The Era of Gravitational Wave Astronomy
GOTO and the challenge of transients

Kendall Ackley
The University of Melbourne
Astrophysics Colloquium
26/09/2018

MONASH University

GOTO
GRAVITATIONAL-WAVE OPTICAL TRANSIENT OBSERVER

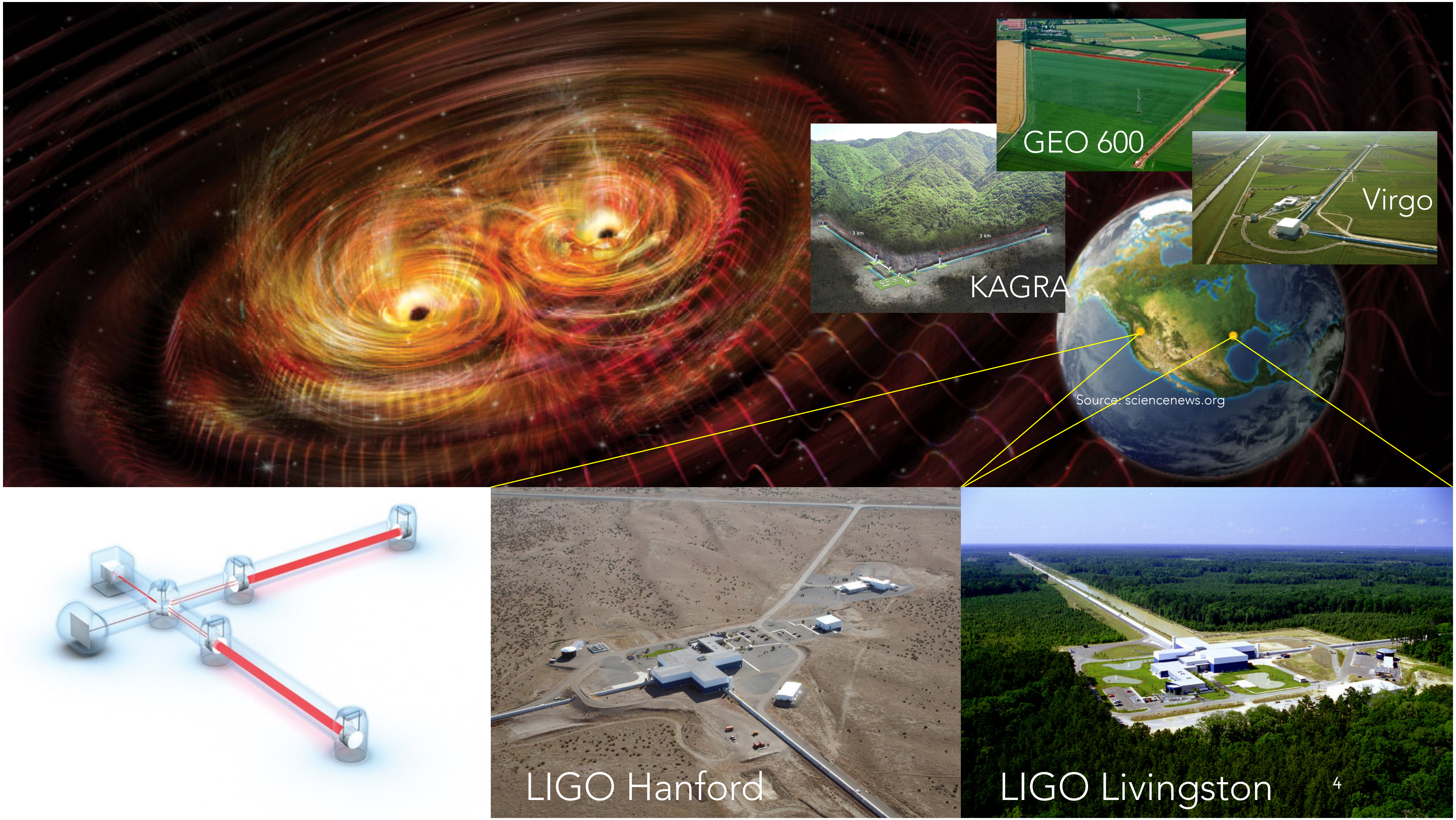
OzGrav

Overview

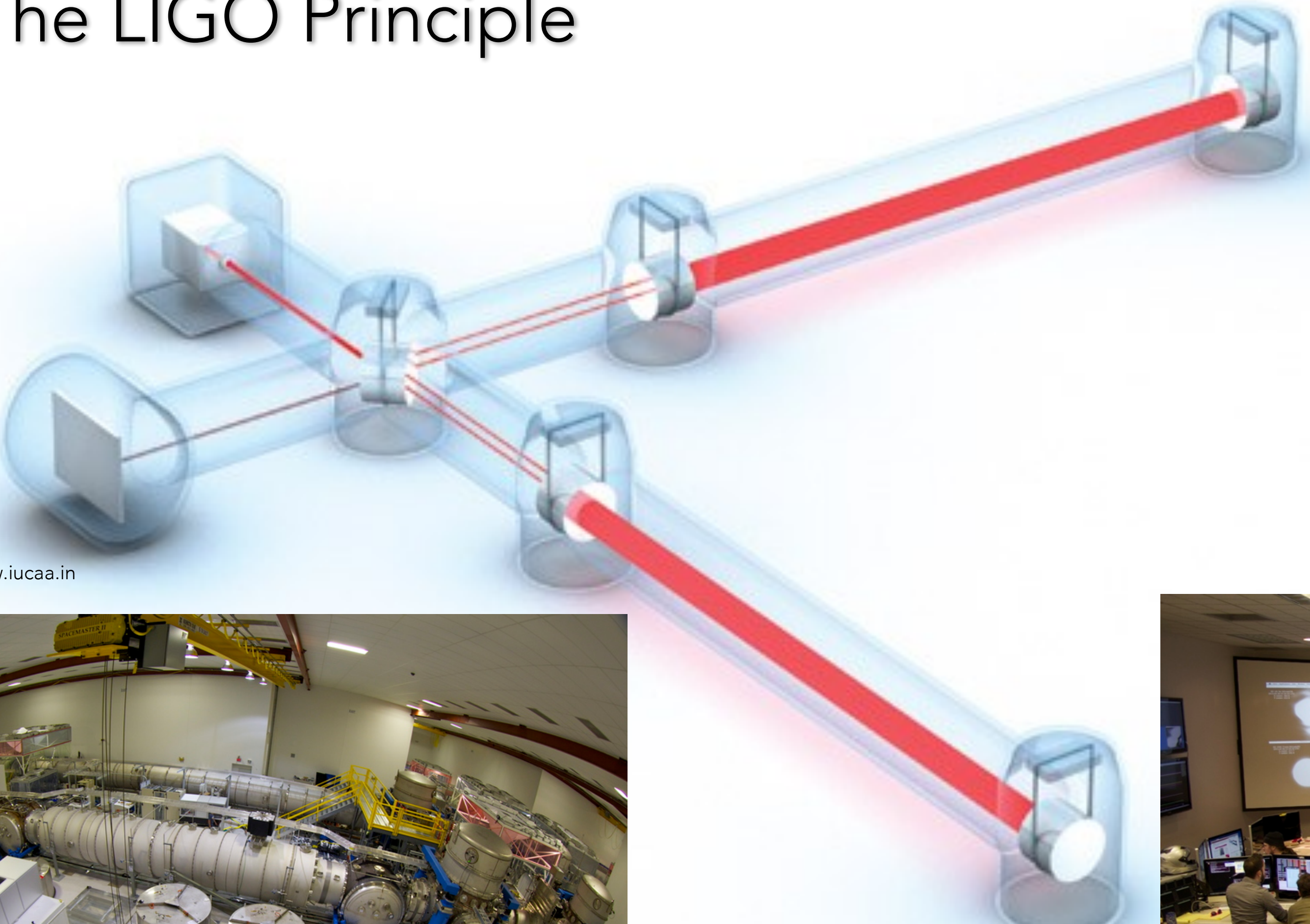
- LIGO & Gravitational Wave Sources
- Sources with Expected Electromagnetic Companions
- Probability Skymaps
- GOTO Instrument
- Transient Detection Pipeline
- The Future

Why combine GW & EM observations?

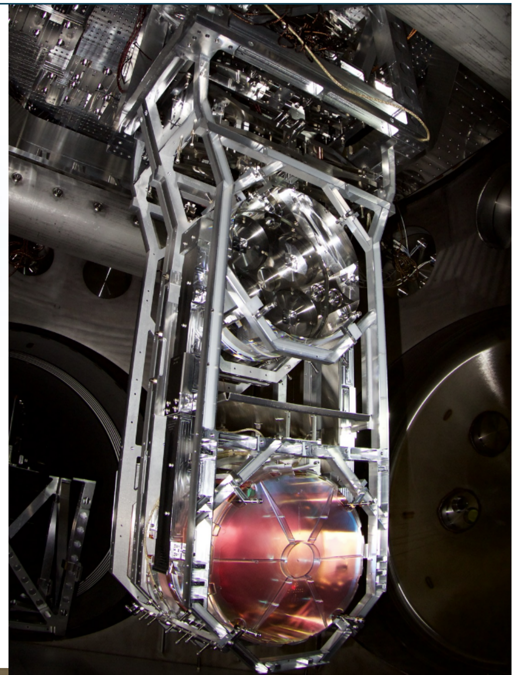
- A coincident EM signal improves confidence in GW detection
- Reduce the number of unconstrained GW parameters
- Cosmology via independent measure of redshift → H_0
- Host galaxy environment, population inferences
- Constrain the NS equation of state
- Constrain the merger rate of compact binary coalescence
- Answer long-standing question: are BNS engines of sGRBs?

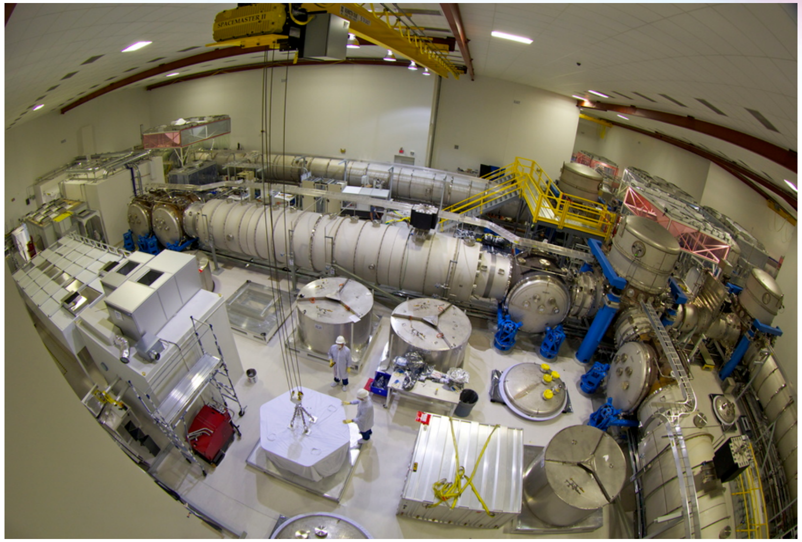

GEO 600
KAGRA
Virgo
Source: sciencenews.org
LIGO Hanford
LIGO Livingston

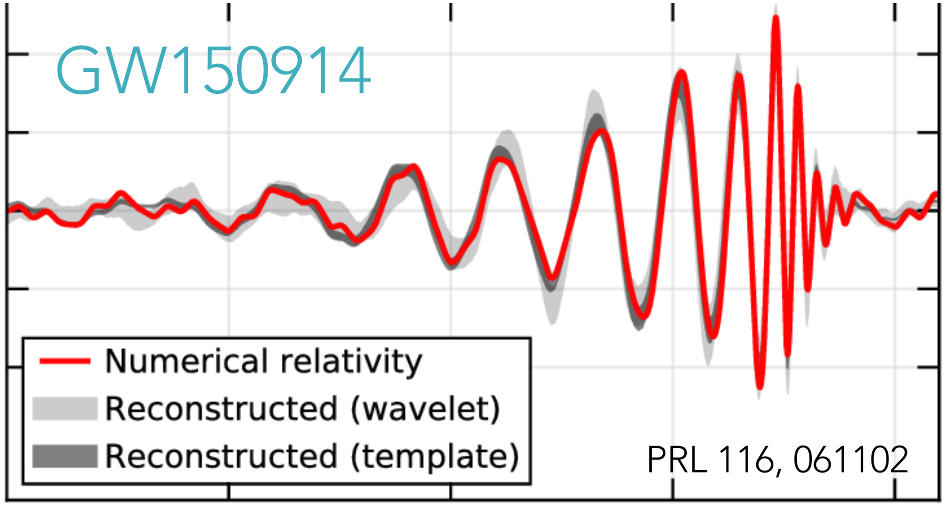
The LIGO Principle



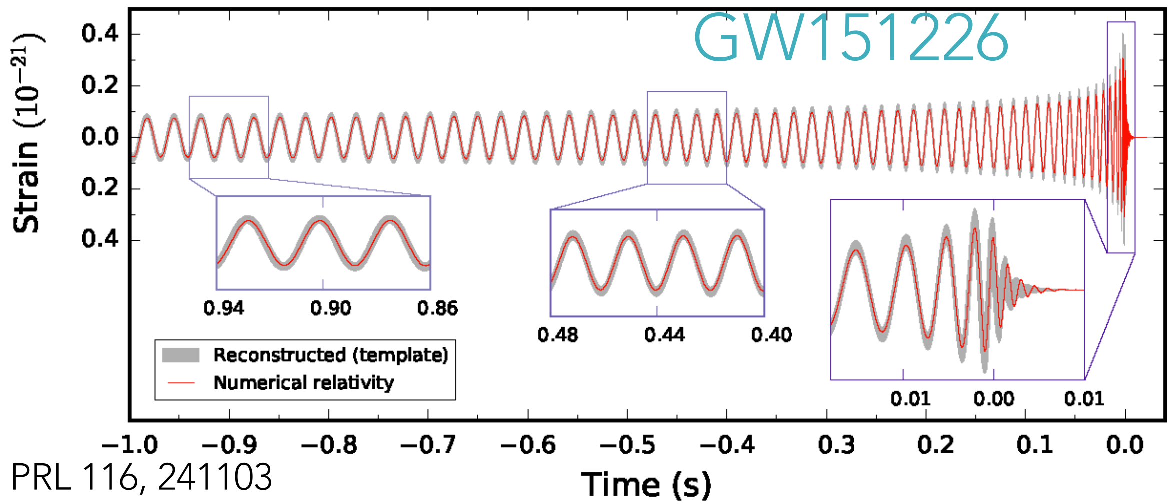
Source: gw.iucaa.in





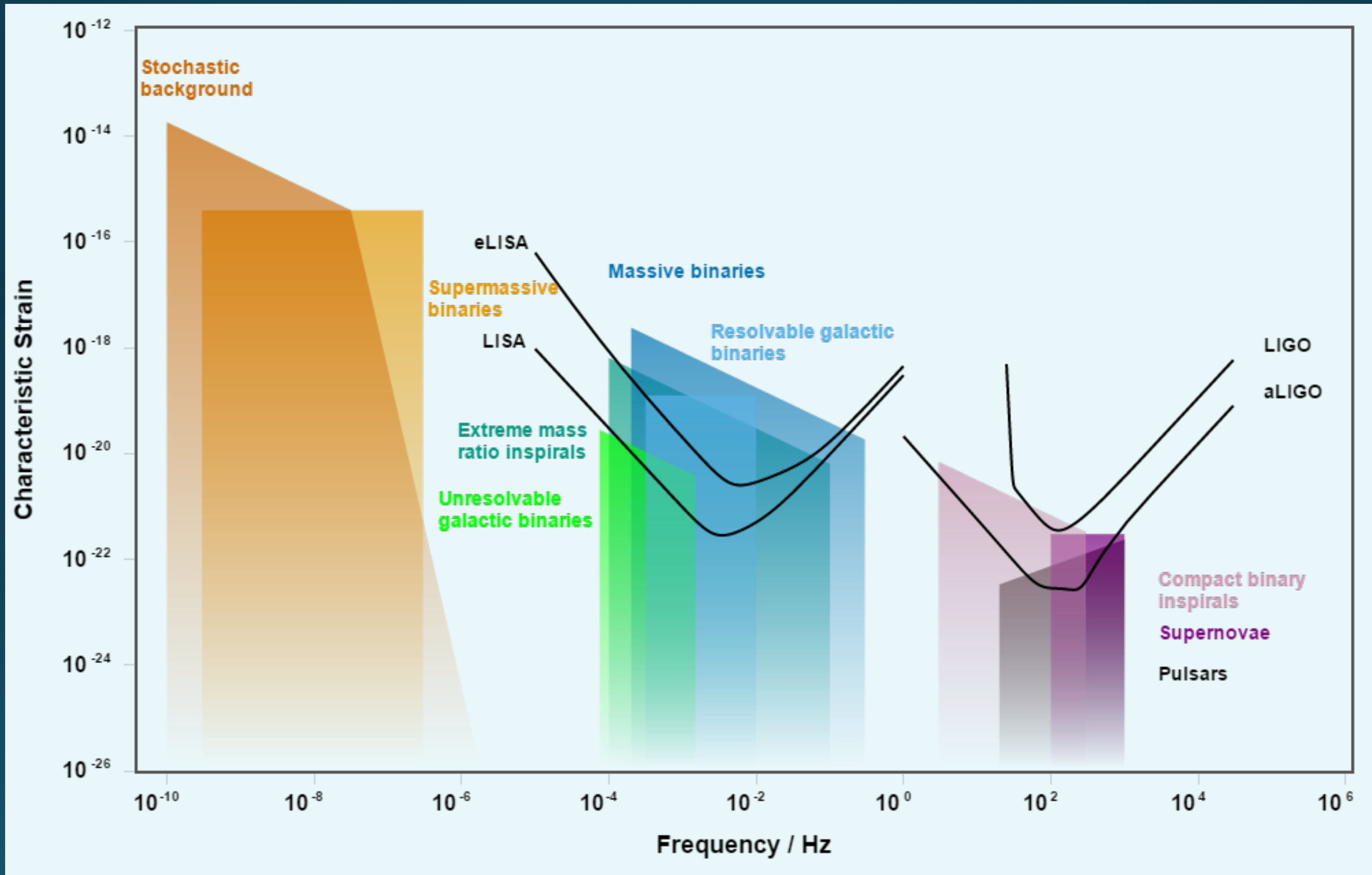


Waveforms contain all gravitational information
At least for black holes, that might be all there is to know



PRL 116, 241103

Astrophysical Sources of Gravitational Waves



GW Sources with LIGO

Compact Binary Coalescence

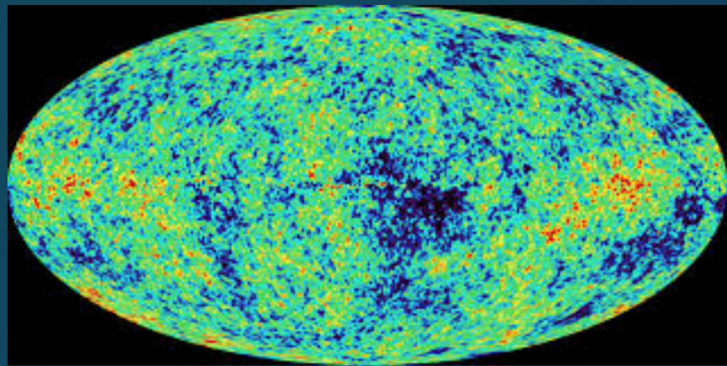
NS-NS, NS-BH, BH-BH

Modeled well with waveforms

Bursts

Supernovae
GRBs

Not well modeled



Stochastic

Primordial GW background

Overlapping signals

Continuous

Pulsars

Periodic

Detection Rates

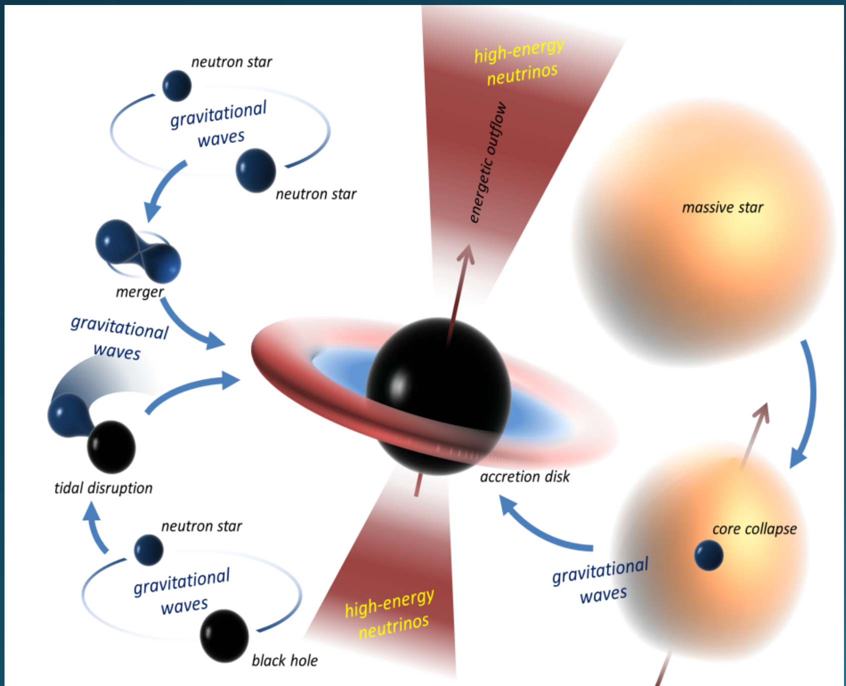
TABLE V: Detection rates for compact binary coalescence sources.

IFO	Source[a]	$\dot{N}_{\mathrm{low}}$ yr^{-1}	$\dot{N}_{\mathrm{re}}$ yr^{-1}	$\dot{N}_{\mathrm{high}}$ yr^{-1}	$\dot{N}_{\mathrm{max}}$ yr^{-1}
	NS-NS	2×10^{-4}	0.02	0.2	0.6
	NS-BH	7×10^{-5}	0.004	0.1	
Initial	BH-BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			< 0.001[b]	0.01[c]
	IMBH-IMBH			10^{-4}[d]	10^{-3}[e]
	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
Advanced	BH-BH	0.4	20	1000	
	IMRI into IMBH			10[b]	300[c]
	IMBH-IMBH			0.1[d]	1[e]

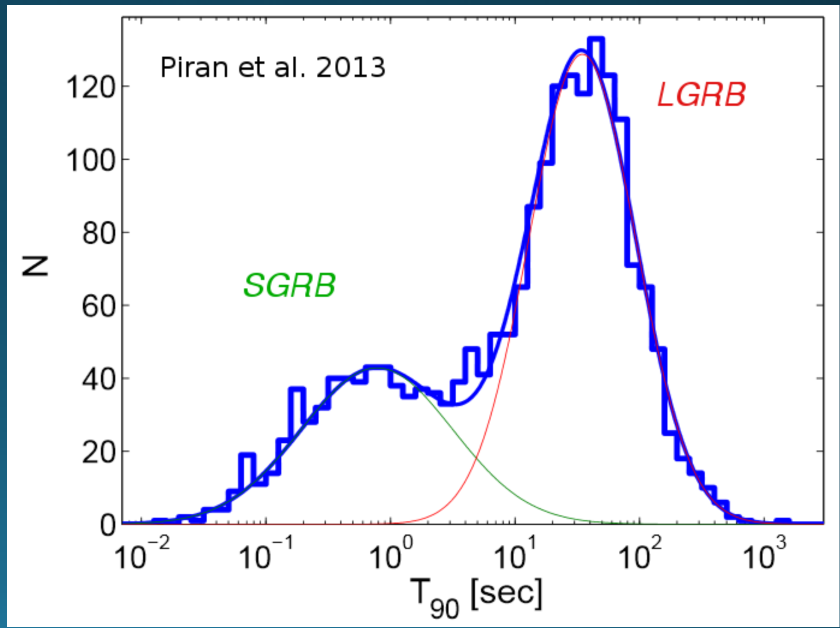
GW Sources with expected EM counterparts

Compact Binary Coalescence (NSNS, NSBH) ⟷ SGRB

Supernova ⟷ ? LGRB



http://ligo.org/science/Publication-GWHEN-IceCube/index.php



Joint BNS & sGRB Rates*

Epoch	Run Duration	BNS Range (Mpc)		Number of GW–GRB detections		
		LIGO	Virgo	All Sky	Fermi GBM	Swift BAT
2015	3 months	40 - 80	-	2×10^{-4} - 0.02	2×10^{-4} - 0.02	3×10^{-5} - 0.003
2016–17	6 months	80 - 120	20 - 60	0.004 - 0.2	0.003 - 0.1	3×10^{-4} - 0.03
2017–18	9 months	120-170	60 - 85	0.02 - 0.8	0.01 - 0.5	7×10^{-4} - 0.1
2019+	(per year)	200	65 - 130	0.1 - 2	0.07 - 1	0.01 - 0.2
2022+	(per year)	200	130	0.2 - 3	0.1 - 2	0.02 - 0.3

Clark et al. 2014

*Assuming that all sGRBs are the products of BNS

GW170817

PRL **119,** 161101 (2017)
Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS
week ending 20 OCTOBER 2017

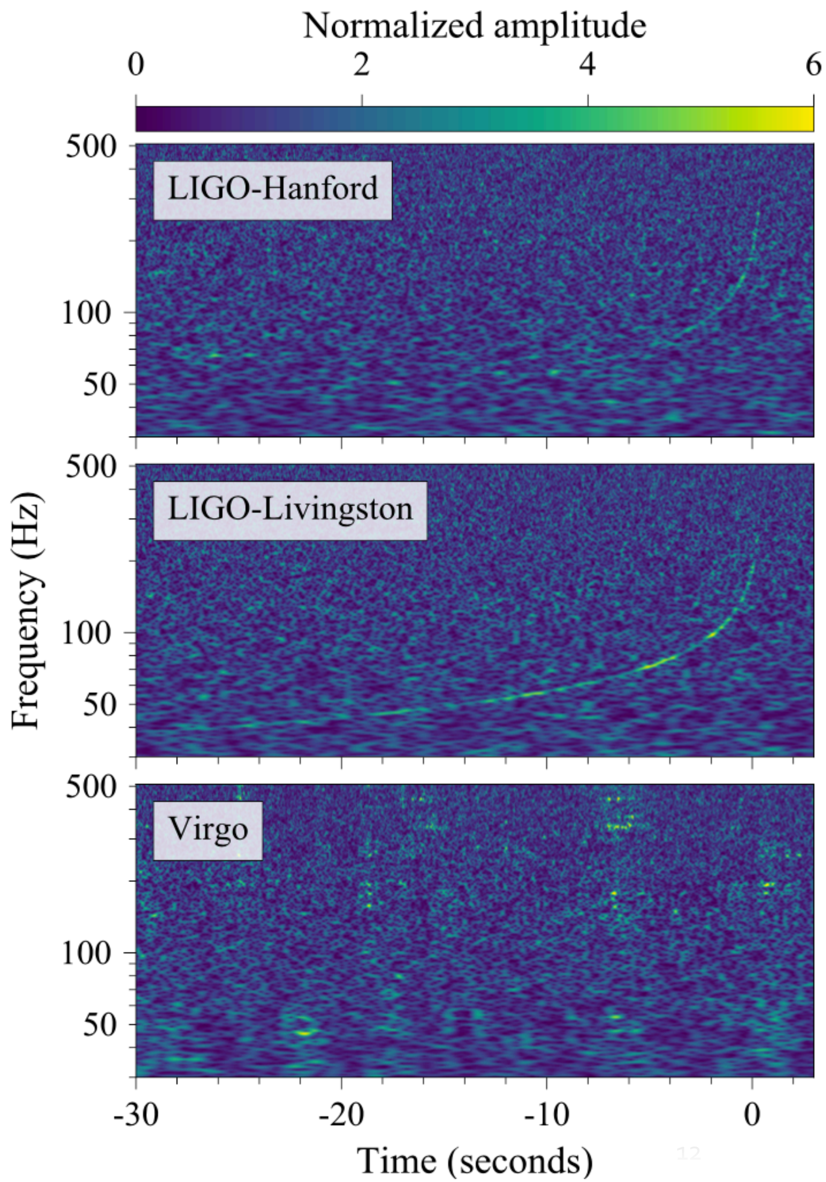
GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)

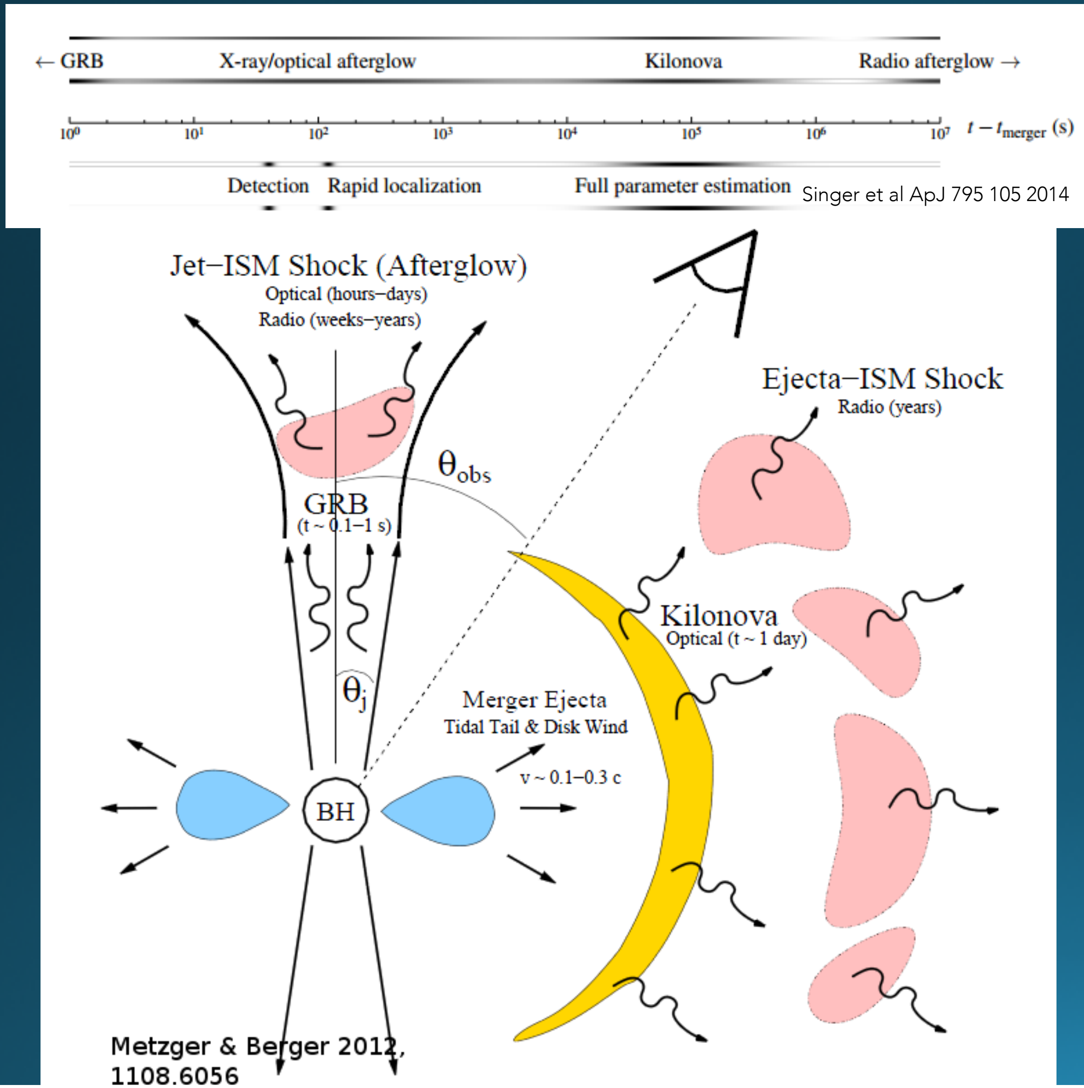
(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

On August 17, 2017 at 12:41:04 UTC the Advanced LIGO and Advanced Virgo gravitational-wave detectors made their first observation of a binary neutron star inspiral. The signal, GW170817, was detected with a combined signal-to-noise ratio of 32.4 and a false-alarm-rate estimate of less than one per 8.0×10^4 years. We infer the component masses of the binary to be between 0.86 and 2.26 $M_\odot$, in agreement with masses of known neutron stars. Restricting the component spins to the range inferred in binary neutron stars, we find the component masses to be in the range 1.17–1.60 $M_\odot$, with the total mass of the system $2.74^{+0.04}_{-0.01} M_\odot$. The source was localized within a sky region of 28 deg^2 (90% probability) and had a luminosity distance of 40^{+8}_{-14} Mpc, the closest and most precisely localized gravitational-wave signal yet. The association with the γ-ray burst GRB 170817A, detected by Fermi-GBM 1.7 s after the coalescence, corroborates the hypothesis of a neutron star merger and provides the first direct evidence of a link between these mergers and short γ-ray bursts. Subsequent identification of transient counterparts across the electromagnetic spectrum in the same location further supports the interpretation of this event as a neutron star merger. This unprecedented joint gravitational and electromagnetic observation provides insight into astrophysics, dense matter, gravitation, and cosmology.

DOI: 10.1103/PhysRevLett.119.161101



EM signature evolution post-merger

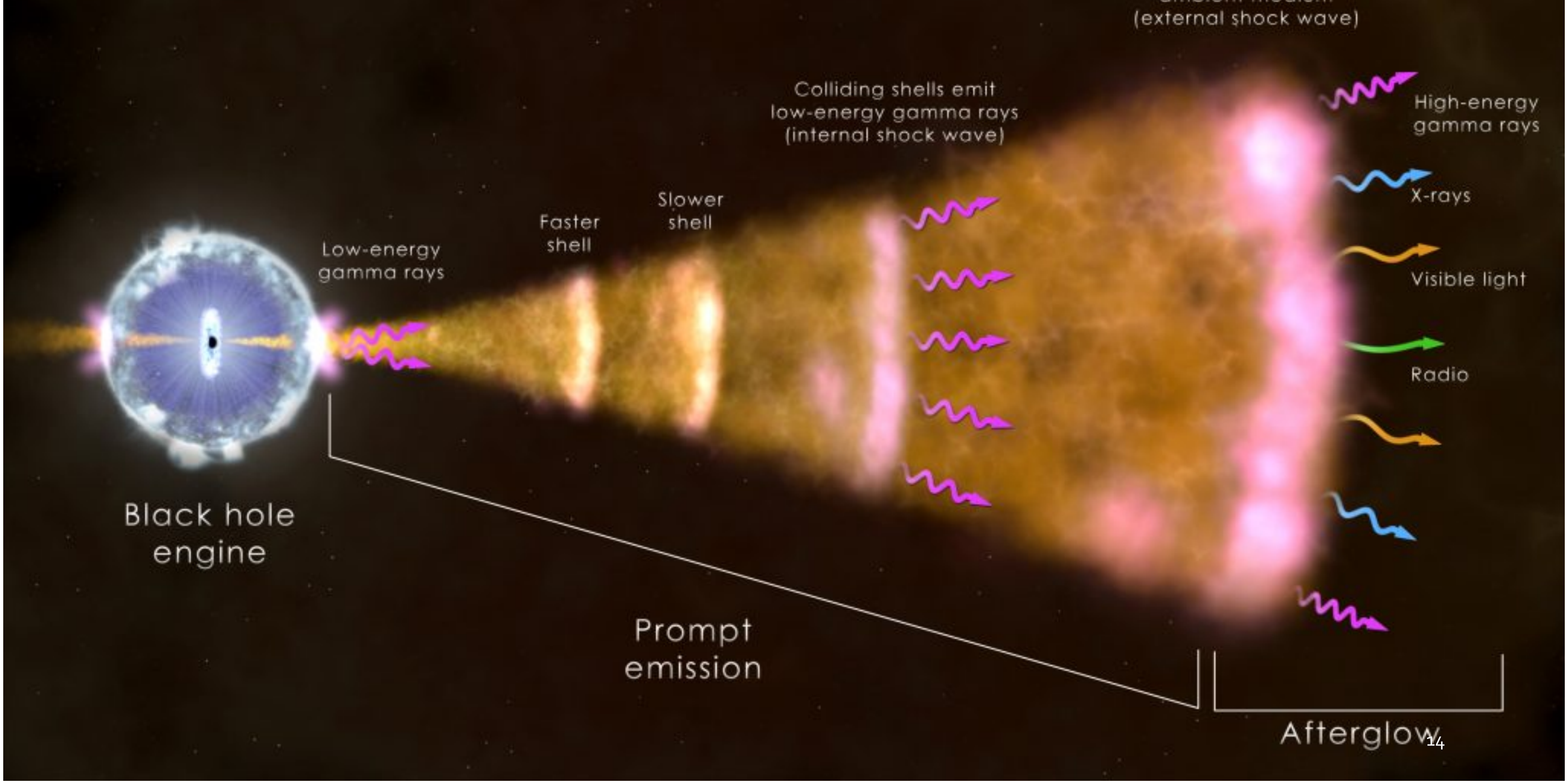


Singer et al ApJ 795 105 2014

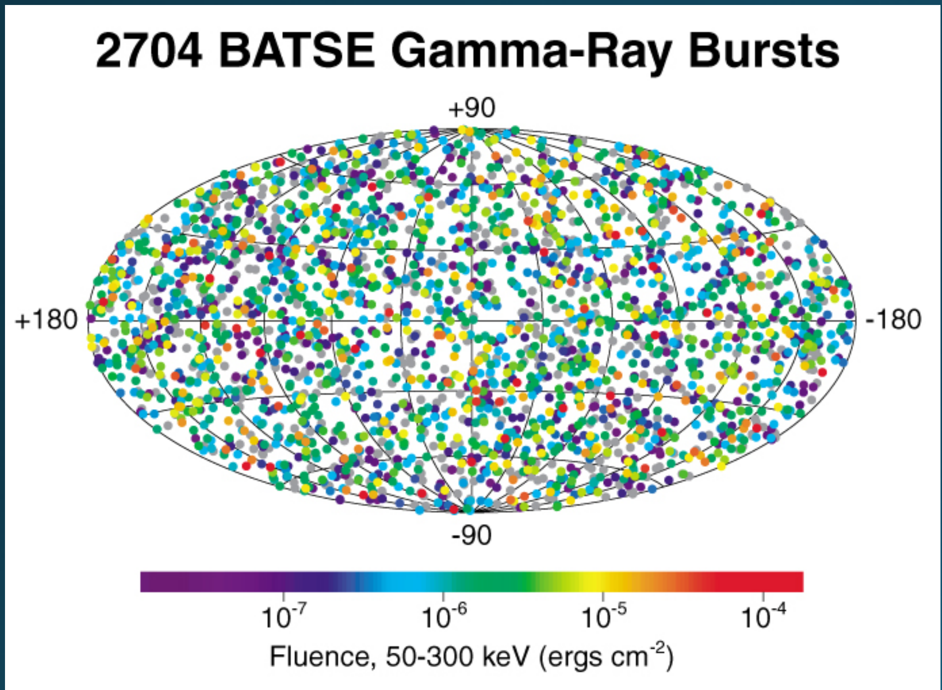
Metzger & Berger 2012, 1108.6056

- Compact binary merger: forms compact object and accretion disk
- Accretion disk feeds pair of jets
- Interaction of jet with surrounding medium: nonthermal afterglow
- Once jet decelerates, afterglow is isotropic

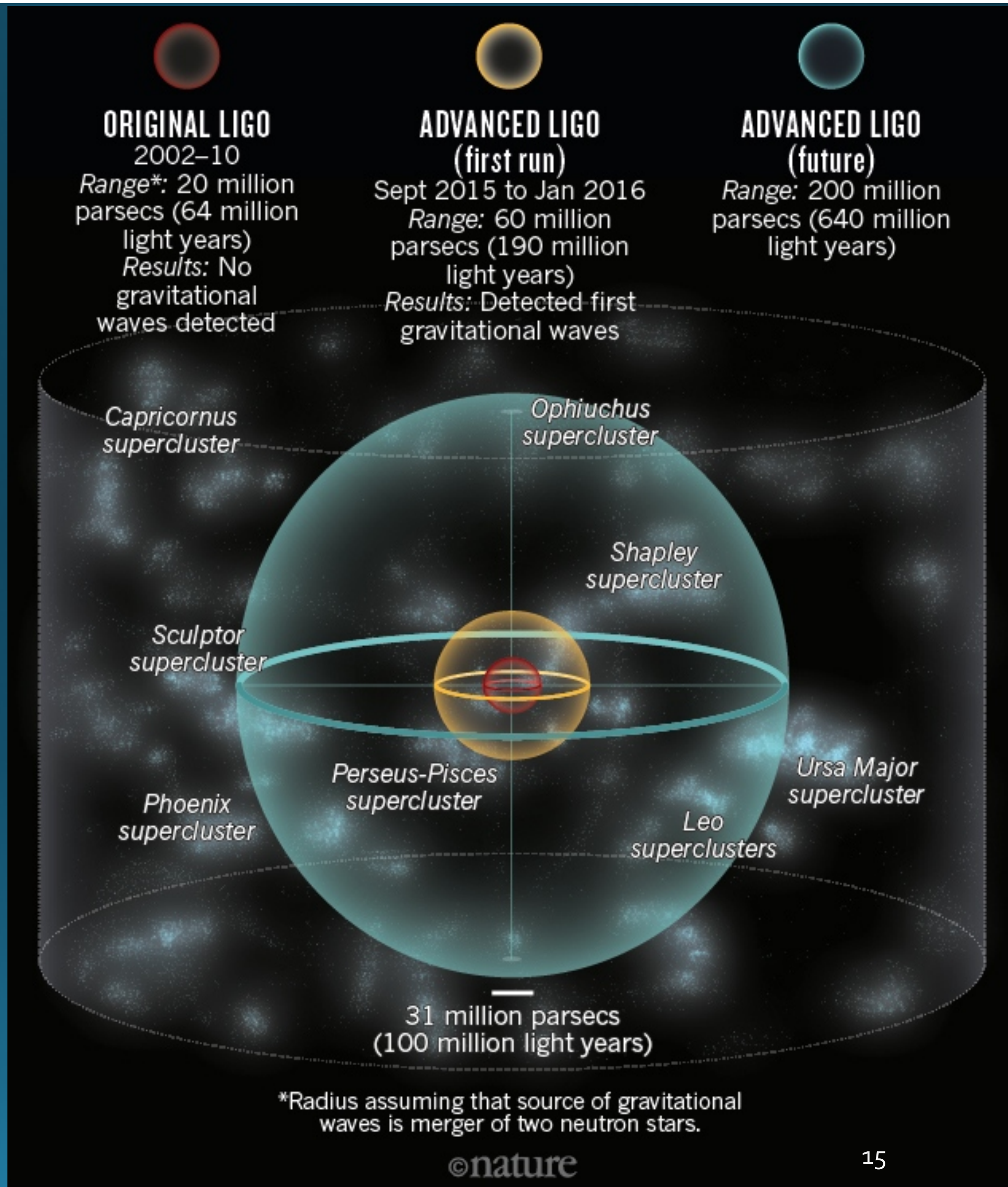
Not spherical emission but along relativistic jets



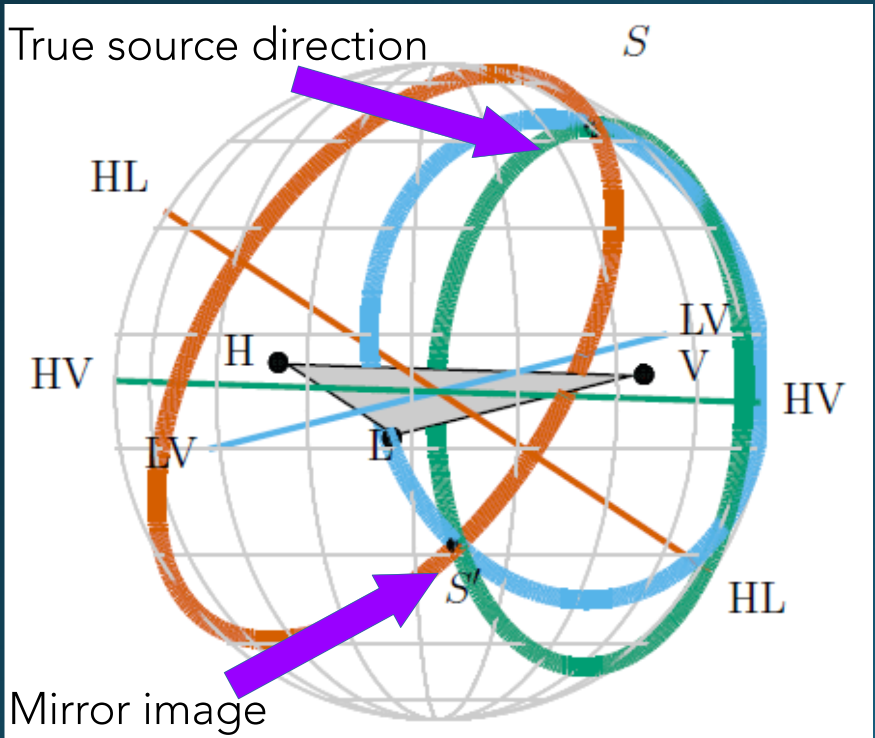
All Sky Antenna

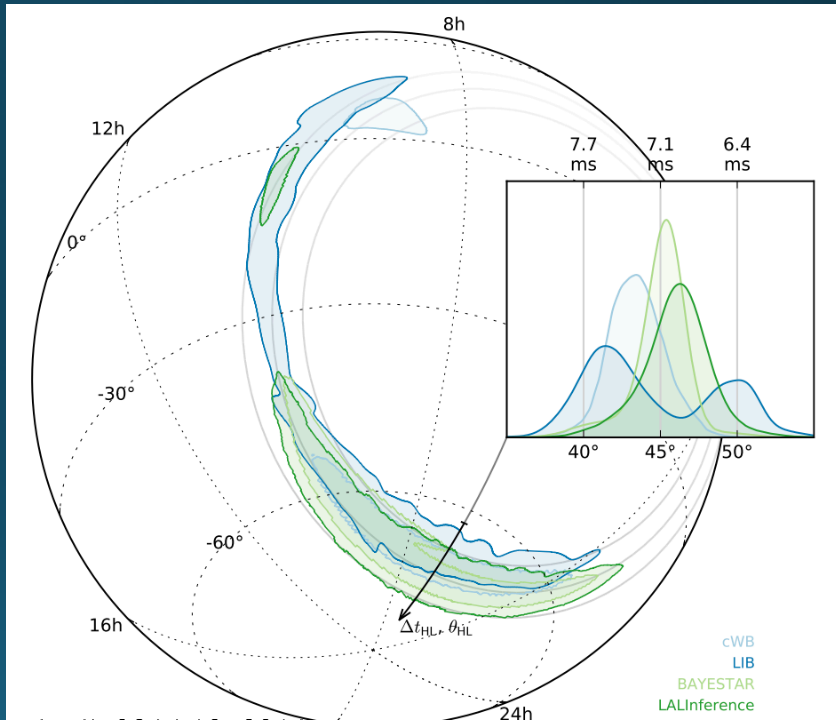


Source: heasarc.gsfc.nasa.gov



Gravitational Wave Source Localization



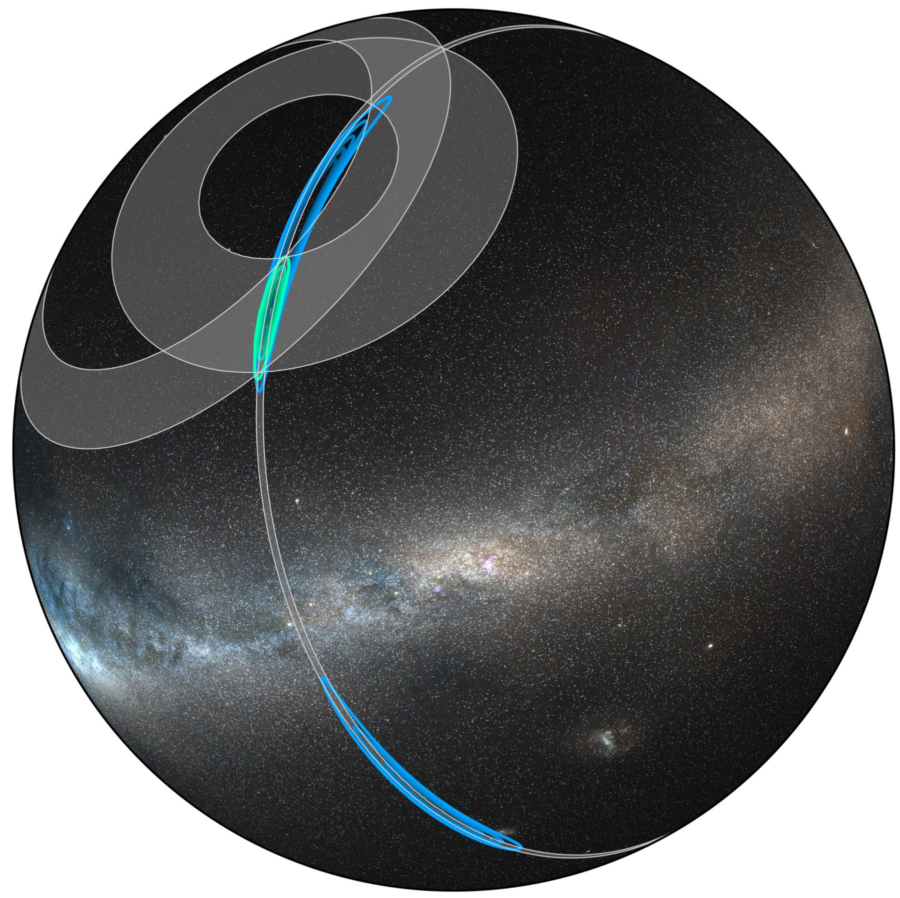


ApJL 826:L13, 2016

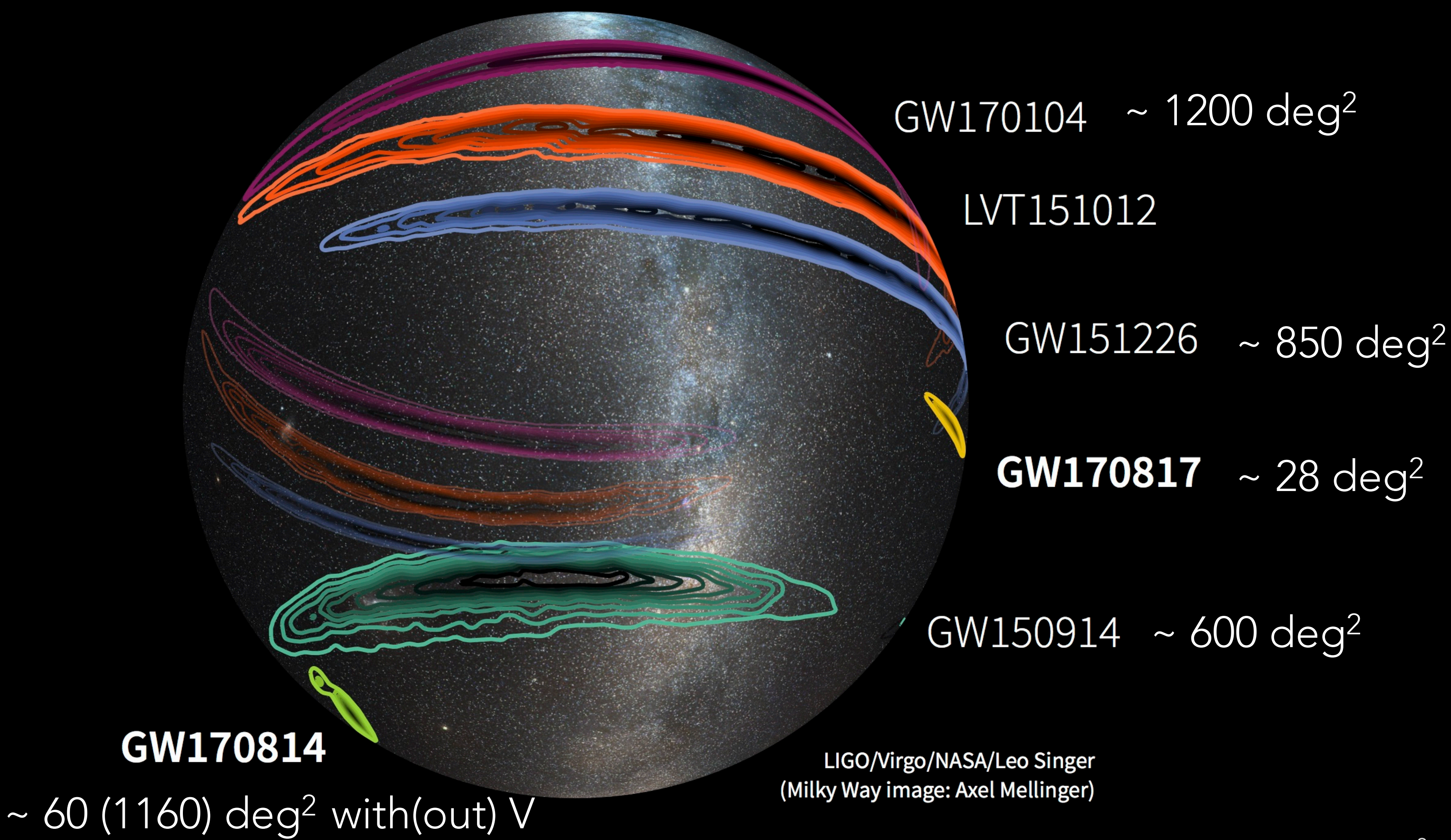
- Time delay (+uncertainty) between 2 detectors: annulus
- Time delay between 3 detectors: annuli intersect in (S,S')

GW170817

- 90% error region ~28 deg^2
- 10,000+ sources in field,
  ideally only 1 transient
- Not typical size historically

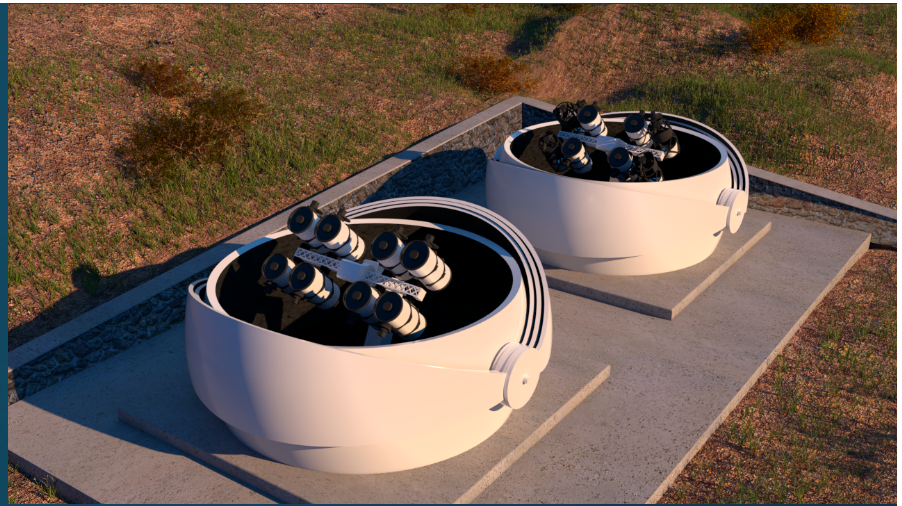


Credit: LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger)


GW170104 ~ 1200 deg^2
LVT151012
GW151226 ~ 850 deg^2
GW170817 ~ 28 deg^2
GW150914 ~ 600 deg^2
GW170814
~ 60 (1160) deg^2 with(out) V
LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)

GOTO

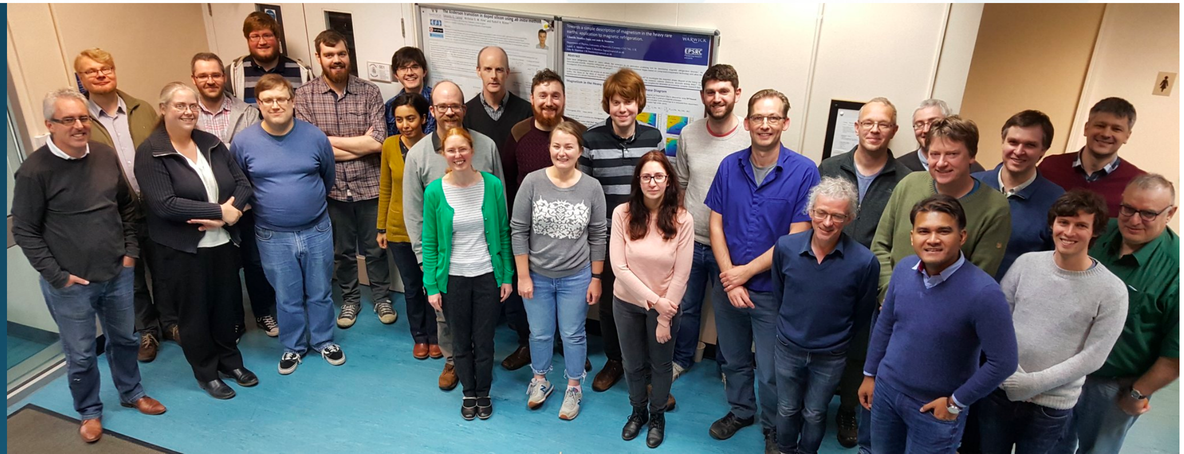
GRAVITATIONAL-WAVE OPTICAL TRANSIENT OBSERVER



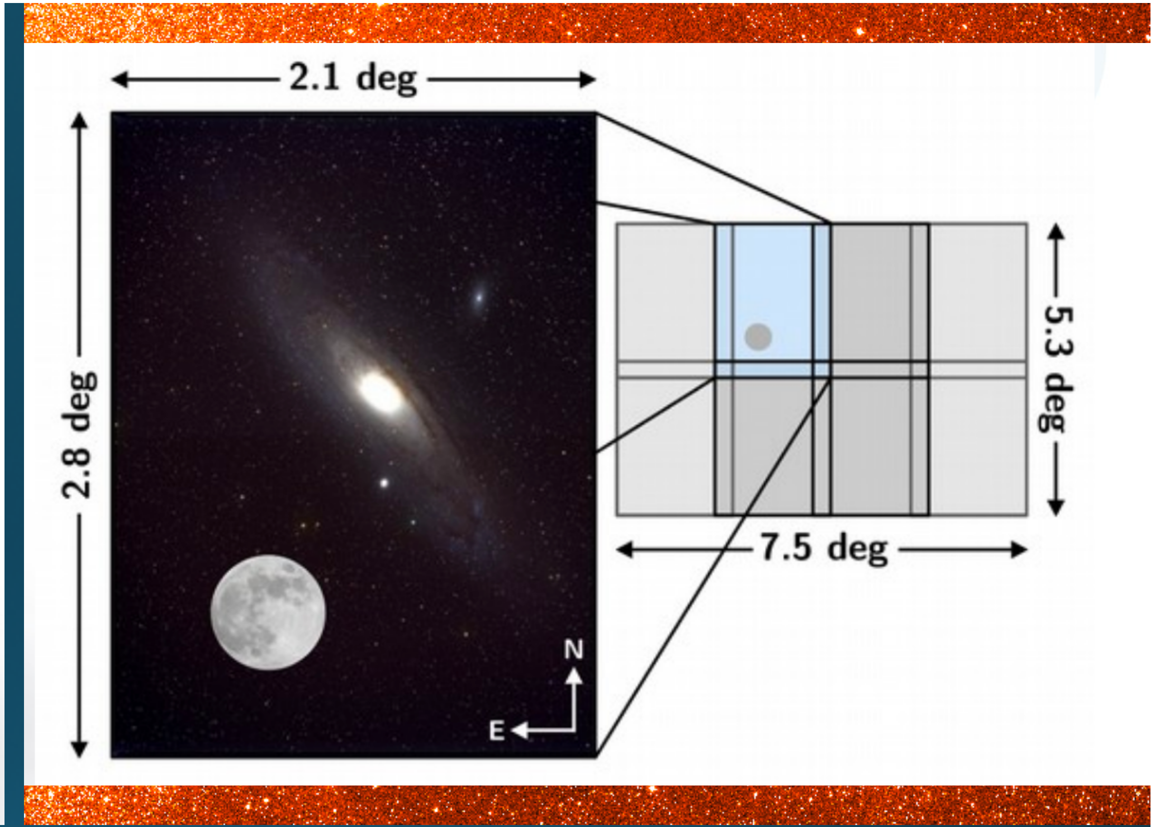
GOTO Collaboration

Membership pending:

- >40 people involved
- 9 institutions (UK, Australia, Thailand, Spain, Finland)
- Co-PIs Danny Steeghs (Warwick) and Duncan Galloway (Monash)
- Funded through Warwick-Monash Alliance and institution contributions

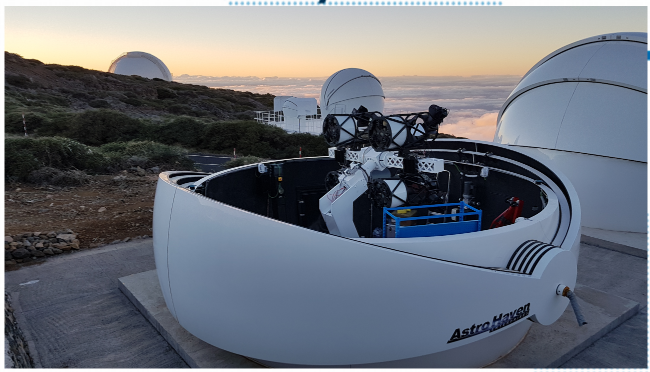


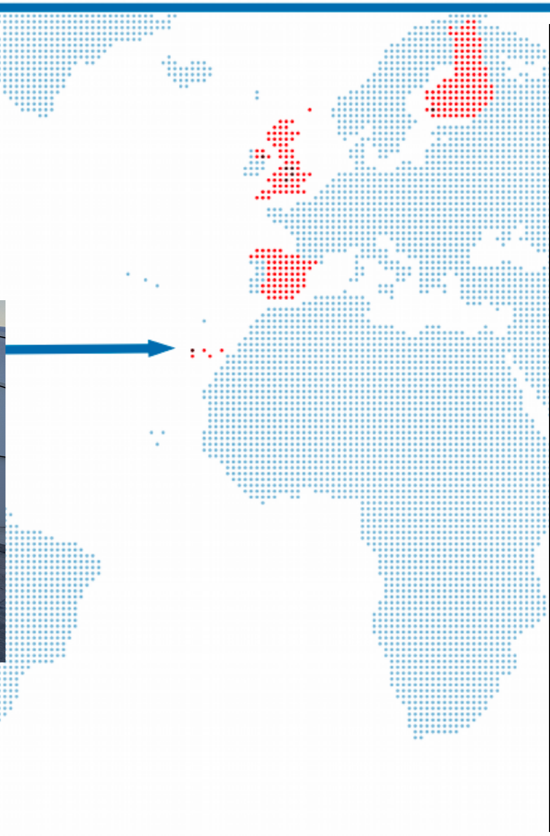
GOTO Science Meeting, Warwick, April 2018



- Dedicated to rapidly detecting optical counterparts to GW events
- Quick-slewing robotic mount with multiple independent 40cm f/2.5 unit telescopes
- Final design: 8 UTs ~ 40 sq. deg
- First light on 11 June 2017

GOTO North
La Palma, Canary Islands



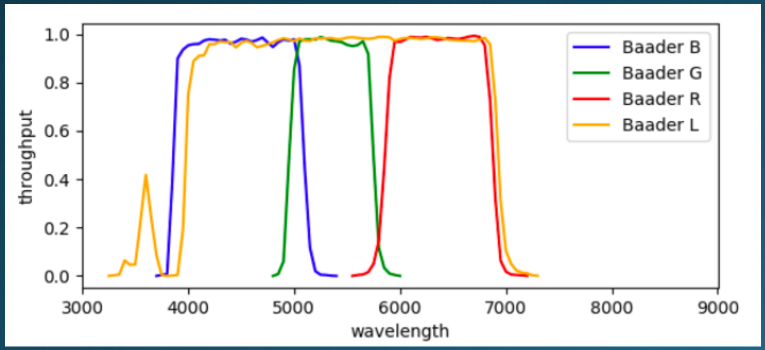


GOTO
GRAVITATIONAL-WAVE OPTICAL TRANSIENT OBSERVER

- Autonomous, custom robotic control system for hardware, nightly operations
- Generate ~40GB data/night (~140 GB /night at full design)
- Transfers from La Palma to Warwick (UK) for real-time processing, then to Monash for backup storage and testing
- Warwick: 8 CPUs for parallel processing of each camera
- Turn around time ~minutes
- All detected sources stored in PostgreSQL database

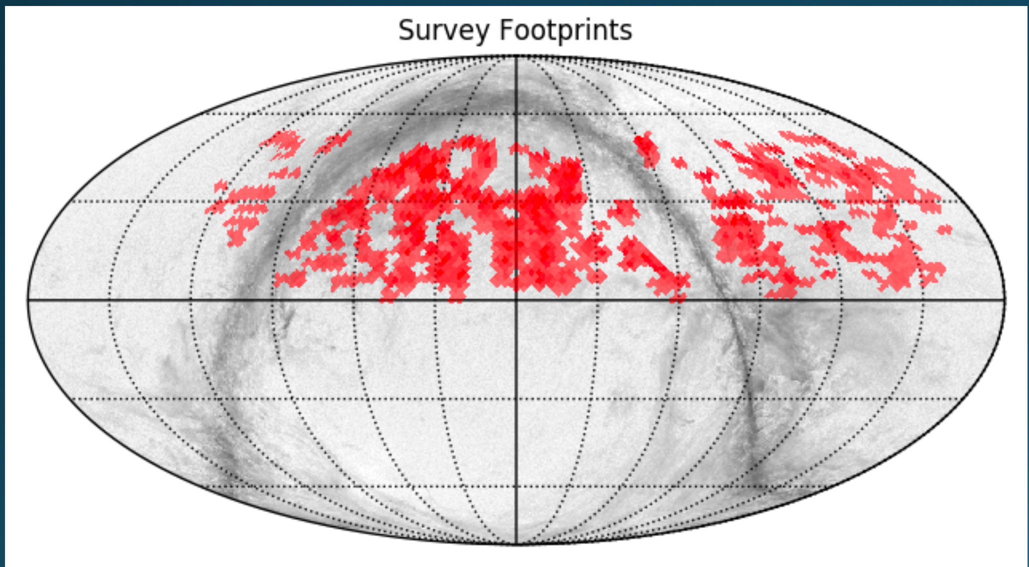
GOTO Specs

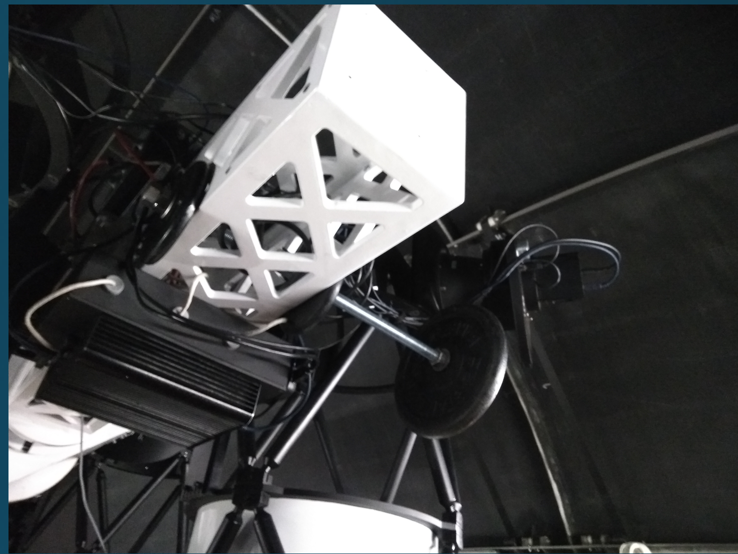
- FLI MicroLine cameras
- Each UT: 8176 x 6132 pix
- Pixel scale ~1.2"/pix
- Limiting magnitude ~20-21 with 2min exposure
- Baader LRGBC filters

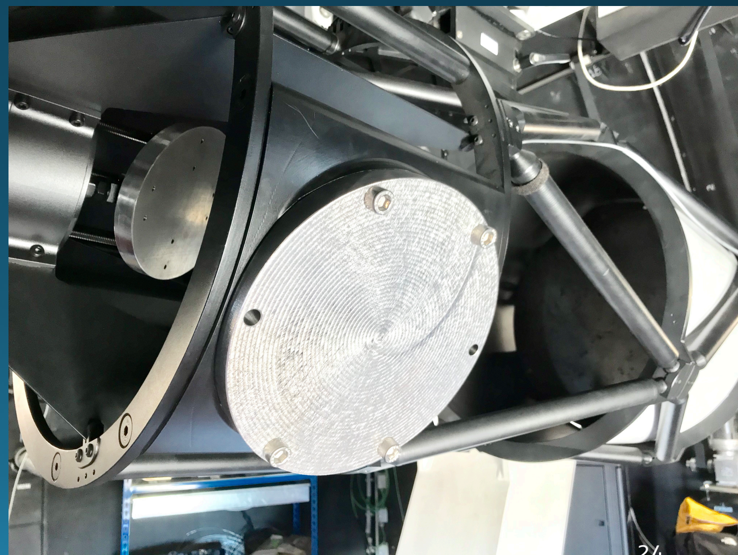


GOTO Status

- Currently in commissioning
- 3 out of 4 cameras observing:
  waiting for the 4th camera to be returned
- Shift weights to mimic 4th camera for observing







GOTO Status

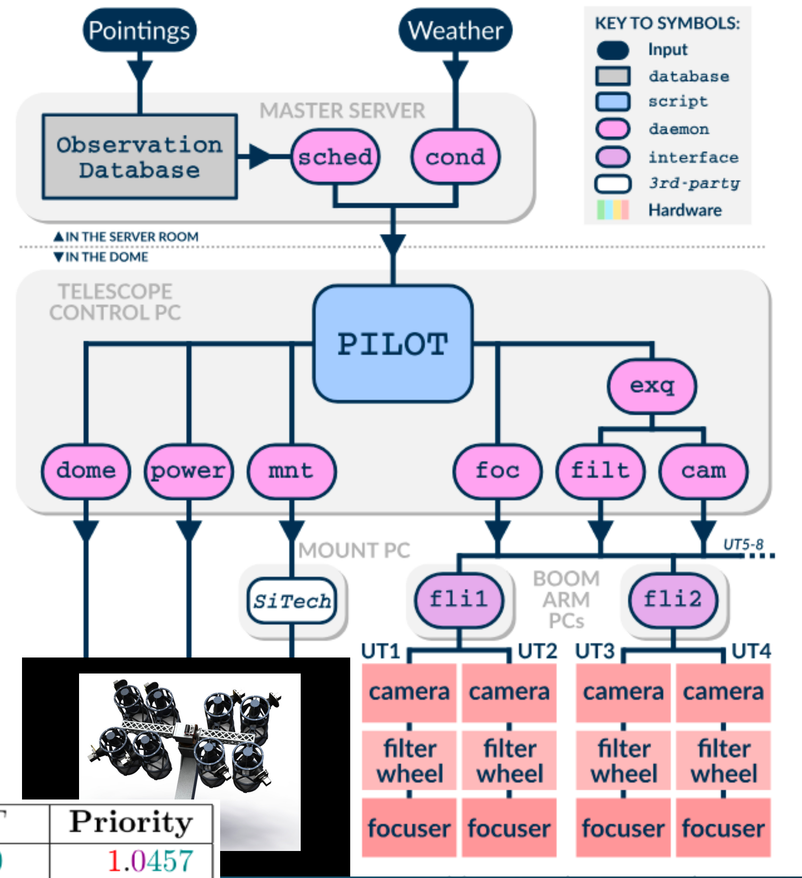
- Currently observing in "survey mode"
- Search ongoing for transients/variables in "discovery mode"
- Following GCNs, Atels

- Pipeline running in real time
- Database running in real time (both discovery and scheduling)

- Finalise commissioning, pipeline readiness, and database for O3
- Combine all potential ML pipelines for transient discovery: both supervised and unsupervised

GOTO Automated Scheduler

- Each hardware type has a control daemon
- pilot is master control program
- Targets are entered into database and schedules as 'just-in-time'
  No fixed night plan – reevaluates every 10s
- Checks altitude, moon distance, … →
  Finds and sorts by priority

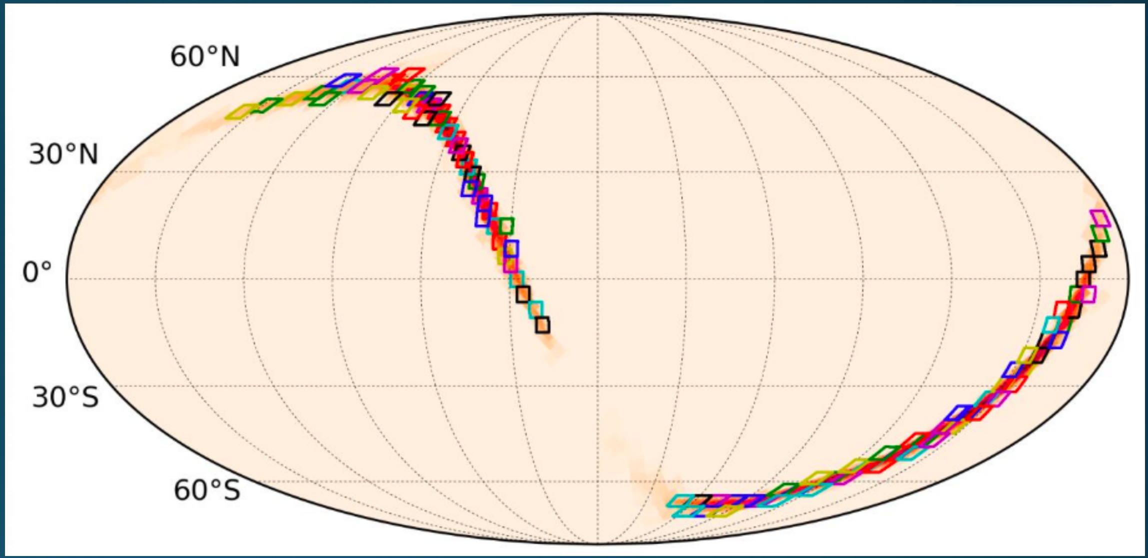


	Target name	R	N_r	ToO	F_{ToO}	Am.	X	Prob.	P	Time	T	Priority
1	GW181202 T4	1	0	True	0	1.1	0.050	4.5%	0.955	–	0	1.0457
2	GW181202 T9	1	0	True	0	1.1	0.050	0.3%	0.997	–	0	1.0477
3	M31	8	0	False	1	1.0	0.000	–	0	–	0	8.1000
4	GW181202 T3	1	1	True	0	1.1	0.050	9.1%	0.909	–	0	11.0435
5	AT 2018bdk	6	2	True	0	1.0	0.000	–	0	–	0	26.0000
6	AT 2018bfe	6	2	True	0	1.2	0.100	–	0	–	0	26.0005
7	M101	6	2	False	1	1.1	0.050	–	0	–	0	26.1024
8	Survey T31	999	–	False	1	1.0	0.000	–	0	4 days	0.429	999.1204
9	Survey T33	999	–	False	1	1.0	0.000	–	0	2 days	0.714	999.1340

Developed by M.J. Dyer

GOTO Automated Tiling + Reference

- Divides the sky into fixed grid of overlapping tiles
- Most nights: all-sky survey over tiles
- GW skymaps are mapped onto grid, each tile containing a fraction of the probability
- When a tile is observed we use previous observations for difference imaging



GOTO-tile GW151226 4-UT configuration

First GCN on 06 Dec 17

```
TITLE:   GCN CIRCULAR
NUMBER:  22190
SUBJECT: GRB 171205A: GOTO detection of the optical counterpart
DATE:    17/12/06 16:56:54 GMT
FROM:    Rhaana Starling at U of Leicester  <rlcs1@leicester.ac.uk>

D.Steeghs, R.Cutter, K.Ulaczyk, D.Pollacco, R.West, A.Levan, J.Lyman, P.Chote, J.McCormac, K.Wiersema (U. Warwick)
G.Ramsay (Armagh O.)
R.Starling, P.O'Brien, R.Eyles (U. Leicester)
D.K.Galloway, E.Rol, E.Thrane, K.Ackley, A.Casey (Monash U.)
V.Dhillon, M.Dyer, S.Littlefair, E.Daw, J.Mullaney, L.Makrygianni, J.Maund (U. Sheffield)
S.Poshyachinda, S.Aukkaravittayapun, U.Sawangwit, S.Awiphan, D.Mkrtichian (NARIT)

report on behalf of the GOTO collaboration:


The Gravitational-wave Optical Transient Observer observed the field of GRB 171205A (trigger=794972, D'Elia et al. GCN Circ. 22177) from Roque de
los Muchachos Observatory beginning at 2017-12-06T04:24:31 UT, 21.07 hours since burst, in several wide-band filters.

In a combined L-band image (400-700nm passband), with a total exposure time of 1440s at a mid-time 04:57:38 UT, 21.36 hours since burst, we
detect the optical counterpart (Selsing et al. GCN Circ. 22180; Emery & D'Elia GCN Circ. 22181; Butler et al. GCN Circ. 22182; Mao et al. GCN
Circ. 22186; Choi & Im GCN Circ. 22188) with a preliminary magnitude of V=18.95 +/- 0.15 based on a comparison to APASS V-band calibrators.
Galaxy contamination is likely leading to an additional systematic uncertainty.
An image can be viewed here: www.arm.ac.uk/~gar/GRB171205A-goto.jpg<http://www.arm.ac.uk/~gar/GRB171205A-goto.tiff>


Further observations are scheduled.

GOTO is operated at the La Palma observing facilities of the University of Warwick on behalf of a consortium including the University of Warwick,
Monash University, Armagh Observatory, the University of Leicester, the University of Sheffield, the National Astronomical Research Institute of
Thailand (NARIT) and the Instituto de Astrofísica de Canarias (IAC)
(https://goto-observatory.org<https://goto-observatory.org/>)
GOTO Observatory<https://goto-observatory.org/>
goto-observatory.org
The first GOTO dome at Roque de Los Muchachos observatory on La Palma. About. The Gravitational-wave Optical Transient Observer (GOTO) is a
project to identify ...
```

Many more since then

TITLE: GCN CIRCULAR
NUMBER: 22728
SUBJECT: GRB 180514A: GOTO Optical Observations
DATE: 18/05/14 21:46:20 GMT
FROM: Ben Gompertz at U of Warwick <b.gompertz@warwick.ac.uk>

TITLE: GCN CIRCULAR
NUMBER: 22878
SUBJECT: GRB 180626B : GOTO optical observations
DATE: 18/07/01 21:14:54 GMT
FROM: Danny Steeghs at U.of Warwick/GOTO <D.T.H.Steeghs@warwick.ac.uk>

TITLE: GCN CIRCULAR
NUMBER: 22879
SUBJECT: GRB 180626C : GOTO optical observations
DATE: 18/07/01 21:15:44 GMT
FROM: Danny Steeghs at U.of Warwick/GOTO <D.T.H.Steeghs@warwick.ac.uk>

TITLE: GCN CIRCULAR
NUMBER: 22924
SUBJECT: GRB 180706A: GOTO optical limits
DATE: 18/07/06 23:16:00 GMT
FROM: Danny Steeghs at U.of Warwick/GOTO <D.T.H.Steeghs@warwick.ac.uk>

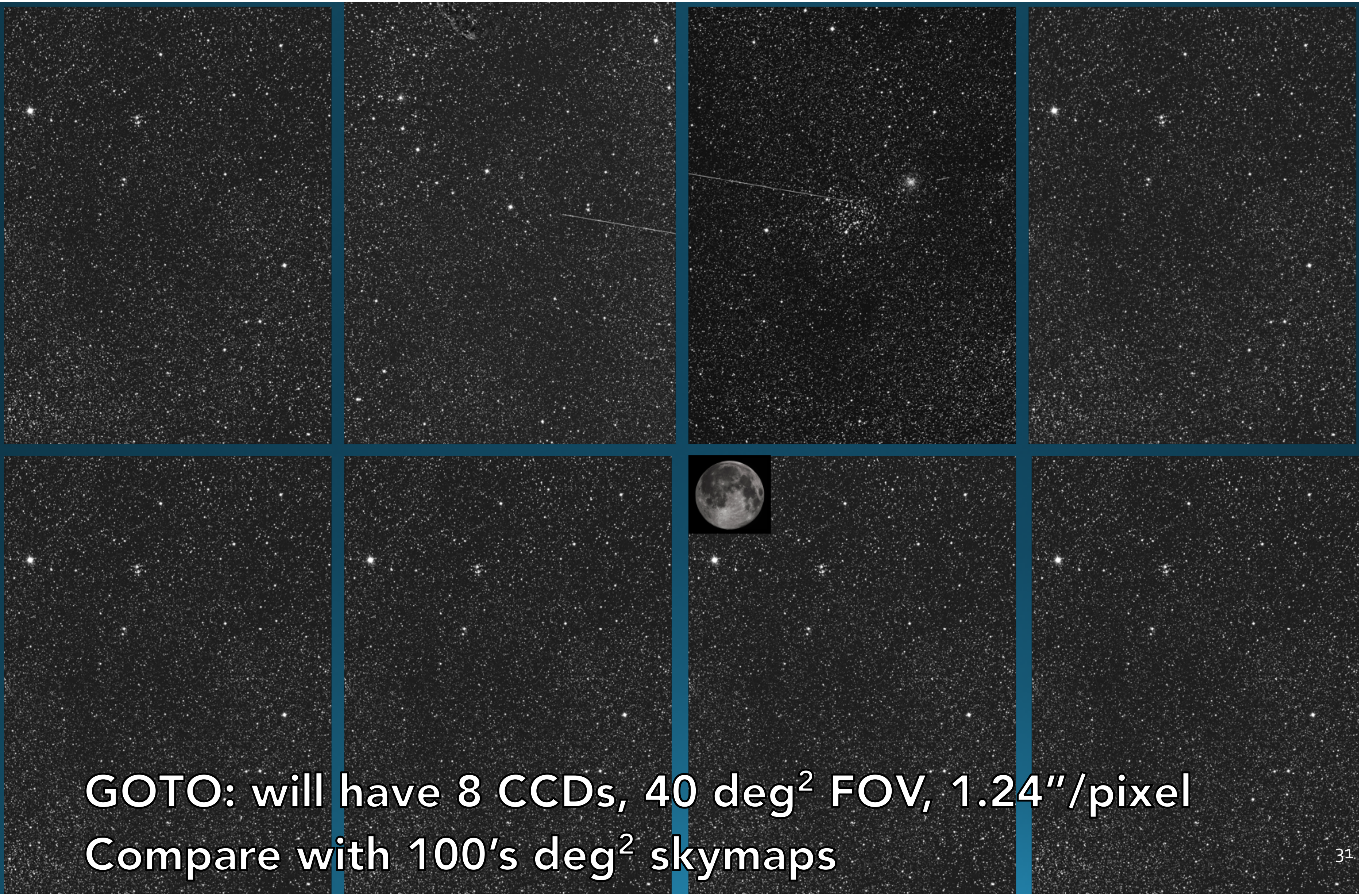
TITLE: GCN CIRCULAR
NUMBER: 22950
SUBJECT: GRB 180715A: GOTO optical limits
DATE: 18/07/15 23:27:04 GMT
FROM: Joe Lyman at U of Warwick <j.d.lyman@warwick.ac.uk>

TITLE: GCN CIRCULAR
NUMBER: 23069
SUBJECT: GRB 180728B: GOTO optical search over IPN region
DATE: 18/07/31 21:56:14 GMT
FROM: Danny Steeghs at U.of Warwick/GOTO <D.T.H.Steeghs@warwick.ac.uk>

TITLE: GCN CIRCULAR
NUMBER: 23087
SUBJECT: GRB 180805B: GOTO optical limits
DATE: 18/08/06 14:26:16 GMT
FROM: Danny Steeghs at U.of Warwick/GOTO <D.T.H.Steeghs@warwick.ac.uk>

TITLE: GCN CIRCULAR
NUMBER: 23252
SUBJECT: GRB 180914B: GOTO optical detection
DATE: 18/09/17 22:22:19 GMT
FROM: Danny Steeghs at U.of Warwick/GOTO <D.T.H.Steeghs@warwick.ac.u

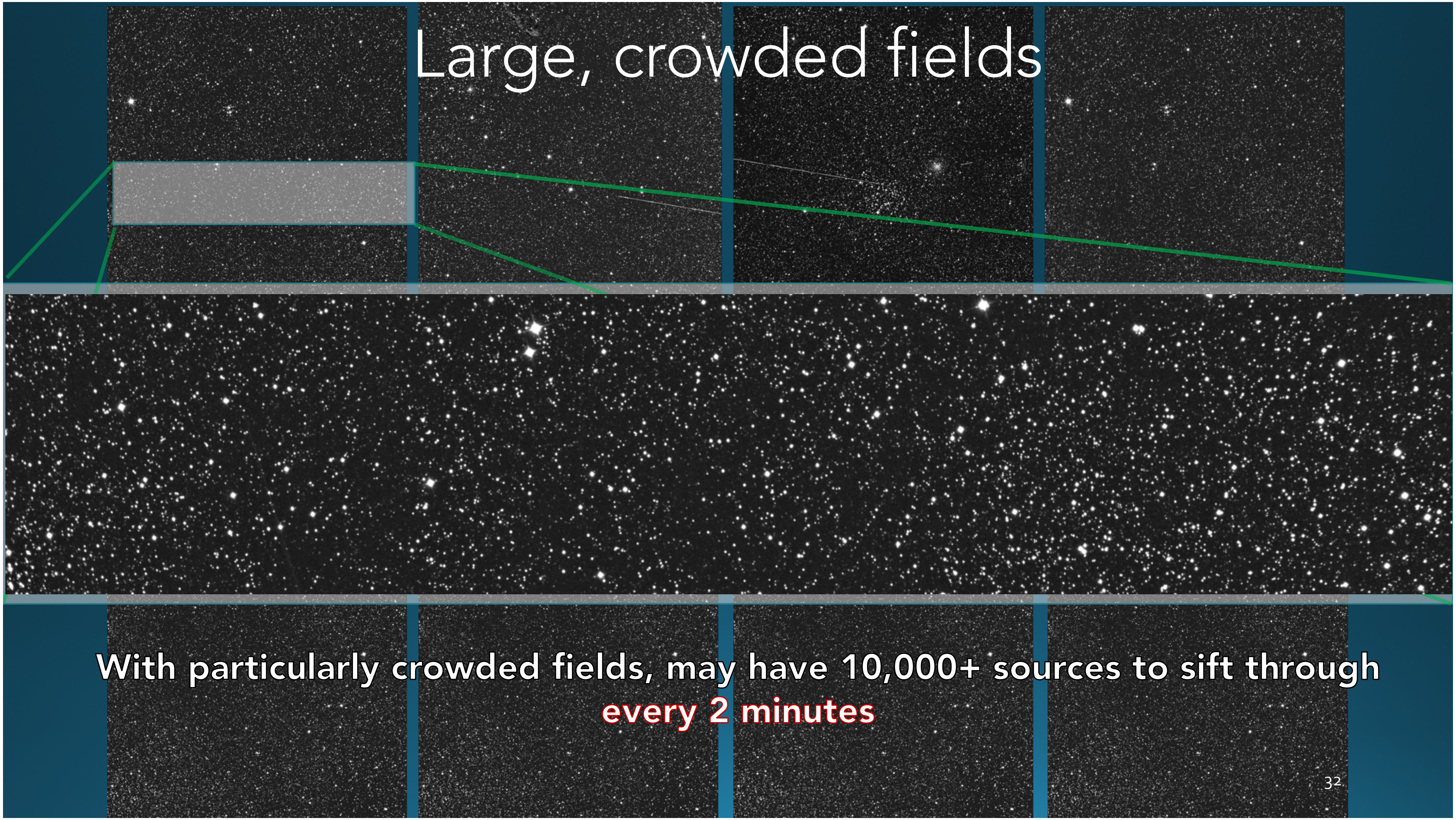
Week 1 of Feb 2018



GOTO: will have 8 CCDs, 40 deg^2 FOV, 1.24″/pixel

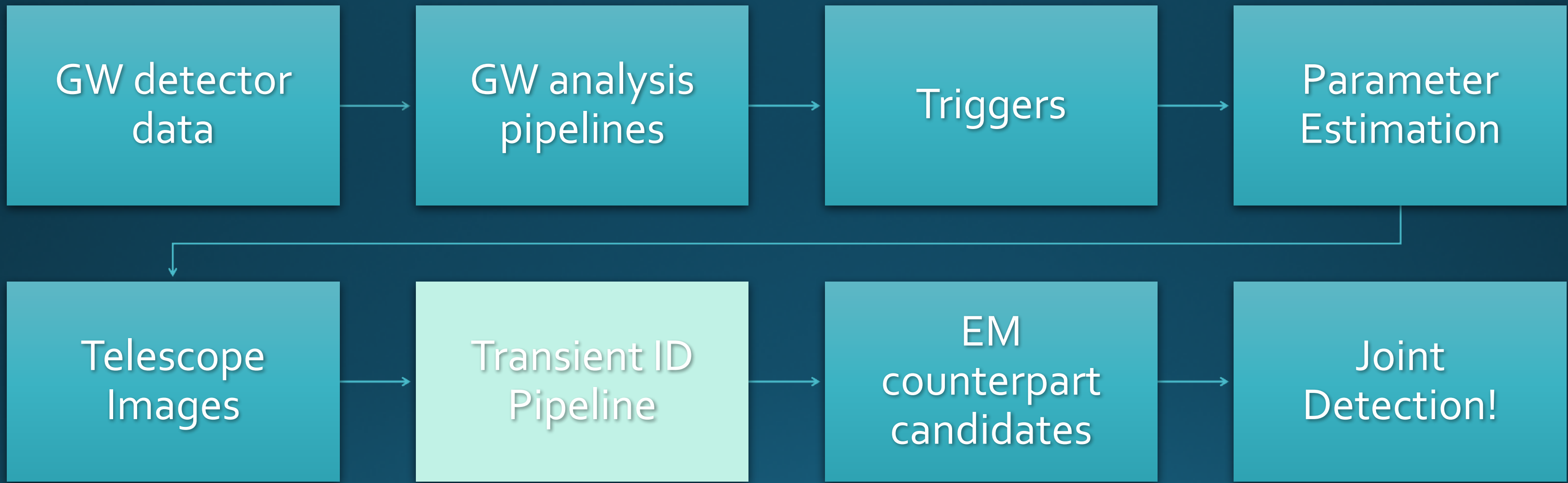
Compare with 100’s deg^2 skymaps

Large, crowded fields

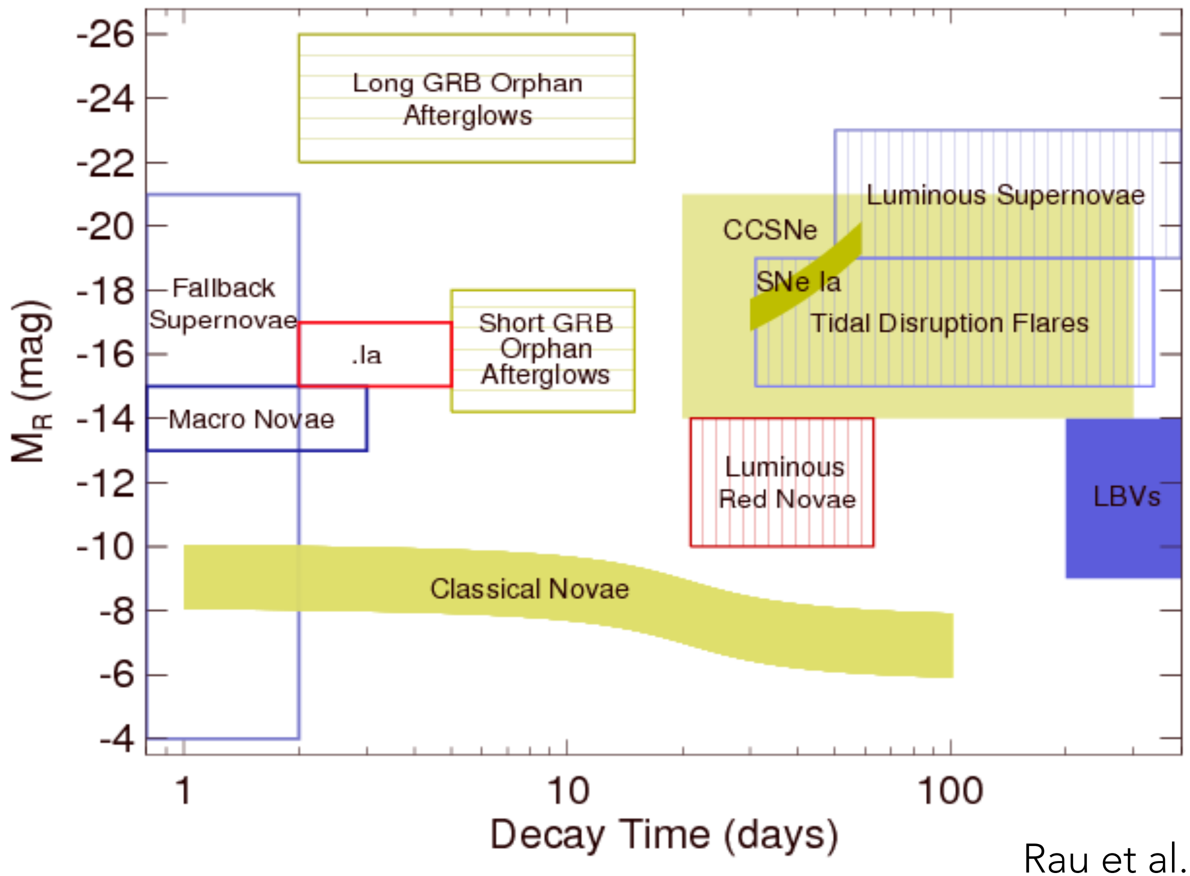


With particularly crowded fields, may have 10,000+ sources to sift through
every 2 minutes

Transient Identification Pipeline

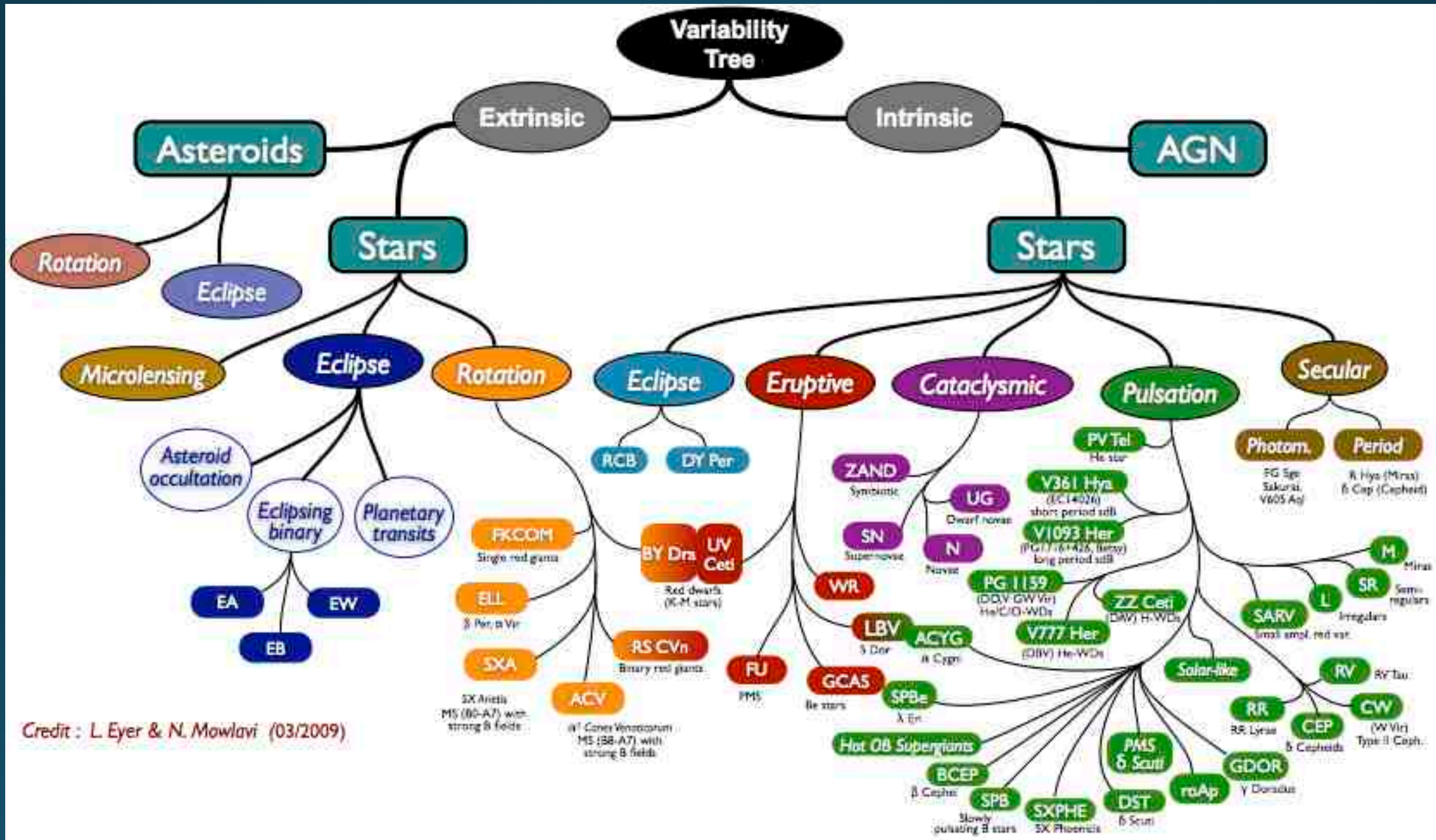


Astrophysical Transients



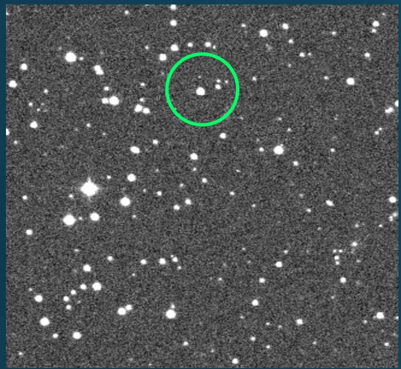
Rau et al. 2009

Astrophysical Variables



Trick of the trade: Difference Imaging

Observation



O

-

Reference

$R * K$

=

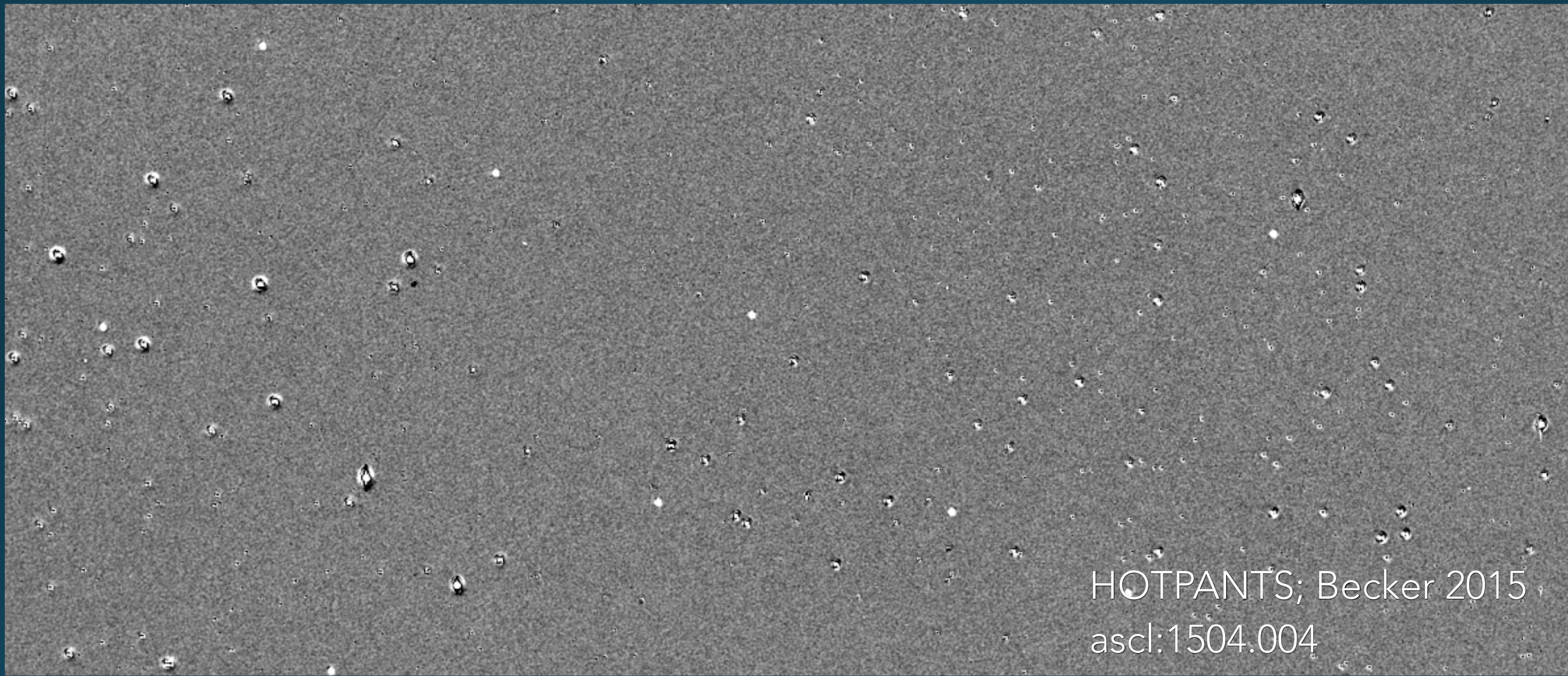
Subtracted

Find Kernel K such that $\sum([R * K] - O)^2$ is minimized

- Quality of subtracted image is affected by:
  - Precision of reference frame transformation
  - Imaging noise
  - Atmospheric disturbances
  - Saturated pixels

With machine-learning techniques, can reduce the set of 10,000+ to only a handful

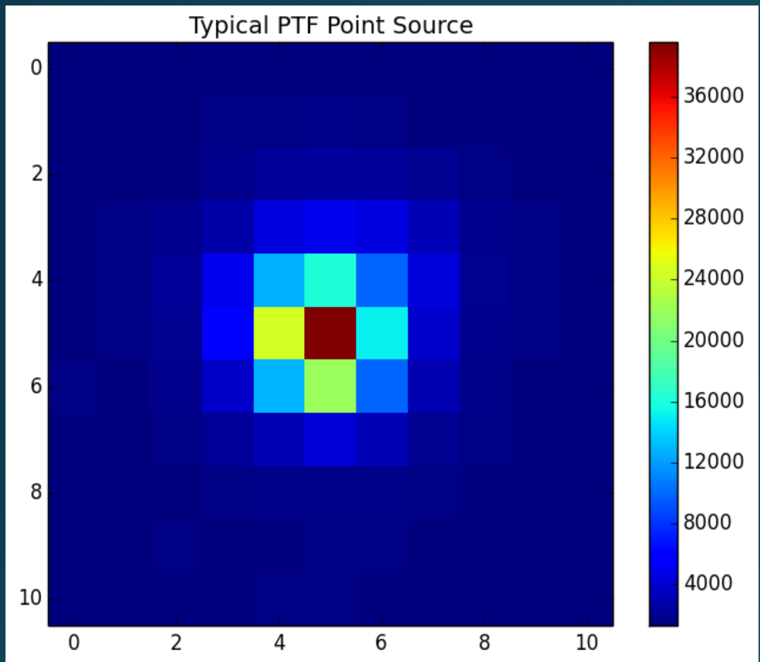
Artifact Overload

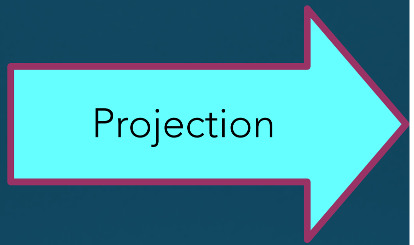


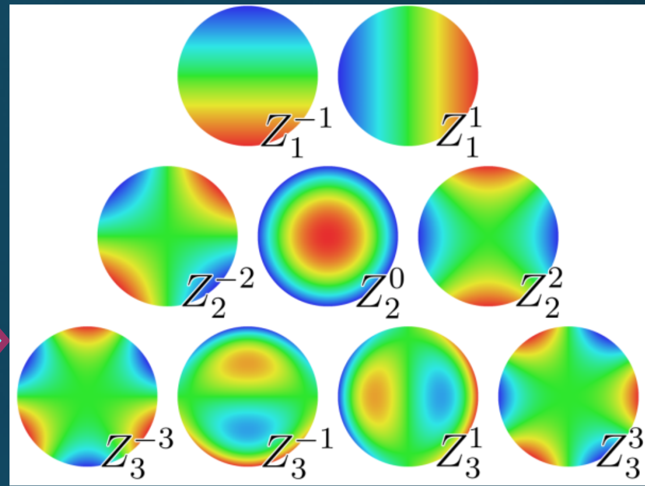
- HOTPANTS algorithm offers flexibility in deriving kernel solution
- Image subtraction in general by no means perfect → leaves too many artifacts

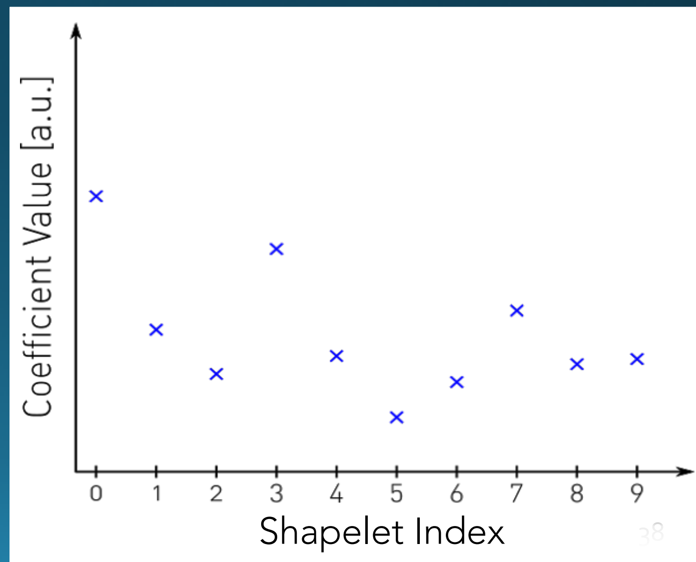
Developed automated unsupervised algorithm to discard artifacts

Decomposition onto Shapelet Basis

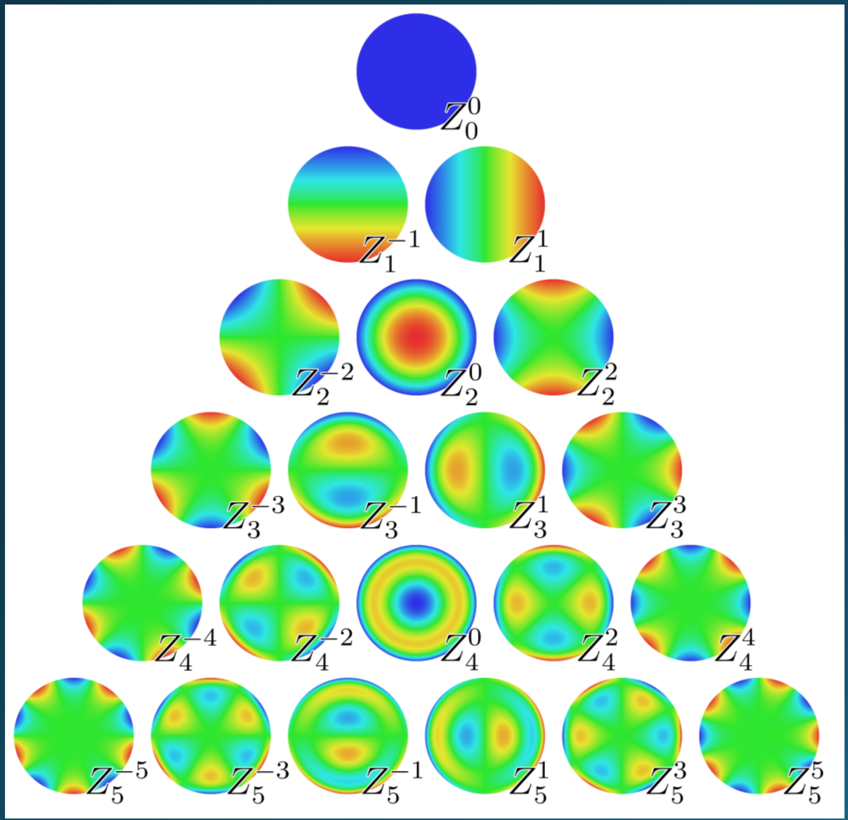








Zernike Decomposition of Sources



$$f(\rho,\varphi) = \sum_{n=0}^{\infty}\sum_{m=0}^{n}\left[a_{n,m}Z_n^m(\rho,\varphi) + b_{n,m}Z_n^{-m}(\rho,\varphi)\right]$$

$$Z_n^m(\rho,\varphi) \ = R_n^m(\rho)\cos(m\varphi)$$

$$Z_n^{-m}(\rho,\varphi) = R_n^m(\rho)\sin(m\varphi)$$

$$R_n^m(\rho,\varphi) = \sum_{k=0}^{(n-m)/2}\frac{(-1)^k(n-k)!\,\rho^{n-2k}}{k!\left(\frac{n+m}{2}-k\right)!\left(\frac{n-m}{2}-k\right)!}$$

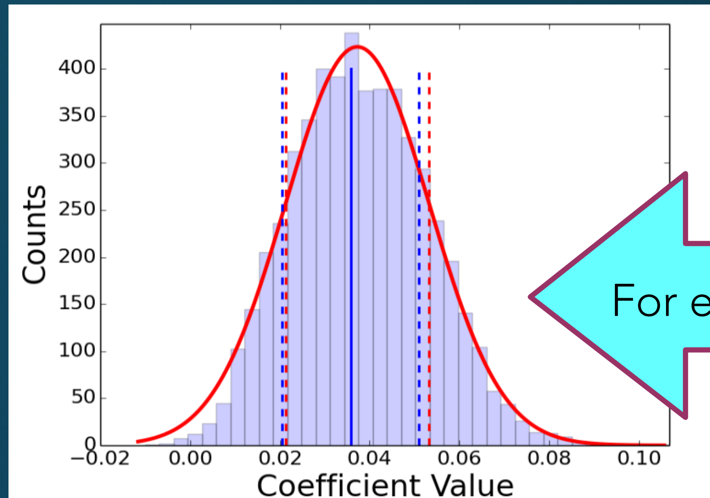
- Used in astronomy for wavefront analysis, characterizing atmospheric turbulence, correction for adaptive optics

Selection Criterion

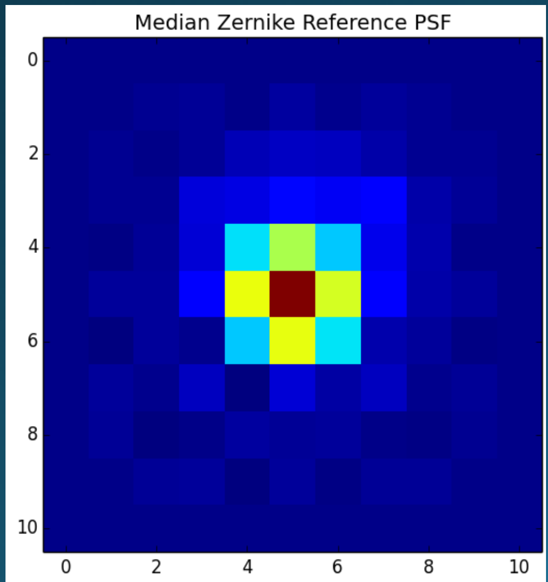
- Ensemble average and characteristic spread for coefficients of each order
- Leads to definition of Zernike Distance

$$D_Z = \sum_{j=1}^{j_{\max}} \frac{(c_j - \bar{c}_j)^2}{\sigma_j^2}$$

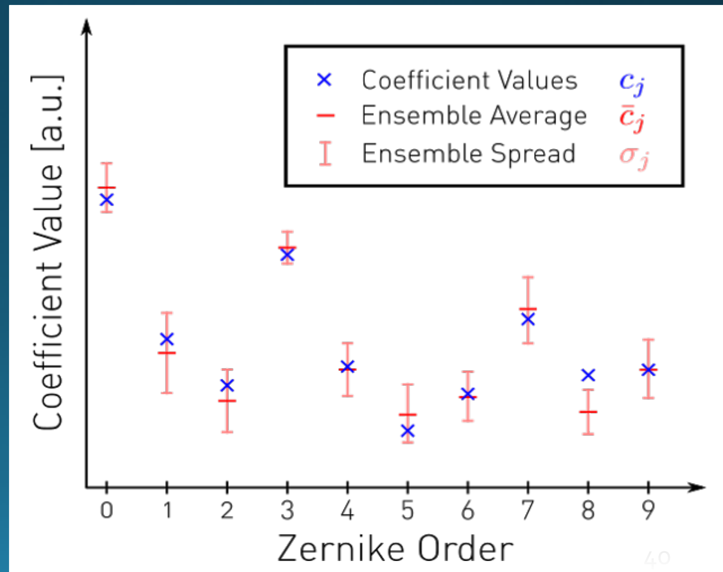
criterion for point-likeness



For each order



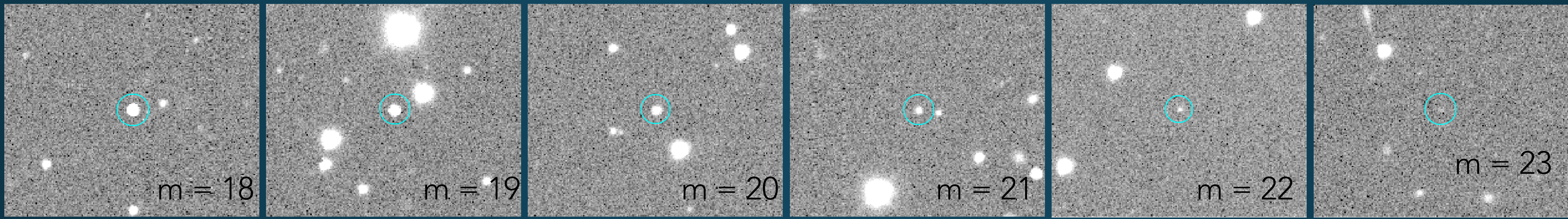
Decomposition

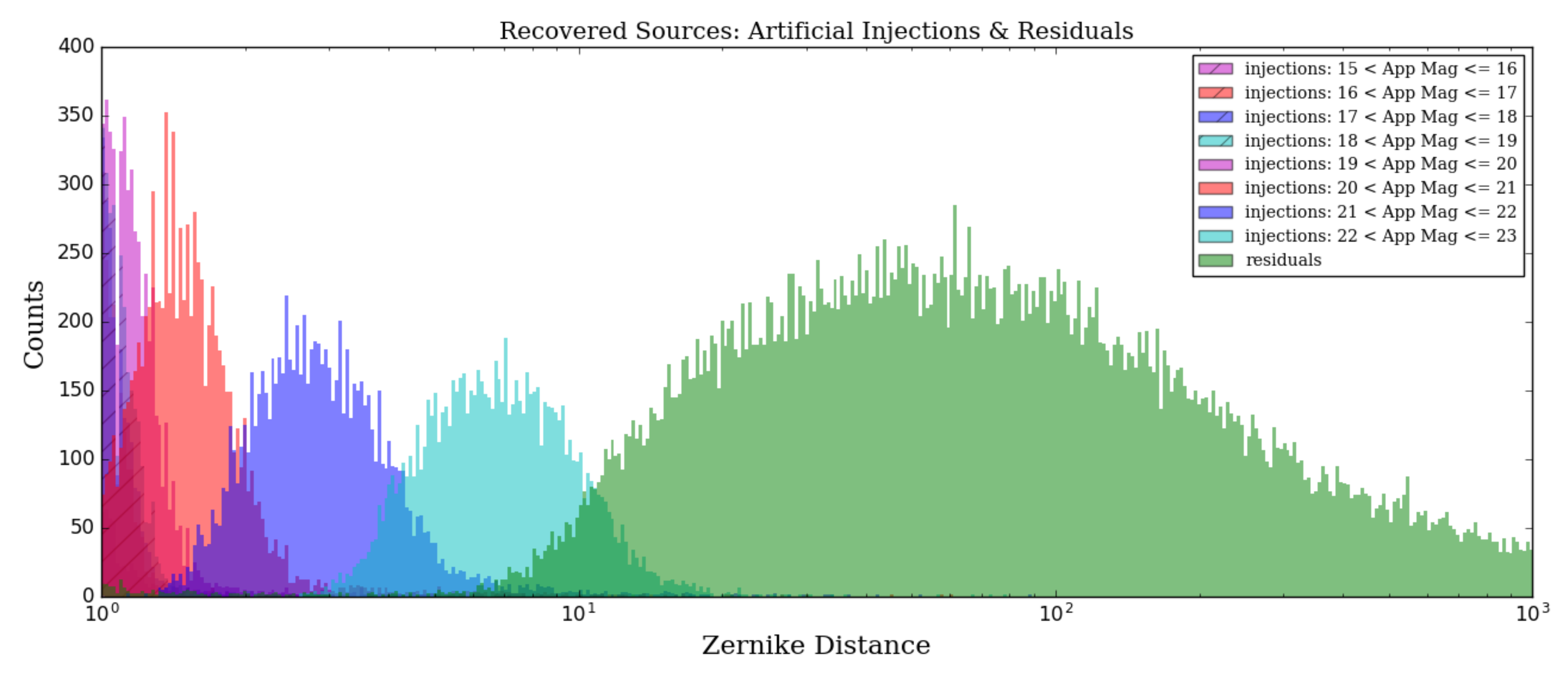


Detection Efficiency Study

- Inject thousands of transients into variety of images
  - Scaled model PSF (point-spread-function)
  - Subject to shot noise
- Vary image quality
  - Increase background noise
  - Additional blurring with Gaussian kernel
- Cross-reference transients with injection catalog
- Determine cut-off criterion for Z-Distance depending on
  - Telescope
  - Viewing conditions
  - Galactic latitude

Example: Injections

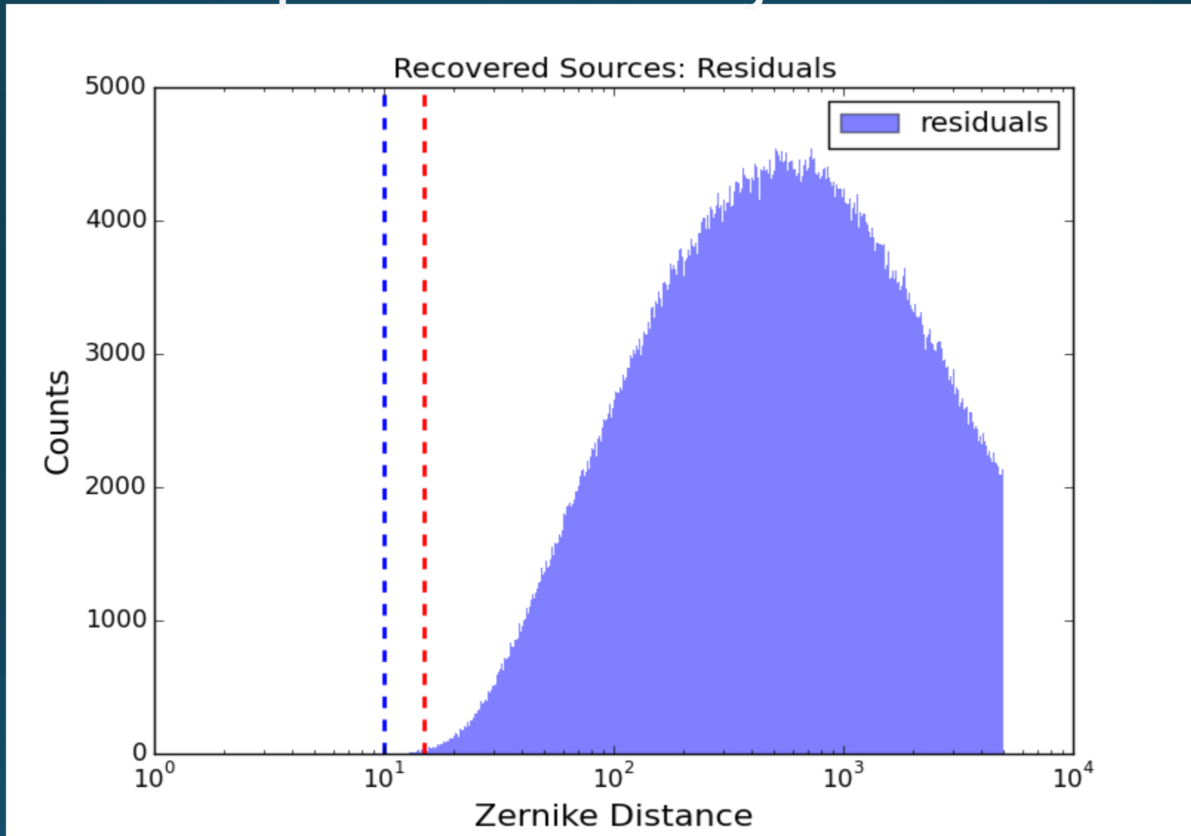




False Alarm Rate Study

- No injections
- Use image as its own reference:
  - But add background and blurring
  - Avoid ‘true’ false positives (actual transients)
- ‘Perfect’ reference image:
  - Study shows limitation of pipeline algorithm itself

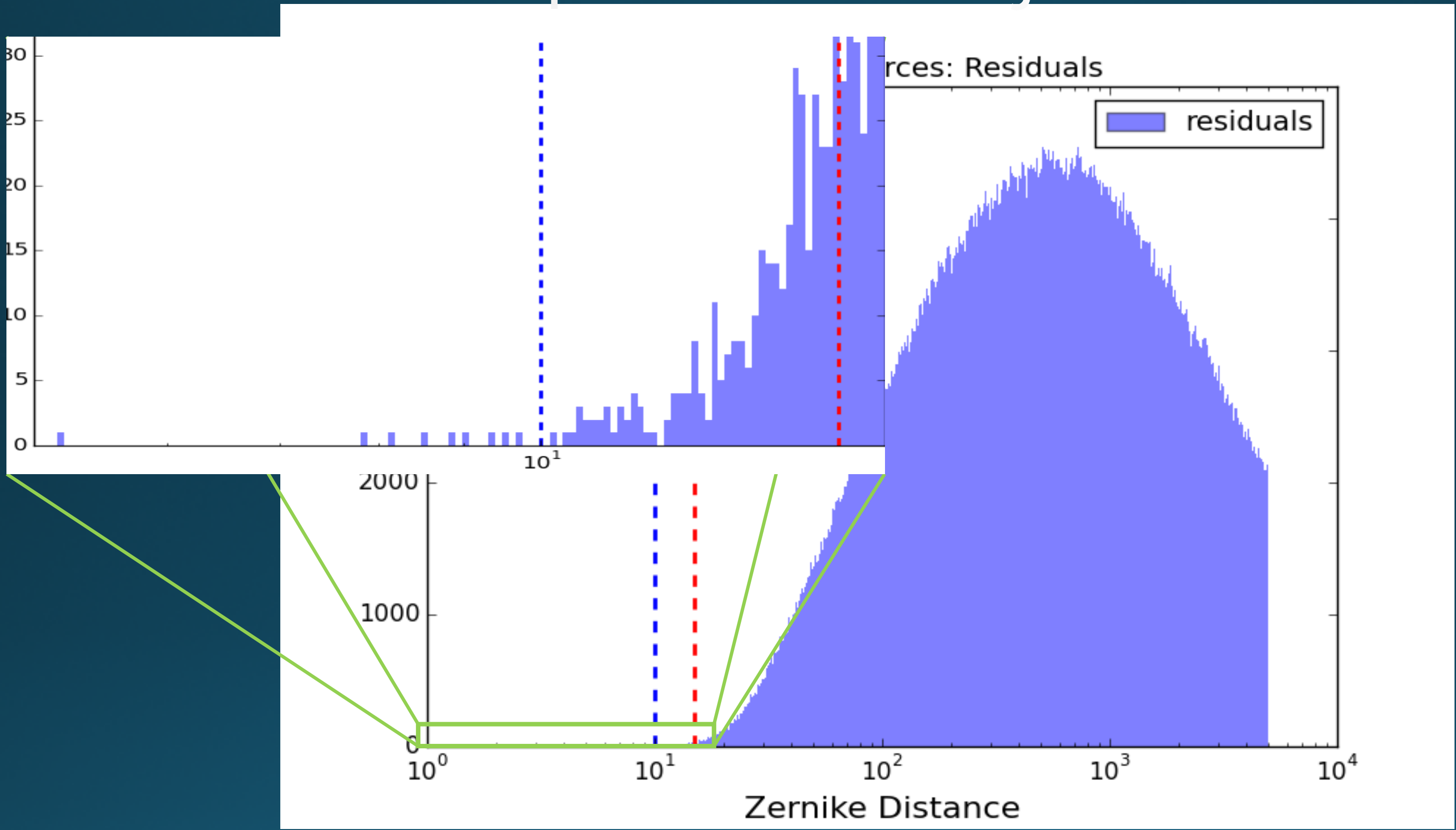
Example: No Injections



Number of objects in images: 88,886,994

Number of objects after image subtraction: 1,756,248

Example: No Injections



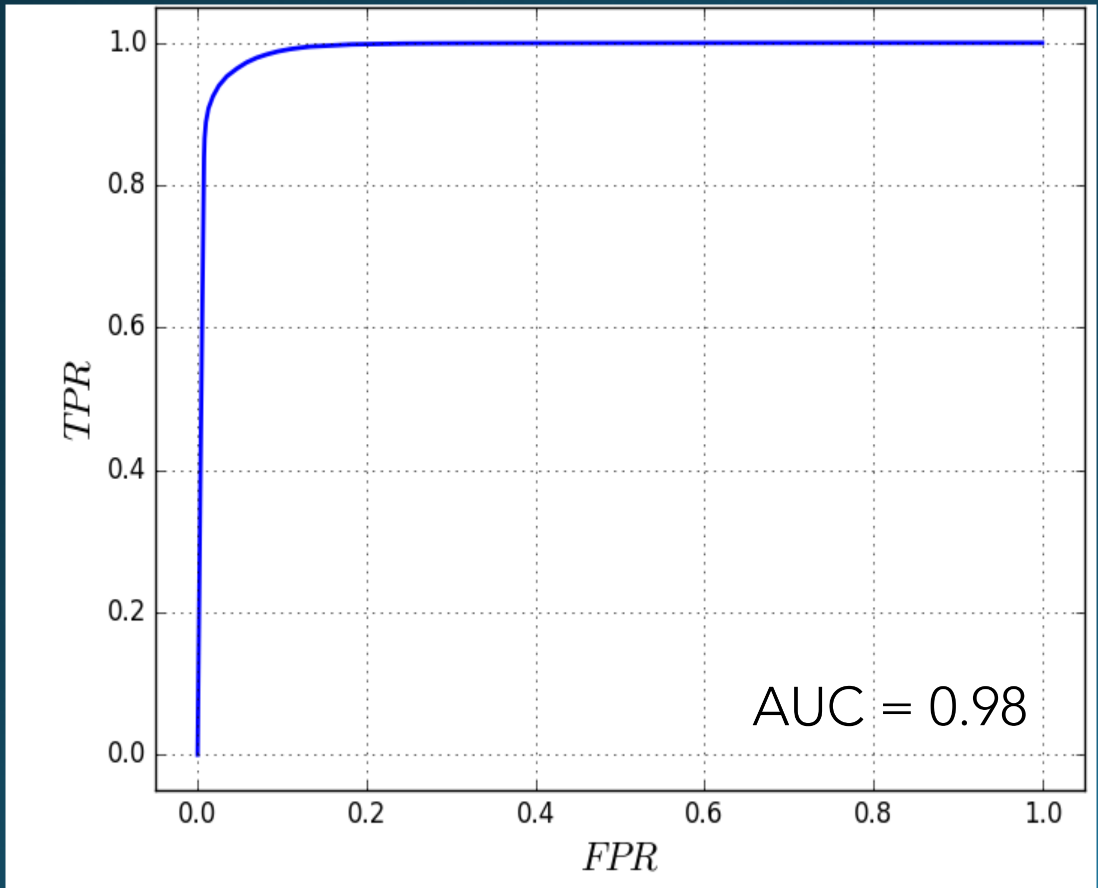
Number of objects in images: 88,886,994

Number of objects after image subtraction: 1,756,248

Total objects DZ <= 15: **366** ------------> 0.545 / deg^2

Total objects DZ <= 10: **9** ------------> 0.013 / deg^2

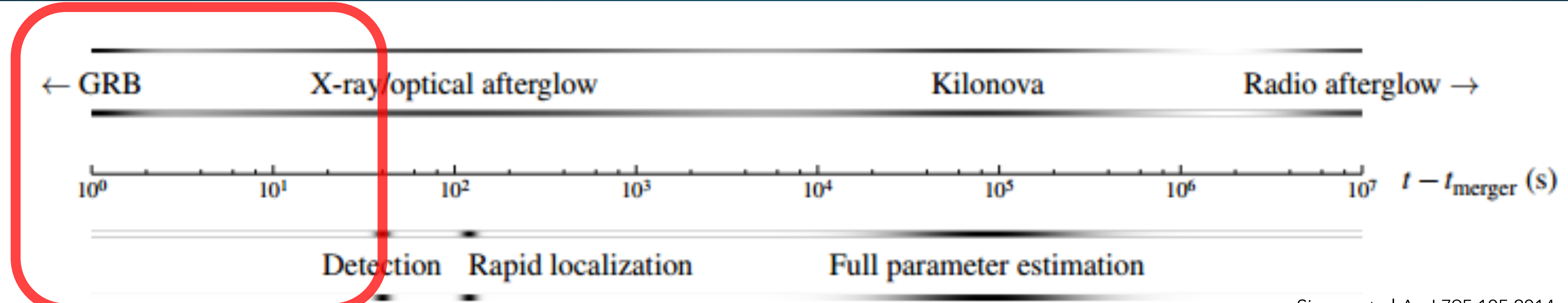
Receiver Operating Characteristic



Survey	TPR (%)	FPR (%)
PTF	92.3	1
Pan-STARRS	90	1
DES-SN	88	1
Nearby SNFactory	95	1
This work	92	1

Merging GW & EM

- From GWs: binary parameters, GW energetics, luminosity distance, etc.
- From EM: precise sky location, EM energetics, redshift, etc.
- But to maximise effort, latency is major obstacle



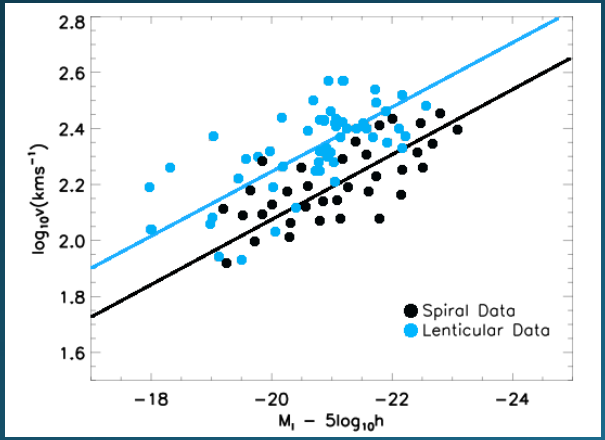
Singer et al ApJ 795 105 2014

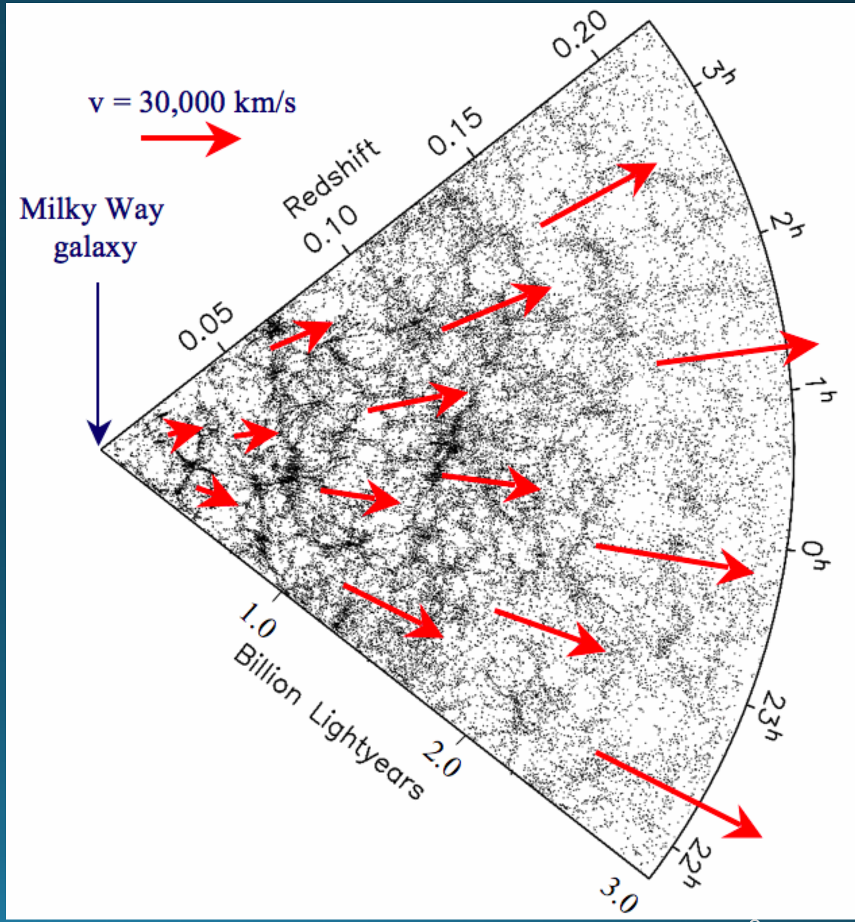
Cosmology with GW-EM

$d = H_0 / v$

Traditionally: use cosmic ``distance ladder" for finding v

- Can use Tully-Fisher (Luminosity/mass vs. angular velocity) or Type Ia Supernovae
- Compare against distant samples (``stable" Hubble flow)





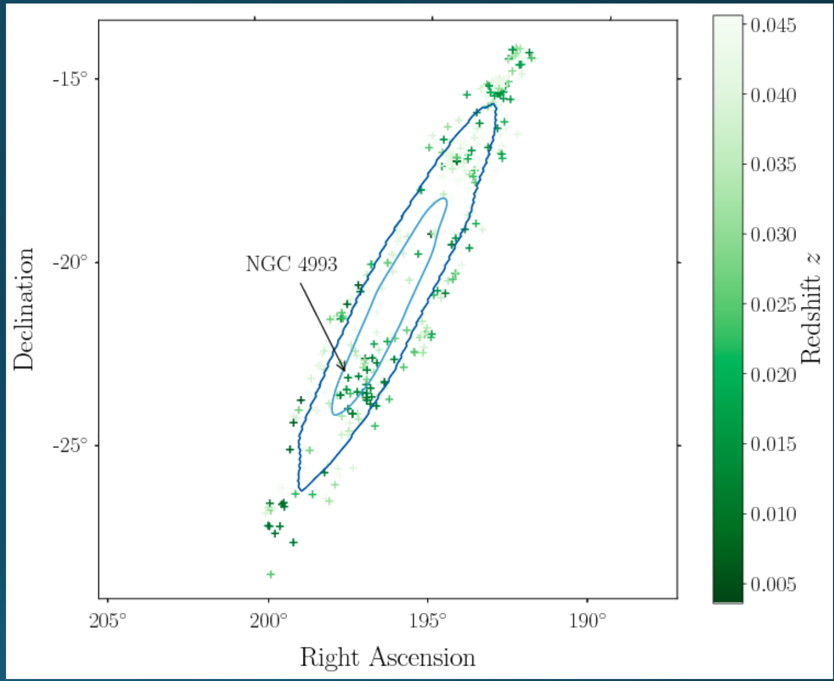
Cosmology with GW-EM

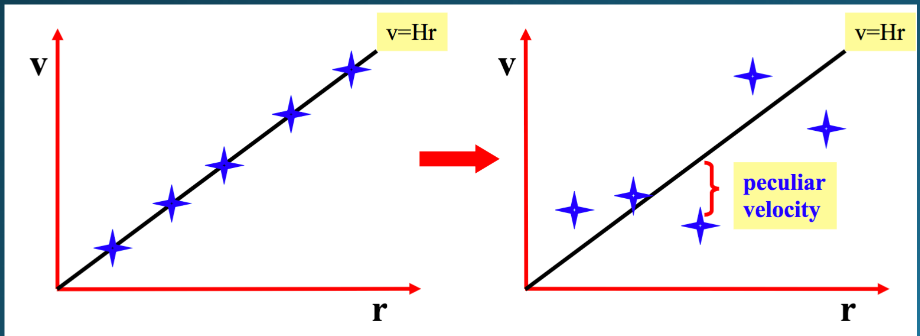
$d = H_0 / v$

$v = v_H + v_p$

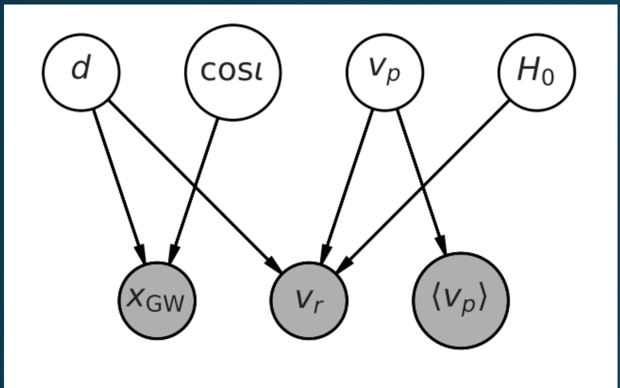
Hubble Flow
constant
Measure from group c.o.m.

Peculiar velocity
Local grav. Field
(6dF)

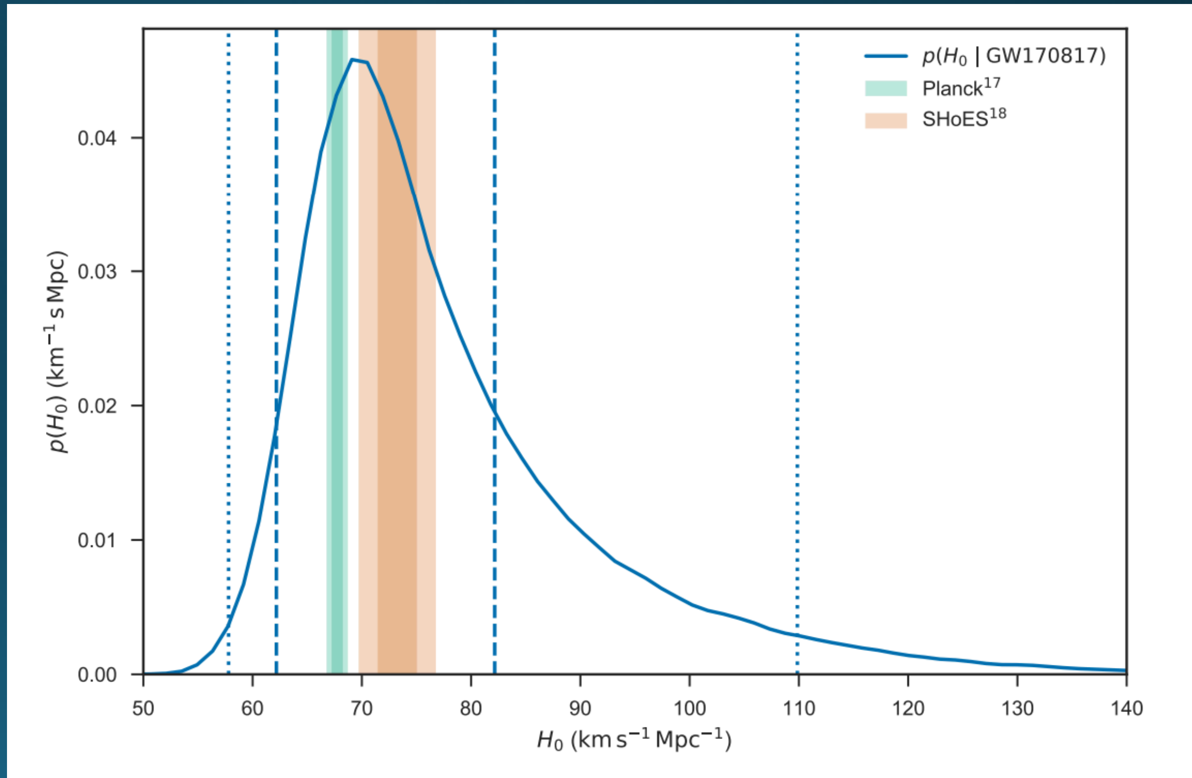




Cosmology with GW-EM

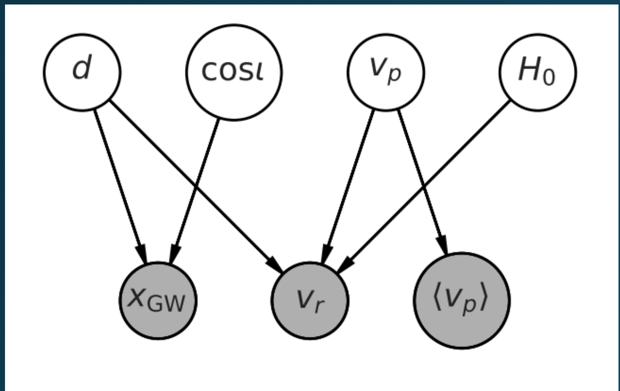


$$p(H_0, \cos\iota | x_{\rm GW}) \propto (v_H/H_0^2)\, p(x_{\rm GW} \mid d = v_H/H_0, \cos\iota) \times p_d(v_H/H_0)\, p_\iota(\cos\iota),$$

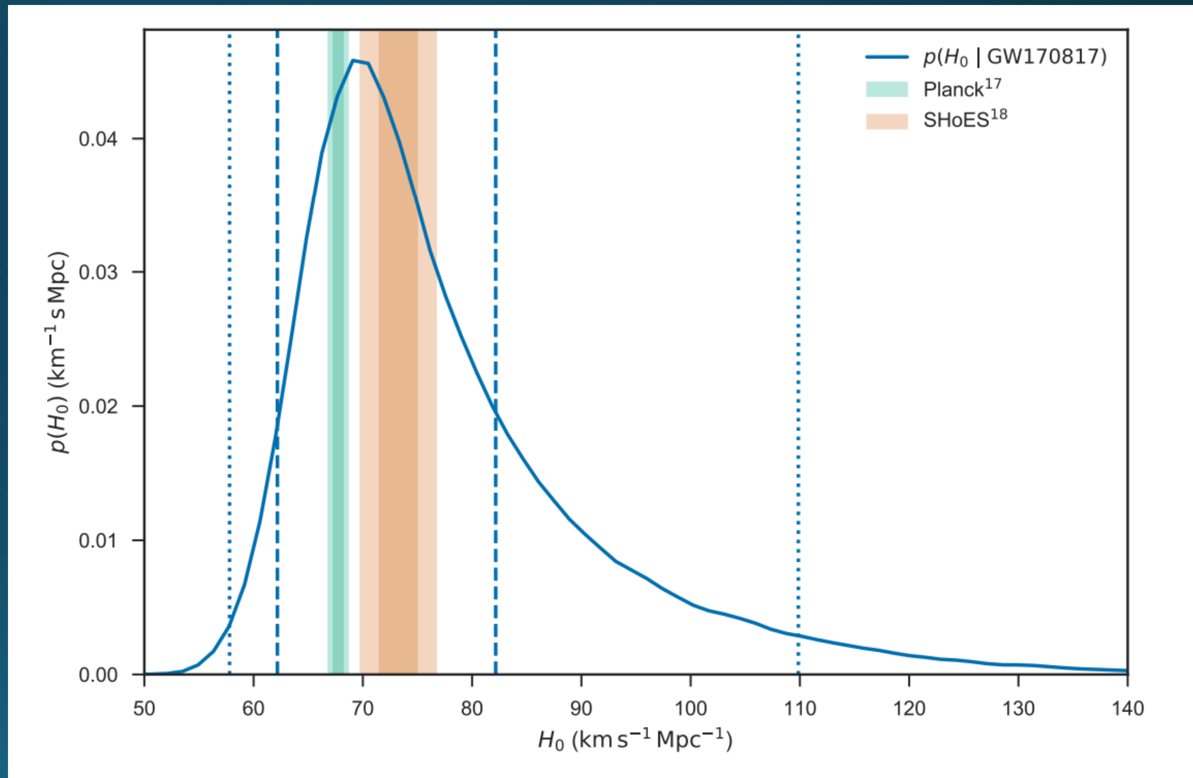


$H_0 = 70.0^{+12.0}_{-8.0}$ km s^{-1} Mpc^{-1}

Cosmology with GW-EM



$$
\begin{aligned}
&p(H_0, \cos\iota | x_{\rm GW}) \\
&\qquad \propto (v_H/H_0^2)\, p(x_{\rm GW} \mid d = v_H/H_0, \cos\iota) \\
&\qquad\qquad \times p_d(v_H/H_0)\, p_\iota(\cos\iota),
\end{aligned}
$$



Even without EM counterpart:
~ 100 independent GW detections* ~ 5% estimate of H_0

$H_0 = 70.0^{+12.0}_{-8.0}$ km s^{-1} Mpc^{-1}

*Each detection has potential host galaxy

Conclusion

- Exciting times ahead!
- With more interferometers due to come online, the better the sky localization will be
- Wide field instruments (GOTO) can image probability skymaps in fewer pointings
- Machine learning algorithms reduce number of sources to vet – ideally leaving a single associated EM counterpart
- With more joint detections – will ultimately uncover new mysteries of the Universe