evolution over cosmic time

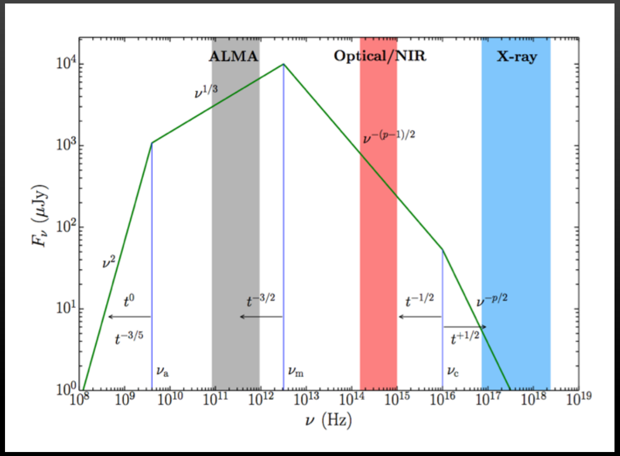


# Relativistic fireball

"Standard picture" ultra-relativistic jet produces prompt emission via internal shocks from shell collisions within jet, and afterglow emission via shocking of ambient medium. Both are very luminous and very broad spectral range.

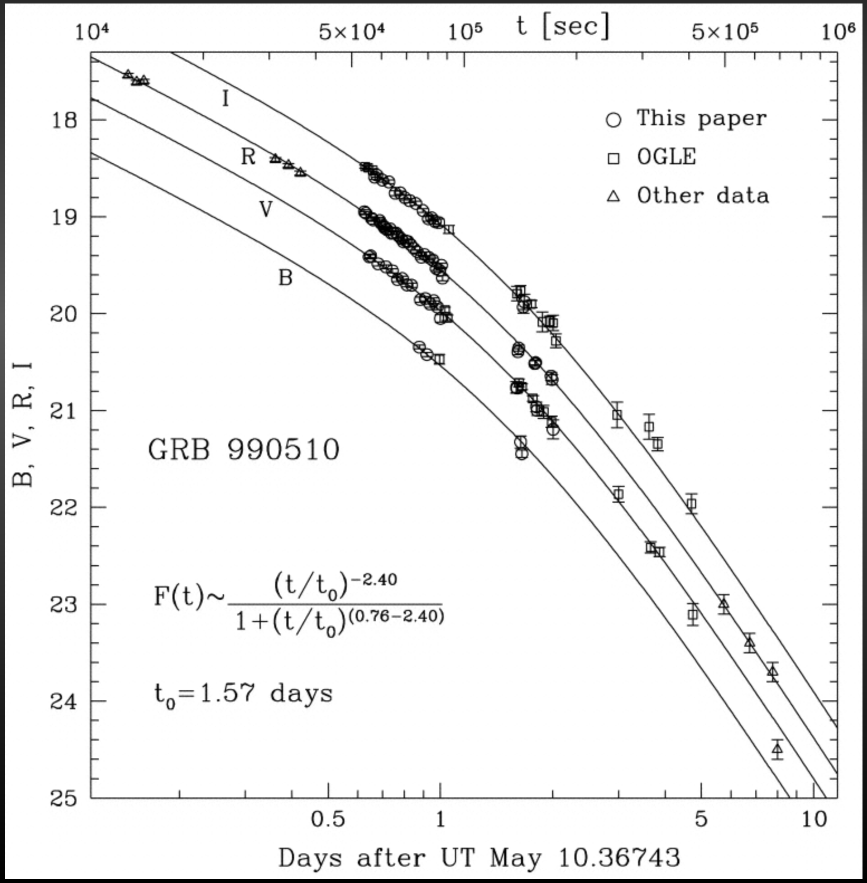


# Why do we think long-GRBs are jetted?

- Although we don't understand them well, we know jets are common in accreting astrophysical systems.
- Easier to conceive of a jet solving baryon loading problem by clearing material to side.
- Alleviates the efficiency problem – total energy requirement reduced by 2-3 orders of magnitude.
- Some GRB light curves show achromatic breaks, a predicted signature of a (decelerating) jetted source with opening angles >~few degrees.



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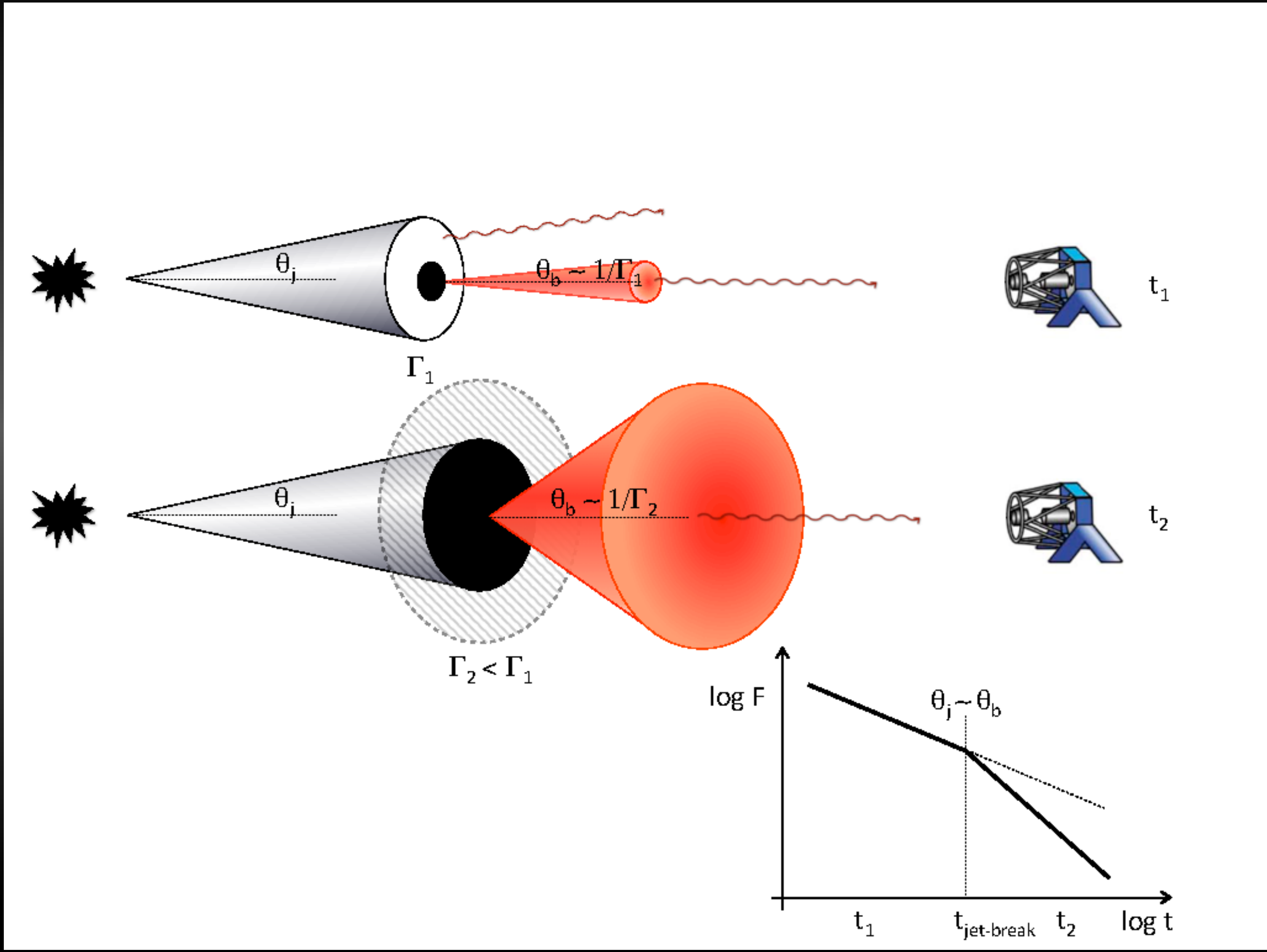
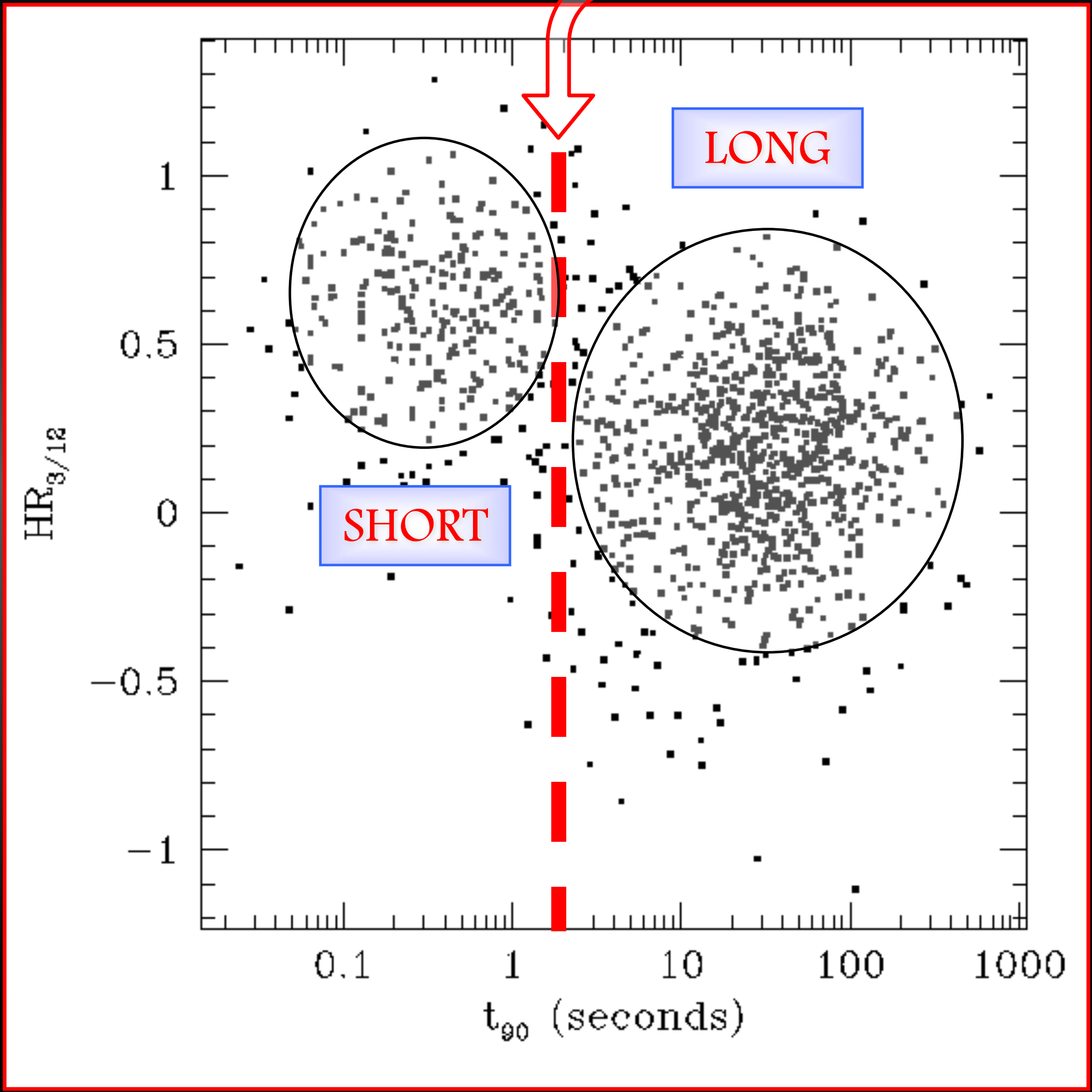


# Two populations




$T_{90}$=2 s

- Obviously overlap
- Detector dependent
- Redshift dependent (in complicated ways)

*Kouveliotou et al. 1993*
*Mazets et al. 1982*

# Why did we think short-GRB have CB progenitors?

$d < ct_{\mathrm{var}} \sim 10^{-2} c$ m

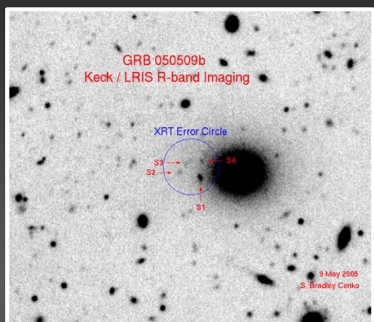
$BE = \frac{GM^2}{R} \approx 10^{47}$ J $\equiv 10^{54}$ erg

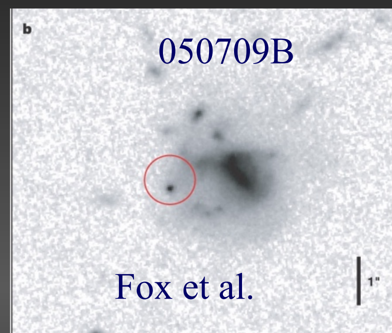
→ Compact enough

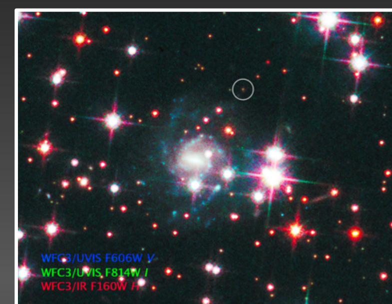
→ Sufficient energy reservoir

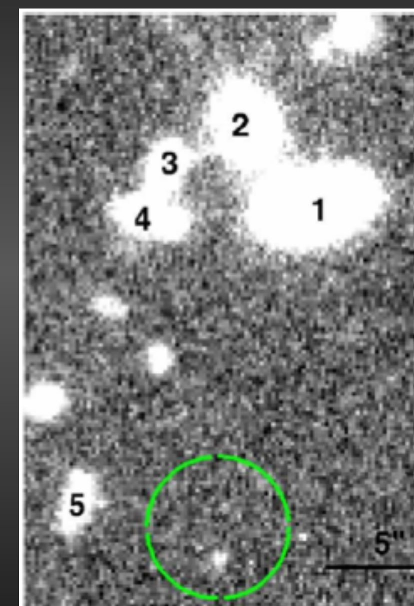
# Why did we think short-GRB have CB progenitors?

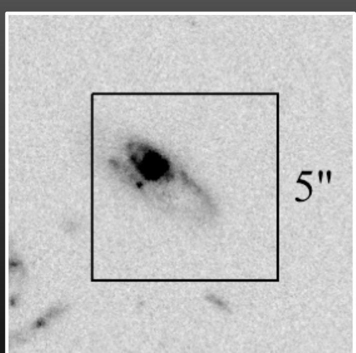
Host galaxies span a much larger range of stellar populations than long-GRBs.

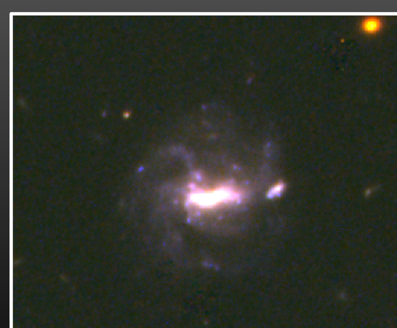


*Fong et al. 2017*

Consistent with NS compact binaries, with long merger times.

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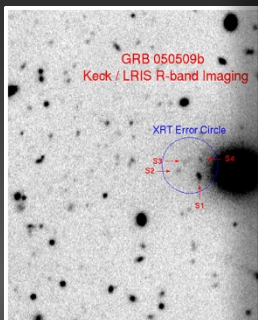
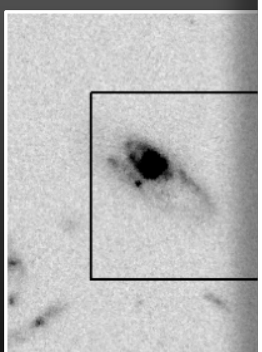
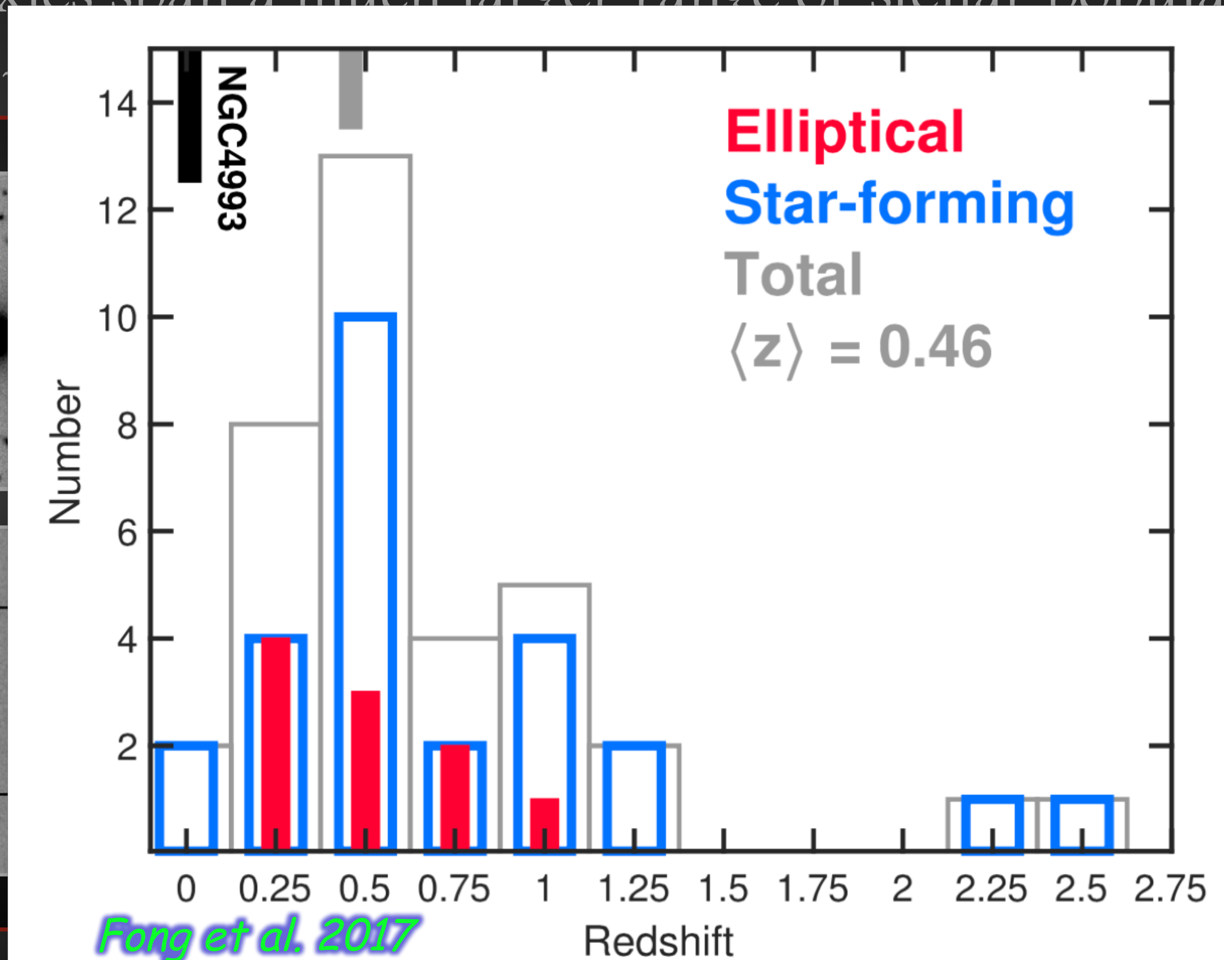
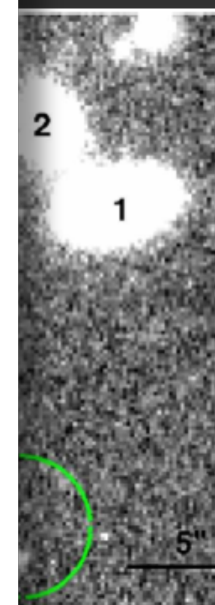





Fong et al. 2017



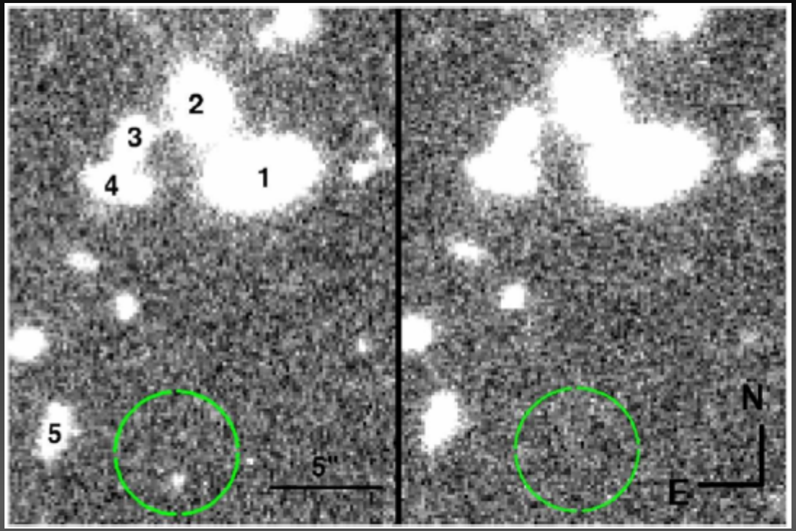

Consistent with NS compact binaries, with long merger times.

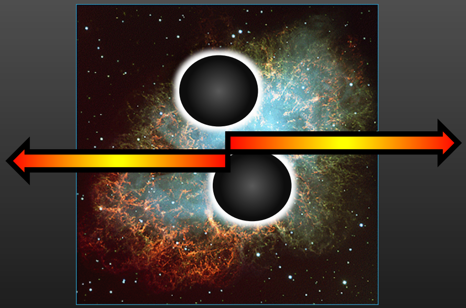
# Why did we think short-GRB have CB progenitors?

Sometimes apparently far from their host.

e.g. GRB090515 afterglow R~26.5 at 2 hours post burst.  No obvious host.

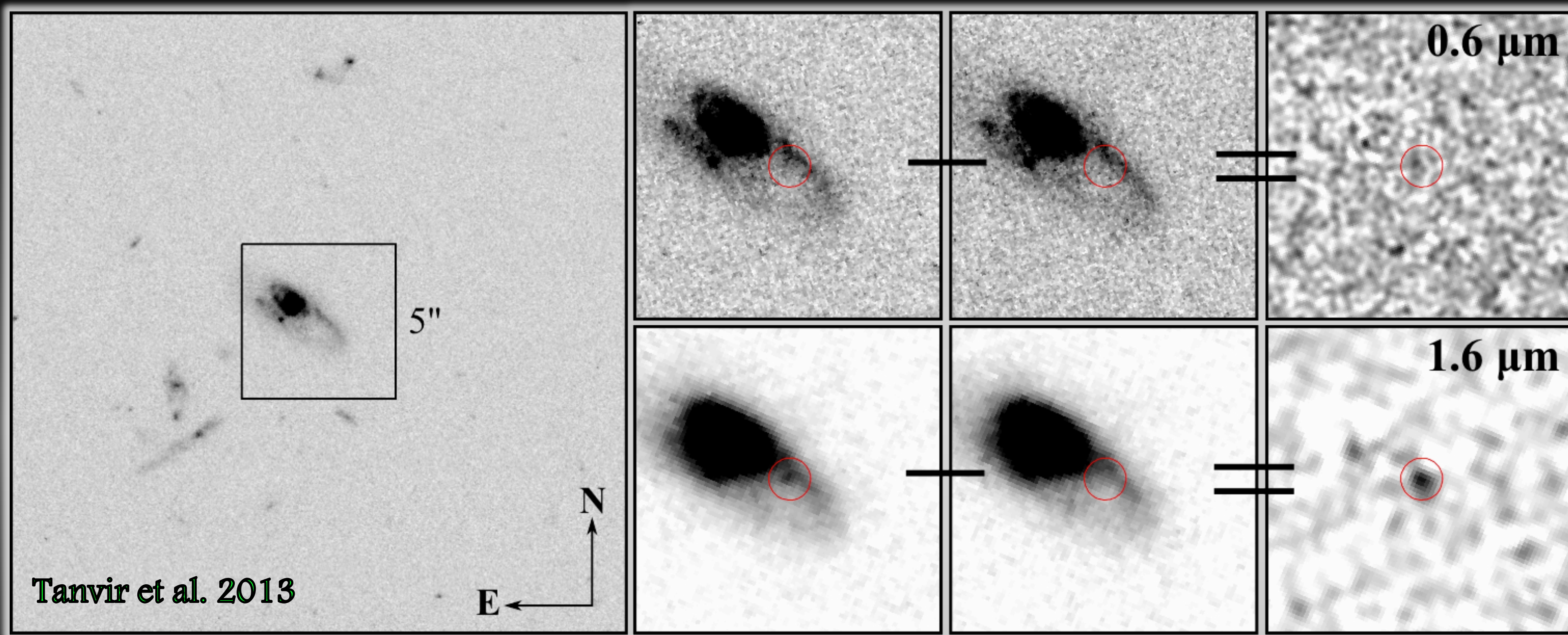
*Rowlinson et al. 2010*



**Consistent with some neutron stars being given large kicks during asymmetric supernvovae (over Gyr can move far from host).**

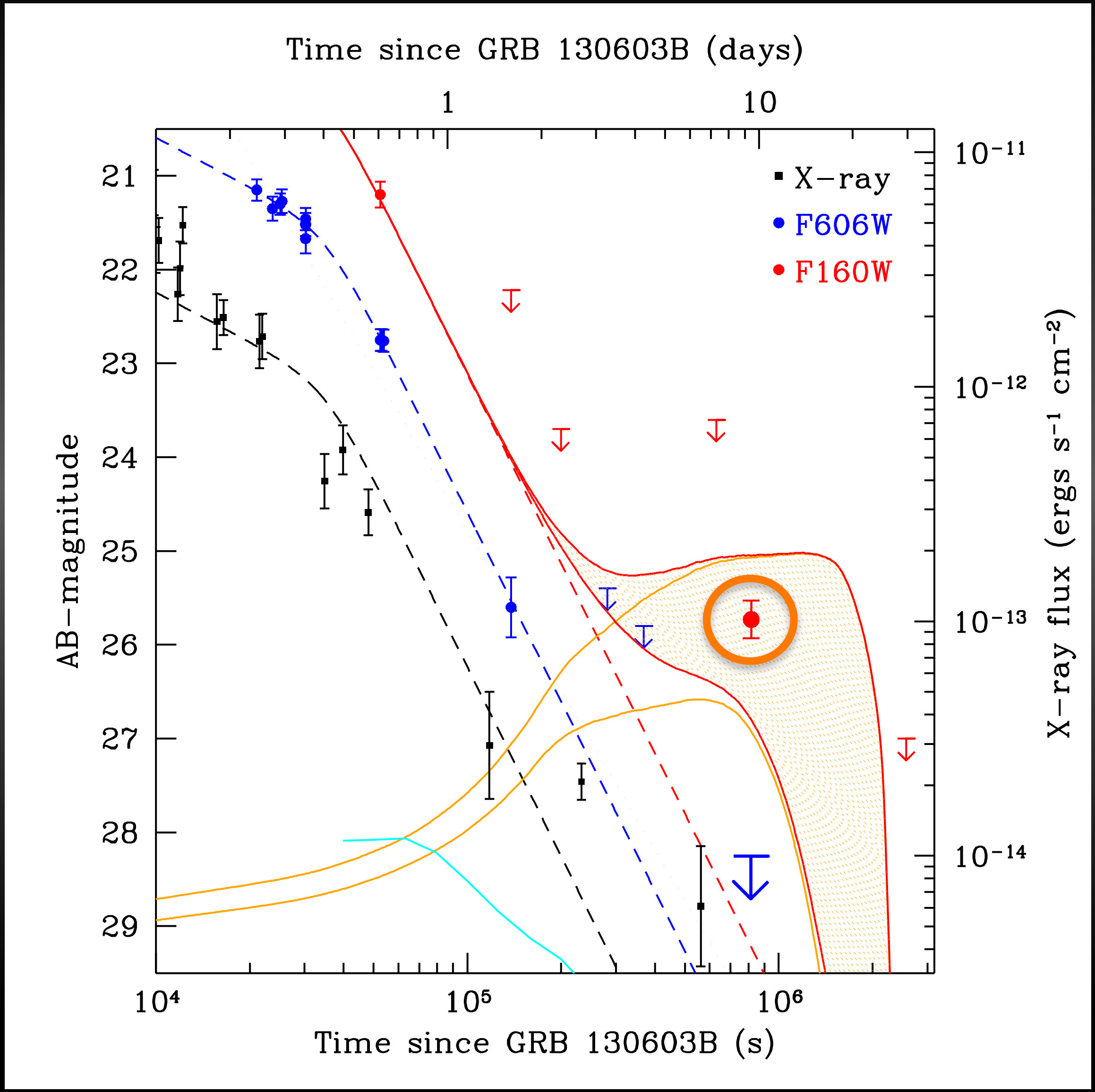
# GRB 130603B




9 day

30 day

# GRB 130603B ...or, much ado about a data-point

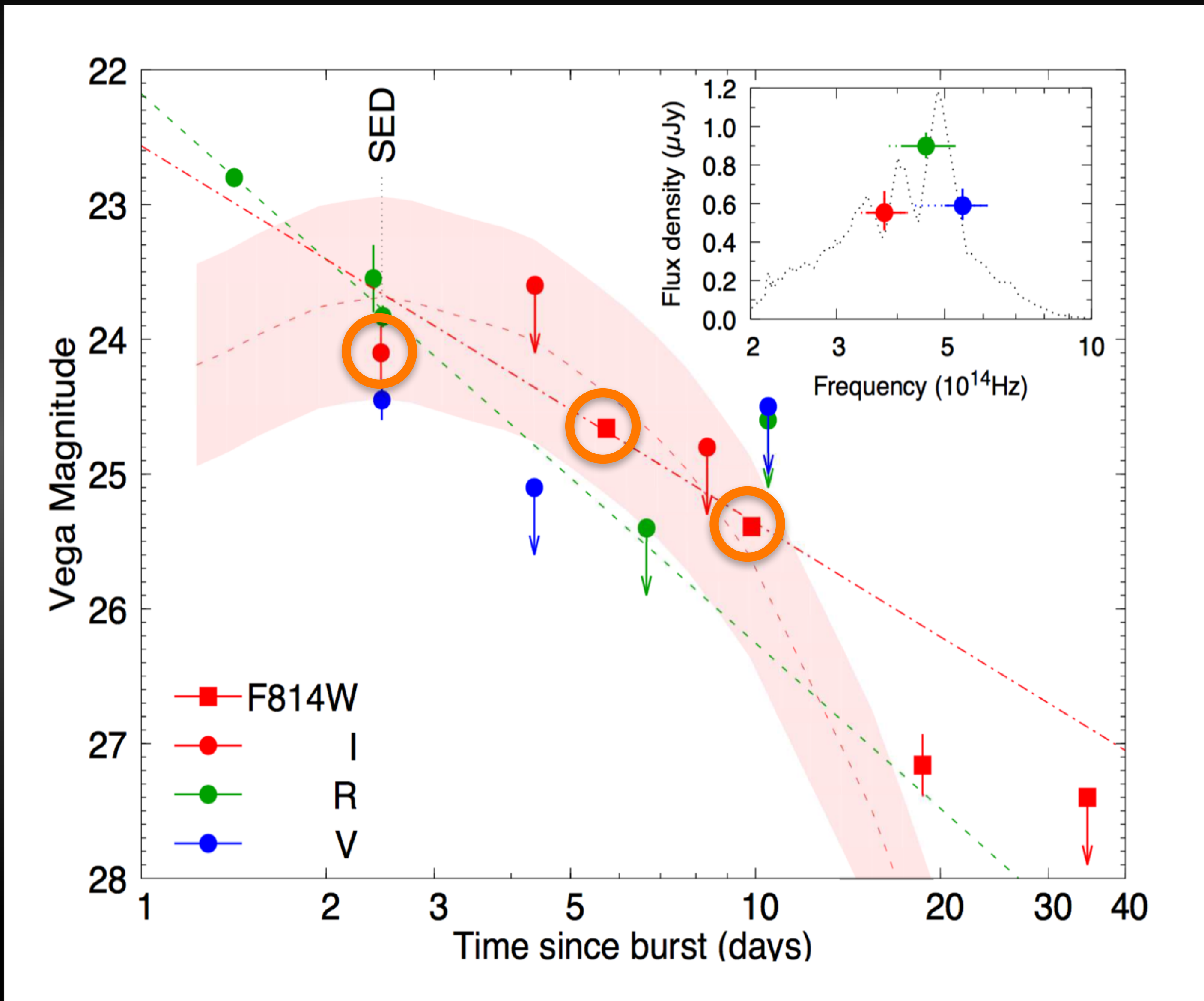



Comparison to Barnes & Kasen (2013) models suggests ejected mass ~0.05 $M_\odot$

Tanvir, Levan et al. 2013
Berger et al. 2013
Fong et al. 2014

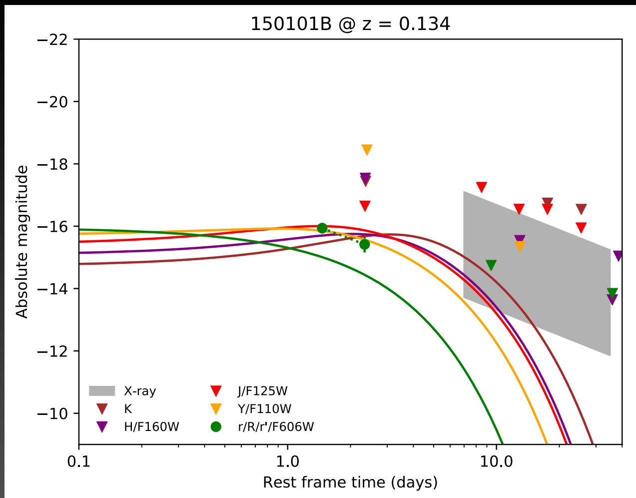
# GRB 050709

SED deviates from PL at 2.5 day, and becomes redder.
Possibly consistent with low-opacity KN in I-band.

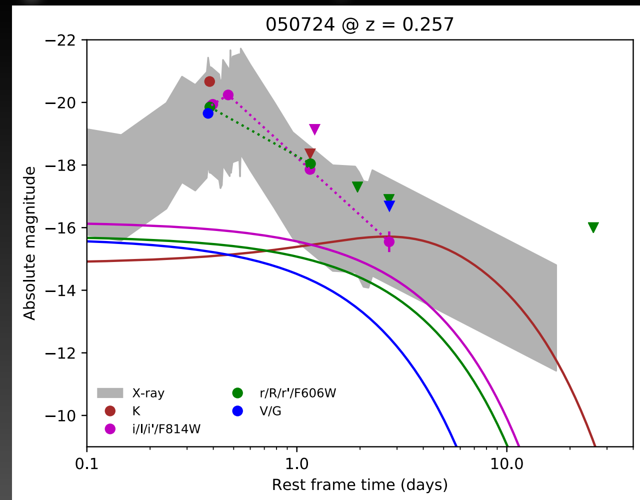



Jin et al. 2016

# But kilonova emission may have been, associated with short-GRBs

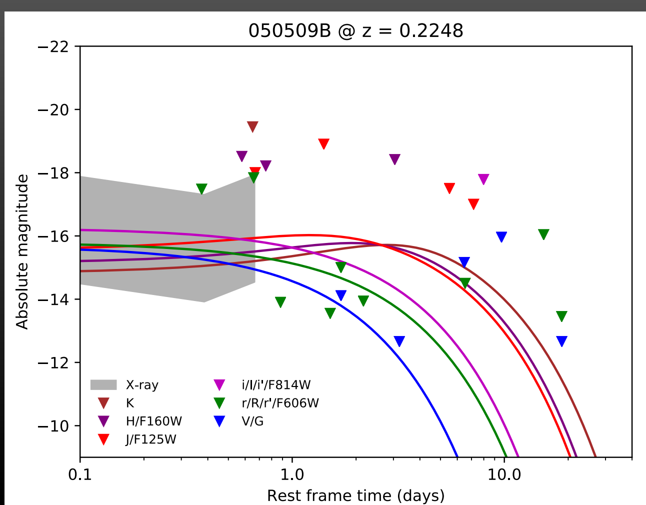



GRB150101B

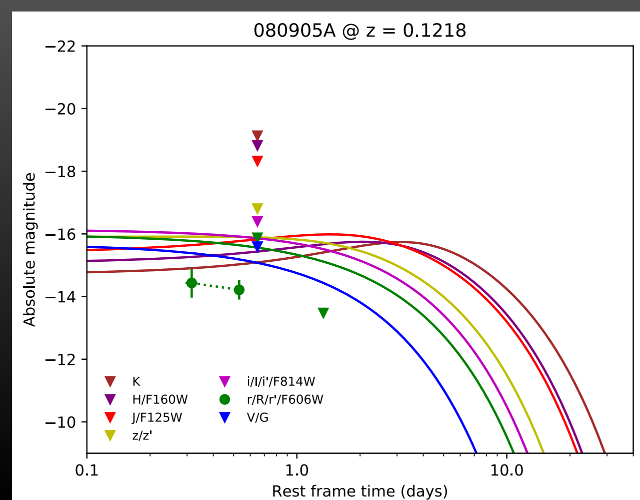



GRB050724

Some appear afterglow dominated, others may have had detected KN component.



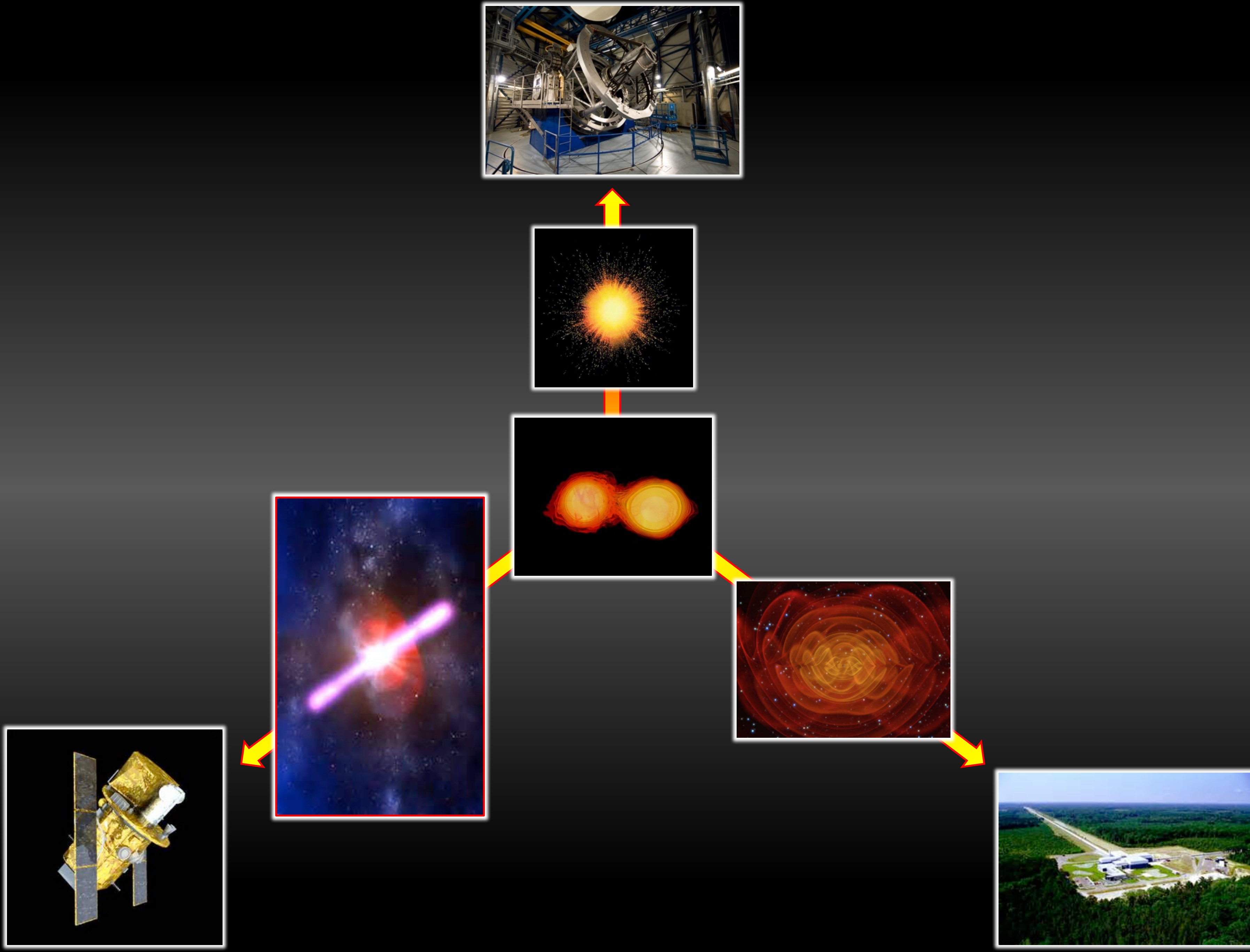

GRB050509B




GRB080905A

Some observed deeply enough to rule out kilonovae as bright as AT2017gfo.

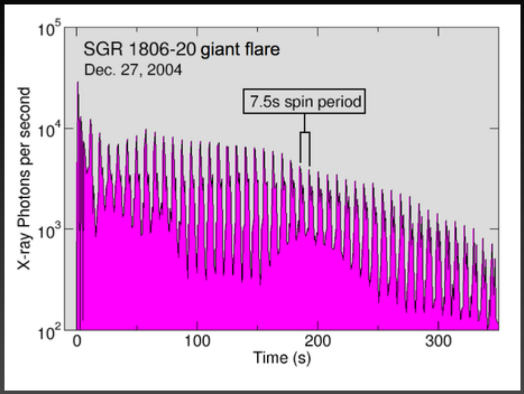
Gompertz et al. 2018

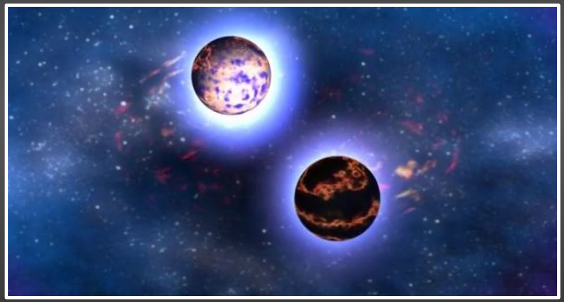


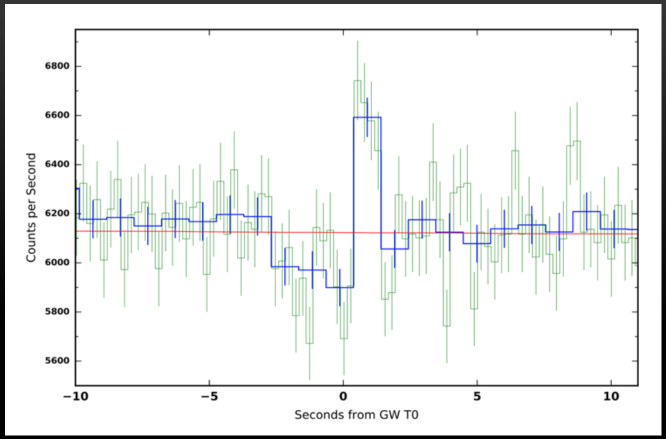
# Potential GW sources

Large time-varying mass-quadrupole:

- Core collapse
- Neutron star reconfiguration
- Binaries involving compact objects
  - NS+NS
  - NS+BH
  - BH+BH
  - SMBH+…
  - WD+…

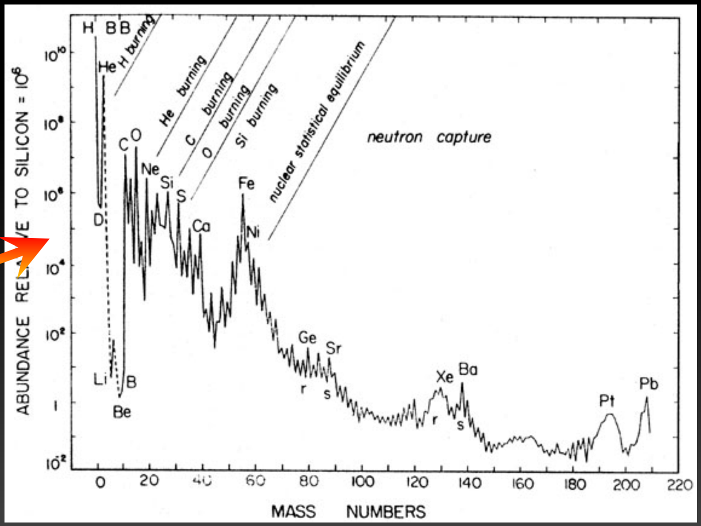




# Some motivations

- Understand r-process budget
- Cosmological parameters – Hubble constant
- Jet launching and structure
- Astrophysical context
- Fundamental physics – speed of light/gravity
- Improved GW parameters
- NS structure



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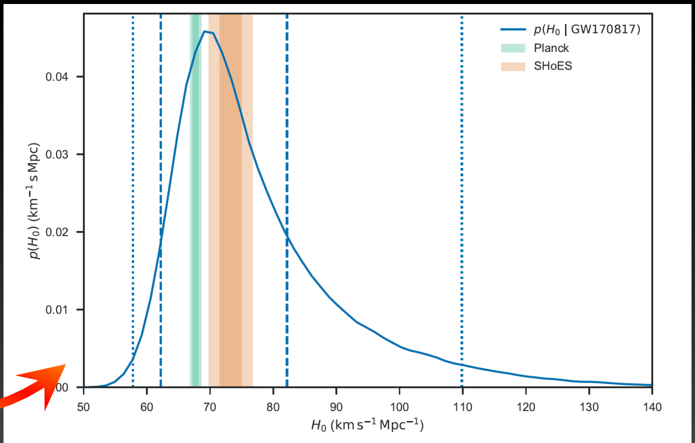

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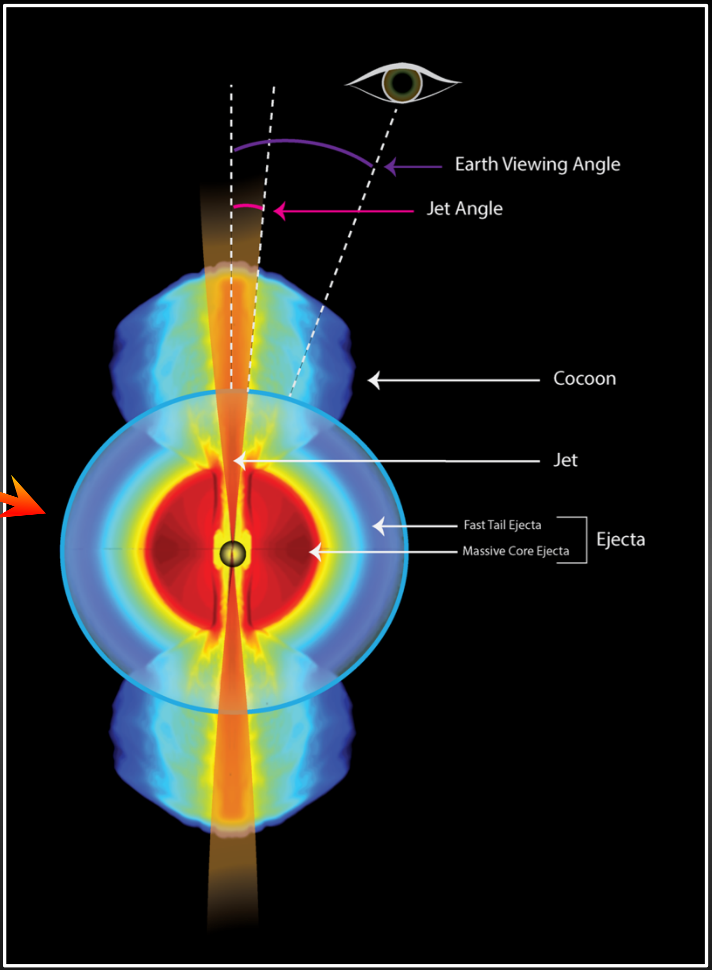

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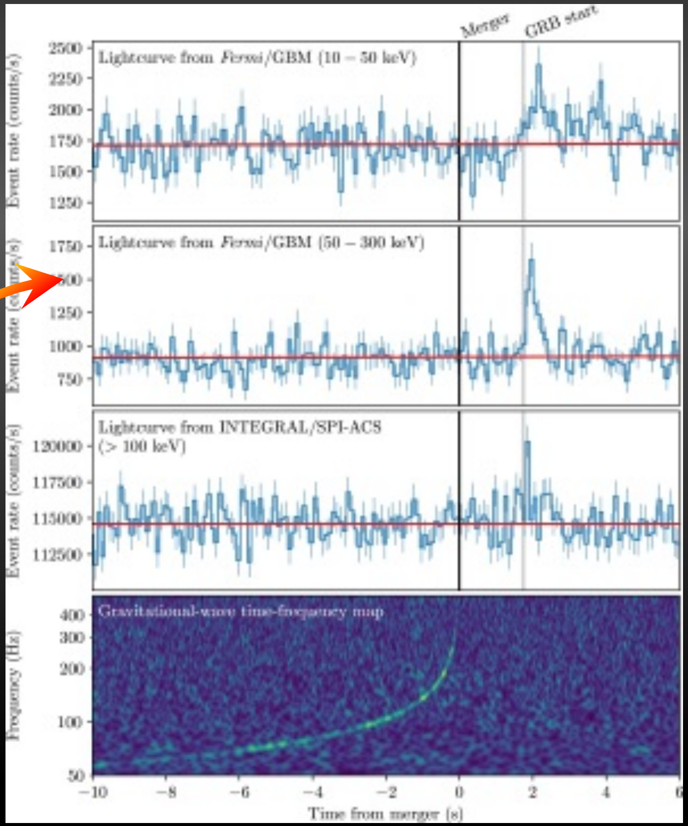

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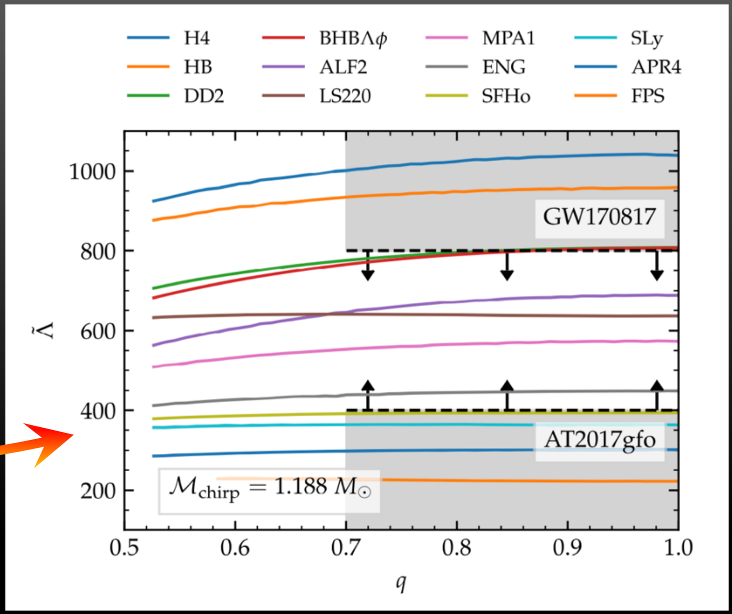
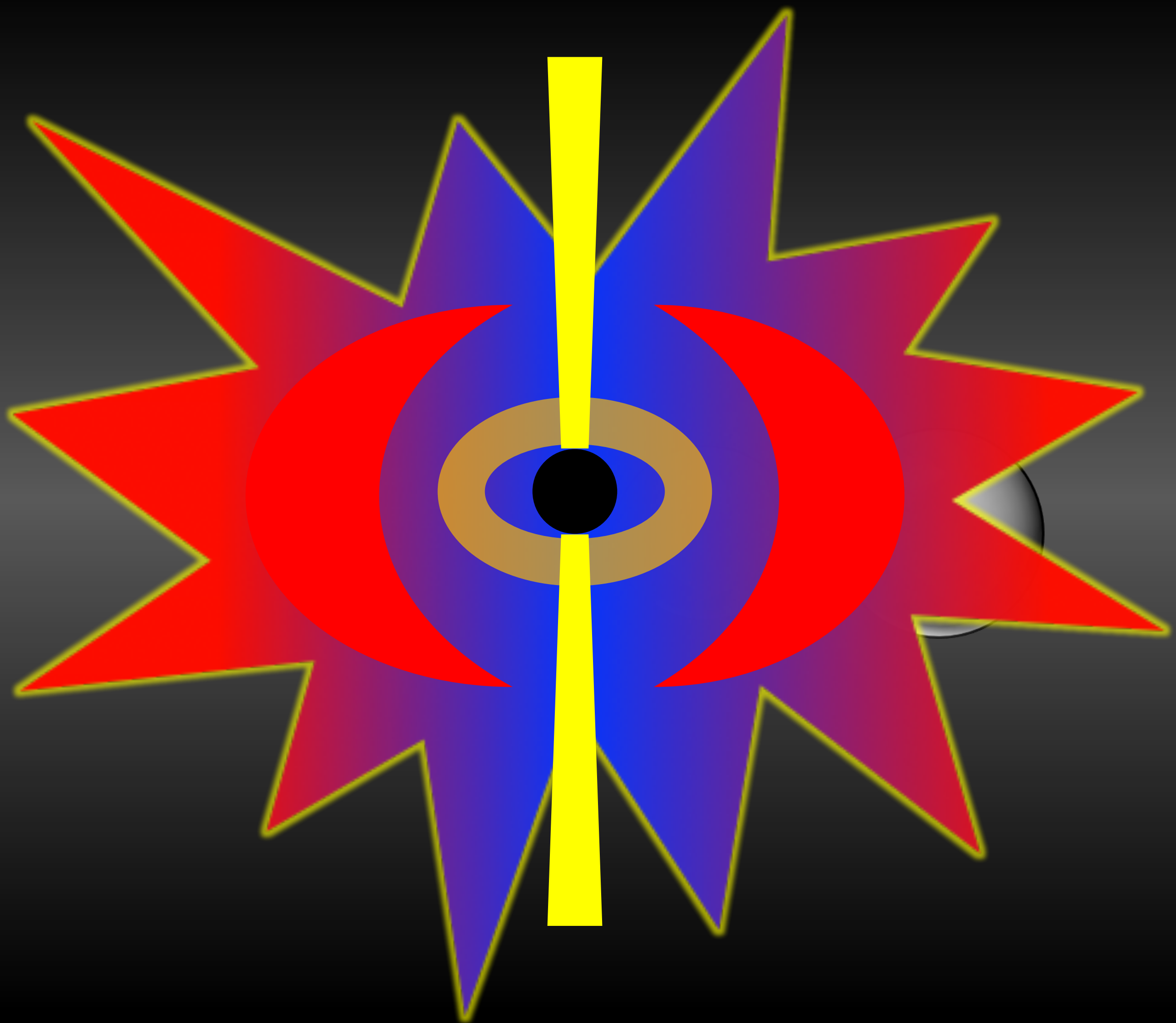


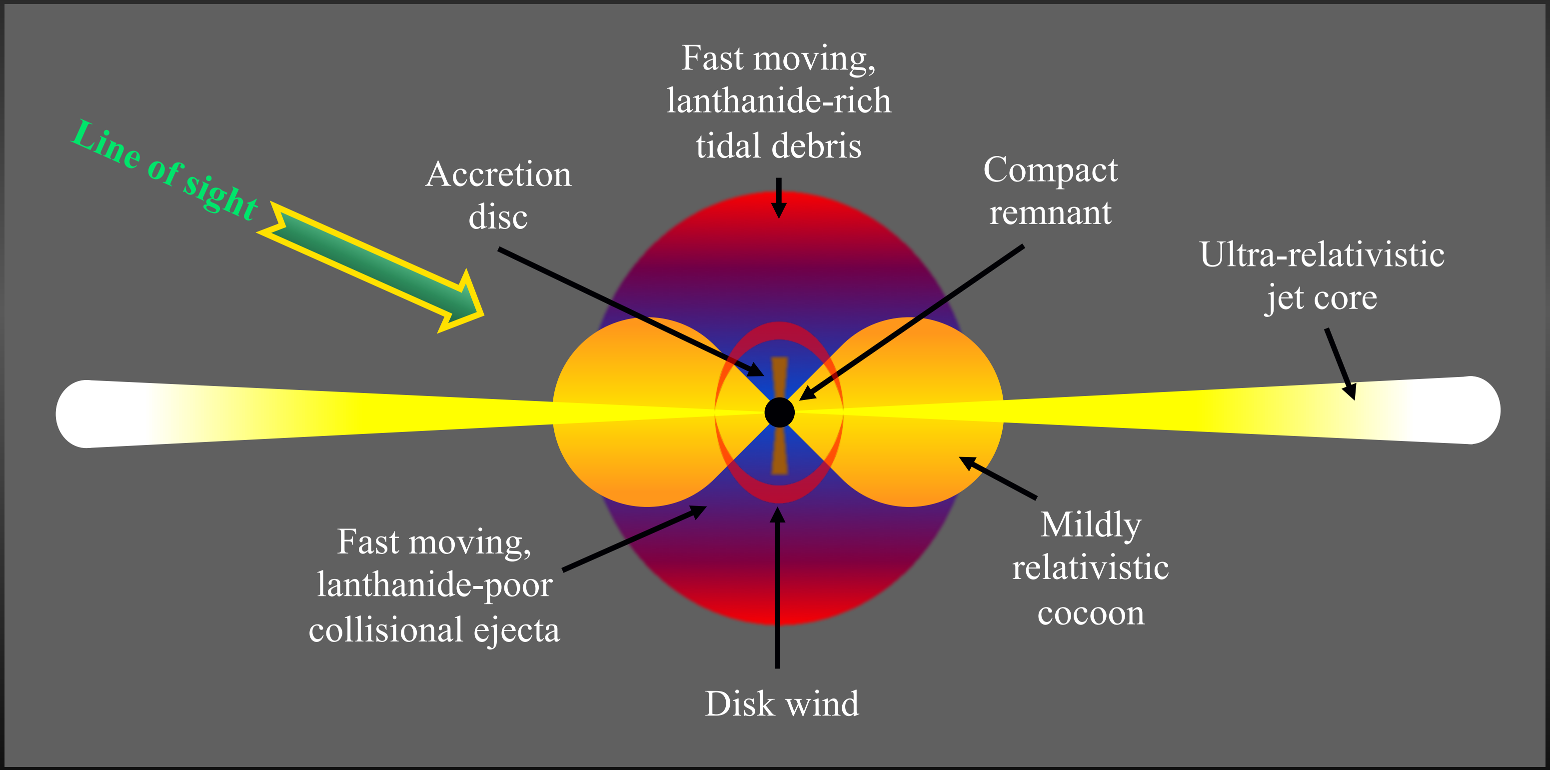
# The electromagnetic view



# Emission components

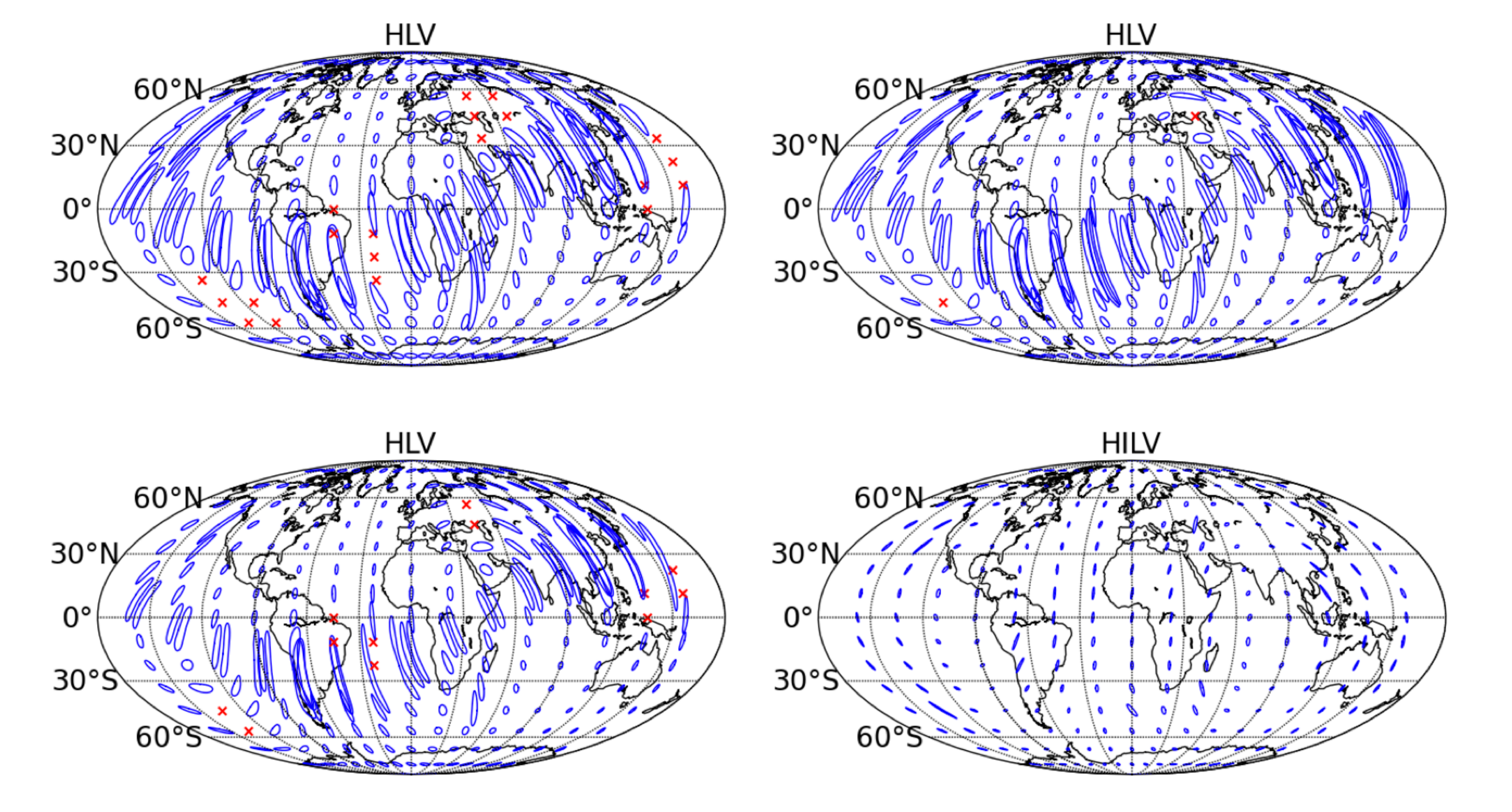
If jet has to penetrate ejected material, then it should form cocoon structure (cf. collapsar jets).

Cocoon may have given rise to the gamma-rays (e.g. Gottlieb et al. arXiv:1710.05896 etc. etc.).



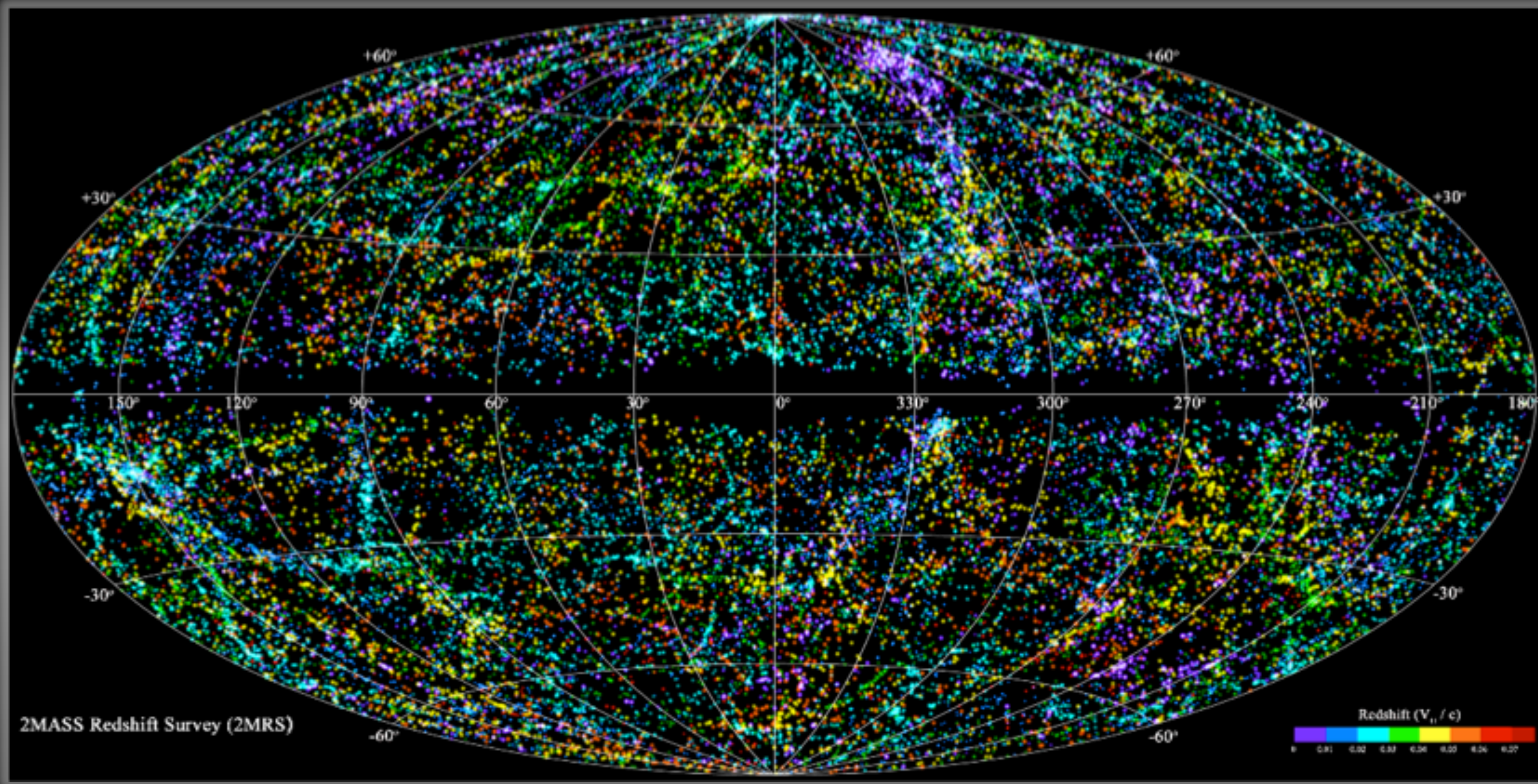

Same figure is indicative of how far different components could be seen.

# Error regions large



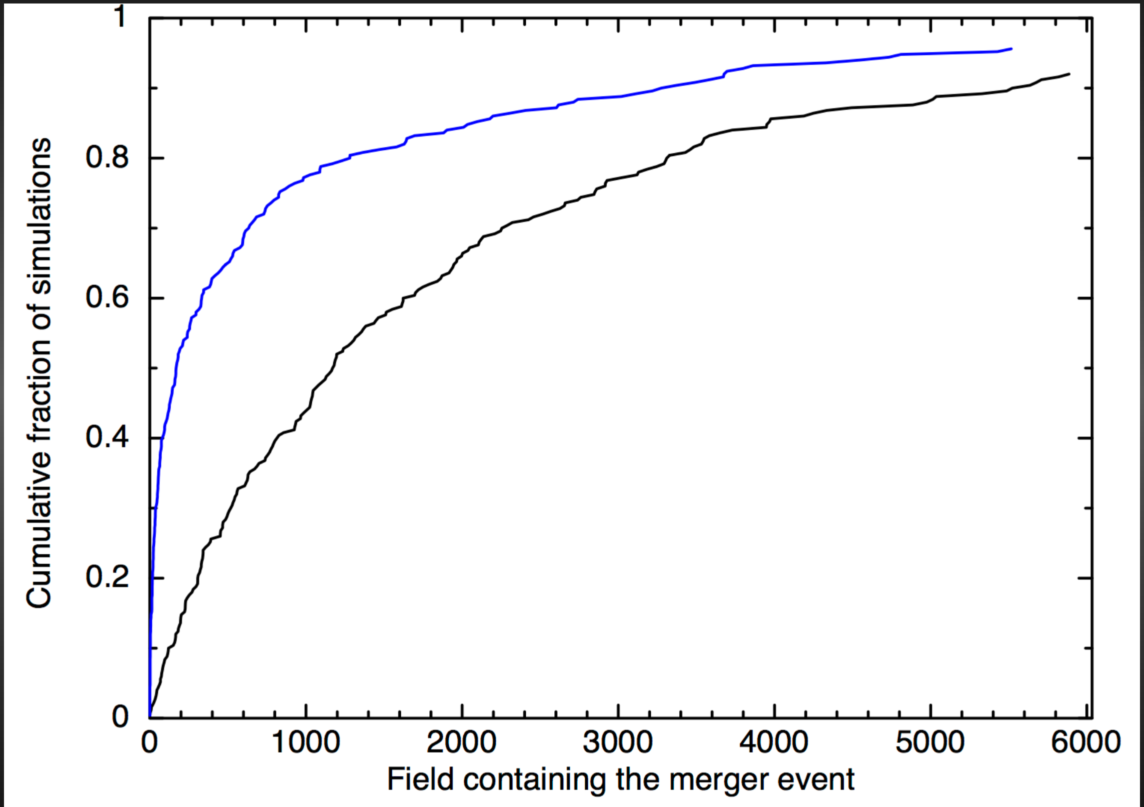

*Abbott et al. LRR*

# Strategies for improving chances




Make use of known locations of low-z galaxies to prioritise more likely fields (although run into limits of current galaxy catalogues)

# Benefits of galaxy targeting

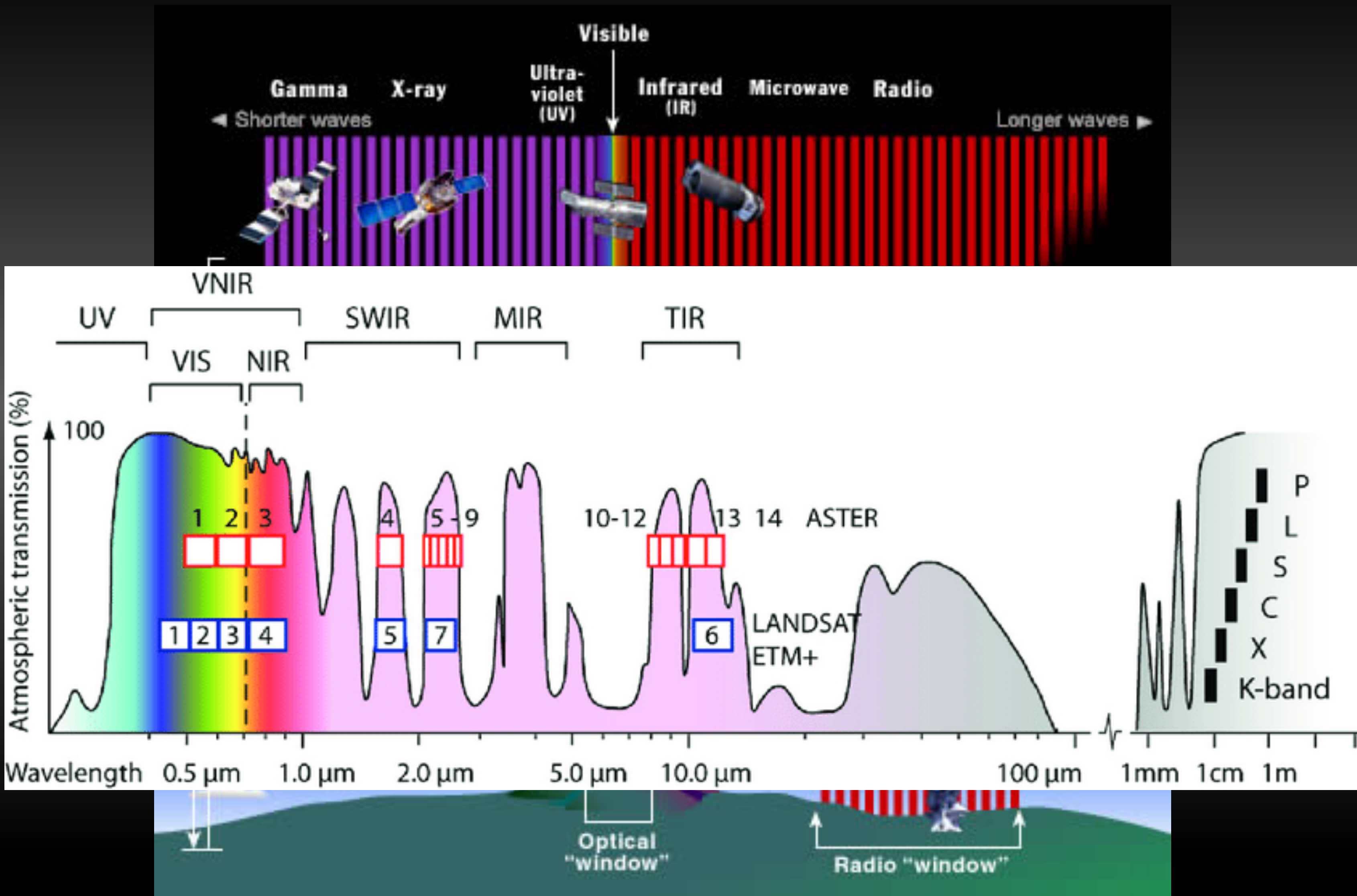



Without galaxy targeting, in the 'median' case we would have to observe nearly 1,200 fields with XRT before we get to the correct location.

With galaxy targeting, in the 'median' case we would have to observe about 170 fields with XRT before we get to the correct location.

*Evans et al. 2016*

# What's the waveband?



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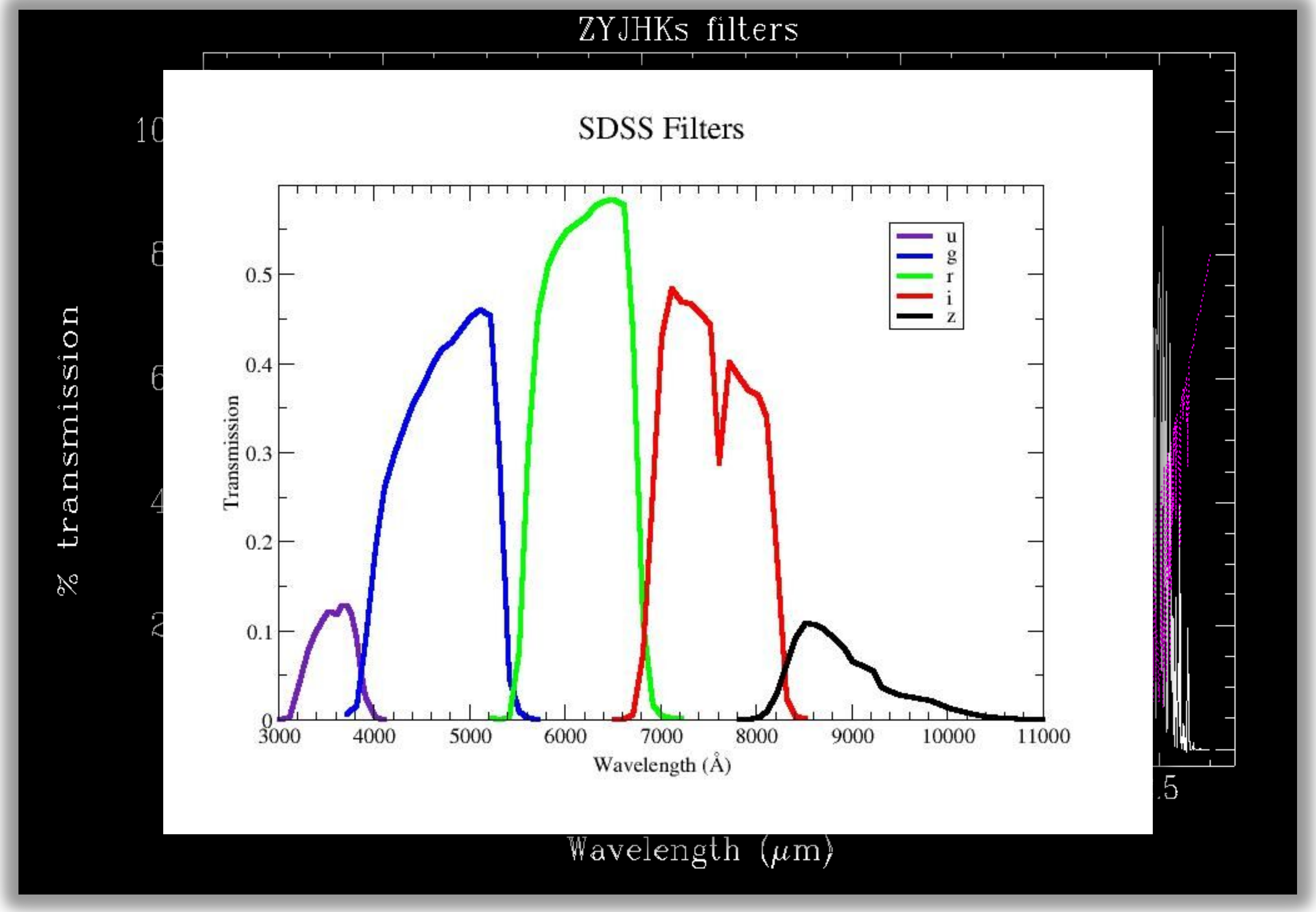
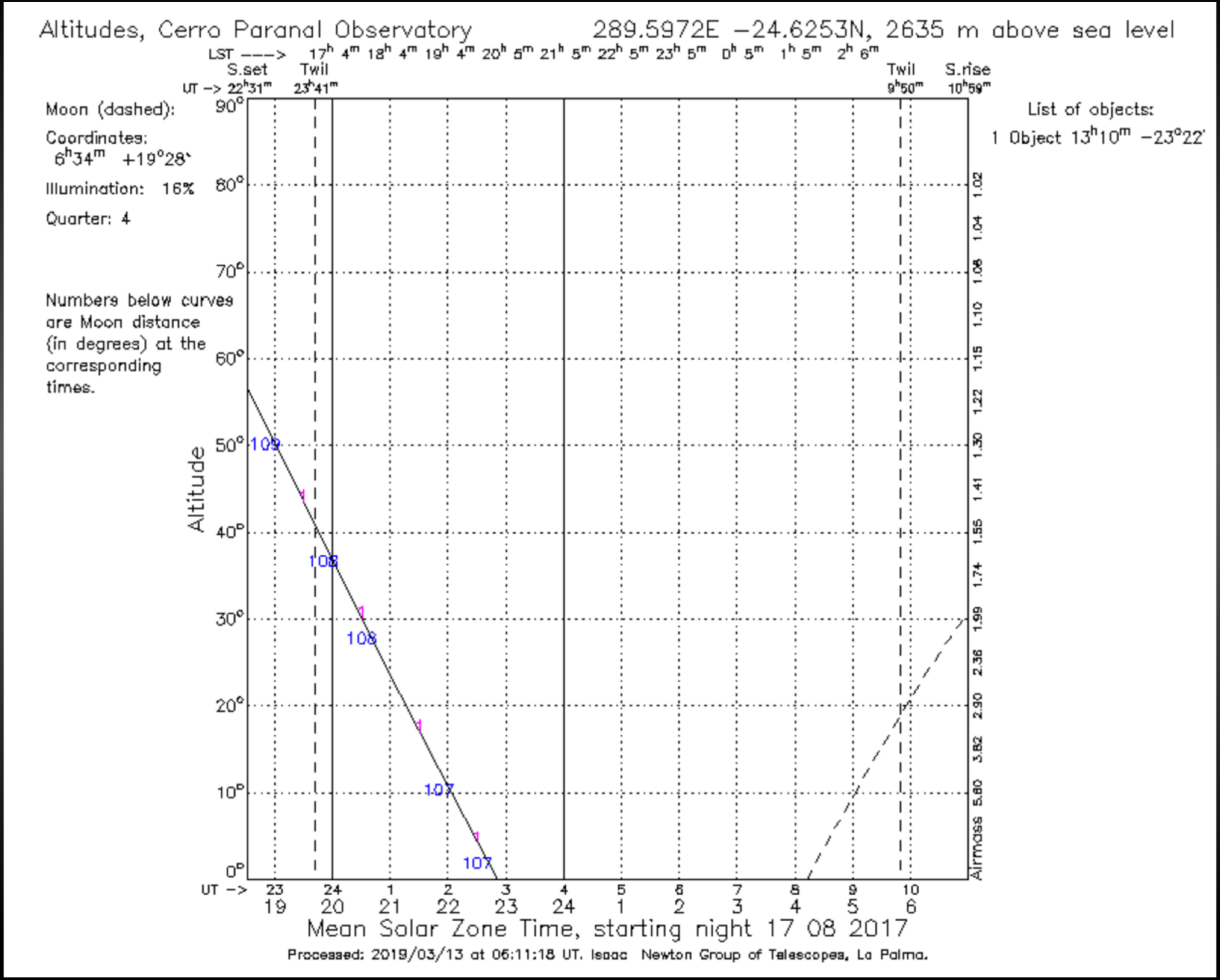


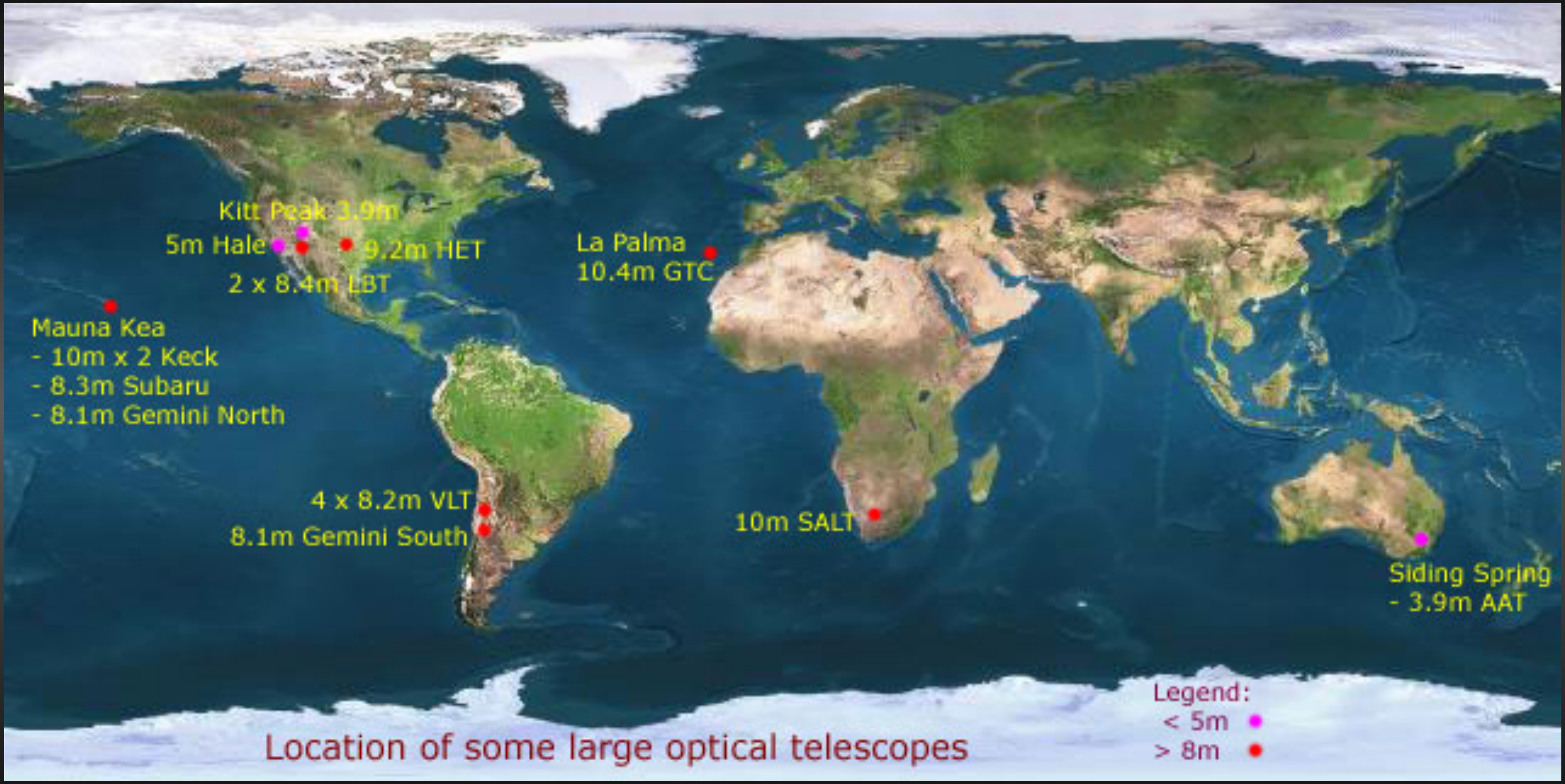

Wavelength, μm

# Where's the target?

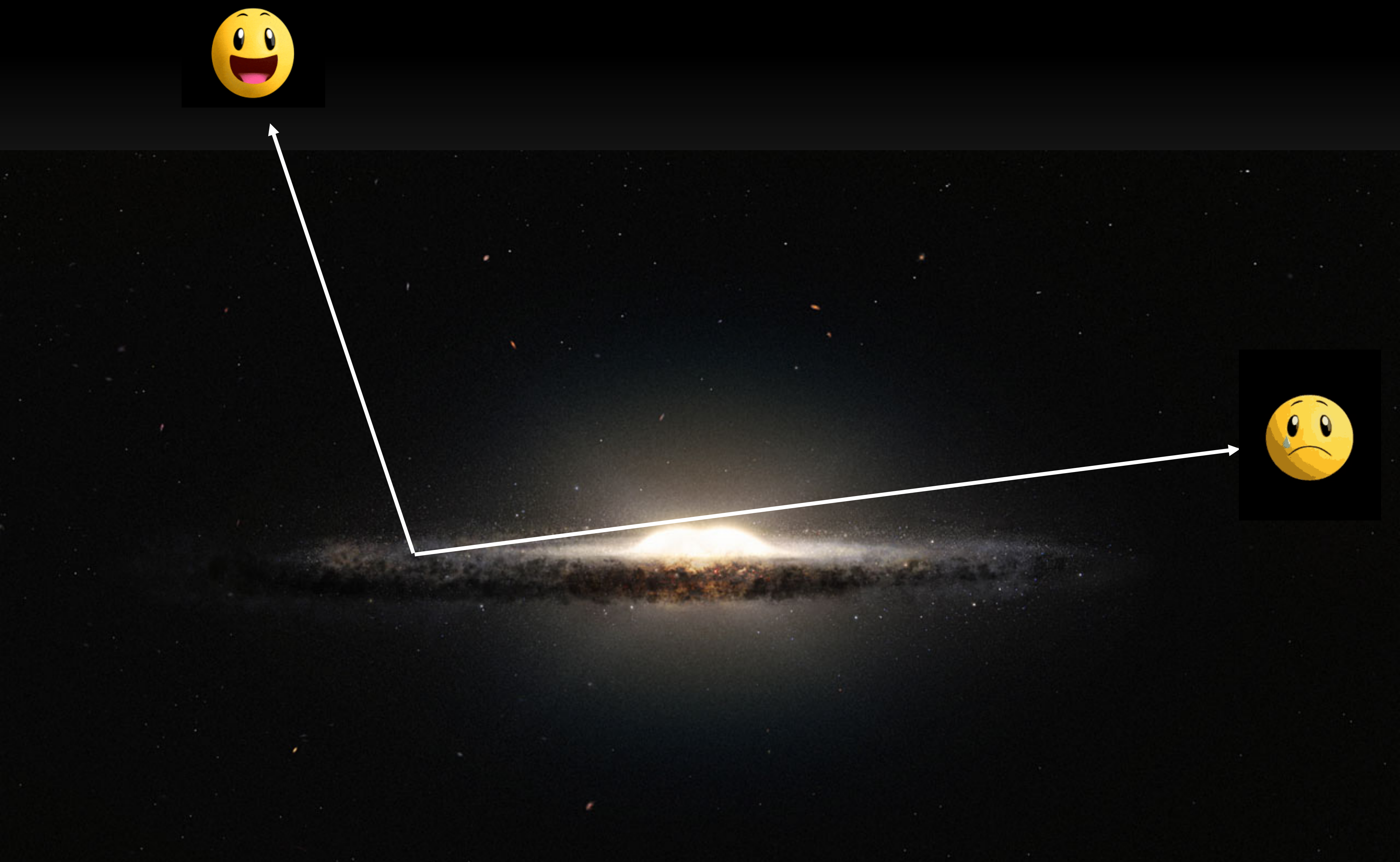
In case of GW 170817, field rather close to Sun



# Where's the glass?

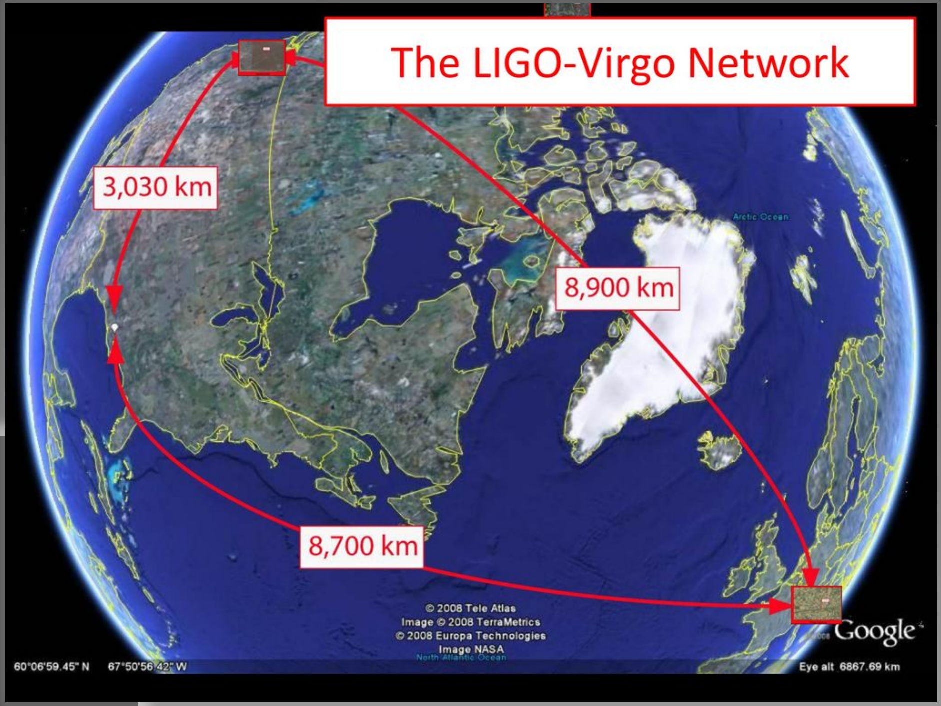


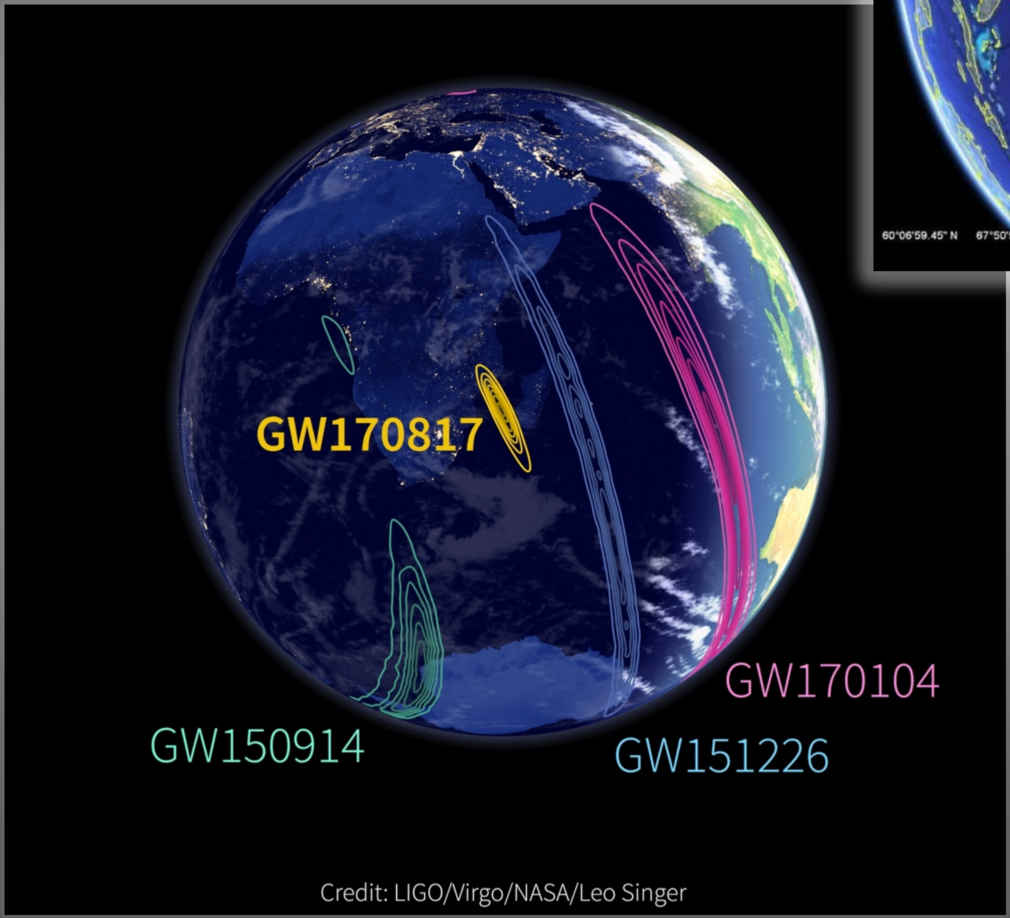

World's largest O/IR scopes (now and planned) occupy limited geographical range



Fields at low galactic latitude generally hard to observe

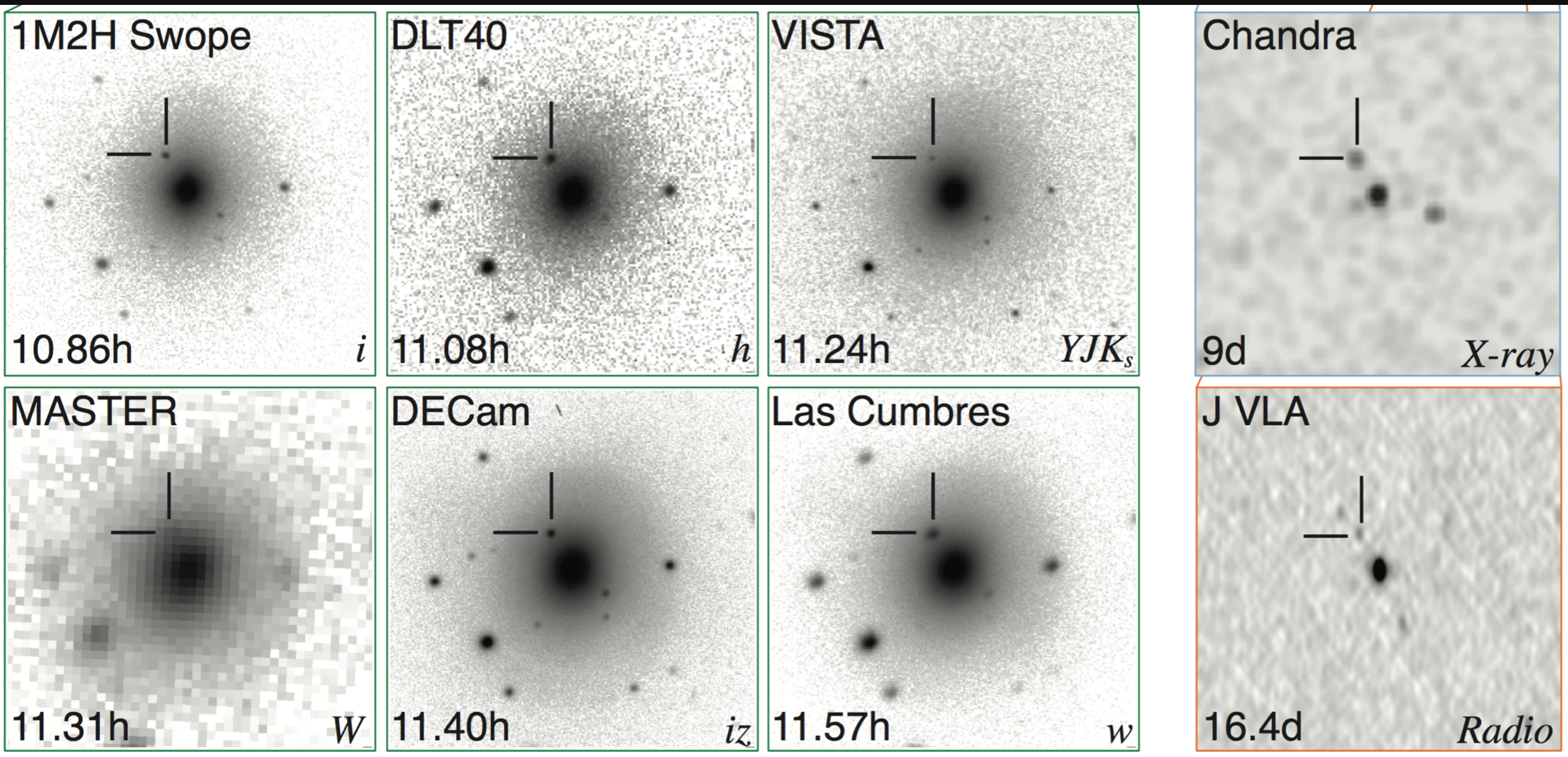
# GW 170817




Occurred at time when not well placed for follow-up

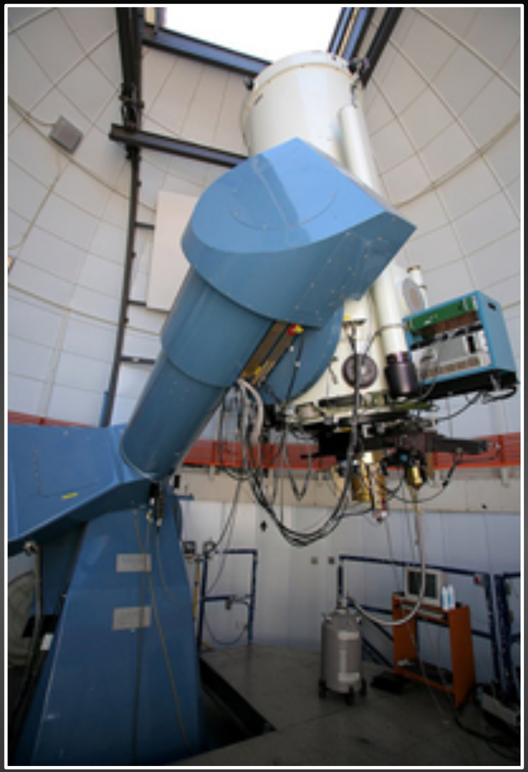
# O/IR (X/Radio) counterpart discovery

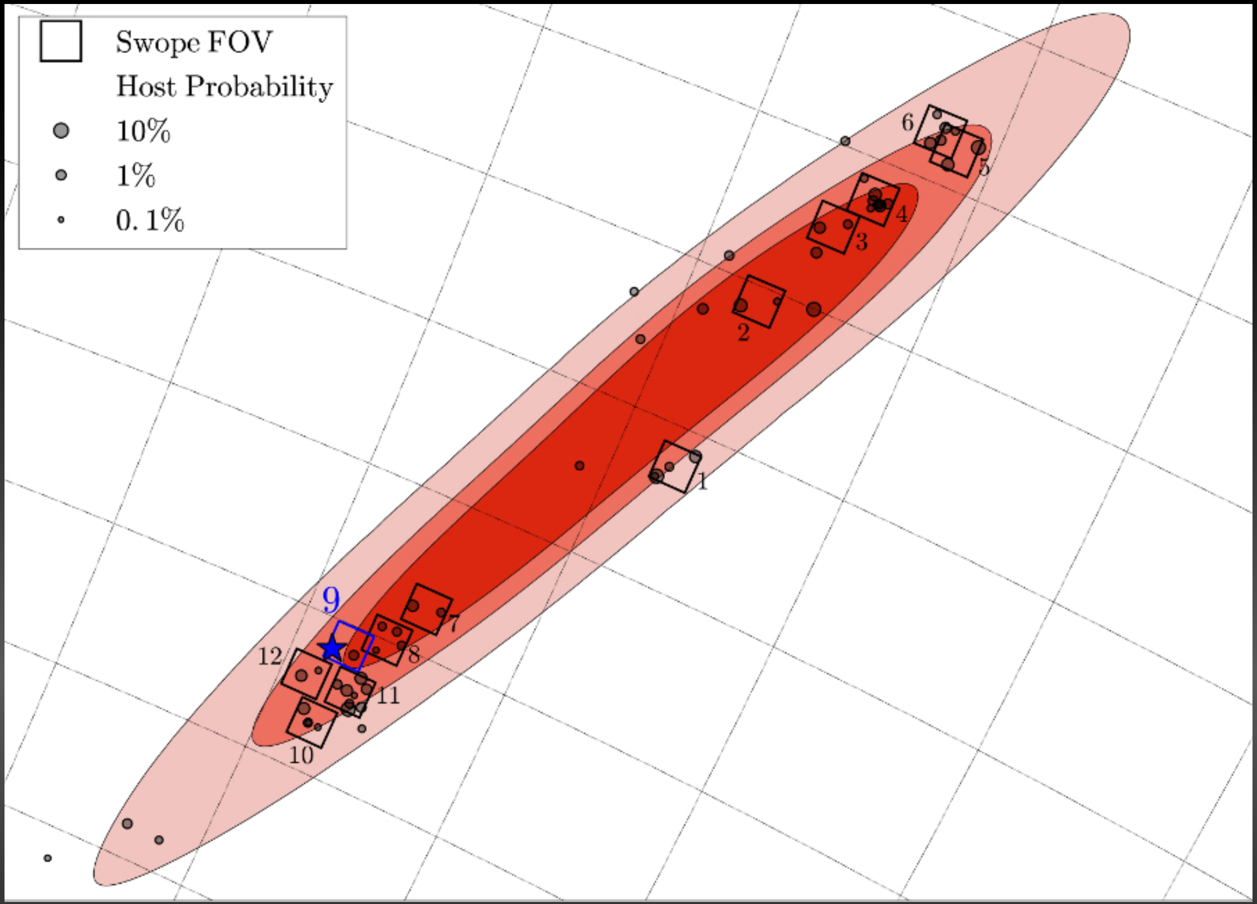



**GW 170817/AT2017gfo**

Abbott et al. 2017, ApJL

# Swope

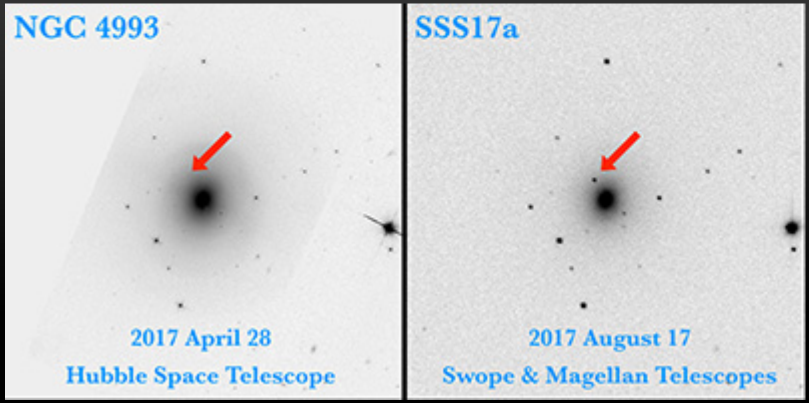





1-m telescope

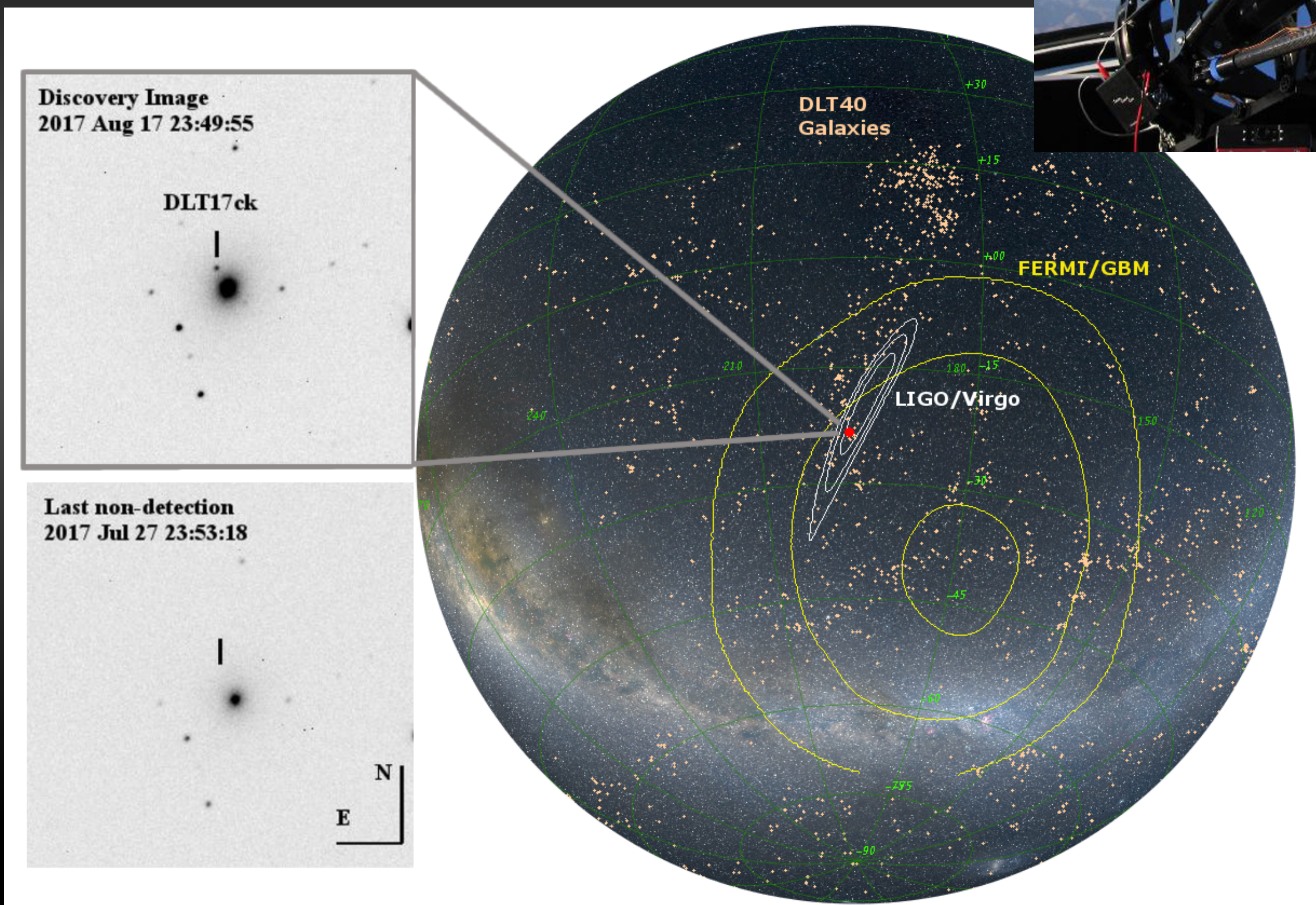
Optical camera

0.5x0.5 degree field



# DLT40

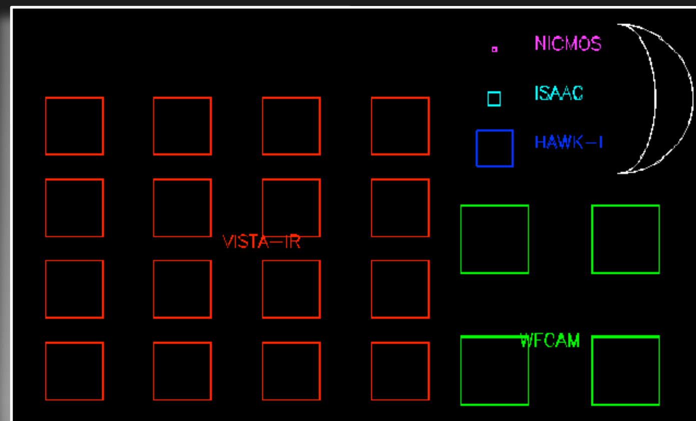
0.4-m optical telescope.

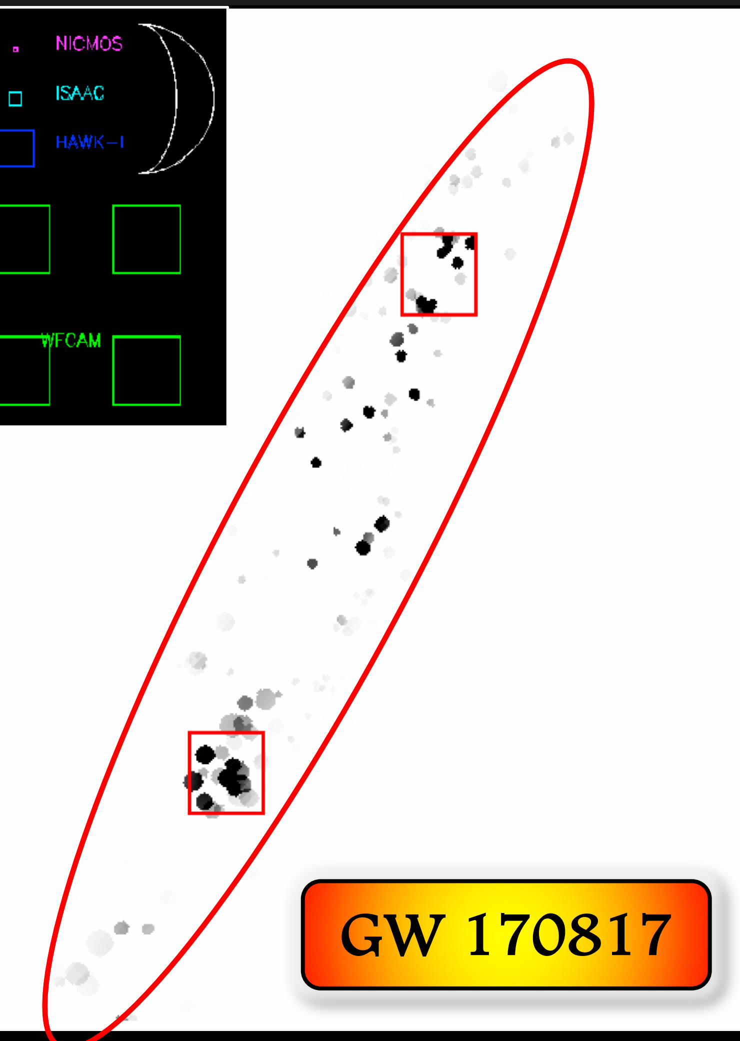


VIN ROUGE

Near-IR optimised 4.1 m

0.6 sq-deg field of view



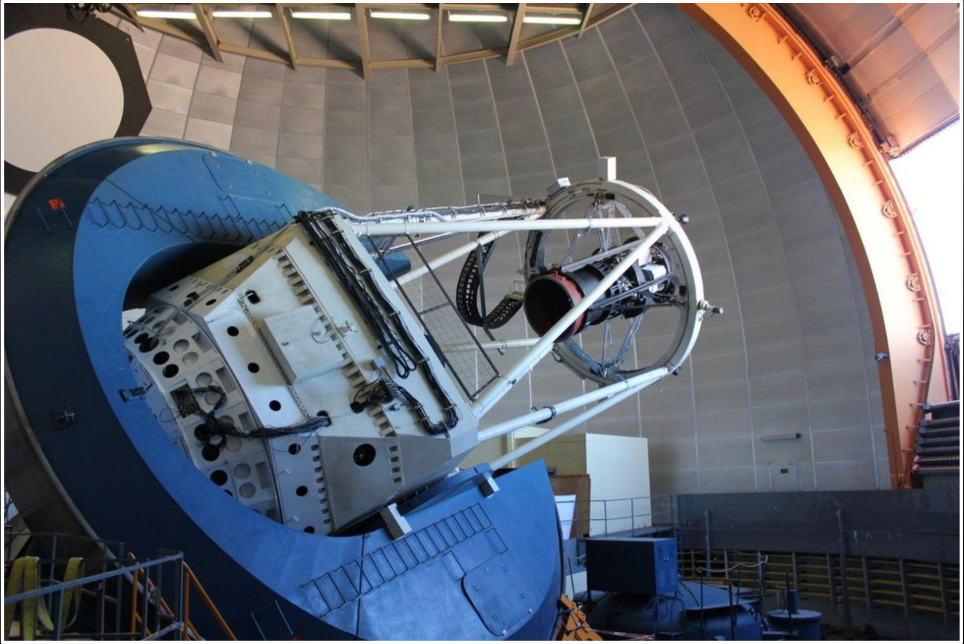

VISTA

# DECam

4-m telescope

Optical camera

3 sq-deg field of view



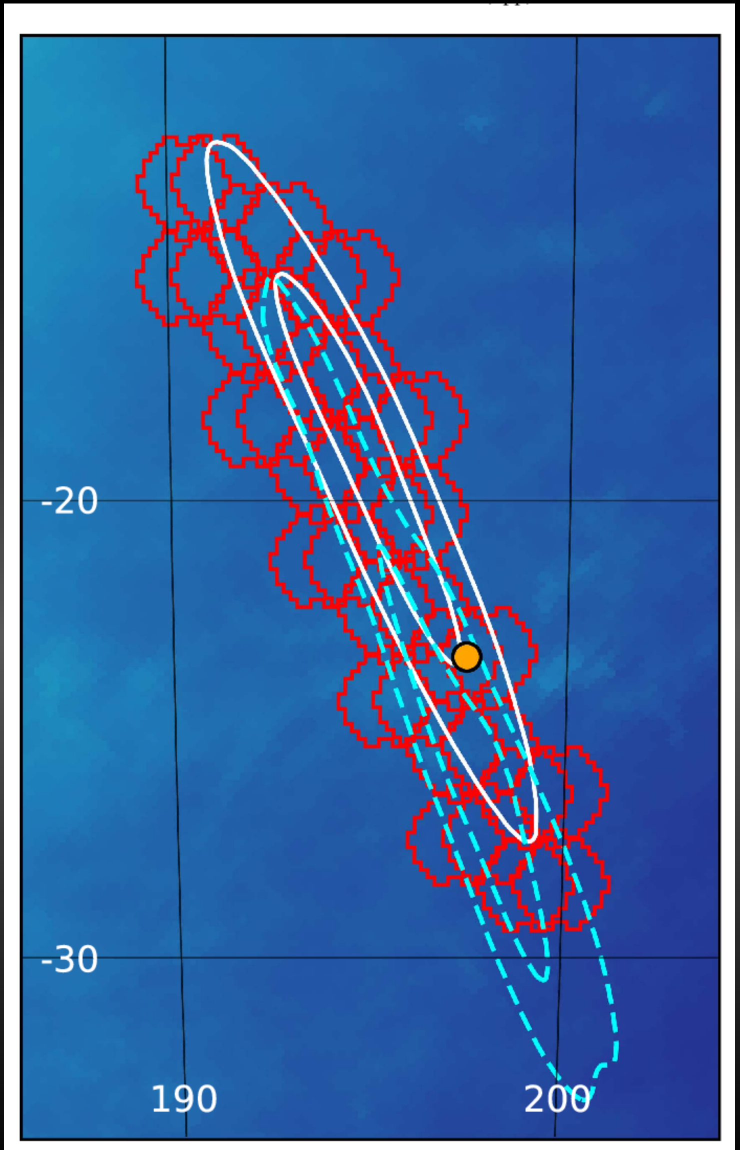



Figure 2. Location of the optical counterpart of GW170817 on the probability

# Hunting kilonovae

**ACRONYM:**

**Observation list**

ID num. Exp (min)

**Notes:**

Camera field of view: $1^\circ \times 1^\circ$

Depth: $m_{\rm lim} \approx 19.0 + 1.25\log_{10}(t_{\rm exp}/{\rm min})$

Distance modulus: $\mu = 25 + 5\log_{10}(d/{\rm Mpc})$

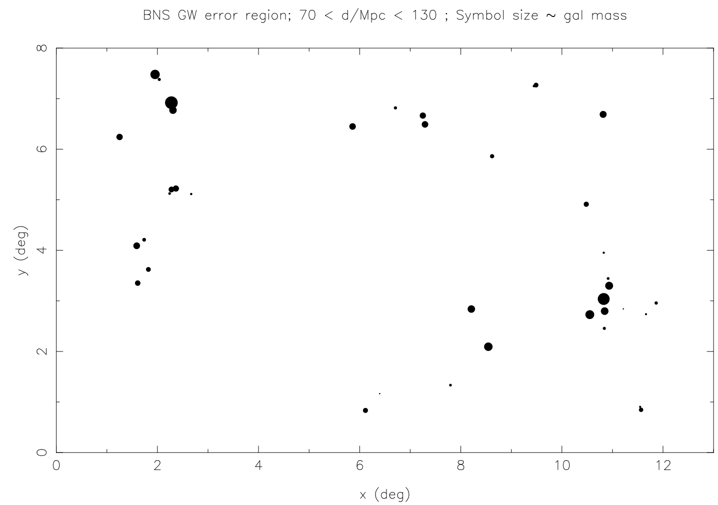
Apparent mag.: $m = M + \mu$

Peak abs. mag. of GW170817: $M = -16.0$

Overhead 2 min per exposure.

Total observing time: 100 min

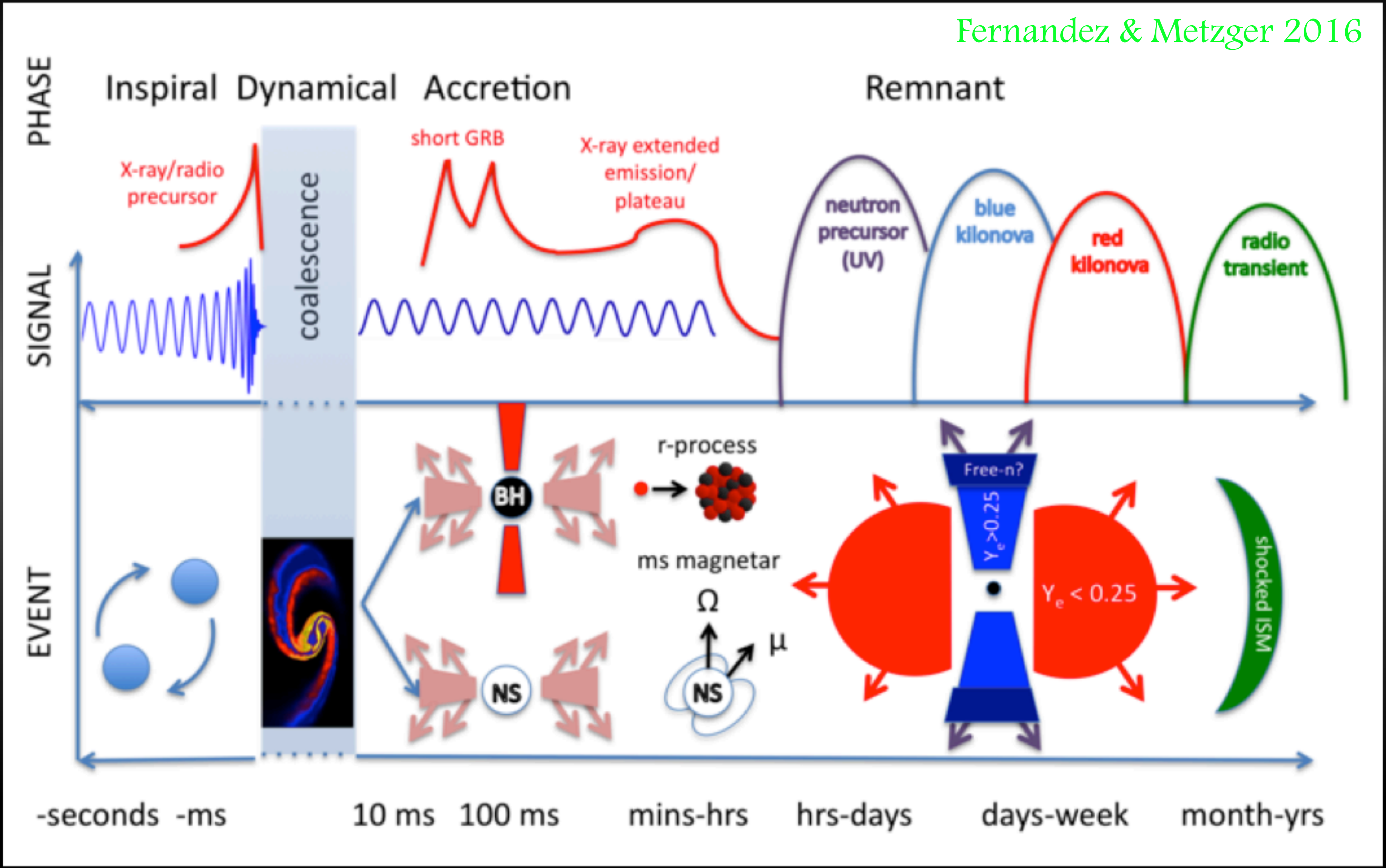
Minimum exposure time: 1 min



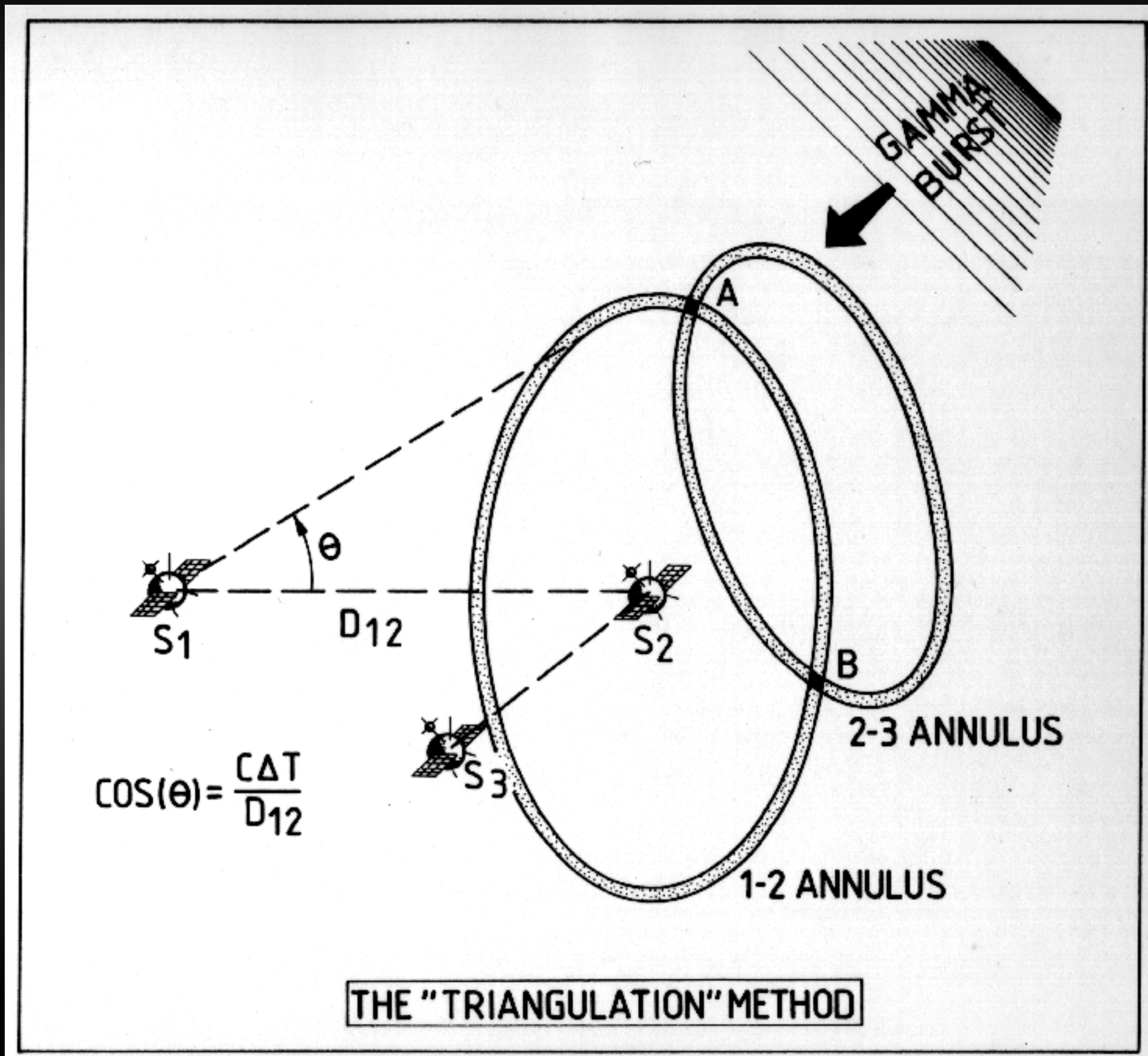

**Instructions:** Draw your target fields on the chart (using squared paper from note pad). Label each field with an ID number, and list it above.

# Compact binary mergers

Potentially rich variety of astrophysical phenomena!



# Localising with gamma-rays




Interplanetary network (IPN) relies on triangulation timing, similar to GW.

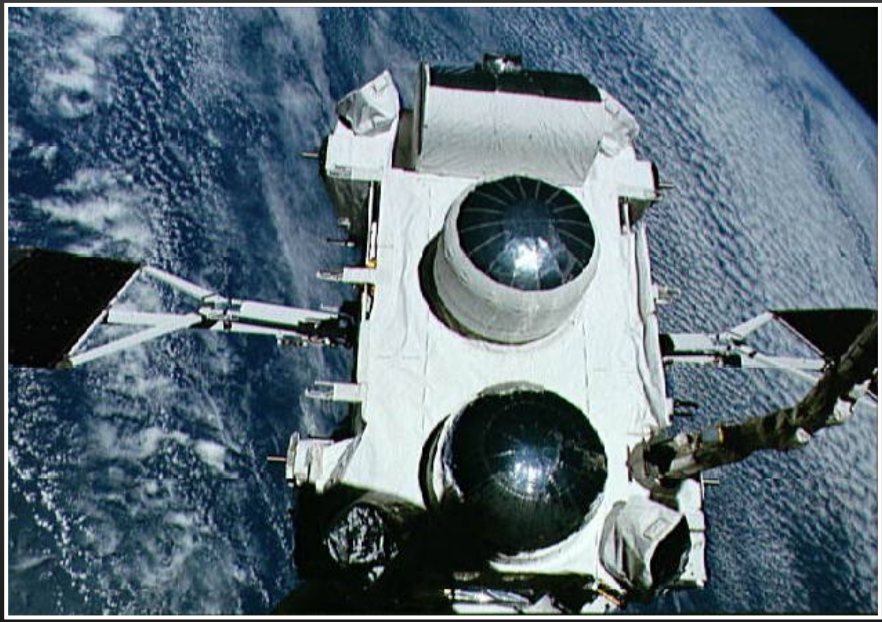
Two nodes produce annulus (large area on sky), but more nodes can give reasonably precise localisations (~100 sq. arcmin).

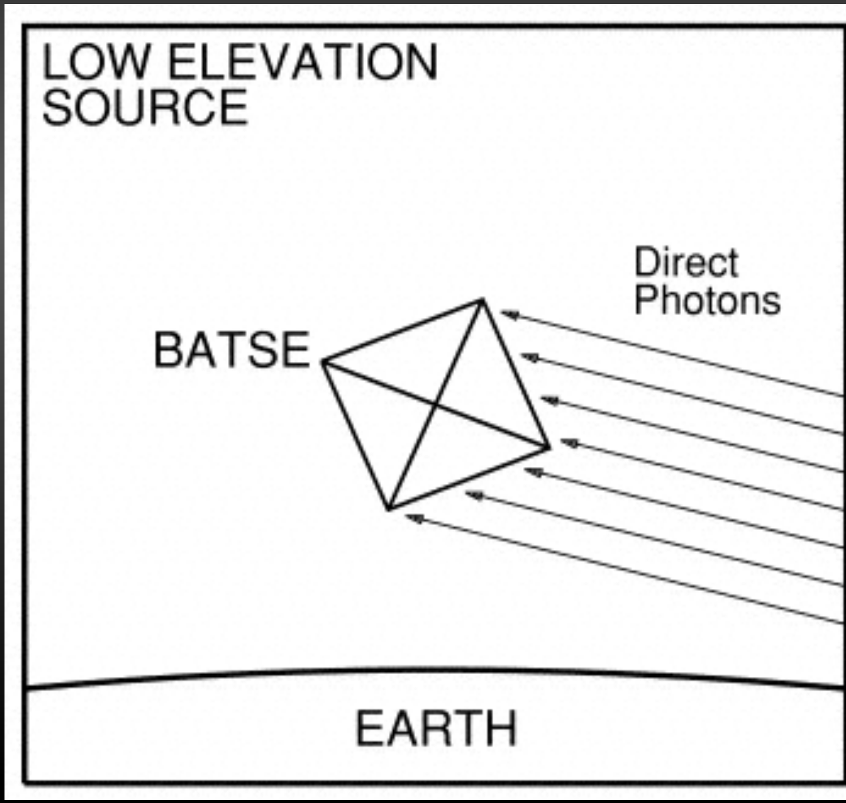
Tends to be slow (~24hr) to report positions.

Field of view ~4$\pi$ SR

# Localising with gamma-rays

Instruments like CGRO/BATSE and Fermi/GBM rely on multiple detectors facing different directions. Differing fluxes detected can be inverted to give direction of source (errors typically many degrees). Field of view ~$2\pi$ SR.

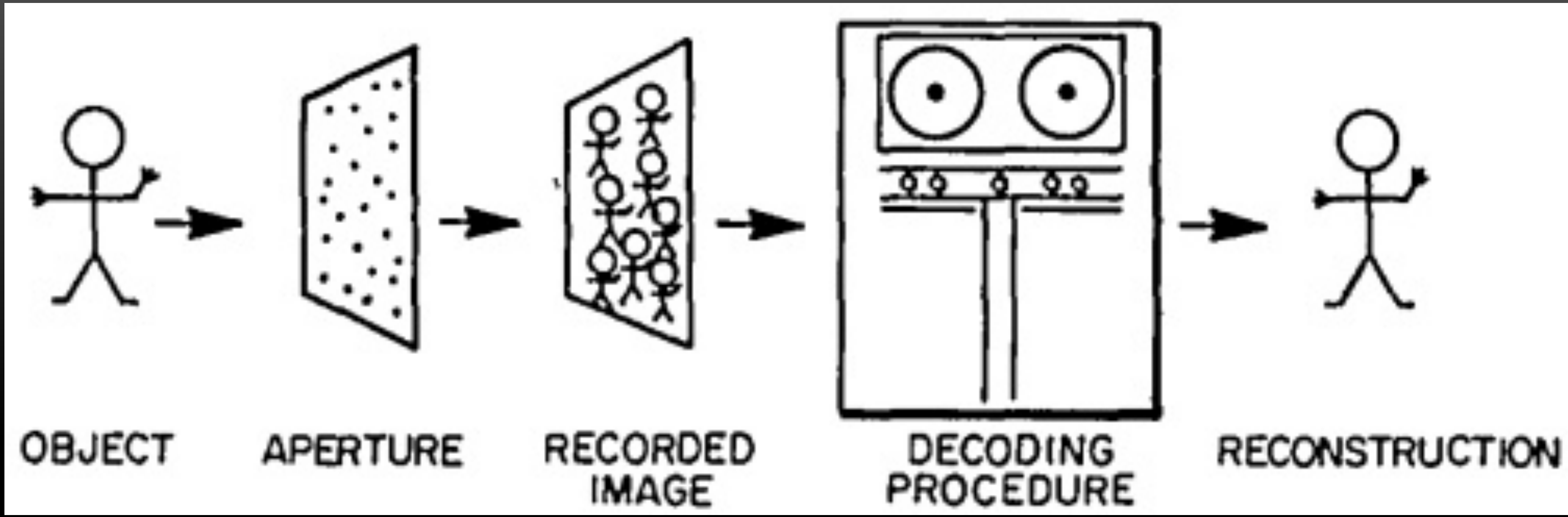




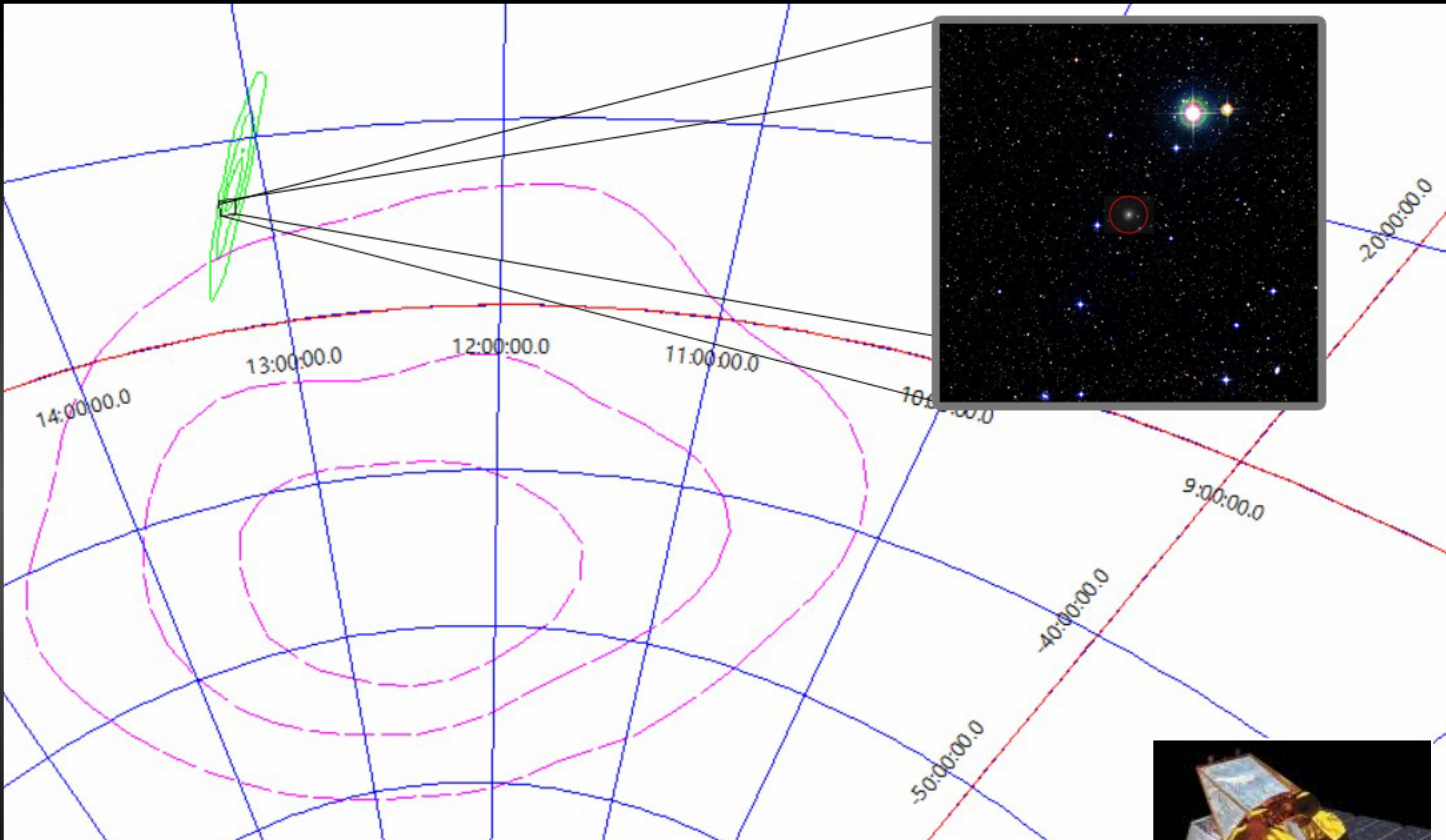
# Localising with gamma-rays

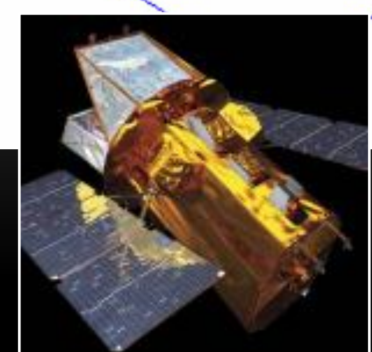
Coded mask detectors rely on inverting "shadow pattern" to obtain image of sky.

Swift/BAT has highly complex mask, and gives positions to few arcmin, but field of view "only" ~2 SR

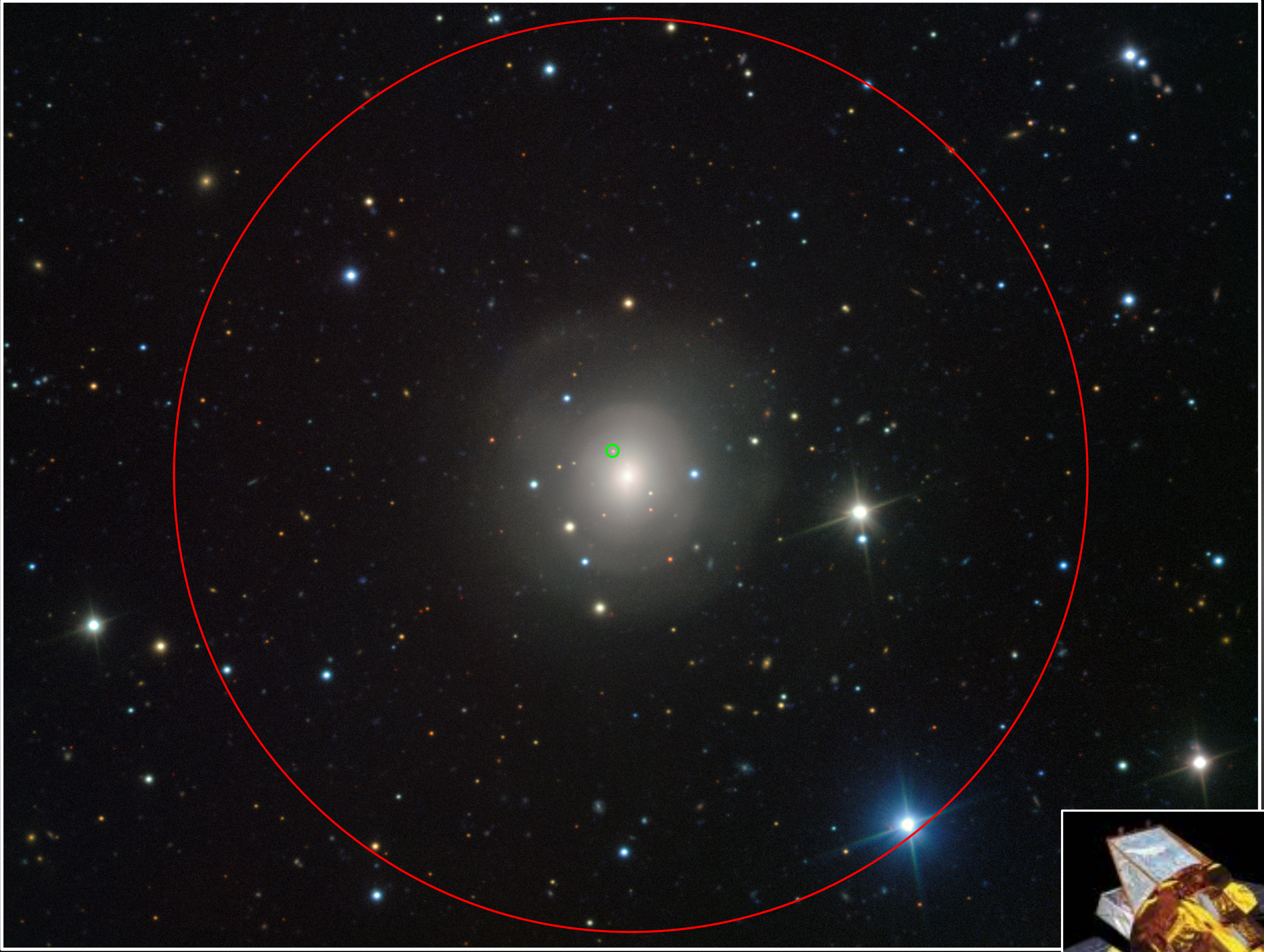


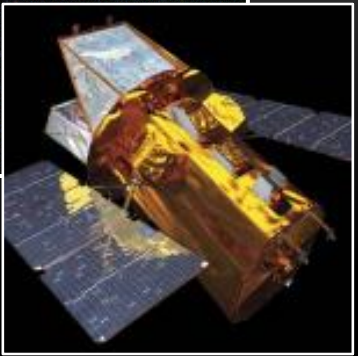
Mandhai et al. 2018



# If *Swift* had been looking…

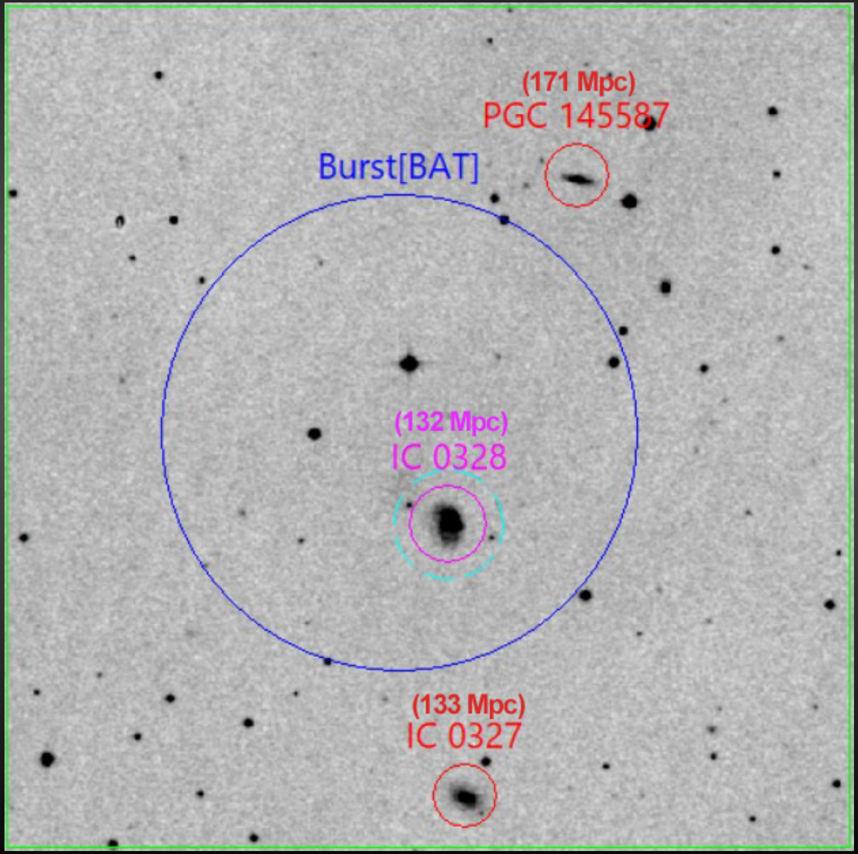




If *Swift* had been looking…

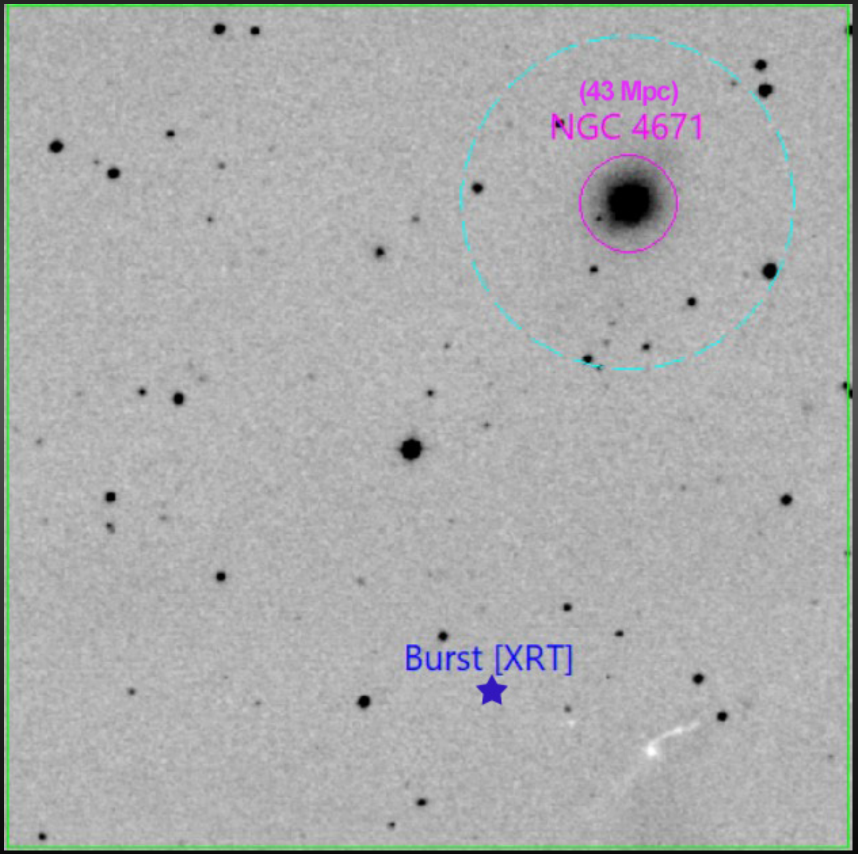
# Such a nearby SGRB not localised before

Out of ~120 short-GRBs from Swift, none consistent with such a low redshift host (unless large kicks).




GRB050906

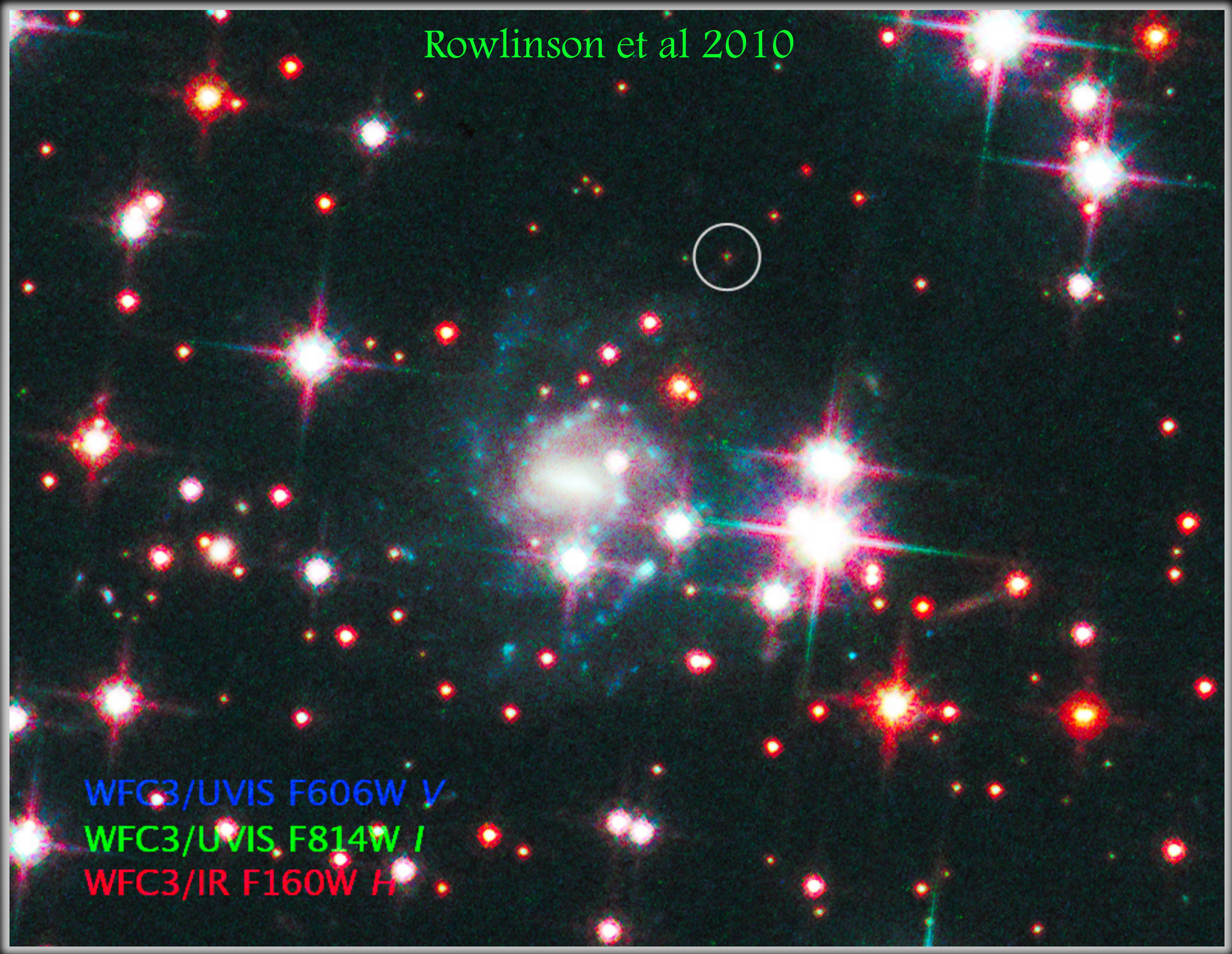
Levan et al. 2007




GRB111210A

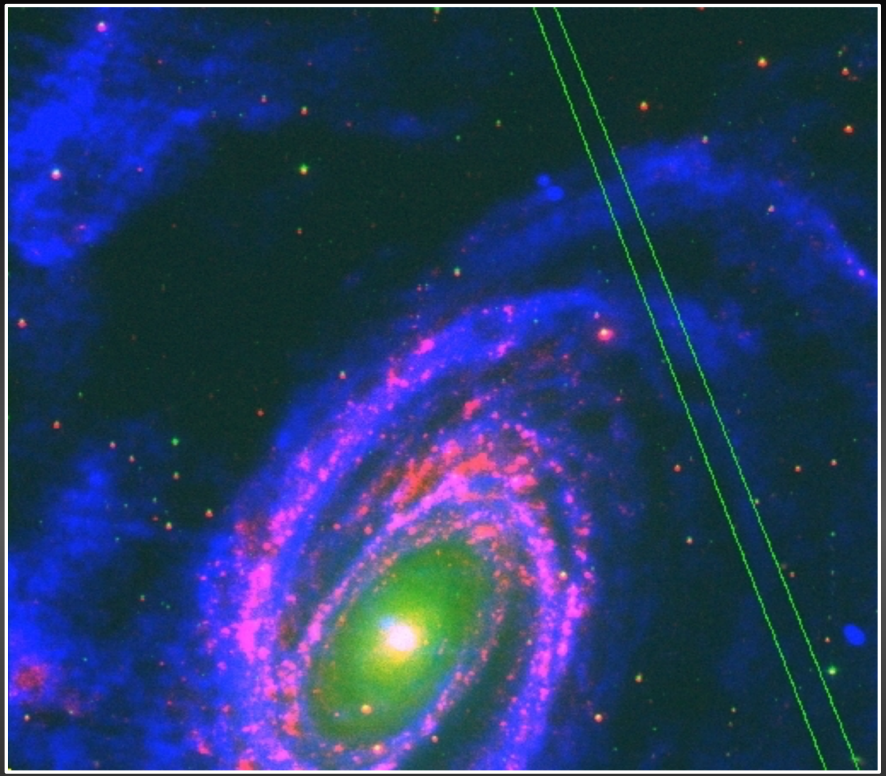
Mandhai et al. 2018

# Such a nearby SGRB not localised before



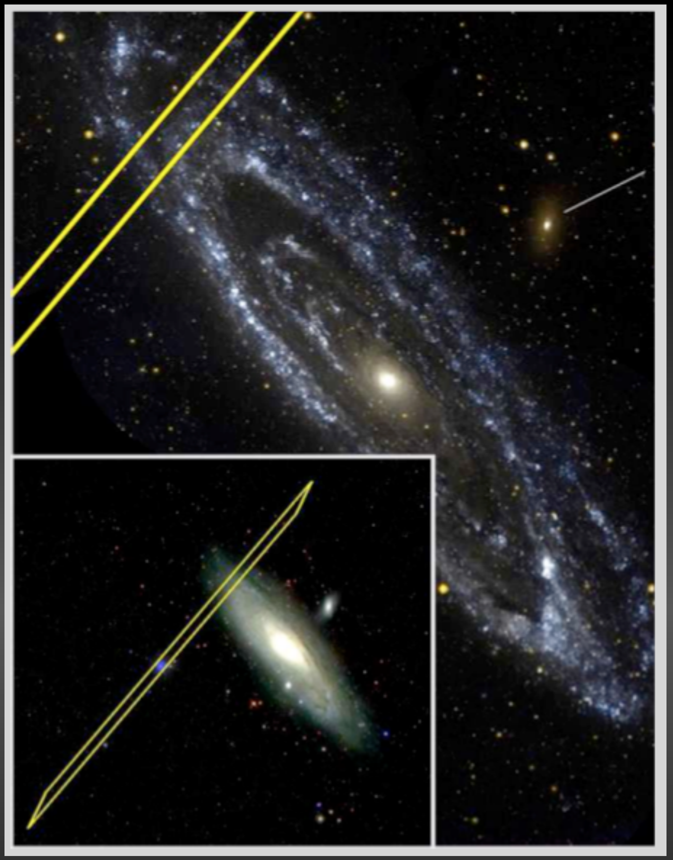

In fact, nearest SGRB discovered by Swift with definite distance is S-GRB 080905A at ~500 Mpc.

# Such a nearby SGRB not localised before



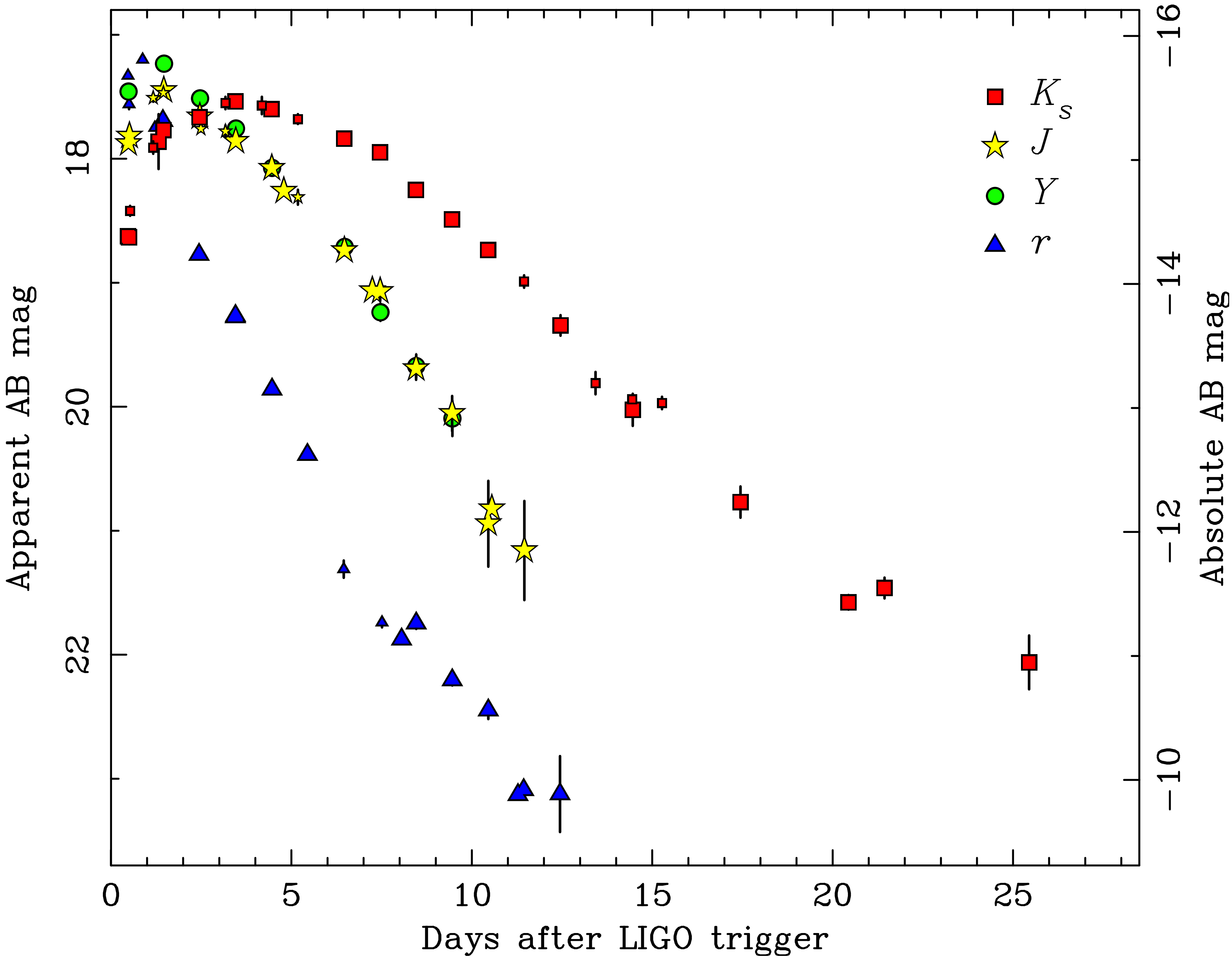
Potentially in M81 (e.g. Hurley et al. 2010), but lack of GW signal rules out BNS binary merger (Abadie et al. 2012).

**GRB051103**



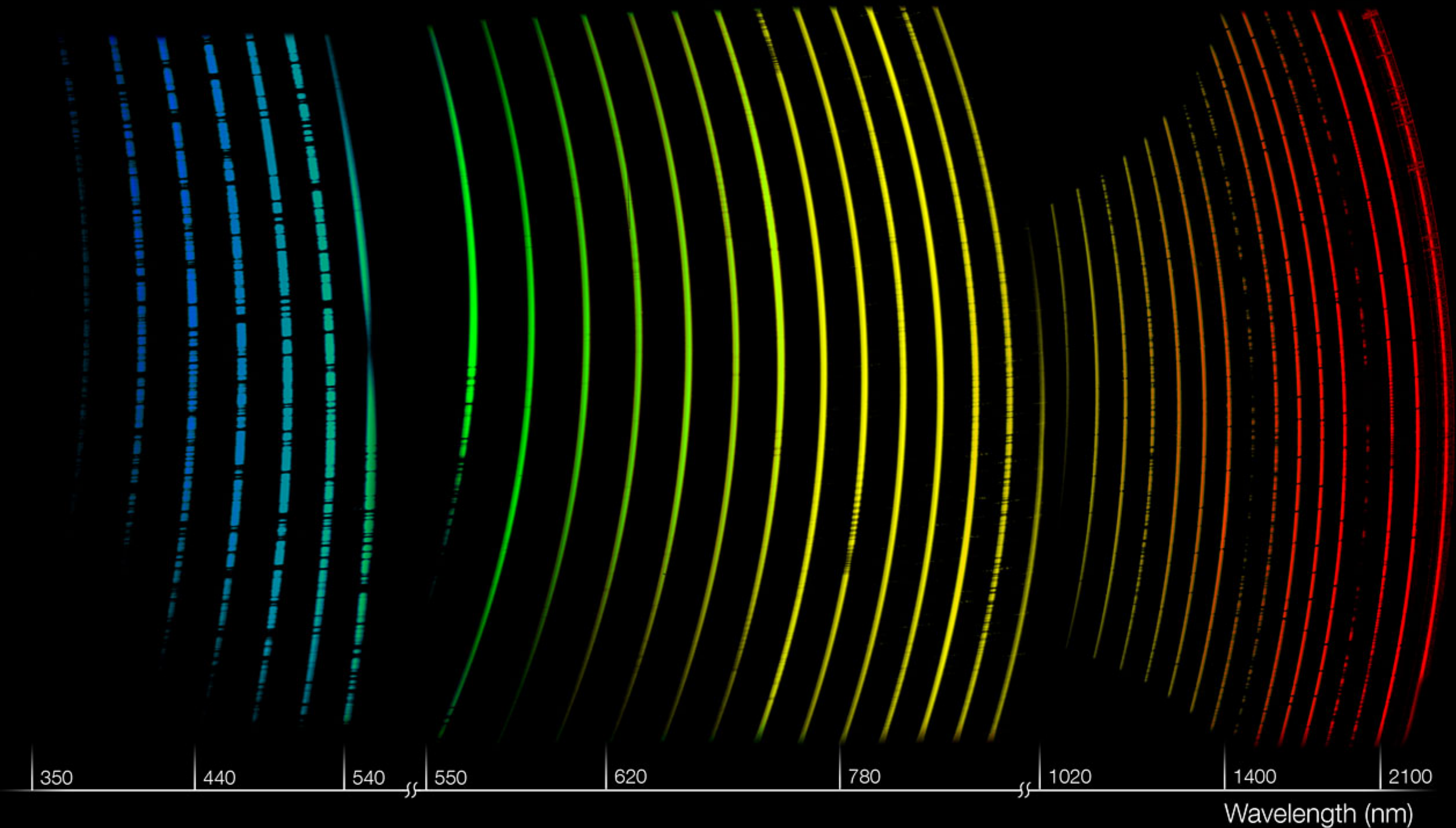
Potentially in M31 (e.g. Hurley et al. 2007) - similarly, lack of GW signal rules out binary merger (Abbott et al. 2008).

**GRB070201**



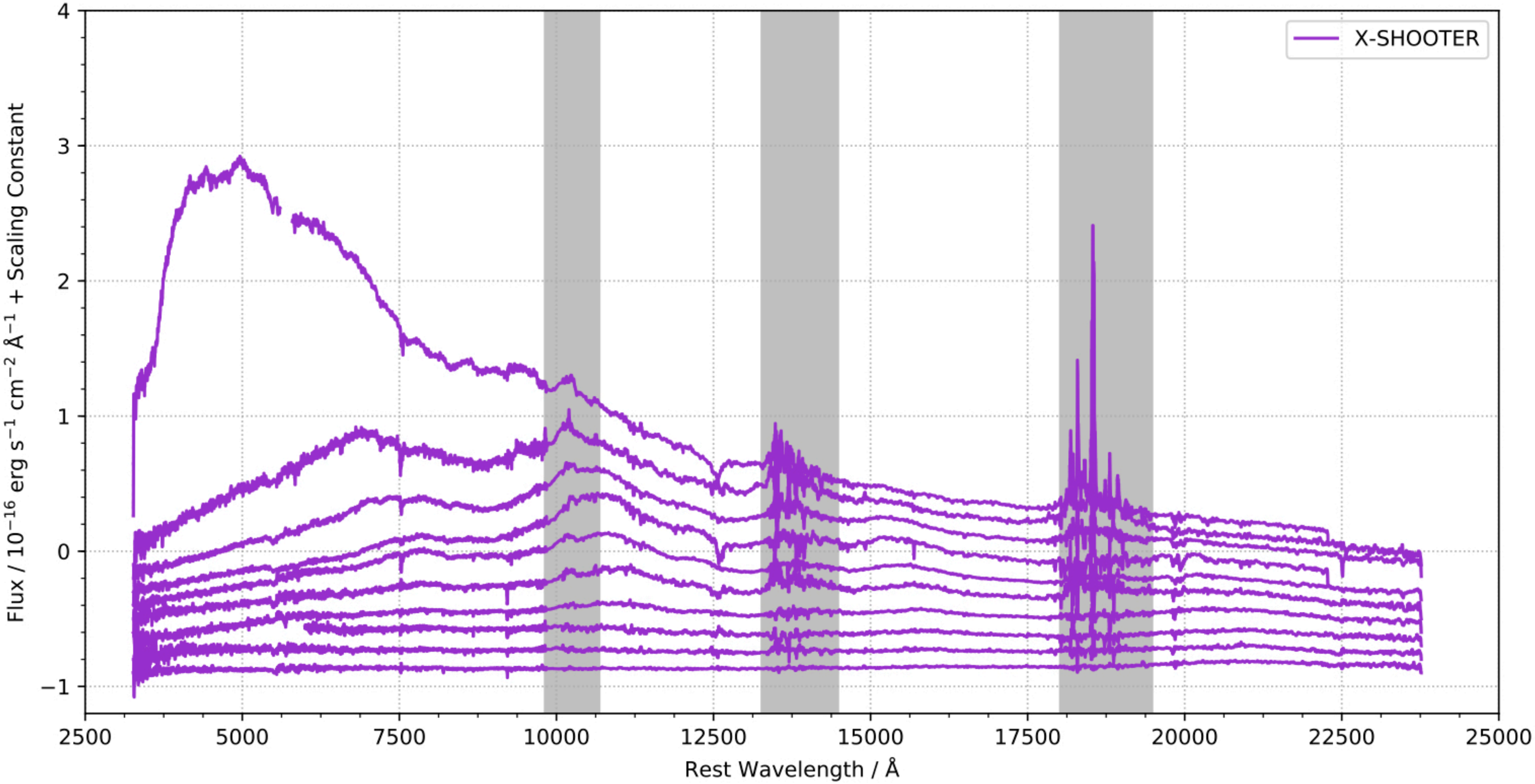
Apparent AB mag
18
20
22
Absolute AB mag
−16
−14
−12
−10
0
5
10
15
20
25
Days after LIGO trigger
$K_s$
$J$
$Y$
$r$

# VLT X-shooter spectroscopy



# VLT X-shooter spectroscopy

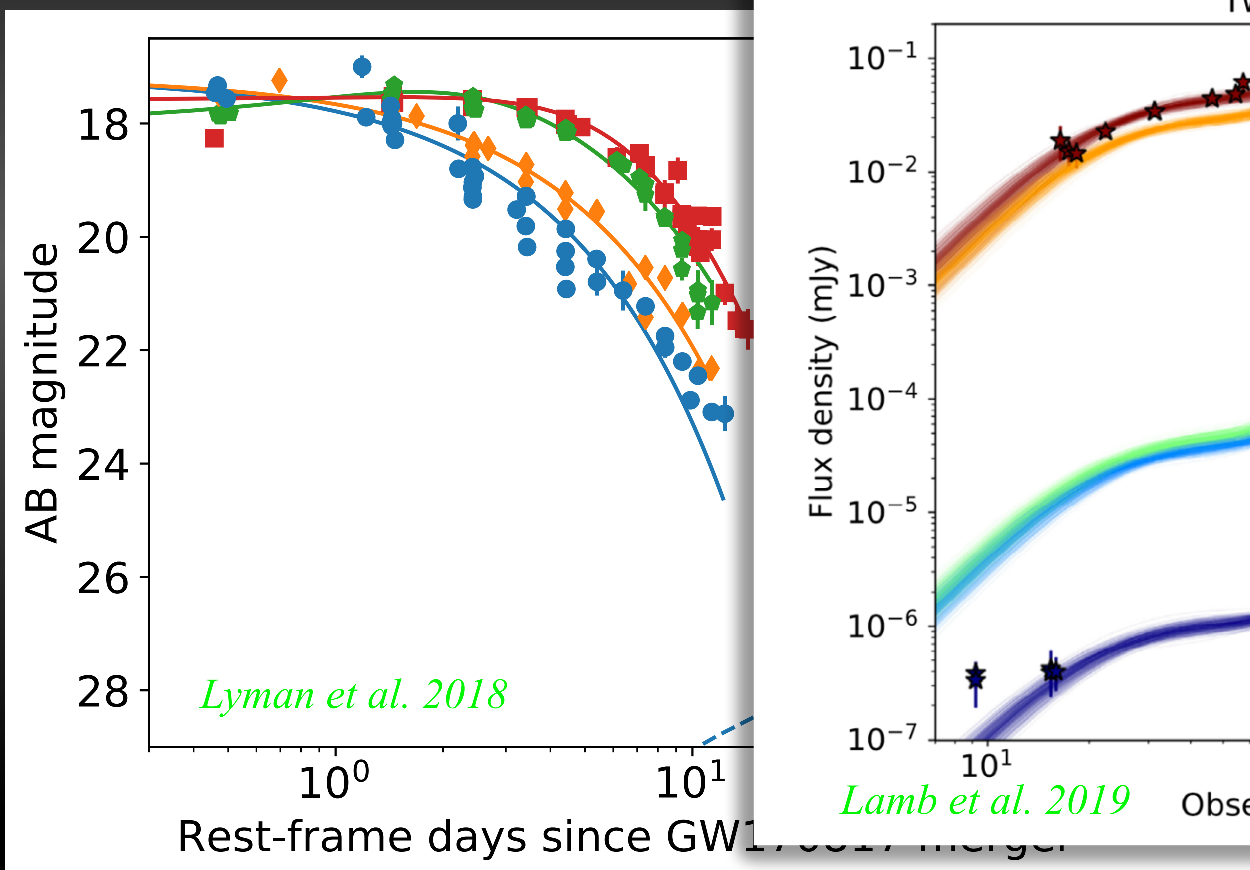
Broad features – high velocities and many lines.

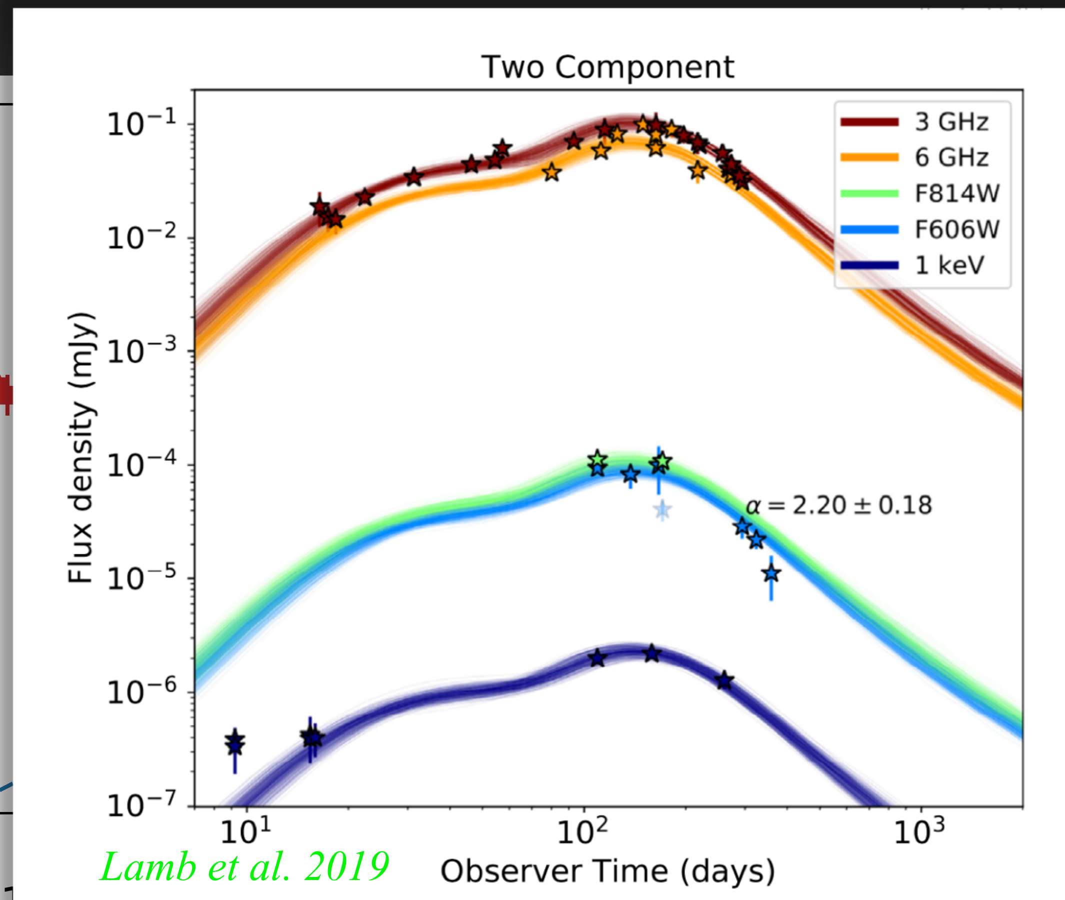



*James Gillanders (Pian et al. 2017, Smartt et al. 2017)*

# Ongoing behaviour

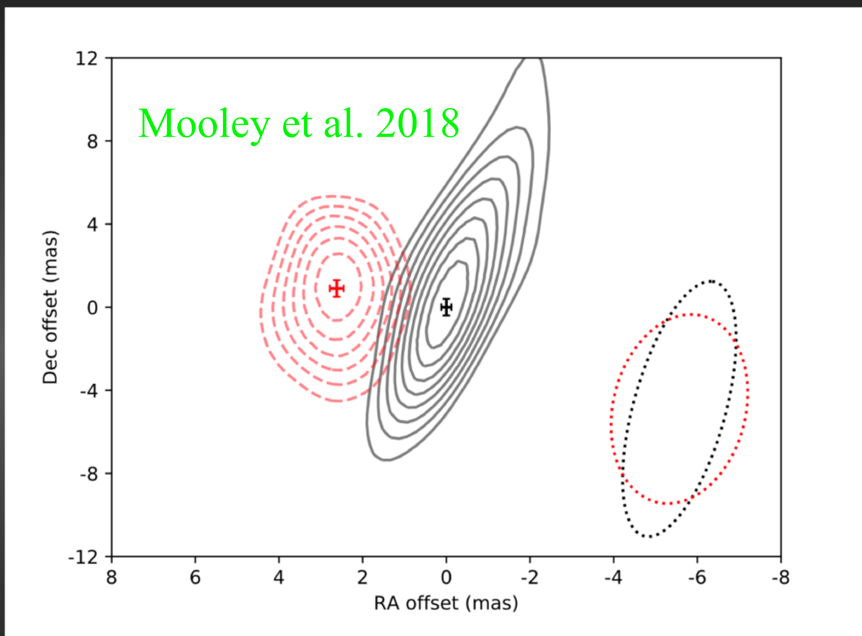
Late-time observations show still visible in optical, radio and X-ray. Explained as afterglow emission from off-axis structured jet.e.g. Troja et al. 2017, Lyman et al. 2018, Margutti et al. 2018, Lazzati et al. 2018, Lamb et al. 2019…

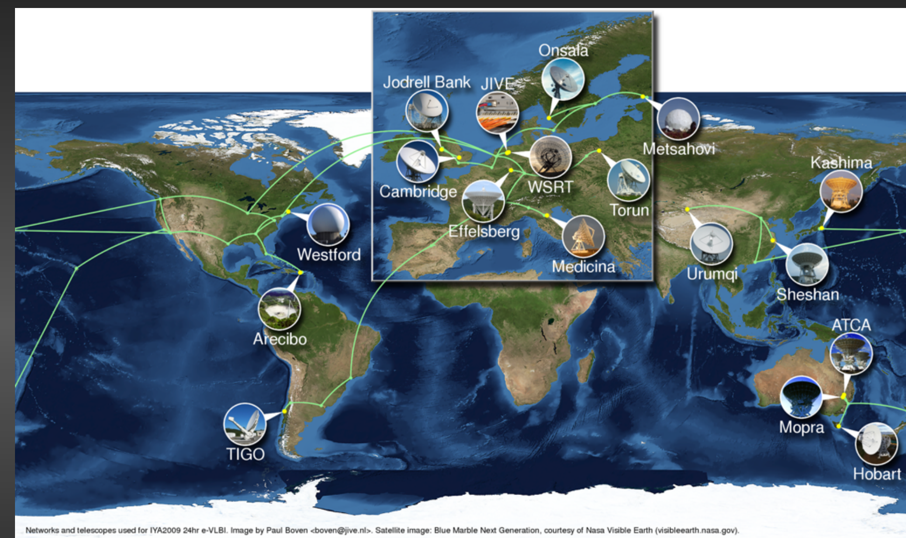


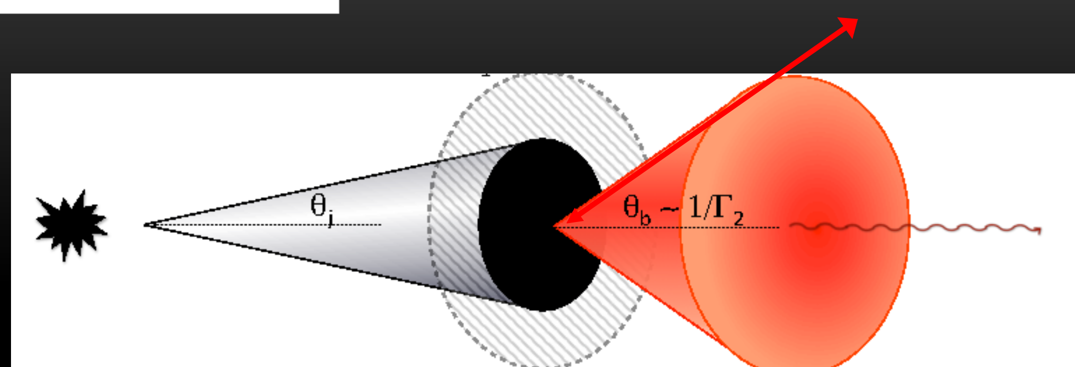
# Ongoing behaviour

(Apparent superluminal) proper motion of radio source from VLBI observations, also consistent with off-axis emission from the head of a jet.

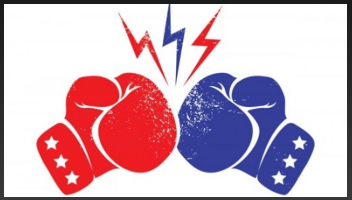



Line of sight 20-25 deg from jet axis. Initial jet opening (half) angle ~2-3 deg.

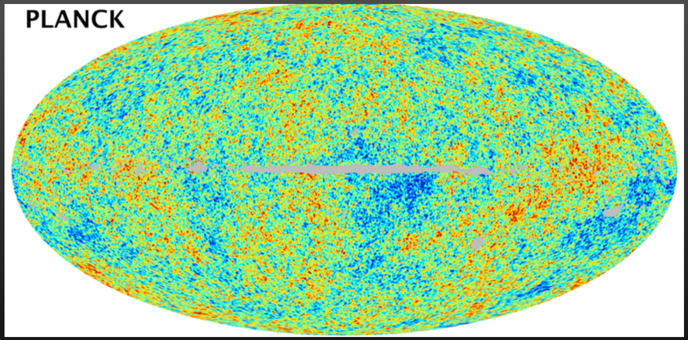


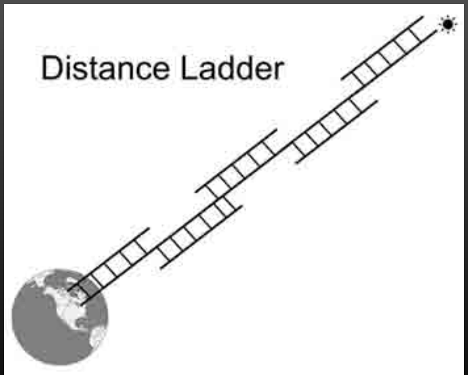
# Hubble constant



Planck Collaboration 2016

Riess+2016 (SHOES)

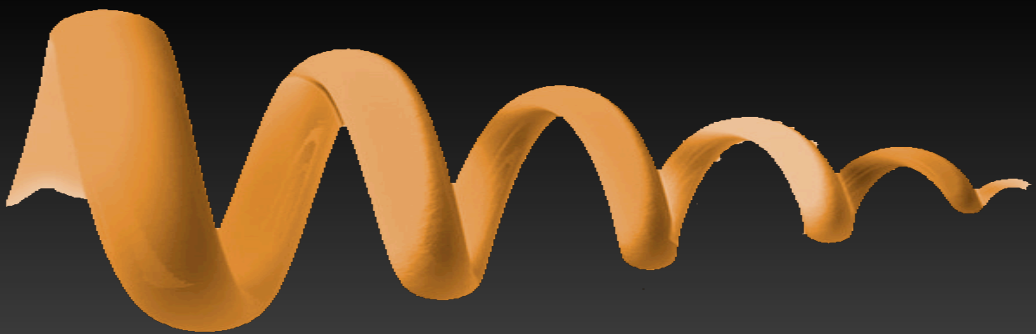



67.8 ± 0.9 km/s/Mpc

73.2 ± 1.8 km/s/Mpc

# Standard sirens



Schutz 1986

$d = 43.8^{+3}_{-7}$ Mpc  Abbott et al. 2017

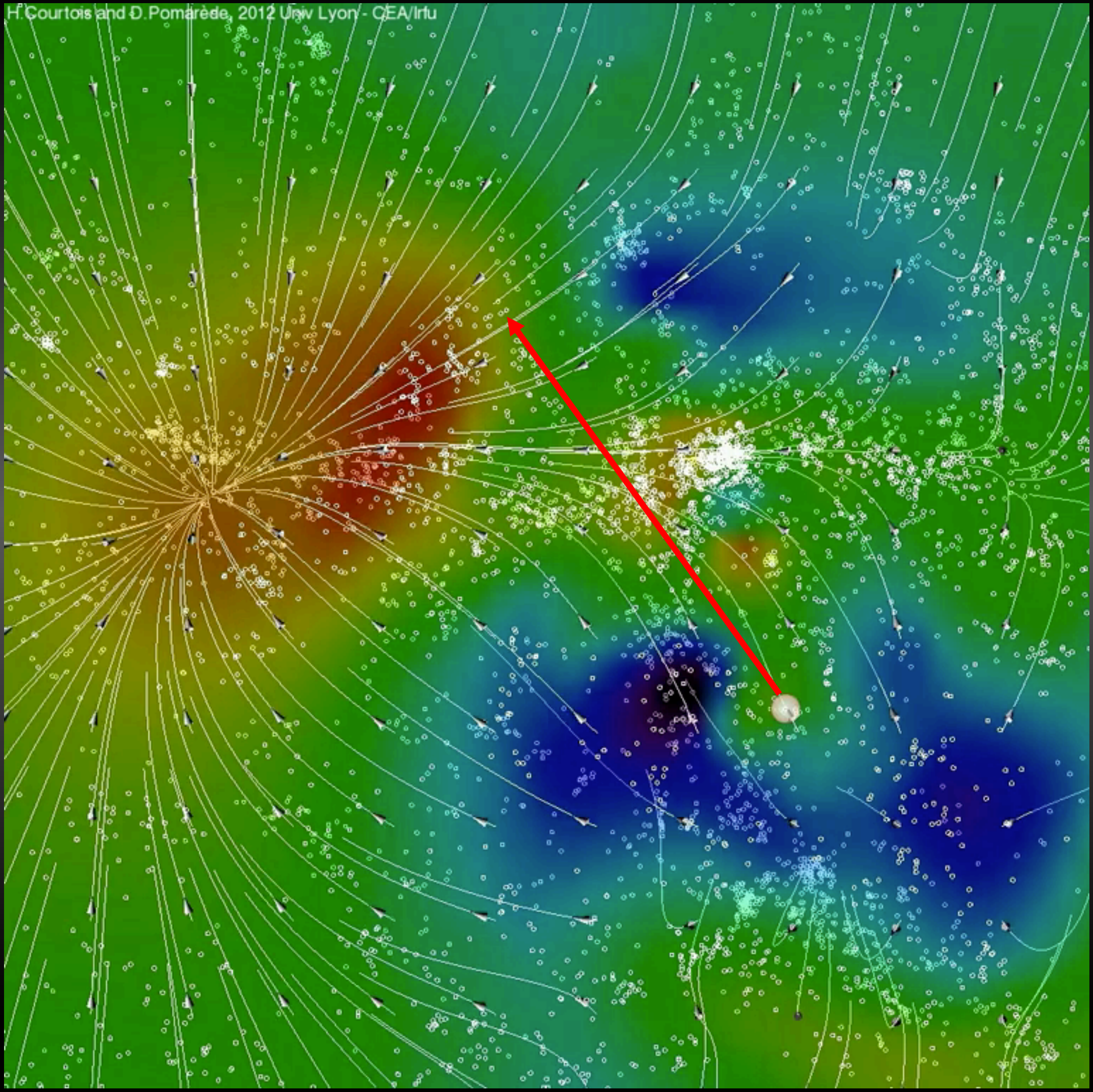
$d = 44 \pm 8$ Mpc (FP)  Hjorth et al. 2017

$d = 38 \pm 9$ Mpc (FP)  Im et al. 2017

$d = 40.7 \pm 1.4 \pm 1.9$ Mpc (SBF)  Cantiello et al. 2018

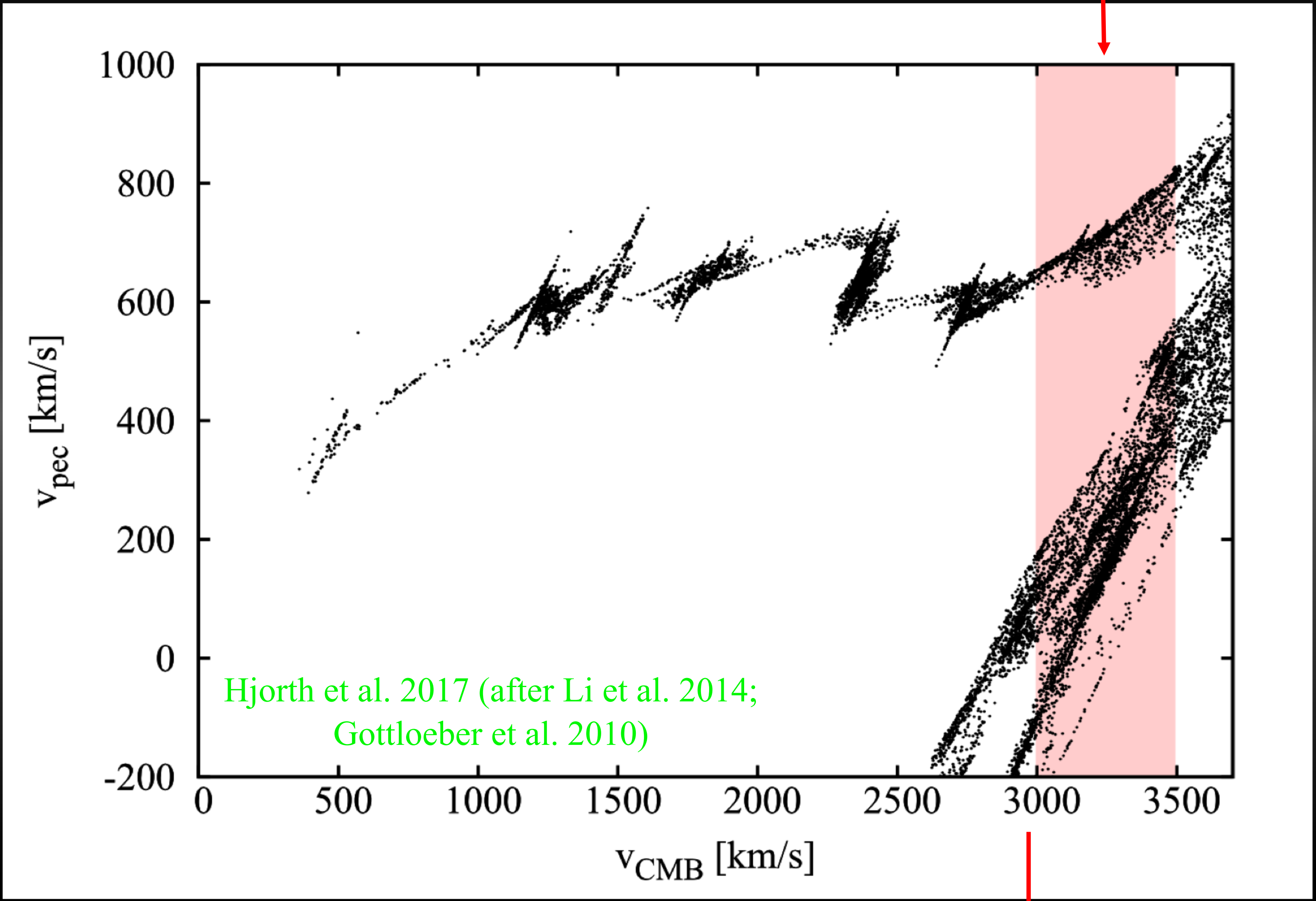
$d = 41.7 \pm 3$ Mpc (GCLF)  Lee et al. 2018

# Recession velocity



# Recession velocity

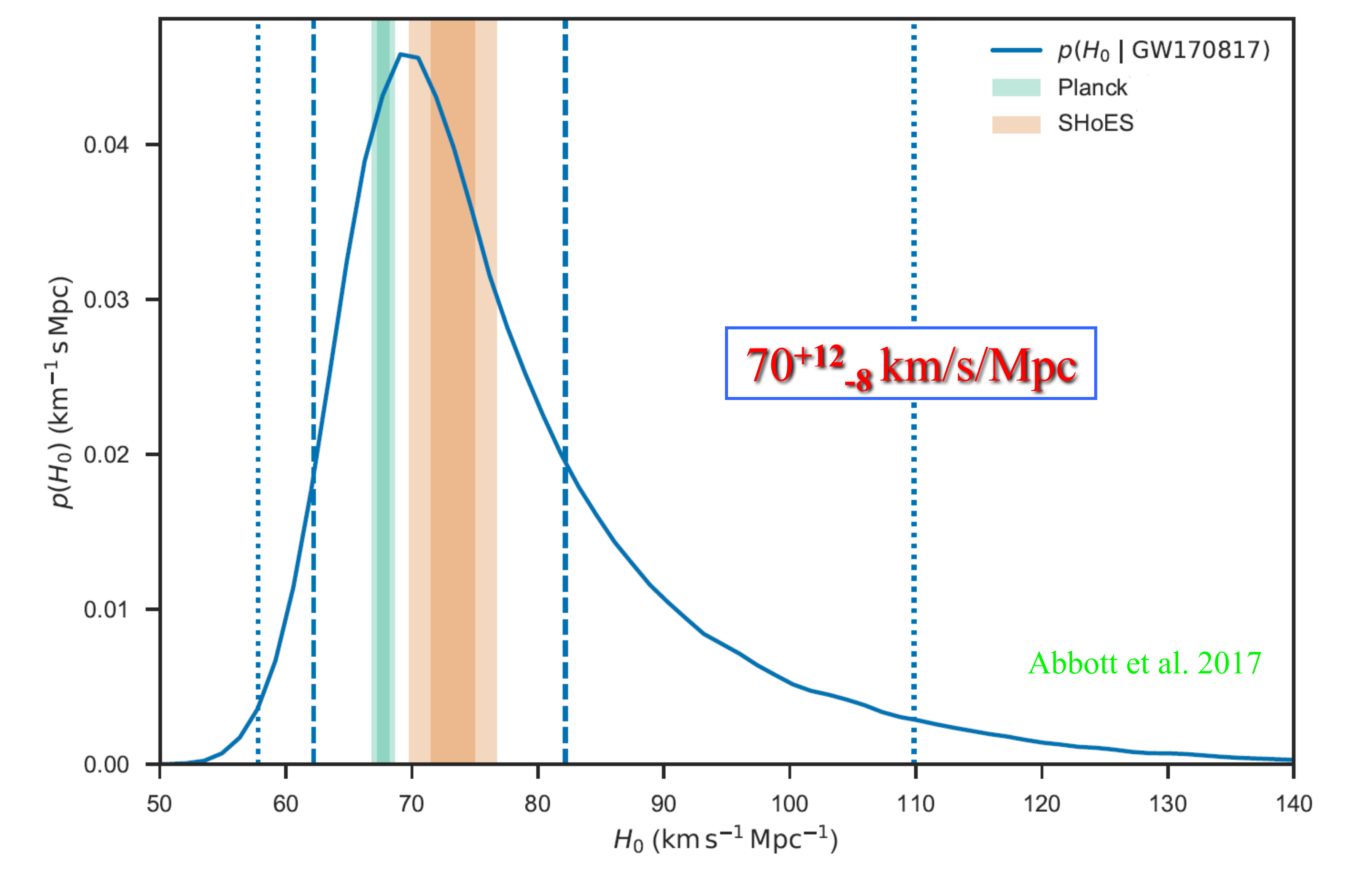
$v_{CMB} = 3231 \pm 53$ km s$^{-1}$



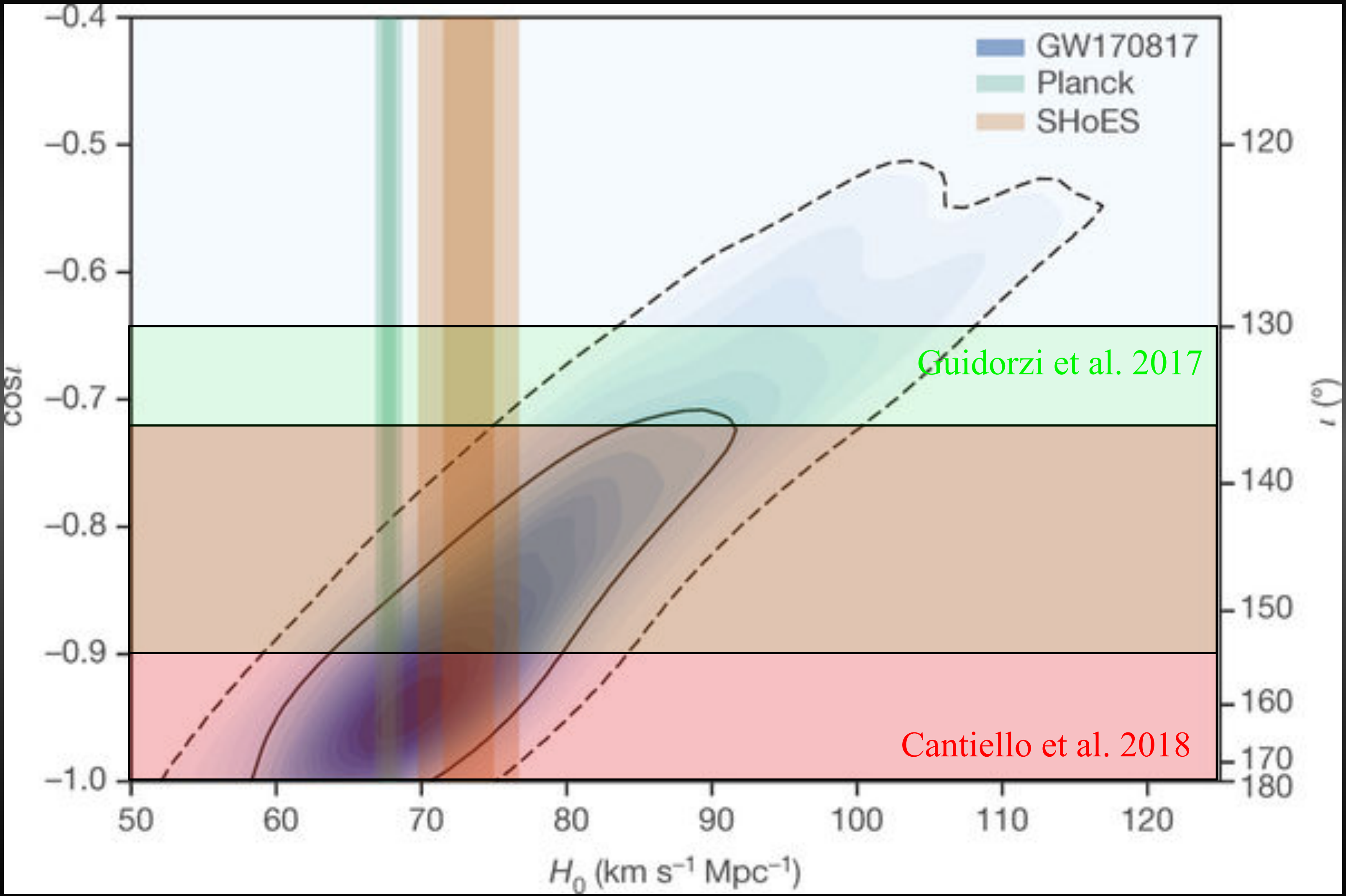

$v_{COSMIC} = 2924 \pm 236$ km s$^{-1}$

# Hubble constant

Adopt $v_{COSMIC} = 3017 \pm 166$ km s$^{-1}$



# Degeneracy with inclination

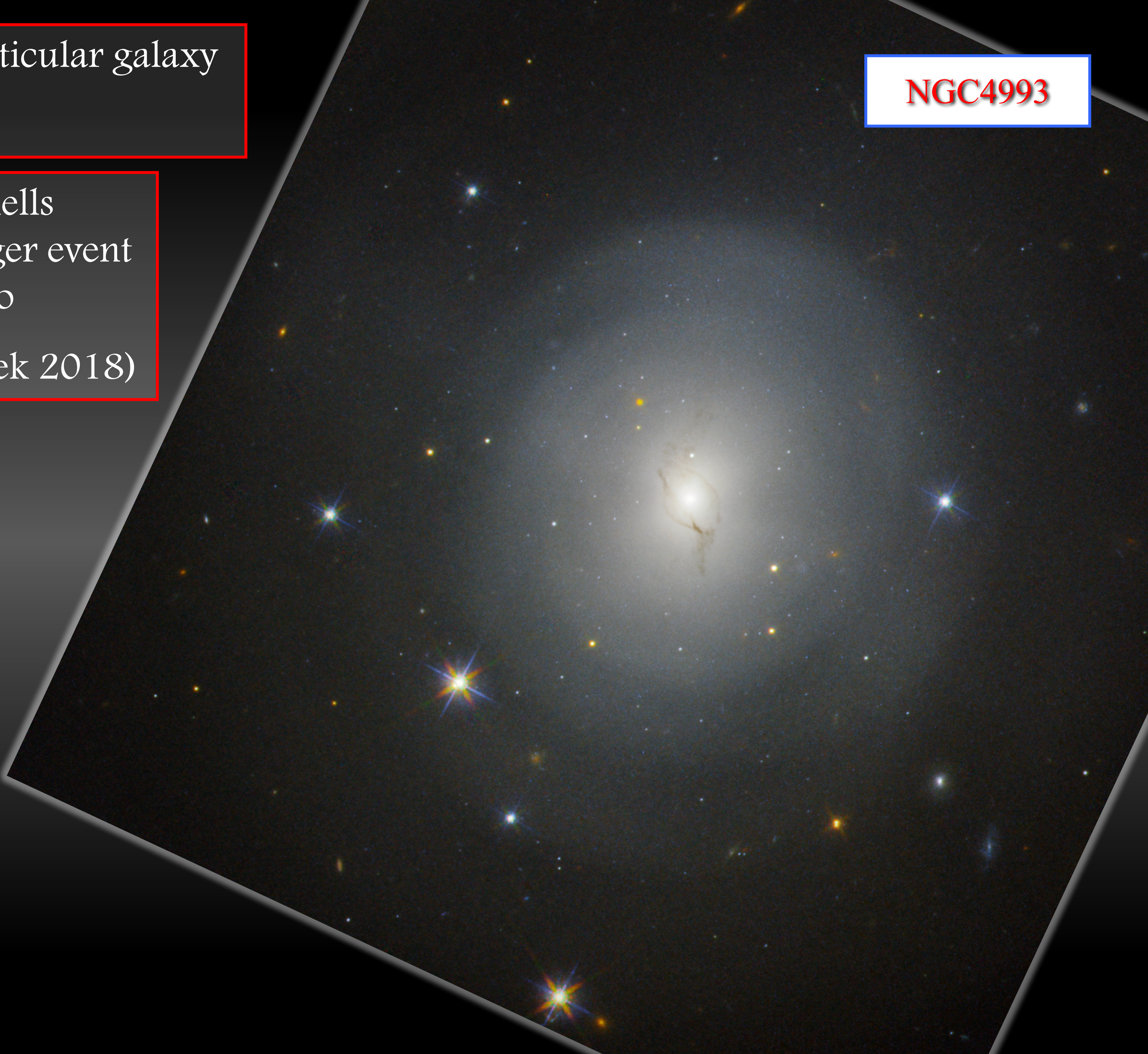


Disturbed lenticular galaxy

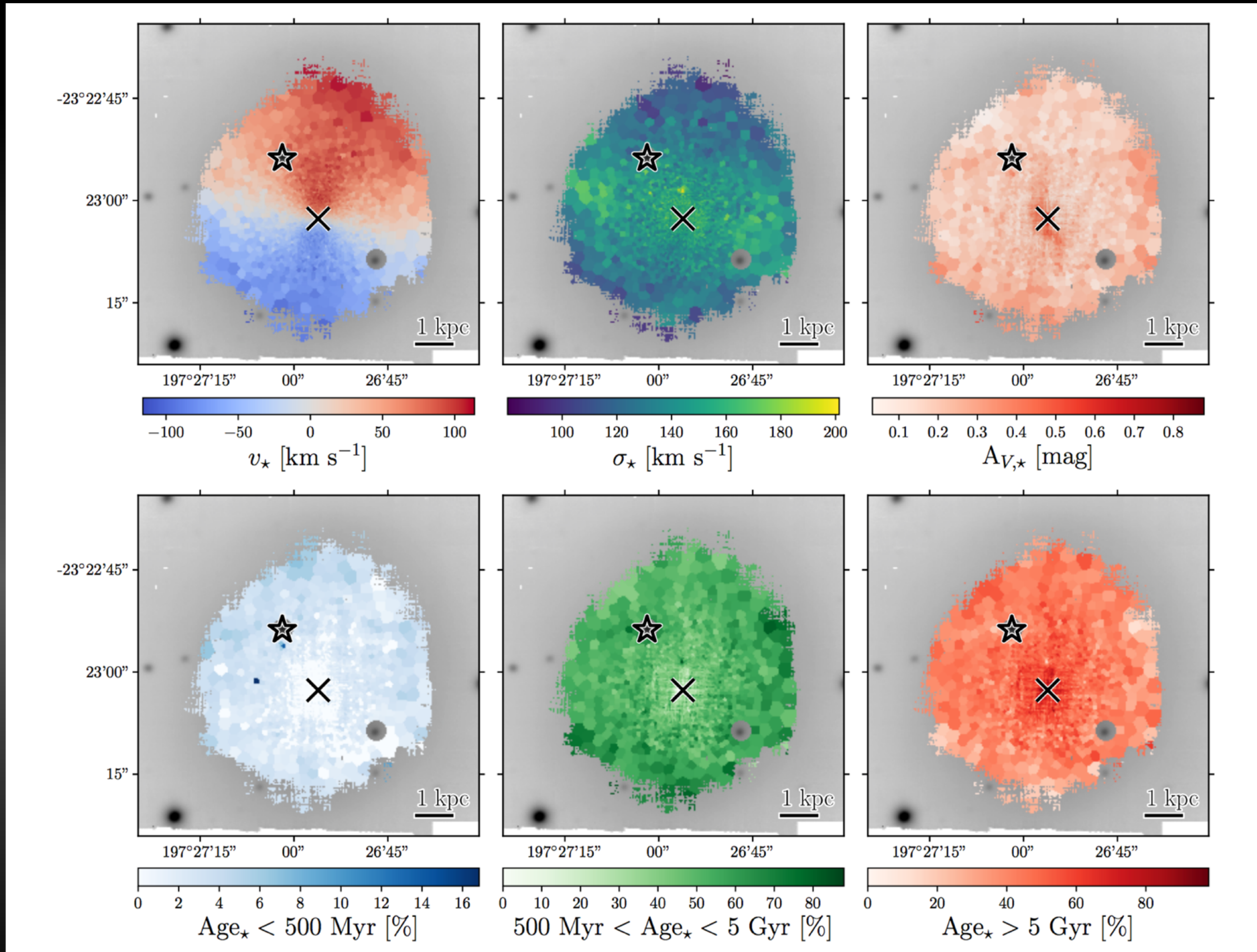
D~40 Mpc

Analysis of shells suggests merger event ~400 Myr ago

(Ebrova & Bilek 2018)



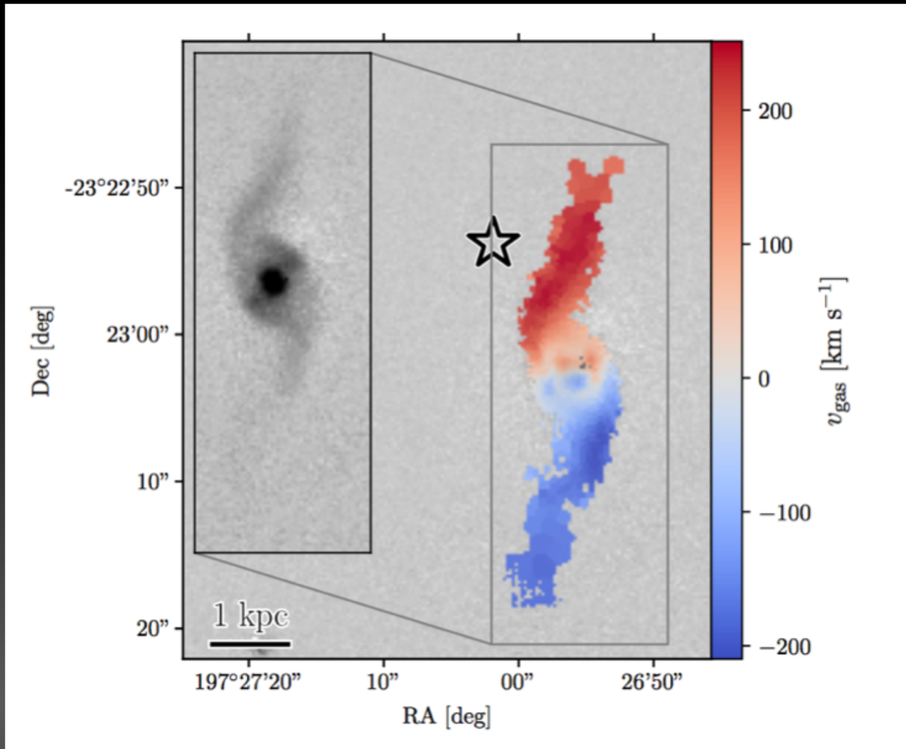

HST



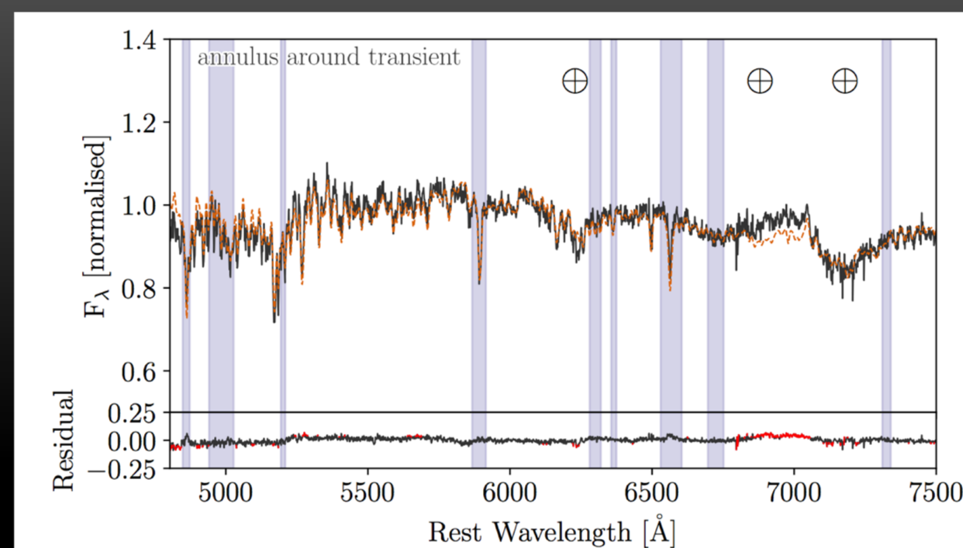

Levan et al. 2017

**VLT/MUSE**

Predominantly old, with some young and intermediate population.




Ionized gas traces a more edge-on and rapidly rotating disk, presumably debris of the merger.




Location of transient – largely old population, with no sign for globular cluster or star formation.

Now

2020

2025

2030

Engrave

New large (~250) consortium– primarily using ESO facilities.


Vetting of candidates.

In-depth follow-up of confirmed counterparts.

Now

2020

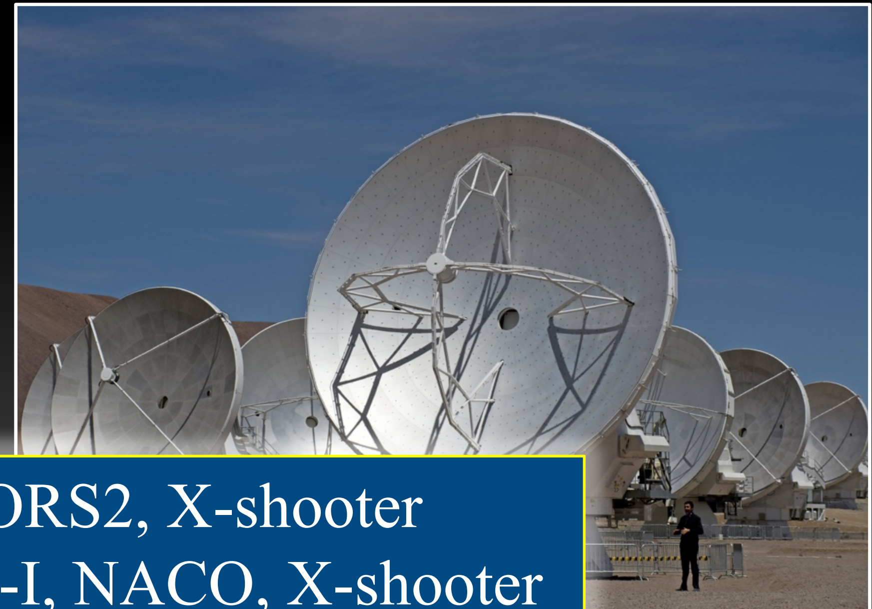
2025

2030

New large (~250)

c

u



Blue kilonova – FORS2, X-shooter
Red kilonova – HAWK-I, NACO, X-shooter
GRB afterglow – FORS, X-shooter
Kilonova polarimetry – FORS

Counterpart discovery: VST, VISTA
(collaborations with ENGRAVE)
Also: ATLAS, BlackGEM, GOTO, PS1, ZTF

f
es.

follow-up
med
arts.

# GOTO

Now

2020

2025

2030

D=40cm f/2.5

Each telescope = 2.85 x 2.114 degrees ,
1.25”/pixel (50 Mpixel CCD)
~ 5 sqr.deg per telescope (x4->16)

5-slot filterwheel (currently LRGBC,
limiting mag L~20.5, 5 sigma)

Now

2020

2025

2030

BLACKGEM

# BlackGEM Array

Dedicated, optical telescope array for GW events.
PI Paul Groot (RU)

- 10 – 15 telescopes with 65cm diameter mirrors
- Field of view per telescope: 2.7 square degrees
- Total field of view: 40 square degrees
- Spatial resolution: 0.57″ / pixel
- 
- Flexible: fish-eye, tied-array, full zoom
- Location: La Silla observatory of ESO
- Robotically, remote-controlled, triggered by Virgo/LIGO

*Dedicated to GW events!*

**Phase1 = 3 telescopes has now started *(NOVA, RU, KU Leuven)***

***www.blackgem.eu*** and **@BlackGEM_Array**

# The developing GW landscape

Now

2020 ← KAGRA?

← O4

← A+ ?

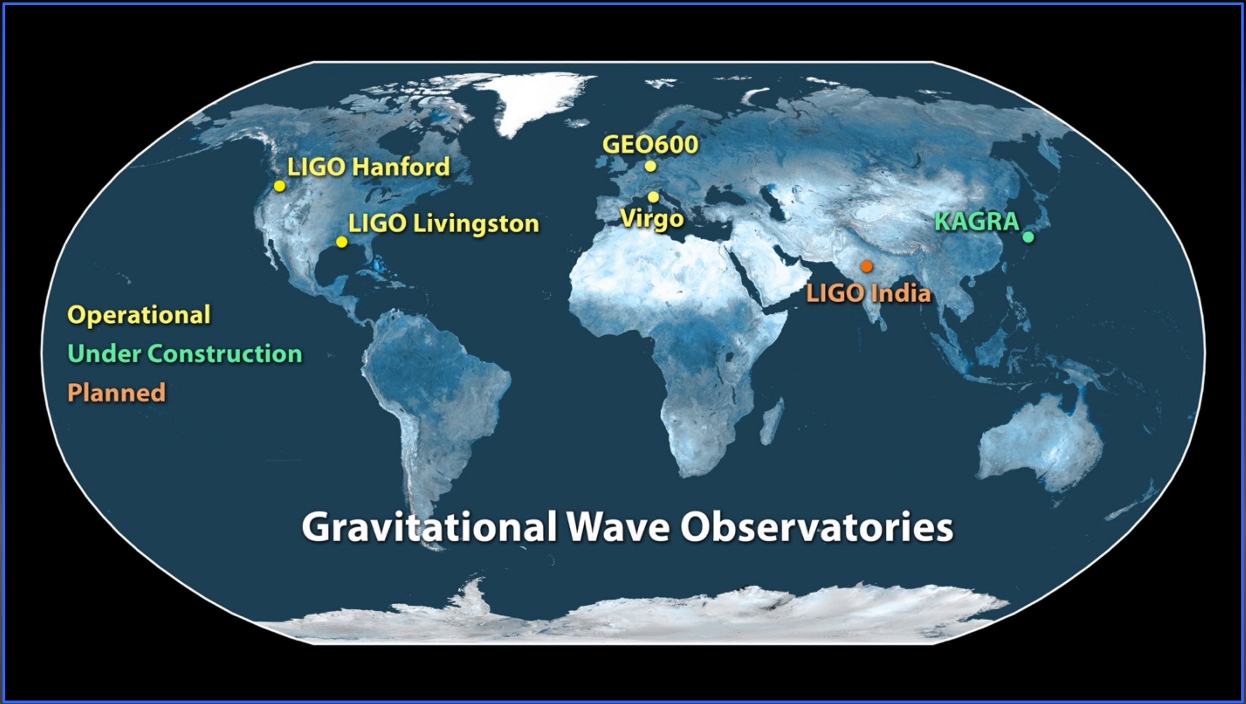
2025 ← InDIGO?

← Voyager?

2030

← LISA?

← ET/Cosmic Explorer?



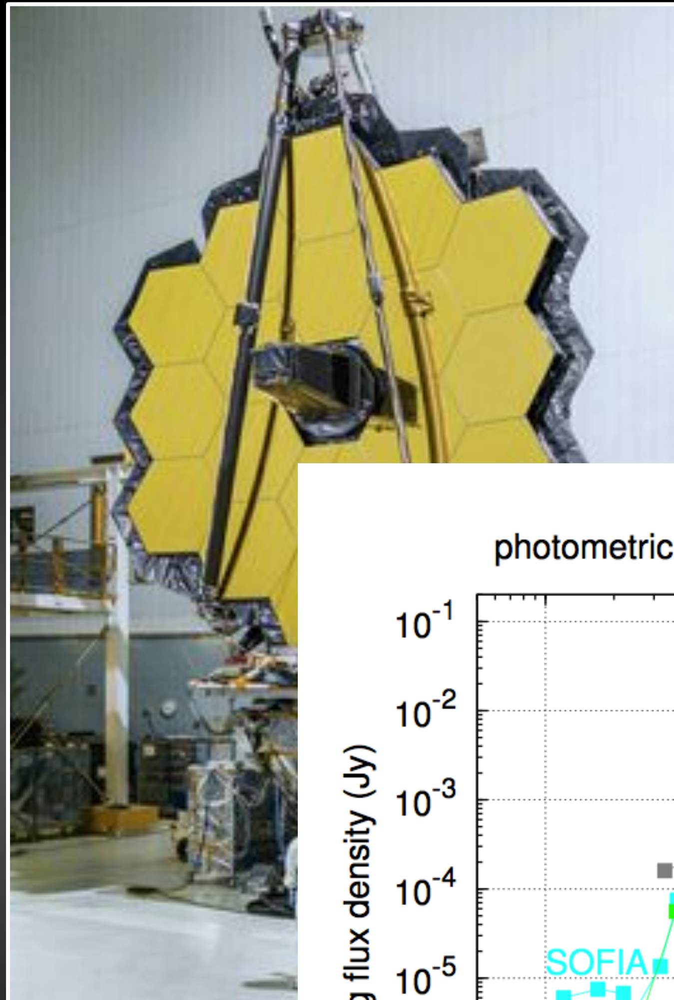
# JWST

Now

2020

2025

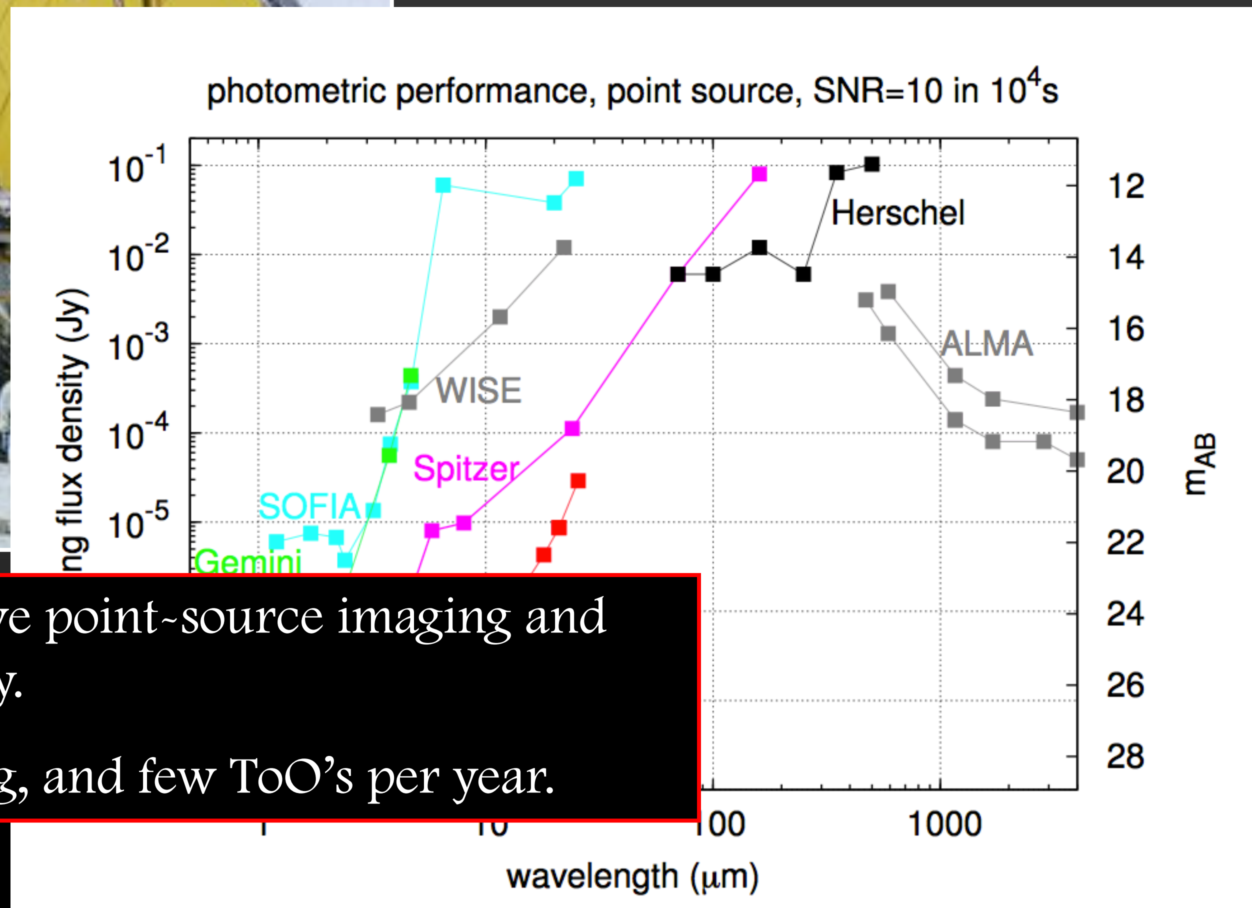
2030



6.5 m primary mirror

Red-optical to mid-IR

L2 location




Very sensitive point-source imaging and spectroscopy.

Slow slewing, and few ToO's per year.

# SVOM

Now

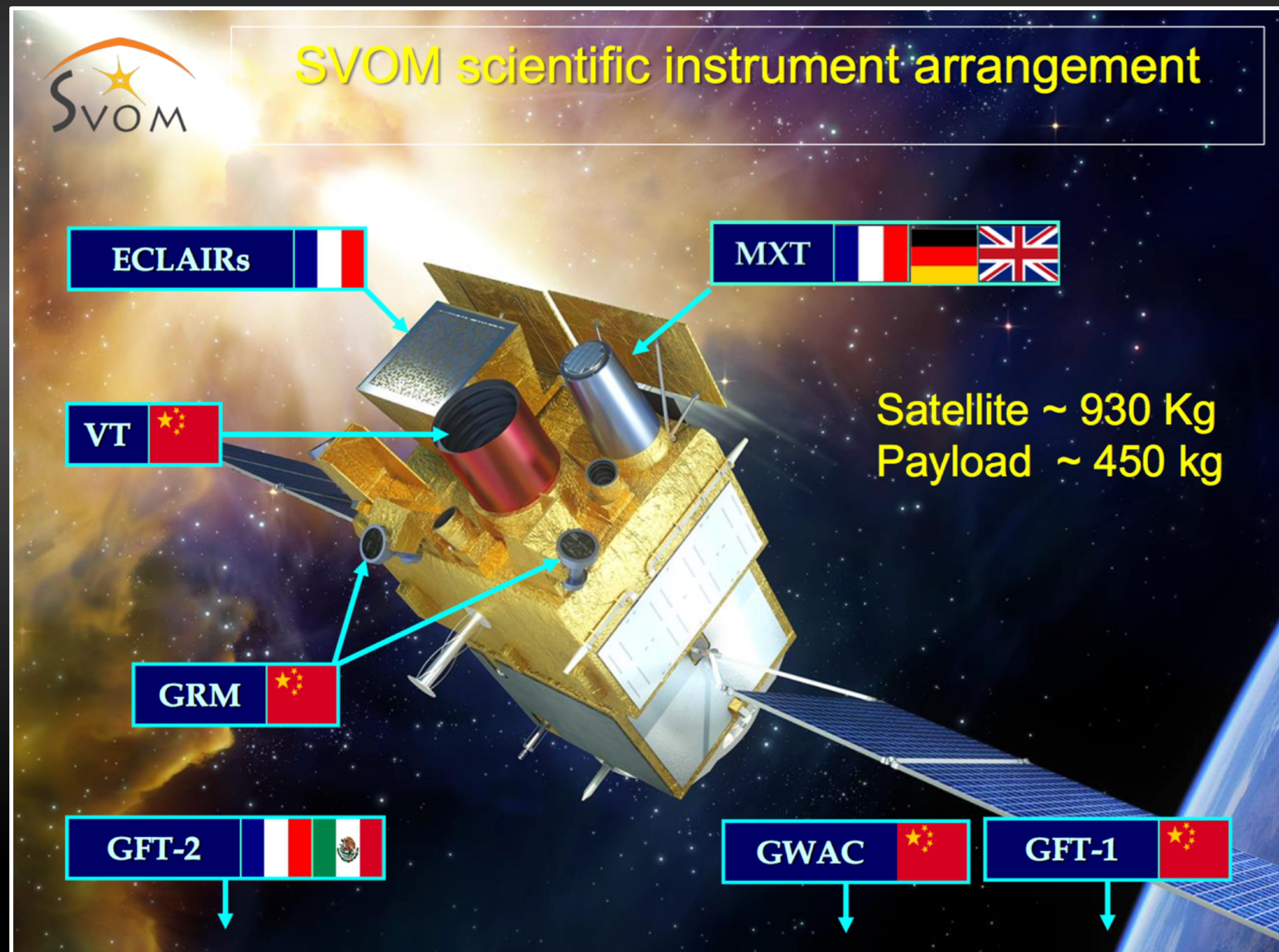
2020

2025

2030

Rapid slewing spacecraft, launch ~2022:

- Gamma-ray monitor (ECLAIRS).
- X-ray telescope (MXT).
- 40 cm Optical telescope.



Now

2020

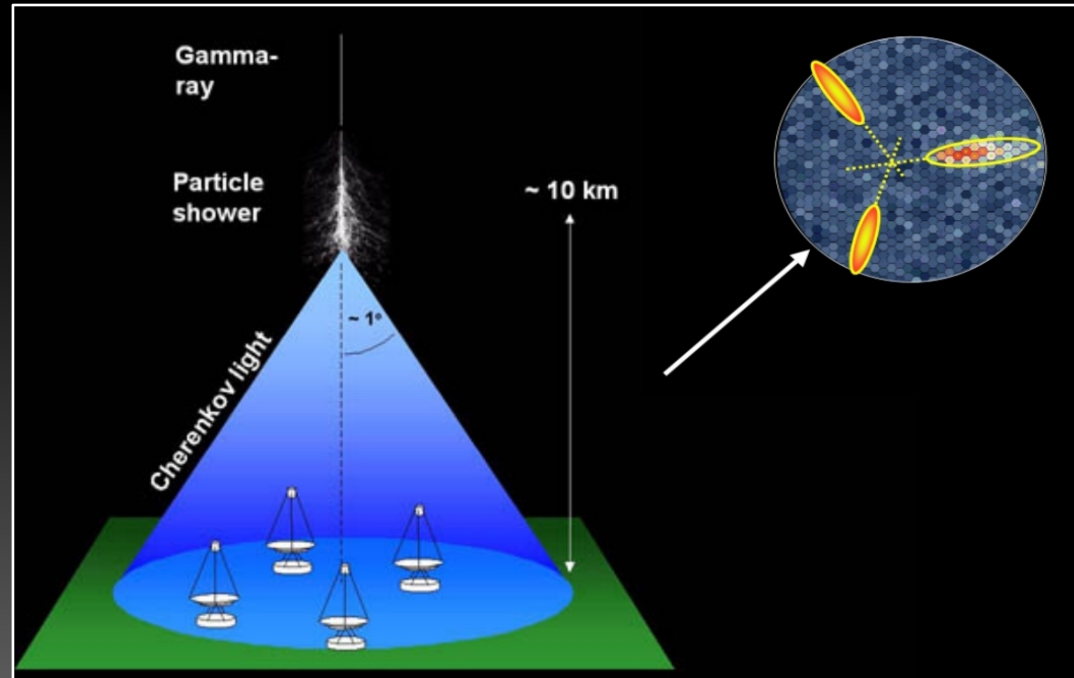
2025

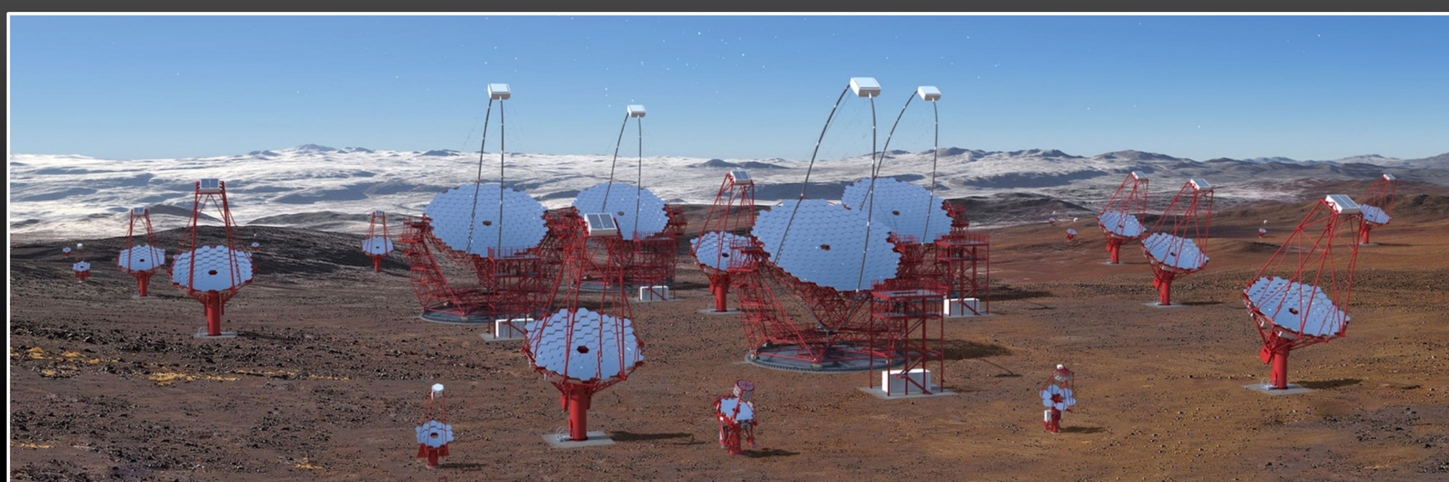
2030

# TeV gamma rays/ CTA

Northern and southern sites.

First TeV by MAGIC detection of L-GRB 190114C!



# LSST

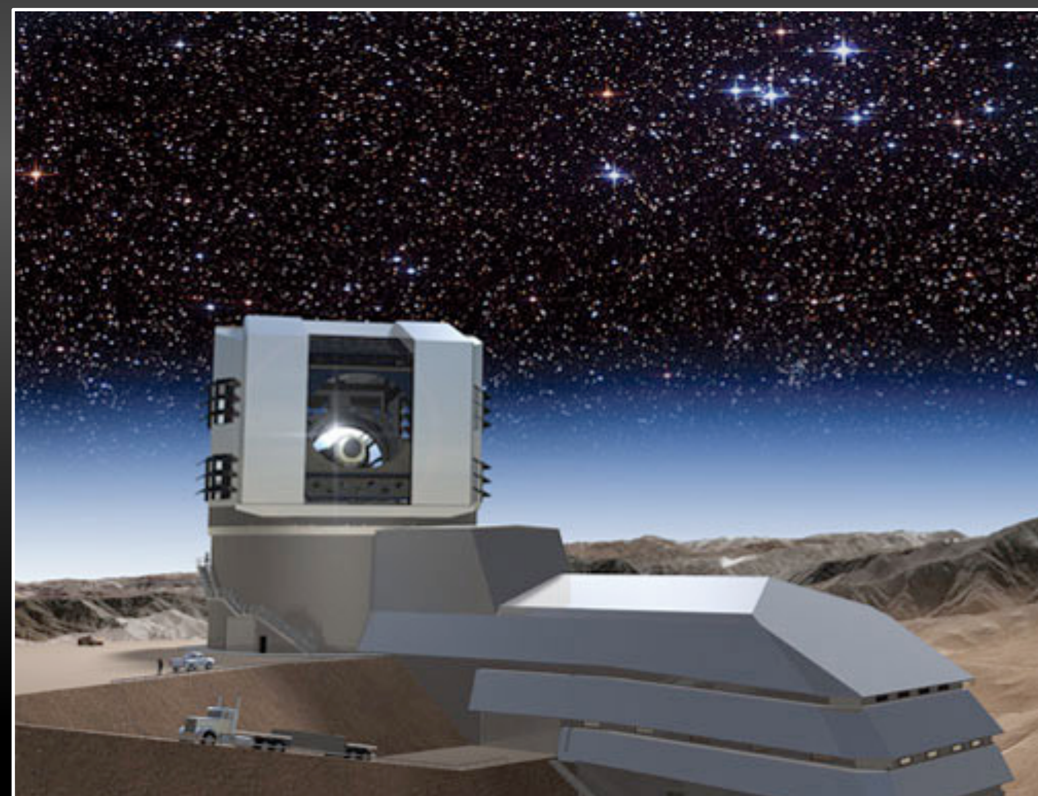
Now

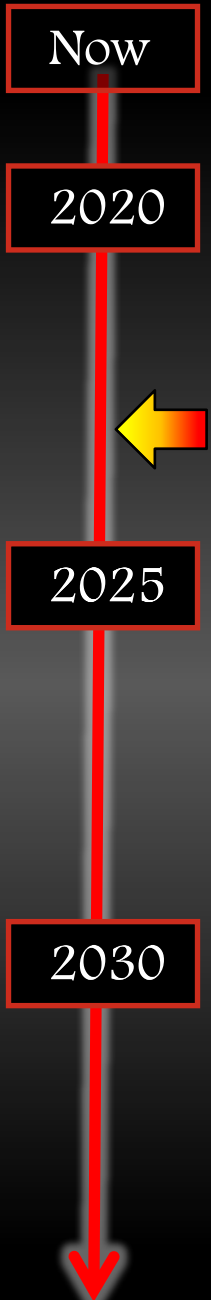
2020

2025

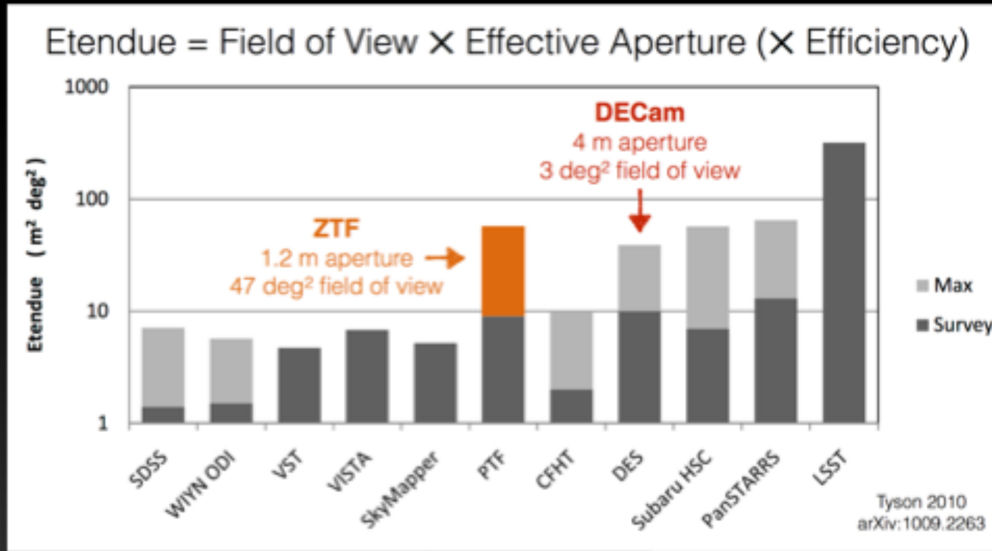
2030

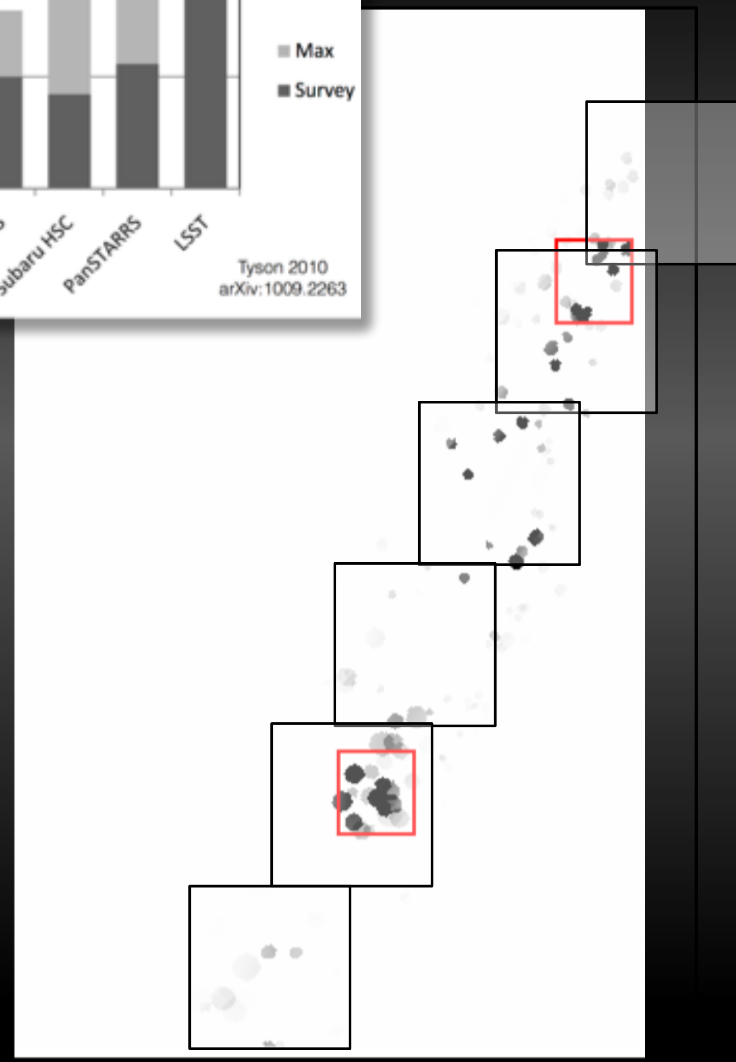

2022/23 Primarily wide-area surveys, but very capable for optical GW follow-up.






# LSST



*r* ~ 25 in 30 s integrations

Also, surveys provide very deep maps of large fraction of sky, and photo-z’s for millions of galaxies.

# SCORPIO on Gemini

Now

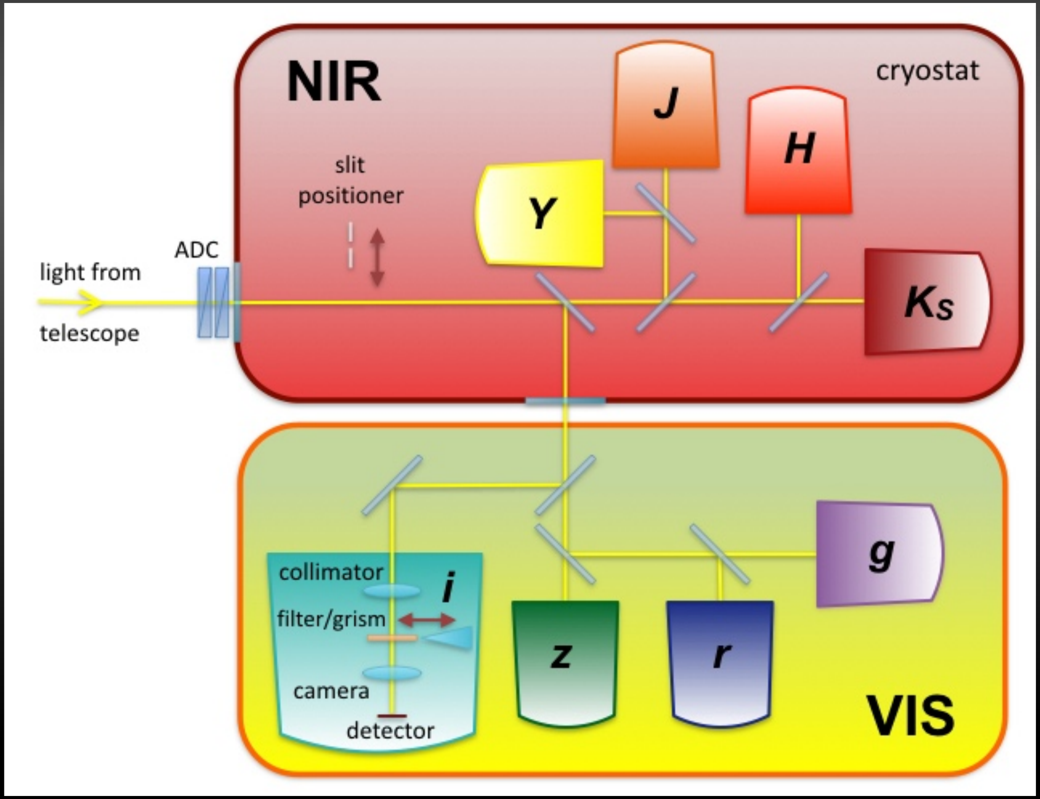
2020

2025

2030

Simultaneous high-throughput optical to nIR imaging, and spectroscopy.

Key science goals are transients (GW, GRBs, SNe etc.)



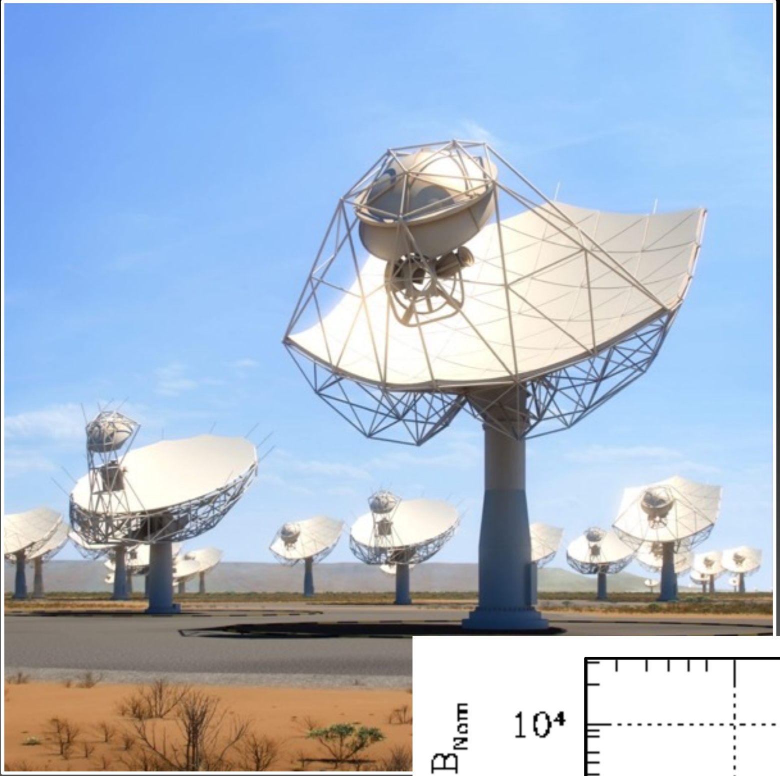

# Square kilometer Array

Now

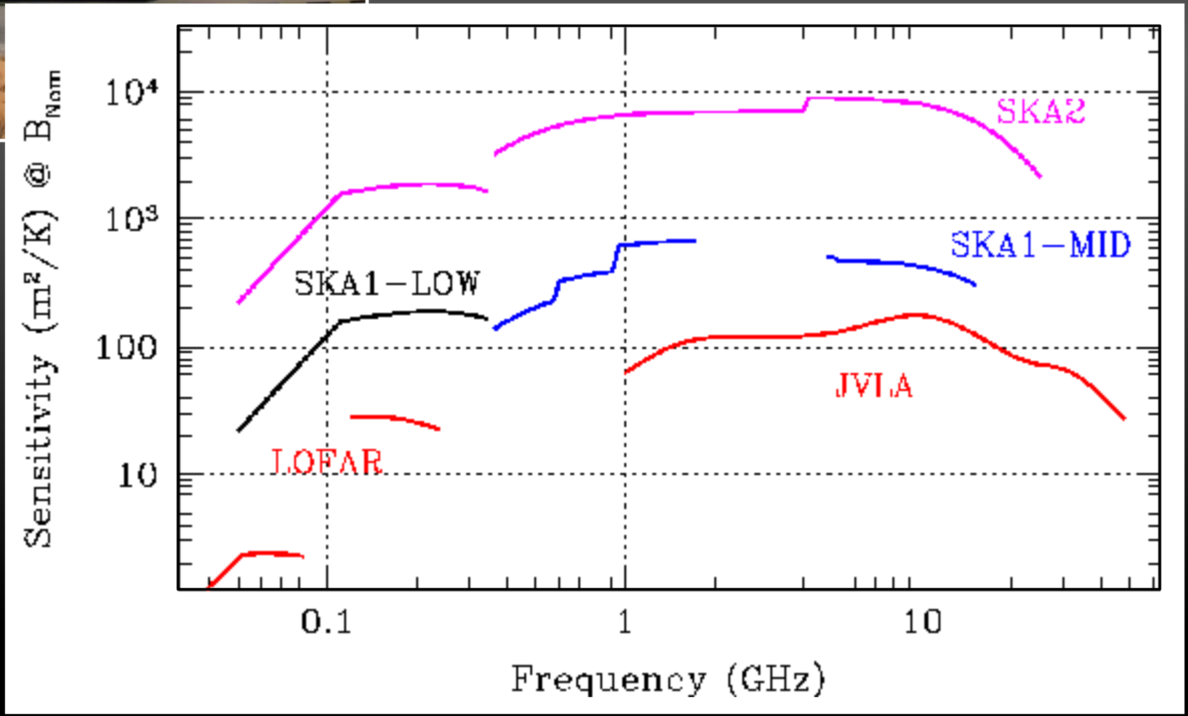
2020

2025

2030



Phased build through 2020s



Now

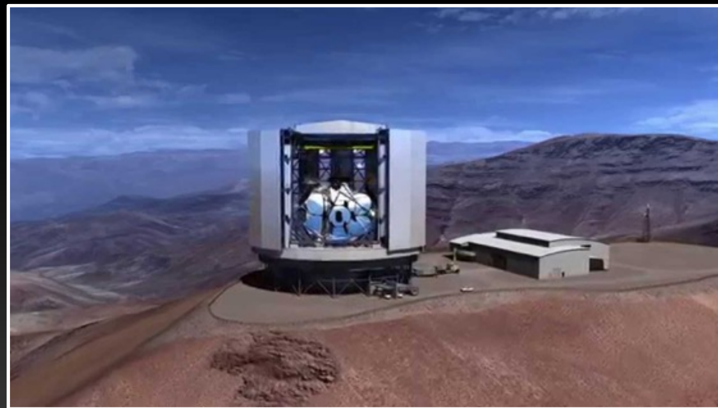
2020

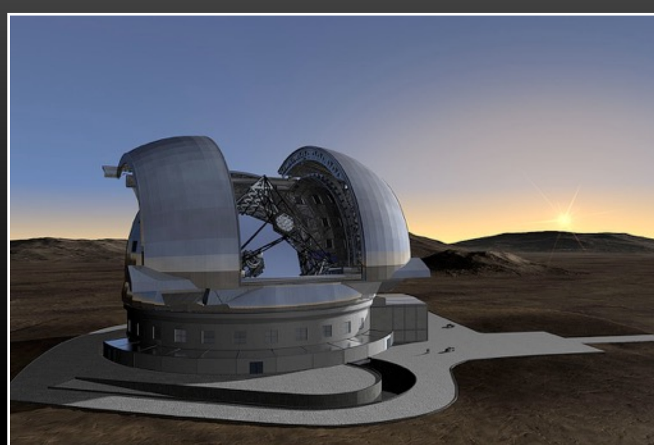
2025

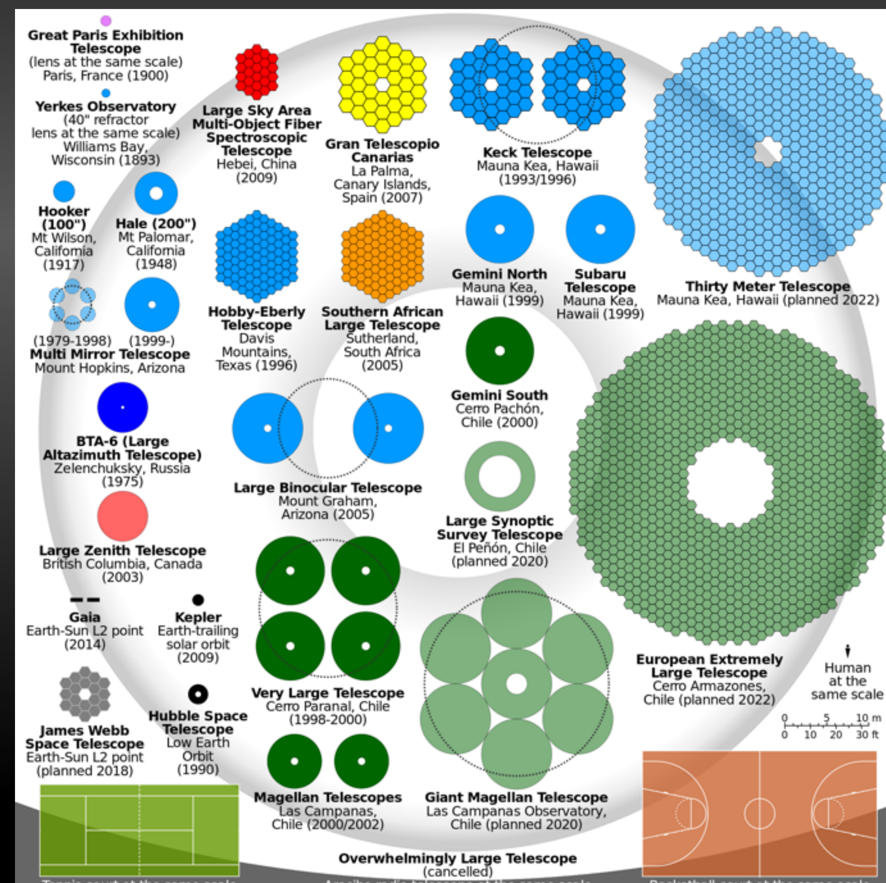
2030

# 30 m class telescopes

Mid-2020s ELT (39m), TMT (30m), GMT (25m)







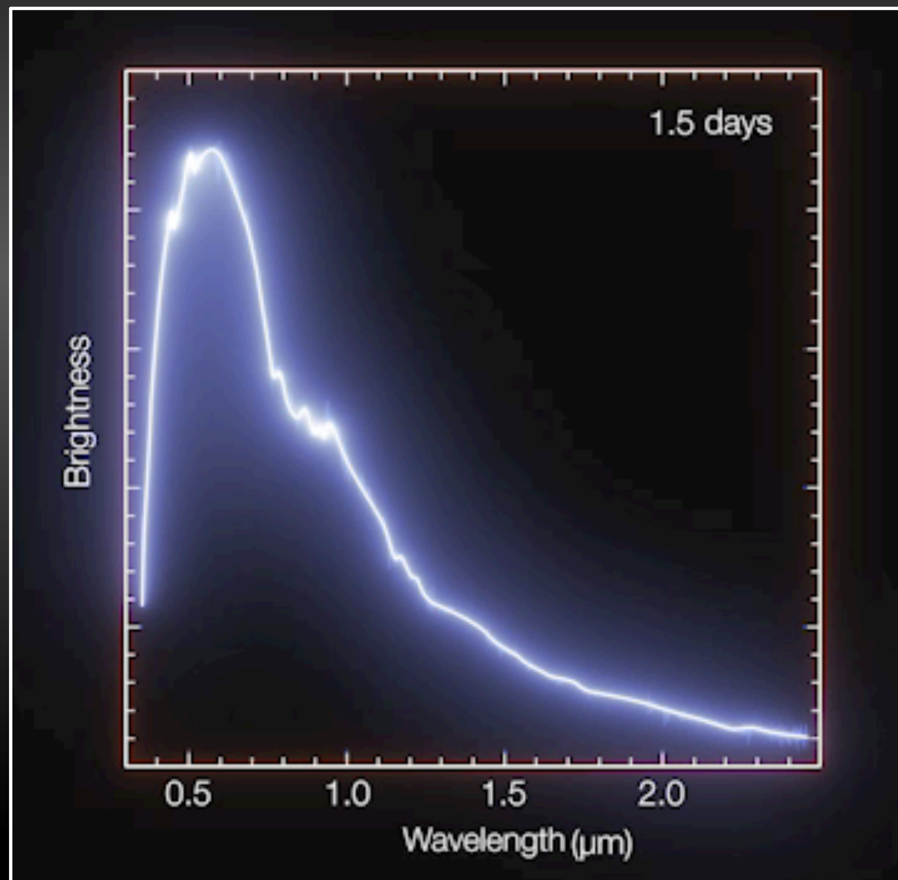
Now

2020

2025

2030

- Extremely powerful for spectroscopy to 2.5 μm.
- Very large apertures, plus high-order adaptive optics.
- Comparable to current 8m for (point) sources at ~10x distance.
- Nebular phase spectroscopy for nearby events.



# ATHENA

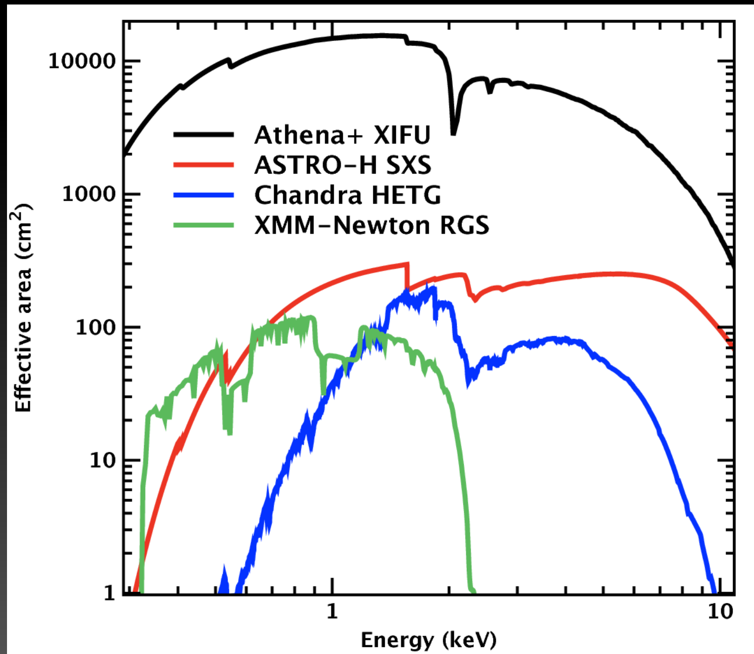
- Large effective area
- High resolution spectroscopy
- Wide field imaging

Now

2020

2025

2030




Now

2020

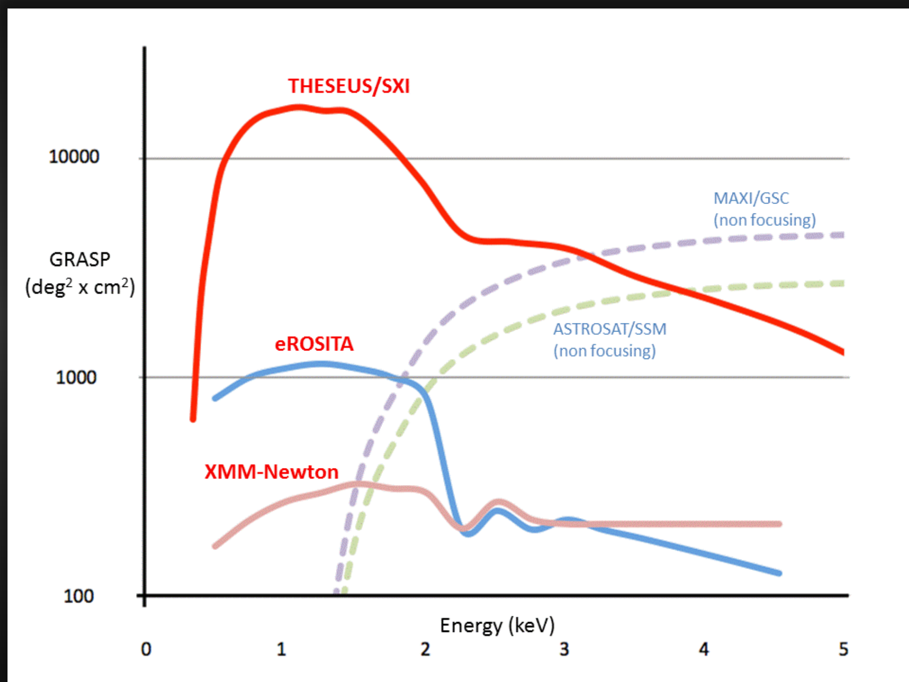
2025

2030

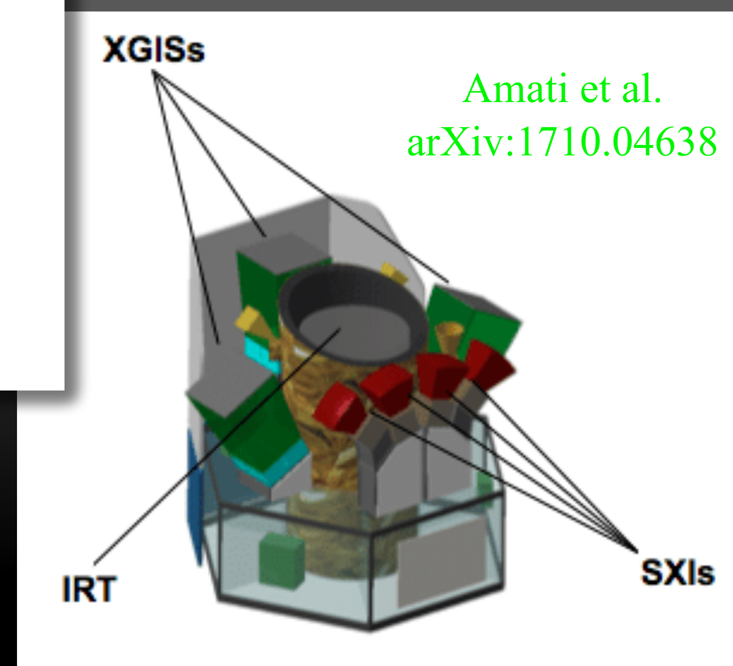
# THESEUS

Selected for phase A study for ESA M5 launch (2032)

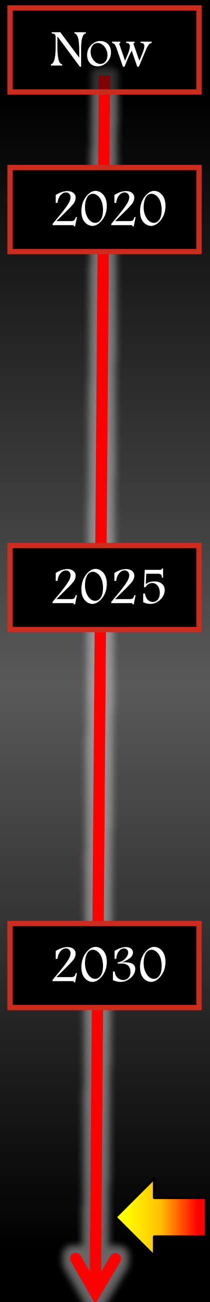
- Rapid slewing.
- On-board 70 cm IR telescope.
- Sensitive wide field X-ray and gamma-ray monitors.

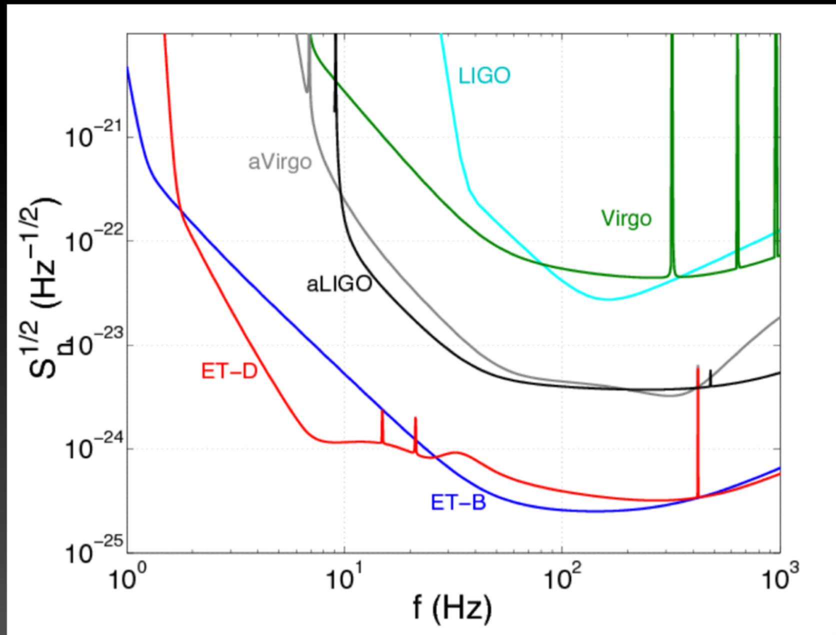



SXI – Lobster optic



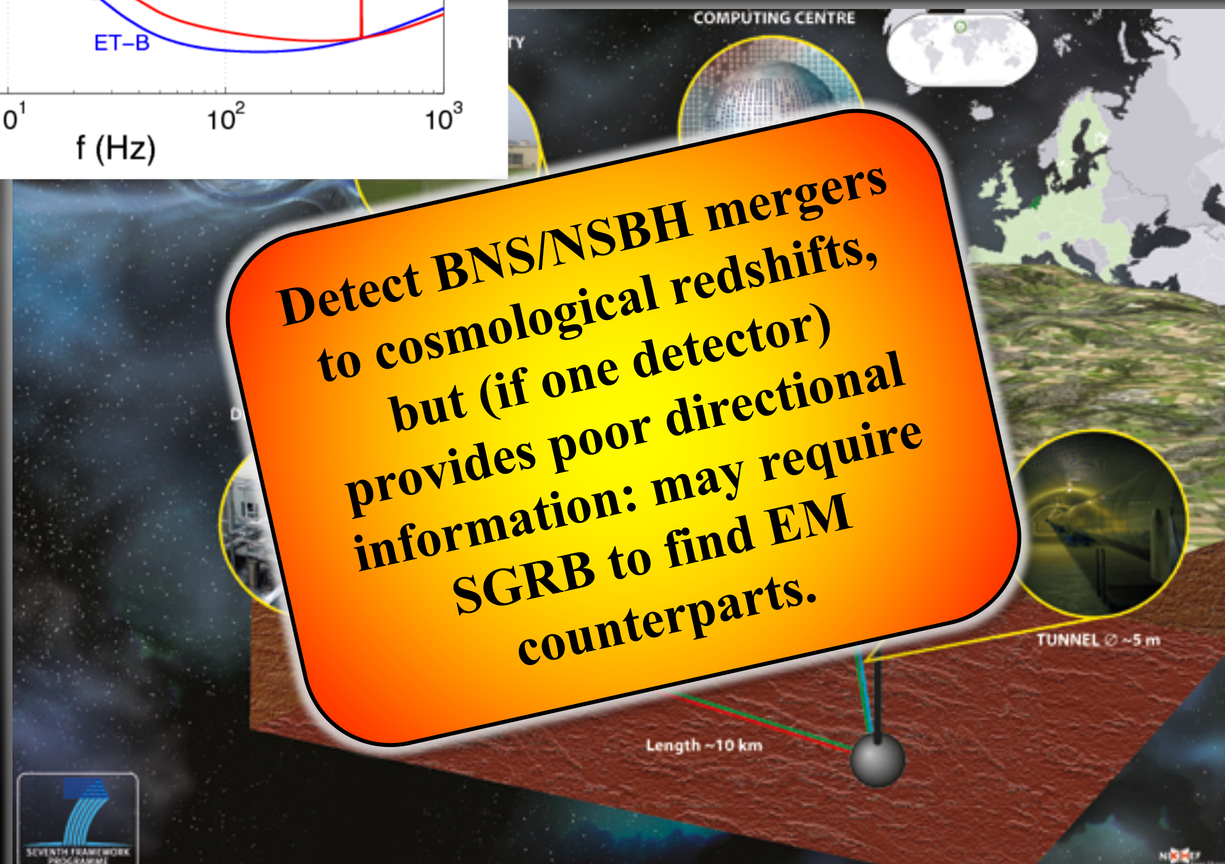

Amati et al. arXiv:1710.04638



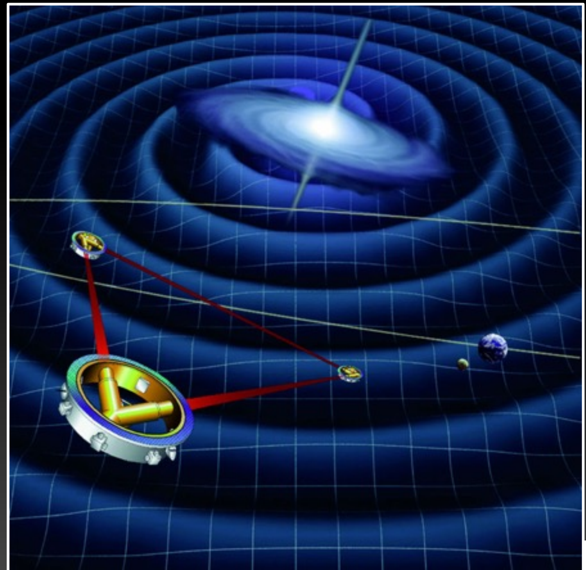




# Einstein Telescope

THESEUS could be very complementary to 3G detectors.

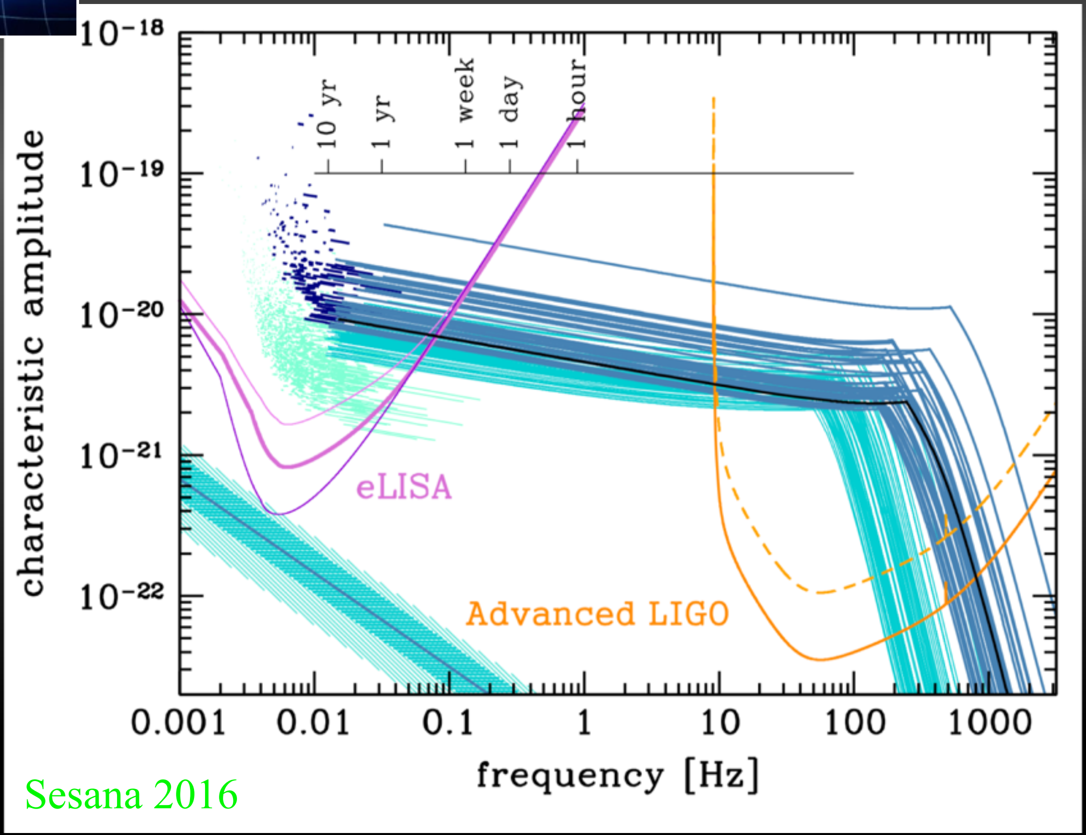



**Detect BNS/NSBH mergers to cosmological redshifts, but (if one detector) provides poor directional information: may require SGRB to find EM counterparts.**

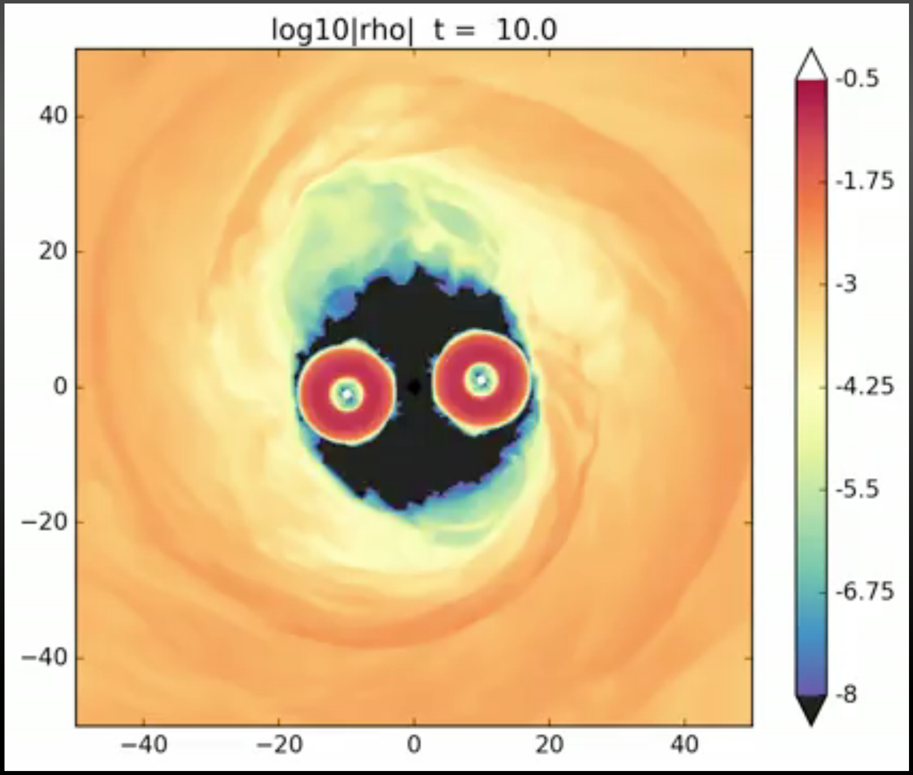
# LISA

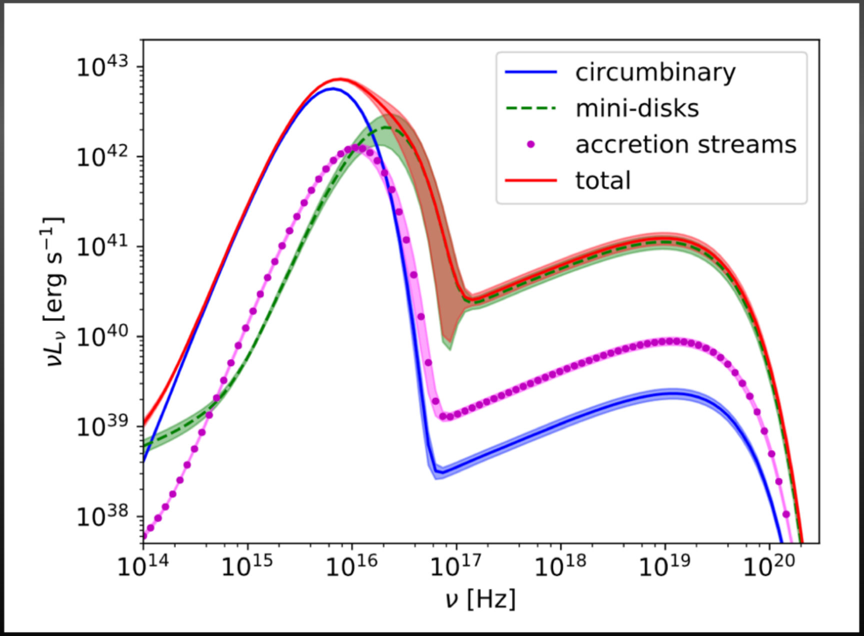
**Advanced warning of (some) mergers (precise times and ~degree locations) will permit large dedicated EM campaigns (admittedly, likely BBH).**



# LISA + EM?

- Localisation region sizes.
- Time-scales (duration, variability and advanced warning).
- Luminosity.
- Spectra.




D'Ascoli *et al.* 2018

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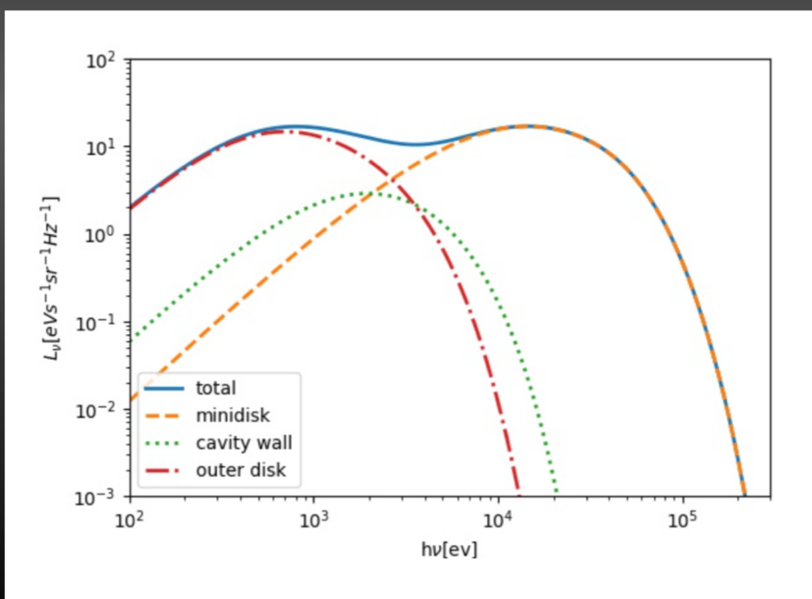


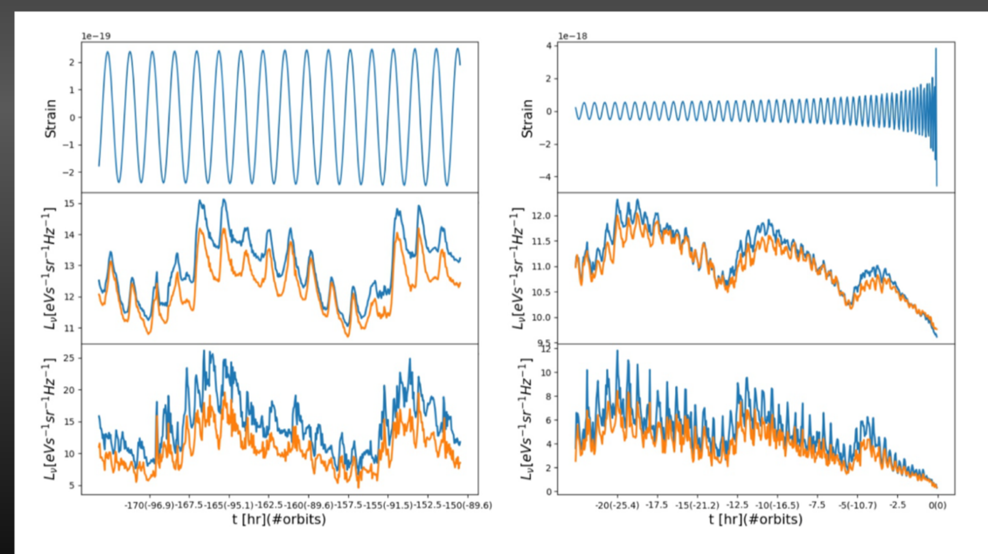


Tang *et al.* 2018

# Some conclusions

- Multi-messenger EM+GW astronomy has arrived and promises great things.
- GW170817 follow-up campaign illustrates many of the challenges and opportunities.
- Inherently multi-wavelength due to wide range of thermal and non-thermal emission.
- Near-IR important for identifying and characterising the low-Ye (r-process rich) ejecta.
- Going forward, key aspect is coordination and optimisation of next generation facilities to work efficiently together.