THE HUNT FOR VHE GAMMA-RAYS IN THE GRAVITATIONAL WAVES ERA˚

Irfu - CEA Saclay
Institut de recherche sur les lois fondamentales de l'Univers

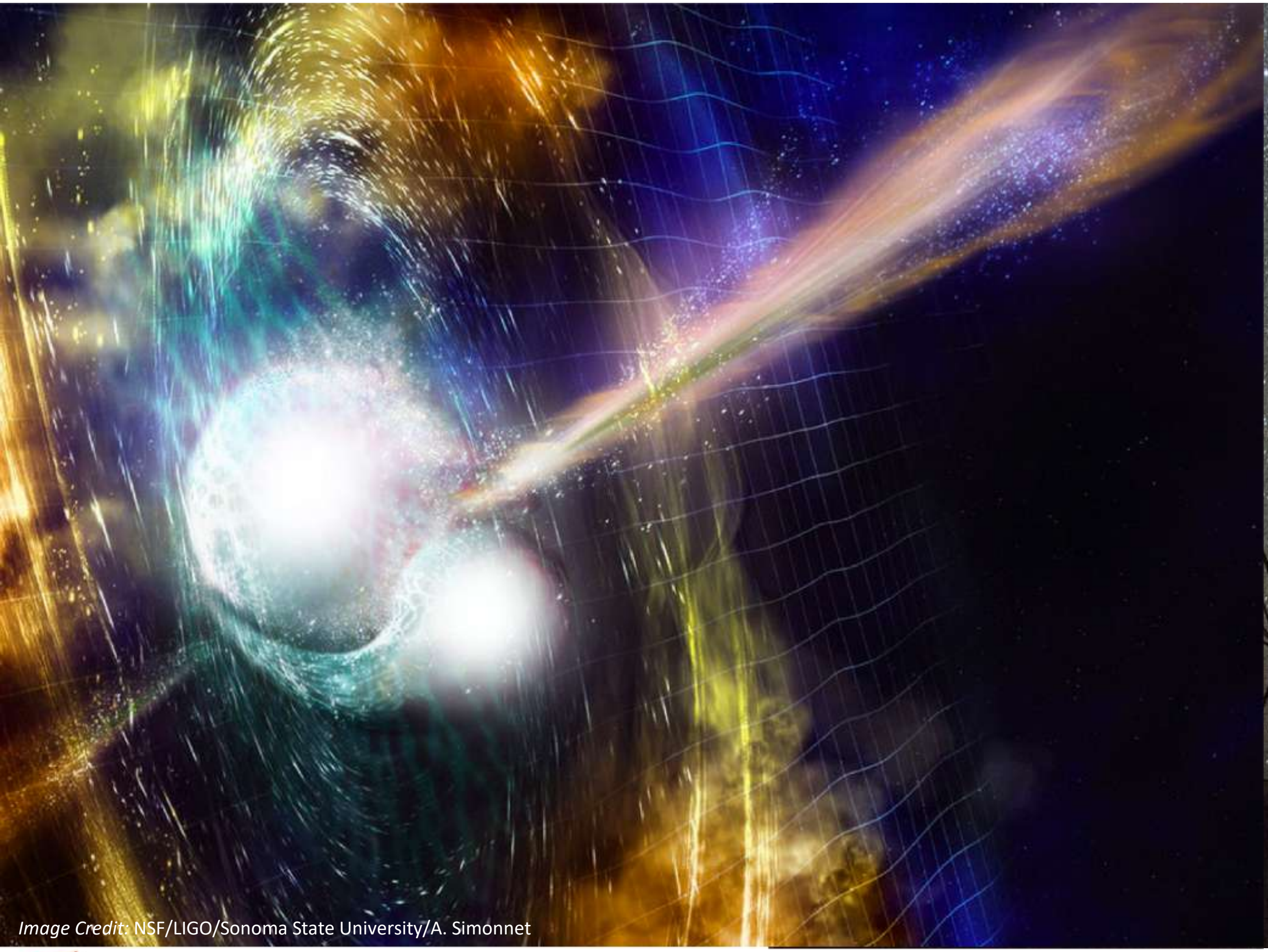


Image Credit: NSF/LIGO/Sonoma State University/A. Simonnet

Image credit: Matthias Lorentz

Halim Ashkar (on behalf of the H.E.S.S. GW team)

JRJC– Bretagne 2019

H.E.S.S.
université PARIS-SACLAY

Science Case: VHE emission in compact binary coalescence

- First BBH in 2015 in **O1** **(LIGO)**: **GW150914**
- First BNS in 2017 in **O2** **(LIGO/Virgo)**: **GW170817**
- **We are now in O3**

- Neutron star - neutron star (BNS)
- Neutron star – black hole (BHNS)
- Black hole – black hole (BBH)

➢ Nature of the merger remnant
➢ Energy spectrum and remnant structures
➢ Better understanding of fundamental physics and emission mechanisms

Deborah Byrd *in* SPACE

Virgo

Ligo

Science Case: VHE emission in compact binary coalescence

Examples of VHE GRB:

- **Space instruments (GeV):**

- GRB 081024B: in prompt phase E_{photon}~ 3 GeV
- GRB 090510: in prompt phase E_{photon}~30 GeV
- GRB 130427A : Ephoton~ 95 GeV (minutes)

E_{photon} ~ 32GeV (hours)

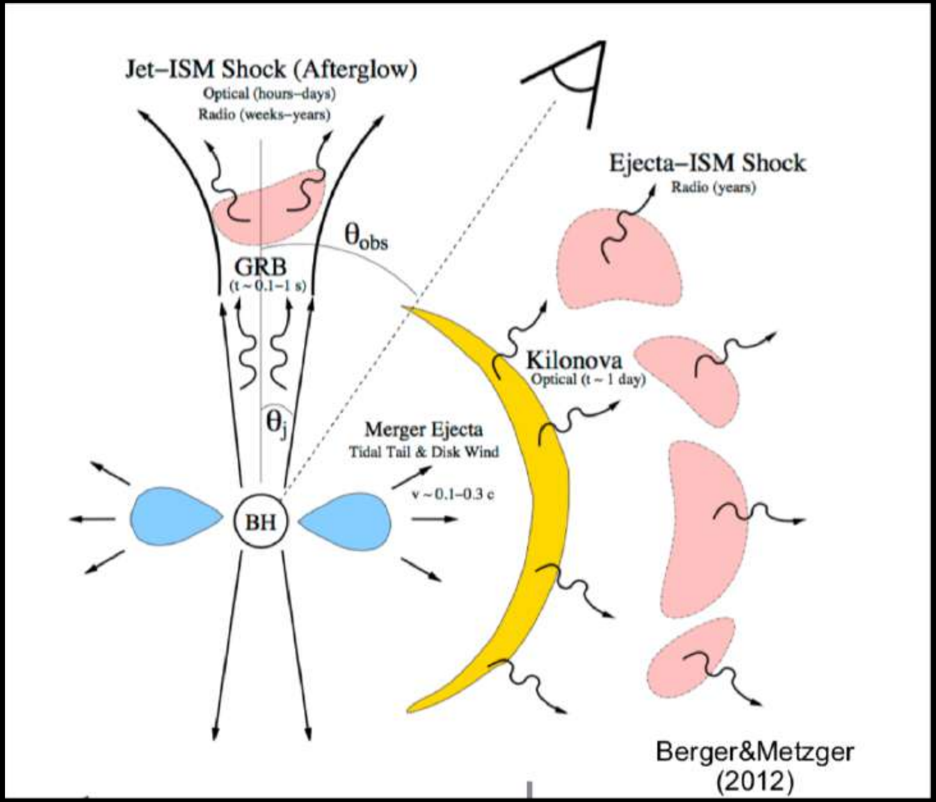
- **Ground instruments (TeV):**
- **GRB180720B detected by H.E.S.S (440GeV-11 hours)**

→ **Nature 575, 464–467 (2019)** doi:10.1038/s41586-019-1743-9

- **GRB 190114C detected by MAGIC (TeV – early afterglow)**

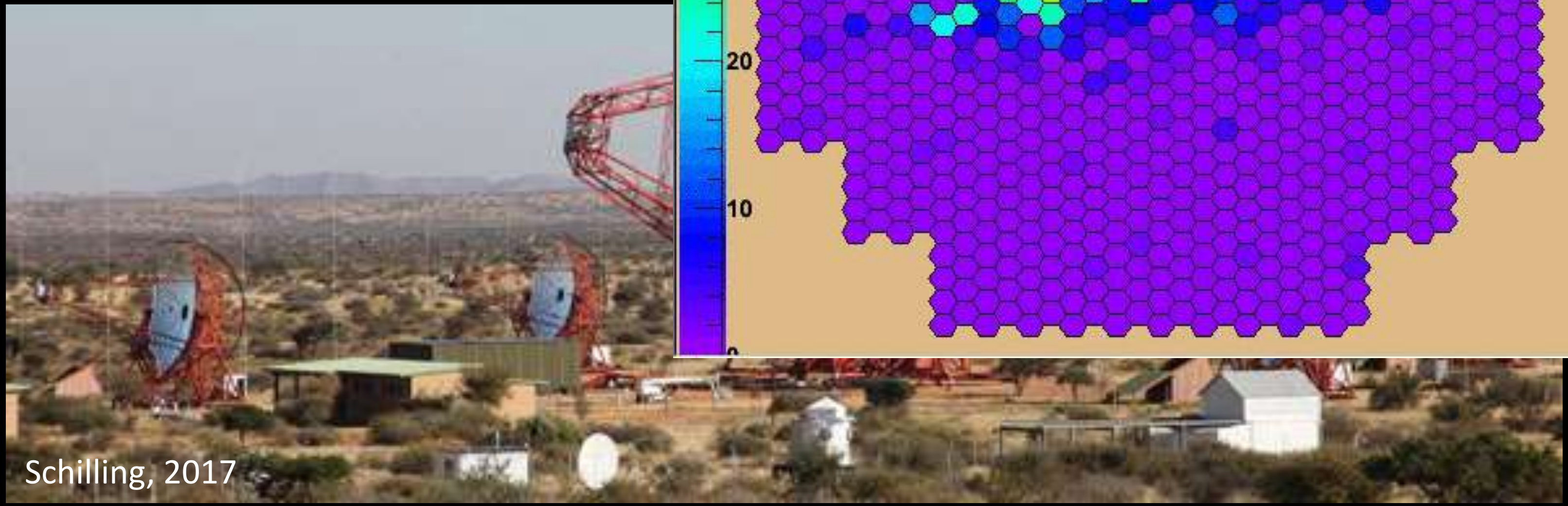
→**Nature 575, 455–458 (2019)** doi:10.1038/s41586-019-1750-x

- **GRB190829A detected by H.E.S.S.**

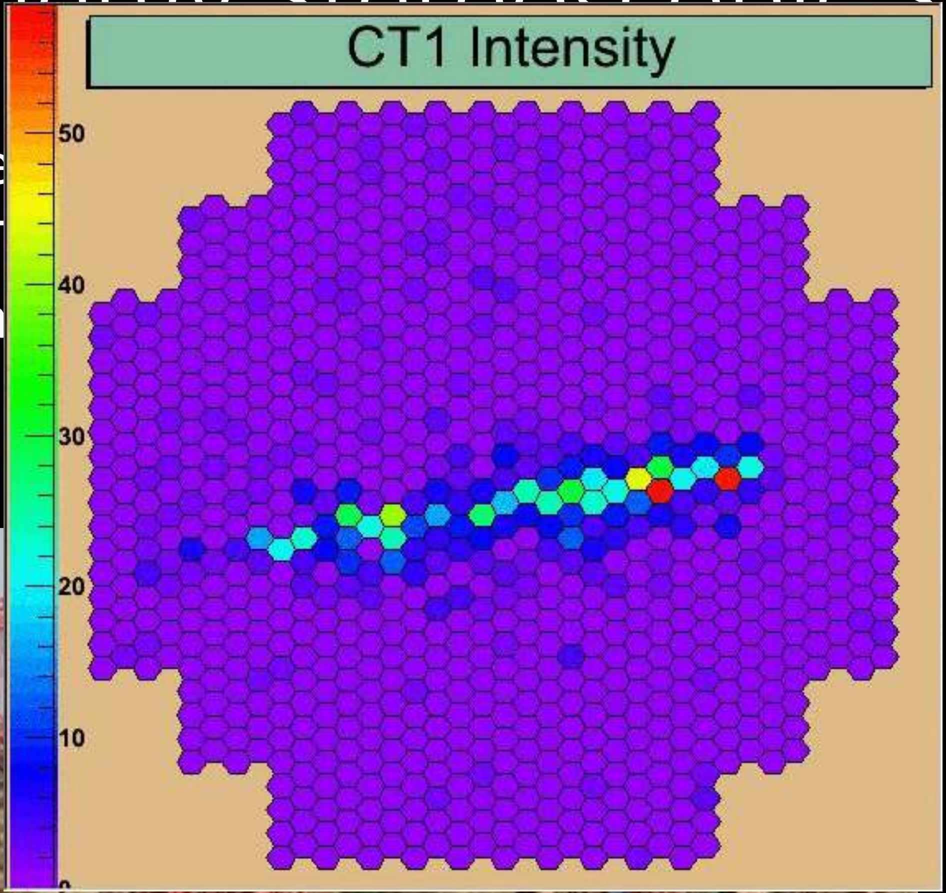


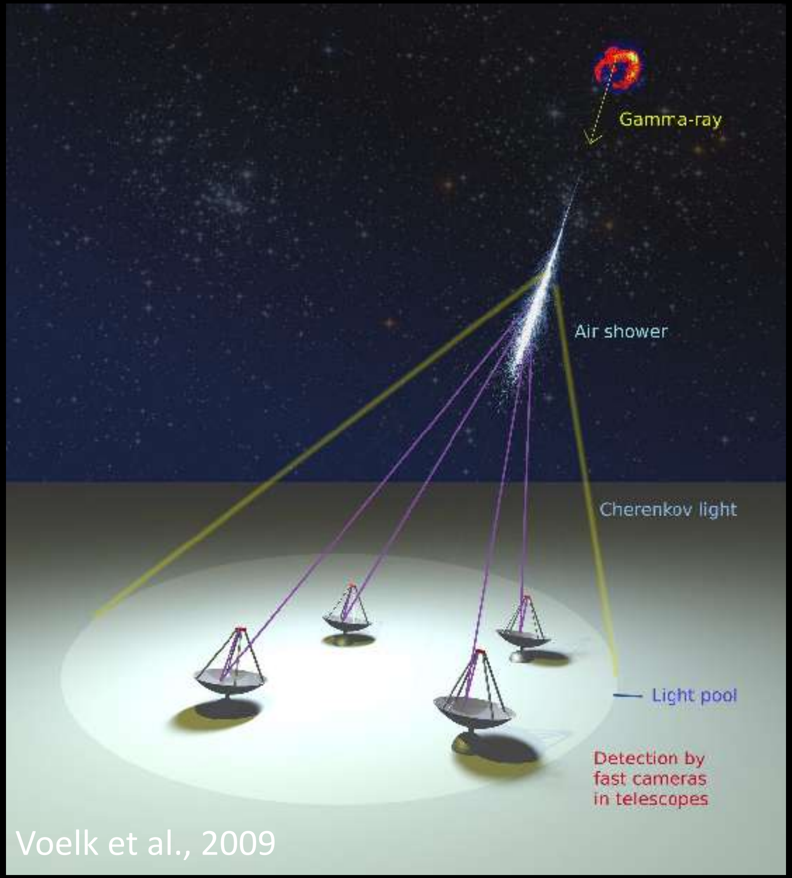
The High Energy Stereoscopic System (H.E.S.S.)

- Imaging Atmosphe
- 0.03TeV < E < 100 T
- Square of four 12n (H.E.S.S. 1: CT1, 2,
- 28 m telescope (in

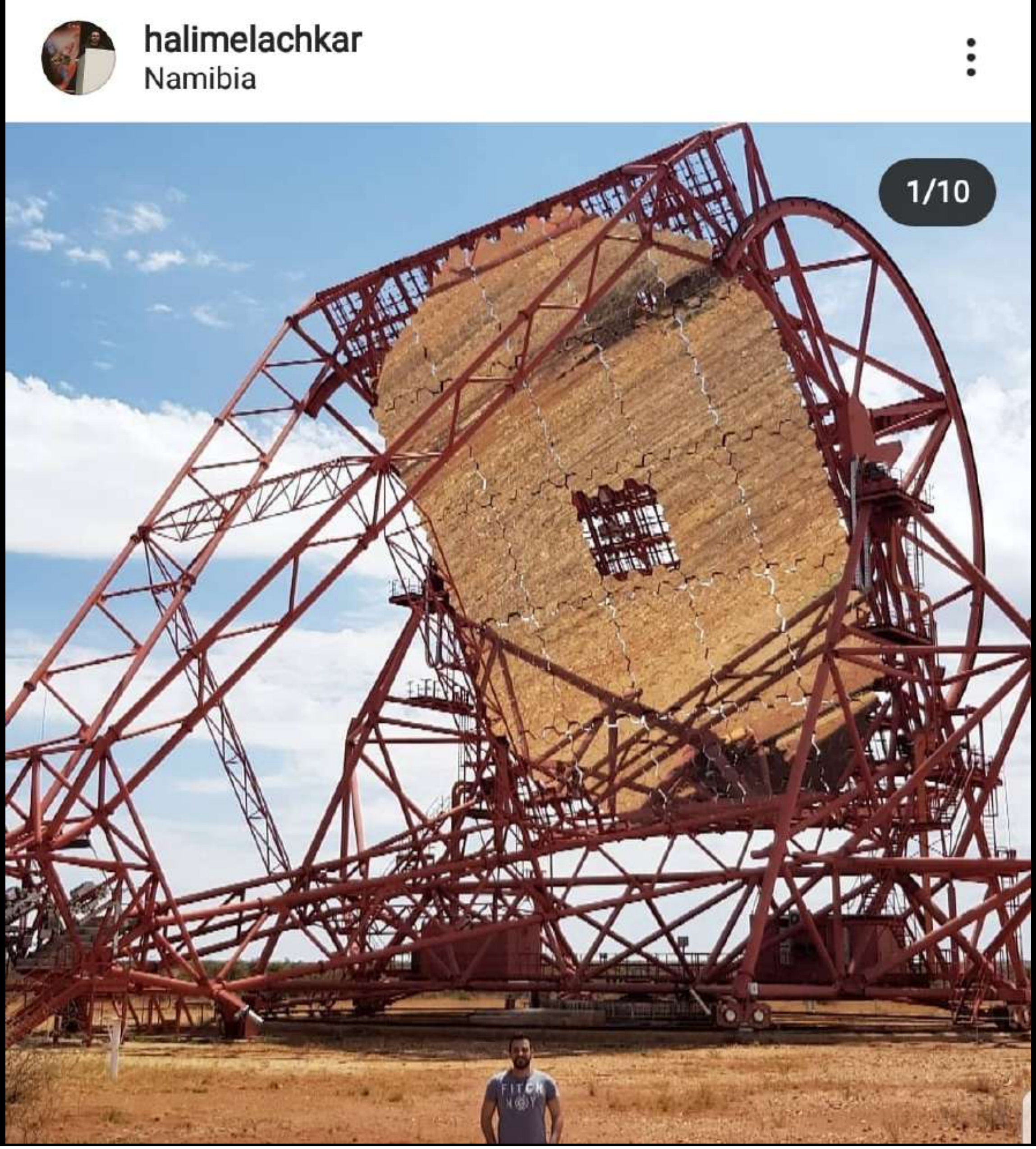


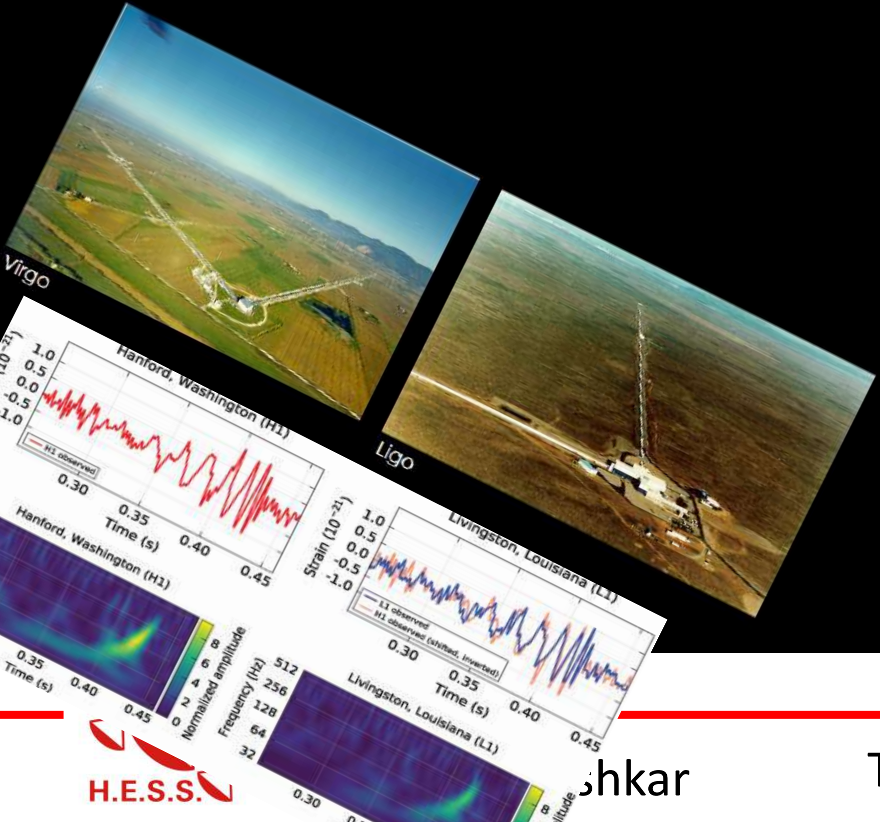
Schilling, 2017



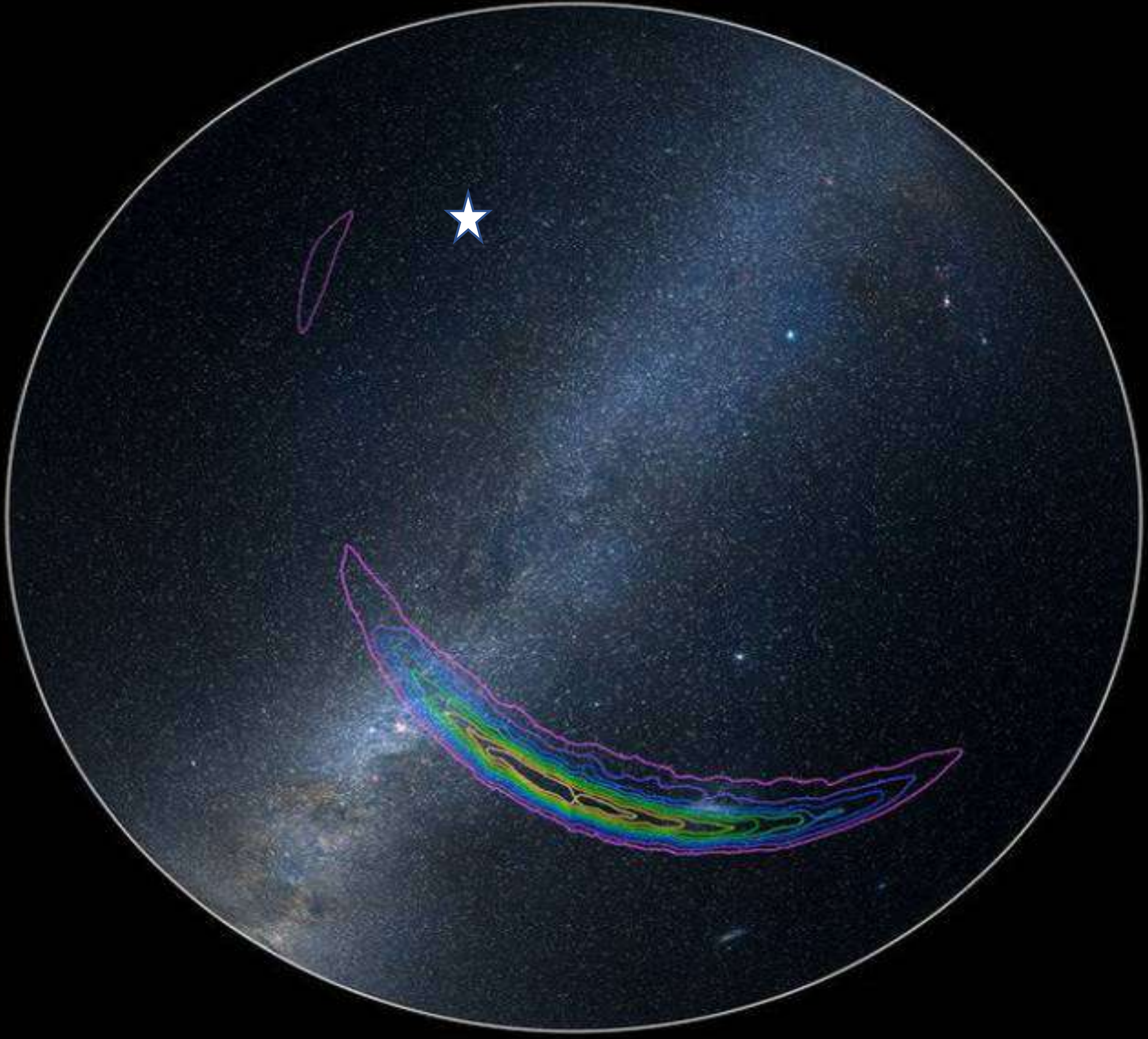


Voelk et al., 2009


halimelachkar
Namibia
1/10


Virgo
Ligo
Hanford, Washington (H1)
Livingston, Louisiana (L1)
Time (s)
Strain (10^-21)
Frequency (Hz)
Normalized amplitude
H1 observed
L1 observed

But localization regions vary from 10s to 1000s deg^2



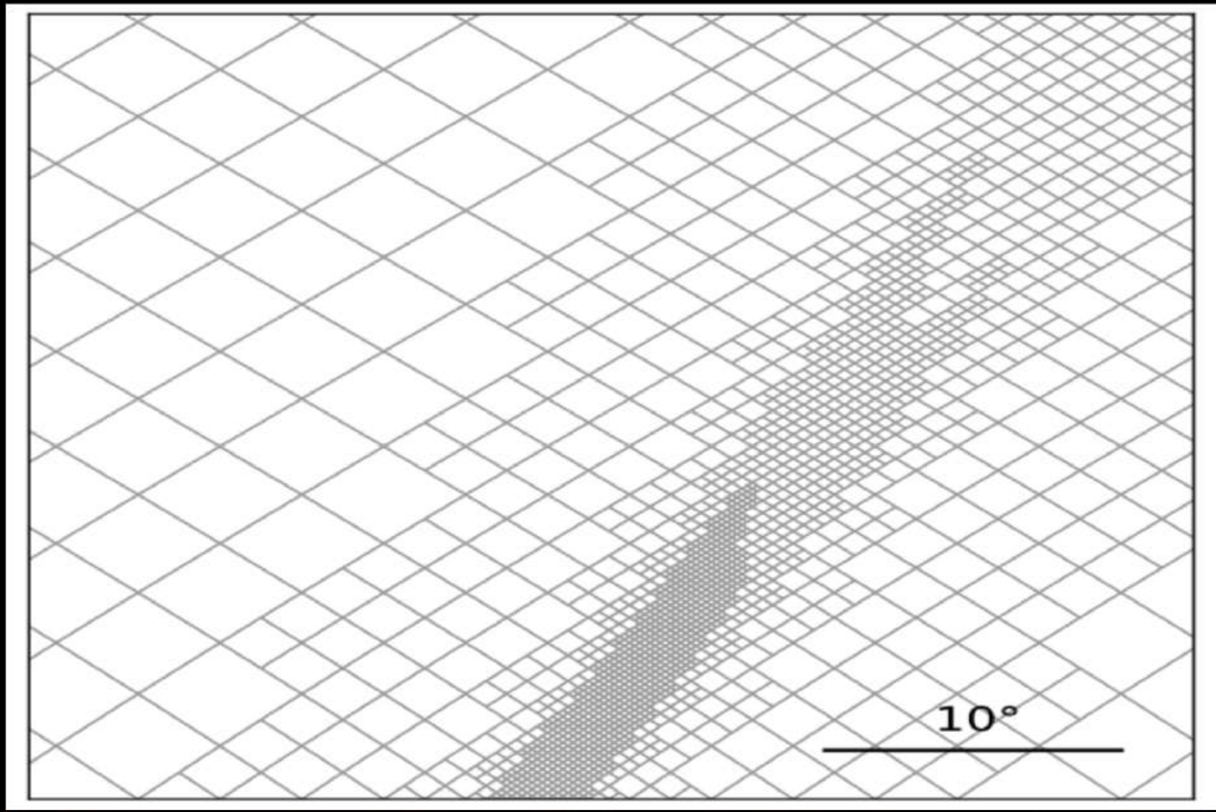
LVC Maps

- Healpix format
- Pixel indices + 4 layers

1. Prob: Probability

- If has3D info:
    2. Distmu: distance average
    3. Distsigma: distance error
    4. Distnorm: normalization

Singer, L. P. et al. 2016, *The Astrophysical Journal Letters*, 829L, 15S



Virgo

Ligo

H.E.S.S. constraints

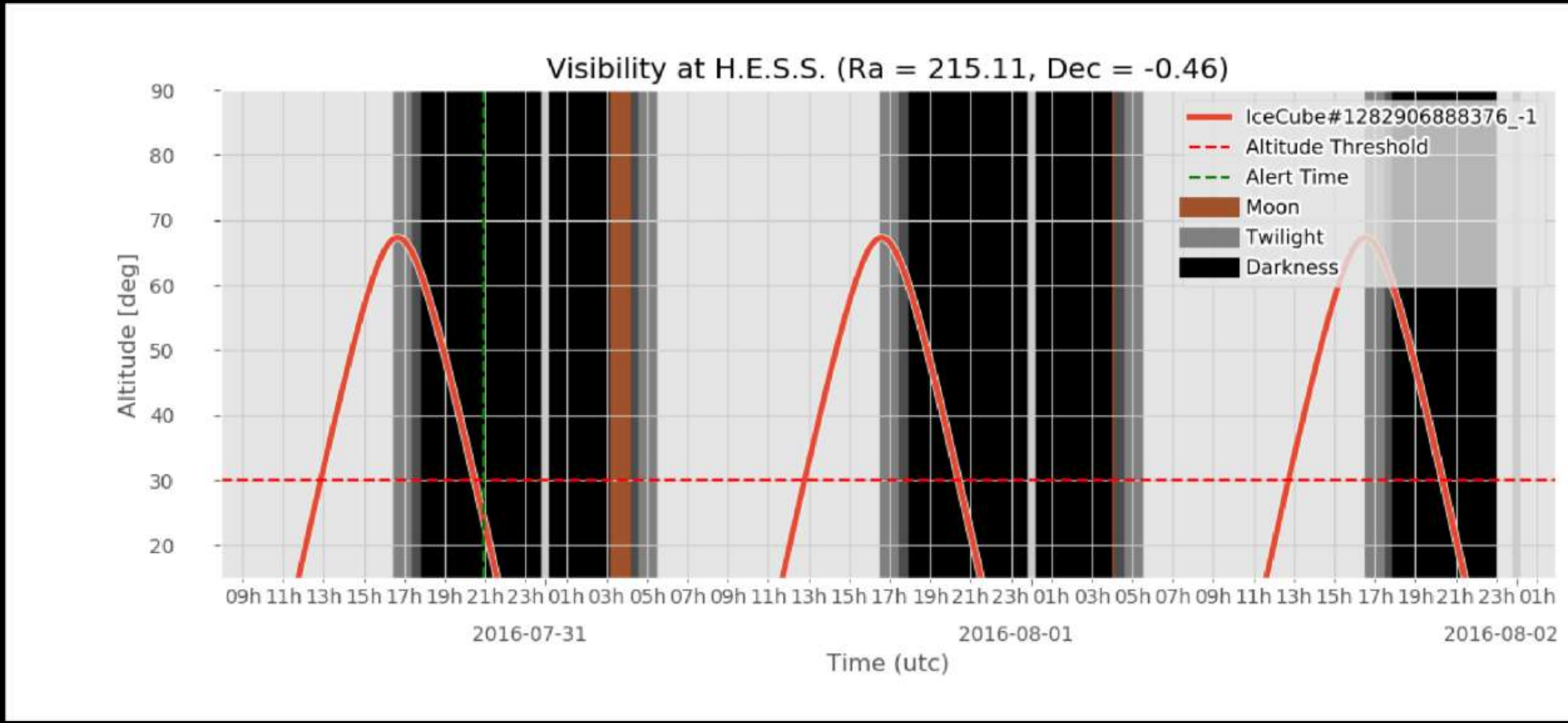
- Obs windows

(Sun and moon position)

<u>Moonlight obs:</u>

  - Phase < 60%
  - Alt < 50°
  - Source separation > 30°

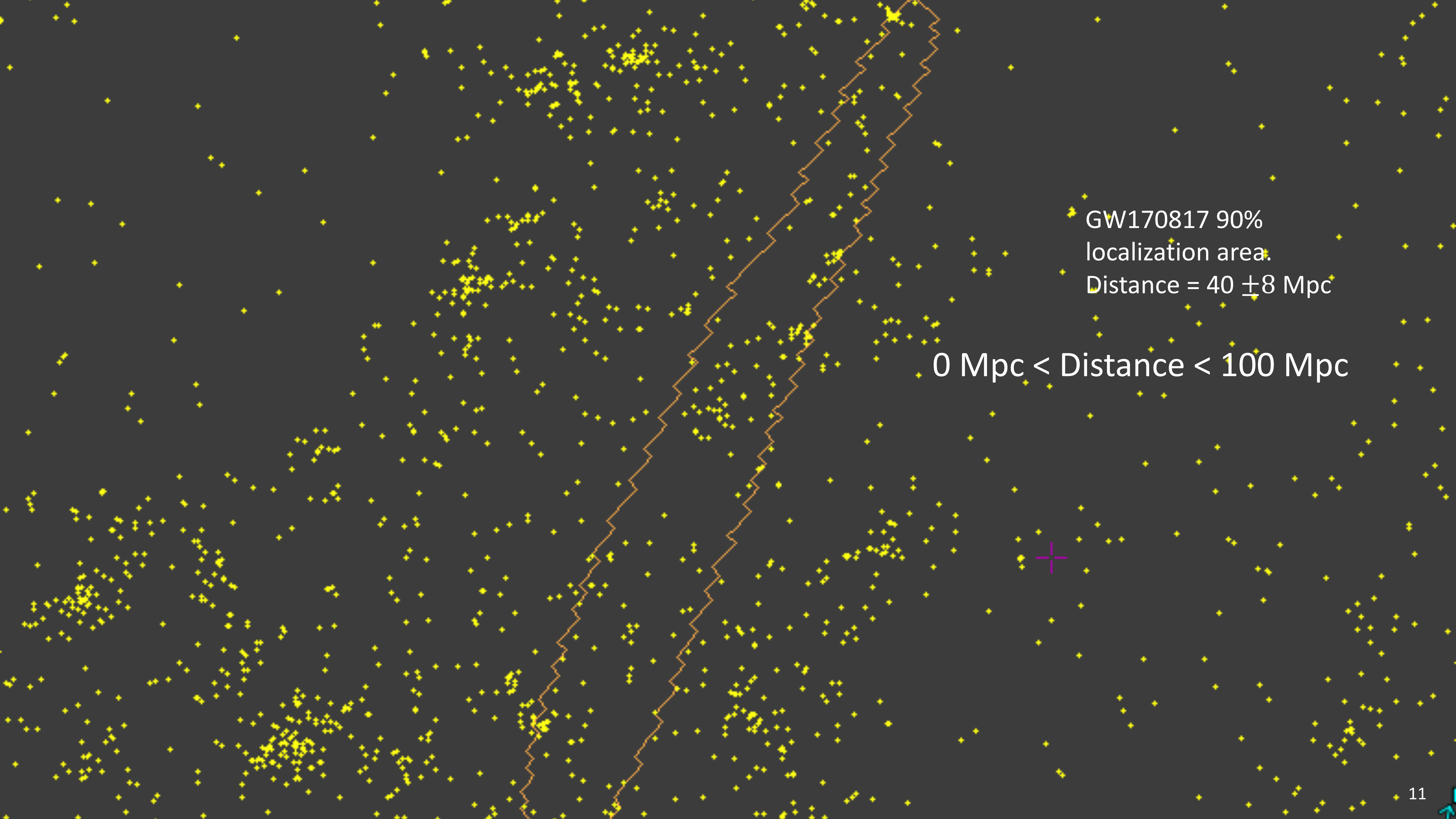
- Visibility of source
- Some parameters:
  - FoV = 1.5° – 2.5°
  - Max zenith angle = 60°

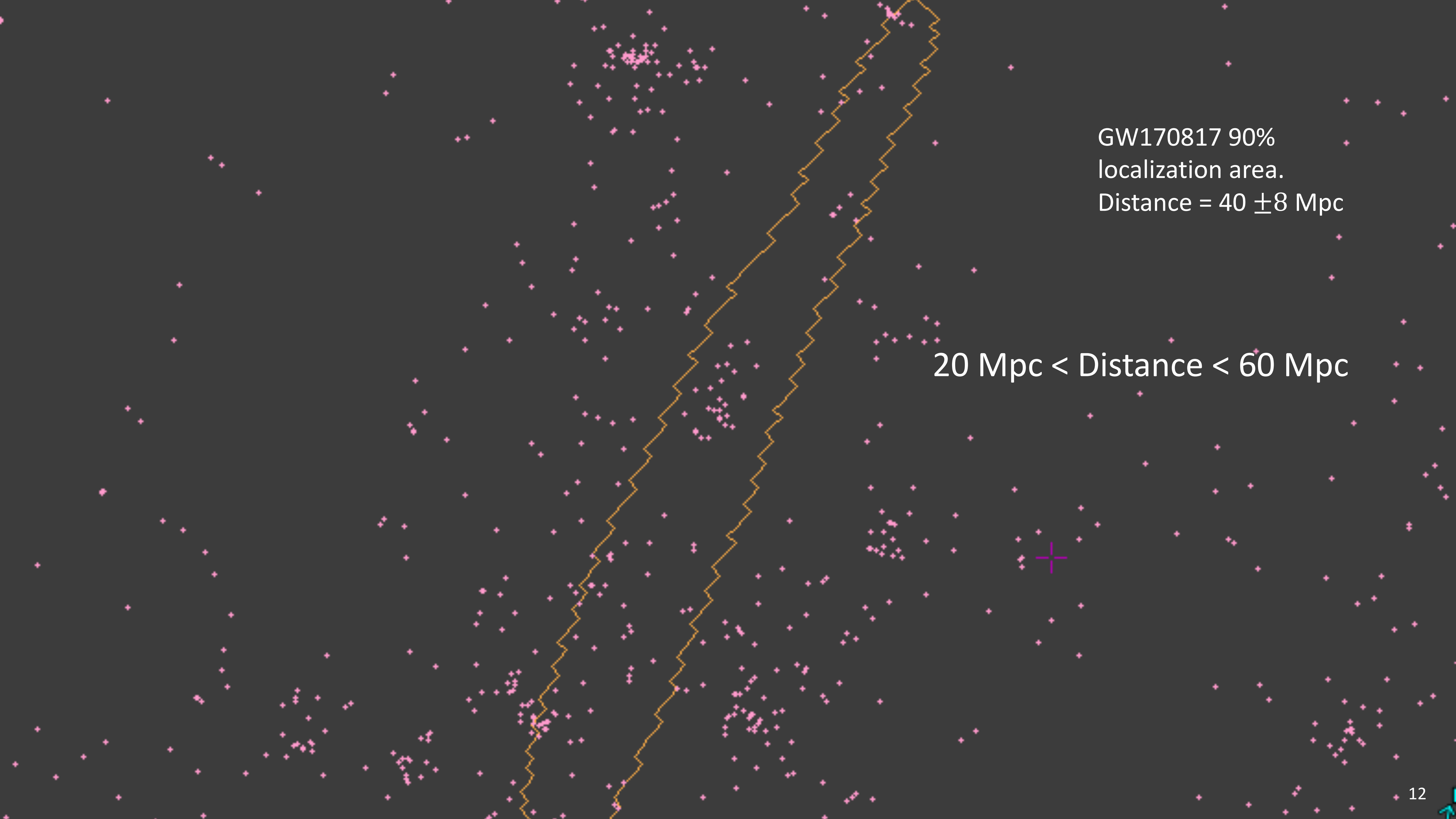


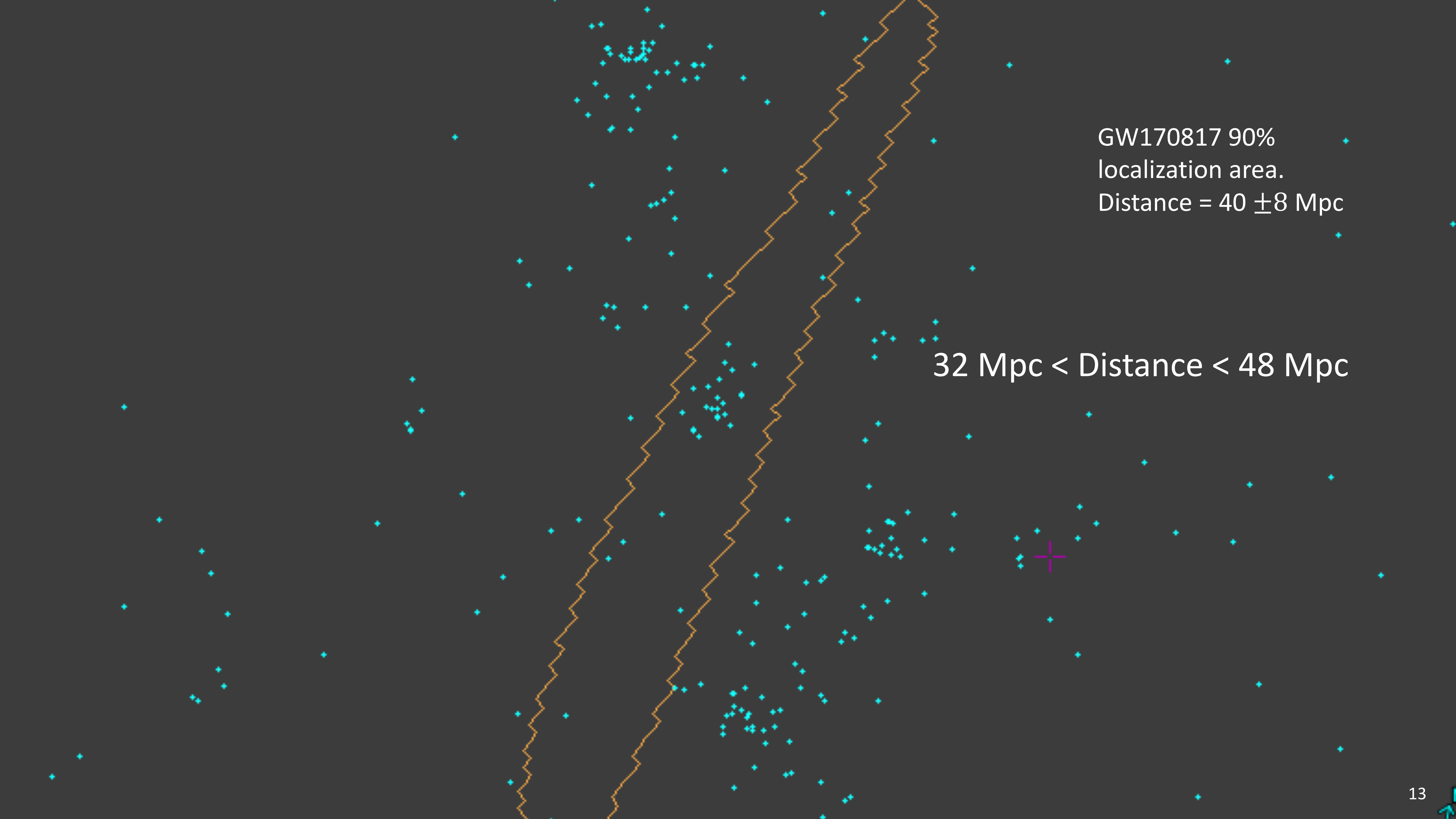
2D strategy:

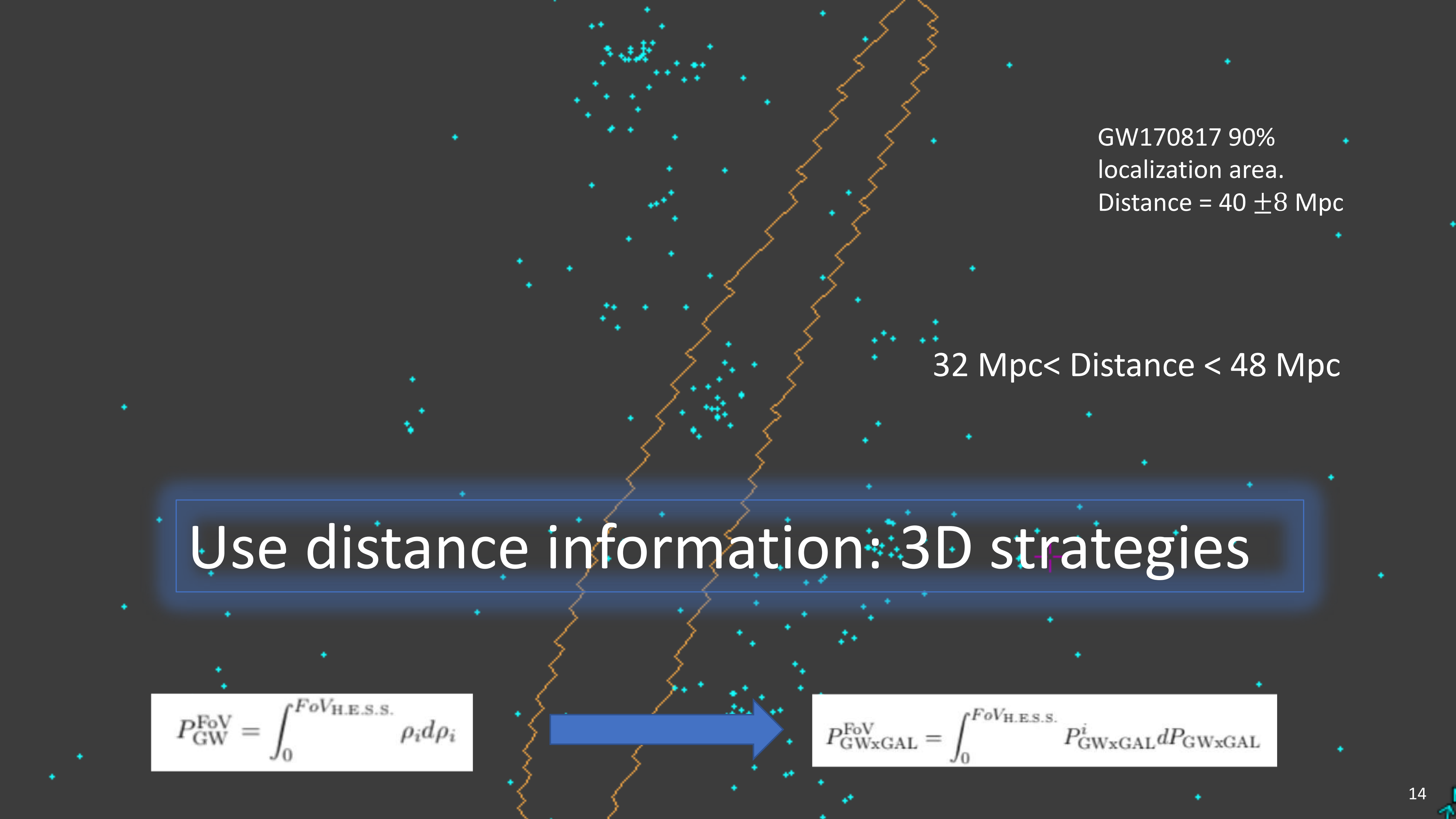
- Compute the total probability inside the FoV
- Choose the pointing with the highest integrated probability for each observation

$$P_{\mathrm{GW}}^{\mathrm{FoV}} = \int_0^{FoV_{\mathrm{H.E.S.S.}}} \rho_i d\rho_i$$


GW170817 90%
localization area.
Distance = 40 ±8 Mpc
0 Mpc < Distance < 100 Mpc


GW170817 90%
localization area.
Distance = 40 ±8 Mpc
20 Mpc < Distance < 60 Mpc


GW170817 90%
localization area.
Distance = 40 ±8 Mpc
32 Mpc < Distance < 48 Mpc



Use distance information: 3D strategies

$$P_{\mathrm{GW}}^{\mathrm{FoV}} = \int_0^{FoV_{\mathrm{H.E.S.S.}}} \rho_i d\rho_i$$

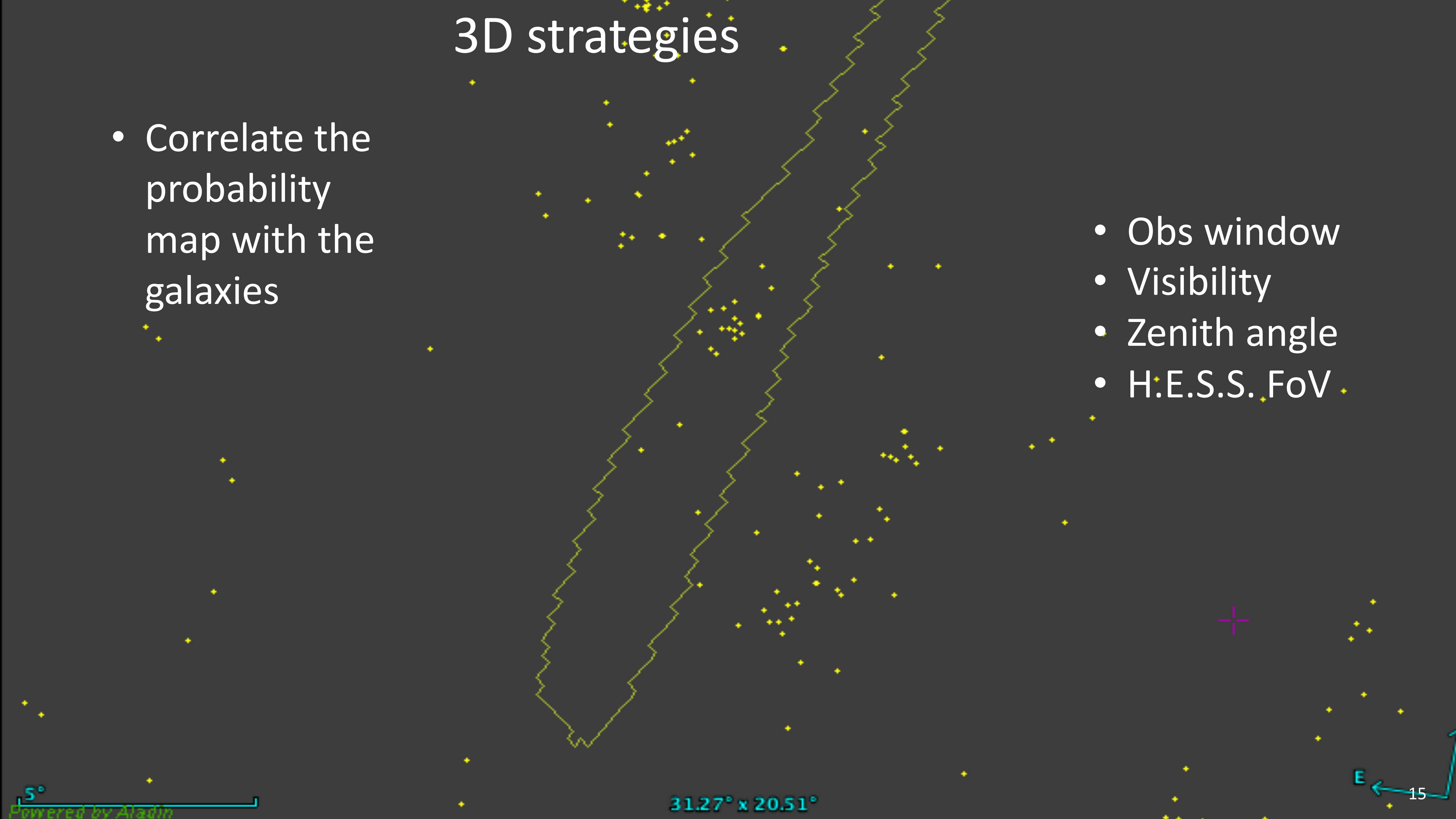
→

$$P_{\mathrm{GWxGAL}}^{\mathrm{FoV}} = \int_0^{FoV_{\mathrm{H.E.S.S.}}} P_{\mathrm{GWxGAL}}^{i} dP_{\mathrm{GWxGAL}}$$

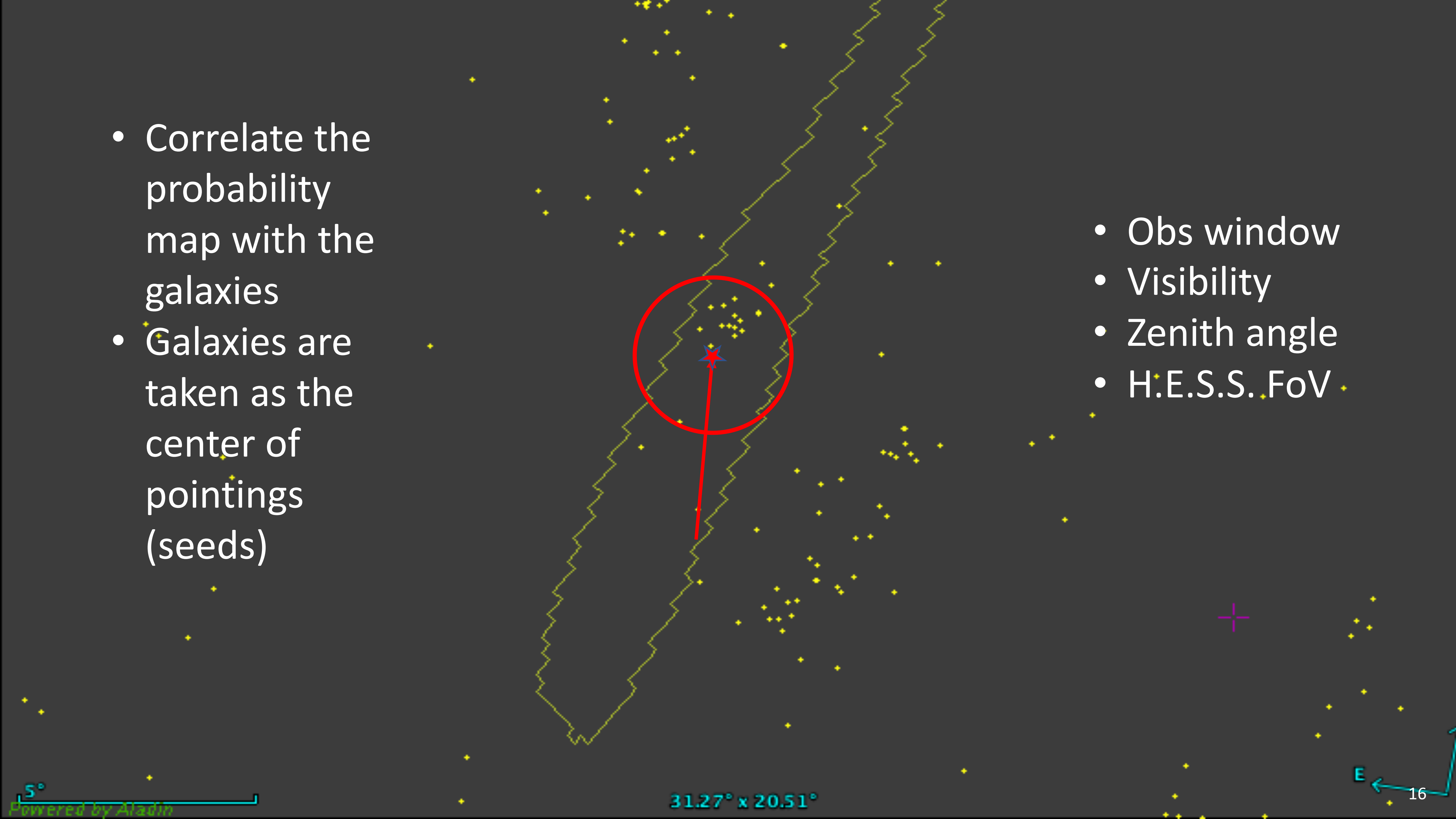
3D strategies

- Correlate the probability map with the galaxies

- Obs window
- Visibility
- Zenith angle
- H.E.S.S. FoV



- Correlate the probability map with the galaxies
- Galaxies are taken as the center of pointings (seeds)



- Obs window
- Visibility
- Zenith angle
- H.E.S.S. FoV

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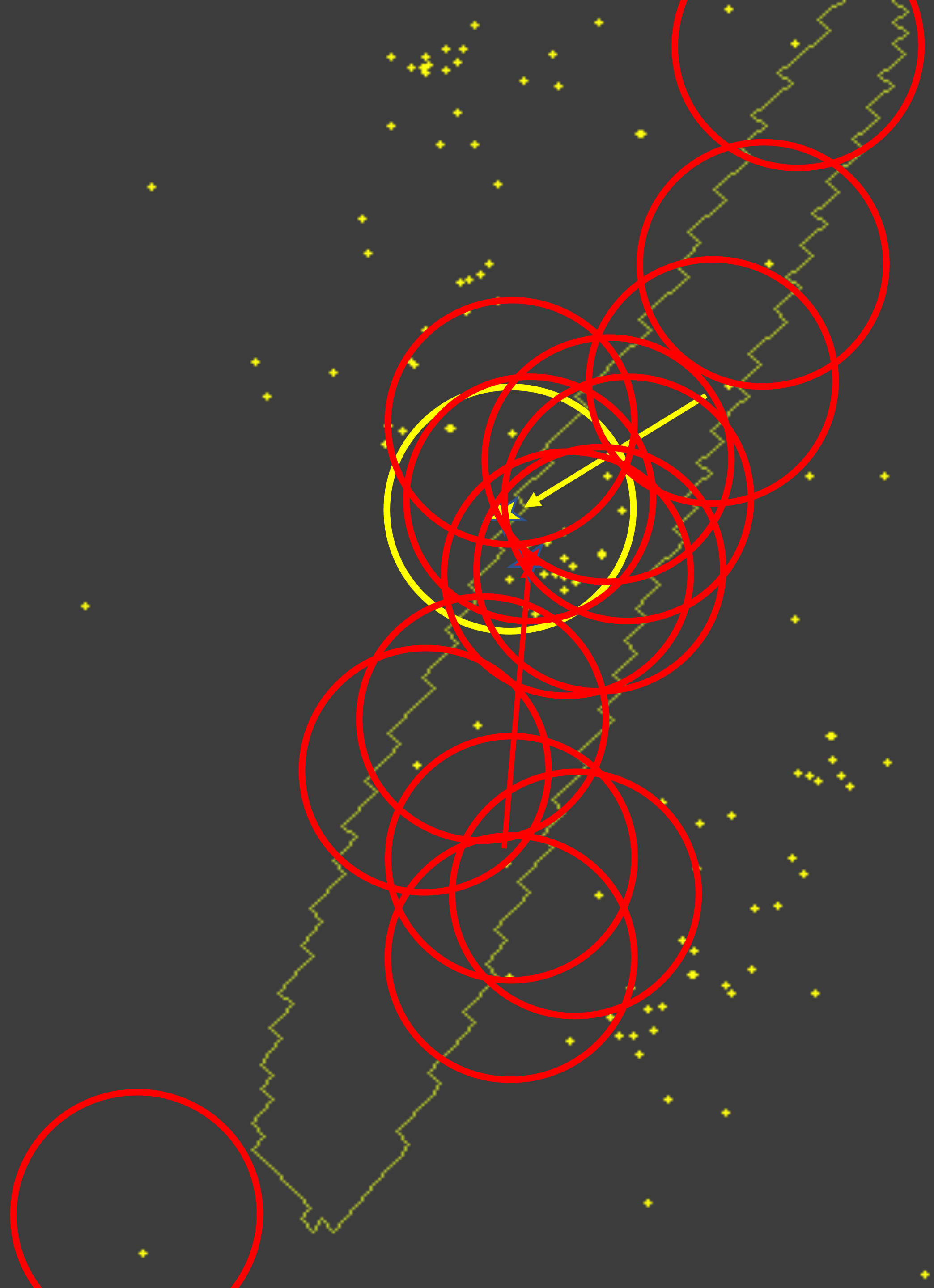
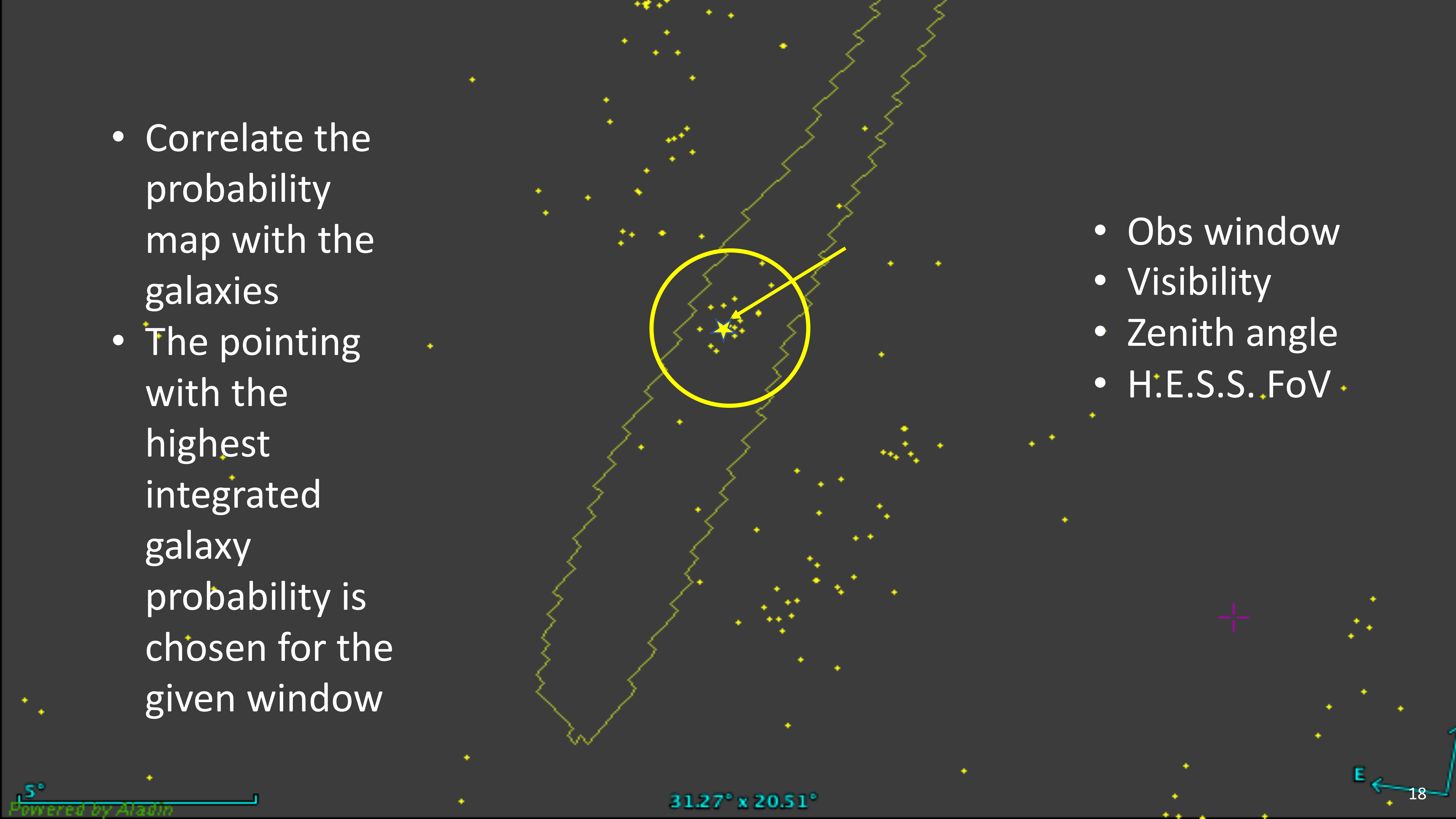


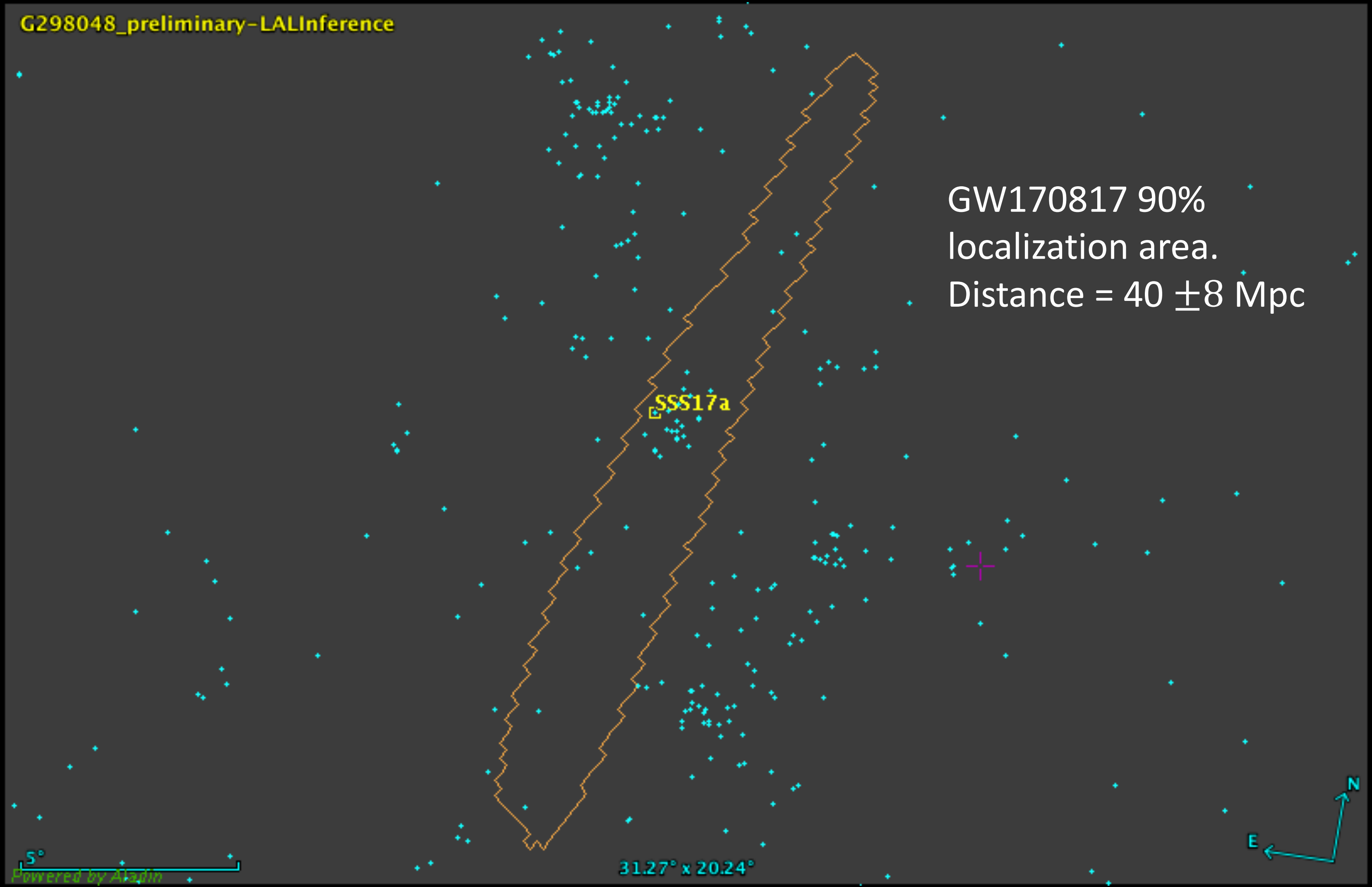
- Obs window
- Visibility
- Zenith angle
- H.E.S.S. FoV

- Correlate the probability map with the galaxies
- The pointing with the highest integrated galaxy probability is chosen for the given window

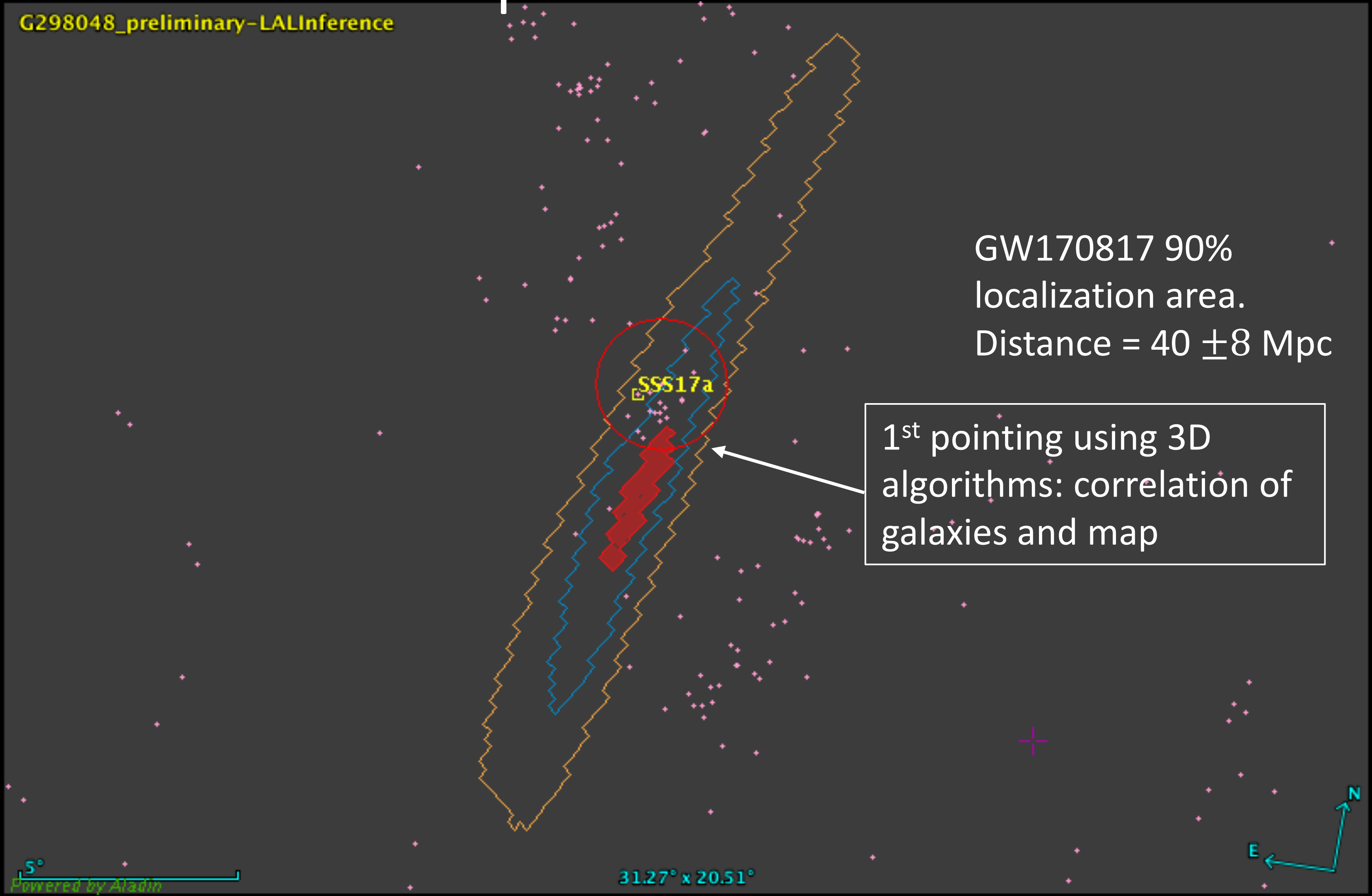


- Obs window
- Visibility
- Zenith angle
- H.E.S.S. FoV

Example: GW170817



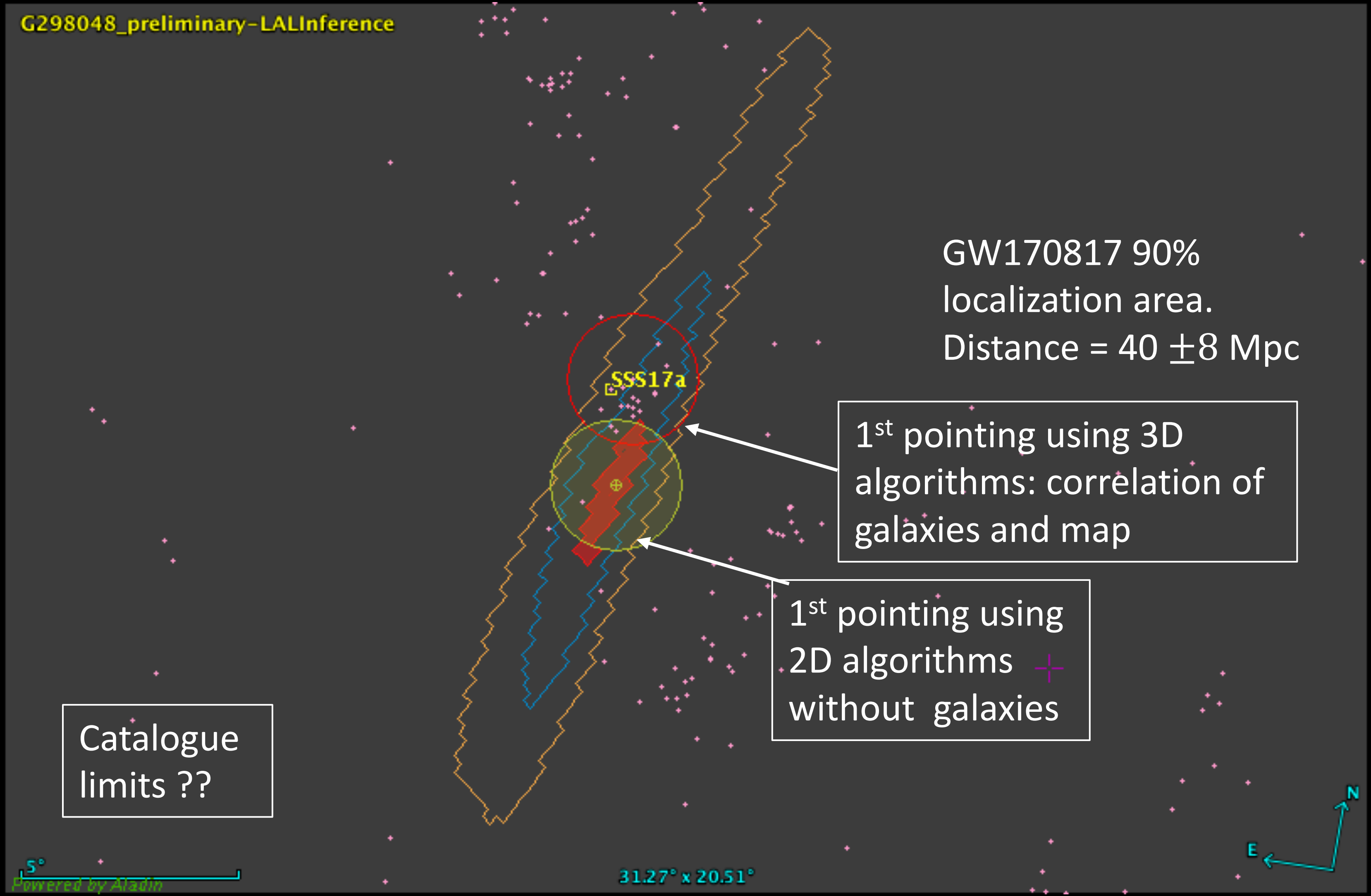
Example: GW170817



GW170817 90% localization area.
Distance = 40 ±8 Mpc

1st pointing using 3D algorithms: correlation of galaxies and map

Example: GW170817



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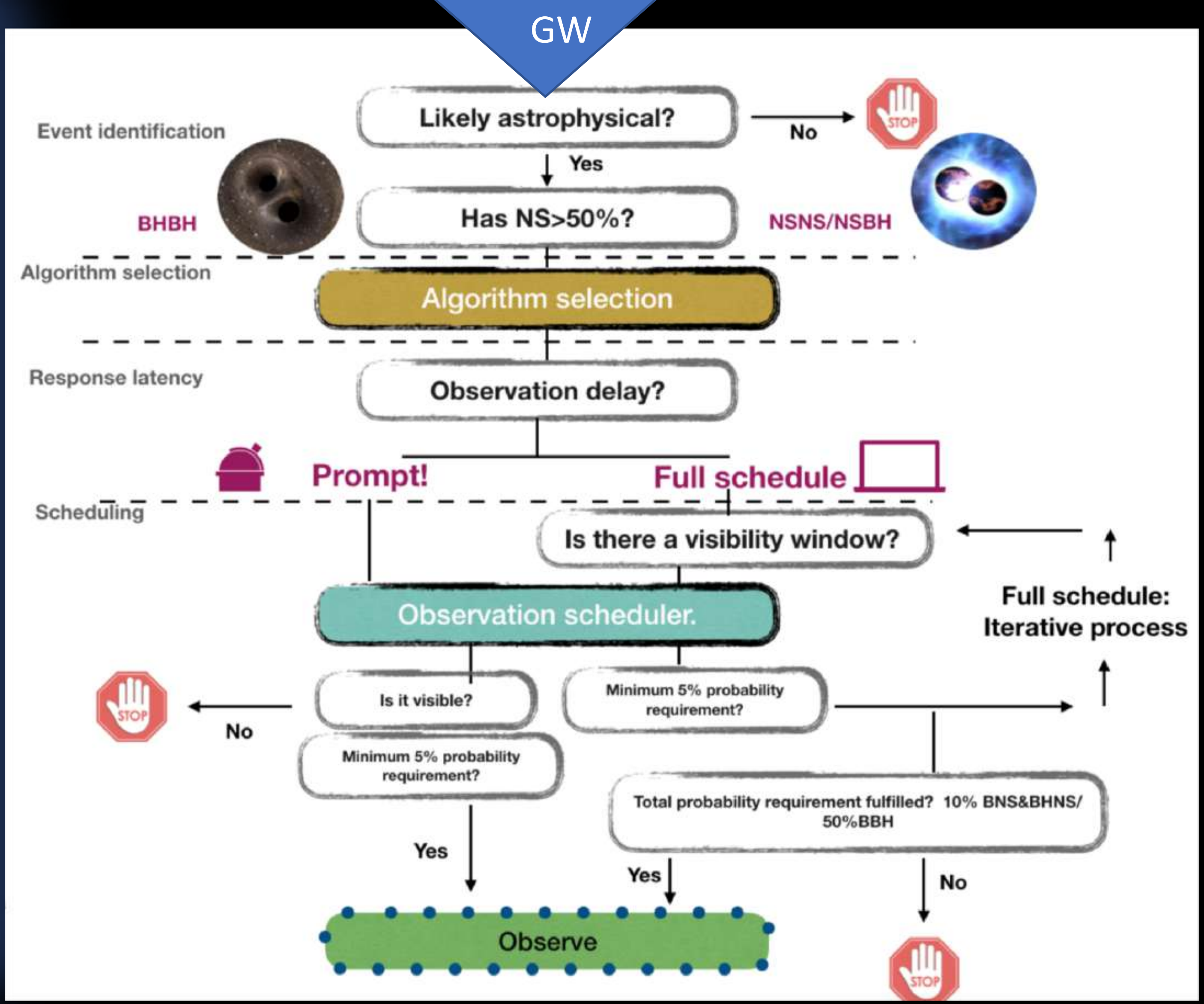
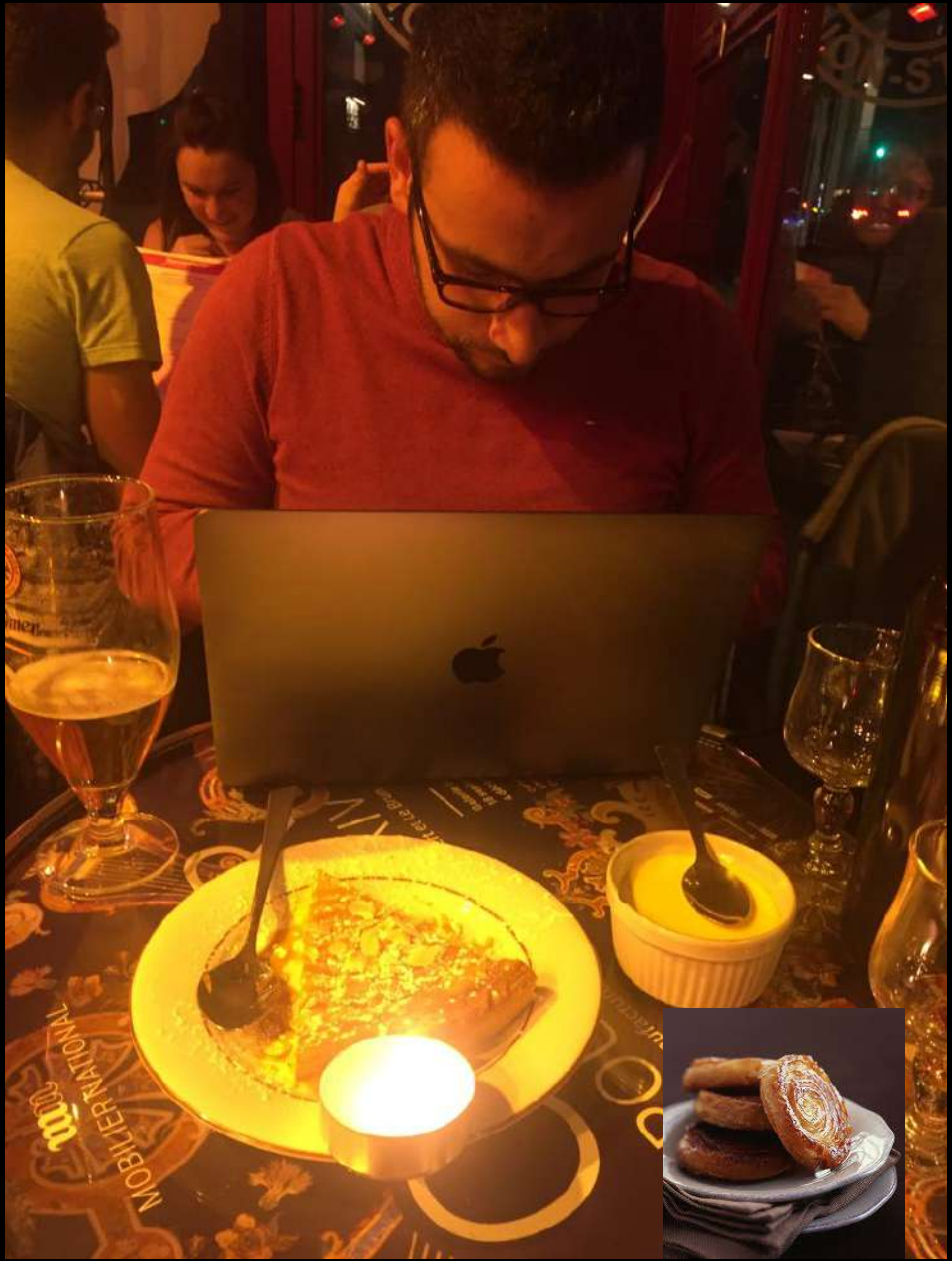
<Group type="GW_SKYMAP" name="bayestar">
    <Param name="skymap_fits" dataType="string" value="https://gracedb.ligo.org/api/superevents/
        S190701ah/files/bayestar.fits.gz" ucd="meta.ref.url">
        <Description>Sky Map FITS</Description>
    </Param>
</Group>
<Group type="Classification">
    <Param name="BNS" dataType="float" value="0.0" ucd="stat.probability">
        <Description>Probability that the source is a binary neutron star merger (both objects lighter
            than 3 solar masses)</Description>
    </Param>
    <Param name="NSBH" dataType="float" value="0.0" ucd="stat.probability">
        <Description>Probability that the source is a neutron star-black hole merger (primary heavier
            than 5 solar masses, secondary lighter than 3 solar masses)</Description>
    </Param>
    <Param name="BBH" dataType="float" value="0.934372647001" ucd="stat.probability">
        <Description>Probability that the source is a binary black hole merger (both objects heavier
            than 5 solar masses)</Description>
    </Param>
    <Param name="MassGap" dataType="float" value="0.0" ucd="stat.probability">
        <Description>Probability that the source has at least one object between 3 and 5 solar masses</
            Description>
    </Param>
    <Param name="Terrestrial" dataType="float" value="0.0656273529992" ucd="stat.probability">
        <Description>Probability that the source is terrestrial (i.e., a background noise fluctuation or
            a glitch)</Description>
    </Param>
    <Description>Source classification: binary neutron star (BNS), neutron star-black hole (NSBH),
        binary black hole (BBH), MassGap, or terrestrial (noise)</Description>
</Group>
<Group type="Properties">
    <Param name="HasNS" dataType="float" value="0.0" ucd="stat.probability">
        <Description>Probability that at least one object in the binary has a mass that is less than 3
            solar masses</Description>
    </Param>
    <Param name="HasRemnant" dataType="float" value="0.0" ucd="stat.probability">
        <Description>Probability that a nonzero mass was ejected outside the central remnant object</
            Description>
    </Param>
    <Description>Qualitative properties of the source, conditioned on the assumption that the signal is
        an astrophysical compact binary merger</Description>
</Group>
```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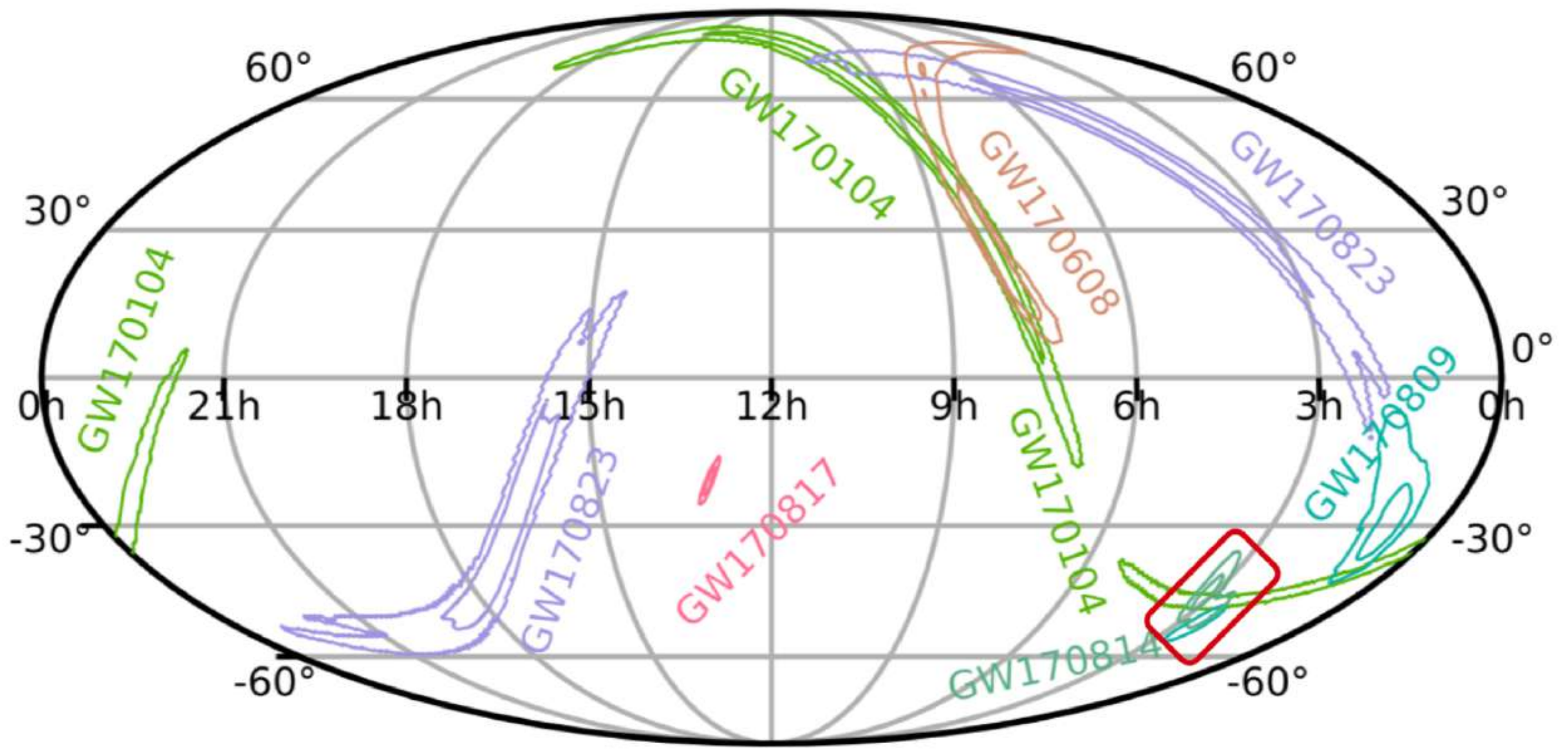
GW follow-up observations and analysis

Observation Run O2

GWTC-1: O2 catalog



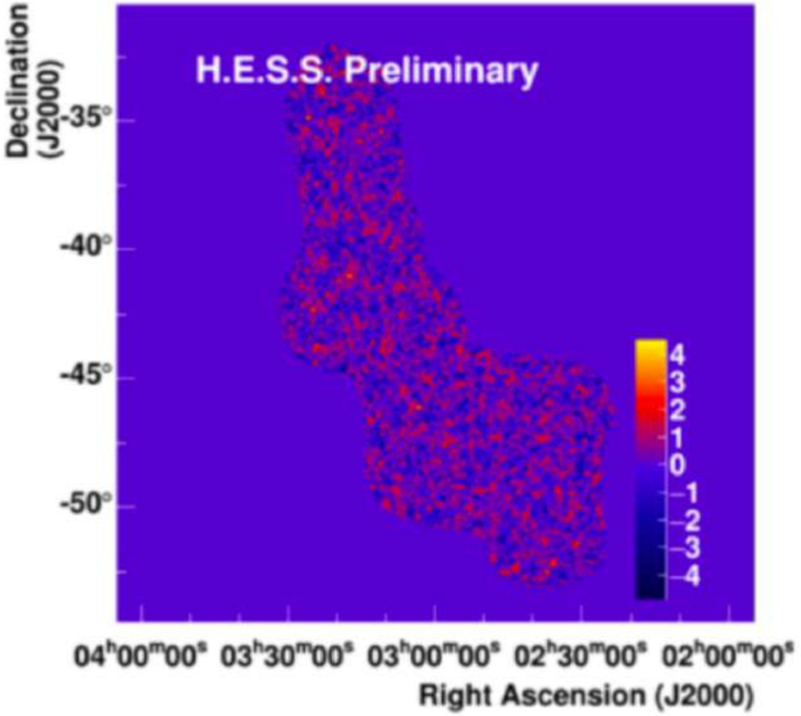
GWTC-1: arXiv:1811.12907

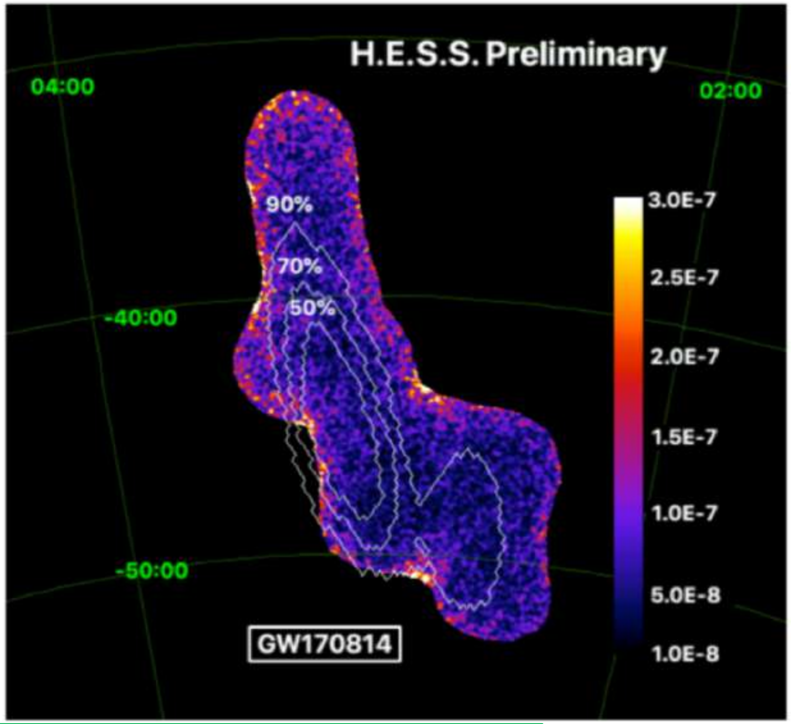
GW170814: BBH

M1: 28-36 M⨀
M2 :21-28 M⨀
MTotal = 53-59 M⨀

- For O2 technical, trial run on BBH: GW170814 (3 days before real NSM trigger!).

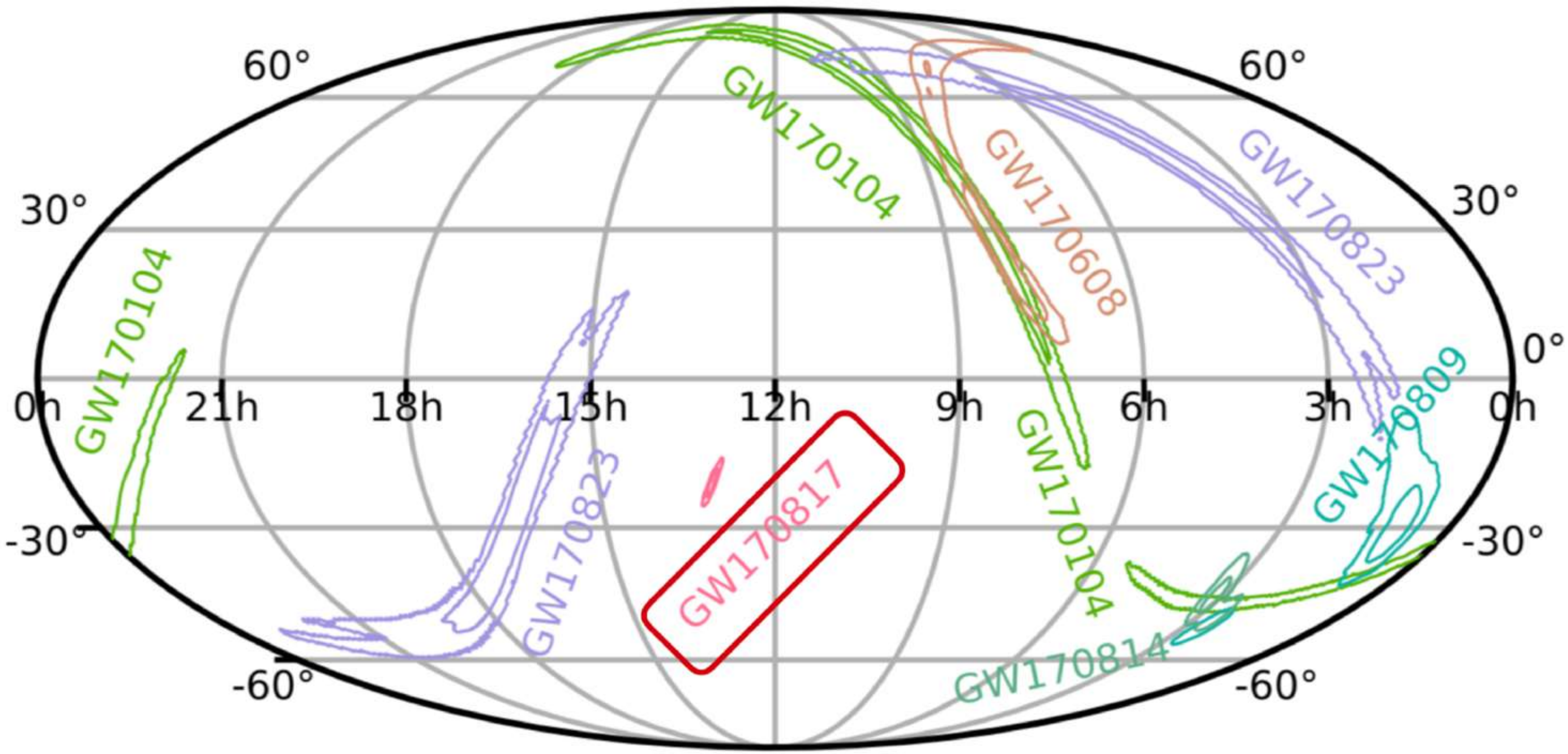
- 14 August 2017, seen by aLIGO-L, aLIGO-H and Virgo
  Credible region sky area (without V1): 1160 deg2 (with V1): 60 deg2





H. Ashkar, F. Schüssler, M. Seglar-Arroy (2019). 12th NTEGRAL conference / 1st AHEAD workshop, *MmSAI*, Arxive 1906.10426, https://arxiv.org/abs/1906.10426

GWTC-1: O2 catalog



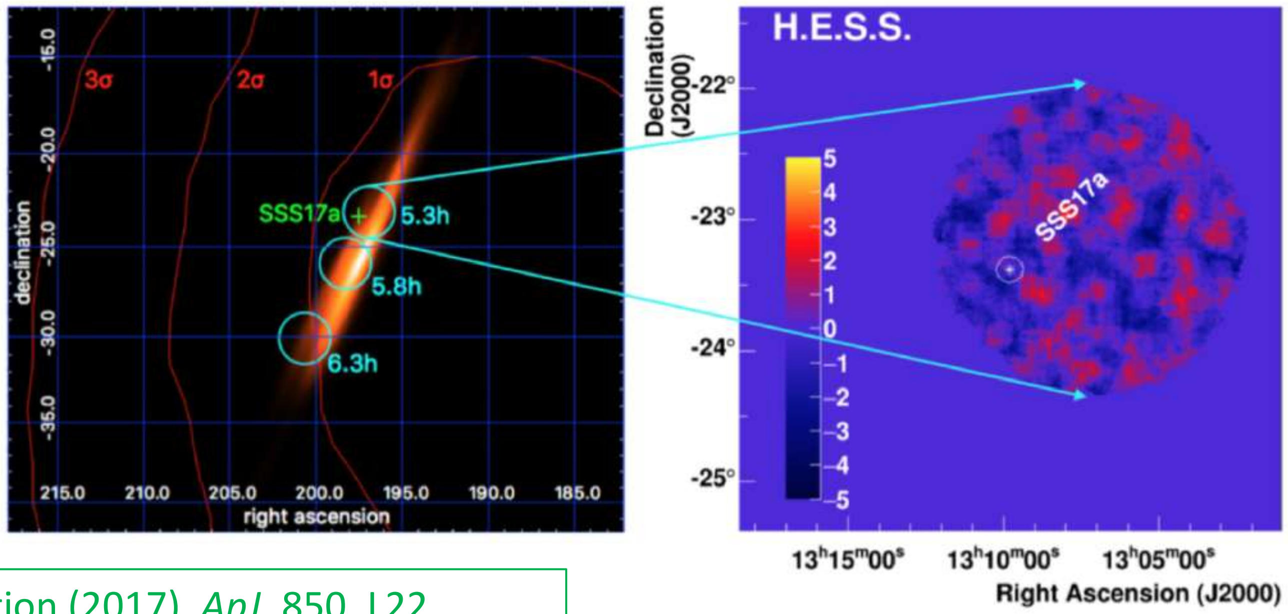
GW170817: BNS

H.E.S.S. was the first ground based instrument on target!

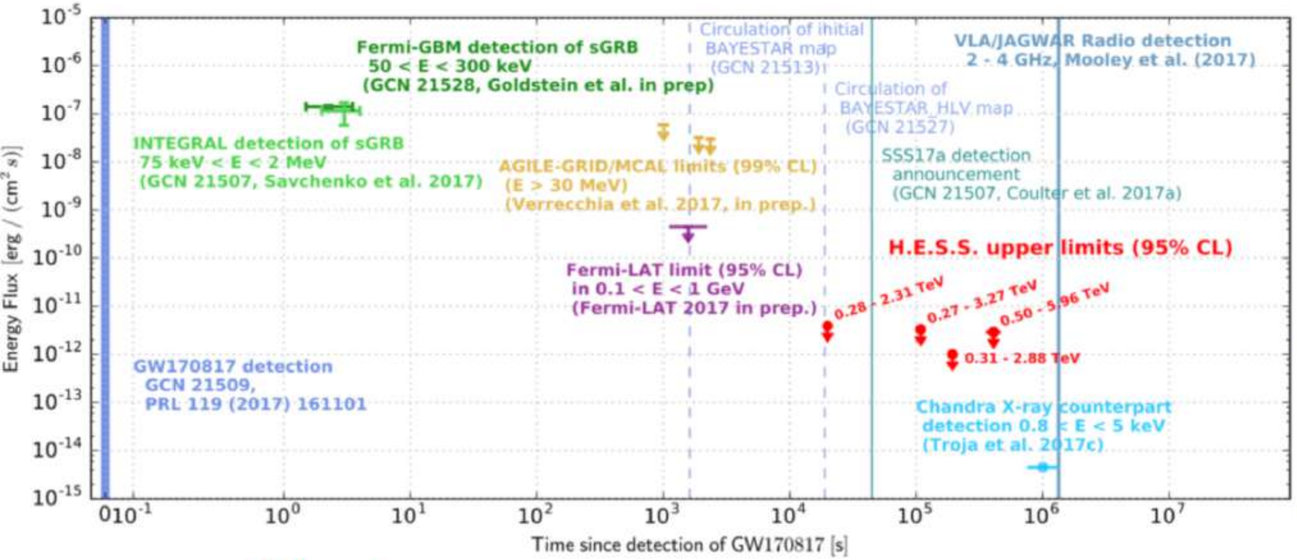
- 5.3 hours after merger
- 5 minutes after the update of the GW skymap

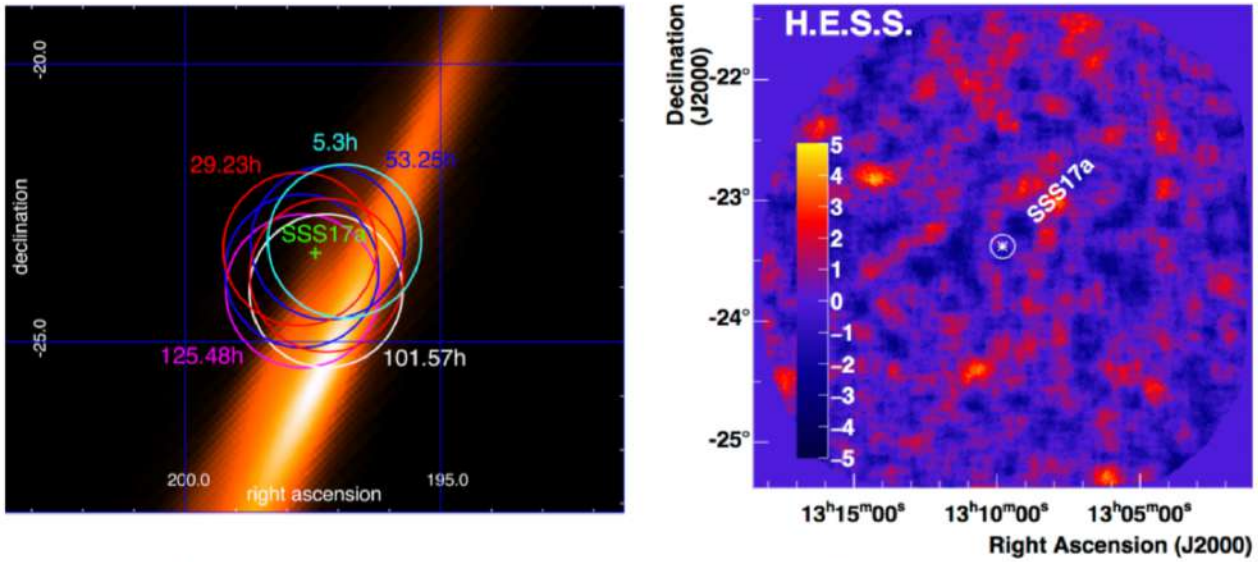
(LV reconstruction)

- The first ground-based observation was on the afterwards identified position of the NS-NS
- In subsequent nights, observations were modified according to the NS-NS location

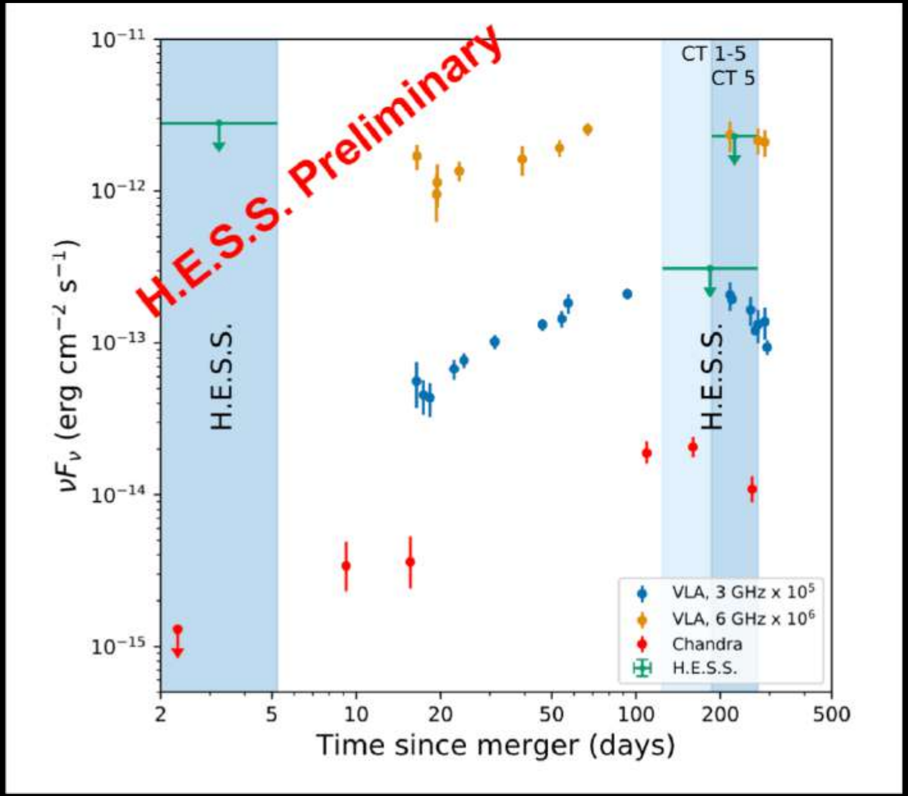


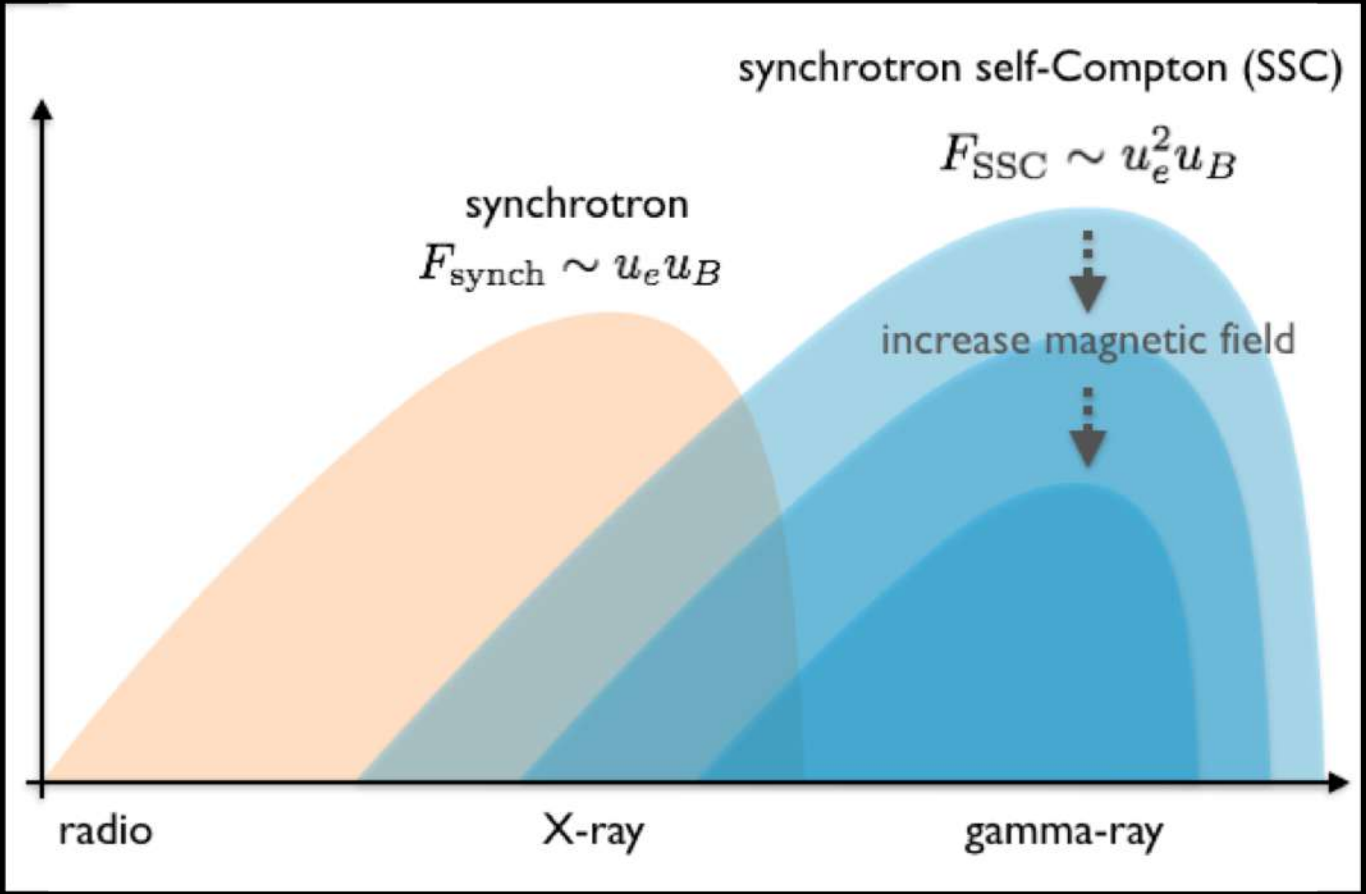
H.E.S.S. collaboration (2017). *ApJ*. 850. L22.





(a) SSS17a: H.E.S.S. pointings (b) SSS17a: H.E.S.S. significance map





Paper submitted to *PRL*

2 scenarios:

Spherical outflow: $\gtrsim$ 200 uG

Off-axis jet: $\gtrsim$ 50 uG

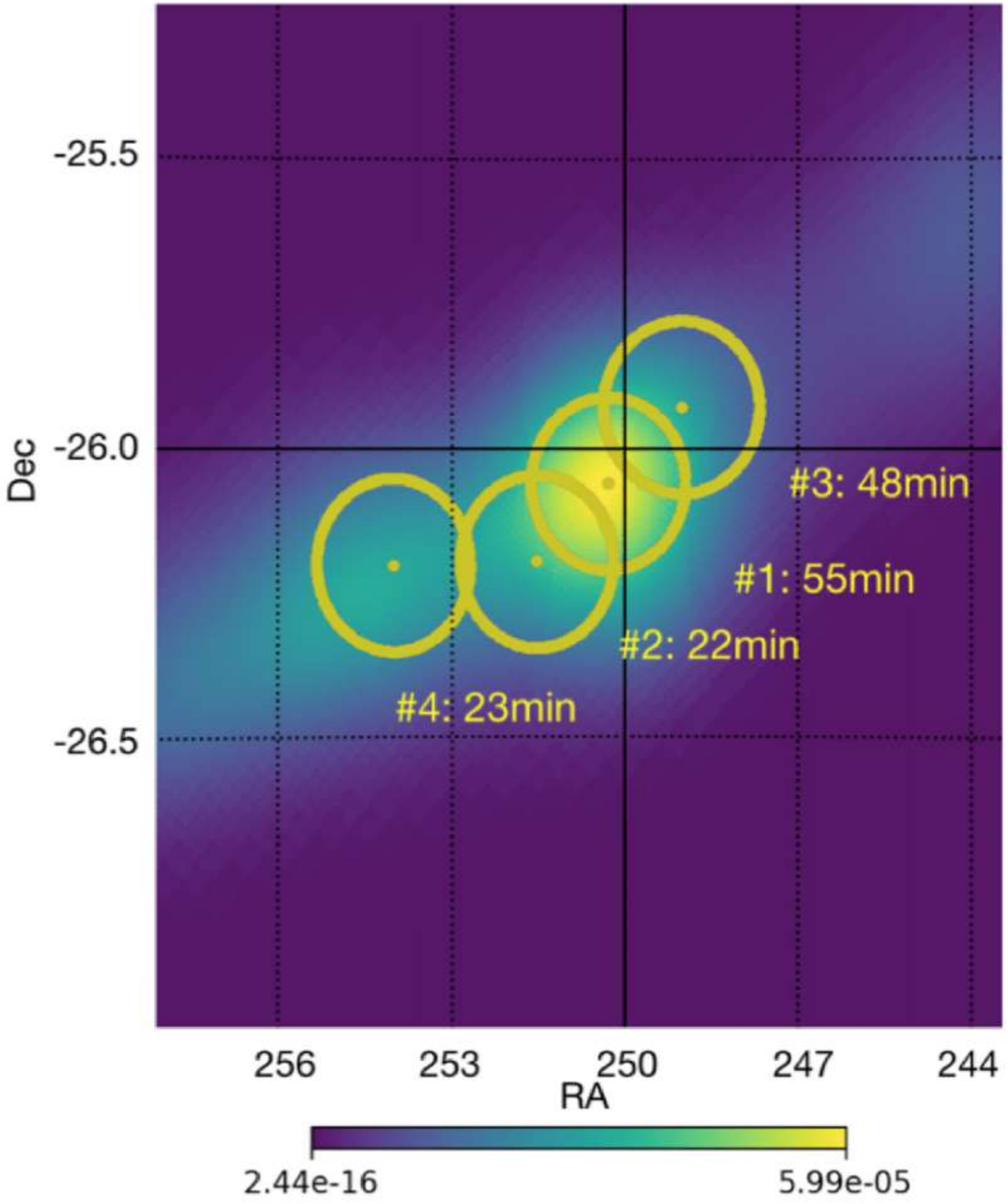
GW follow-up observations and analysis

Observation Run O3

Follow-up of O3 gravitational wave events

ID	Time (UTC)	Type	90% C.R.	Δ_t	N_p	P_{GW}	Follow-up
S190408	19-04-08 18:18	BH-BH	387 deg^2	-	-	-	No
S190412	19-04-12 05:31	BH-BH	156 deg^2	$\sim$ 13h	6	66%	No
S190425	19-04-25 08:18	NS-NS	7461deg^2	-	-	-	No
S190426	19-04-26 15:22	NS-NS	1262 deg^2	$\sim$ 6h	9	4 %	No
S190503	19-05-03 18:54	BH-BH	443 deg^2	-	-	-	No
S190512	19-05-12 18:07	BH-BH	339 deg^2	5h30m	9	34%	Yes
S190513	19-05-13 20:54	BH-BH	691deg^2	4h20m	1	9%	No
S190519	19-05-19 15:36	BH-BH	967 deg^2	> days	-	-	No
S190521	19-05-21 03:03	BH-BH	1163 deg^2	> days	-	-	No
S190521-II	19-05-21 07:44	BH-BH	488 deg^2	> days	-	-	No
S190602	19-06-02 18:00	BH-BH	1172 deg^2	> days	-	-	No
S190630	19-06-30 18:52	BH-BH	8493 deg^2	-	-	-	No
S190701	19-07-01 20:33	BH-BH	67 deg^2	6h	3	51%	No
S190706	19-07-06 22:26	BH-BH	1100 deg^2	> days	-	-	No
S190707	19-07-07 09:33	BH-BH	1375 deg^2	15h	-	-	No
S190718	19-07-18 14:35	Terrestrial	7246 deg^2	-	-	-	No
S190720	19-07-20 00:09	BH-BH	1599 deg^2	> days	-	-	No
S190727	19-07-27 06:03	BH-BH	841 deg^2	> days	-	-	No
S190728	19-07-28 06:45	MassGap	104 deg^2	13h	4	50%	Yes

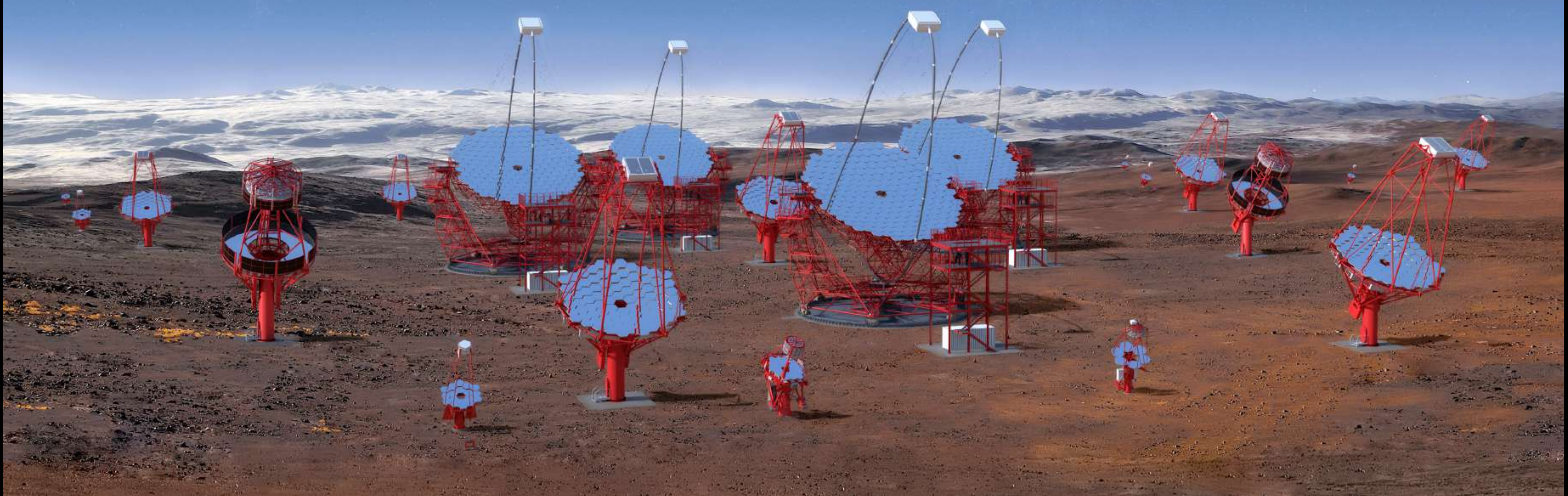
S190512



-25.5
-26.0
-26.5
Dec
#3: 48min
#1: 55min
#2: 22min
#4: 23min
256
253
250
247
244
RA
2.44e-16
5.99e-05

Future prospects:
GW follow-up with CTA

Low-latency gravitational waves follow-up program of CTA



Simulation of BNS mergers and GW detection with GWCOSMoS:

Patricelli, B., et al. (2018)

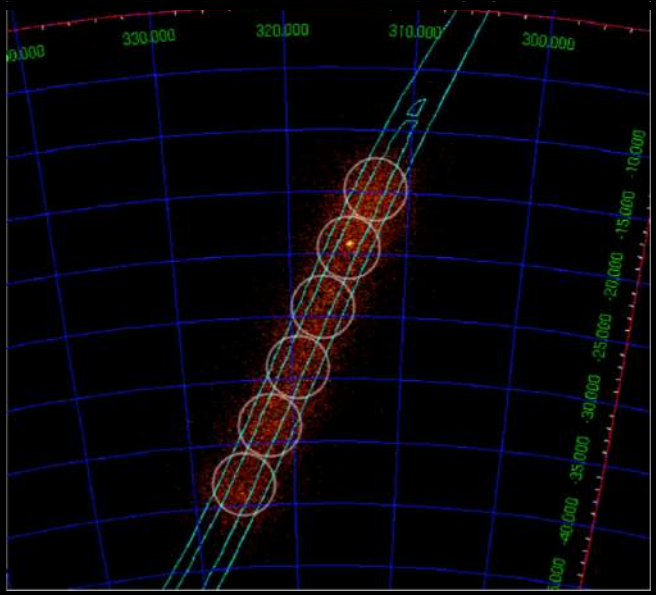
Simulation of VHE emission from sGRBs:

from typical properties of LAT GRBs (in particular GRB090510)

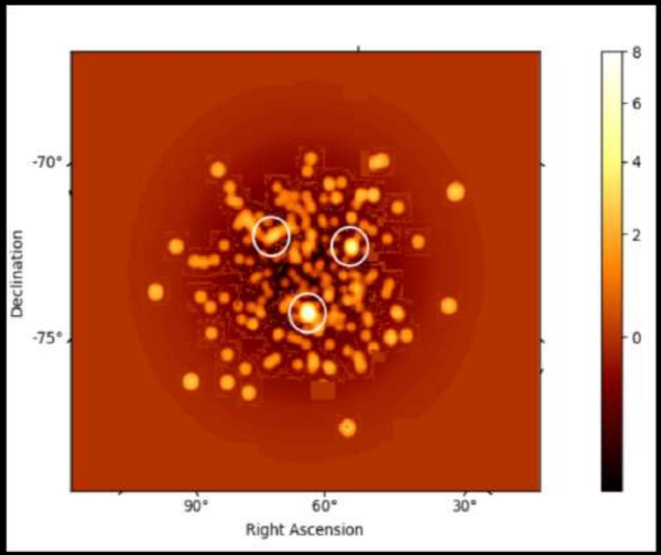
- Alert injection & GW follow-up observation
- Scheduling:
  - Low-energy coverage (zenith angle optimization)
  - Probability coverage maximization
  - $T_J = T_{alert} + T_{slew} + \sum_1^{J-1} T_J$

$$\int_{t_0}^{t_0+T_{obs}} \frac{dF(t)}{dt} dt = F_{5\sigma}^{int}(t_0, t_0+T_{obs})$$

CTA observation searching for an EM counterpart



Analysis of the CTA scheduled observations (run-by-run)



Seglar-Arroyo, M., et al (2019). ICRC2019 (PoS 790), https://arxiv.org/abs/1908.08393

Thank you

- Have you noticed ?

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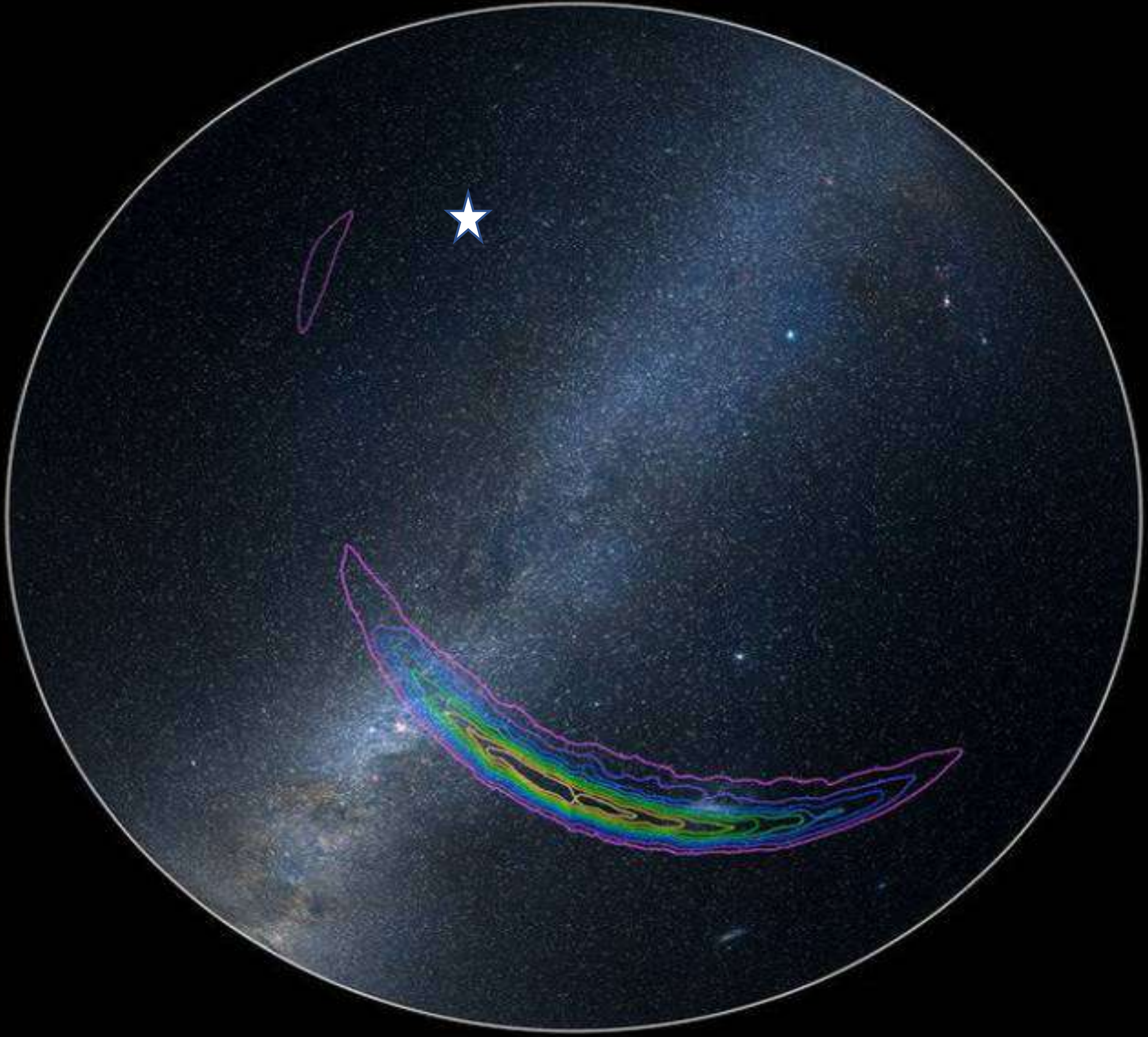
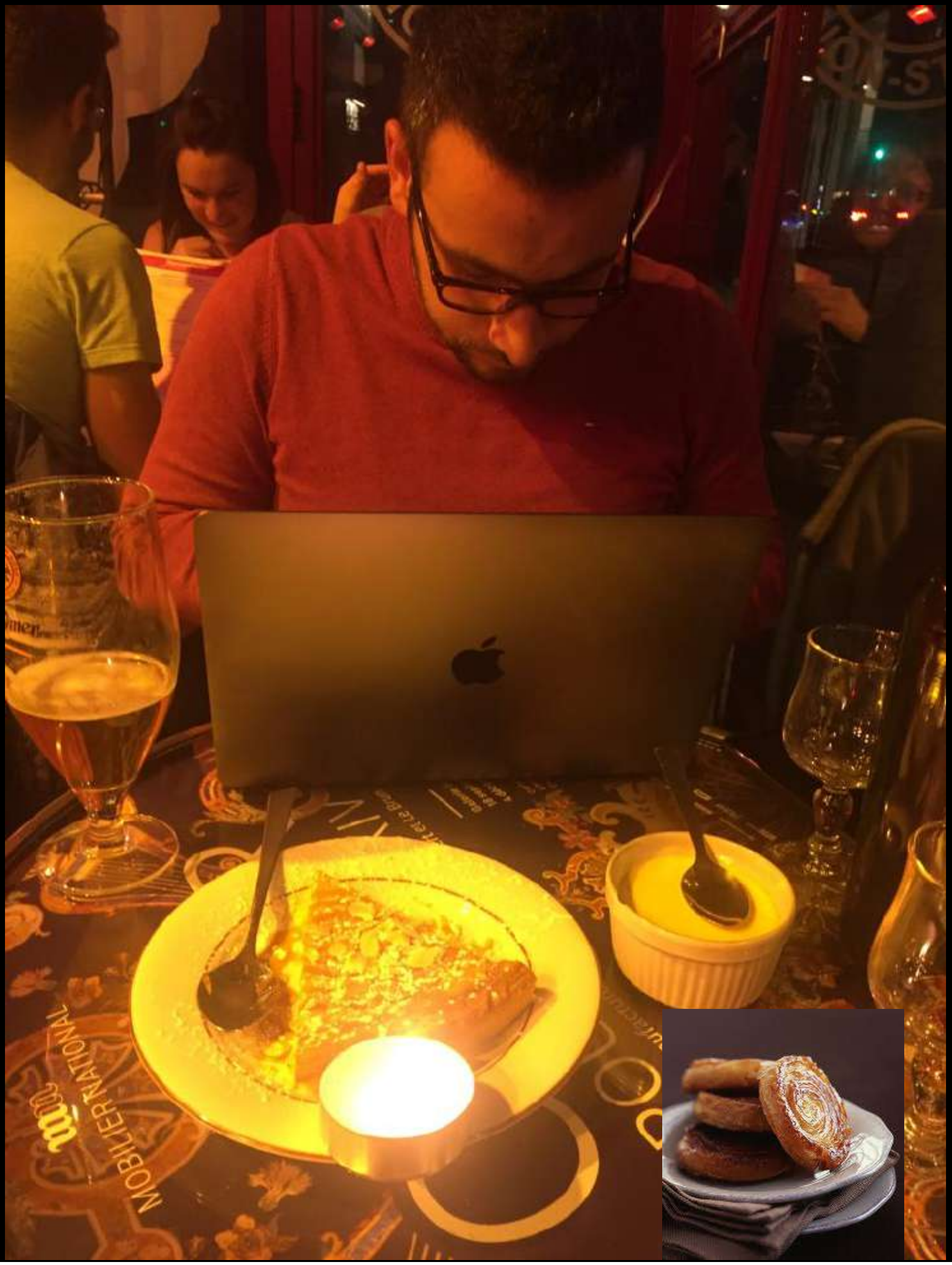
But localization regions vary from 10s to 1000s deg^2

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