A3D3 Post-Bacc Final Presentation/Research Update

Abby Gray

PI: Prof. Michael Coughlin
University of Minnesota
Multi-Messenger Astrophysics

OUTLINE

- Multi-Messenger Astrophysics Domain, science questions and Machine Learning implementation motivation

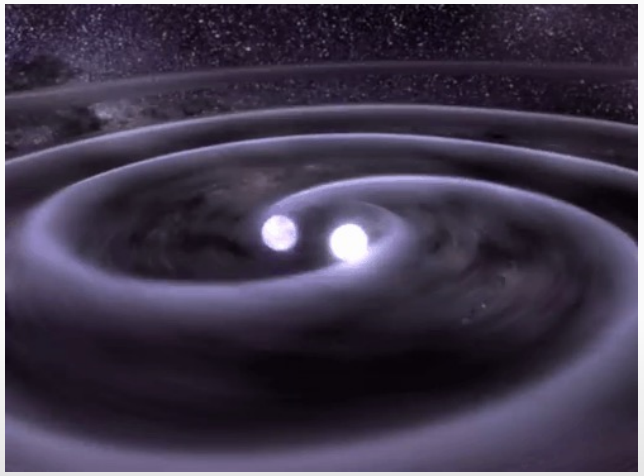
- Projects

  Observing Scenarios Paper

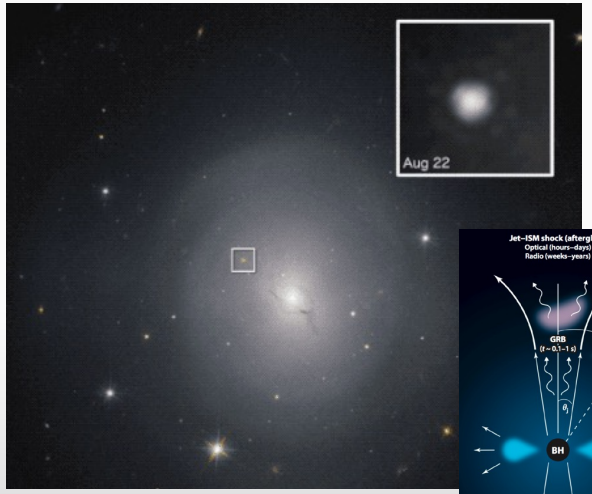
  Training dataset for Low-Latency EM Follow-up

- My A3D3 experience

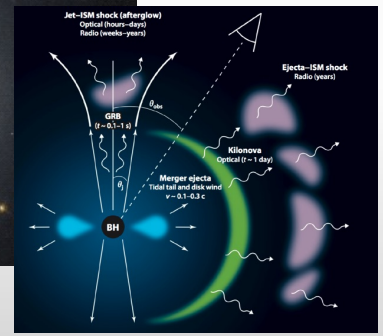
Gravitational Waves



Electromagnetic Waves

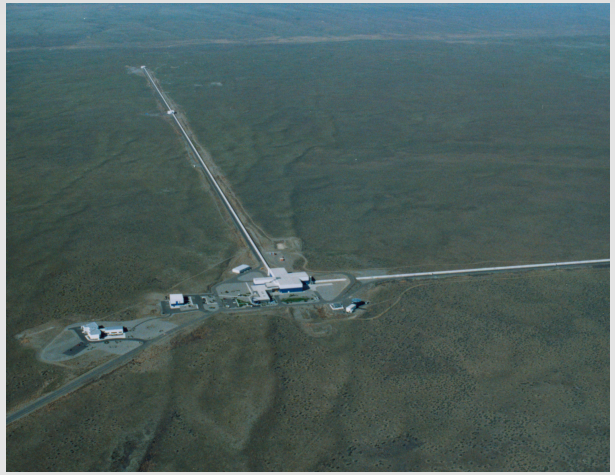


Kilonovae



Search for coincident GW-EM signal

LIGO (Hanford)



Zwicky Transient Facility

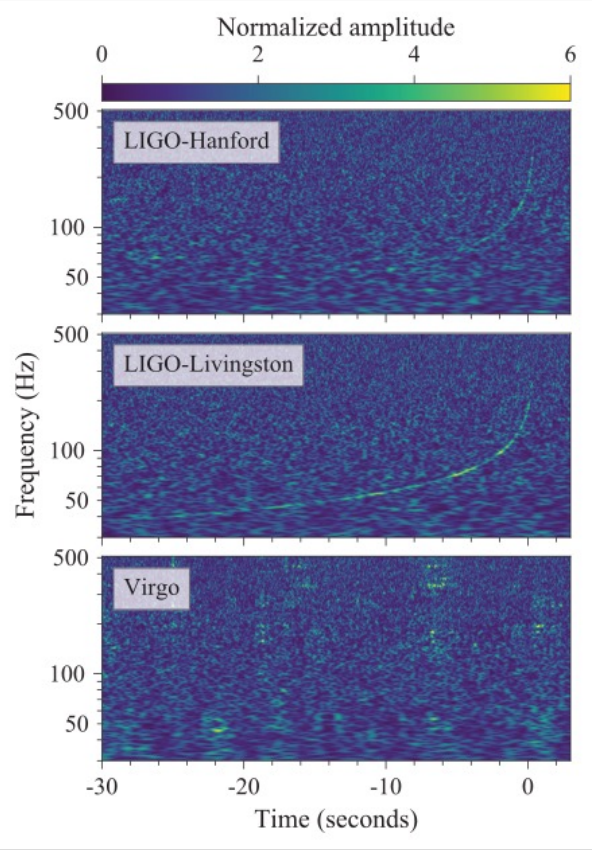
LSST (Rubin)

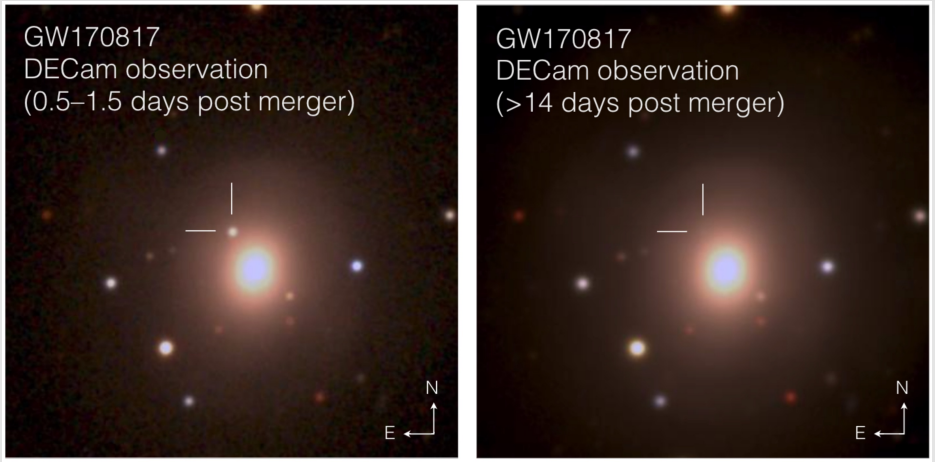
GW170817

- Fueled many gravitational wave (GW) follow-up campaigns (ZTF, LSST) and project efforts

- BNS follow-up science cases
  - Neutron star equation of state constraints
  - Hubble constant calculations
  - R-process nucleosynthesis

We need to observe more GW-EM events!!





Observing Scenarios

Now on arxiv!

Weizmann Kiendrebeogo et all. : https://arxiv.org/abs/2306.09234

End-to-end GW-EM simulation

- Goal

  1) Present updated predictions and statistics for O4 and O5 observing runs by the IGWN (LIGO/Virgo/KAGRA)

  2) Provide updated analysis of physical constraints based on GW170817

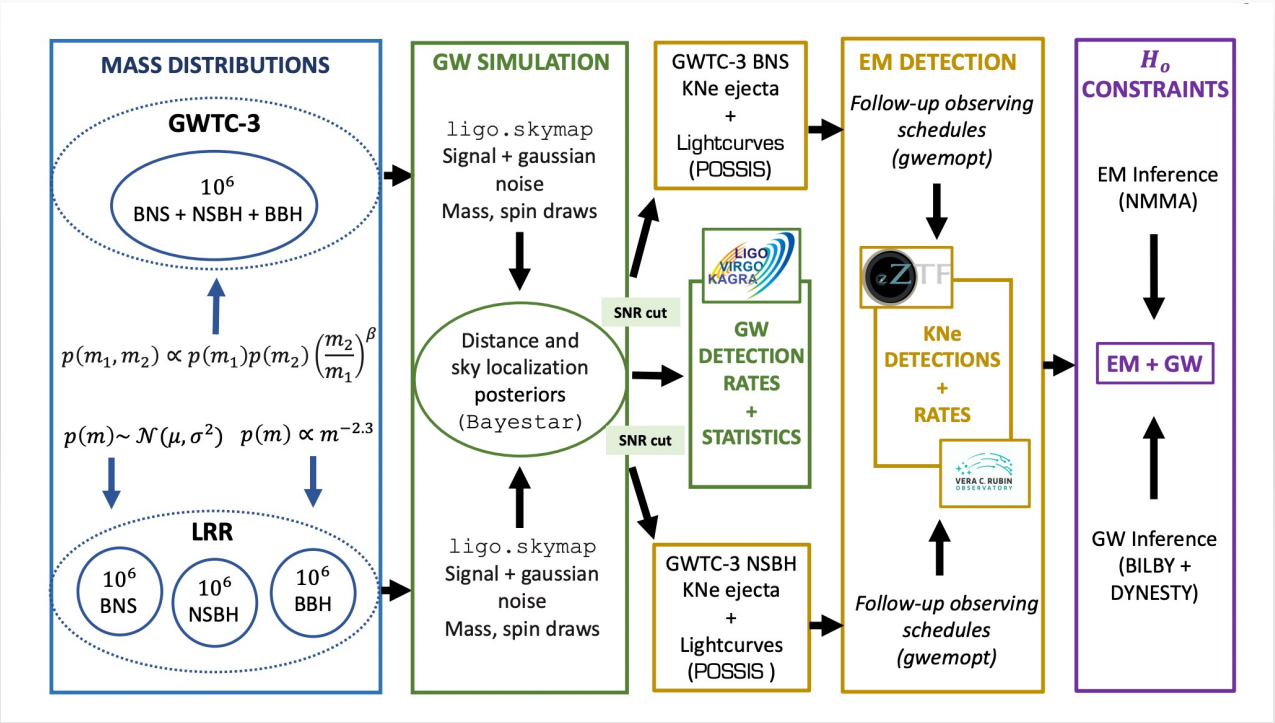
- Impact

  Inform the scientific community, especially EM follow-up efforts to maximize the scientific output

Observing Scenarios - Flow

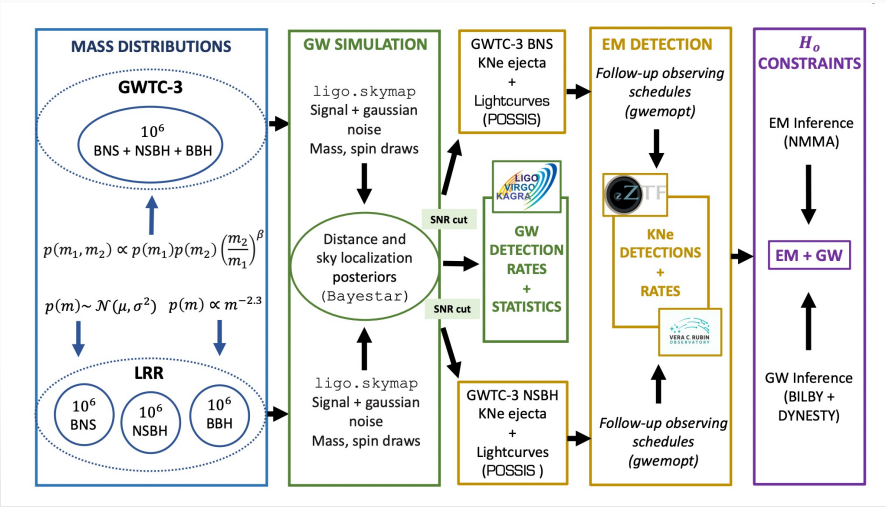
- GWTC-3 Distribution
- Split populations based on mass and spin thresholds
- Draw distances and sky localizations (ligo.skymap code for LIGO/Virgo/KAGRA), and extrinsic parameters (lat., long., incl.)
- Apply SNR threshold of 8 (bayestar)
- Statistical predictions/calculate summary statistics

Protocol/Simulation Flow

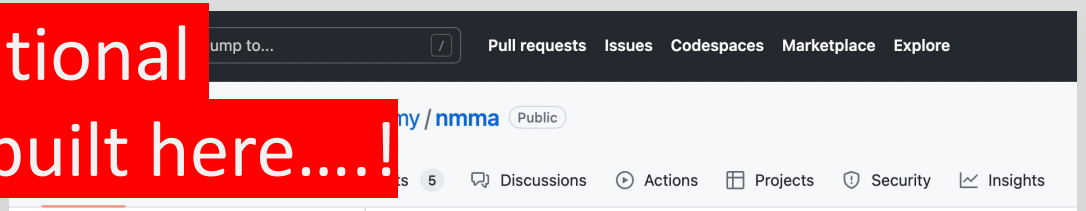


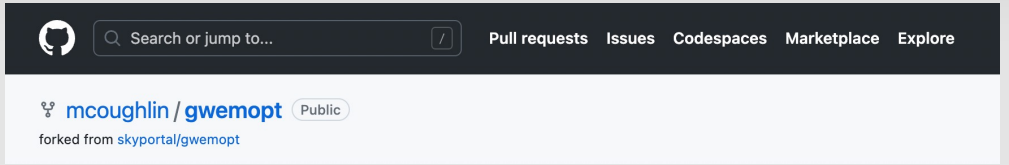
Observing Scenarios – Tools

- Nuclear Multimessenger Astronomy (NMMA) + Bilby
  - Bayesian multi-messenger pipeline for GW+EM analyses
  - Ejecta quantities/parameter estimation
  - EM models (KNe: Bulla2019, POSSIS)
  - Combined analysis (Ho)
- Bayestar
  - Rapid Sky localization code (used for IGWN)
- Gwemopt
  - Perform optical simulation campaign/ observing schedules
- Ligo.skymap
  - Read, write, generate, and visualize skymaps
  - Command-line tools



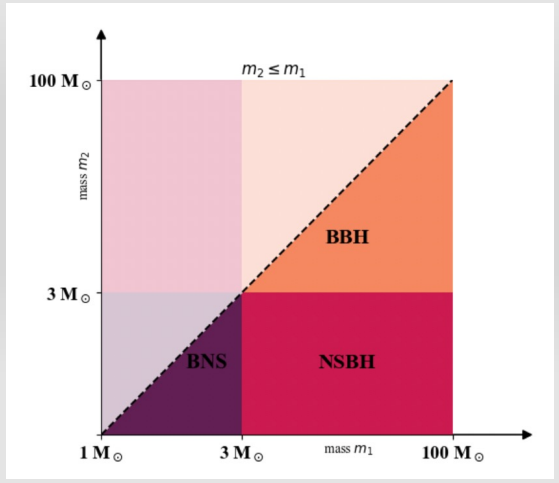
A lot of computational experience was built here….!





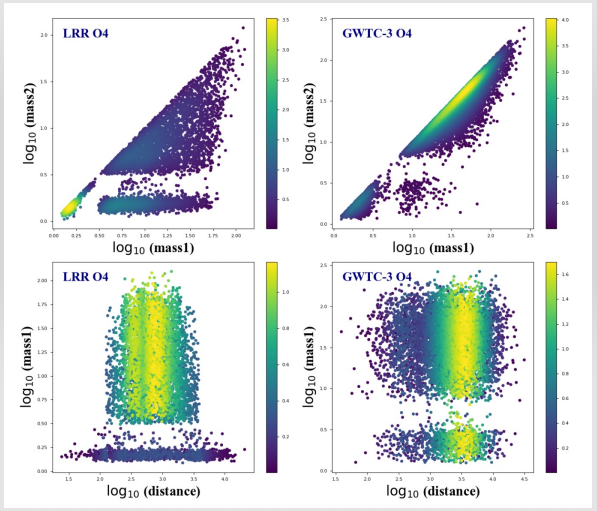
Observing Scenarios – Results

Population component masses

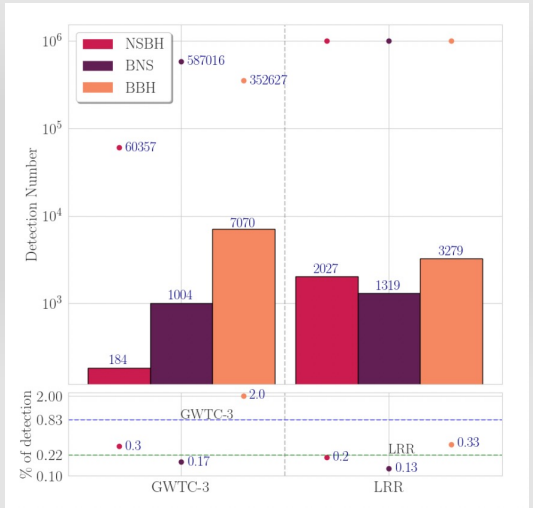


Spin magnitudes
m < 2.5 M_{sun}, [0,.4]
m >2.5 M_{sun}, [0,1]

Mass distributions which survive SNR threshold (O4)



Number of events detected per distribution



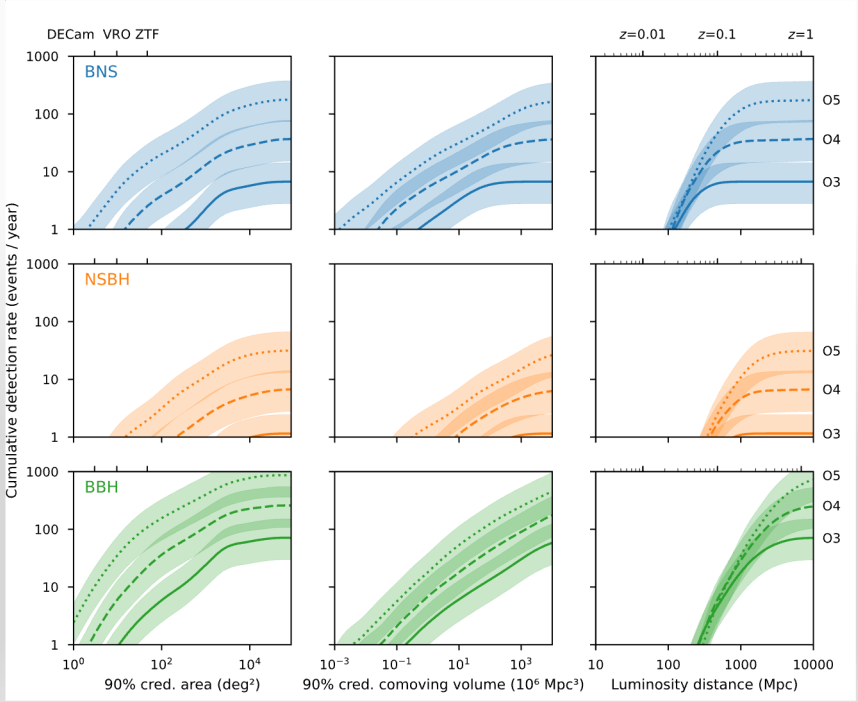
Summary Statistics

Run	Dist.	BNS	NSBH	BBH
Median 90% credible area (deg^2)				
O4	LRR	2100^{+150}_{-220}	2090^{+130}_{-130}	653^{+53}_{-36}
	GWTC-3	1860^{+250}_{-170}	2140^{+480}_{-530}	1428^{+60}_{-55}
O5	LRR	2050^{+100}_{-160}	2110^{+100}_{-100}	682^{+25}_{-30}
	GWTC-3	2050^{+120}_{-120}	2000^{+350}_{-220}	1256^{+48}_{-53}
Median 90% credible Comoving Volume (10^3 Mpc^3)				
O4	LRR	$46.5^{+6.6}_{-7.0}$	159^{+26}_{-16}	207^{+21}_{-20}
	GWTC-3	$67.9^{+11.3}_{-9.9}$	232^{+101}_{-50}	3400^{+310}_{-240}
O5	LRR	240^{+29}_{-26}	785^{+68}_{-62}	857^{+63}_{-60}
	GWTC-3	376^{+36}_{-40}	1350^{+290}_{-300}	8580^{+600}_{-550}
Median Luminosity Distance (Mpc)				
O4	LRR	349^{+12}_{-14}	564^{+15}_{-13}	1102^{+33}_{-32}
	GWTC-3	398^{+15}_{-14}	770^{+67}_{-70}	2685^{+53}_{-40}
O5	LRR	619^{+15}_{-19}	1007^{+20}_{-22}	1948^{+34}_{-24}
	GWTC-3	738^{+30}_{-25}	1318^{+71}_{-100}	4607^{+77}_{-82}
Sensitive volume : detection rate / merger rate: (Gpc^3)				
O4	LRR	$0.1011^{+0.0066}_{-0.0064}$	$0.403^{+0.021}_{-0.020}$	$1.861^{+0.077}_{-0.074}$
	GWTC-3	$0.172^{+0.013}_{-0.012}$	$0.78^{+0.14}_{-0.13}$	$15.15^{+0.42}_{-0.41}$
O5	LRR	$0.507^{+0.027}_{-0.026}$	$1.809^{+0.070}_{-0.068}$	$7.62^{+0.19}_{-0.19}$
	GWTC-3	$0.827^{+0.044}_{-0.042}$	$3.65^{+0.47}_{-0.43}$	$50.7^{+1.2}_{-1.2}$

Annual GW detection rates

Run	Distribution	BNS	NSBH	BBH
		Annual number of detections		
O4	LRR	17^{+35}_{-13}	10^{+18}_{-8}	46^{+23}_{-17}
	GWTC-3	36^{+49}_{-22}	6^{+11}_{-5}	260^{+330}_{-150}
O5	LRR	86^{+171}_{-59}	48^{+71}_{-30}	190^{+80}_{-58}
	GWTC-3	180^{+220}_{-100}	31^{+42}_{-20}	870^{+1100}_{-480}

Cumulative Histogram, Public Alert Rate



Warning: Data Overload!!

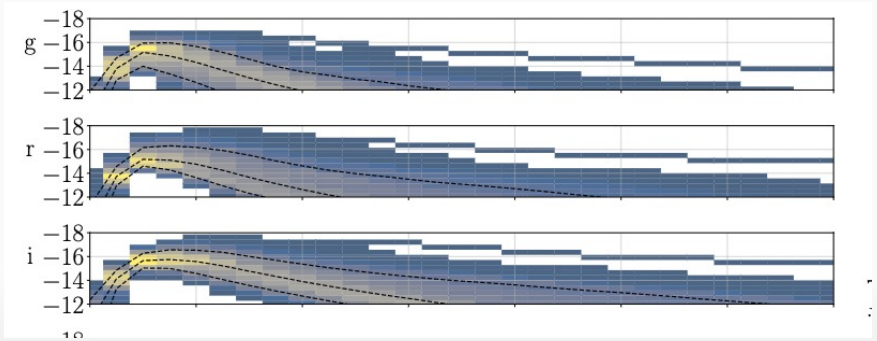
- More detections than reasonable to handle by current (O3) follow-up capabilities
- Detector sensitivity increasing! Localization not so much…

Run	Dist.	BNS		NSBH	
		Telescopes			
		ZTF	LSST	ZTF	LSST
O4	GWTC-3	10.06 %	90.34 %	2.72 %	60.87 %
O5	GWTC-3	2.6 %	69.4 %	0.28 %	30.62 %

BNS, O4, ZTF

KNe Classification

In collaboration with Niharika Sravan and more



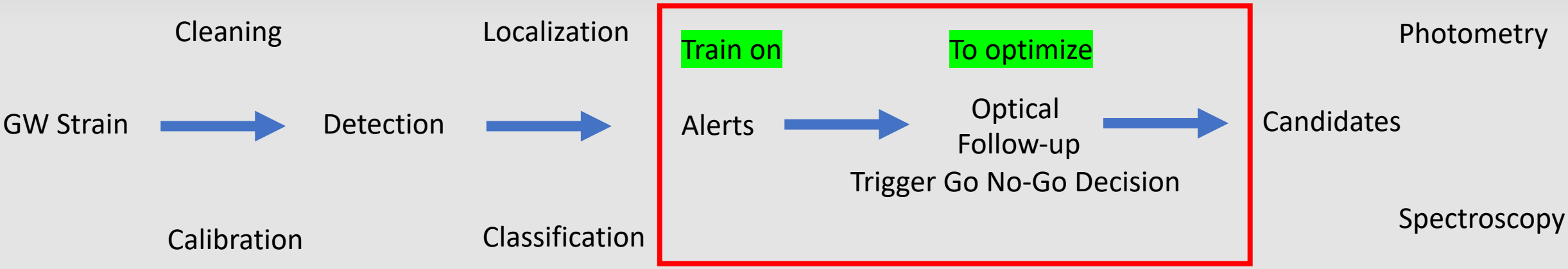
- Bottlenecks/motivations
  - Faint transient (light curve lasting <1week in optical)
  - Large detection rates expected in O4 and O5 observing runs
  - Localization remains poor
  - Images can include tens of contaminating transients

Human-run classification does not remain a reasonable method

ML implementation and real-time classification is crucial to maximize observational resources and scientific return

Comprehensive Low Latency Dataset

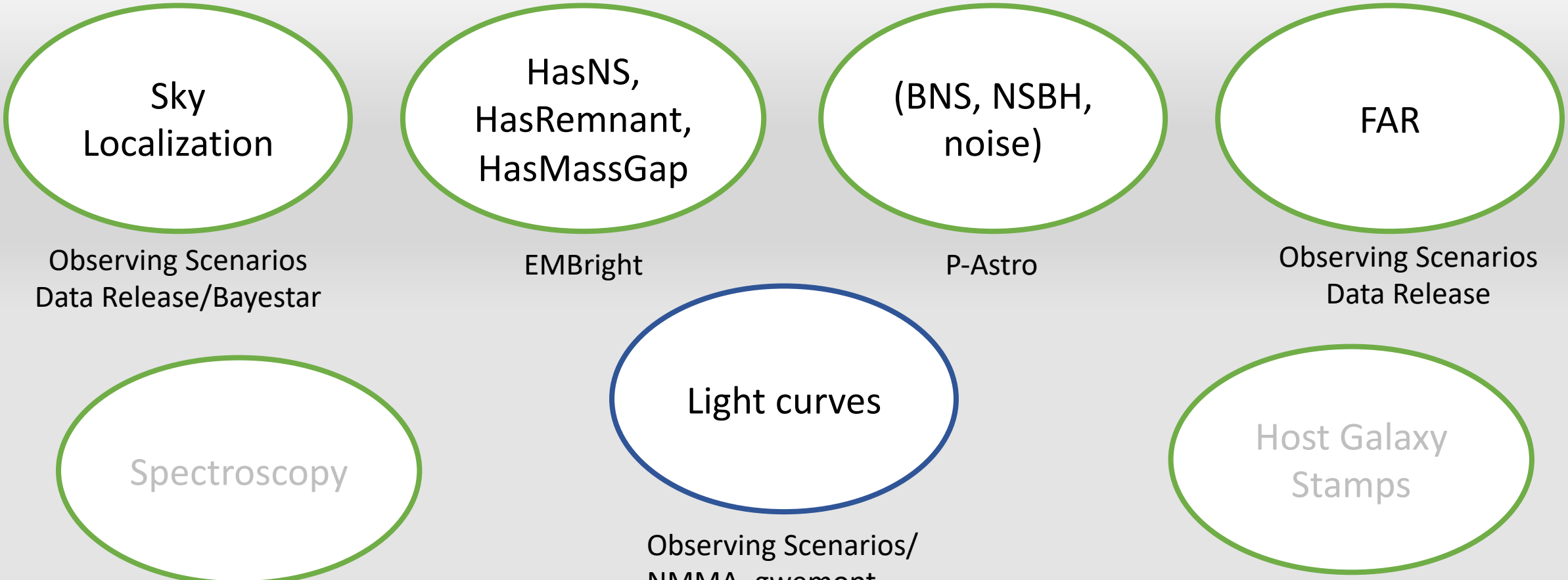
- Train Machine Learning classifiers on low-latency GCN Alert data
- Help pipelines meet realistic demand for follow-up observations
- Autonomous Real-Time Decision-Making, algorithms aimed at follow-up strategy and classification – already interest, more to be explored
- Current KNe focus, expanding to SNe



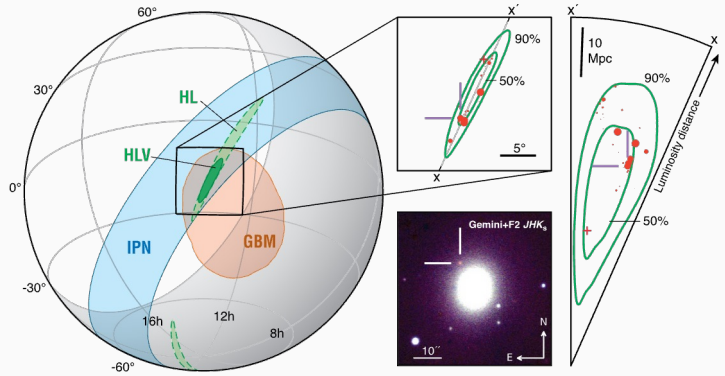
Low-Latency Alert Products (GCN)

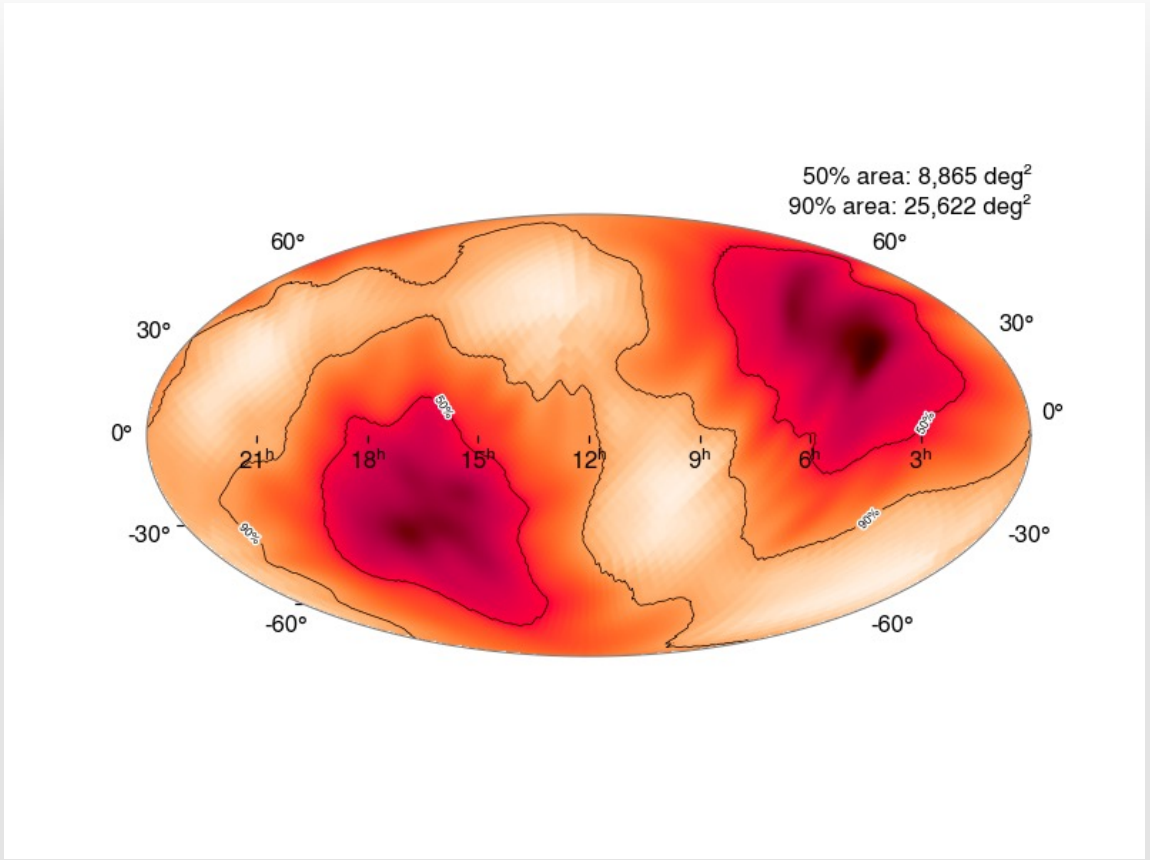
LIGO/Virgo/KAGRA Observing Capabilities: Simulated Detections and Localization for O4 and O5 (October 2022 edition)

https://zenodo.org/record/7026209



Sky Location
SupereventID: S230529ay



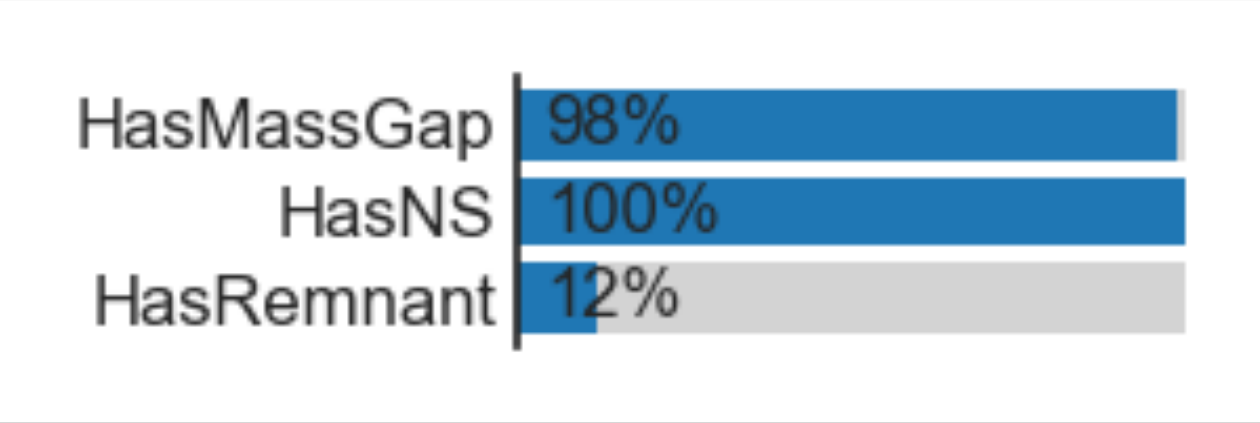


Posterior probability of sky position
Format: Healpix projection, fits file

Bayestar data products
SNR
Distmean: mean luminosity distance estimated by detectors
Searched_prob: area covered in 90% credible region before finding injection (assuming searched first)

coinc_event_id	simulation_id	far	snr	searched_area	searched_prob	searched_prob_dist	searched_vol	searched_prob_vol	offset	runtime	distmean	diststd	log_bci	log_bsn	area(20)	area(50)	area(90)	dist(20)	dist(50)	dist(90)	vol(20)	vol(50)	vol(90)
1	1	0.0	8.831118857554092	15.789211700535065	0.03860276192777975	0.003533976175607857	7983258.690038086	0.5119537334598179	3.698036211043959	144.4915667369496	490.3362239542748	139.6459058949126	9.788489355142108	3.544499932564645	98.90036380380806	353.65121453419886	1424.9431334204862	71.39436340219095	189.8870588920691	460.1931040594944	1861164.2409447683	7638120.3179158475	41770604.09901262
18	18	0.0	8.394219043945947	349.9854500530138	0.4801613000393890	6	0.28022615949048946	6333620.543831693	0.33742110237083284	5.326999310771009	95.5068057780154	598.8145325893807	170.3769343193808	9.031101536214273	2.28662577654379	82.1377108834828	376.75316280920146	2134.2254368103595	87.01994869601049	231.45296412622474	561.081816638032	2546351.552001068	13558413.36225862	109804961.19157445
42	42	0.0	8.14374979664682	1685.9311098177234	0.3525761861610556	0.8529268427210832	283680288.50503576	0.6045921616598037	29.175384577091194	159.3485032040626	721.7193378933847	250.7184481990015	4.589213301803087	3.116127601707961	741.3735577052731	2870.856396821726	11845.965656240975	129.11770804143964	343.25428539213385	830.301115981471	41465827.01456165	191036067.55606583	1025157350.0281245
47	47	0.0	8.180035012697285	12972.96187403048	0.6581207444021223	0.47310316118733337	168875219.35840654	0.527628277334737	109.77095392709262	123.1493616740336	433.1124816802593	170.7515127777477	2.379140052621395	4.749867099326703	2786.5692215480353	8609.370482293816	25000.32222517265	89.96417920296682	238.0950642421995	563.7396293698314	51546028.18616132	156927916.33320373	480403806.817209

EMBright
SupereventID: S230529ay



	simulation_id	HasNS	HasRemnant
1			
2	0	0.0	0.0
3	1	1.0	1.0
4	2	0.0	0.0
5	3	0.0	0.0
6	4	0.0	0.0
7	5	0.0	0.0
8	6	0.0	0.0
9	7	0.0	0.0
10	8	0.0	0.0
11	9	0.0	0.0
12	10	0.0	0.0

HasNS = Probability (assuming source is not noise) that at least one of the compact objects was a neutron star

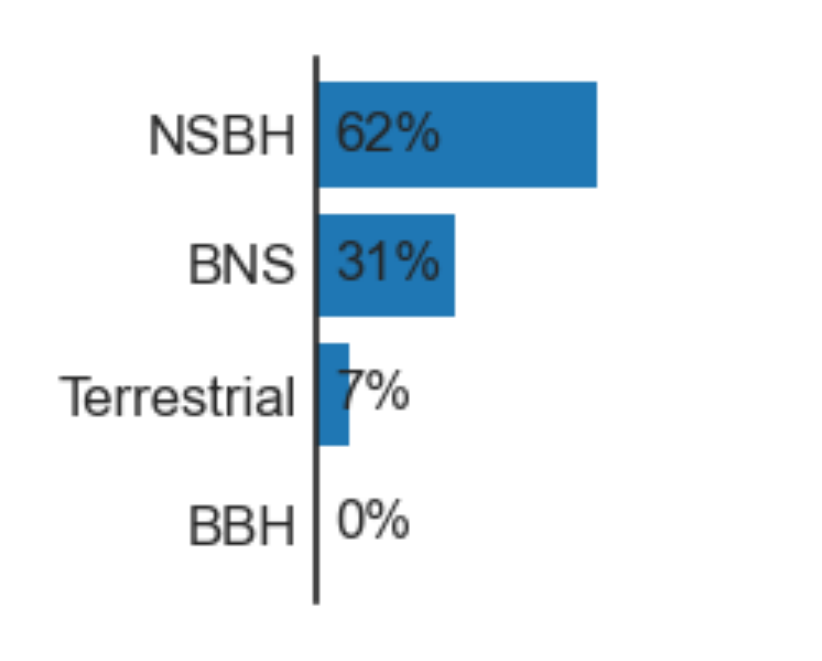
HasMassGap = probability that at least one source's mass falls between 3 and 5 solar masses

HasRemnant = Probability that the system ejected a nonzero amount of neutron star matter/tidal disruption occurred

1 = 100%
0 = 0%

Inputs: mass, spin, snr

P-Astro
SupereventID: S230529ay



Probability that the GW source is a BNS, NSBH, BBH, or Terrestrial (noise)

Observing scenarios Bayestar skymap data

Alert Rate, FAR, and SNR dependent

Light curves/simulated follow-up

- Population

Observing scenarios injections (passed SNR)

O4

1004 injected BNS → 236 detected

184 injected NSBH → 4 detected

O5

2003 injected BNS → 118 detected

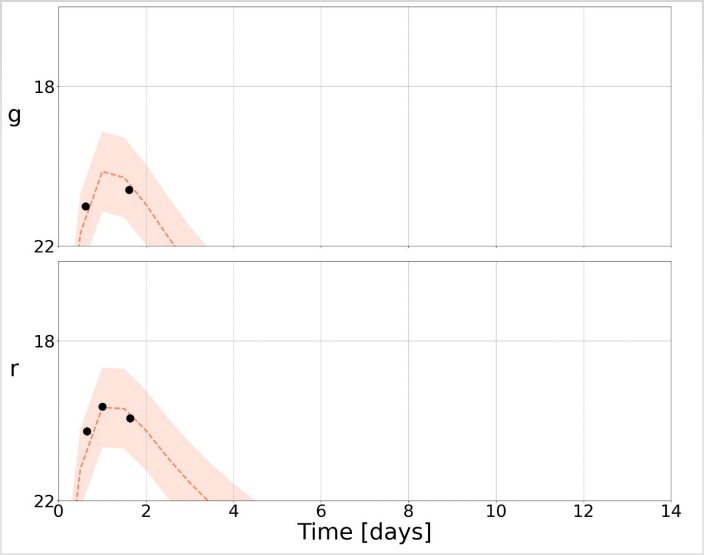
356 injected NSBH → 0-1 detected

	mjd	passband	ToO	mag	mag_err	tc
1	44244.614889651326	g	True	21.00126996361575	0.05495515122451153	44244.00021990741
2	44244.652459151366	r	True	20.263716172349007	0.11220276878191449	44244.00021990741
3	44245.001764473775	r	False	19.643648404791723	0.03818148217968515	44244.00021990741
4	44245.614889651326	g	True	20.585681425741832	0.09314624604855593	44244.00021990741
5	44245.63454235138	r	True	19.93323099006488	0.05341985343762061	44244.00021990741

- Triggering criteria

ZTF: g,r,i bands, 21.7, 21.4, 20.9 mag respectfully

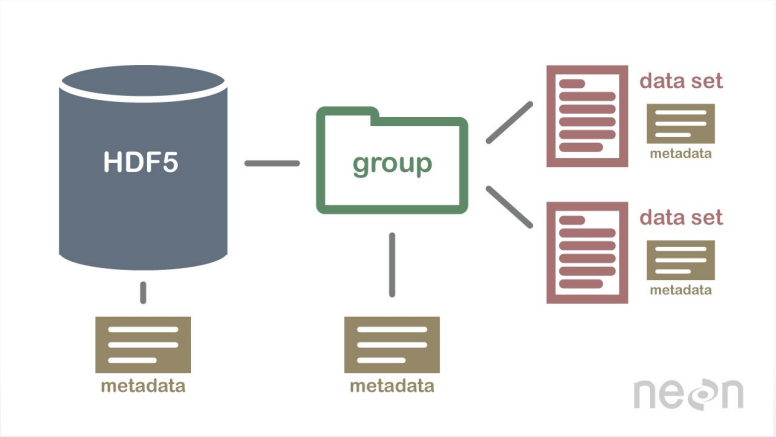
180s and 300s exposure during first and second day



Status

Data products and (some) codebase uploaded to Github

Officially record pipeline and workflow



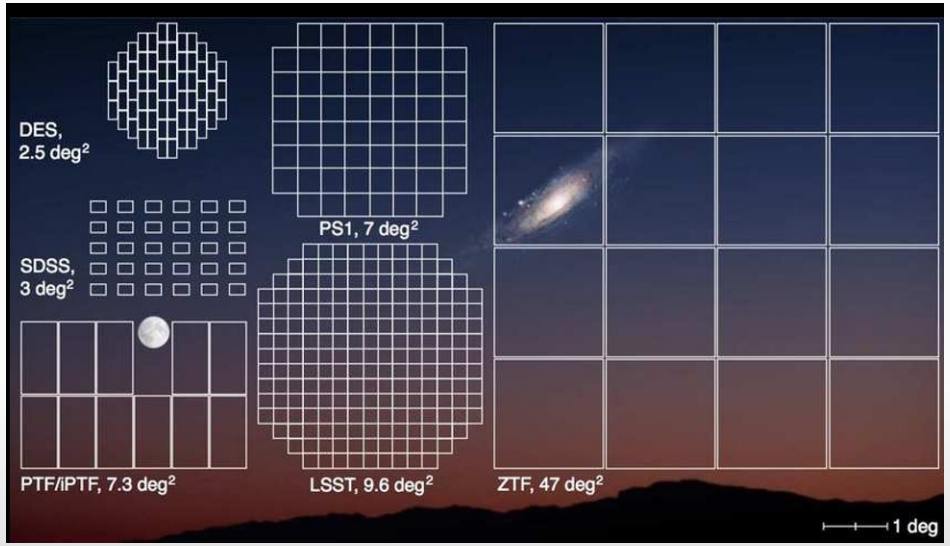
GW

Sim ID	Skymap metadata	Skymap fits file	Distance posterior	Probability Contour	Location of true KNe	Observable Coverage
☺	☺	☺	☺	☺	☺	☺

EM

Sim ID	t	g	r	i	Detected (1)	Not Detected (0)	HasNS	HasRemnant	HasMassGap	BNS	NSBH	BBH	Terrestrial
☺		☺			☺	☺	☺	☺	☺				

Looking Forward…



- Implement data!

- Finalize Pipeline, easy to use, sustainable

Which KNe is the true KNe?

Speed up inference by isolating KNe from SN, gamma-ray bursts, etc.

- Generate fixed-grid of KNe light curves
- Spectra
- Host-Galaxy Images (especially for poorly localized sources)
- Expand Observing Scenario’s sky localization data products based on GWTC-3

My Experience as an A3D3 Post-bacc

Invaluable experience in a highly active research field

Able to interact with and observe graduate students and postdocs

Real-world computational experience

- Thoughts

  More structured initial few months would have added value

  Initial meet with fellow post-baccs

  ML Intro in each domain, intentional exposure to important research questions, literature review

  Github and similar organizational resources

  Goals/expectations

Thank you to the entire A3D3 committee for this experience, and to Michael Coughlin for his guidance

THANK YOU!

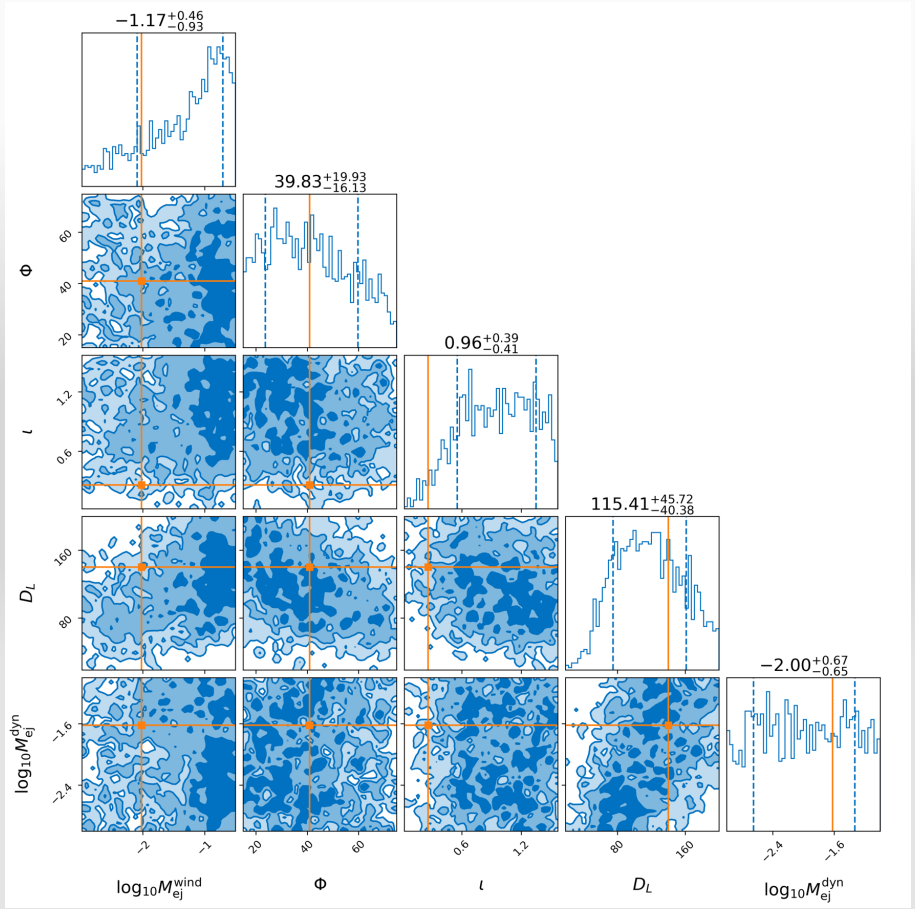
BACKUP SLIDES

Table 6. Triggering based on GW candidate event properties

Parameter	Go-deep	Go-wide	Deliberate	No Go
Strategy	300 sec Push distance	30 sec Push localization	Action Item: human interaction	
Frequency of triggers	1 per month 3 nights	2 per month 5 nights		
FAR min(FAR) - 'Best'	$<$ 1 per century Any pipeline	$<$ 1 per decade Any pipeline	1 per year - century	$>$ 1 per year All pipelines
max(p-astro)	> 0.9	> 0.9	$0.1 - 0.9$	< 0.1
HasNS	> 0.9	> 0.9	$0.1 - 0.9$	< 0.1
log(BCI)	> 4	> 4	$-1 - 4$	< -1
HasRemnant?	> 0	> 0	-	$= 0$
pBNS/pNSBH	> 0	> 0	-	$= 0$

Table 5. Annual detection rate of EM counterparts that we expect for ZTF and Rubin Observatory during the Run O4 and O5.

Run	Telescope	BNS	NSBH
EM annual number of detections			
O4	ZTF	$0.43^{+0.58}_{-0.26}$	$0.13^{+0.24}_{-0.11}$
	Rubin	$1.97^{+2.68}_{-1.2}$	$0.03^{+0.06}_{-0.03}$
O5	ZTF	$0.43^{+0.44}_{-0.2}$	$0.09^{+0.12}_{-0.06}$
	Rubin	$5.39^{+6.59}_{-2.99}$	$0.43^{+0.59}_{-0.28}$



- root:
  - injections:
    - __dataframe__: true
    - content:
      - simulation_id: [] 1004 items
      - mass_1: [] 1004 items
      - mass_2: [] 1004 items
      - luminosity_distance: [] 1004 items
      - psi: [] 1004 items
      - phase: [] 1004 items
      - geocent_time: [] 1004 items
      - ra: [] 1004 items
      - dec: [] 1004 items
      - theta_jn: [] 1004 items
      - a_1: [] 1004 items
      - a_2: [] 1004 items
      - tilt_1: [] 1004 items
      - tilt_2: [] 1004 items
      - phi_12: [] 1004 items
      - phi_jl: [] 1004 items
      - KNphi: [] 1004 items
      - inclination_EM: [] 1004 items
      - KNtimeshift: [] 1004 items
      - log10_mej_dyn: [] 1004 items
      - log10_mej_wind: [] 1004 items