S. Bradley Cenko - NASA GSFC and Univ. Maryland

Electromagnetic Counterparts to Gravitational Waves

GROWTH
Global Relay of Observatories Watching Transients Happen

NSF

PIRE

A Most Remarkable Discovery

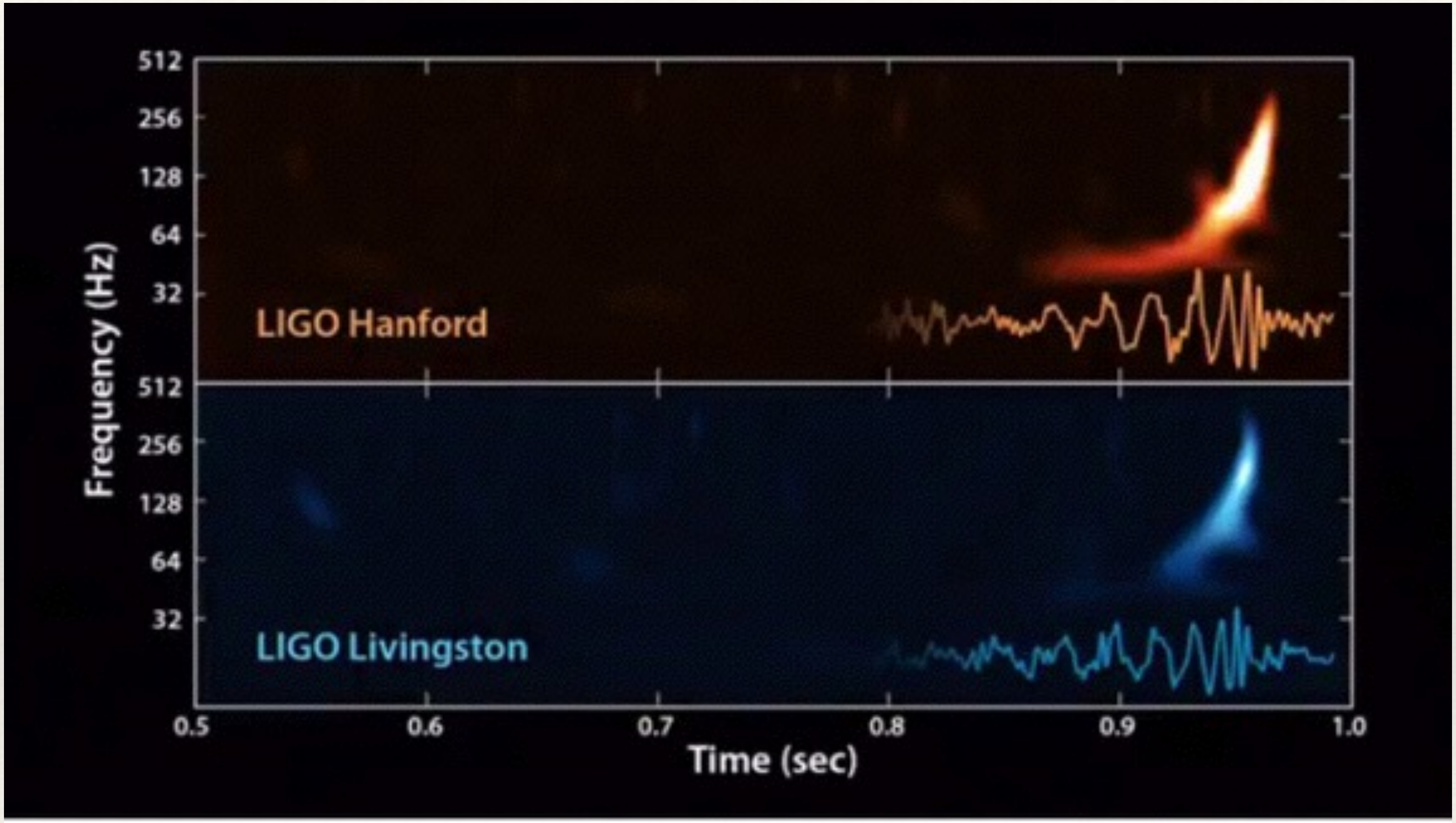

Image Credit: NSF

GW150914: The first direct detection of gravitational waves!

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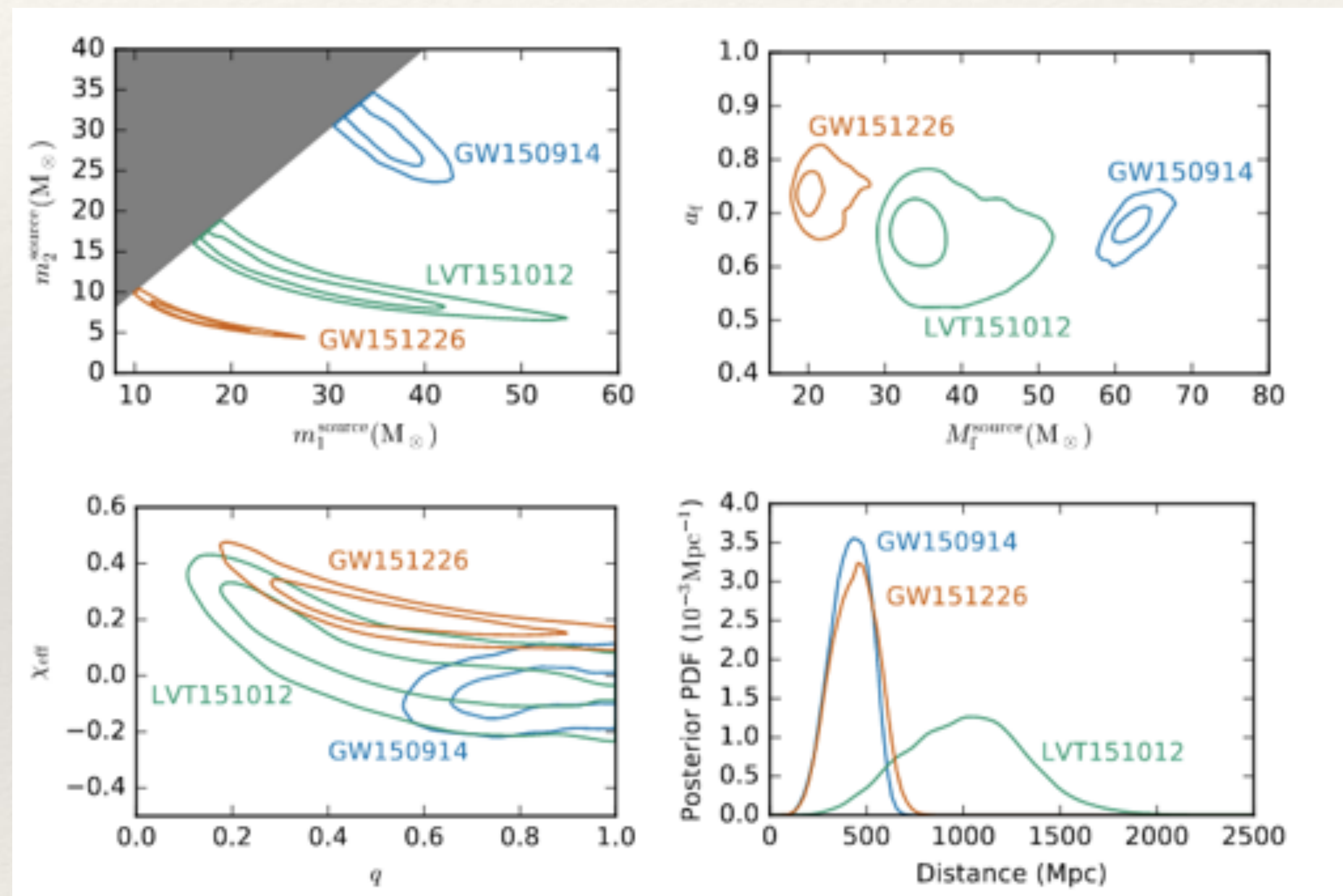
GW Parameter Estimation

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. 2016

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Astrophysical Implications

- LIGO discoveries are only *confirmed* binary black hole systems, and *most massive* “stellar-mass” black holes ever found
- Two competing hypotheses for how to generate such massive black holes:
  - Low metallicity environment (leads to very massive progenitor stars)
  - Dynamical interactions in dense stellar environments (e.g., clusters)

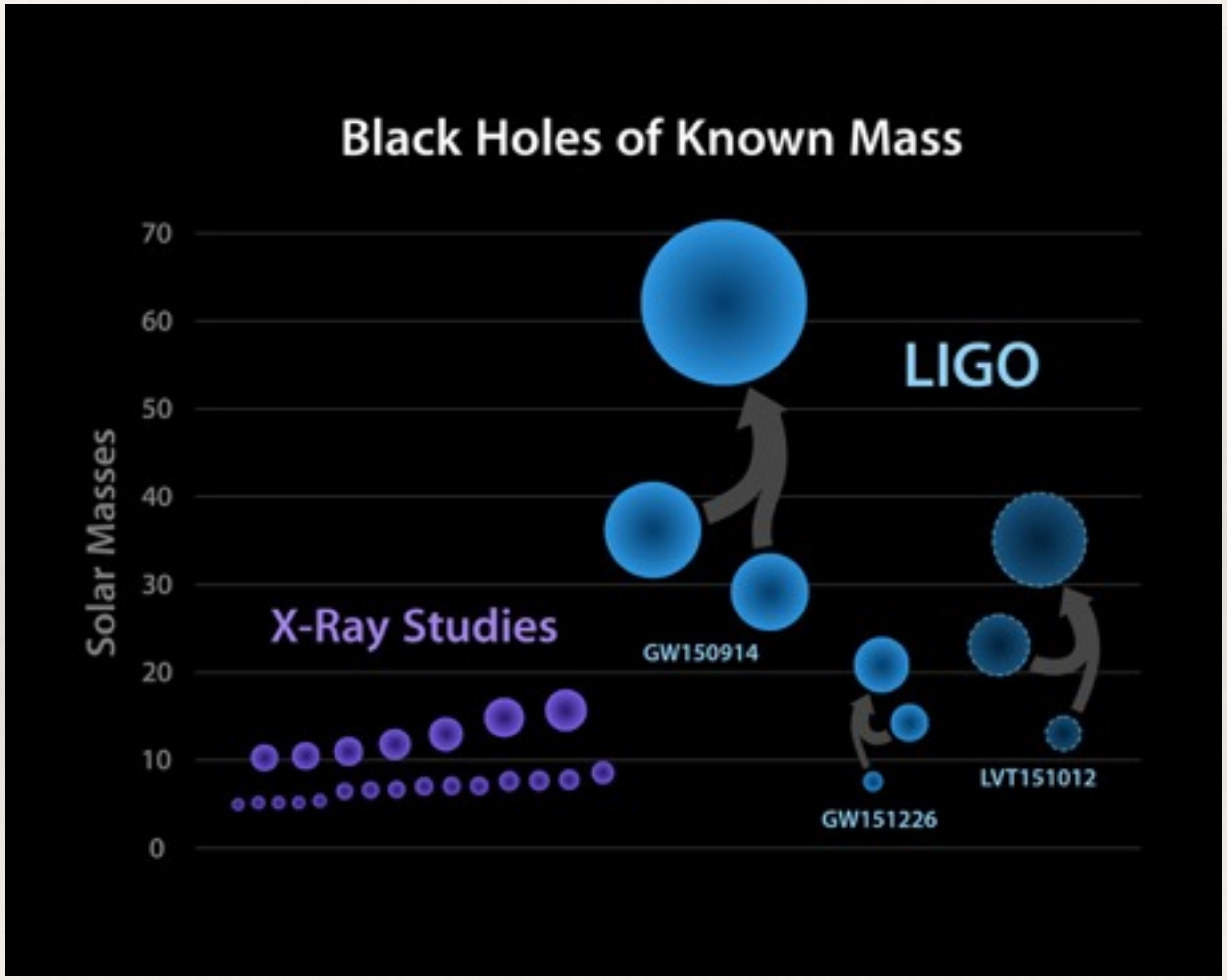

Image Credit: LVC

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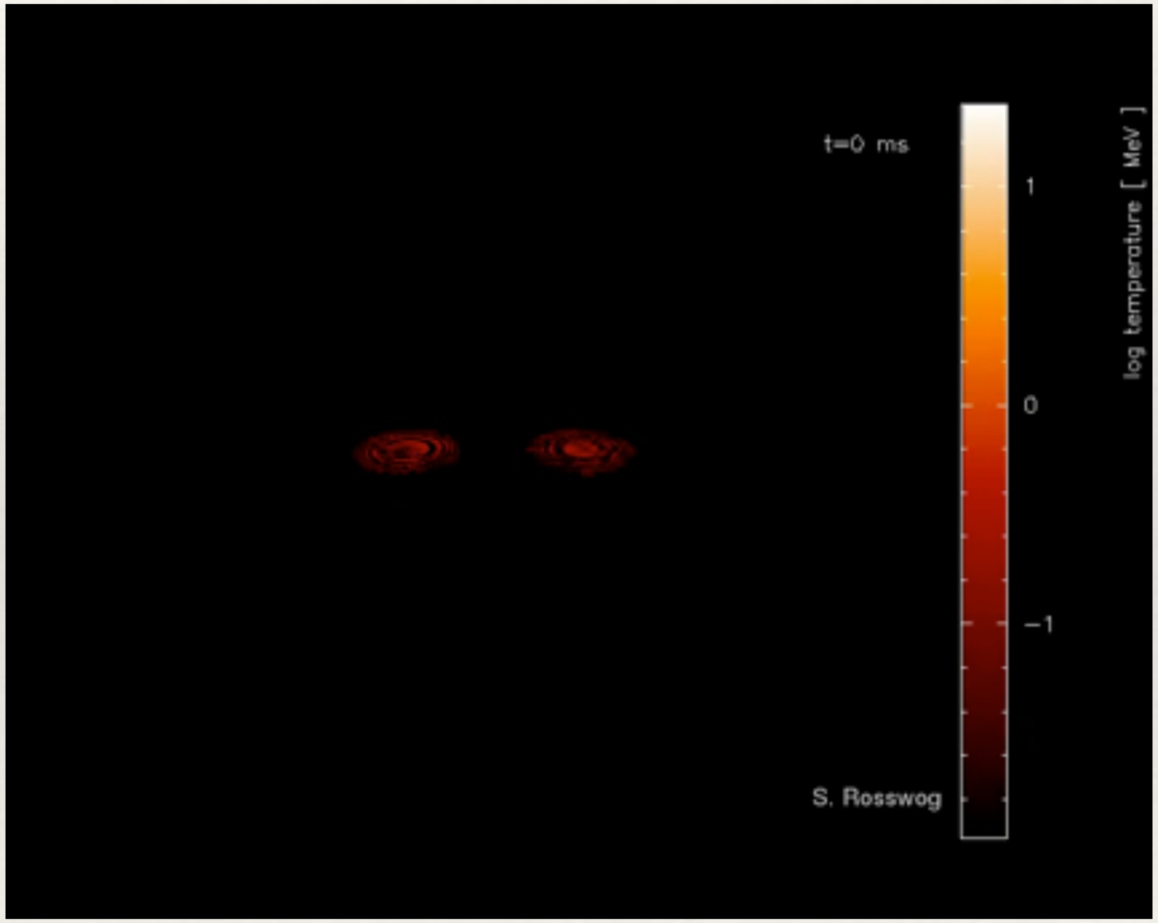
Why Electromagnetic Counterparts?

- Redshifts (together with improved distances, can do cosmology)
- Astrophysical context (host galaxy, stellar populations, star formation, metallicity, …)
- r-process nucleosynthesis (possibly dominant source of heavy elements such as Au and Pt)



Rosswog *et al*., 2013

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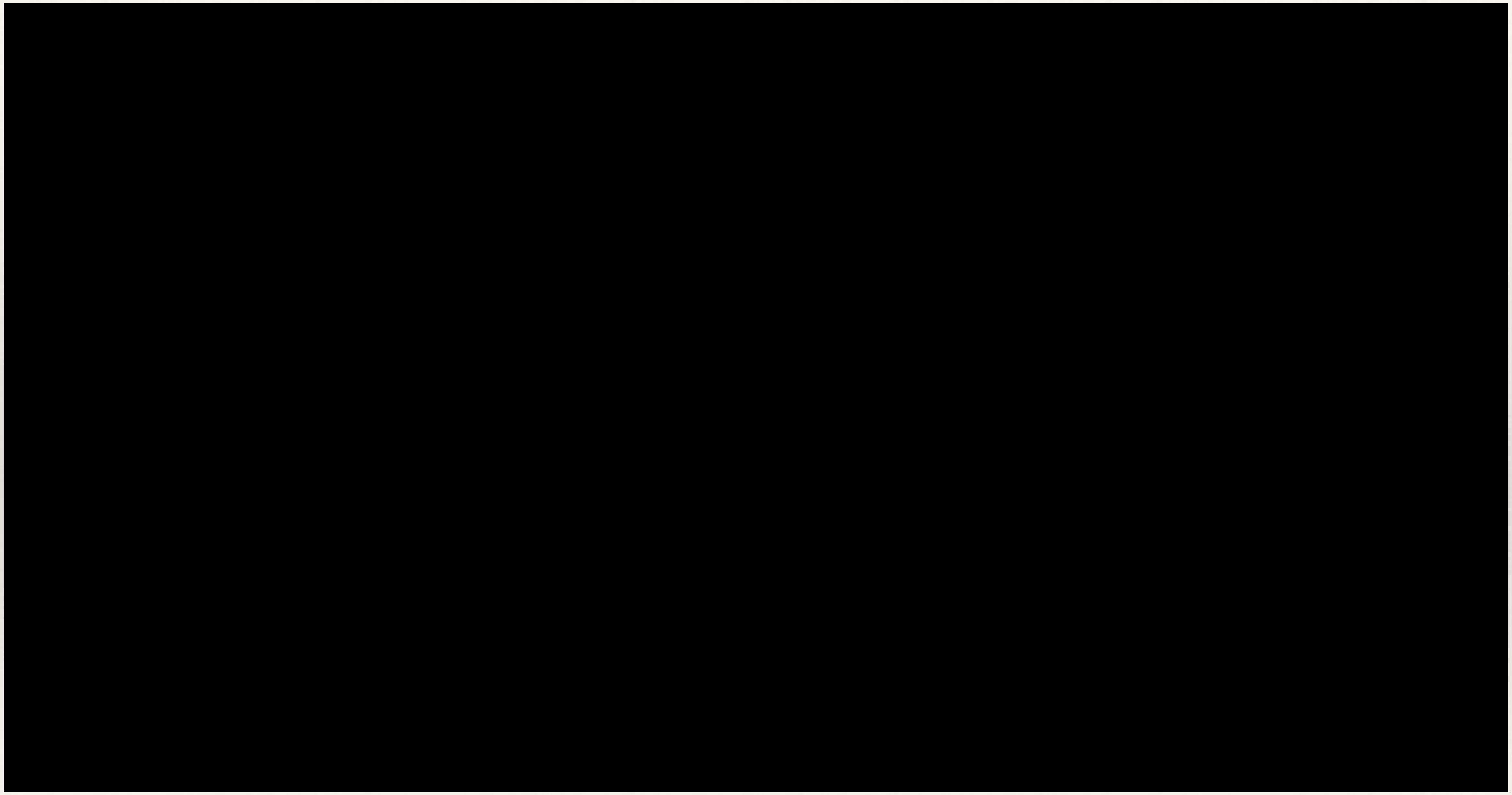
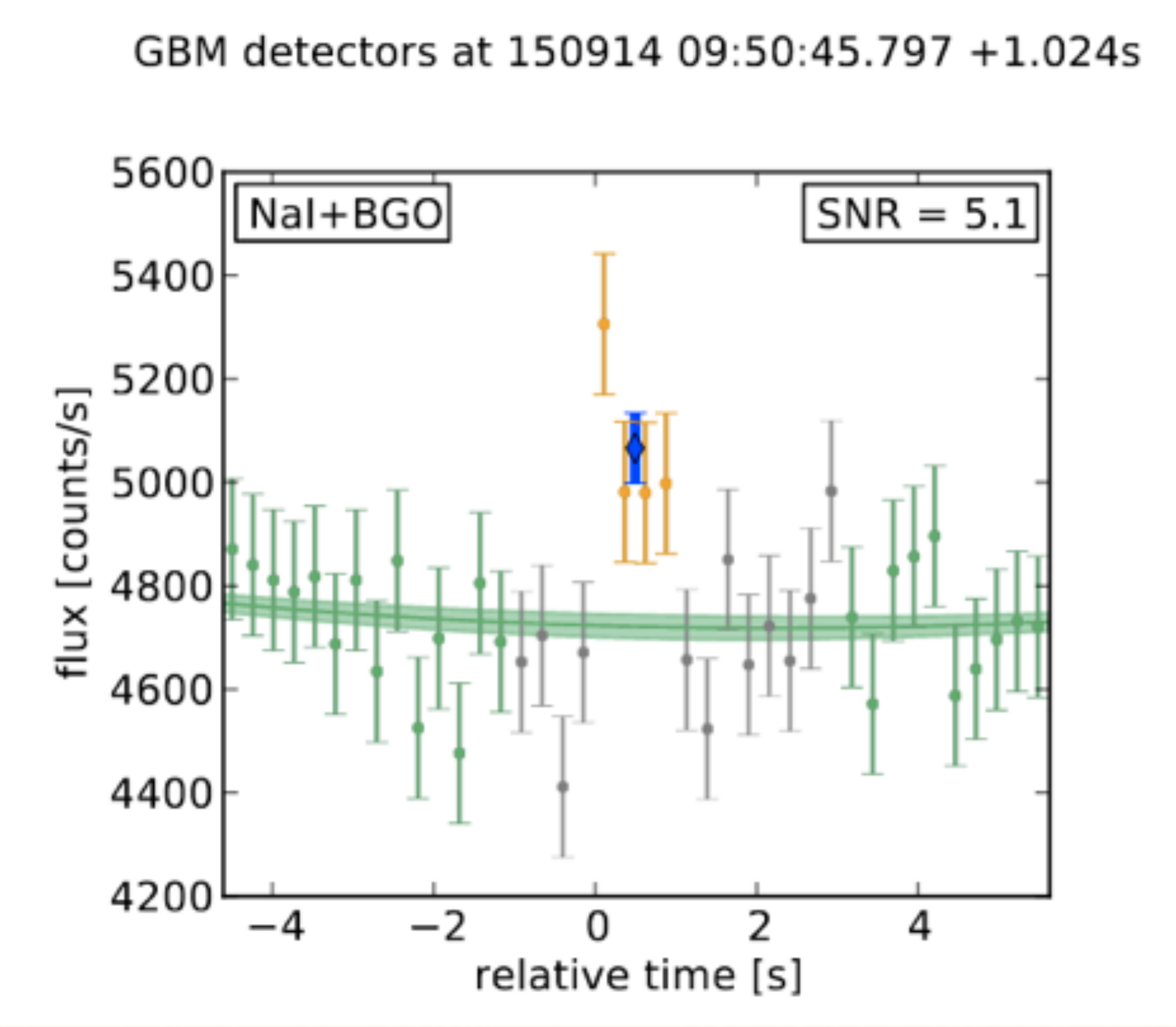
EM Counterparts I: Binary Stellar-Mass BH

EM Counterparts I: Binary Stellar-Mass BH



Cenko et al. 2014: Theory of BBH Mergers, ESP Journal of The Obvious

EM Counterparts I: Binary Stellar-Mass BH



Connaughton *et al.* 2016

Weak γ-ray signal 0.4 s after the GW150914 detection identified with *Fermi*-GBM. But no such signal seen from other events (despite more favorable orientations)

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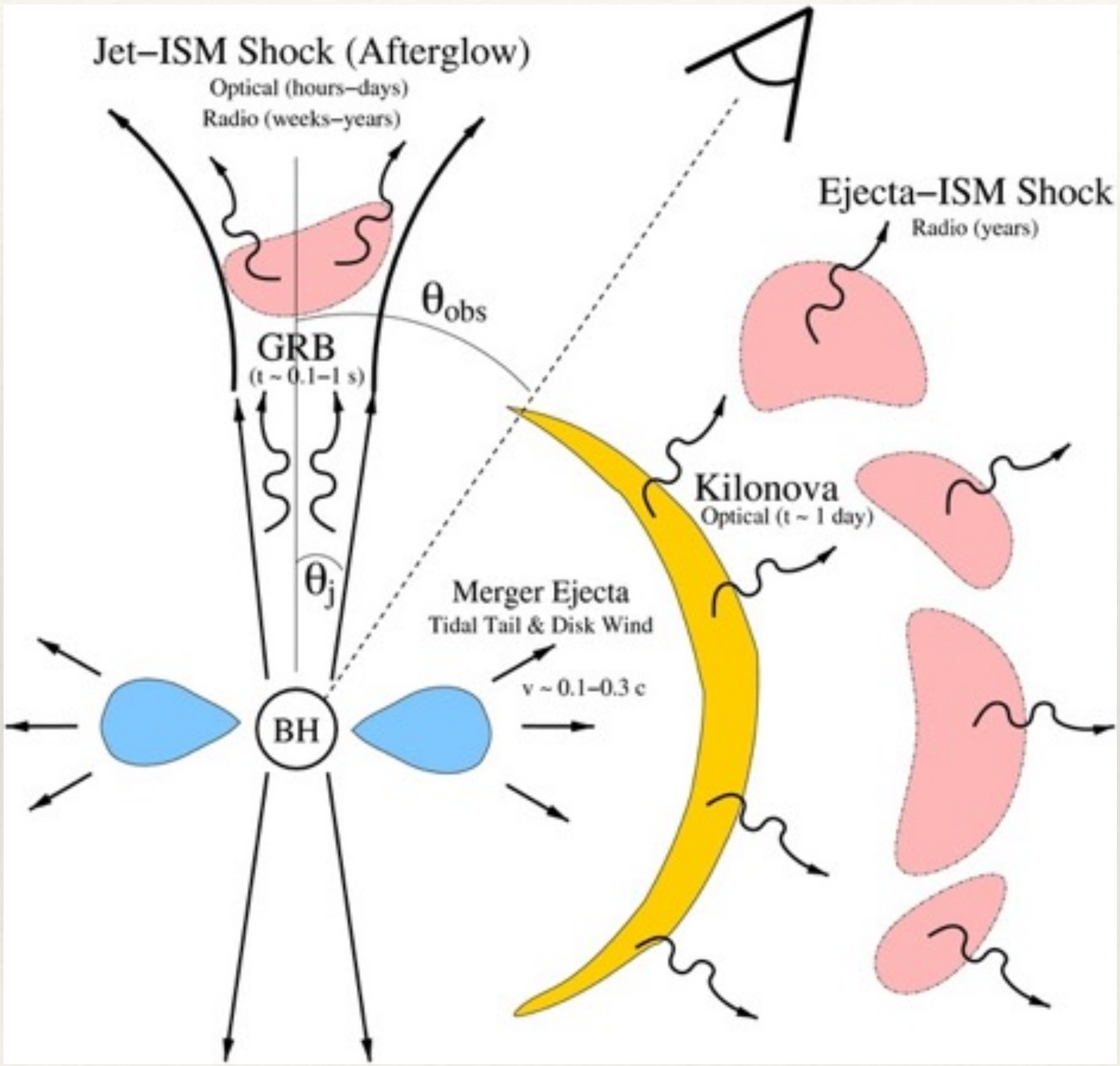
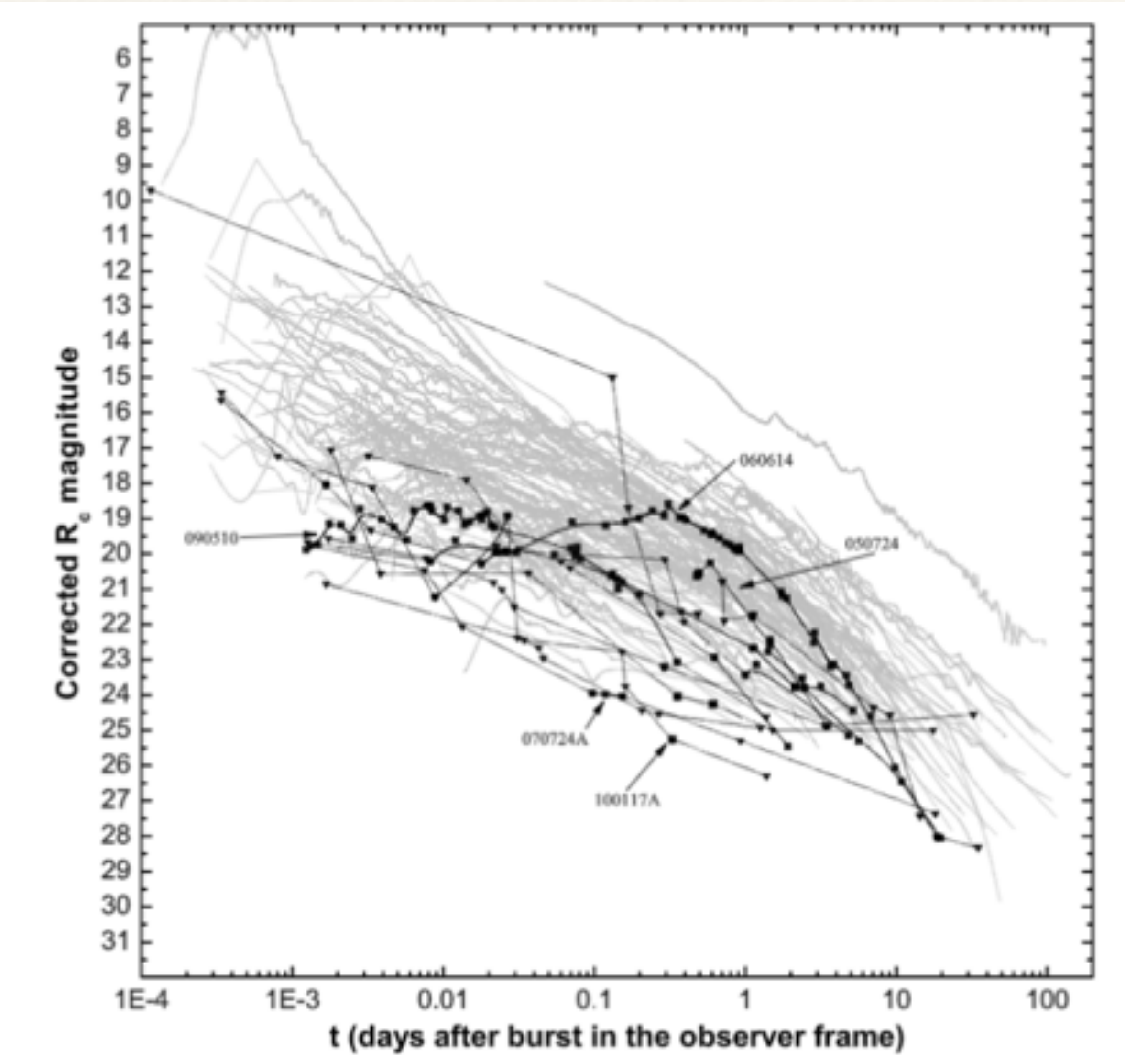
EM Counterparts II: Binary Neutron Star



Metzger & Berger 2013

- For binary NS system, accretion onto newly formed BH can lead to bright EM emission
- Gamma-Ray Burst: Relativistic Ejecta along merger axis
- "Kilonova": r-process nucleosynthesis from dynamical ejecta (i.e., isotropic)

EM Counterparts II: Binary Neutron Star



Kann *et al.* 2011

- Short GRB *afterglows*: very bright (up to 18 mag observed, not correcting for GW horizon distance), but:
  - Fade rapidly (time scale of hours to days)
  - **Highly beamed** (only 1 in ~ 25 events will have jet oriented towards Earth)

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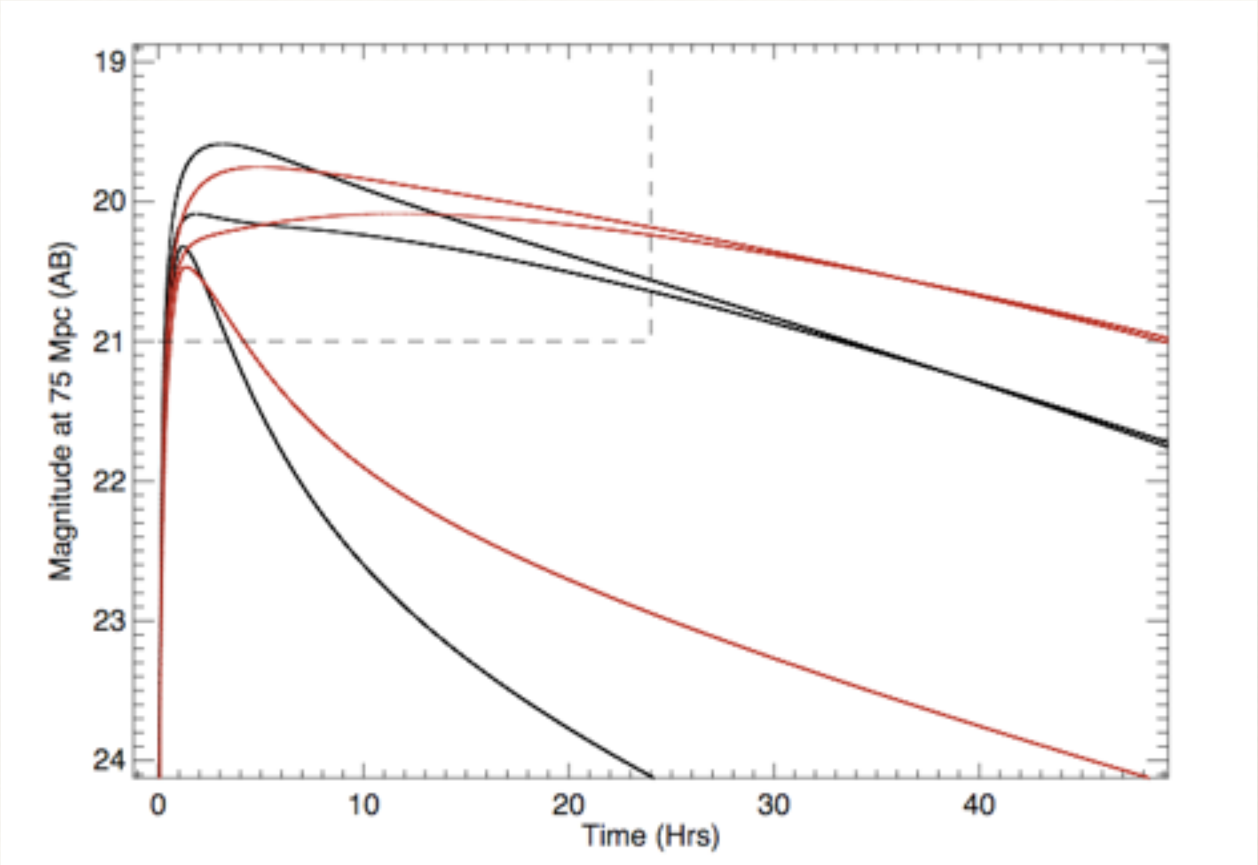
EM Counterparts II: Binary Neutron Star



Kasliwal *et al.* 2016

- Kilonova emission:
  - Relatively faint and red (due to opacity from heavy elements)
  - Lasts hours to ~ week (depending on composition)
  - But should be **isotropic**

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EM Sky Localizations

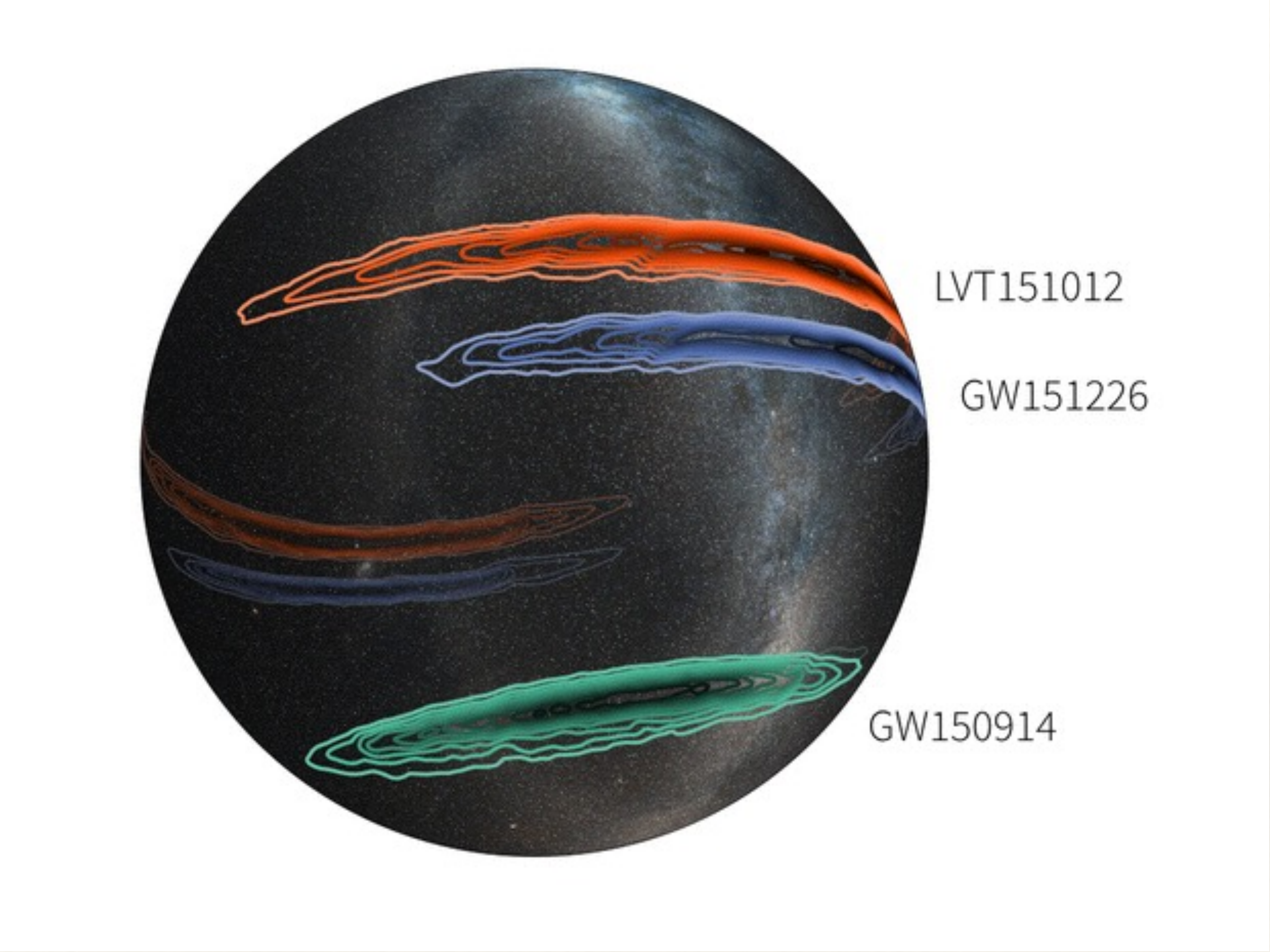

Image Credit: LIGO/Leo Singer

Localizations of hundreds to thousands of square degrees ⇒ Large-area Facilities

EM+GW Strategy: GROWTH!

- Tile large-area GW localizations with wide-field P48 telescope
- Targeted follow-up of interesting transient candidates with facilities in the GROWTH network
- Intra-night cadence critical for (expected) short variability time scales

The GW Dining Experience

Course	Timeline	Detectors	BNS Horizon Distance	Results
Amuse-bouche (O1)	**Sep-Dec 2015**	**2 LIGO**	**75 Mpc**	**3 BBHs : 0/1 Counterparts**
Appetizer (O2)	Aug-Dec 2016	2 LIGO + Virgo	100 Mpc	TBD (Soon!)
Soup/Salad (O3)	2017-2018	2 LIGO + Virgo	150 Mpc	TBD
Main Course (O4+)	2019+	2 LIGO + Virgo + KAGRA + Indigo (2023)	200 Mpc	TBD

Abbott et al. 2016

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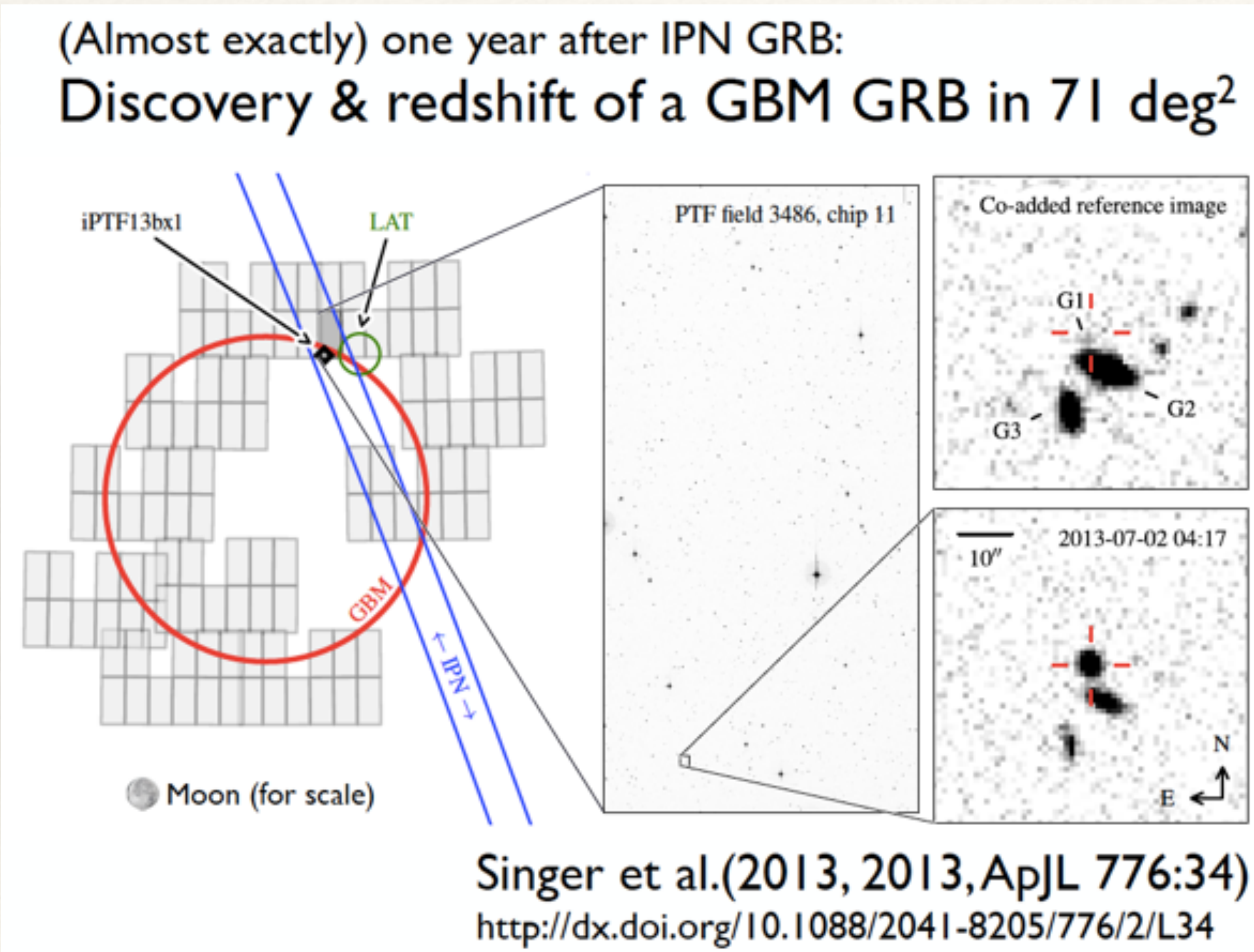
Pre-O1 Results: *Fermi*-iPTF Follow-Up



Singer et al. 2013

- Test run for aLIGO: GRBs discovered by *Fermi* GBM
- Poorly localized (>~ 100 square degrees) with bright, but rapidly fading optical counterparts
- Identified 8 optical afterglows (out of 35 searched fields), including several very nearby (and hence rare events)
- Thesis project of Leo Singer

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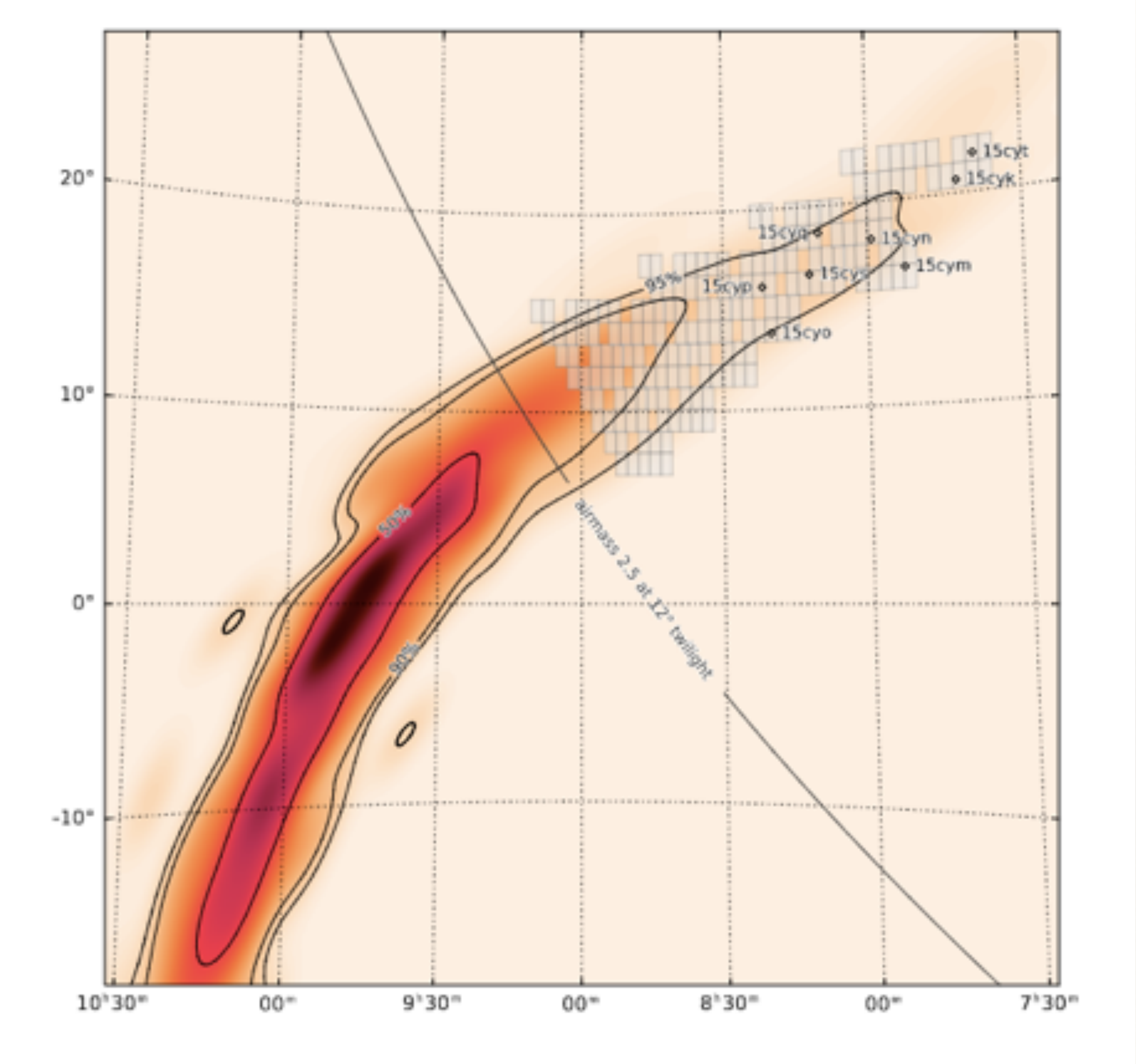
O1 Results: GW150914



Kasliwal et al. 2016

- First GW trigger localization largely in Southern hemisphere (only ~ 2% of initial localization accessible to iPTF!)
- Nonetheless, went through standard iPTF image subtraction and vetting to identify 8 candidates in the error region

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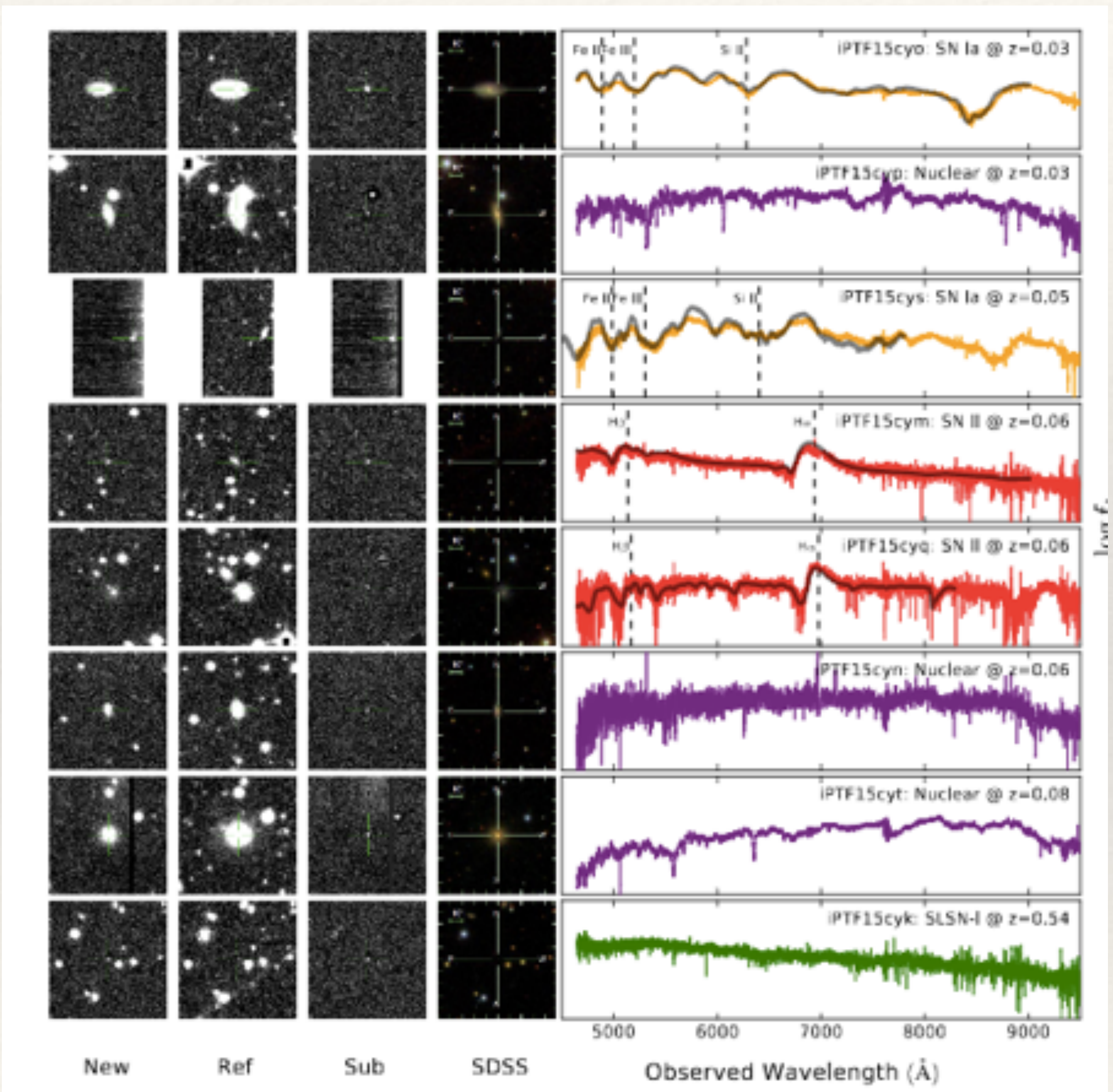
O1 Results: GW150914



Kasliwal et al. 2016

- **All** candidates acquired prompt same-night (few hours!) spectroscopic classification
- Not surprisingly, all unrelated to GW event
- Nice demonstration of pipeline capabilities and follow-up from GROWTH facilities

O1 Results: GW150914

iPTF SEARCH FOR AN OPTICAL COUNTERPART TO GRAVITATIONAL WAVE TRIGGER GW150914

M. M. Kasliwal [1], S. B. Cenko [2, 3], L. P. Singer [2, 4], A. Corsi [5], Y. Cao [1], T. Barlow [1], V. Bhalerao [6], E. Bellm [1], D. Cook [1], G. E. Duggan [1], R. Ferretti [7], D. A. Frail [8], A. Horesh [9], R. Kendrick [10], S. R. Kulkarni [1], R. Lunnan [1], N. Palliyaguru [5], R. Laher [11], F. Masci [12], I. Manulis [9], A. A. Miller [1,13,14], P. E. Nugent [15,16], D. Perley [17], T. A. Prince [1], R. M. Quimby [18,19], J. Rana [6], U. Rebbapragada [13], B. Sesar [20], A. Singhal [6], J. Surace [11], A. Van Sistine [21]

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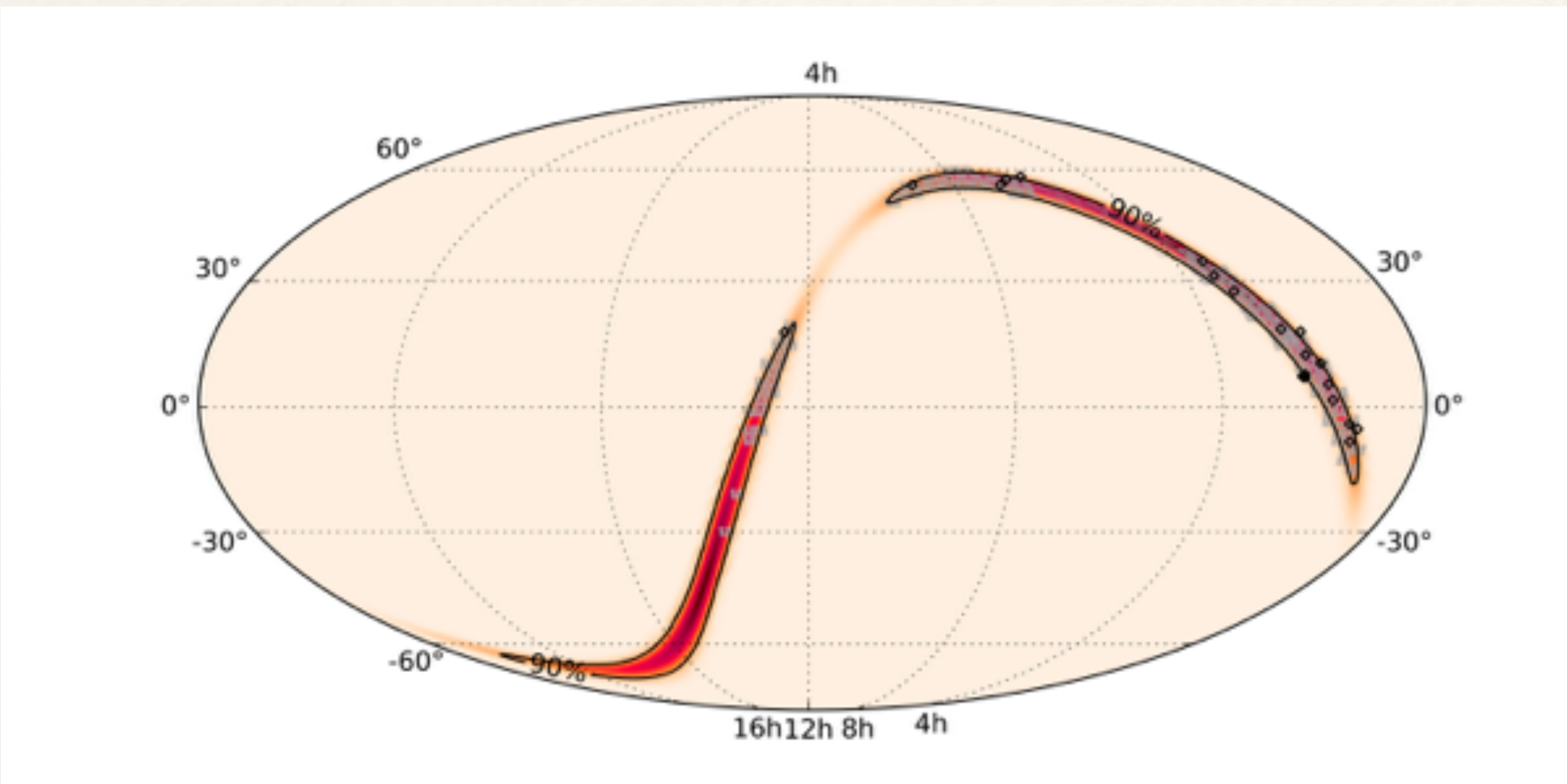
O1 Results: GW151226



- Second (bona fide) GW trigger localization much better positioned: able to image ~ **50%** localization region with P48

Kasliwal et al, in prep

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O1 Results: GW151226

name	RA Dec (iPTF) (hh:mm:ss deg:mm:ss)	Classification	VLA epoch (MJD)	Frequency (GHz)	Flux or 3σ UL (μJy beam^{-1})
iPTF15fhl	12:28:13.60 17:37:01.4	Ic	57386.436	4.9	358 ± 22
"	"	"	"	7.3	258 ± 18
"	"	"	57394.386	4.9	339 ± 20
"	"	"	"	7.3	203 ± 14
"	"	"	57408.299	4.9	414 ± 34
"	"	"	"	7.3	322 ± 28
iPTF15fgl	02:32:59.78 +18:38:07.7	Ibn	57395.175	4.9	60.6 ± 8.9
"	"	"	"	7.3	37.7 ± 8.5
"	"	"	57401.127	4.9	75.4 ± 9.4
"	"	"	"	7.3	29.5 ± 9.1
"	"	"	57400.096	2.9	86 ± 26
"	"	"	"	9.0	35.5 ± 7.0
"	"	"		14.6	25.2 ± 6.5
"	"	"	57407.126	5.2	59 ± 11
"	"	"	"	7.4	57 ± 11
"	"	"	57409.070	3.0	97 ± 28
"	"	"	"	9.0	31.2 ± 7.2
"	"	"	"	14.7	28.3 ± 6.7

Palliyaguru et al. 2016

- Over course of O1, 16 iPTF candidates followed up with radio observations (for all 3 triggers)
- Radio observations useful to distinguish "ordinary" transients (e.g., SNe) from potential GW counterparts

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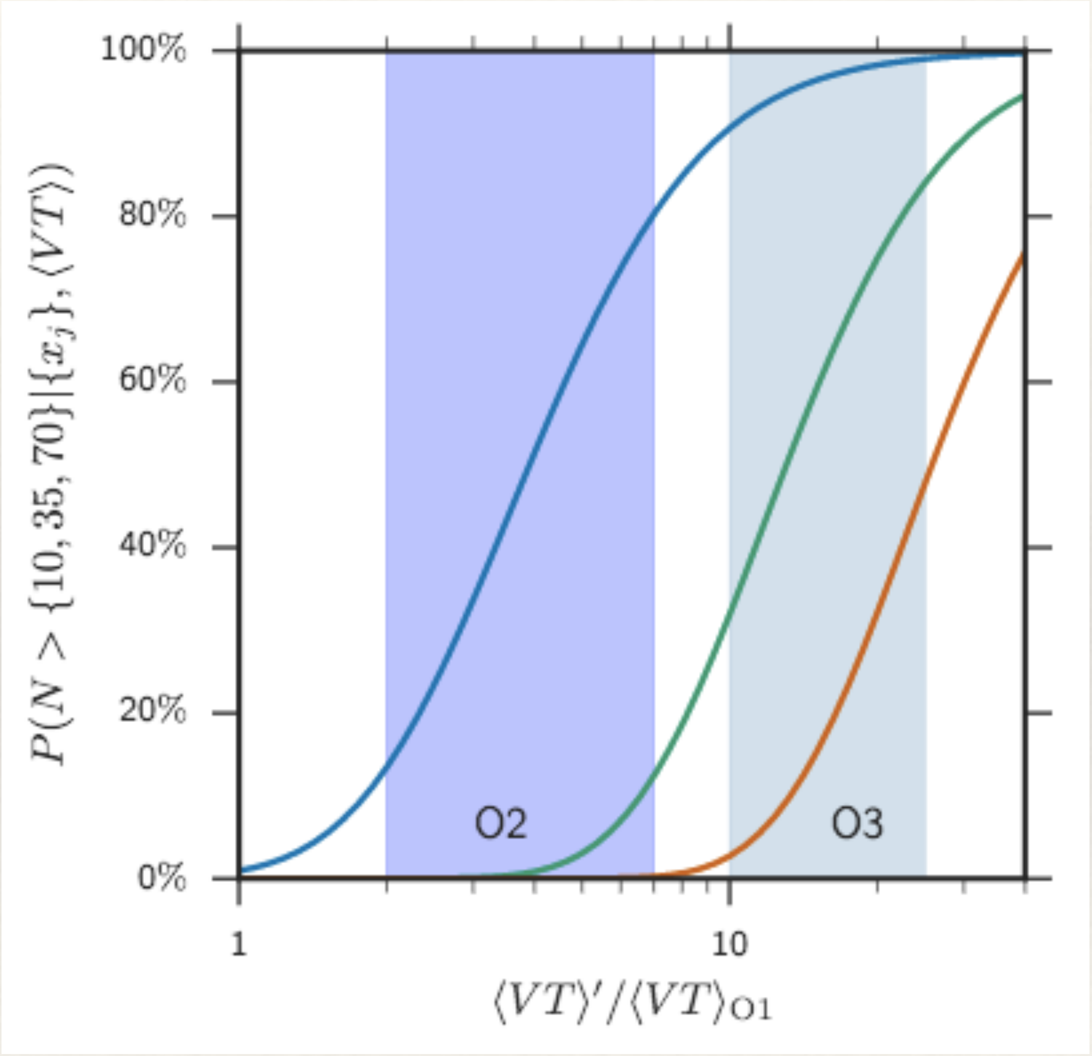
O2 Prospects (Aug 16 - Jun 17)

- O2 run expected to begin ~ August 2016
- aLIGO detectors upgraded sensitivity ⇒ O(10) BBH detections expected
- Possible first direction detection of NS-NS or NS-BH merger
- aVirgo expected to come online at end of run, will greatly reduce size of localizations

Probability of N > 10, 35, 70 BBH mergers



Abbott et al. 2016

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O3+ Prospects: Zwicky Transient Facility

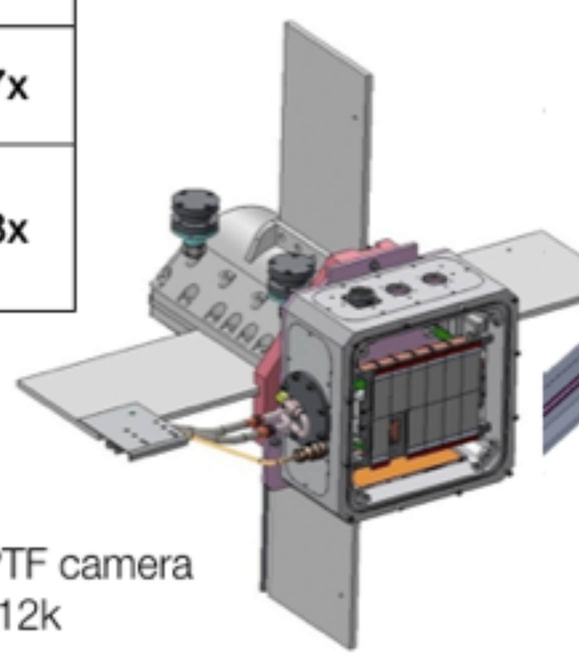
ZTF will survey an order of magnitude faster than PTF.

	PTF	ZTF
Active Area	7.26 deg^2	47 deg^2
Overhead Time	46 sec	<15 sec
Optimal Exposure Time	60 sec	30 sec
Relative Areal Survey Rate	1x	**14.7x**
Relative Volumetric Survey Rate	1x	**12.3x**

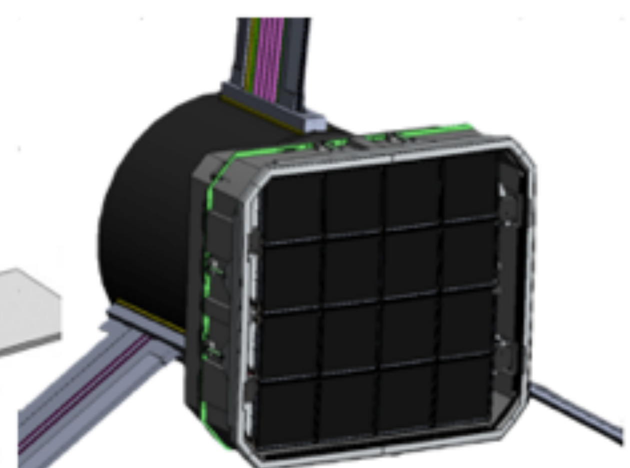
3750 deg^2/hour

⇒ 3π survey in 8 hours

>250 observations/field/year
for uniform survey



Existing PTF camera
MOSAIC 12k



New ZTF camera:
16 6k x 6k e2v CCDs

Together with increased detection rate of NS binaries, ZTF will be significantly more powerful for optical counterpart searches: same depth but 10x area!

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EM+GW Summary

- Detection of EM counterparts would enable extremely exciting advances in what is already a groundbreaking new field (gravitational wave astronomy)
- Our GROWTH network of global telescopes is ideally suited to this complex task: wide-field searches with iPTF/ZTF and same-night follow-up by partners around the globe
- First NS binaries (either NS-NS or NS-BH) expected in next few years, same timeline as ZTF, so watch this space!

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