Follow the Roar: Electromagnetic (EM) follow-up of GW150914

Samaya Nissanke

Radboud University Nijmegen
EM Follow-up Group in the LVC Collaboration, BlackGEM Science Team

The first observation of a binary black hole merger: Status and future prospects Conference , AEI-Hannover, May 25th, 2016

"Was that you I heard just now, or was it two black holes colliding?"

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3.5 weeks old

Main Characters

LOCALIZATION AND BROADBAND FOLLOW-UP OF THE GRAVITATIONAL-WAVE TRANSIENT GW150914

arXiv: 1602.08492, accepted to ApJL

=

GW 150914 !

+

+

LSC LIGO Scientific Collaboration

VIRGO

+

25 [/63] EM groups

= 1551 authors

EM Partners

Photometric (energetics) and spectroscopic (chemical, redshift) facilities over a wide-range of electromagnetic wavelengths

HIGH ENERGY

OPTICAL/NEAR-IR

RADIO

ASKAP, LOFAR, MWA, Fermi/GBM, Fermi/LAT, INTEGRAL, IPN, Swift, MAXI, BOOTES, MASTER, Pi of the Sky, DES/DECam, INAF/GRAWITA, iPTF, J-GEM/ KWFC, La Silla–QUEST, Liverpool Telescope, PESSTO, Pan-STARRS, SkyMapper, TAROT, Zadko, TOROS, VIST

Plan of Talk

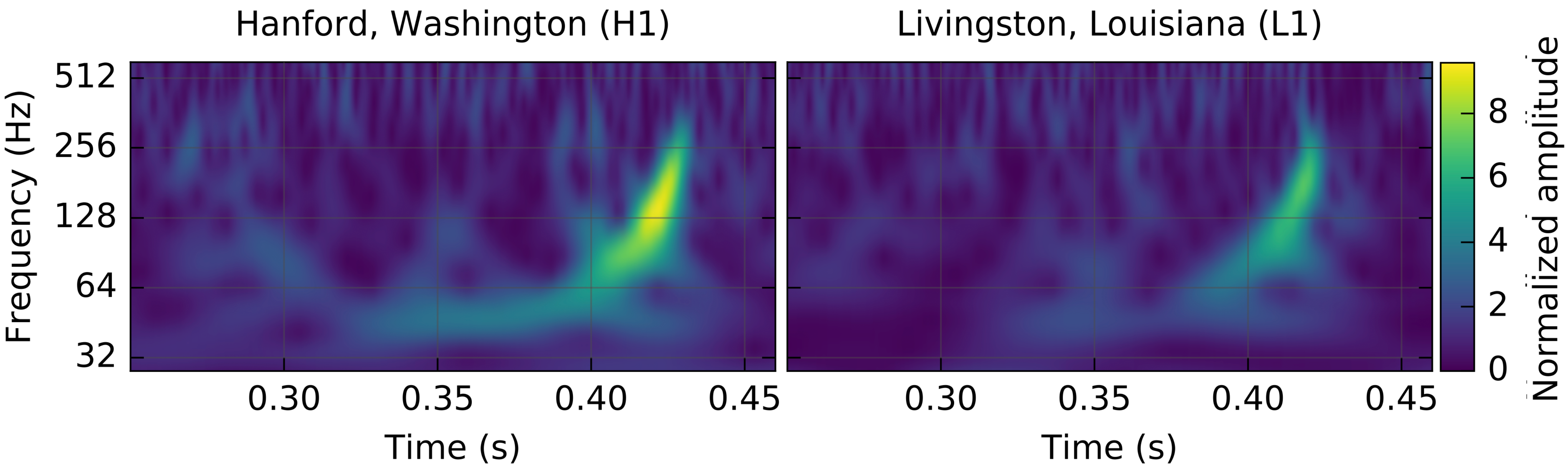
Part 1: Introduction to GW-EM astronomy

Part 2: Case study — follow up of GW150914

Part 3: What's next for EM follow-up?

Part I: Introduction to EM-GW astronomy

Binary Black Hole (BBH) merger !

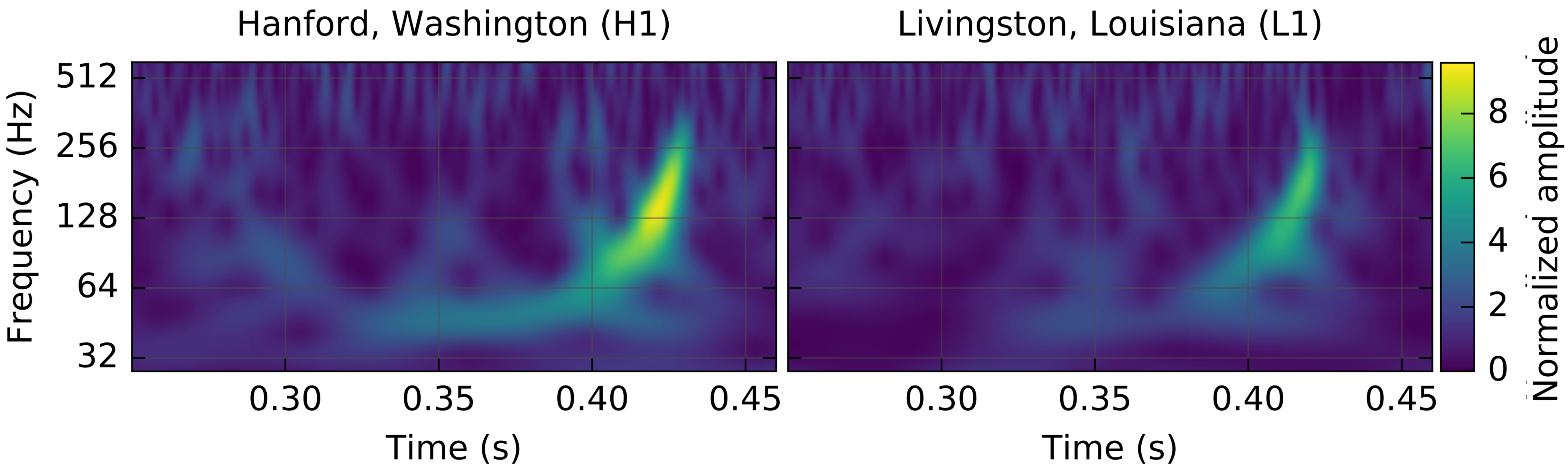


A surprise: 4 days before the first Science Run …

Burst search (cWB): SNR of 23.45 and FAR < 0.371 yr^{-1} [1 month^{-1}]

Max Frequency → Orbital Frequency → Total mass > 70 $M_{\odot}$

BBH merger ! …



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Max Frequency → Orbital Frequency → Total mass > 70 $M_\odot$

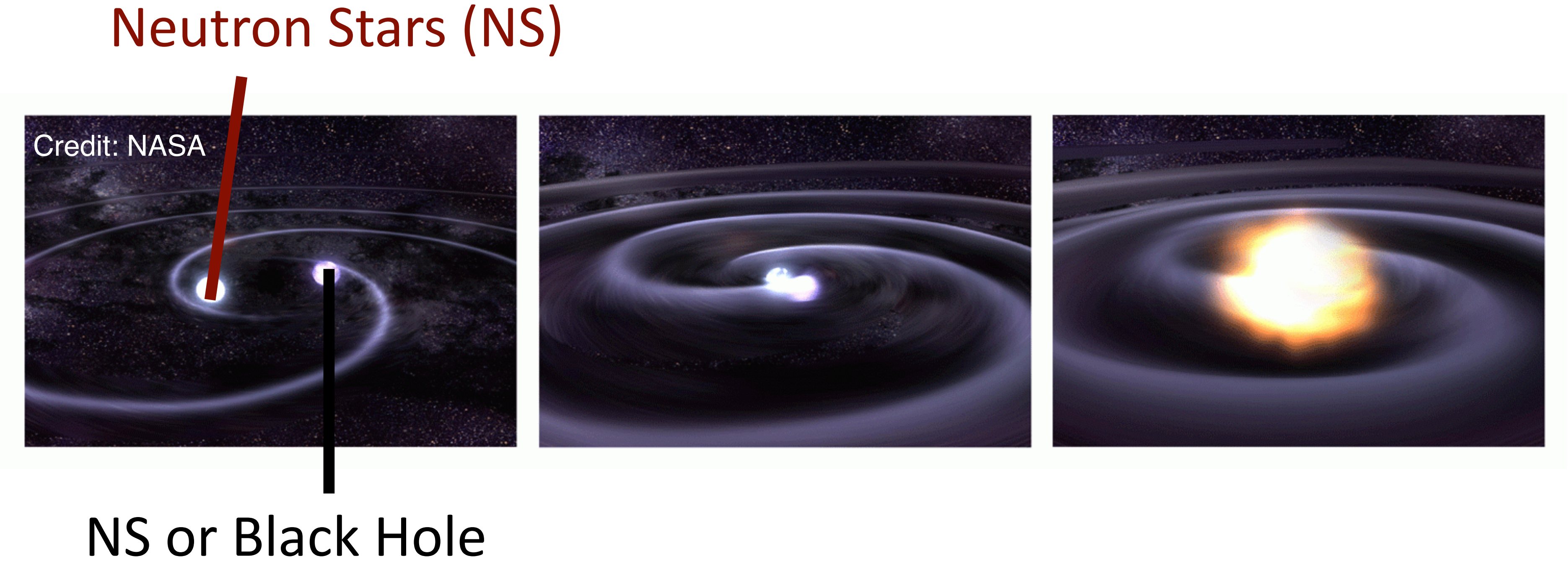
NO EM COUNTERPART IS GENERALLY EXPECTED

(unless in highly dense magnetized plasmas or in extremely gas rich environments)

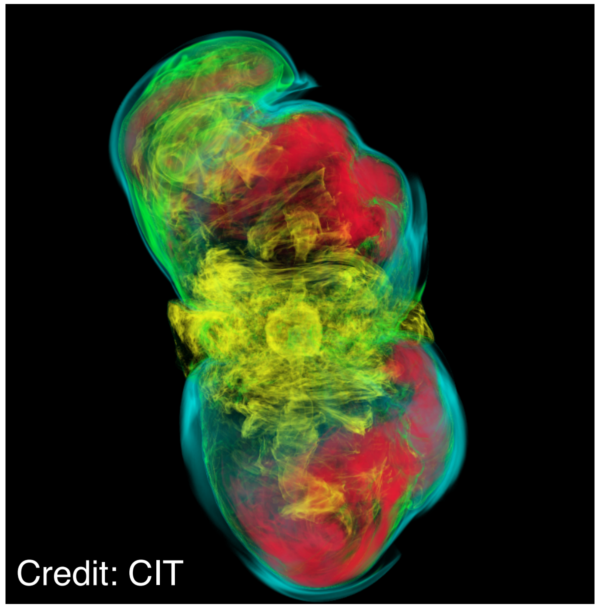
… cf. traditional high-frequency GW sources with EM counterparts

Delayed outflows during merger or core-collapse that

are responsible for EM signatures

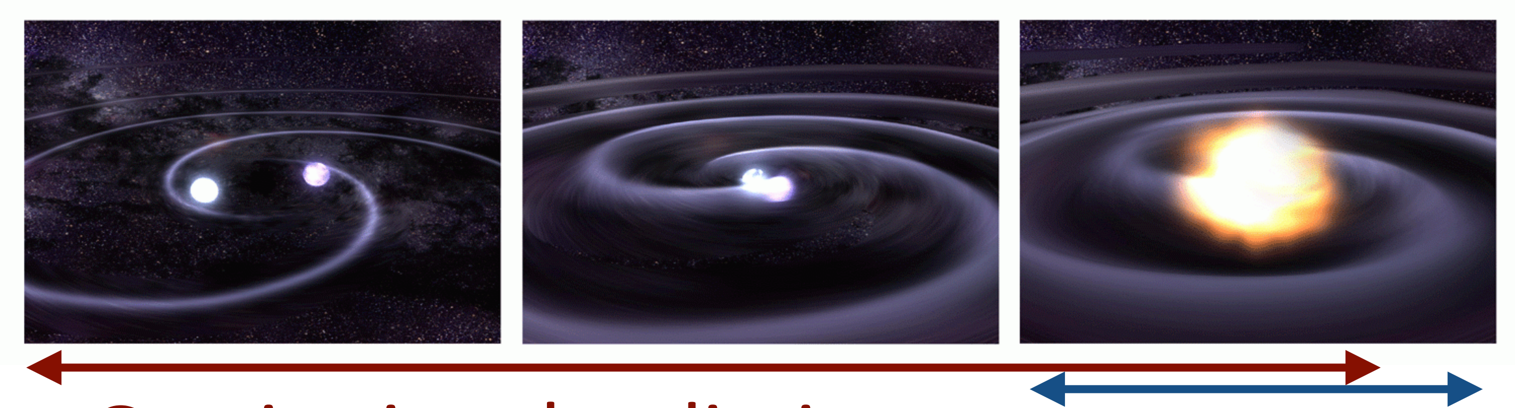


Neutron Star Binary Mergers



Supernova

Recent change: we can today detect GW and EM radiation



Gravitational radiation

EM radiation

Learn about sources' <u>dynamic</u> and <u>fundamental properties</u>

Learn about sources' <u>environment</u> and <u>energetics</u>

EM counterparts: motivation

1. Strong field gravity astrophysics
   Physical processes in strongly curved space-times

2. Stellar Evolution
   Understanding the fate of compact binary stellar systems?

3. Cosmic Enrichment
   Sites of r-process nucleosynthesis

4. Cosmological Probes
   Measuring the expansion history of the Universe

EM from Two Types of Matter Outflows

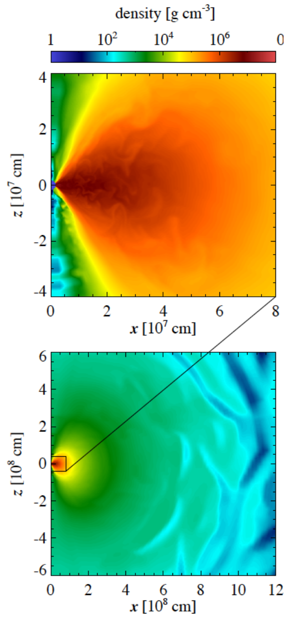
[see Shibata and Kiuchi talks]

1. Tidal Tails + Disk Winds

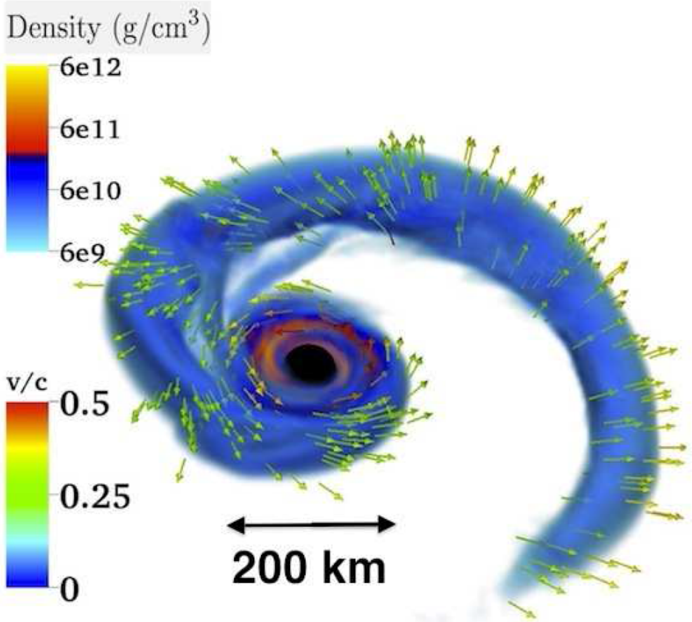
$M_{ej} \approx 10^{-4}$ - 0.01 $M_\odot$

E $\approx 10^{49}$- 10^{50} ergs

v ≈ 0.1-0.3c



[Fernandez & Metzger 2013]



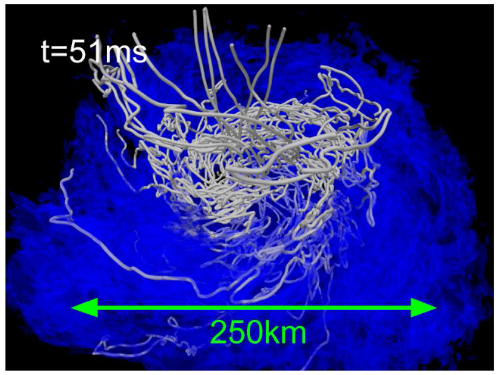
[Foucart et el. 2014]

2. Ultra-relativistic Jet

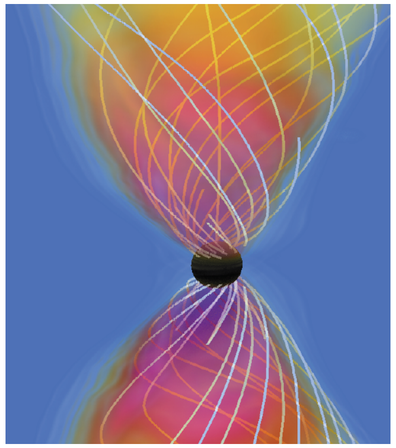
$M_{ej} \approx 10^{-6}$ $M_\odot$

E $\approx 10^{49}$- 10^{51} ergs

$\Gamma \approx 100$ (v ~ 0.99995c)



[Kiuchi et al. 2015]

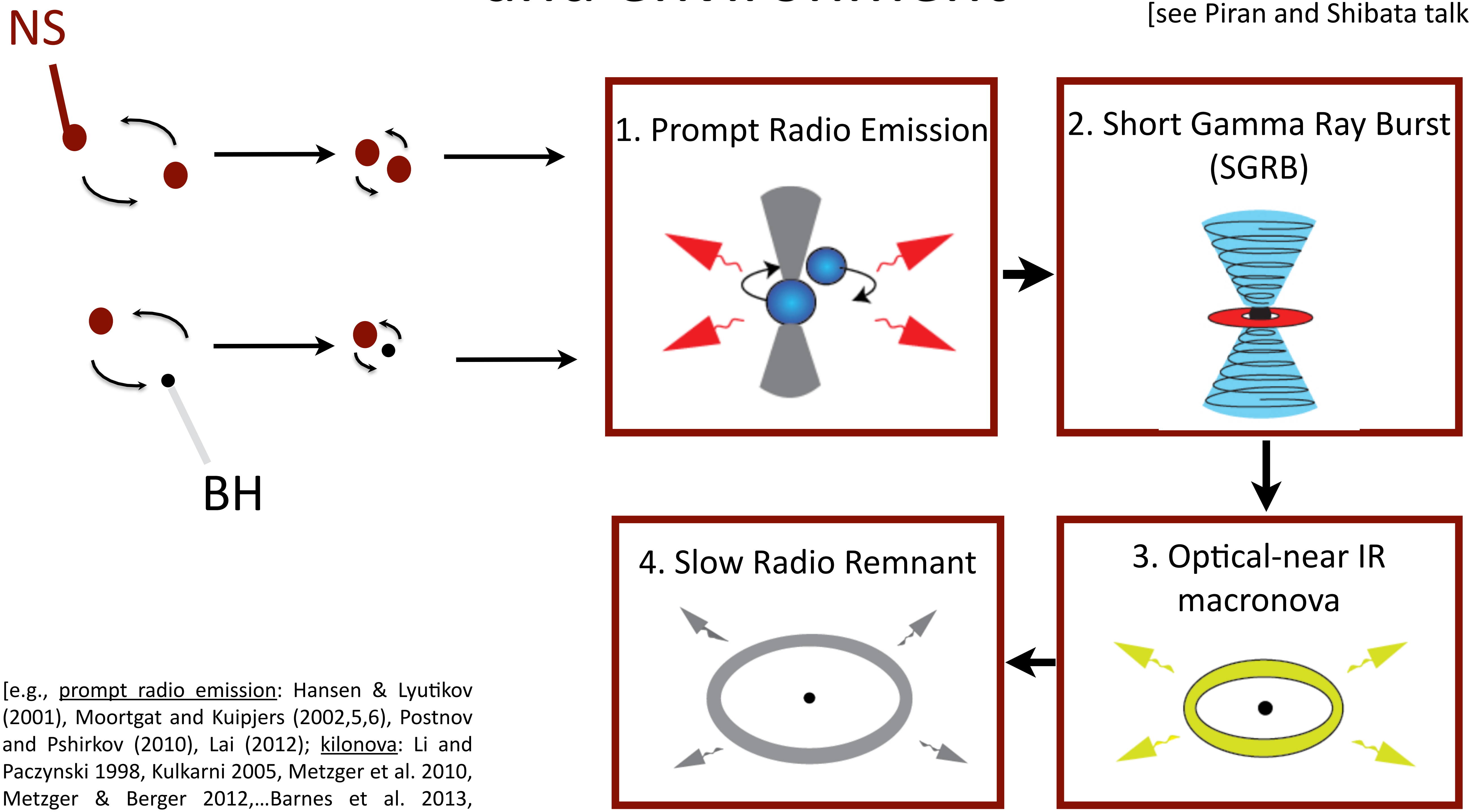


[Paschalidis et al. 2015]

Outflows' kinetic energy is converted into internal energy.
Expands, cools and heated by shocks or radioactivity.

EM emission provides merger energetics and environment

[see Piran and Shibata talks]



1. Prompt Radio Emission

2. Short Gamma Ray Burst (SGRB)

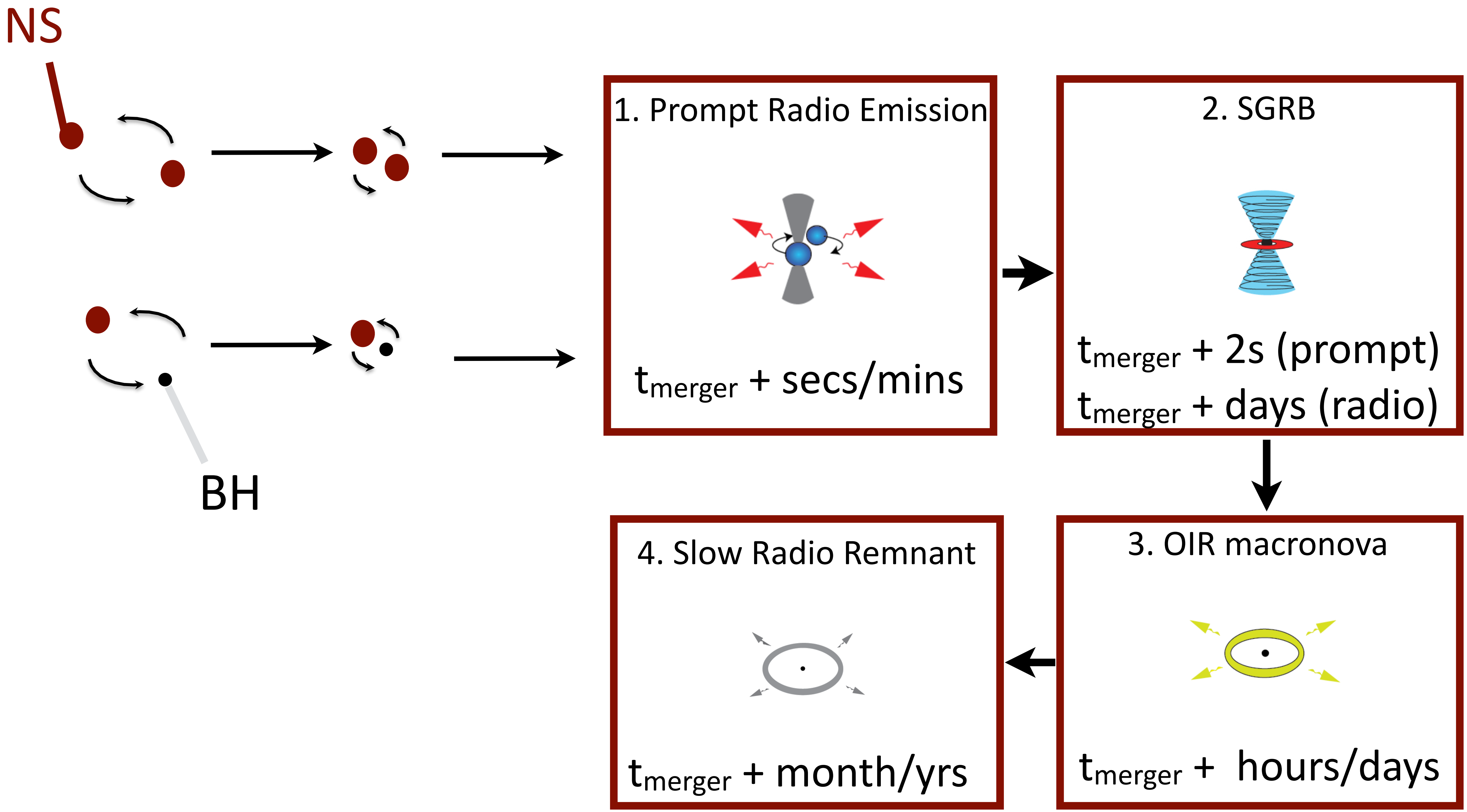
3. Optical-near IR macronova

4. Slow Radio Remnant

[e.g., prompt radio emission: Hansen & Lyutikov (2001), Moortgat and Kuipjers (2002,5,6), Postnov and Pshirkov (2010), Lai (2012); kilonova: Li and Paczynski 1998, Kulkarni 2005, Metzger et al. 2010, Metzger & Berger 2012,…Barnes et al. 2013, Grossman et al. 2013, Tanaka et al. 2013, Tanvir et al. 2013, Berger et al. 2013, … ; slow radio: Nakar and Piran 2011, Hotokezaka et al., 2015]

1. Four different EM observable timescales

[see Piran and Shibata talks]



1. Prompt Radio Emission

t_{merger} + secs/mins

2. SGRB

t_{merger} + 2s (prompt)
t_{merger} + days (radio)

3. OIR macronova

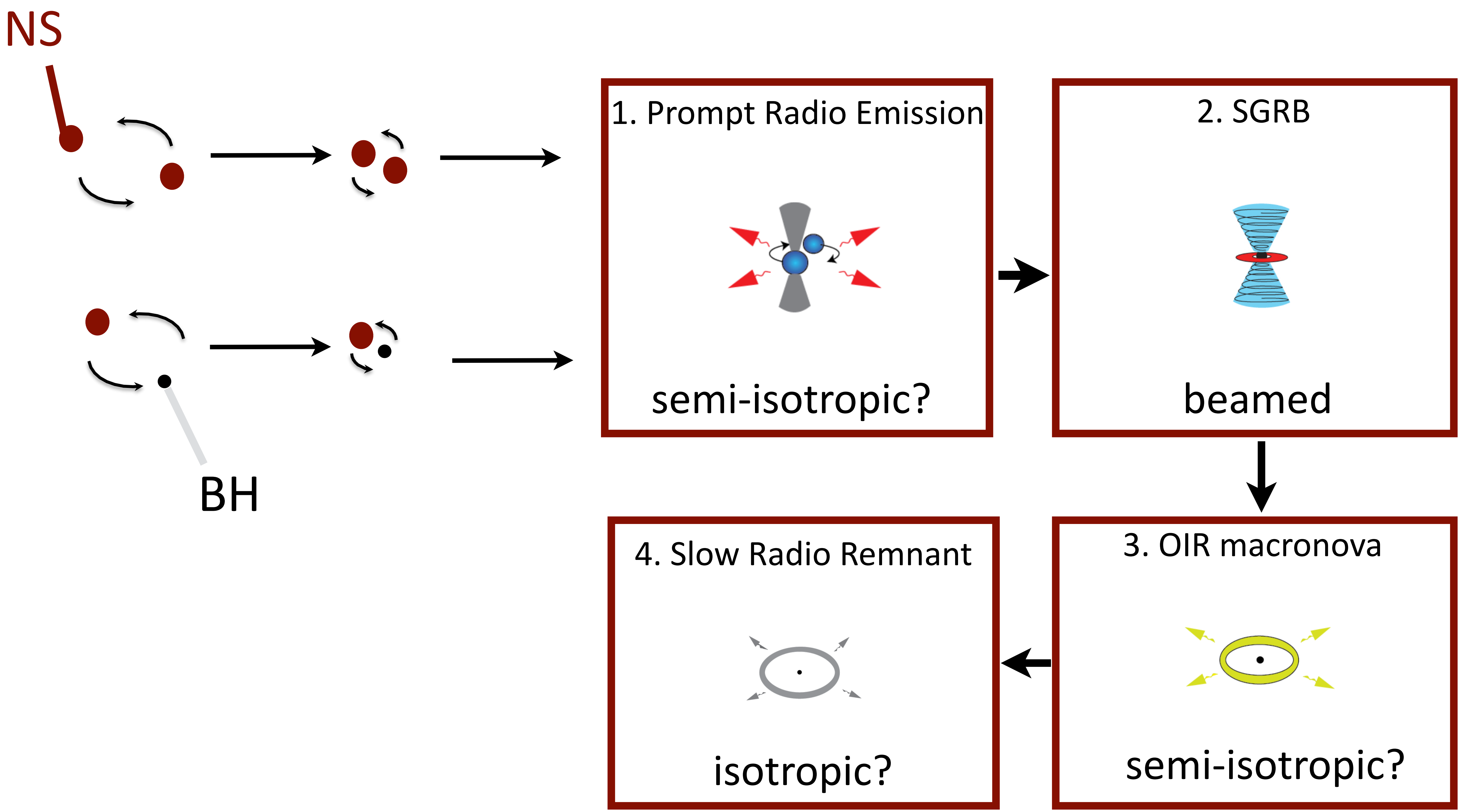
t_{merger} + hours/days

4. Slow Radio Remnant

t_{merger} + month/yrs

2. EM emission geometry

[see Piran and Shibata talks]



NS

BH

1. Prompt Radio Emission

semi-isotropic?

2. SGRB

beamed

3. OIR macronova

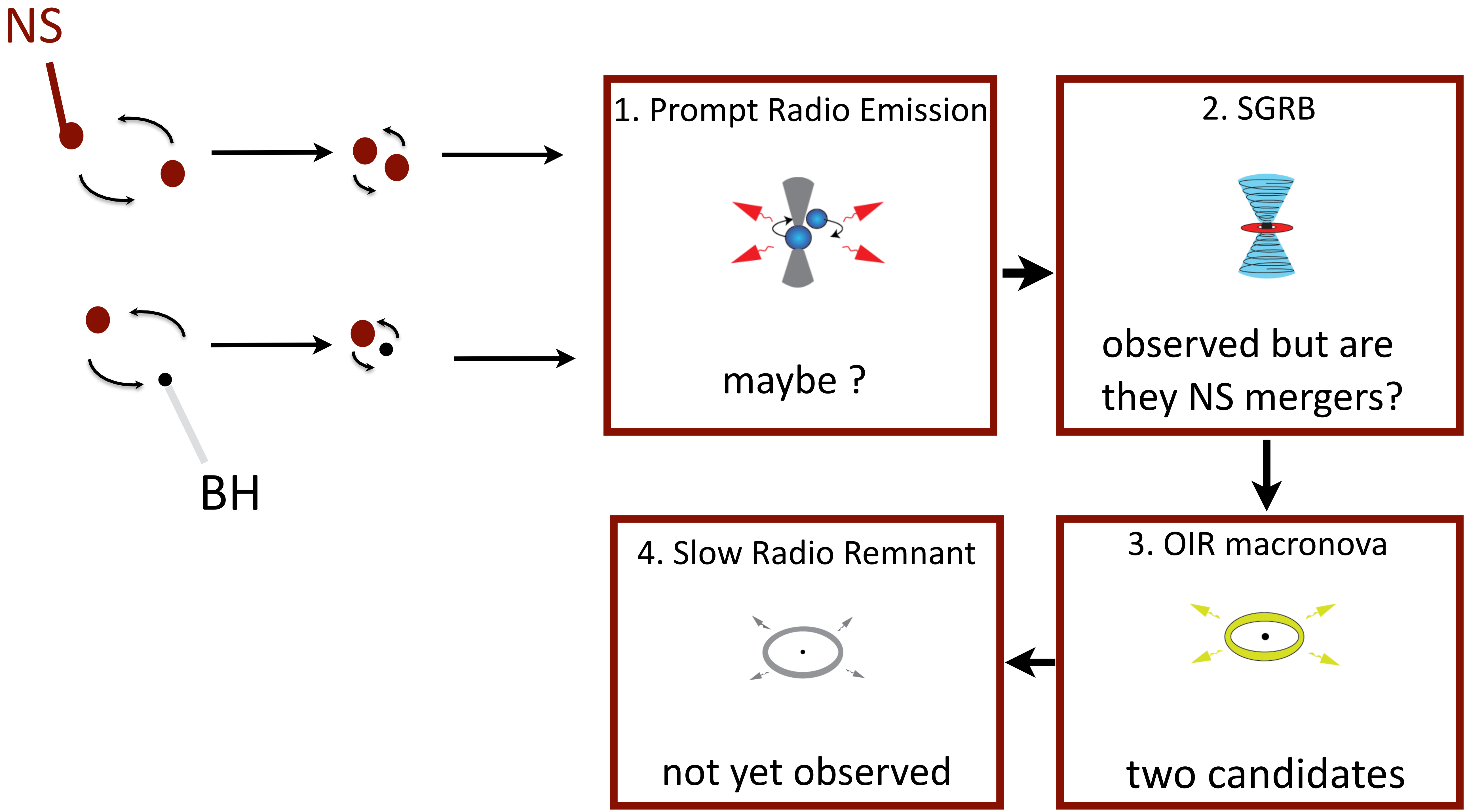
semi-isotropic?

4. Slow Radio Remnant

isotropic?

3. EM counterparts already observed?

[see Piran and Shibata talks]



NS

BH

1. Prompt Radio Emission

maybe ?

2. SGRB

observed but are they NS mergers?

3. OIR macronova

two candidates

4. Slow Radio Remnant

not yet observed

[e.g., fast radio bursts: Thornton + (2013), Spitler + (2013), Burke-Spolar + (2014), Petroff + (2015) …; kilonova: Tanvir + 2013, Berger + 2013, Yang et al. 2015]

Next step: combine and interpret GW + EM

from the GW chirp

- Masses (several to tens of %)
- Spins (several to tens of %)
- NS radii (tens of %)
- Geometric properties: (tens of %)
  - Inclination angle
  - Source Position
  - Luminosity distance

from EM signature

- Mass ejecta and velocity
- Magnetic field strength
- Energetics and Beaming
- Redshift, Accurate Position

- Nuclear Physics -> Opacities

- Stellar populations
- Previous binary evolution & mass loss

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- Nuclear Physics -> Opacities

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Strong signal binary: Characterization

Population: Demographics, ecology and census

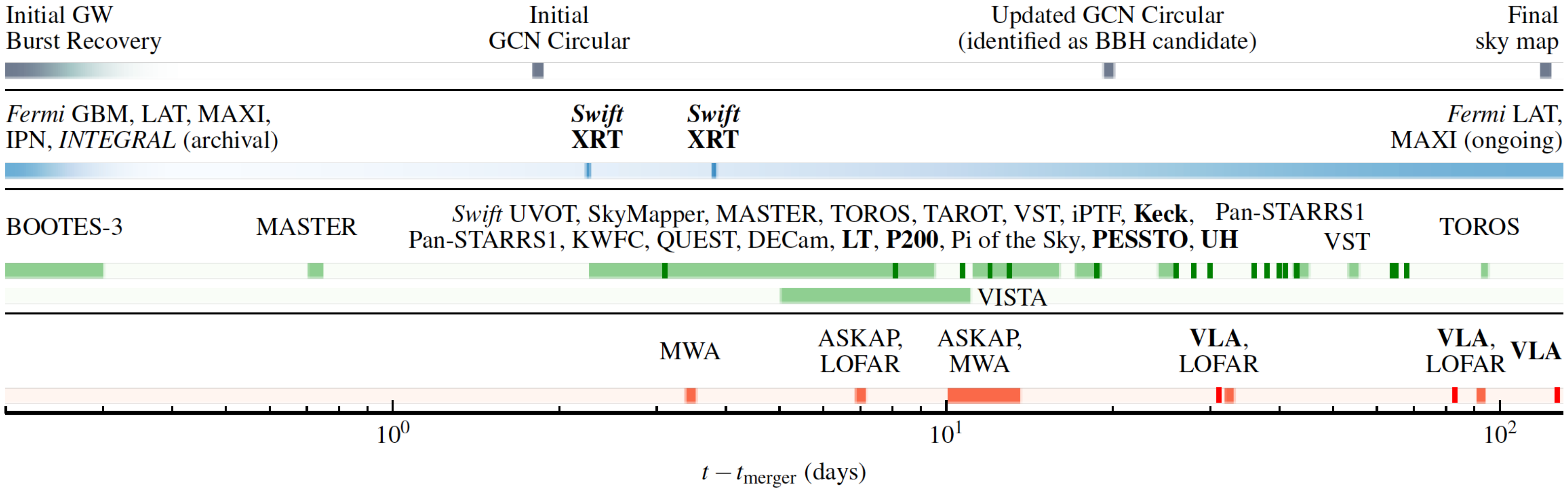
Part II: Follow-up of GW150914

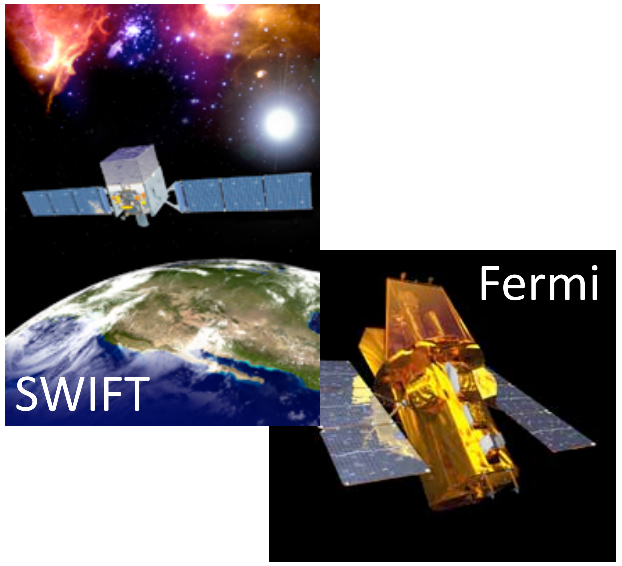
Timeline of EM Follow-up

HIGH ENERGY

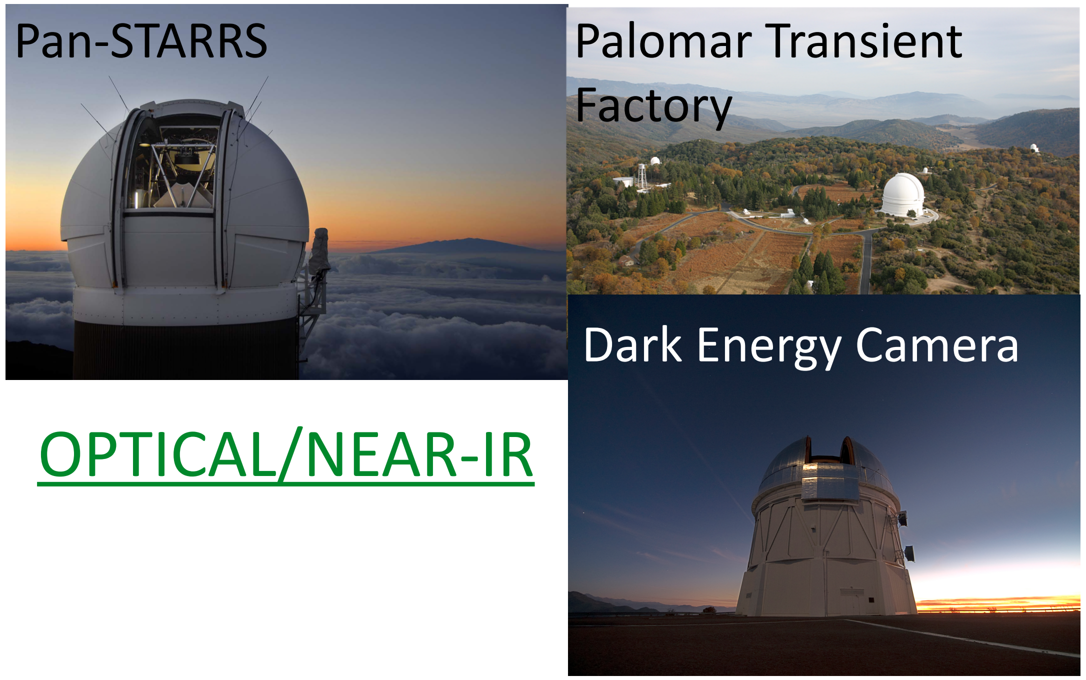
OPTICAL/NEAR-IR

RADIO

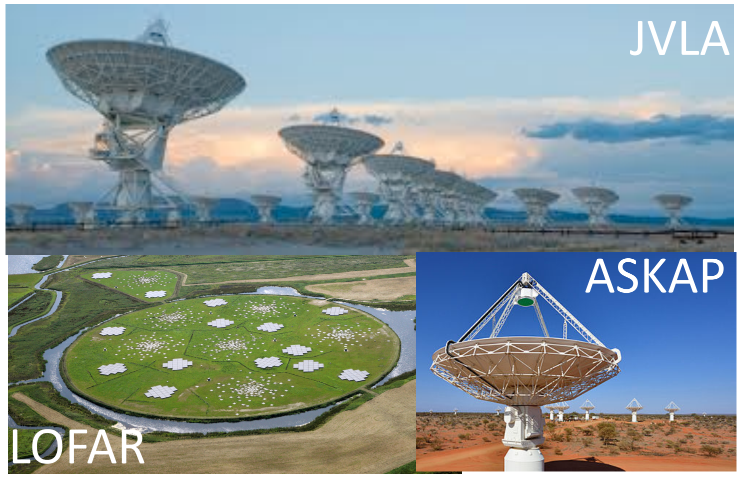




HIGH ENERGY

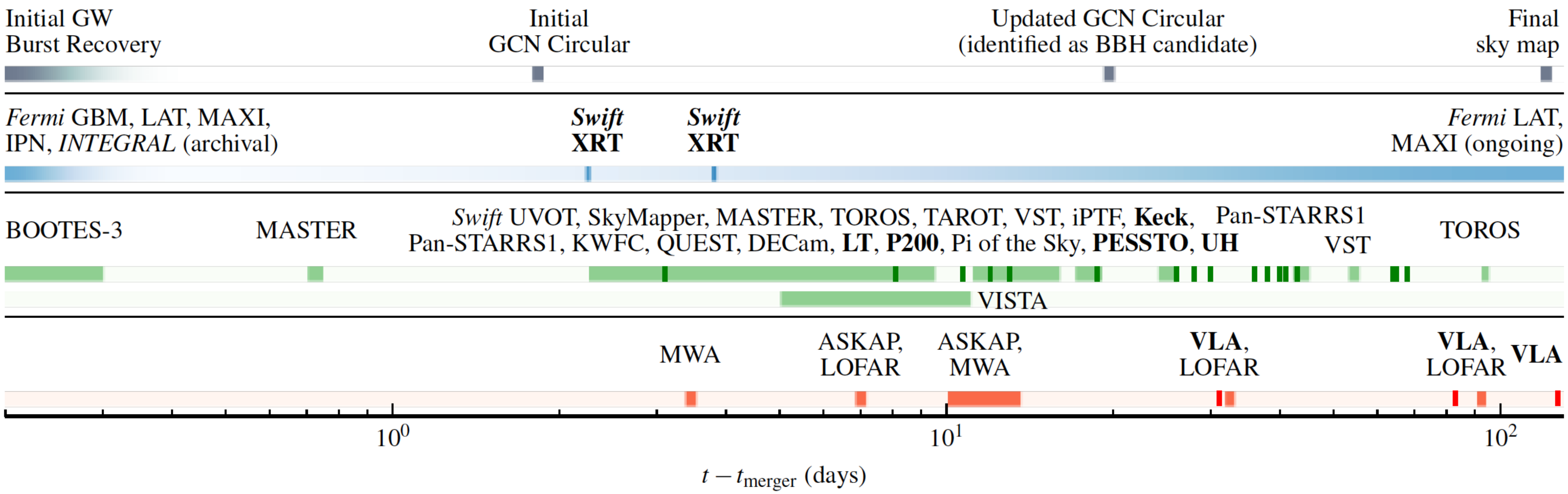


OPTICAL/NEAR-IR



RADIO

Timeline of EM Follow-up



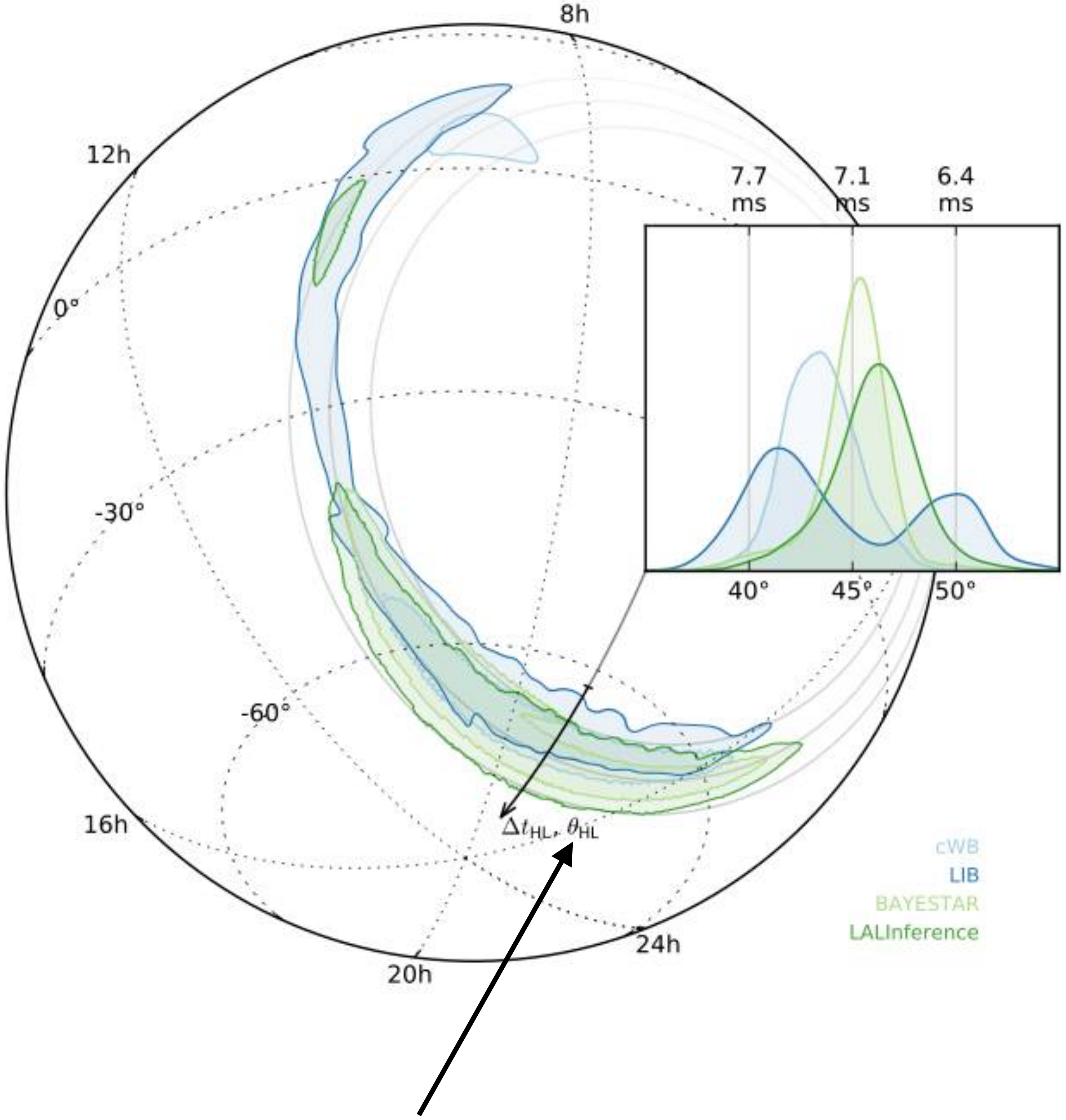
Three announcements sent via GW-alert GCN to MOU EM partners:

+ 1 (2 days after) — first set of sky maps

+ 2 (3 weeks after) — BBH candidate

+ 3 (4 months after) — final sky map

Sky Maps

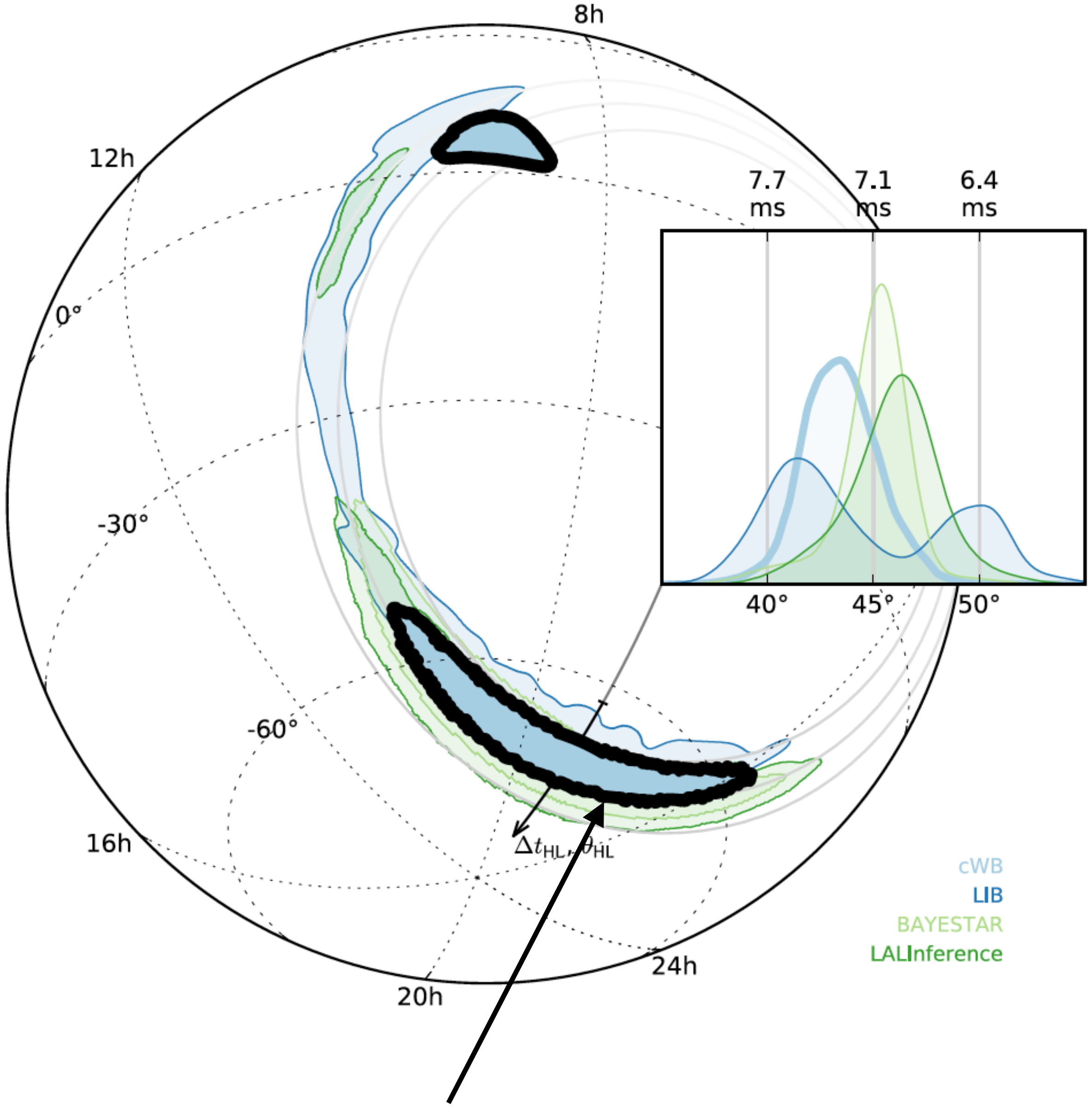


1 & 2. <u>Unmodelled burst searches</u>:
continuous Wave Burst (cWB, 17 min, 310 deg.^{2}) and
Omicron LAL-Inference Burst (LIB, 14hour, 750 deg.^{2})

3. <u>Compact Binary Coalescence modelled parameter estimation:</u>
LALInference (several weeks, 590 deg.^{2})

annulus where polar angle is determined by the arrival time at two detectors

Sky Maps



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[see Klimenko et al. 2016]

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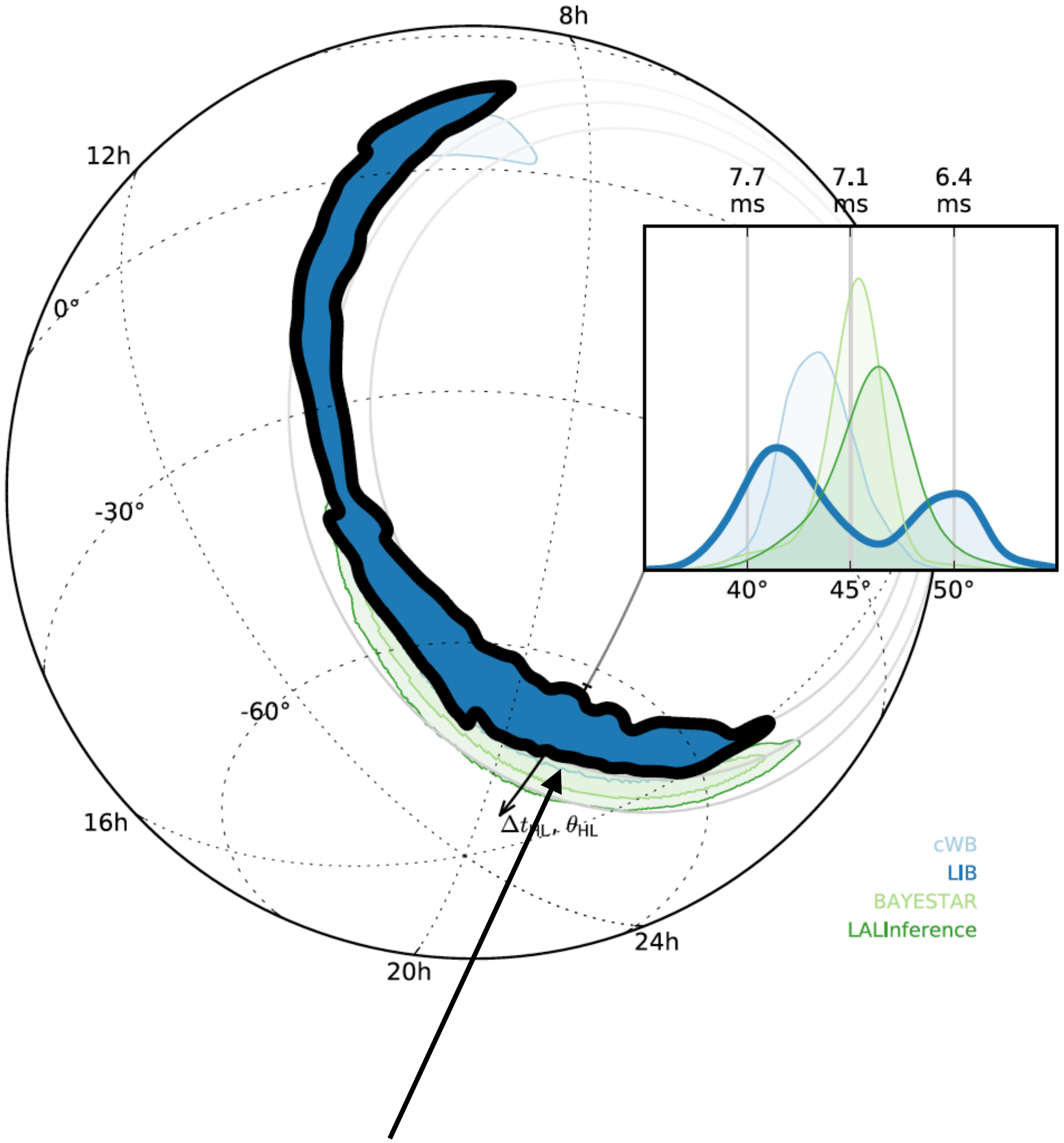
Sky Maps



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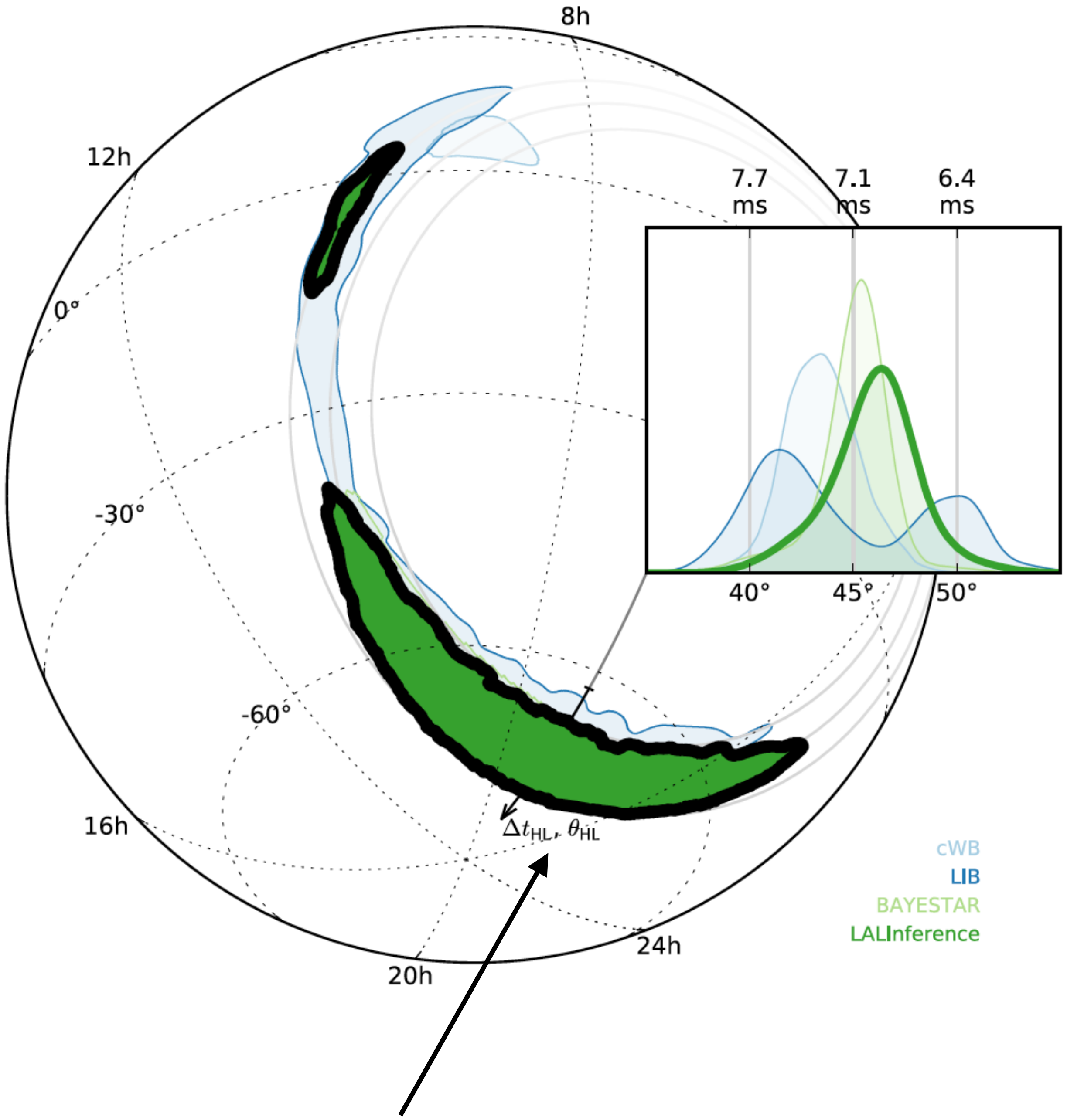
[see Lynch et al. 2015]

Sky Maps



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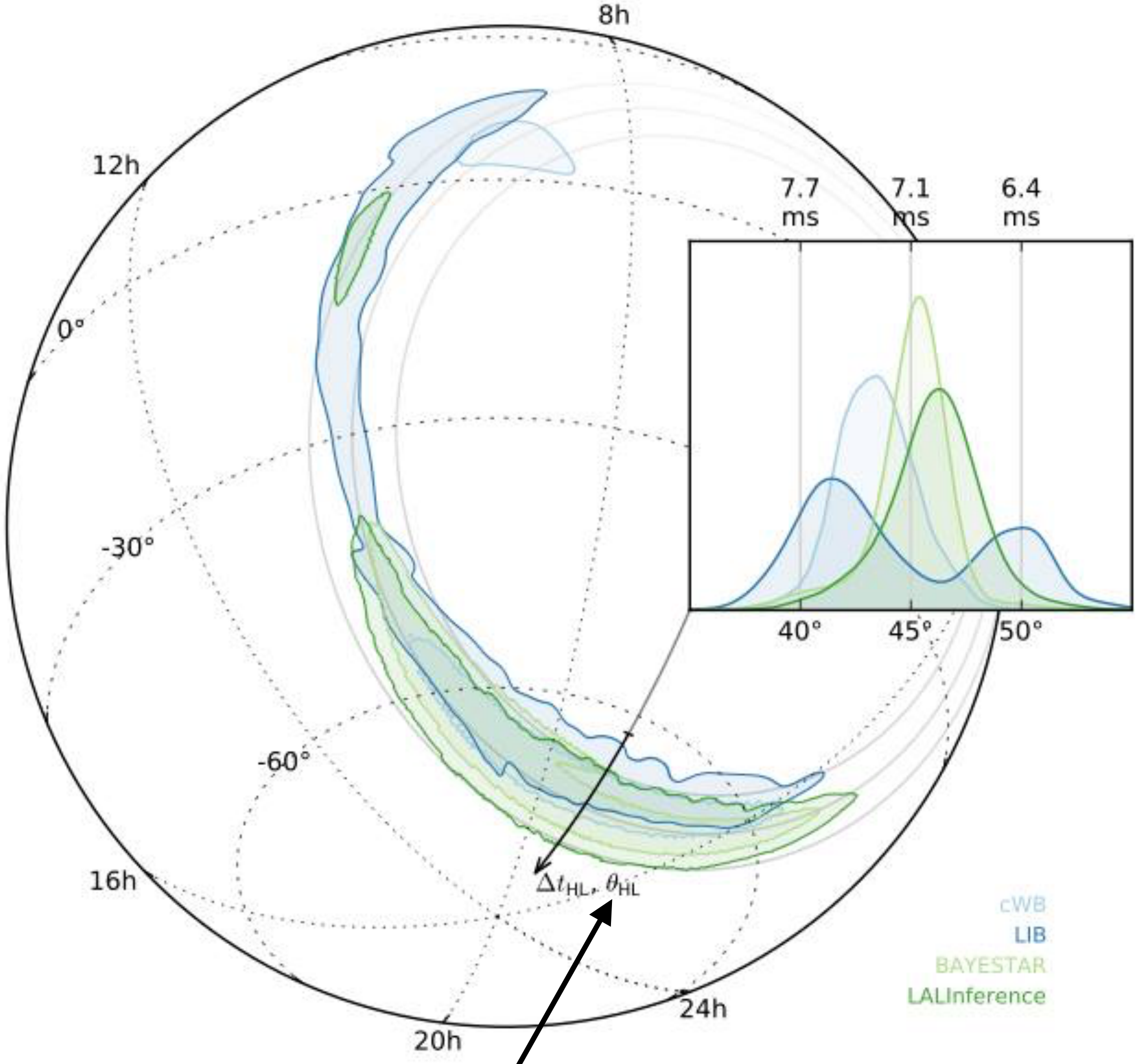
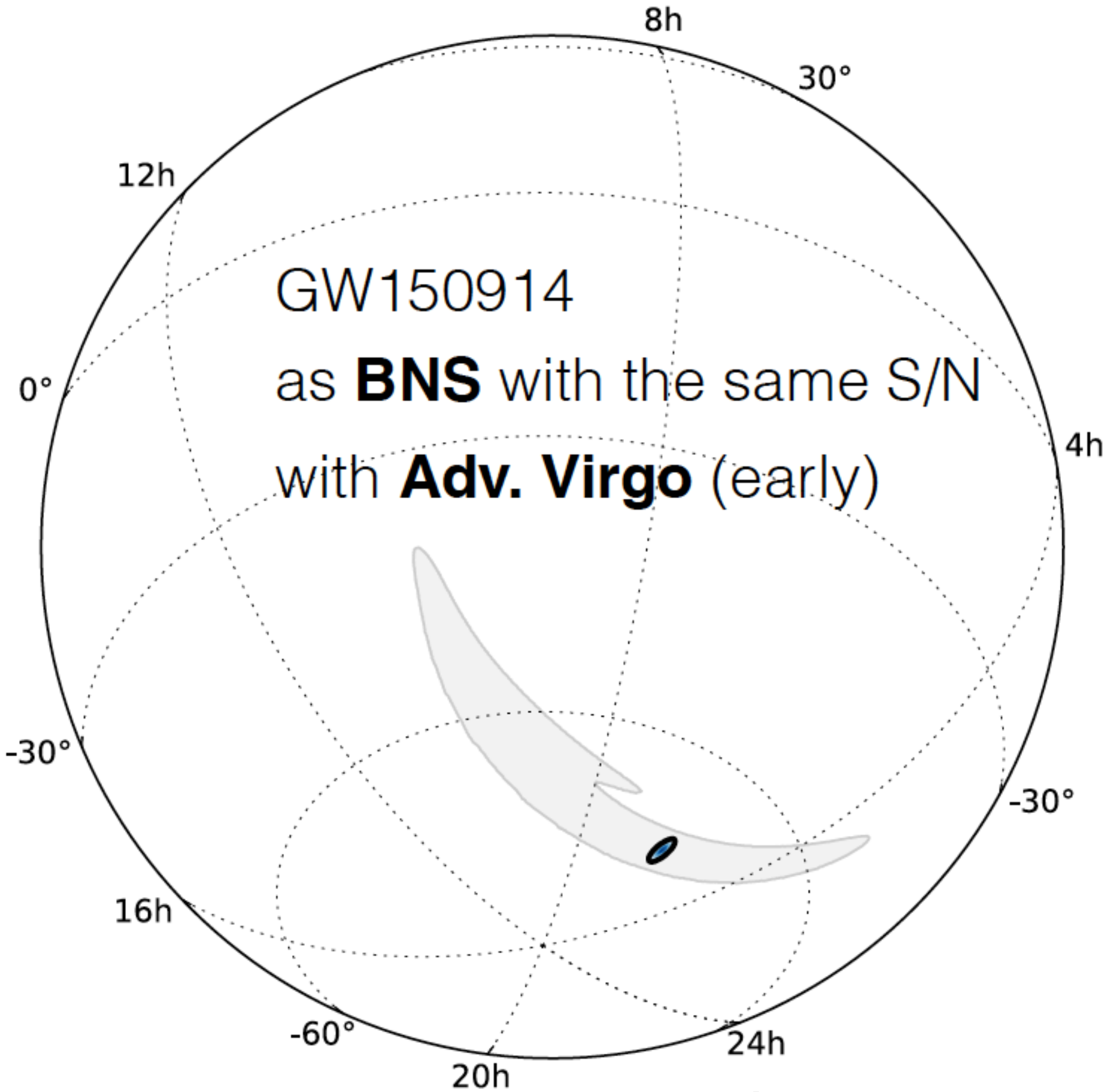
[see Veitch et al. 2015]

annulus where polar angle is determined by the arrival time at two detectors

Sky Maps + Virgo/LIGO India



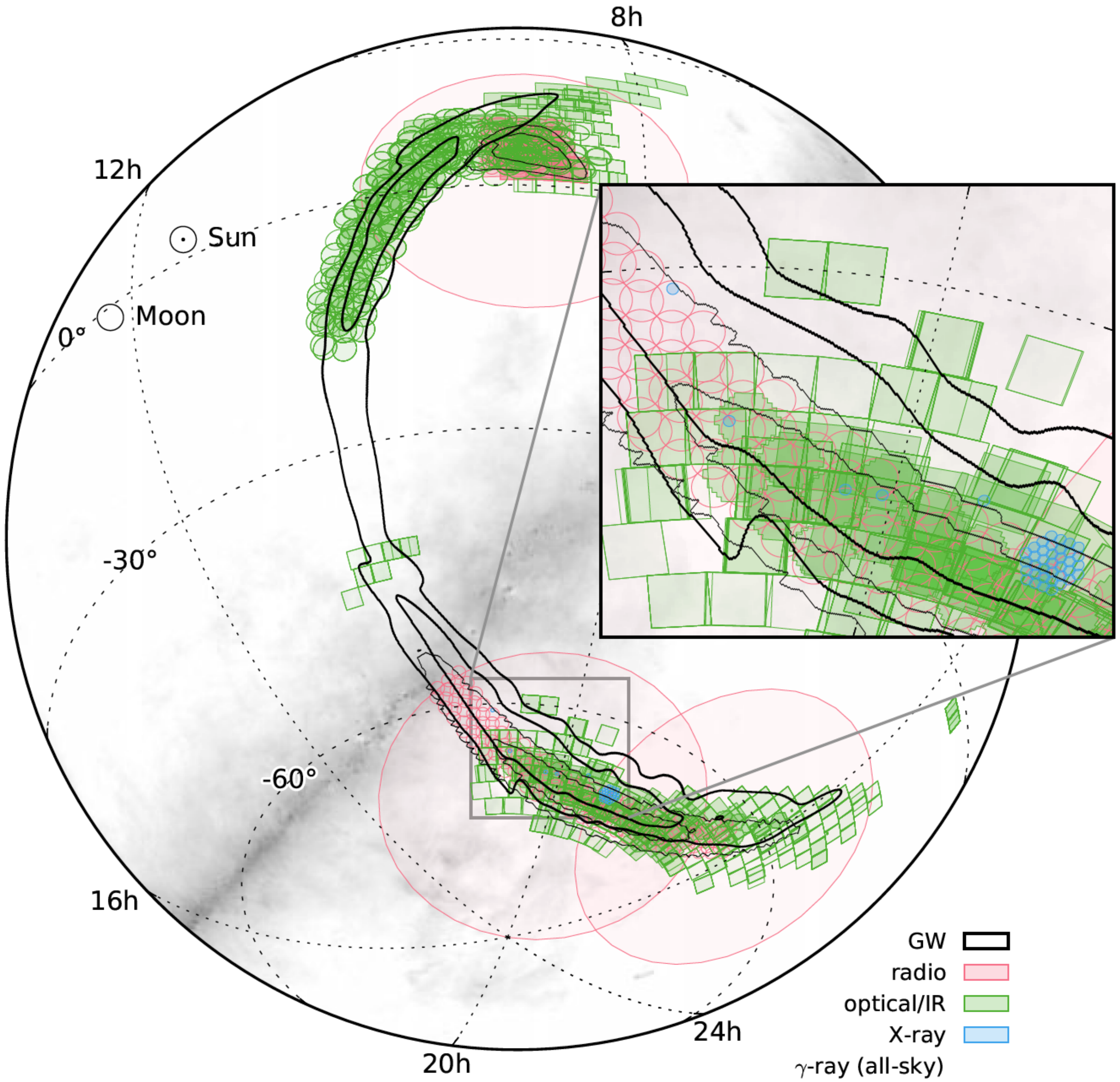
annulus where polar angle is determined by the arrival time at two detectors



[courtesy Singer & Bhalerao]

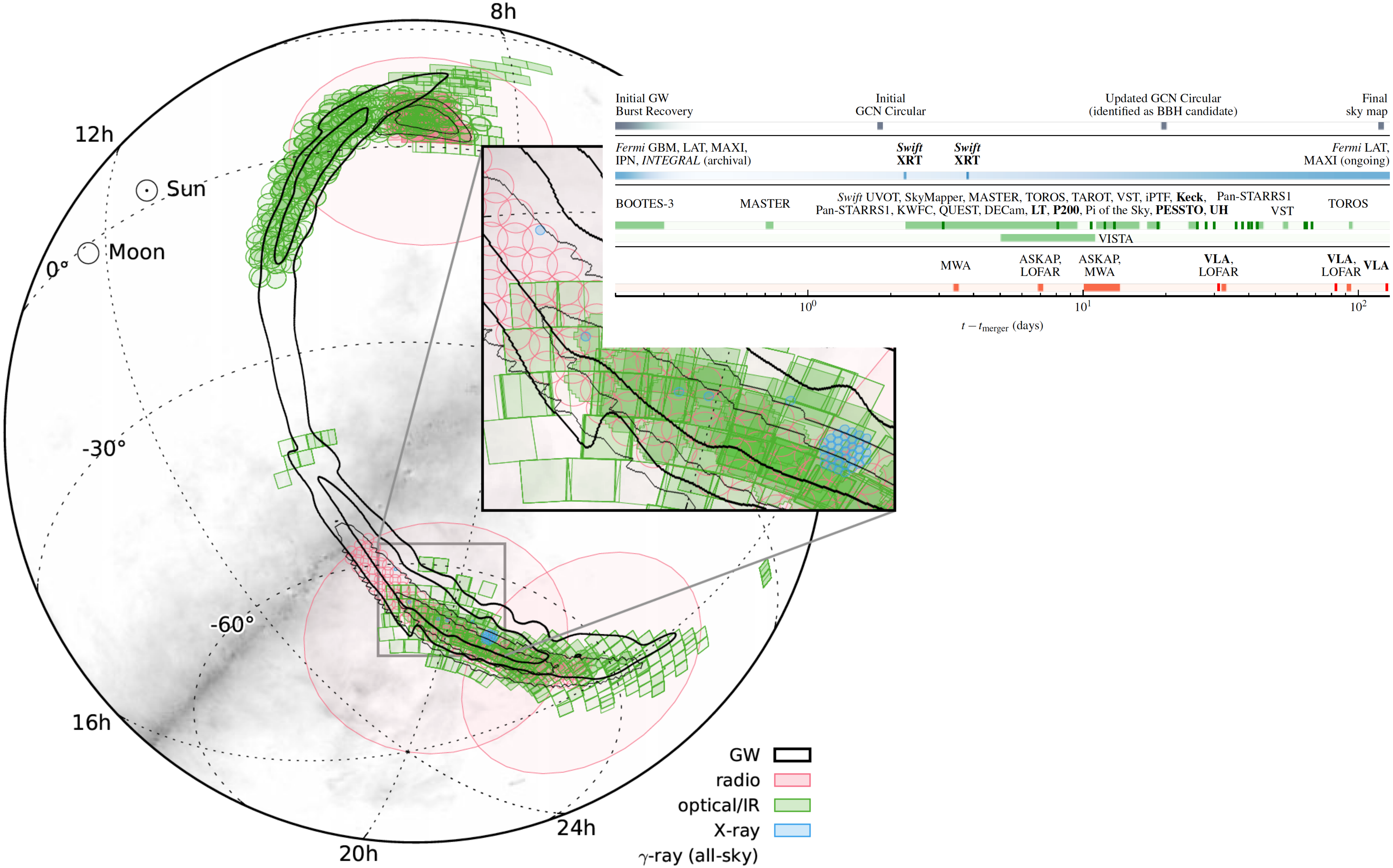
factor of 10 - 30 (Virgo);
further improvement of 1.2 -2
(LIGO India)

Multi-wavelength EM Sky Coverage



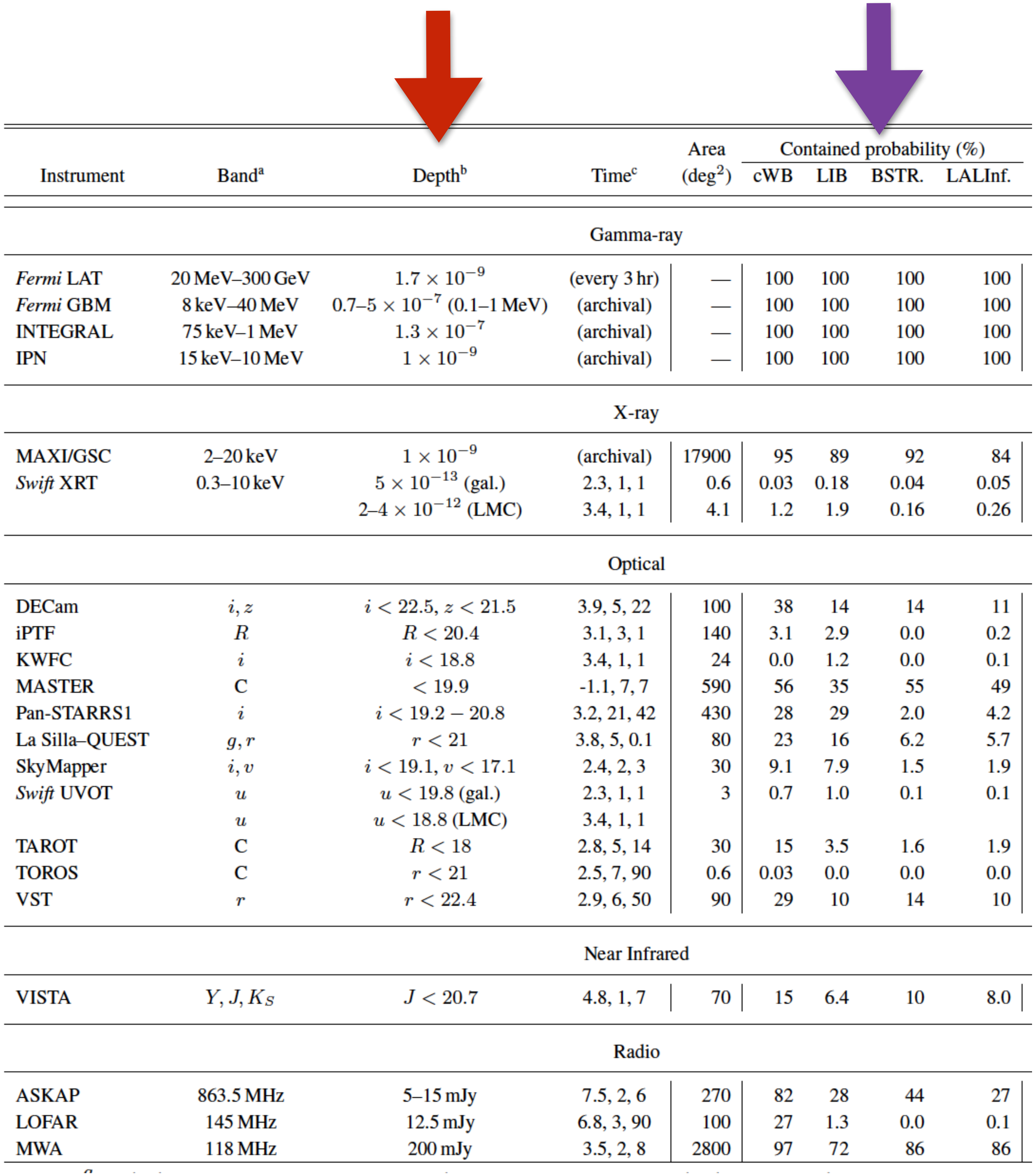
19 orders of magnitude in frequency space

Sky Coverage versus time



19 orders of magnitude in frequency space

Coverage of Sky Map and Depth



Instrument	Band[a]	Depth[b]	Time[c]	Area	Contained probability (%)			
				(deg^2)	cWB	LIB	BSTR.	LALInf.
			Gamma-ray					
Fermi LAT	20 MeV–300 GeV	1.7×10^{-9}	(every 3 hr)	—	100	100	100	100
Fermi GBM	8 keV–40 MeV	$0.7–5 \times 10^{-7}$ (0.1–1 MeV)	(archival)	—	100	100	100	100
INTEGRAL	75 keV–1 MeV	1.3×10^{-7}	(archival)	—	100	100	100	100
IPN	15 keV–10 MeV	1×10^{-9}	(archival)	—	100	100	100	100
			X-ray					
MAXI/GSC	2–20 keV	1×10^{-9}	(archival)	17900	95	89	92	84
Swift XRT	0.3–10 keV	5×10^{-13} (gal.)	2.3, 1, 1	0.6	0.03	0.18	0.04	0.05
		$2–4 \times 10^{-12}$ (LMC)	3.4, 1, 1	4.1	1.2	1.9	0.16	0.26
			Optical					
DECam	i, z	$i < 22.5$, $z < 21.5$	3.9, 5, 22	100	38	14	14	11
iPTF	R	$R < 20.4$	3.1, 3, 1	140	3.1	2.9	0.0	0.2
KWFC	i	$i < 18.8$	3.4, 1, 1	24	0.0	1.2	0.0	0.1
MASTER	C	< 19.9	-1.1, 7, 7	590	56	35	55	49
Pan-STARRS1	i	$i < 19.2 - 20.8$	3.2, 21, 42	430	28	29	2.0	4.2
La Silla–QUEST	g, r	$r < 21$	3.8, 5, 0.1	80	23	16	6.2	5.7
SkyMapper	i, v	$i < 19.1$, $v < 17.1$	2.4, 2, 3	30	9.1	7.9	1.5	1.9
Swift UVOT	u	$u < 19.8$ (gal.)	2.3, 1, 1	3	0.7	1.0	0.1	0.1
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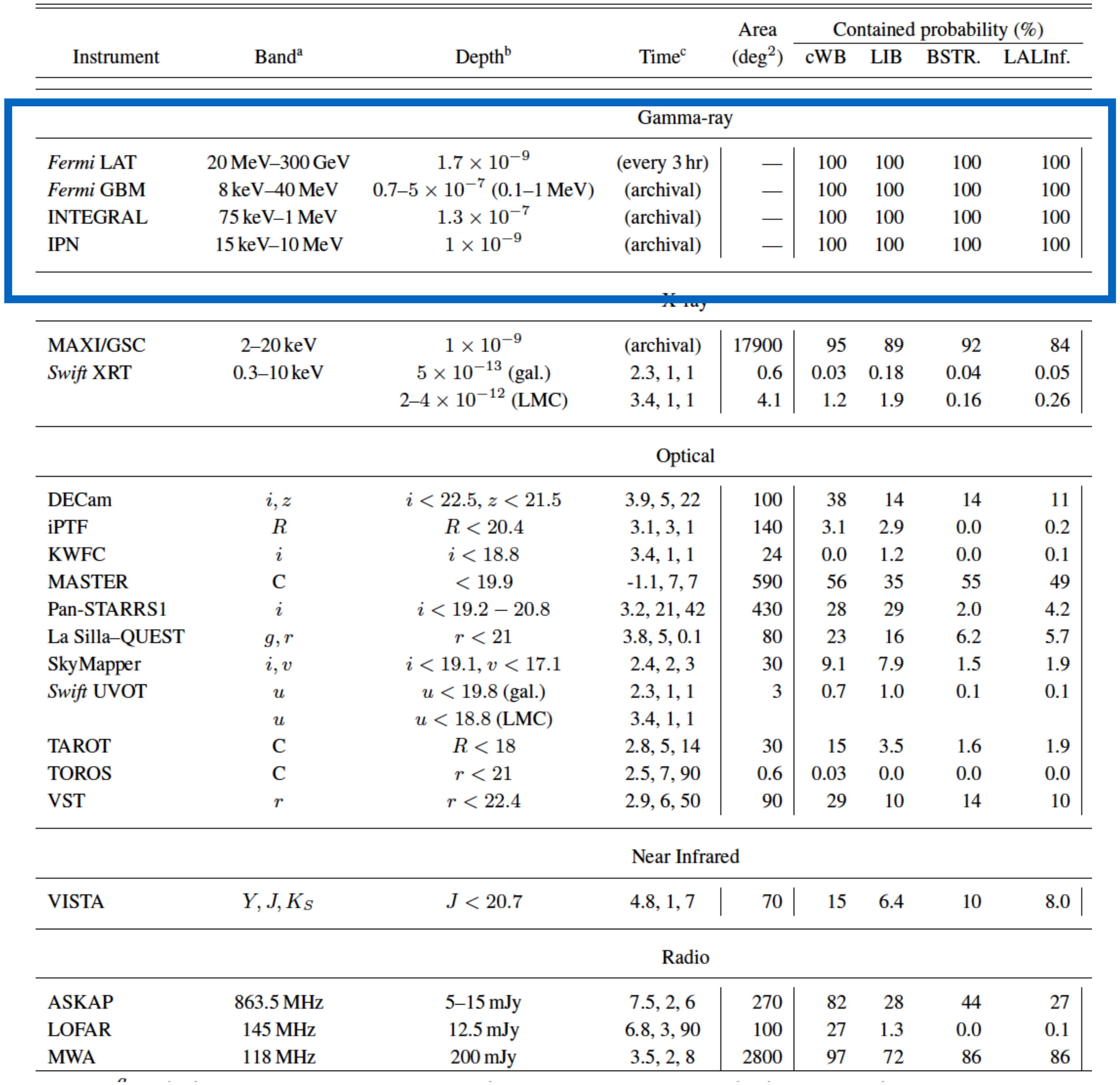
TAROT	C	$R < 18$	2.8, 5, 14	30	15	3.5	1.6	1.9
TOROS	C	$r < 21$	2.5, 7, 90	0.6	0.03	0.0	0.0	0.0
VST	r	$r < 22.4$	2.9, 6, 50	90	29	10	14	10
			Near Infrared					
VISTA	Y, J, K_S	$J < 20.7$	4.8, 1, 7	70	15	6.4	10	8.0
			Radio					
ASKAP	863.5 MHz	5–15 mJy	7.5, 2, 6	270	82	28	44	27
LOFAR	145 MHz	12.5 mJy	6.8, 3, 90	100	27	1.3	0.0	0.1
MWA	118 MHz	200 mJy	3.5, 2, 8	2800	97	72	86	86

targeted 5 galaxies

+ 1-4m class telescopes
+ 1/3 of OIR facilities
targeted galaxies
+ 57% (cWB) and
36% (LAL Inference)

+ 86% (LAL Inference)

Coverage of Sky Map and Depth



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Gamma Ray

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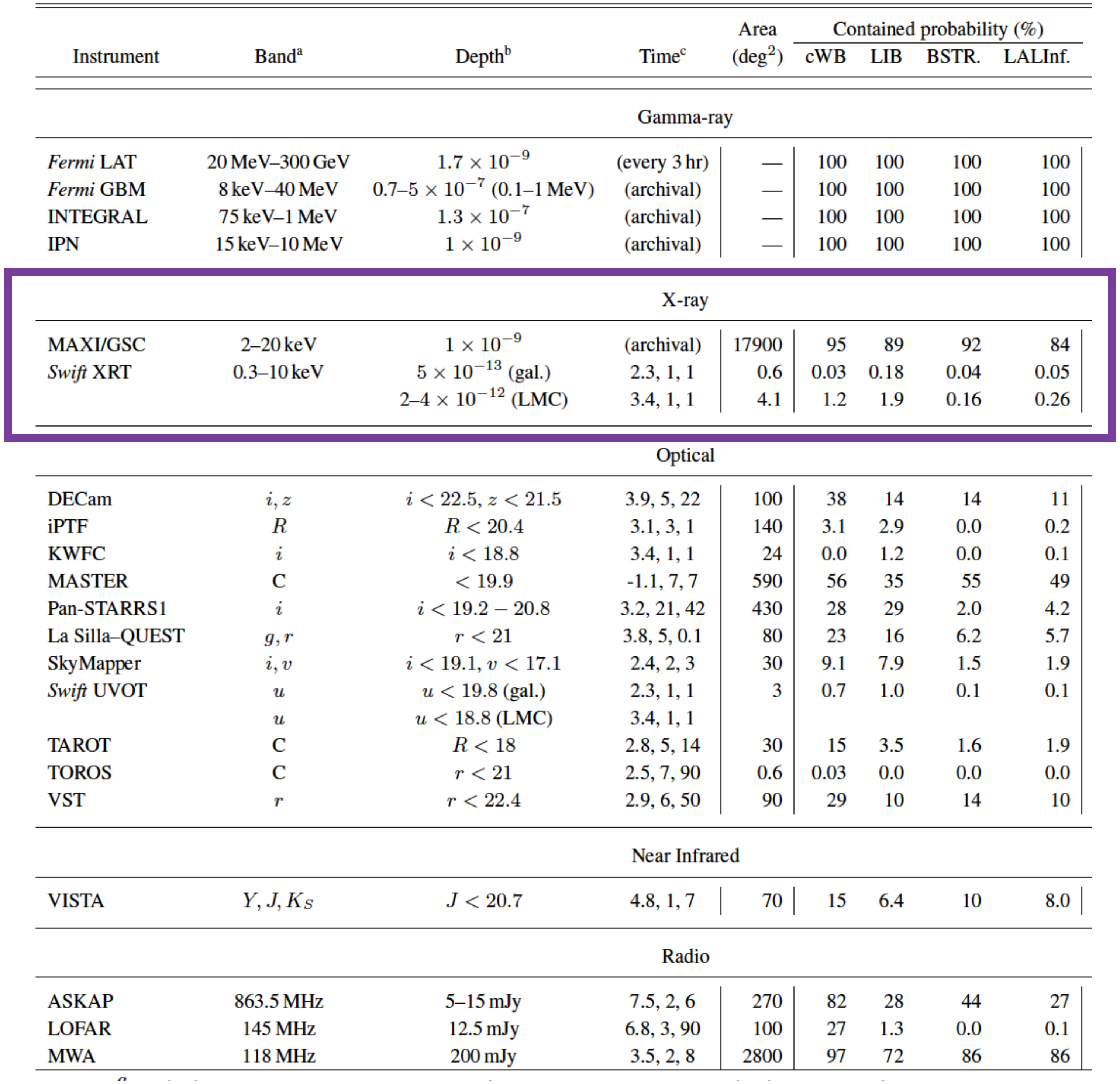

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		$2–4 \times 10^{-12}$ (LMC)	3.4, 1, 1	4.1	1.2	1.9	0.16	0.26
Optical								
DECam	i, z	$i < 22.5$, $z < 21.5$	3.9, 5, 22	100	38	14	14	11
iPTF	R	$R < 20.4$	3.1, 3, 1	140	3.1	2.9	0.0	0.2
KWFC	i	$i < 18.8$	3.4, 1, 1	24	0.0	1.2	0.0	0.1
MASTER	C	< 19.9	-1.1, 7, 7	590	56	35	55	49
Pan-STARRS1	i	$i < 19.2 - 20.8$	3.2, 21, 42	430	28	29	2.0	4.2
La Silla–QUEST	g, r	$r < 21$	3.8, 5, 0.1	80	23	16	6.2	5.7
SkyMapper	i, v	$i < 19.1$, $v < 17.1$	2.4, 2, 3	30	9.1	7.9	1.5	1.9
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VST	r	$r < 22.4$	2.9, 6, 50	90	29	10	14	10
Near Infrared								
VISTA	Y, J, K_S	$J < 20.7$	4.8, 1, 7	70	15	6.4	10	8.0
Radio								
ASKAP	863.5 MHz	5–15 mJy	7.5, 2, 6	270	82	28	44	27
LOFAR	145 MHz	12.5 mJy	6.8, 3, 90	100	27	1.3	0.0	0.1
MWA	118 MHz	200 mJy	3.5, 2, 8	2800	97	72	86	86

X-Ray

targeted 5 galaxies

+ 1-4m class telescopes
+ 1/3 of OIR facilities
  targeted galaxies
+ 57% (cWB) and
  36% (LAL Inference)

+ 86% (LAL Inference)

Coverage of Sky Map and Depth

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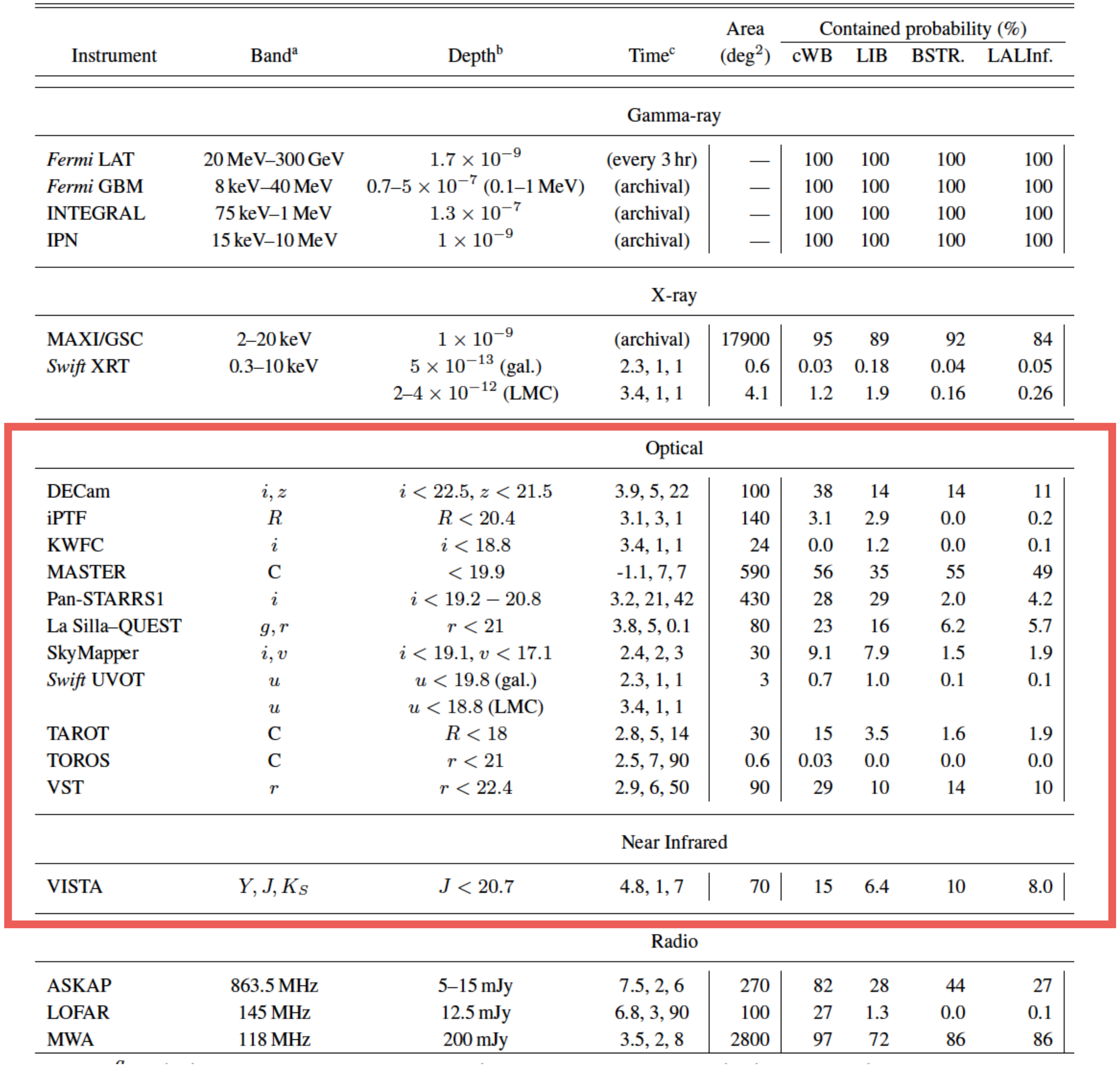

Instrument	Band[a]	Depth[b]	Time[c]	Area (deg^2)	Contained probability (%) cWB	LIB	BSTR.	LALInf.
Gamma-ray								
Fermi LAT	20 MeV–300 GeV	1.7×10^{-9}	(every 3 hr)	—	100	100	100	100
Fermi GBM	8 keV–40 MeV	$0.7–5 \times 10^{-7}$ (0.1–1 MeV)	(archival)	—	100	100	100	100
INTEGRAL	75 keV–1 MeV	1.3×10^{-7}	(archival)	—	100	100	100	100
IPN	15 keV–10 MeV	1×10^{-9}	(archival)	—	100	100	100	100
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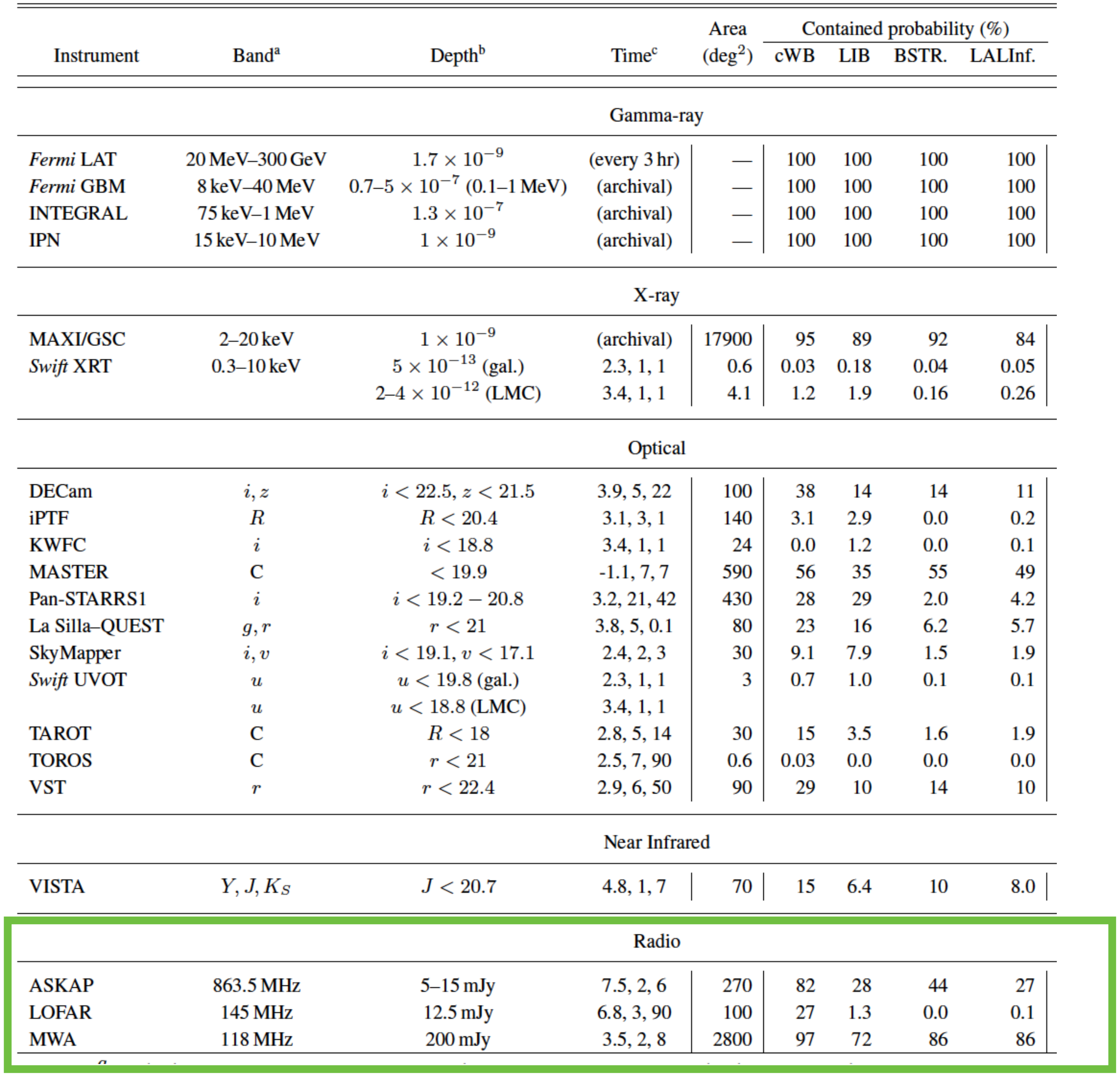
Optical-IR

Coverage of Sky Map and Depth



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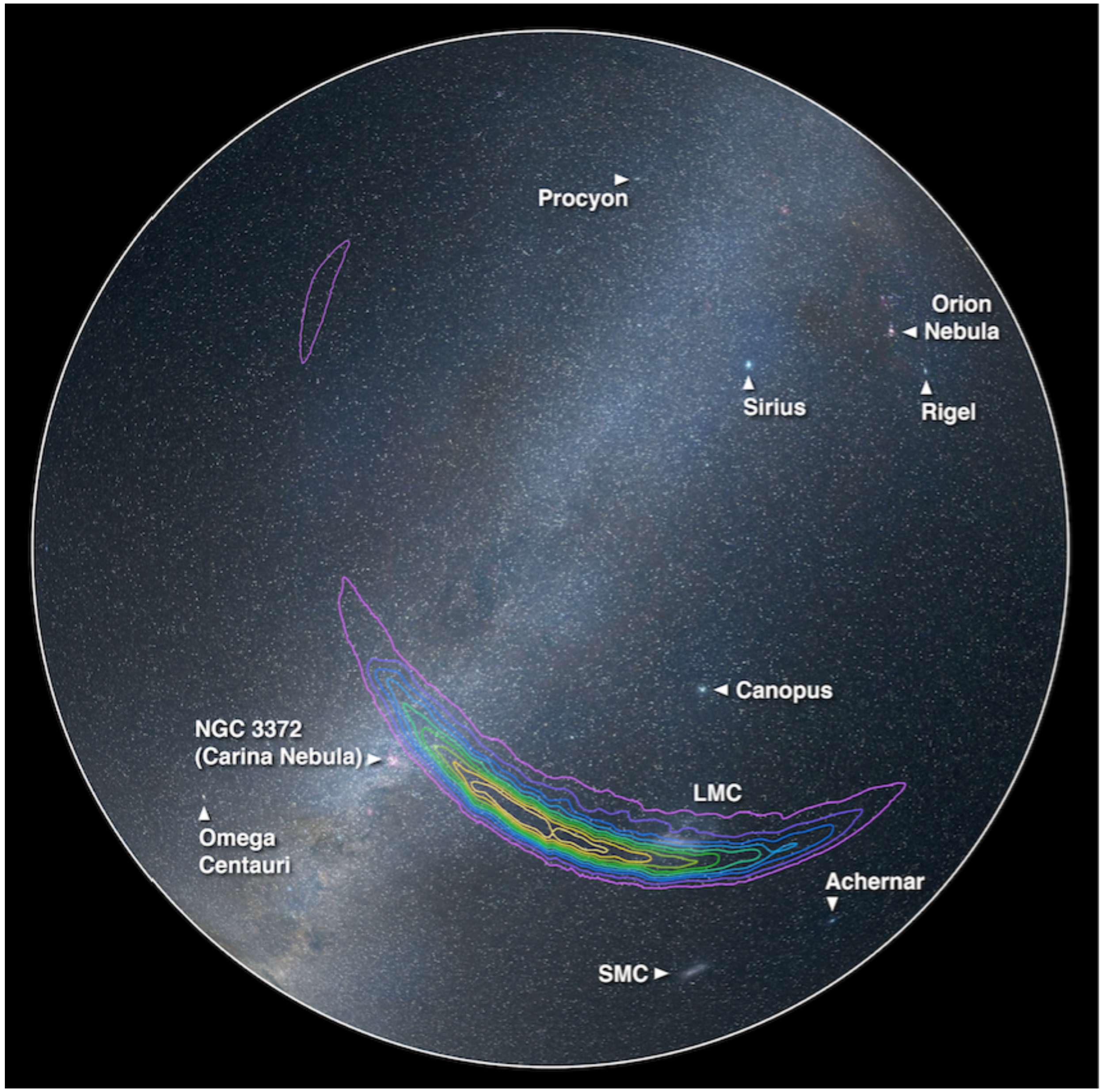
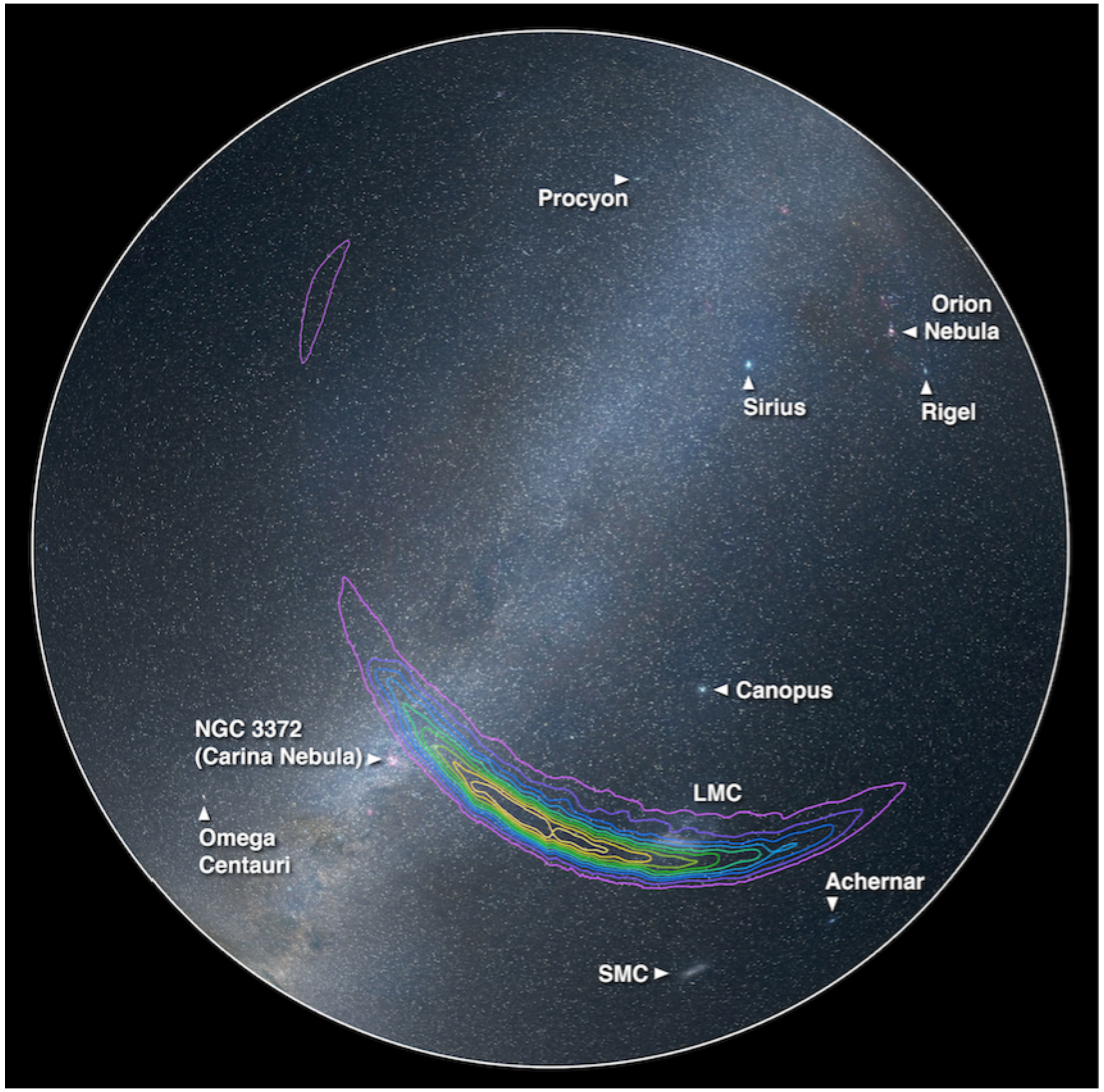
Radio

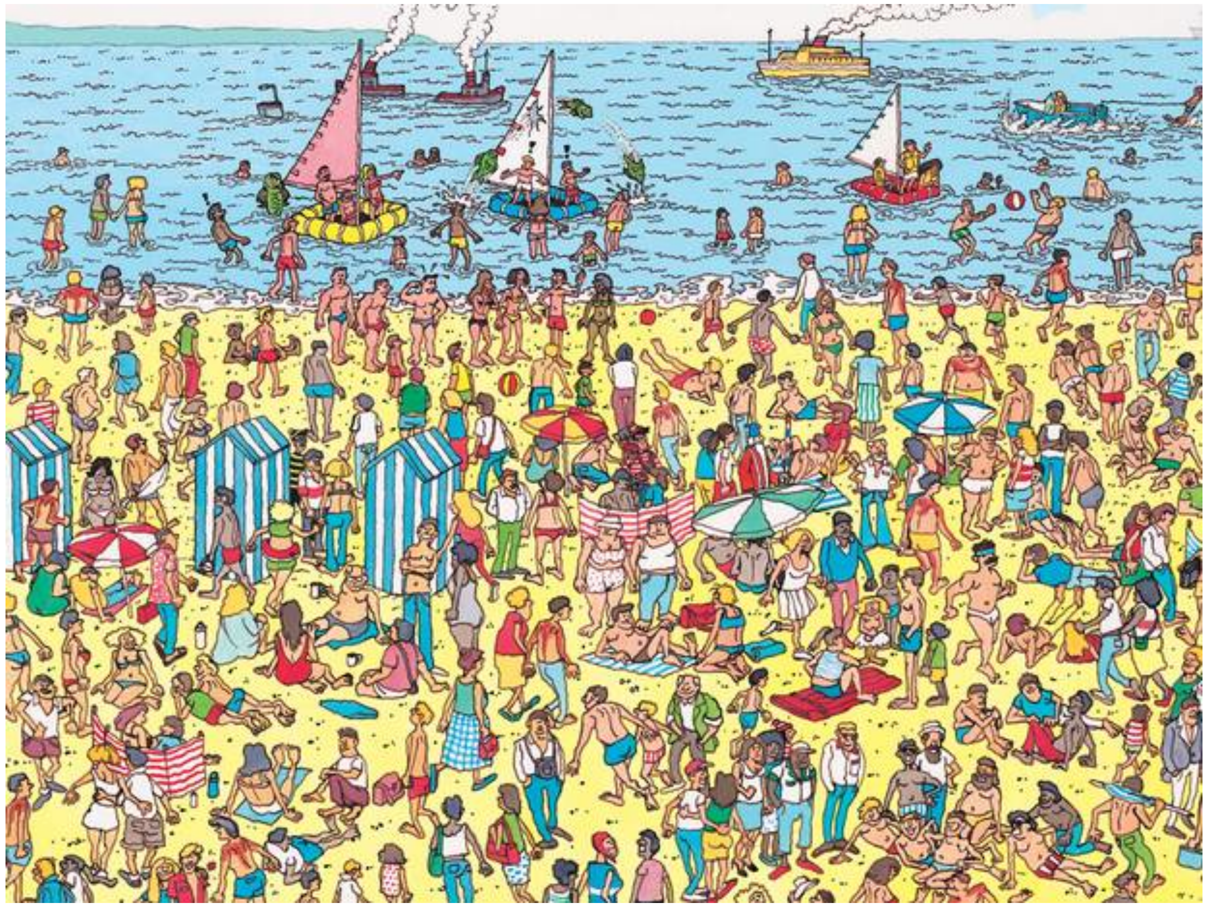
What about other transients and variables?



590 deg^2 (90% credible region)

What about other transients and variables?





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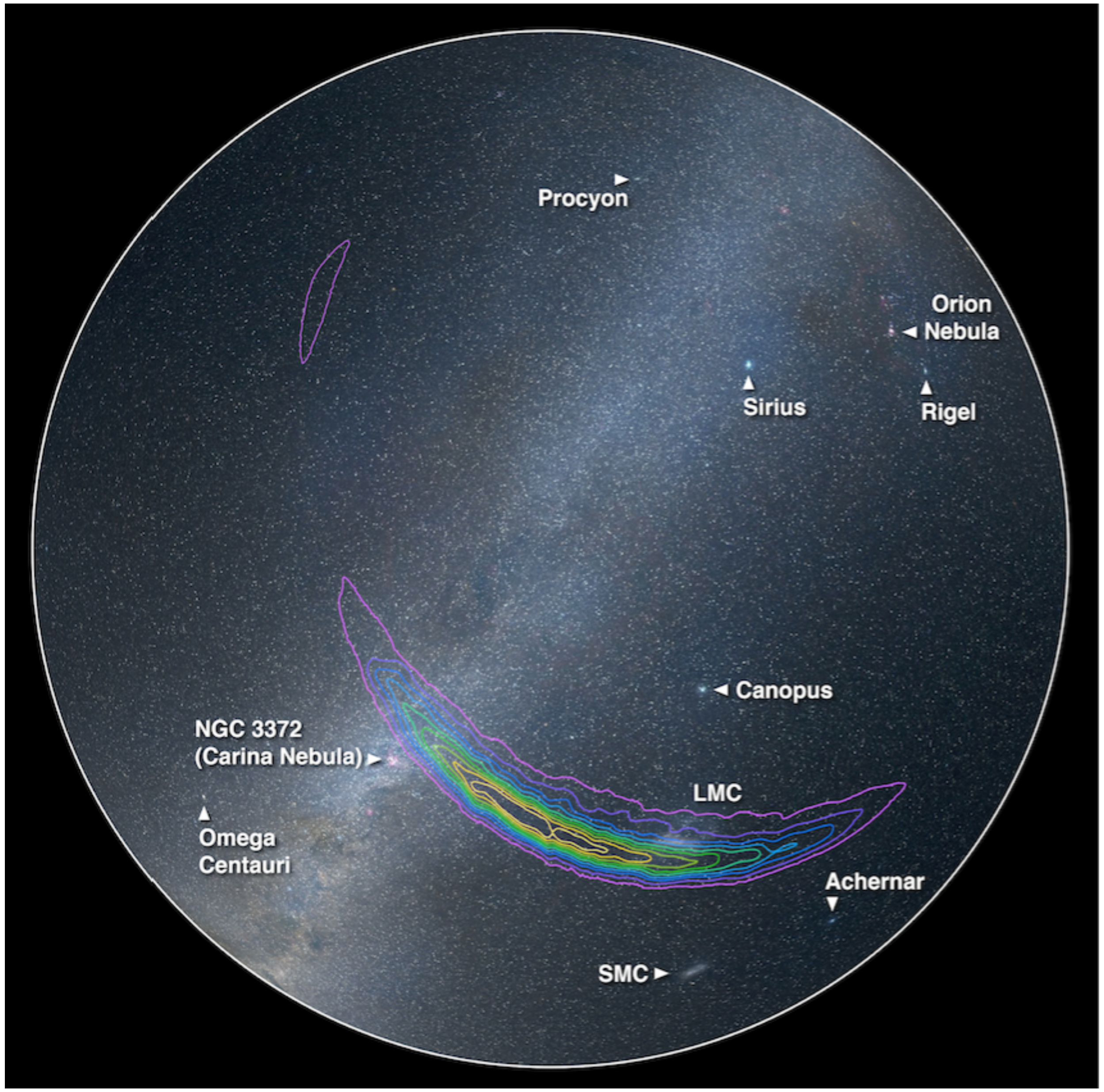
What about other transients and variables?



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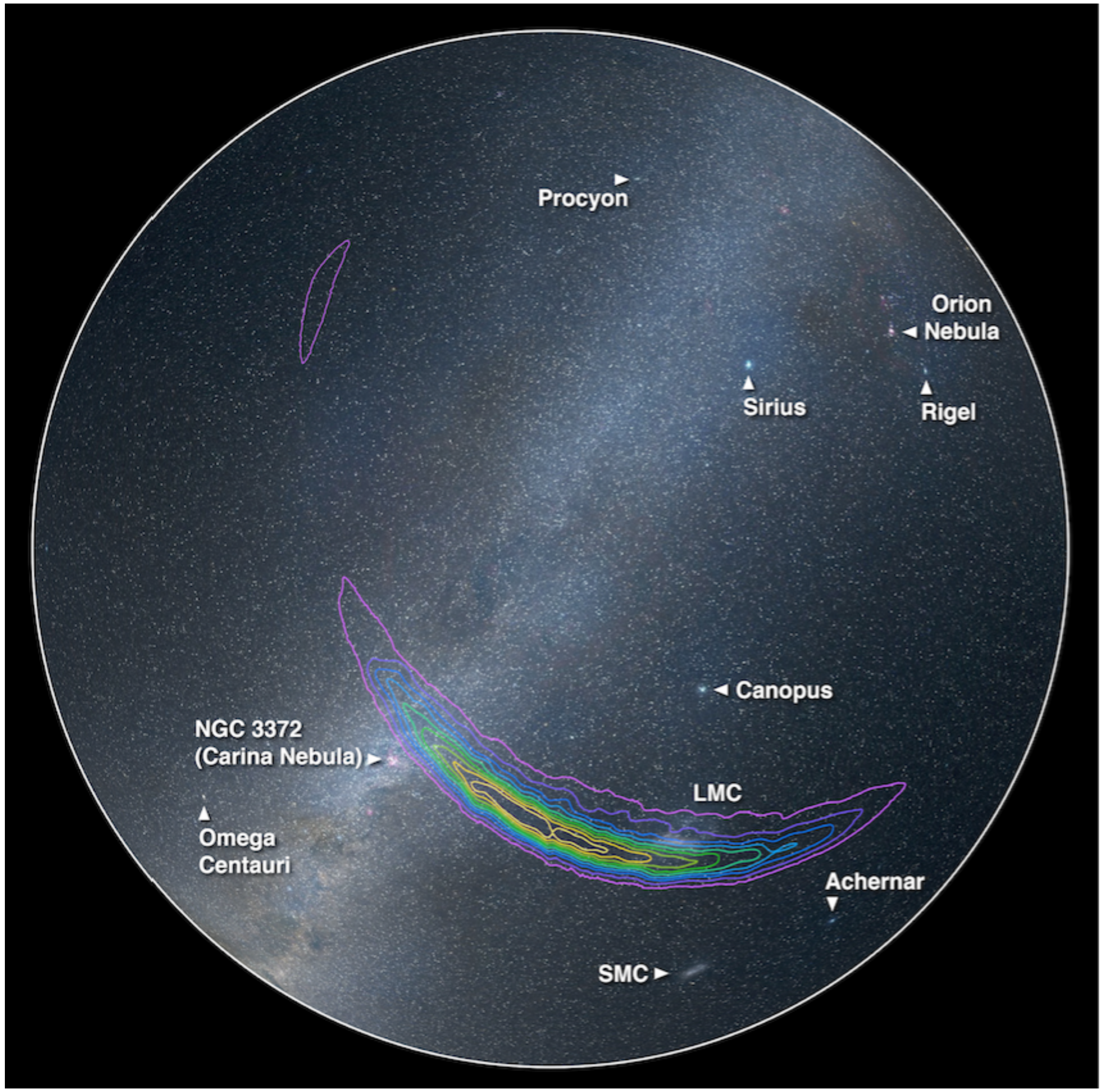

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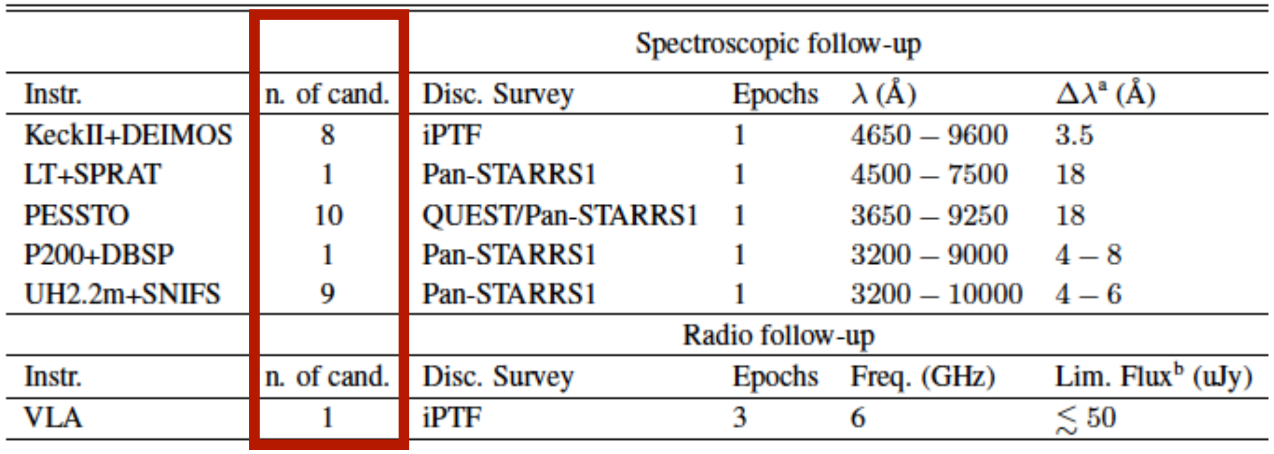


Instr.	n. of cand.	Disc. Survey	Epochs	λ (Å)	$\Delta\lambda^a$ (Å)
		Spectroscopic follow-up			
KeckII+DEIMOS	8	iPTF	1	4650 – 9600	3.5
LT+SPRAT	1	Pan-STARRS1	1	4500 – 7500	18
PESSTO	10	QUEST/Pan-STARRS1	1	3650 – 9250	18
P200+DBSP	1	Pan-STARRS1	1	3200 – 9000	4 – 8
UH2.2m+SNIFS	9	Pan-STARRS1	1	3200 – 10000	4 – 6
		Radio follow-up			
Instr.	n. of cand.	Disc. Survey	Epochs	Freq. (GHz)	Lim. Flux^b (uJy)
VLA	1	iPTF	3	6	$\lesssim 50$

e.g.,

- Supernova type Ia and II
- Active Galactic Nucleii
- a few dwarf nova

comparison with GW redshift and distance is critical

[e.g., SWIFT; arXiv:1602.03868
DES; arXiv:1602.04199 and 1602.04200
Pan-STARRS;arXiv:1602.04156
iPTF; arXiv:1602.08764]

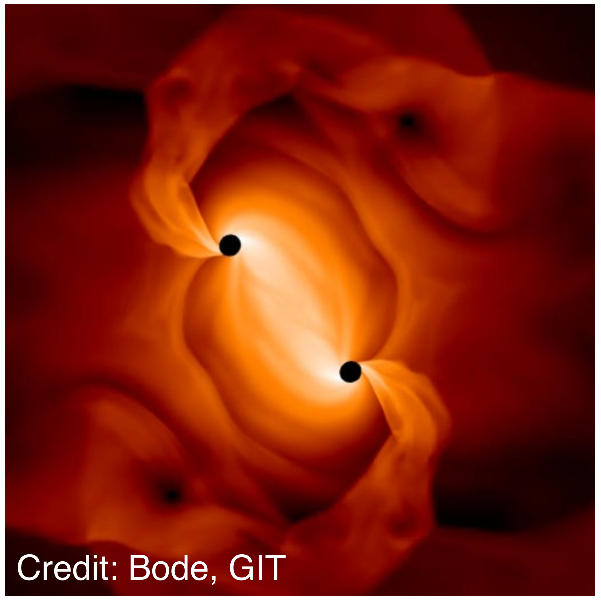
BBH counterpart - Fermi GBM ?

[see von Kienlin talk]

No reported real-time observed EM counterpart to GW 150914
(see companion papers from EM partners) …

..bar de facto, the FERMI GBM detected a sub-threshold event above 50 keV, 0.4 s after the GW event was detected, with a FAP of 0.0022 and lasting 1s.
<u>Ill-constrained</u> location (if it was a counterpart, would reduce 600 -> 200 deg.^{2}).
Hard X-ray emission between 1 keV and 10 MeV of 1.8×10^{49} ergs/s.
No candidates reported by Integral.

e.g. arXiv in the week following the announcement:
Short Gamma-Ray Bursts from the Merger of Two Black Hole
Perna et al. 2016
Electromagnetic Counterparts to Black Hole Mergers Detected by LIGO
Loeb 2016
Electromagnetic Afterglows Associated with Gamma-Ray Emission Coincident with Binary Black Hole Merger Event GW150914
Yamazaki et al. 2016
Mergers of Charged Black Holes: Gravitational Wave Events, Short Gamma-Ray Bursts, and Fast Radio Bursts
Zhang 2016
Implication of the association between GBM transient 150914 and LIGO Gravitational Wave event GW150914
Li et al. 2016



Credit: Bode, GIT

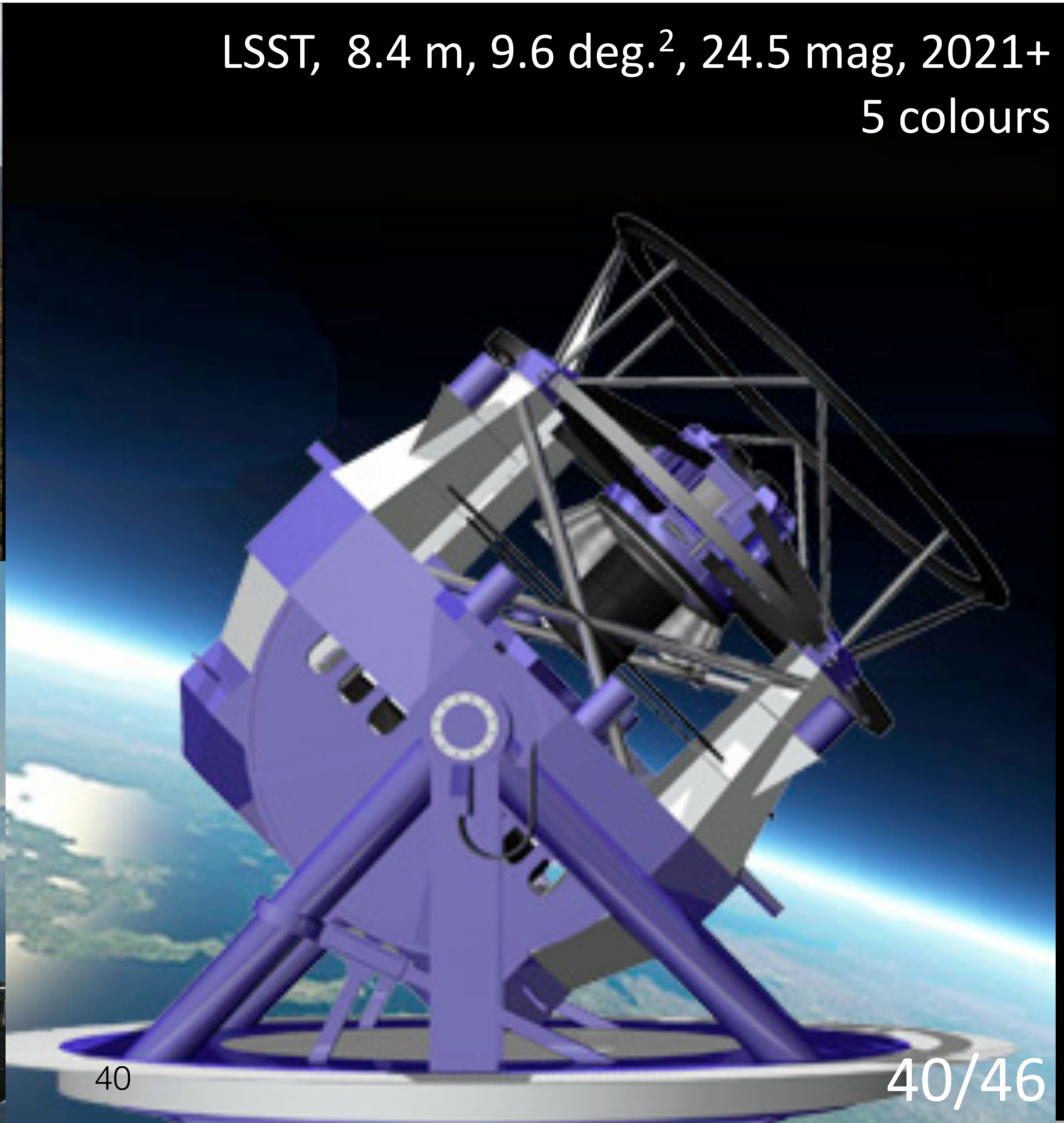
Part III: The immediate future of EM follow-up

The future: Upcoming wide-field optical telescopes

Zwicky Transient Facility (ZTF),
1.2m, 45 deg.^{2}, 21 mag, 2017
2 colours

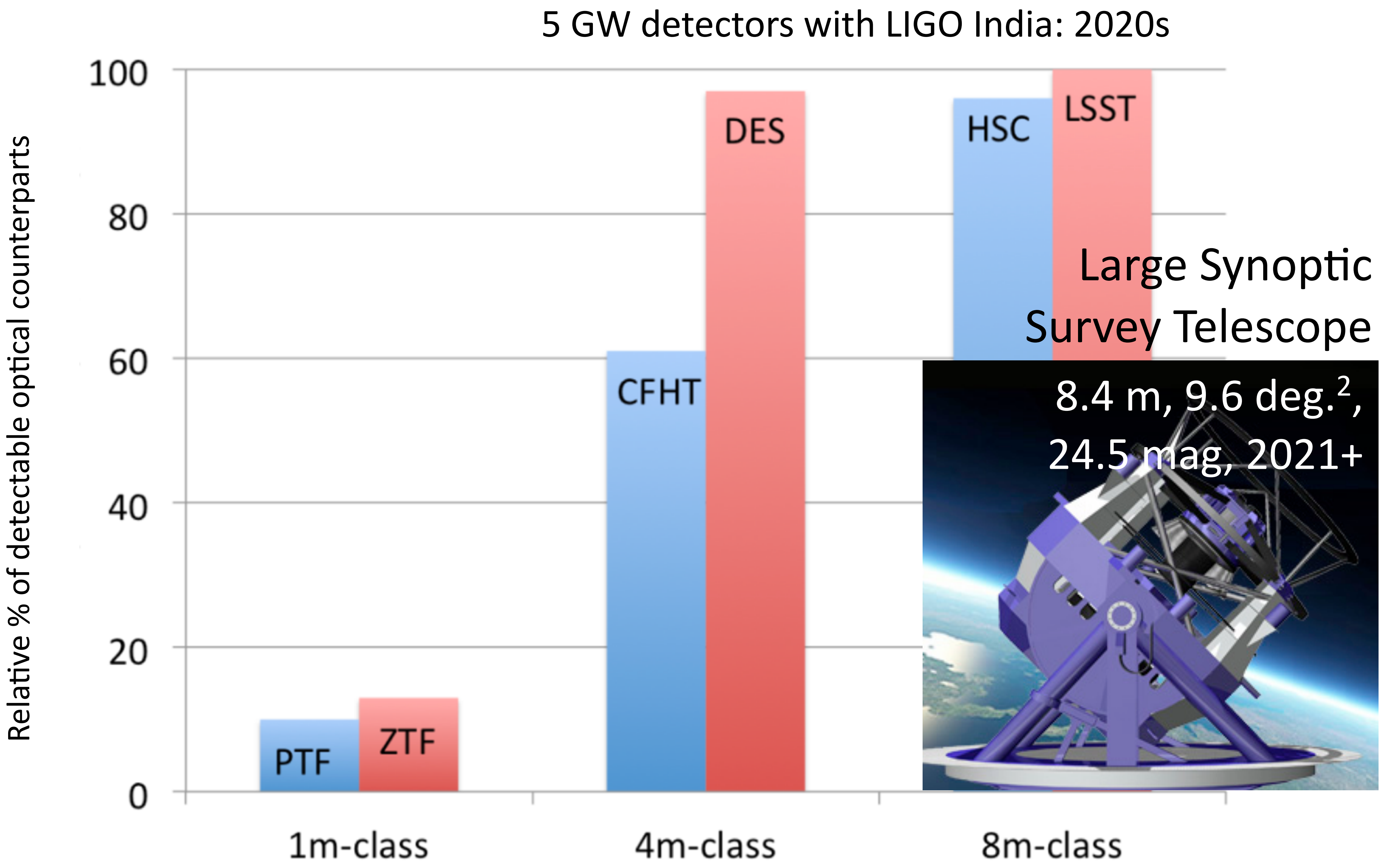
BlackGEM, 21 mag, 11/40 deg.^{2} , 2017
5 colours
www.blackgem.eu

PanSTARRS II & GOTO



LSST, 8.4 m, 9.6 deg.^{2}, 24.5 mag, 2021+
5 colours

Optical detection in LIGO INDIA era



Large Synoptic Survey Telescope

8.4 m, 9.6 deg.^{2}, 24.5 mag, 2021+

[Nissanke, Kasliwal, Georgieva 2013]

The future: Current & Upcoming Radio facilities

[see Piran talk]

300 MHz

LOFAR, Netherlands, now

0.25 sq. deg.; 5 μ Jy hr^{-1}

JVLA, USA, now

1.4 - 3 GHz

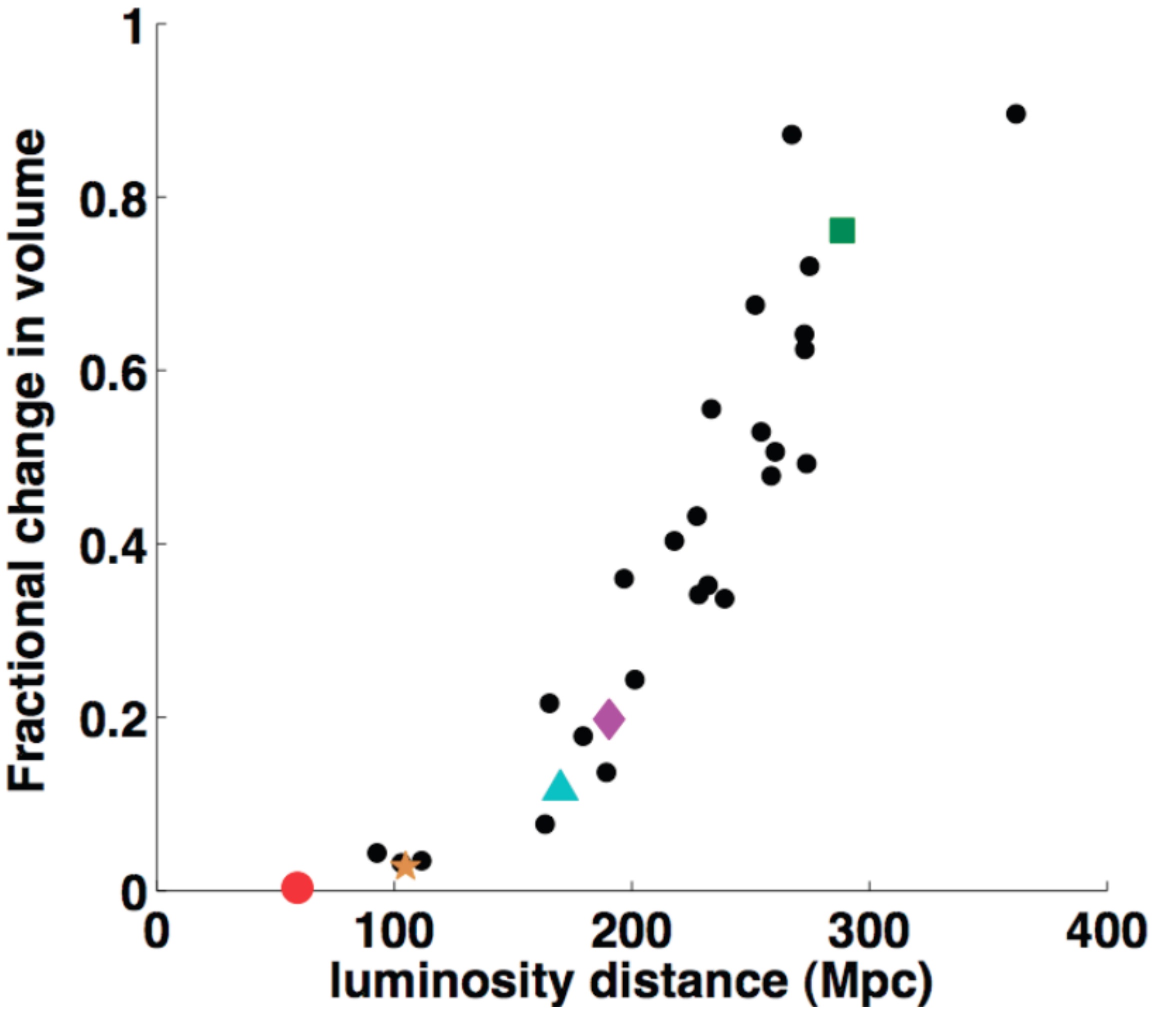
ASKAP, Australia

MeerKAT, South Africa

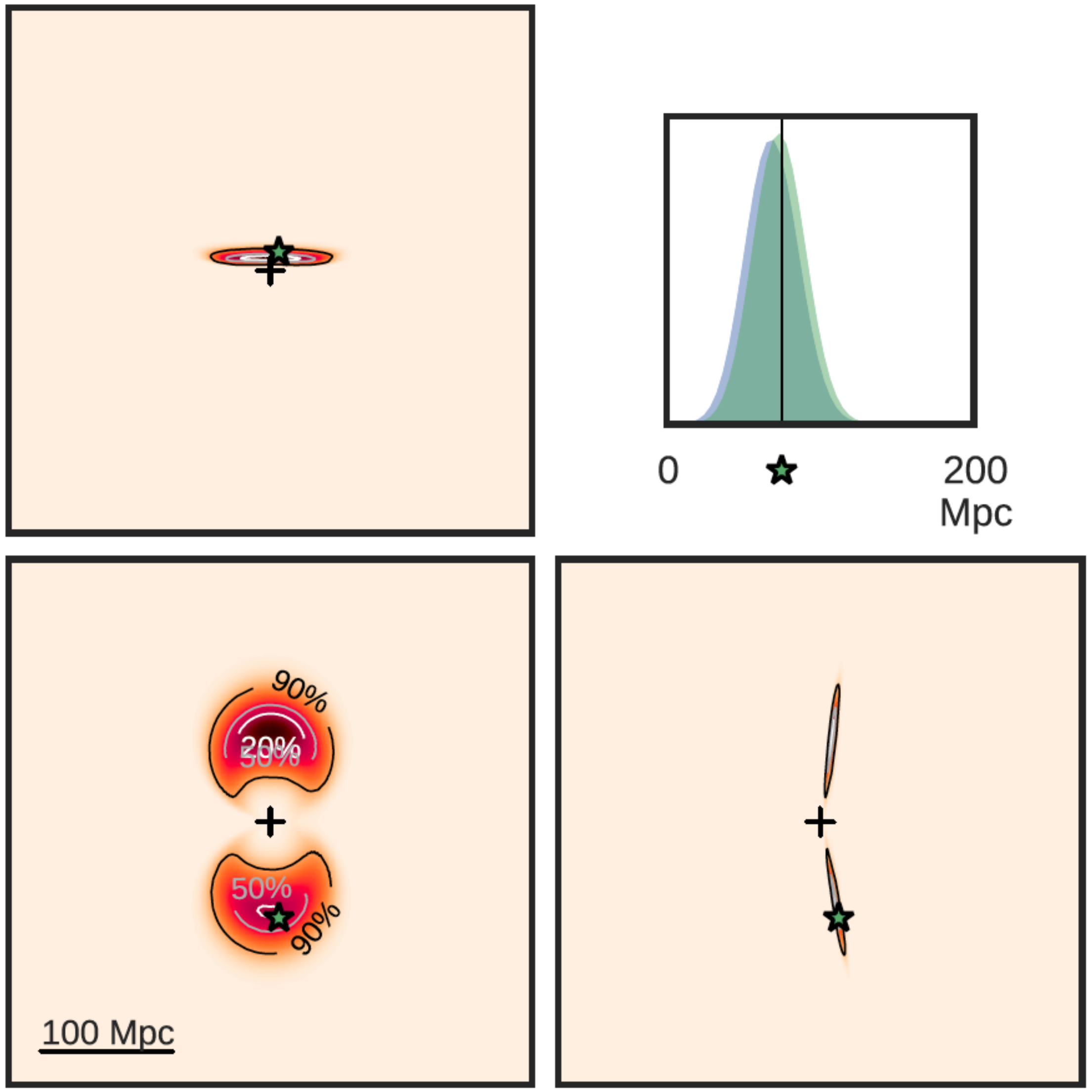
0.86 sq. deg.;
4 μ Jy hr^{-1}

Strategy I) reduce false-positive rate with GW volumes

[LIGO, Virgo, advanced design sensitivity noise curves]

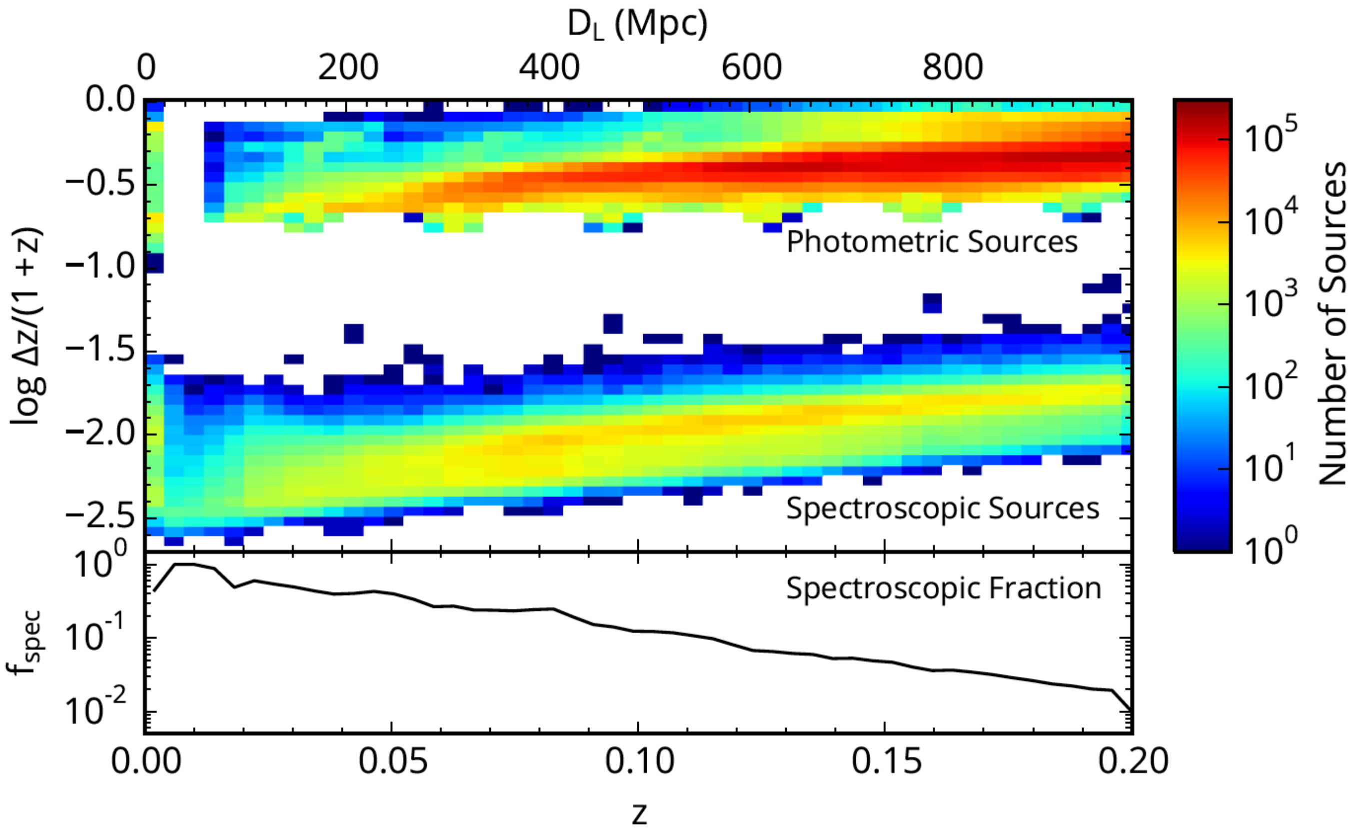


[Nissanke, Kasliwal, Georgieva 2013]



[Singer et al., arXiv:1603.07333, 2016]

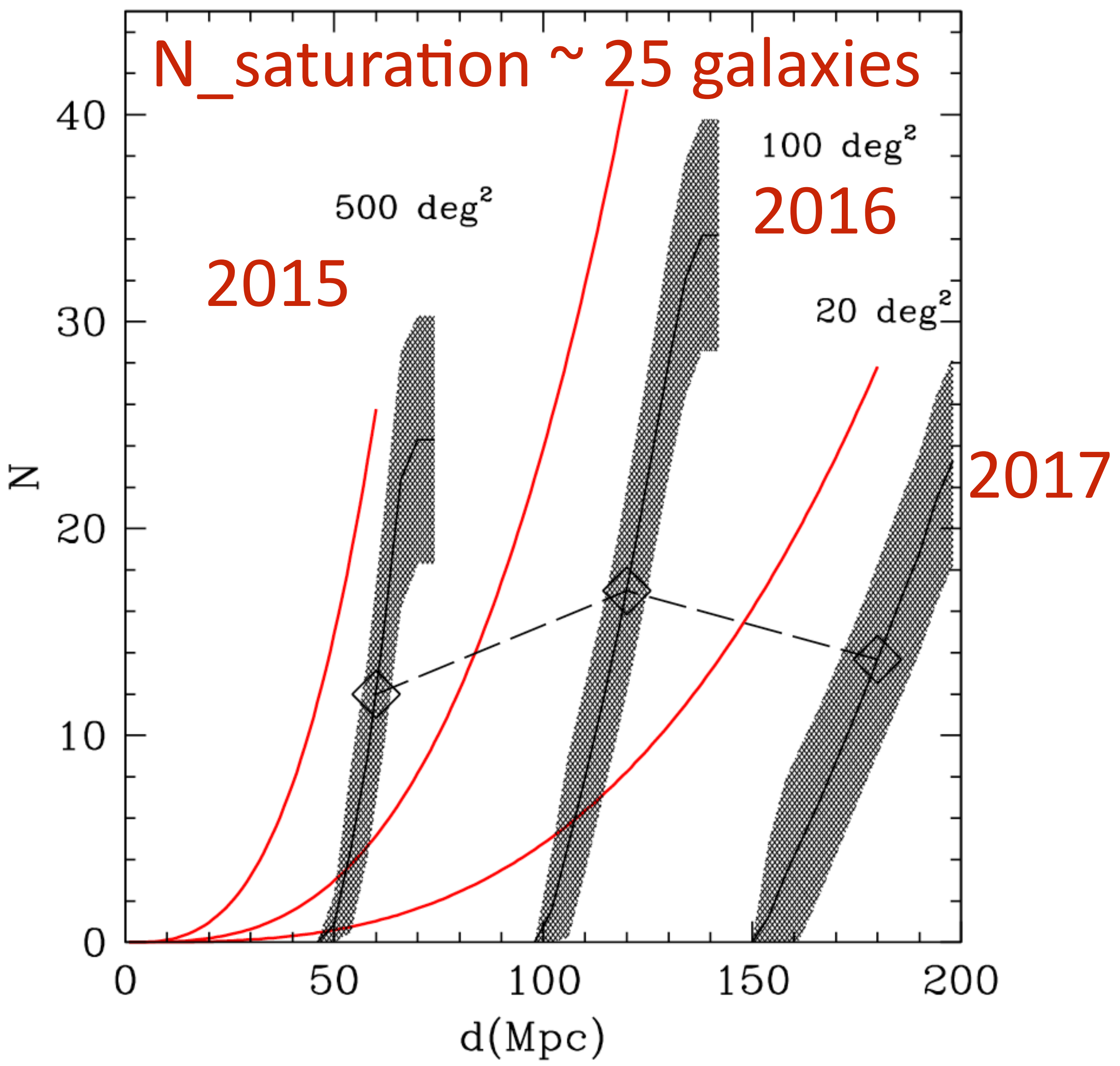
Strategy II) Reduce false-positive rate with GW volumes & galaxy catalog



SDSS GW galaxy catalog
see https://astro.ru.nl/catalogs/sdss_gwgalcat/index.html

[Rahman, Nissanke + in prep]

brightest galaxies that produce 50% of the light

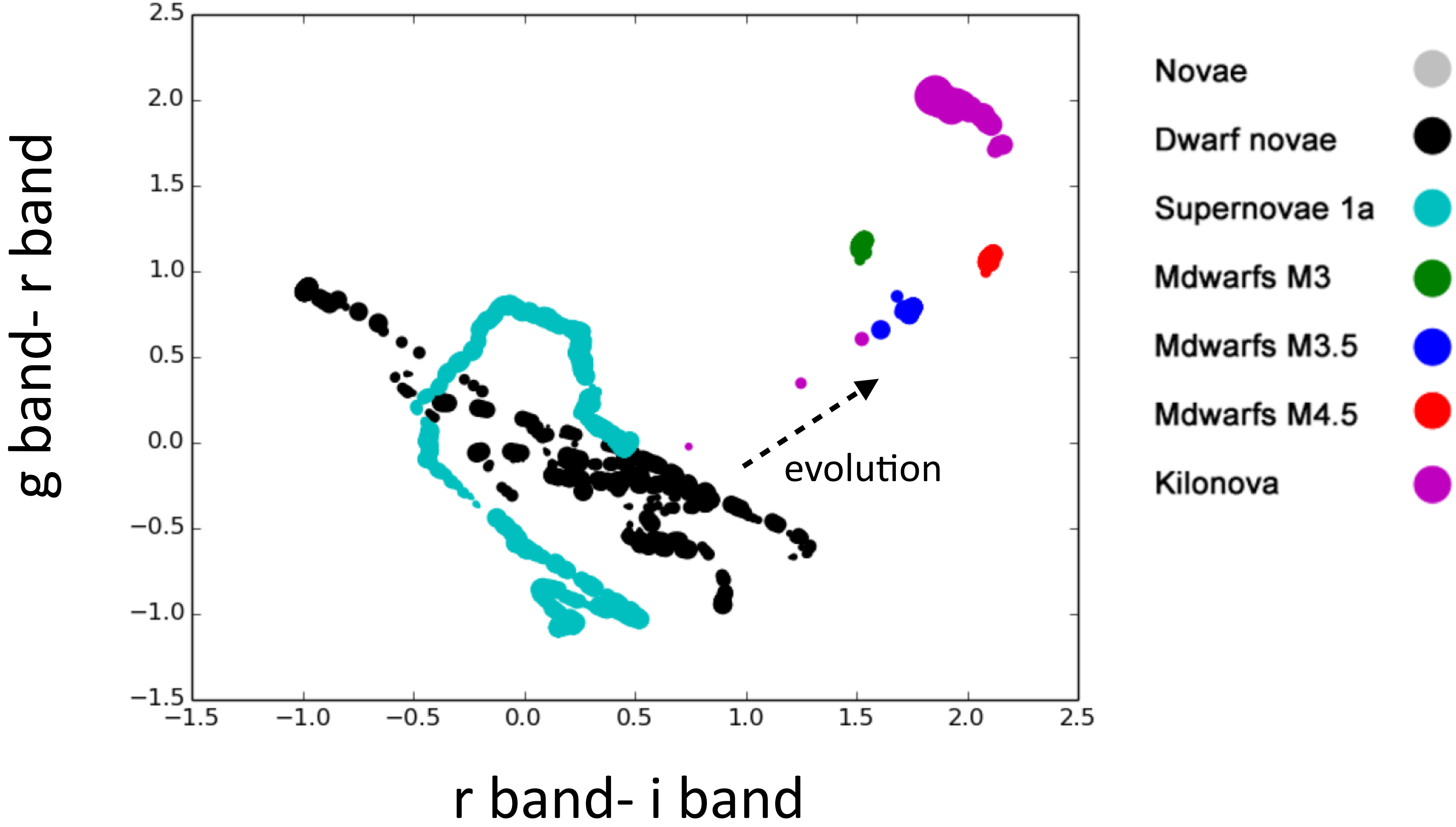


[Gehrels, Canizzaro, … Nissanke + 2015]

Reduce false positive by factor of 10-100s

Strategy III) Probabilistic Identification through different colors

[Jacobs, Nissanke et al. in prep]



[Jacobs, Nissanke et al. in prep;
use in Astrophysical Transient Toolkit for LIGO-Virgo EM Follow up
with Berry, Hu, RU members]

Conclusions: lessons to take forward

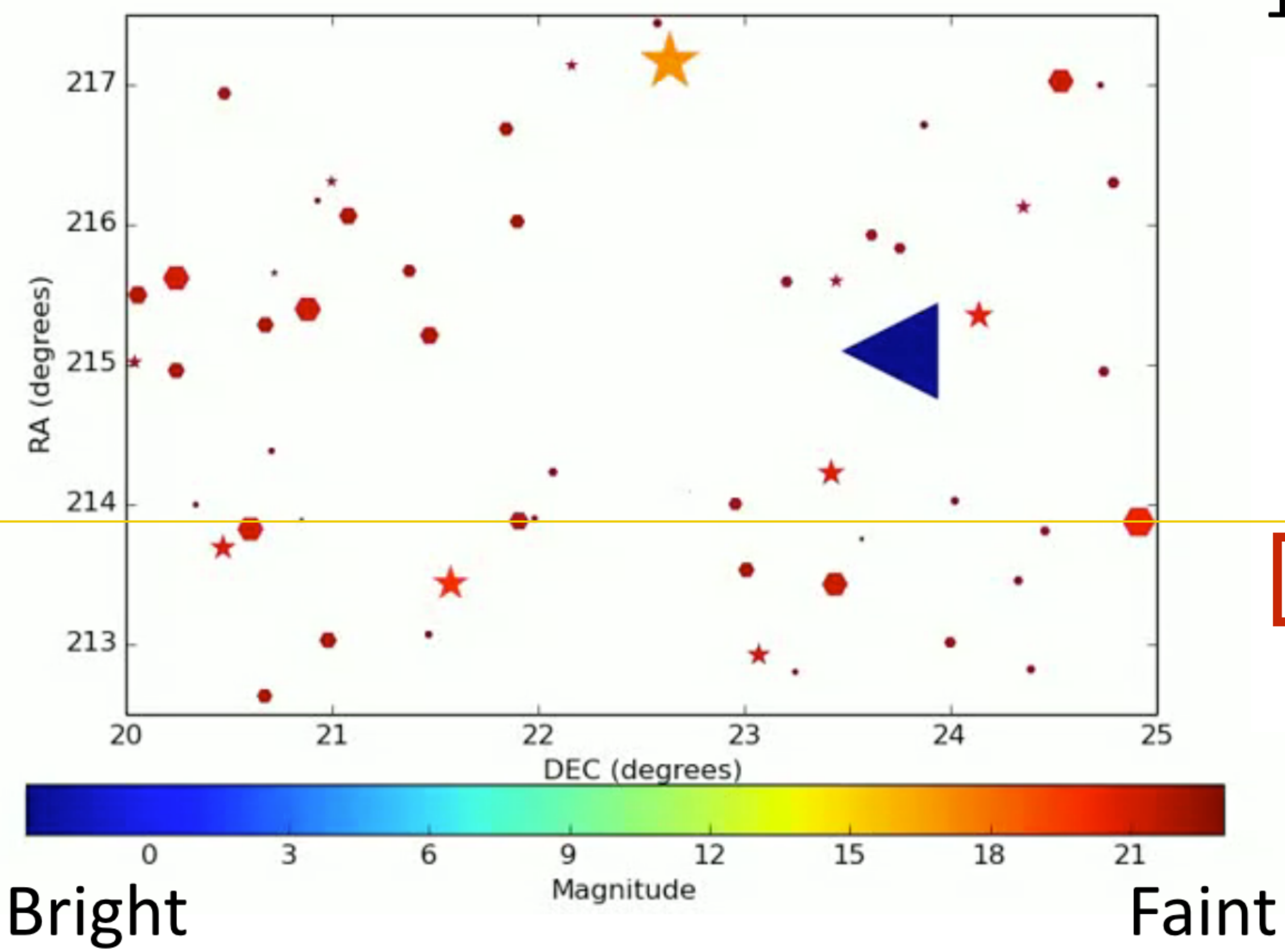
Extremely positive and heroic multi-wavelength effort using wide-field synoptic and spectroscopic capabilities to follow-up GW150414.

- EM follow-up should be prepared for BBH (at a weekly rate perhaps!) and NSBH mergers beyond NS-NS mergers.
i.e. prepare galaxy catalogs out to much larger z (photo-zs).

- GW sky position, source type (and distance), [any information on binary's inclination angle, masses and spin] released as soon as possible.

- Systematic and comprehensive understanding of the astrophysical transient and variable skies across wavebands.

Identification: Galactic Transient Sky Simulator



10 sq. deg. over 7 days

		Nr. visible
Novae	●	0
Dwarf novae	★	40
Supernovae 1a	⬢	3482 (per year)
Mdwarfs M3	▲	146
Mdwarfs M3.5	▶	159
Mdwarfs M4.5	◀	77
Kilonova	◆	1

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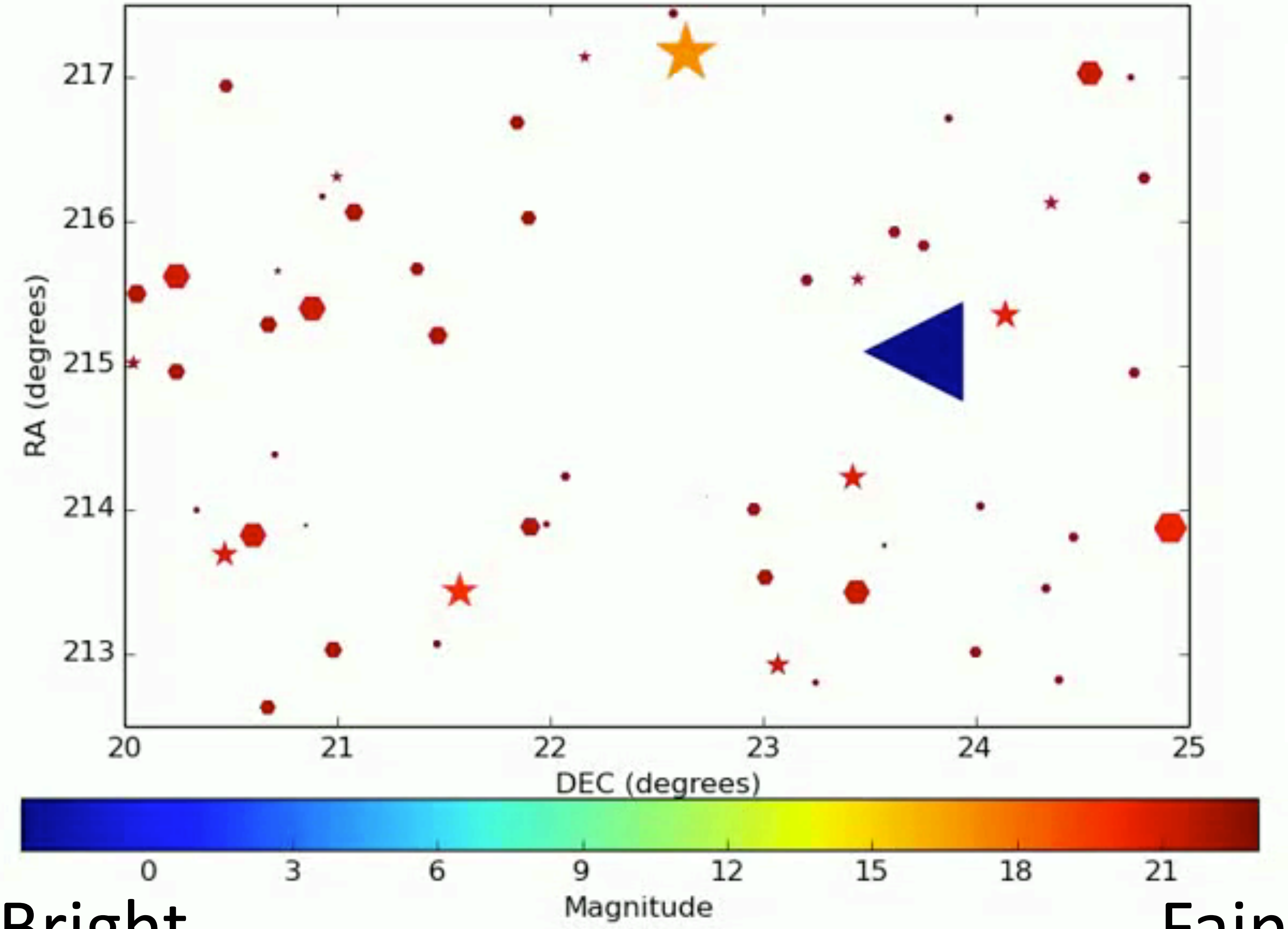

Bright

Faint

10 sq. deg. over 7 days

		Nr. visible
Novae	●	0
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[Jacobs, Nissanke et al. in prep;
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New EM facilities coming online: the BlackGEM telescope array in 2017

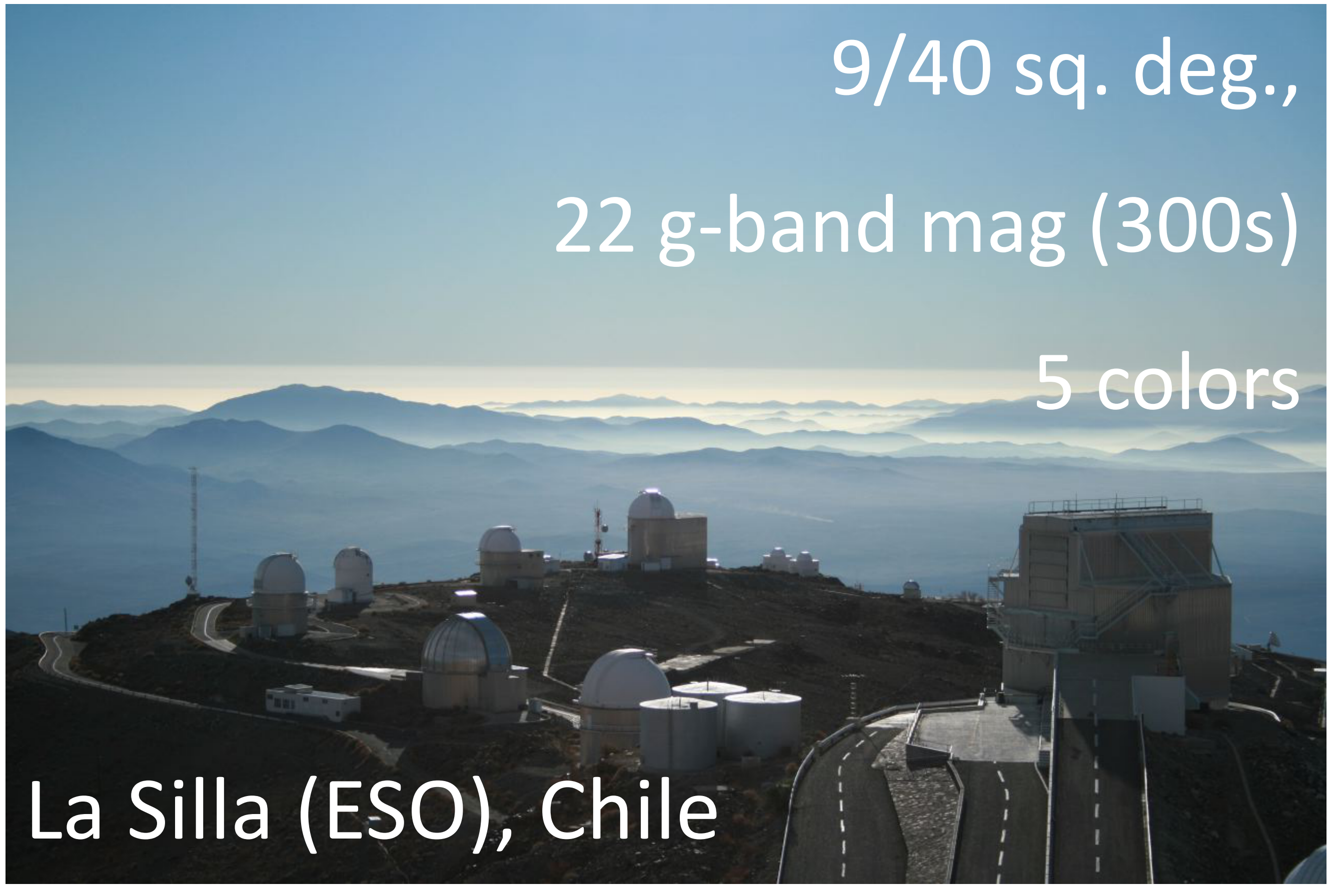
Phase-I: 3 telescopes, each with 65 cm diameter mirrors
Funded by Netherlands and KU Leuven

Phase-II: 15 telescopes

Southern sky: La Silla

- Complementarity to N. Hemisphere
- GW source positions often split
- Spectroscopic follow-up Gemini/GMT/VLT/E-ELT, ALMA, SKA, etc.
- Good seeing allows for smaller mirror

Y1+2: All Sky and Fast Synoptic Surveys



9/40 sq. deg.,

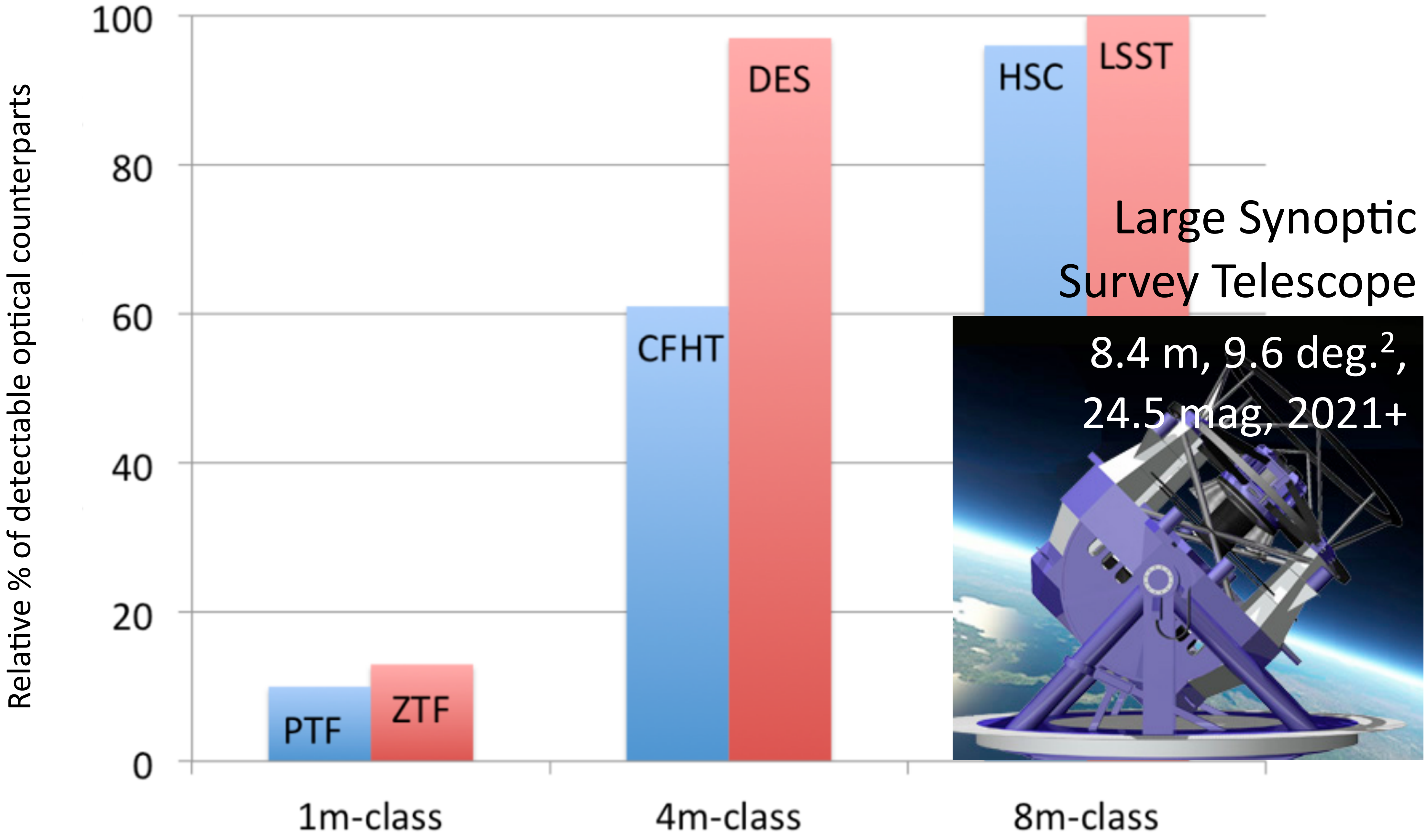
22 g-band mag (300s)

5 colors

La Silla (ESO), Chile

Prototype: MeerLICHT slewed to MeerKAT (contemporaneous optical-radio)

Optical detection in LIGO INDIA era



5 GW detectors with LIGO India: 2020s

Large Synoptic Survey Telescope

8.4 m, 9.6 deg.^{2}, 24.5 mag, 2021+

[Nissanke, Kasliwal, Georgieva 2013]

1. EM radiation: luminosity & flux

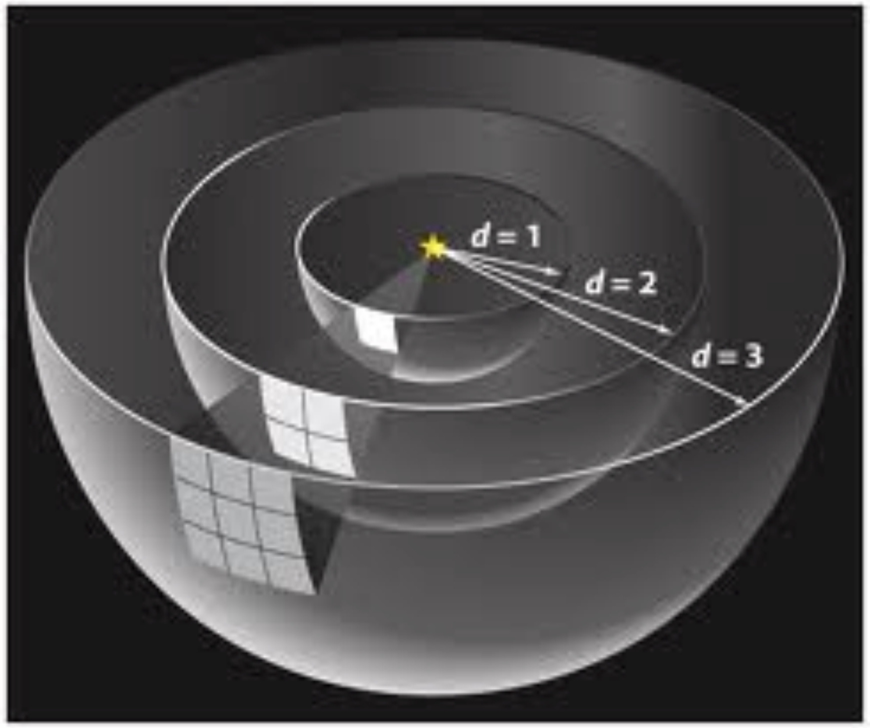
1. Luminosity - intrinsic: amount of energy radiated by an object per unit time.

$$L = \frac{dE}{dt}$$

[L_{sun}: 4 x 10^{26} W or 4 x 10^{33} erg/s]

Units: erg/s or W

2. Flux - Observable:

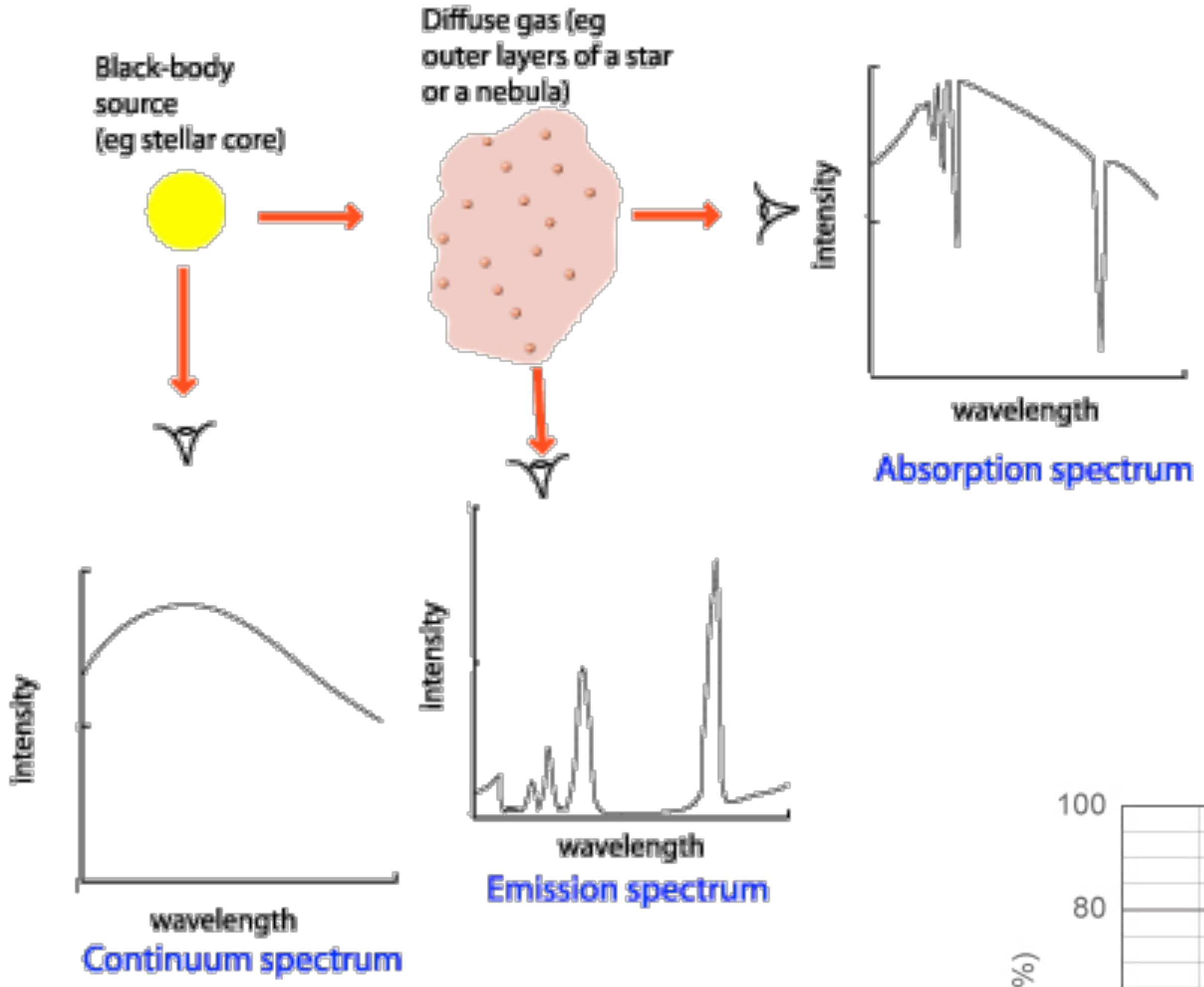


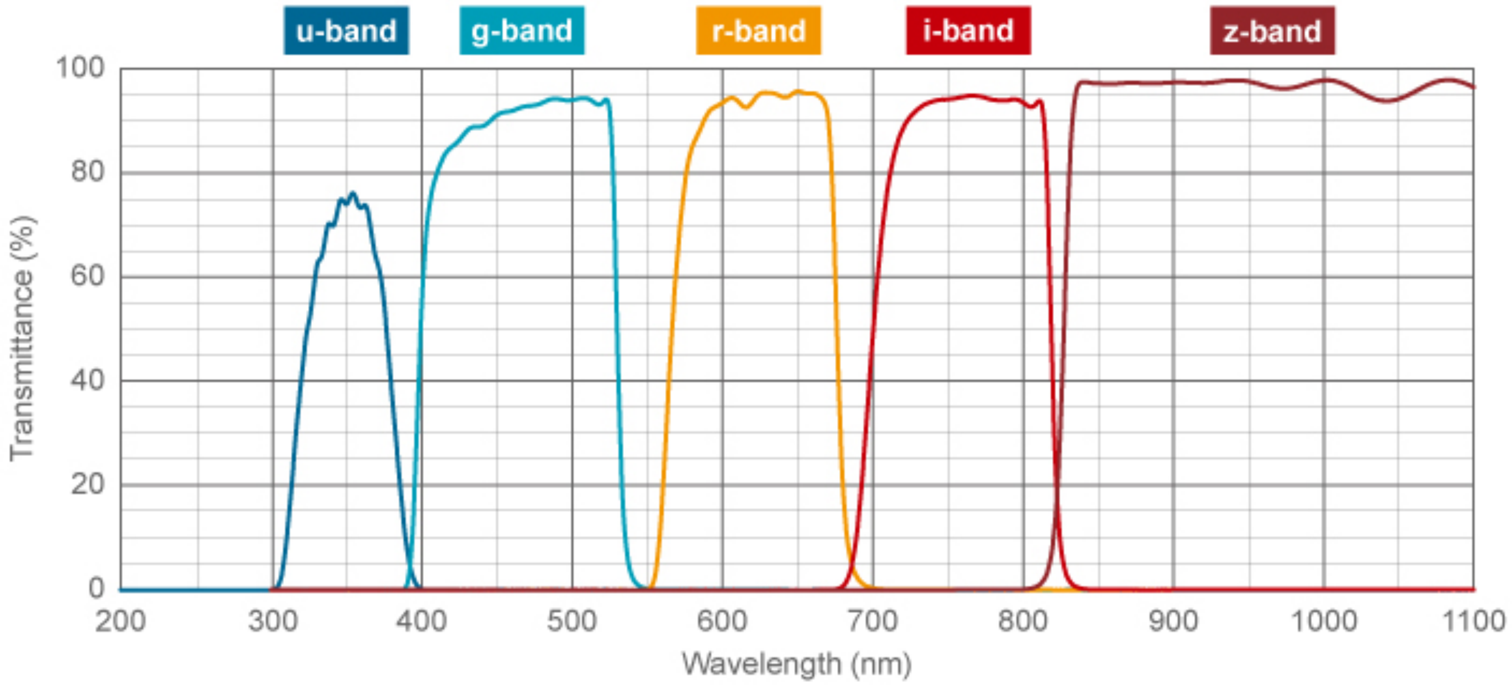
Intensity follows $1/r^2$ law

$$f = \frac{L}{4\pi d^2}$$

Units: erg/s/cm^2 or W/m^2

2. EM radiation: observable flux





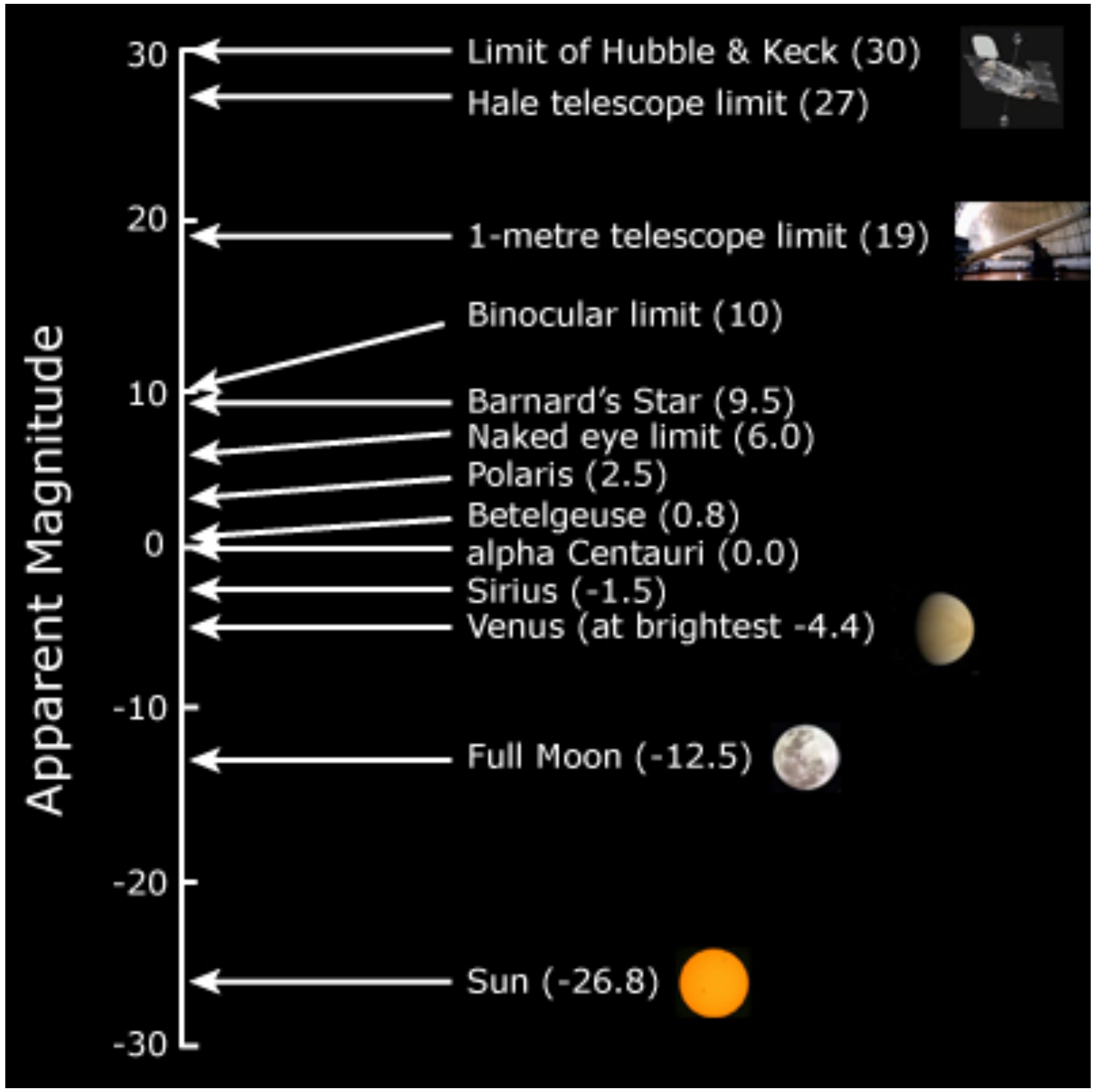
3. EM radiation: magnitudes

apparent magnitude (Hipparchus, 2100 years ago!)

$$m_1 - m_2 = -2.5\log_{10}(f_1 / f_2)$$

- logarithmic scale.

- Increase in mag. 2.5 is equiv. to x 10 dimmer in brightness.



absolute magnitude:

apparent magnitude at 10 pc

(1pc = 3.1 x 10^{18}m = 3.3 ly)

$$M = m - 5\log_{10} d + 5$$