A Systematic Search for TeV Halos associated with known pulsars

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University of Maryland, College Park
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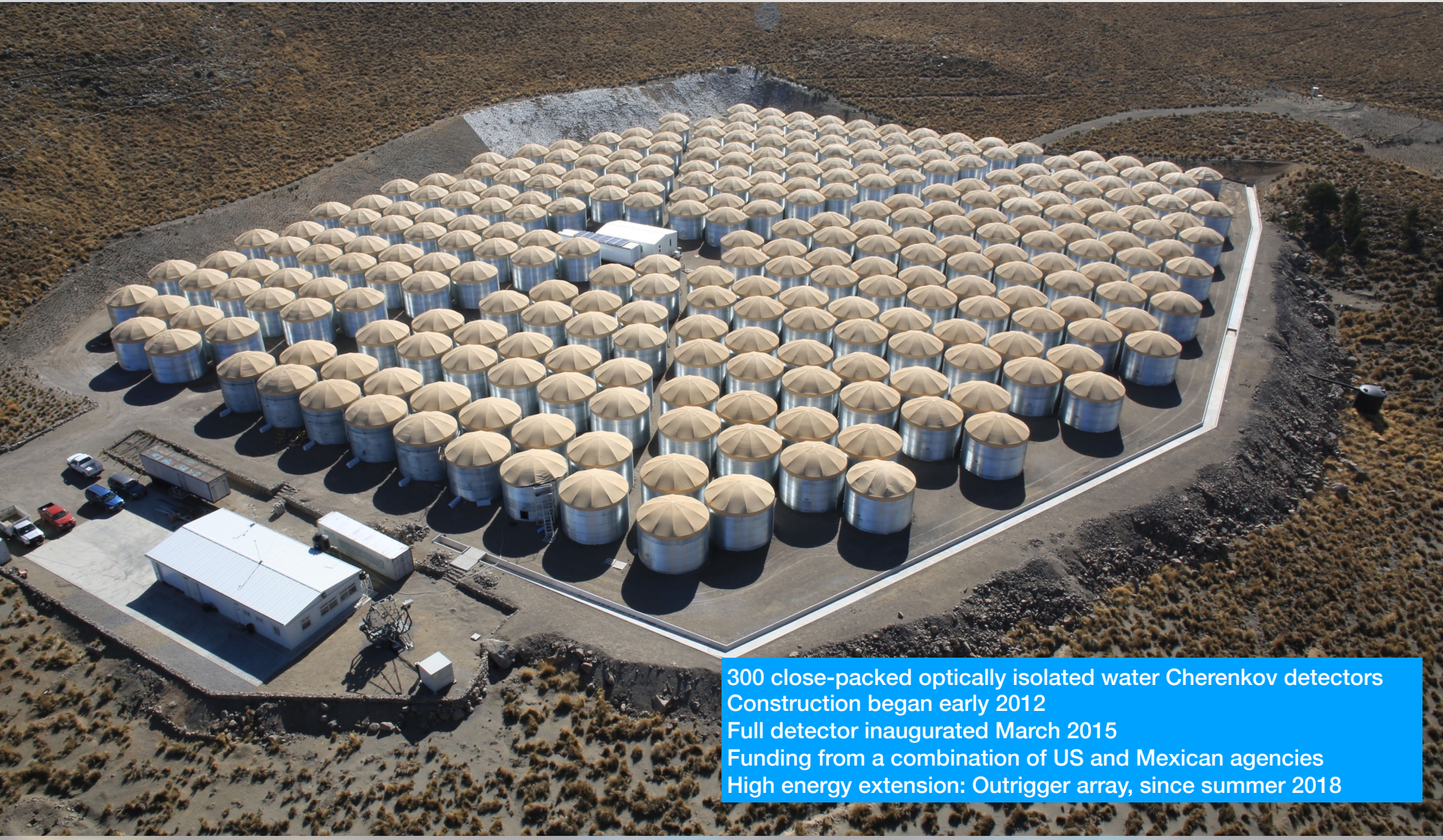
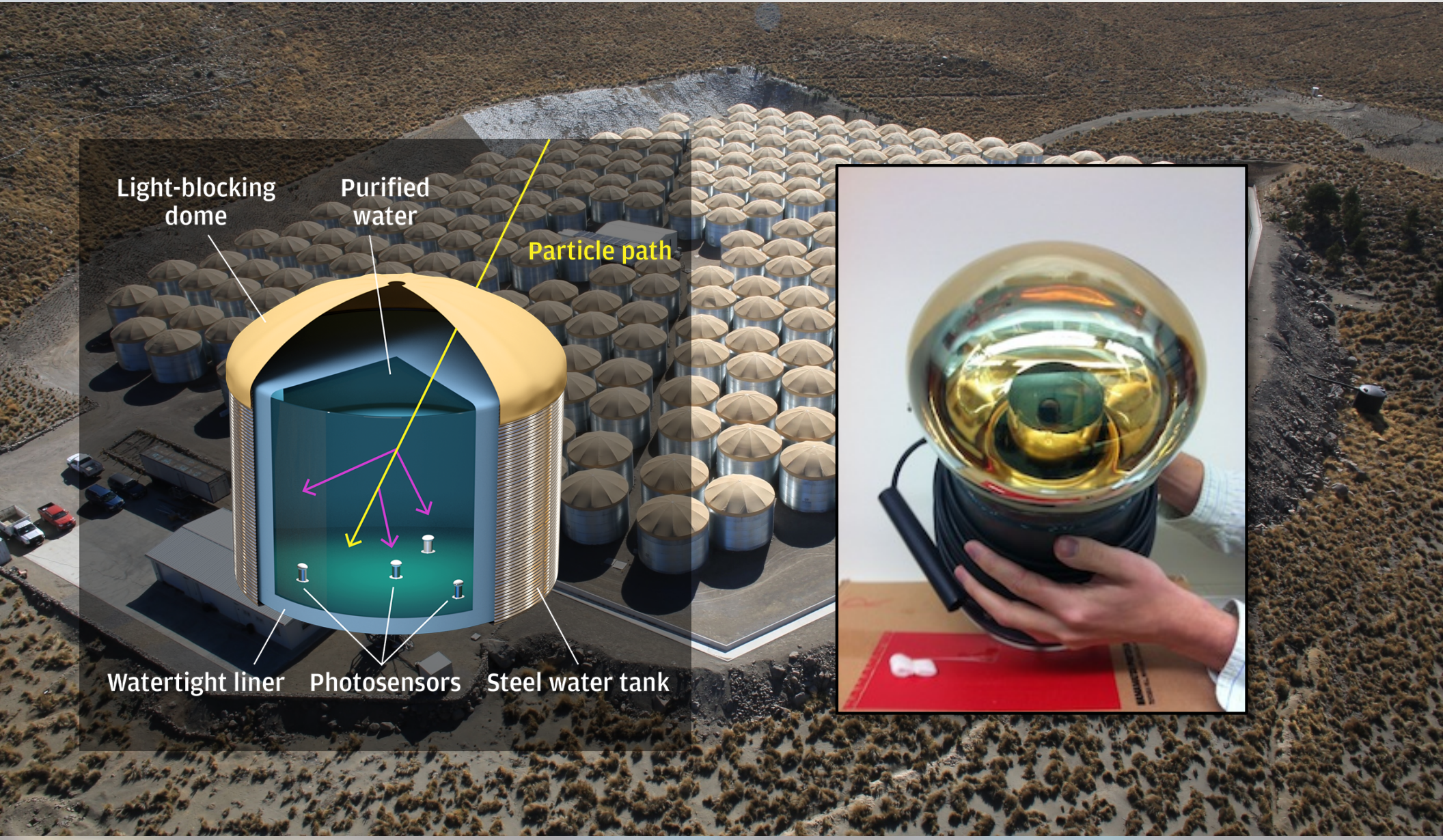
HAWC Collaboration (Mexico, USA, Germany, Poland, Costa Rica and Italy)

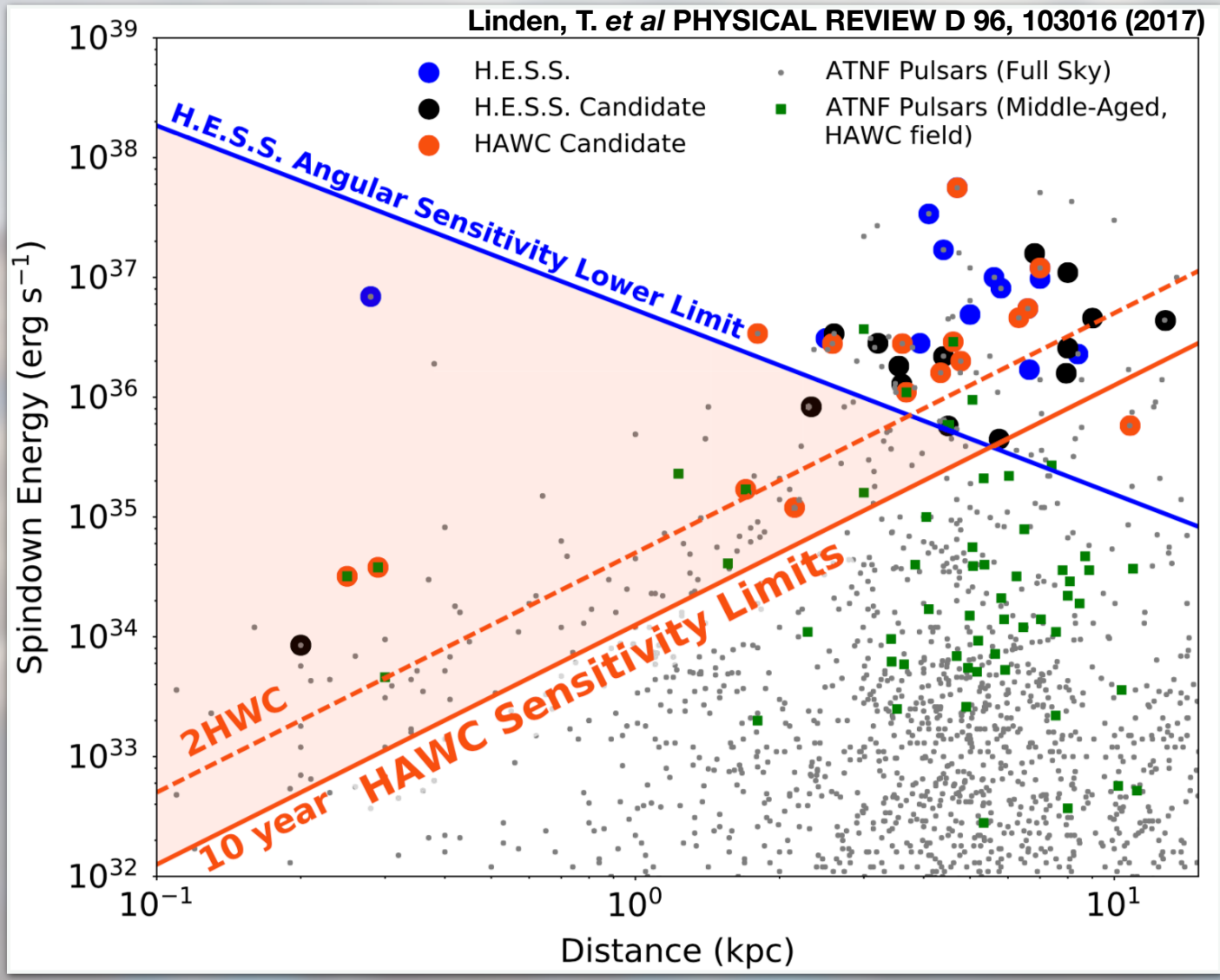


300 close-packed optically isolated water Cherenkov detectors
Construction began early 2012
Full detector inaugurated March 2015
Funding from a combination of US and Mexican agencies
High energy extension: Outrigger array, since summer 2018


Light-blocking dome
Purified water
Particle path
Watertight liner
Photosensors
Steel water tank

Pulsar Halos Ubiquitous?

- ‘Mature’ pulsars have VHE ‘halos’ from interaction accelerated electrons diffusing into the ISM.
- Halo geometry can be used to assess the charged particle diffusion rates vs in the vicinity of pulsars.
- Are halos ubiquitous and if so, are accelerated electron populations similar for all halos?
- Does not include sensitivity vs size, declination.
- Would also like to observe younger pulsars.



Search Method

- Assume a single position, at pulsar.
- Assume a Gaussian morphology.
  - A Gaussian is more compact than a full energy dependent diffusion model, leading to less confusion with neighboring sources.
- Use Geminga as a baseline to predict the size of each pulsar candidate, the search can be done taking only a single trial for each.
- Use the known distance and age to predict the size of each candidate.
- If you want to hear about understanding diffusion in the vicinity of PWNe, see contributions by : Hao Zhou and Chad Brisbois
- Data set used: 1128d of HAWC Live Time.

Search Method (2)

- Many candidates not ‘mature’, defined as 100ky by Linden et al, so they won’t have grown to their nominal Geminga-like size

- Need a simple model for evolution.

- Use Geminga as a baseline. Apparent size (S) is just the predicted size (based on age) divided by the ratio with the size of Geminga, scaled with distance (d)

$$S_{PWN} = S_{Geminga} \times \frac{d_{Geminga}}{d_{PWN}} \times Size(Age)$$

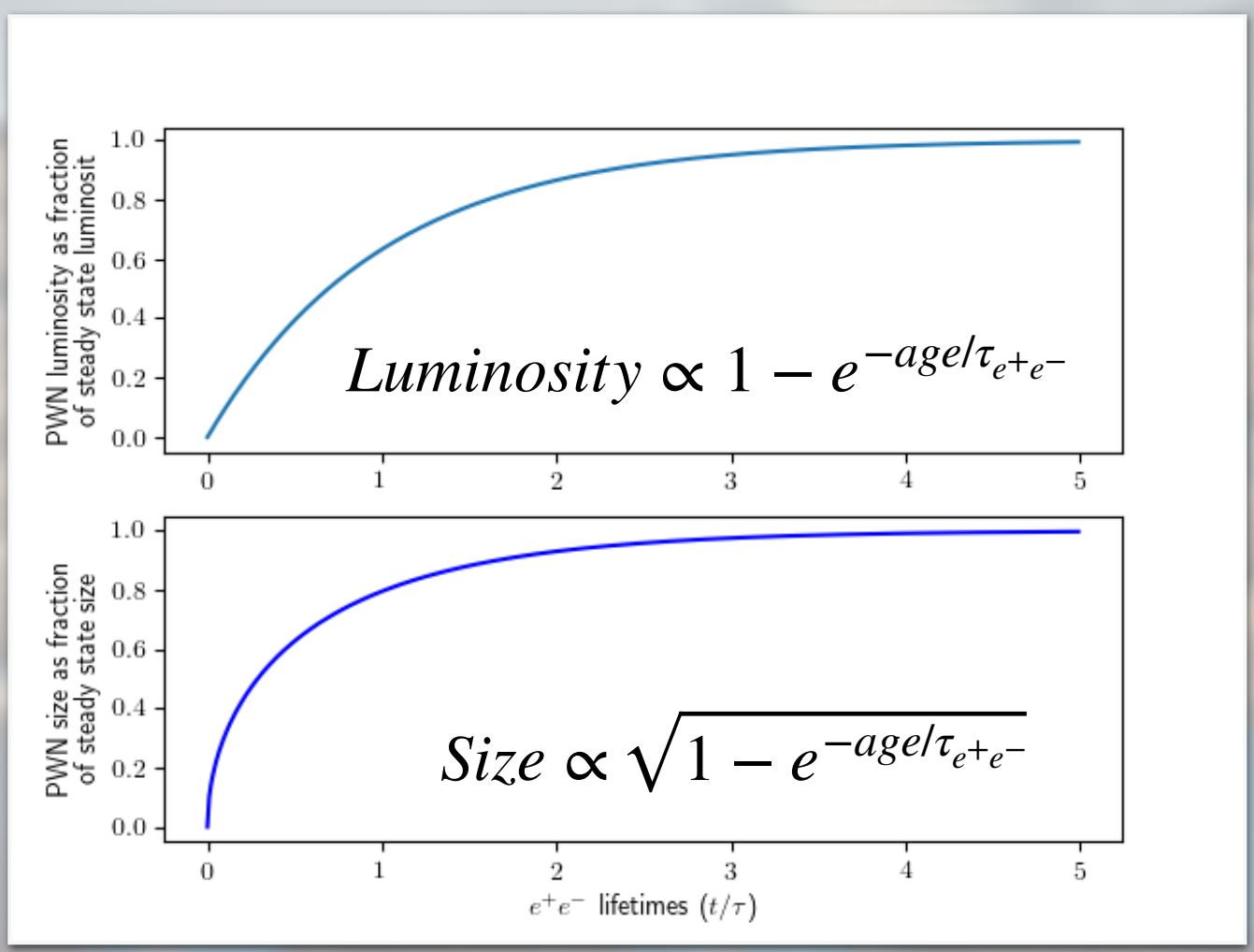
Age dependent evolution correction

- And similarly with flux (F)…

$$F_{PWN} = F_{Geminga} \times \frac{\dot{E}_{PWN}}{\dot{E}_{Geminga}} \times \frac{d^2_{Geminga}}{d^2_{PWN}} \times Luminosity(Age)$$

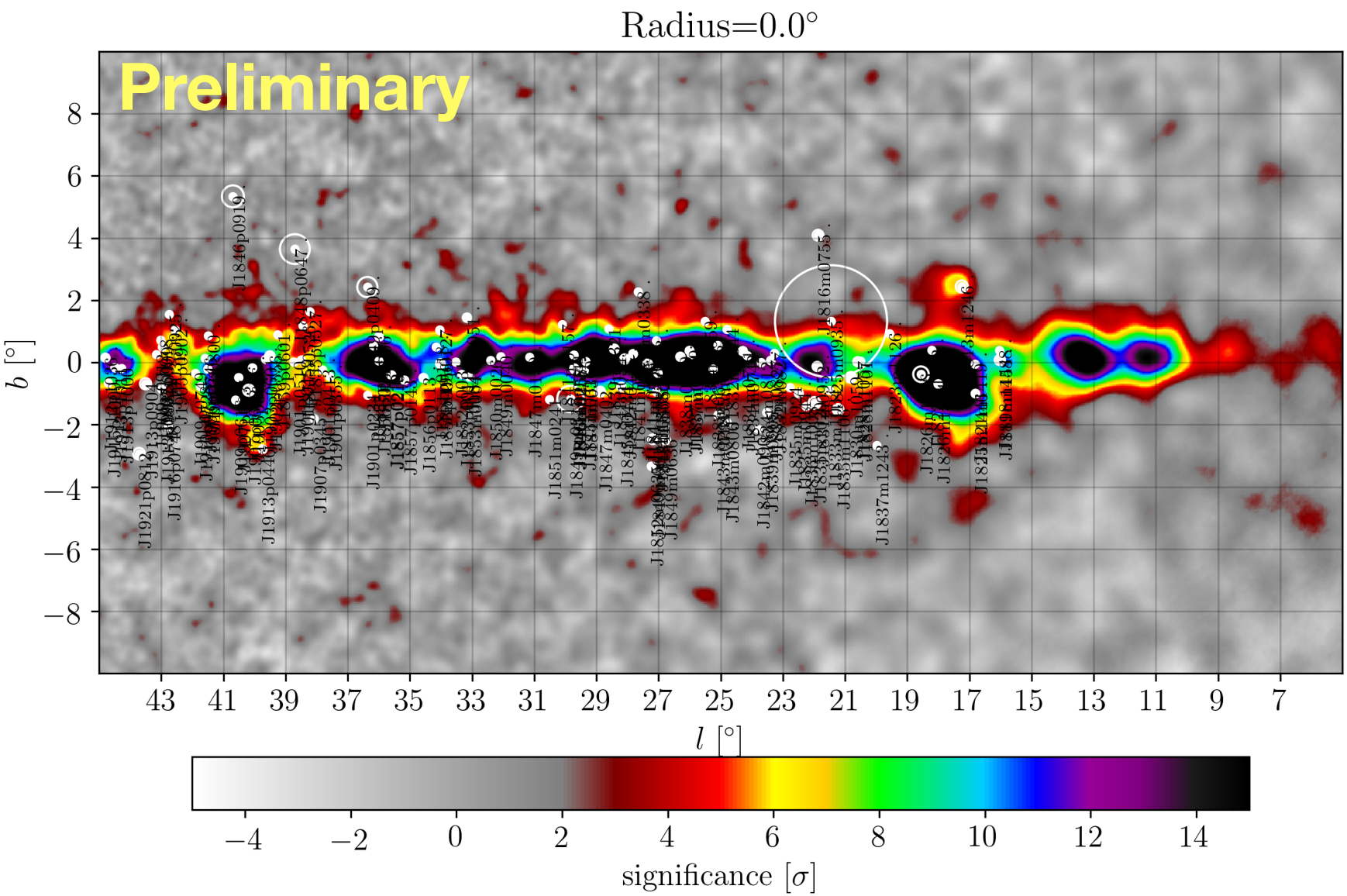
Pulsar Evolution

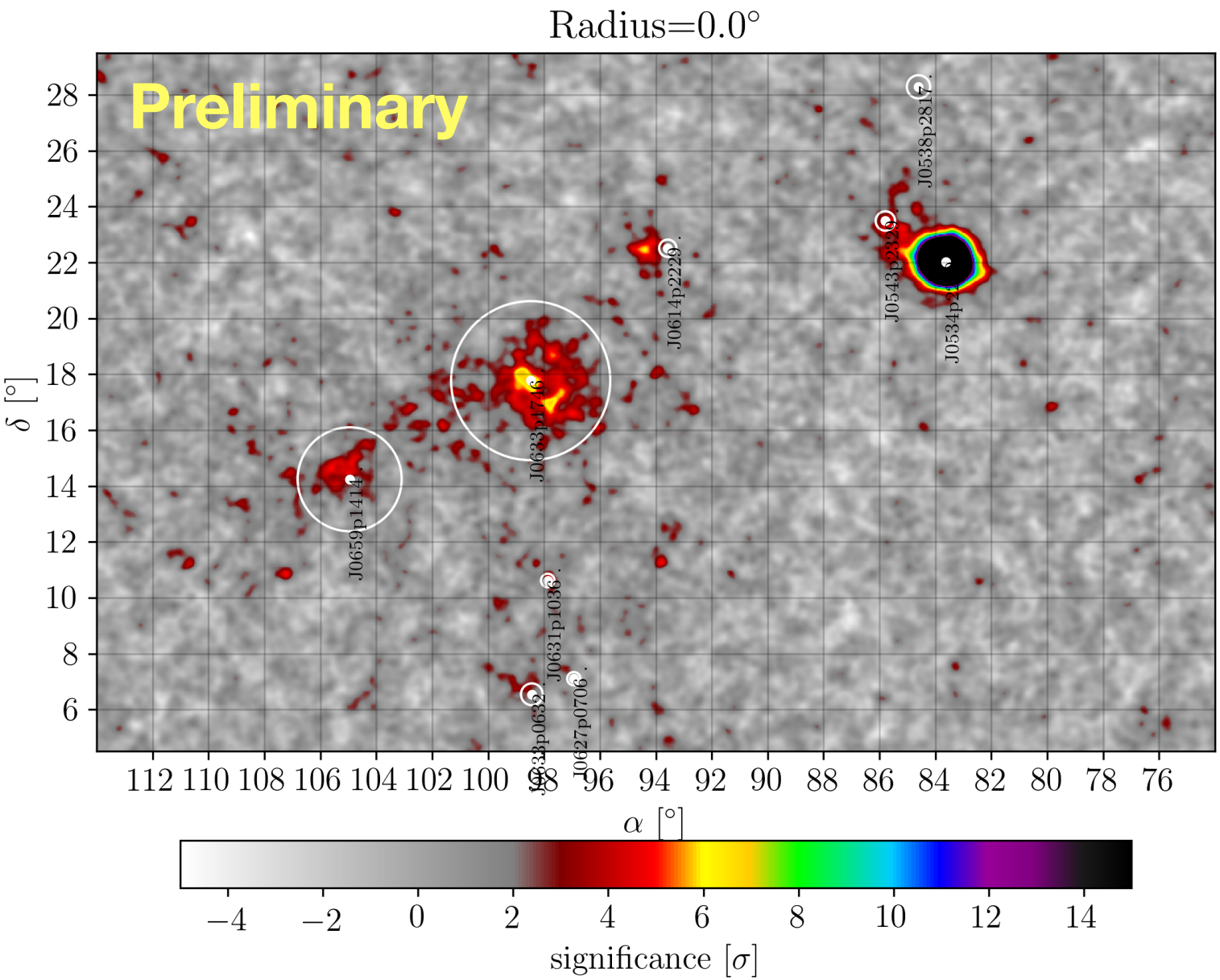
- Want to predict the properties of young pulsars (not reached full luminosity or size.
- Assume pulsar halos evolve and asymptotically approach Geminga-like halos as they mature.
- use τ = 20ky
- Full time dependent evolution model is better, but this gets the job done. (see M. Di Mauro *et al* for details of how to do this)

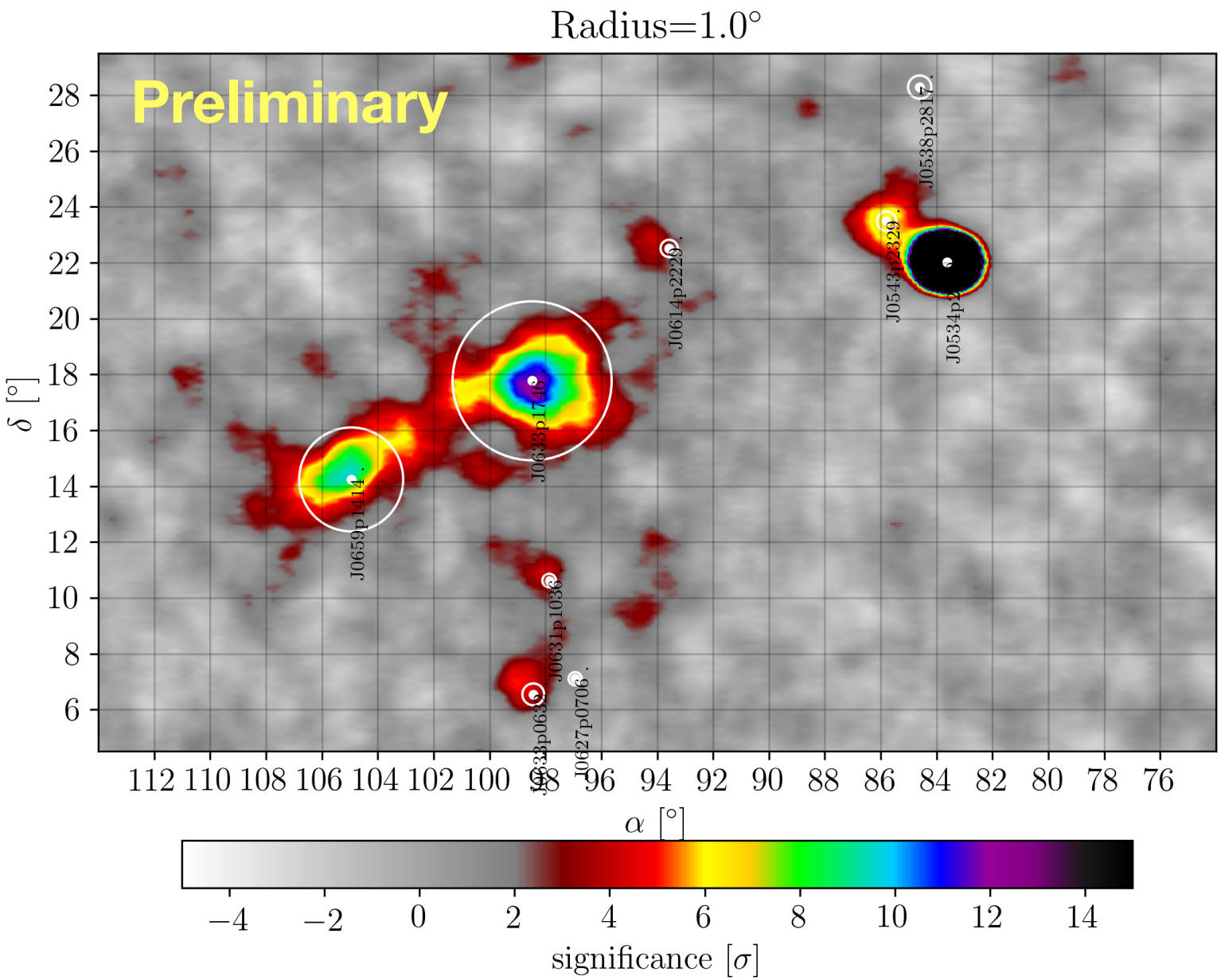


ATNF Catalog

- ATNF Catalog (v1.6) identifies 2702 pulsar locations
- 450 have measured spin down power (E-dot) and distances and measured age<1My
- 177 are within the HAWC field of view declination in [-16°,+54°]

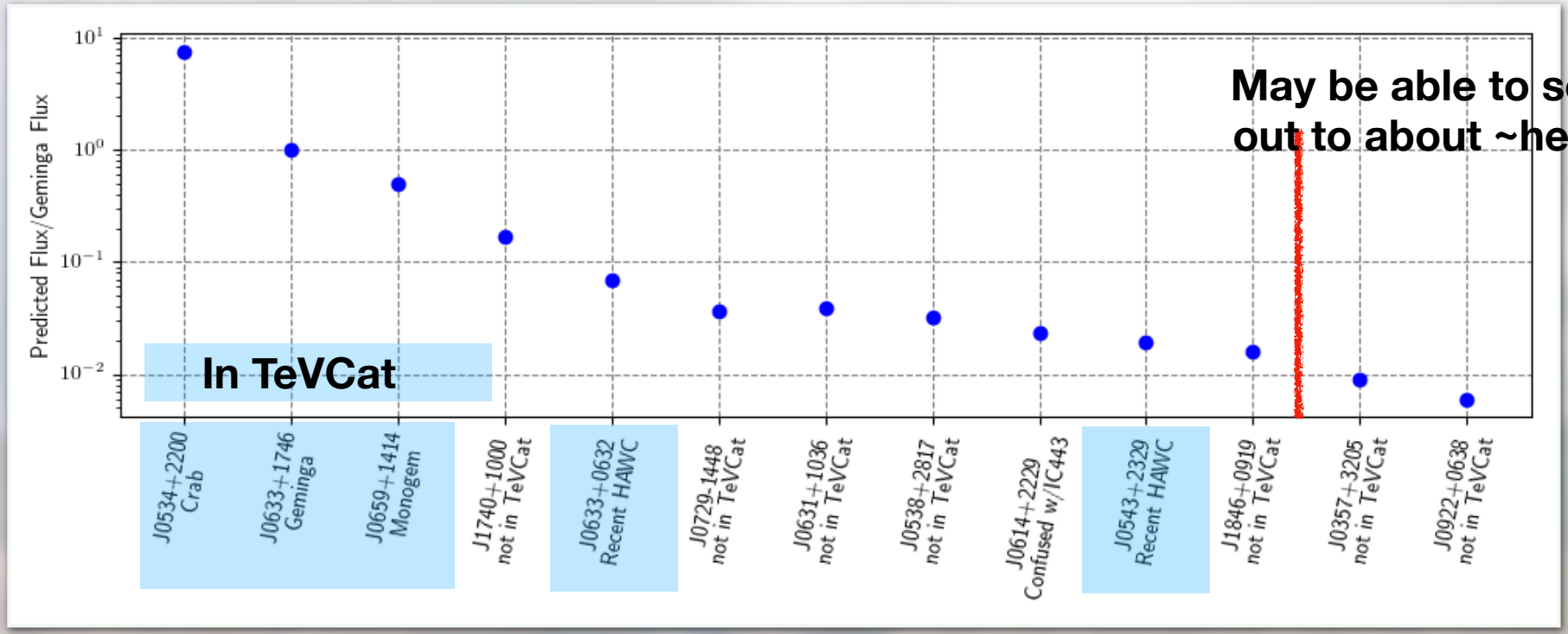

Radius=0.0°
Preliminary
b [°]
l [°]
significance [σ]

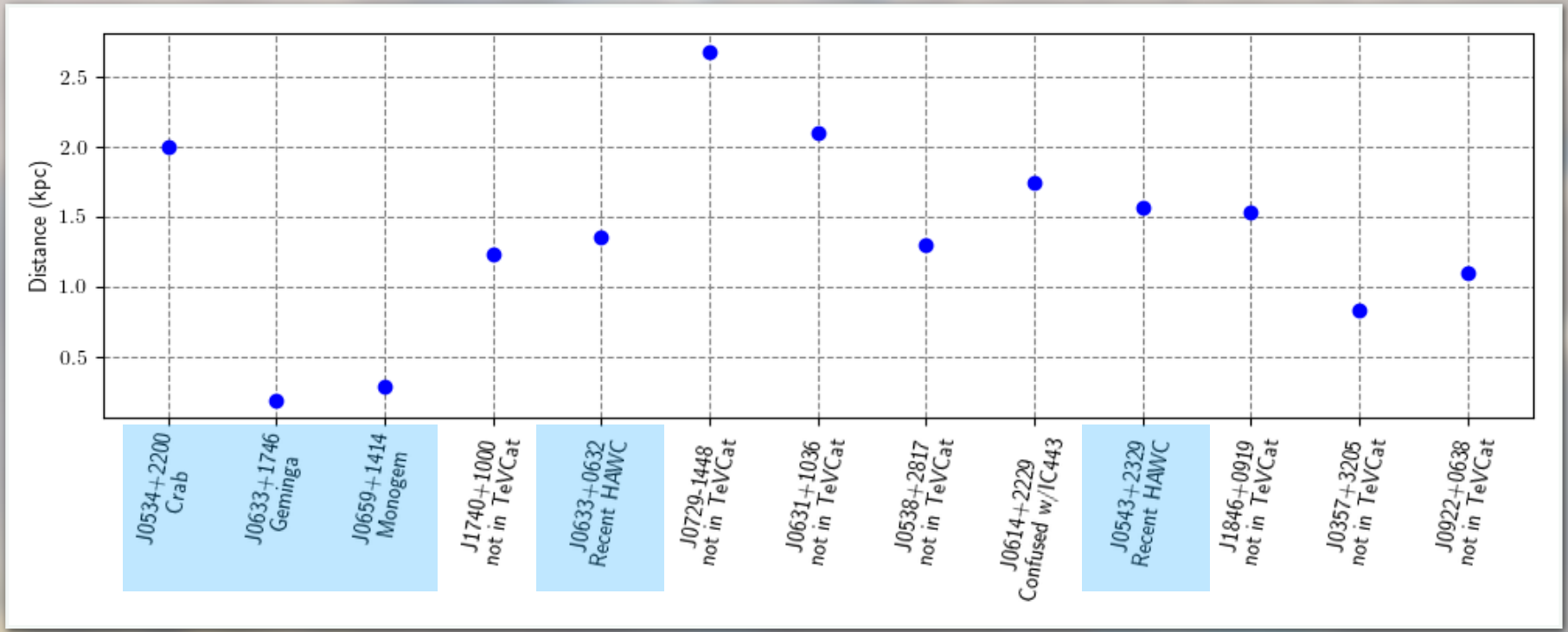

Radius=0.0°
Preliminary
J0538p2817
J0543p2329
J0534p22
J0614p2220
J0633p1746
J0659p1414
J0631p1036
J0633p0632
J0627p0706
δ [°]
α [°]
significance [σ]


Radius=1.0°
Preliminary
J0659p1414
J0633p1746
J0614p2229
J0543p2329
J0538p2817
J0534p2
J0631p1036
J0627p0706
δ [°]
α [°]
significance [σ]

Confused Regions

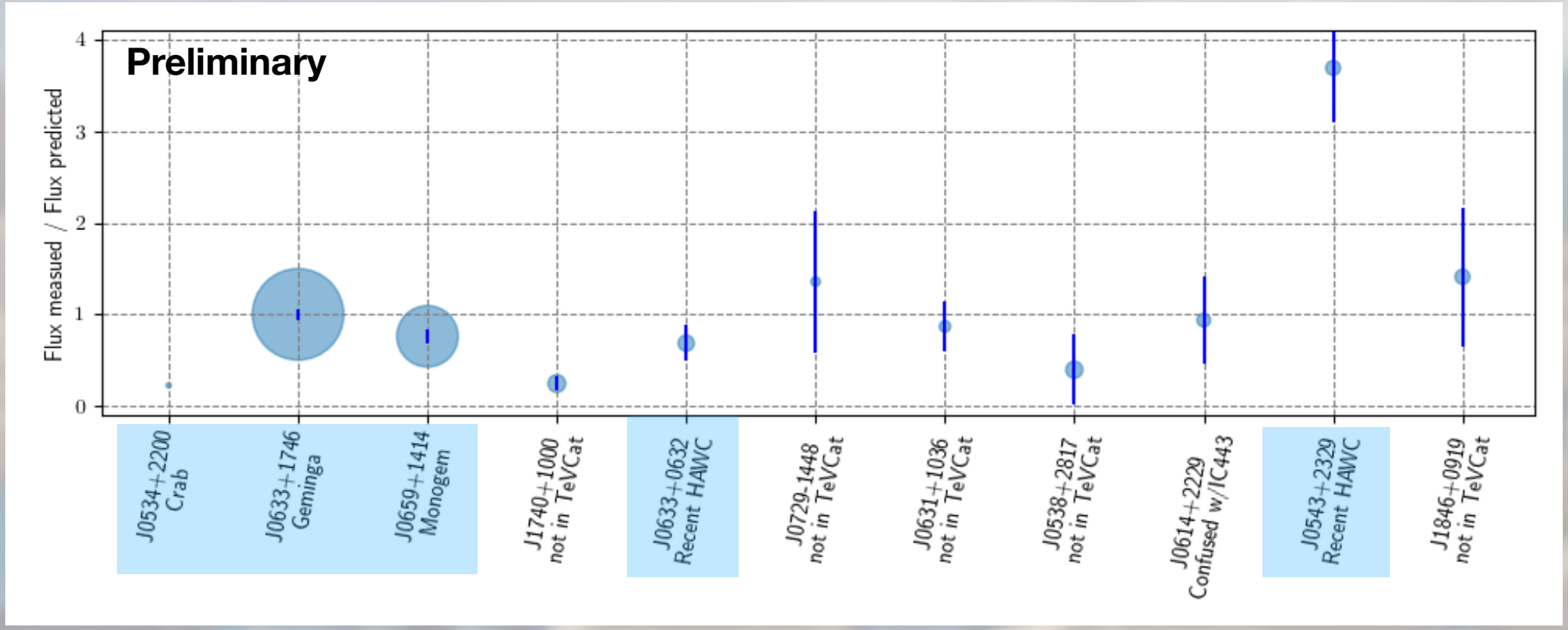
- Many of these pulsars are in complex regions, where source confusion may be an issue.
  - Multi-source fit required for most targets.
  - Exclude plane: $|b|<4$ and l in [0,100] for this analysis.


Predicted Flux/Geminga Flux
10^1
10^0
10^{-1}
10^{-2}
In TeVCat
May be able to see out to about ~here
J0534+2200 Crab
J0633+1746 Geminga
J0659+1414 Monogem
J1740+1000 not in TeVCat
J0633+0632 Recent HAWC
J0729-1448 not in TeVCat
J0631+1036 not in TeVCat
J0538+2817 not in TeVCat
J0614+2229 Confused w/IC443
J0543+2329 Recent HAWC
J1846+0919 not in TeVCat
J0357+3205 not in TeVCat
J0922+0638 not in TeVCat


Distance (kpc)
2.5
2.0
1.5
1.0
0.5
J0534+2200 Crab
J0633+1746 Geminga
J0659+1414 Monogem
J1740+1000 not in TeVCat
J0633+0632 Recent HAWC
J0729-1448 not in TeVCat
J0631+1036 not in TeVCat
J0538+2817 not in TeVCat
J0614+2229 Confused w/IC443
J0543+2329 Recent HAWC
J1846+0919 not in TeVCat
J0357+3205 not in TeVCat
J0922+0638 not in TeVCat

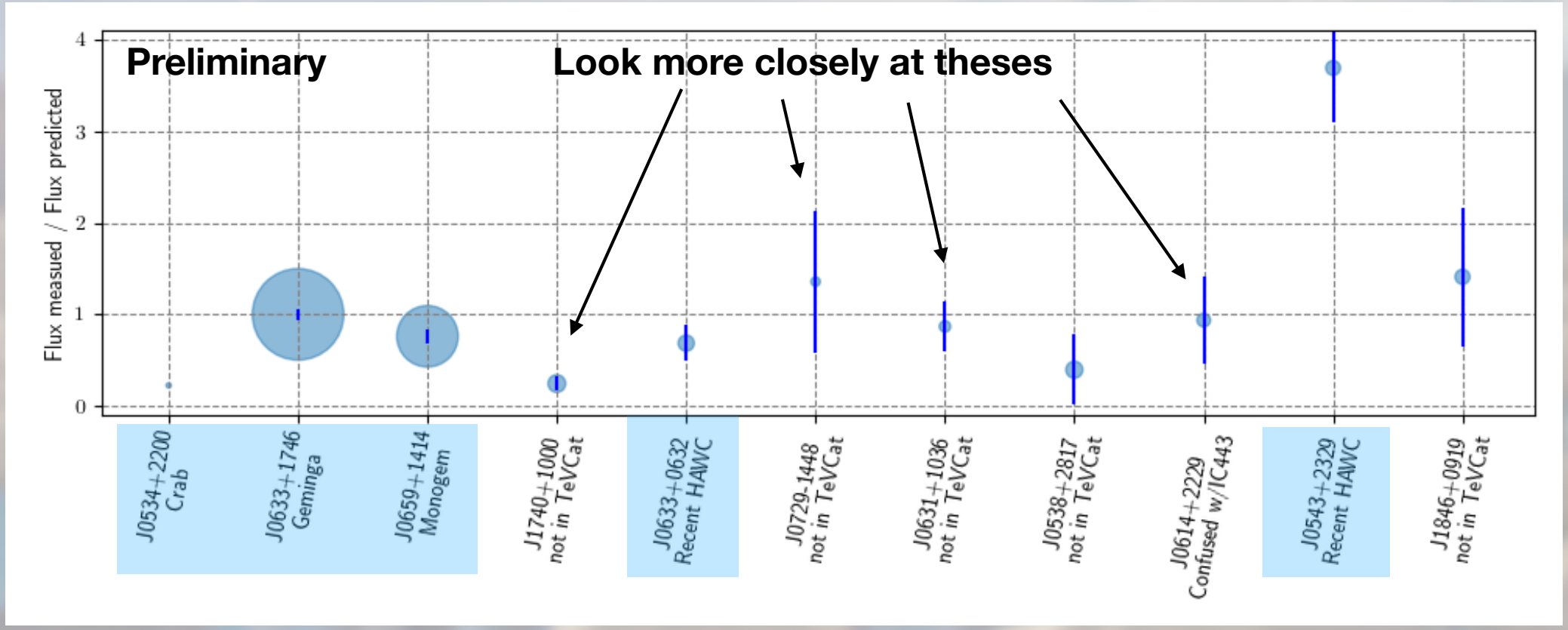
Results:

Size indicates size of target



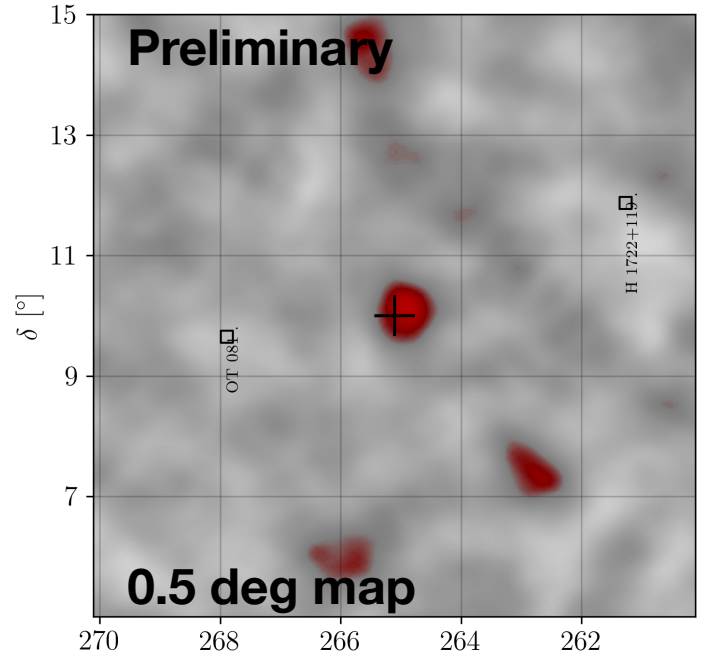
Results:

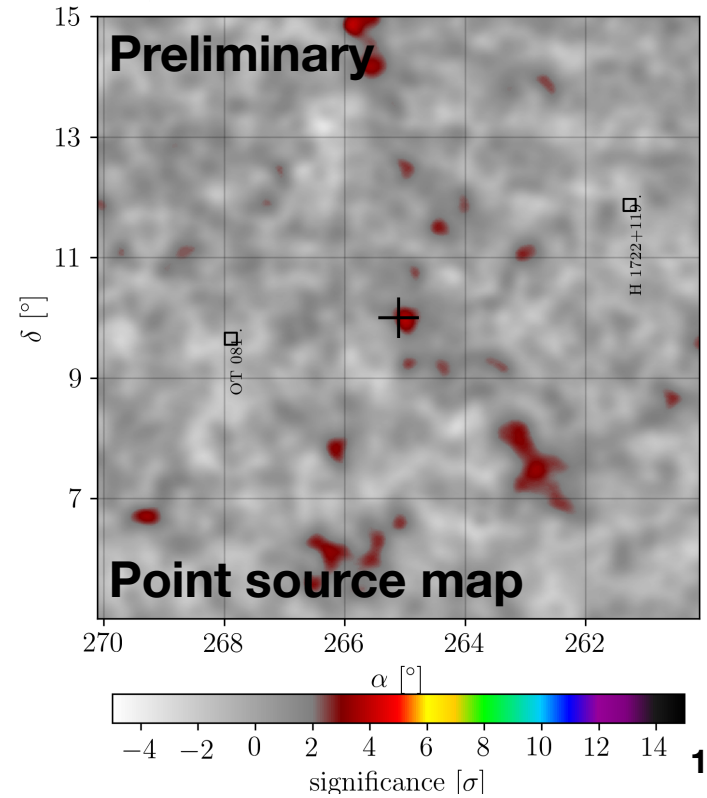
Size indicates size of target



PSR J1740+1000

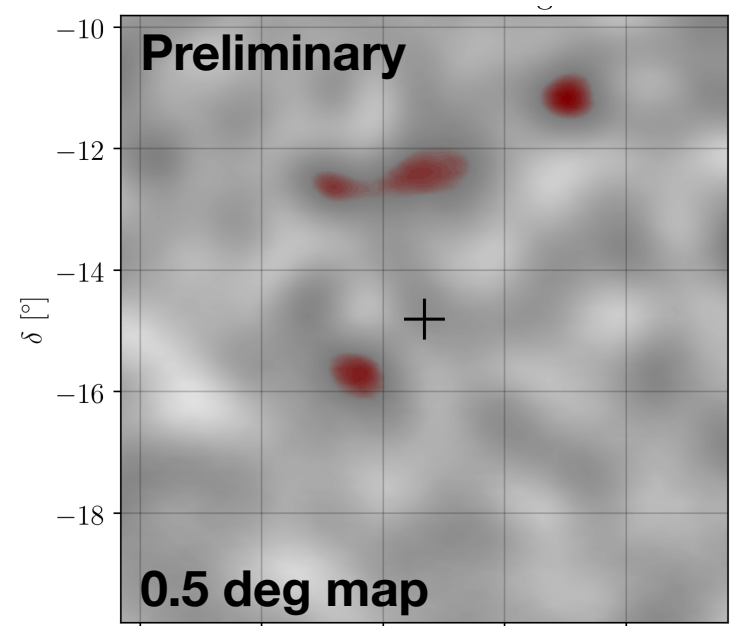
- Age: 114 ky
- Distance: 1.23 kpc
- Pred Size: 0.276 deg
- Signif: 3.0σ (12.8σ pred)
- Meas / Pred Flux = 0.24
- b=20.3°, ejected from the plane? may have a large proper motion?
- Unusual emission: Radio quiet, absorption lines possibly due to an anomalously small B-field.
- VERITAS limit of <1% Crab, consistent with this observation considering extension, spectrum…

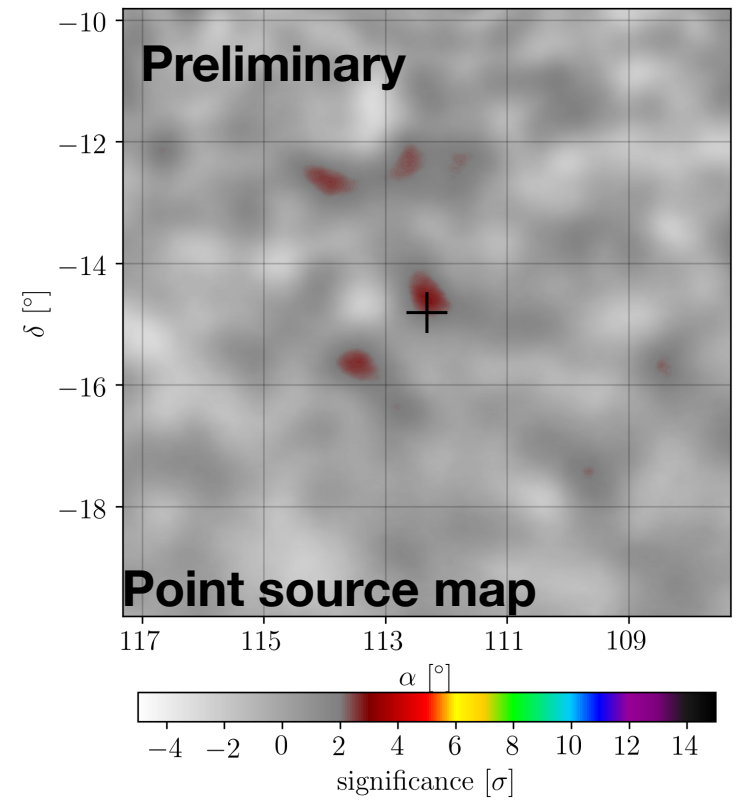




J0729-1448 (in outer galaxy, poor declination)

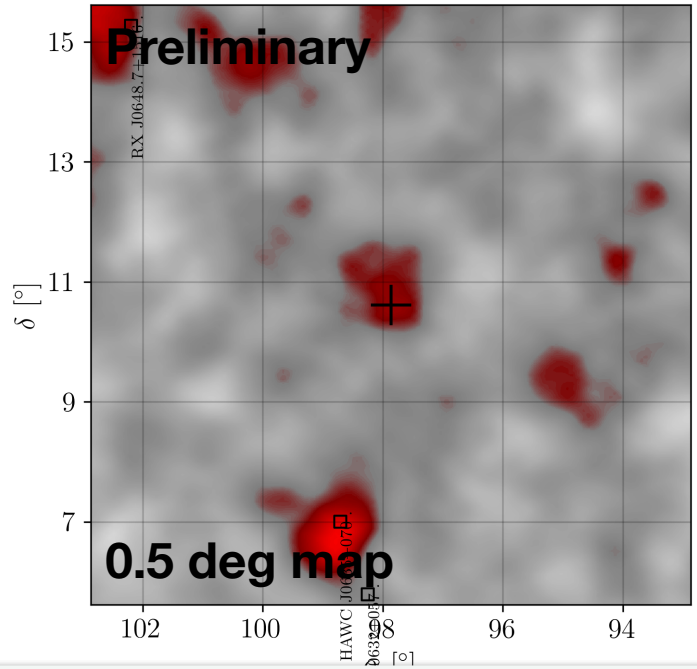
- Age: 35.2 ky
- Distance: 2.68 kpc
- Pred Size: 0.115 deg
- Signif: 1.7σ (1.3σ pred.)
- Measured/Expected Flux = 1.35

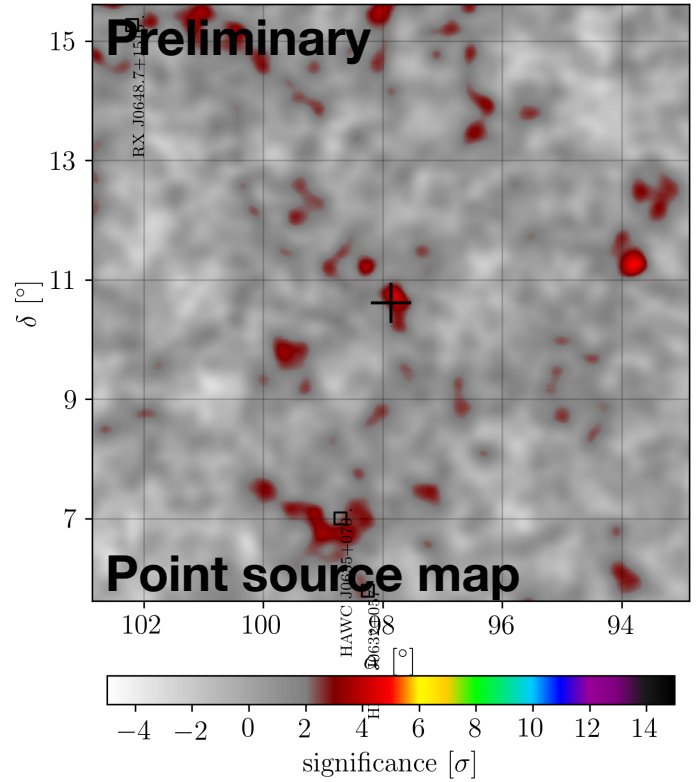




J0631+1036 (South of Geminga)

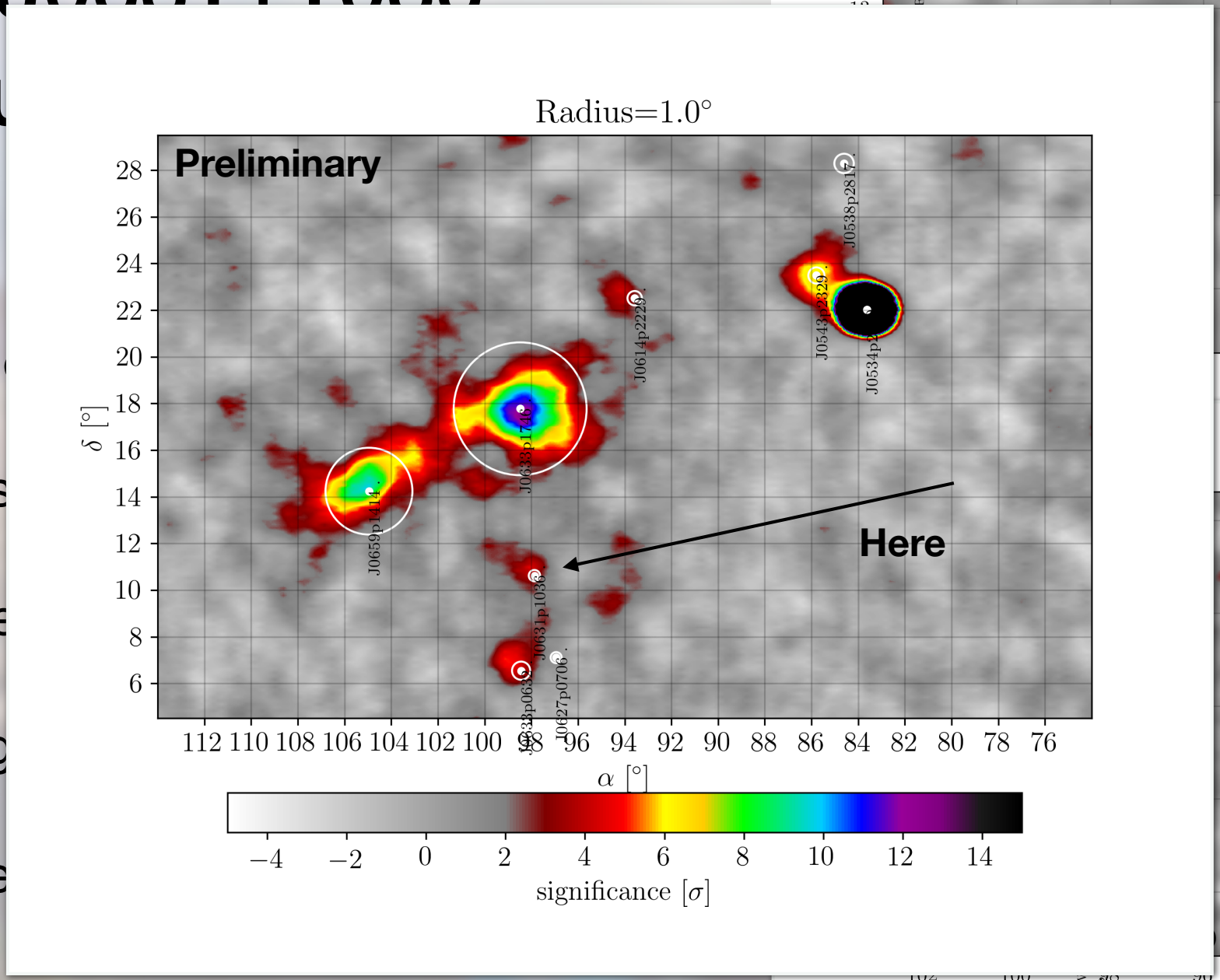
- Age: 43.6 ky
- Distance: 2.10 kpc
- Pred Size: 0.153 deg
- Signif: 3.3σ (3.9σ pred.)
- Meas/Pred Flux = 0.81





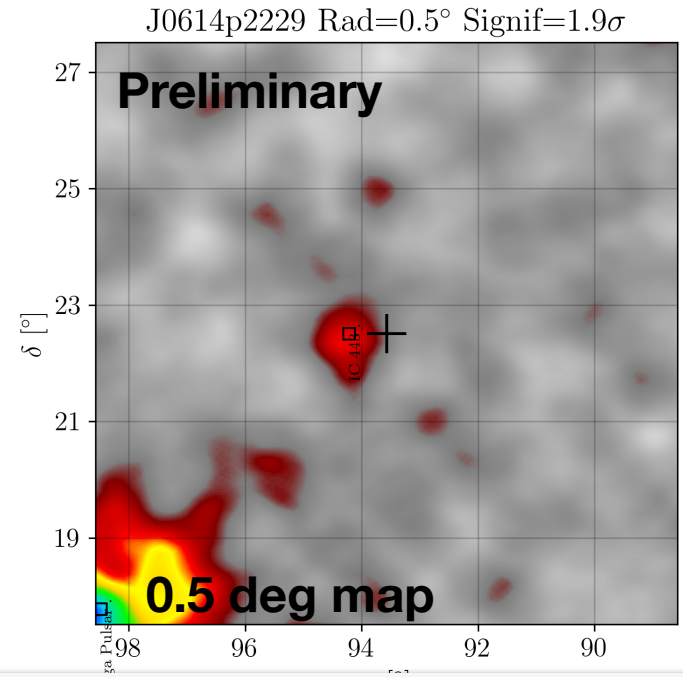
J0631+1036 (Sou

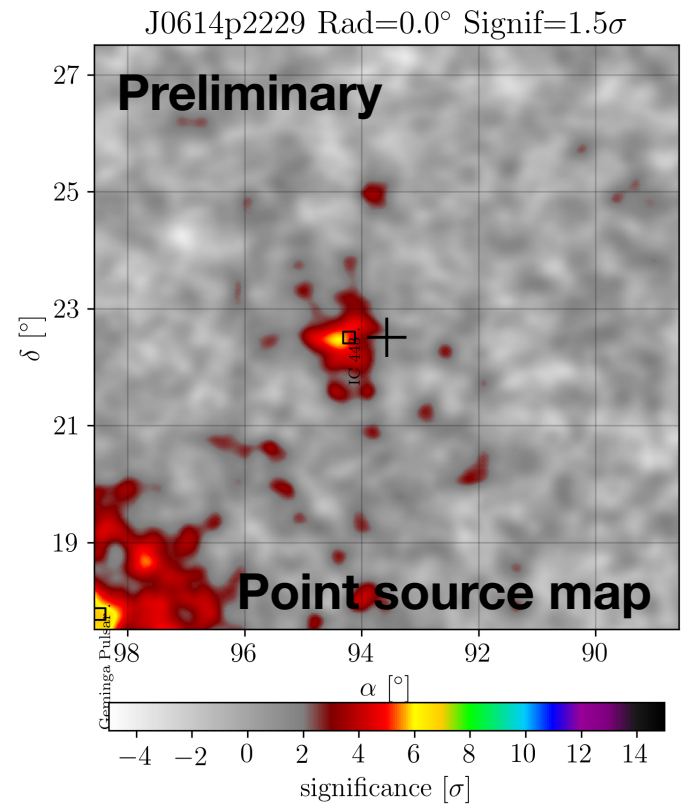
- Ag
- Dis
- Pre
- Sig
- Me



J0614+2229 (near IC443)

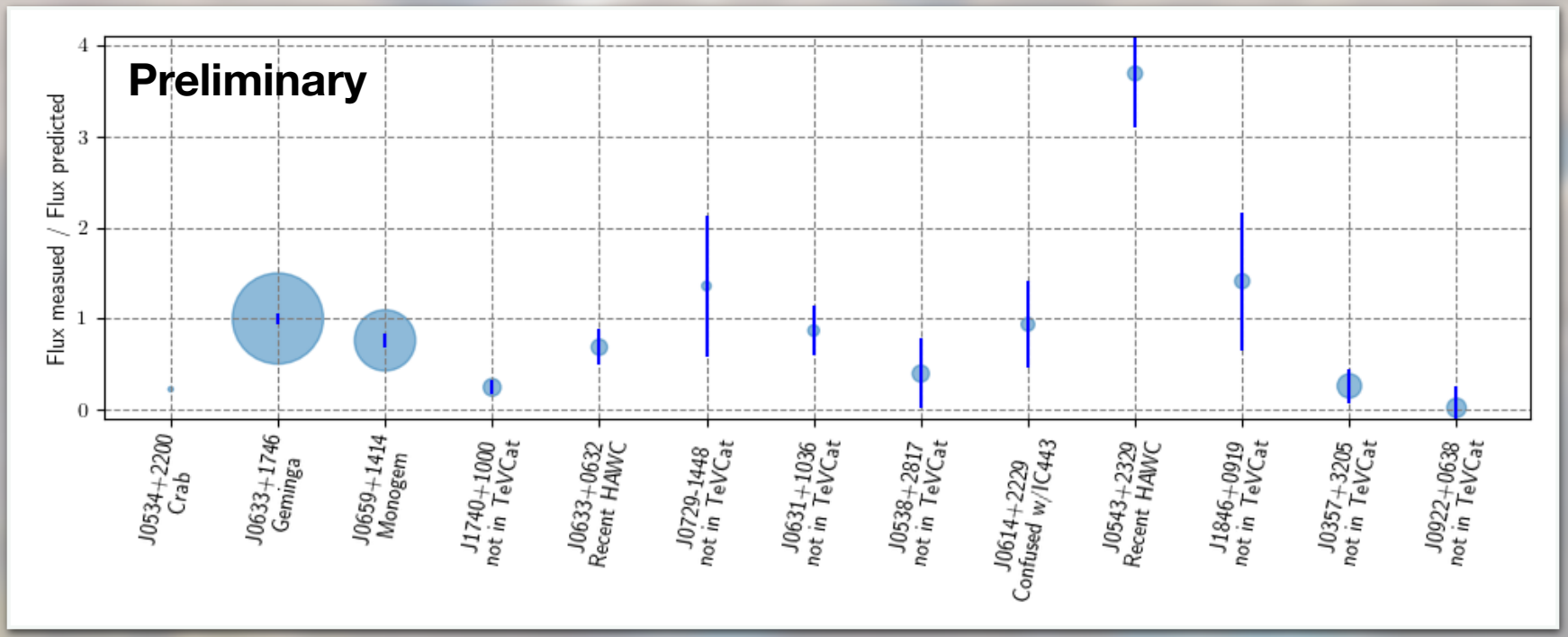
- Age: 89 ky
- Distance: 1.74 kpc
- Pred Size: 0.194 deg
- Signif: 1.9σ (2.2σ pred.)
- Meas / Pred Flux = 0.84
- Fits model well, but is clearly confused region with IC443.





Conclusions

- Indication of possible emission from several candidates.
- Source confusion is a problem for all but a handful of targets.
- Need to do multi-source fits to isolate source contributions.



Backup

Crab
(this is a extreme case for my evolution model, so don't take it too seriously)

- Age: 1.26ky
- Distance: 2.00kpc
- Pred Size: 0.042° (HESS measures extent at 0.014°)
- Signif: 162σ
- Meas./Pred Flux = 0.22
- Sub-luminous

Extra

HESS measures Crab as 52" = 0.014°