Optimal follow-up observations of gravitational wave events with small optical telescopes

arXiv:1705.04008

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Abstract

- We discuss optimal direction for follow-up observations by 1-3 m class optical telescopes.
- Effects of distance prior on localization for the first three O1 events
  - We evaluate the 3D posterior probability distribution for them by restricting the distance prior to a nearby region where small telescopes can observe the EM counterparts.
- Cases for edge-on binaries
  - It is possible that the true direction is not included in the 90% posterior region.
- Based on our results, we discuss the optimal strategy to perform optical follow-up observation with small aperture telescopes.

EM counterparts of GWs from CBC

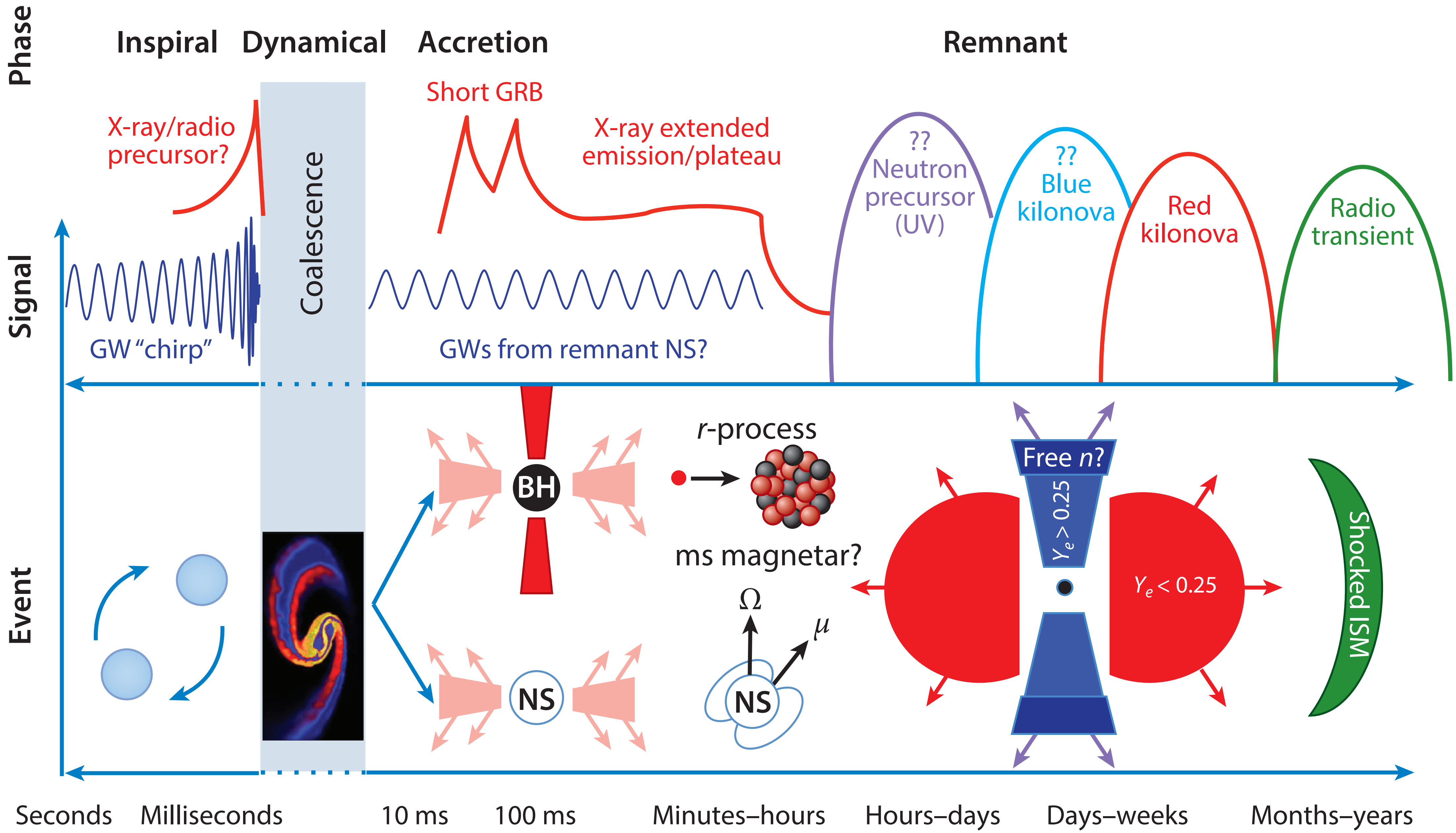
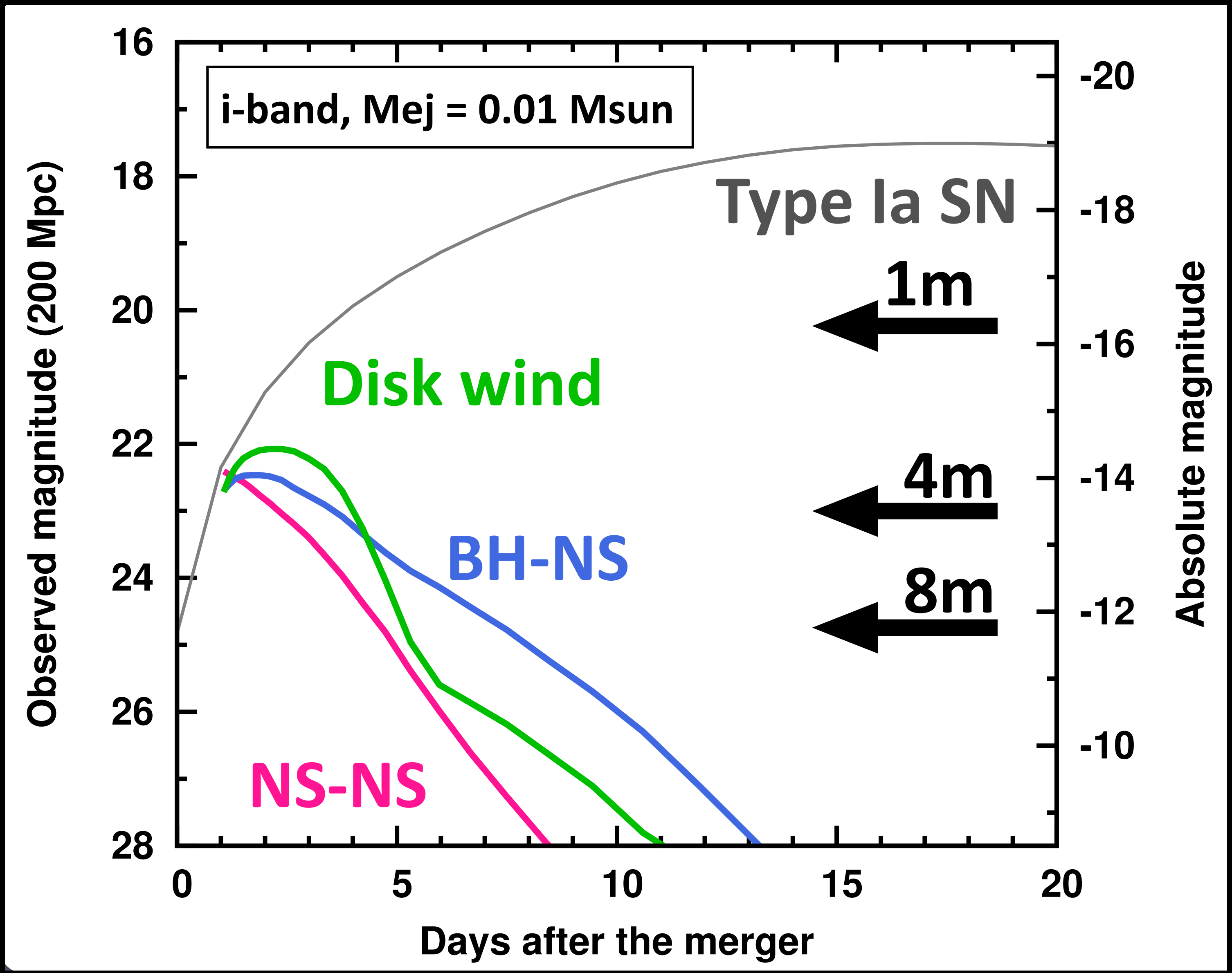


Figure 1

Phases of a neutron star (NS) merger as a function of time, showing the associated observational signatures and underlying physical phenomena. Abbreviations: BH, black hole; GRB, γ-ray burst; GW, gravitational wave; ISM, interstellar medium; n, neutron; UV, ultraviolet; Y_e, electron fraction. Coalescence inset courtesy of D. Price and S. Rosswog (see also Reference 15).

[Fernandez, Metzger, ARNPS 66, 23-45 (2016).]

Radiative transfer simulations of NS-NS/BH-NS mergers => Kilonova/Macronova emission

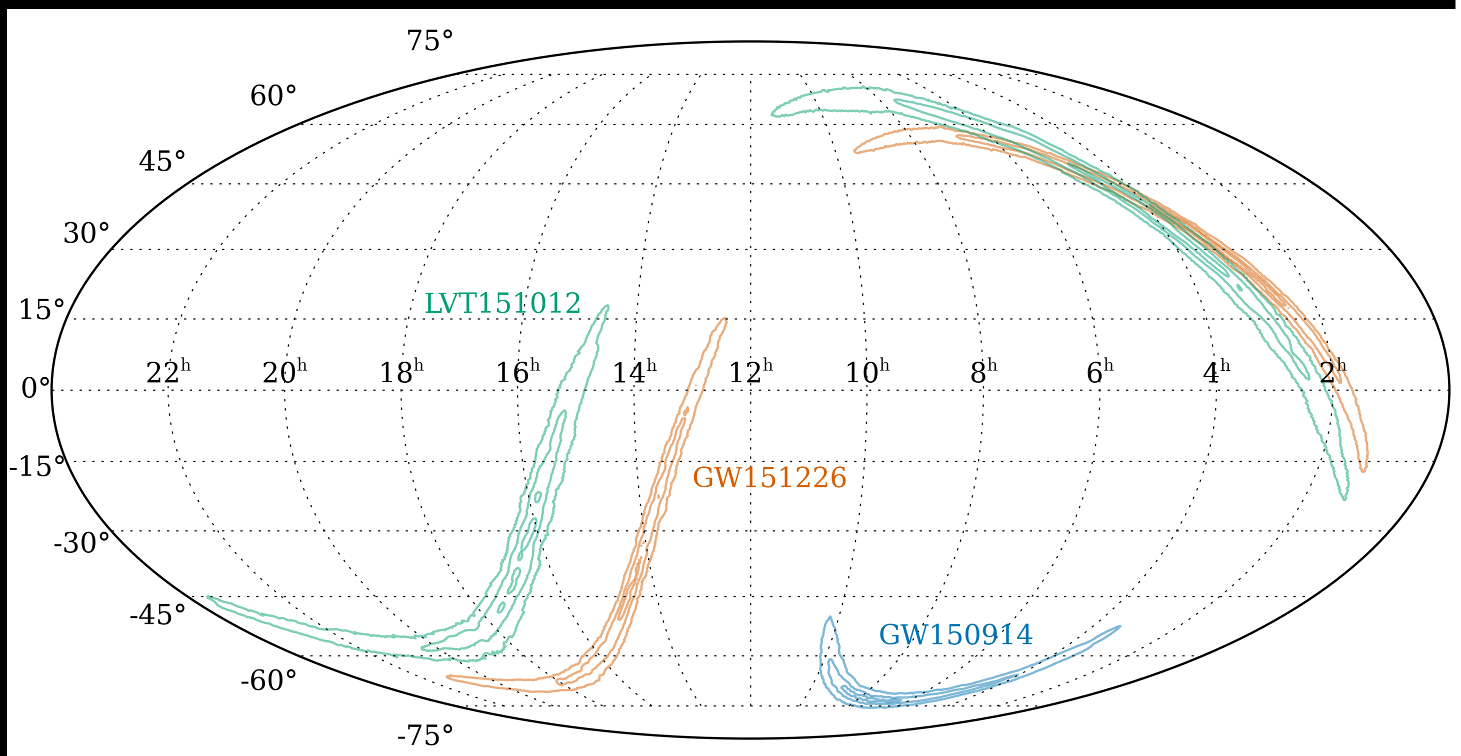


[Tanaka & Hotokezaka, 2013 ApJ, 755, 113.]

Kilonova/Macronova @~100Mpc can be observed with small aperture telescopes.

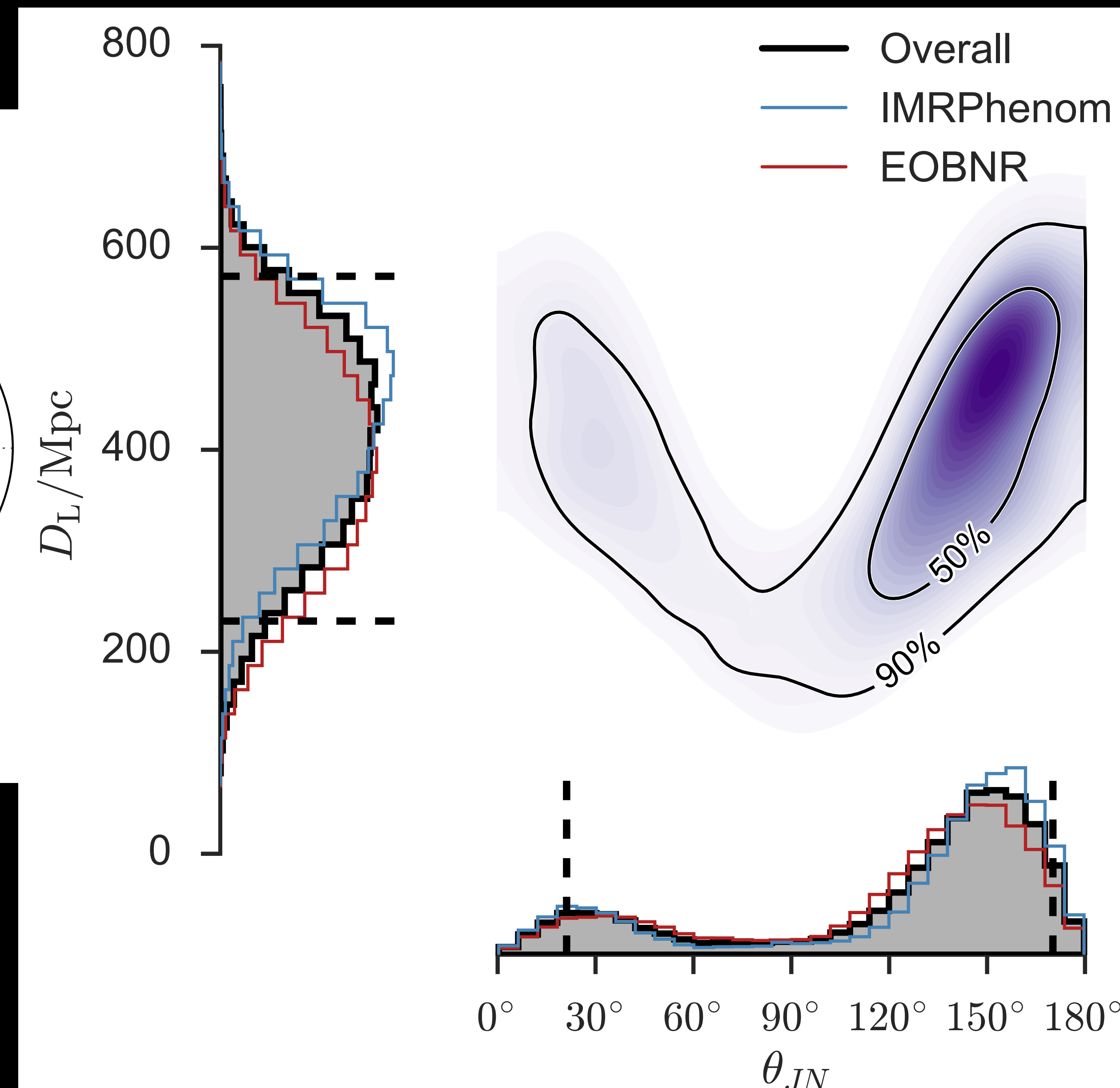
Results of GW150914, GW151226, LVT151012

Posterior sky maps determined with two detectors (HL) spread widely, including the distant region, and nearly face-on/off are favored.



2D sky map.

[LSC & Virgo, PRX 6, 041015 (2016).]



Luminosity distance and orbit inclination for GW150914.

[LSC & Virgo, PRL 116, 1102 (2016).]

Optical follow-up observations with telescopes

Japanese

Subaru/HSC, KWFC, MOA-II carried out wide-field surveys overlapped with the high probability sky map by LIGO.

[Yoshida, et al., "J-GEM Follow-up of GW151226", arXiv:16111.01588.]

Small telescopes observed the galaxies overlapped with LIGO's sky map.

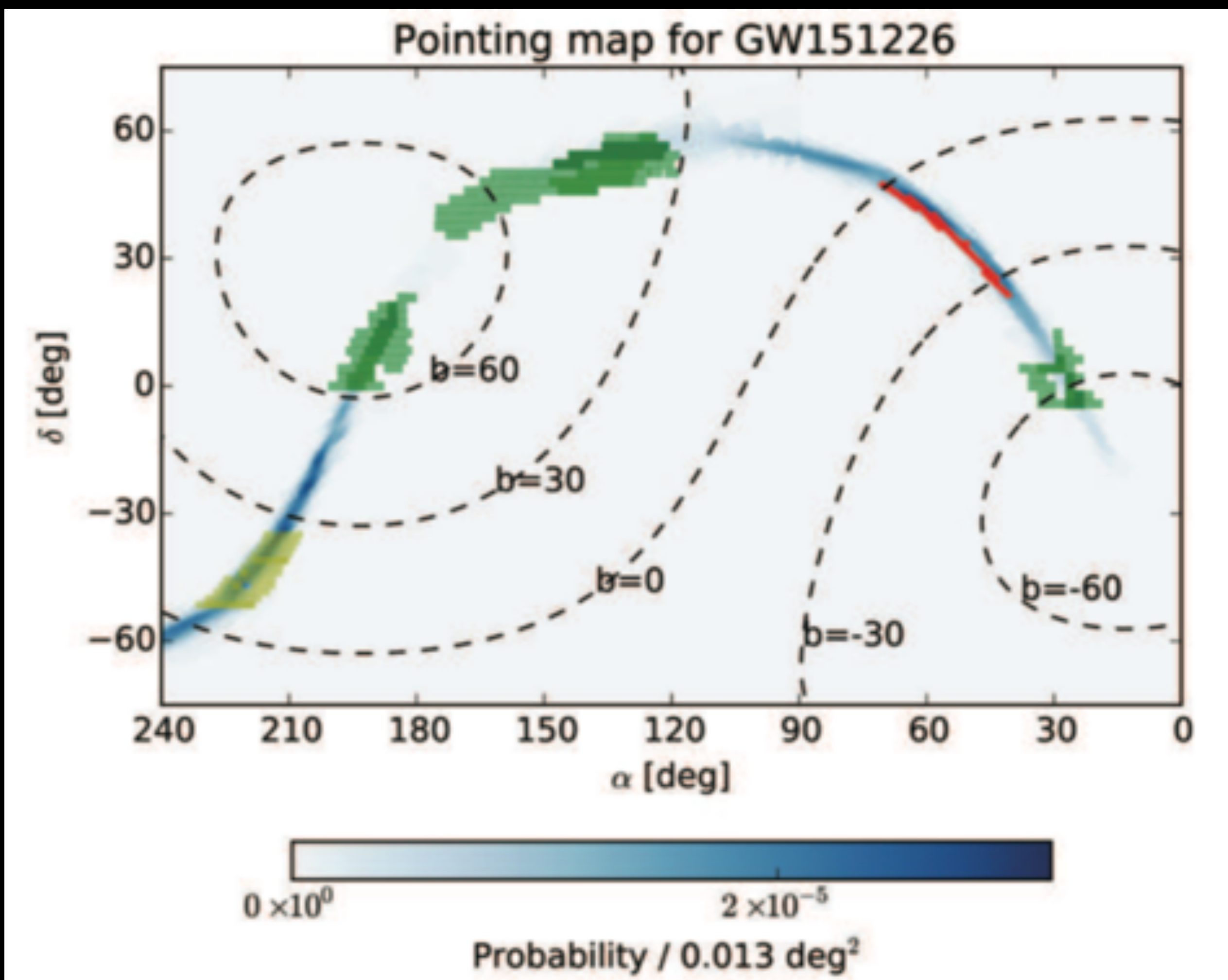


Fig. 1. The observed area of the wide-field surveys of the J-GEM follow-up observation of GW151226 overlaid on the probability skymap (dark blue scale). Green, red, and yellow colored regions represent the areas observed with KWFC, HSC, and MOA-cam3, respectively.

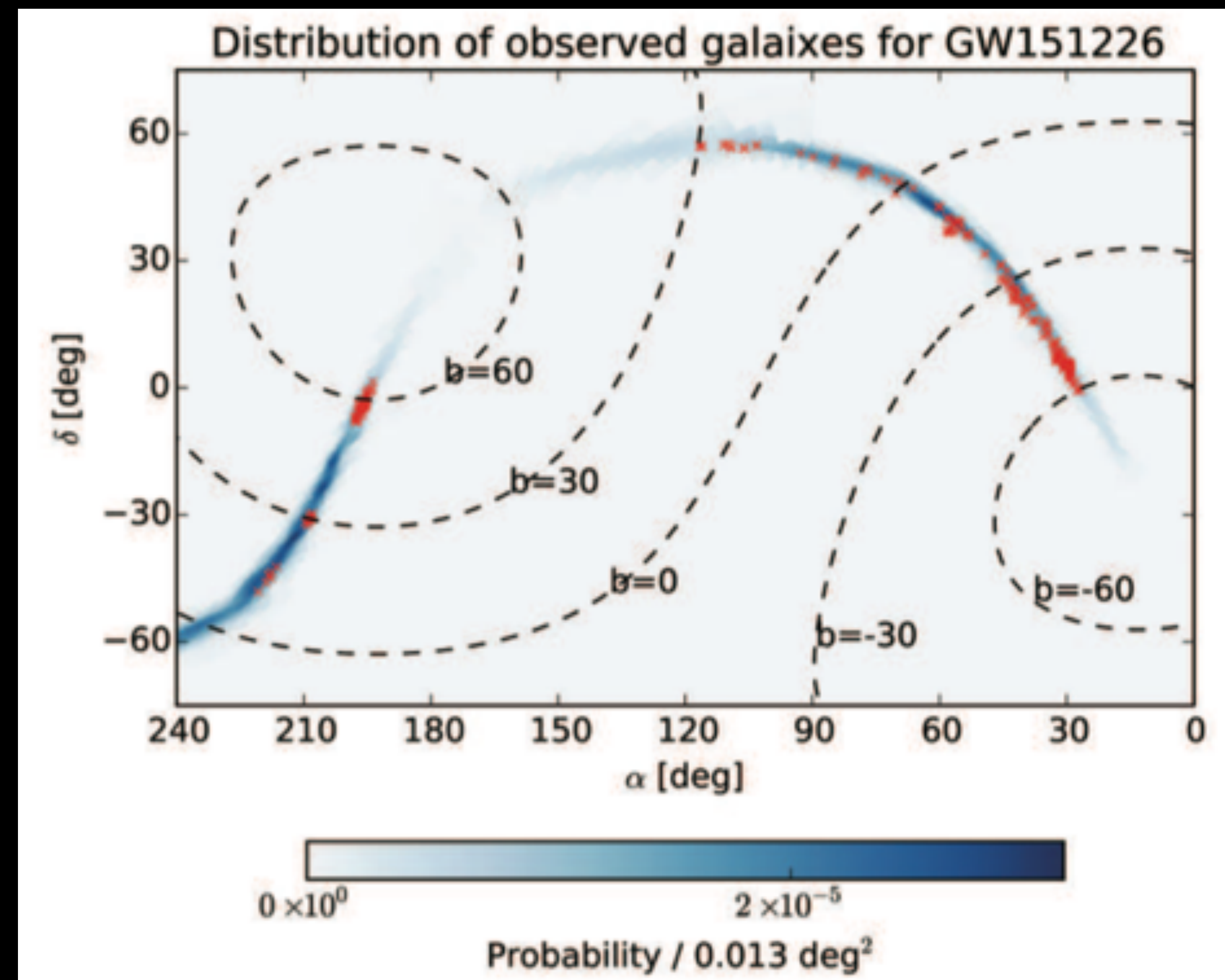


Fig. 3. The positions of the galaxies observed in the J-GEM follow-up observation of GW151226 (red points).

Follow-up observation with Small class telescopes

1-3 m class aperture-size telescopes are main facilities of optical-wavelength follow-up observations for GW events.

[Photo by TN, (August 2007).]

e.g.,

Higashi-Hiroshima (Kanata)

diameter=1.5 m

FoV: 10'×10' (HONIR)

Kilonova@~100Mpc

⇔ ~21mag within a few days

⇔ t_{exp}~10min with Kanata

⚠ For small telescopes, it is not easy to observe objects with 21 magnitude at large distance.

It is possible for small telescopes to detect EM counterparts only if the source is located nearby, e.g., within 100 Mpc.

Effects of distance prior on localization for O1 events

[TN, Kaneyama, Tagoshi, 2017]

We evaluate the three dimensional posterior probability distribution for the first three O1 events by restricting the distance prior to a nearby region where small telescopes can observe the EM counterparts.

We compute evidences based on Bayesian inference, especially nested sampling [Skilling, 2006; Veitch & Vechio, 2010] by using the LALInference, which is one of the LIGO Algorithm Library (LAL) software suite.

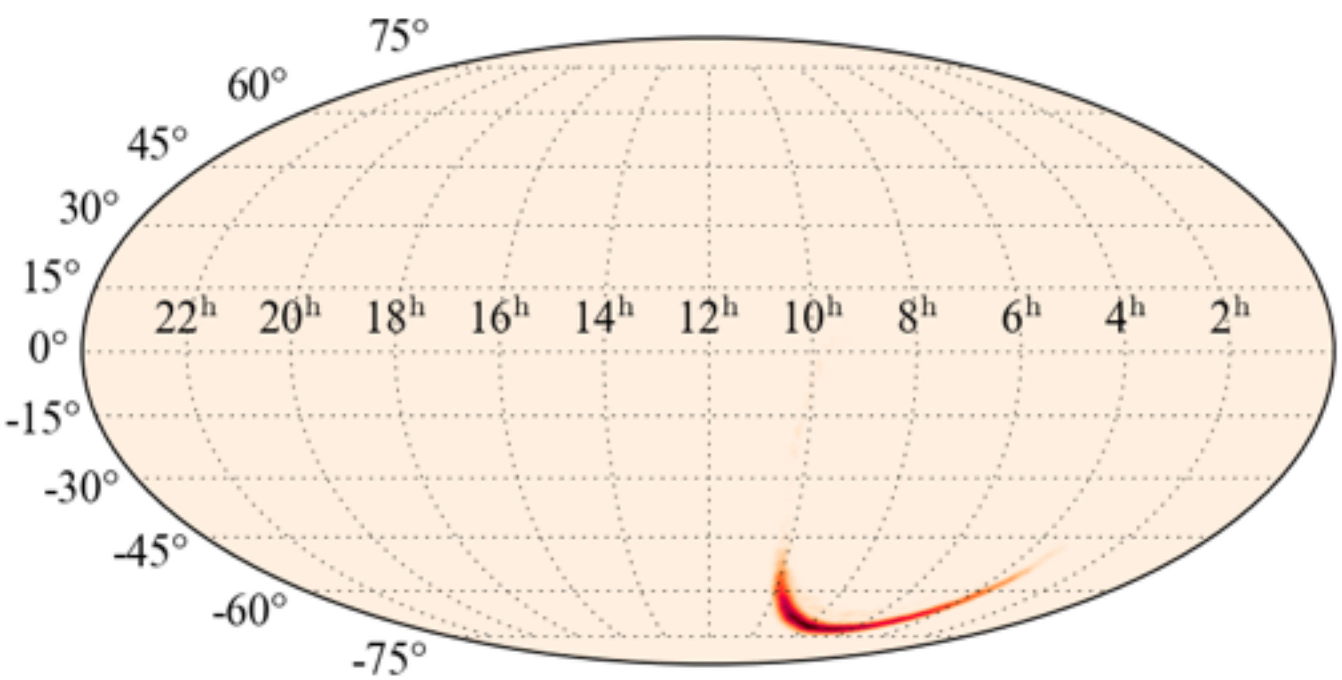
Data available from https://losc.ligo.org/events/.

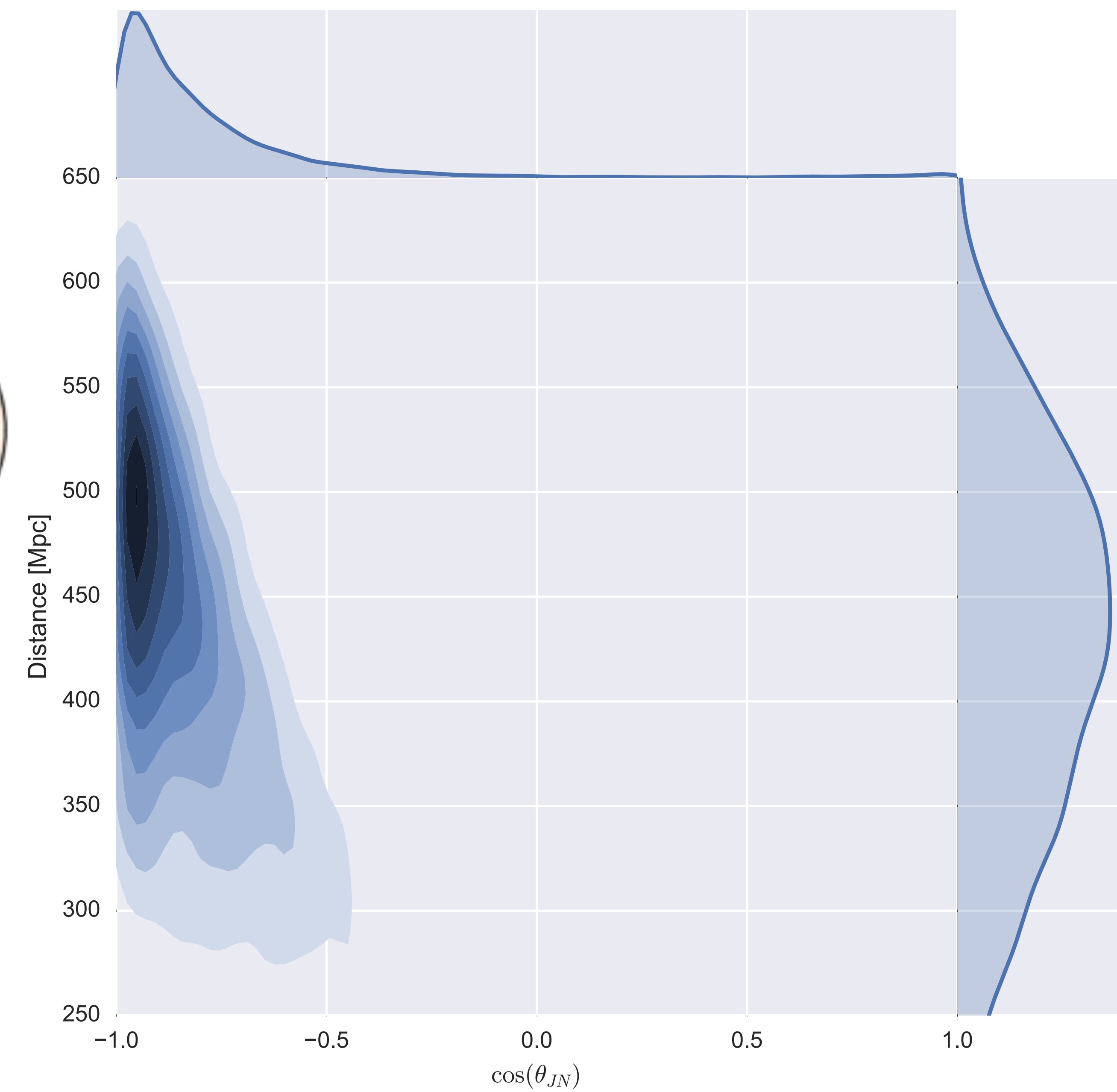
3D posterior for GW150914

Template: Inspiral-Merger-Ringdown, Precession (IMRPhenomPv2)

In the case of no strong distance prior =>
SNR=23.9
$\Delta\Omega$=193 deg^2

Nearly face-off is favored.

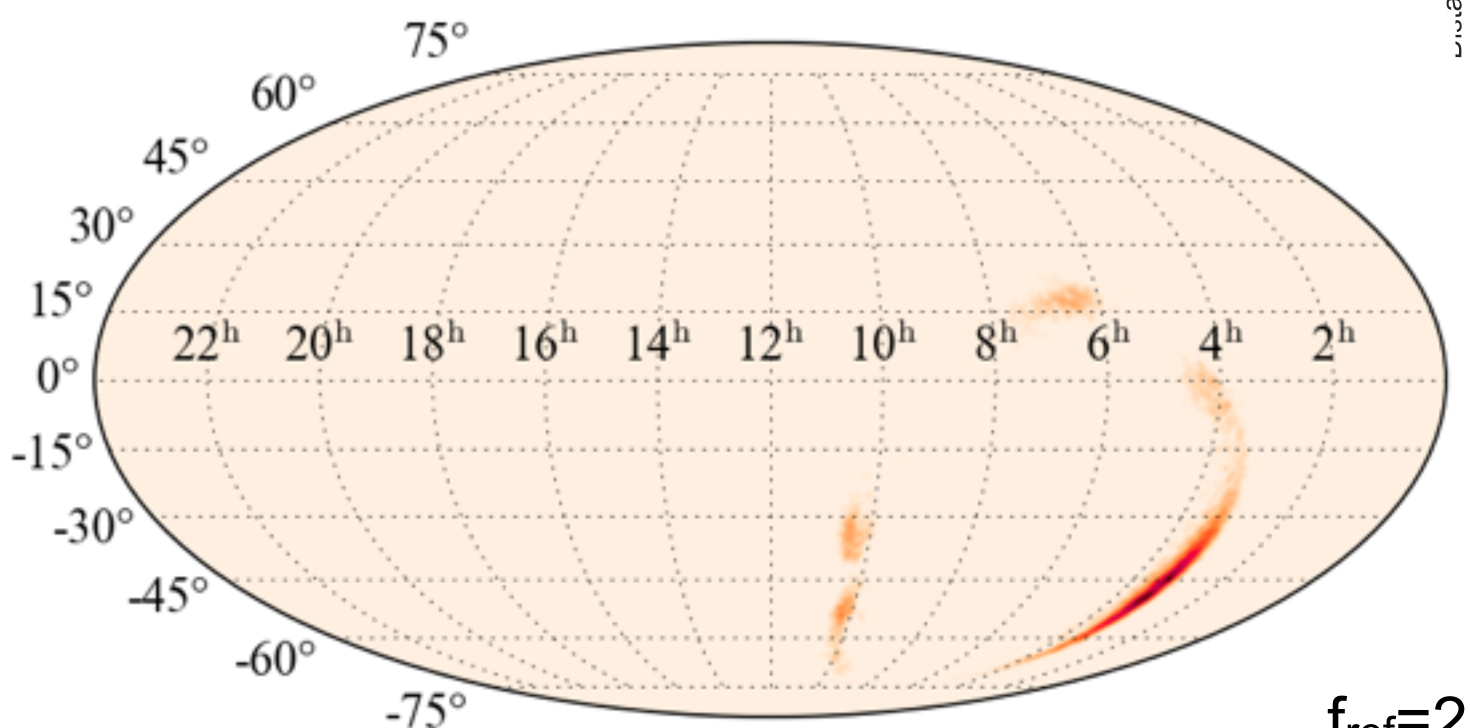


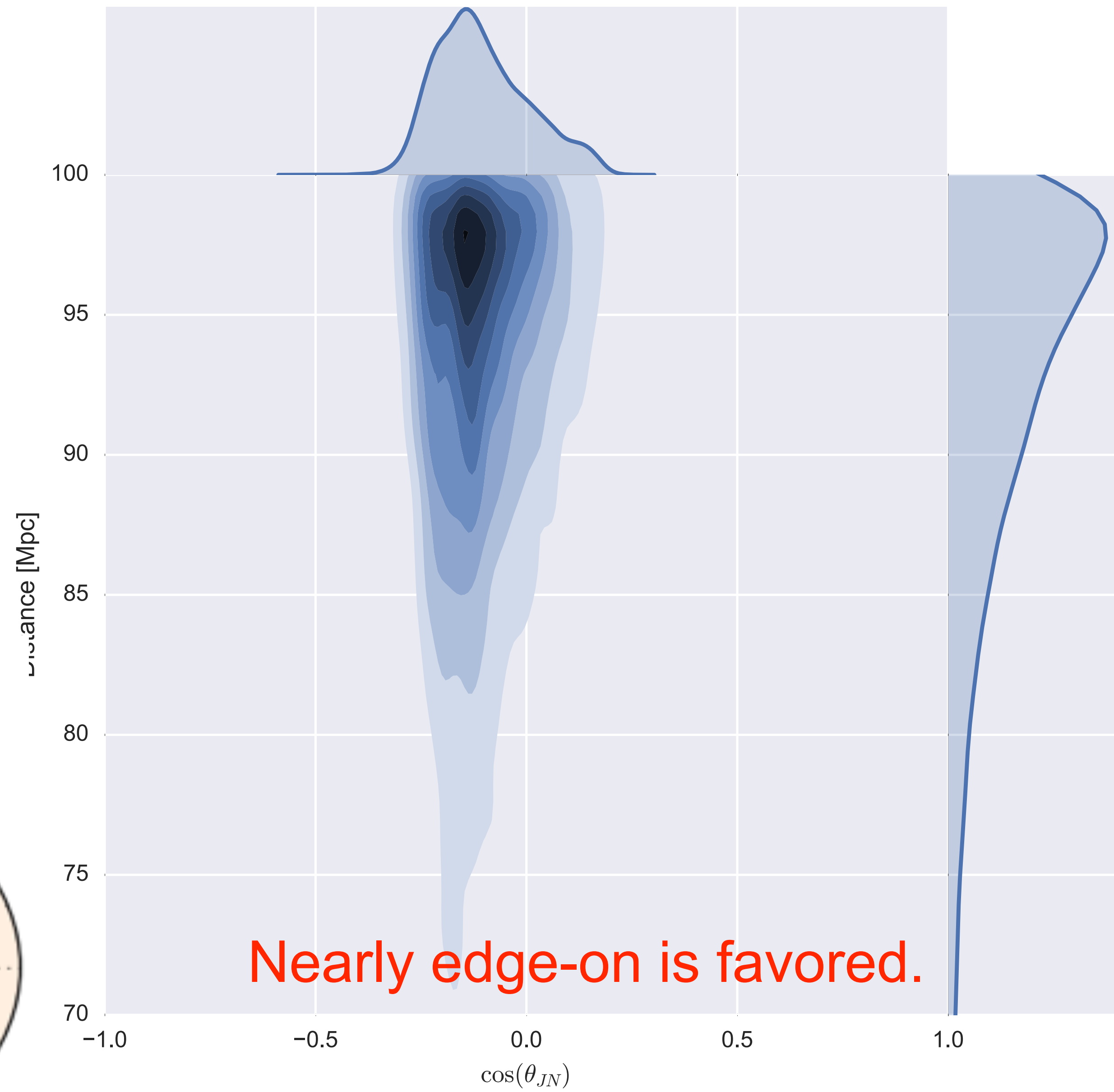


f_{ref}=20Hz

3D posterior for GW150914

In the case of restricted distance prior: D_L<100Mpc =>
SNR=23.9
616deg^2





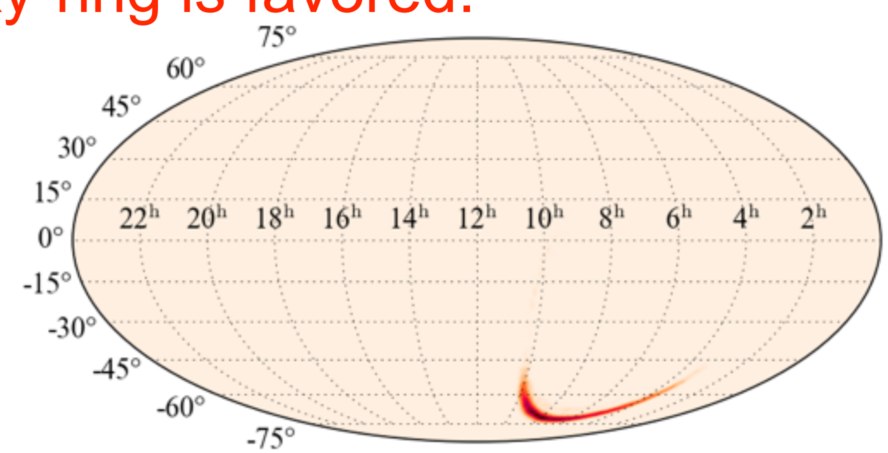
Nearly edge-on is favored.

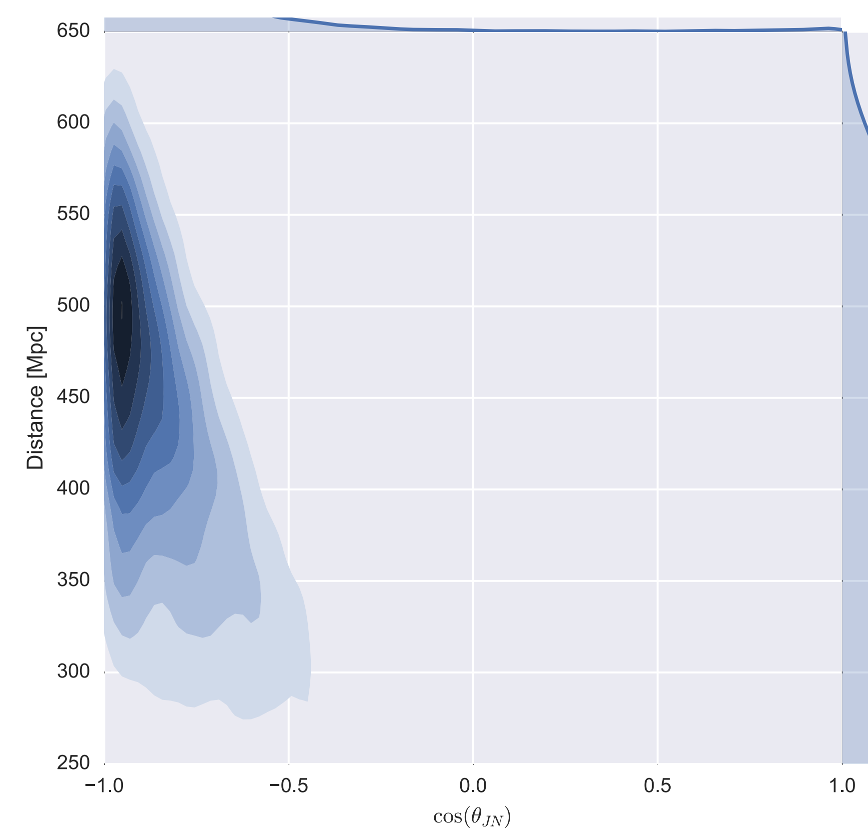
f_{ref}=20Hz

Different region of the same sky-ring is favored.

In the case of no strong distance prior =>
SNR=23.9, ΔΩ=193 deg^2

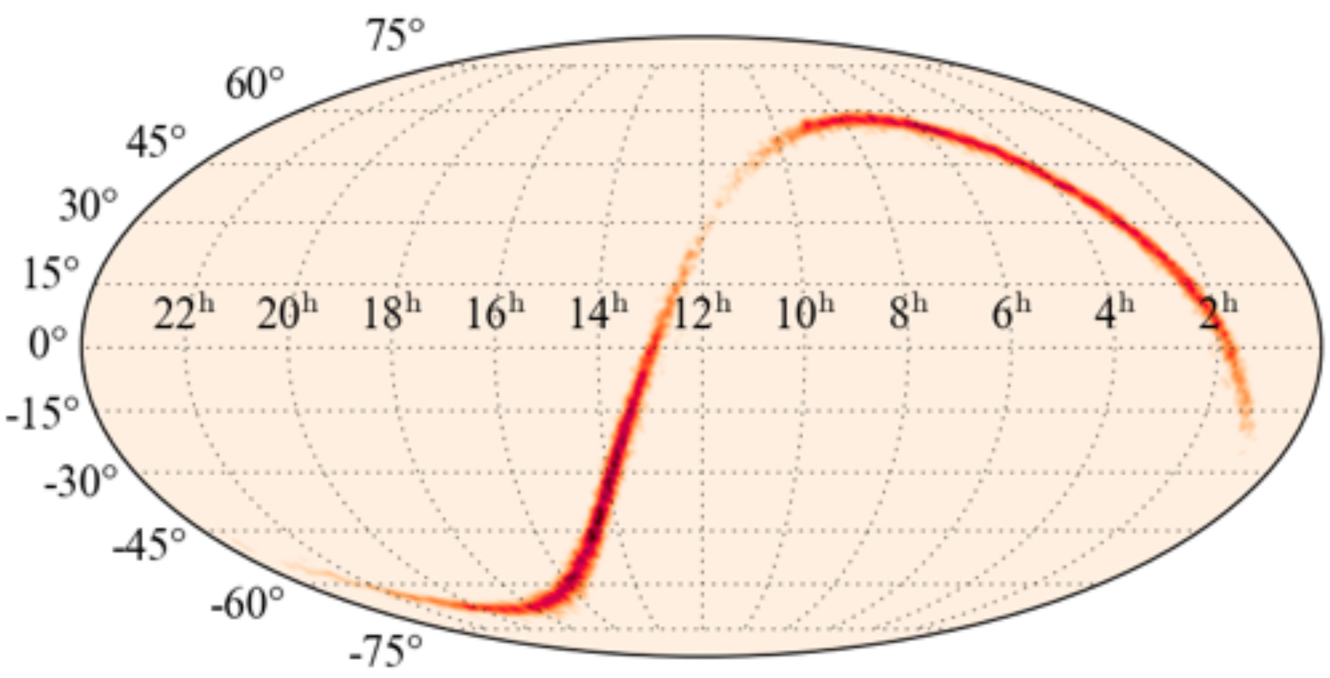
Nearly face-on is favored.



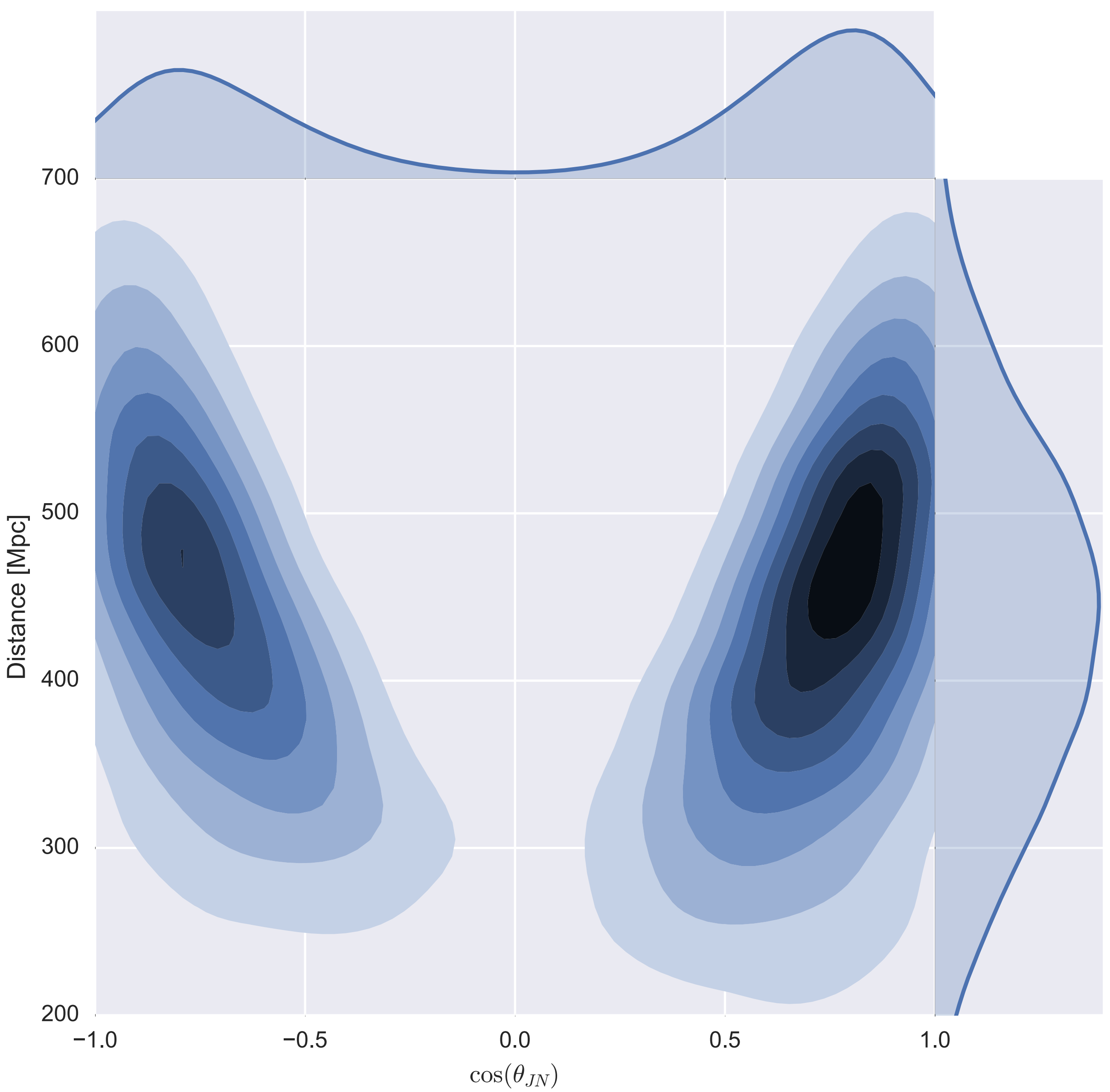


3D posterior for GW151226

In the case of no strong distance prior =>
SNR=12.5, 1032deg^2



Nearly face-on/off is favored.

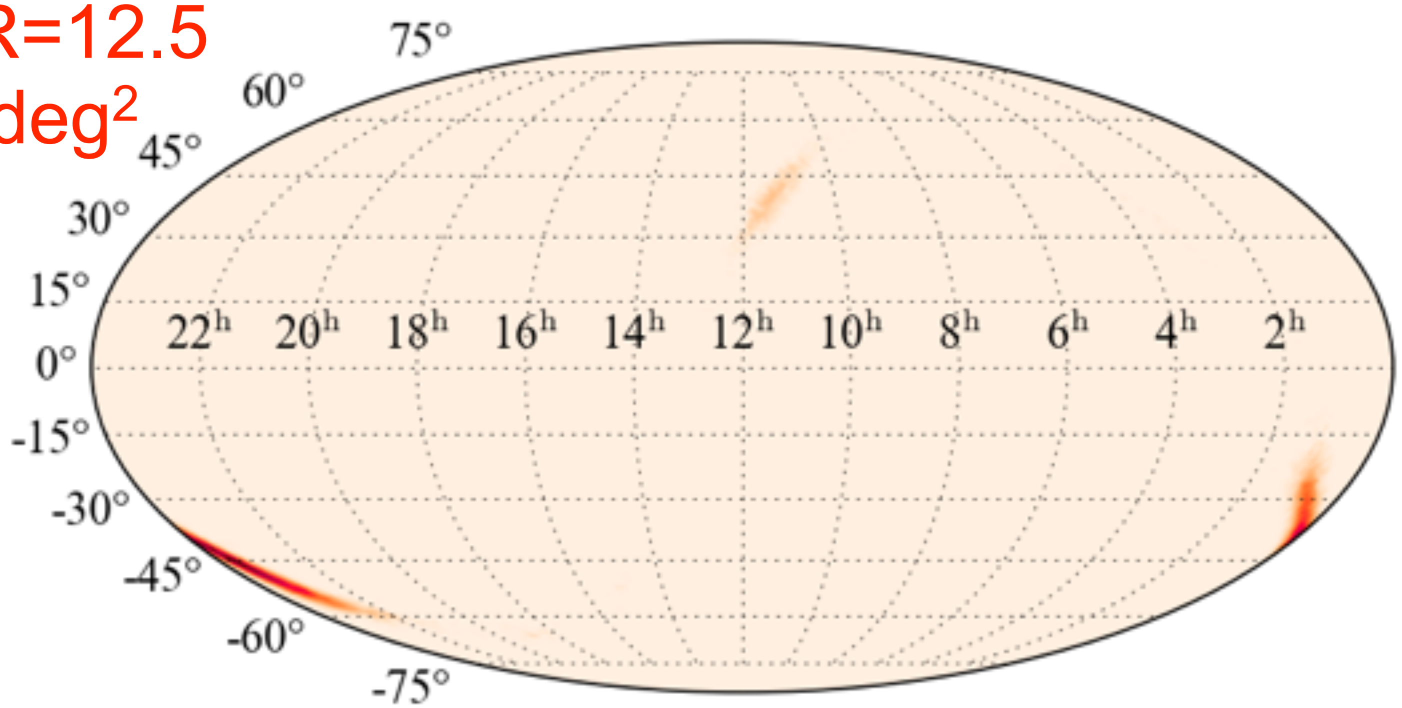


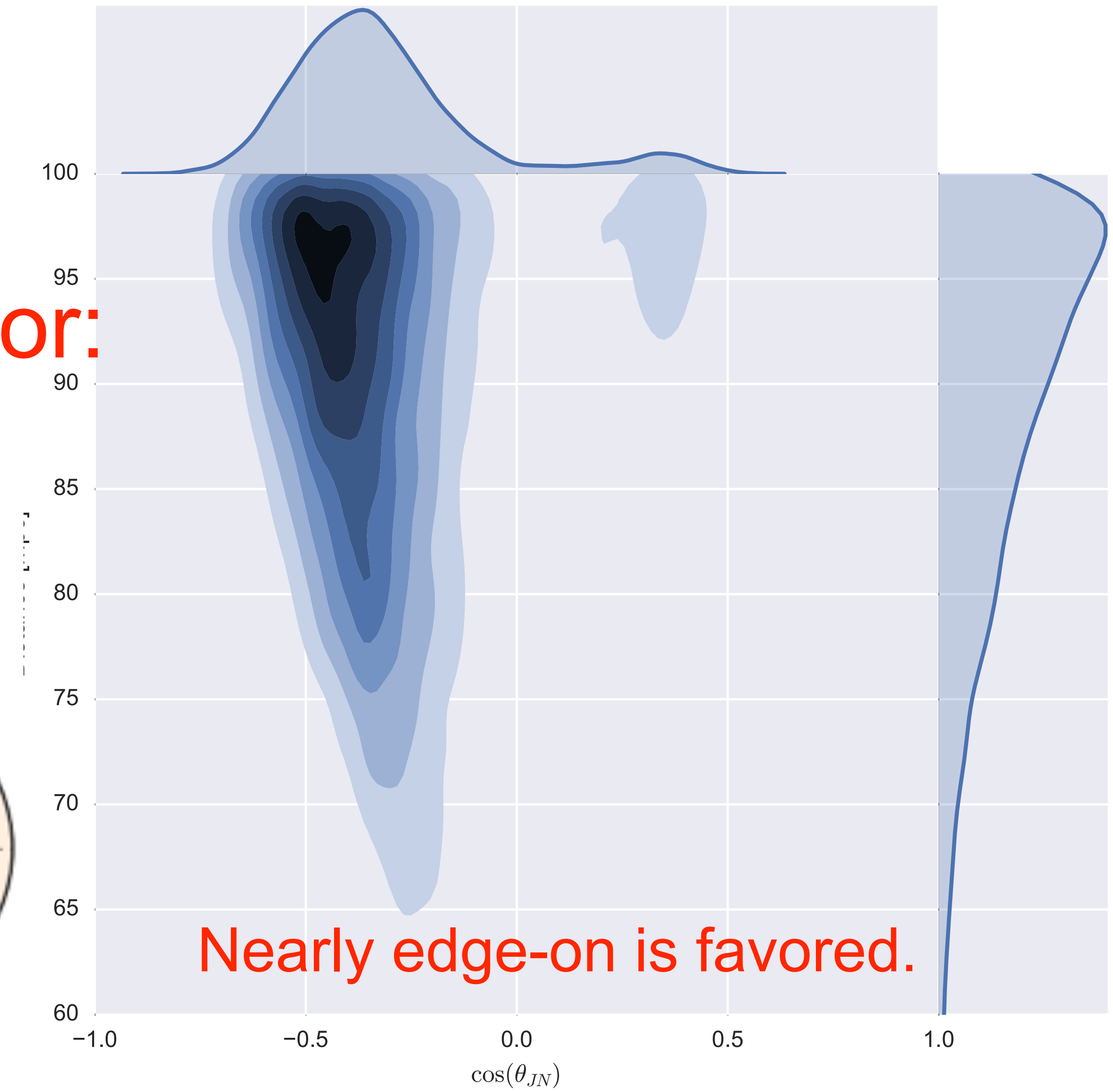
3D posterior for GW151226

In the case of restricted distance prior: D_L<100Mpc =>

SNR=12.5

335deg^2



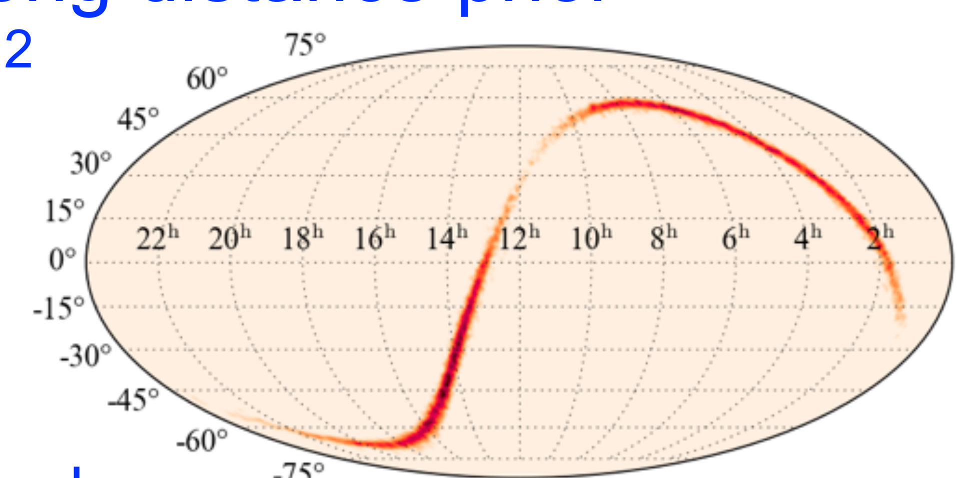


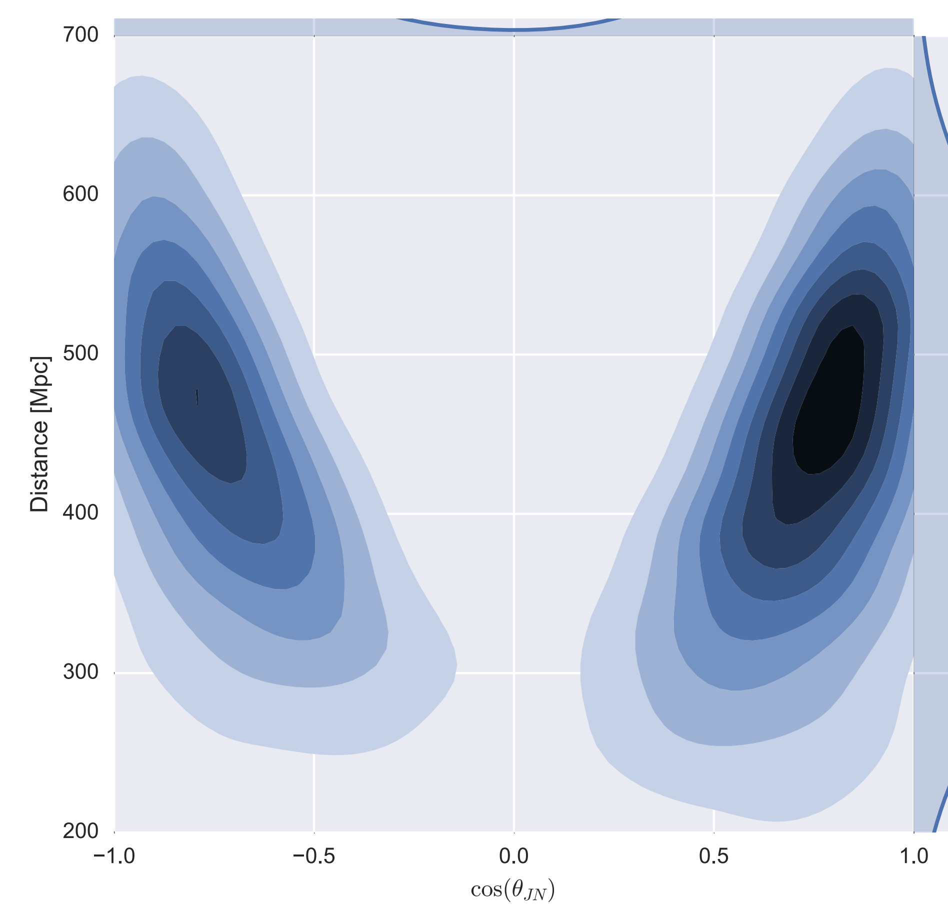
Nearly edge-on is favored.

Different region of the same sky-ring is favored.

In the case of no strong distance prior =>

SNR=12.5, 1032deg^2

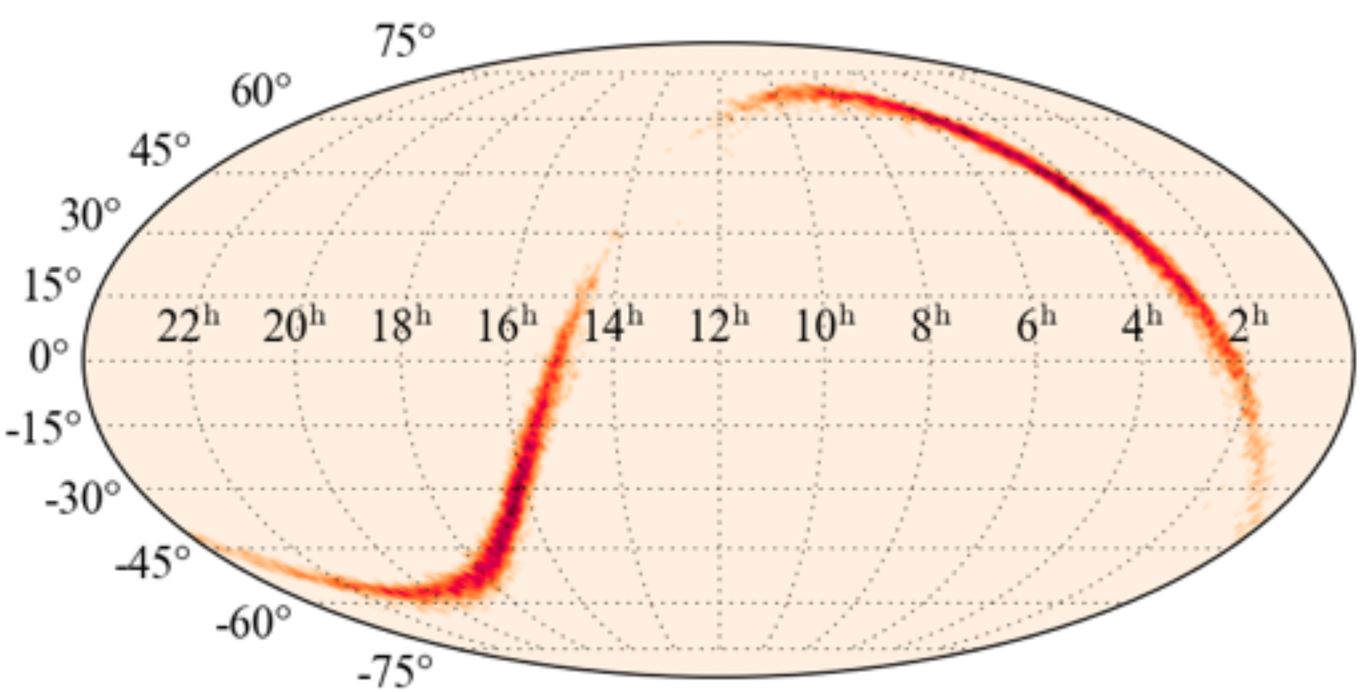




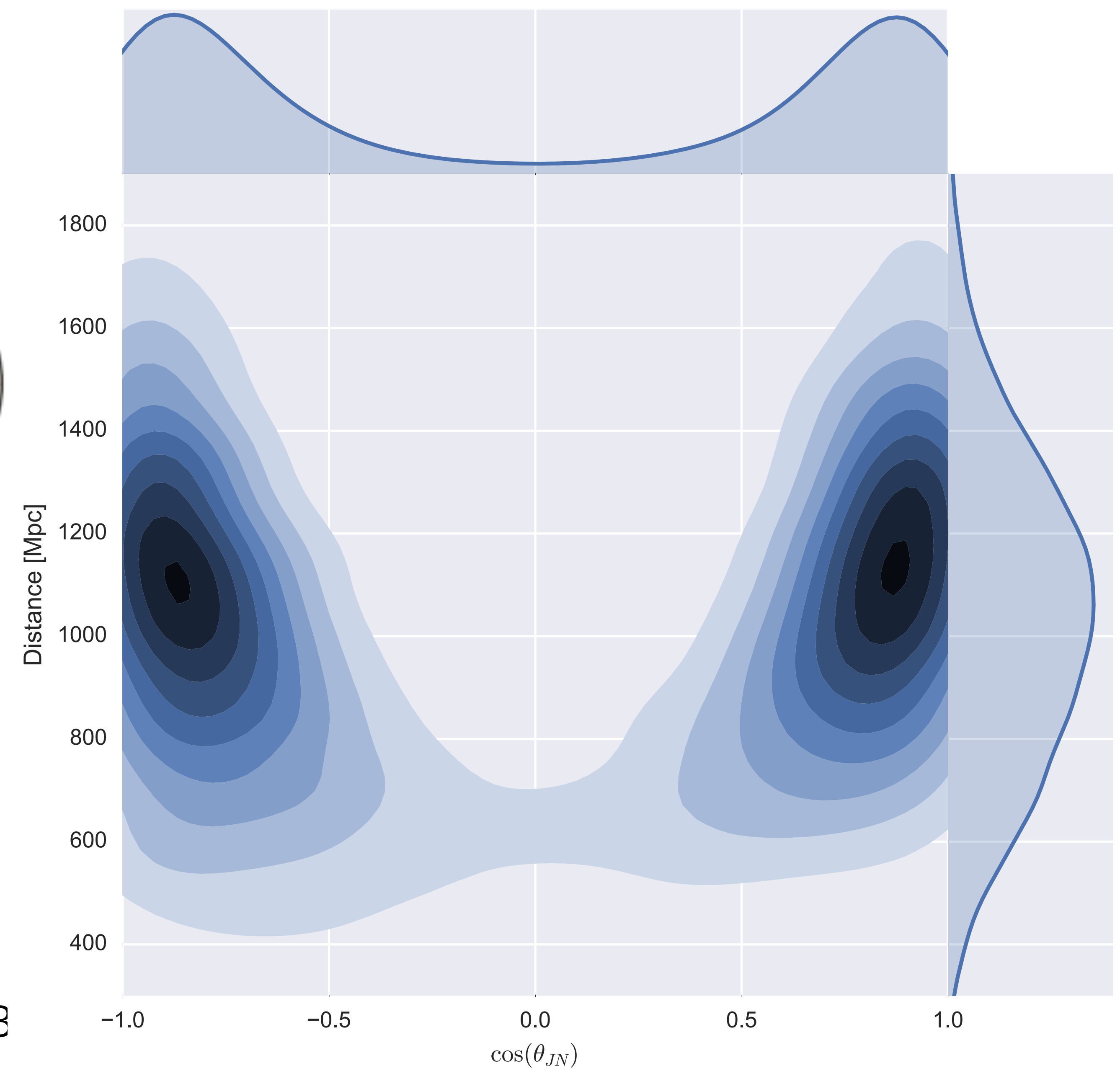
Nearly face-on/off is favored.

3D posterior for LVT151012

In the case of no strong distance prior =>
SNR=9.65, 1415deg^2

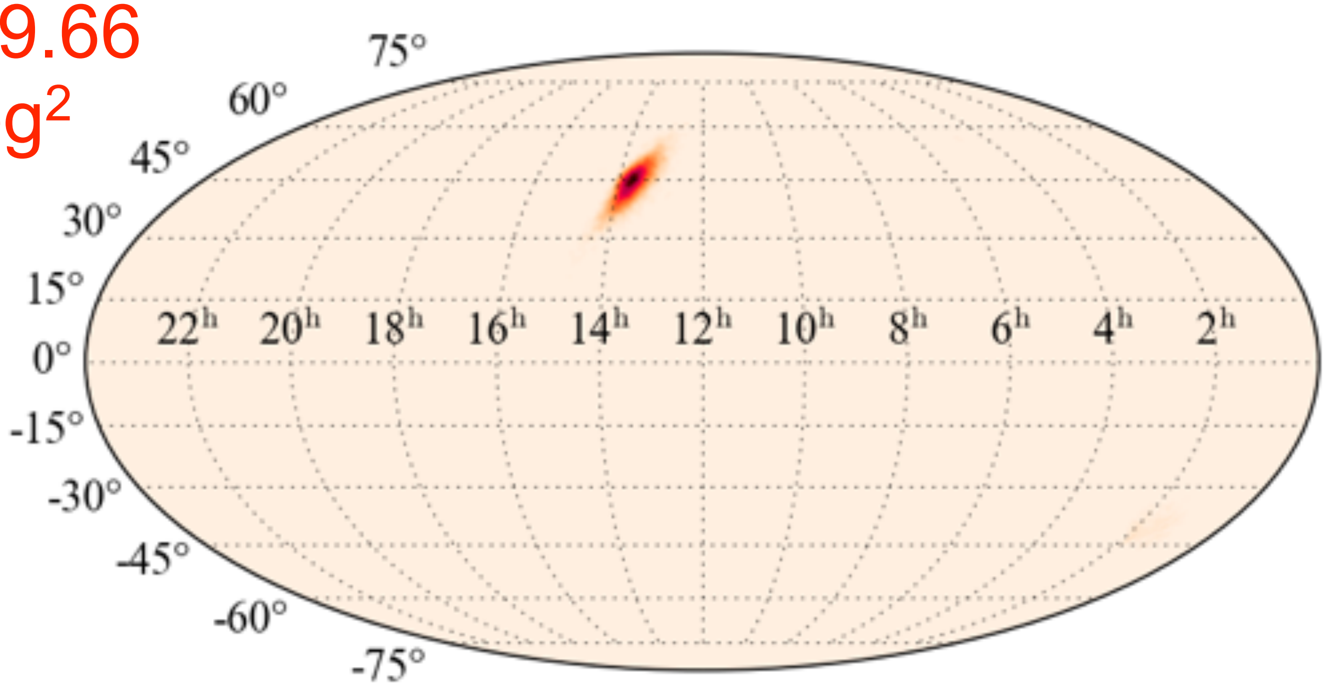


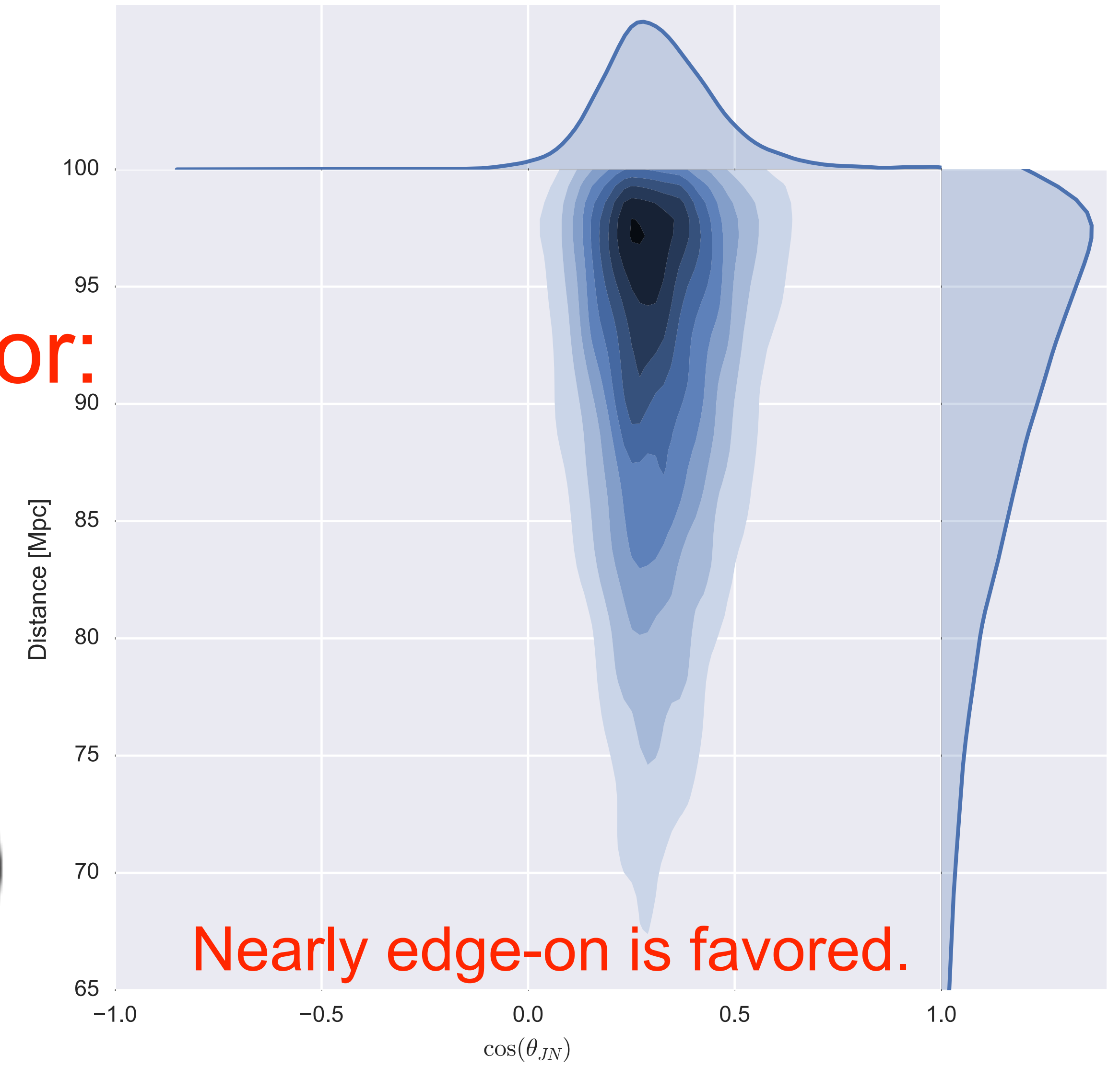
Nearly face-on/off is favored.



3D posterior for LVT151012

In the case of restricted distance prior:
D_L<100Mpc =>
SNR=9.66
157deg^2

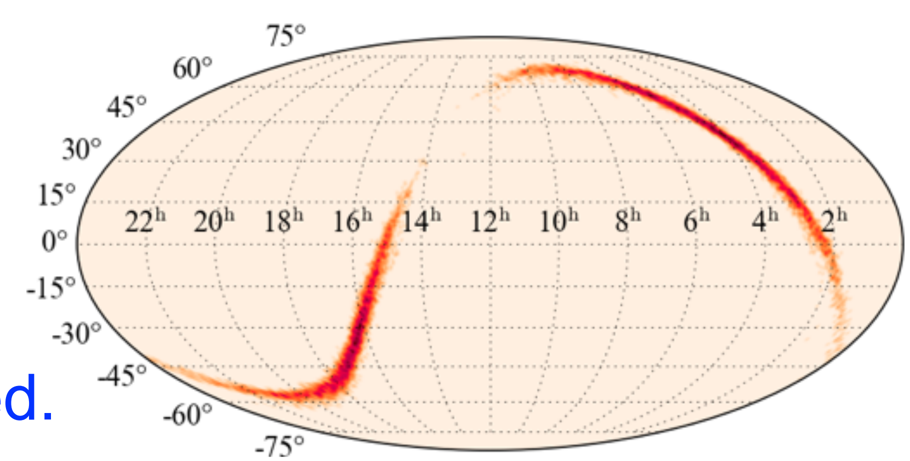


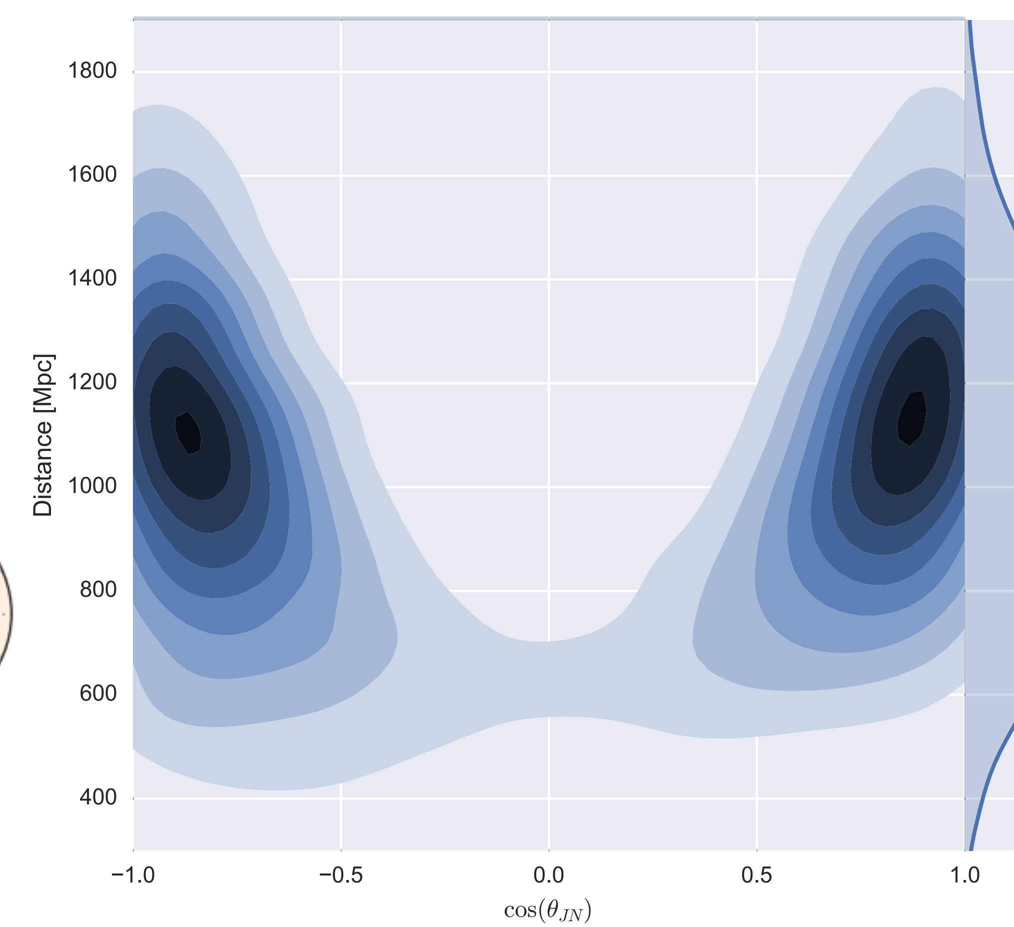


Nearly edge-on is favored.

Different region of the same sky-ring is favored.

In the case of no strong distance prior =>
SNR=9.65
1415deg^2





Nearly face-on/off is favored.

Short summary

Effects of distance prior on localization for the first three O1 events

We evaluated the three dimensional posterior probability distribution for the first three O1 events by restricting the distance prior to a nearby region where small telescopes can observe the EM counterparts.

- ➢ The probability sky maps estimated with HL spread widely. They include the distant region where it is difficult for small telescopes to observe the optical counterparts.
- ➢ For small telescopes, there is a possibility that it is more advantageous to search for nearby region even if the probability inferred is low.

- ➢ Our results suggests that the optimal direction for small telescopes are different from what has been searched so far.
- ➢ Optimal direction may be the direction derived with a restricted distance prior.

How the difference of the sky map appears?

Among the parameters which describe the waveform, five parameters, including distance d_L, inclination angle of the orbital plane θ_{JN}, polarization angle, and two angle parameters (sky direction), determine the amplitude of GWs together with two mass parameters.

These five parameters appear in the amplitude of waveform in the form,

$$\left[F_{+}^{2}\left(\frac{1+\cos^{2}\theta_{\mathrm{JN}}}{2}\right)^{2}+F_{\times}^{2}\cos^{2}\theta_{\mathrm{JN}}\right]^{1/2} d_{\mathrm{L}}^{-1}$$

This suggests that those parameters are correlated.

When we evaluate the posterior probability density for a given signal candidate, we assume that the source is distributed uniformly in the comoving volume. Thus, within a unit distance interval, there are more sources at larger distance. This suggests that the posterior probability density of distance becomes larger at larger distance.

We find that for a given amplitude of a signal, if larger distance is preferred, larger value of $|F_+|$, $|F_\times|$ and $\cos(\theta_{JN})$ are also preferred. The sky map is determined in this way.

When the distance prior is limited to nearby region, in order to realize the same amplitude of the signal data, the sky location with smaller value of $|F_+|$, $|F_\times|$ and $\cos(\theta_{JN})$ are favored. This produces the sky map which is located along the ring determined by the time delay, but very different from the original map.

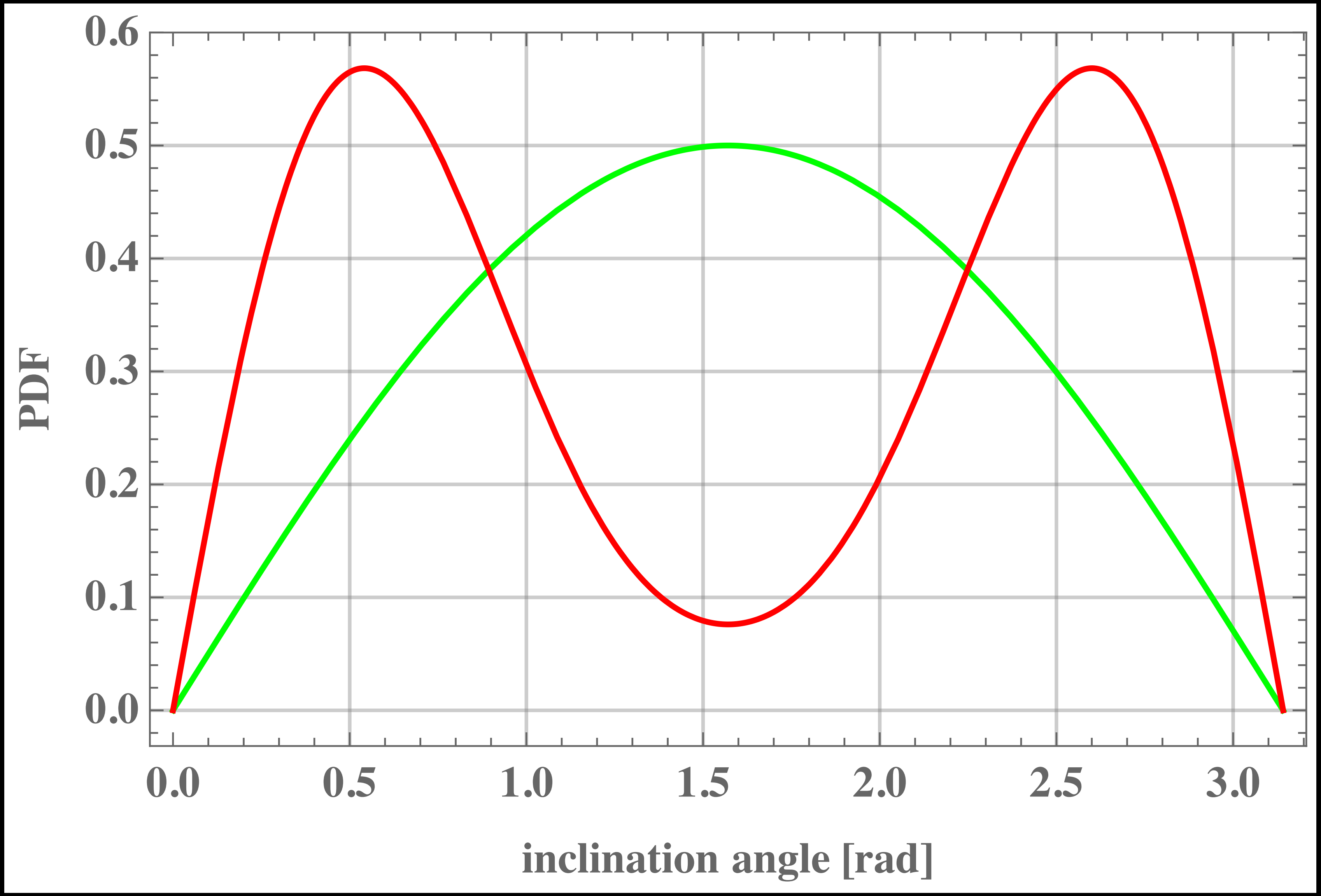
The origin of this effect is the similar to that known as the GW Malmquist effect, which states that GW detectors detect more face-on/off binaries located at relatively larger distance.

GW Malmquist effect

[Schutz, CQG 28, 125023 (2011).]

GW detection criterion preferentially selects for more face-on/off with cos i → ±1.

The probability distribution of "detected" values of inclination



green: injection

red: detected

The selection bias toward low inclinations due to the anisotropic pattern of a binary is clear.

Cases for edge-on CBCs: two examples

- We also discussed the observation of nearly edge-on binaries, it is possible that the true direction is not included in the 90% posterior region.

Injected signals: BNS at 20 Mpc
two different sky location
on expected O2 sensitivities with Gaussian noise

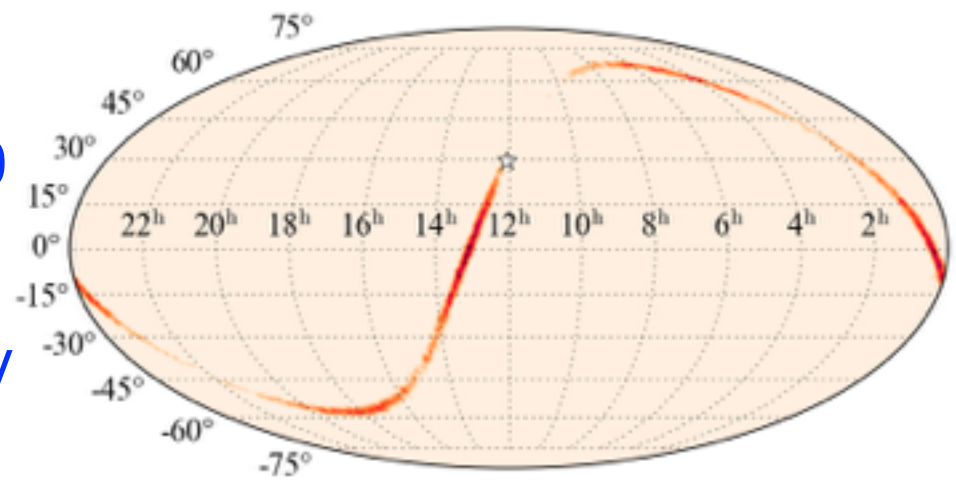
We consider three cases.
Case A: HL, no strong distance prior
Case B: HL, restricted distance prior < 30 Mpc
Case C: HLV, no strong distance prior

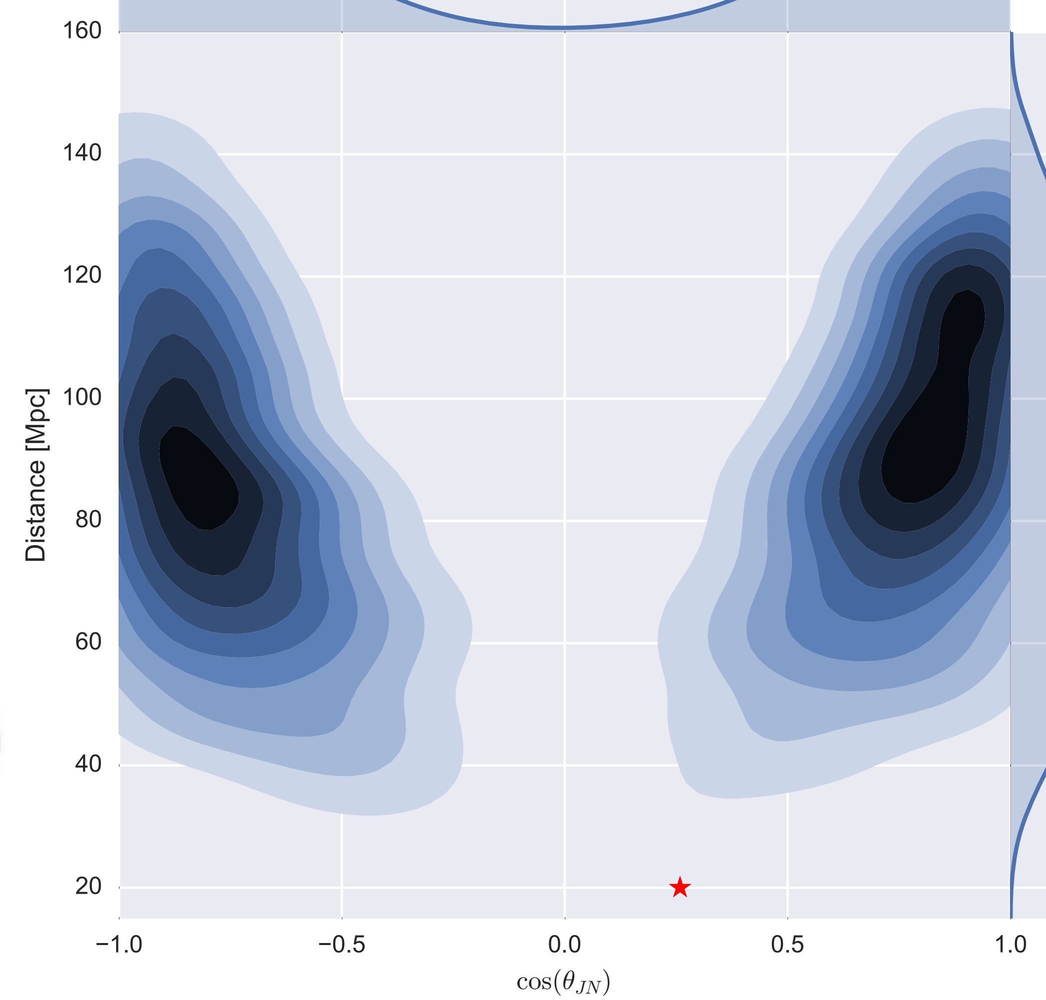
Example 1 **Edge-on binary**

Injected signal: BNS, nearly edge-on, 20Mpc

Case A: HL, no strong distance prior

SNR=16.3
735deg2
cos(angle offset)=-1.00



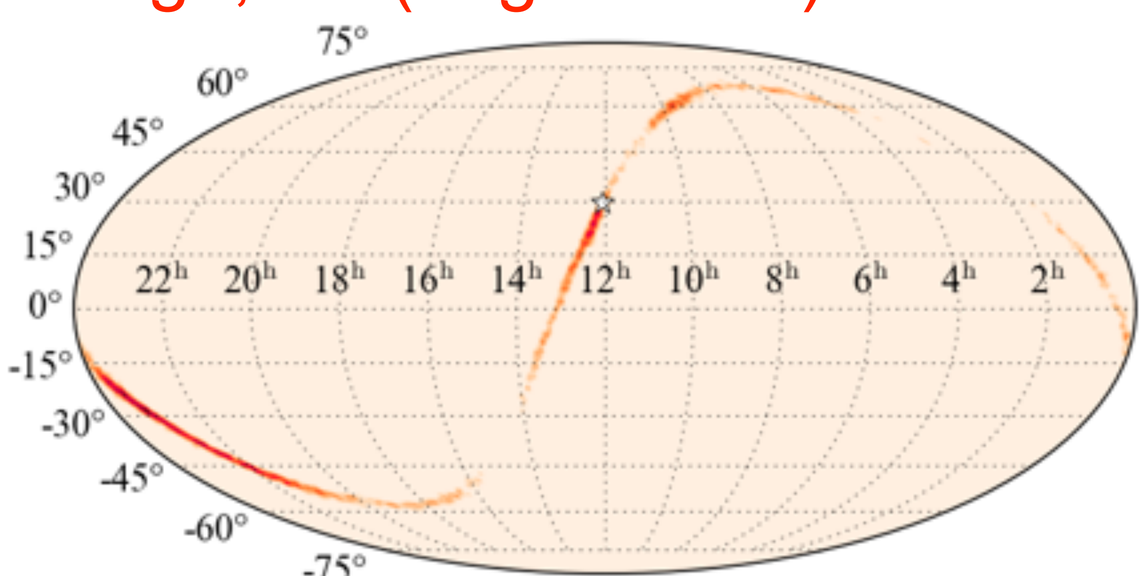


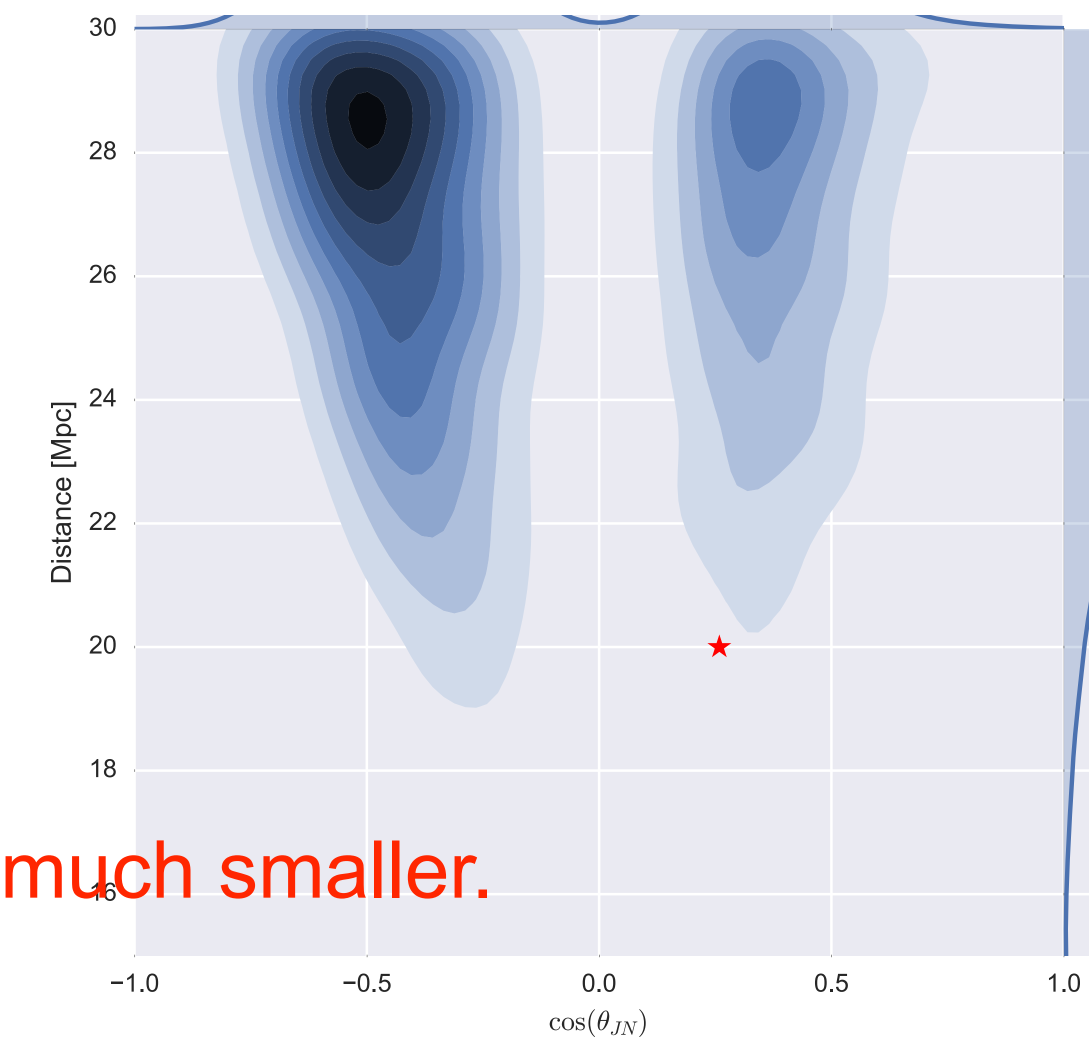
Both the estimated sky location and θ_{JN} are largely biased.

c.f., GW Malmquist effect

Case B: HL, distance prior D_L<30Mpc

SNR=19.8, 605deg2, cos(angle offset)=0.960



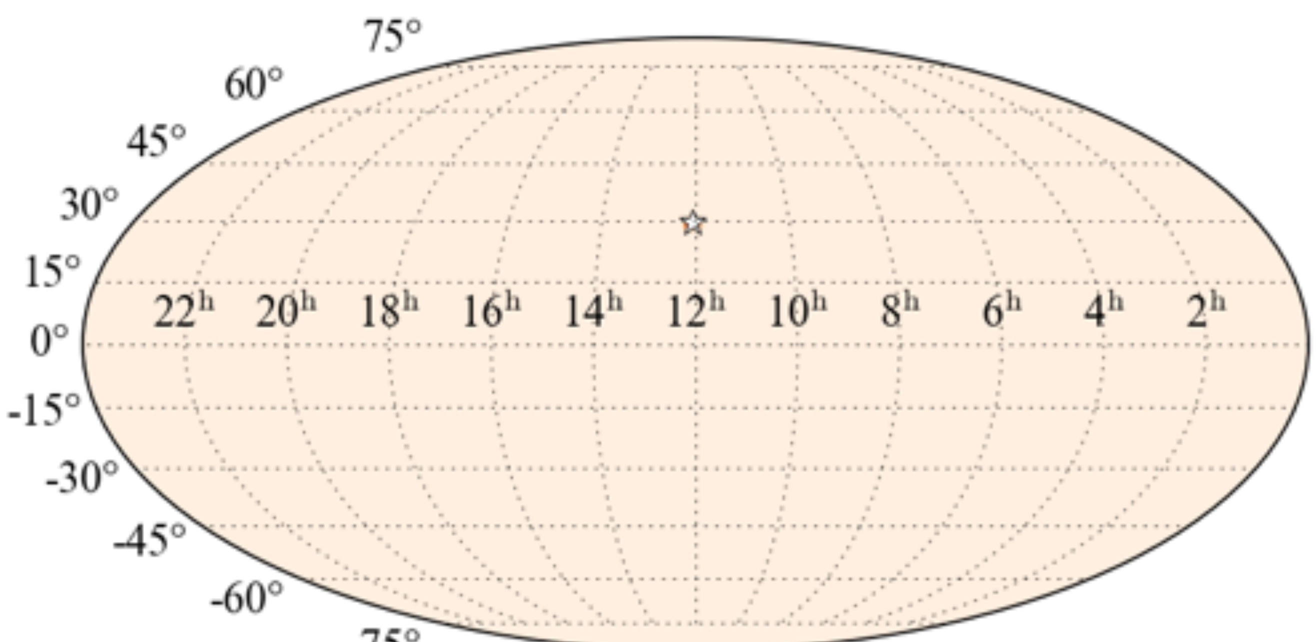


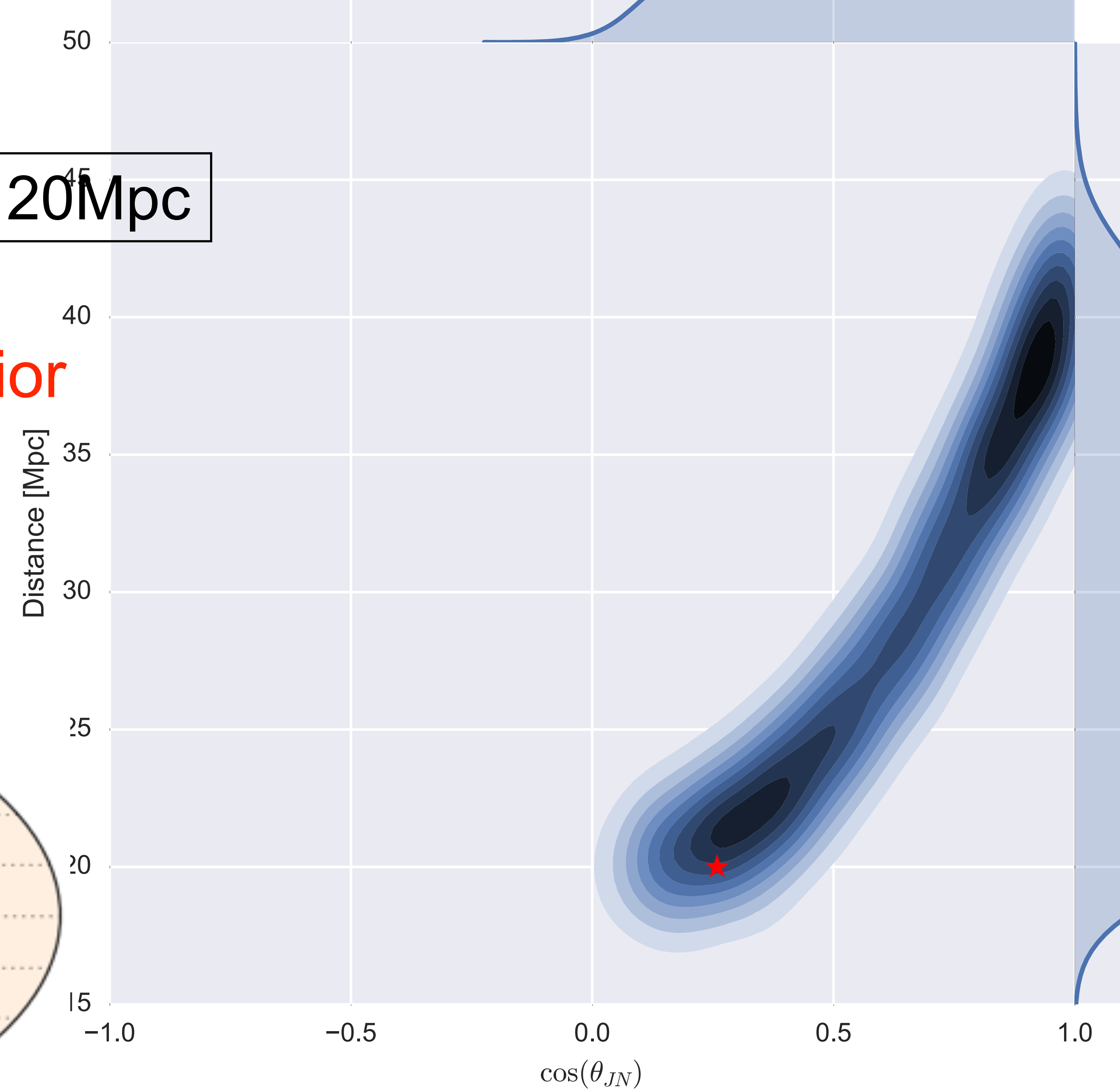
The bias of the sky location and θ_{JN} become much smaller.
However, $\Delta\Omega$ is still not good.

Example 1 **Edge-on binary**

Injected signal: BNS, nearly edge-on, 20Mpc

Case C: HLV, no strong distance prior
SNR=22.1
10.8deg2
cos(angle offset)=1.00





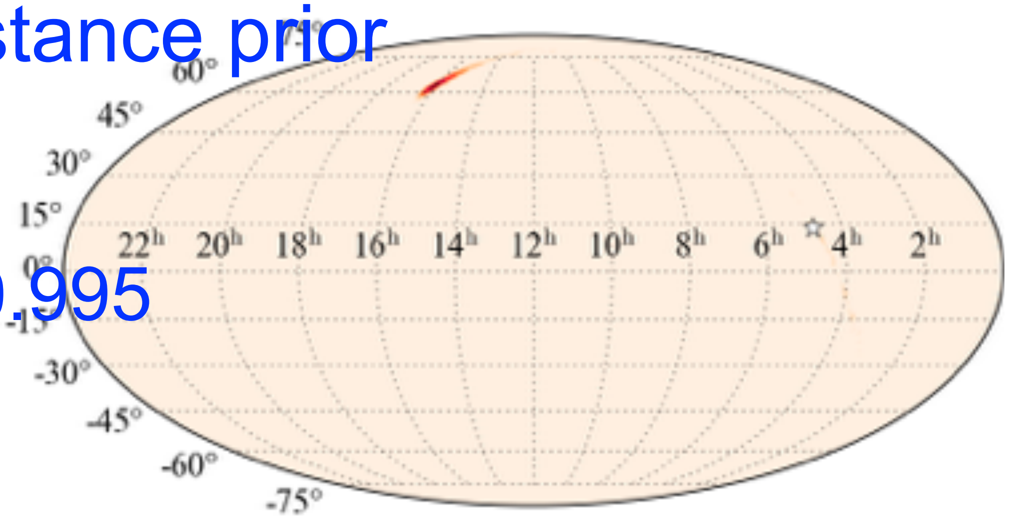
Dramatic improvement: ΔΩ becomes about 10 deg^2. Even if the sensitivity of the third detector is only about 1/3 of other two detectors, the presence of the third detector is essential to improve the sky localization accuracy.

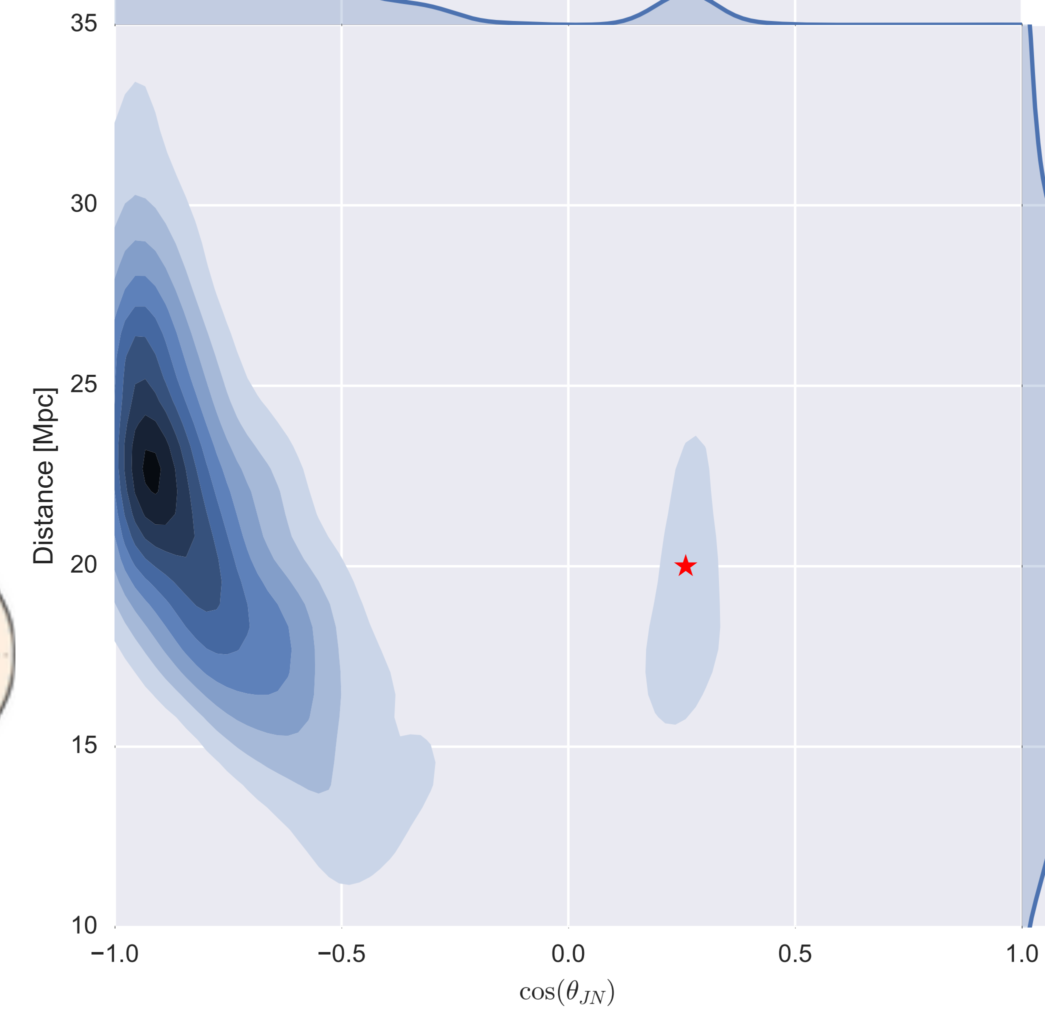
However, the maximum probability density of the inclination angle points $\cos(\theta_{JN})$~1.00. Corresponding to this, there is a second peak of the posterior of the d_L around 38 Mpc.

Example 2 **Edge-on binary**

Injected signal: BNS, nearly edge-on, 20Mpc

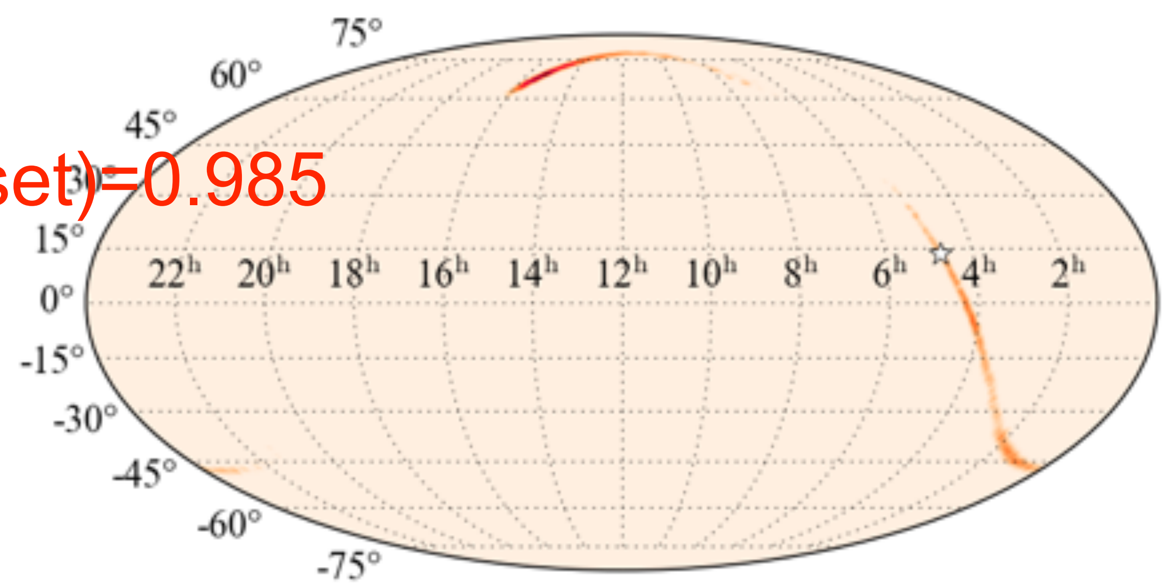
Case A: HL, no distance prior
SNR=29.7
77.4deg2
cos(angle offset)=-0.995

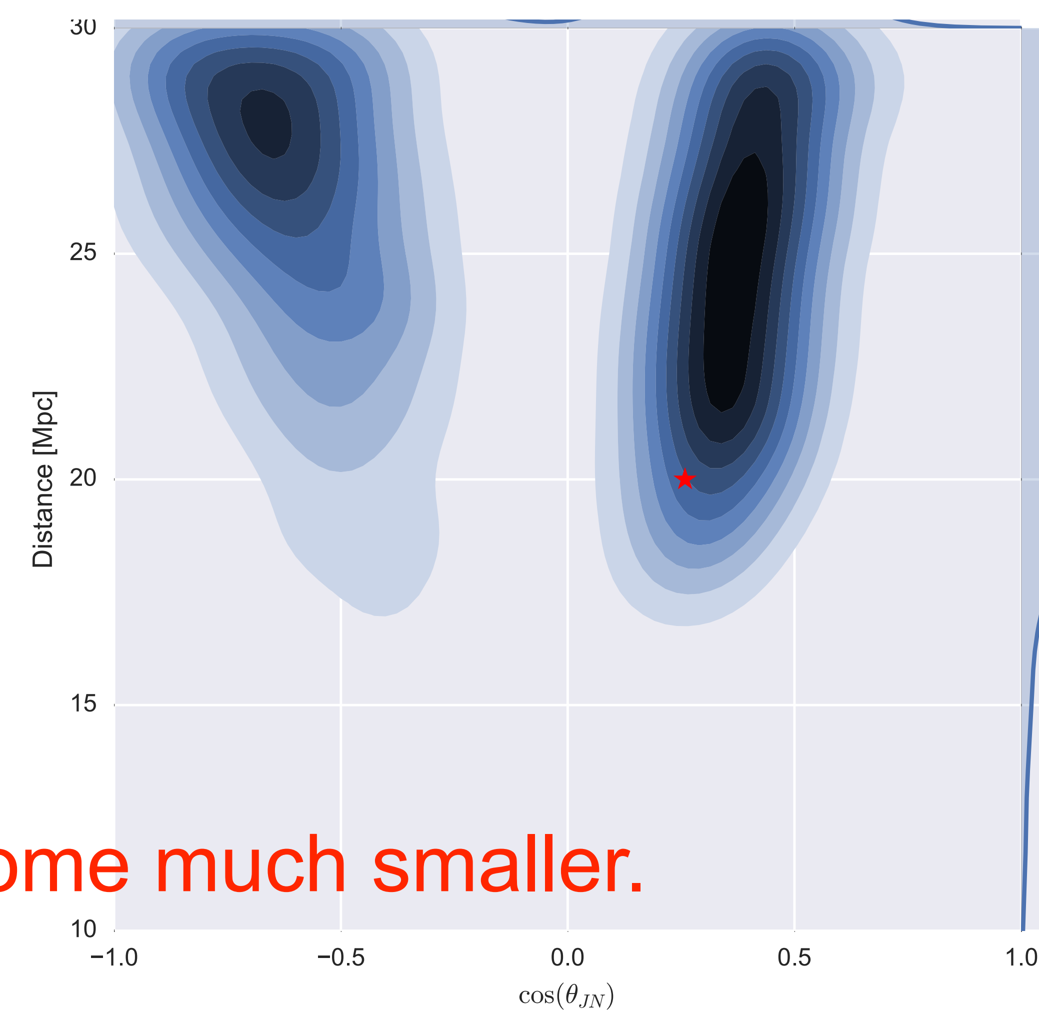




The estimated sky location points completely different direction from the true one.

Case B: HL, distance prior D_L<30Mpc
SNR=27.8
336deg2
cos(angle offset)=0.985



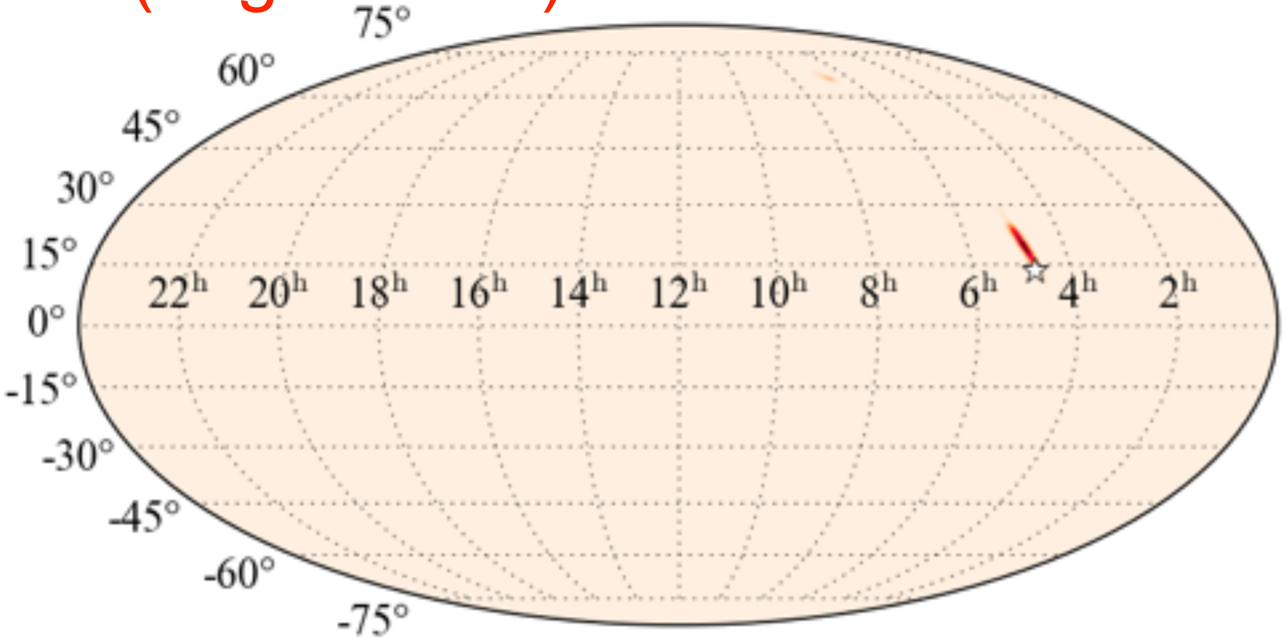


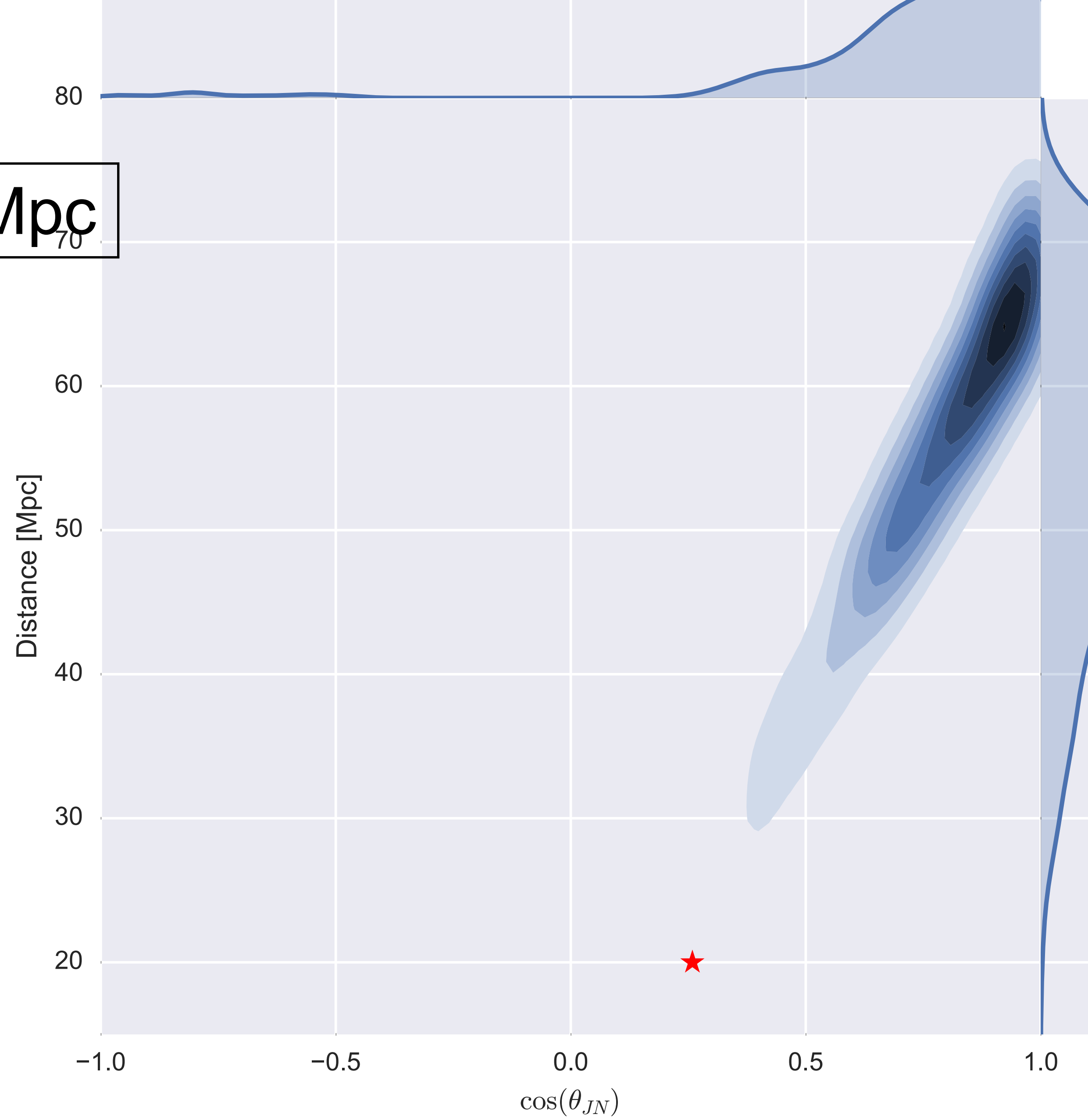
The difference of the sky location and θ_{JN} become much smaller.
However, $\Delta\Omega$ is still not good.

Example 2 **Edge-on binary**

Injected signal: BNS, nearly edge-on, 20Mpc

Case C: HLV, no strong distance prior
SNR=28.1
31.9deg2
cos(angle offset)=0.994





The sky location indicates the correct direction, and the sky localization accuracy is improved dramatically again.

However, the accuracy of the inclination angle and the distance are still not good. Much larger distance (~ 60 Mpc) than the injected signal and the inclination angle of face-on ($\cos(\theta_{JN})$~1.00) are favored.

Short summary

Cases for edge-on CBCs: two examples

Case A: HL, no strong distance prior => miss the true location
Case B: HL, distance prior < 30 Mpc => much smaller $\Delta\Omega$
Case C: HLV, no distance prior => the best way! dramatically improvement on $\Delta\Omega$! However, still not good enough accuracy

- It is effective to evaluate the PDF by restricting the distance prior to a nearby region in order to improve the sky localization and the inclination. However, the accuracy is still not good enough for performing the follow-up observation.
- The best way to improve the situation is to add one more detector. The sky location and the sky localization accuracy can be improved dramatically with three detectors.
- However, even in Case C, there can appear large bias in the estimated d_L and θ_{JN}. It is thus important to search the large region of the d_L including nearby region in order not to miss EM counterparts.
- It is worth performing follow-up observations for wide region as much as possible.

Summary and Discussion

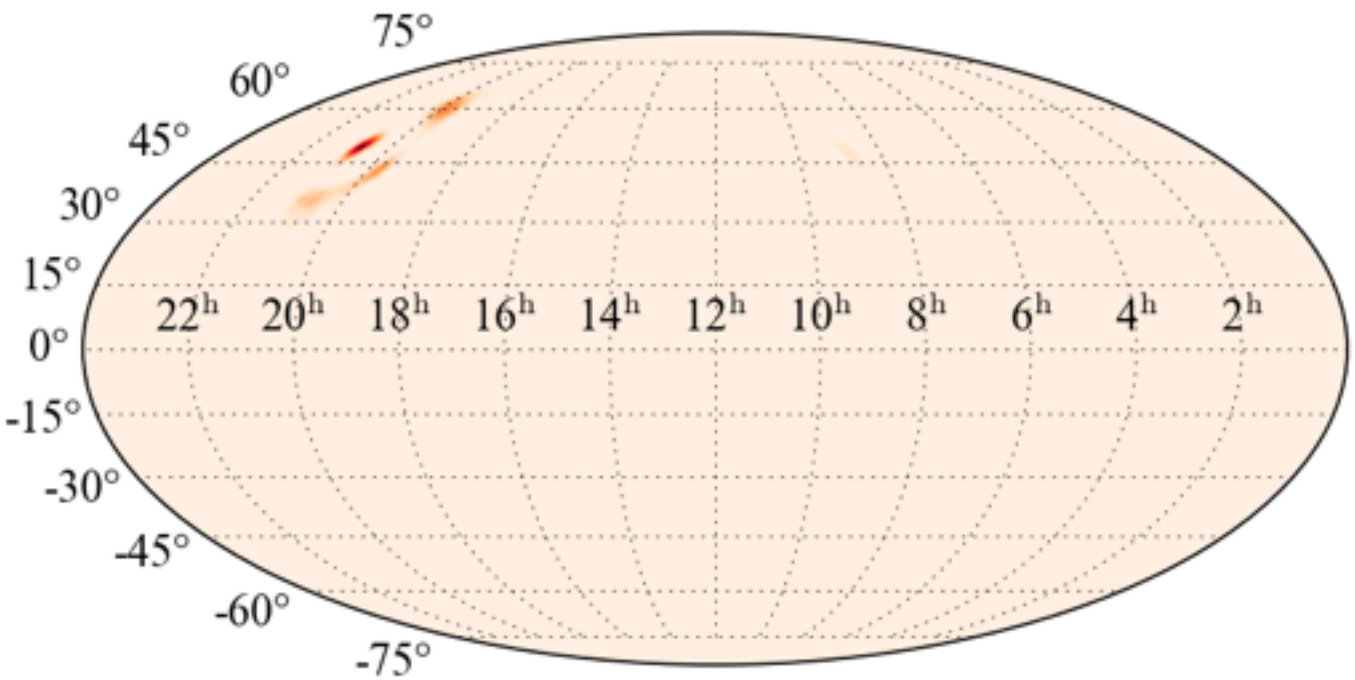
- In the case of first three events, the posterior probability maps derived by restricting a distance prior to a nearby region, are different from that derived without such restriction. It means that the direction which has been observed so far by follow-up observations may not be optimal direction for small aperture telescopes. Optimal direction may be the direction derived with a restricted distance prior.
- Examples of nearly edge-on binaries located nearby.
- In these cases, with the two-detector network of LIGO, the direction of the maximum posterior an be different from the true one.
- The sky location and the sky localization accuracy can be improved dramatically with three detectors, Virgo, KAGRA, etc.
- In O2 run, 3D information of the posterior probability distribution in the direction and distance space is provided. With that information, small aperture telescope can observe only nearby region.
- There is ambiguity in the model of Kilonova/Macronova emission.

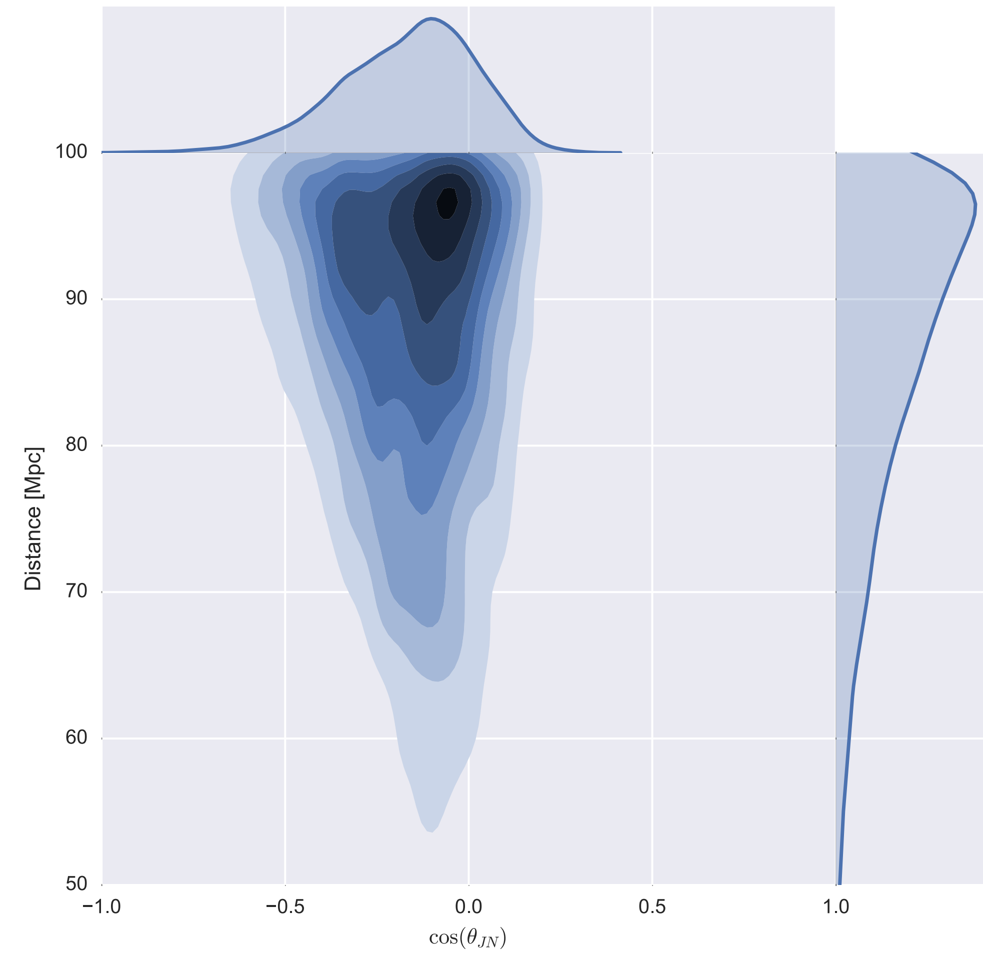
3D posterior for GW170104

Template: IMRPhenomPv2

Limited prior of distance d_L<100Mpc

SNR=12.9
213deg^2

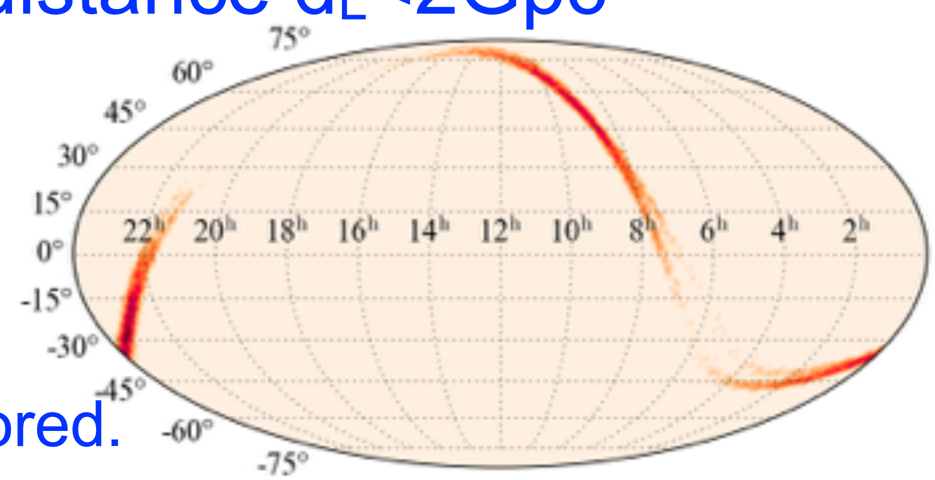




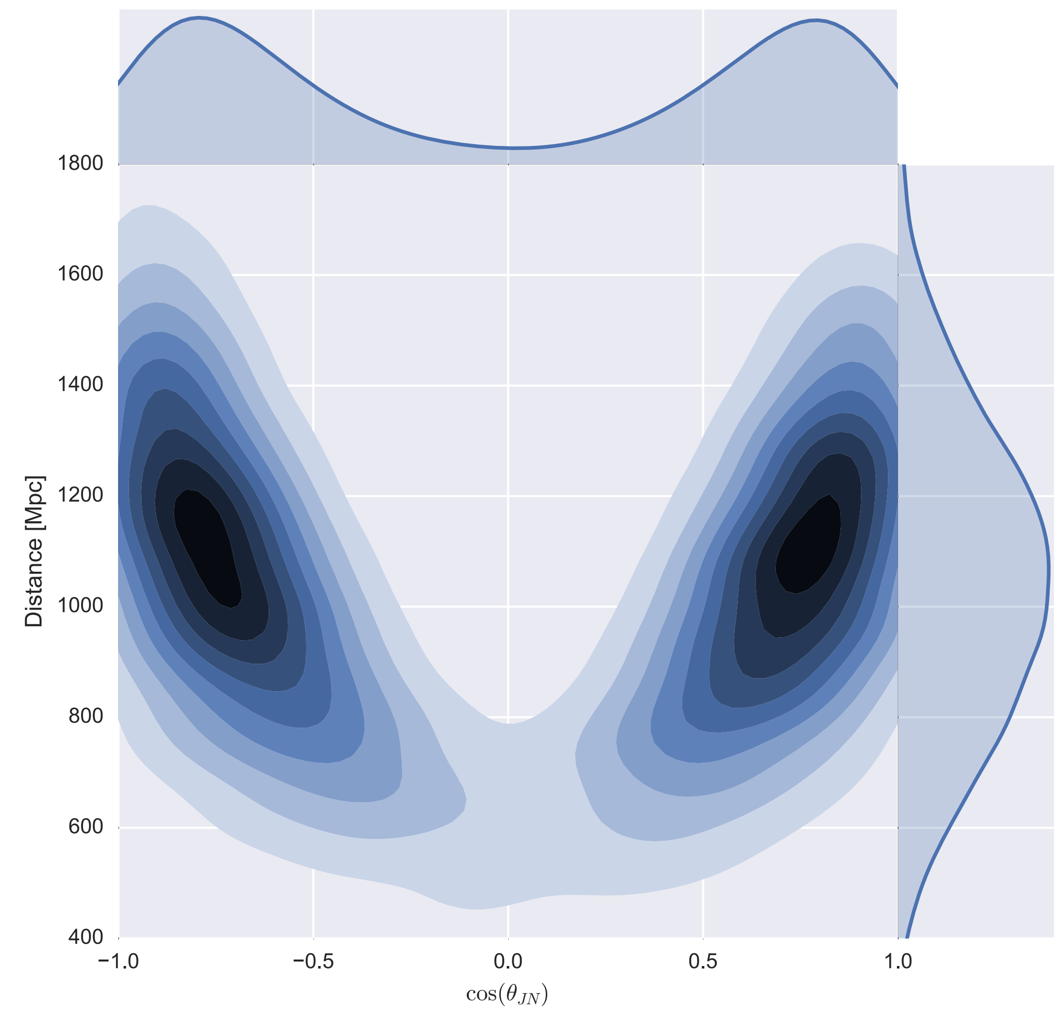
Different region of the same sky-ring is favored.

Unlimited prior of distance d_L<2Gpc

SNR=12.9
1086deg^2



Nearly face-on is favored.

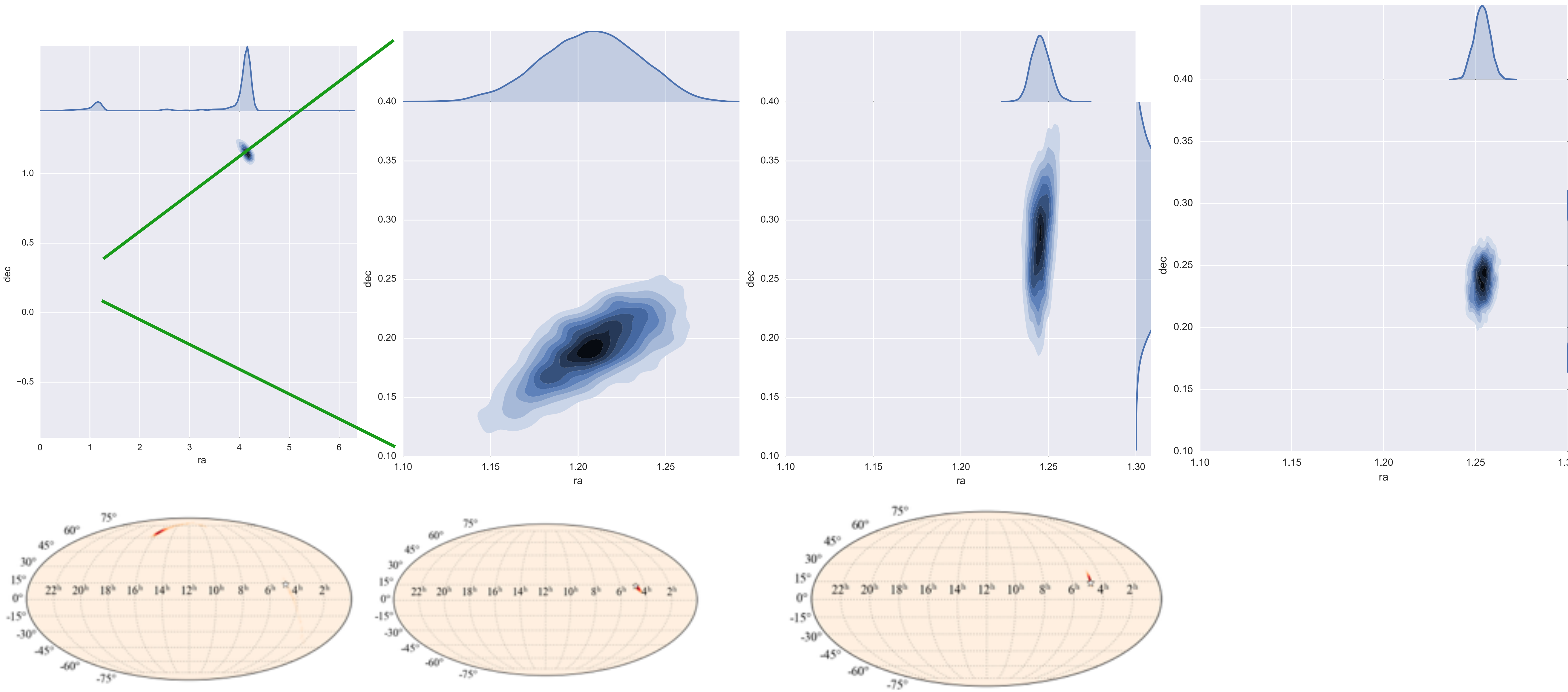


Example 2 Edge-on binary

Impact of KAGRA

Inject signal: BHNS (25,1.4), 50Mpc, i=75deg
Template: TaylorF2

Design-HL	Design-HLV	Design-HLK	Design-HLVK
SNR=54.1	SNR=55.5	SNR=62.0	SNR=61.4
245.5 deg^2	29.5 deg^2	21.3 deg^2	8.6 deg^2

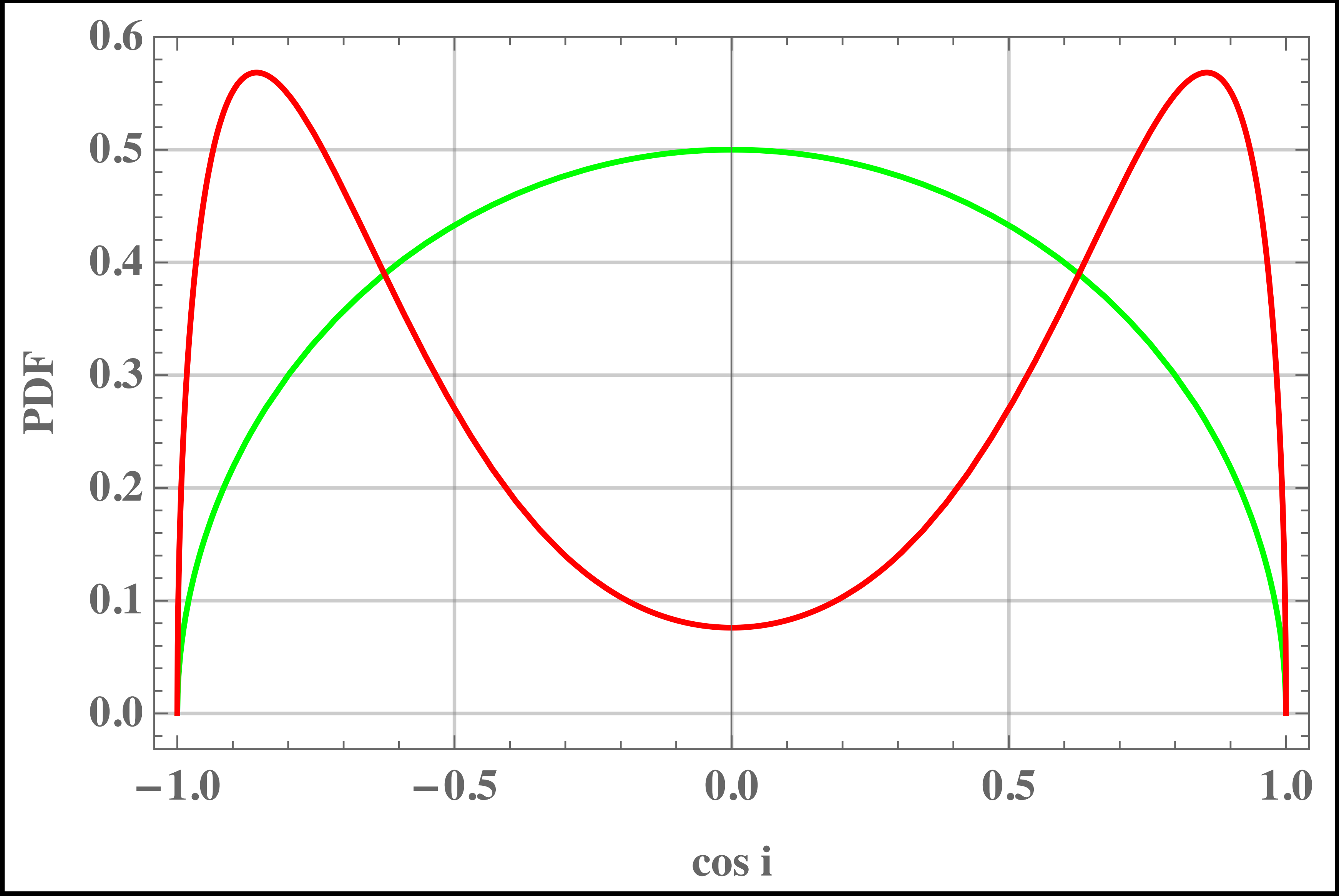


GW Malmquist effect

[Schutz, CQG 28, 125023 (2011).]

GW detection criterion preferentially selects for more face-on/off with cos i → ±1.

The probability distribution of "detected" values of inclination



green: injection

red: detected

The selection bias toward low inclinations due to the anisotropic pattern of a binary is clear.