Multi-messenger II

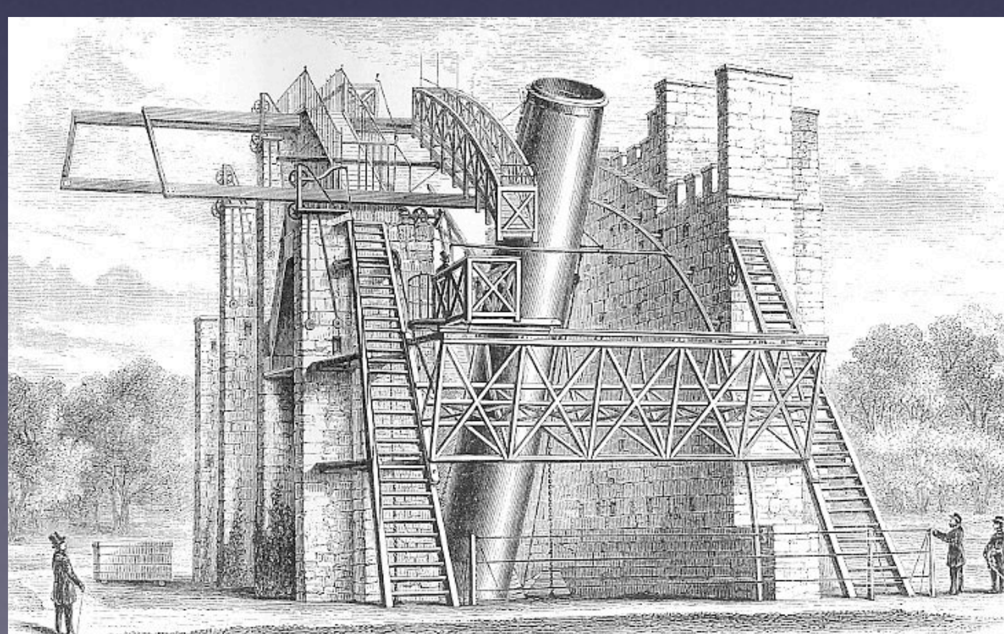
Searching for electromagnetic counterparts to gravitational waves - the basics

Stephen Smartt
Queen's University Belfast

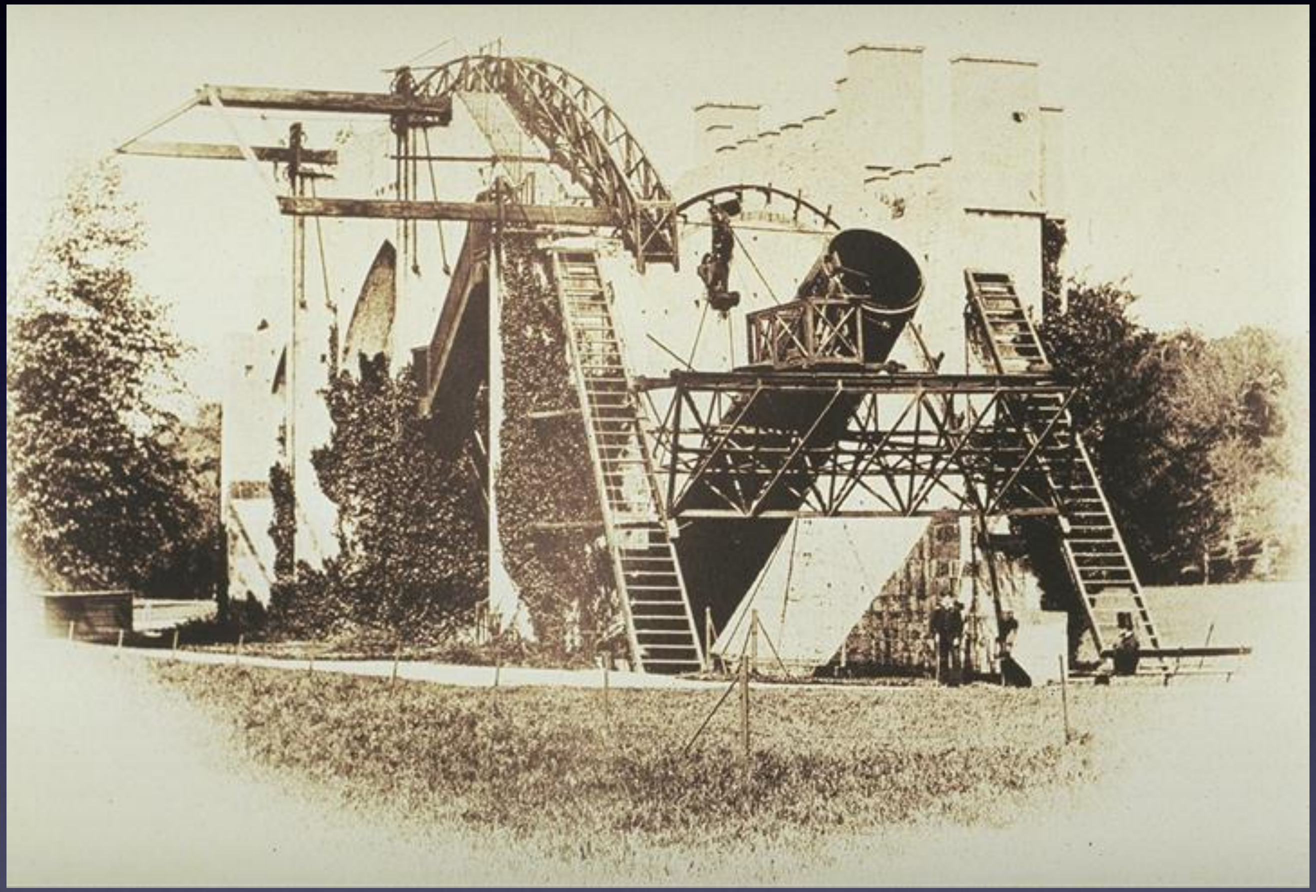
Pan-STARRS
PS1 Science Consortium

PESSTO
ESO

Which country has had the world's largest telescope for the longest period in history ?



Birr Castle,
Co. Offaly
Ireland



Binary Black Hole mergers 2015-17

4 secure detections

TABLE I. Source properties for GW170104: median values with 90% credible intervals. We quote source-frame masses; to convert to the detector frame, multiply by $(1+z)$ [50,51]. The redshift assumes a flat cosmology with Hubble parameter $H_0 = 67.9\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ and matter density parameter $\Omega_m = 0.3065$ [52]. More source properties are given in Table I of the Supplemental Material [11].

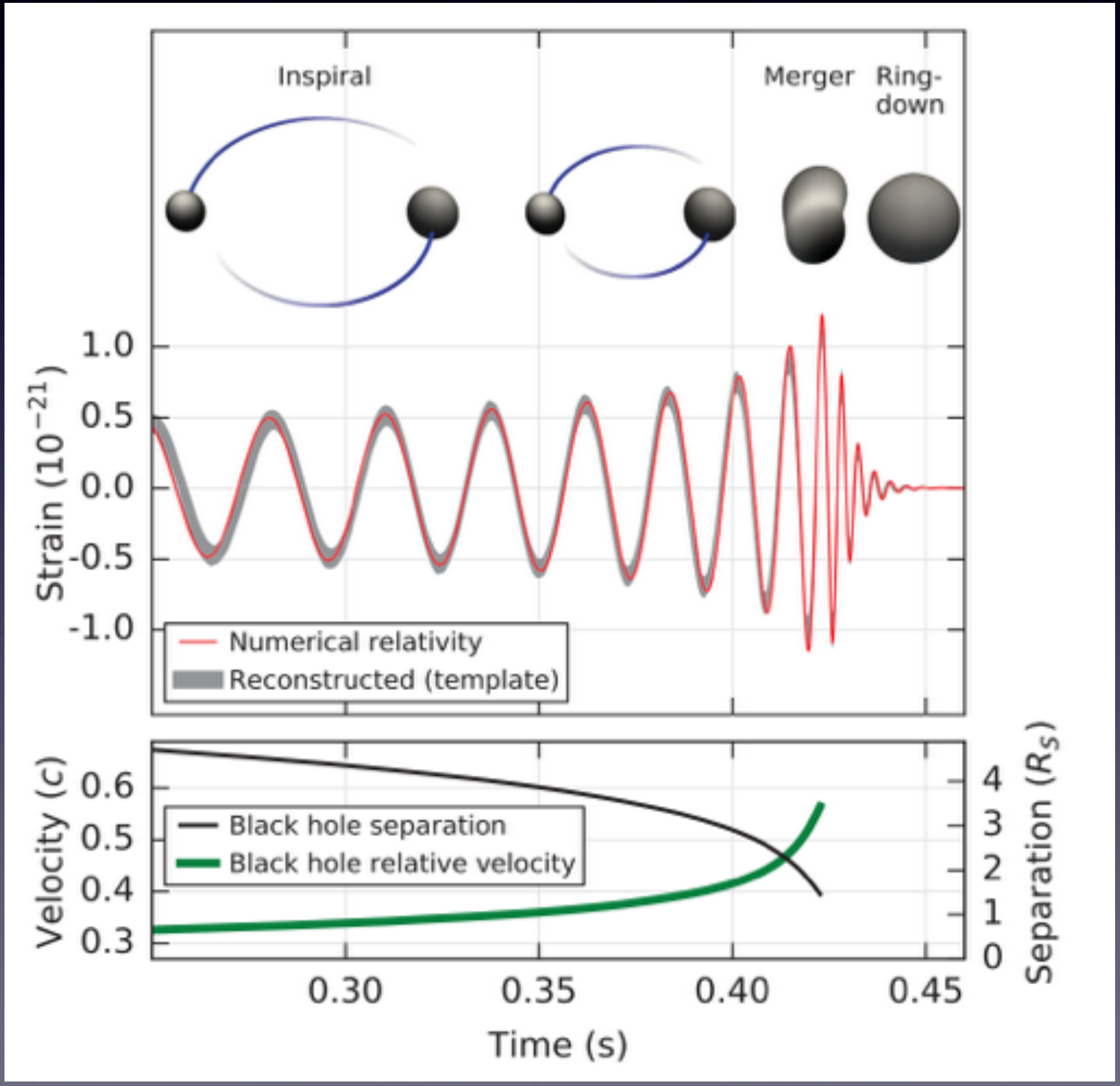
Primary black hole mass m_1	$31.2^{+8.4}_{-6.0} M_\odot$
Secondary black hole mass m_2	$19.4^{+5.3}_{-5.9} M_\odot$
Chirp mass $\mathcal{M}$	$21.1^{+2.4}_{-2.7} M_\odot$
Total mass M	$50.7^{+5.9}_{-5.0} M_\odot$
Final black hole mass M_f	$48.7^{+5.7}_{-4.6} M_\odot$
Radiated energy E_{rad}	$2.0^{+0.6}_{-0.7} M_\odot c^2$
Peak luminosity ℓ_{peak}	$3.1^{+0.7}_{-1.3} \times 10^{56} \mathrm{erg\,s^{-1}}$
Effective inspiral spin parameter χ_{eff}	$-0.12^{+0.21}_{-0.30}$
Final black hole spin a_f	$0.64^{+0.09}_{-0.20}$
Luminosity distance D_L	880^{+450}_{-390} Mpc
Source redshift z	$0.18^{+0.08}_{-0.07}$

Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate FAR/yr^{-1}	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\,\sigma$	$> 5.3\,\sigma$	1.7σ
Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathcal{M}^{\mathrm{source}}/\mathrm{M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\mathrm{source}}/\mathrm{M}_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effective inspiral spin χ_{eff}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_f^{\mathrm{source}}/\mathrm{M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin a_f	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\mathrm{peak}}/(\mathrm{erg\,s^{-1}})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance D_L/Mpc	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization $\Delta\Omega/\mathrm{deg}^2$	230	850	1600

Abbott et al. 2017 PRL 118, 221101
Abbott et al. 2016,
Phys.Rev. X6 (2016) no.4, 041015

LIGO discoveries and EM

- Can electromagnetic counterparts be found ?
- New opportunities for compact remnants, high energy physics,
- nucleosynthesis of r-process elements,
- velocity of the graviton vs c
- standard “sirens”
- Genuine excitement of “seeing” the source and secure the host galaxy, stellar population



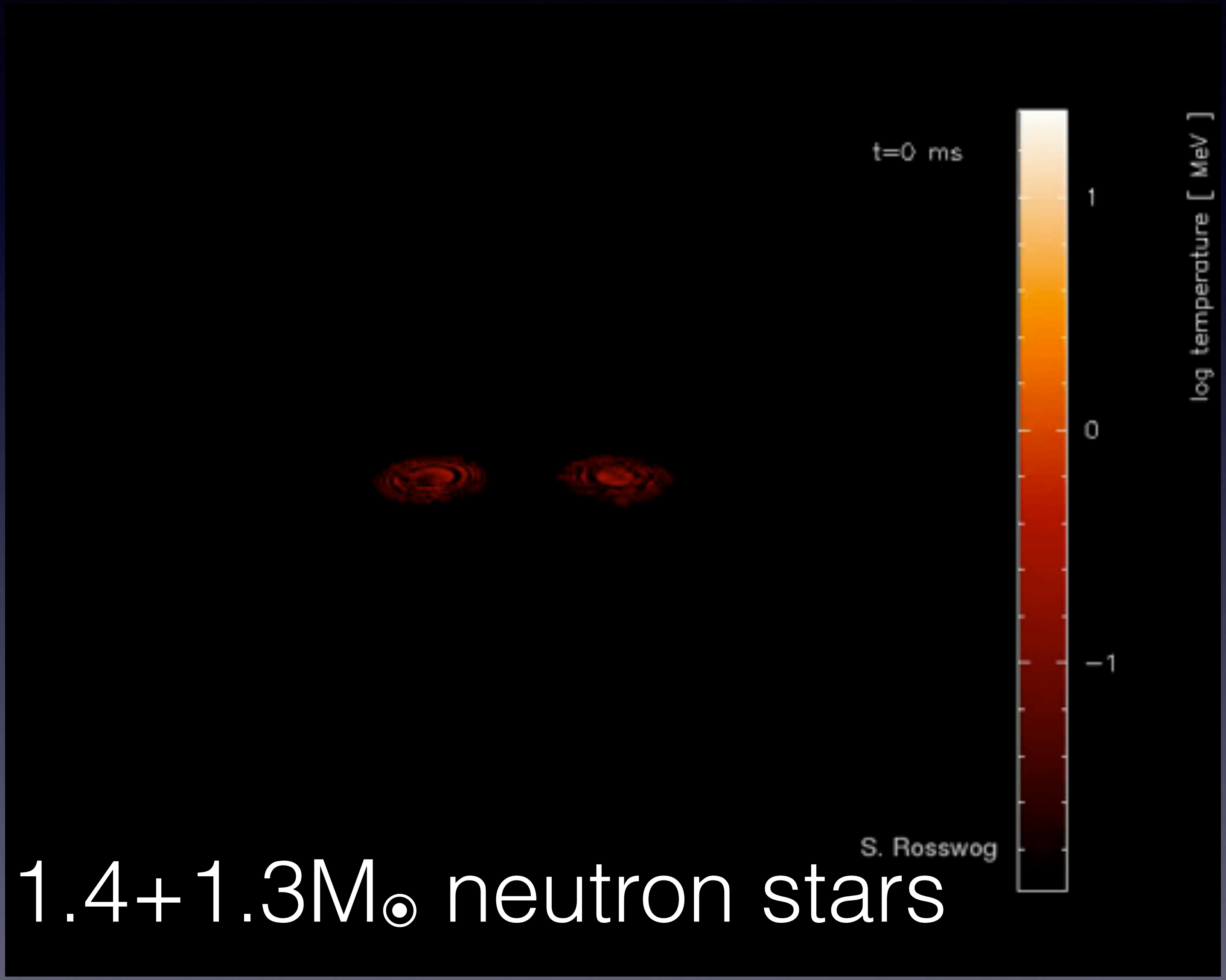
Abbott et al. 2016a, 2016b

GW sources -what can we expect ?

- NS-NS mergers and BH-NS mergers
- Predicted to be strong emitters of EM radiation

- Short GRBs : working model is NS-NS mergers
- Gamma rays are beamed from relativistic jet

- Beam opening angle ~ 10^{o} (see Berger ARA&A 2014)

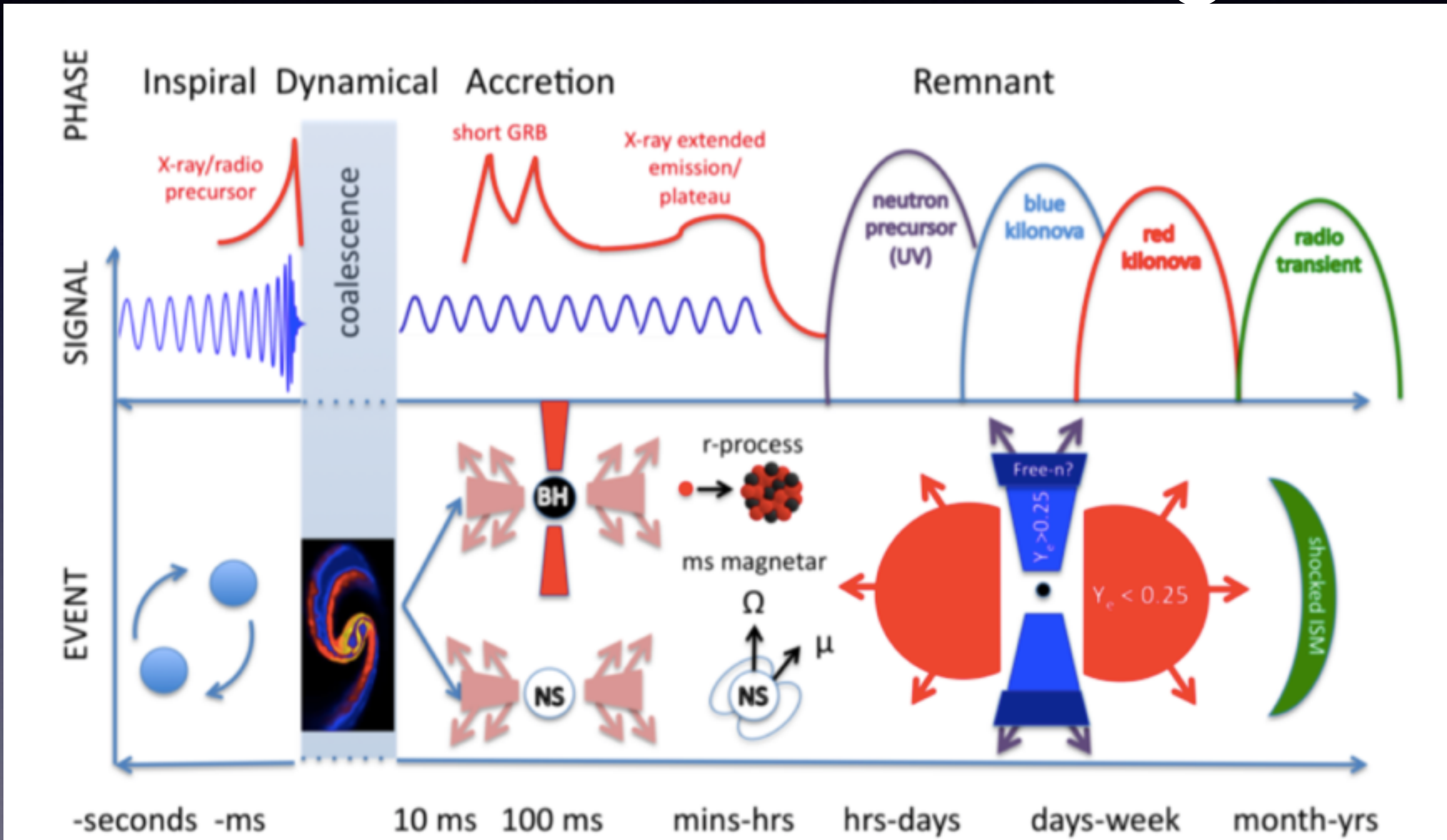


1.4+1.3M$_{\odot}$ neutron stars

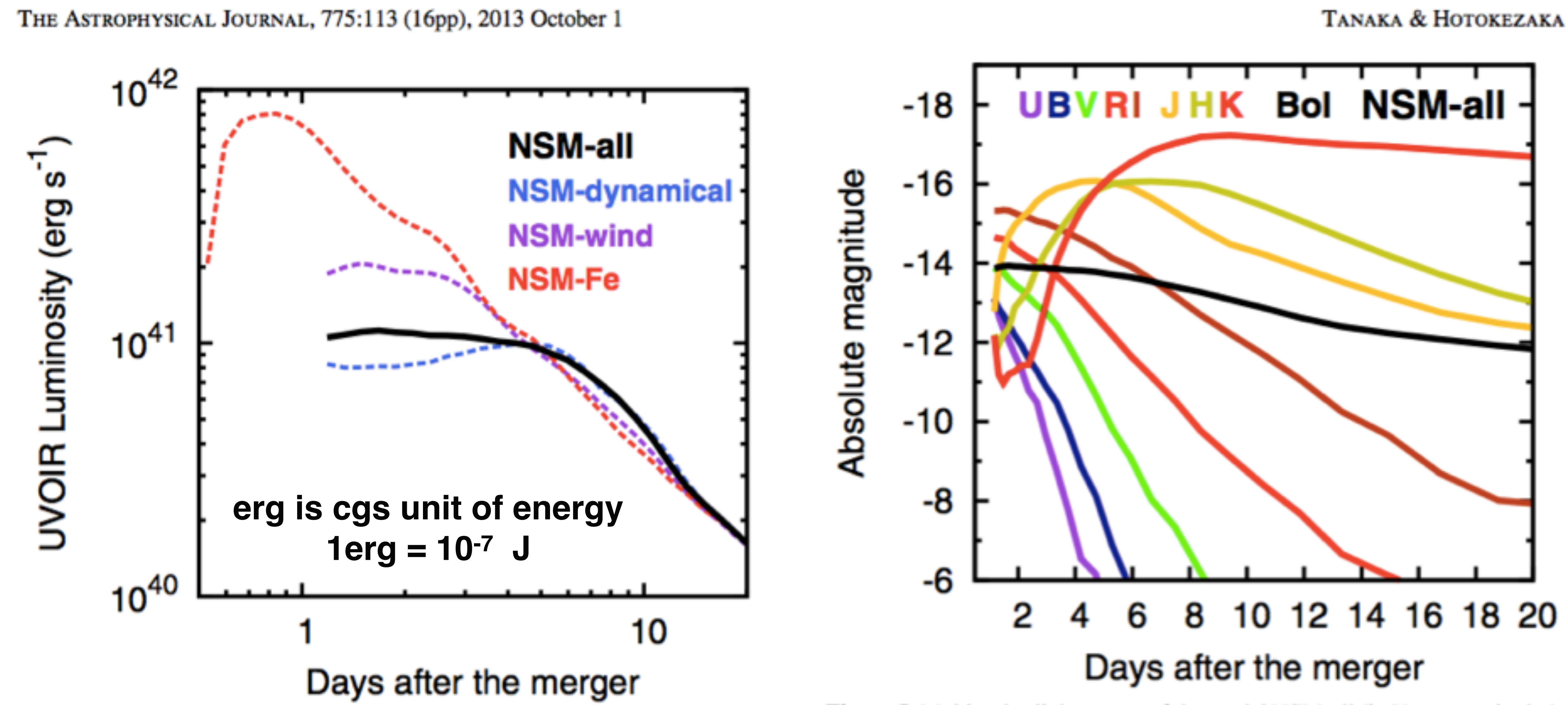
http://compact-merger.astro.su.se/

See Rosswog, Piran & Nakar 2013

GW and EM transients from NS-NS or NS-BH mergers



Fernandez & Metzger 2015



Barnes and Kasen 2013
Kasen, Badness & Barnes 2013
Kasen, Fernandez & Metzger 2015
Quantitative radiative transfer models with different components

Radiative transfer calculations, critical.

Must include Ga to U

Opacity higher by factor 100 than in normal supernova

Tanaka & Hotokezaka 2013

ELECTROMAGNETIC SIGNALS FOLLOWING STELLAR–MASS BLACK HOLE MERGERS

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Accepted for publication in Astrophysical Journal Letters: March 18, 2017

ABSTRACT

It is often assumed that gravitational wave (GW) events resulting from the merger of stellar–mass black holes are unlikely to produce electromagnetic (EM) counterparts. We point out that the progenitor binary has probably shed a mass $\gtrsim 10\,M_\odot$ during its prior evolution. If a tiny fraction of this gas is retained until the merger, the recoil and sudden mass loss of the merged black hole shocks and heats it within hours of the GW event. Whether the resulting EM emission is detectable uncertain. The optical depth through the disk is likely to be high enough that the prompt emission consists only of photons from its optically thin skin, while the majority may take years to emerge. However, if some mechanism can release more photons in a time comparable to the few–hour energy production time, the peak luminosity of the EM signal could be detectable. For a disk retaining only $\sim 10^{-3}$ of the mass shed in the earlier binary evolution, medium–energy X–rays to infrared emission would be observable hours after the GW event for source distances $\sim 500\,\mathrm{Mpc}$. Events like this may already have been observed, but ascribed to unidentified active galactic nuclei. Improved sky–localization should eventually allow identification based on spatial coincidence. A detection would provide unique constraints on formation scenarios and potentially offer tests of strong–field general relativity. Accordingly we argue that the high scientific payoff of an EM detection fully justifies search campaigns.

Subject headings: gravitational waves — black hole physics — binaries: close — X-rays: general

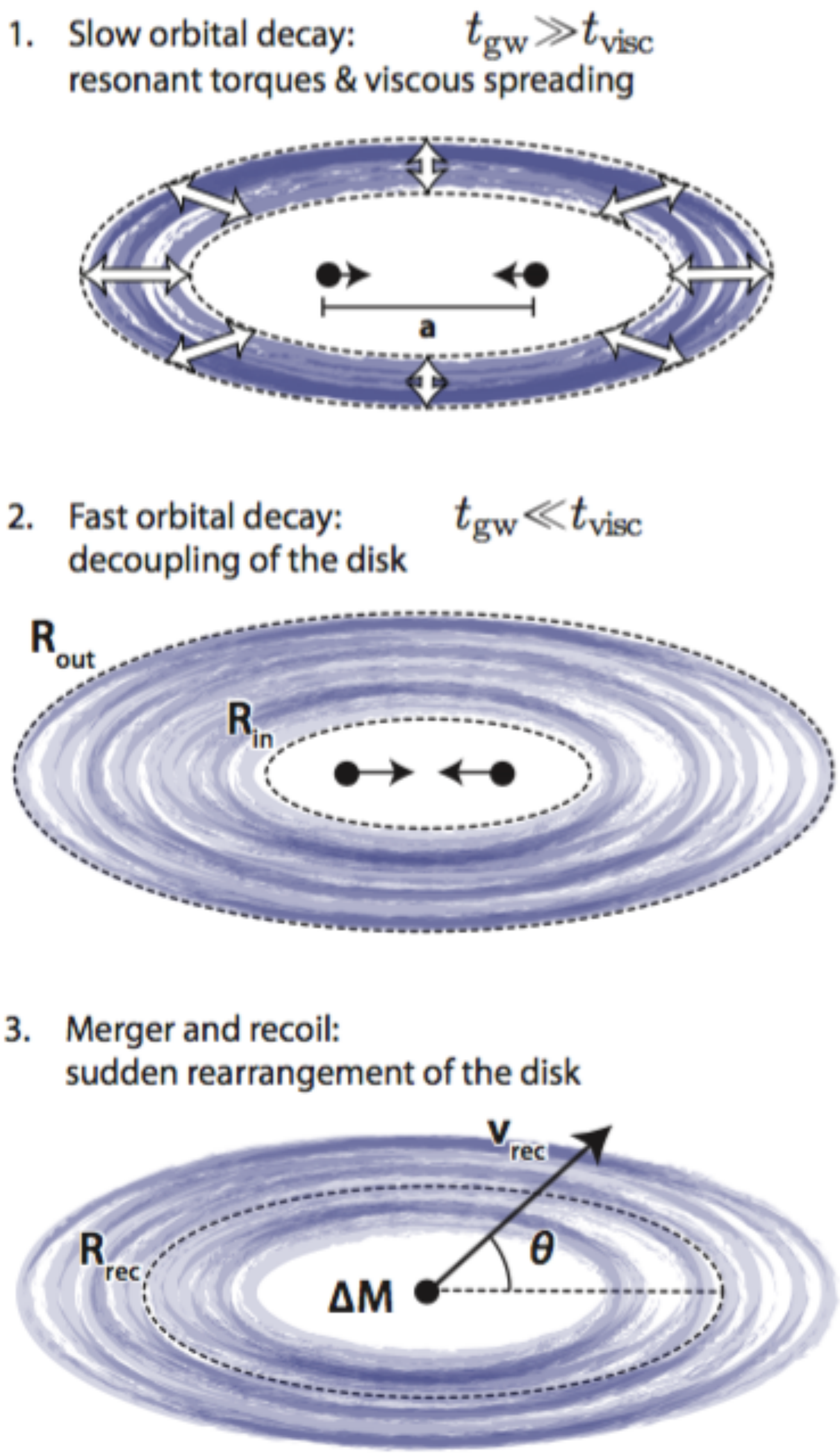


FIG. 1.— Cartoon depicting the evolution of a circumbinary disk.

1. Time delay and duration: Heating of the disk by shocks occurs on a characteristic timescale of order the dynamical time

$$t_{\rm dyn} \sim \frac{GM}{v^3} \sim 2.2 \frac{M_{60}}{v_3^3} \text{ hrs}, \qquad (3)$$

where $v_3 = v/(10^3\,{\rm km\,s^{-1}})$ and v is the greater of the Keplerian velocity at the inner orbit and the recoil velocity imparted to the center of mass, i.e. $v \equiv \max\{v_K(R_{\rm in}), v_{\rm rec}\}$. The light–travel time required to tell

3. Peak luminosity: the expected rate of dissipation of kinetic energy is

$$L \sim f \frac{M_{\rm d} v^2}{t_{\rm dyn}} \sim f\, \frac{v^5}{G} q_d \qquad (5)$$

where f is a scaling factor. We calibrate the factor $f \sim 0.1$ against the numerical simulations by Rossi et al. (2010), which assume an angle of $\theta = 15°$ between the recoil direction and the orbital plane

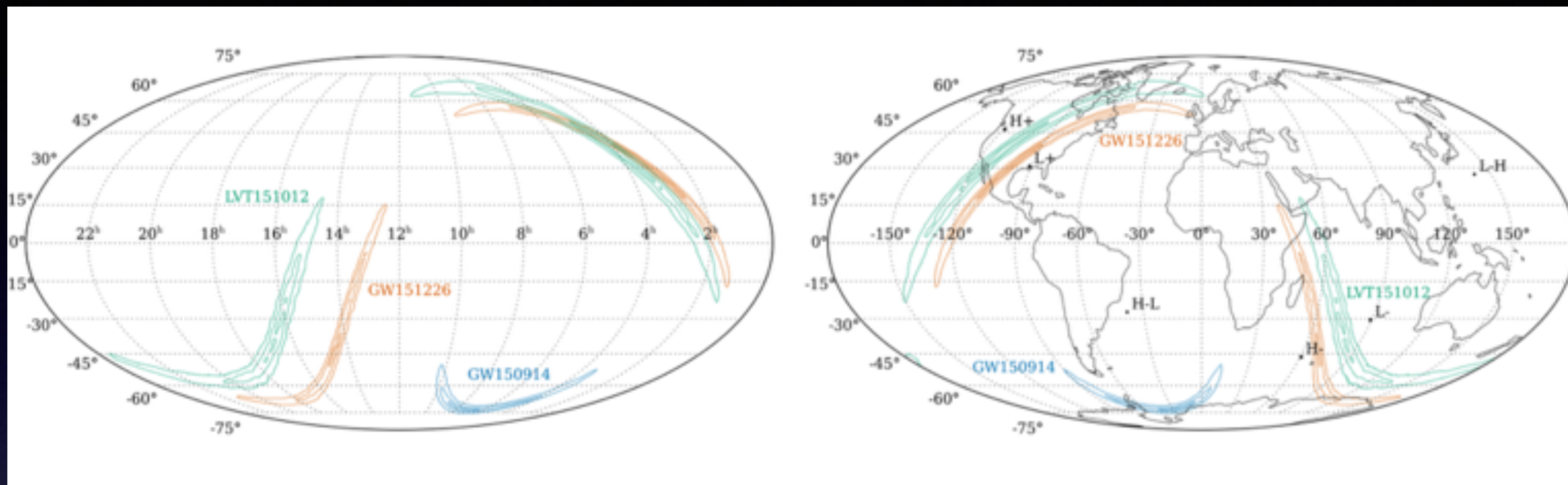
$$L \sim 5 \times 10^{42} \left(\frac{f}{0.1}\right) v_3^5 \left(\frac{q_{\rm d}}{10^{-3}}\right) {\rm erg\,s^{-1}}, \qquad (6)$$

$q = M_d/M_{total}$

i.e. ratio of disk mass to total

See also Perna, Lazzati & Giacomazzo 2016

Very large sky areas

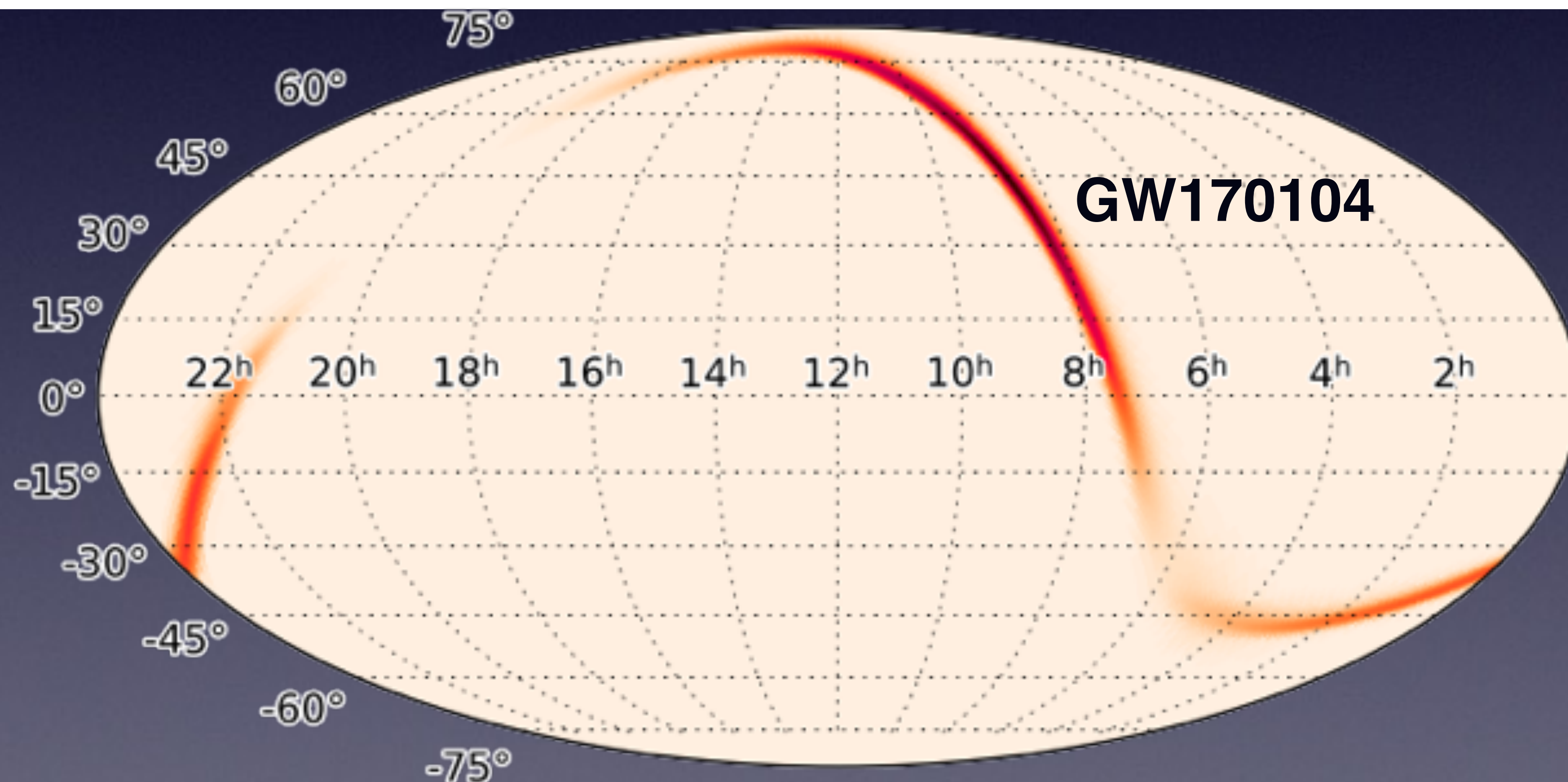


LVT151012
1600 sq deg

Abbott et al.
arXiv:1606048526

GW151226
850 sq deg

GW150914
230 sq deg



GW170104
1608 sq deg

- LIGO/Virgo are all sky monitors
- 90% enclosed probability has ~200 - 2000 deg^2

The first optical counterpart to a Gamma-ray burst

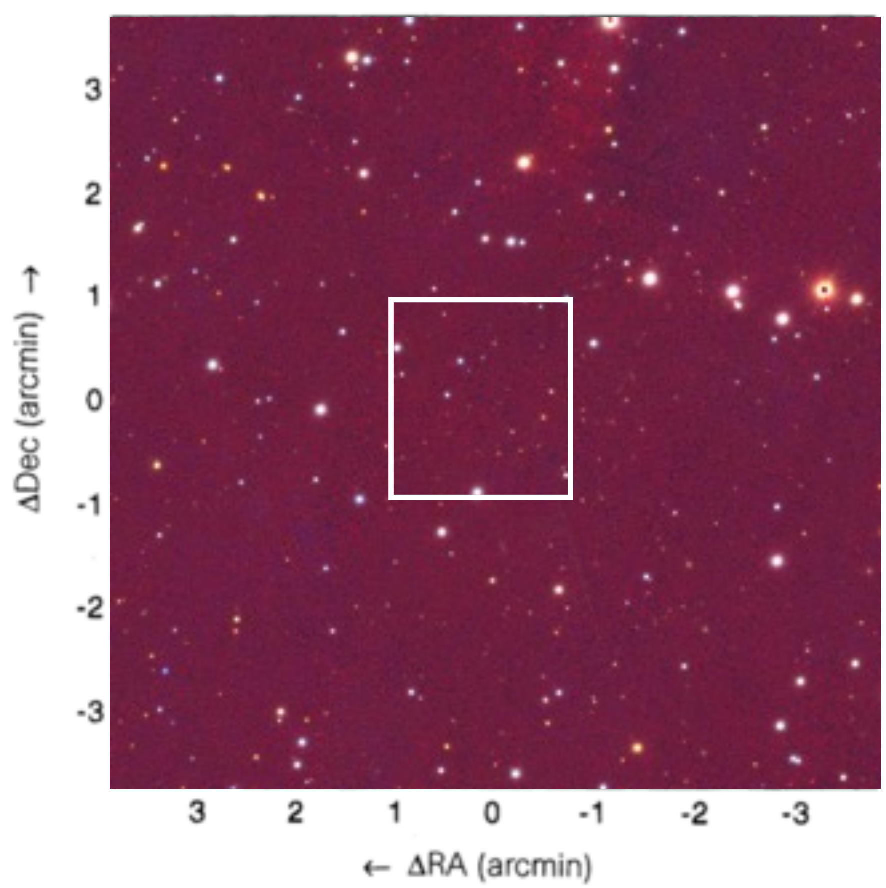
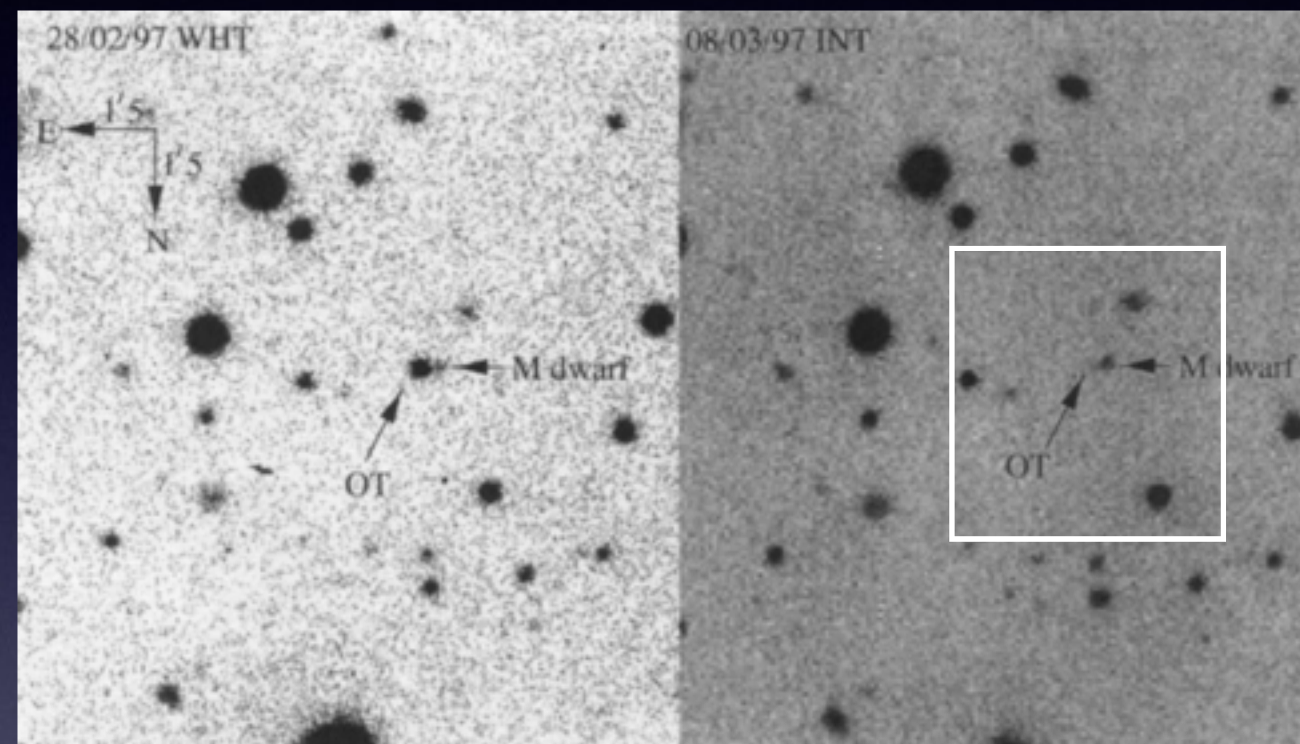
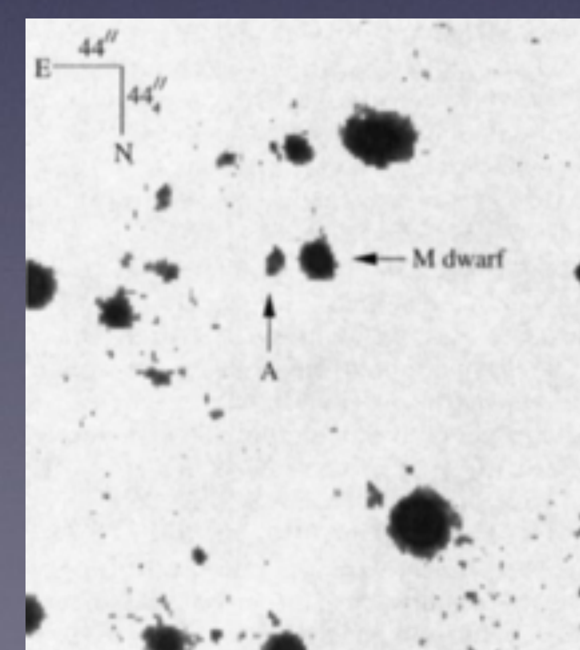


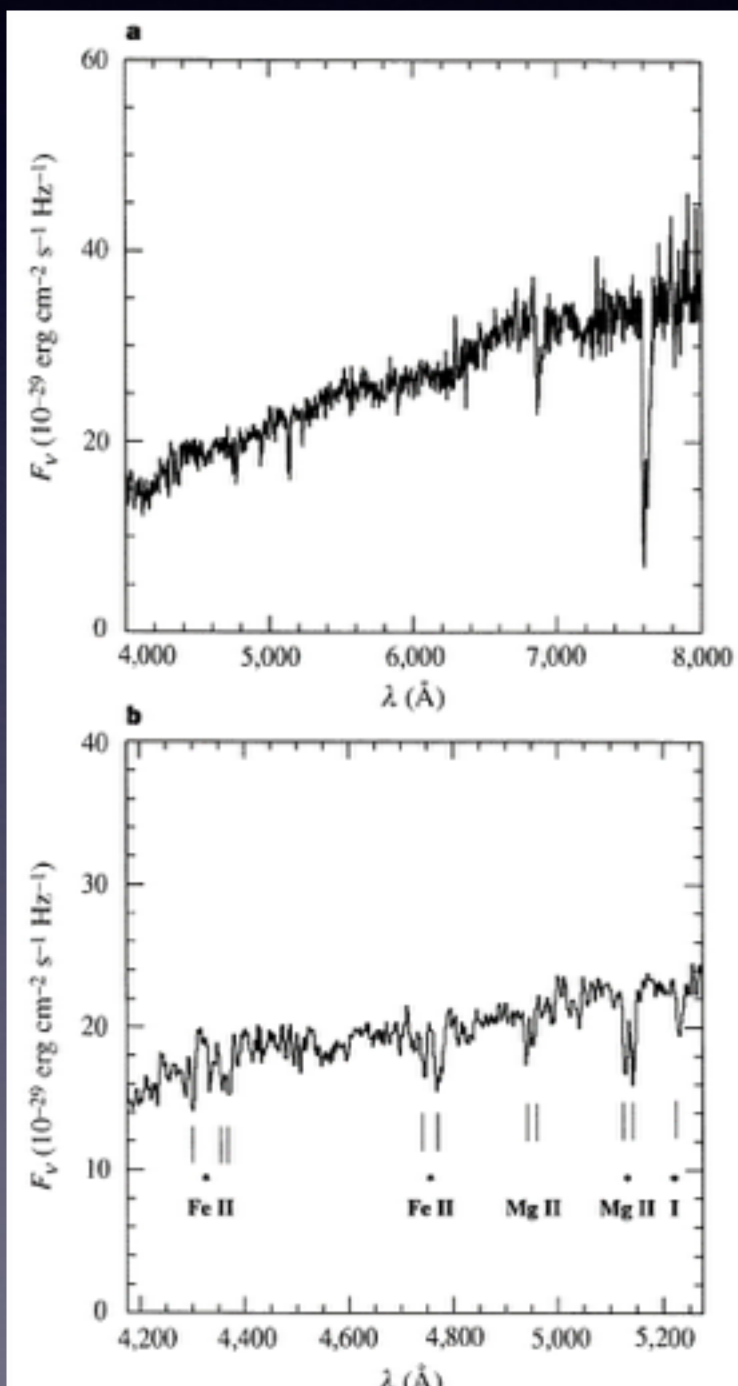
Figure 1 The position of the optical transient, indicated with an asterisk, is shown with respect to the 3′ (radius) WFC location error circle, the 50″ (radius) error circles of the BeppoSAX X-ray transient, and the two annuli obtained from the differences between the times the GRB was detected with Ulysses, and with BeppoSAX and Wind, respectively. The area in common between these error regions in hatched. The coordinates are given in units of arcmin with respect to the position of the optical transient (RA 05 h 01 min 46.665 dec +11°46′ 53.9″, J2000). The position of an unrelated radio source[49] in the error circle of the X-ray transient is indicated with the square symbol.



GRB970228
Van Paradijs et al. Nature, 1997

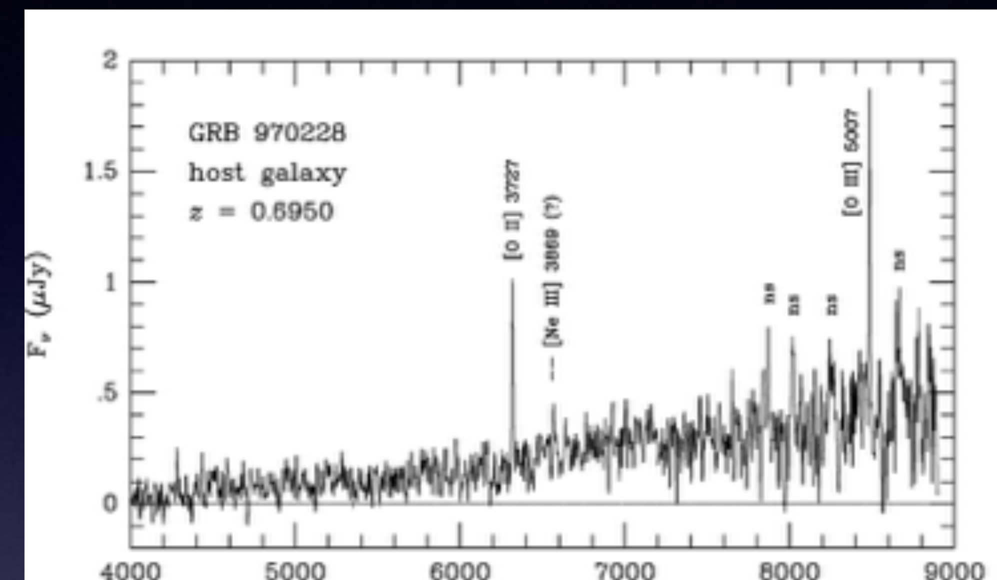


Optical or NIR critical for redshift



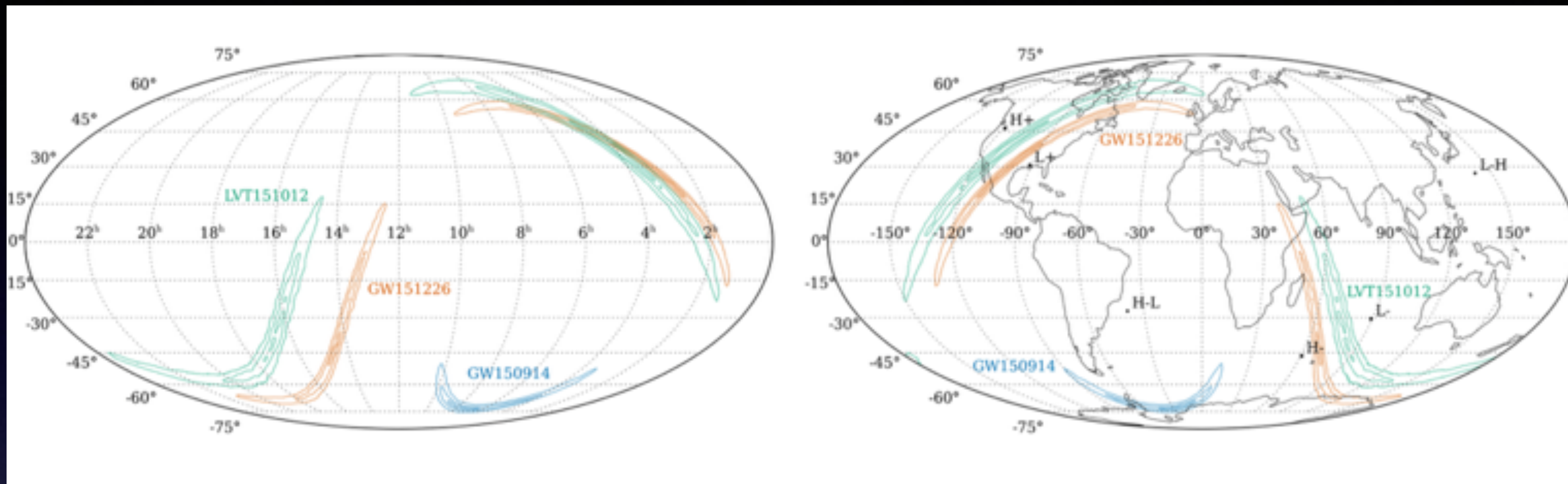
First redshift,
z = 0.835
Metzger et al. 1997, Nature

GRB970508
From the GRB after-glow emission itself



Redshift of the first GRB with optical counterpart
Bloom et al. 2001

Very large sky areas

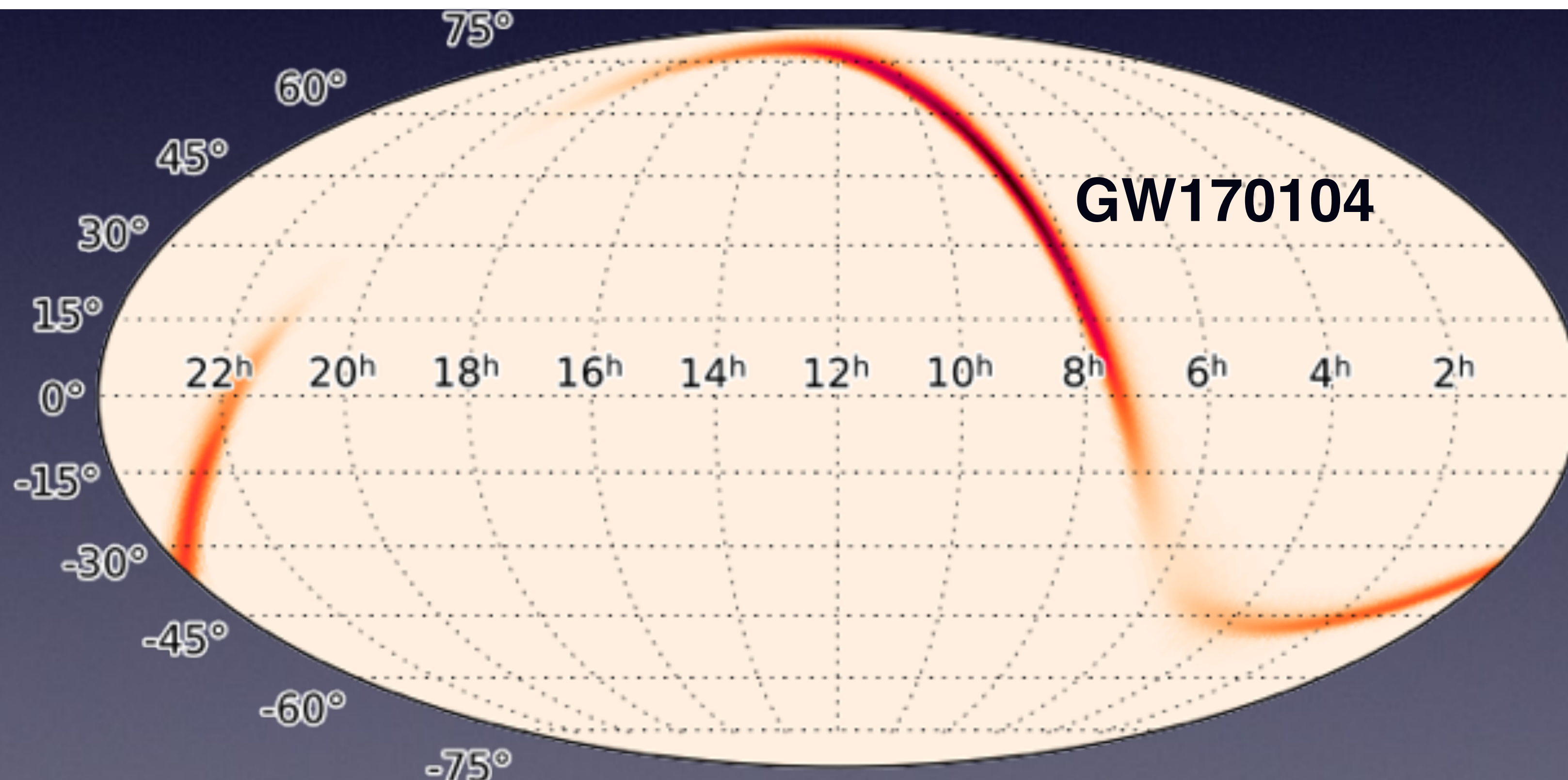


LVT151012
1600 sq deg

Abbott et al.
arXiv:1606048526

GW151226
850 sq deg

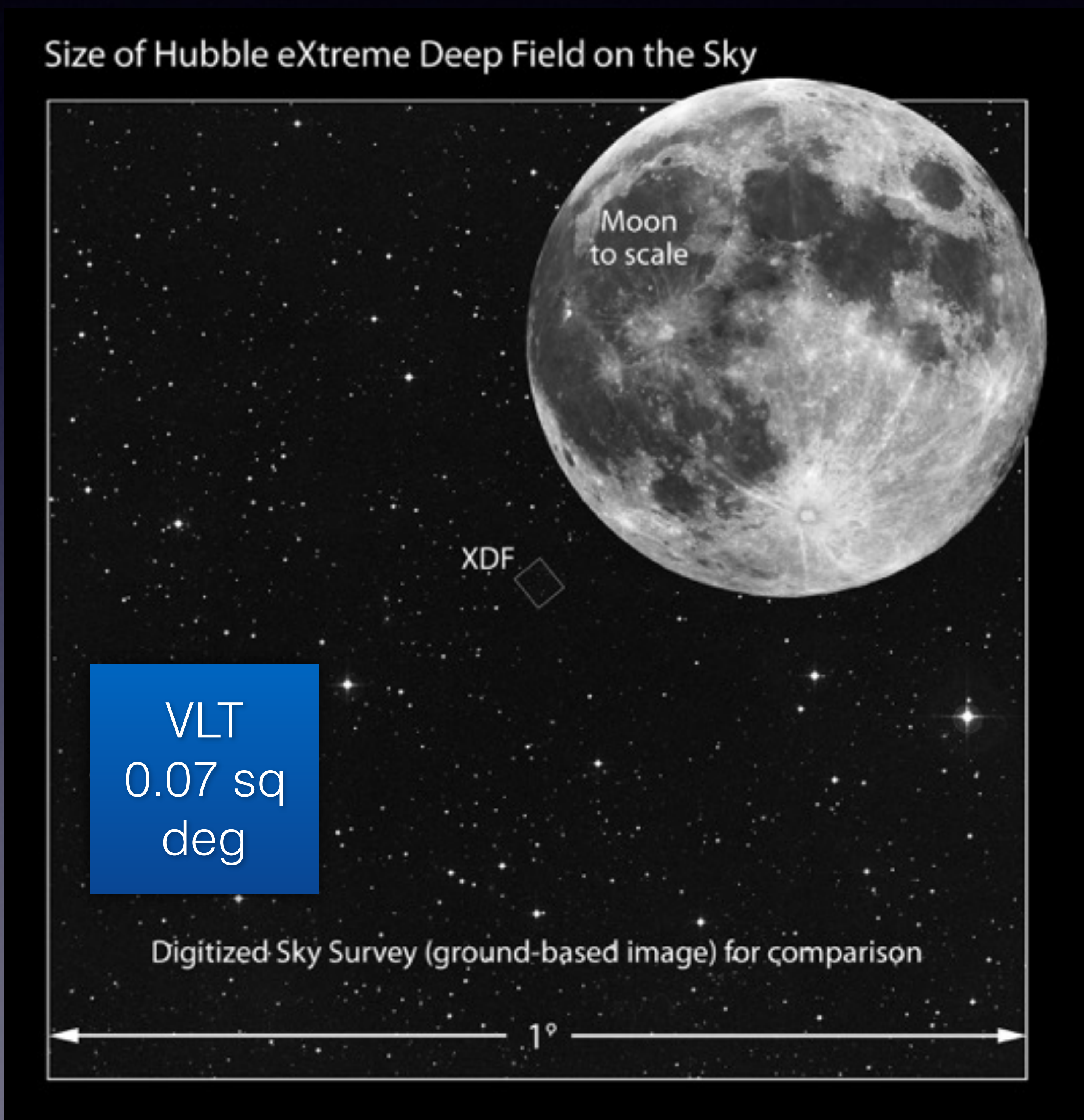
GW150914
230 sq deg



GW170104
1608 sq deg

- LIGO/Virgo are all sky monitors
- 90% enclosed probability has ~200 - 2000 deg^2

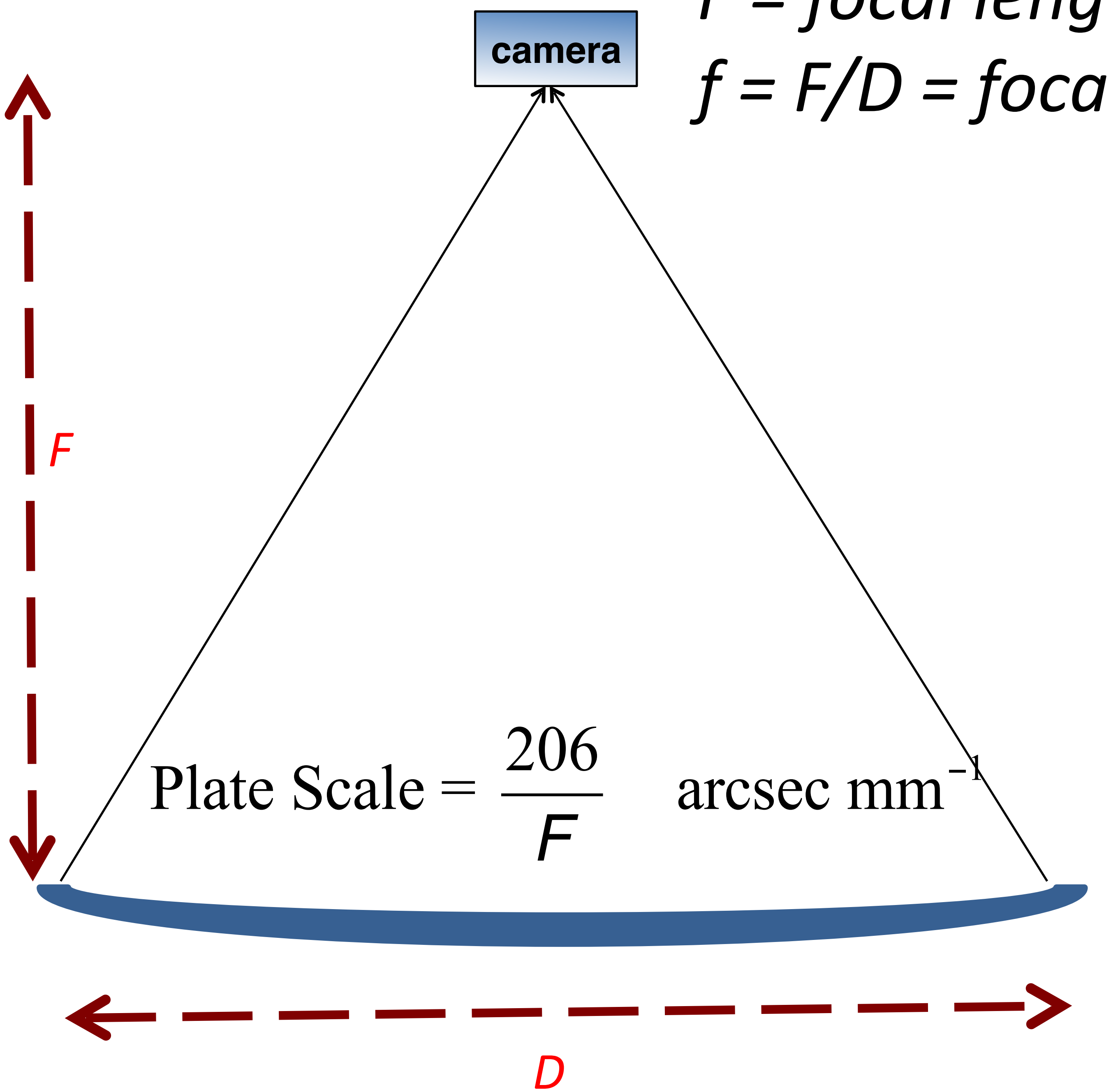
Our most sensitive telescopes



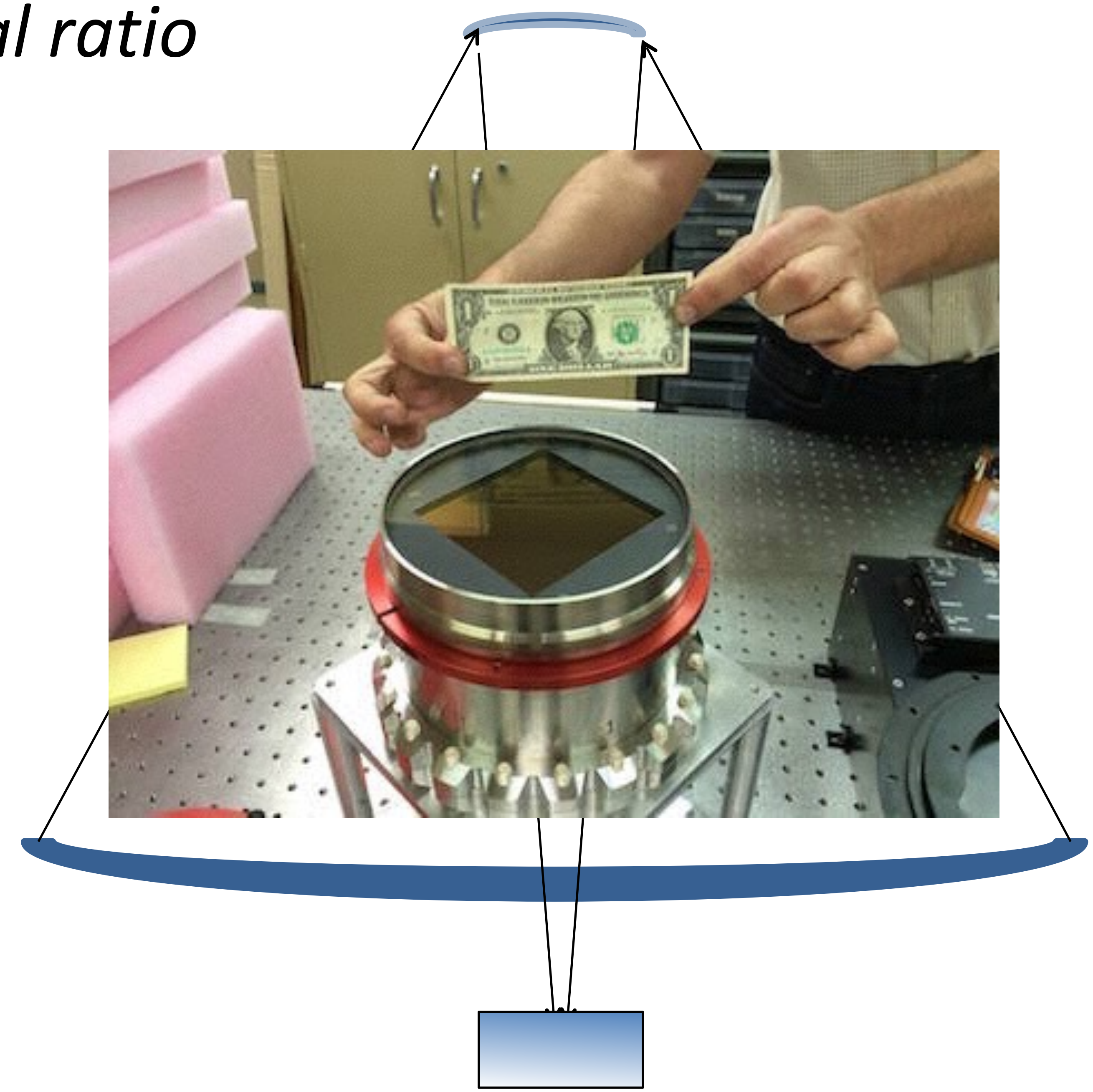
VLT
0.07 sq deg

The basics of telescope optics and dimensions

D = diameter of primary mirror
F = focal length
f = F/D = focal ratio



$$\text{Plate Scale} = \frac{206}{F} \ \text{arcsec mm}^{-1}$$



Focal length = 2F , but plate scale is half
Therefore 4 times more pixels !

ASASSN = All Aky Automated Survey for Supernova

- Each telescope has four 14cm lenses on common mount
- f/2.8
- Cameras have 2k x 2k CCD detectors
- 15 micron pixels
- What is the plate scale, or pixel scale ?
- What is the total FOV ?

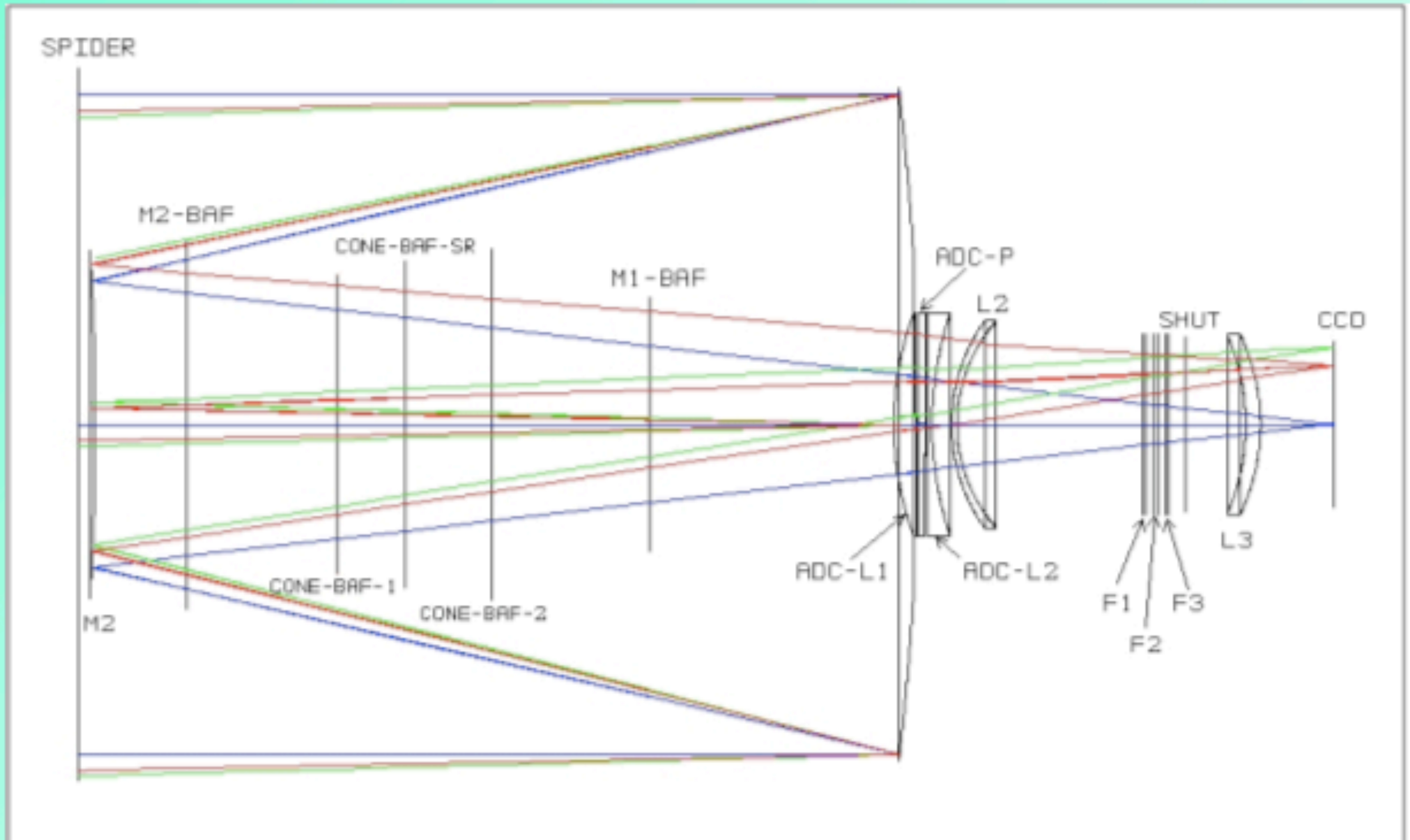
ASAS-SN

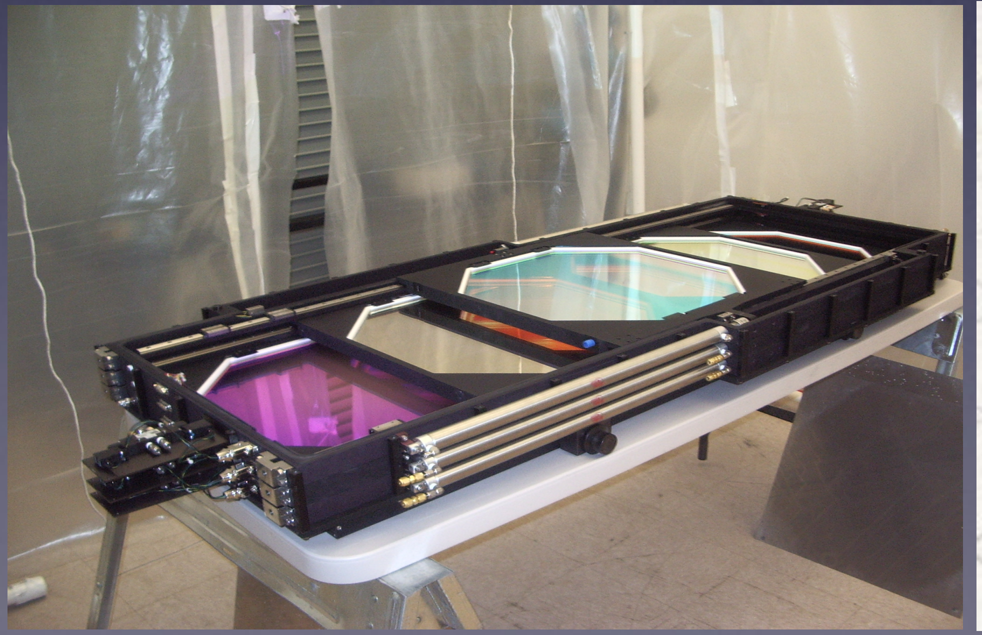
THE OHIO STATE UNIVERSITY
DEPARTMENT OF ASTRONOMY

Pan-STARRS : Panoramic survey telescope and rapid response system

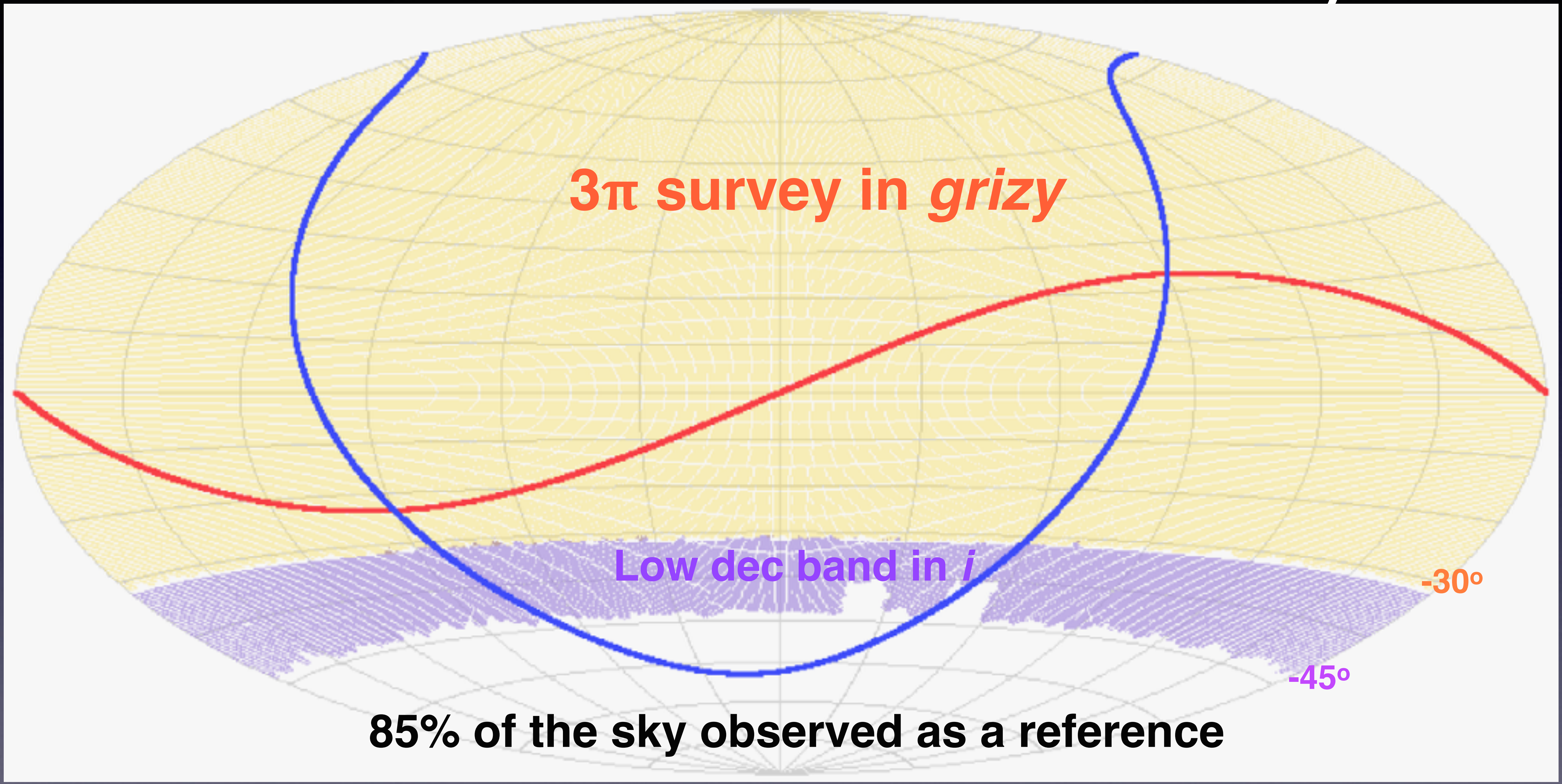
- One 1.8m telescope (2nd one being commissioned)
- D= 1.8m , F = 8m
- f/4.4
- The “Gigapixel camera” has 60 4.8k x 4.8k CCD detectors
- 10 micron pixels
- What is the plate scale, or pixel scale ?
- What is the total FOV ?

PS-1 Optical Desgin:
Ritchey-Chretien with 3 element Wide Field Corrector





The Pan-STARRS Sky

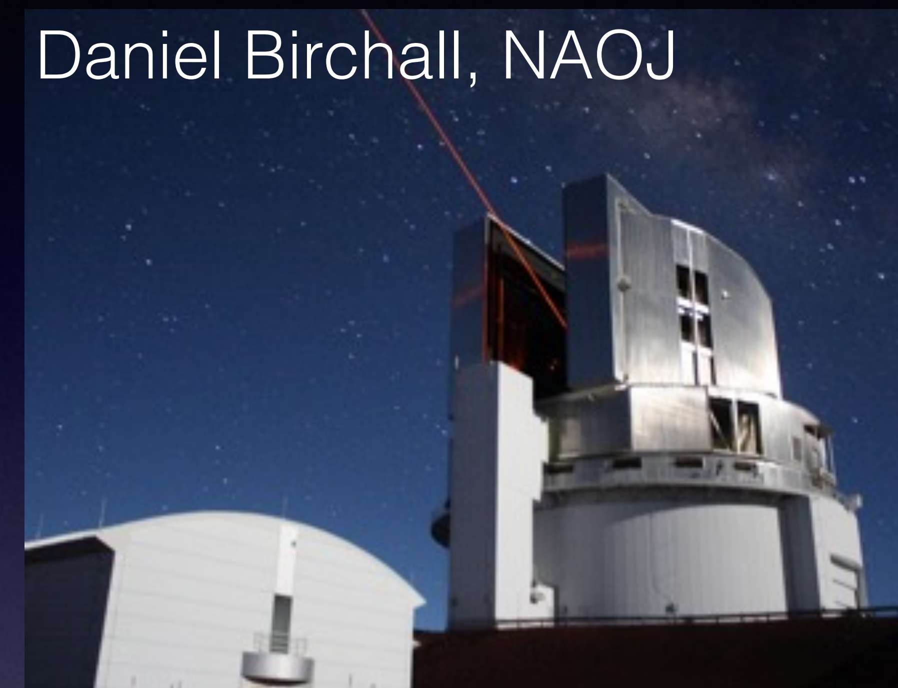


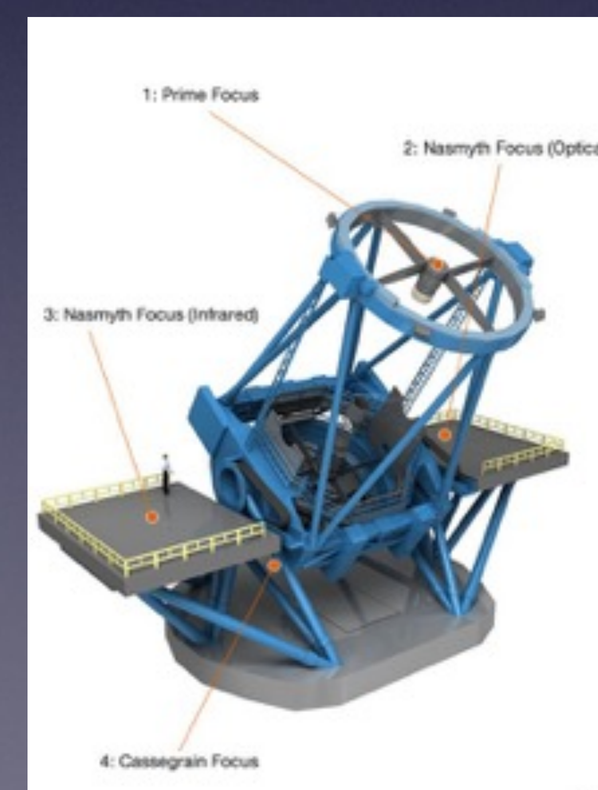
with over 100 epochs.

First public data release from Space Telescope Science Institute (MAST archive system and tools)
December 2016

Subaru 8.2m telescope

- 8.2m telescope, National Astronomical Observatory of Japan (on Mauna Kea)
- D= 8.2m , F = 15m
- f/1.9 (at Prime Focus, with corrector lens)
- The “HSC camera” has 100 2k x 4k CCD detectors
- 15 micron pixels
- What is the plate scale, or pixel scale ?
- What is the total FOV ?





sabarutelescope.org

Sensitivity

	ASASSN	Pan-STARRS	HSC
Aperture (m)	0.14	1.8	8.2
Exptime	90s	30s	30s
Filter	V	g	g
Mag lim	17.5	21.5	24.5
FOV (sq deg)	80	7	1.8

Étendue and survey power

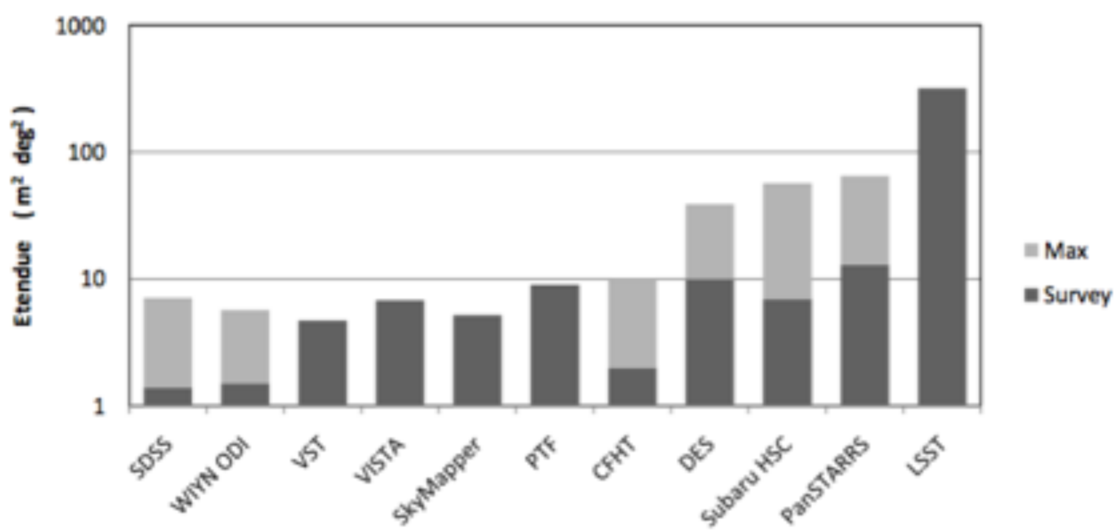


Figure 4. Étendue of current and planned survey telescopes and cameras. Some are dedicated 100% to surveys ("*Survey*"). Others could have higher effective étendue if used 100% in survey mode or if duplicated ("*Max*"). Above an étendue of 200-300 m^2deg^2 it becomes possible to undertake a single comprehensive multi-band survey of the entire visible sky serving most of the science opportunities, rather than multiple special surveys in series.

Survey power :

$P = A\Omega$

where

A = aperture area (m^2)

Ω = FOV (sq deg)

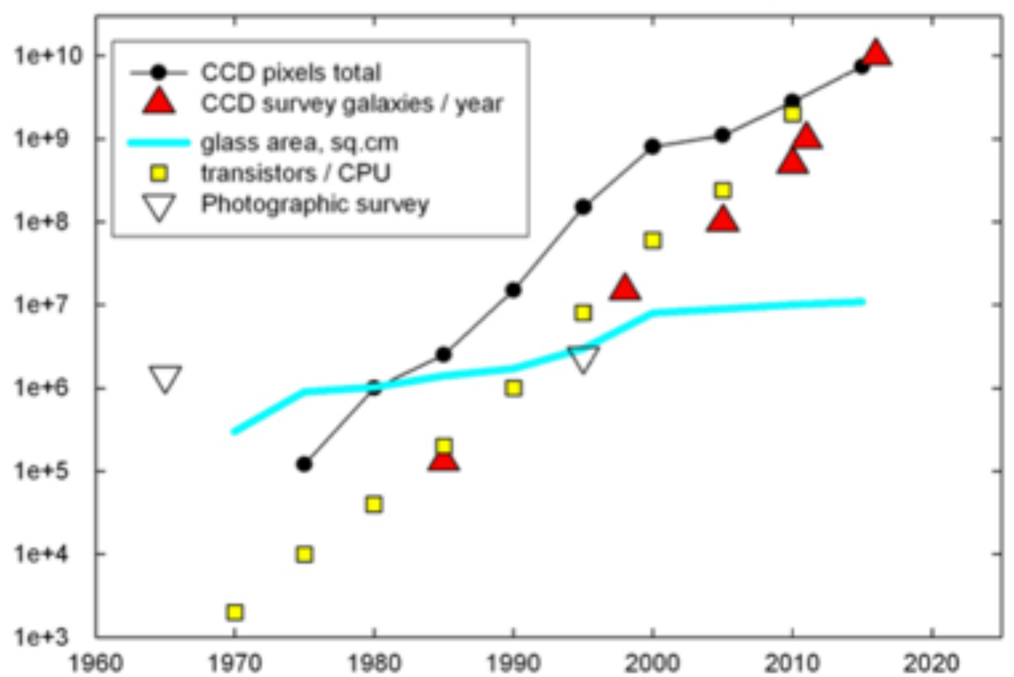


Figure 1 Data trends in optical surveys of the sky. While photographic surveys covered large area, the data were not as usable as digital data and did not go as faint. Information content (in galaxies surveyed per unit time to a given S/N ratio) in CCD digital surveys roughly follows Moore's law. Processing capability has kept up with pixel count. The most recent survey will scan the sky 100 times faster than the 2000 era survey. These next generation wide-fast-deep surveys will open the time window on the universe.

Tyson, 2010, arXiv:1009.2263

Totals are <u>all</u> facilities

Re-cap of Part 1

- LIGO produces large skymaps of order 200-2000 sq degrees
- Challenging to map these areas
- Optical is critical to identify an electromagnetic counterpart and its galaxy and redshift and distance
- Distance gives energy emitted - crucial
- Wide-field optical surveys : have reviewed the challenges, techniques and capabilities
- Now … what might we expect to be able to detect ?

END OF PART 1

OBSERVATIONS OF THE GRB AFTERGLOW ATLAS17AEU AND ITS POSSIBLE ASSOCIATION WITH GW170104

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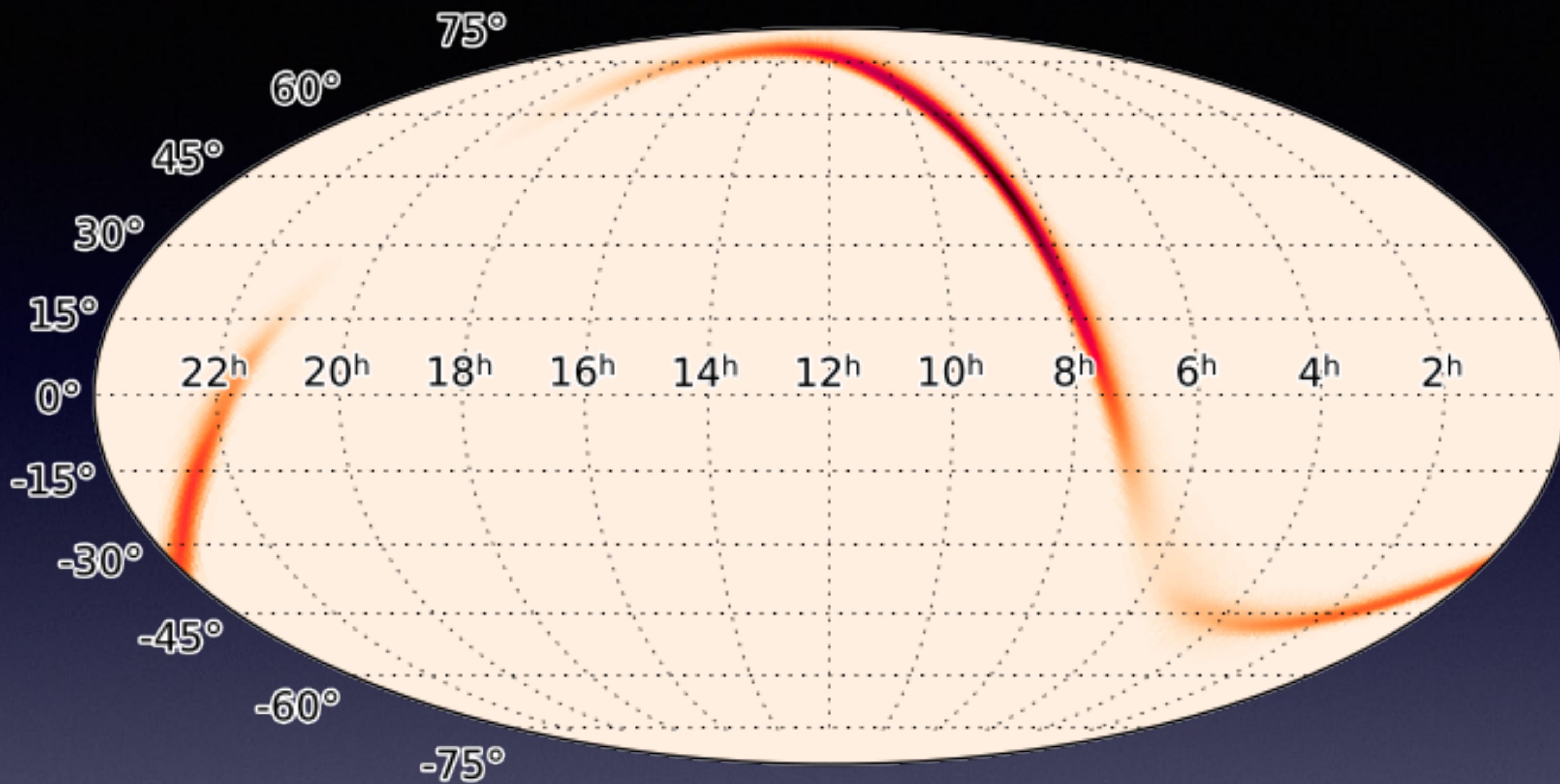
ABSTRACT

We report the discovery and multi-wavelength data analysis of the peculiar optical transient, ATLAS17aeu. This transient was identified in the skymap of the LIGO gravitational wave event GW170104 by our ATLAS and Pan-STARRS coverage. ATLAS17aeu was discovered 23.1hrs after GW170104 and rapidly faded over the next 3 nights, with a spectrum revealing a blue featureless continuum. The transient was also detected as a fading x-ray source by Swift and in the radio at 6 and 15 GHz. A gamma ray burst GRB170105 was detected by 3 satellites 19.04 hrs after GW170104 and 4.10 hrs before our first optical detection. We analyse the multi-wavelength fluxes in the context of the known GRB population and discuss the observed sky rates of GRBs and their afterglows. We find it statistically likely that ATLAS17aeu is an afterglow associated with GRB170105, with a chance coincidence ruled out at the 99% confidence or 2.6σ. A long, soft GRB within a redshift range of $1 \lesssim z \lesssim 2.9$ would be consistent with all the observed multi-wavelength data. The Poisson probability of a chance occurrence of GW170104 and ATLAS17aeu is $p = 0.04$. This is the probability of a chance coincidence in 2D sky location and in time. These observations indicate that ATLAS17aeu is plausibly a normal GRB afterglow at significantly higher redshift than the distance constraint for GW170104 and therefore a chance coincidence. However if a redshift of the faint host were to place it within the GW170104 distance range, then physical association with GW170104 should be considered.

Keywords: gravitational waves, stars: black holes, gamma-ray burst: general, gamma-ray burst: individual: GRB170105

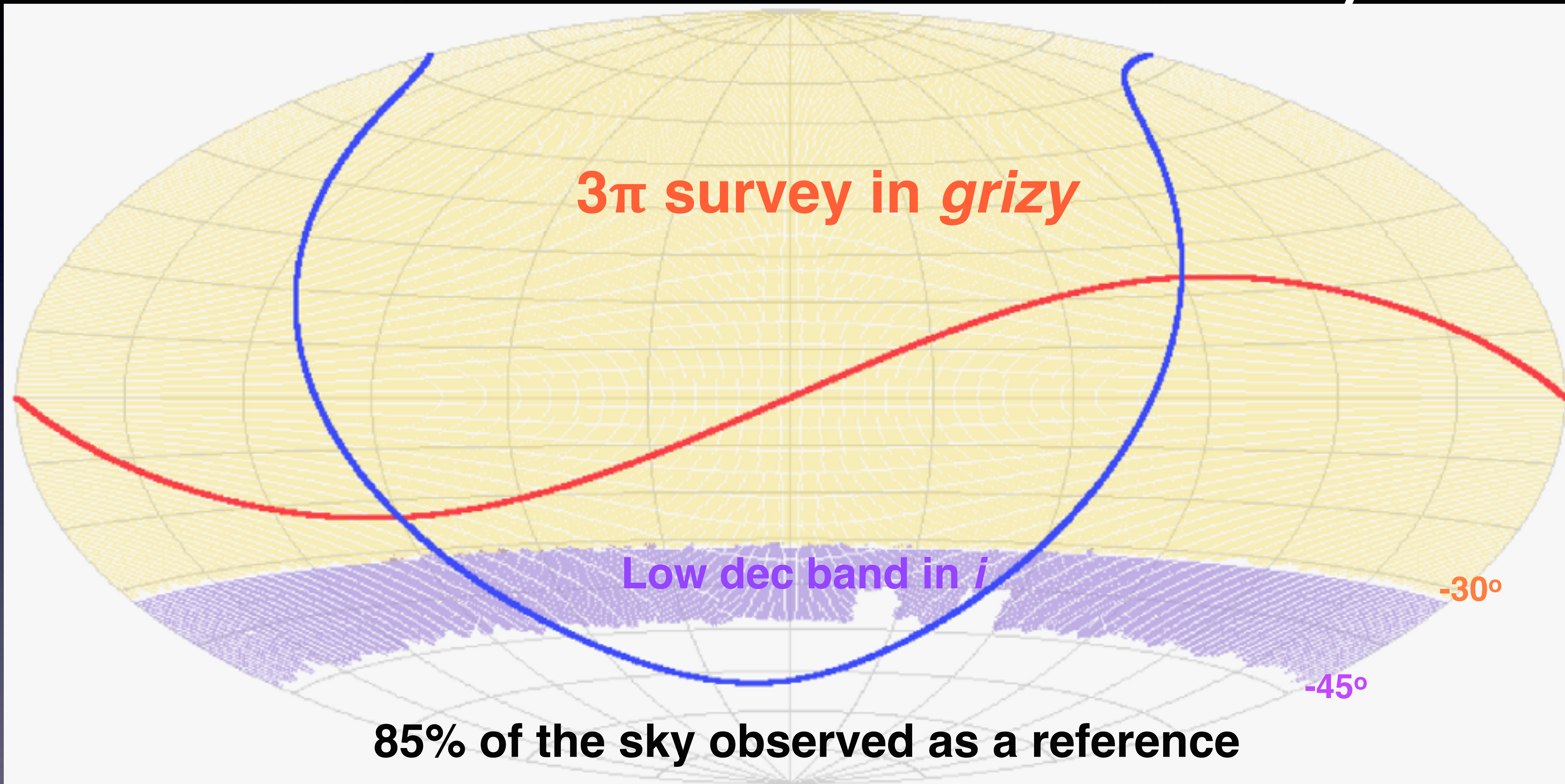


MJD=57756. Shortly after the break, the internal system distributed the alert of a candidate gravitational wave (GW) transient, designated as event G268556 at 2017-01-04 10:11:58.599 UTC or MJD = 57757.42498378. It was later given the name GW170104 after the offline analysis provided very strong confirmation of its astrophysical origin (as presented in Abbott et al. 2017). The 90% probability area of the associated GW skymap is 2000 square degrees or 5% of the sky. Throughout this paper we use

ATLAS coverage : 42 %

Pan-STARRS : 43 %

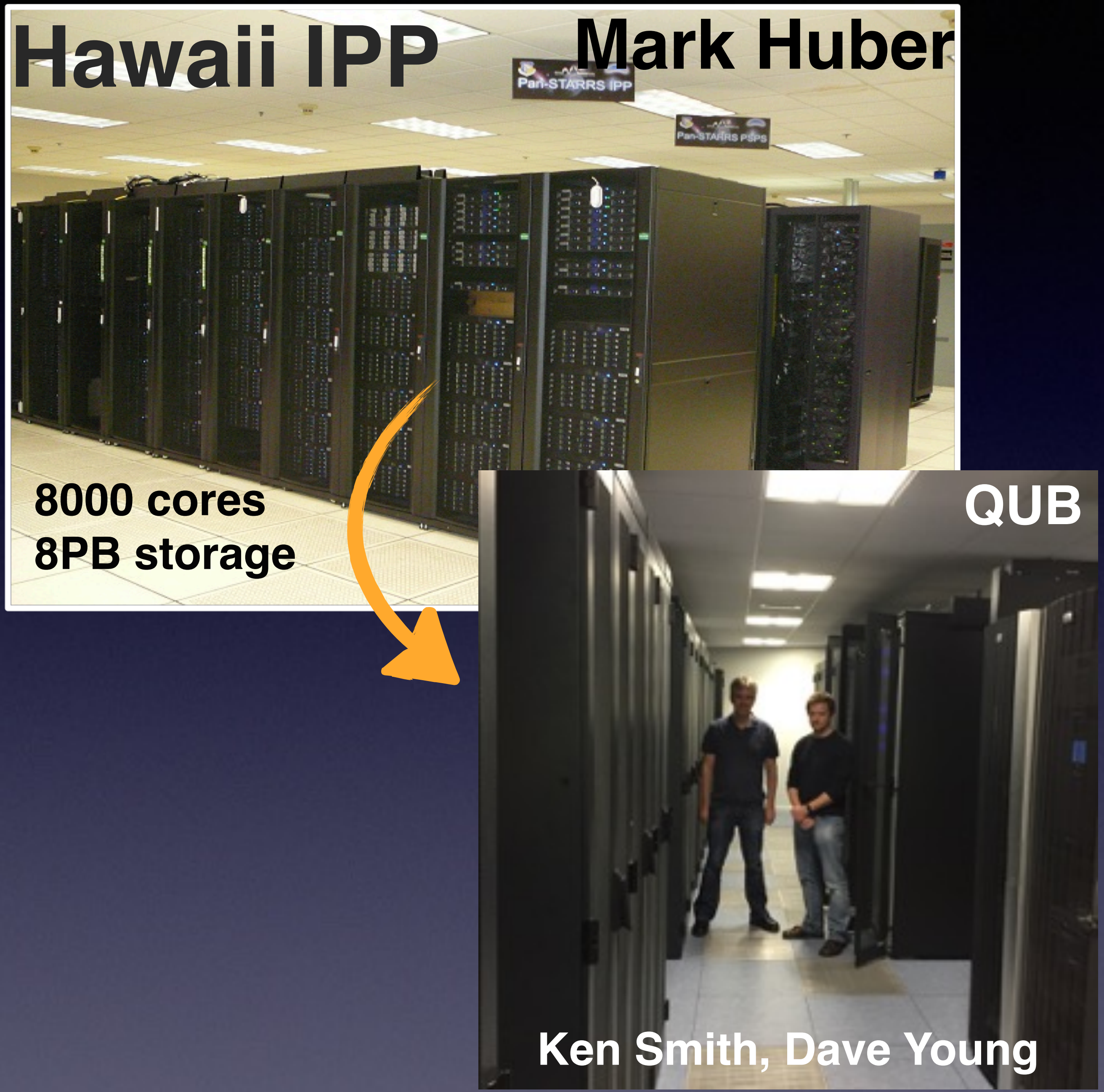
The Pan-STARRS Sky



with over 100 epochs.

First public data release from Space Telescope Science Institute (MAST archive system and tools)
December 2016

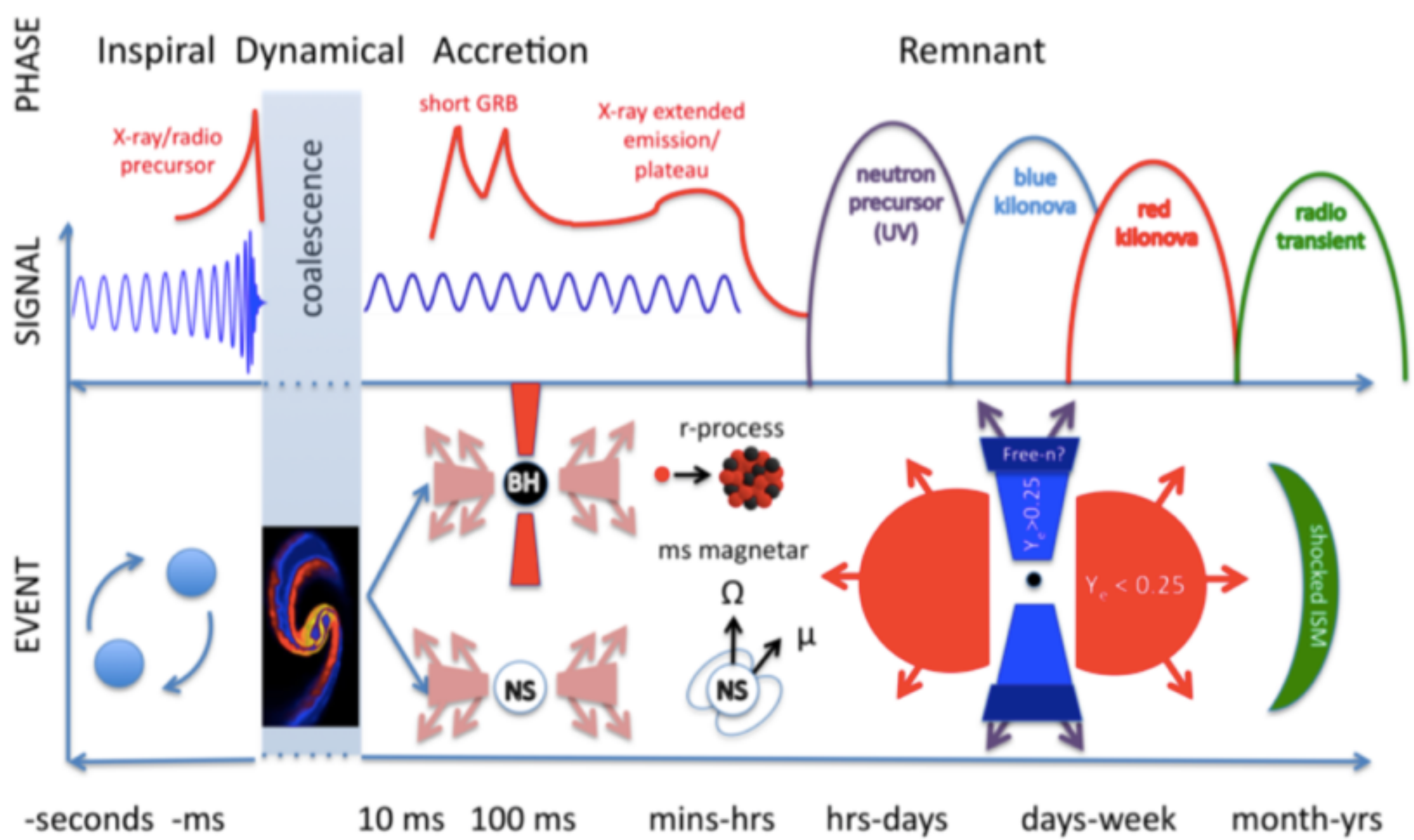
Pan-STARRS Cyber-Infrastructure



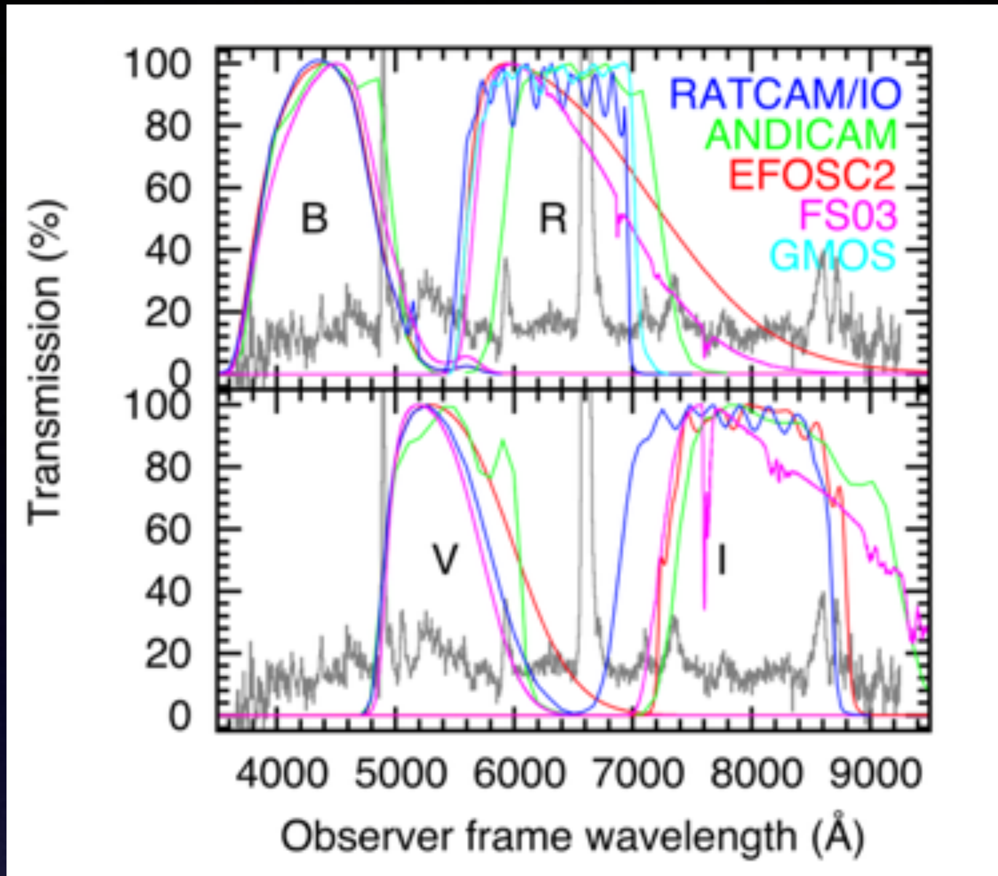
- Hawaii : Image Processing Pipeline
- PSPS : hierarchical database. All sky catalogues
- High i/o rate, large cpu requirement. Large local storage required - large computer science project
- QUB Transient Science Server in Belfast

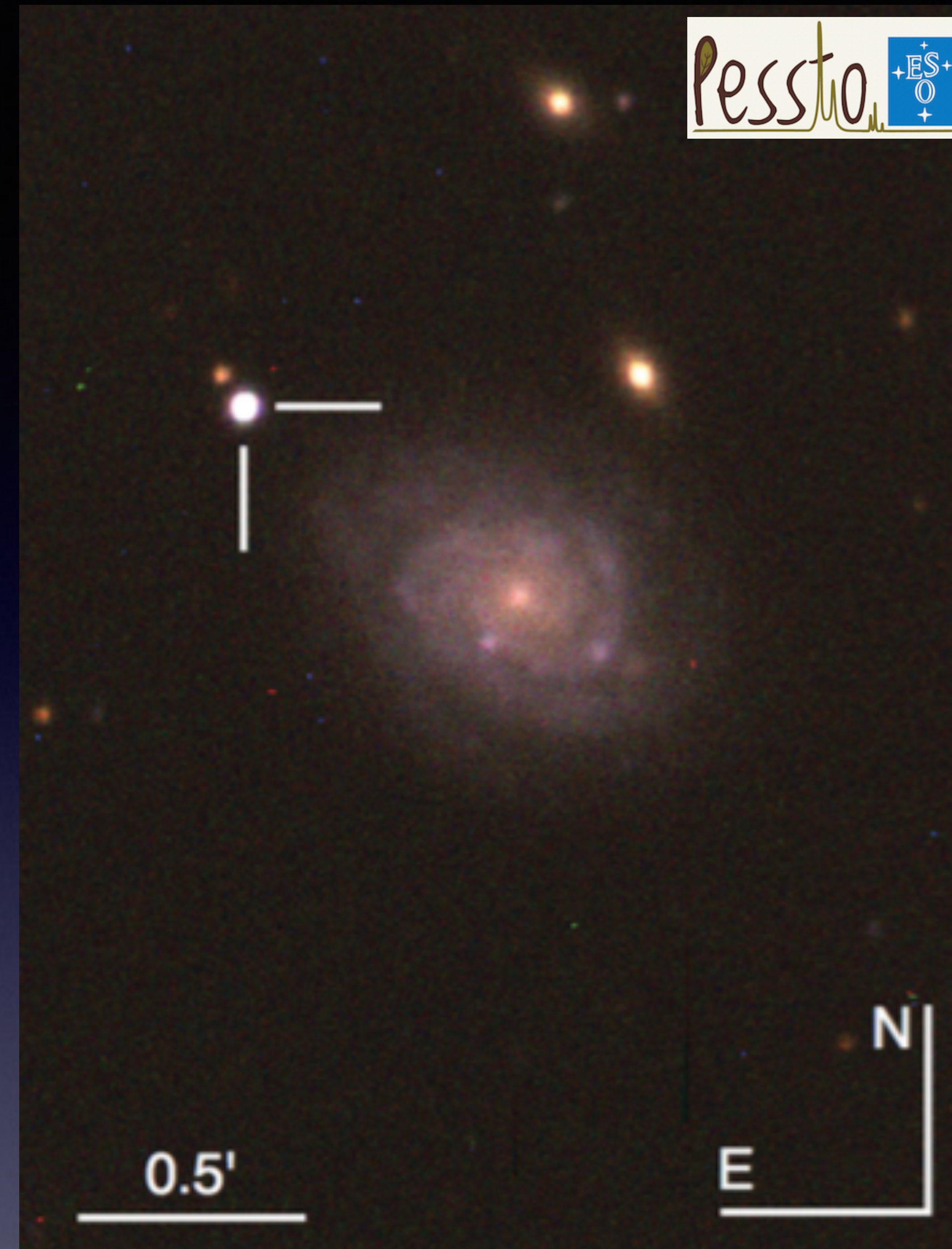
Ship catalogues : 10^7 detections per day to Belfast “Transient Science Server”
Database, algorithms - machine learning and boosted decision trees. Classify all transients

GW and EM transients from NS-NS or NS-BH mergers

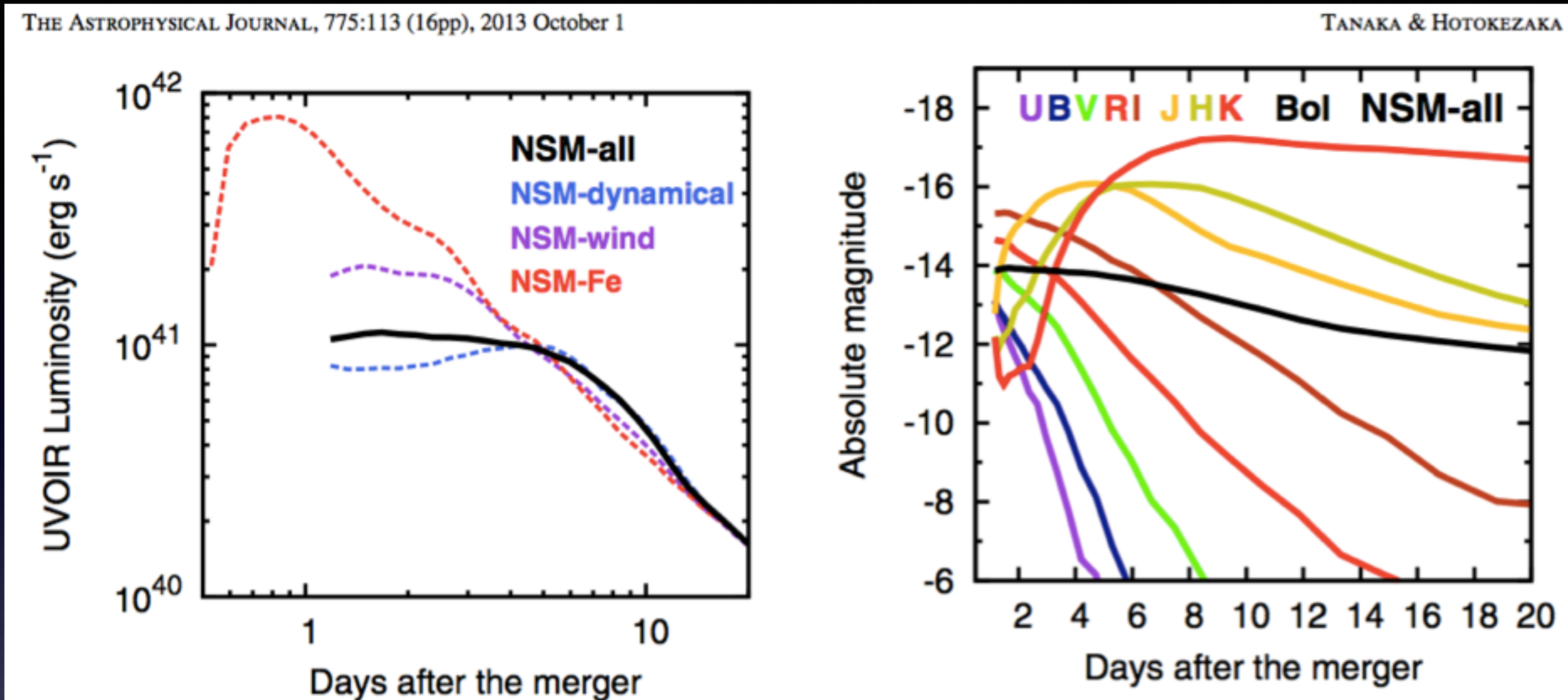


Fernandez & Metzger 2015





Fraser et al. 2013



Radiative transfer calculations, critical.

Must include Ga to U

Opacity higher by factor 100 than in normal supernova

Tanaka & Hotokezaka 2013

Barnes and Kasen 2013
Kasen, Badness & Barnes 2013
Kasen, Fernandez & Metzger 2015
Quantitative radiative transfer models with different components

Basic calcs

Distance Modulus :

$m_f - M_f = 5\log_{10} d - 5 + A_f$ *(where d in pc)*

$= 5\log_{10} d + 25 + A_f$ *(where d in Mpc)*

Luminosity and mags useful rule of thumb (but you will be working out exact!)

$V = 0$ *corresponds to* $F = 3.75 \times 10^{-9}$ *erg/s/cm²/Ang*

can work out

$V \sim -16$ *is about* $F = 10^{42}$ *erg/s*

Values to keep in your head

Distance	Dist mod	z (redshift)
1 Mpc	25	0.00025
10 Mpc	30	0.0025
100 Mpc	35	0.025
1000 Mpc	40	0.21

What does this redshift depend upon ?

Radioactive transfer models of NS-NS mergers

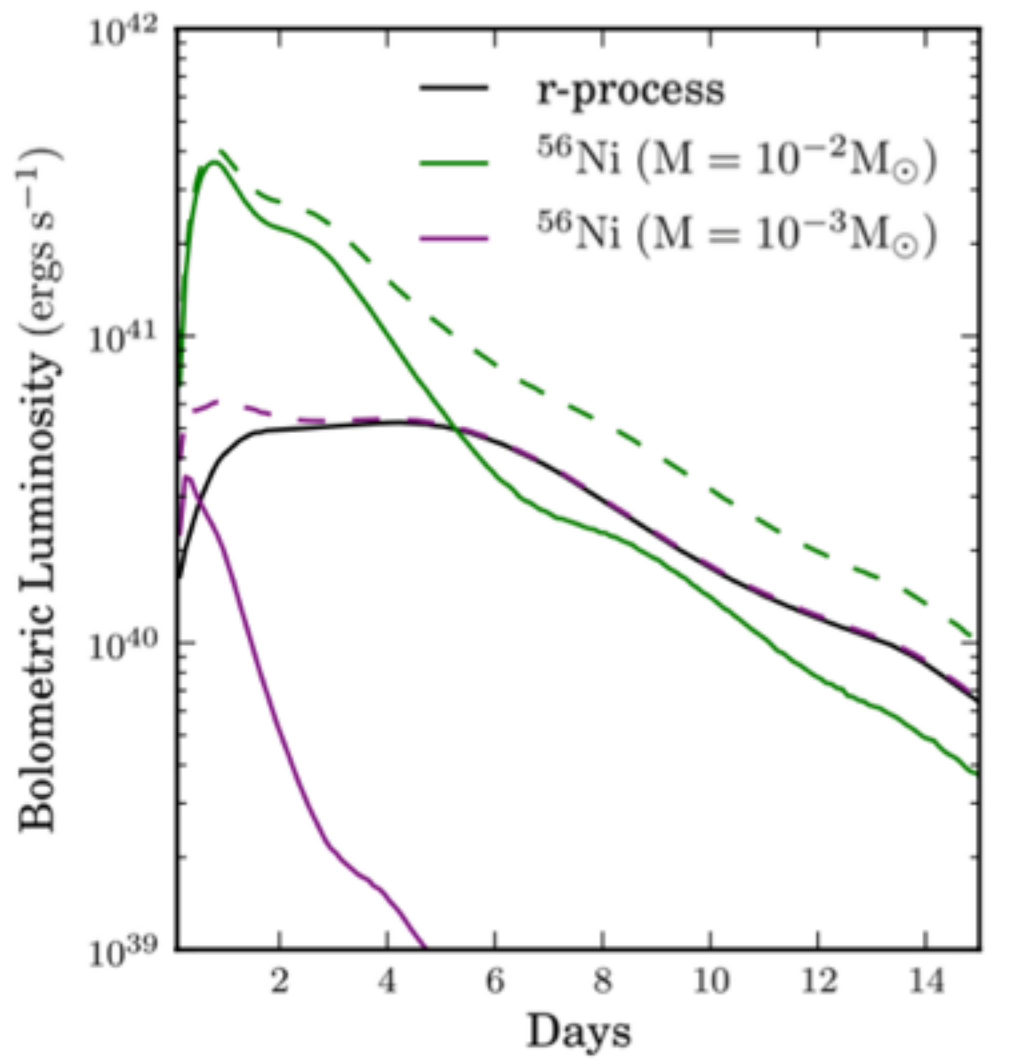
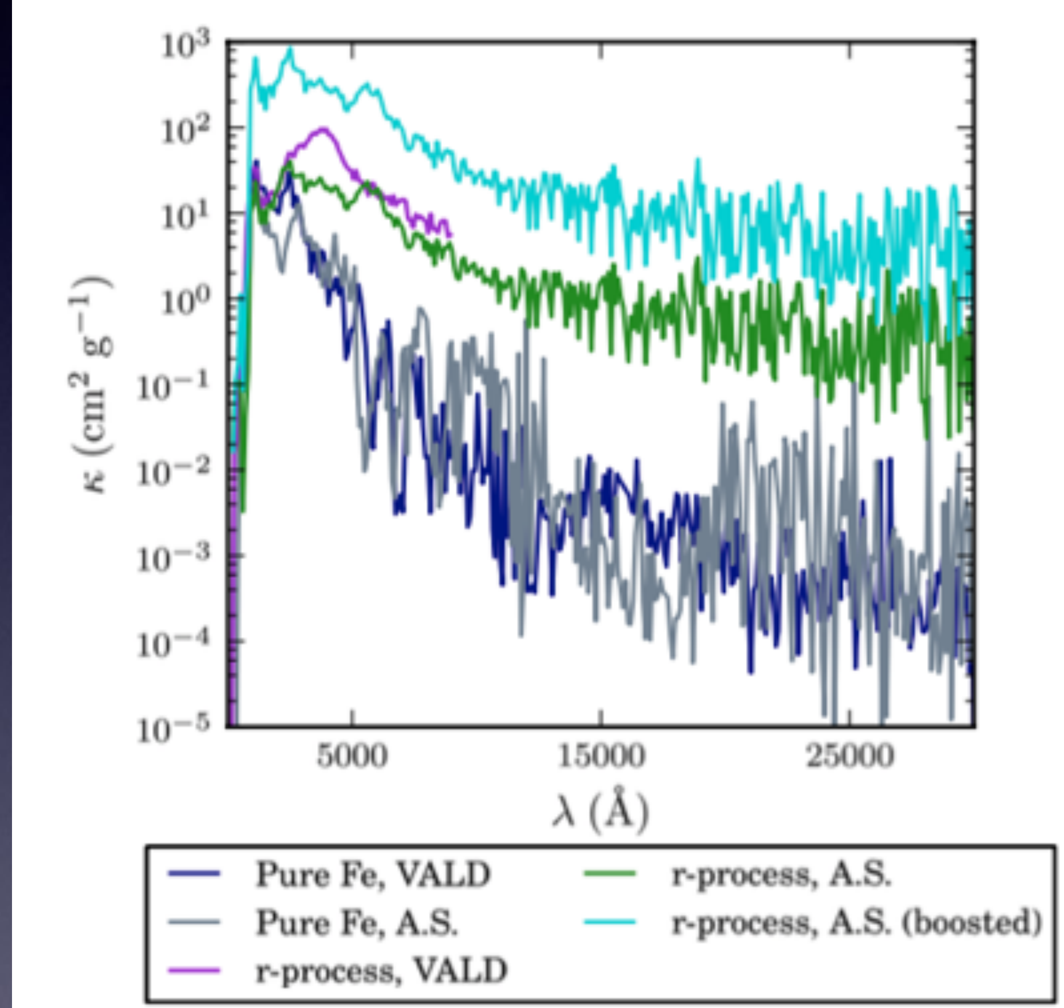
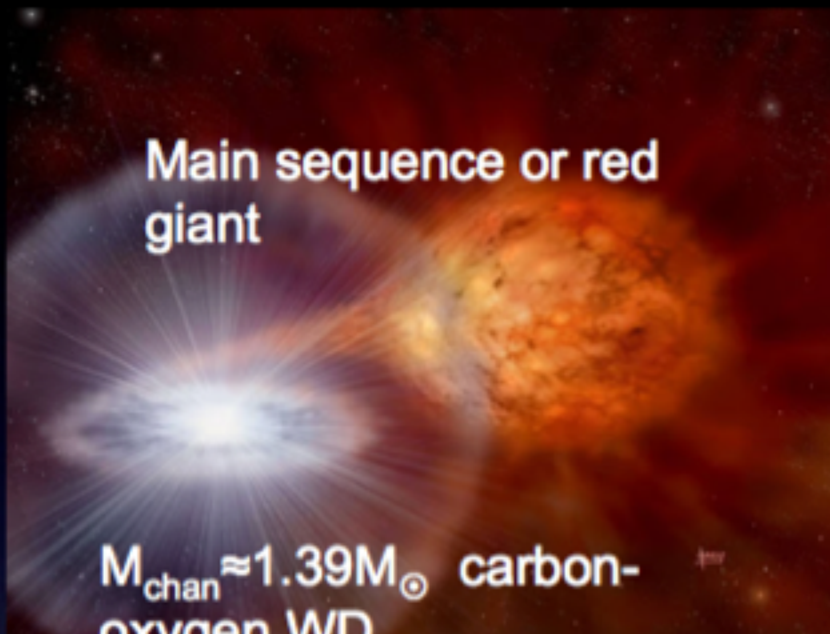


Figure 8. Bolometric light curves for models that include two components: *r*-process material (from tidal tails) and ^{56}Ni (from a disk wind) in dot-dashed lines. We show the fiducial model *r*-process light curve in a black-dashed line and light curves for two different masses of ejected ^{56}Ni in solid lines.



Barnes and Kasen 2013
Quantitative radiative transfer models with different components

Type Ia : thermonuclear



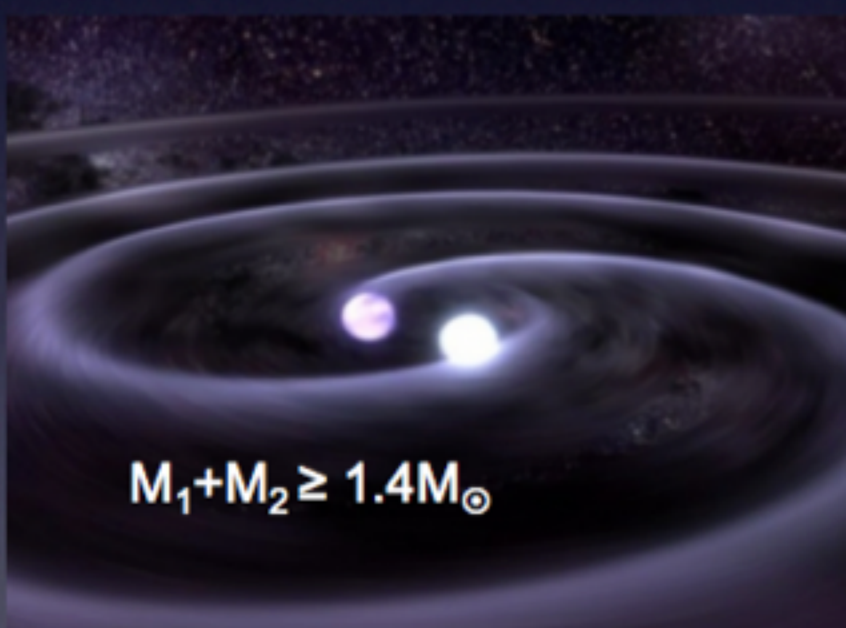
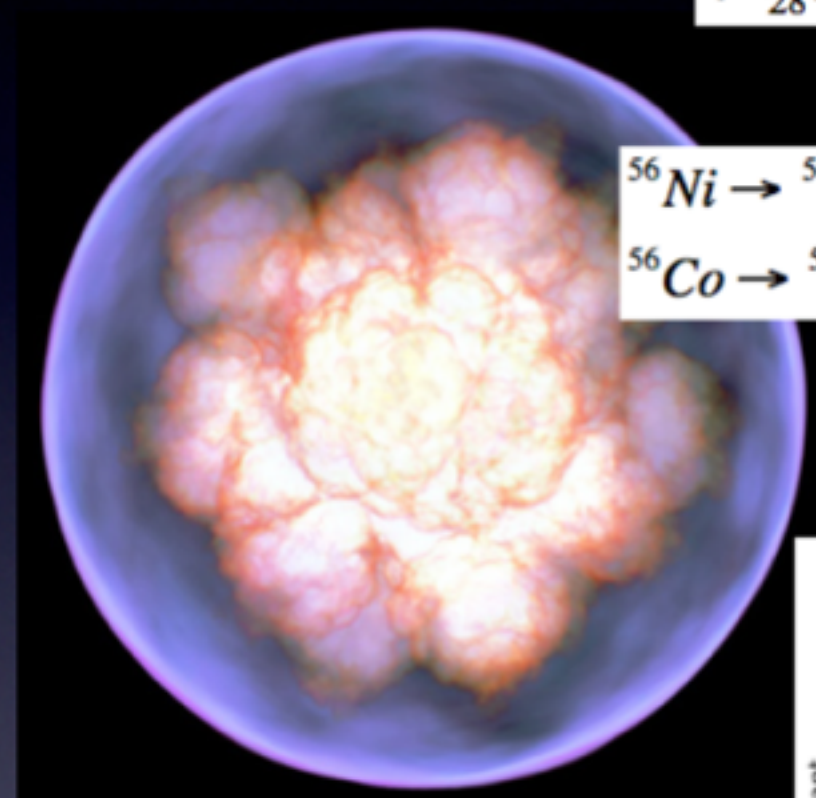
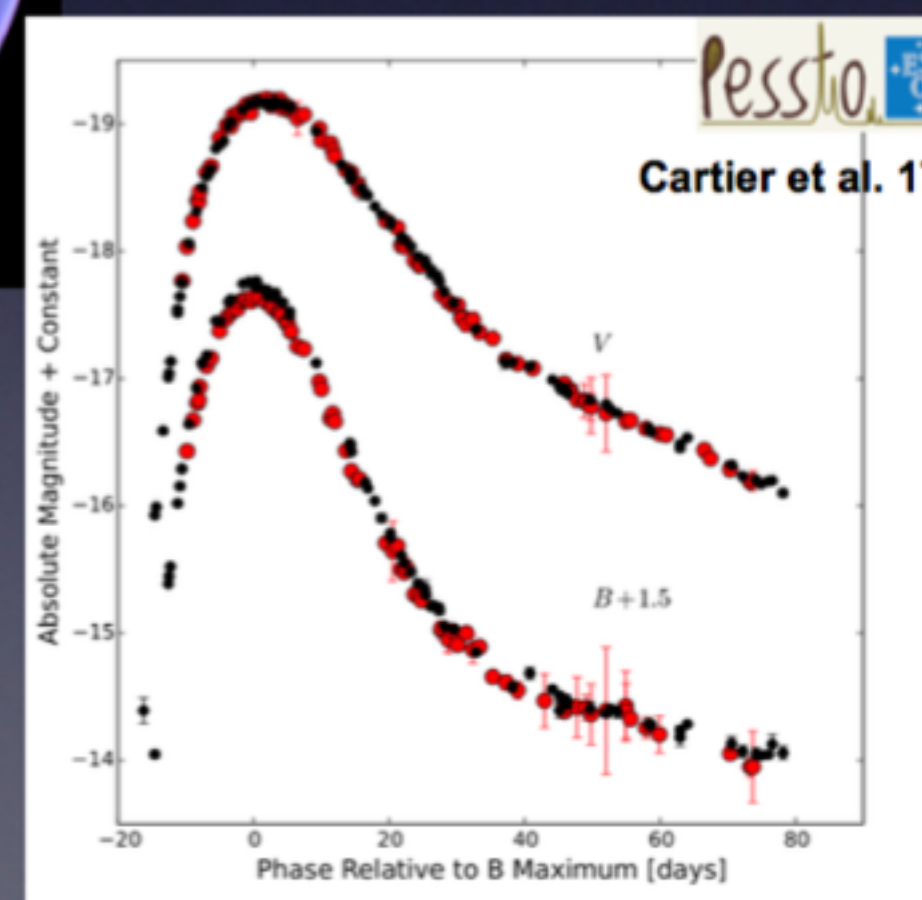


Image Credits : D. Hardy, GSFC/D. Berry/F. Ropke

$$^{12}_{6}C,\ ^{16}_{8}O \rightarrow\ ^{24}_{12}Mg,\ ^{28}_{14}Si,\ ^{32}_{16}S,\ ^{40}_{20}Ca$$
$$+\ ^{56}_{28}Ni\ (0.7 M_{Sol})$$



$$^{56}Ni \rightarrow\ ^{56}Co + e^{+} + \nu_e + \gamma \qquad (\tau_{1/2} = 6 \text{ days})$$
$$^{56}Co \rightarrow\ ^{56}Fe + e^{+} + \nu_e + \gamma \qquad (\tau_{1/2} = 77.1 \text{ days})$$



What we might expect

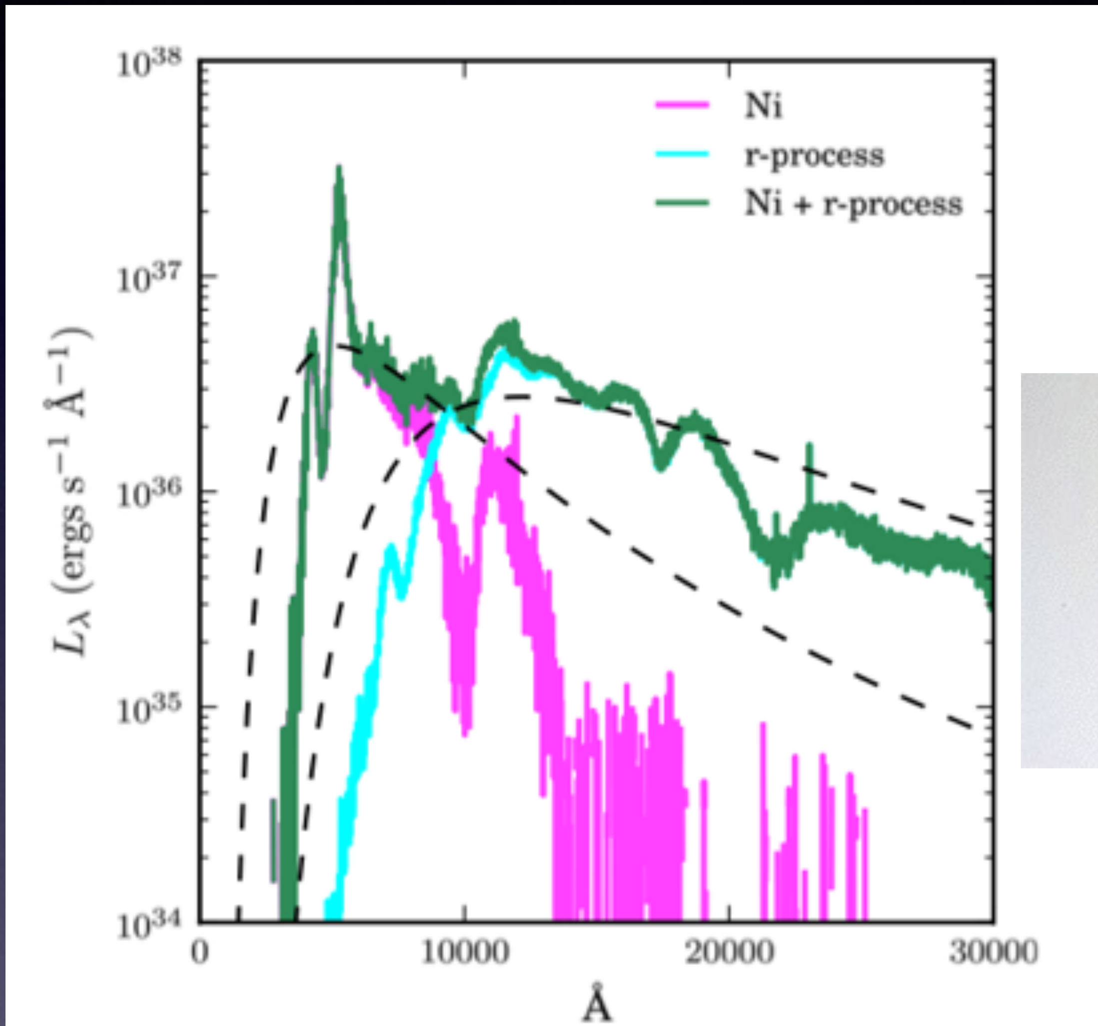


Figure 10. A combined ^{56}Ni and *r*-process spectrum at $t = 7$ days, taking $M_{\rm ni} = M_{\rm rp} = 10^{-2}\, M_\odot$. The peak at blue wavelengths is due to the ^{56}Ni, while the *r*-process material supplies the red and infrared emission. The best-fit blackbody curves to the individual spectra are overplotted in dashed black lines ($T_{\rm ni} \simeq 5700$ K, $T_{\rm rp} \simeq 2400$ K). The combined spectrum generally resembles a superposition of two blackbodies at different temperatures.

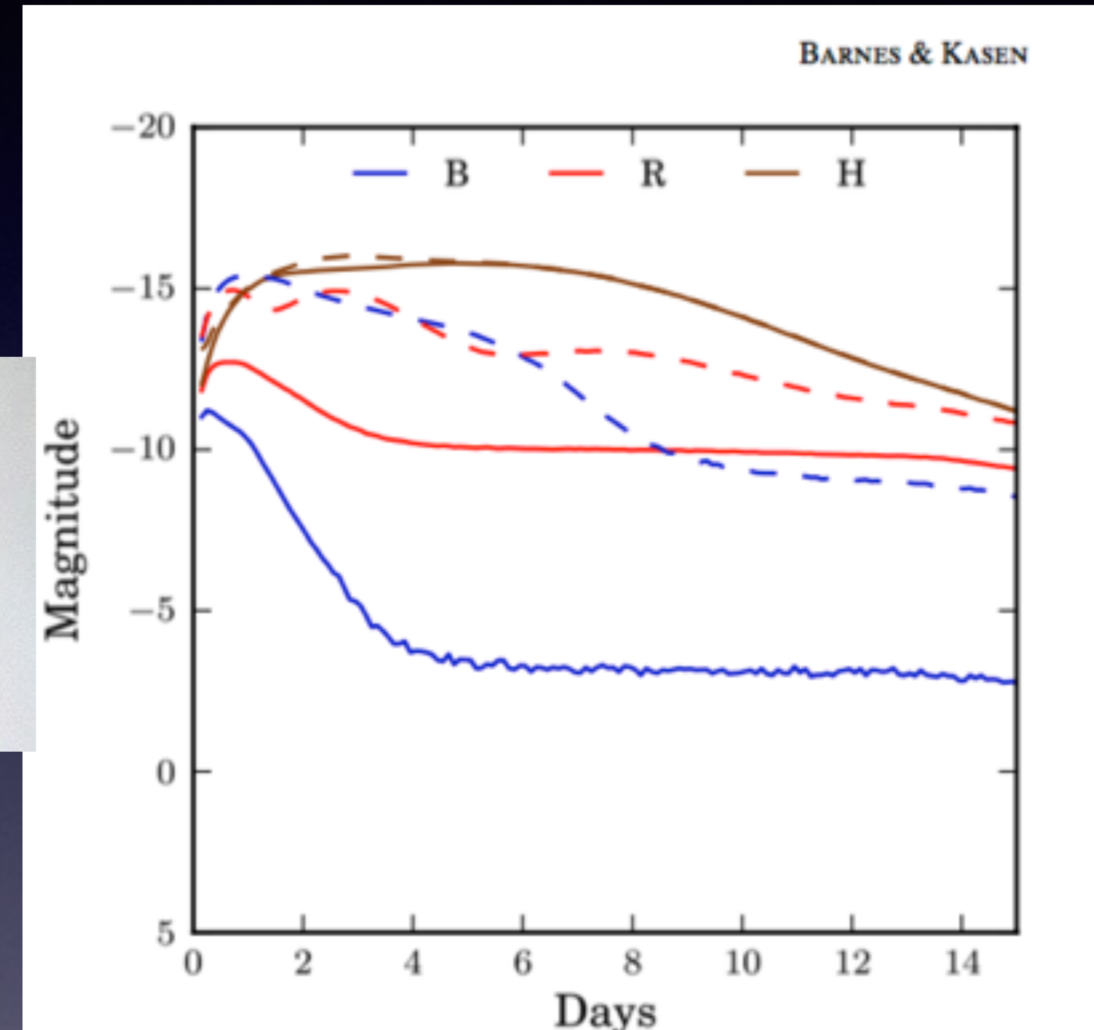


Figure 9. A comparison of select broadband light curves for a pure *r*-process transient (solid lines) and an *r*-process transient occurring in concert with a ^{56}Ni-powered outflow (dashed lines). The bluer SED from the ^{56}Ni shifts the magnitudes of the bluer bands of the combined SED upward relative to a pure *r*-process model. This plot is for $M_{\rm ni} = M_{\rm rp} = 10^{-2}\, M_\odot$.

Barnes and Kasen 2013

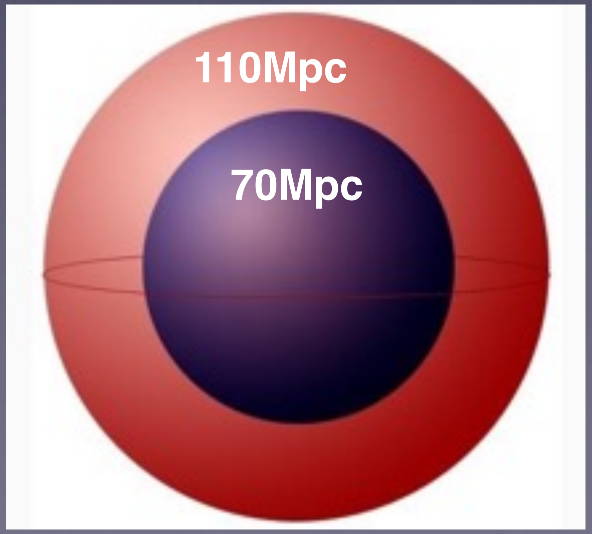
What distance and volume might we be sensitive to ?

- What do we need to consider ?

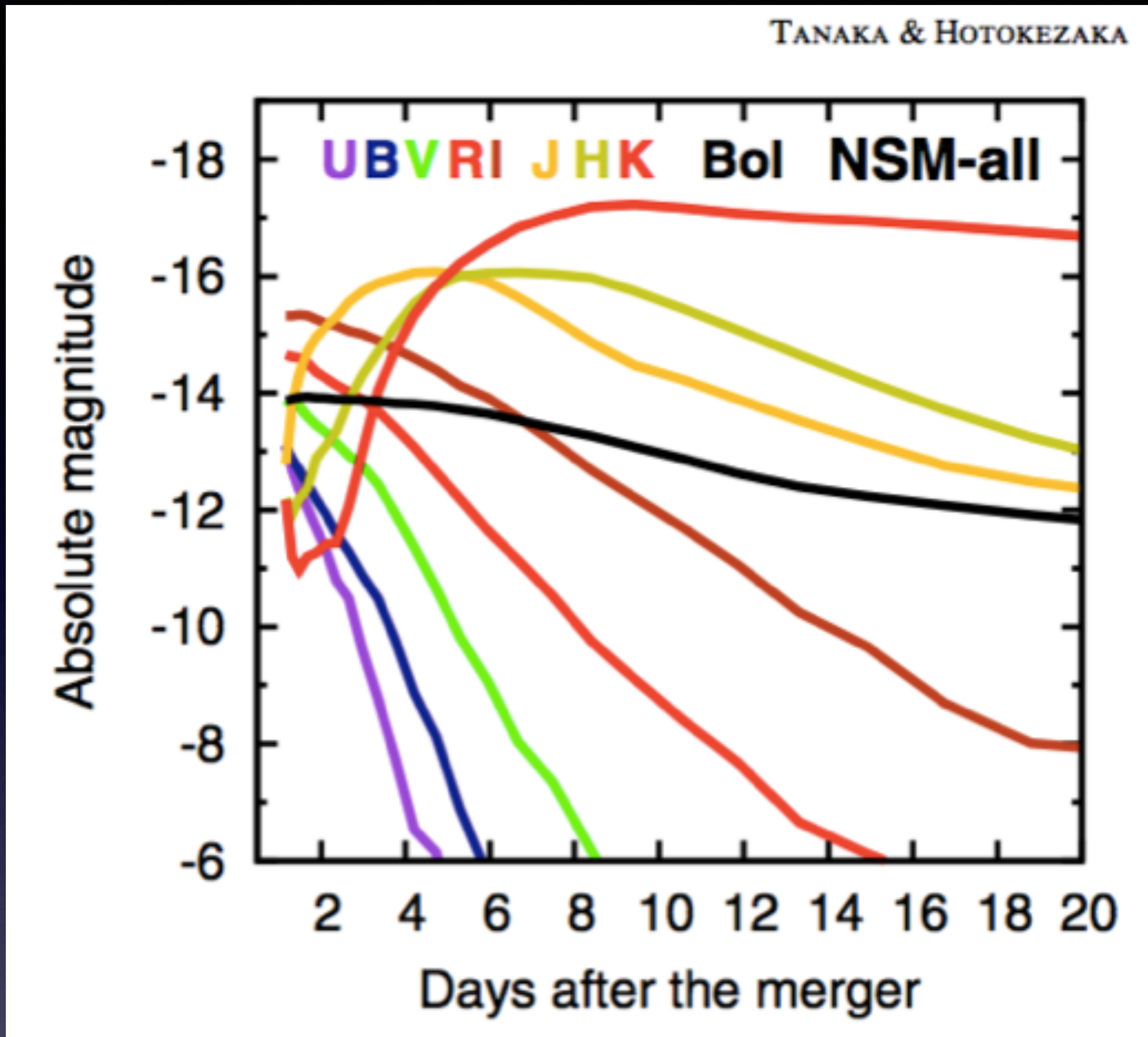
- What distance is LIGO (+ VIRGO) sensitive to ?

NS - NS mergers (1.4 solar masses) d < 70 Mpc

NS - BH mergers (1.4 + 5 solar masses) d < 110 Mpc



$V_{110}/V_{70} = (110/70)^3 \simeq 3.9$



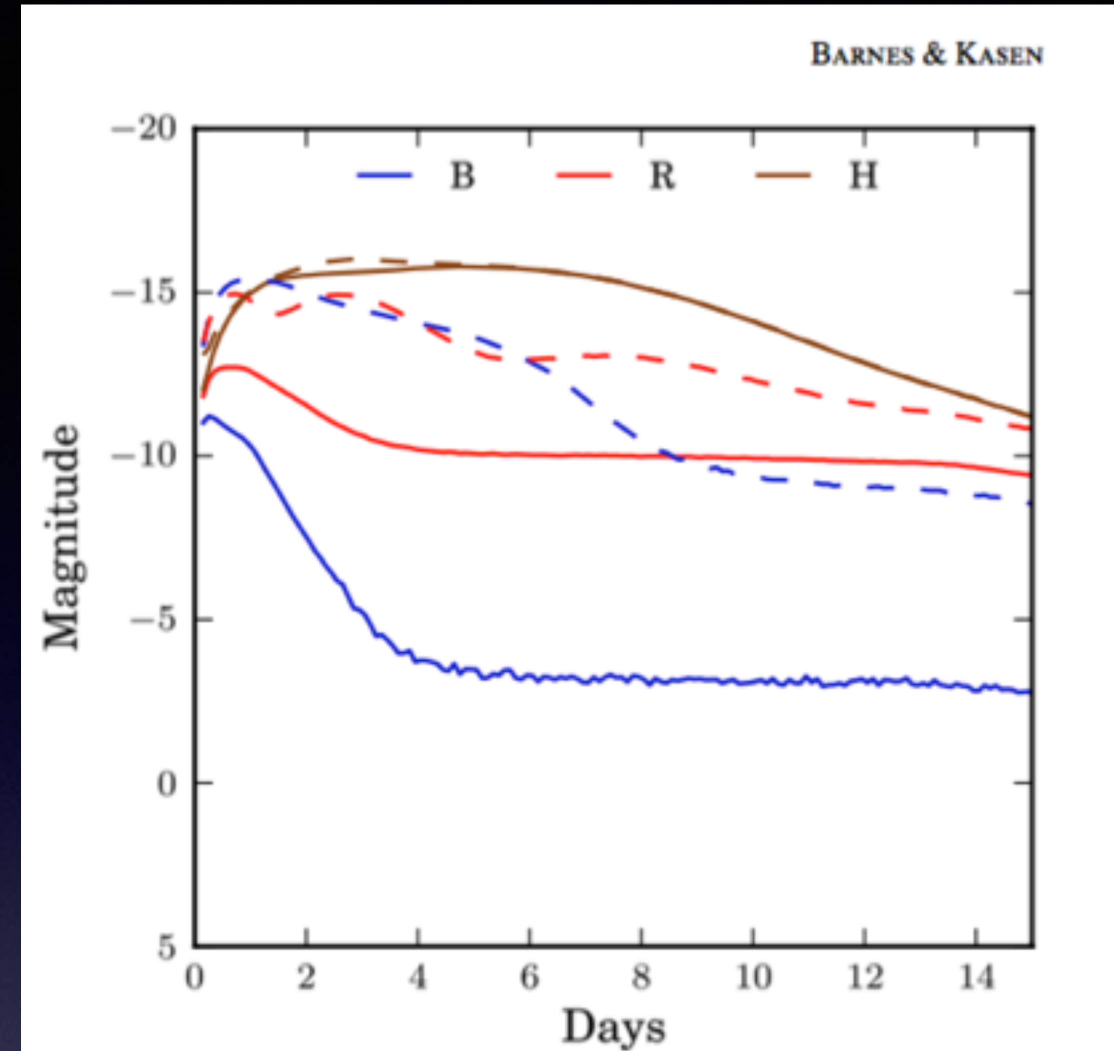


Figure 9. A comparison of select broadband light curves for a pure *r*-process transient (solid lines) and an *r*-process transient occurring in concert with a ^{56}Ni-powered outflow (dashed lines). The bluer SED from the ^{56}Ni shifts the magnitudes of the bluer bands of the combined SED upward relative to a pure *r*-process model. This plot is for $M_{ni} = M_{rp} = 10^{-2}\,M_{\odot}$.

At 100Mpc - what magnitudes do we need to reach ?

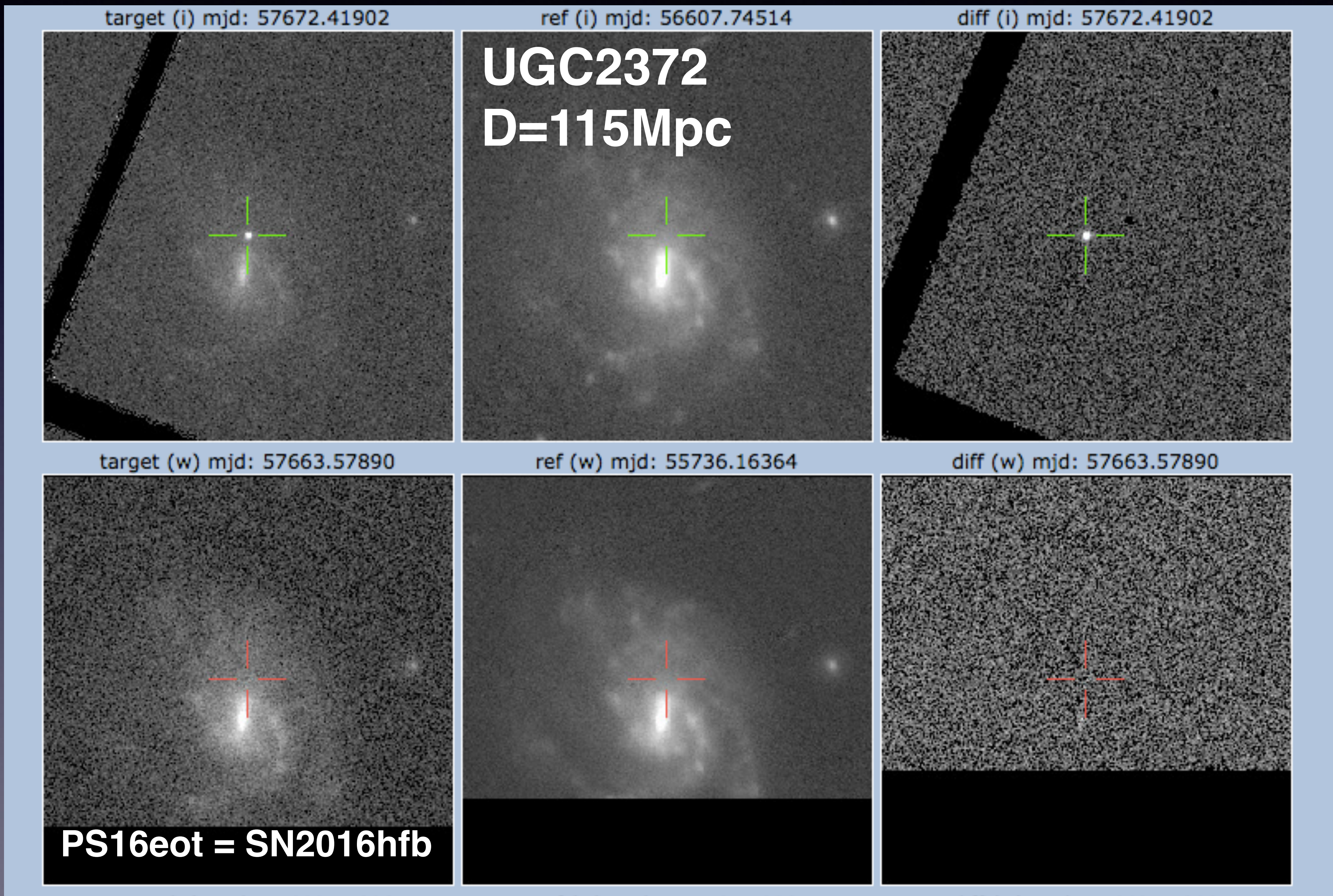
10min task

- How long will it take to map out a typical LIGO sky localisation region to the depths required ?

- Assume :
    1. Area = 1000 sq degrees
    2. Distance of source = 100 Mpc
    3. Peak mag of source $M_r = -15$
    4. $t_{exposure} \propto (\Delta \text{flux})^2$

- What practical issues do we need to consider ?
- If we do this experiment and identify all new sources in 1000 sq deg, what are we likely to find ?

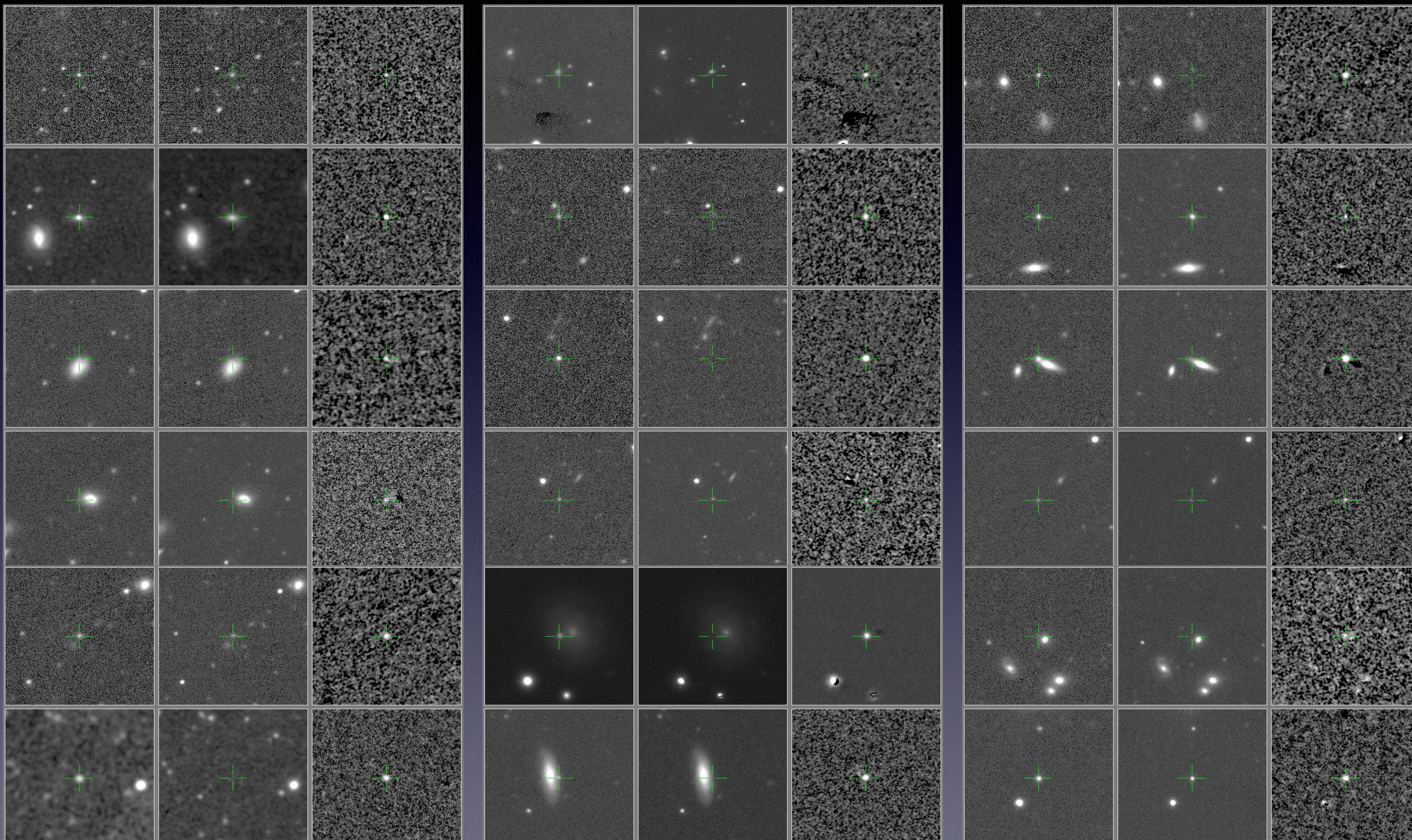
Within ~100 Mpc



***i*=20**
M_i = -15

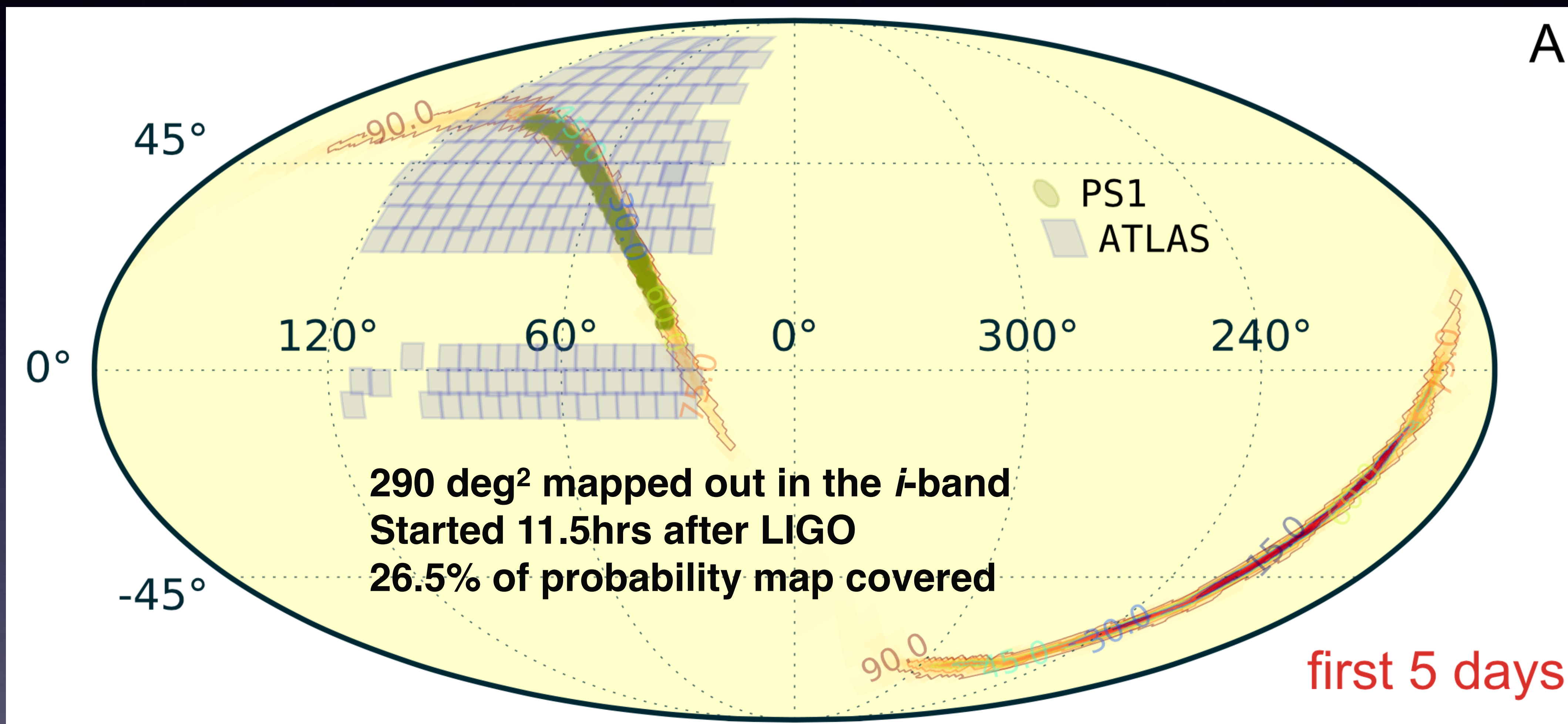
LIGO O1 upper limits Abbott et al. 2016, NS+NS mergers
N < 52 yr^{-1}

DES search for kilonovae (Doctor et al. 2017)
N < 100 yr^{-1}



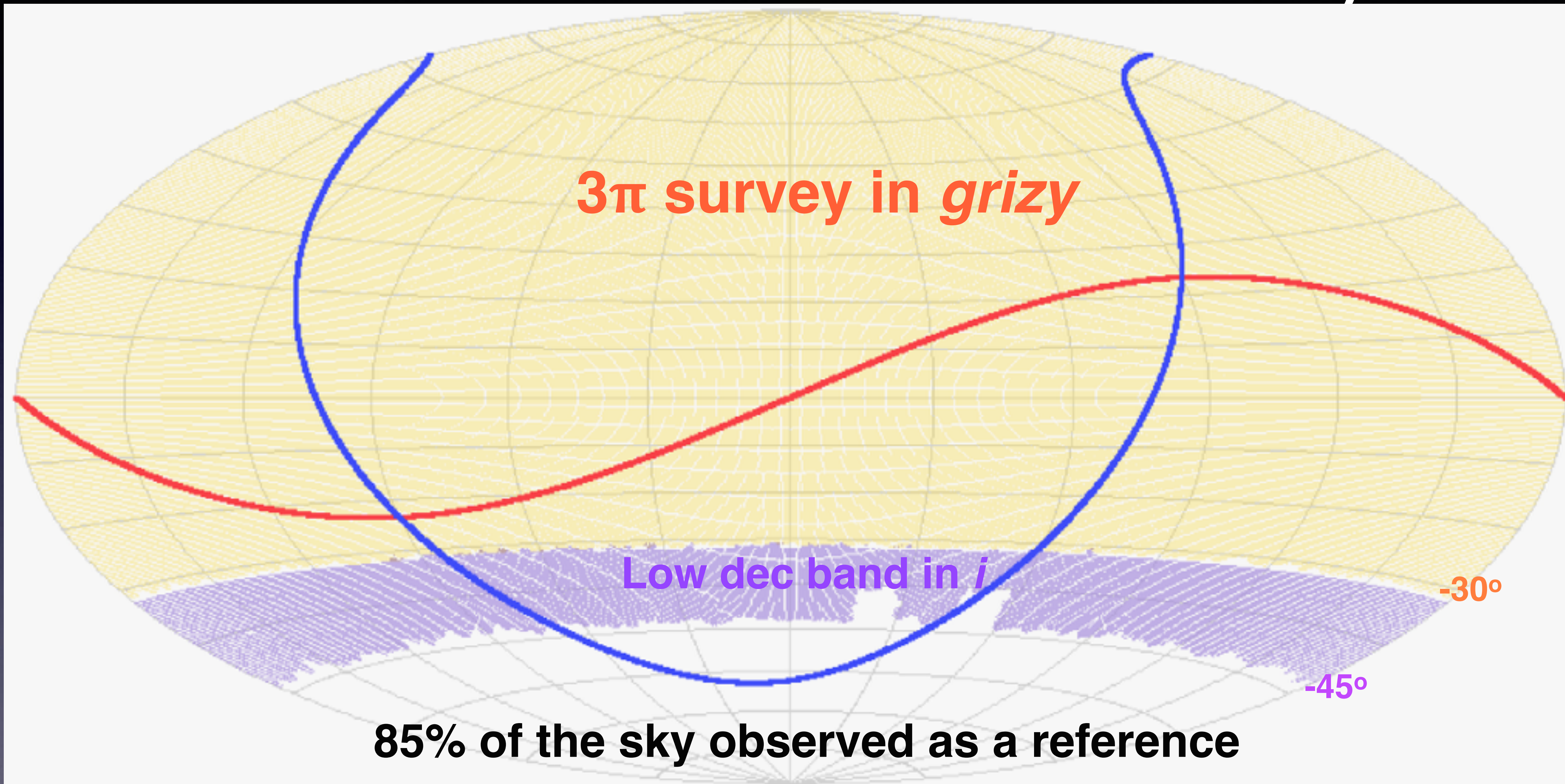
Experience to date : 3 BH-BH mergers

GW150914 + GW151226



- Two sources released in LIGO O1 to EM follow-up teams
- BH - BH mergers : EM radiation not likely to be luminous
- Smartt et al. (2016a, 2016b) : proof of concept for follow-up, meaningful limits for GW151226

The Pan-STARRS Sky

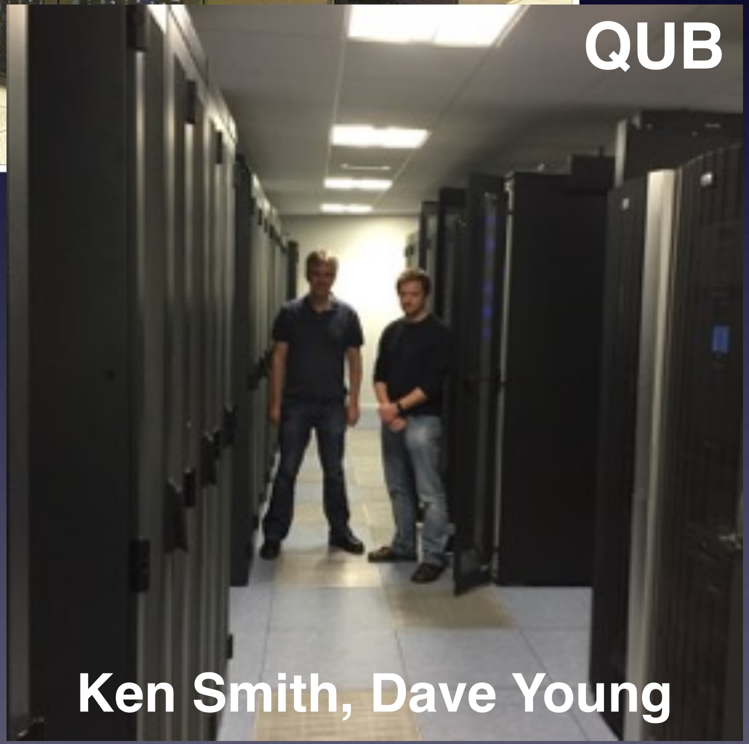


with over 100 epochs.

First public data release from Space Telescope Science Institute (MAST archive system and tools)
December 2016

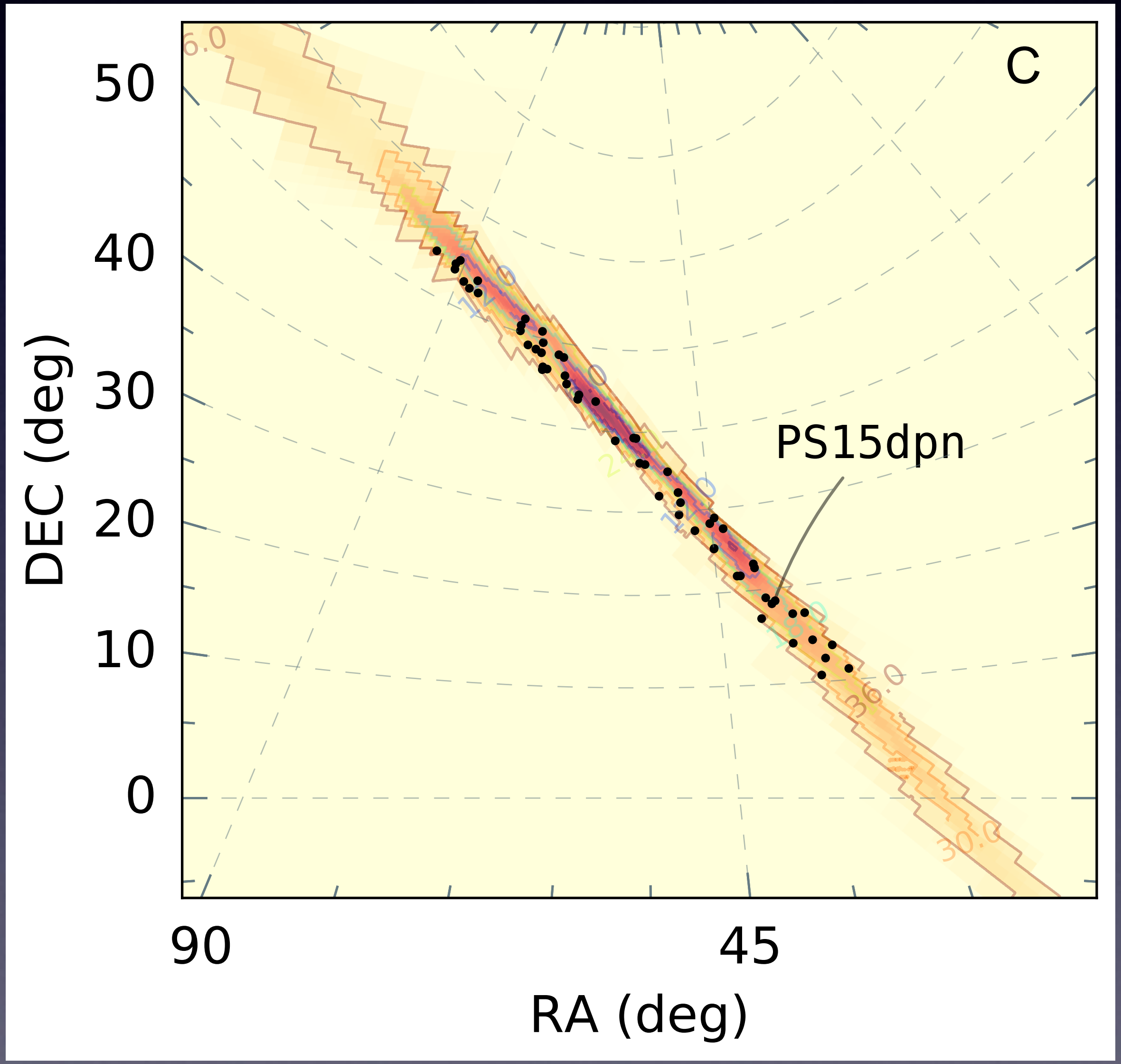
Pan-STARRS Cyber-Infrastructure

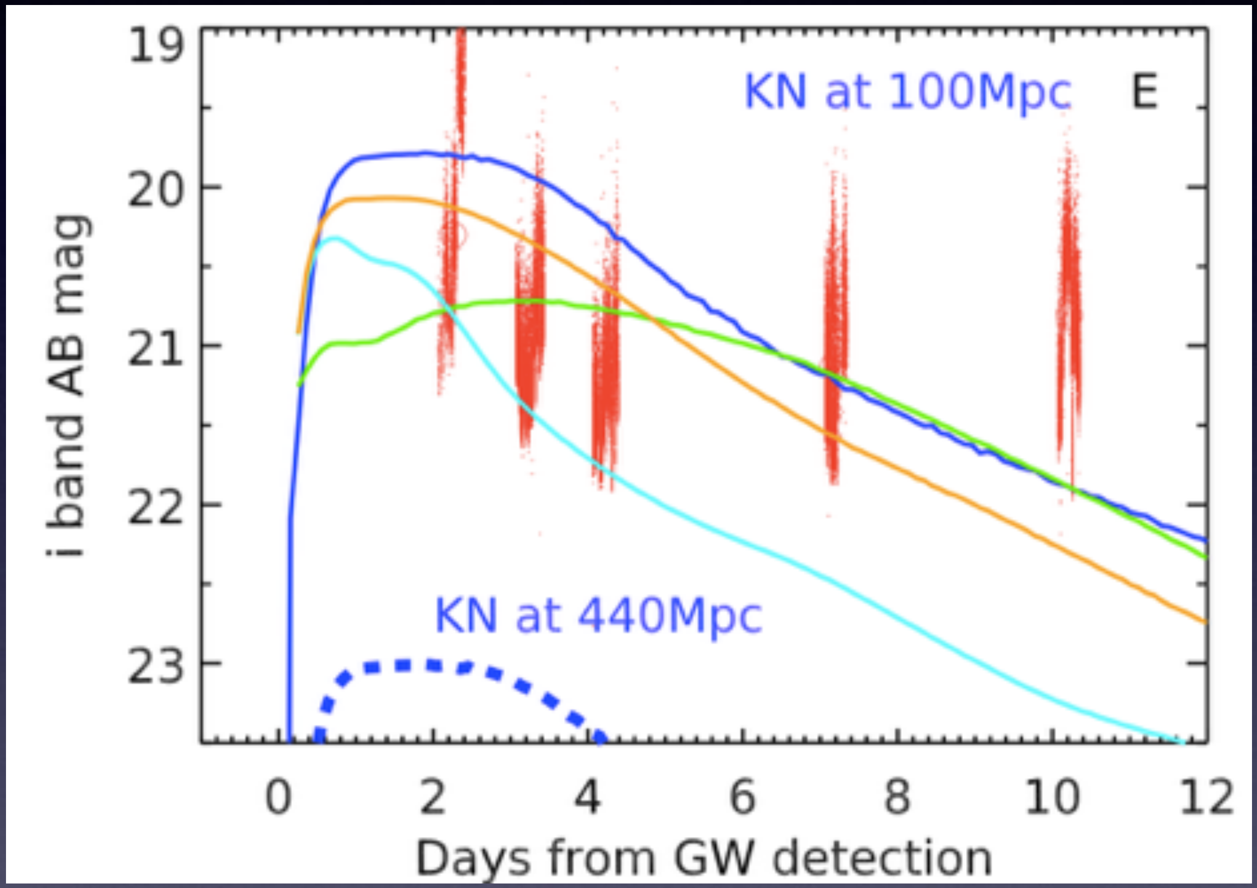
- Hawaii : Image Processing Pipeline
- PSPS : hierarchical database. All sky catalogues
- High i/o rate, large cpu requirement. Large local storage required - large computer science project
- QUB Transient Science Server in Belfast



Ship catalogues : 10^7 detections per day to Belfast "Transient Science Server"
Database, algorithms - machine learning and boosted decision trees. Classify all transients

Location of transients and limits on emission



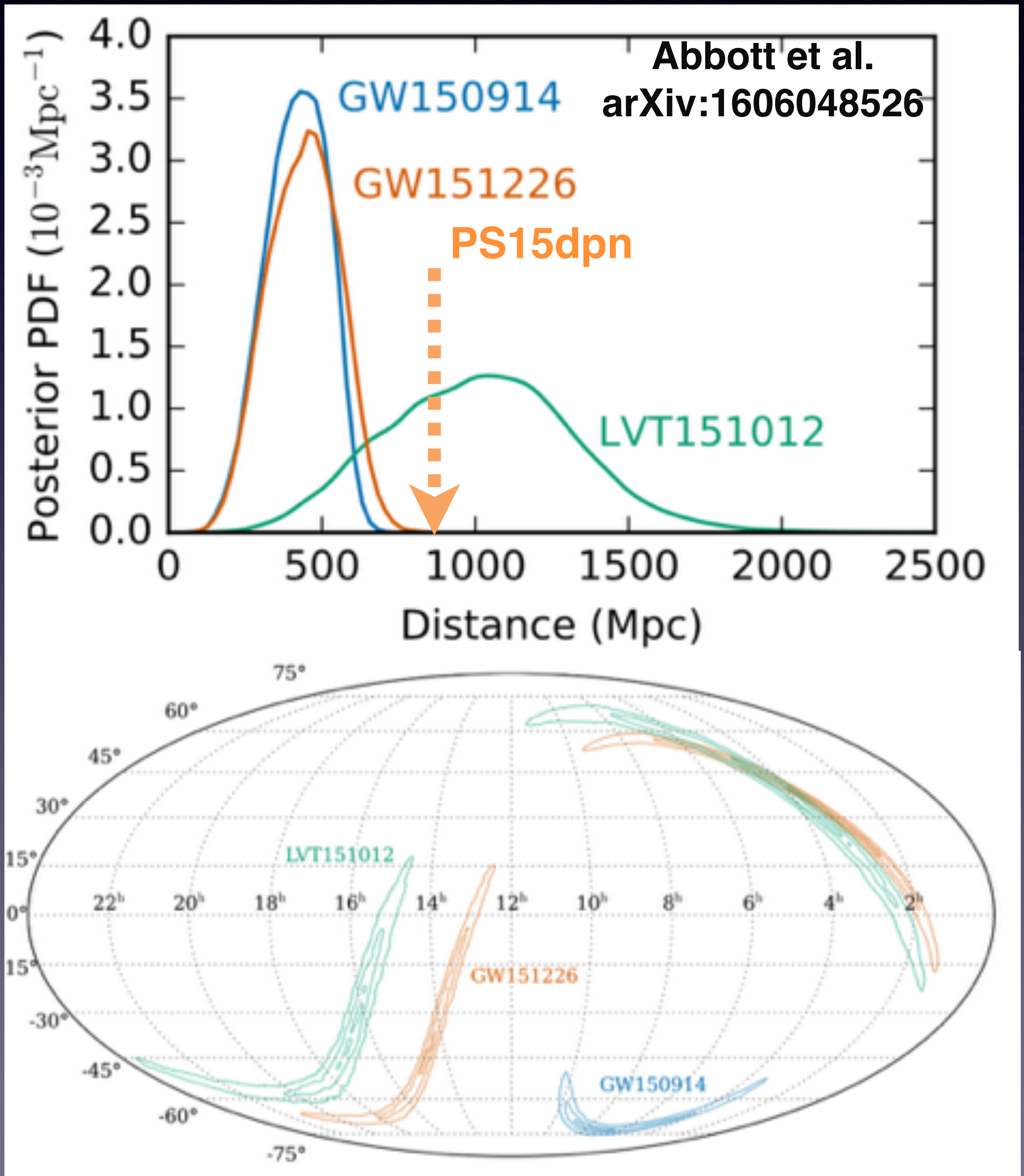


- **49 extragalactic transients found**
- **Spectral classification of 20**
- **All apparently normal supernova - apart from one stand out case**
- **At time we didn't know the distance to GW151226**

Smartt et al. 2016b
Kasen et al. models

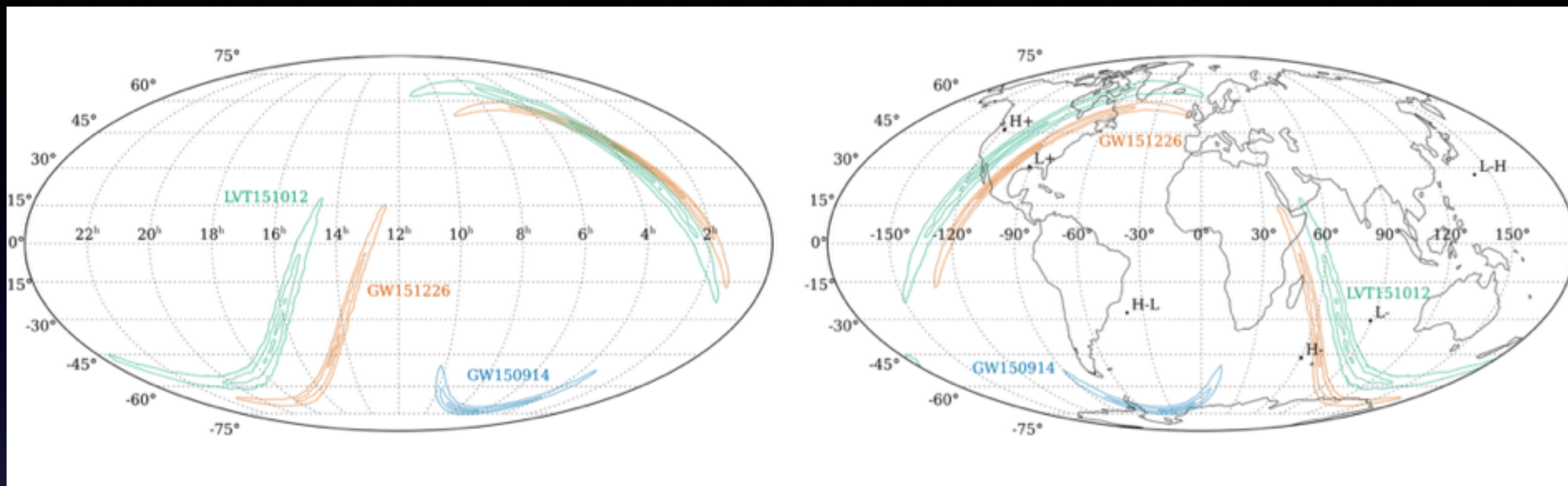
Outlook for O2 with LIGO+ Virgo

- O2 will produce approximate distance estimates
- And probability that system contains *a NS mass component*
- These two factors will allow EM teams to prioritise resources and efforts
- Can adjust survey strategy during first 1-2 days based on these two numbers from LIGO/ Virgo



See Singer et al. 2016 : 3D probability skymaps

Very large sky areas

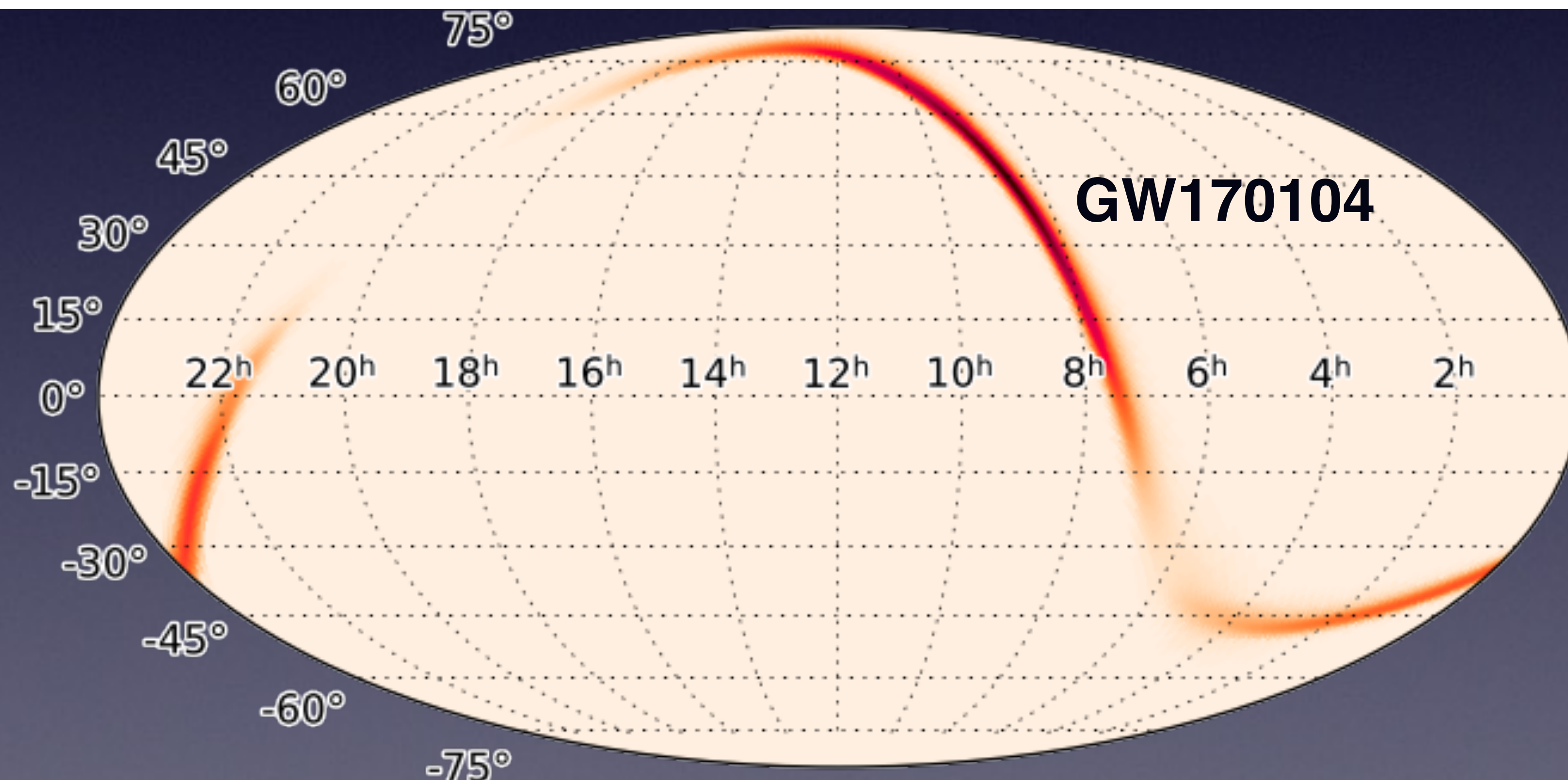


LVT151012
1600 sq deg

Abbott et al.
arXiv:1606048526

GW151226
850 sq deg

GW150914
230 sq deg



GW170104
1608 sq deg

- LIGO/Virgo are all sky monitors
- 90% enclosed probability has ~200 - 2000 deg^2

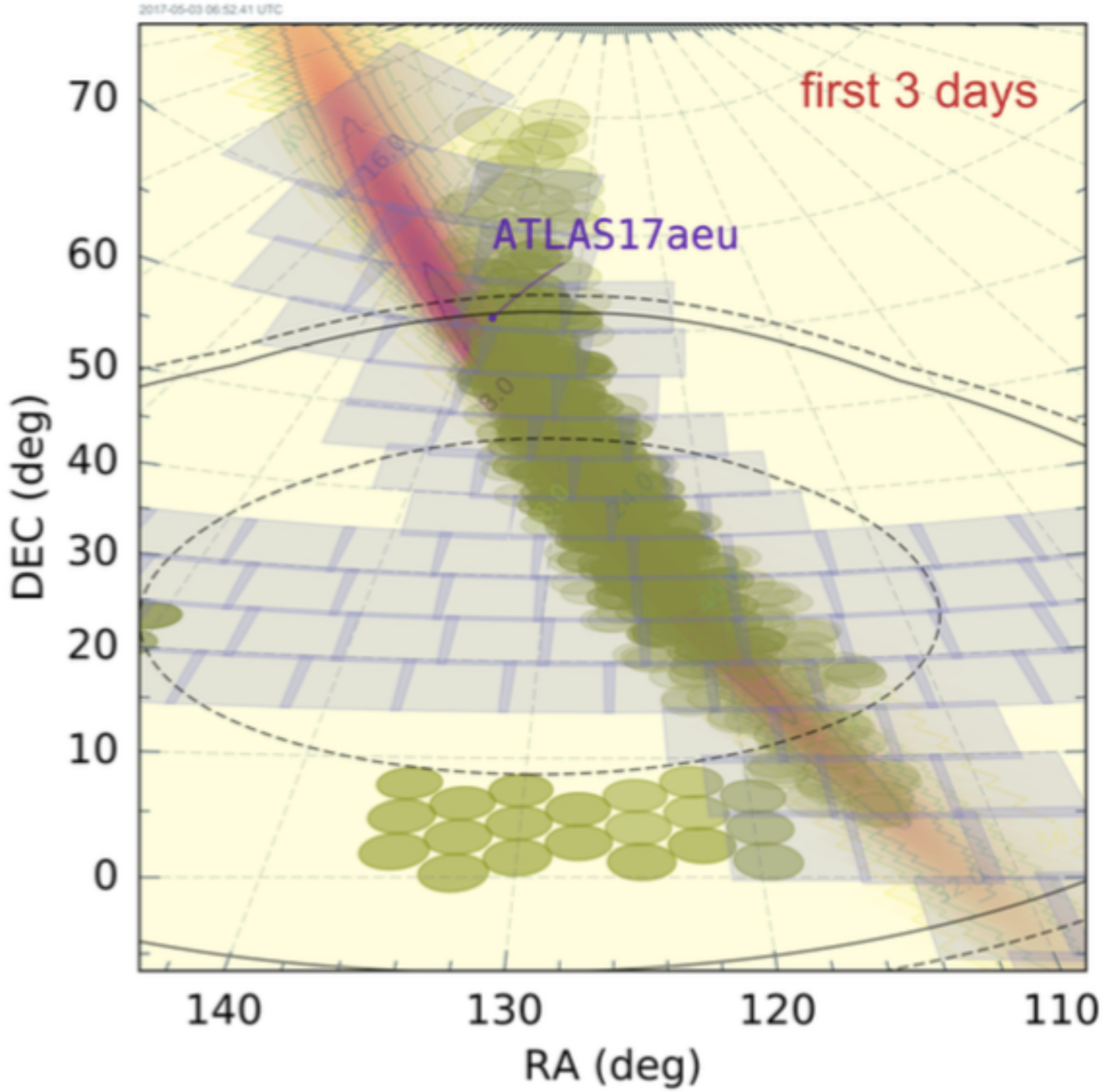


Figure 1. LALInference likelihood map (`LALInference_f.fits`) showing ATLAS (purple squares) and Pan-STARRS1 pointings (green circles). The black solid circle is the best estimate localization of GRB170105 with the black dashed circles representing the Konus-Integral triangulation annulus of Svinkin et al. (2017)

O'ahu

IfA, Manoa

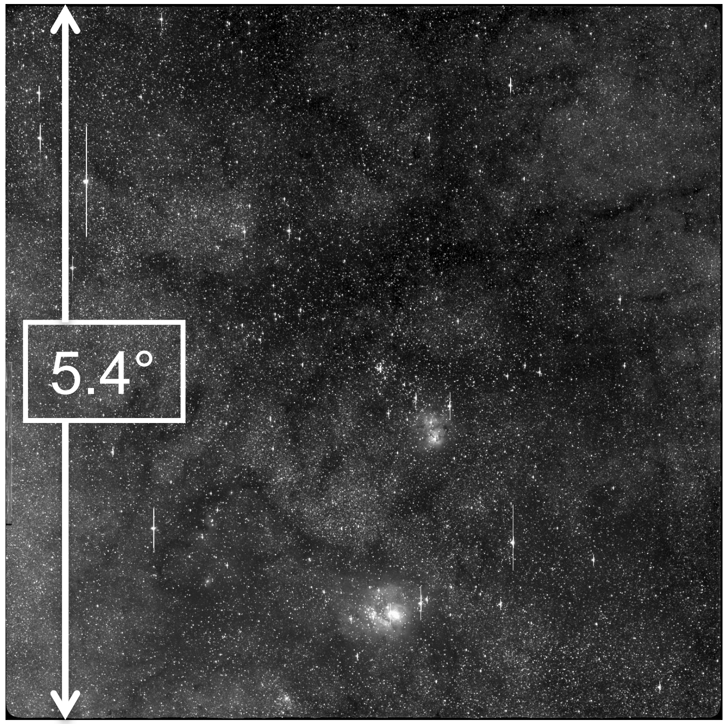
PS1 + PS2
Haleakala
Maui

ATLAS1 :
Haleakala
3000m

Big Island

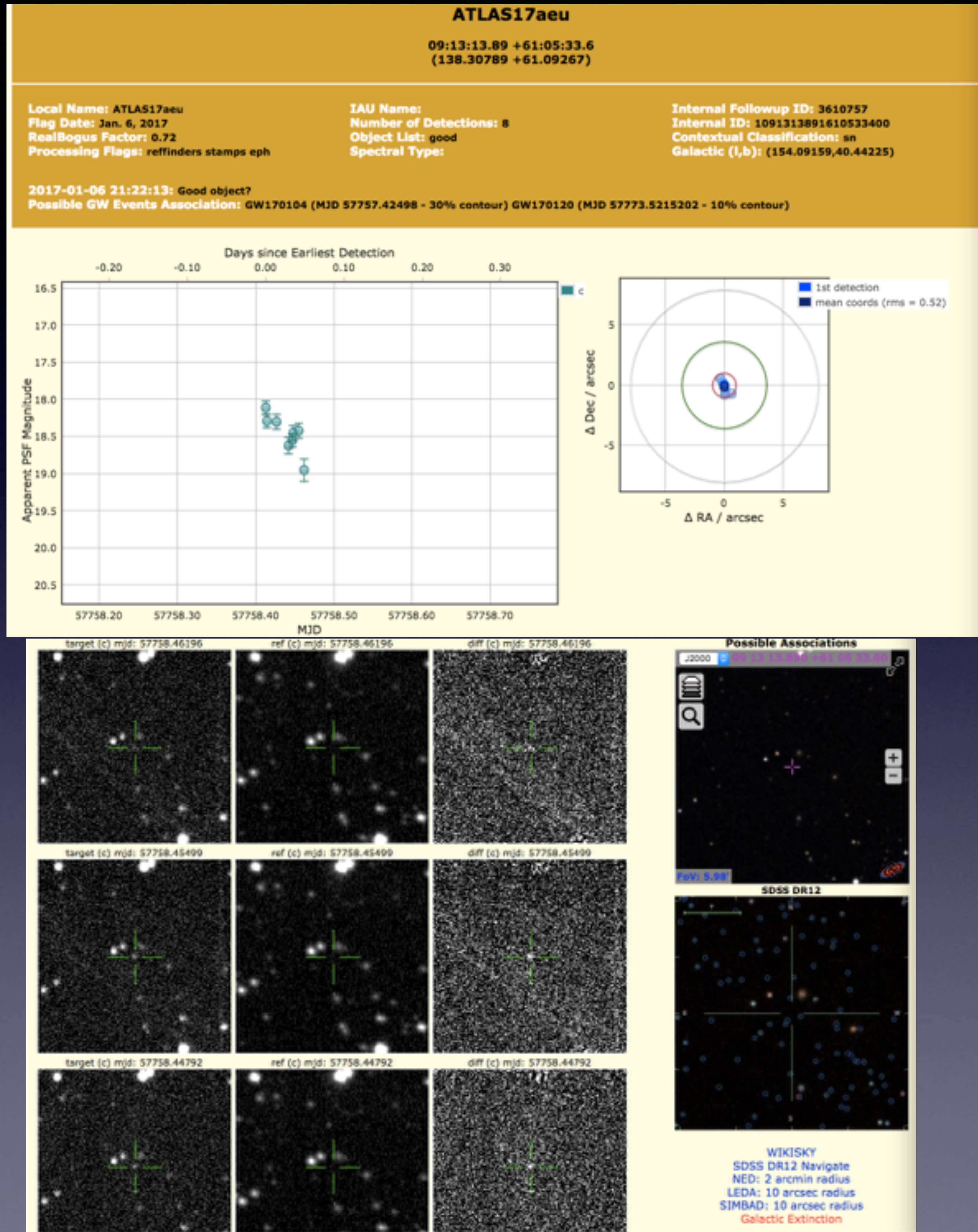
ATLAS2 :
Mauna Loa
3400m

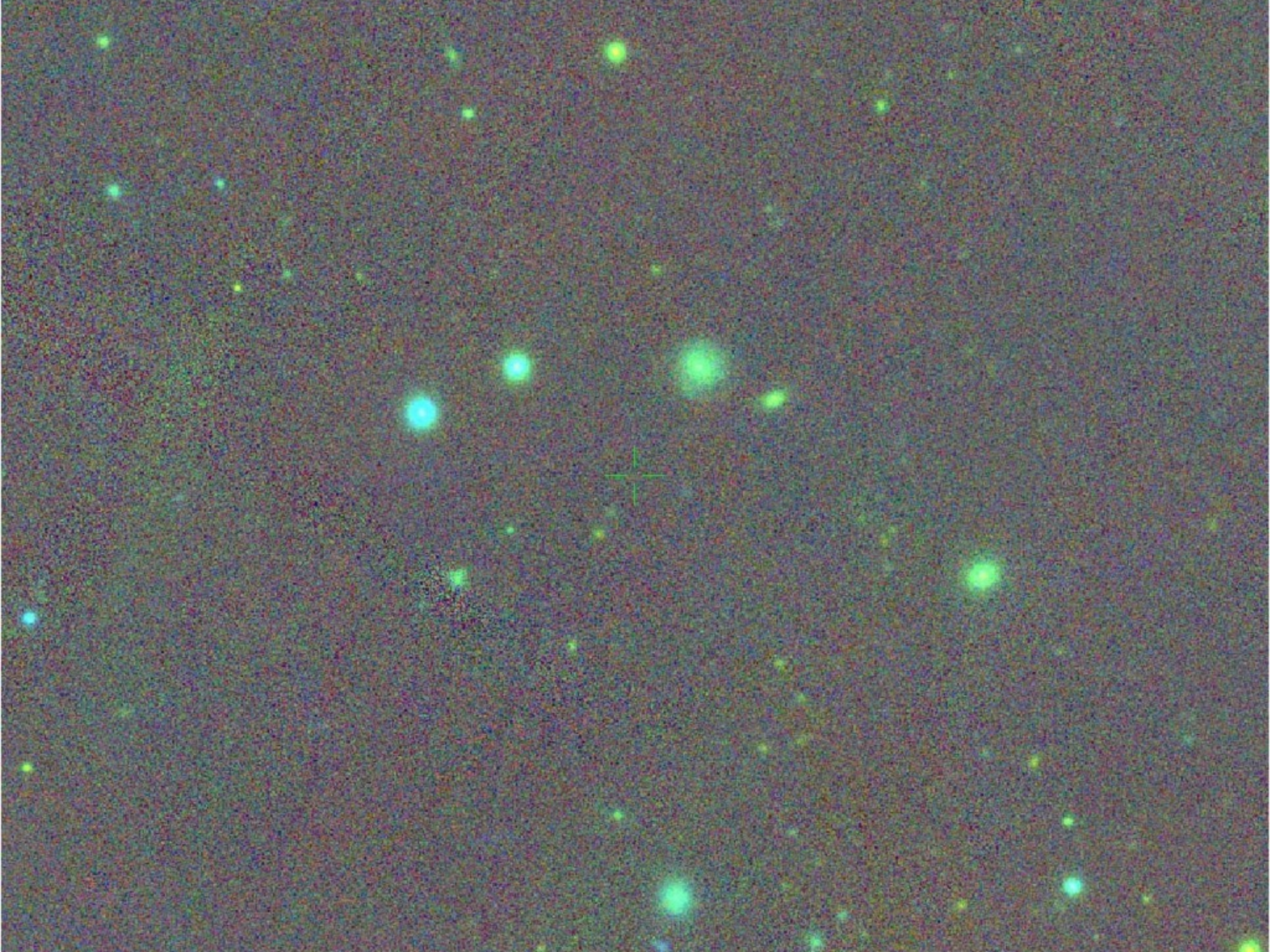
Specs and sky coverage goals



- 2 x 50cm telescopes : 7.5° diameter FOV,
- f/2 Wright-Schmidt telescopes
- Cameras (ACAM) = 10560 x 10560 pixel CCDs (STA 1600)
- CCDs – excellent science grade quality, 7 sec readout
- Plate scale : 9 micron pixels = 1.86 arcsec (with focal length $F = 2$)
- Single image size = 29.2 square degrees

- **Goal 60,000 sq degrees coverage per night to *m ≈ 20***
- ***Each telescope 30,000 sq degrees per night***
- ***Footprint of 15,000 sq degrees (4 times - for NEO tracklets and fast transients)***


ATLAS17aeu
09:13:13.89 +61:05:33.6
(138.30789 +61.09267)
Local Name: ATLAS17aeu
Flag Date: Jan. 6, 2017
RealBogus Factor: 0.72
Processing Flags: reffinders stamps eph
IAU Name:
Number of Detections: 8
Object List: good
Spectral Type:
Internal Followup ID: 3610757
Internal ID: 1091313891610533400
Contextual Classification: sn
Galactic (l,b): (154.09159,40.44225)
2017-01-06 21:22:13: Good object?
Possible GW Events Association: GW170104 (MJD 57757.42498 - 30% contour) GW170120 (MJD 57773.5215202 - 10% contour)
Days since Earliest Detection
Apparent PSF Magnitude
MJD
1st detection
mean coords (rms = 0.52)
Δ Dec / arcsec
Δ RA / arcsec
target (c) mjd: 57758.46196
ref (c) mjd: 57758.46196
diff (c) mjd: 57758.46196
target (c) mjd: 57758.45499
ref (c) mjd: 57758.45499
diff (c) mjd: 57758.45499
target (c) mjd: 57758.44792
ref (c) mjd: 57758.44792
diff (c) mjd: 57758.44792
Possible Associations
SDSS DR12
WIKISKY
SDSS DR12 Navigate
NED: 2 arcmin radius
LEDA: 10 arcsec radius
SIMBAD: 10 arcsec radius
Galactic Extinction



GRB170105

Table 1. Photometry and multiwavelength fluxes for ATLAS17aeu and data for GW170104 and GRB170105 for comparison. Data not presented in this paper were released as the GCNs cited. The Swift observations and data were reported in Evans et al. (2017a,b) but we re-analysed the data in the archvie to produce the numbers quoted. The AMI data are availabe publicly at the quoted website.

Telescope	Magnitude/Flux/Fluence	Filter/Waveband	MJD	Position	Ref
GW170104	...	...	57757.42498		Abbott et al. (2017)
GRB170105				see Fig. 1	
POLAR		80-500 keV	57758.218137		Marcinkowski et al. (2017)
AstroSAT CZTI		40-200 keV	57758.218125		Sharma et al. (2017)
Konus-Wind	$2.56^{+0.18}_{-0.13} \times 10^{-6}$ erg cm^{-2}	20 keV - 10 MeV	57758.218174	Centre : 129.749,+27.904	Svinkin et al. (2017)
INTEGRAL-SPIACS		80keV - 8MeV	57758.218125	Annulus radius :$34.255^{+1.812}_{-14.832}$	Marcinkowski et al. (2017)

Bhalerao et al Arxiv:1706.00024

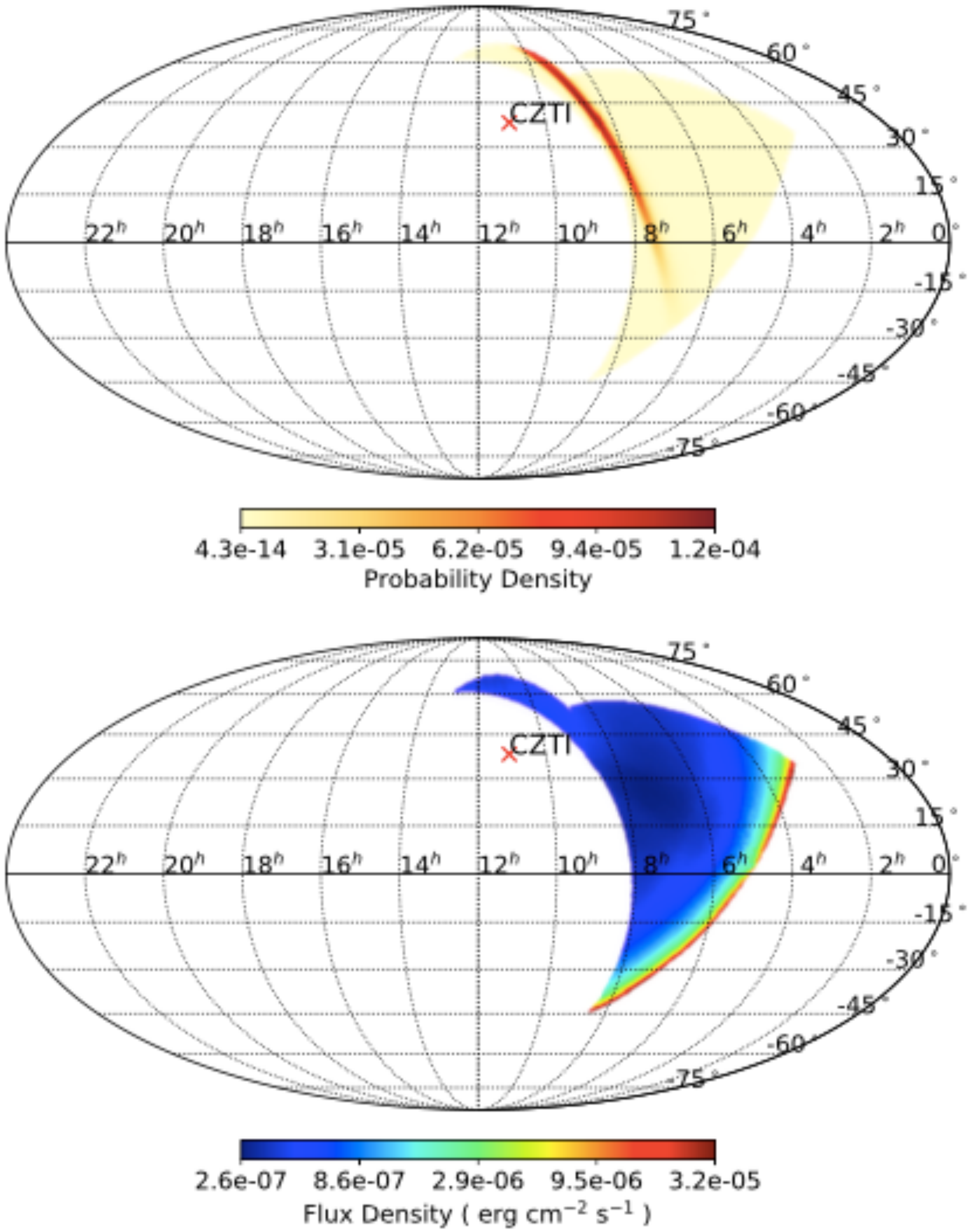


Figure 1. *Upper panel:* The LIGO sky position probability map for GW170104, masked to show only the sky visible to CZTI. The red cross marks the boresight of CZTI. Parts of the sky obscured by earth or by satellite elements are shown in white. The visible area encloses a 50.3% probability of containing the GW source. *Lower panel:* The upper limits on hard X-ray emission from GW170104, from a search for 1 s transients. The variation of upper limits with position for other timescales is identical modulo an overall scaling factor.

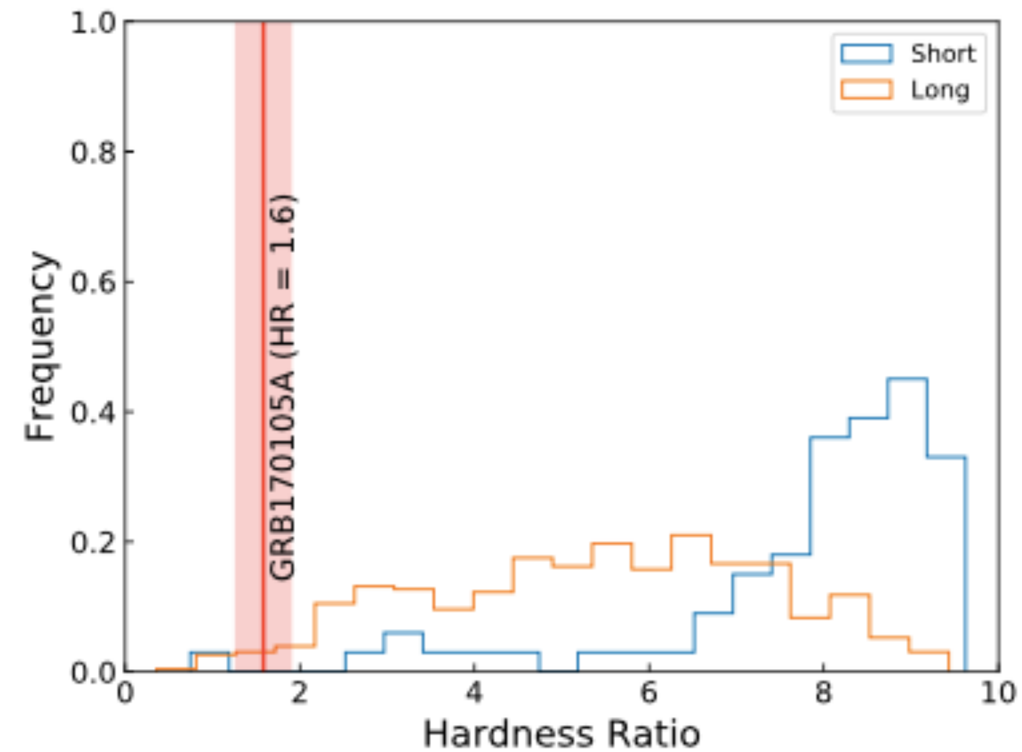


Figure 5. Simulated (70–200 keV)/(20–50 keV) hardness ratio distributions for our GRB sample. We use GRB spectral parameters from the IceCube GRB Web, and simulate CZTI hardness ratios assuming that these GRBs were at the same position as ATLAS17aeu in the CZTI instrument reference frame. The red line and the shaded red region mark HR= 1.6±0.3 for GRB 170105A. We see that it is softer than most long and short GRBs. In particular, only one simulated short hard burst has hardness softer than GRB 170105A.

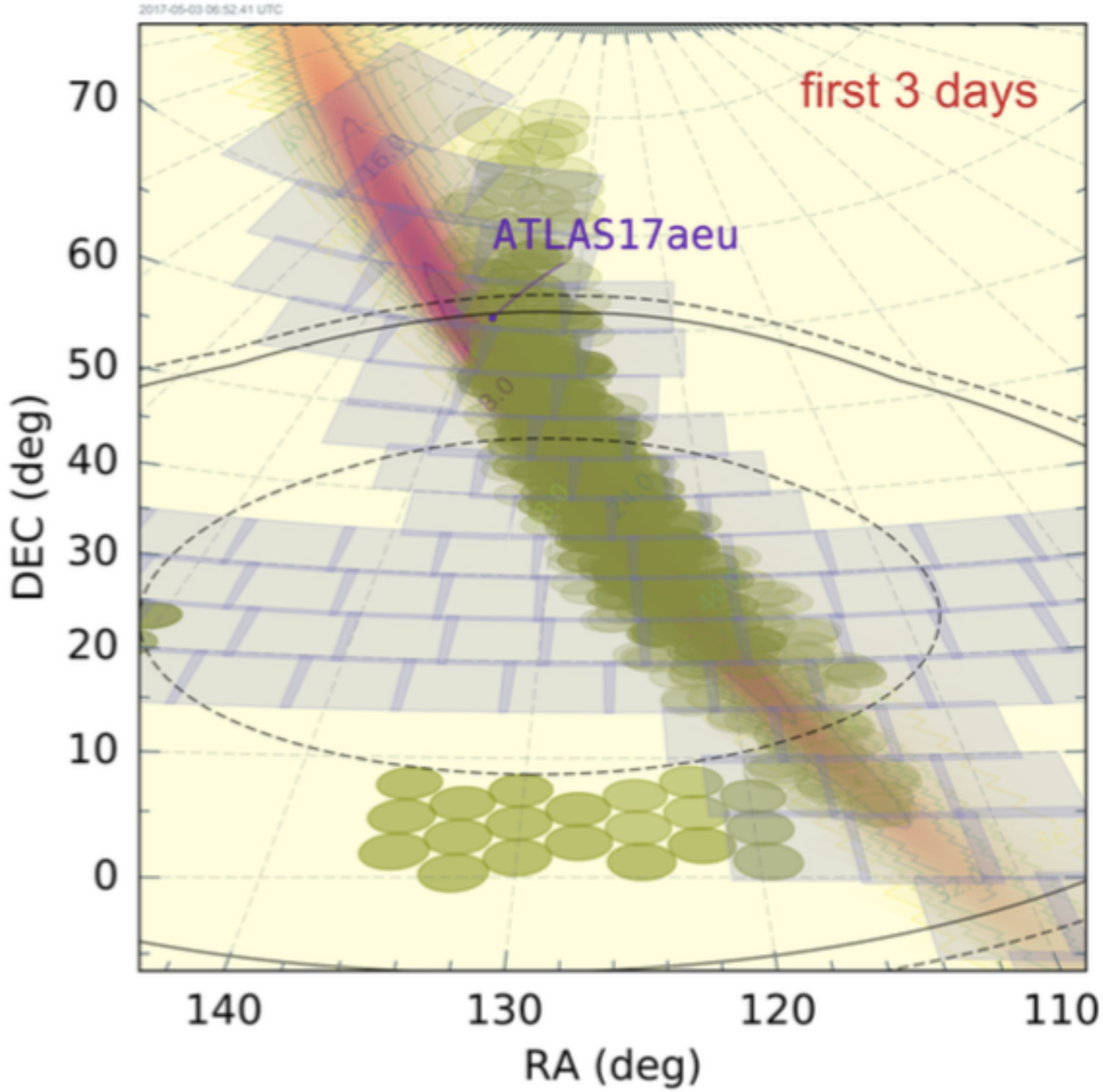


Figure 1. LALInference likelihood map (`LALInference_f.fits`) showing ATLAS (purple squares) and Pan-STARRS1 pointings (green circles). The black solid circle is the best estimate localization of GRB170105 with the black dashed circles representing the Konus-Integral triangulation annulus of Svinkin et al. (2017)

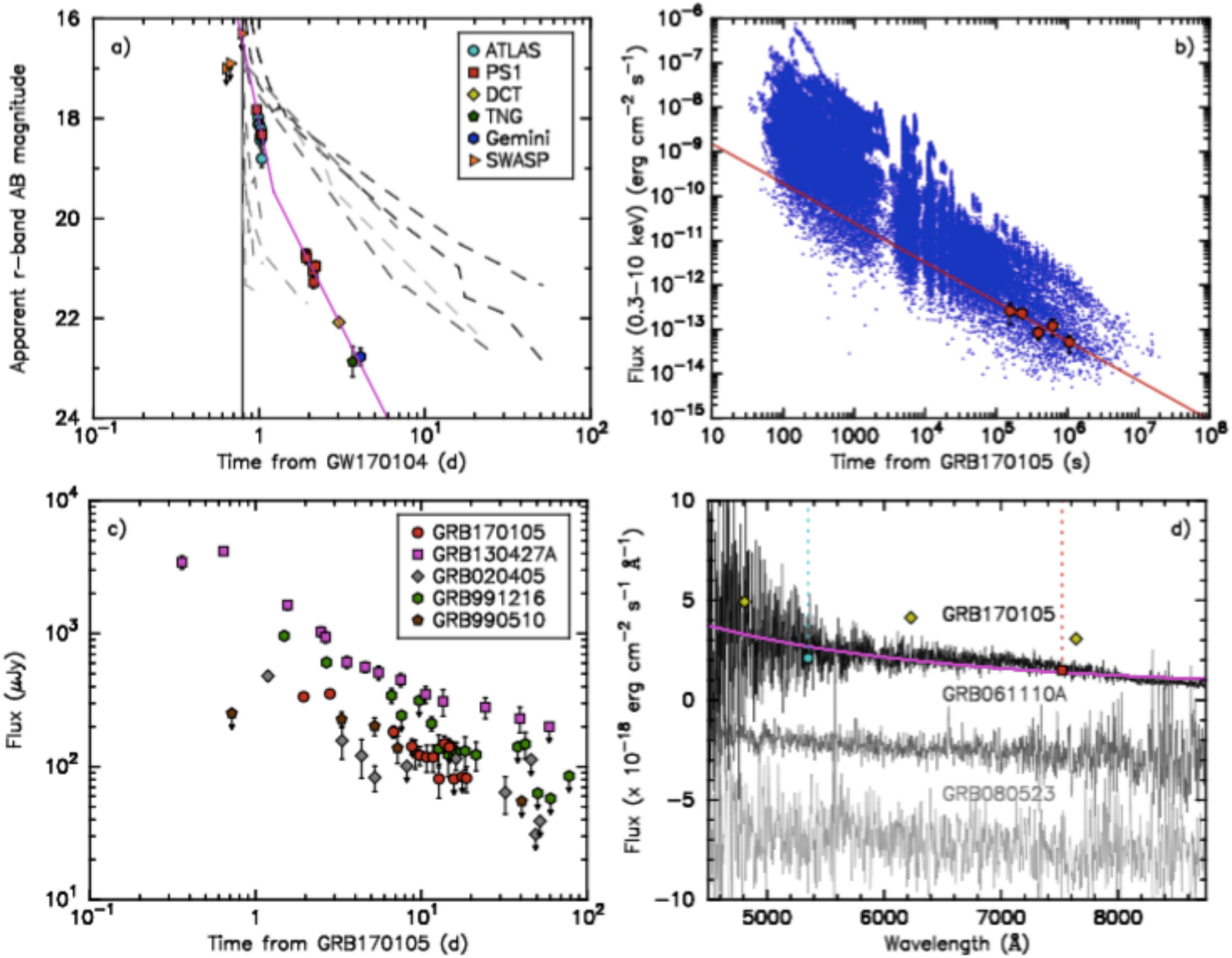
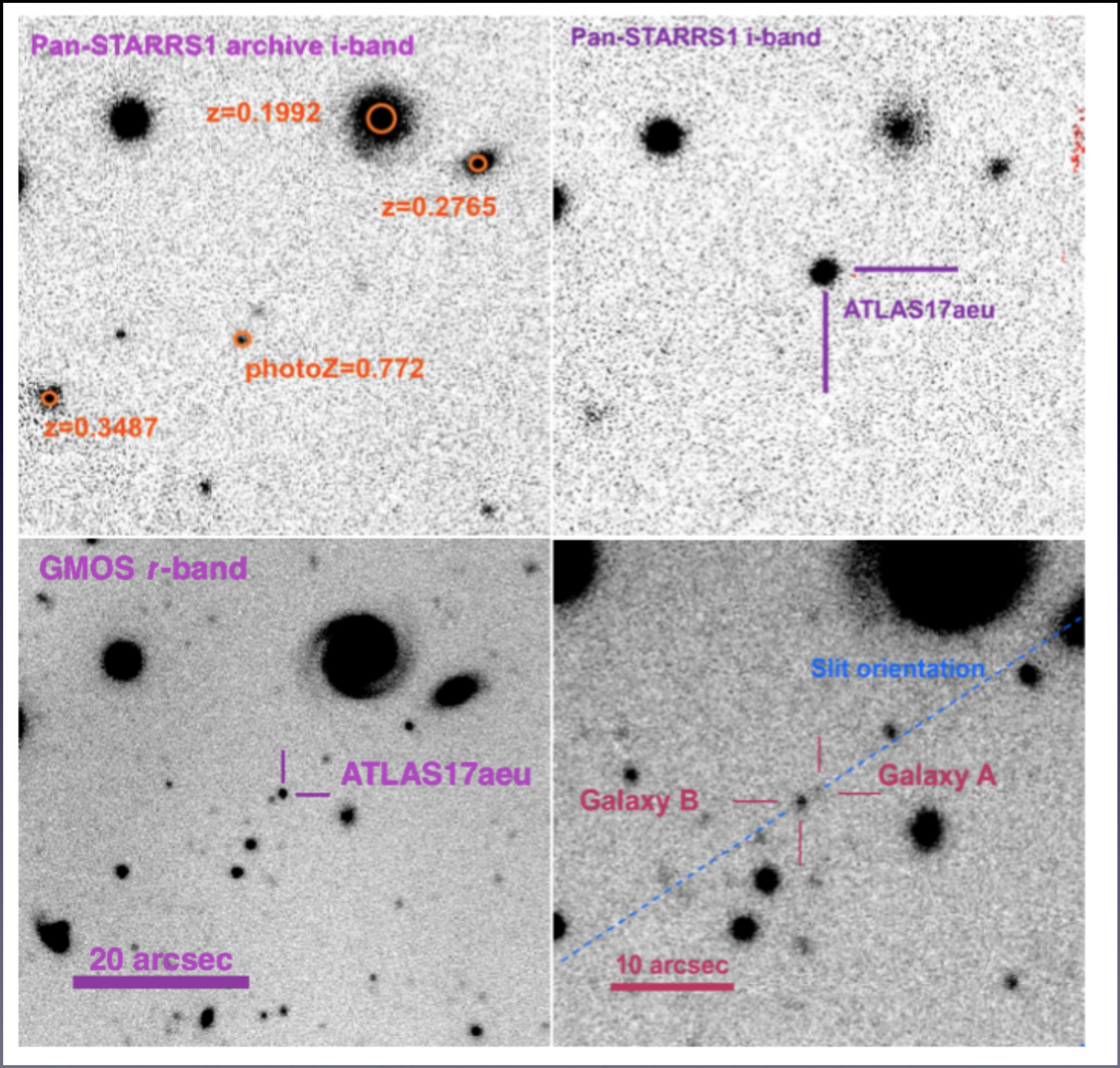
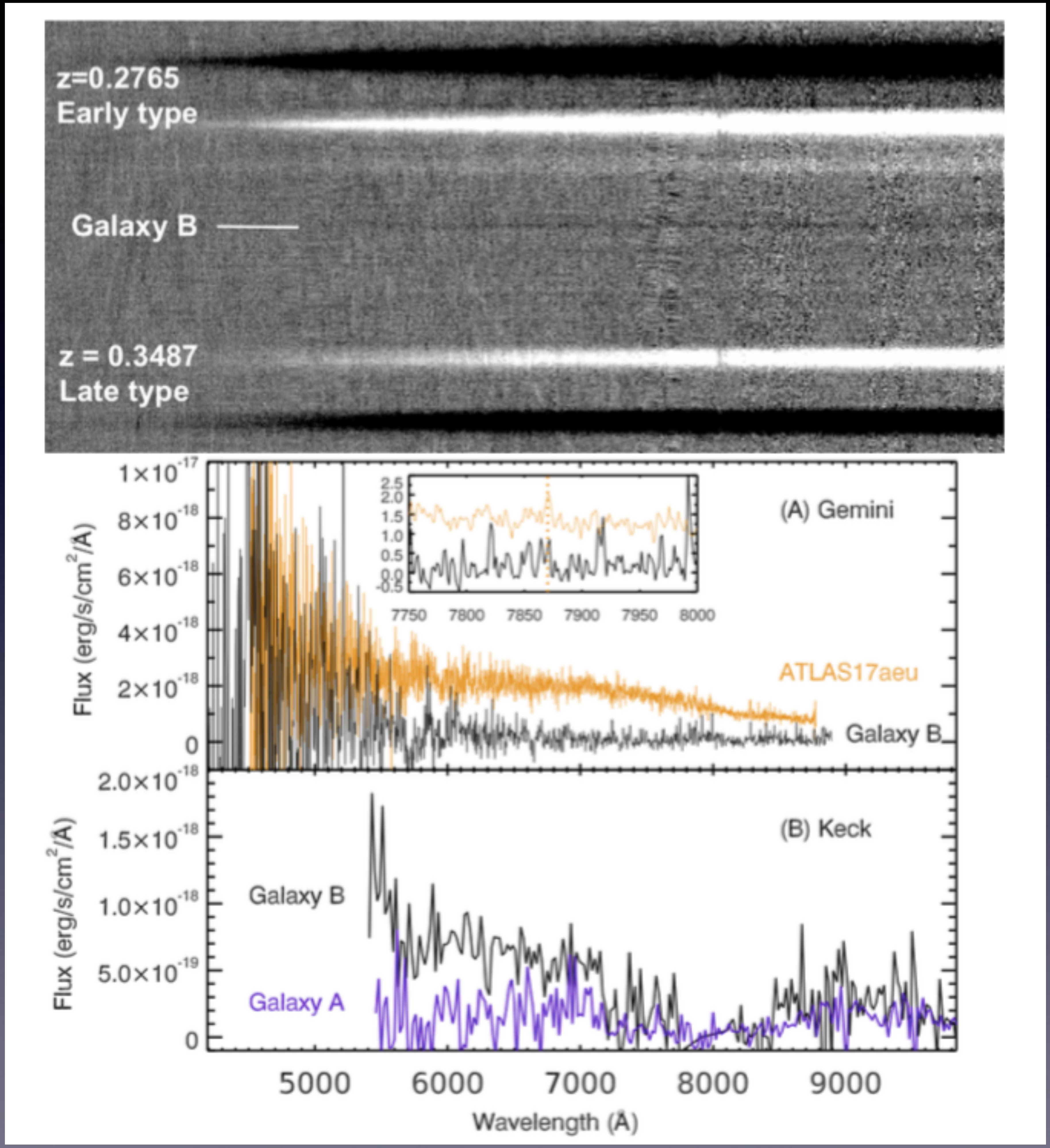


Figure 2. **(a):** The *r*–band lightcurve of ATLAS17aeu with our own data , supplemented with the photometry reported in LIGO-VIRGO GCNs as listed and referenced in Table 1. The time of GRB170105 is the vertical black line. All the detections have been colour corrected to observer frame *r*–-band using the spectrum in panel (d). **(b):** The x-ray afterglow lightcurves of Swift GRBs with known redshifts from 2005 to present. The ATLAS17aeu fluxes from Swift XRT are in red. **(c):** The radio fluxes of ATLAS17aeu and other GRBs with radio measurements in the 8-15 GHz bands. **(d):** The GMOS spectrum of ATLAS17aeu at +3.3 days after GRB170105. The SED from the *gri* points of Cenko & Troja (2017) at +2.3 days are shown for reference. We also show the relative SED of our photometry (ATLAS cyan and Pan-STARRS i_{P1} scaled with the same factor) at only +4.8 hr after GRB170105. This indicates the color of the afterglow was relatively constant over the first 3 days.


Pan-STARRS1 archive i-band
z=0.1992
z=0.2765
photoZ=0.772
z=0.3487
Pan-STARRS1 i-band
ATLAS17aeu
GMOS r-band
ATLAS17aeu
20 arcsec
Slit orientation
Galaxy A
Galaxy B
10 arcsec


z=0.2765
Early type
Galaxy B
z = 0.3487
Late type
(A) Gemini
ATLAS17aeu
Galaxy B
Flux (erg/s/cm^2/Å)
1×10^-17
8×10^-18
6×10^-18
4×10^-18
2×10^-18
0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
7750
7800
7850
7900
7950
8000
(B) Keck
Galaxy B
Galaxy A
2.0×10^-18
1.5×10^-18
1.0×10^-18
5.0×10^-19
0
5000
6000
7000
8000
9000
Wavelength (Å)

We now calculate the probability that the γ-ray burst is independent of ATLAS17aeu (i.e. just a chance coincidence). We use Poisson statistics, where the probability of an occurrence of n events is given by

$$P(n) = \frac{e^{-\lambda}\lambda^n}{n!} \tag{1}$$

where λ is the expectation value. The value of λ is the product of a number of factors given by the rate of each

$$\lambda = \prod_{i=1}^{k} r_i \tag{2}$$

The rates we will discuss in this section are listed for reference in Table 2. In this case, we will derive the Poisson probabilities of getting one or more random coincidences, which simplifies Eqn. 1 to

$$p = 1 - e^{-\lambda} = 1 - e^{-\prod_{i=1}^{k} r_i} \tag{3}$$

Prob ATLAS17aeu and GRB are coincidence

r_1 = 0.75 GRB per day

r_2 = 0.18 days

r_3 = 0.07 (sky overlap)

p = 0.01

i.e. 1% chance of random coincidence

Hypothesis rejected at 2.6σ

Properties of gamma ray, x-ray/radio and optical (and faint host) all consistent with a GRB at

$1 < z < 2.9$

Therefore chance coincidence with GW170104 if this distance is true

We now calculate the probability that the γ-ray burst is independent of ATLAS17aeu (i.e. just a chance coincidence). We use Poisson statistics, where the probability of an occurrence of n events is given by

$$P(n) = \frac{e^{-\lambda}\lambda^n}{n!} \quad (1)$$

where λ is the expectation value. The value of λ is the product of a number of factors given by the rate of each

$$\lambda = \prod_{i=1}^{k} r_i \quad (2)$$

The rates we will discuss in this section are listed for reference in Table 2. In this case, we will derive the Poisson probabilities of getting one or more random coincidences, which simplifies Eqn. 1 to

$$p = 1 - e^{-\lambda} = 1 - e^{-\prod_{i=1}^{k} r_i} \quad (3)$$

Prob ATLAS17aeu/GRB and GW170104 are coincidence

r_1 = 0.75 GRB per day

r_2 = 0.05 (LIGO skymap)

p = 0.04

i.e. chance of random coincidence or hypothesis can be rejected 96% confidence level at 2.1σ

If we had redshift of Galaxy A (or B), and it was within the LIGO range of ~ 500-1300 Mpc
it would force reconsideration of physical link

ELECTROMAGNETIC SIGNALS FOLLOWING STELLAR–MASS BLACK HOLE MERGERS

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Accepted for publication in Astrophysical Journal Letters: March 18, 2017

ABSTRACT

It is often assumed that gravitational wave (GW) events resulting from the merger of stellar–mass black holes are unlikely to produce electromagnetic (EM) counterparts. We point out that the progenitor binary has probably shed a mass $\gtrsim 10\,M_\odot$ during its prior evolution. If a tiny fraction of this gas is retained until the merger, the recoil and sudden mass loss of the merged black hole shocks and heats it within hours of the GW event. Whether the resulting EM emission is detectable uncertain. The optical depth through the disk is likely to be high enough that the prompt emission consists only of photons from its optically thin skin, while the majority may take years to emerge. However, if some mechanism can release more photons in a time comparable to the few–hour energy production time, the peak luminosity of the EM signal could be detectable. For a disk retaining only $\sim 10^{-3}$ of the mass shed in the earlier binary evolution, medium–energy X–rays to infrared emission would be observable hours after the GW event for source distances $\sim 500\,\mathrm{Mpc}$. Events like this may already have been observed, but ascribed to unidentified active galactic nuclei. Improved sky–localization should eventually allow identification based on spatial coincidence. A detection would provide unique constraints on formation scenarios and potentially offer tests of strong–field general relativity. Accordingly we argue that the high scientific payoff of an EM detection fully justifies search campaigns.

Subject headings: gravitational waves — black hole physics — binaries: close — X-rays: general

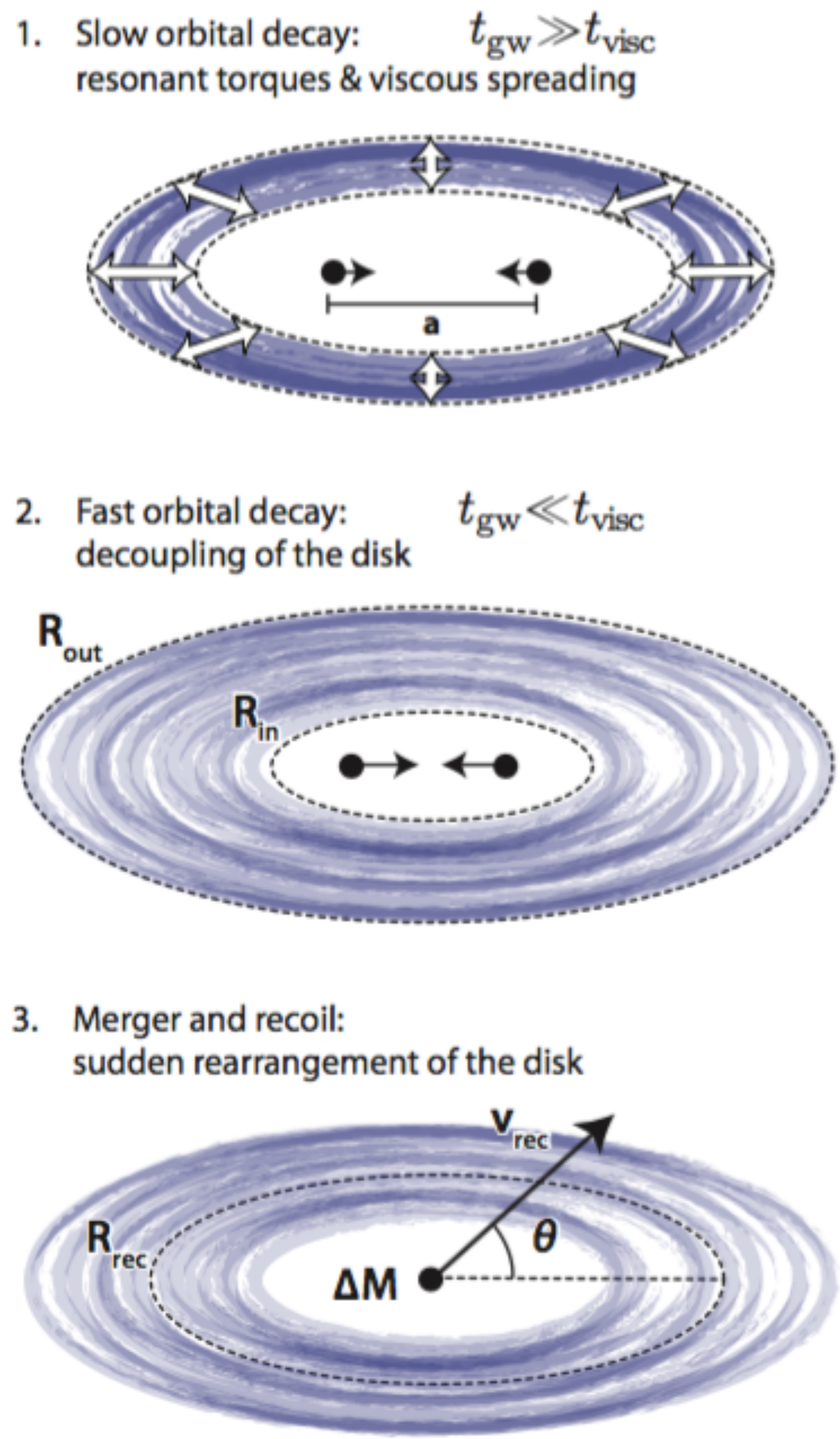


FIG. 1.— Cartoon depicting the evolution of a circumbinary disk.

1. *Time delay and duration:* Heating of the disk by shocks occurs on a characteristic timescale of order the dynamical time

$$t_{\rm dyn} \sim \frac{GM}{v^3} \sim 2.2 \frac{M_{60}}{v_3^3} \text{ hrs}, \quad (3)$$

where $v_3 = v/(10^3\,{\rm km\,s^{-1}})$ and v is the greater of the Keplerian velocity at the inner orbit and the recoil velocity imparted to the center of mass, i.e. $v \equiv \max\{v_K(R_{\rm in}), v_{\rm rec}\}$. The light–travel time required to tell

3. *Peak luminosity*: the expected rate of dissipation of kinetic energy is

$$L \sim f \frac{M_{\rm d} v^2}{t_{\rm dyn}} \sim f \, \frac{v^5}{G} q_d \quad (5)$$

where f is a scaling factor. We calibrate the factor $f \sim 0.1$ against the numerical simulations by Rossi et al. (2010), which assume an angle of $\theta = 15°$ between the recoil direction and the orbital plane

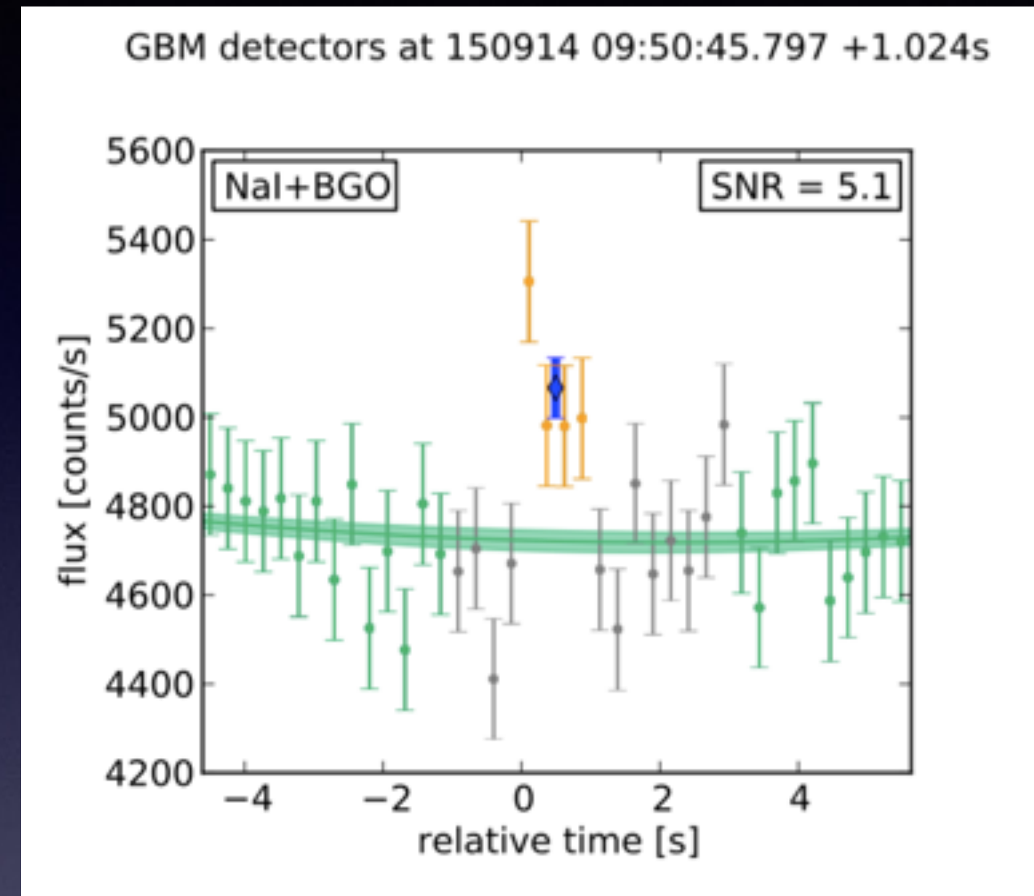
$$L \sim 5 \times 10^{42} \left(\frac{f}{0.1}\right) \, v_3^5 \left(\frac{q_{\rm d}}{10^{-3}}\right) \, {\rm erg\,s^{-1}}, \quad (6)$$

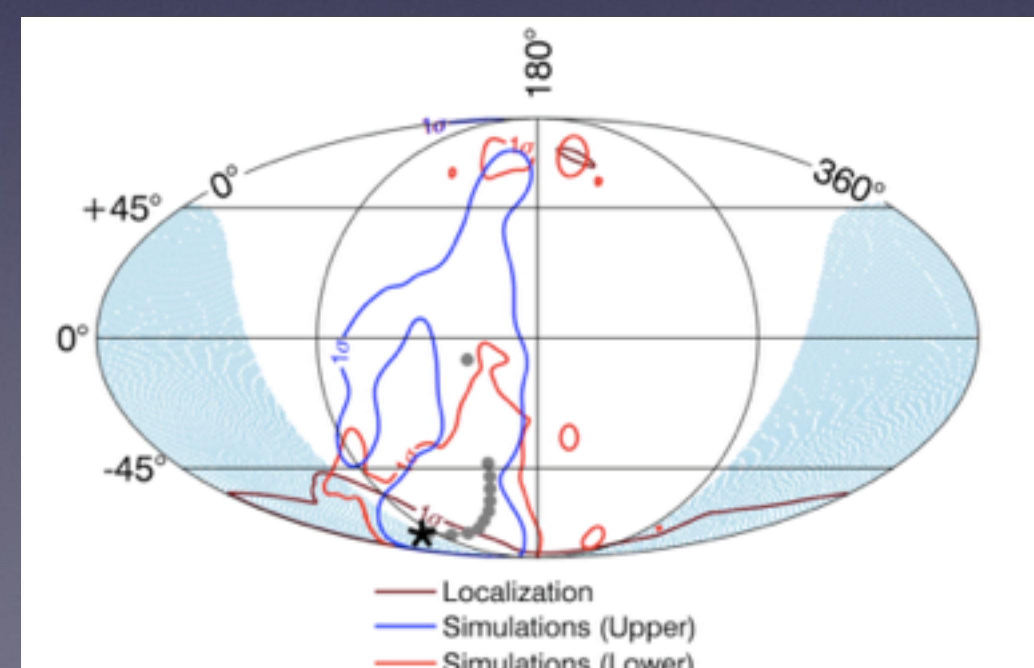
$q = M_d/M_{dtotal}$

GW150914: Fermi x-ray detection ?

Connaughton et al. 2016 ApJL:

- Fermi hard x-ray transient (*E*>50 keV), 0.4 s after the GW event, with a false alarm probability of 2.9σ
- Poor sky localisation (3000 deg^2) - not inconsistent with LIGO error region
- Duration is less than 2 sec - and it is not unlike short GRBs.
- Perna et al. (2016) : “fossil” disk, accretion restarted





Greiner et al. 2016 ApJL :

- Consider it to be background fluctuation
- Not detected by Integral

AGILE detection ? ArXiv:1706.00029
F. Verrecchia et al.

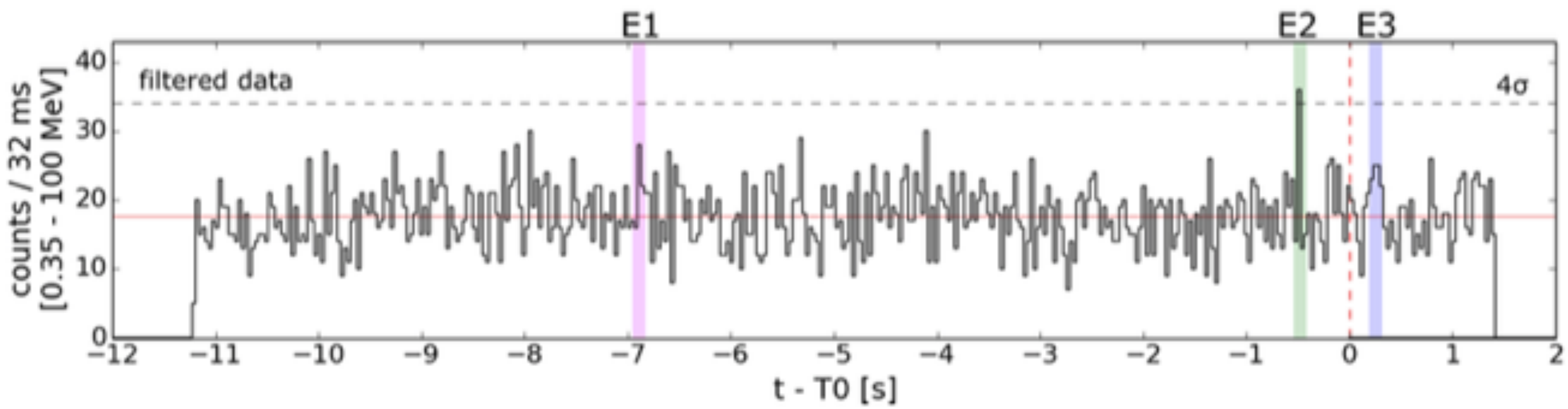


Fig. 4.— Light curve of MCAL data which includes the GW170104 event time. Data are displayed with a 32 ms time binning for the MCAL full energy band (0.35–100 MeV), after refined data processing. The E1, E2 and E3 event times are marked by vertical magenta, green and light blue lines, while the T_0 is marked by a dashed red line. The horizontal dashed grey line indicates the $4\,\sigma$ level, estimated on the whole data acquisition interval (12.6 s). The orange horizontal line marks the average background level.

“post-trial significance of 3.4**σ** for a temporal coincidence with GW170104”.

Outlook for O3 and beyond

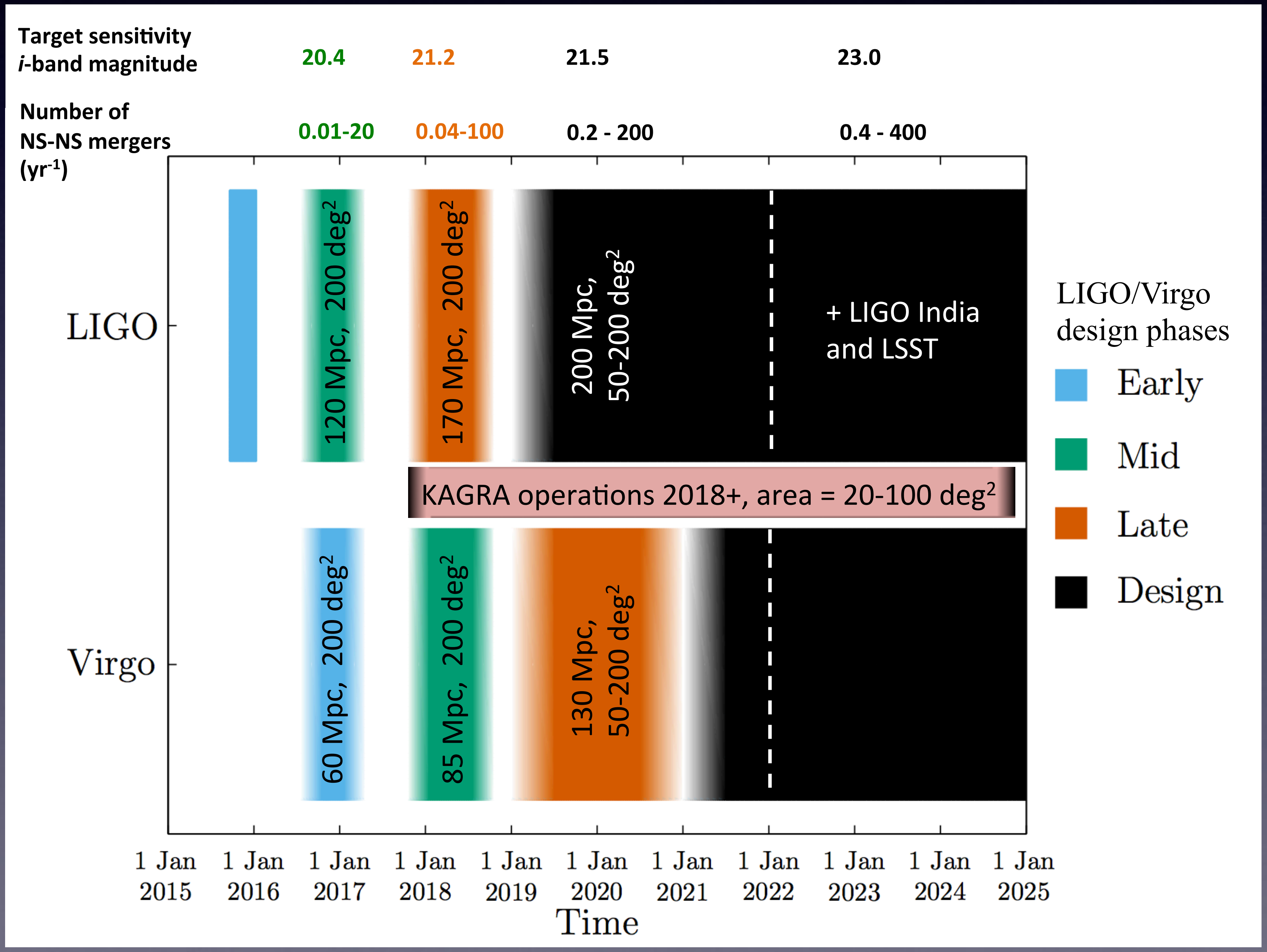
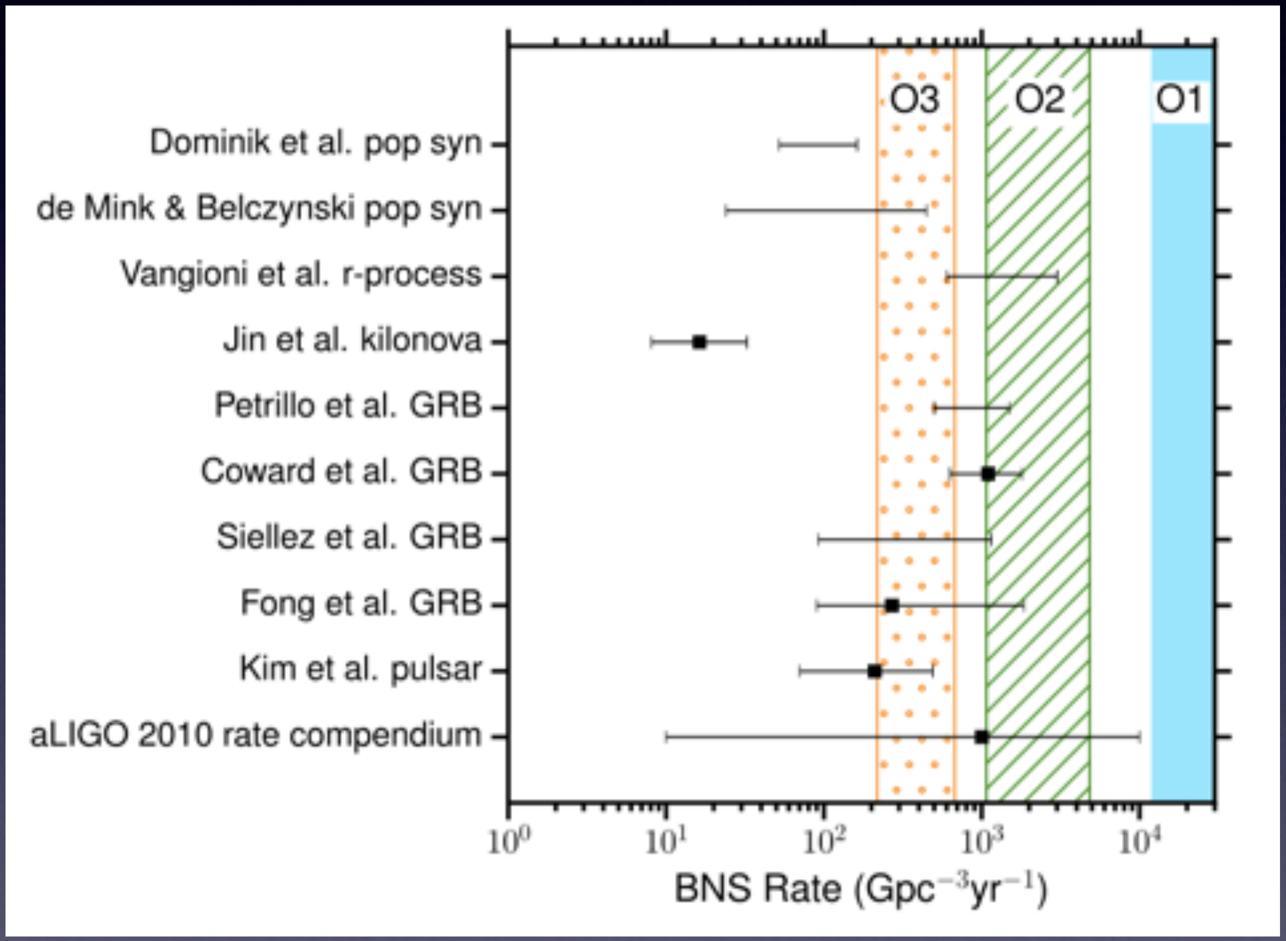
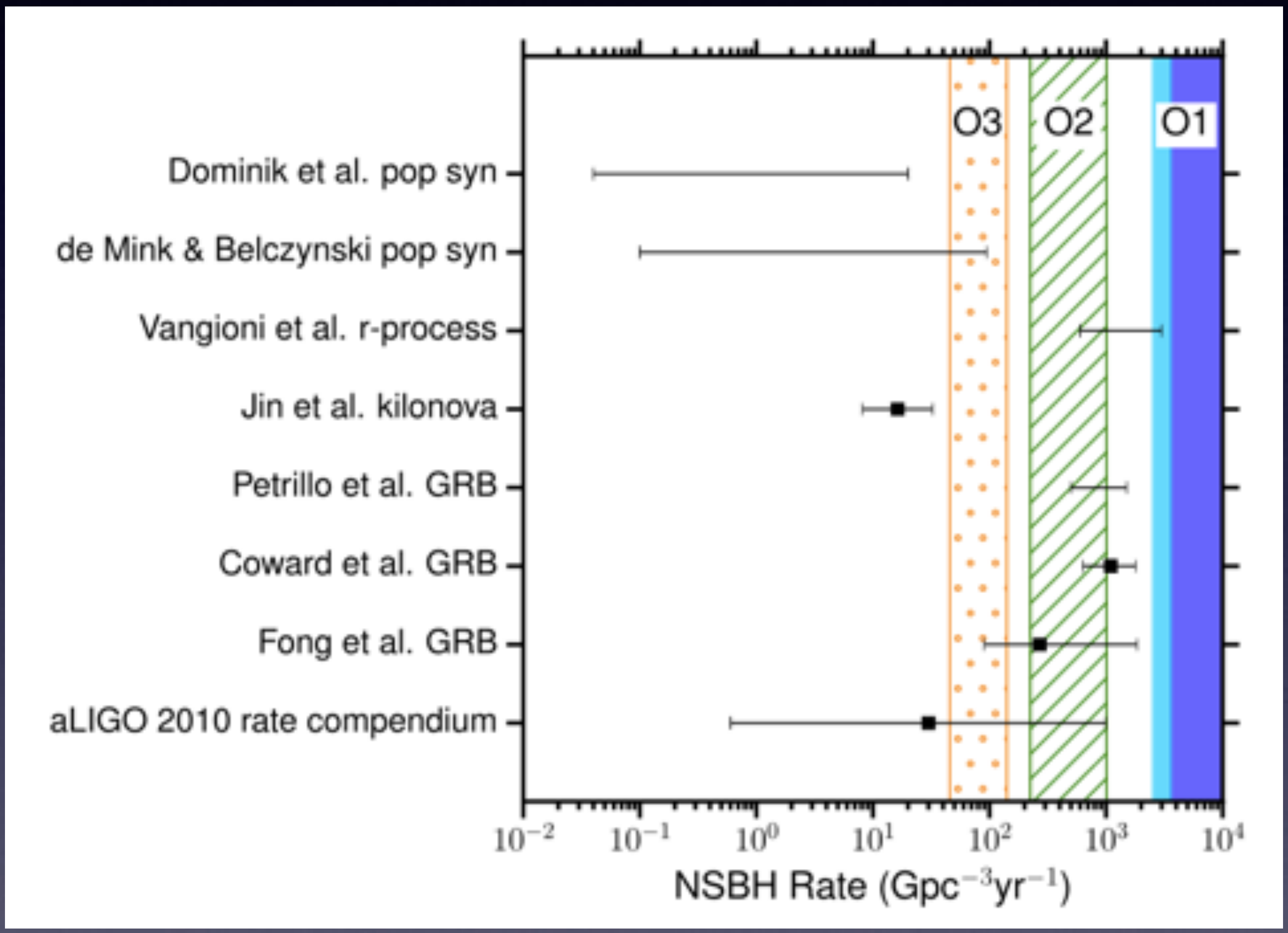


Figure : adapted from Abbott et al.
Living Rev. Relativity, 2016

Limits on rates



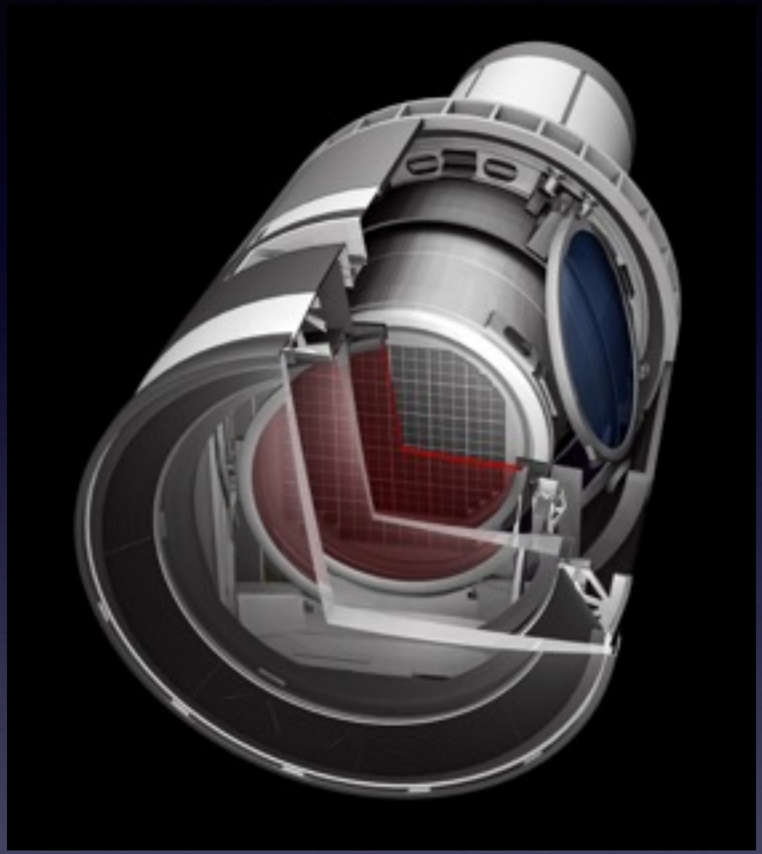


LIGO's best estimates of rates of binary NS and NS+BH systems

Abbott et al. 2016, ApJ, 832, L21

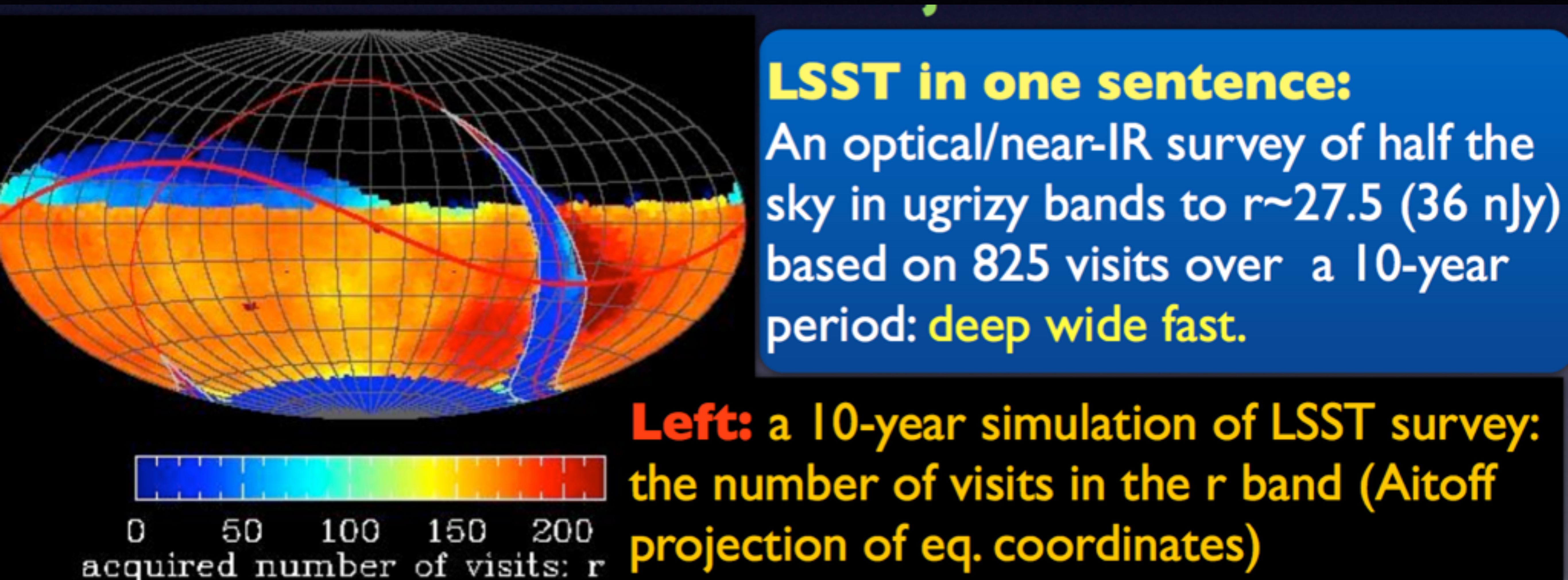
Large Synoptic Survey Telescope : 2022-2032

Most ambitious survey telescope and facility ever built



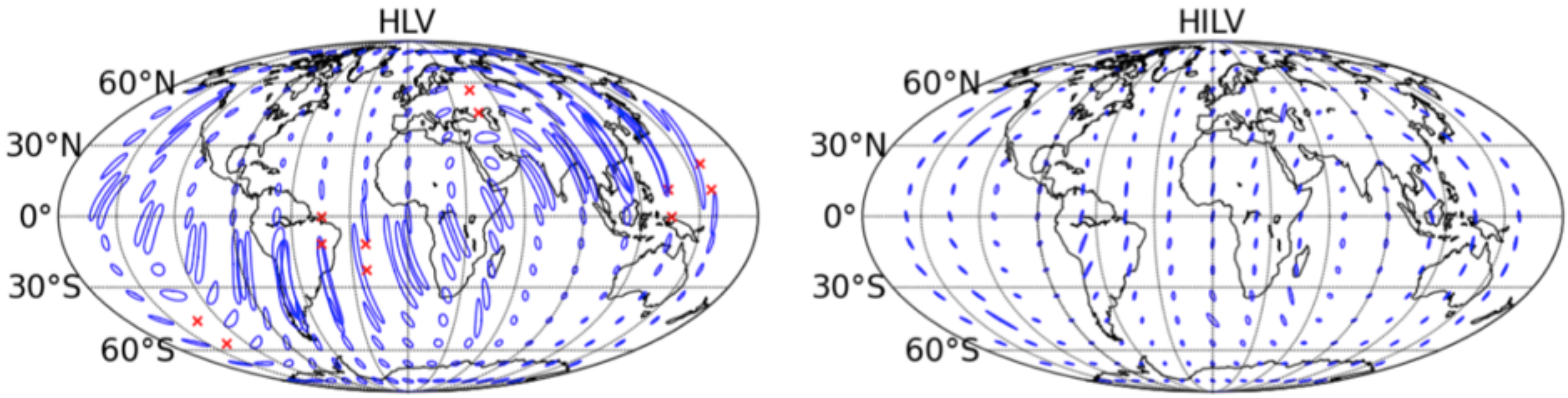
- 8.4m telescope with 3.2 Gigapix camera
- FOV is 10 square degrees
- Dedicated to surveys : USA, Chile, France, UK, Italy (plus likely many more)

LSST



- Survey operations to cover southern sky - but possible interruptions for ToO

Full LIGO/Virgo + LSST



Abbott et al. 2016, Liv. Rev. Rel.

- In 2020's : LIGO H+L + VIRGO +LIGO-India
- Error boxes 5-20 sq deg
- Exact match to LSST FoV : can reach m = 26-27 in one night, depending on coverage will easily determine if kilonovae or other EM counterparts exist

END OF PART2

OBSERVATIONS OF THE GRB AFTERGLOW ATLAS17AEU AND ITS POSSIBLE ASSOCIATION WITH GW170104

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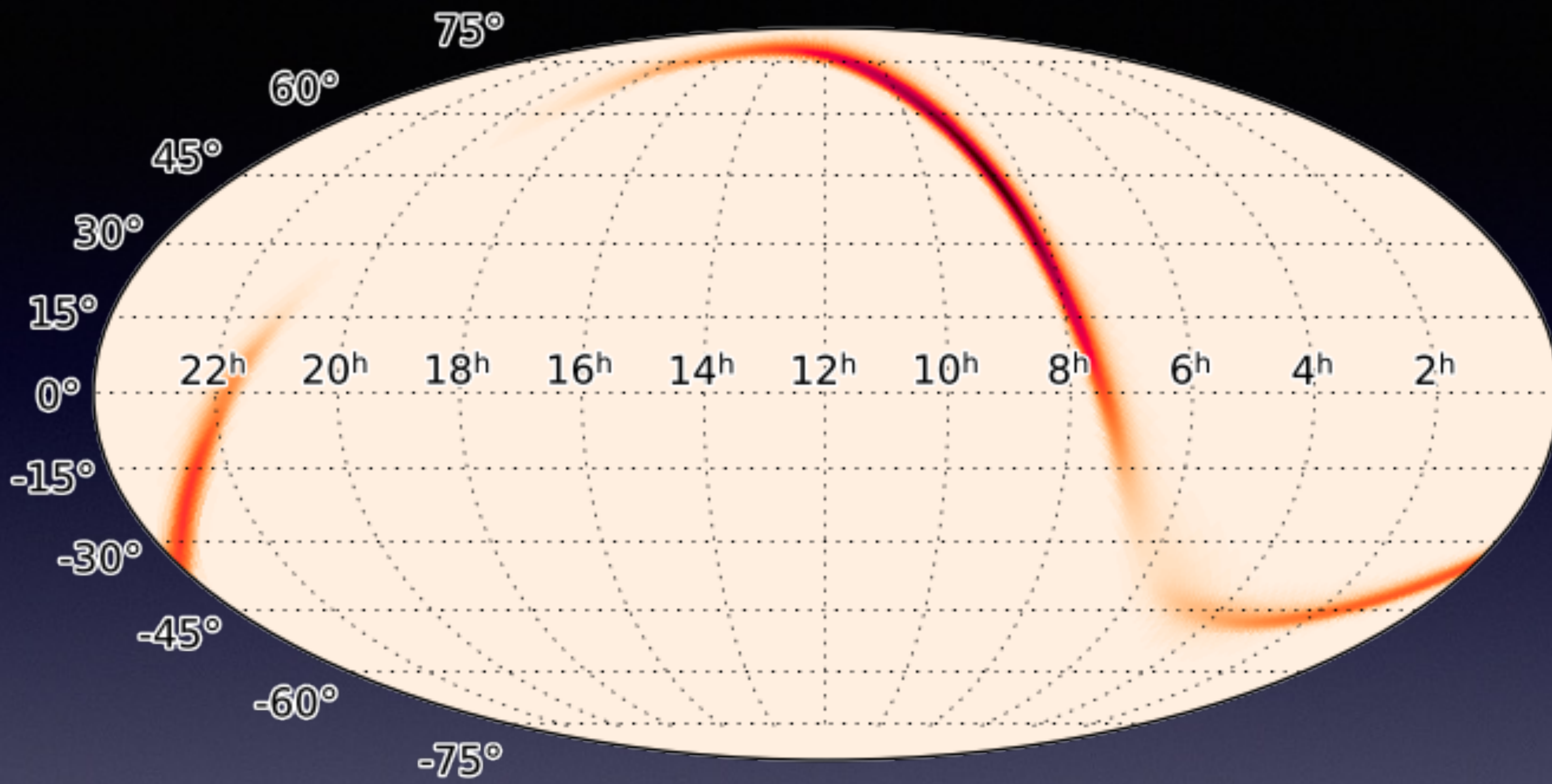
ABSTRACT

We report the discovery and multi-wavelength data analysis of the peculiar optical transient, ATLAS17aeu. This transient was identified in the skymap of the LIGO gravitational wave event GW170104 by our ATLAS and Pan-STARRS coverage. ATLAS17aeu was discovered 23.1hrs after GW170104 and rapidly faded over the next 3 nights, with a spectrum revealing a blue featureless continuum. The transient was also detected as a fading x-ray source by Swift and in the radio at 6 and 15 GHz. A gamma ray burst GRB170105 was detected by 3 satellites 19.04 hrs after GW170104 and 4.10 hrs before our first optical detection. We analyse the multi-wavelength fluxes in the context of the known GRB population and discuss the observed sky rates of GRBs and their afterglows. We find it statistically likely that ATLAS17aeu is an afterglow associated with GRB170105, with a chance coincidence ruled out at the 99% confidence or 2.6σ. A long, soft GRB within a redshift range of $1 \lesssim z \lesssim 2.9$ would be consistent with all the observed multi-wavelength data. The Poisson probability of a chance occurrence of GW170104 and ATLAS17aeu is $p = 0.04$. This is the probability of a chance coincidence in 2D sky location and in time. These observations indicate that ATLAS17aeu is plausibly a normal GRB afterglow at significantly higher redshift than the distance constraint for GW170104 and therefore a chance coincidence. However if a redshift of the faint host were to place it within the GW170104 distance range, then physical association with GW170104 should be considered.

Keywords: gravitational waves, stars: black holes, gamma-ray burst: general, gamma-ray burst: individual: GRB170105

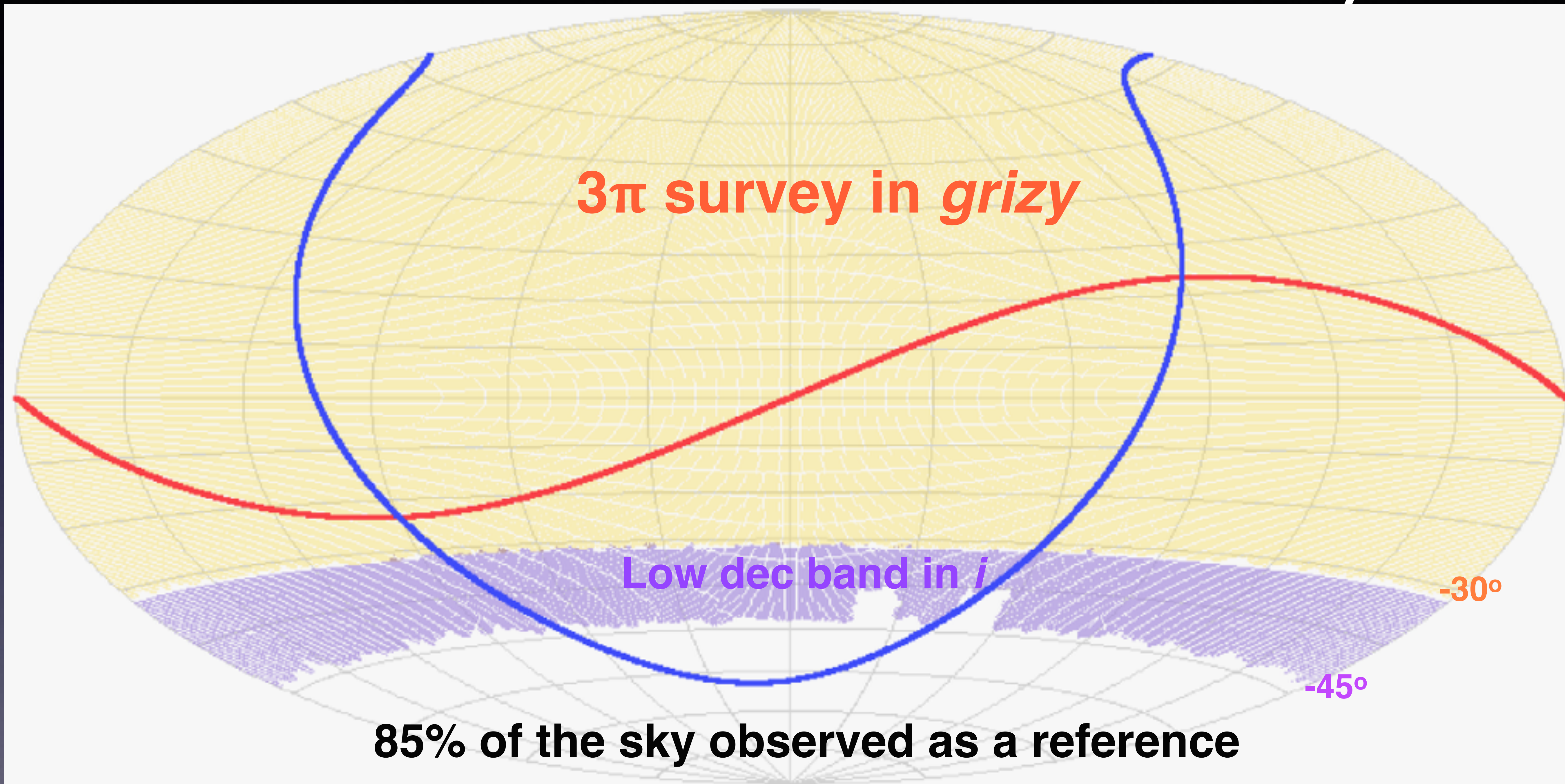


MJD=57756. Shortly after the break, the internal system distributed the alert of a candidate gravitational wave (GW) transient, designated as event G268556 at 2017-01-04 10:11:58.599 UTC or MJD = 57757.42498378. It was later given the name GW170104 after the offline analysis provided very strong confirmation of its astrophysical origin (as presented in Abbott et al. 2017). The 90% probability area of the associated GW skymap is 2000 square degrees or 5% of the sky. Throughout this paper we use

ATLAS coverage : 42 %

Pan-STARRS : 43 %

The Pan-STARRS Sky

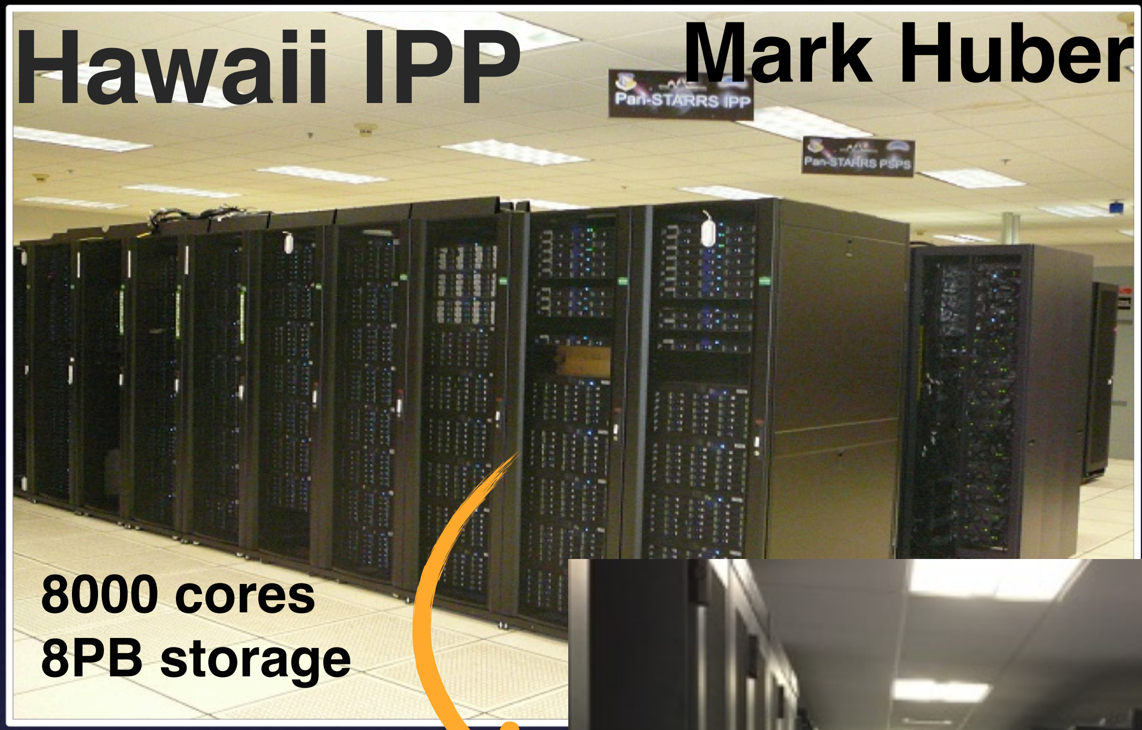


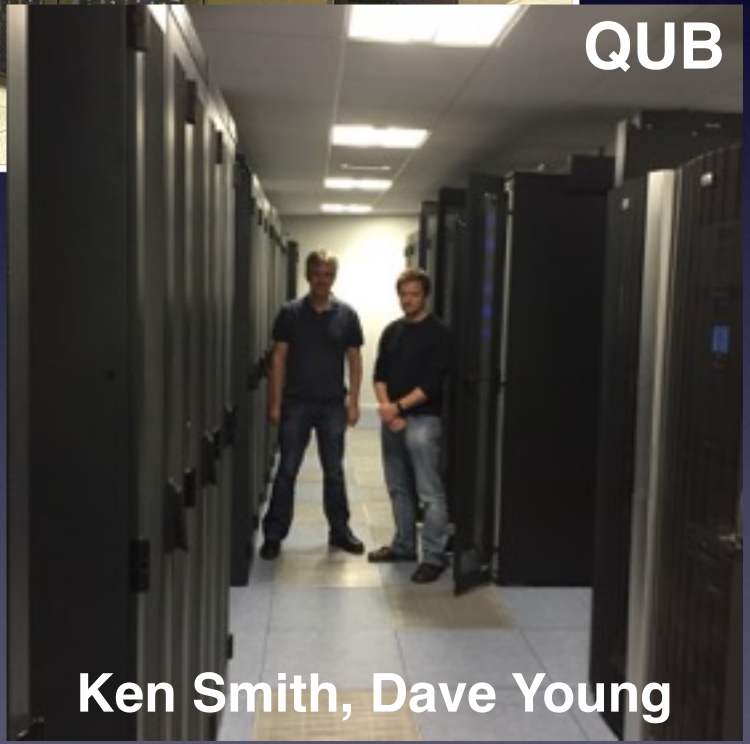
with over 100 epochs.

First public data release from Space Telescope Science Institute (MAST archive system and tools)
December 2016

Pan-STARRS Cyber-Infrastructure

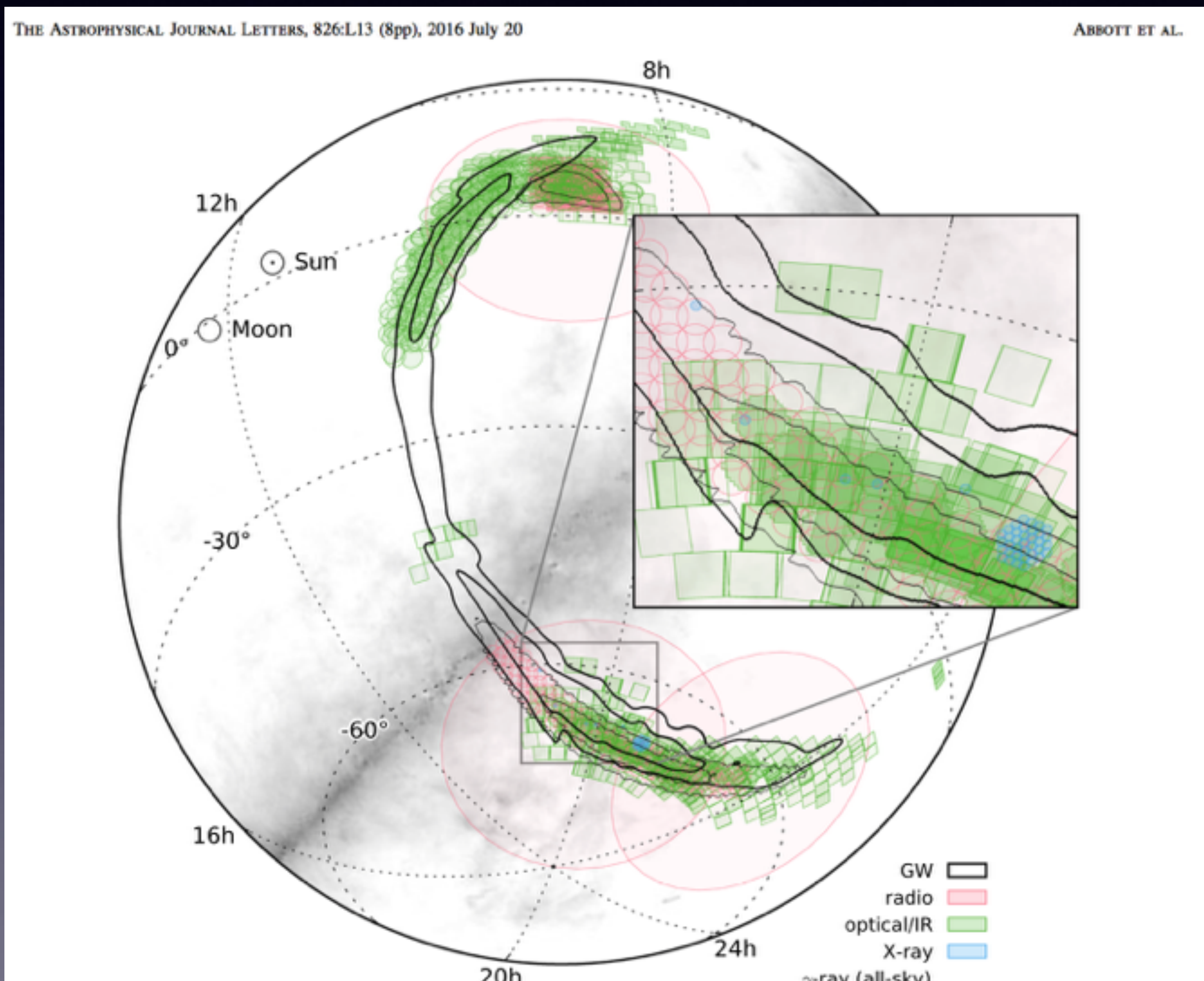
- Hawaii : Image Processing Pipeline
- PSPS : hierarchical database. All sky catalogues
- High i/o rate, large cpu requirement. Large local storage required - large computer science project
- QUB Transient Science Server in Belfast





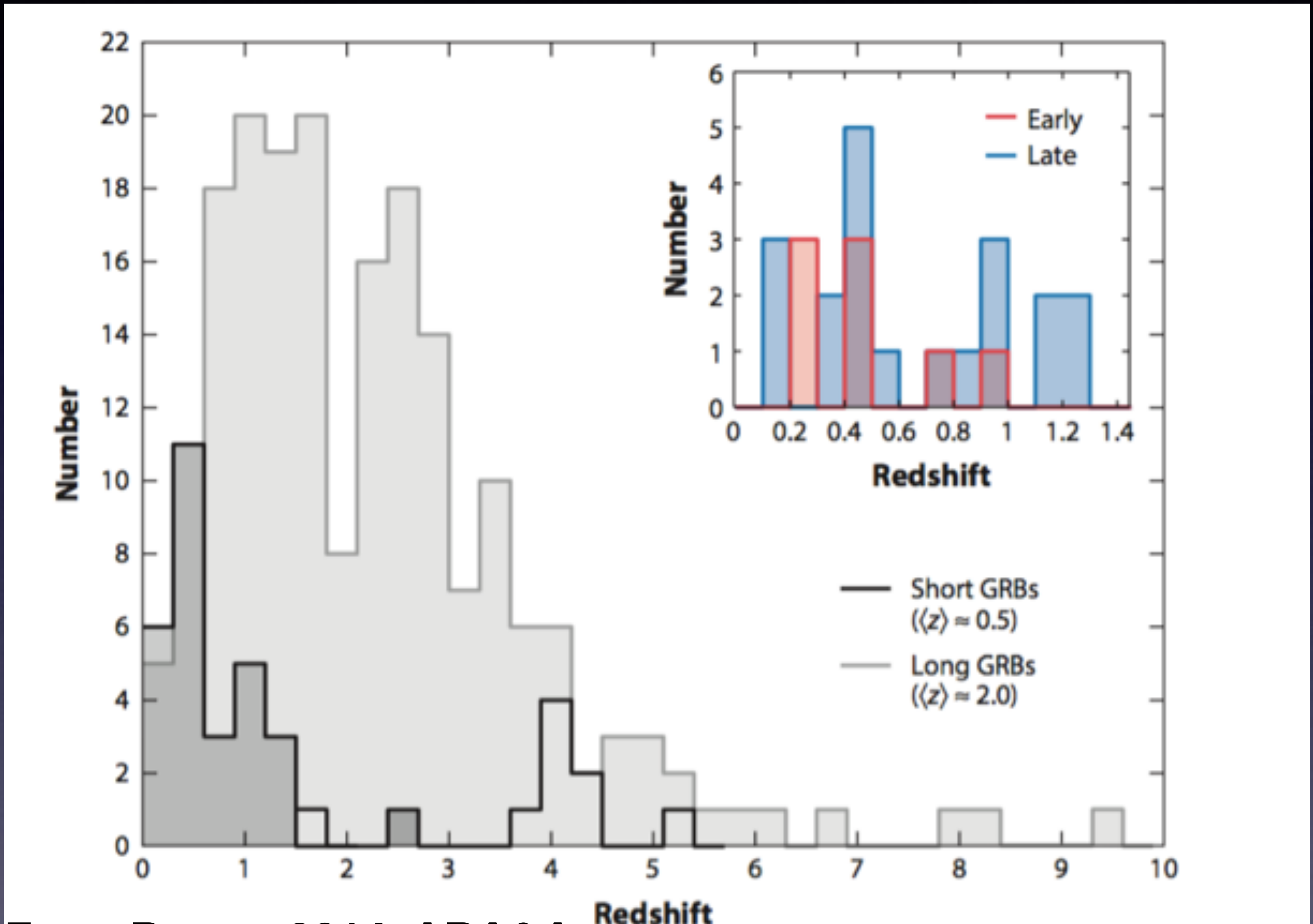
Ship catalogues : 10^7 detections per day to Belfast "Transient Science Server"
Database, algorithms - machine learning and boosted decision trees.
Classify all transients

γ and x-ray to radio follow-up of GW150914



- Abbott et al. 2016c
- Followup by **25** teams of observers from gamma, x-ray to radio
- Three different skymaps released, before final analysis focused >95% of the probability in the southern arc
- One summary paper and many project papers
- Proof of concept for Pan-STARRS and PESSTO in Smartt et al. 2016a,b
- No detections but …. Fermi claim

Swift's low redshift deficit



From Berger 2014, ARA&A

- **No sGRB known with *z* < 0.1 in <u>10 yrs of Swift operations</u>**
- Nothing within *D* < 400 Mpc
- Not surprising if $\theta \sim 10^o$, $f_{on\text{-}axis} = 1.5\%$
- LIGO/Virgo horizon distance for NS-NS is *D* < 200 Mpc

Numbers per yr :

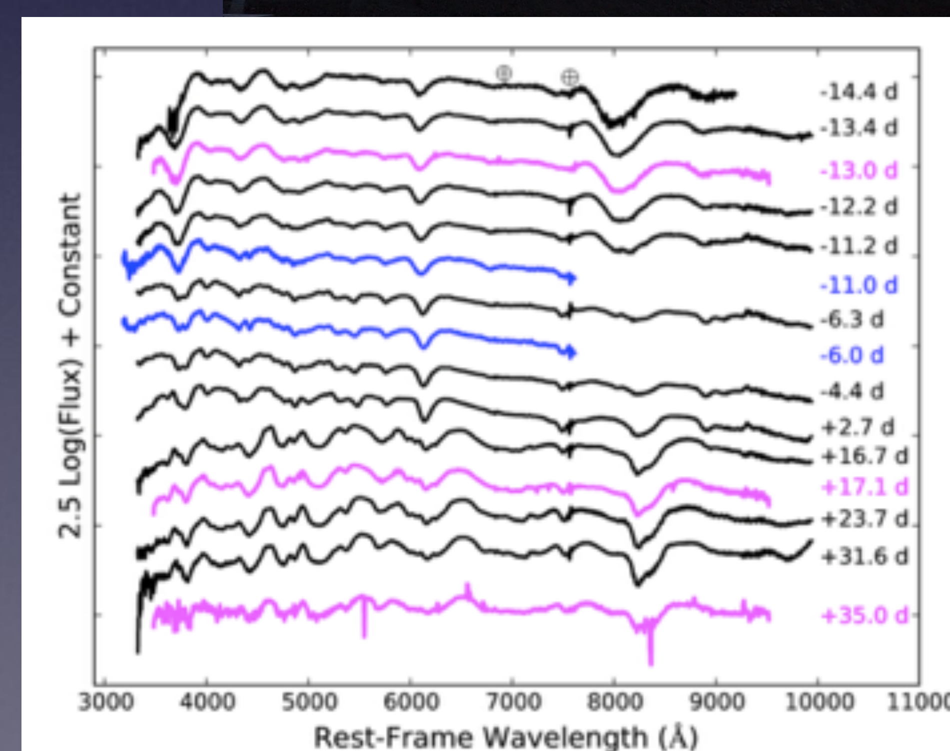
Swift ~ 40

Fermi ~ 35 (offline, unverified)

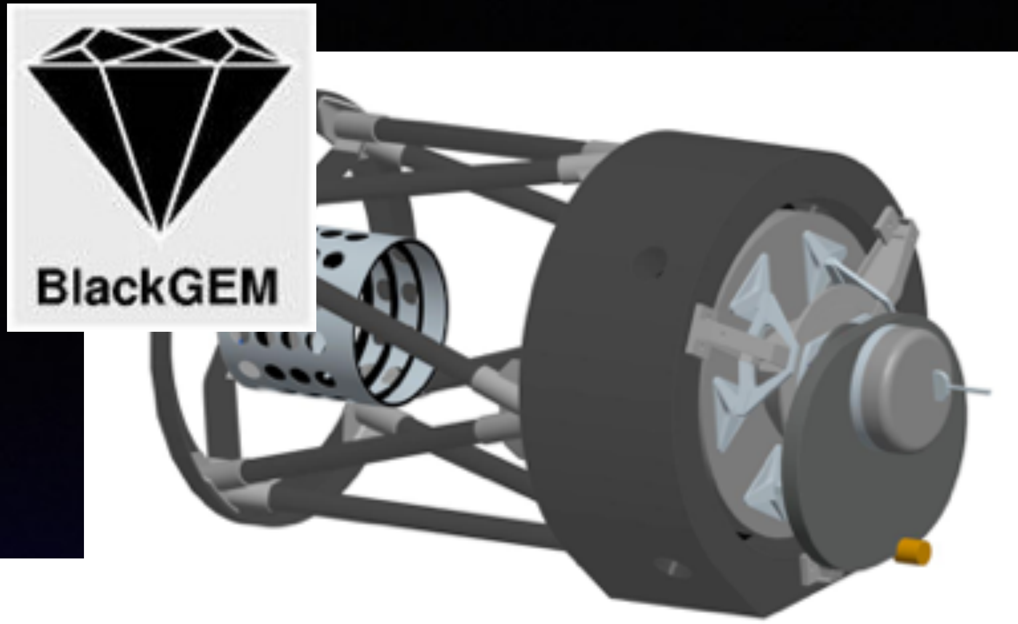
www.pessto.org

- Public ESO Spectroscopic Survey for Transient Objects

- 43 institutes, 185 scientists from ESO, Chile, Australia, USA
- 90N per year on ESO NTT (2012-2017)
- 870 transients classified - reduced data released publicly within 24hrs
- 43 papers (>50 end of 2016)
- Major resource for classification of GW candidates
- Low-resolution filter for VLT and Gemini

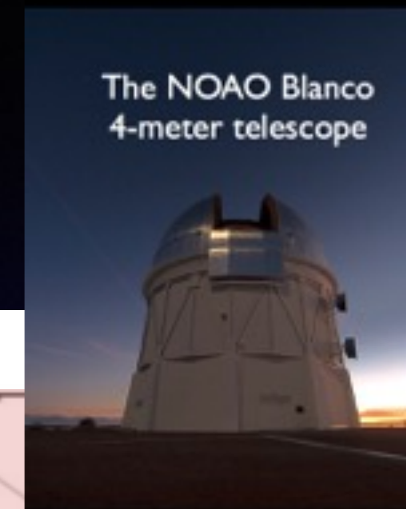


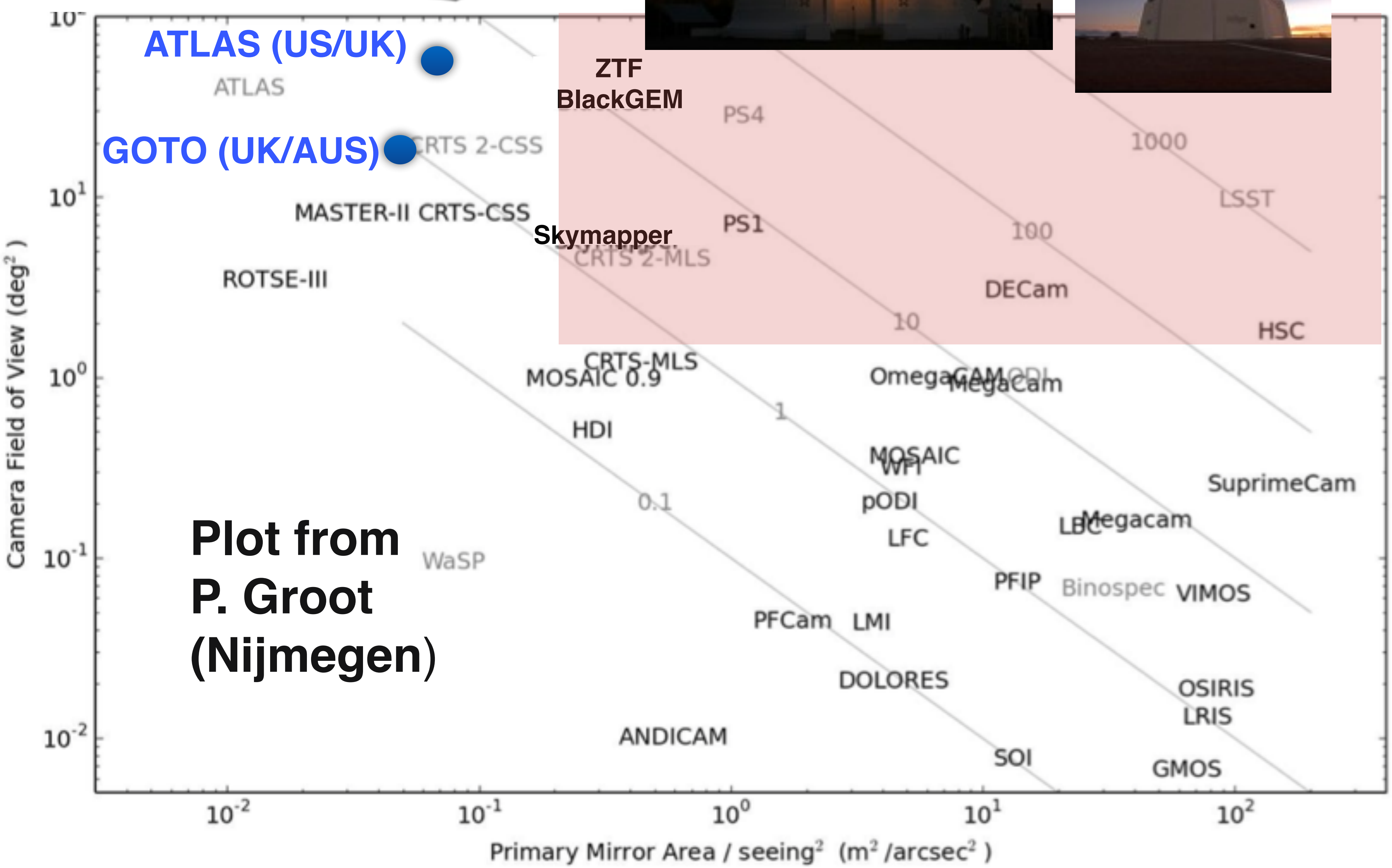
SN2015F; Cartier et al. 2016



Kasliwal et al 2016

Soares-Santos et al. 2016





Pan-STARRS : ready for 85% of sky