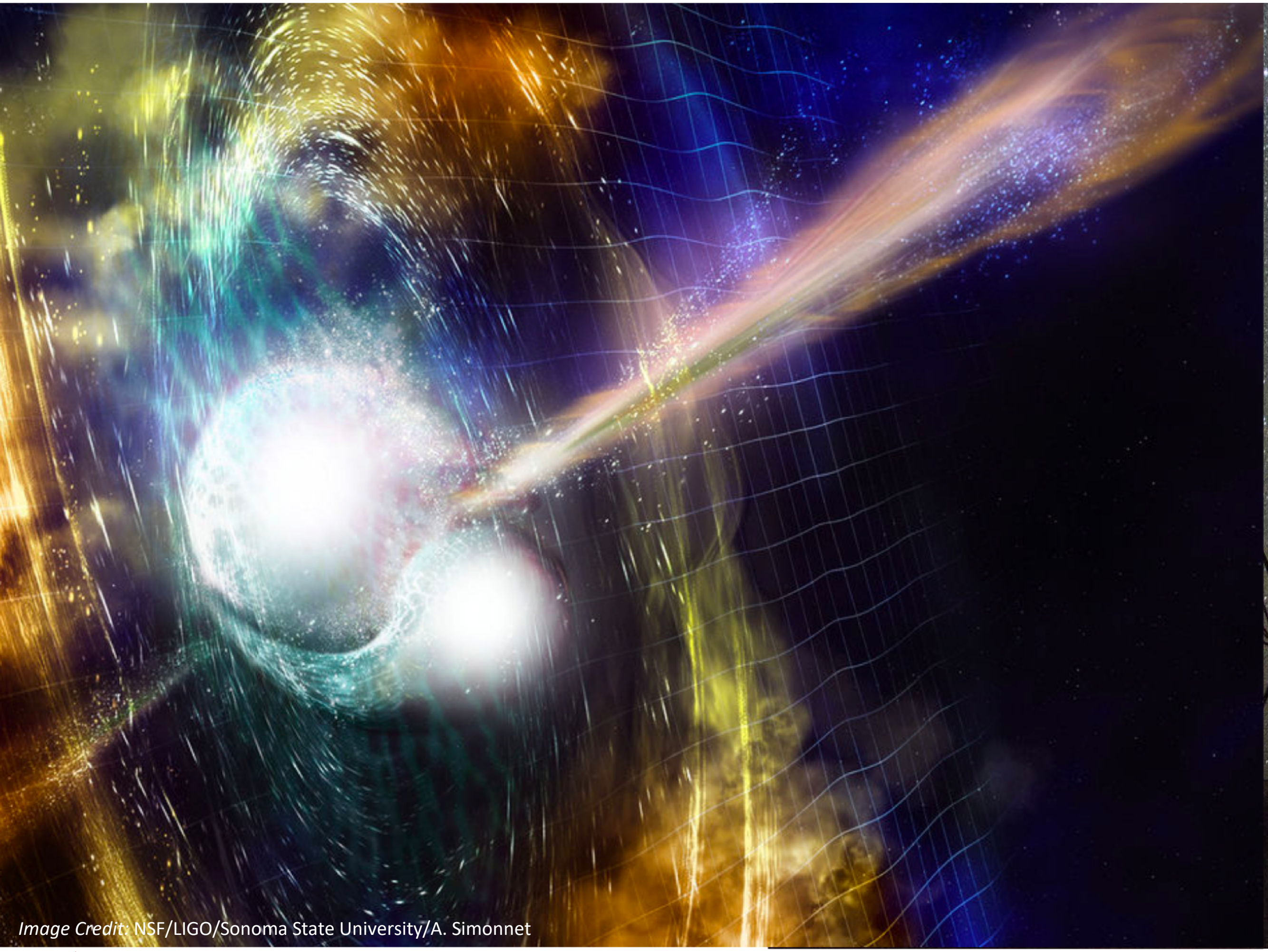
GW follow-up with IACTs

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



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

Transient Sky 2020 – Paris 2019

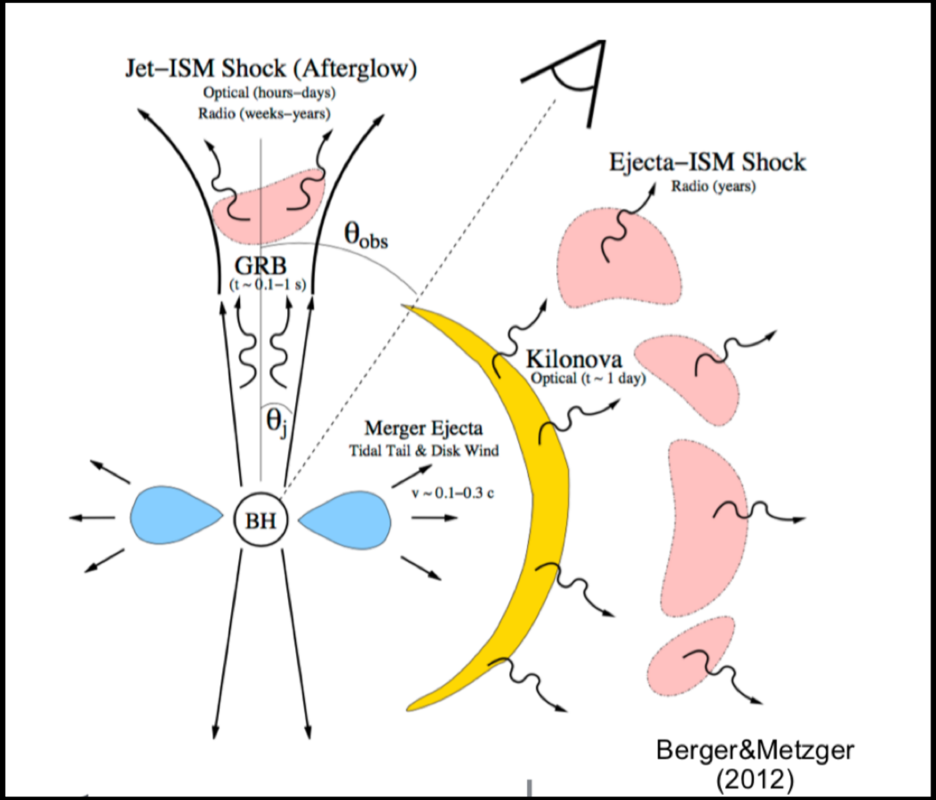
H.E.S.S.

université PARIS-SACLAY

Science Case: VHE emission in compact binary coalescence

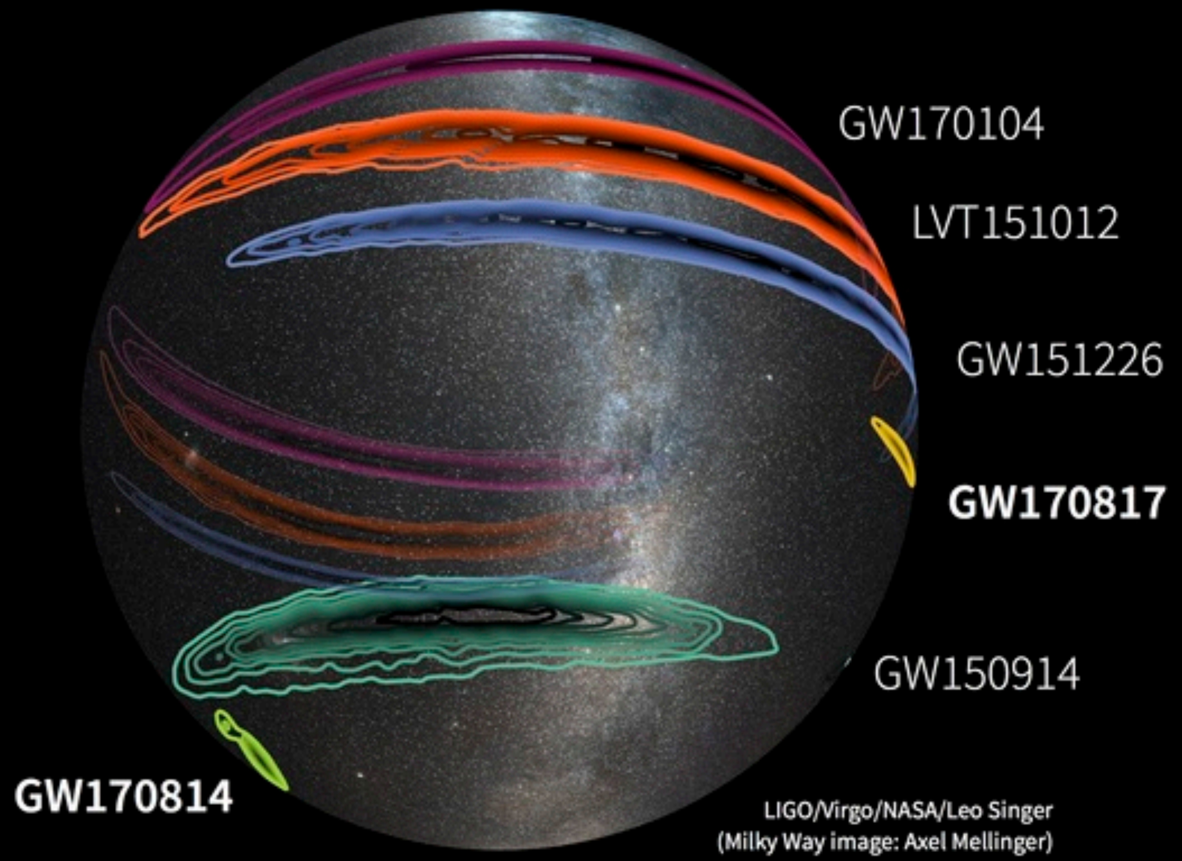
- Neutron star - neutron star
- Neutron star – black hole
- Black hole – black hole ???

- Examples of VHE GRBs:
    - **GRB190829A detected by H.E.S.S.**
    - **GRB 190114C detected by MAGIC**
    - **GRB180720B detected by H.E.S.S**
    - GRB 130427A : Ephoton~ 95 GeV (minutes) - 32GeV(hours)
    - GRB 090510: in prompt phase E_{photon}~30 GeV
    - GRB 081024B: in prompt phase E_{photon}~ 3 GeV



➢ Get information on GRB spectra and remnant structures

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



H.E.S.S. constraints

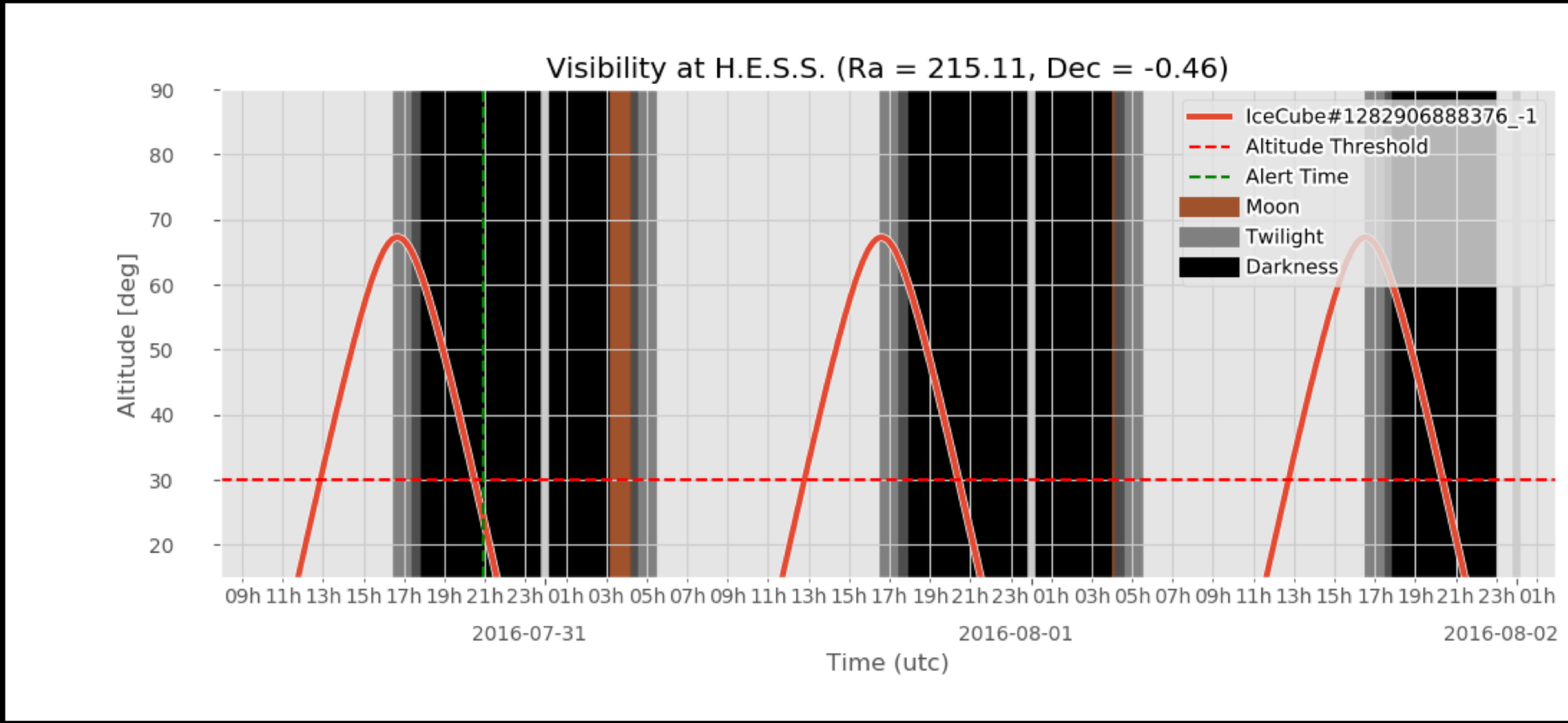
- Obs windows

(Sun and moon position)

Addition: Moonlight obs

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

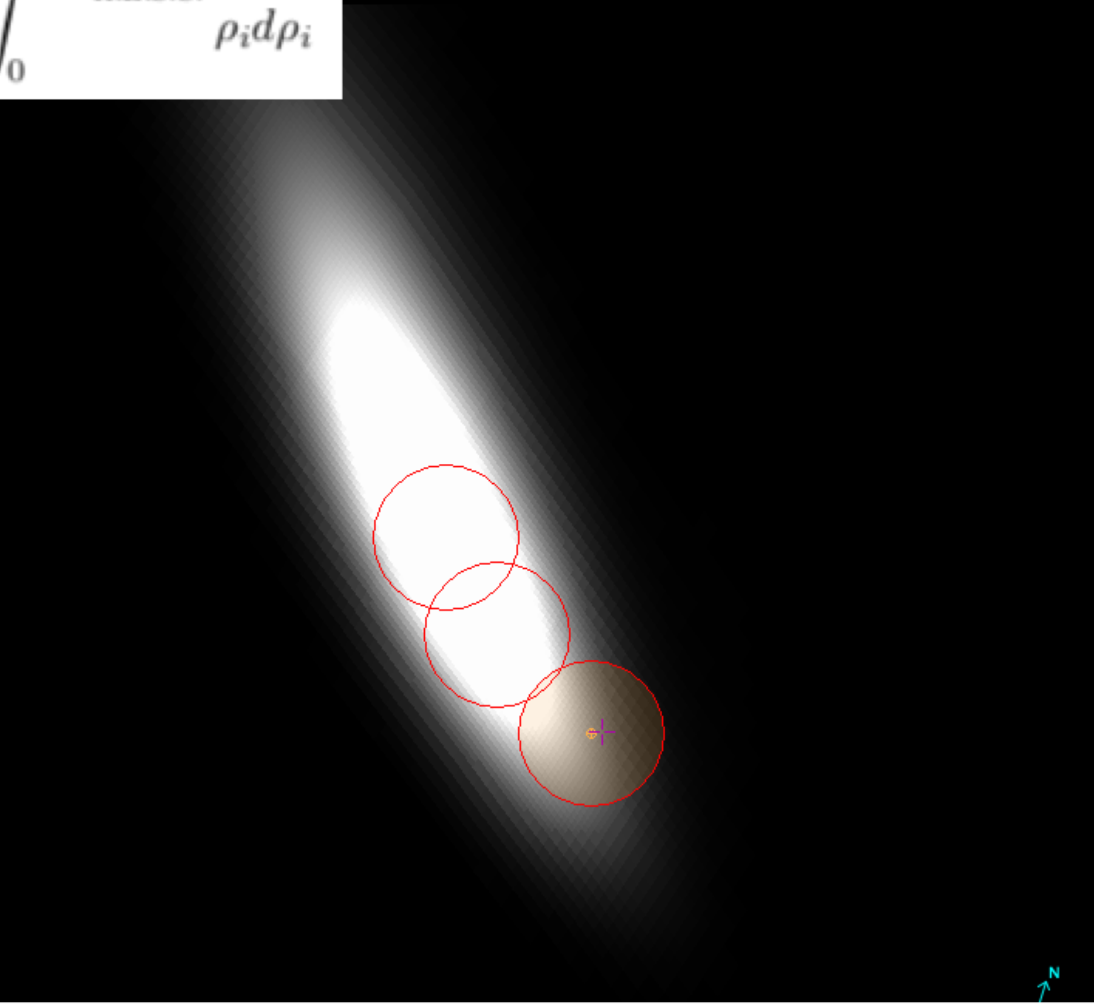
- Visibility of source
- Some parameters:
  - FoV = 1.5º – 2.5º
  - Max zenith angle = 60º

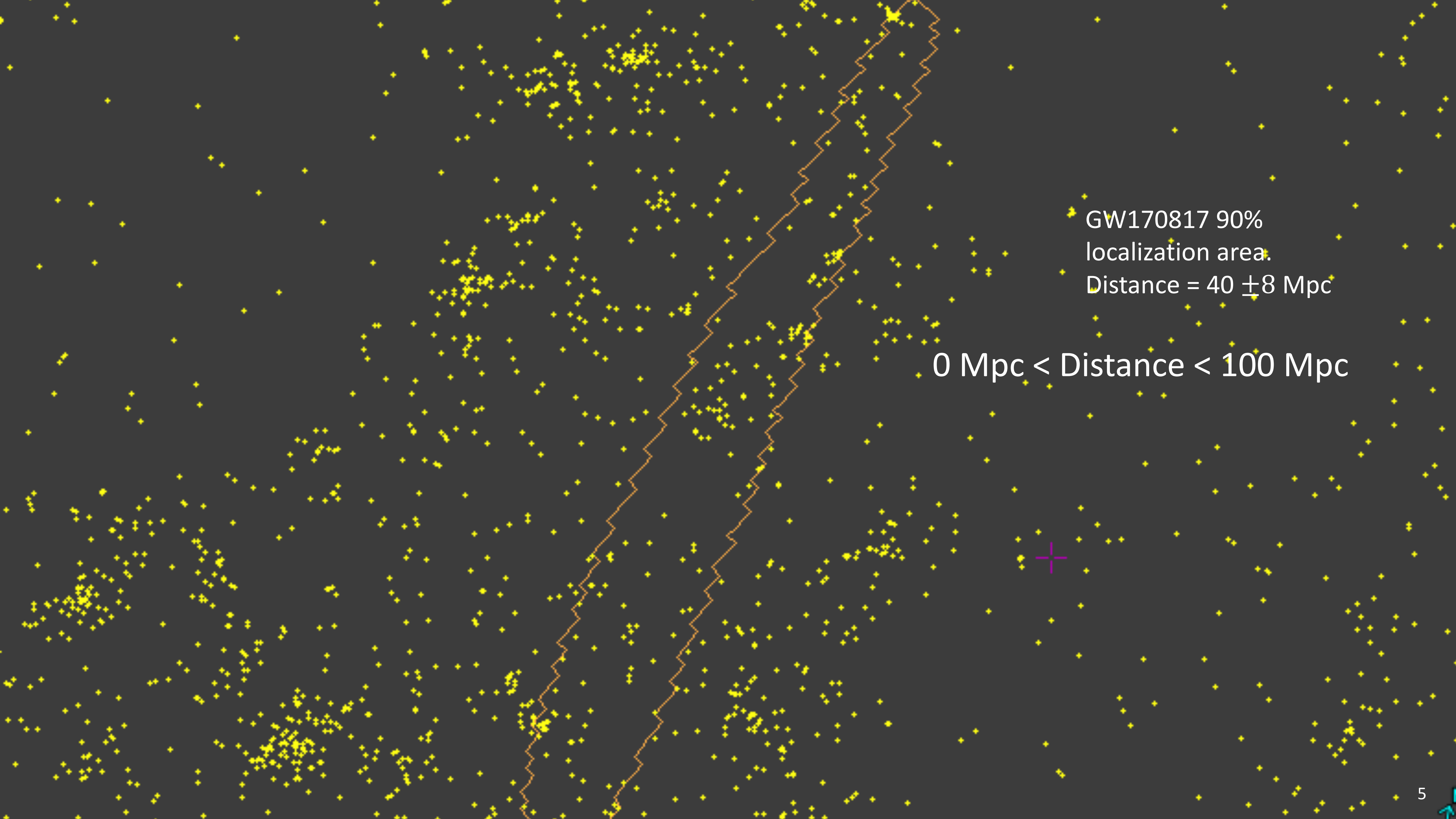


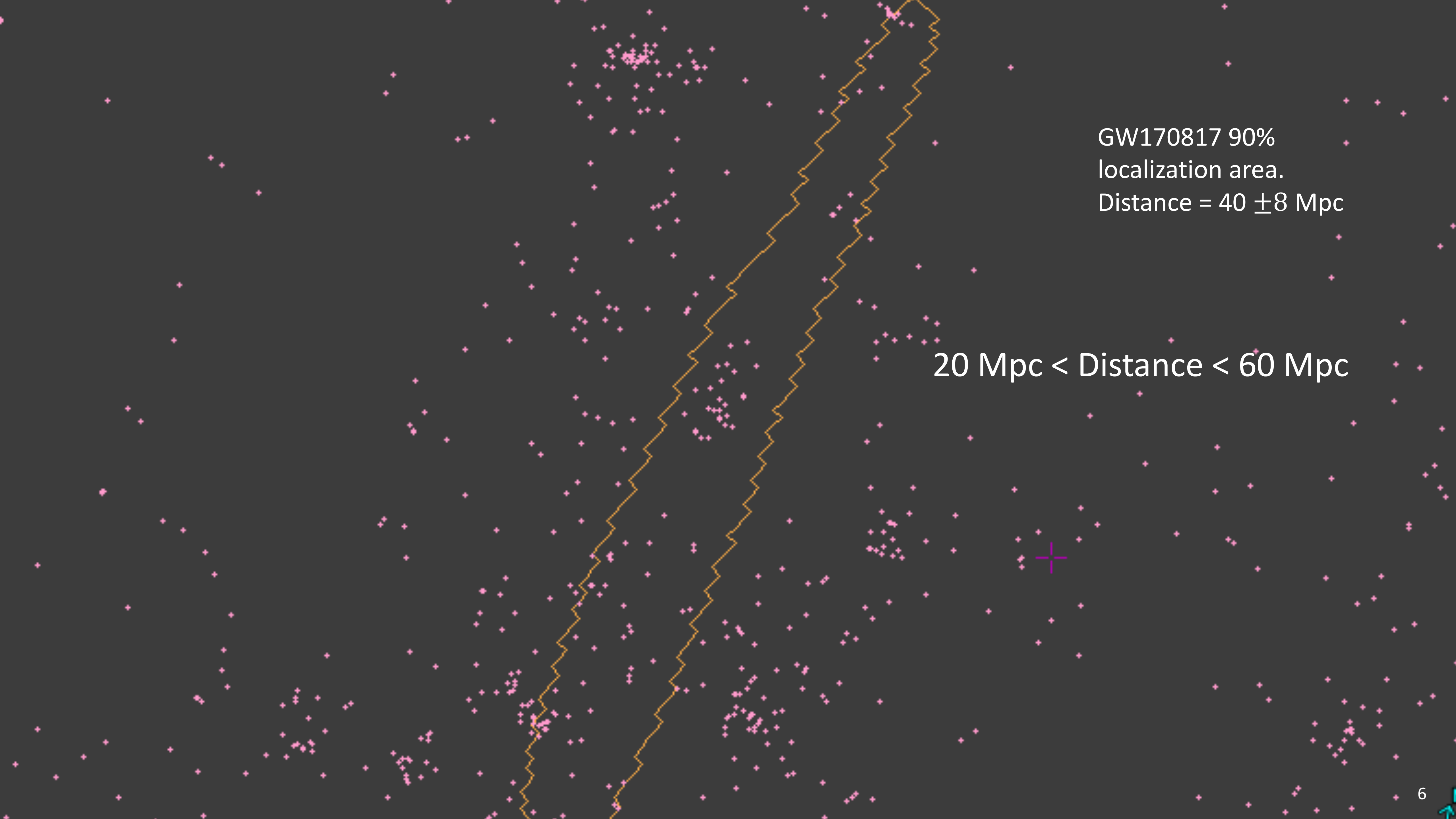
2D strategy:

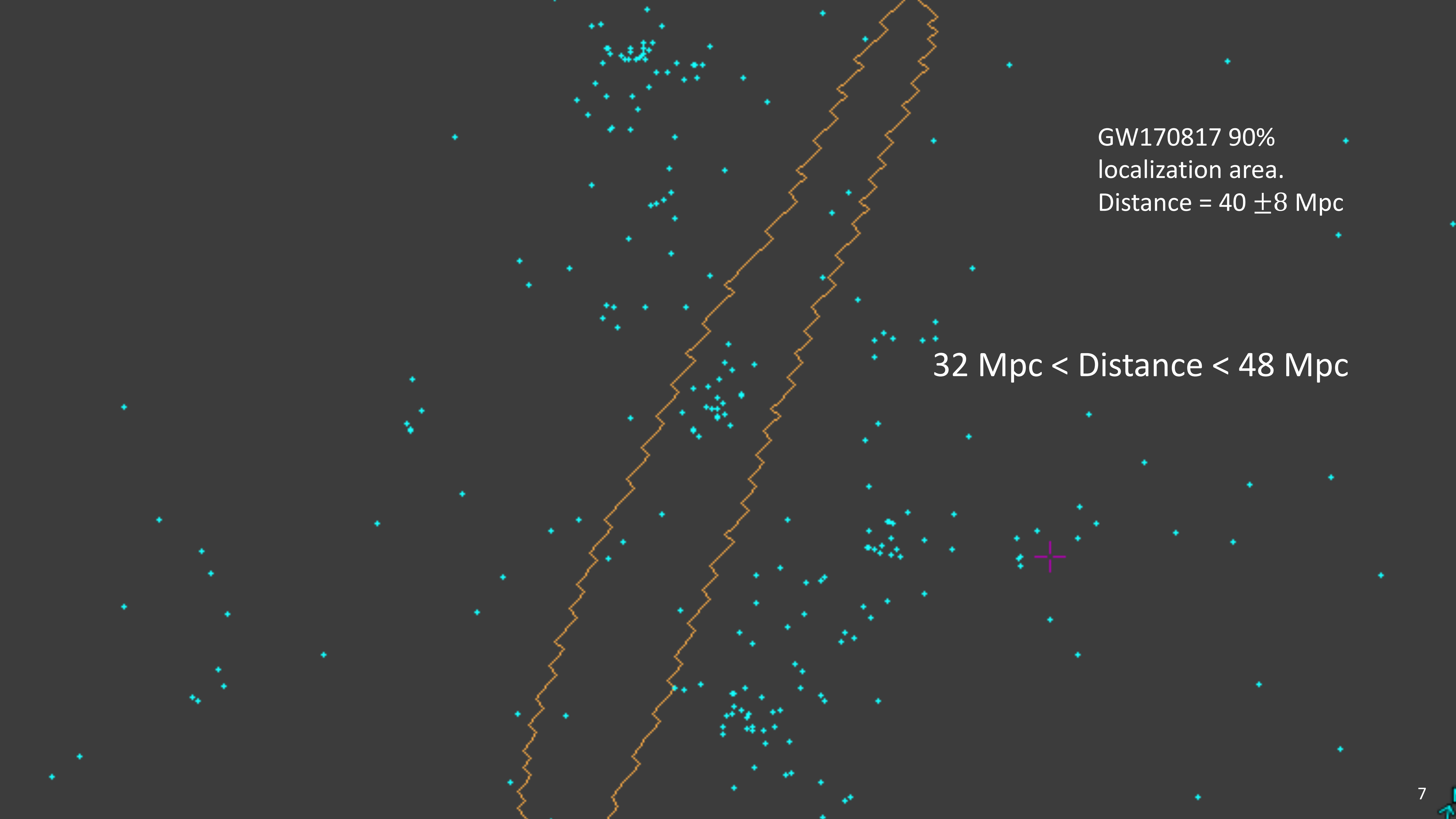
$$P_{\rm GW}^{\rm FoV} = \int_0^{FoV_{\rm H.E.S.S.}} \rho_i d\rho_i$$

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

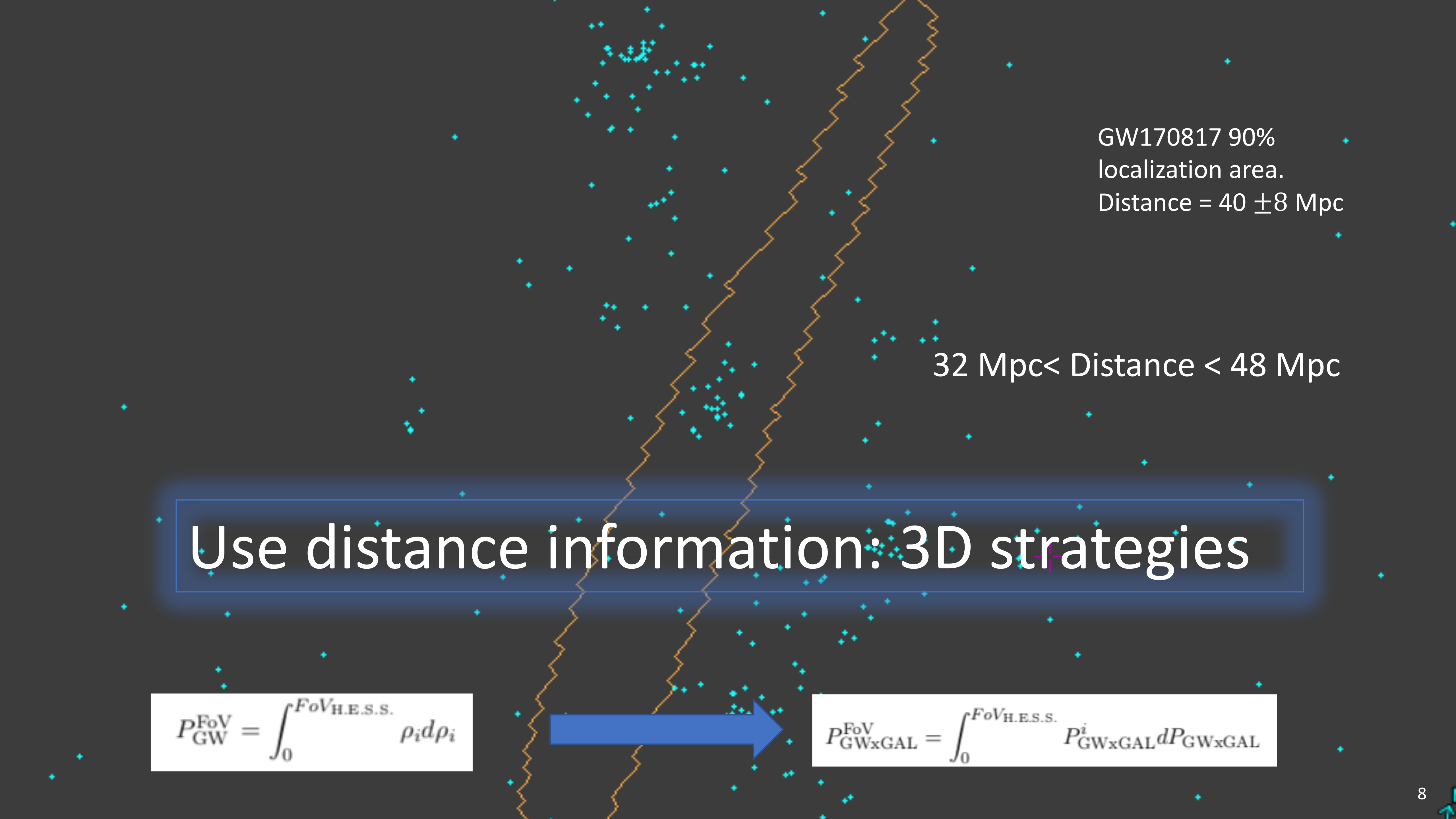



GW170817 90%
localization area.
Distance = 40 ±8 Mpc
0 Mpc < Distance < 100 Mpc


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



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

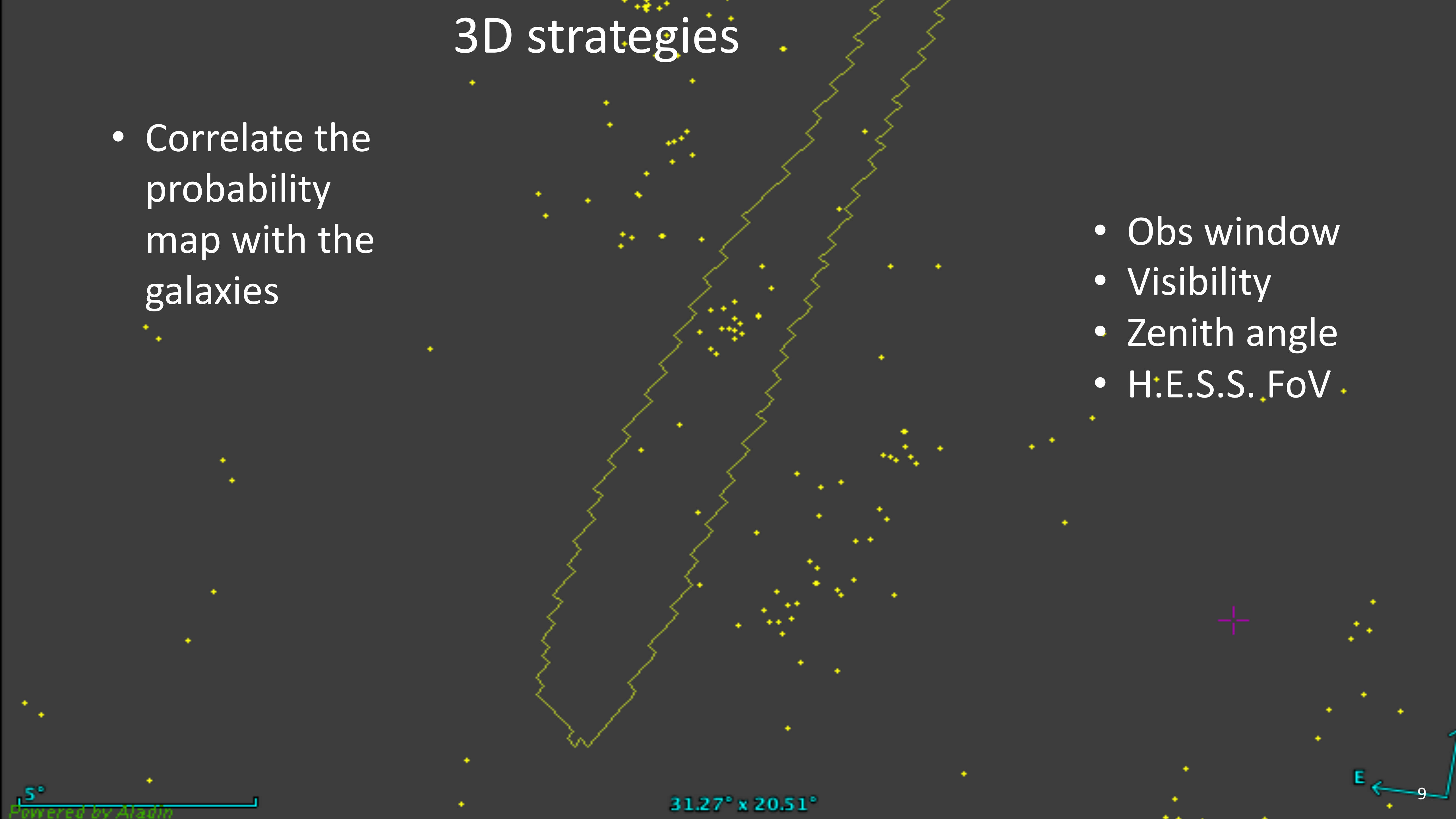
→

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

3D strategies

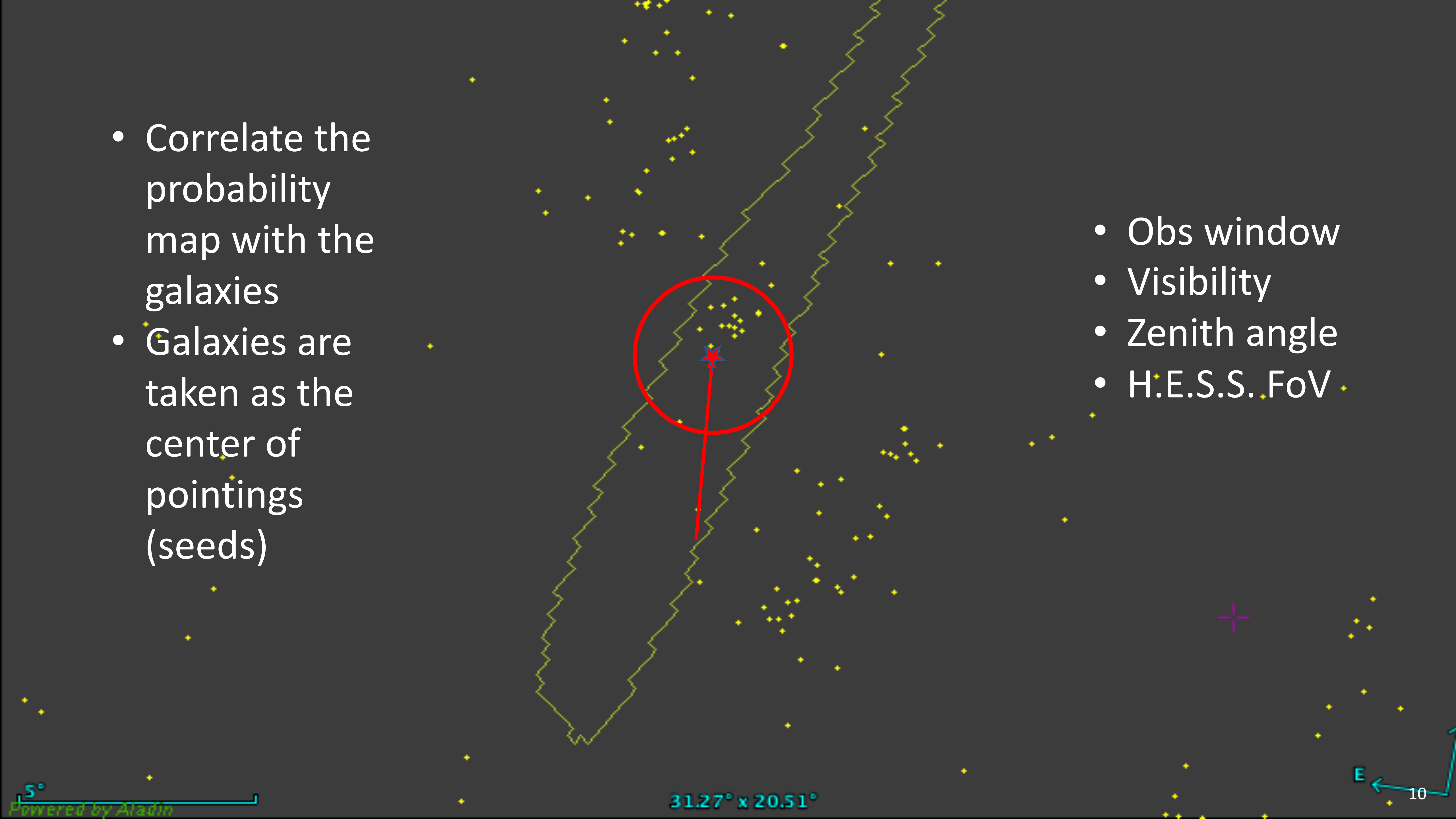
- Correlate the probability map with the galaxies

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

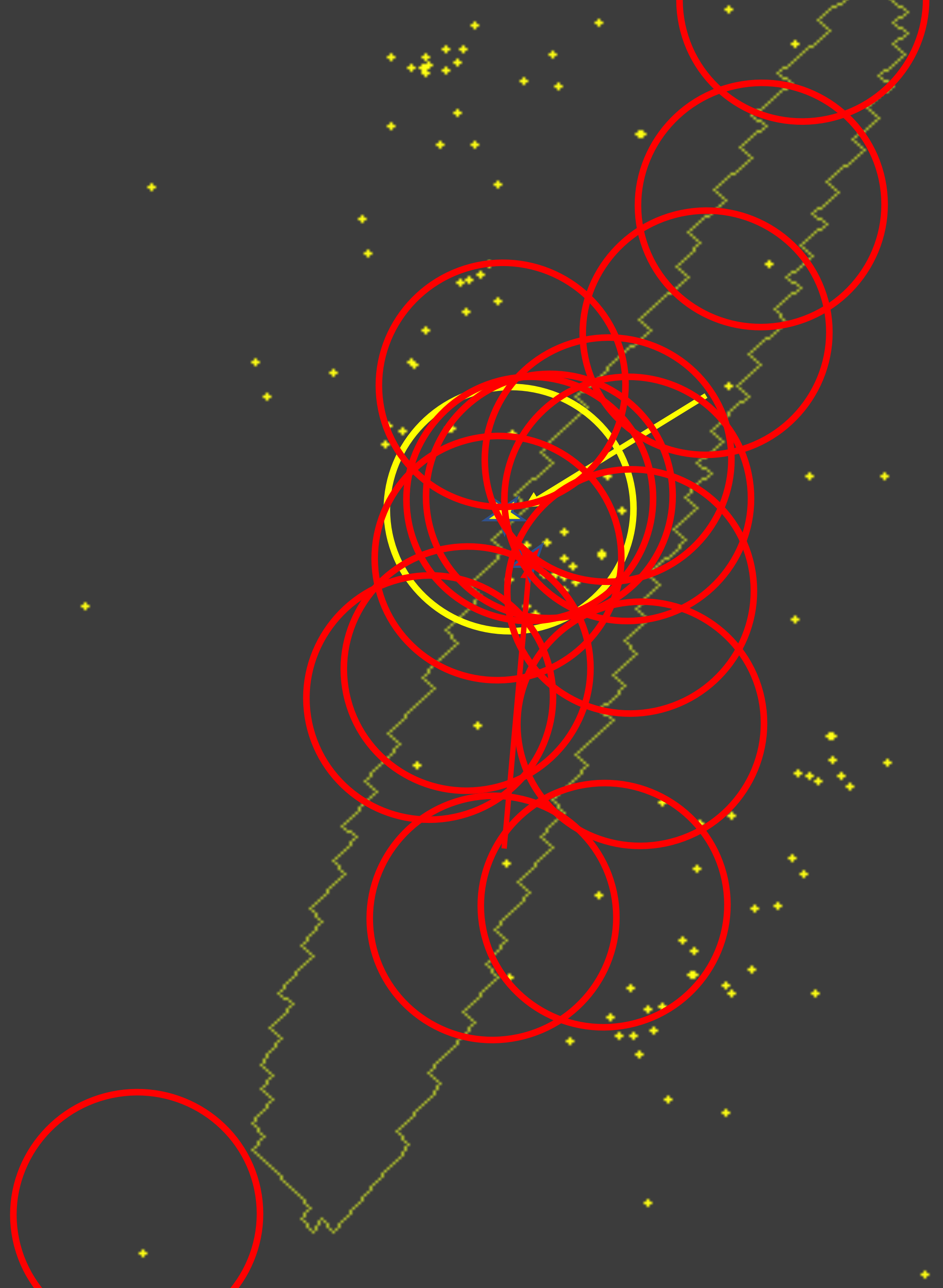


- Correlate the probability map with the galaxies
- Galaxies are taken as the center of pointings (seeds)

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

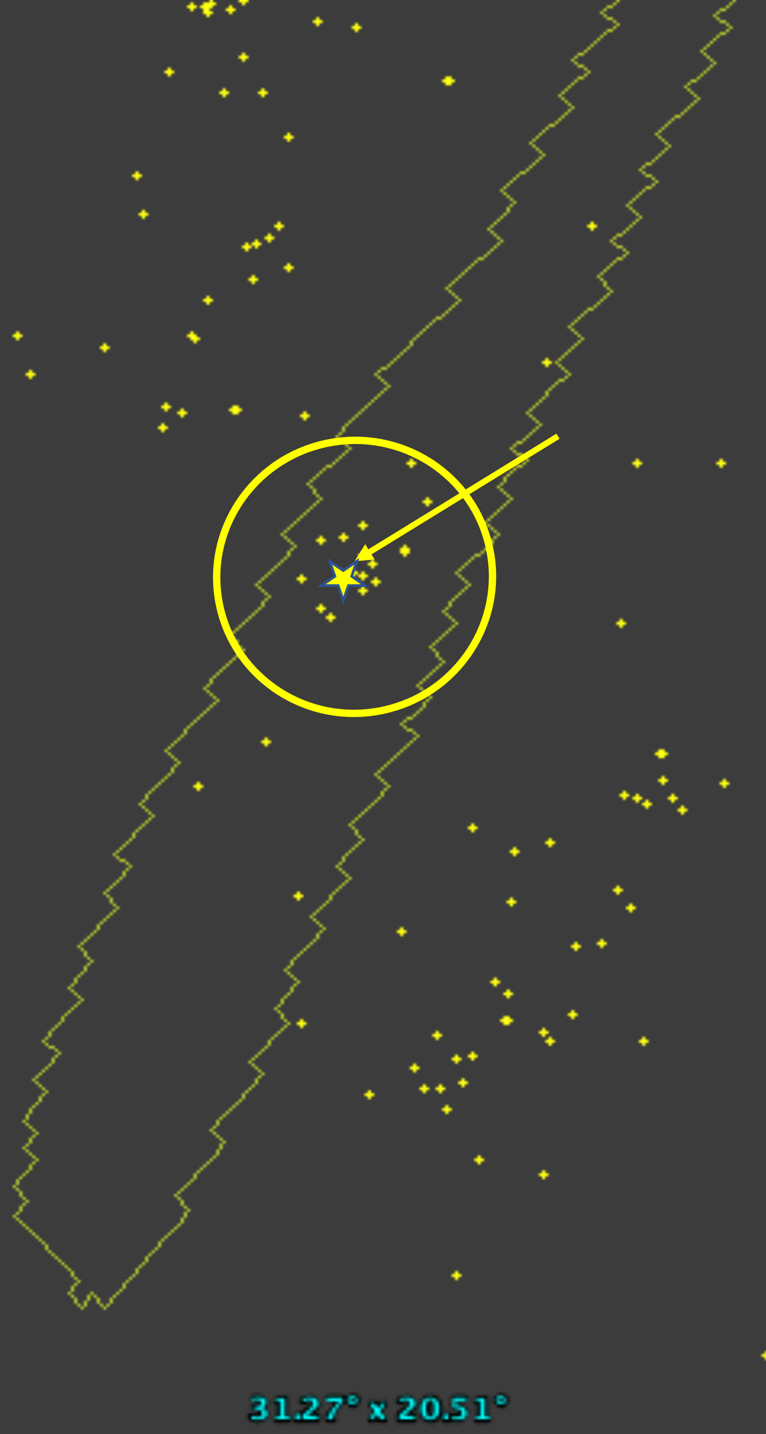


- Correlate the probability map with the galaxies
- Galaxies are taken as the center of pointings (seeds)



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

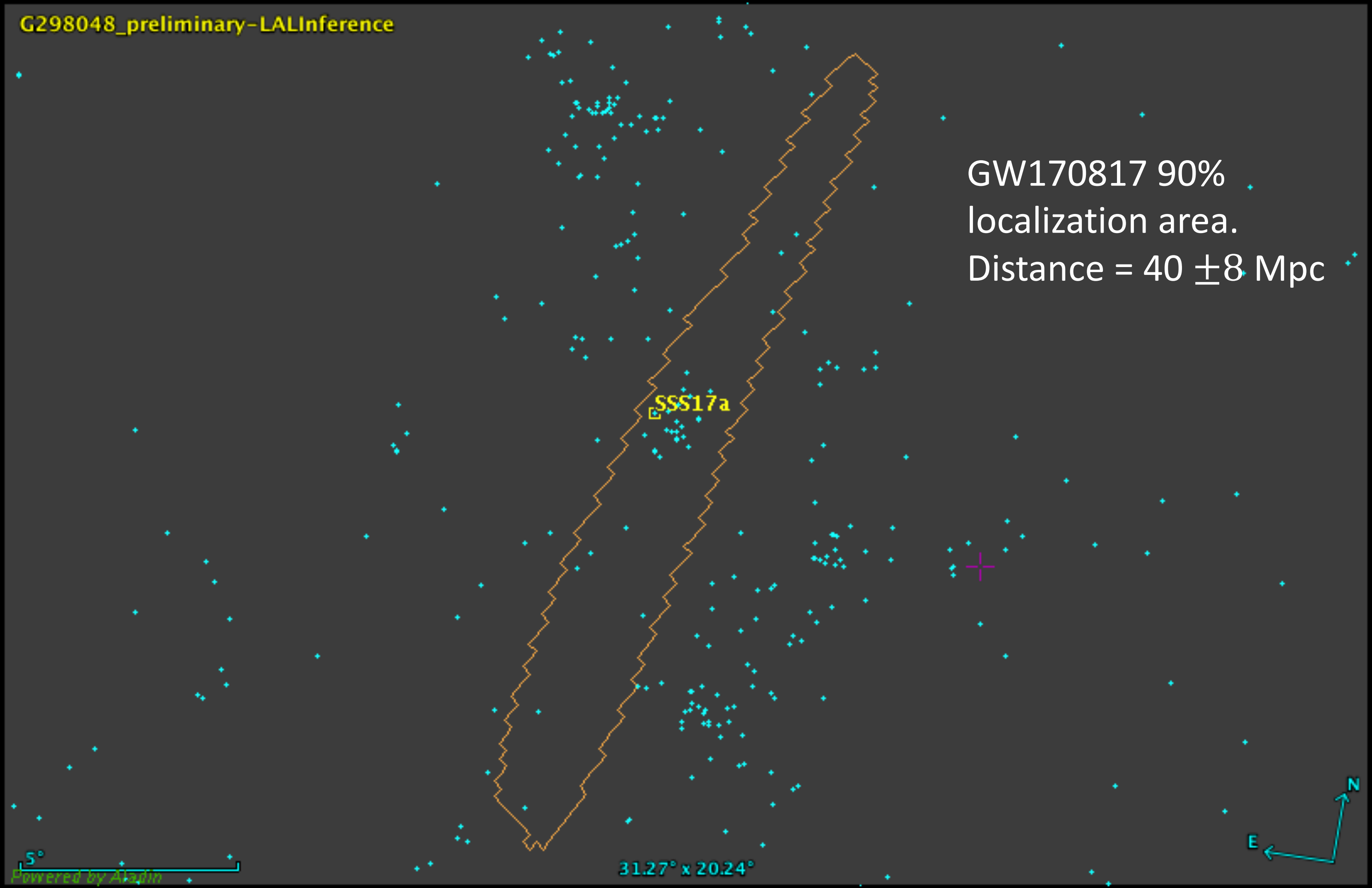
- Correlate the probability map with the galaxies
- The pointing with the highest integrated galaxy probability is chosen for the given window



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

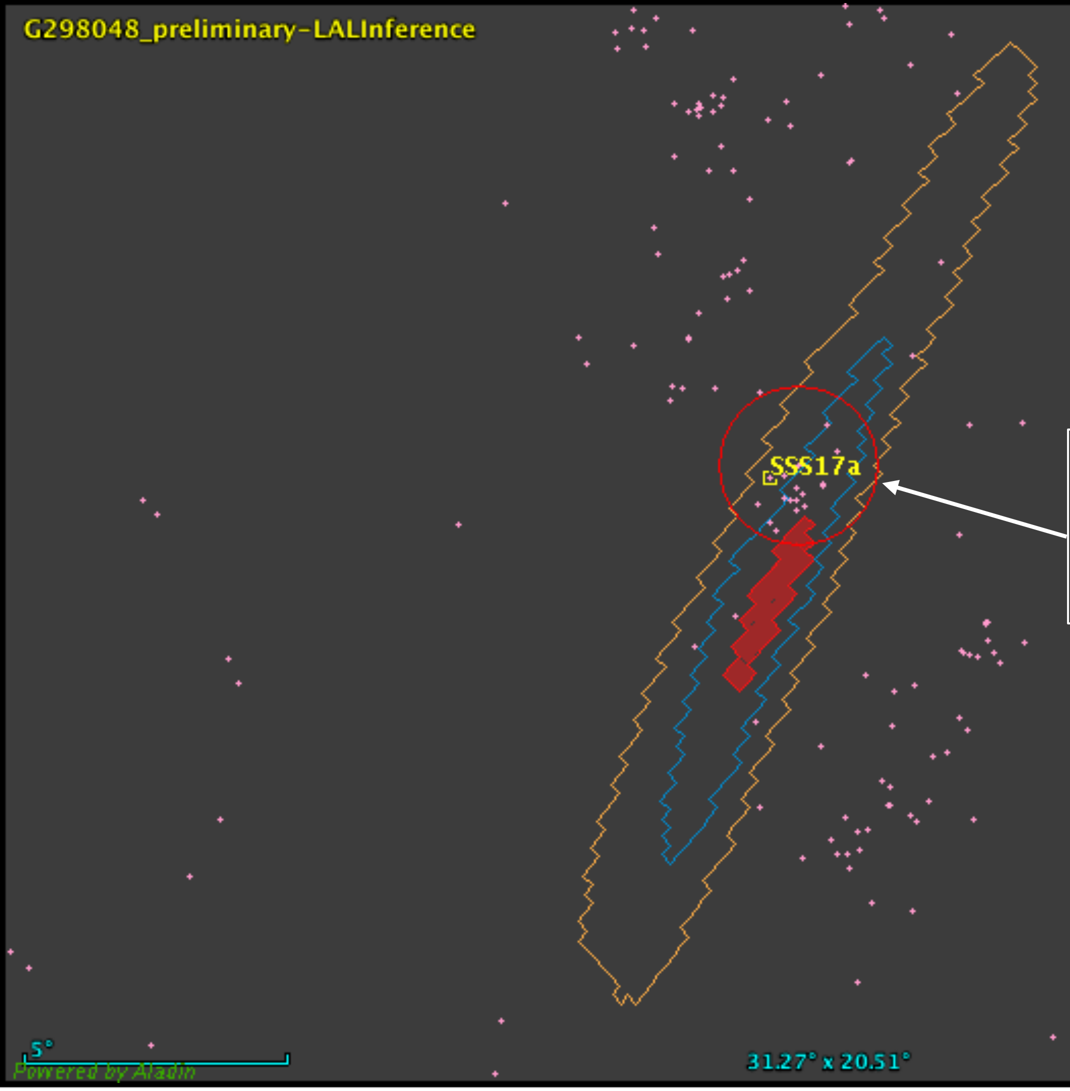
5°
Powered by Aladin
E

Example: GW170817



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

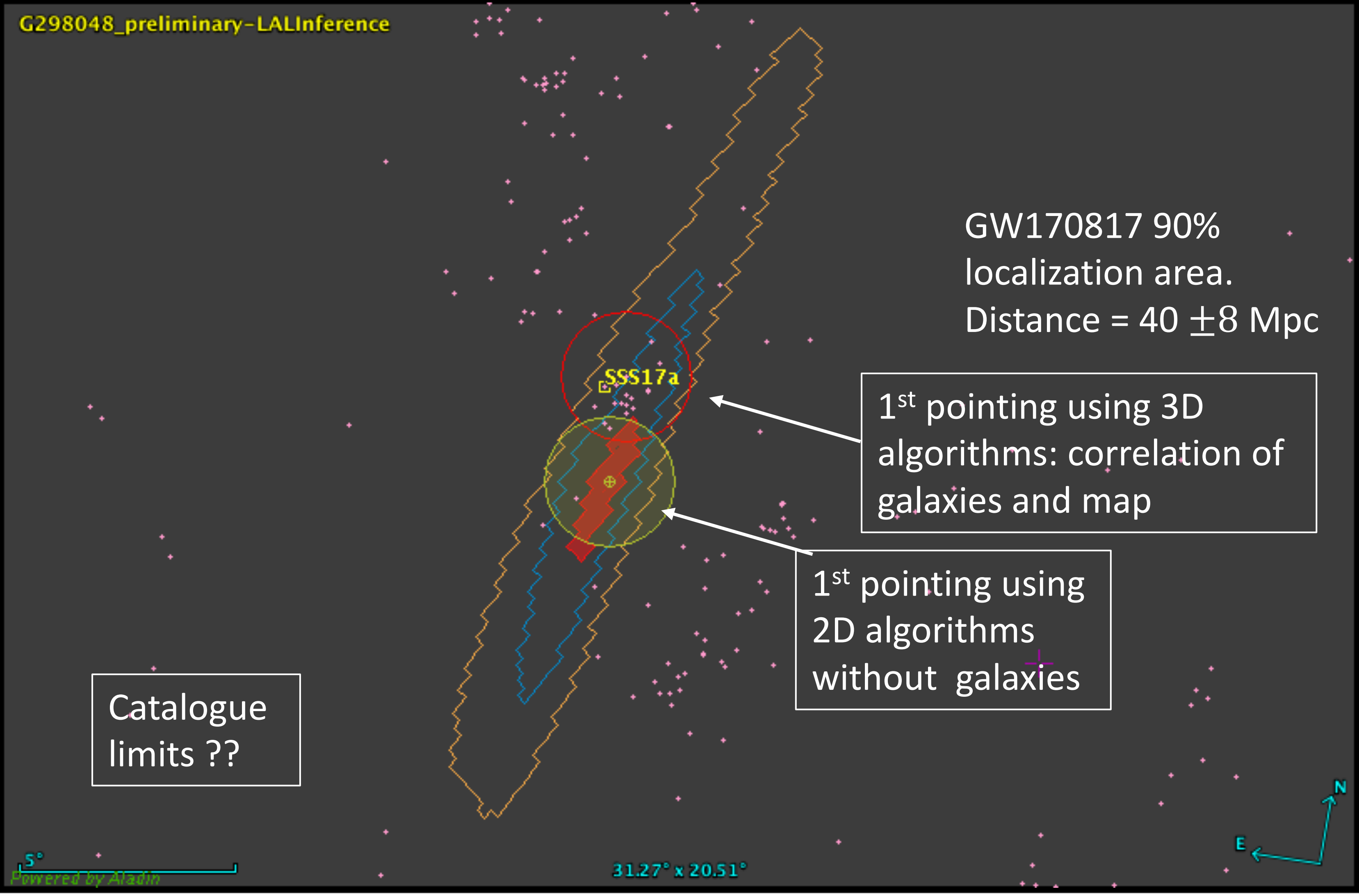
Example: GW170817



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

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

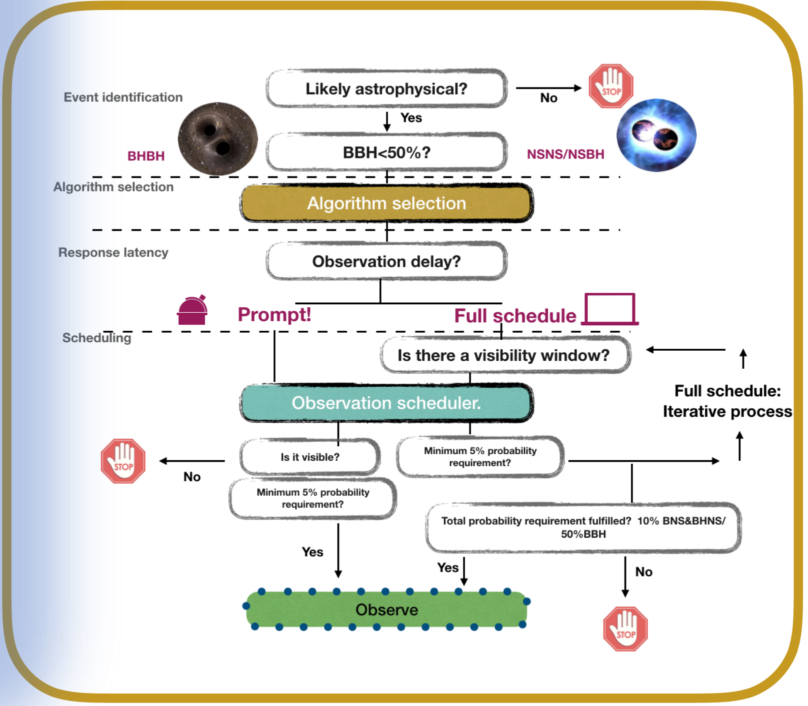
Example: GW170817

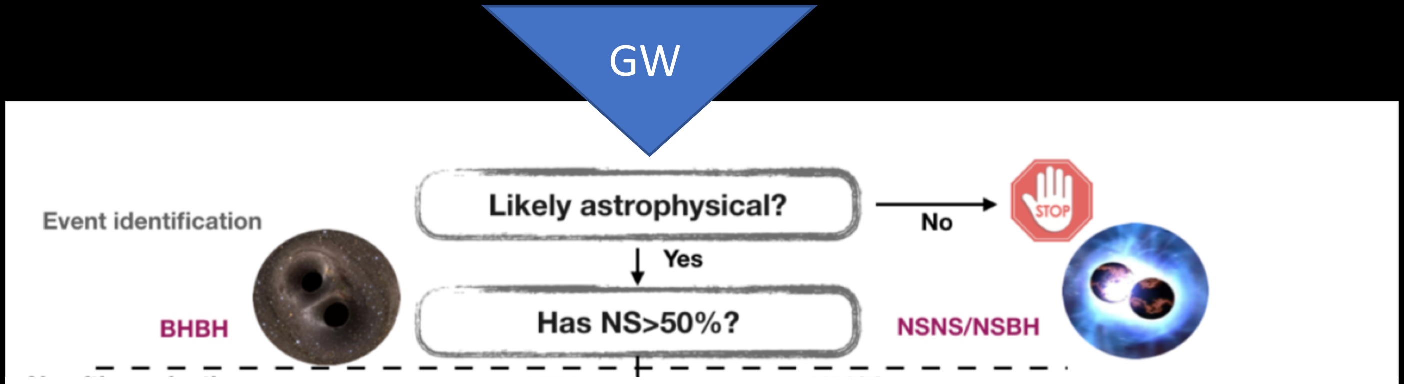


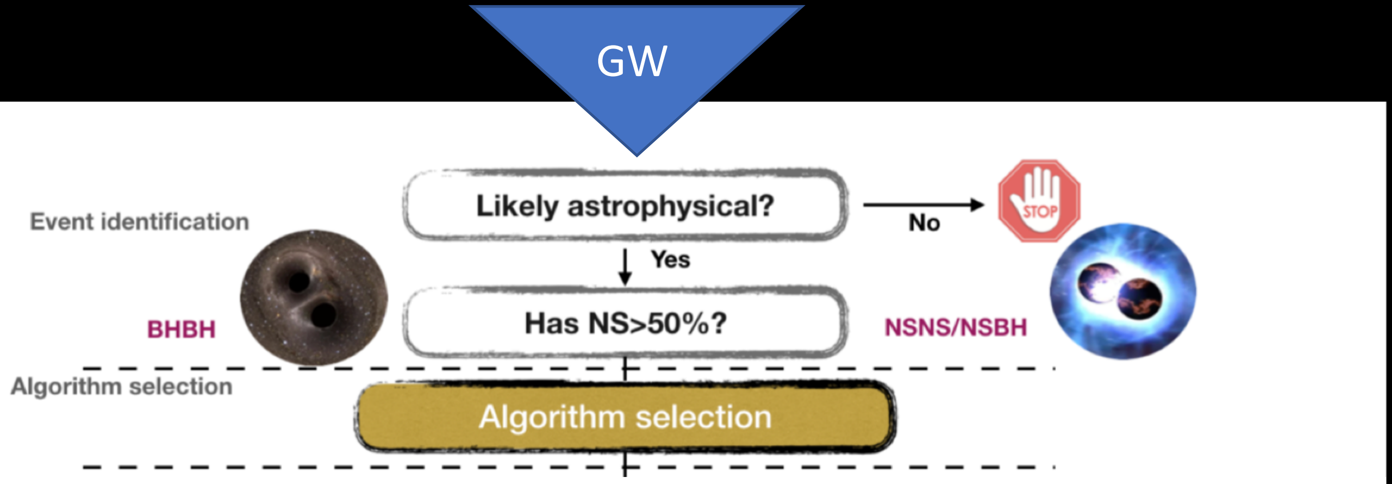
rt system

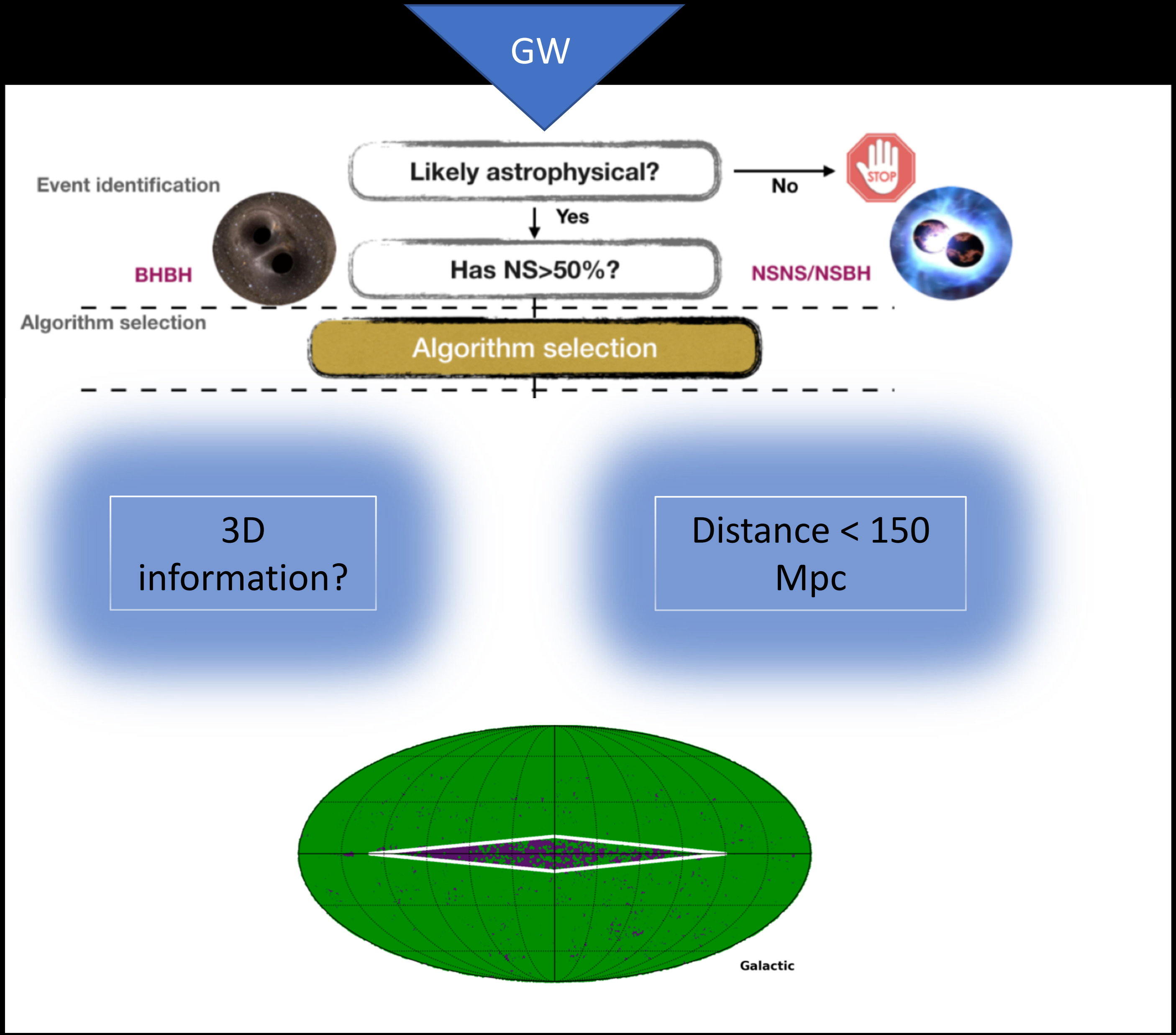

```xml
</Param>
<Group type="GW_SKYMAP" name="bayestar">
    <Param name="skymap_fits" dataType="string" value="https://gracedb.ligo.org/api/superevents/
        S190701ah/files/bayestar.fits.gz" ucd="meta.ref.url">
        <Description>Sky Map FITS</Description>
    </Param>
</Group>
<Group type="Classification">
    <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>
```

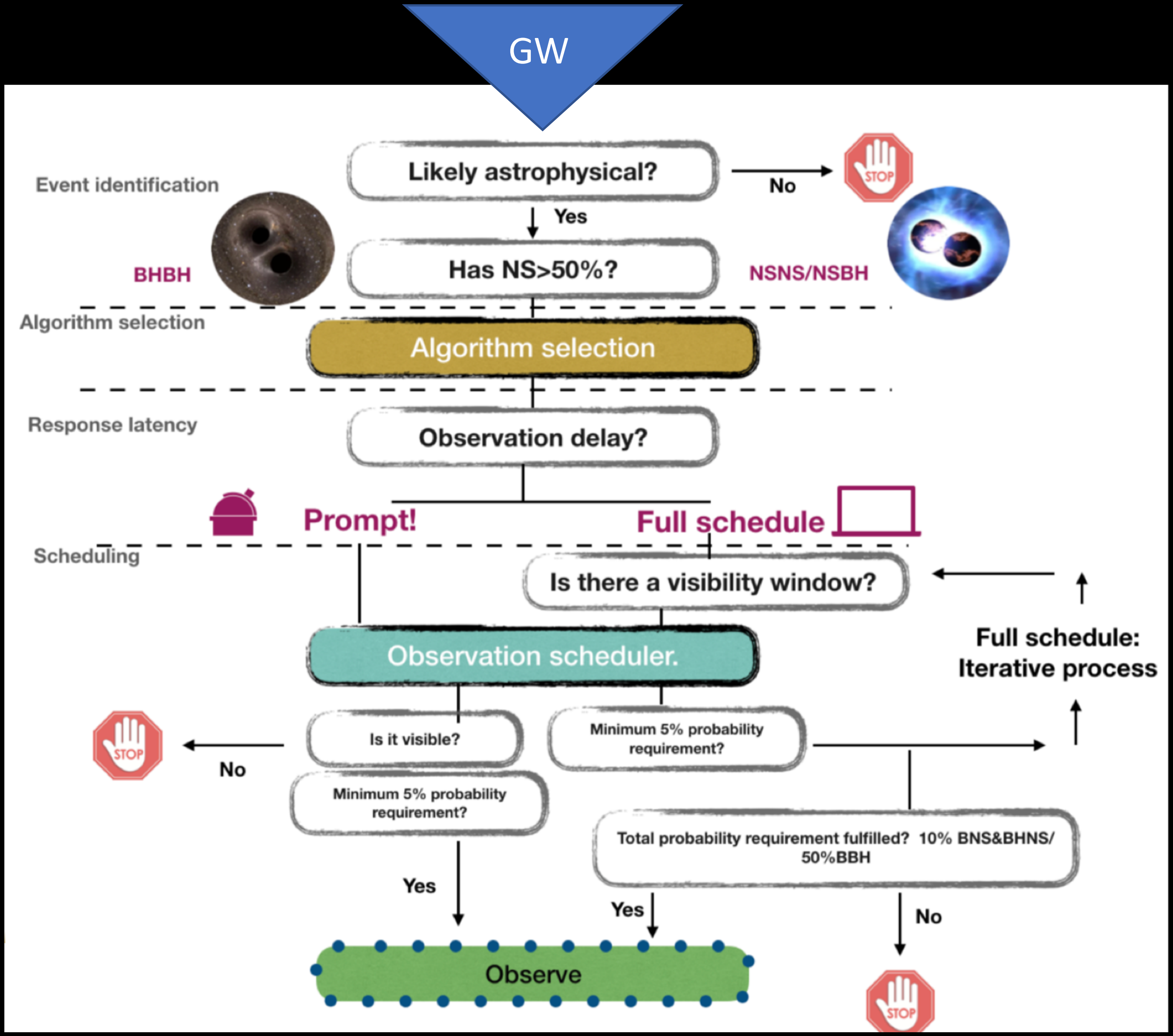

Fully automatic handling of alerts and data acquisition by the VoAlerter




GW
Event identification
Likely astrophysical?
No
STOP
Yes
Has NS>50%?
BHBH
NSNS/NSBH


GW
Event identification
Likely astrophysical?
No
STOP
Yes
BHBH
Has NS>50%?
NSNS/NSBH
Algorithm selection
Algorithm selection


GW
Event identification
Likely astrophysical?
No
Yes
BHBH
Has NS>50%?
NSNS/NSBH
Algorithm selection
Algorithm selection
3D information?
Distance < 150 Mpc
Galactic

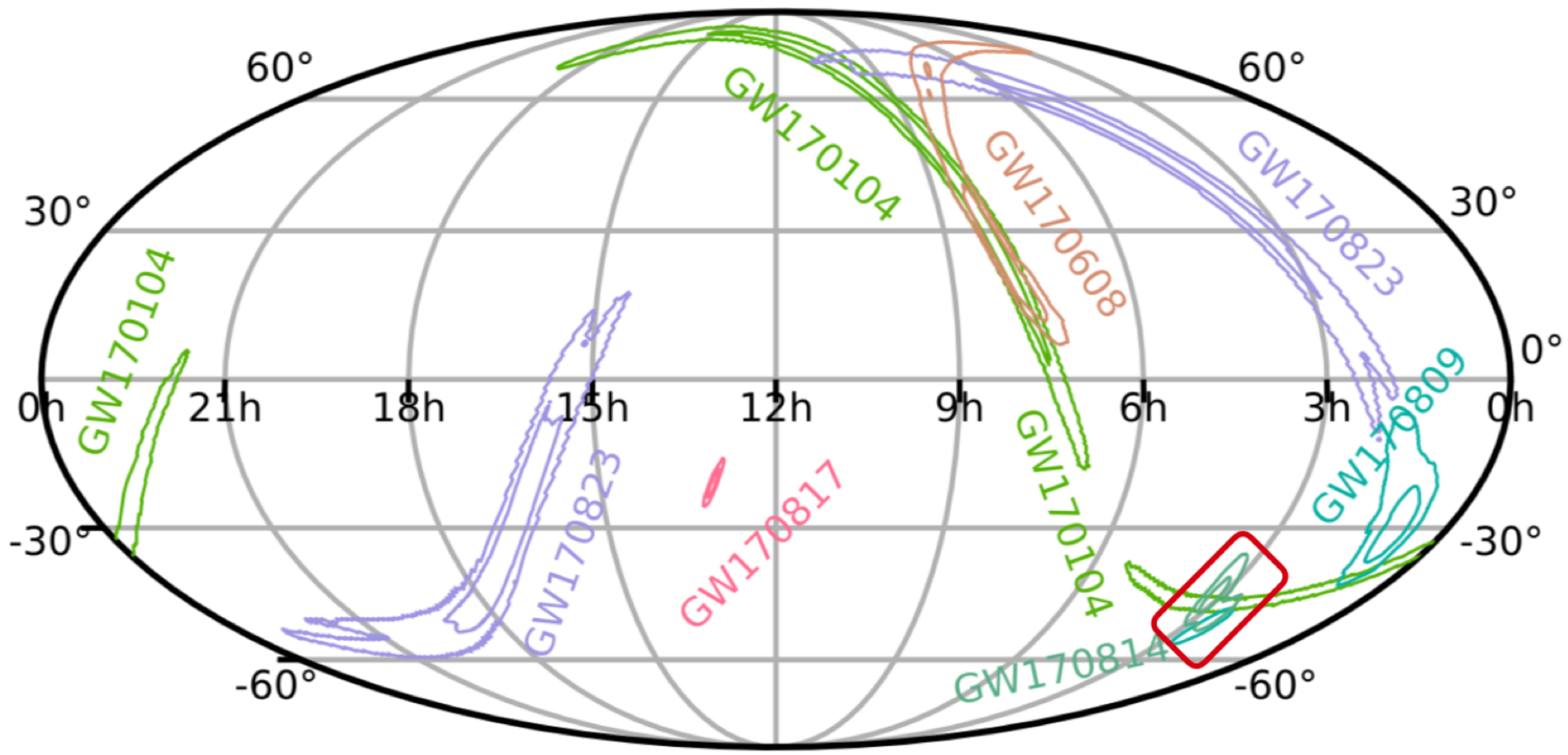


GW
Event identification
Likely astrophysical?
No
Yes
BHBH
Has NS>50%?
NSNS/NSBH
Algorithm selection
Algorithm selection
Response latency
Observation delay?
Prompt!
Full schedule
Scheduling
Is there a visibility window?
Observation scheduler.
Full schedule:
Iterative process
Is it visible?
No
Minimum 5% probability requirement?
Minimum 5% probability requirement?
Total probability requirement fulfilled? 10% BNS&BHNS/ 50%BBH
Yes
Yes
No
Observe
STOP

GW follow-up observations and analysis

Observation Run O2

GWTC-1: O2 catalog



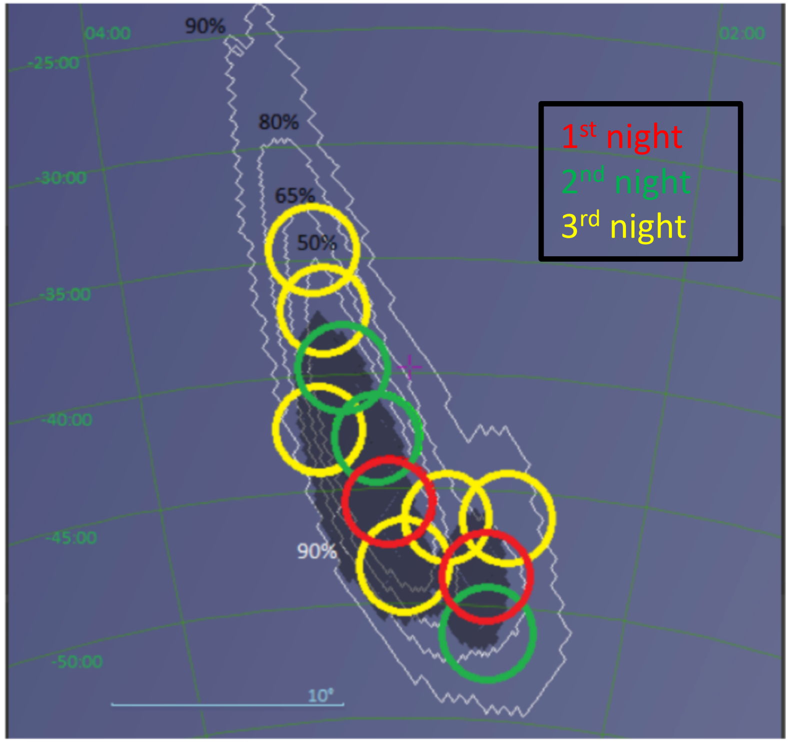
GWTC-1: arXiv:1811.12907

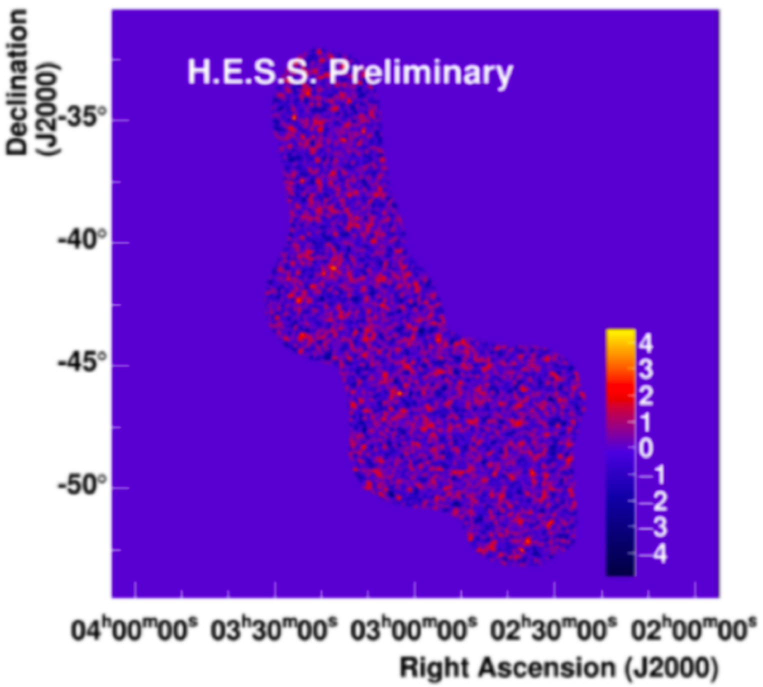
H.E.S.S.

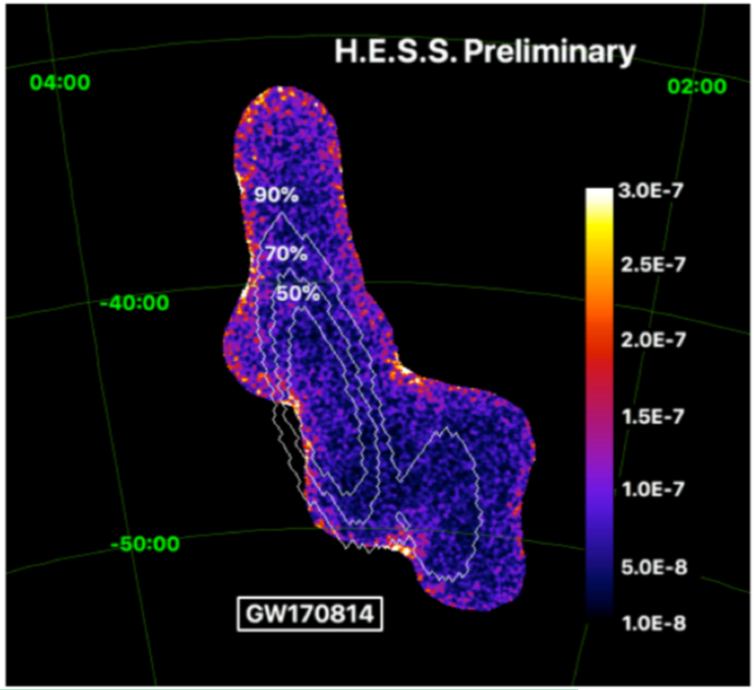
GW170814: BBH

- 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

M1: 28-36 M☉
M2 :21-28 M☉

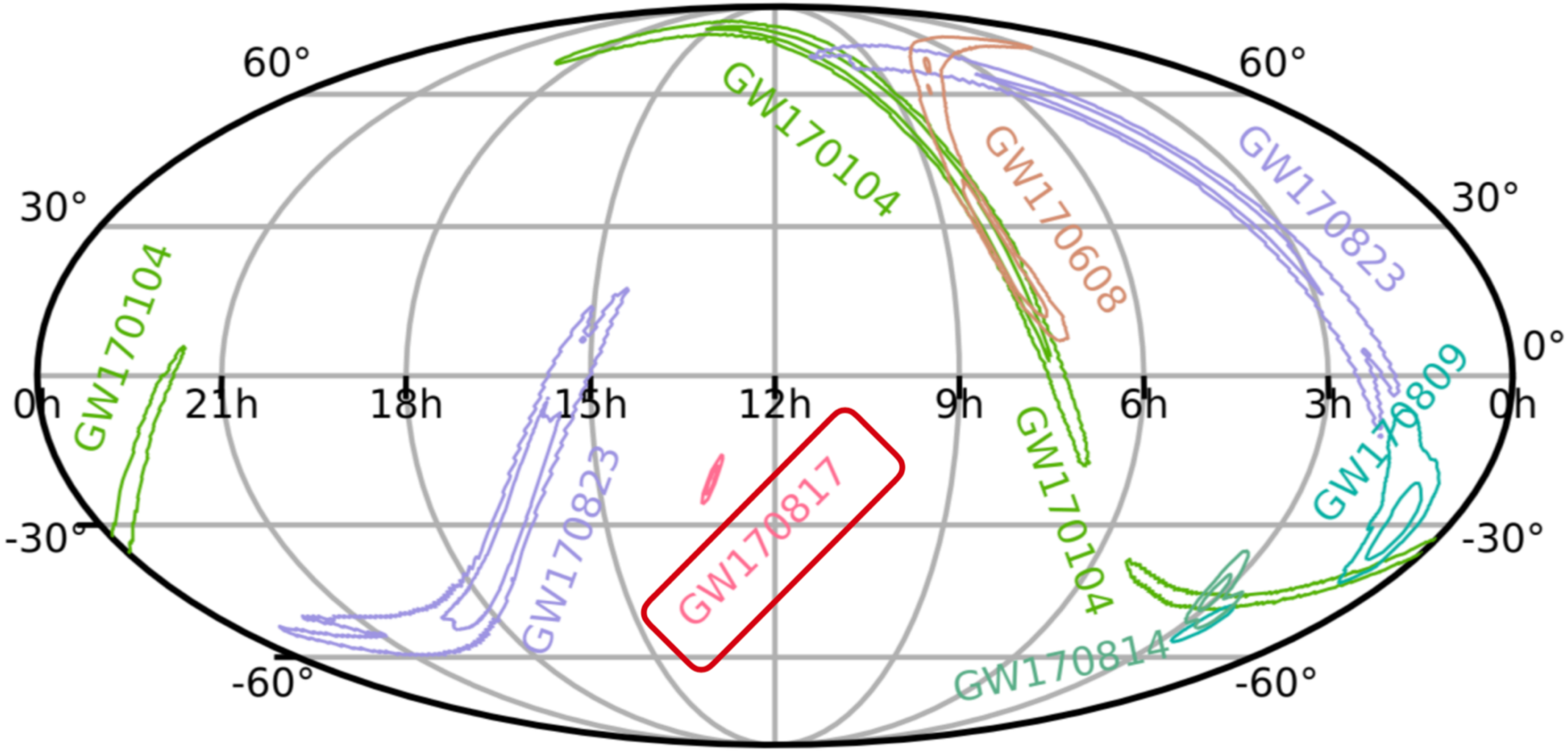






H. Ashkar, F. Schüssler, M. Seglar-Arroy (2019). 12th NTEGRAL conference / 1st AHEAD workshop, *MmSAI*, Arxive 1906.10426, https://arxiv.org/abs/1906.10426

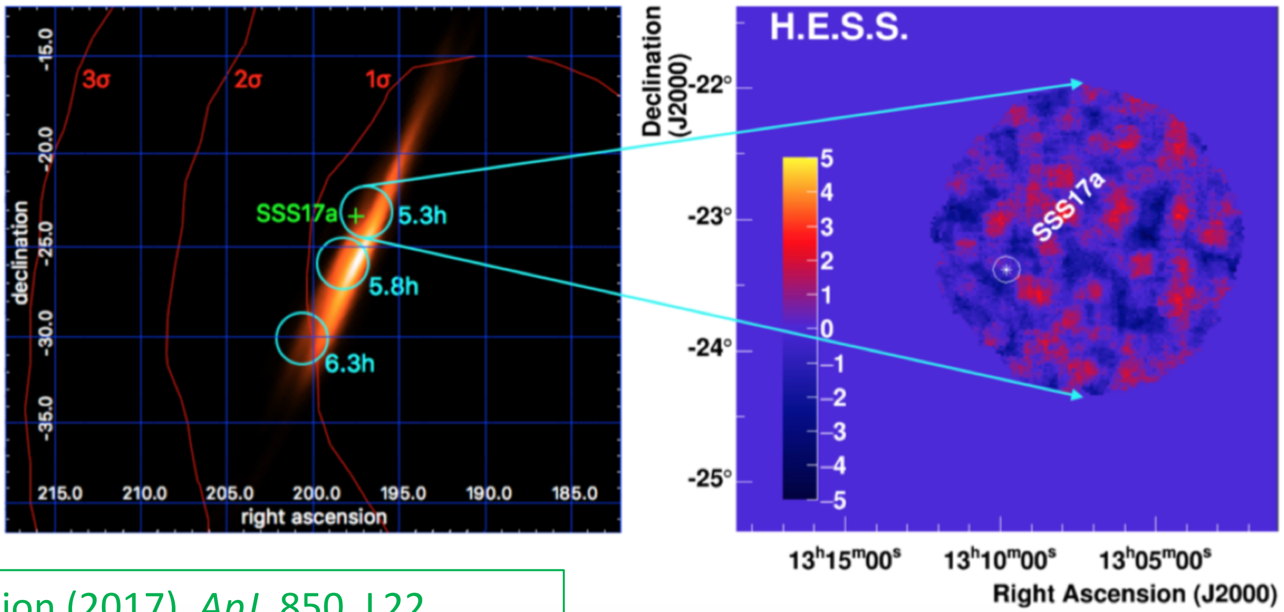
GWTC-1: O2 catalog



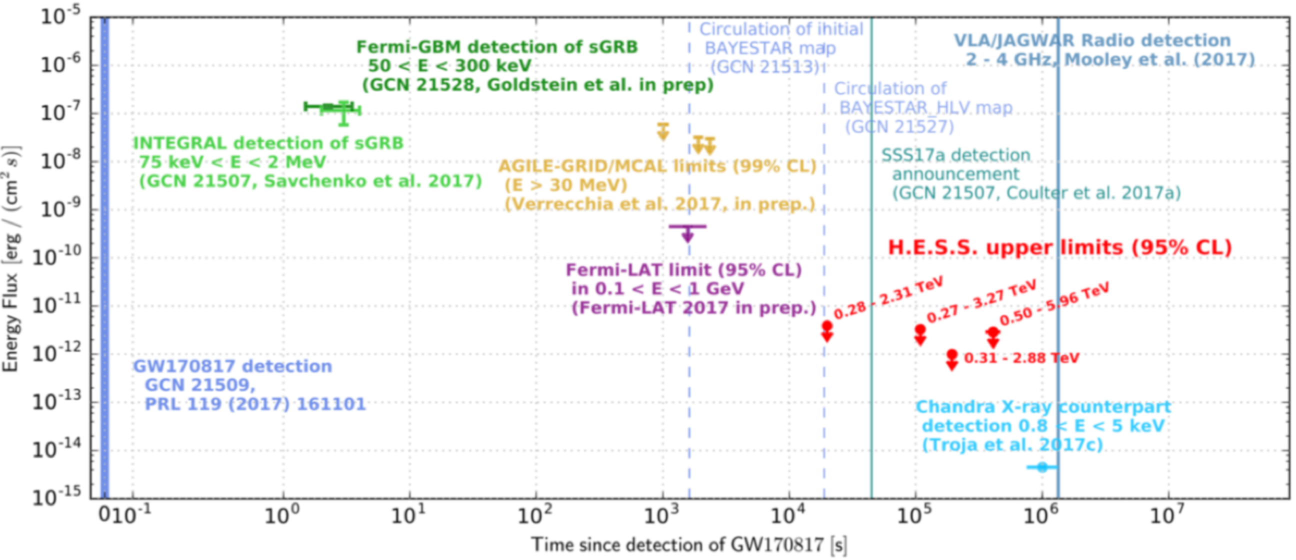
GW170817: BNS

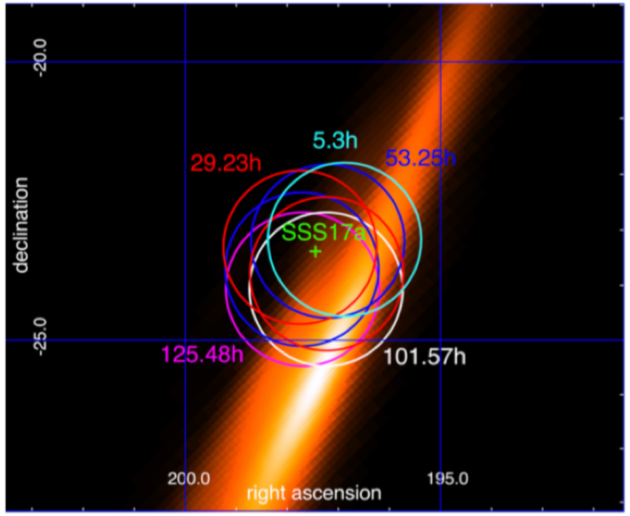
H.E.S.S. was the first ground based instrument on target!

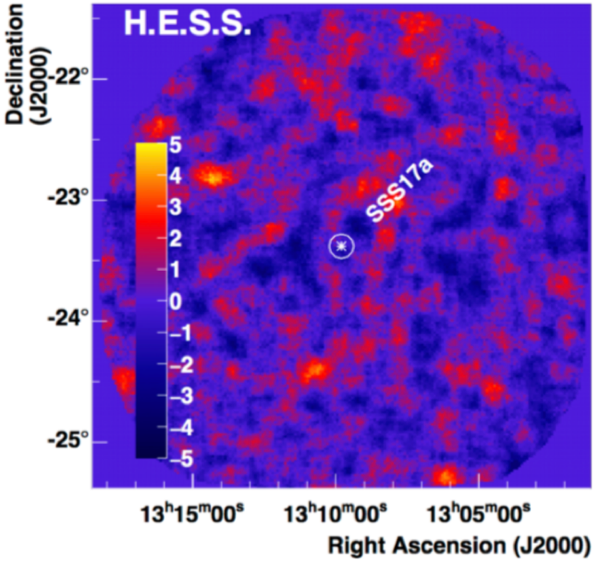
- 5.3 hours after merger
- 5 minutes after the update of the GW skymap (LIGO+Virgo reconstruction)
- The first observation covered the afterwards identified position of the NS-NS
- In subsequent nights: monitoring of the EM counterpart



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

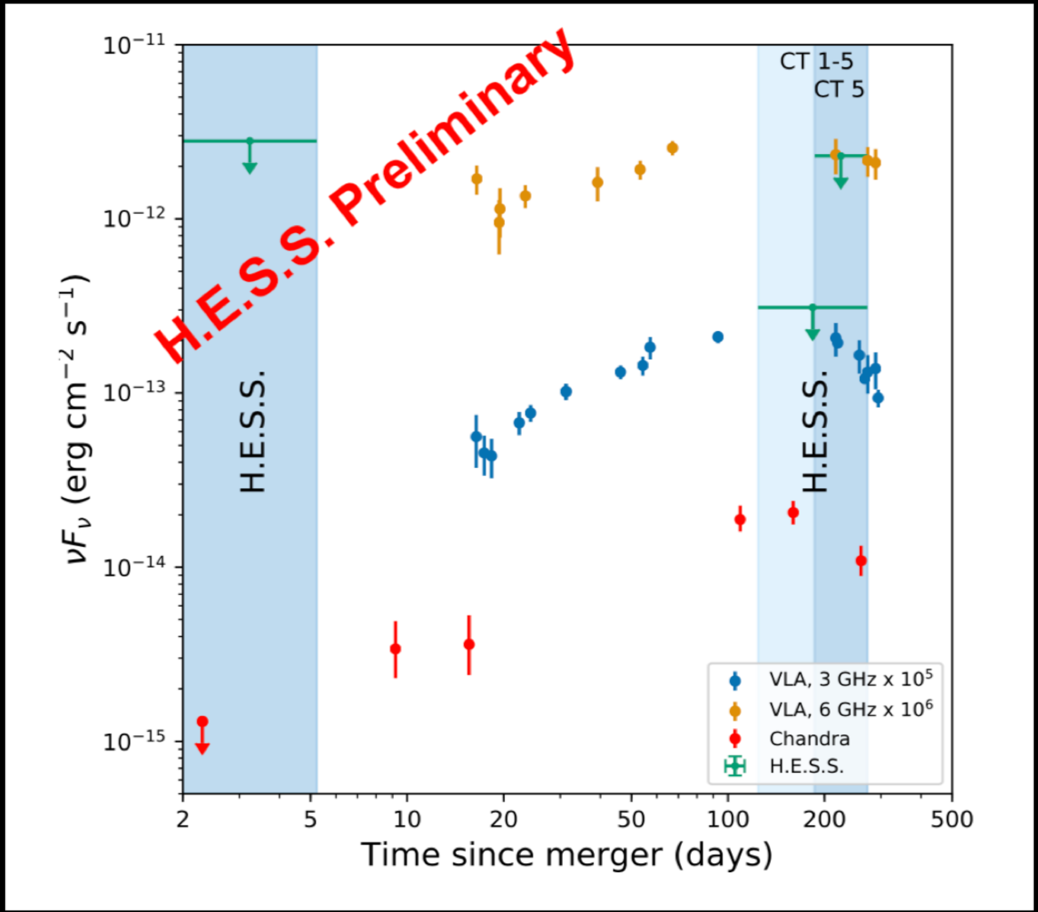






EM170817 long-term follow-up →implications on time dependent magnetic field

- The "late-time" follow-up of GW/GRB170817:
  - Radio and x-ray:
    - 10x flux increase in 150 days
    - Efficient electron acceleration synchrotron emission in merger remnants magnetic field
    - Plateau and turnover after 160 days
  - TeV γ rays ??
    - Good condition for γ-ray production via ssc



- Pointed observation covering plateau and fading of non-thermal emission (125 to 270 days)

- 32 hours exposure with CT5

- 54 hours exposure with CT1-5

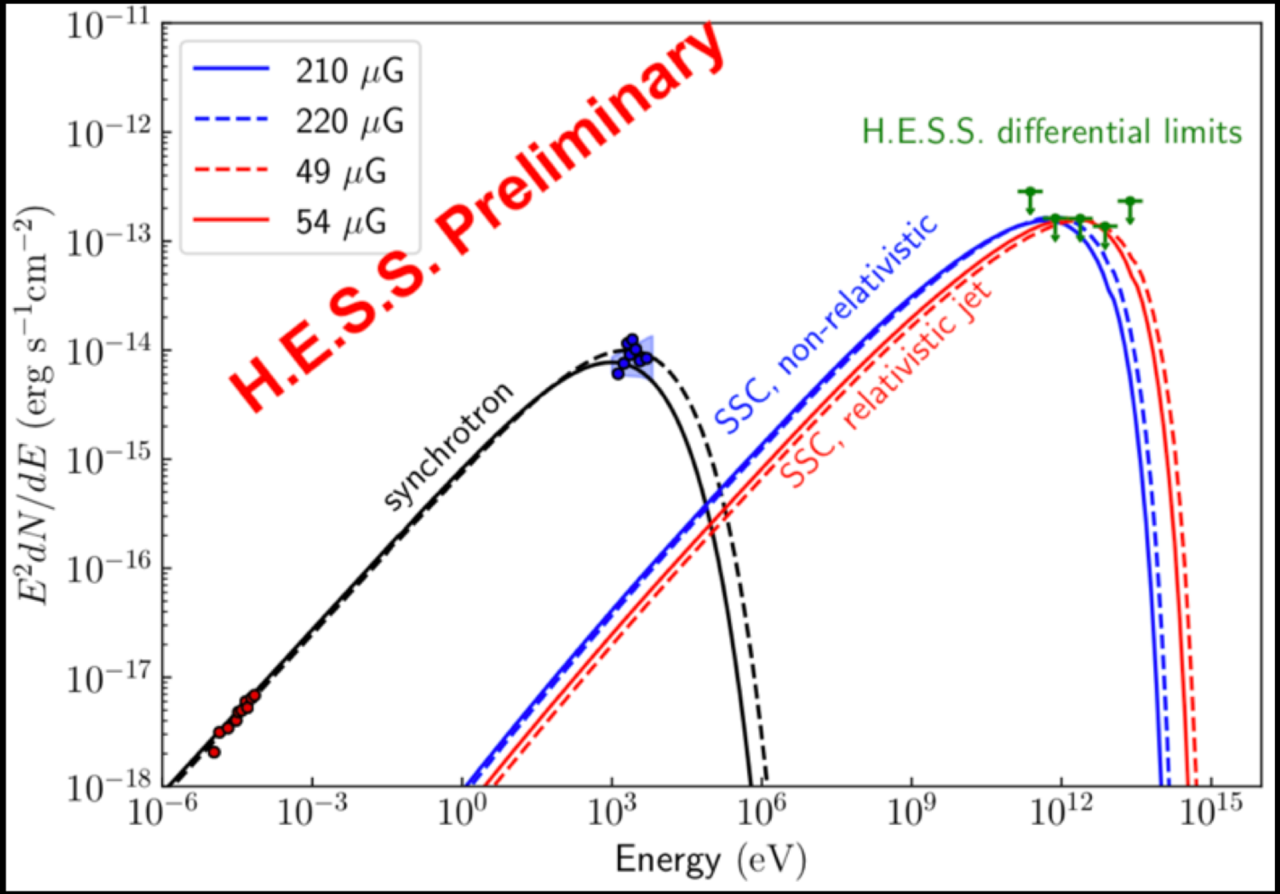
- Radio & X-rays probe synchrotron emission
  - Provides $N_e * U_B$
  - Provides lower limit on $E_{max,e}$
  - Alone cannot disentangle the two components
- γ-rays probe inverse Compton emission
  - Provides $N_e * N_e * U_B$ ($N_e * U_B$ ~ fixed via ssc)

➢Radio, X-ray, γ-ray can break ambiguity

2 scenarios:
Spherical outflow: ≳ 200 uG
Off-axis jet: ≳ 50 uG

Paper in preparation

- Model SSC emission in two scenarios at 110 days after the merger
- Peak of IC component expected in core H.E.S.S. energy range



GW follow-up observations and analysis

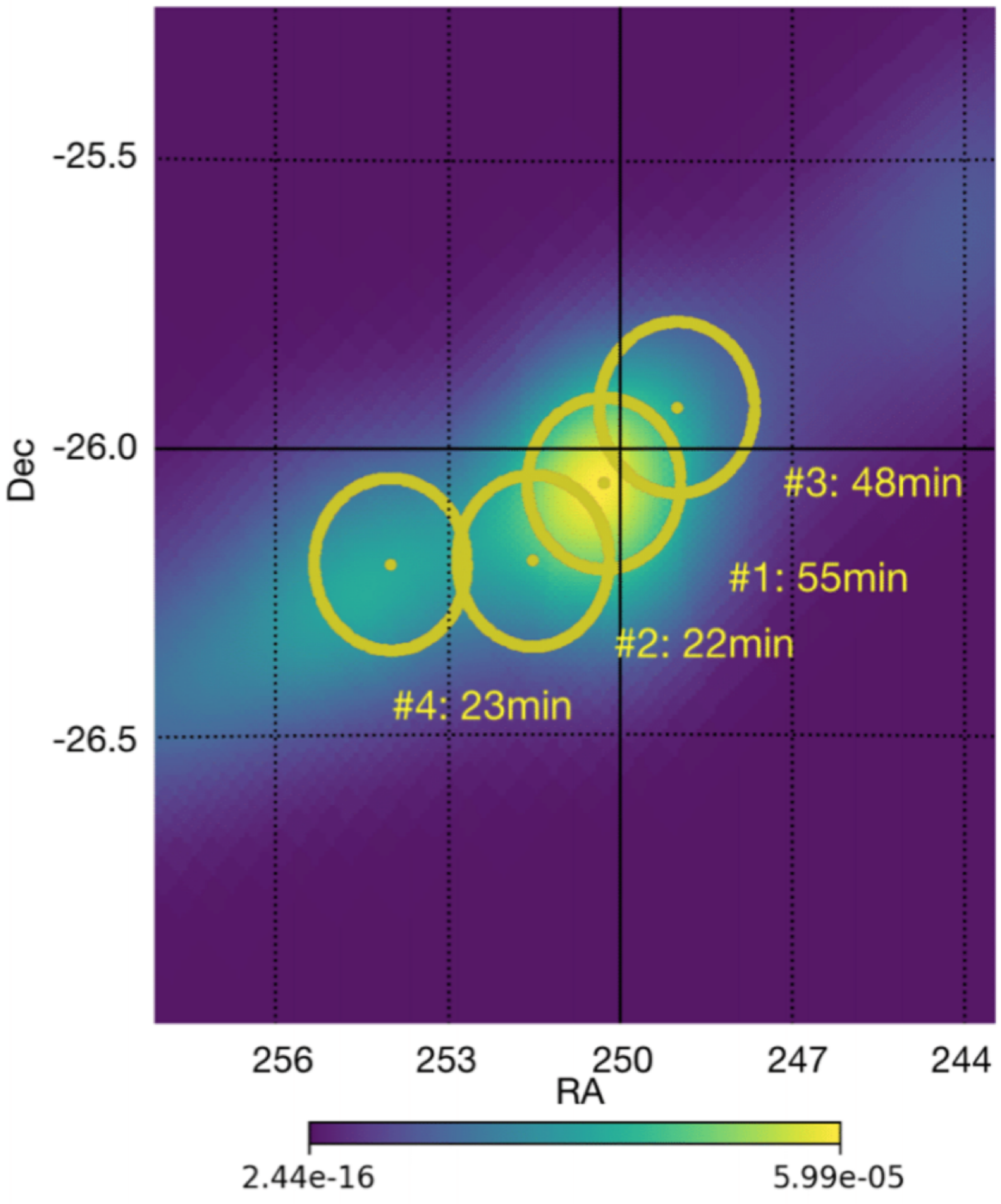
Observation Run O3

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

GCN 25237:
https://gcn.gsfc.nasa.gov/gcn3/25237.gcn3

S190512



Re-observation based on RTA

GW follow-up with CTA

Low-latency gravitational waves follow-up program of CTA

Simulations of VHE counterpart searches in GW follow ups with CTA

Simulation of BNS mergers and GW detection with GWCOSMoS:

Patricelli, B., et al. (2018)

- Merger rate of 830 Gpc-3 yr-1
- Max distance = 500 Mpc
- Localisation using BAYESTAR
- Distance and angle with respect to the line of sight are known from mock catalog of BNS merger

↔

Simulation of VHE emission from sGRBs:

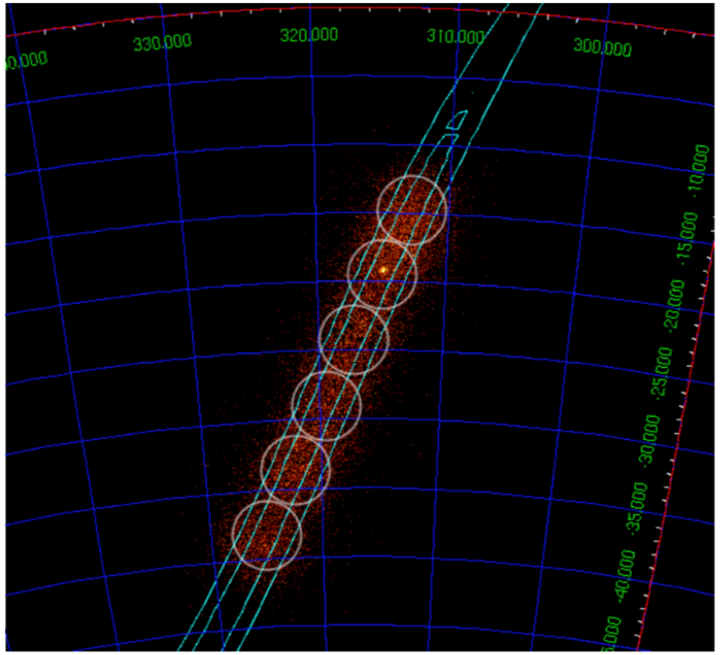
- 0.1-10 GeV luminosity as a function of time derived from typical properties of LAT GRBs (in particular GRB090510)
- Light curve normalized from the correlation found in Nava L., et al. (2014) between *Eiso and* $L_{LAT}^{t=60S}$. for a sample of 10 LAT GRBs
- During initial phase flux is proportional to t^2
- Deceleration phase luminosity decreases as $t^{-1.4}$
- The spectral shape is considered a simple power-law with photon index-2.1 ($NE \propto E^{-2.1}$) spectrum, extrapolated up to 10 TeV (normalization derived from the integrated luminosity 0.1-10 GeV)

H.E.S.S.

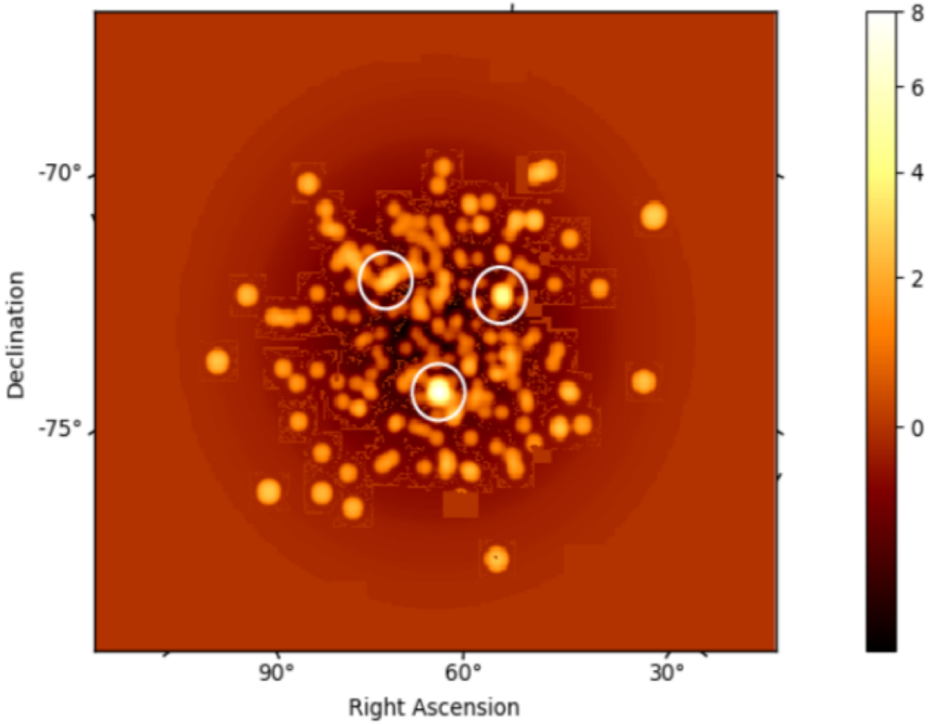
- Alert injection & GW follow-up observation
- Scheduling:
  - Low-energy coverage (zenith angle optimization)
  - Probability coverage maximization
  - $T_J = T_{alert} + T_{slew} + \sum_1^{J-1} T_J$

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

CTA observation searching for an EM counterpart

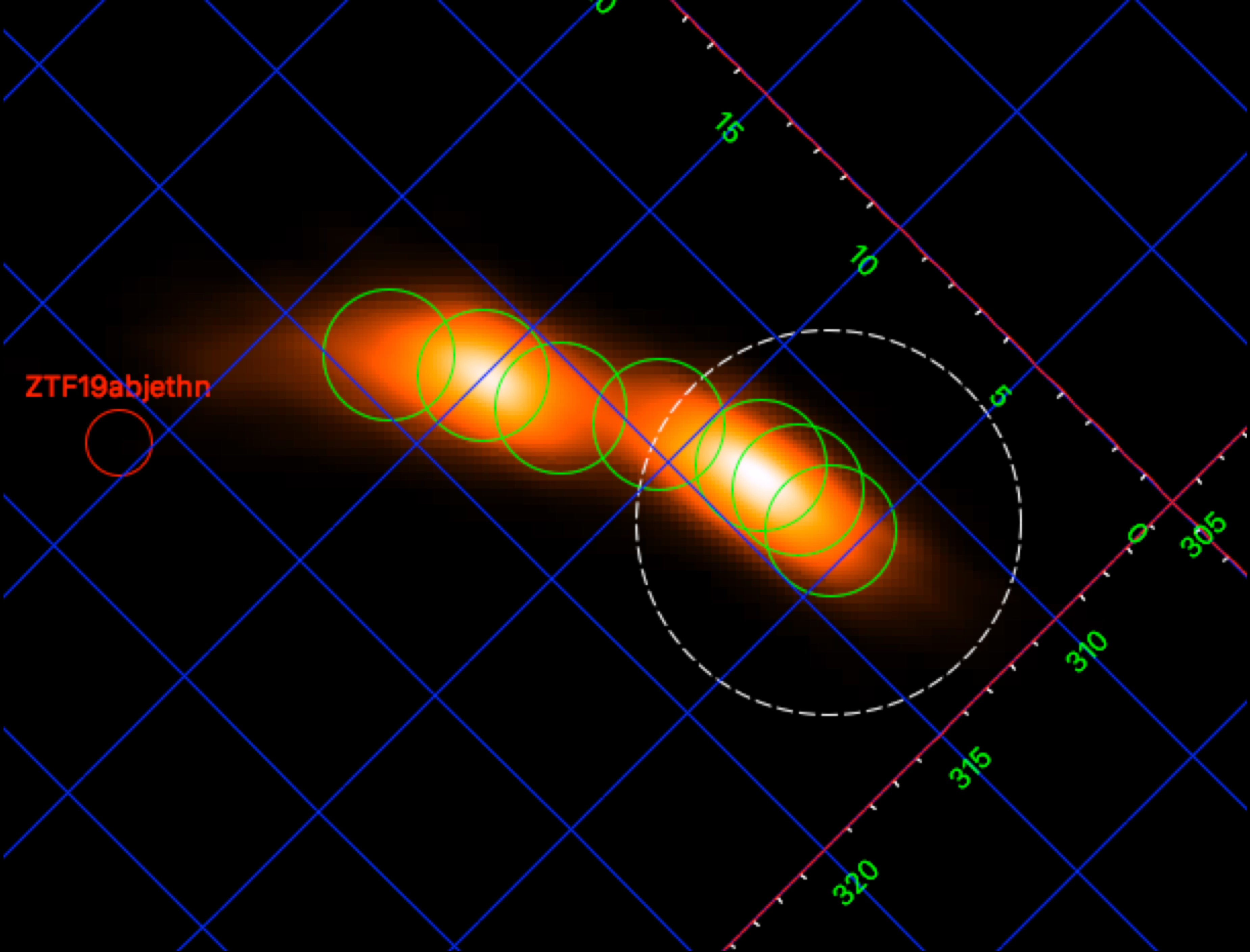


Analysis of the CTA scheduled observations (run-by-run)



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

Thank You



ZTF19abjethn
15
10
5
0
305
310
315
320

The search for Compact Binary Mergers in a nutshell

Burst searches

- Look for excess power time – frequency patterns consistent in multiple detectors
- Can search for un-modeled & un-expected sources (ex: SN)

Template searches

- Anticipates GR waveforms (from models) as a and finds the template that fits data best
- Confident detection & parameter estimation
- Probable 3D information

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