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Development of an Analytical model of TeV Halos as they could be detected by HAWC.

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Geminga

PSR B0656+14

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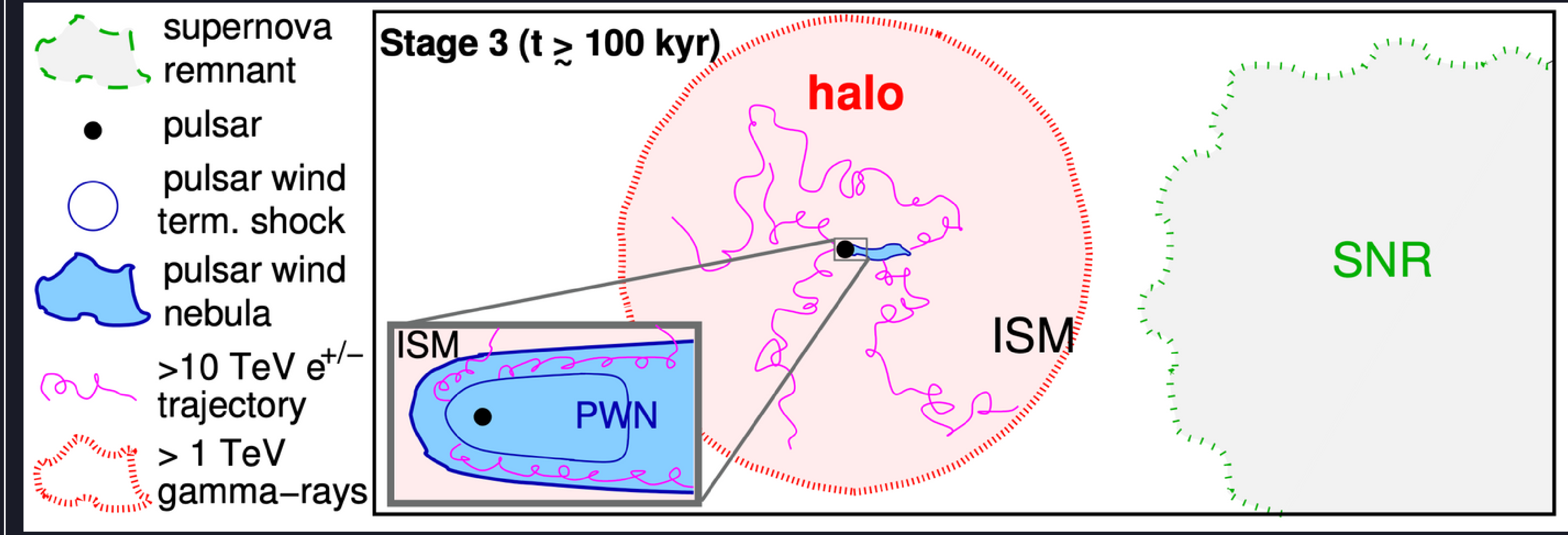
- TeV Halos: new type of gamma-ray sources.
- Associated to middle-age pulsars.
- Potential tool for blind searches of "invisible" pulsars.
- We present a simple model to predict:
    - size
    - luminosity
- Extra evidence of the presence of halos around pulsars

TeV Halos

- Different to PWN and SNR.
- Product of Inverse Compton interactions
  - e and e+ accelerated by pulsar
  - ISM photons
- Size of ~10s pc.
- Particle propagation by difussion.

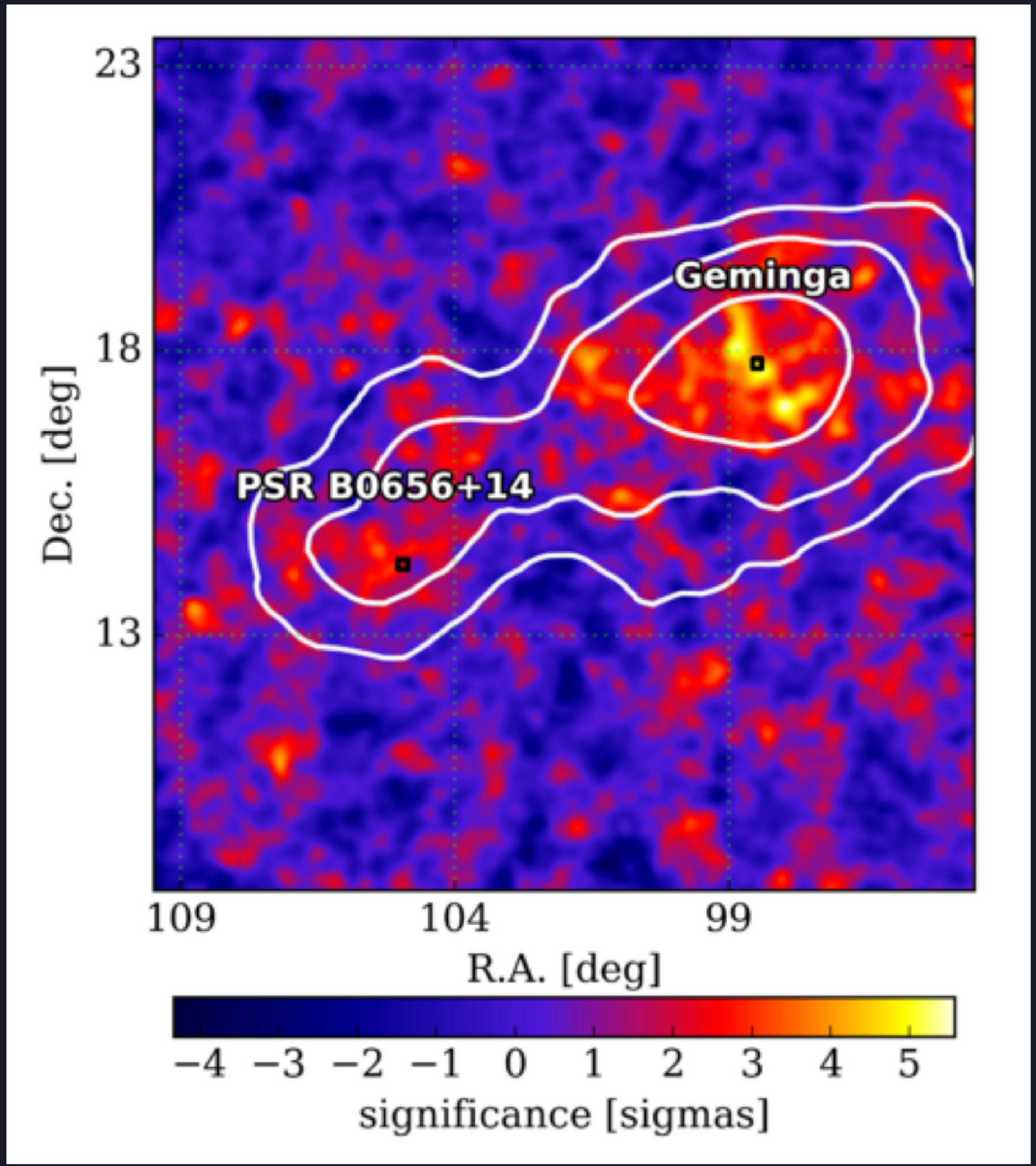


Giacinti et al, 2020

- Smaller diffusion coefficient
- Around pulsars no longer confined by the SNR
- Sudoh et al, 2019, predicted ~50-240 detections from HAWC and CTA observations.
- HAWC identifies gamma-ray sources associated with 14 pulsars.

Geminga and Monogem

- First two Halos detected in 2017 by HAWC.
- Associated to the middle-aged pulsars Geminga and Monogem (PSR B0656+14).
- Extended sources.
- Two orders of magnitude greater than the X-ray nebulae.
- Morphology consistent with diffuse emission.
- Estimated diffusion coefficient of $4.15 \pm 1.2 \times 10^{27}$ cm² s⁻¹ (smaller than previous ISM estimates of ~ 5×10^{28} cm² s⁻¹)



Abeysekera et al, 2017

Why study TeV Halos?

Potential probes for "invisible" pulsars.

Indirect measurment of local difussion coefficients.

Evidence of emission above 100 TeV

TeV Halos are potential probes for dark matter candidates, such as ALP's.

Contribution to galactic and extragalactic diffuse emission

Study of pulsar distribution in other galaxies.

Our model

- We retake a previous work by Smith, A., 2019.
    - Geminga as a standard halo
    - size and flux as functions of pulsar age, spin-down luminosity and distance

    - Differences:
        - Instead of young and middle-aged pulsar, we take only middle-aged
        - Instead of flux, we work with luminosity
        - We parameterize spin-down luminosity as a function of age based on the psr catalogue (ATNF psr cat)
        - We parameterize gamma-ray luminosity as a function of spin-down luminosity (three halos and three halo candidates).

Six pulsars and their respective high-energy associated source to fit size and luminosity expression:

- Geminga
- Monogem
- J0622+3749, associated to 3HWC J0621+382, reported by LHAASO as a TeV Halo.

Three sources reported as Halo Candidates.

- PSR J0543+2329, identified as a Halo on TeVCat
- PSR J1740+1000, recently associated to a gamma-ray extended source.
- PSR J2032+4127, has association to a HAWC and a LHAASO source.

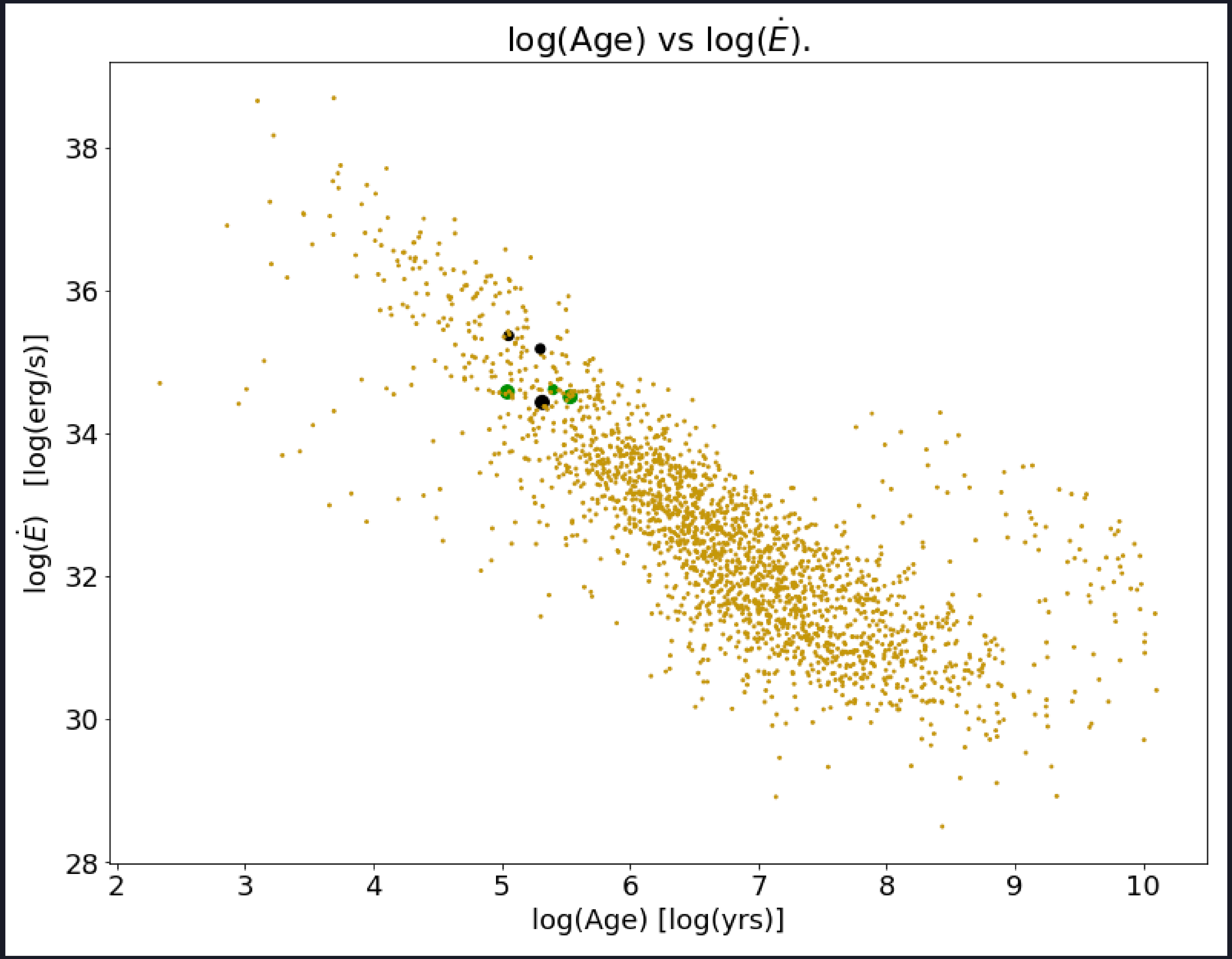
The ATNF Catalogue

- Public catalogue of all the pulsars reported in any type of survey or publication.
- 67 parameters available.
- Not all pulsars have all parameters reported.
- Presently, composed of over 3000 pulsars.
  - 142 of them are middle-aged and in HAWC's fov.

An analytical expression of $\dot{E}$

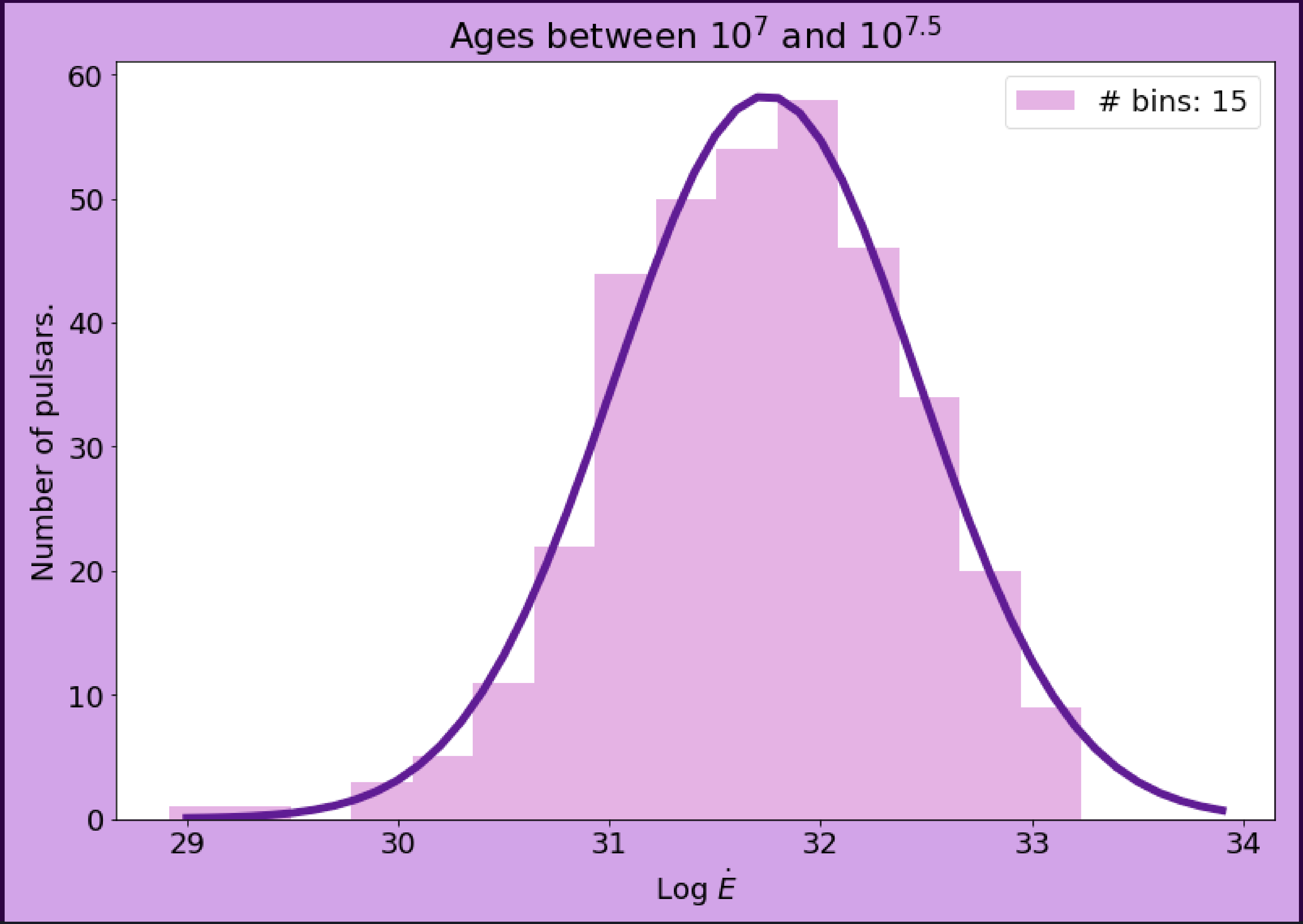
- Not of interest:
  - very young pulsars
  - recycled pulsars
  - pulsar with no spin-down luminosity reported.

How psrs with ages between 10^4 and 10^8 yrs behave.



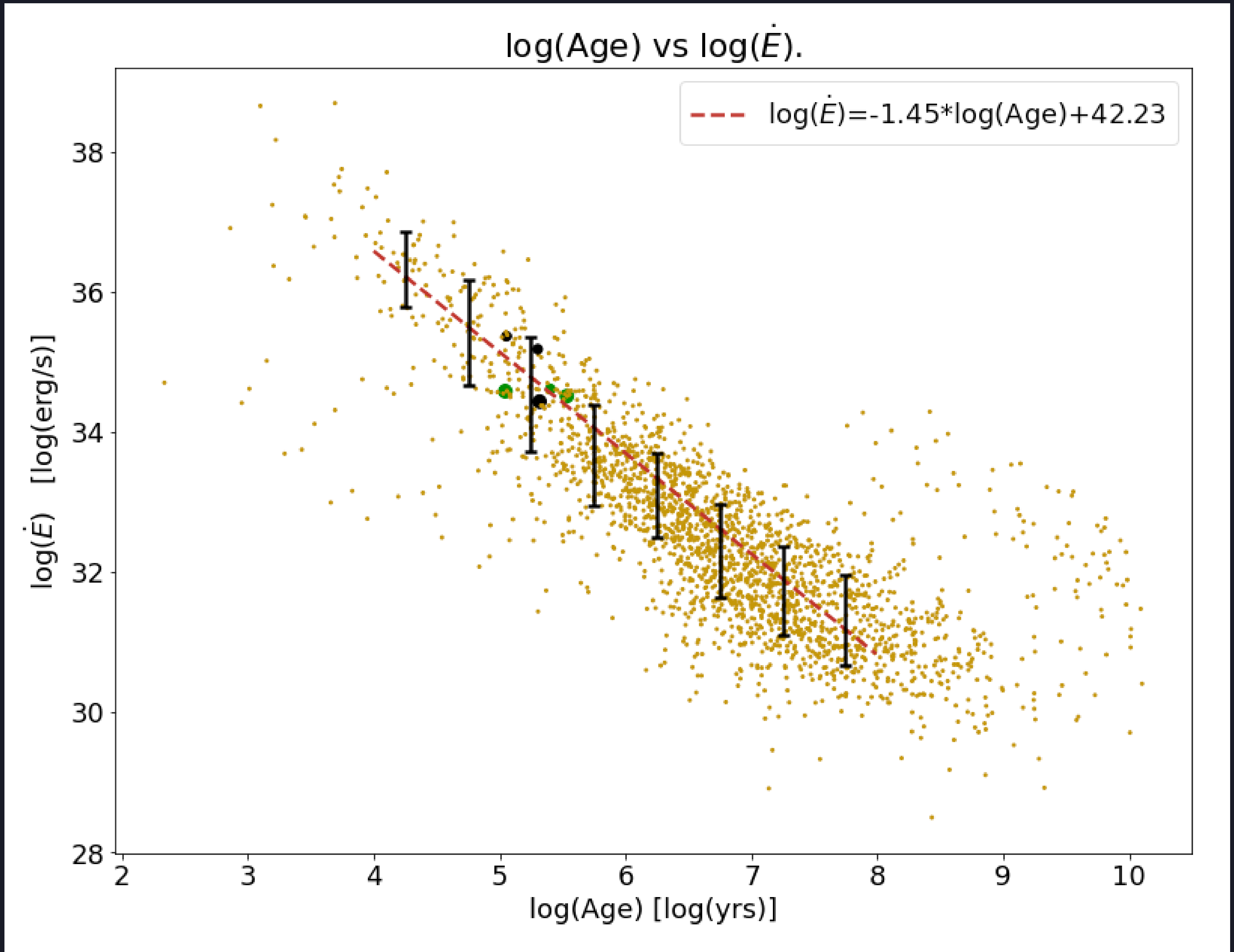
An analytical expression of $\dot{E}$

- We divided our psrs of interests into 8 age groups.
- A Gaussian is a good distribution for all age bins.
- As an example:



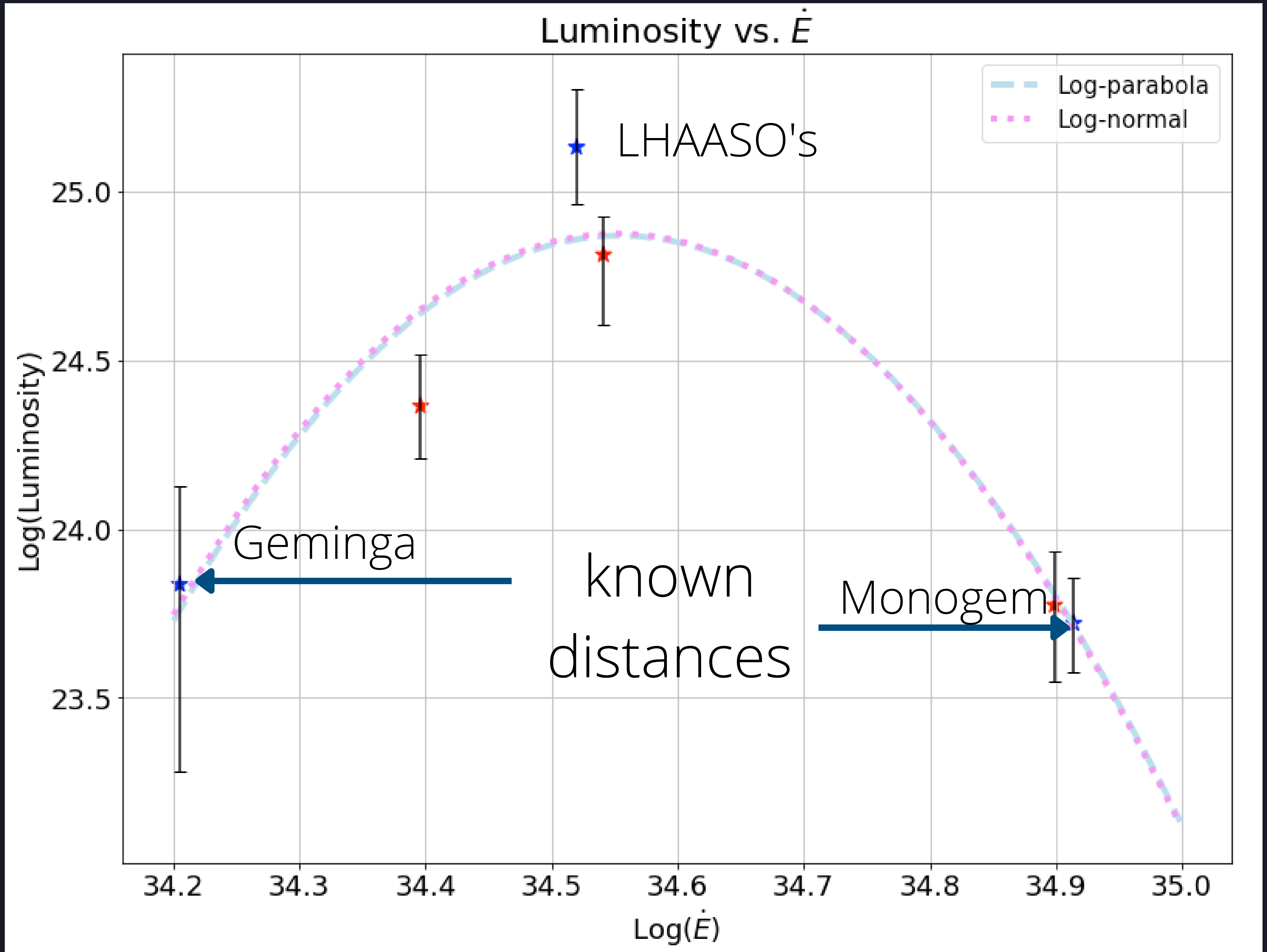
An analytical expression of $\dot{E}$

$$\log(\dot{E}) = -1.45 \log(\text{Age}) + 42.23$$



The simple model: gamma-ray lumiosity

With our new spin-down luminosity



$$\log(L) = 24.65 \frac{\log \dot{E}}{34.4}^{3.9-442.7\ln(\log \dot{E}/34.4)}$$

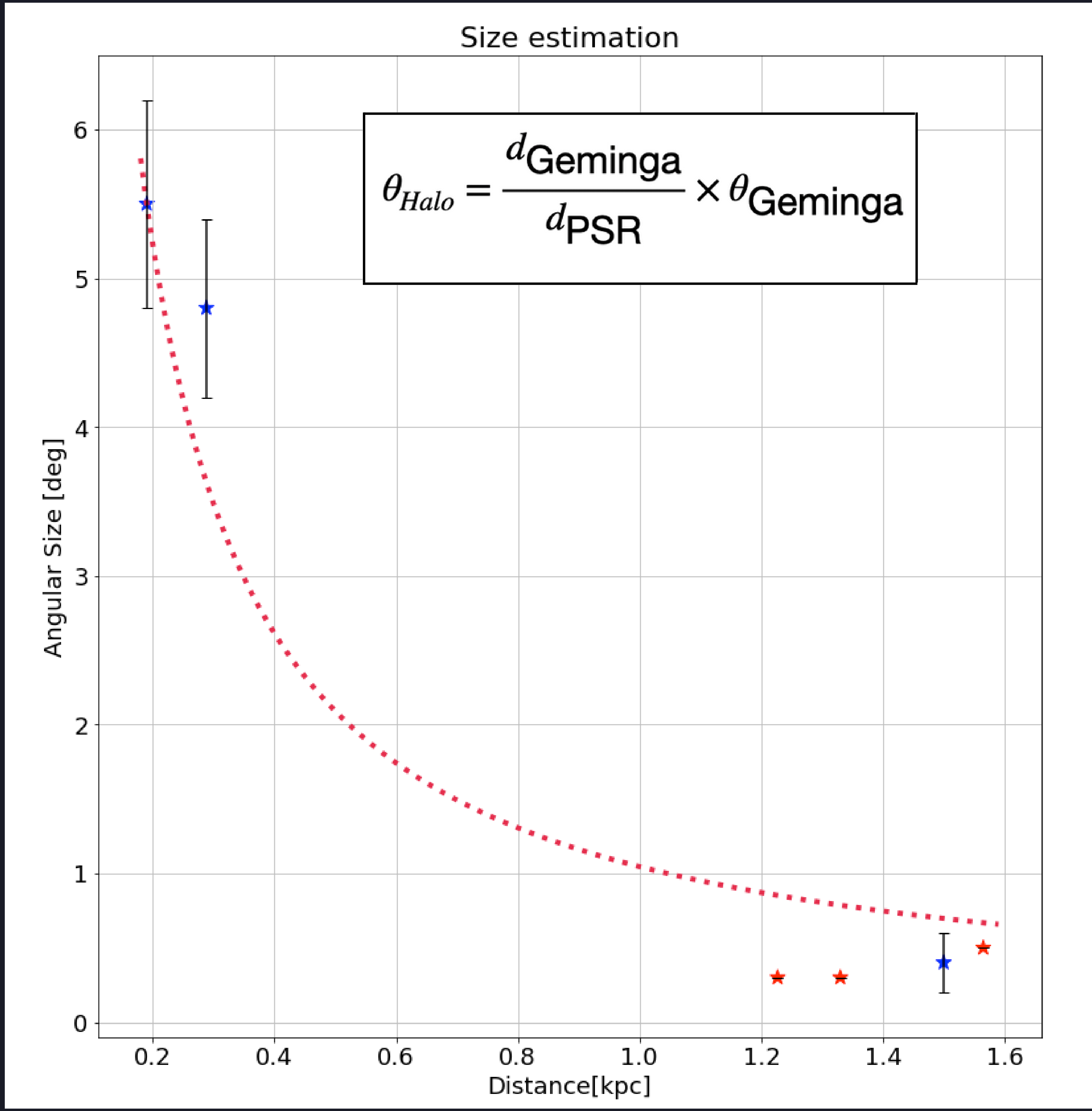
$$\log(L) = \frac{72.43}{0.03\sqrt{2\pi}} \frac{e^{-(\ln(\log \dot{E})-3.54)^2/0.0018}}{\log \dot{E}}$$

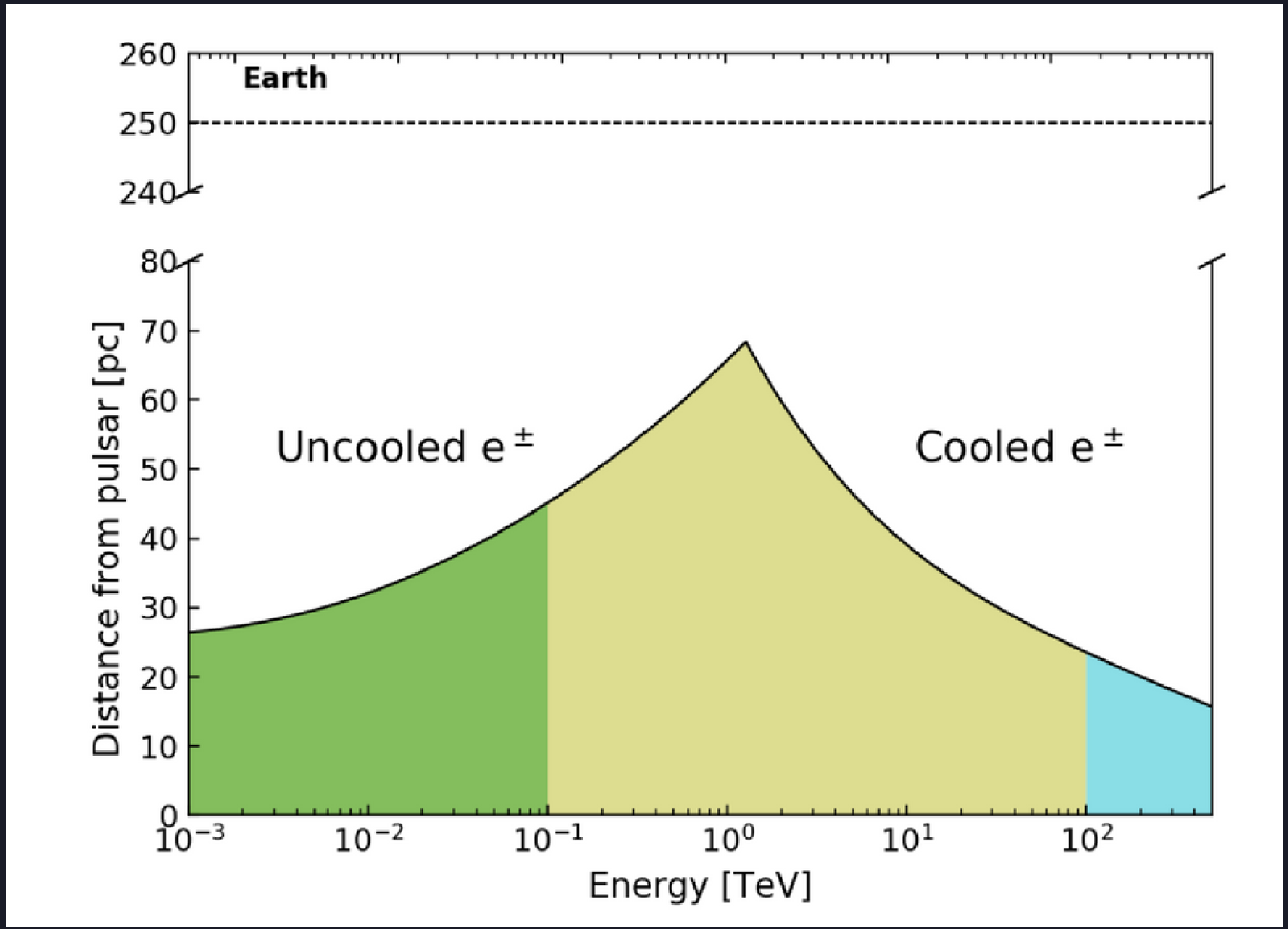
About the uncertainties:

- flux uncertainty reported and their renormalization to 7 TeV pivot Energy
- distance uncertainties (10% for unknown distances errors)

Unknown distances might underestimate uncertainties in the luminosity.

The simple model: angular size





Diffusion radius of electrons as a function of energy. Colors represent 100 GeV in green, 1 TeV in light green and 100 TeV in blue. Abeysekera et al, 2017

- **LHAASO's is observed "smaller" due to working at higher energy range.**

Calculated results

J Pulsar	Flux Normalization $[(\text{TeV cm}^2\text{s})^{-1}]$	Calculated Flux $[(\text{TeV cm}^2\text{s})^{-1}]$	Reported Angular size [deg]	Calculated Angular size [deg]
J0622+3749 (LHAASO's Halo)	5.03 E-14	2.67 E-14	0.4	0.74
J0633+1746 (Geminga)	1.59 E-13	1.33 E-13	5.5	5.9
J0659+1414 (Monogem)	5.3 E-14	5.2 E-14	4.8	3.9
J0543+2329	7.9 E-15	1.49 E-14	0.5	0.71
J1740+1000	3.3 E-15	3.55 E-15	0.3	0.9
J2032+4127	3.07 E-14	3.48 E-14	0.3	0.83

Simulations

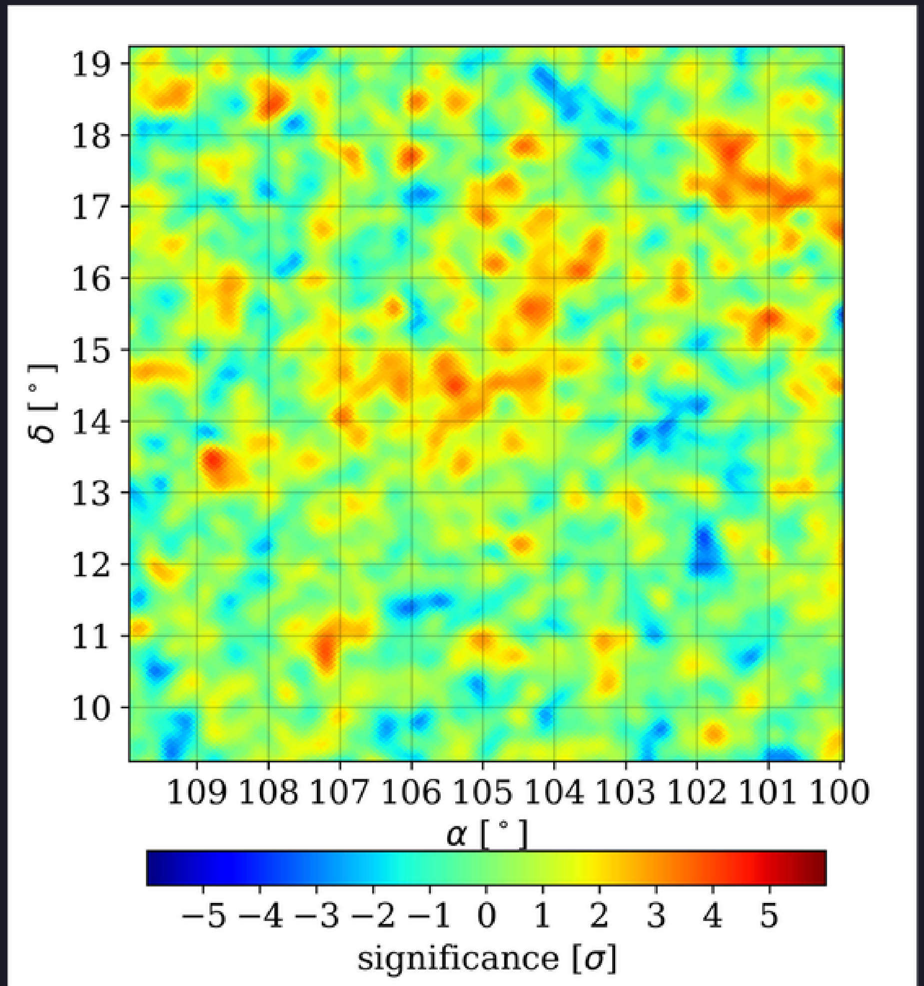
Using HAWC's software

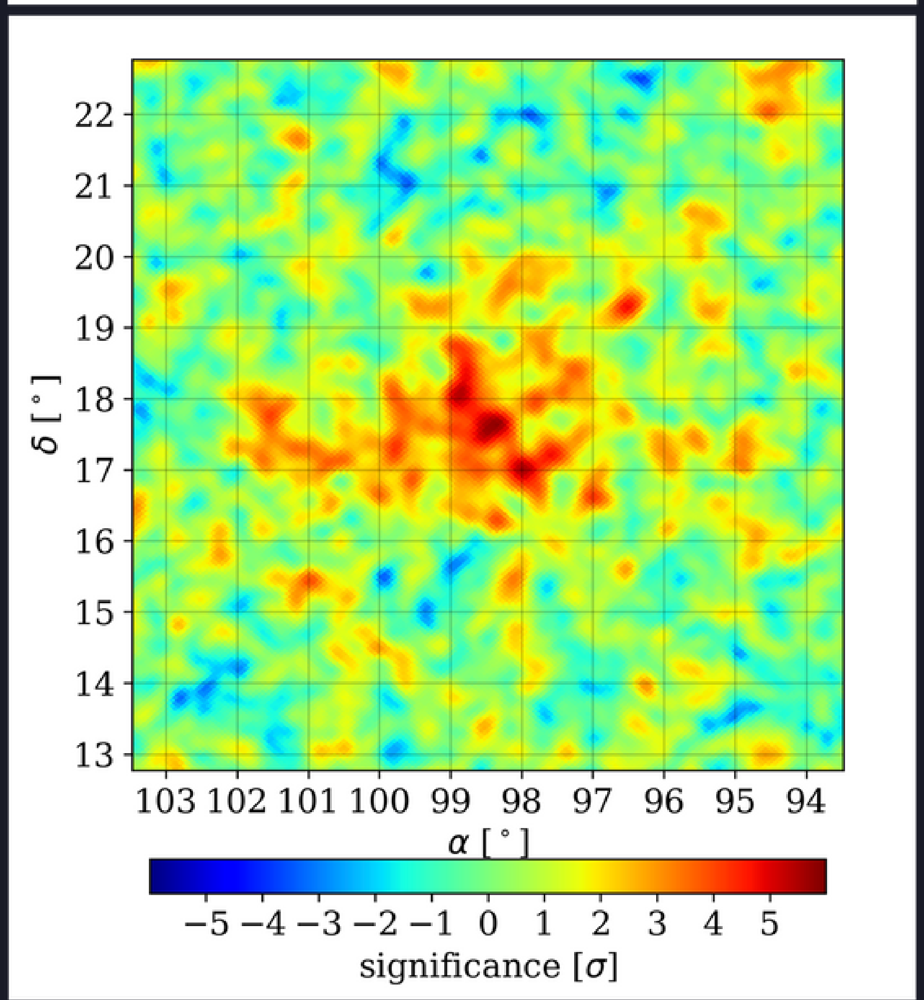
J0659+1414
(Monogem)

508 days of data.
Flux as a simple
power-law with index
2.34 (Geminga).

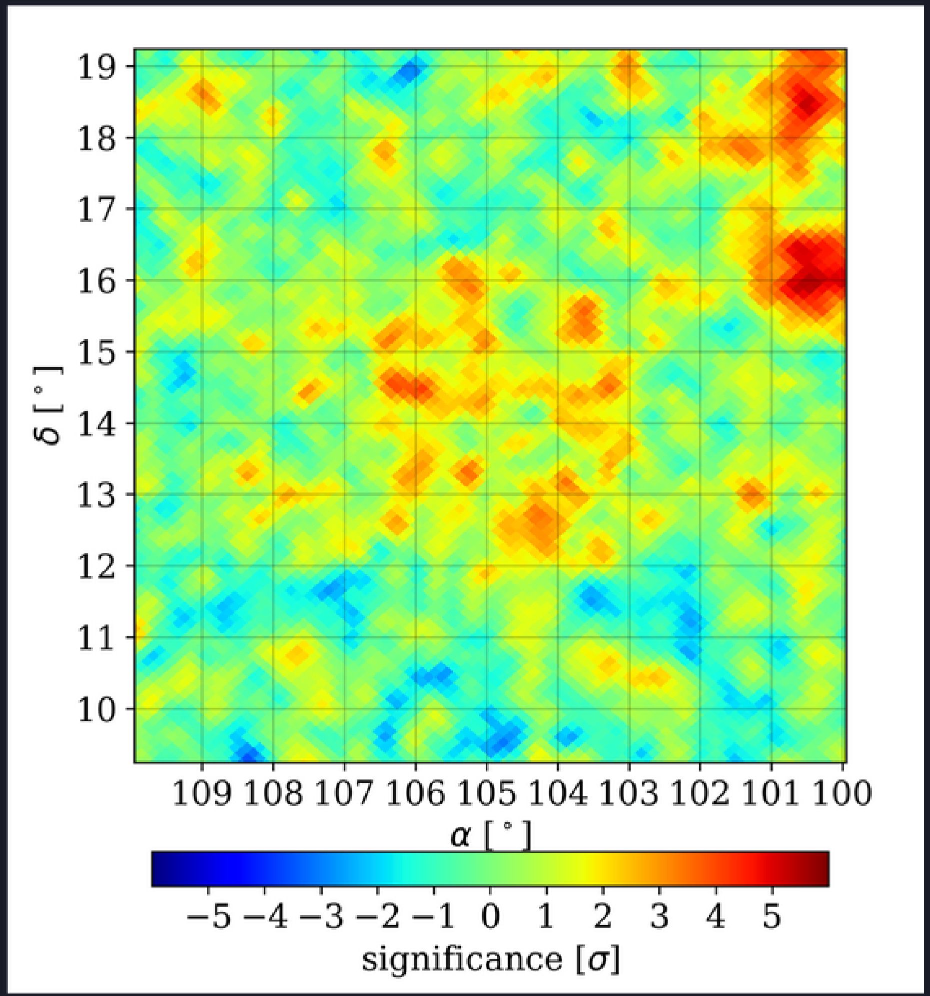
J0633+1746
(Geminga)

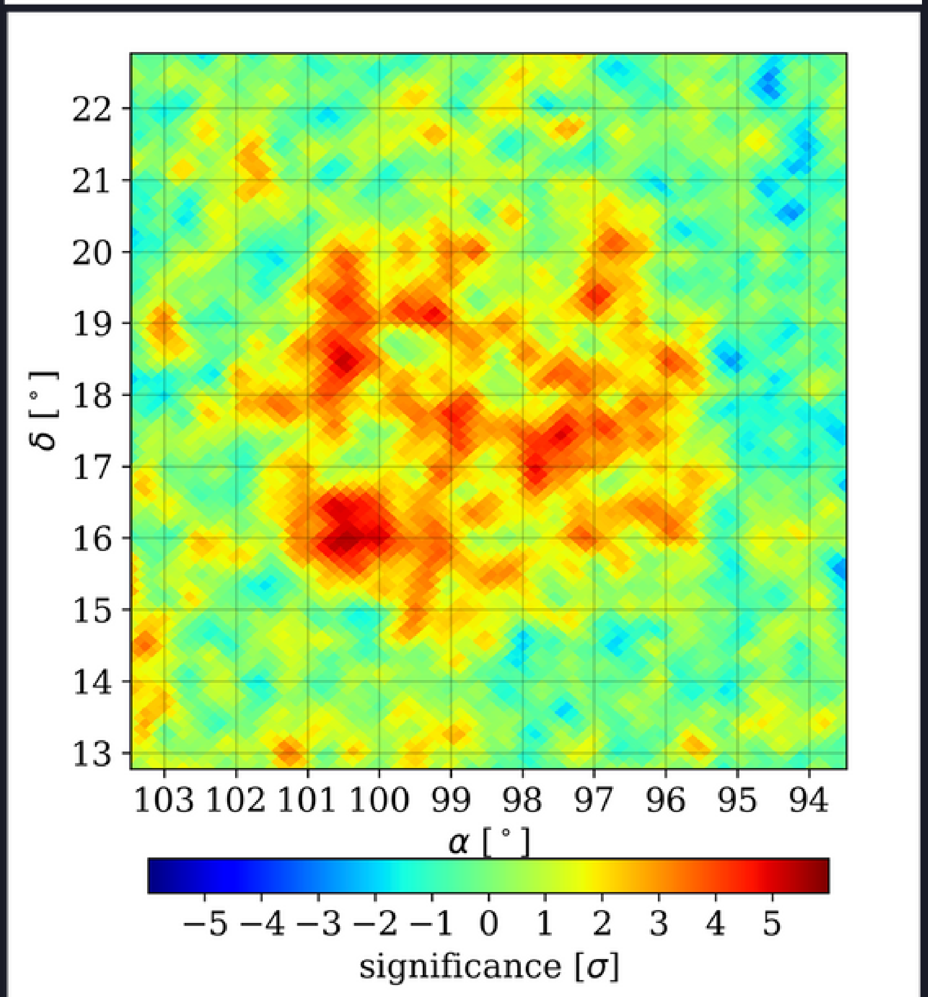
Real Maps





Simulated Maps





Remarks

- Our model is a good estimate of size, flux and HAWC significance.
- Dependency of the morphology with energy and distance to the pulsar needs to be added
    - Simulated source is injected as a disk with constant flux across.
- HAWC maps shown are for 1.5 year
    - more recent data spans 5 years!!
- HAWC sensitivity is improved with new software.
- 142 pulsars to be compared with HAWC's observations
- Need false positive rate