Transient surveys
&
Gravitational Wave follow-up

Danny Steeghs
University of Warwick

Long history of surveys

Sky surveying a long standing tool:

- plate surveys (still a great resource)
- CCD era surveys
- time-domain aspects

Key eras in time-domain surveys:

- Variable stars

[OGLE, SDSS, VST surveys]

- SN cosmology

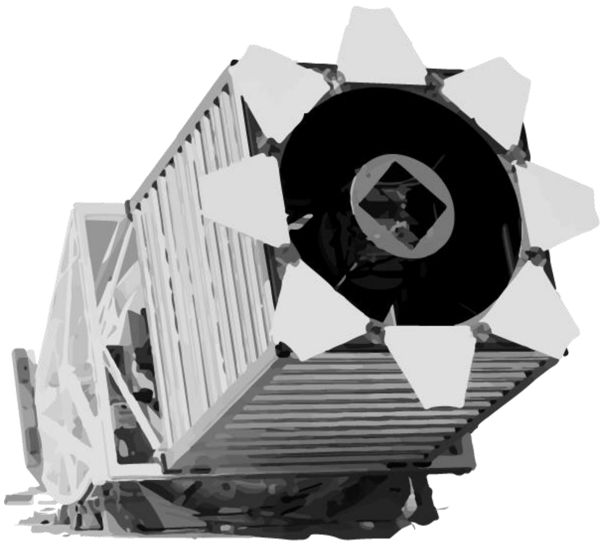
[SNF, (i)PTF, SLS, DES ….]

- exotic and explosive events (GRBs, TDEs)

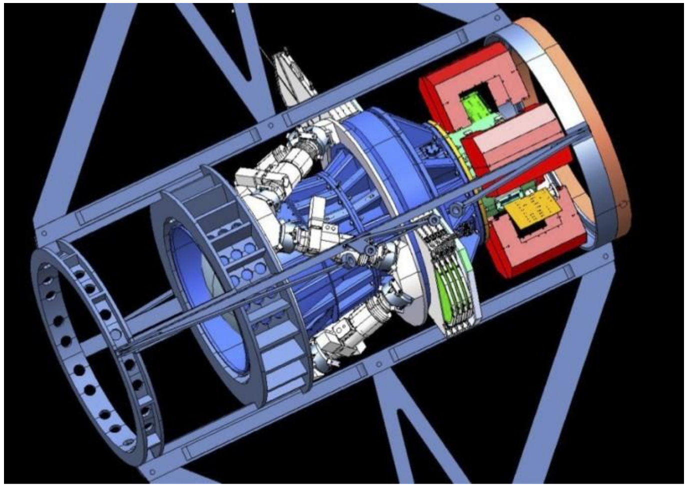
- Asteroids and NEOs

[CRTS , ATLAS, Pan-Starrs]

- Now *Gravitational Wave follow-up* has become a main driver

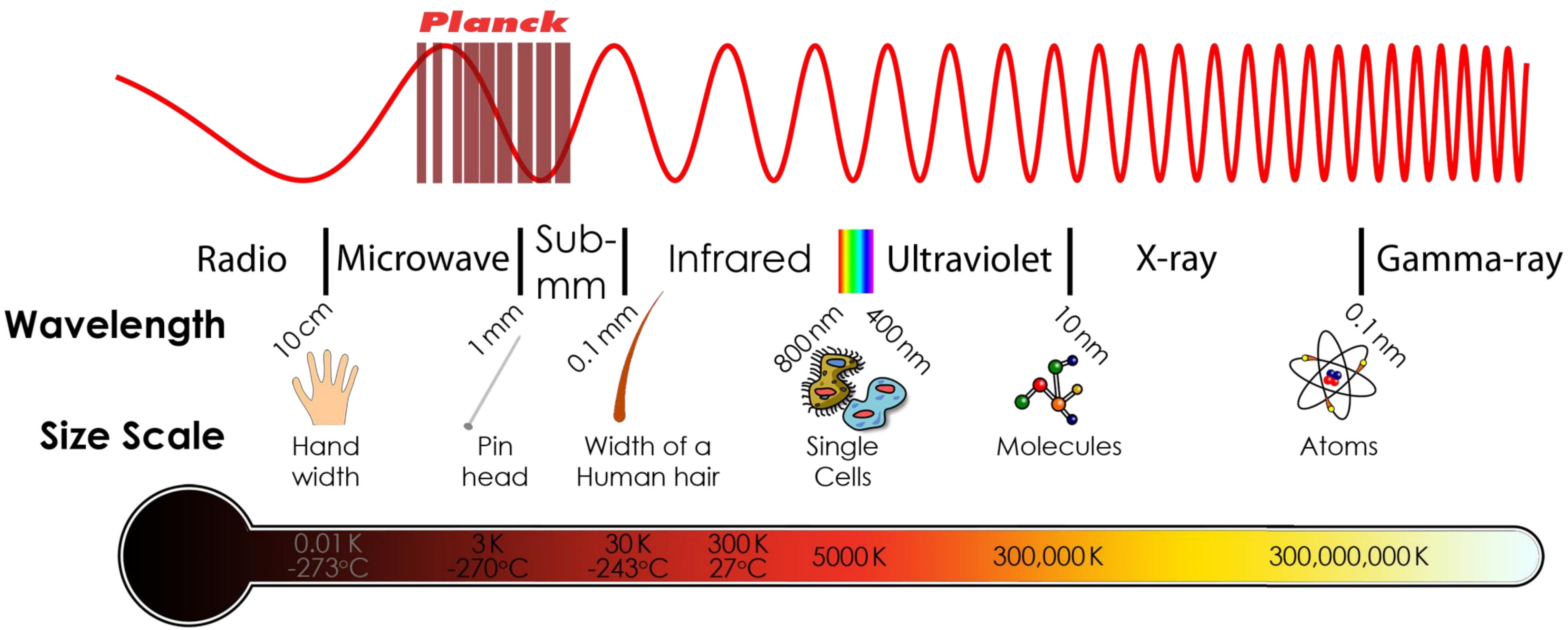


SDSS



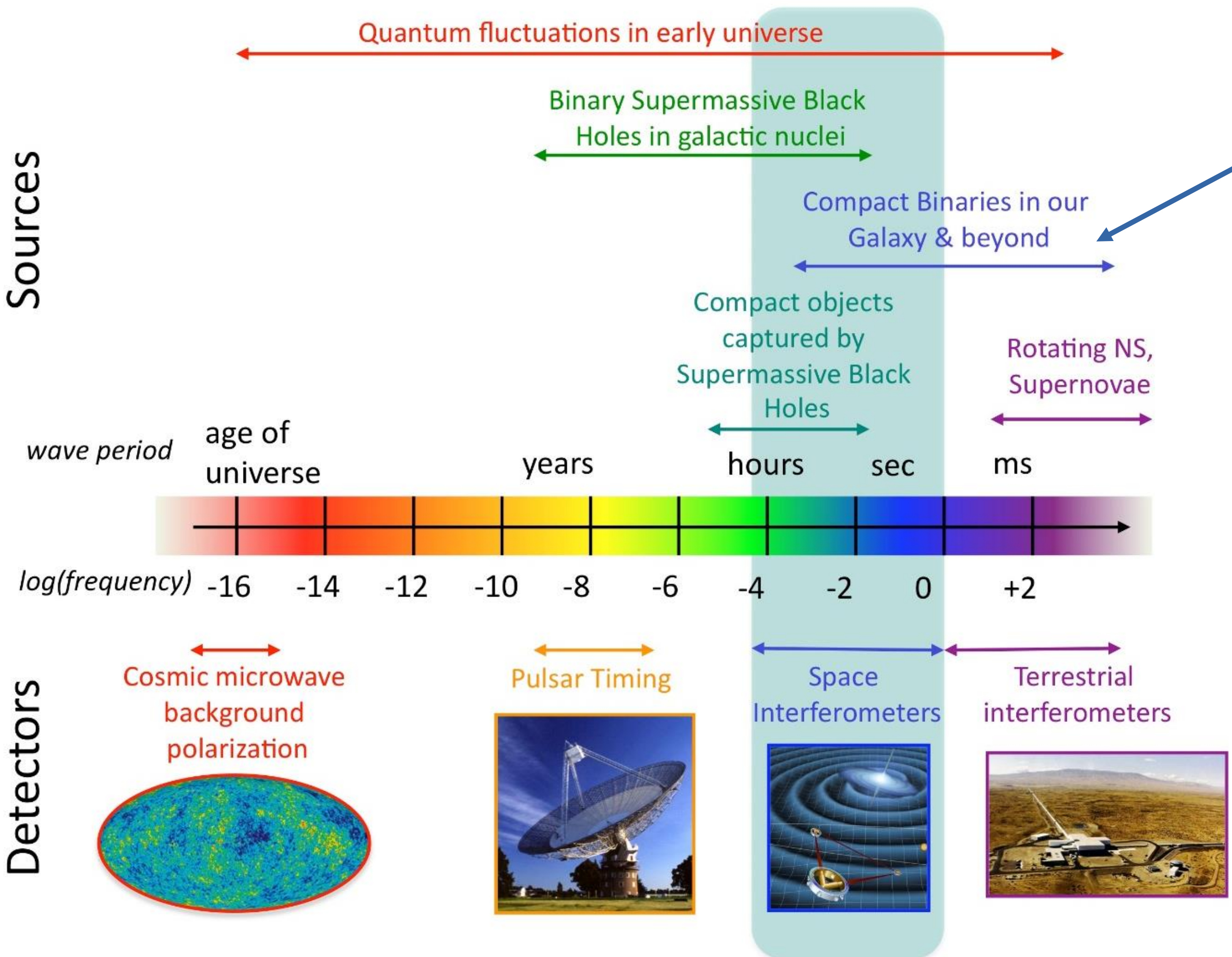
DECAM

Multi-wavelength Astronomy



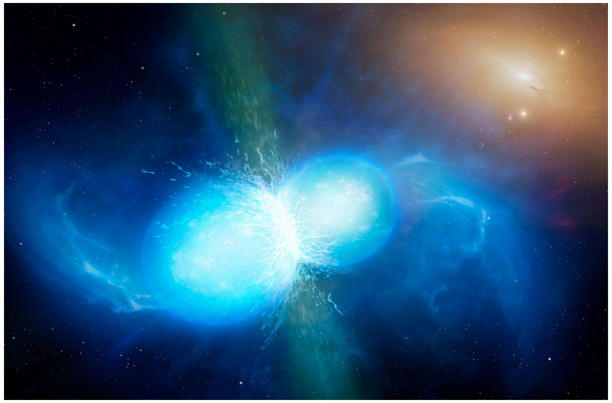
Lots of amazing missions and facilities coming that jointly will offer all-sky data across the EM spectrum

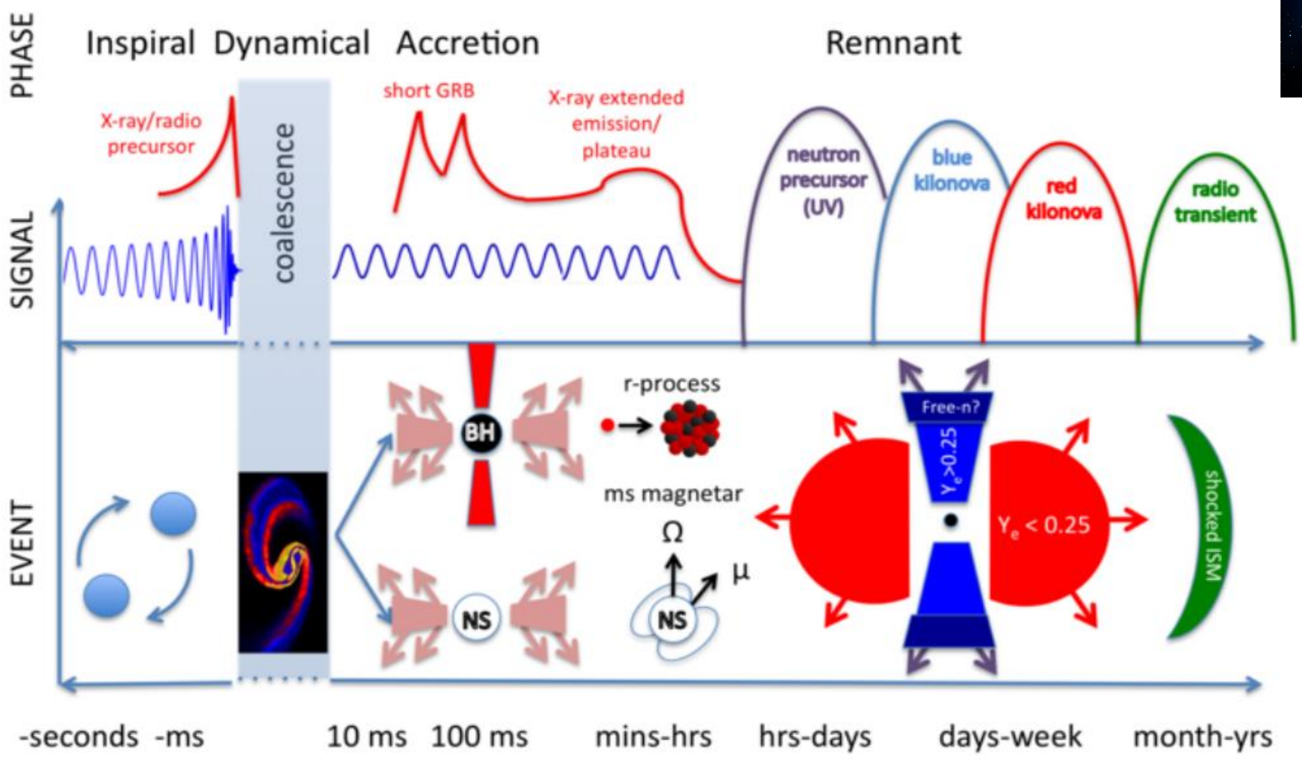
Spectrum of gravitational waves



Powering EM emission

Binary Neutron Star merger events were considered (and still are) the main multi-messenger type of events thanks to a disruptive merger process with key ejecta components



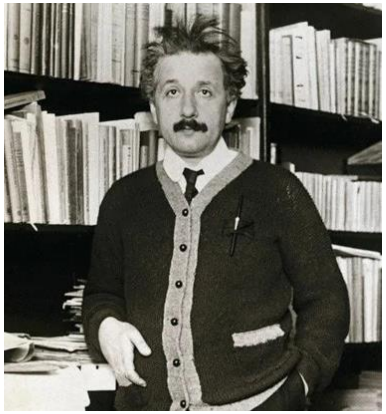


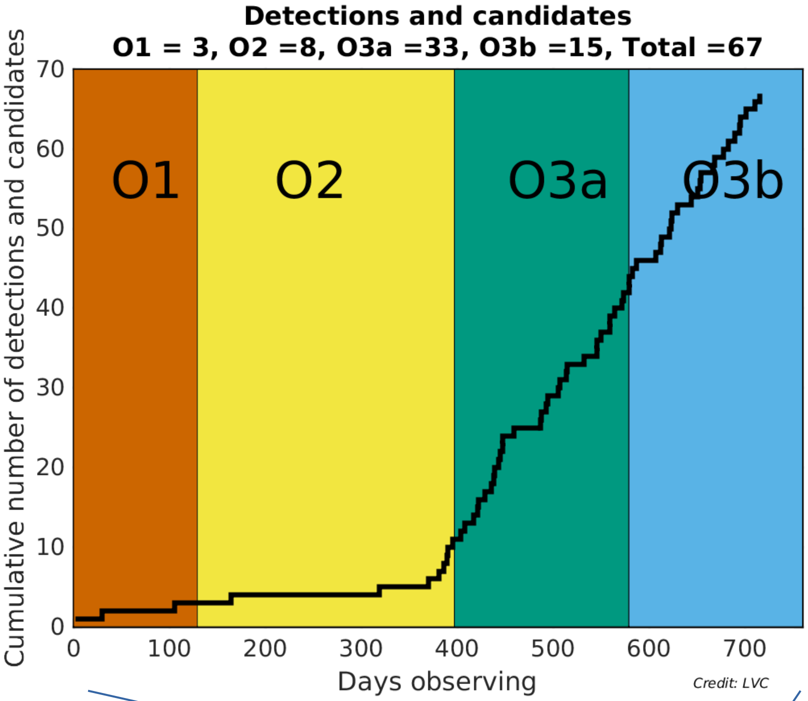
Metzger (2016)

Lots of astrophysics here:

- compact objects & stellar evolution
- relativistic outflows
- formation of the elements
- BH formation
- ….

GW: it took some time

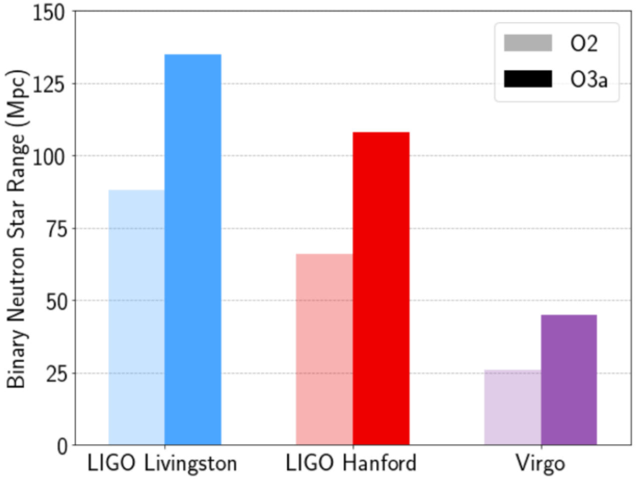




1915

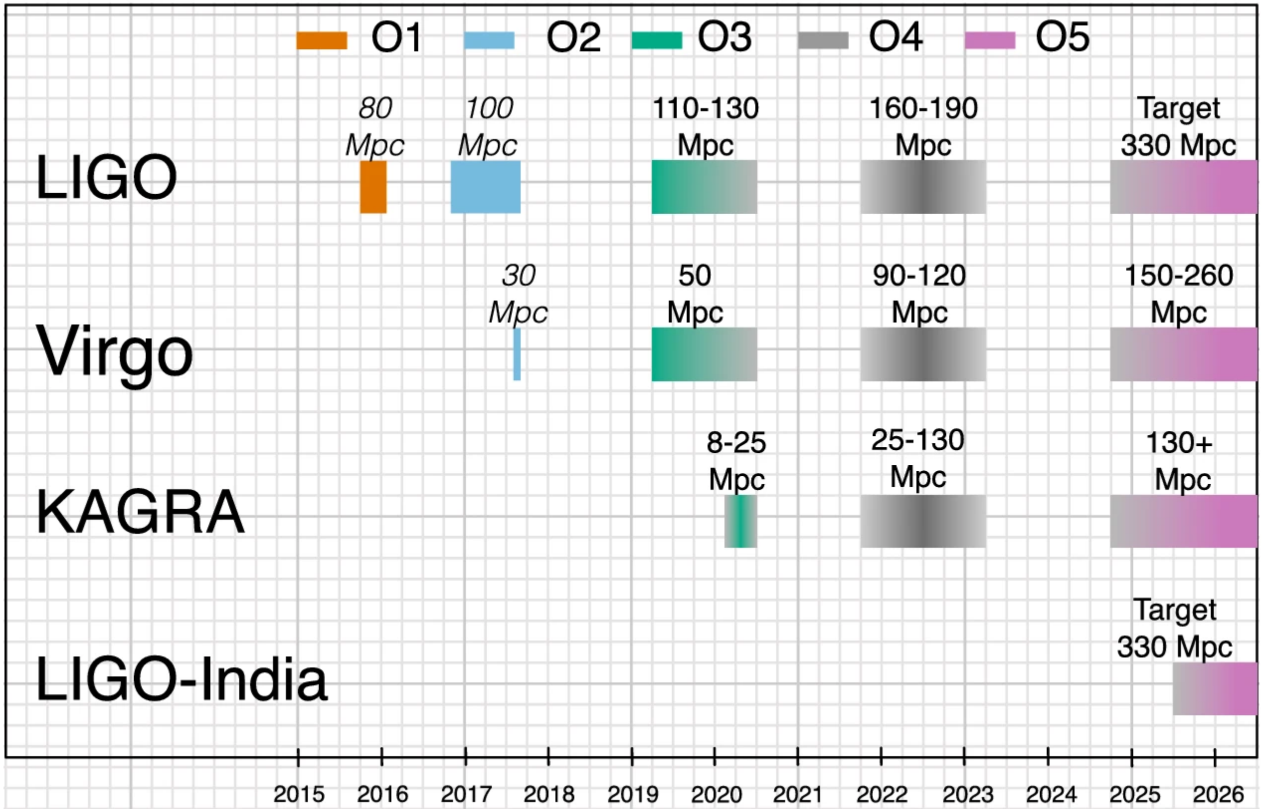
2015-2020

GW detector network



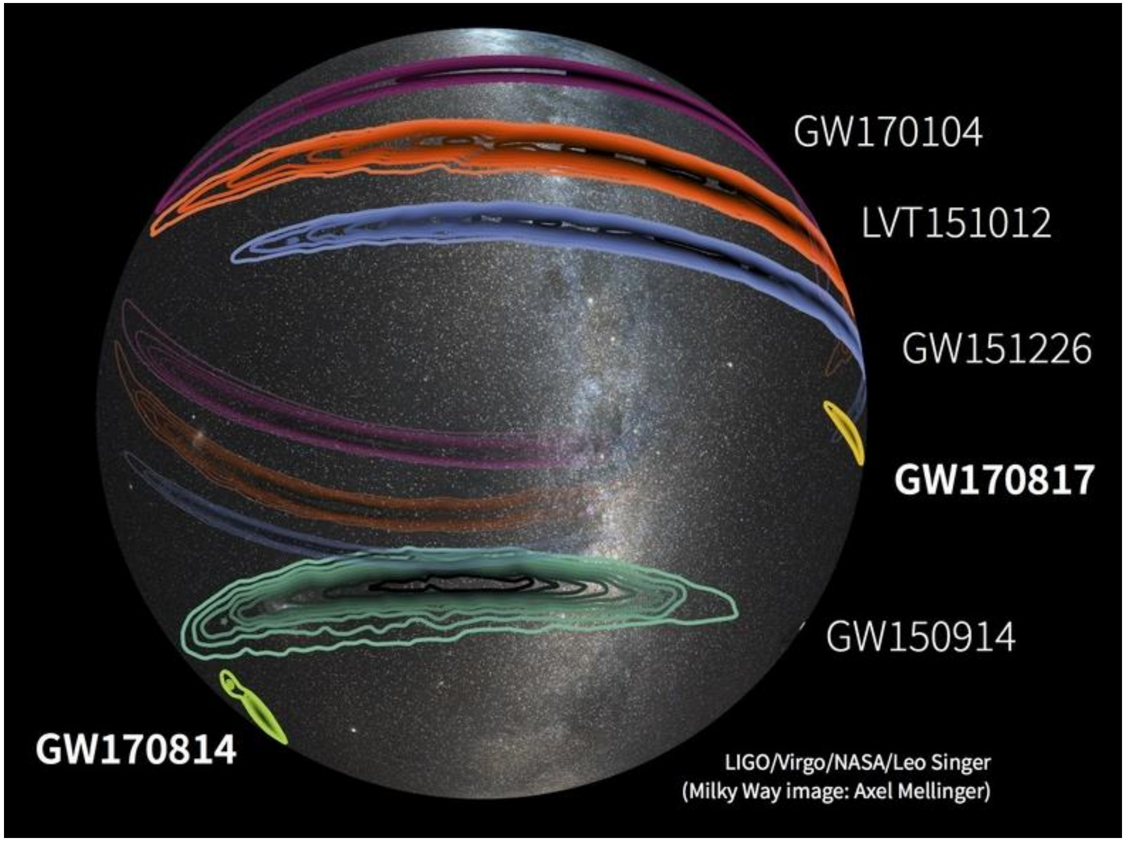
Credit: LIGO-Virgo Collaboration / Eve Chase / Caitlin Rose / Northwestern / University of Wisconsin-Milwaukee

Currently into first few seasons with advanced arrays



Abbott et al. (2020)

GW follow-up challenge

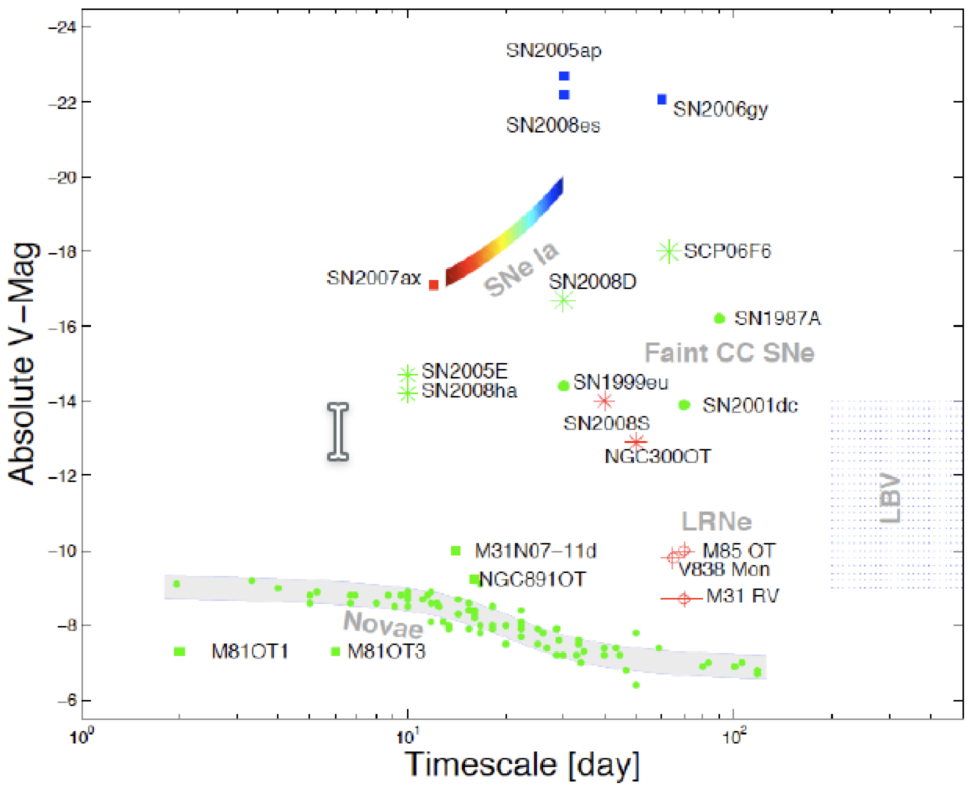


- We have short-lived EM signals, particularly in optical
- We have limited sky **localisation** information
- We have a tremendous amount of foreground

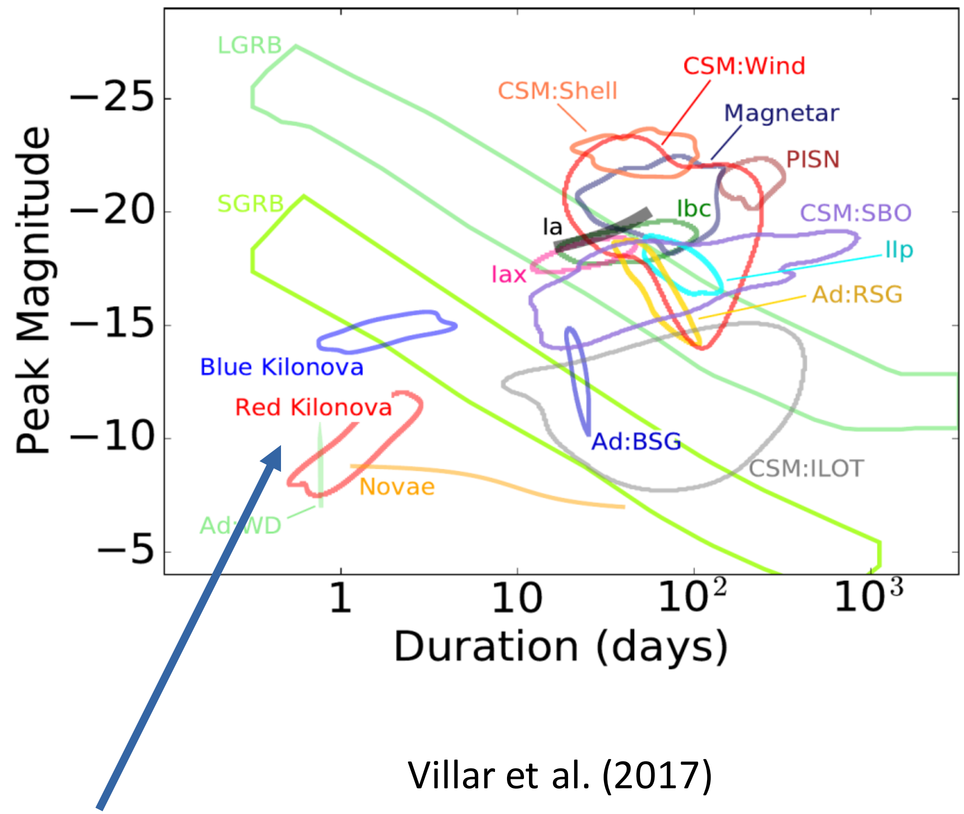
(The bigger the area, the harder it is)

Transient Phase Space

I will here focus on optical transient searches in connection with GW followup of binary merger events involving neutron stars



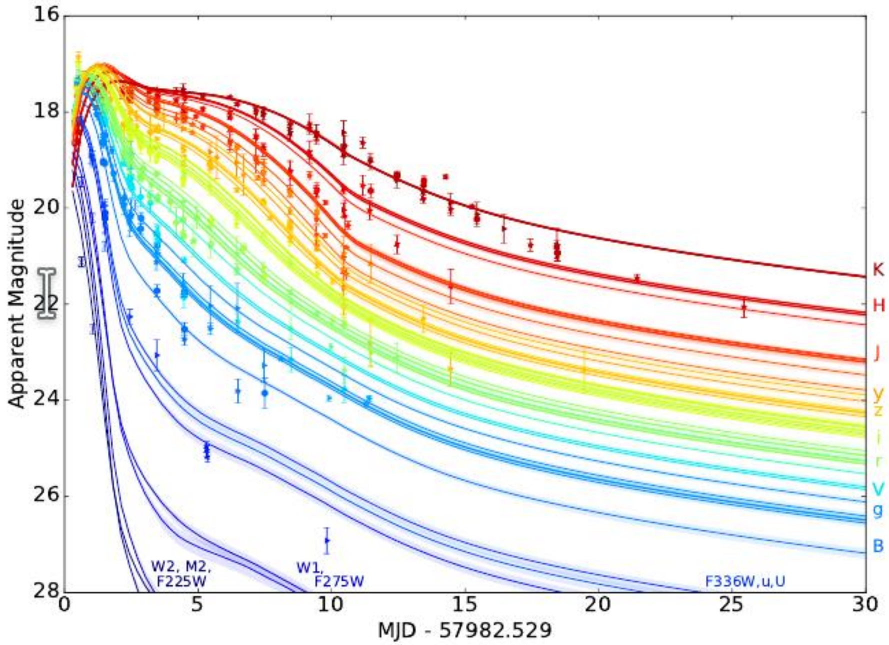
LSST Science Handbook



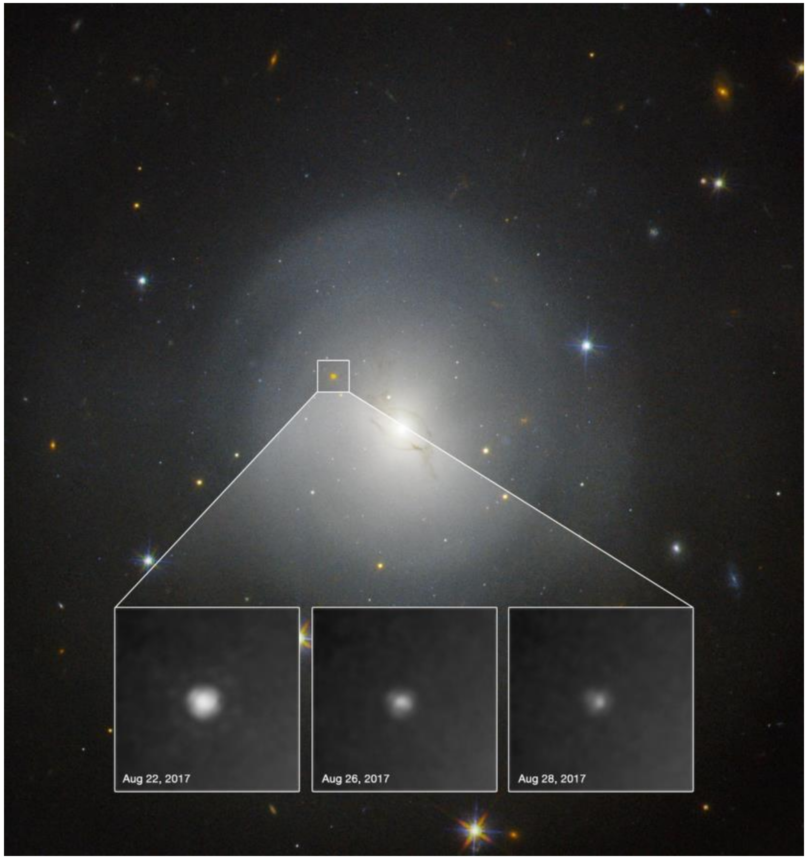
Villar et al. (2017)

Challenge is short duration and moderate luminosity

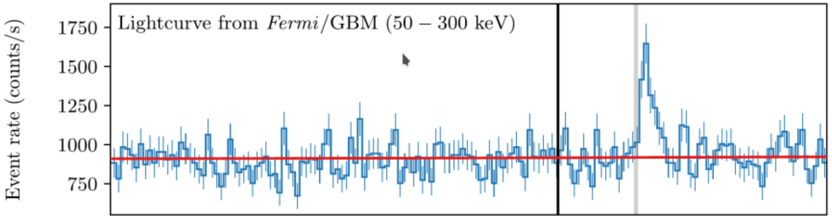
Gemstone BNS: GW170817



lightcurve



kilonova



short-GRB link

What a treat it was!

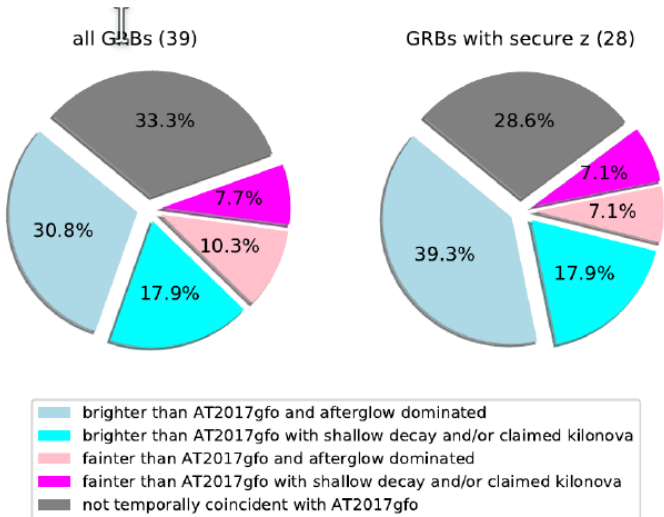
Nice Review:

Margutti & Chornock (2020)
arXiv:2012.04810

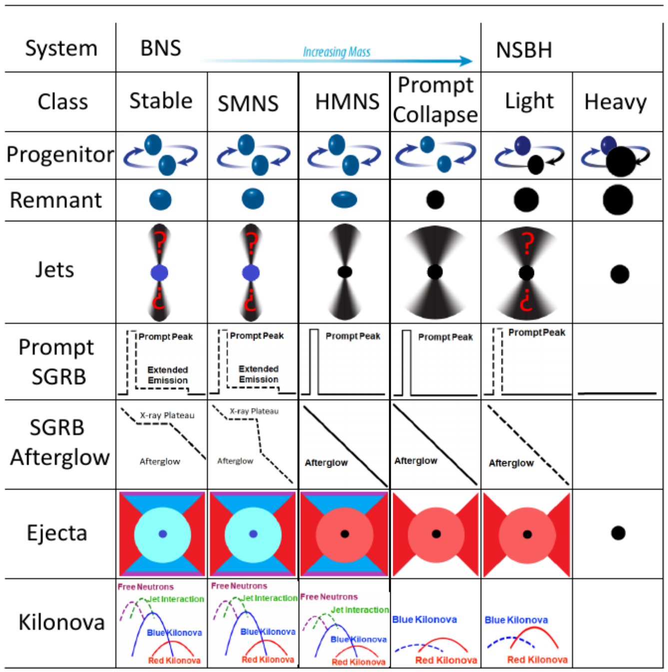
Short-GRB constraints

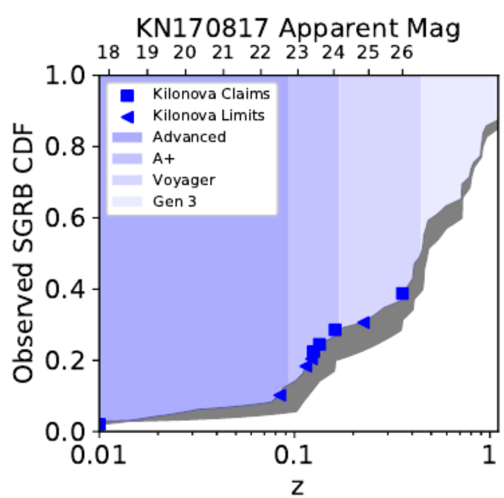
1 excellent datapoint, but diversity expected

For now best constraints from (possible) Kilonova signals in short-GRBs



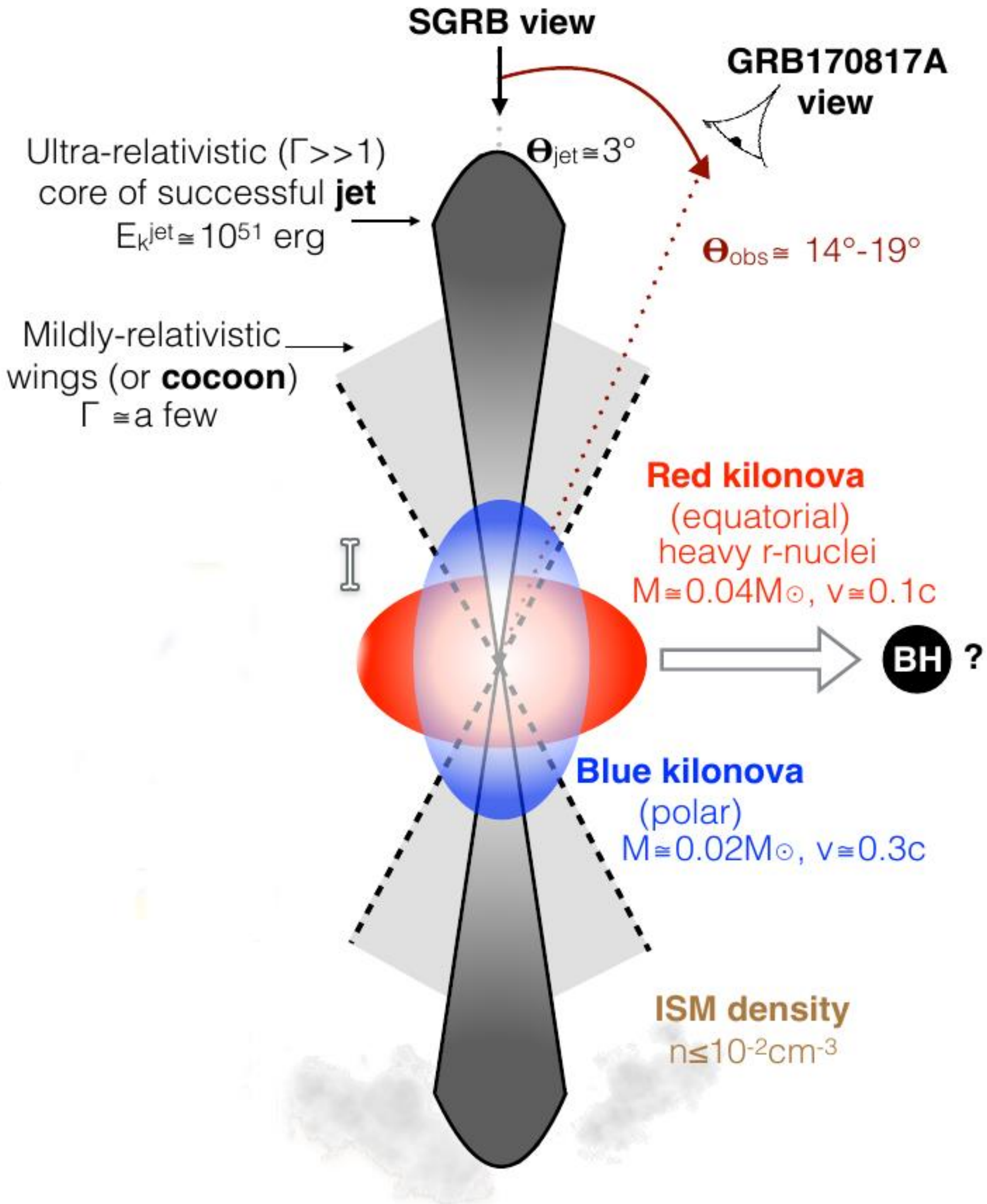
Rossi et al. (2019)





Burns (2020)

BNS ejecta and EM emission



Key parameters:

- Mass and velocity of components

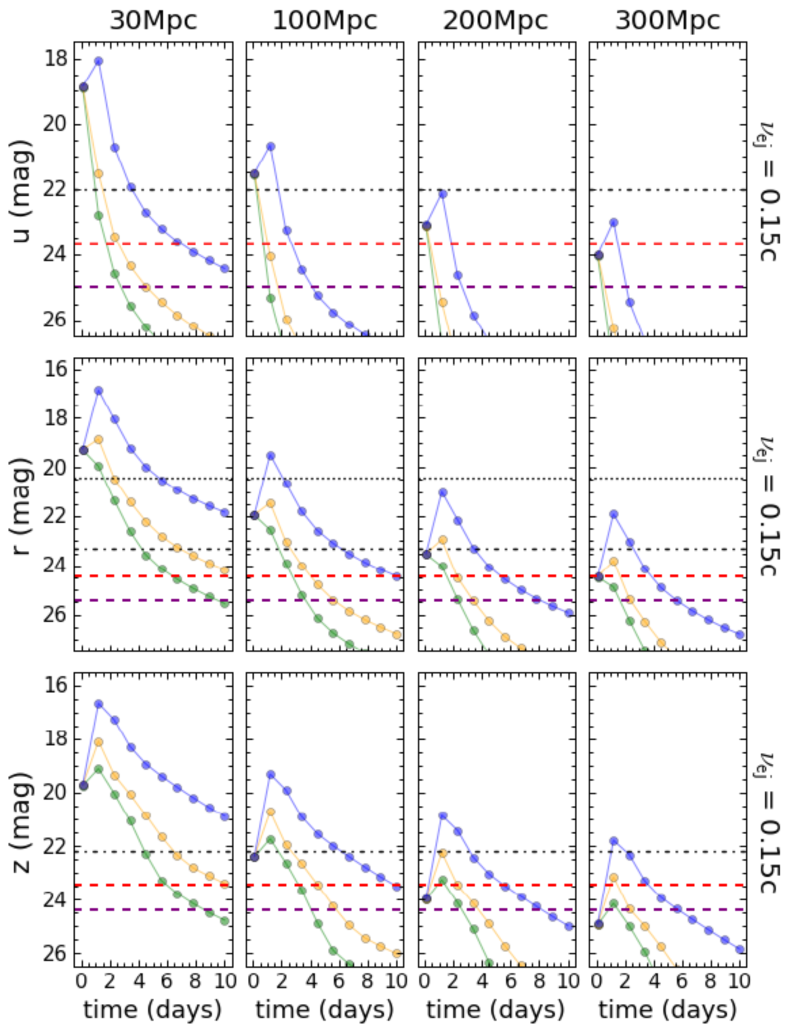
- Collimation of ejecta

- Observer line of sight

Hard:

- Radiation transport & nuclear physics

Need samples, rates, ...



Only just the beginning

- Rates maybe not as high as we thought

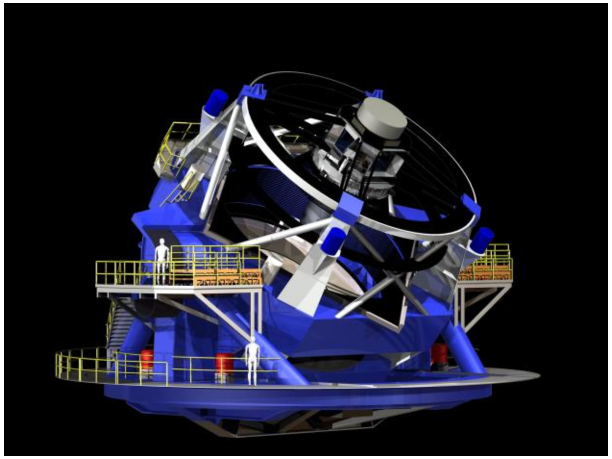
- Diversity

- Many events not as cooperative

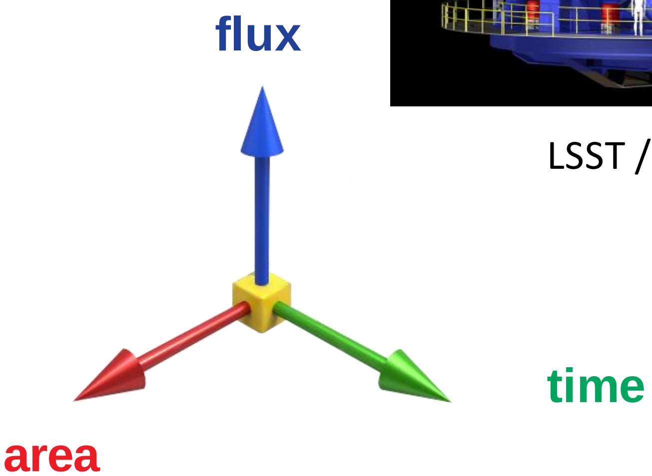
- So again patience is required and a systematic approach

- Need facilities that can search quickly, with sufficient sensitivity and being able to cover substantial areas

Alternative Approaches



LSST / Vera Rubin



ASAS-SN

GOTO

WARWICK

GRAVITATIONAL-WAVE OPTICAL TRANSIENT OBSERVER

WARWICK
THE UNIVERSITY OF WARWICK

MONASH University

MANCHESTER 1824
The University of Manchester

The University Of Sheffield.

UNIVERSITY OF TURKU

NARIT

UNIVERSITY OF LEICESTER

INSTITUTO D ASTROFISICA D CANARIAS · IAC ·

UNIVERSITY OF PORTSMOUTH

ARMAGH OBSERVATORY & PLANETARIUM
EXPLORING THE COSMOS SINCE 1790

UKRI Science and Technology Facilities Council

goto-observatory.org

GOTO origins

Key motivations:

Specifically designed for wide, rapid response searches of exotic transients and GW-EM in particular

Wide area capability to sufficient depth

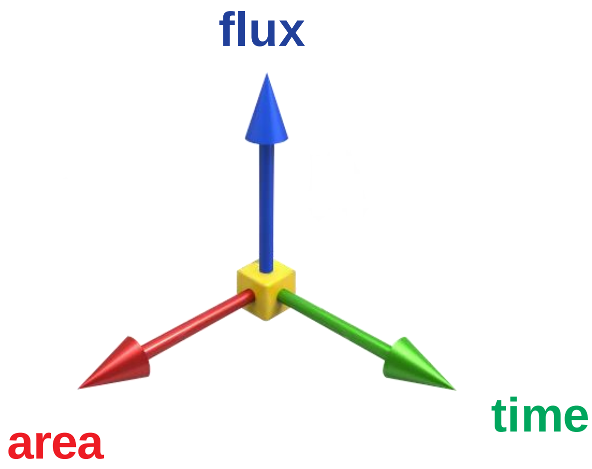
Aim to catch counterparts early to allow follow-up with other facilities

Complements other facilities both geographically and its balance between cadence and depth

Need to deploy it timely, cost effectively

Needs autonomous control & automated pipeline

[this was all before any actual GW detection, let alone multi-messenger]



- patrol all-sky
- reach BNS horizon
- good cadence
- control false positives

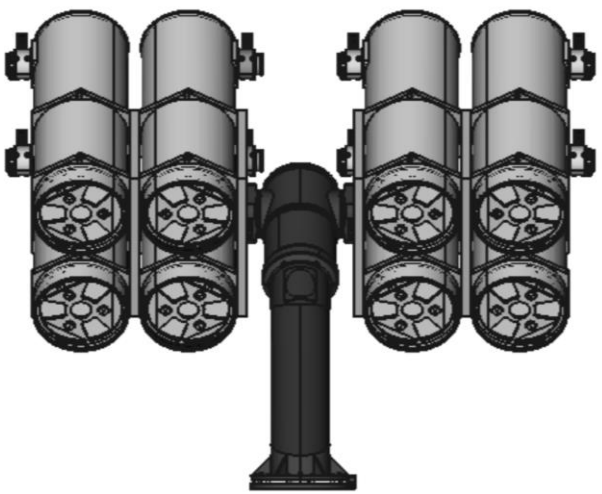
GOTO design (around 2014)

- Pixel scale key in balance between field and depth
- 1-2” pixels good compromise at good site (sky)
- Biggest constraint: affordable detector pixels

Figure 1. KAF–50100 Full Frame CCD Image Sensor

- Cost of telescope sensitive to aperture
- Co-mounting of multiple telescopes on shared mount

- 30-40cm aperture feasible, require f/2.5 for pixel-scale
- 4-8 telescopes per mount feasible



vendor concept

full node with multiple mounts

GOTO Prototype (2017)

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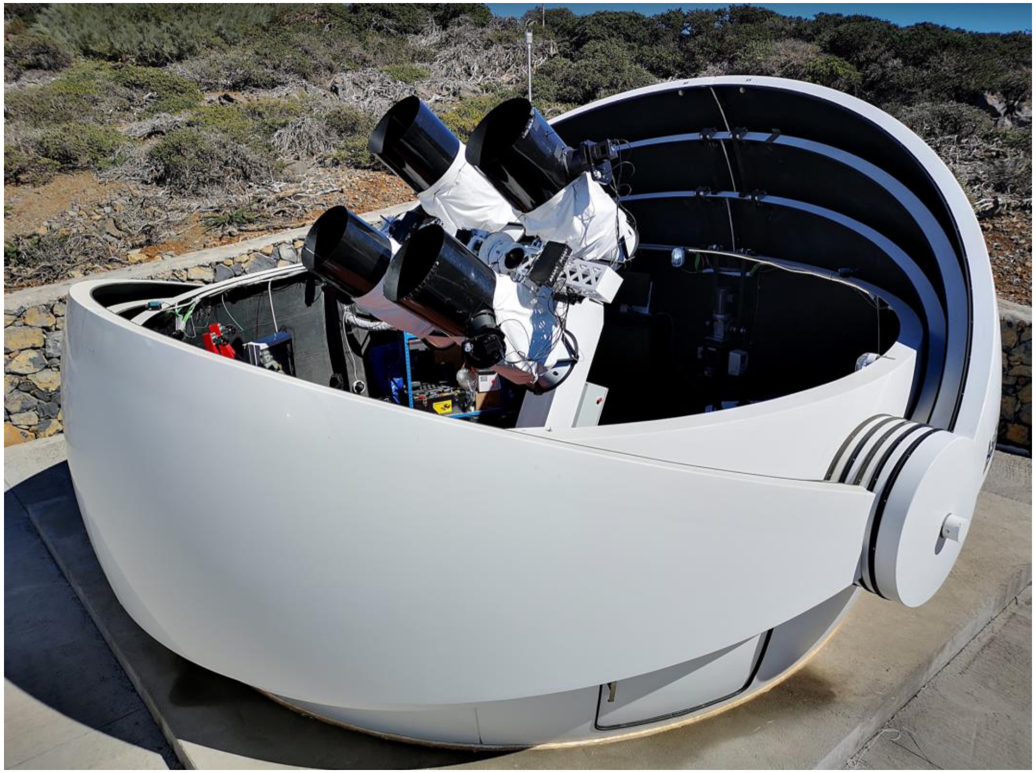
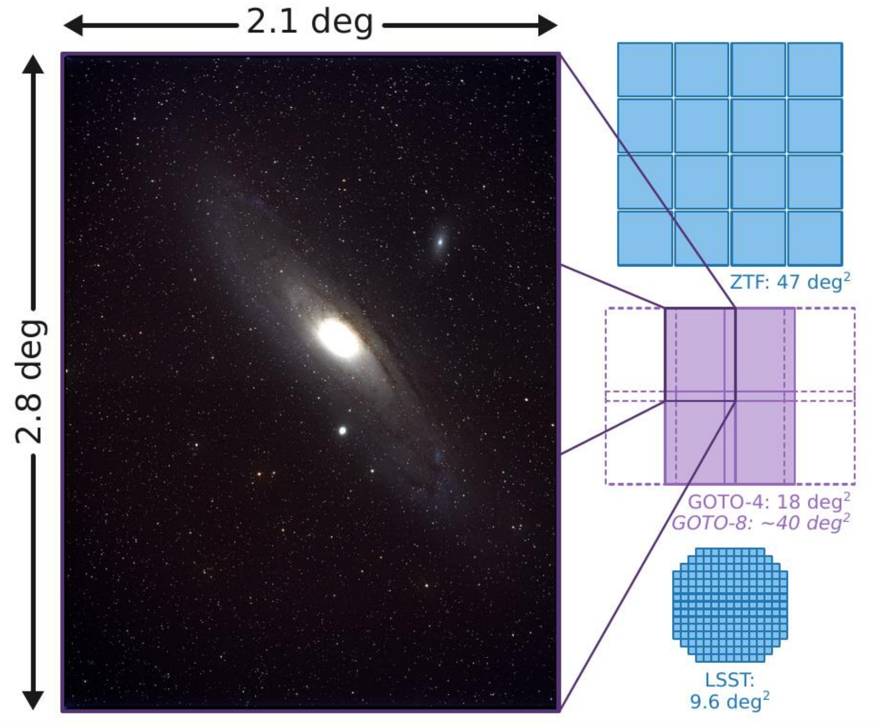


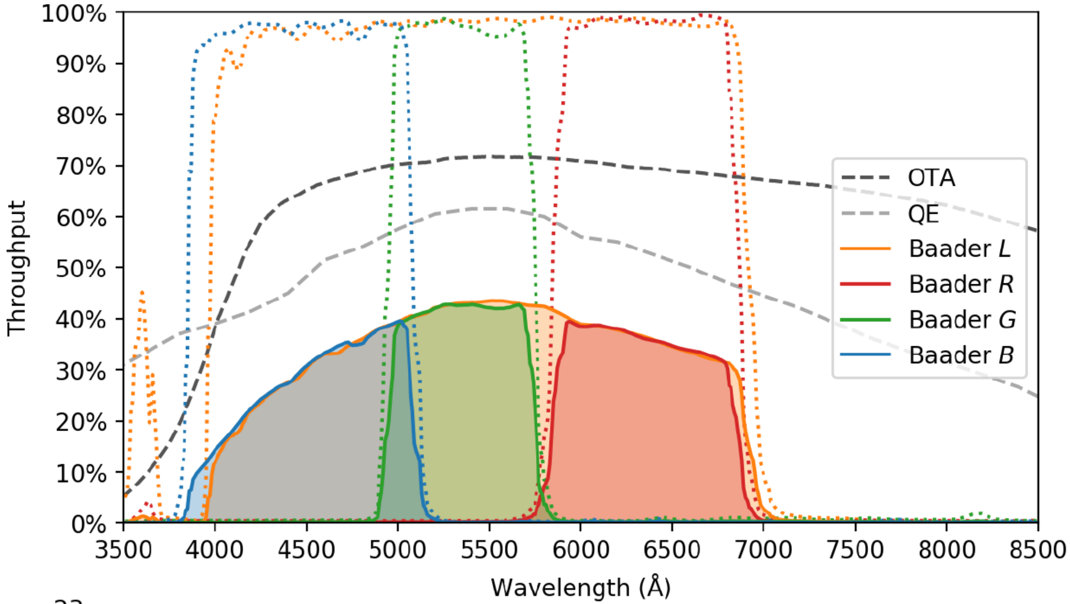


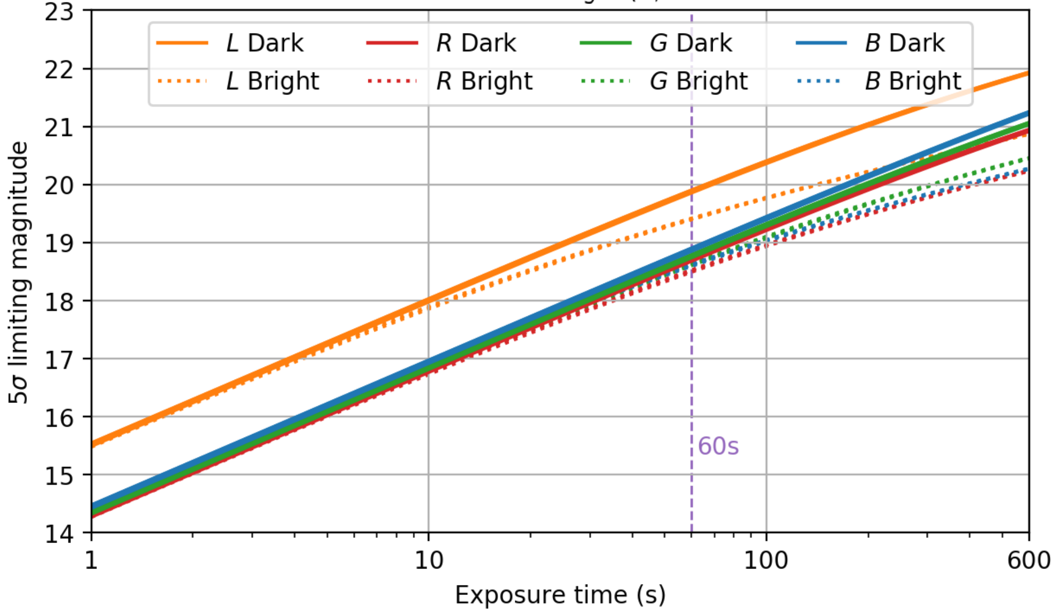
D=40cm f/2.5 Newtonian Wynne-Riccardo unit telescopes
5-slot filterwheel

2.85 x 2.114 degrees @ 1.25”/pixel (50 Mpixel CCD)
~5 sqr.deg / telescope

GOTO
GRAVITATIONAL-WAVE OPTICAL TRANSIENT OBSERVER

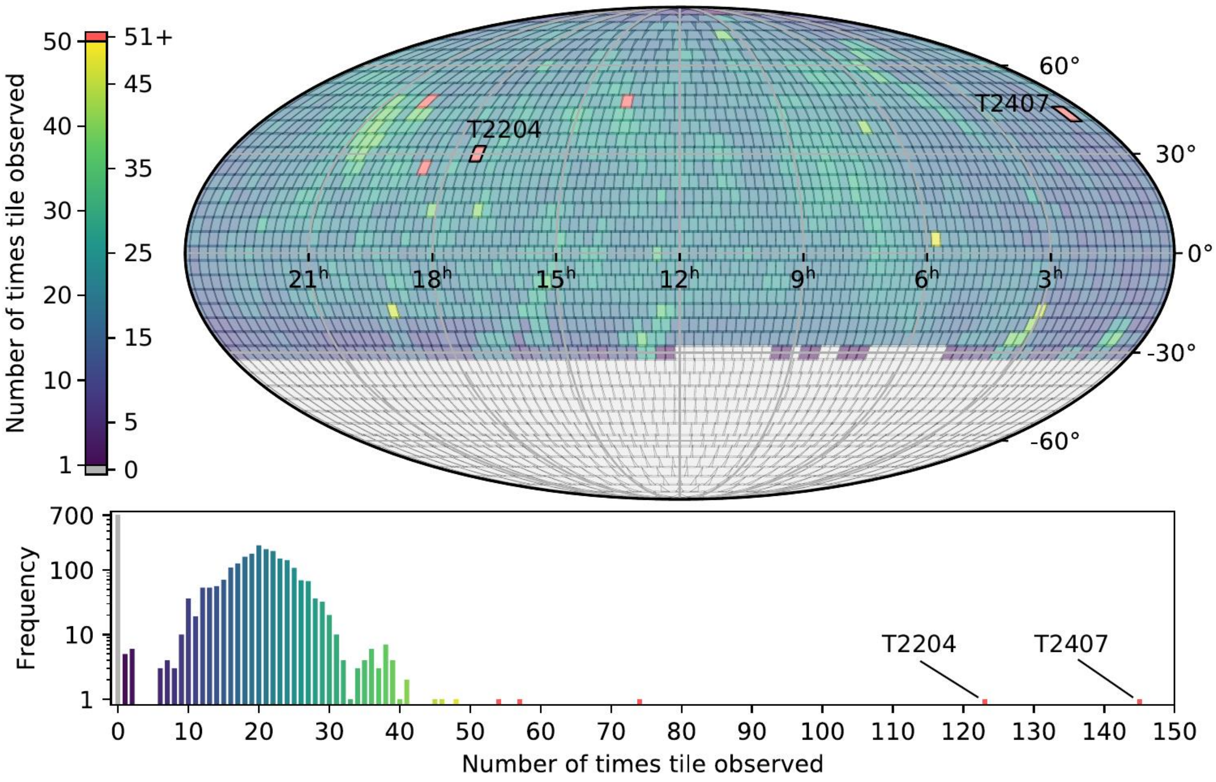
GOTO Prototype Performance





Prototype Operations

- Fixed sky grid survey with 4UTs
- Many O3 GW events observed (Steeghs et al. 2019; Gompertz et al. 2020; Ackley et al. 2020)
- High-cadence tiles
- GRB/neutrino follow-up
- SNe



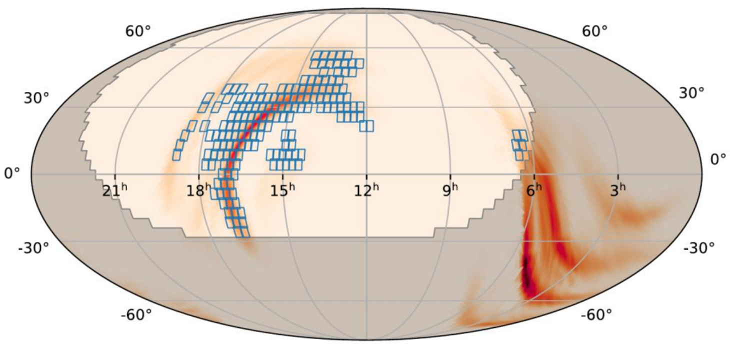
Fully autonomous control &

Real-time dataflow:

- Shutter open within 30s from trigger
- Data processed within 10 mins
- Diff. Imaging candidates within 30mins

GOTO Prototype in O3

Event	Response Time δt_{trig} (hours)	δt_{alert} (hours)	2D Coverage Area (deg^2)	pA (%)	pA_{vis} (%)
S190408an†	11.4	10.8	156.1	20.2	23.8
S190412m†	15.0	14.0	295.2	94.4	94.7
S190421ar	48.3	29.1	114.3	8.88	36.6
S190425z	12.4	9.50	2667.1	22.0	38.1
S190426c	5.30	5.00	772.7	54.1	70.2
S190510g	1.42	0.40	116.1	0.21	0.55
S190512at	2.78	2.50	315.1	87.1	92.4
S190513bm†	0.55	0.05	116.2	28.5	76.3
S190517h†	15.9	15.2	112.7	14.8	51.6
S190519bj†	5.35	4.35	664.8	84.7	85.3
S190521g	0.13	0.05	393.2	43.7	86.7
S190521r†	15.2	15.1	720.7	91.9	92.9
S190630ag	2.40	2.40	1170.3	60.9	79.5
S190706ai	0.33	0.03	543.9	36.7	48.5
S190707q	12.4	11.7	722.9	34.4	59.3
S190718y†	6.58	6.10	242.5	61.2	72.9
S190720a	0.08	0.04	1358.3	62.1	73.3
S190727h	15.0	14.9	714.7	42.3	93.5
S190728q	14.8	14.5	146.9	89.5	94.0
S190814bv	1.83	1.50	717.9	94.1	99.1
S190828j	16.1	15.8	442.2	9.11	81.6
S190828l	16.9	16.5	453.6	1.94	50.5
S190901ap	0.12	0.04	2523.5	38.3	45.3
S190910d	0.13	0.03	1675.0	41.2	85.1
S190915ak	29.9	29.8	18.2	0.08	0.08
S190923y†	13.8	13.7	723.7	39.4	59.7
S190924h	2.97	2.90	281.3	70.2	73.1
S190930s	6.28	6.20	2139.9	92.2	92.2
S190930t†	12.8	12.7	918.2	6.84	9.91
Mean	9.90	8.79	732.3	45.3	64.4
Median	6.58	6.20	543.9	41.2	73.1



Part of a world-wide effort

GOTO prototype was playing to its strength of searching wide areas

Mean area was 732 sqr. deg.

Searched binary BHs as well to test and tune strategies/operations

Alas no GW170817-like trigger

Gompertz et al. (2020)
Cutter (2021)

http://treasuremap.space/

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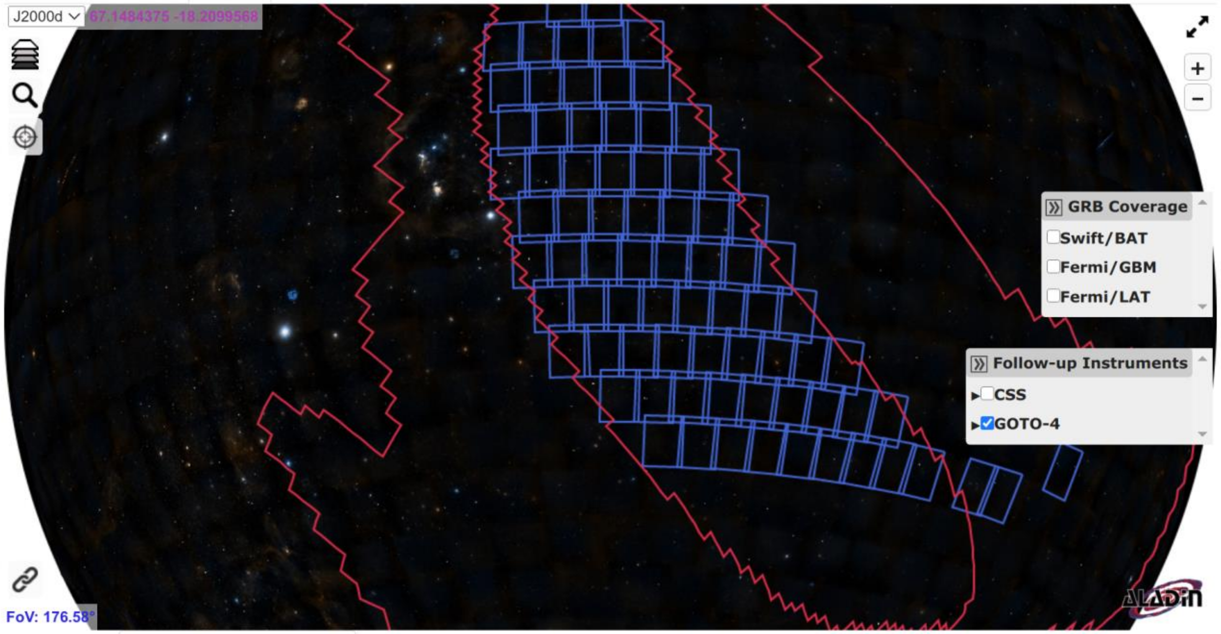
Treasure Map | Home | GW Events | Query Pages | Submit Pages | Observatory Statuses | Documentation | Login | Register

Gravitational Wave Events

Choose an event: Events

Gravitational Wave Localization and Pointings: S190901ap [GraceDB]

Preliminary | Initial | Update



Pointing Status completed

Date range (days since Time of Signal): 0.08 - 3.51

Information	
Detectors	L1,V1
Time of Signal	2019-09-01 23:31:01.840182 UTC
False Alarm Rate	once per 4.51 years
Distance	240.869 +/- 78.648 Mpc

Classification (CBC Only)	
BNS	0.860671959529
NSBH	0.0
Mass Gap	0.0
BBH	0.0

O3: S190814bv

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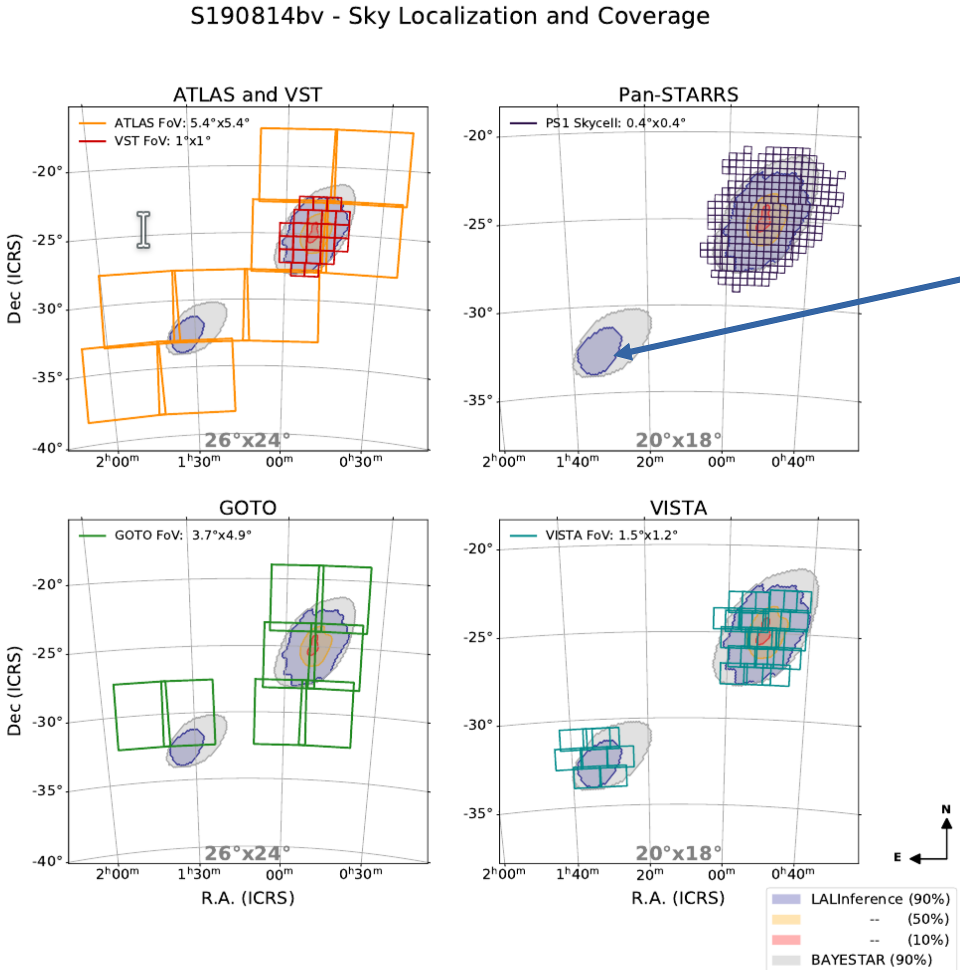
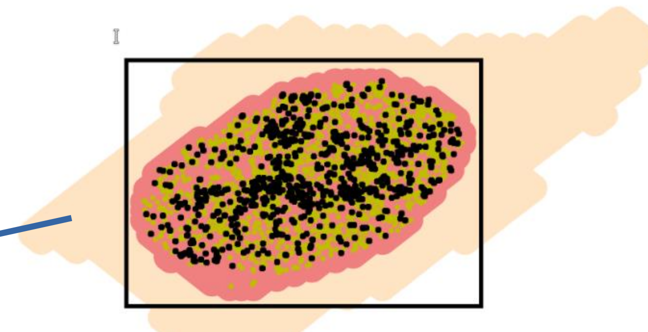
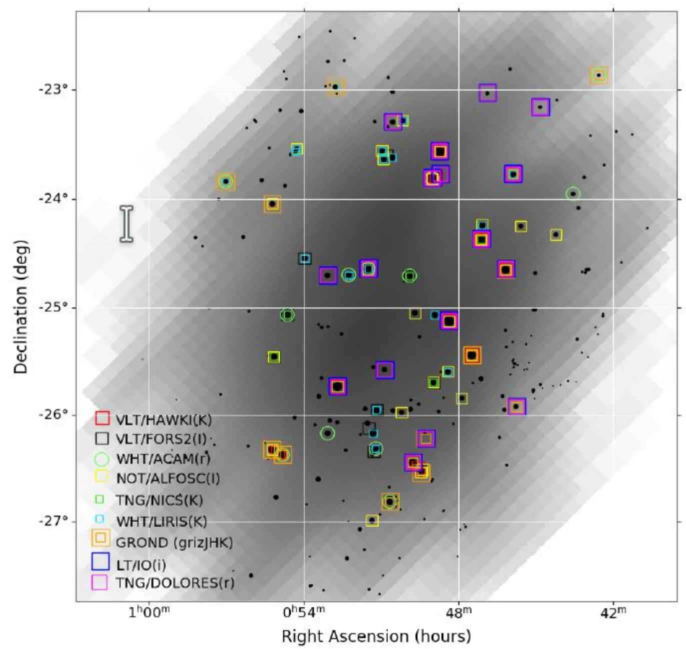
Tiling approach



Galaxy targeting





ENGRAVE; Ackley et al. (2020)

Technical Developments

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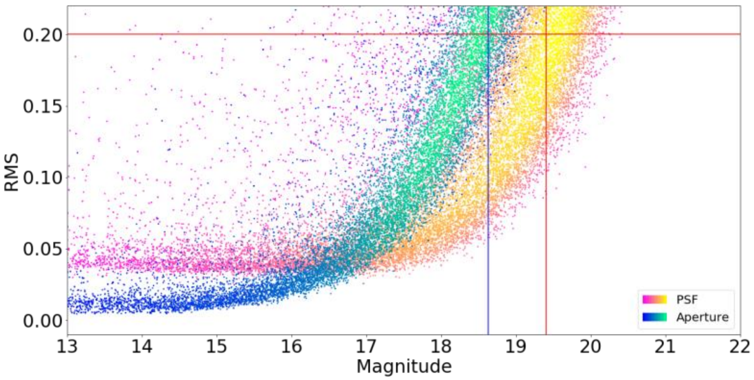
- Having to deal with the same challenges as other time-domain projects

- Pipeline : in-house bespoke stack versus the LSST stack

GOTO as testbed for Vera Rubin ST data reduction:

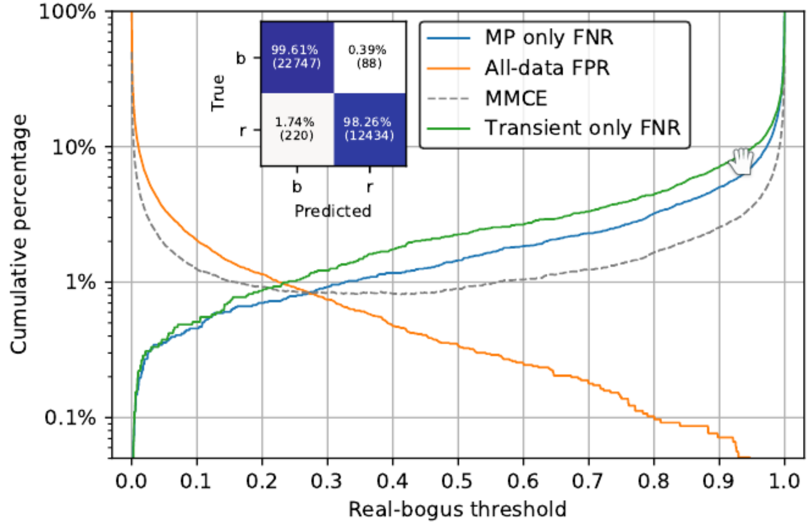
Mullaney et al. (2020) ; Makrygianni et al. (2020)



- Real-Bogus classifier:

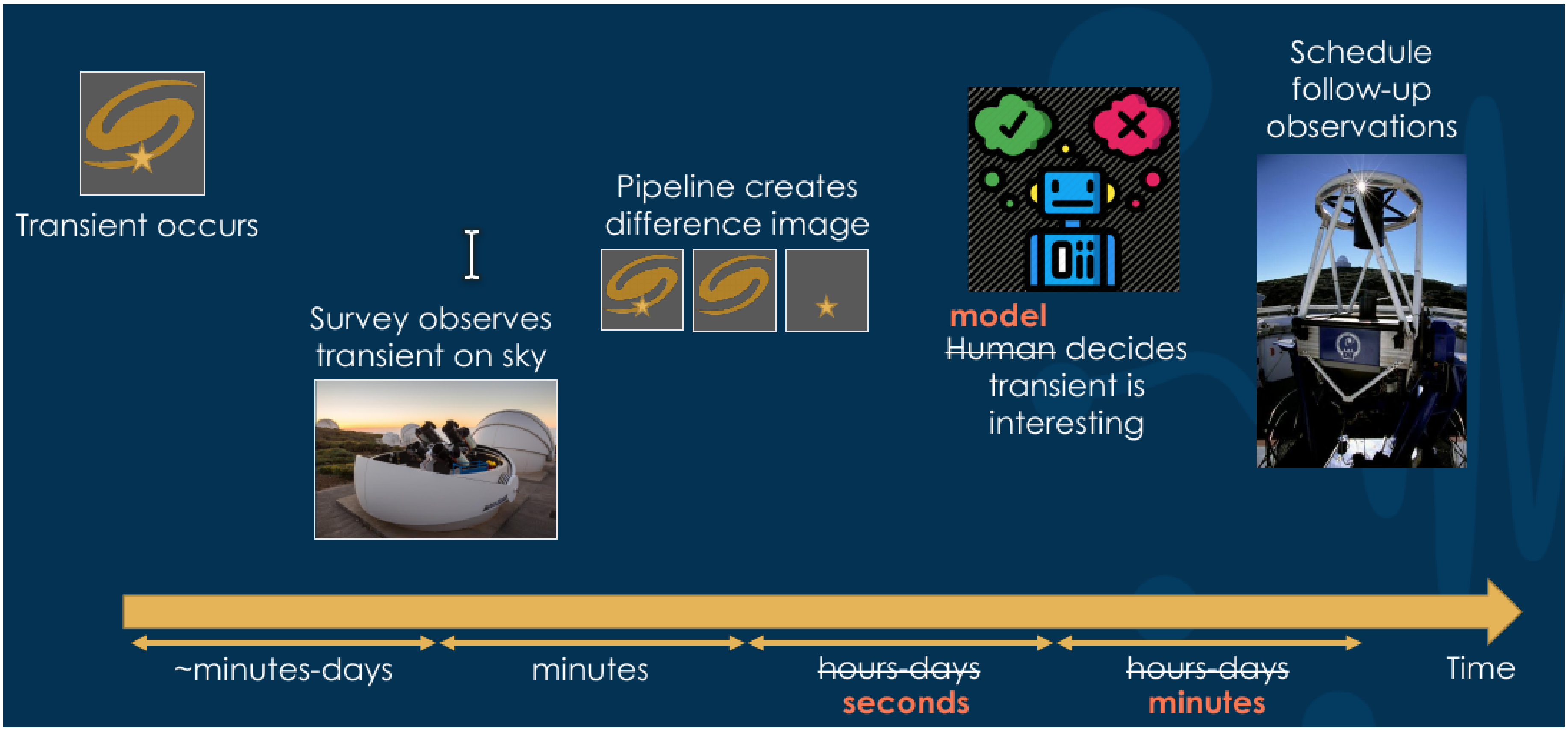
Bayesian CNN

Killestein et al. (2021)



- Marshall / Brokers / Contextual Agents / Astrophysical Classification / Foreground

Automation for speed



GOTO flow courtesy of Joe Lyman

GOTO vision

Full node = 16x40cm covering 80 deg^2
Two antipodal sites

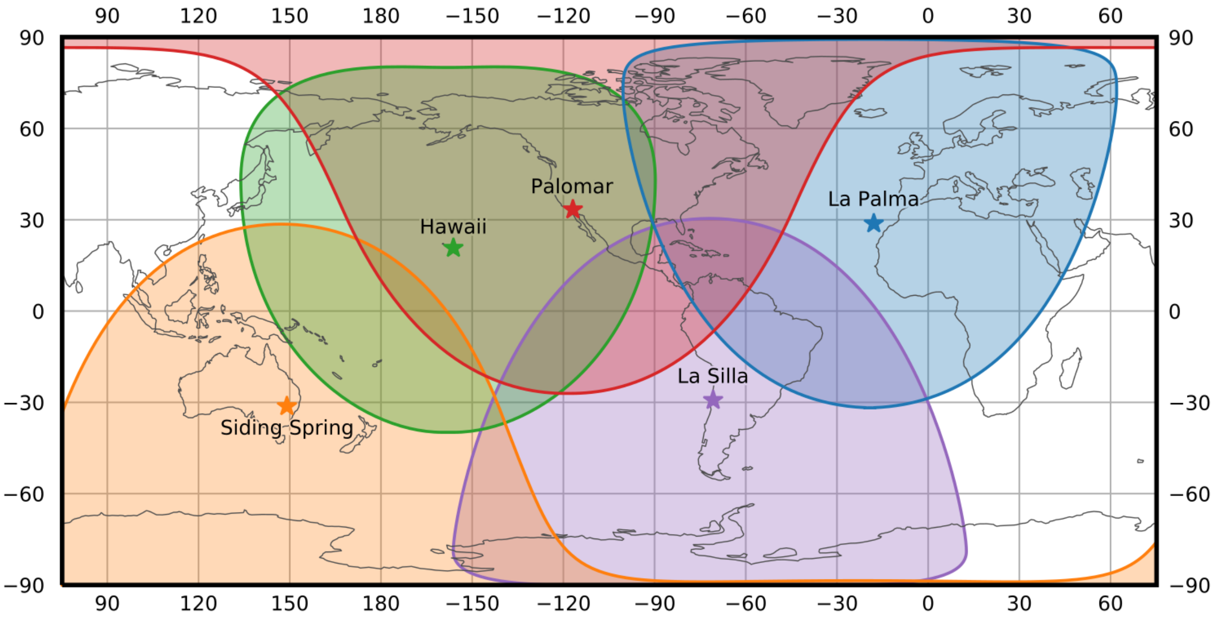
Sky survey patrol mode
Responsive mode

Science and Technology Facilities Council

PPRP Award late 2019

La Palma complete in 2021
Siding Spring in two phases

Operational ahead of O4



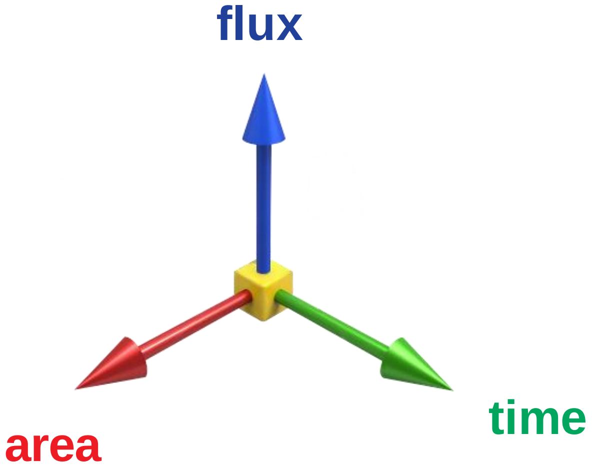
Global Landscape

Complements other facilities

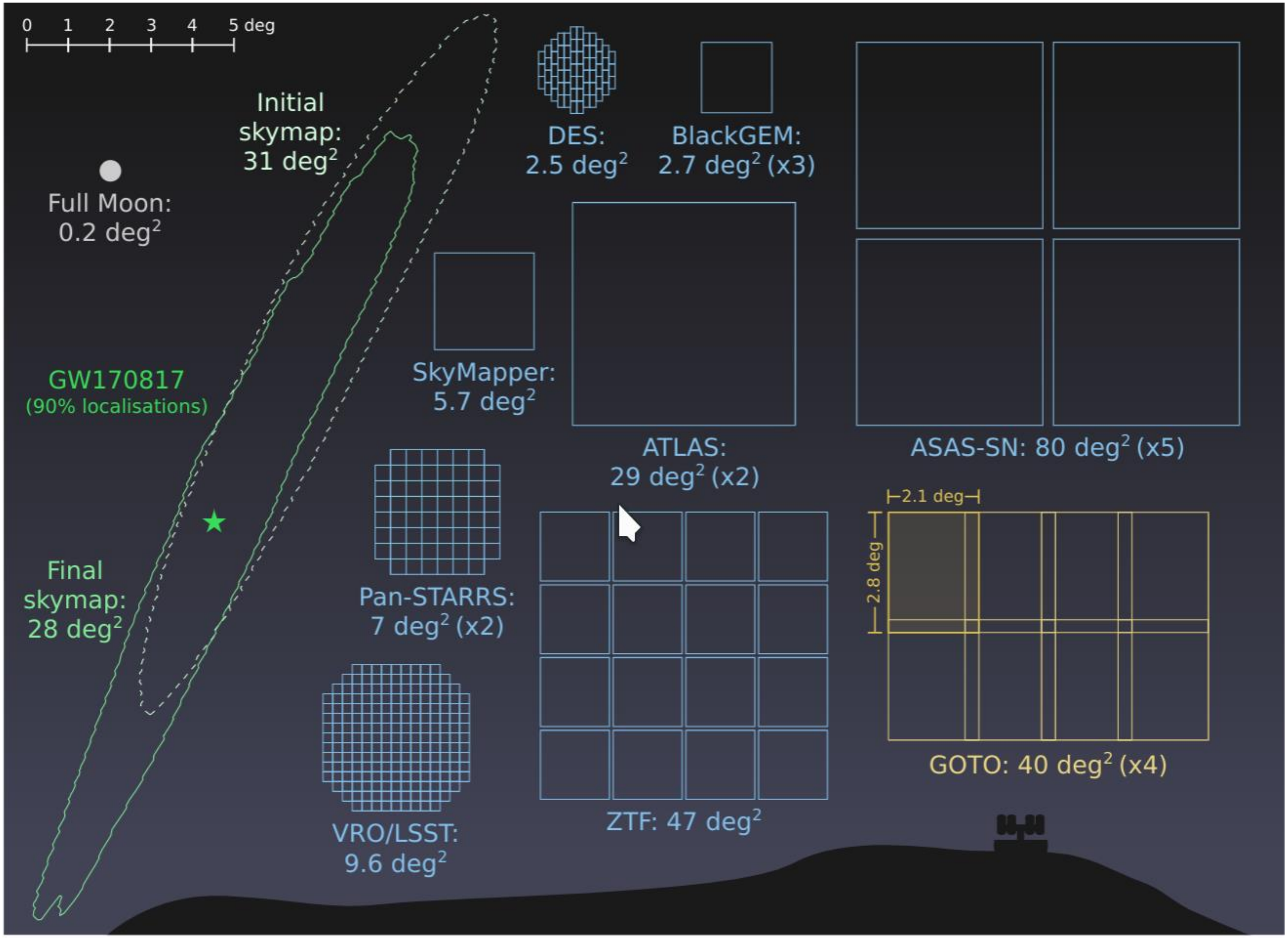
Extends geographic coverage

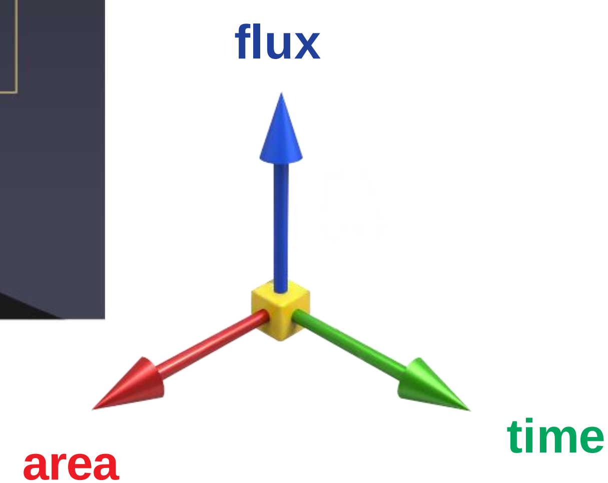
Facilitates identification and **follow-up**

Need collaborative frame-work



Global Landscape





LSST

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VERA C. RUBIN
OBSERVATORY

No doubt transformative facility and coming quite soon

Unprecedented depth thanks to its aperture, camera and location

Multi-colour, multi-epoch

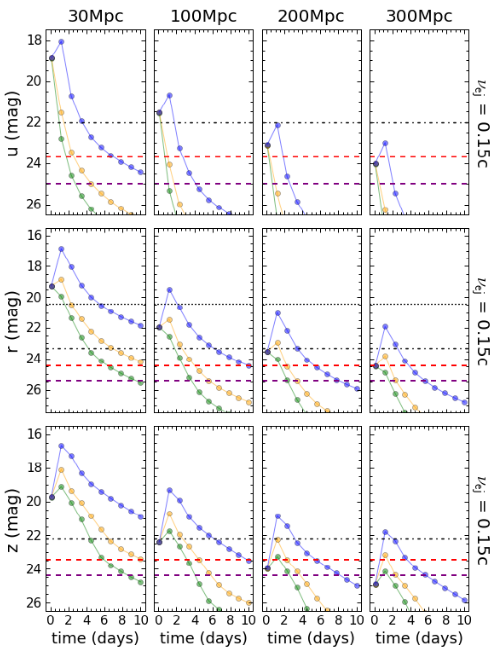
Unprecedented data mining and follow-up challenge, too

LSST and GW-EM

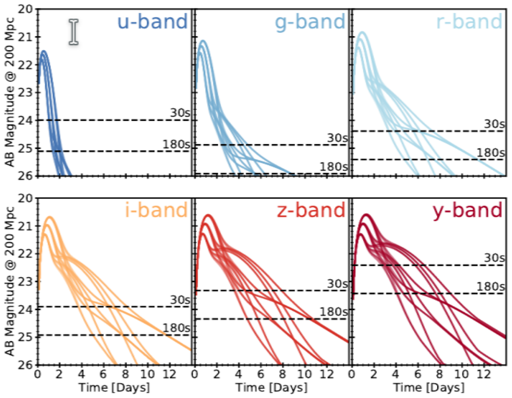
- In its core mode *not* optimized for GW / Target of Opportunity (cadence)

- Community has been appealing for this as it is uniquely placed to probe the more distant GW events that are out of reach of smaller projects

- Project recognizes this and negotiations are ongoing concerning survey strategy, ToO opportunities



Margutti et al. (2018)



Cowperthwaite et al. (2018)

LSST-UK

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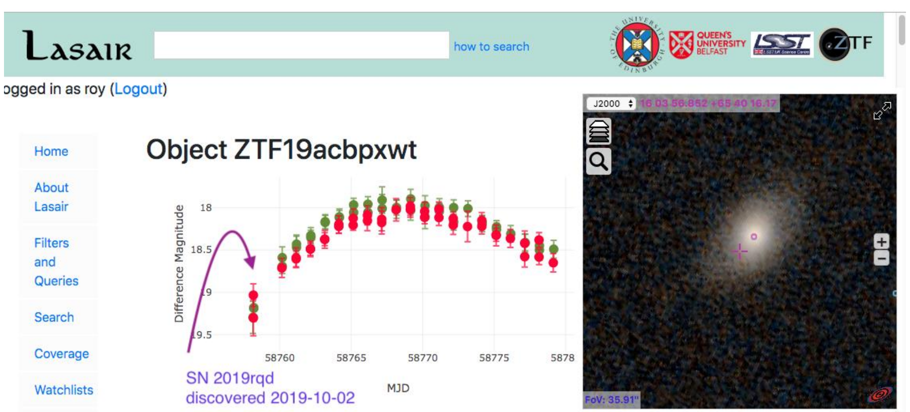
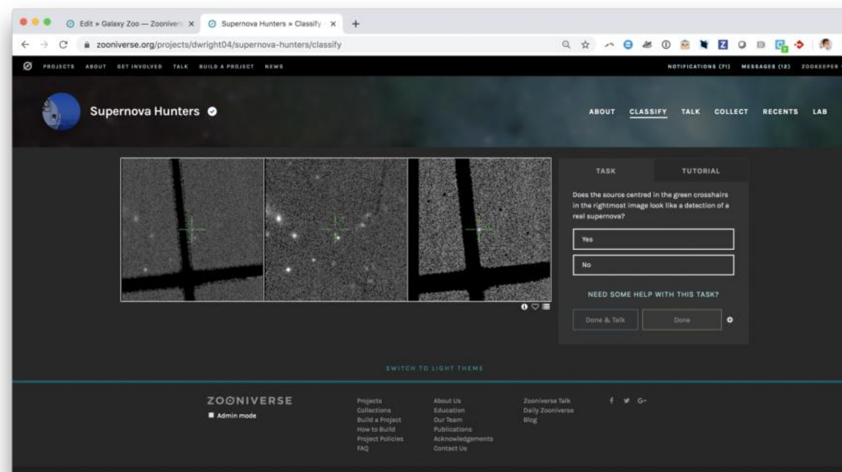
LSST:UK Consortium

Key involvement of UK community via LSST-UK

- access
- data mining tools
- expertise (both technical and astrophysical)



Lasair broker

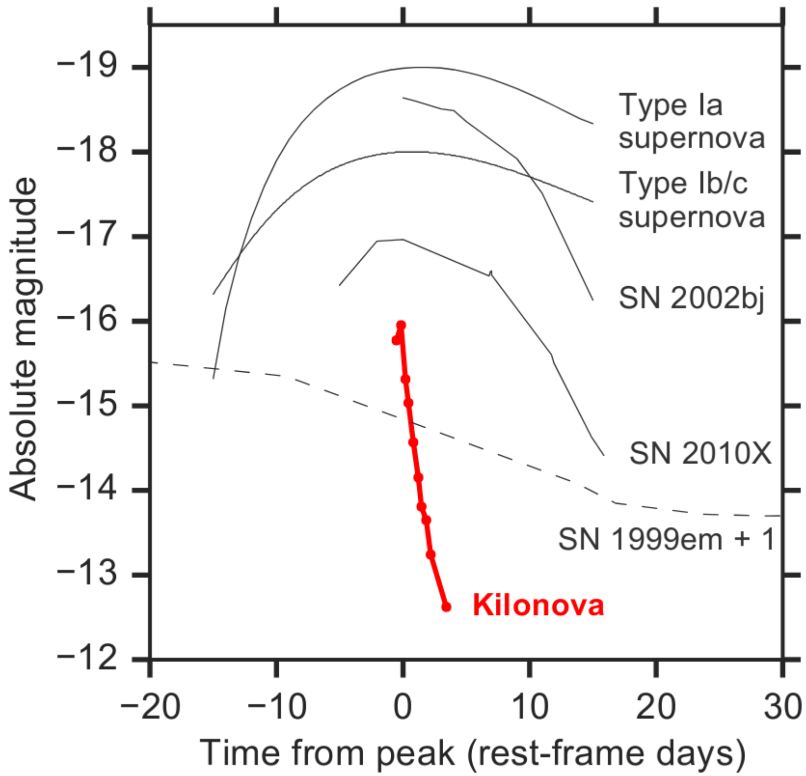


Citizen Science

Science beyond GW follow-up

- Blind kilo-nova searches / fast transients
- Luminous transients in the SN arena
  - Early stages [need cadence]
  - Rare subset [need large area]
- TDEs
- New AGN
- Fermi & SVOM GRB triggers, particularly short
- Neutrinos from IceCube & Antares
- Pulsar binaries via Fermi cross-matches
- Radio transients

- Rapid discovery allows rapid follow-up
- Spectroscopically target early stages
- Rare bright events offer key insights



Arcavi et al. (2017)

Summary

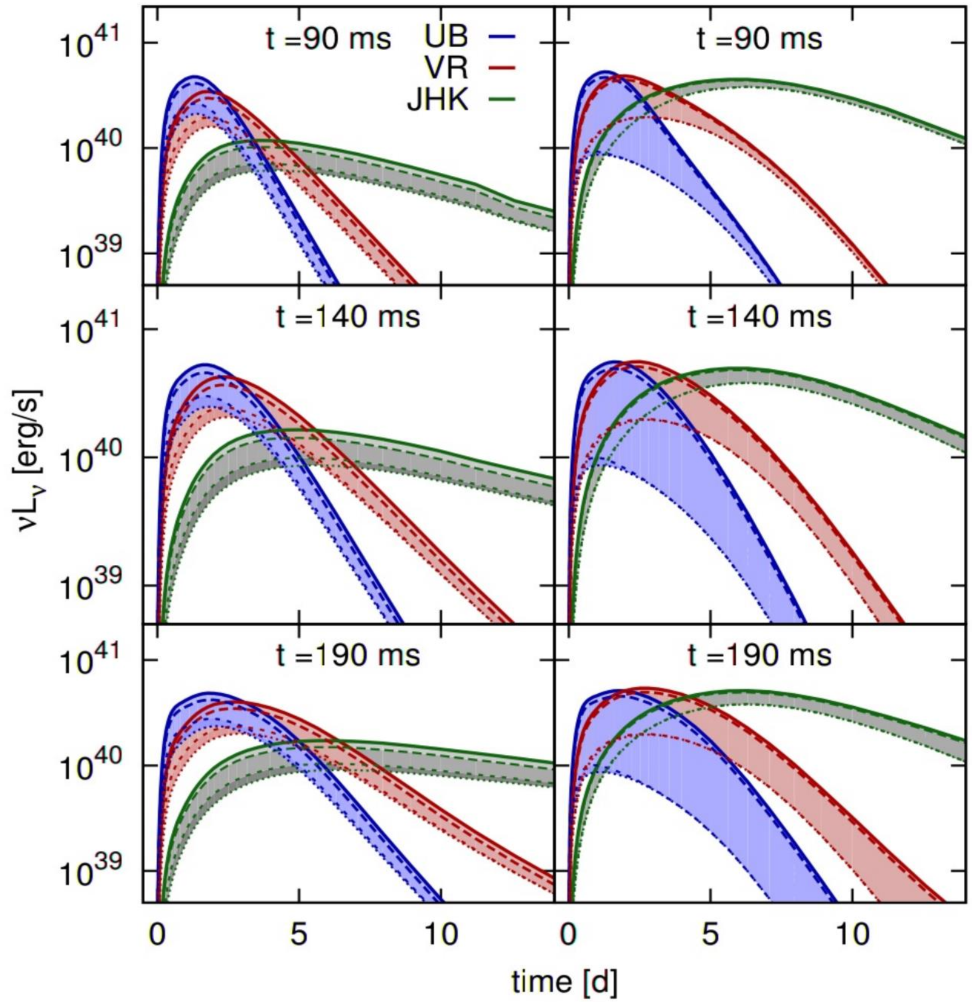
- A great time for time-domain and multi-messenger astronomy
- GW detectors and the EM search facilities primed, with the best to come
- A long-term opportunity, with an excellent facilities roadmap
- Probes a broad variety of (astro)physics
- UK community plays a very active and leading role
  - Key partner in LIGO
  - Leads GOTO, strong role in LSST, many others, survey heritage
  - Good links with other facilities (also beyond optical/IR)
- Need systematic search capacity, but also follow-up and modelling

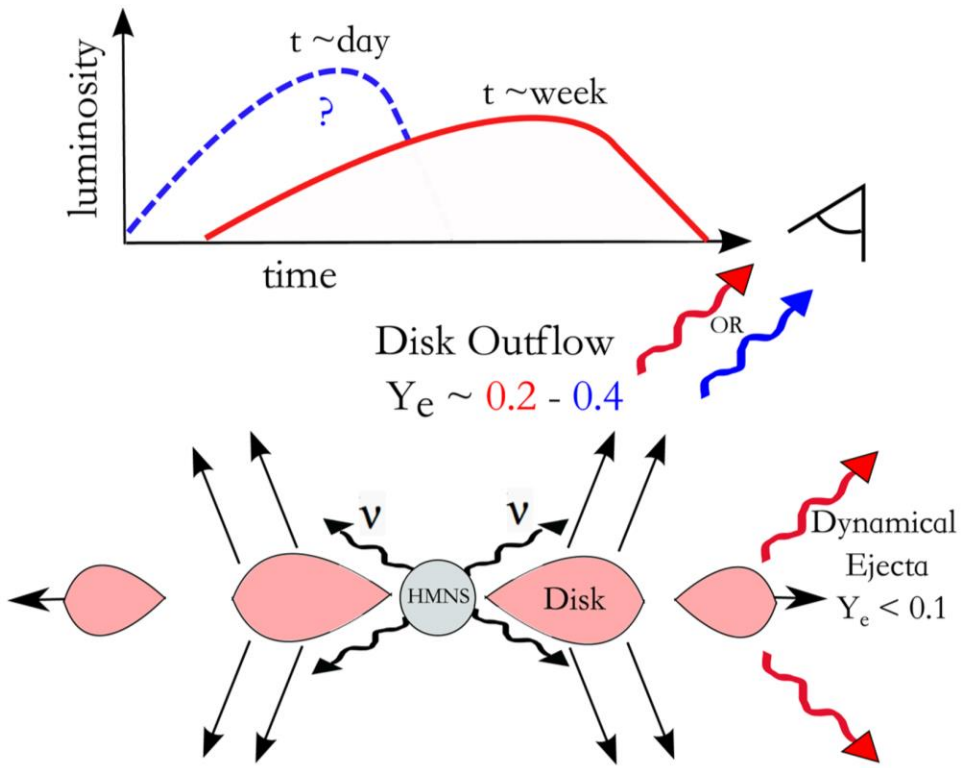
(spectroscopy, broad SED lightcurves, host characterisation)

Thank You

EXTRAS

Expectations





Martin et al. (2015)

Timeline

- Deployed 2nd generation unit telescopes on prototype mount
- 2nd generation mount systems at manufacturing stage
- All CCD sensors secured
- La Palma expansion to full node Q1 2021
- Siding Springs deployment Q3 2021
- Control System, pipeline & DB devel.

- Key milestone : ready for O4
- Public-facing alerts/candidates/

lightcurves

current configuration

Array approach

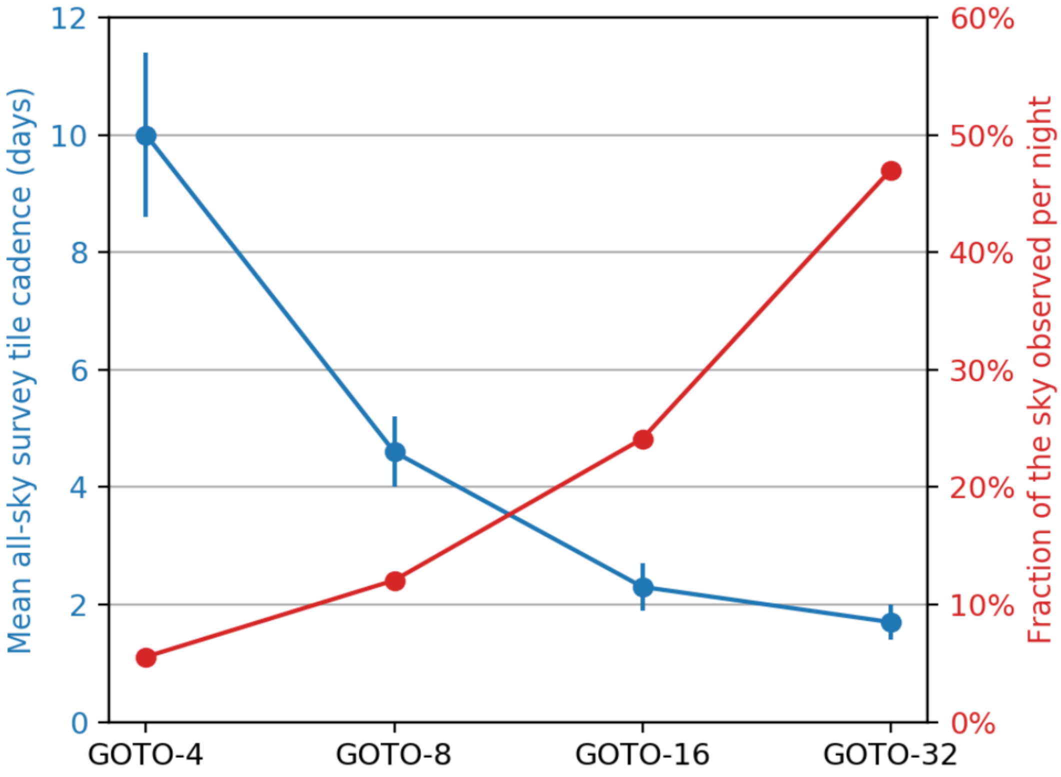
- Survey capability set by size of telescope array
- Need to cover all-sky
- Need to keep cadence low
- Need to go deep enough

- Array **flexibility**:

balance speed versus depth

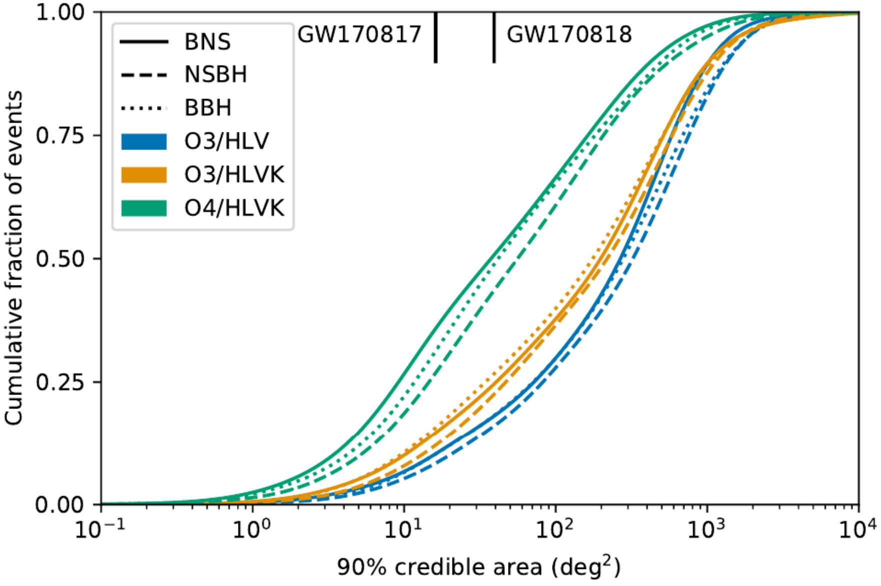
or colour versus wide-band

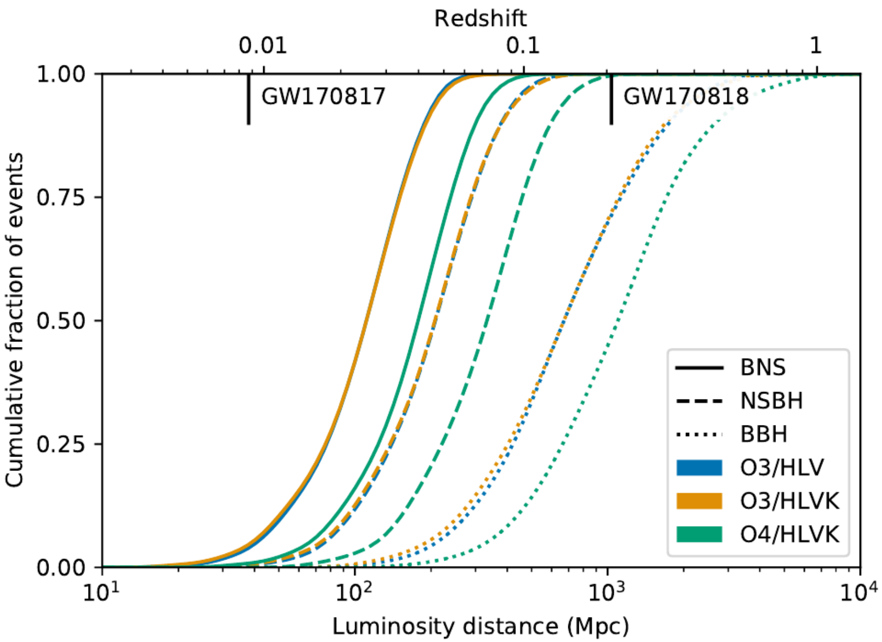
- Kilonova timescale ~ few days
- SN searches ~1/week



coverage and cadence for nominal sampling

GW Evolution & Strategy



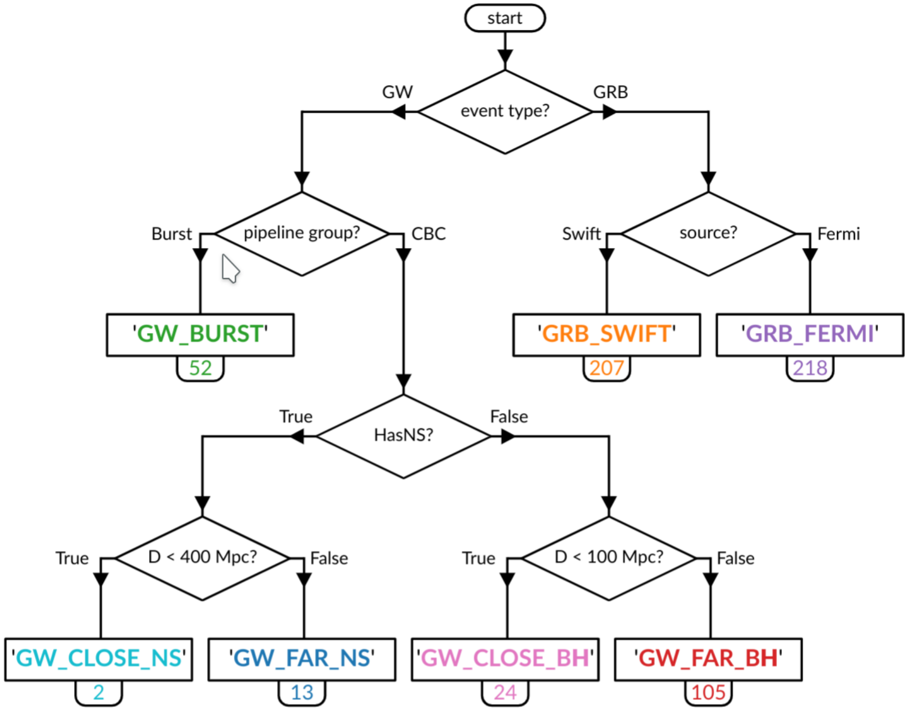


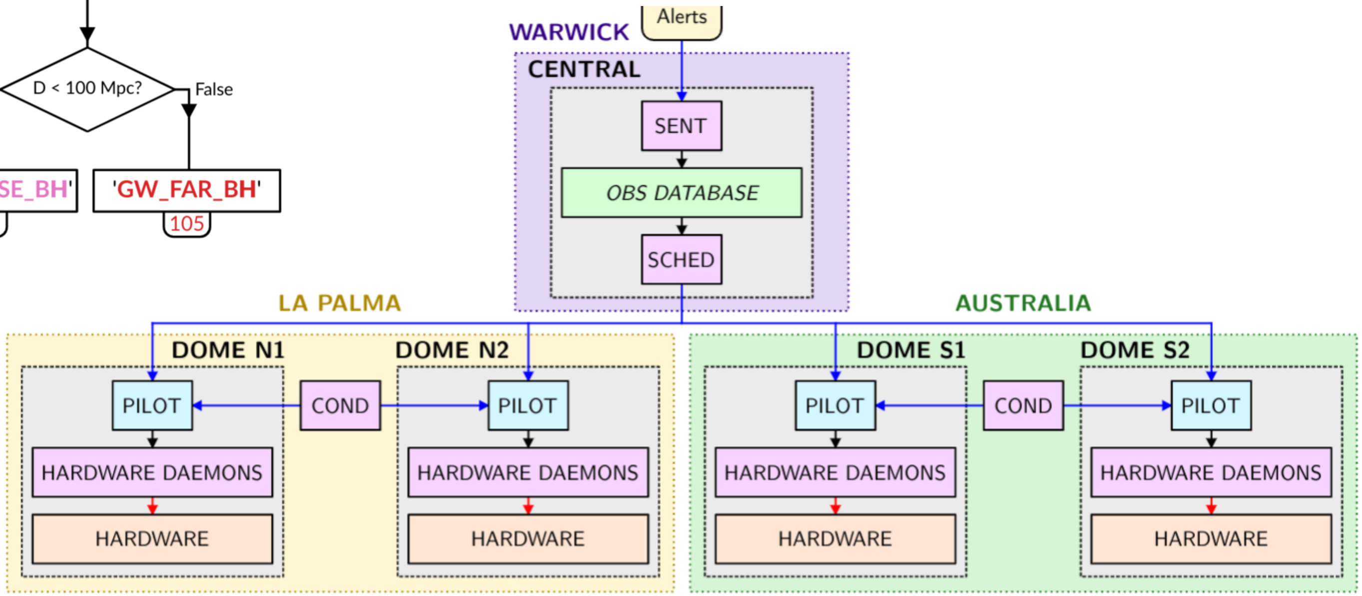
General evolution towards higher rates, larger horizons and better localisations

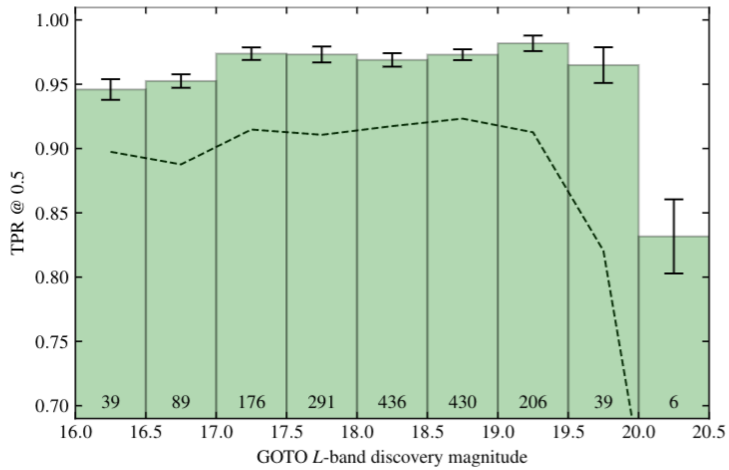
Huge diversity remains

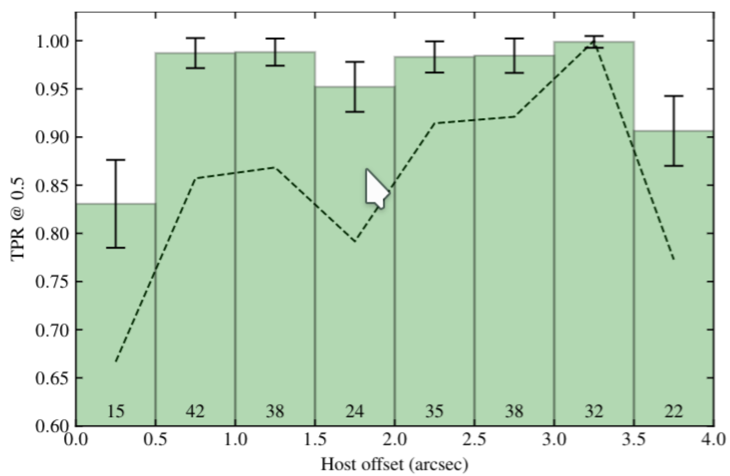
GOTO's modular approach permits event-specific strategy

- type of event (BNS, NSBH, …)
- FAP/p value
- distance constraints
- 90% localisation area
- time since trigger


start
event type?
GW
GRB
pipeline group?
Burst
CBC
source?
Swift
Fermi
'GW_BURST'
52
'GRB_SWIFT'
207
'GRB_FERMI'
218
HasNS?
True
False
D < 400 Mpc?
True
False
D < 100 Mpc?
True
False
'GW_CLOSE_NS'
2
'GW_FAR_NS'
13
'GW_CLOSE_BH'
24
'GW_FAR_BH'
105

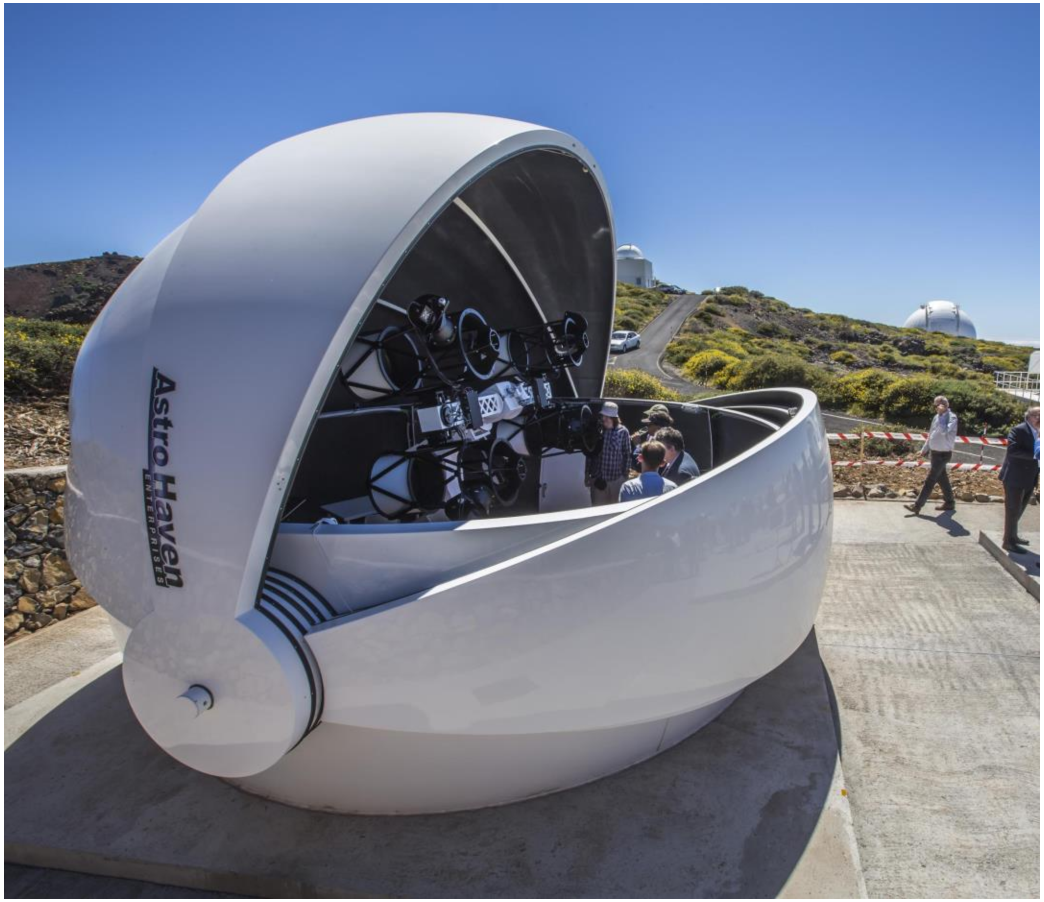

Alerts
WARWICK
CENTRAL
SENT
OBS DATABASE
SCHED
LA PALMA
AUSTRALIA
DOME N1
DOME N2
DOME S1
DOME S2
PILOT
COND
PILOT
PILOT
COND
PILOT
HARDWARE DAEMONS
HARDWARE DAEMONS
HARDWARE DAEMONS
HARDWARE DAEMONS
HARDWARE
HARDWARE
HARDWARE
HARDWARE

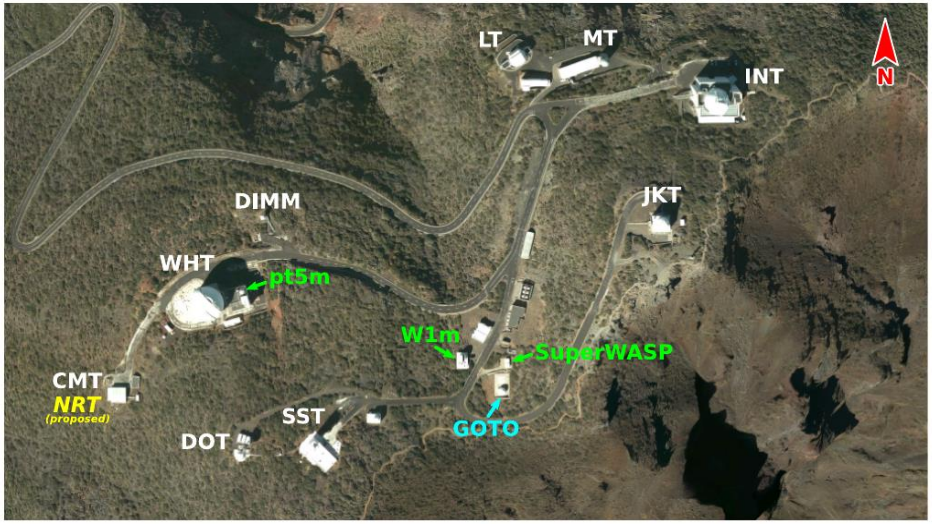

TPR @ 0.5
1.00
0.95
0.90
0.85
0.80
0.75
0.70
39
89
176
291
436
430
206
39
6
16.0
16.5
17.0
17.5
18.0
18.5
19.0
19.5
20.0
20.5
GOTO L-band discovery magnitude


TPR @ 0.5
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
15
42
38
24
35
38
32
22
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Host offset (arcsec)

GOTO @ La Palma

WARWICK





GOTO

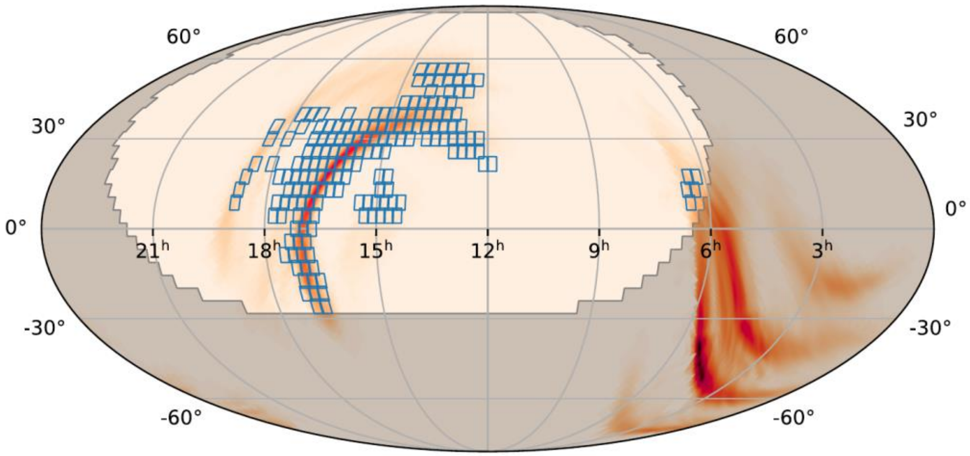
GRAVITATIONAL-WAVE OPTICAL TRANSIENT OBSERVER

GOTO Prototype GW Follow-up

WARWICK

- Chased 32 GW events in O3a
- Gompertz et al. 2020

[if you want to read the table]



- Mean area covered = 732 sqr.deg
- Up to 94% probability coverage
- Decent KN range

Event	Response Time		2D Coverage			3D Coverage				KN Range		
	δt_{trig} (hours)	δt_{alert} (hours)	Area (deg^2)	pA (%)	pA_{vis} (%)	pV_{bazin} (%)	pV_{GRB} (%)	$pV_{off-axis}$ (%)	pV_{c19} (%)	D_{90} (Mpc)	D_{50} (Mpc)	D_0 (Mpc)
S190408an†	11.4	10.8	156.1	20.2	23.8	1.20×10^{-5}	1.47×10^{-2}	2.82×10^{-7}	3.22×10^{-5}	31	70	135
S190412m†	15.0	14.0	295.2	94.4	94.7	8.68×10^{-3}	3.48	0	1.07×10^{-2}	107	117	151
S190421ar	48.3	29.1	114.3	8.88	36.6	4.92×10^{-5}	3.97×10^{-3}	3.89×10^{-7}	3.49×10^{-4}	57	61	66
S190425z	12.4	9.50	2667.1	22.0	38.1	5.90	20.6	2.57×10^{-3}	8.10	46	134	227
S190426c	5.30	5.00	772.7	54.1	70.2	1.10×10^{-2}	8.98	0	1.42×10^{-2}	4	44	136
S190510g	1.42	0.40	116.1	0.21	0.55	2.06×10^{-3}	0.21	0	3.60×10^{-2}	48	55	57
S190512at	2.78	2.50	315.1	87.1	92.4	8.52×10^{-5}	0.37	0	1.26×10^{-4}	22	60	154
S190513bm†	0.55	0.05	116.2	28.5	76.3	1.35×10^{-5}	0.59	0	2.51×10^{-5}	56	83	120
S190517h†	15.9	15.2	112.7	14.8	51.6	1.40×10^{-6}	1.25×10^{-4}	0	1.62×10^{-6}	49	67	84
S190519bj†	5.35	4.35	664.8	84.7	85.3	2.41×10^{-6}	9.55×10^{-4}	0	3.64×10^{-6}	43	69	161
S190521g	0.13	0.05	393.2	43.7	86.7	8.30×10^{-6}	7.57×10^{-2}	0	1.11×10^{-5}	94	107	126
S190521r†	15.2	15.1	720.7	91.9	92.9	3.85×10^{-6}	1.17×10^{-3}	0	7.32×10^{-6}	9	51	93
S190630ag	2.40	2.40	1170.3	60.9	79.5	1.33×10^{-3}	19.0	1.66×10^{-7}	3.09×10^{-3}	71	112	150
S190706ai	0.33	0.03	543.9	36.7	48.5	8.03×10^{-6}	1.07	1.67×10^{-8}	2.86×10^{-5}	55	94	168
S190707q	12.4	11.7	722.9	34.4	59.3	2.06×10^{-5}	2.77×10^{-2}	0	2.54×10^{-5}	18	53	122
S190718y†	6.58	6.10	242.5	61.2	72.9	1.12	28.9	1.54×10^{-2}	2.45	10	27	90
S190720a	0.08	0.04	1358.3	62.1	73.3	1.89×10^{-4}	9.51	7.67×10^{-7}	5.45×10^{-4}	42	54	163
S190727h	15.0	14.9	714.7	42.3	93.5	5.72×10^{-7}	6.03×10^{-5}	0	1.43×10^{-6}	52	66	140
S190728q	14.8	14.5	146.9	89.5	94.0	5.55×10^{-4}	1.03	0	8.62×10^{-4}	114	124	139
S190814bv	1.83	1.50	717.9	94.1	99.1	1.23×10^{-2}	89.6	2.33×10^{-6}	2.12×10^{-2}	55	61	81
S190828j	16.1	15.8	442.2	9.11	81.6	1.01×10^{-5}	2.30×10^{-3}	6.45×10^{-8}	1.27×10^{-5}	34	105	149
S190828l	16.9	16.5	453.6	1.94	50.5	5.60×10^{-5}	9.20×10^{-3}	4.66×10^{-7}	7.34×10^{-5}	127	138	154
S190901ap	0.12	0.04	2523.5	38.3	45.3	0.34	30.2	8.40×10^{-4}	1.16	62	88	144
S190910d	0.13	0.03	1675.0	41.2	85.1	5.43×10^{-3}	17.6	0	1.87×10^{-2}	28	69	148
S190915ak	29.9	29.8	18.2	0.08	0.08	3.63×10^{-11}	2.39×10^{-9}	0	8.42×10^{-11}	10	10	15
S190923y†	13.8	13.7	723.7	39.4	59.7	1.91×10^{-2}	8.95	0	2.29×10^{-2}	46	95	120
S190924h	2.97	2.90	281.3	70.2	73.1	4.52×10^{-5}	26.4	5.05×10^{-8}	3.59×10^{-4}	61	75	101
S190930s	6.28	6.20	2139.9	92.2	92.2	2.20×10^{-3}	14.2	1.06×10^{-6}	4.48×10^{-3}	13	89	142
S190930t†	12.8	12.7	918.2	6.84	9.91	1.24	6.55	1.06×10^{-3}	2.01	48	109	130
Mean	9.90	8.79	732.3	45.3	64.4	0.30	9.91	6.87×10^{-4}	0.48	48	79	126
Median	6.58	6.20	543.9	41.2	73.1	8.52×10^{-5}	1.03	0	3.59×10^{-4}	48	70	136