Tiling strategies for follow-up of gravitational wave sources

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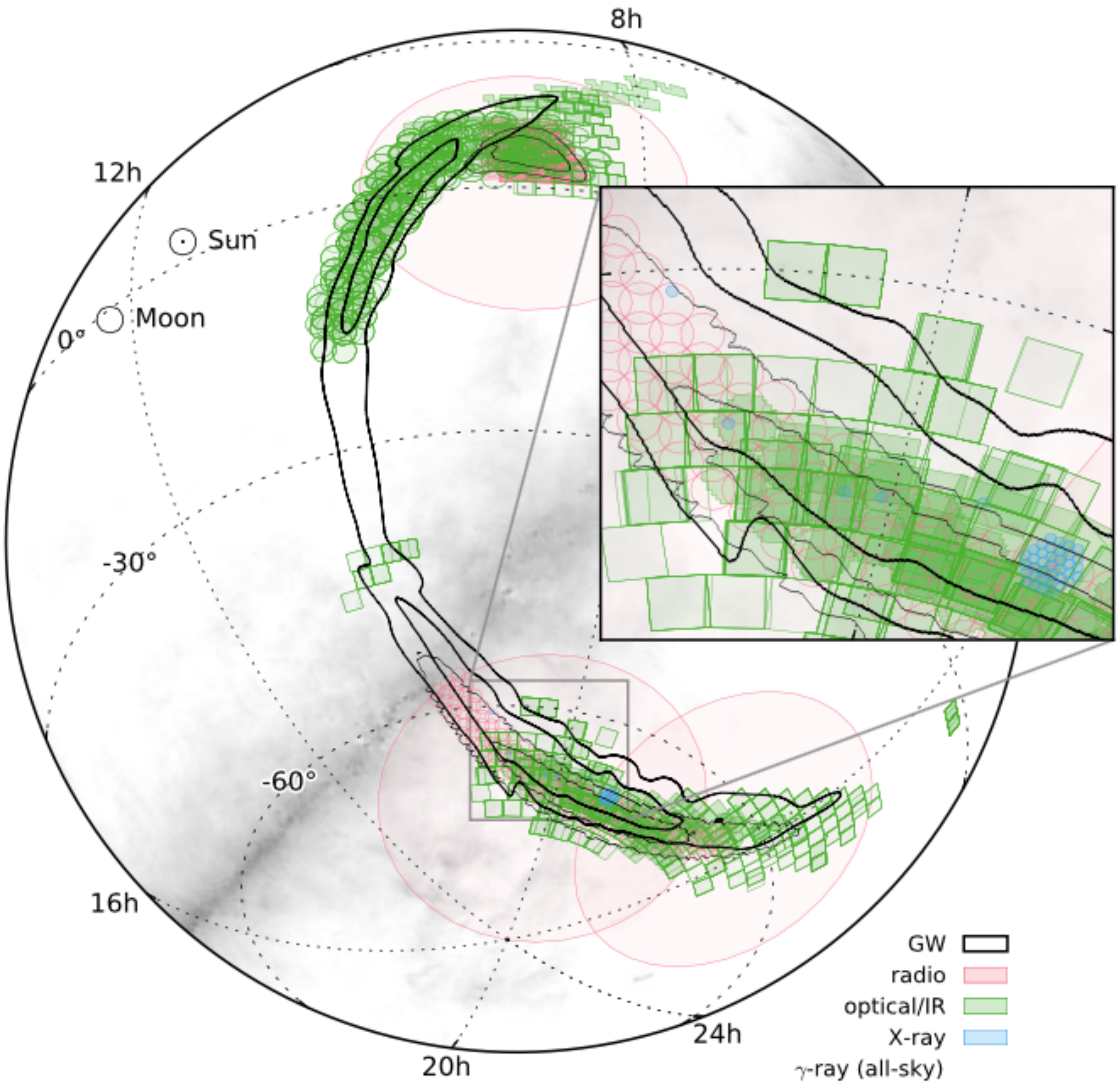
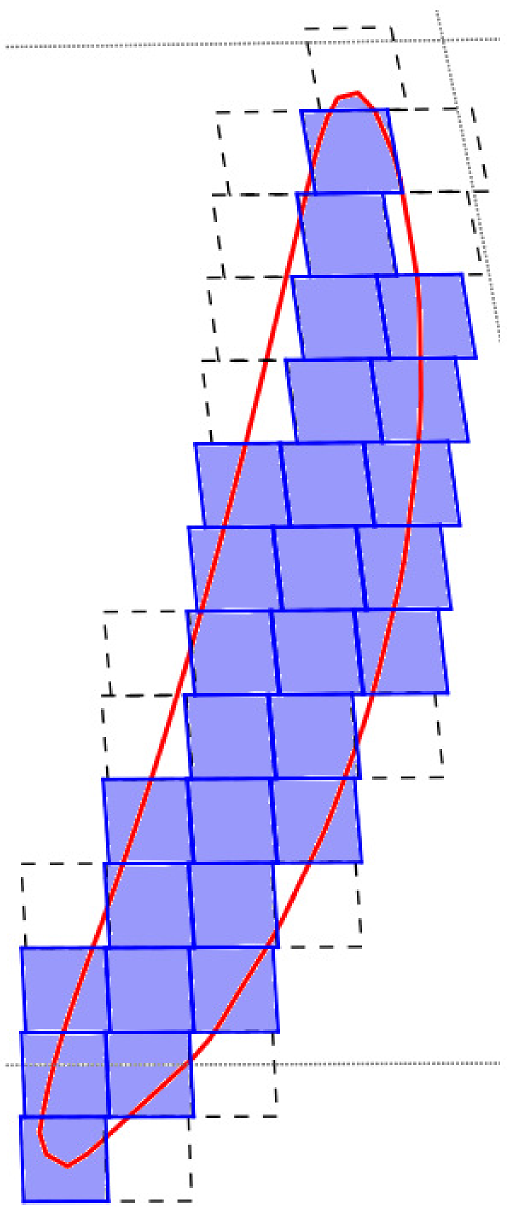


arXiv:1602.08492

Tiling strategy

- Goal: Coverage of largest possible sky-localization in a given number of telescope pointing.
- Contour-Covering: Given X% sky-localization confidence interval contour, create a set of tiles that completely enclose this contour.
- Ranked-Tiling: Sample the sky-localization in discrete 2D intervals of the telescope FOV. Select from the top of the list of these samples the top X% containing tiles.

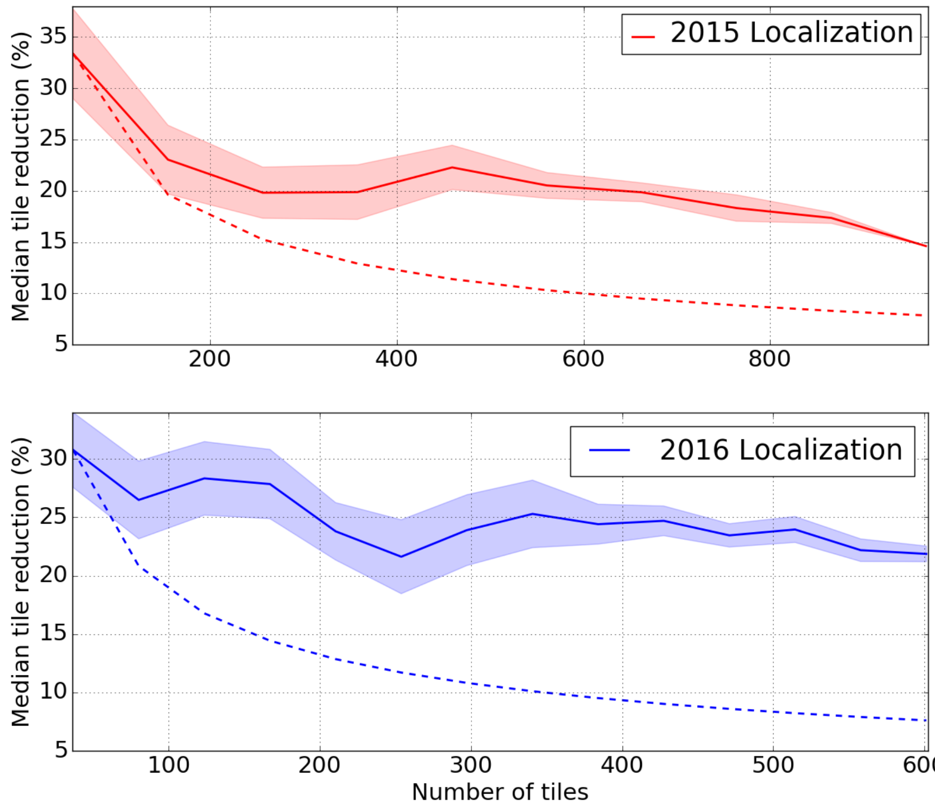


Scenario study

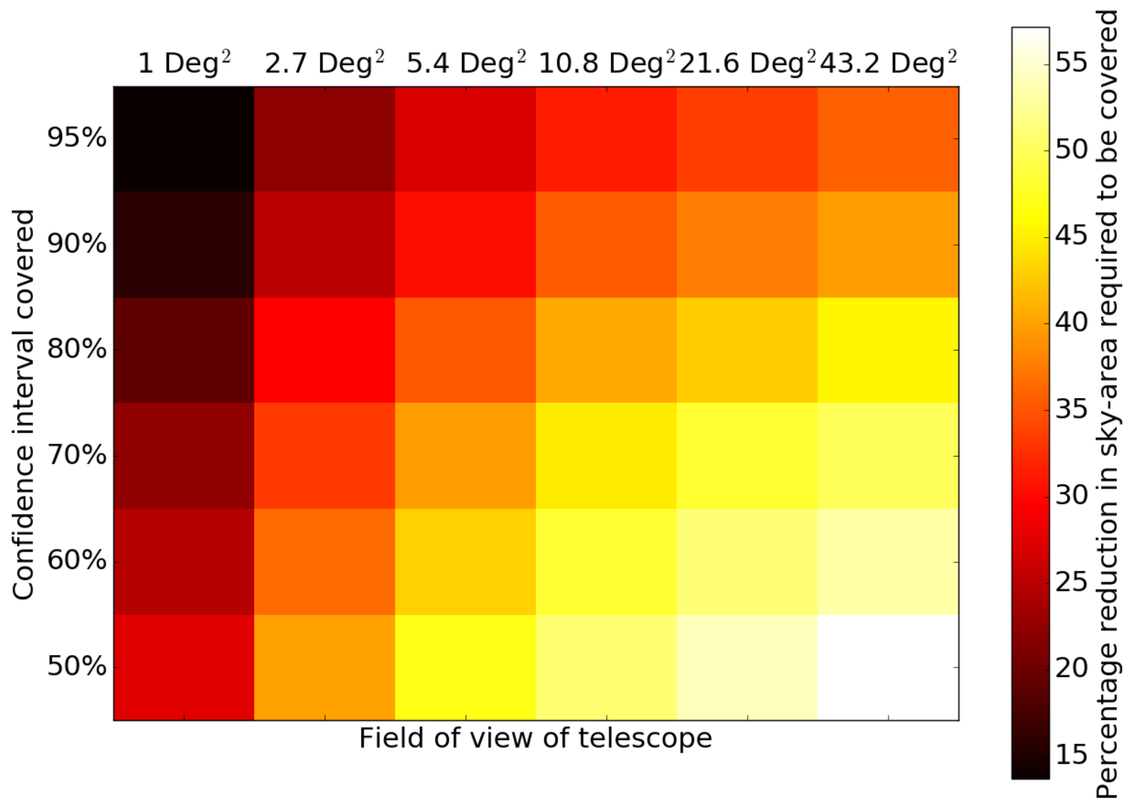
- A 100,000 Binary neutron star GW waveforms were injected in simulated LIGO-Virgo noise from 2015-16 (Singer et al. (2014))
- Around 1000 of these were detected in low-latency pipeline.
- We used the sky-localization maps to study and compare the various tiling strategies.

Results

Ranked-Tiling method mathematically gives the minimum number of tiles to cover X%.



Larger FOVs and smaller confidence intervals benefits most



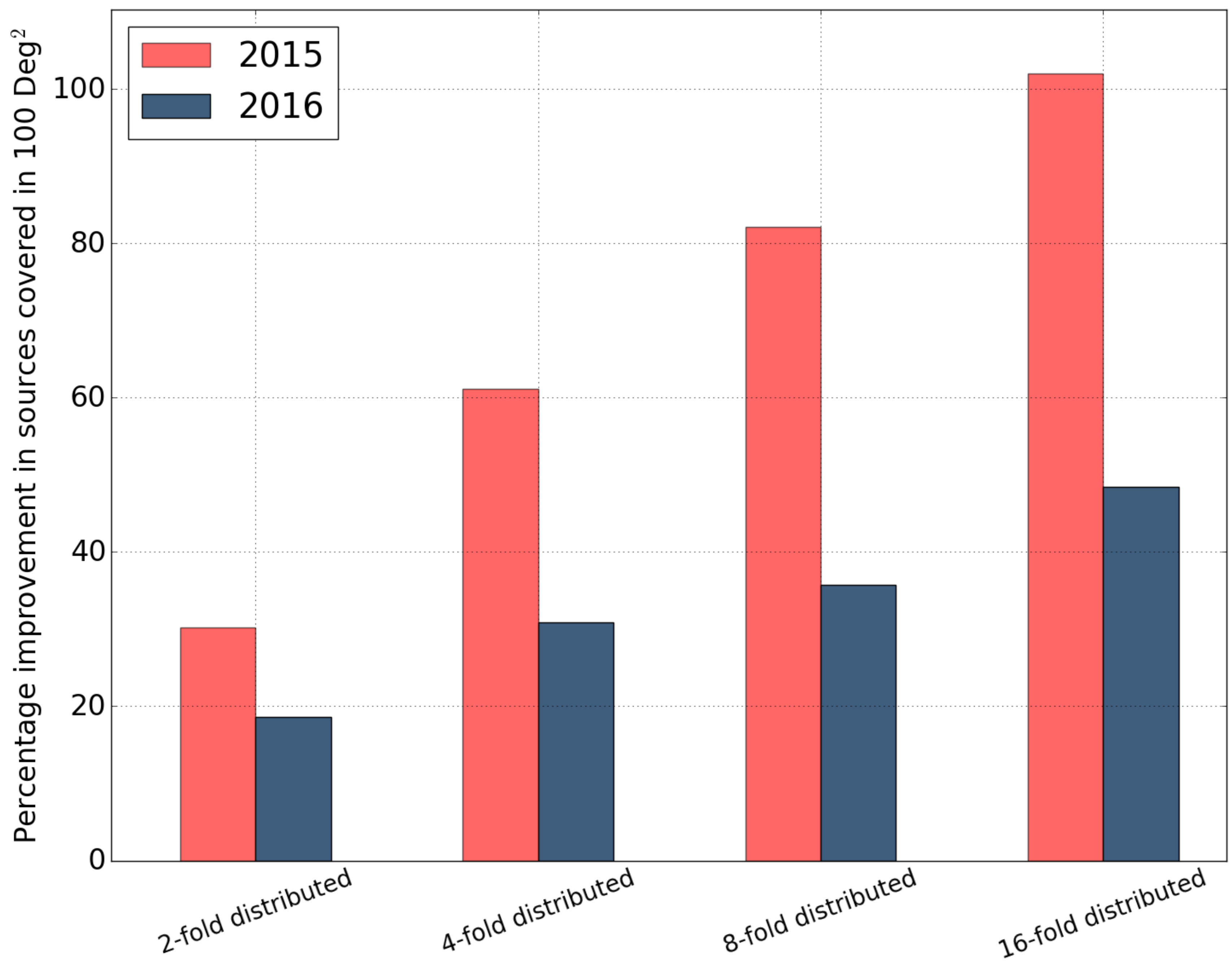
Optimization of tiles

- Caveat: Observers might not have freedom to optimize tiles.
- Optimization is an NP-complete problem.
- We conducted the optimization by iteratively shifting the position of the tiles to.

ID	CC tiles	CC-Optimized	Tile reduction (%)	RT tiles	RT-Optimized	Tile reduction (%)
288172	531	462	12.99	422	418	0.95
288830	38	37	2.63	29	29	0.0
303684	129	117	9.3	96	96	0.0
313831	5	4	20.0	3	3	0.0
1087	385	359	6.75	302	302	0.0
468530	307	273	11.07	217	213	1.84
588762	466	437	6.22	365	364	0.27
1065078	264	237	10.23	192	189	1.56
1027955	10	9	10.0	9	9	0.0
687313	469	453	3.41	426	425	0.23

Monoliths vs distributed FOV

- Gravitational wave sky-localizations - complex structures, elongated, often multimodal.
- Observing area scales linearly with FOV of telescopes, coverage scales less strongly.
- False positive is proportional to observing area.
- Distribute FOV into multiple smaller FOV telescopes.



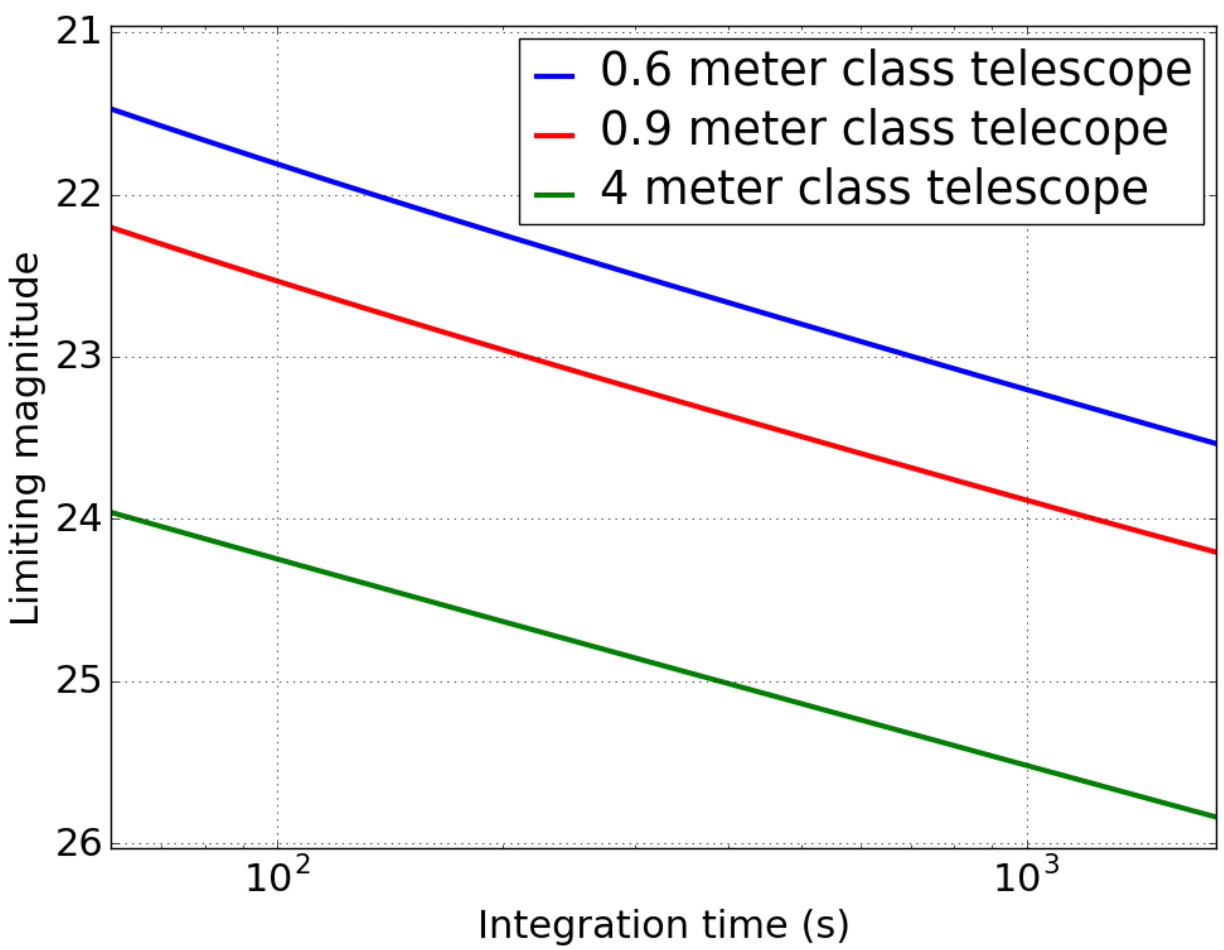
Depth-vs-Coverage

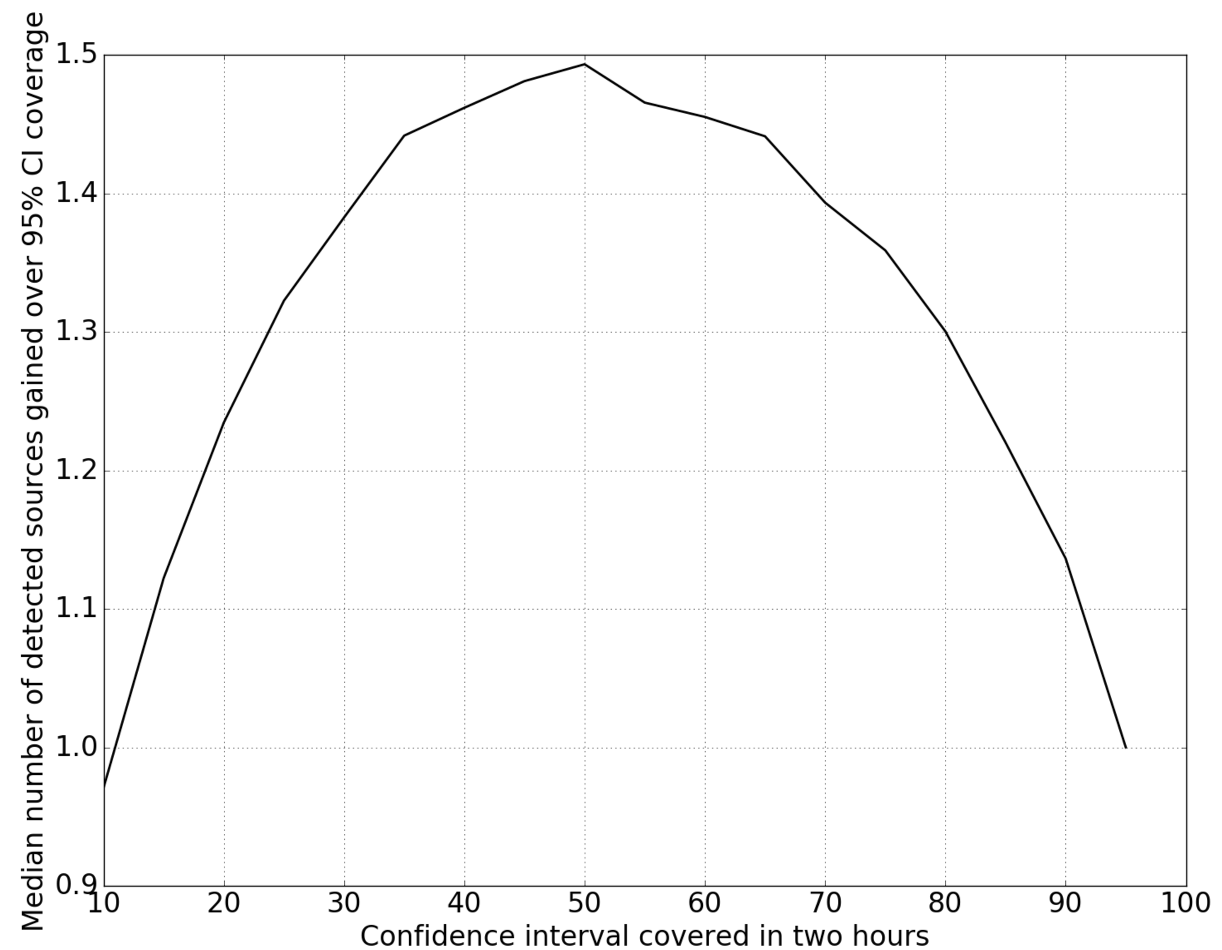
- Detection depends on coverage of the sky-localization and depth of observation.
- With finite time available over a night, depth of observation is at the expense of coverage.
- Is there any benefit in the initial era of LIGO-Virgo operation to go deeper rather than wider?

Sources distributed uniformly in volume

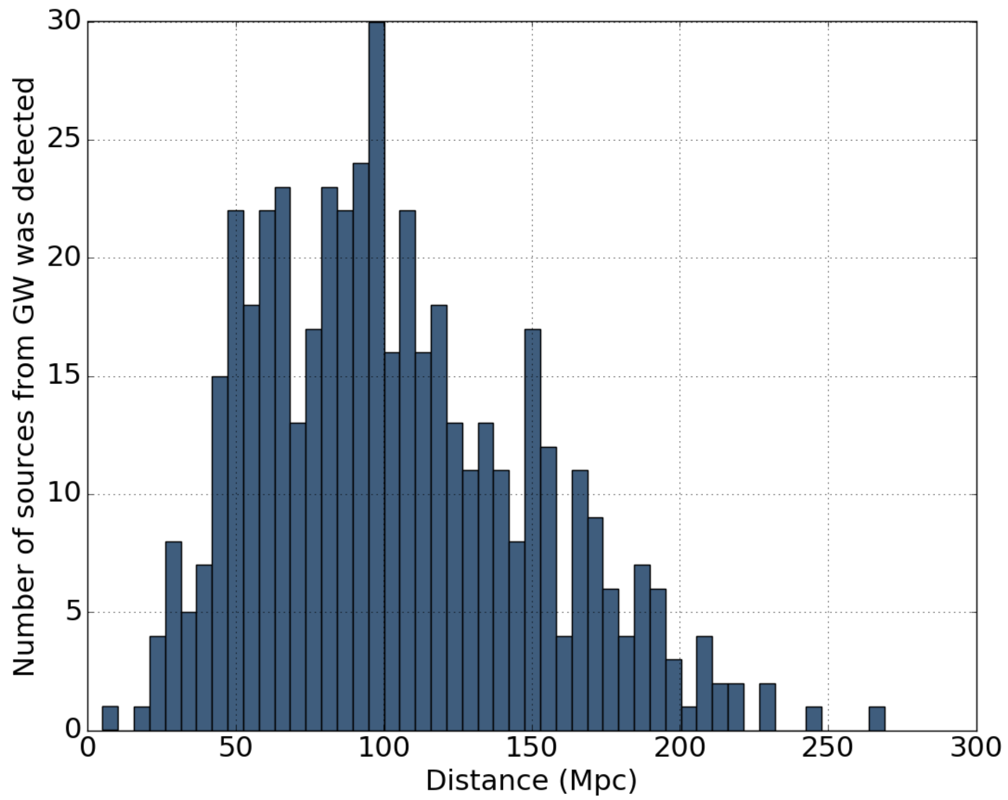
- Total observation time = 2 hours

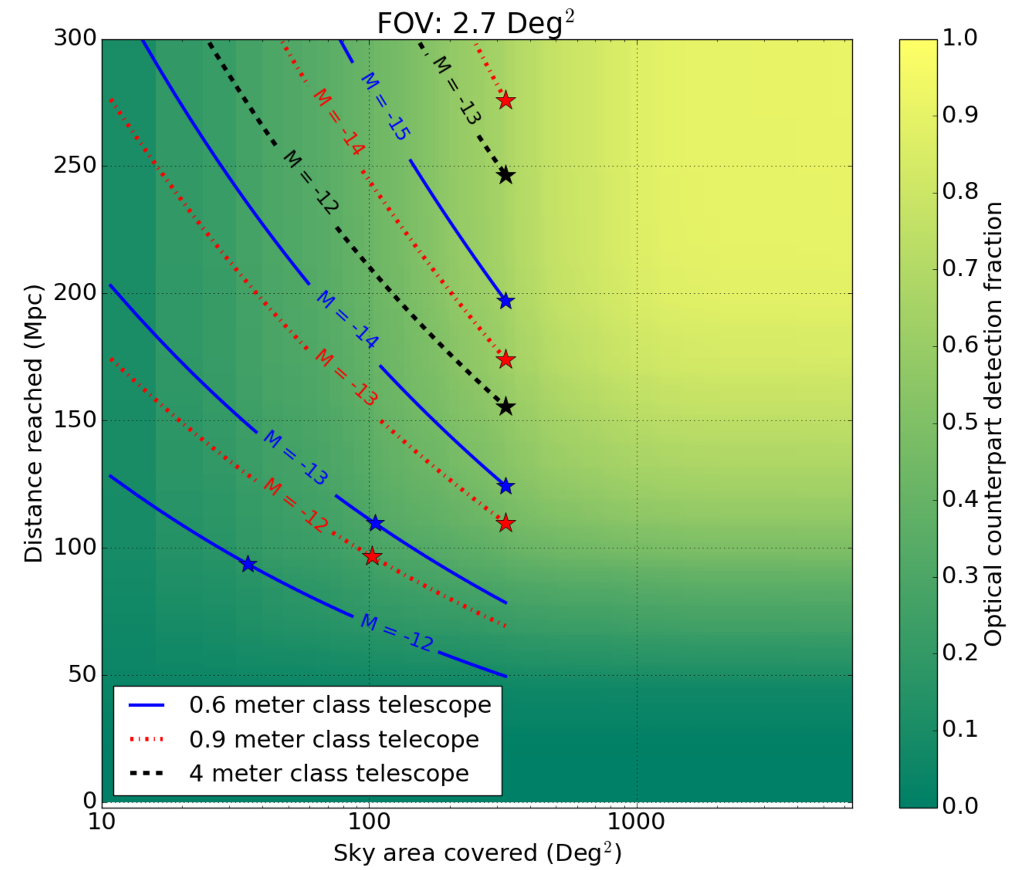
$$\frac{n_A}{n_B} = x^3 \left(\frac{P_A}{P_B}\right) \qquad \text{where, } x = \frac{D_L^A}{D_L^B} = 10^{\frac{1}{5}[m(t_A) - m(t_B)]}$$

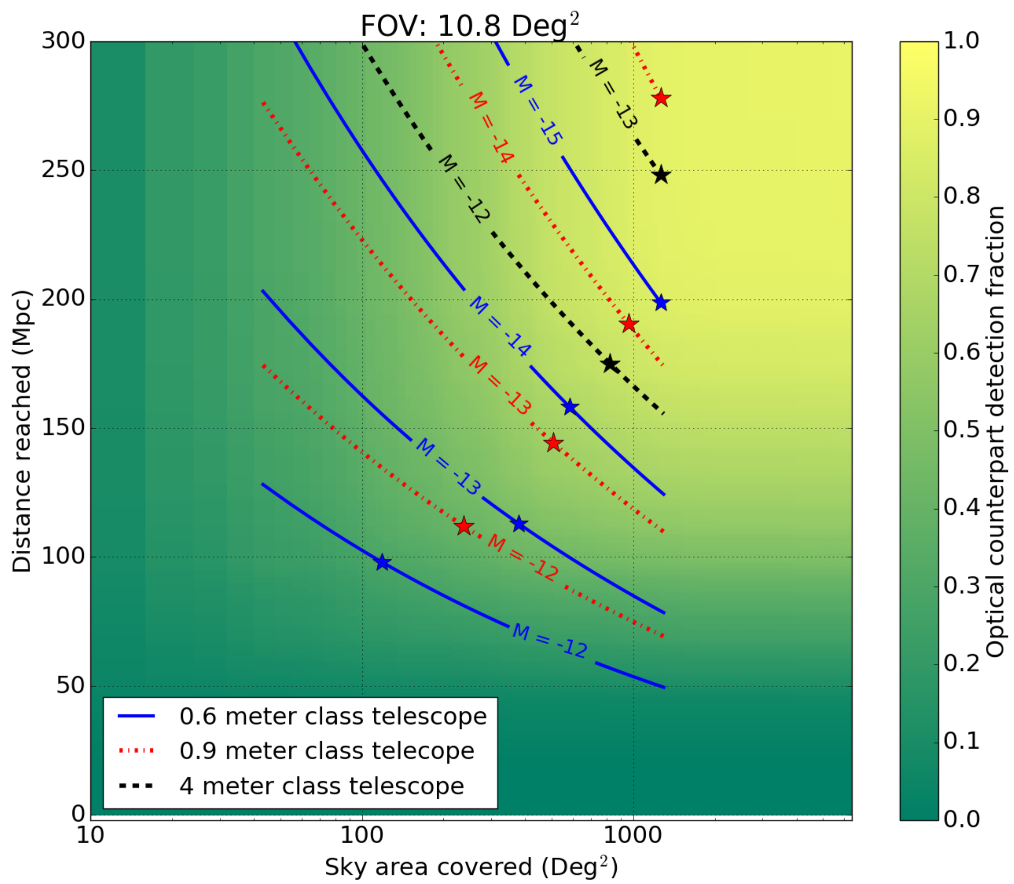


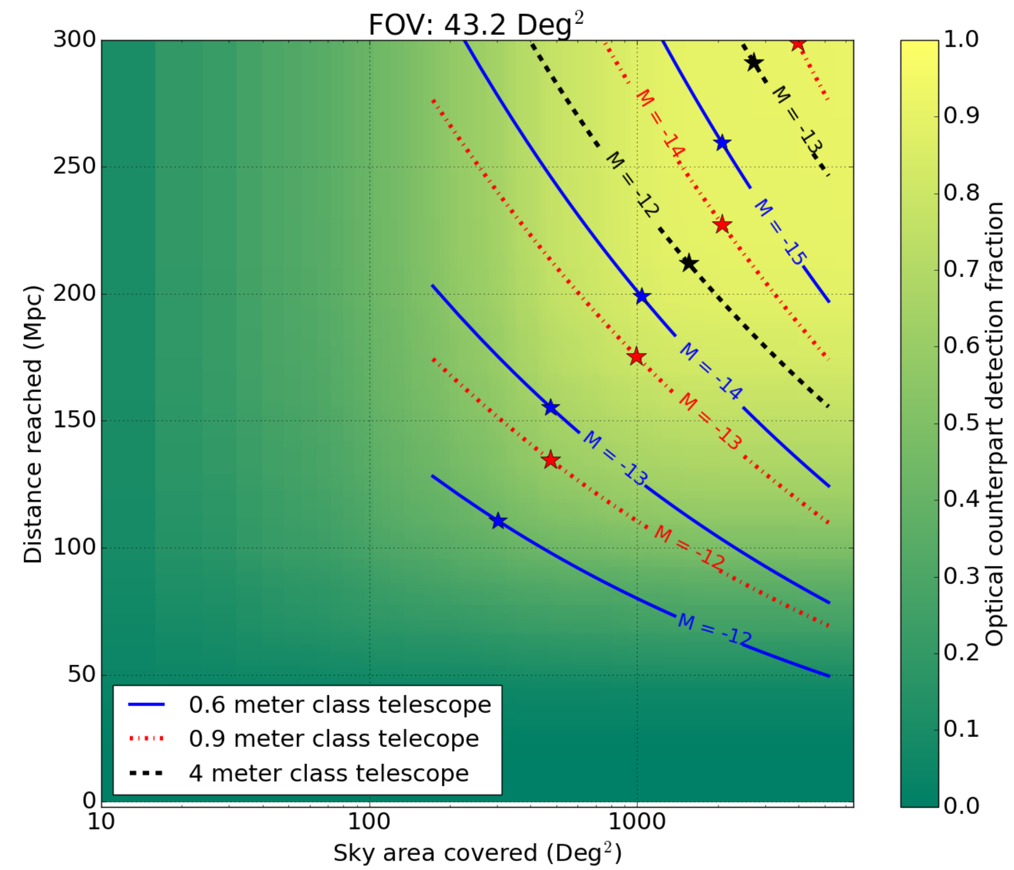


Depth vs coverage for detected sources









- All the results of this work can be found in arXiv: 1511.02673
- Questions? (Before I move to the second part of the talk)

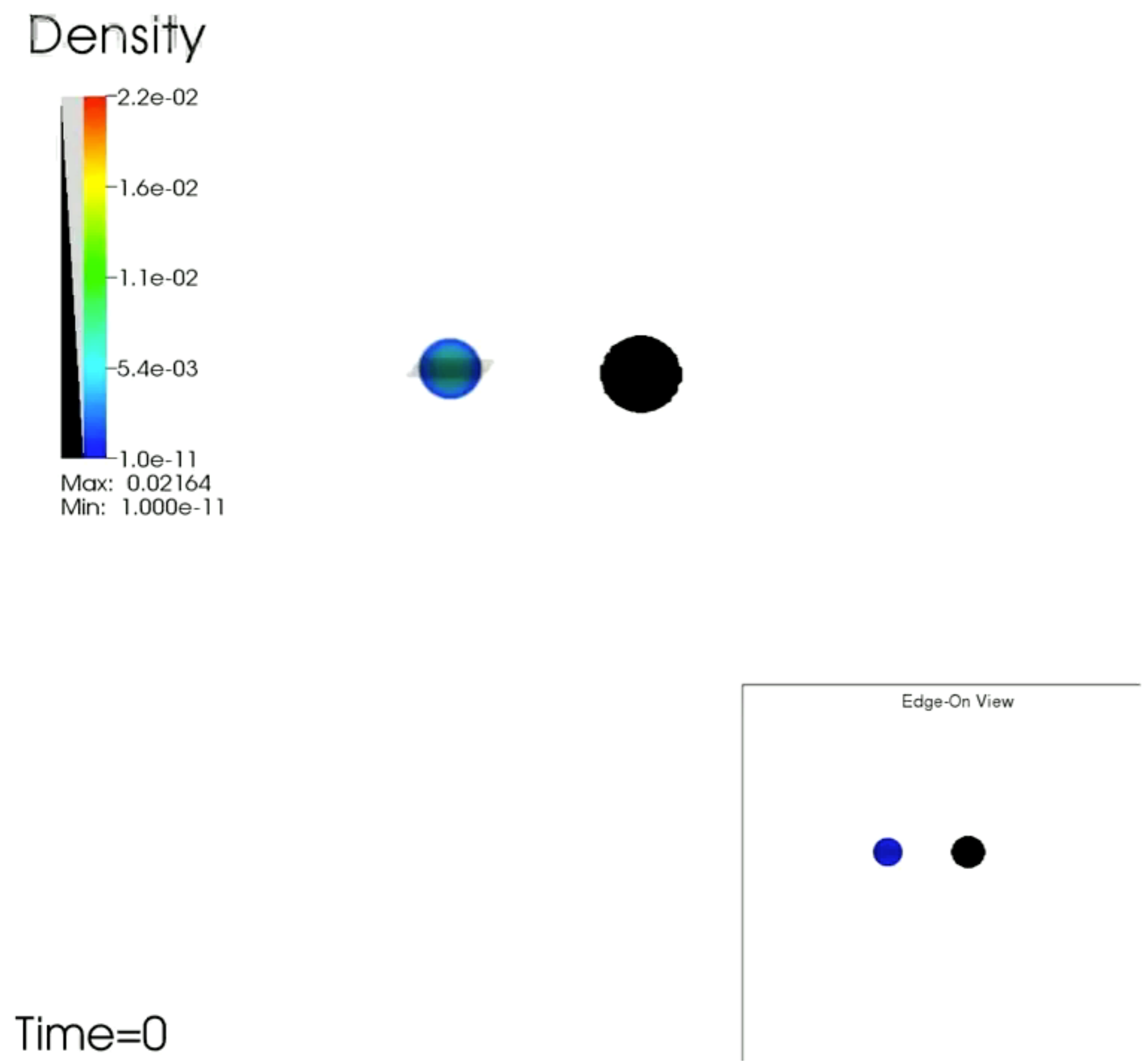
EM-Bright Classification Framework

The Goal

Given a gravitational-wave detection by the low latency pipeline and rapid parameter estimation, what is/are the best quantitative information(s) we can provide to our observing partners regarding likelihood of EM-counterpart of the event.

The Physics

- The compact object(s) get tidally disrupted to create the mater that power the EM-counterpart
- ISCO of the central object is key.
- Mass ratio, spin of BH, NS EoS.



The Method

- We are using Foucart's fitting formula (arXiv: 1207.6304) to estimate the remnant mass outside the black hole at the late times.
- Setting a threshold on this mass allows us to quantify the likelihood of EM emission.
- As an input we are using the mass and spin posteriors from Bayesian parameter estimation samples.
- Computation of likelihood of EM-emission from detection pipeline point estimates using ambiguity ellipse.

Sample result from MCMC runs

a_1	Misalignment (degrees)	Remnant mass (solar mass)	p(NS)	p(EM-bright)
0.7	0.0	0.16	0.896	0.272
0.7	60.0	0.00	0.865	0.0
0.9	0.0	0.39	0.722	0.512
0.9	60.0	0.09	0.986	0.029

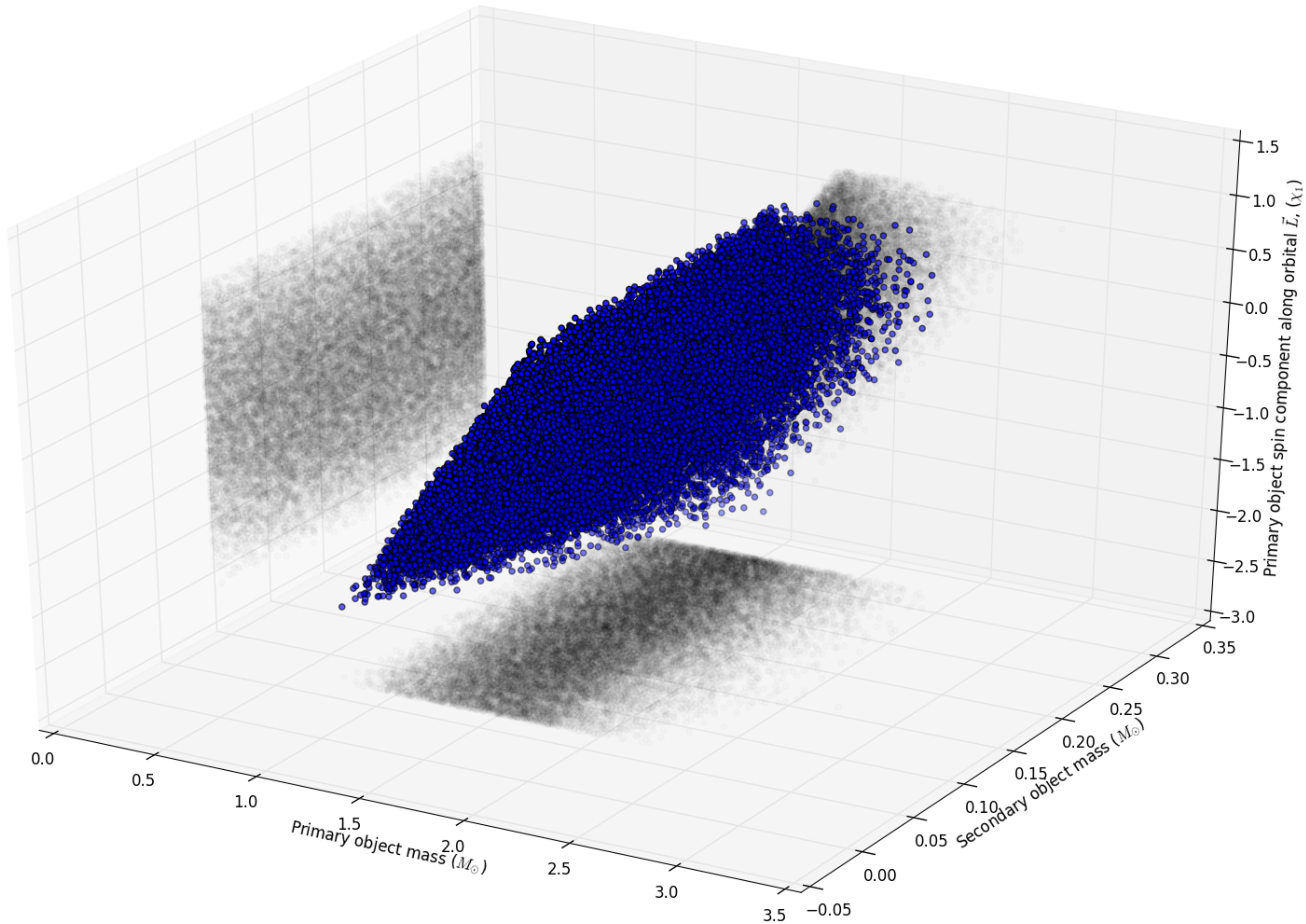
Injection parameters: m_1 = 10.0, m_2 = 1.4, waveform = SpinTaylorT4

Template waveform = SpinTaylorT4 aligned, m_1 = 10.0, m_2 = 1.4

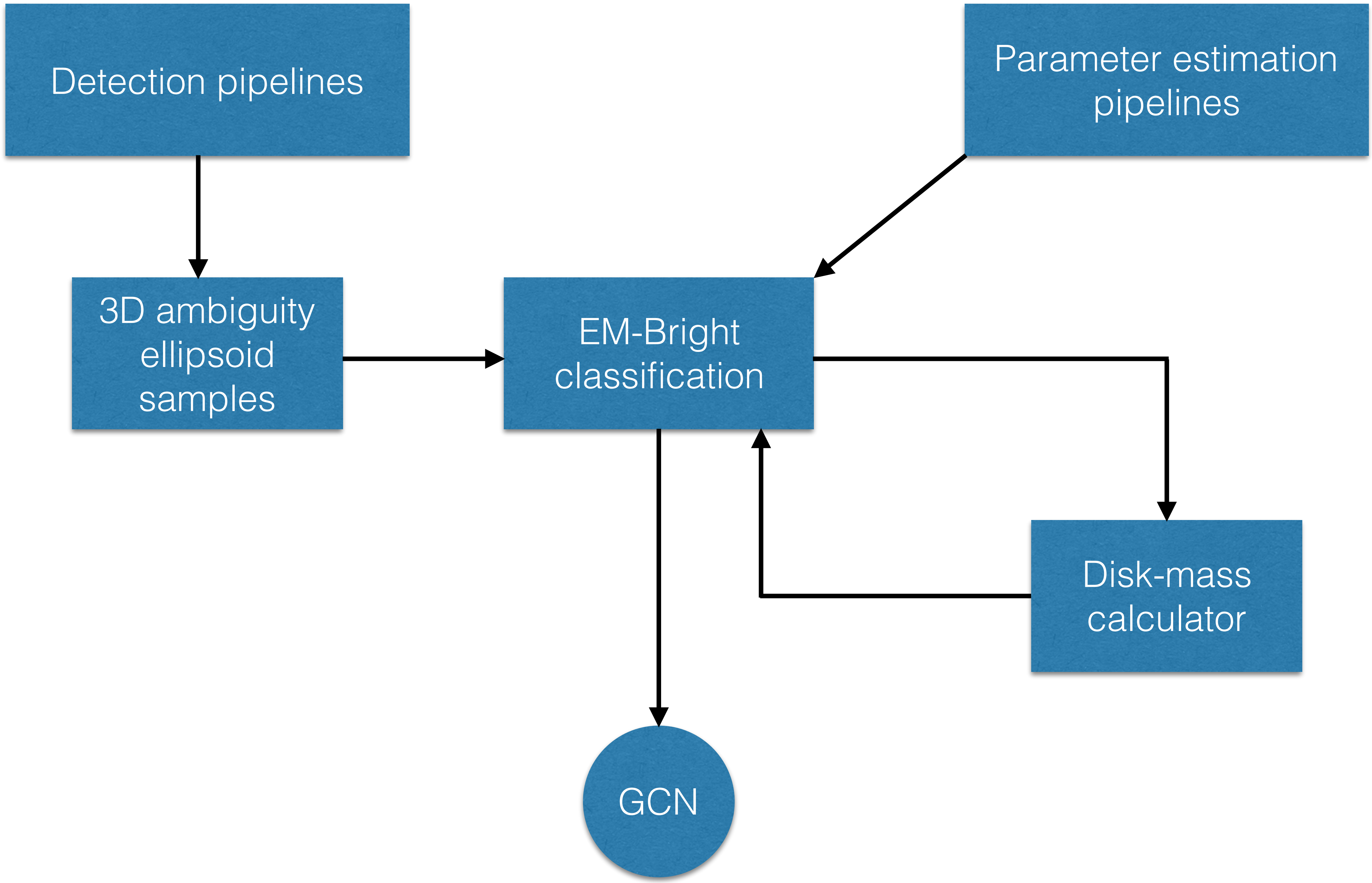
EM-probability from GW triggers

- GW trigger will give us point estimates of masses and the spin components along the orbital angular momentum.
- Before the low-latency parameter estimation results start coming, we can use compute ambiguity ellipse for the trigger parameters.
- We construct the ambiguity ellipses by computing the 3D Fisher matrix around the triggered parameter.
- The 2D ellipses has been extended for this work to 3D ellipsoids (m_1, m_2, χ_1) .

3D Ambiguity Ellipsoid



Basic model

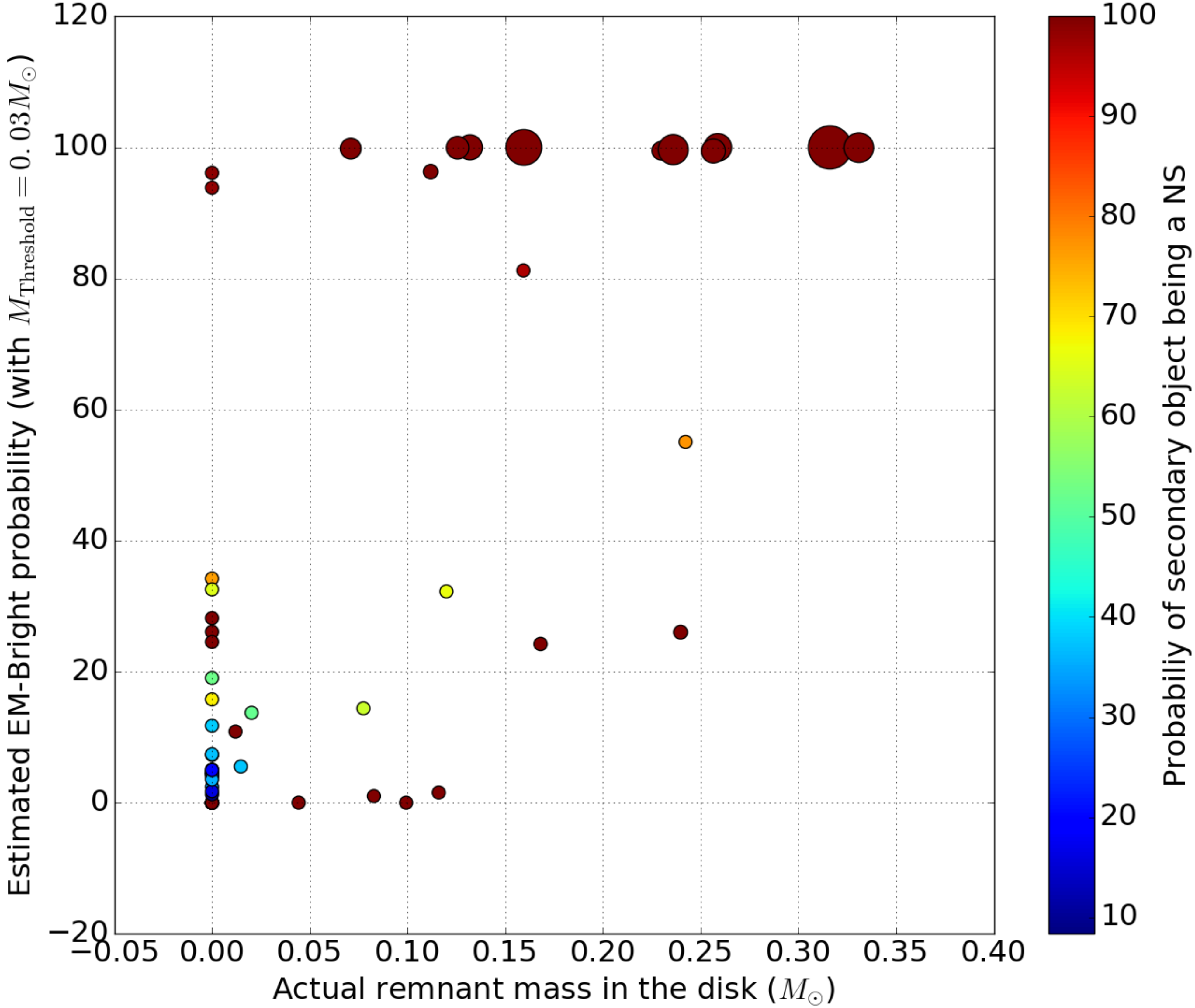


Detection pipelines
Parameter estimation pipelines
3D ambiguity ellipsoid samples
EM-Bright classification
Disk-mass calculator
GCN

Preliminary test

- Conducted initial tests on 100+ Neutron star-Black hole coalescence events.
- Here we are skipping the detection pipeline, pretending the trigger parameters same as injected.
- Computing 3D ambiguity ellipsoid for each cases and populating it with a million sample points.
- Pruning unphysical points: $(\eta > 0.25 \text{ or } \eta < 0, |\chi_1| > 1.0)$
- Computing probability of remnant disk mass greater than threshold

Result



120
100
80
60
40
20
0
−20
−0.05
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
Estimated EM-Bright probability (with $M_{\mathrm{Threshold}} = 0.03M_{\odot}$)
Actual remnant mass in the disk ($M_{\odot}$)
100
90
80
70
60
50
40
30
20
10
Probabiliy of secondary object being a NS

Thanks you