Are pulsar halos rare ?

Pierrick Martin (CNRS/IRAP, Toulouse)
with Luigi Tibaldo, Alexandre Marcowith, and Soheila Abdollahi

Are pulsar halos rare ?

Modeling the halos around PSRs J0633+1746 and B0656+14 in the light of *Fermi*-LAT, HAWC, and AMS-02 observations and extrapolating to other nearby pulsars

Pierrick Martin[1], Alexandre Marcowith[2], and Luigi Tibaldo[1]

Accepted in A&A
arXiv:2206.11803

Population synthesis of pulsar wind nebulae and pulsar halos in the Milky Way

Predicted contributions to the very-high-energy sky

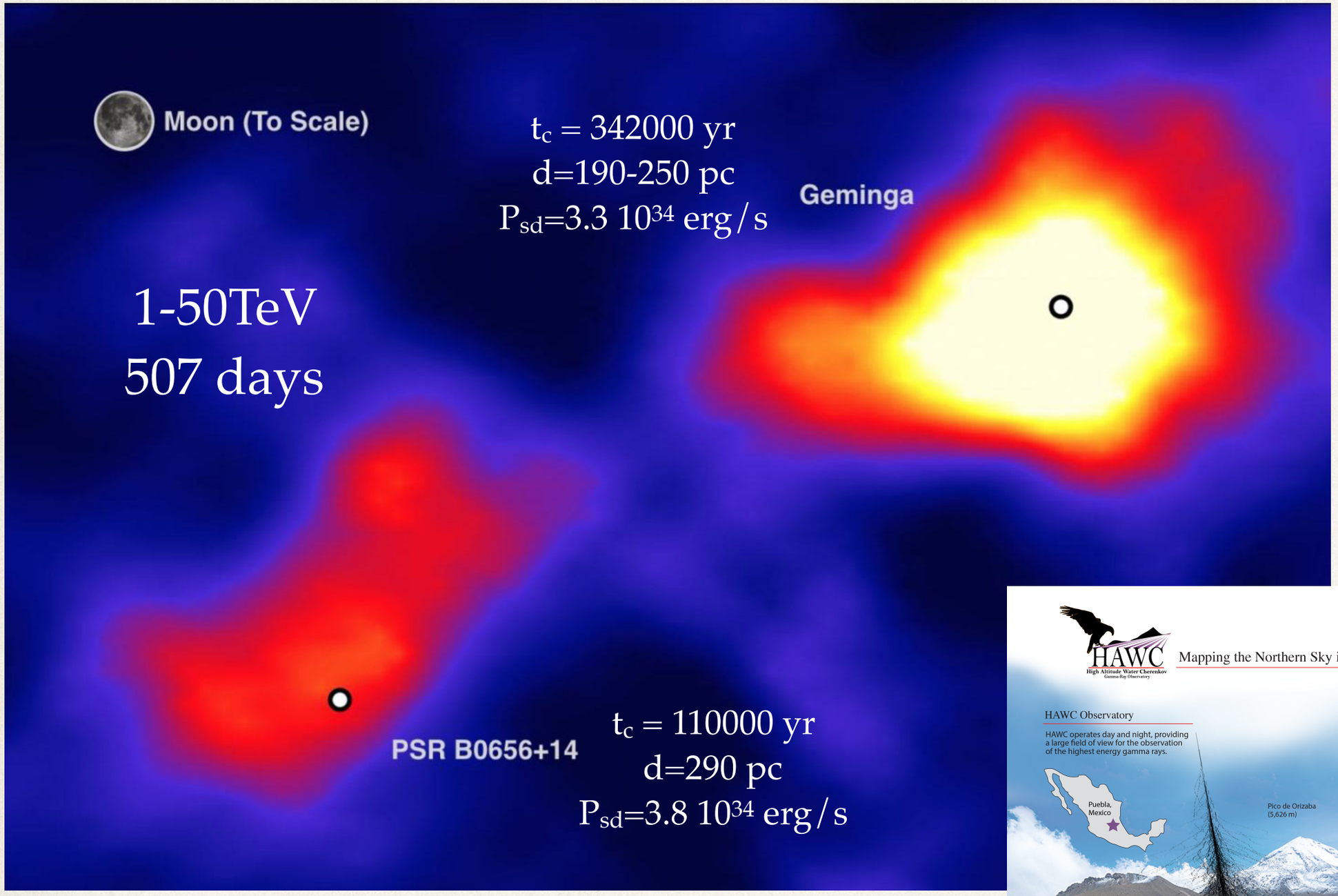
Pierrick Martin[1], Luigi Tibaldo[1], Alexandre Marcowith[2], and Soheila Abdollahi[1]

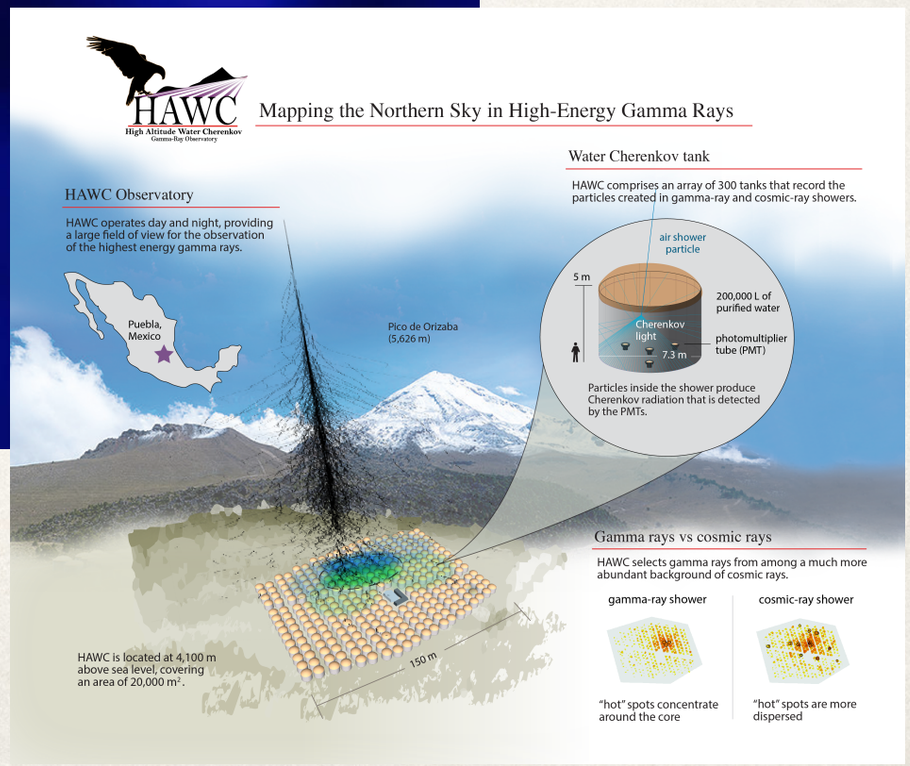
Submitted to A&A

7th Heidelberg Symposium - 04-08 July 2022

cnrs ANR AGENCE NATIONALE DE LA RECHERCHE

Brief recap on pulsar halos

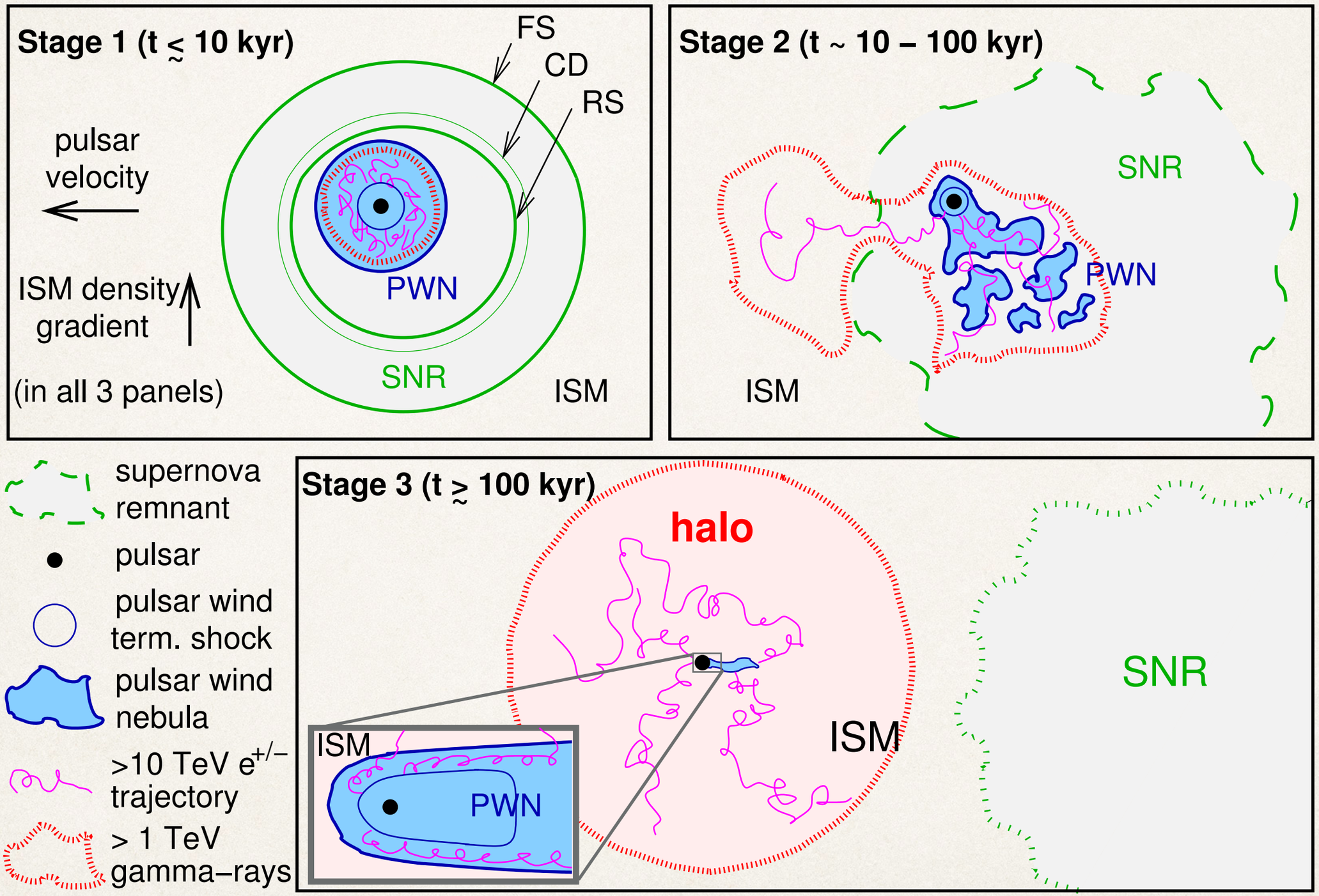




Abeysekara et al. 2017,Science, 358

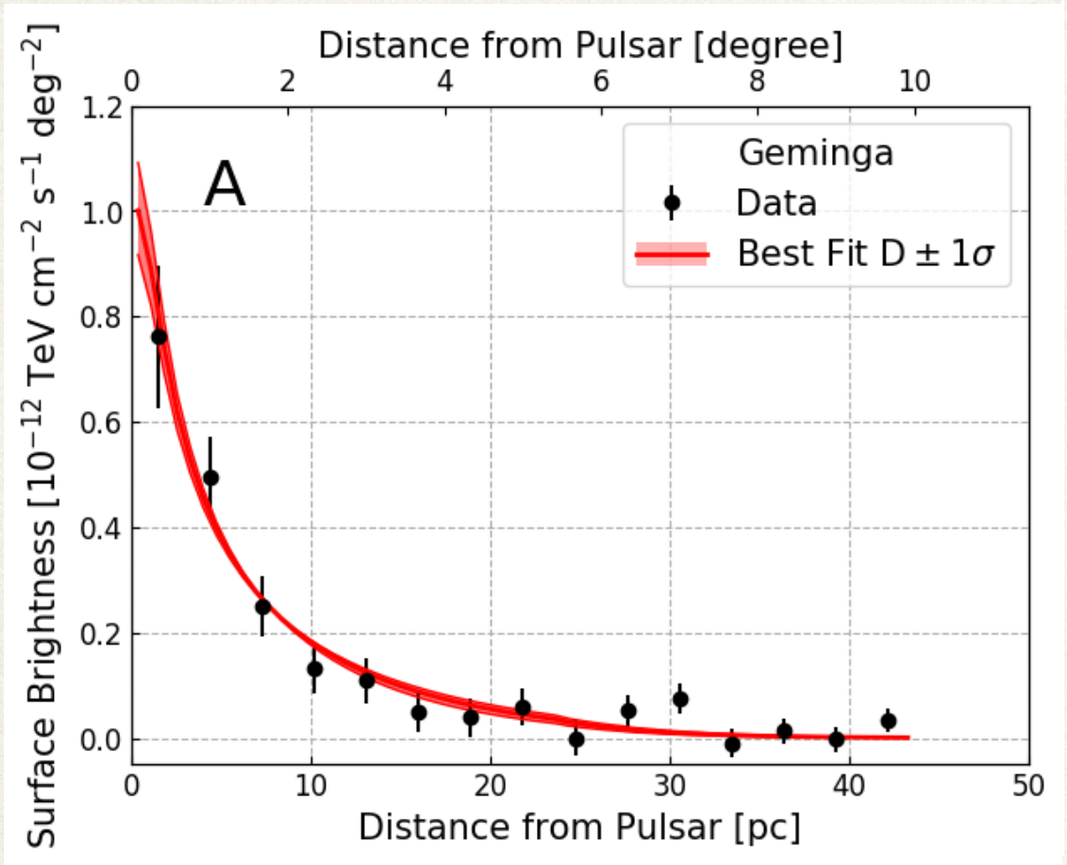
Abdo et al. 2009

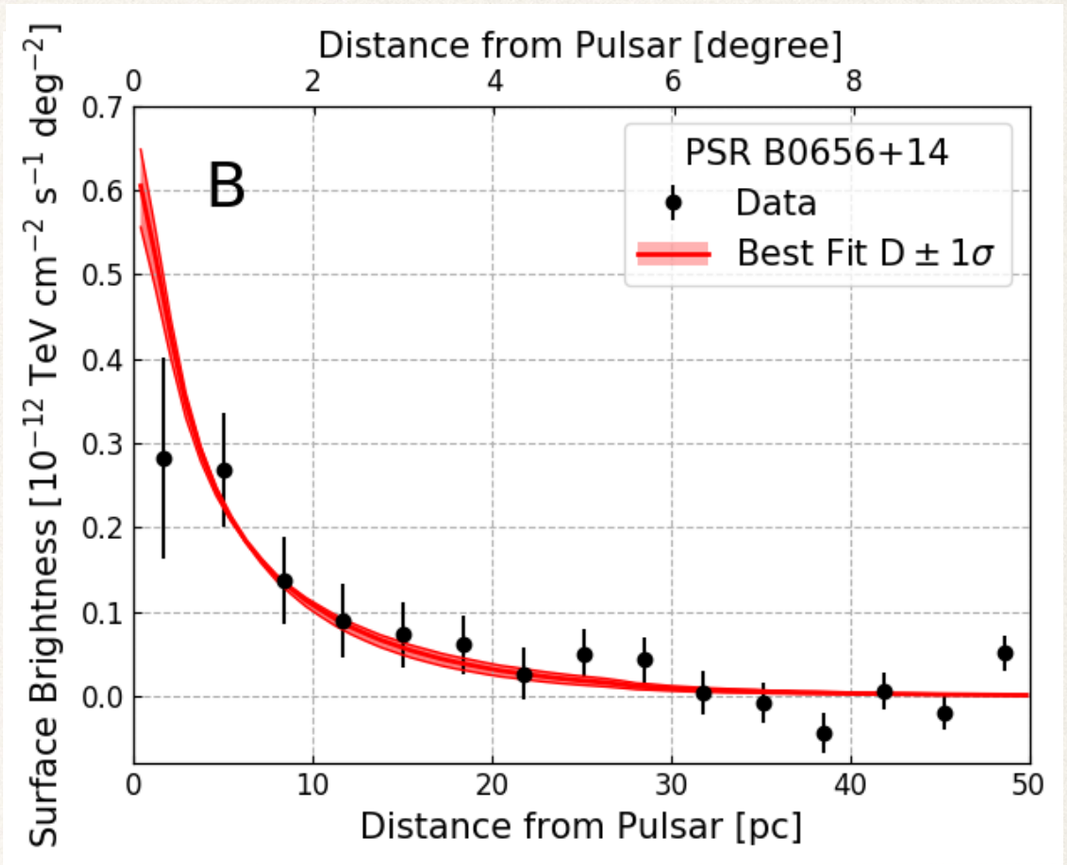
Brief recap on pulsar halos



Giacinti et al. 2020

Brief recap on pulsar halos





- Modeling the observed intensity profiles
  - **continuous injection** of pairs with power-law spectrum
  - homogeneous **diffusion-loss** transport **in the CSM/ISM**
  - **suppressed diffusion** within at least 20-30pc, with $\mathbf{D_{HALO} \sim D_{ISM}/100\text{-}1000}$
  - **inverse-Compton** scattering of ambient photons (CMB, IR)

Alternative scenarios: Recchia et al. 2021 (but see Bao et al. 2021)
Liu et al. 2019 (but see De La Torre Luque et al. 2022)

Goals of the works

- Motivations
  - Theoretical difficulty to achieve high levels of late confinement
  - Fraction of real halos in known gamma-ray sources unclear

Evoli et al. 2018, Lopez-Coto&Giacinti 2018, Fang et al. 2019, Mukhopadhyay&Linden 2021

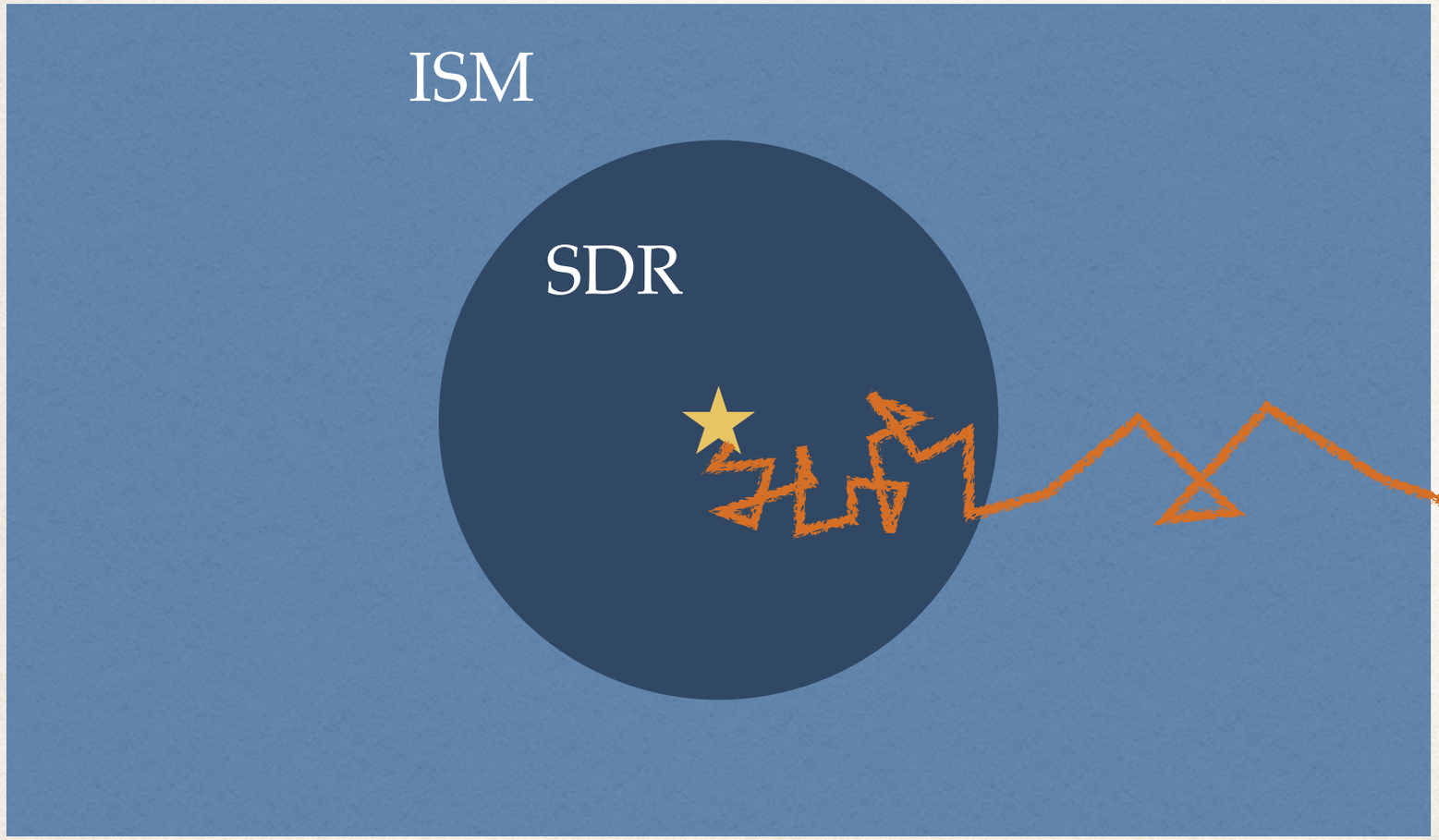
- Goal 1/3: Find a minimal model for halos around J0633 and B0656
  - Minimizing diffusion suppression extent and magnitude

- Goal 2/3: Extrapolate to other nearby middle-aged pulsars d<1kpc
  - Can they all develop a halo ?

- Goal 3/3: Assess the contribution of halos to the VHE landscape
  - Are current TeV observations consistent with widespread halos ?
  - How many halos could be detectable in future surveys ?
  - What is the level of unresolved emission from halos ?

Model framework

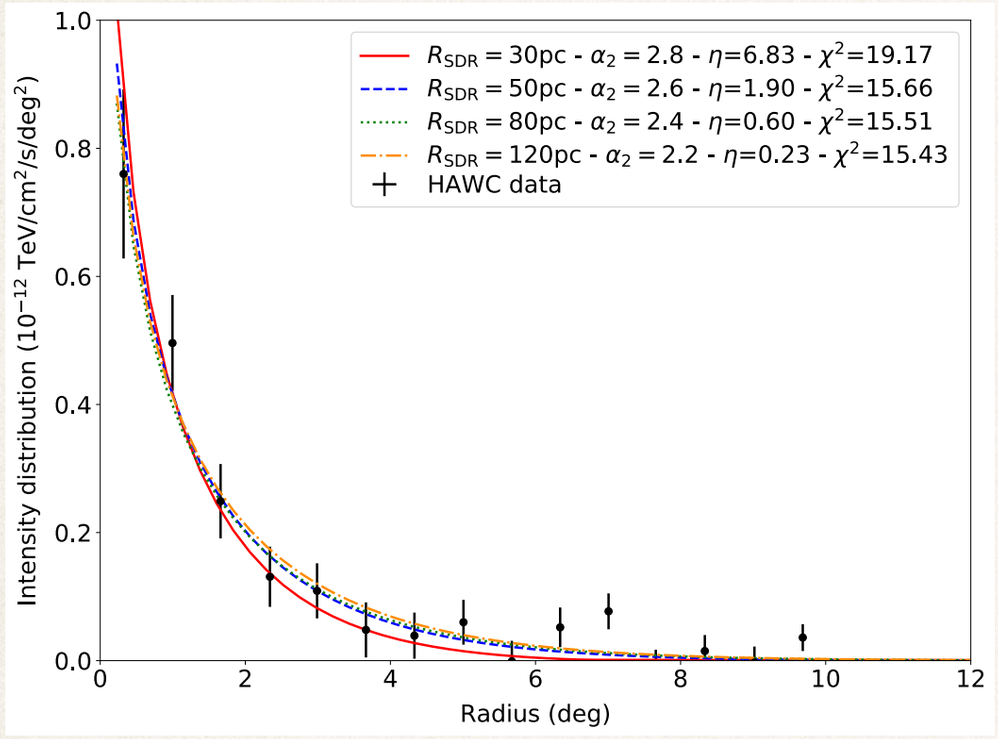
- Phenomenological halo model
  - Static two-zone diffusion-loss model *(Di Mauro et al 2019, Tang&Piran 2019)*
  - Injection is typical of PWNe but delayed *(Bucciantini et al 2011, Torres et al. 2014)*
    - Broken power law with index 1.5/2.0-2.8 below/above 100GeV
    - Constant efficiency 10-100% of pulsar spinning down with n=3
    - Start time 20-80kyr

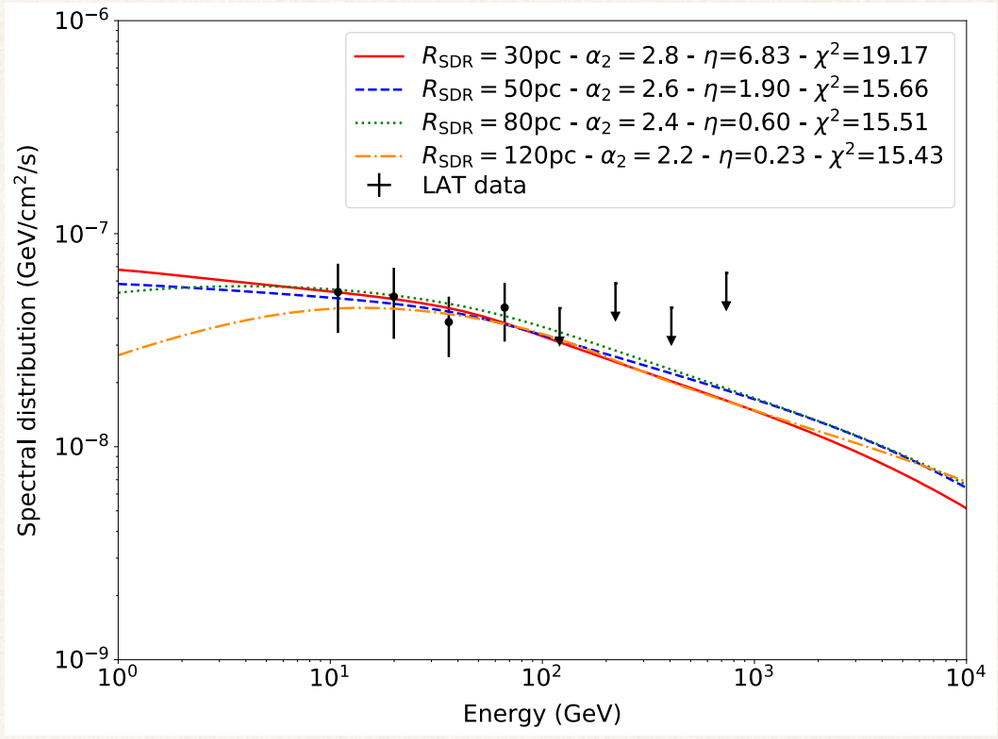


Suppressed diffusion region
Extent >20-30pc
Suppression level 100-1000

Note: Neglect pulsar's motion (not interested in morphology)

Model fits for J0633+1746

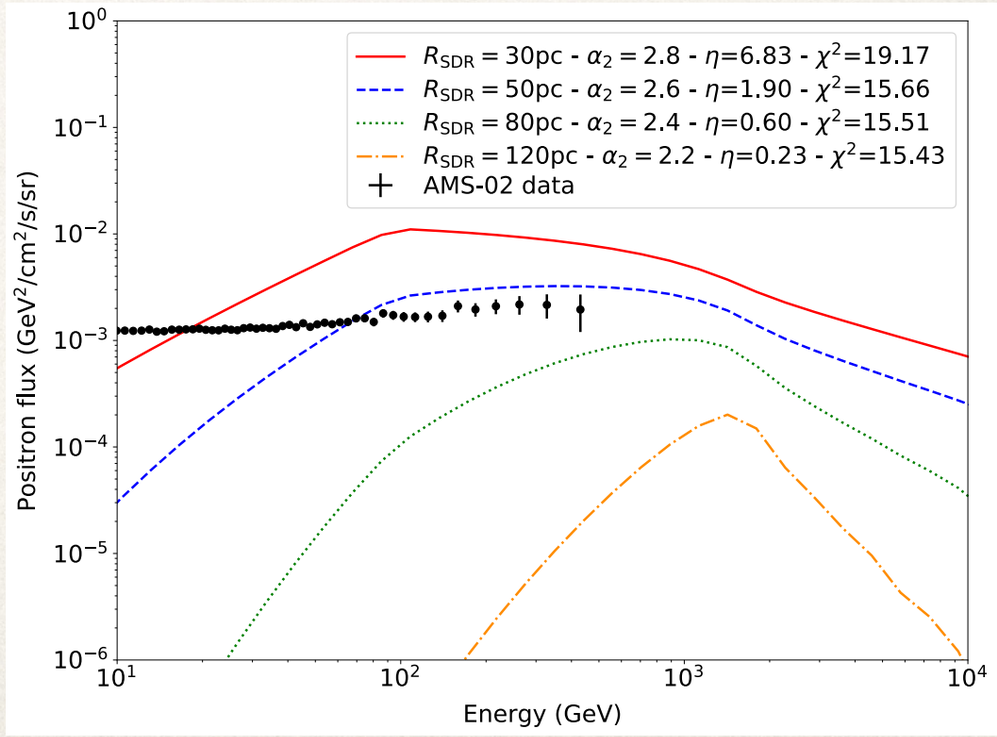




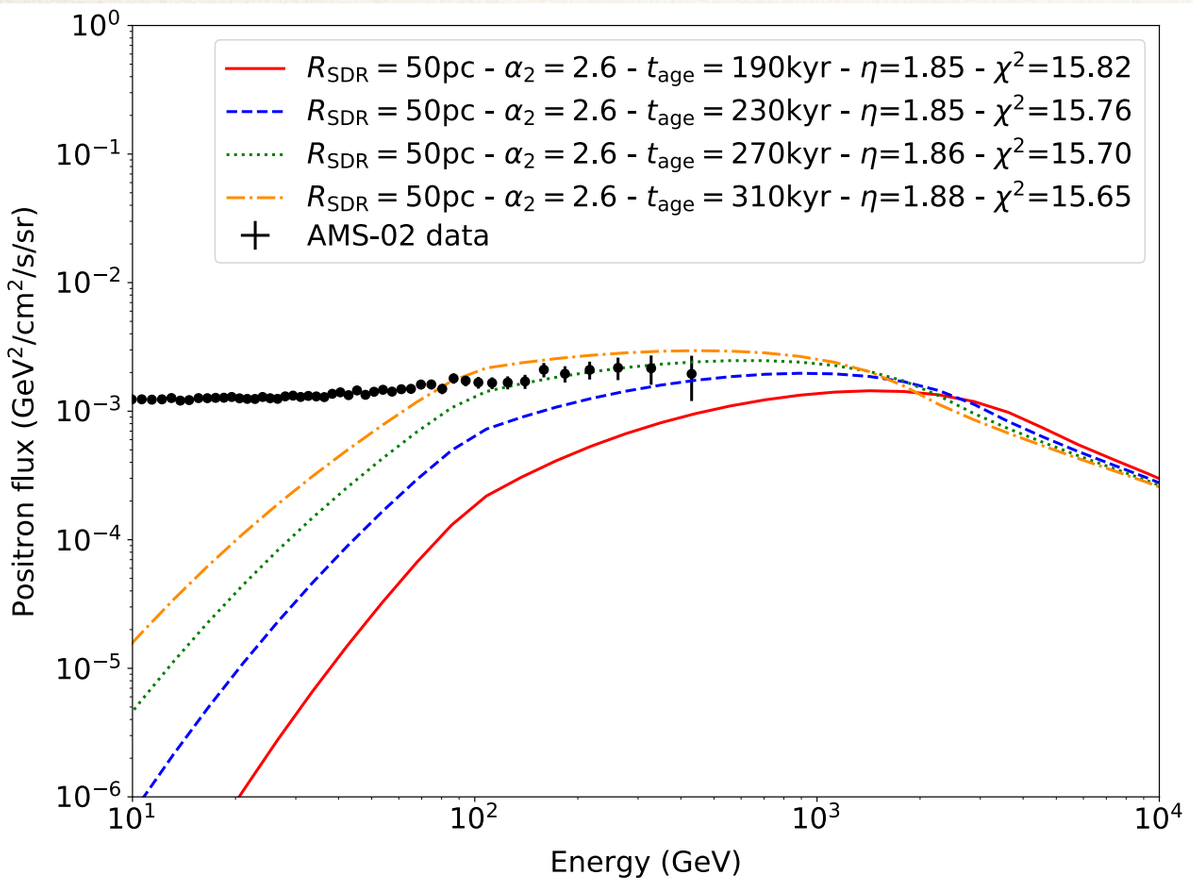
HAWC data require diffusion suppression by ~500 around Geminga

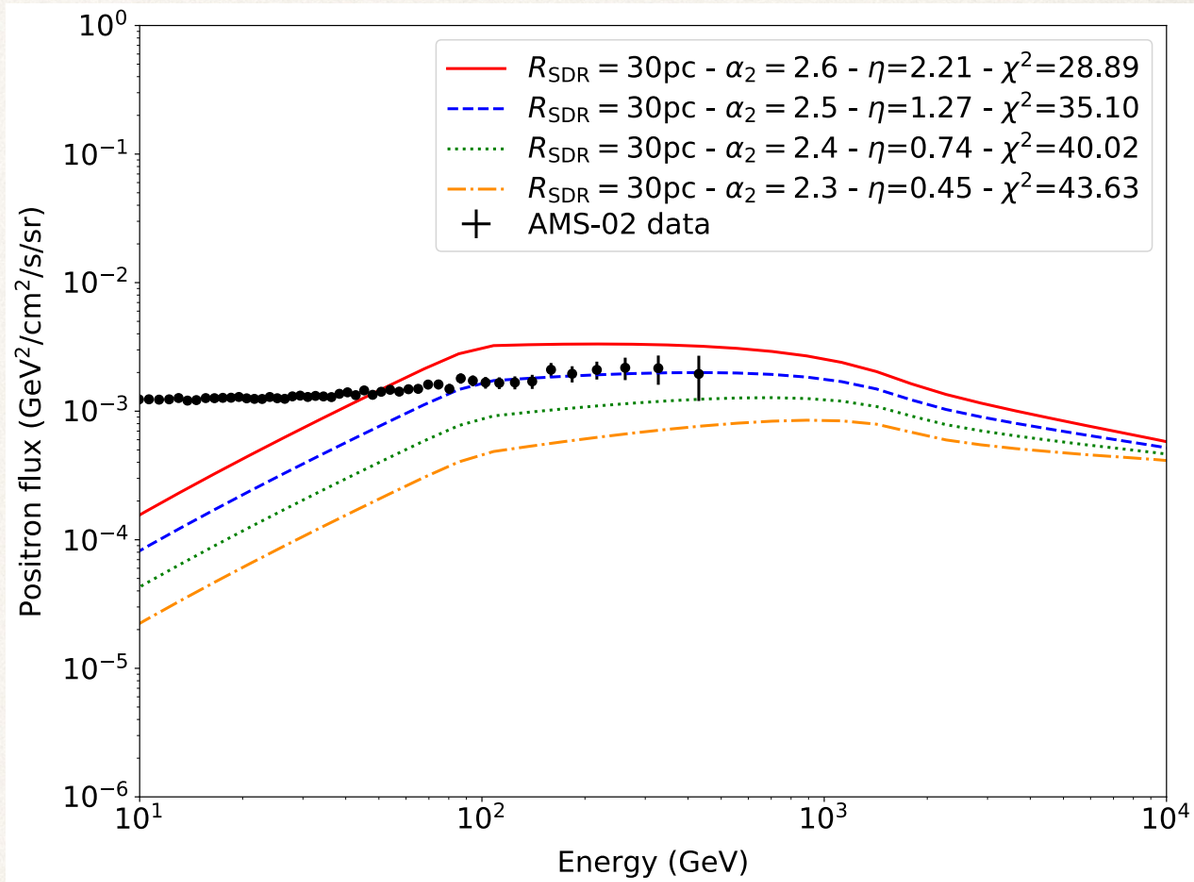
Small sizes 30-50pc require >200% efficiency (because steep injection) and lead to excessive positron flux

(Martin et al. 2022)



Model fits for J0633+1746





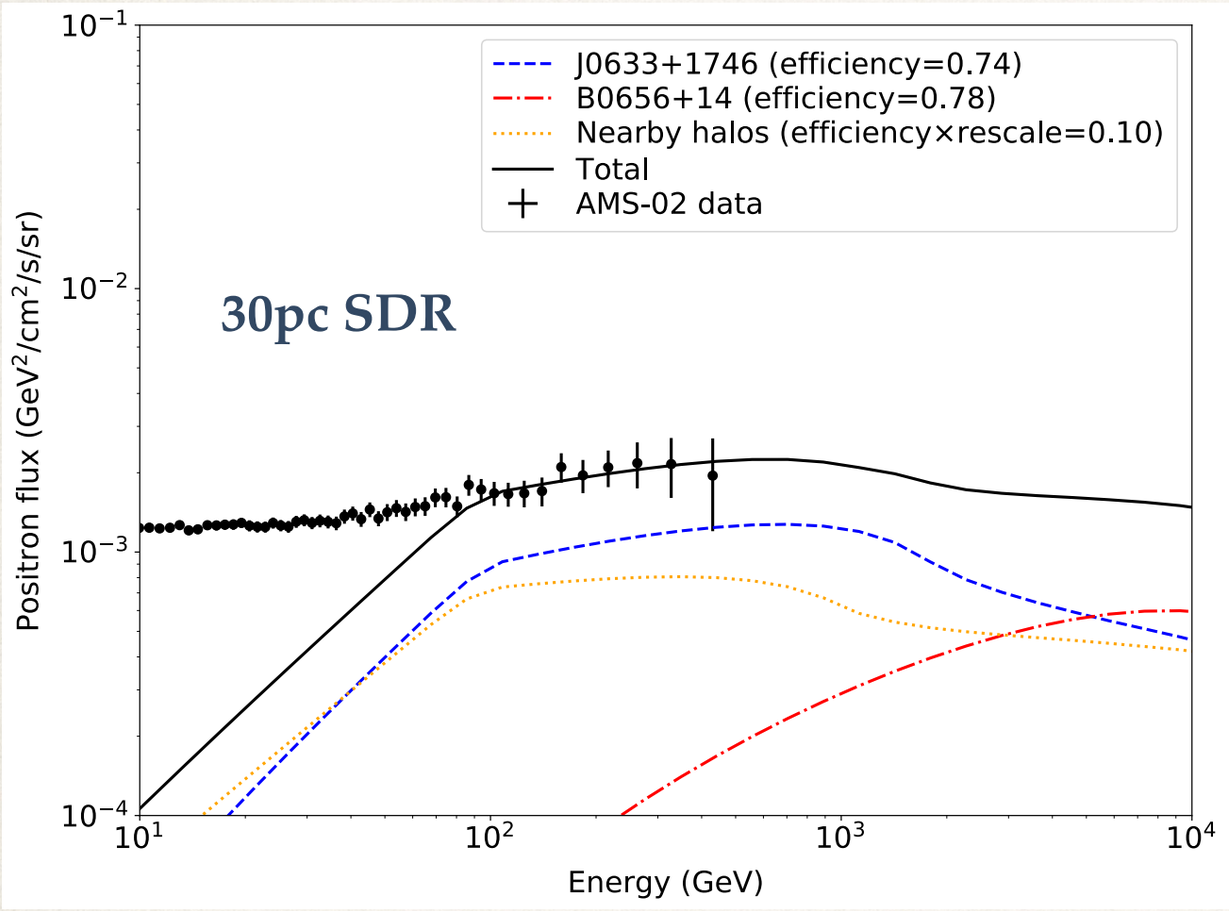
Solutions to excessive positron flux and efficiency for Geminga: Smaller ages to reduce time for diffusion and shift positron flux peak and/or relaxing LAT constraint to allow harder injection (Xi et al. 2019) (and/or higher than average ISRF locally)

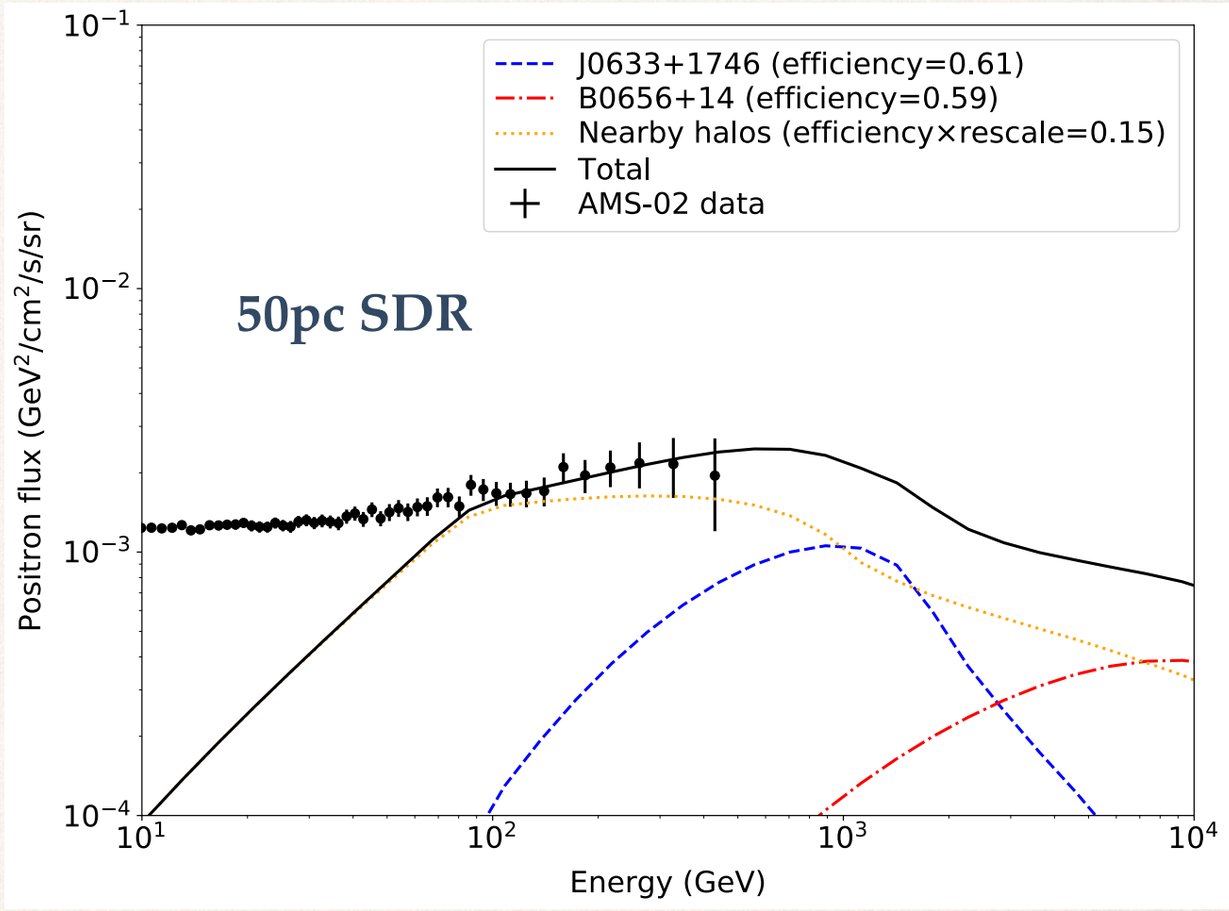
Summary for goal 1

- There are solutions for B0656 and J0633
  - with injection spectrum typical of (young) PWNe
  - with injection efficiencies ~50-100% typical of PWNe
  - with smallest possible diffusion suppression extent ~30pc
  - with diffusion suppression levels ~50-500

What if all other nearby middle-aged pulsars develop halos ?
(14 in the ATNF data base within 1kpc)

Positron flux from nearby pulsars

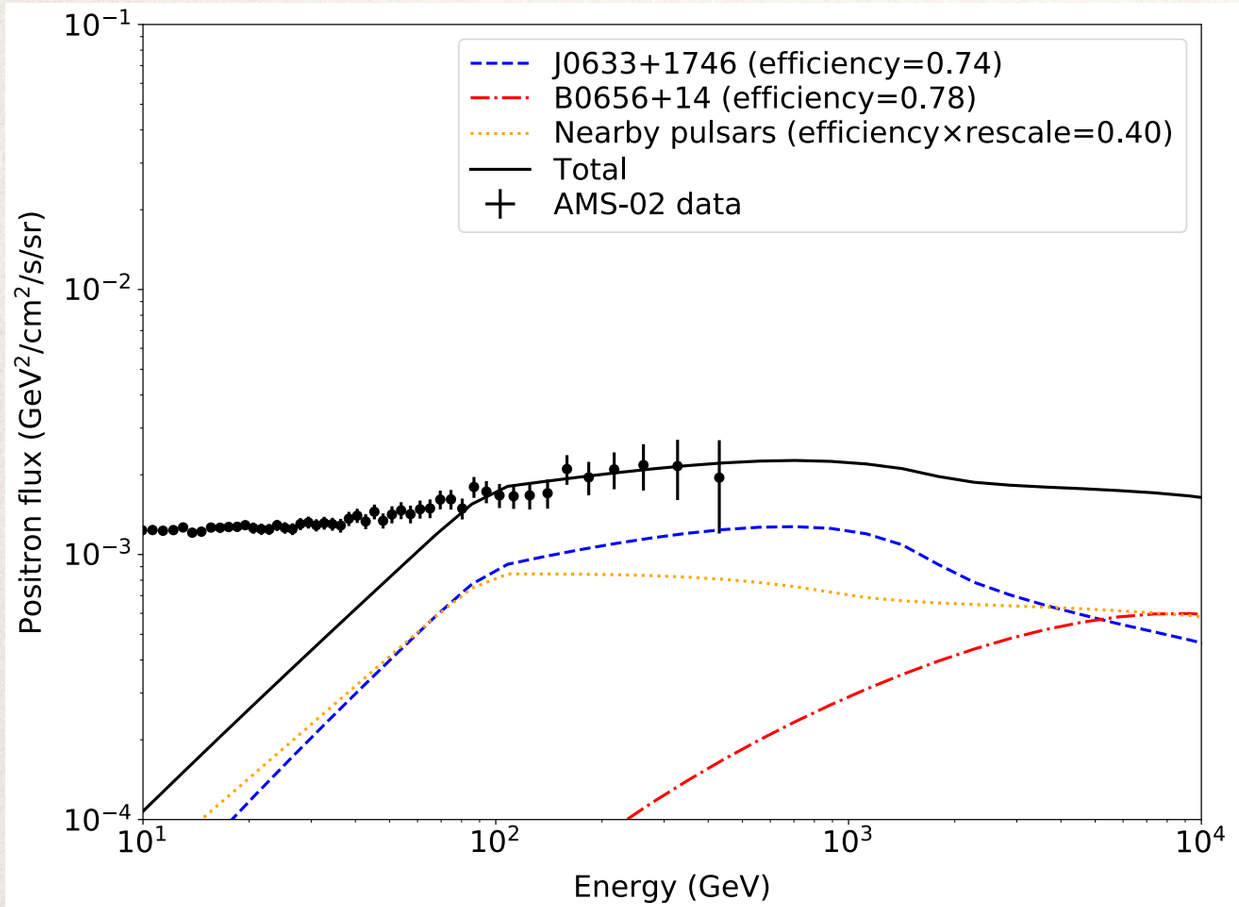


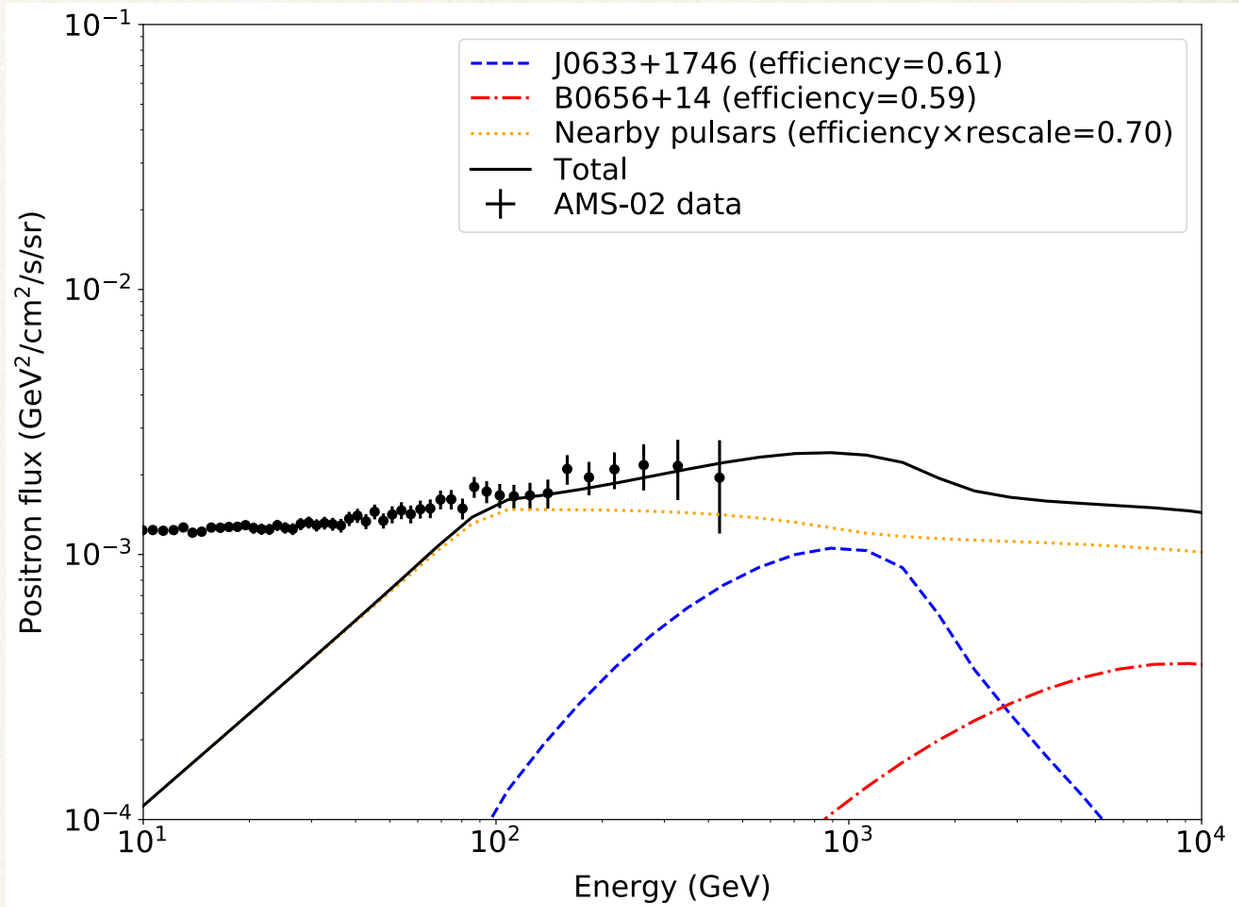


If other nearby <1kpc middle-aged pulsars DO develop Geminga-like halos:
Total positron flux exceeds measurement unless injection efficiency < 10-15 %

Not typical of PWNe. Not even typical of halos.
Decrease of injection efficiency between young PWNe and older halos ?
But why did J0633 and B0656 retain high efficiencies ?

Positron flux from nearby pulsars

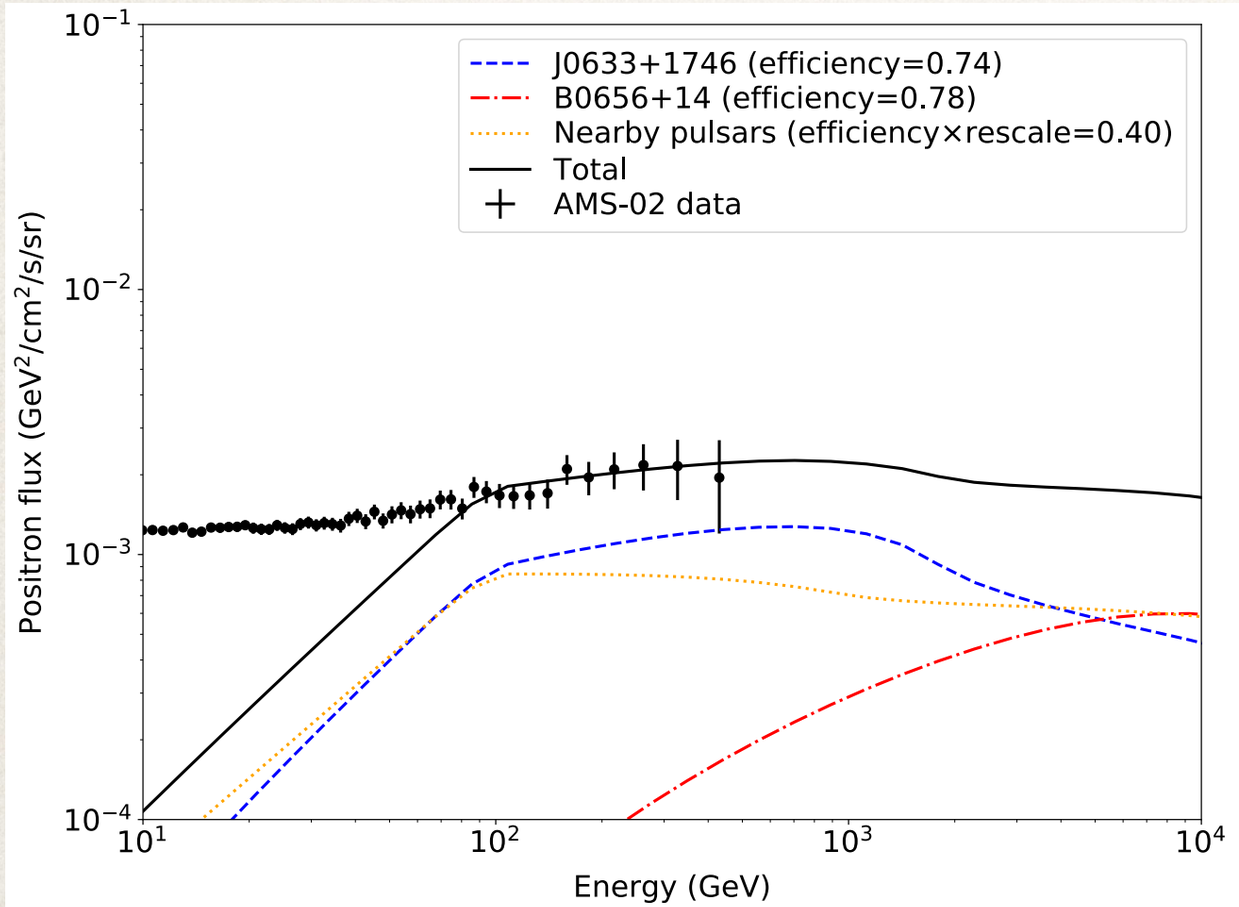


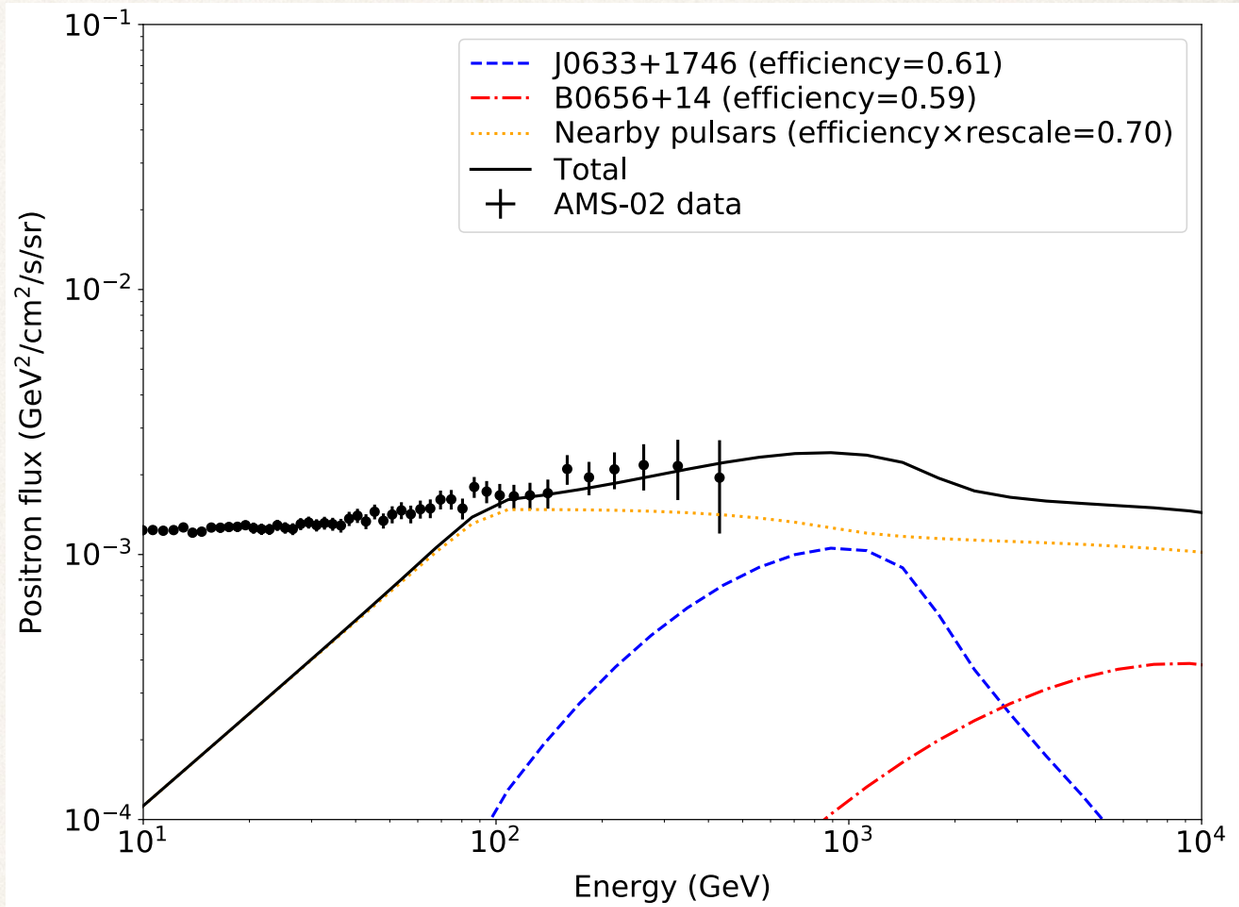


If all other nearby <1kpc middle-aged pulsars DO NOT develop halos:
Injection efficiencies 40-70% allowed

All pulsars have similar injection properties over first few 100kyr
This requires no exceptional status for J0633 and B0656

Positron flux from nearby pulsars





A more simple scenario is that pulsar halos are rare
Halo occurrence rate would be 5-10% (2 objects out of >16 nearby pulsars)

BUT ! Injection discrepancy between scenarios
very much dependent on actual population properties
and pair injection in early times

Summary for goal 2

- More simple solution is that halos are rare
  - Halo occurrence rate could be as low as 5-10%
  - BUT ! this conclusion very much dependent on
    - actual population properties
    - pair injection in early times

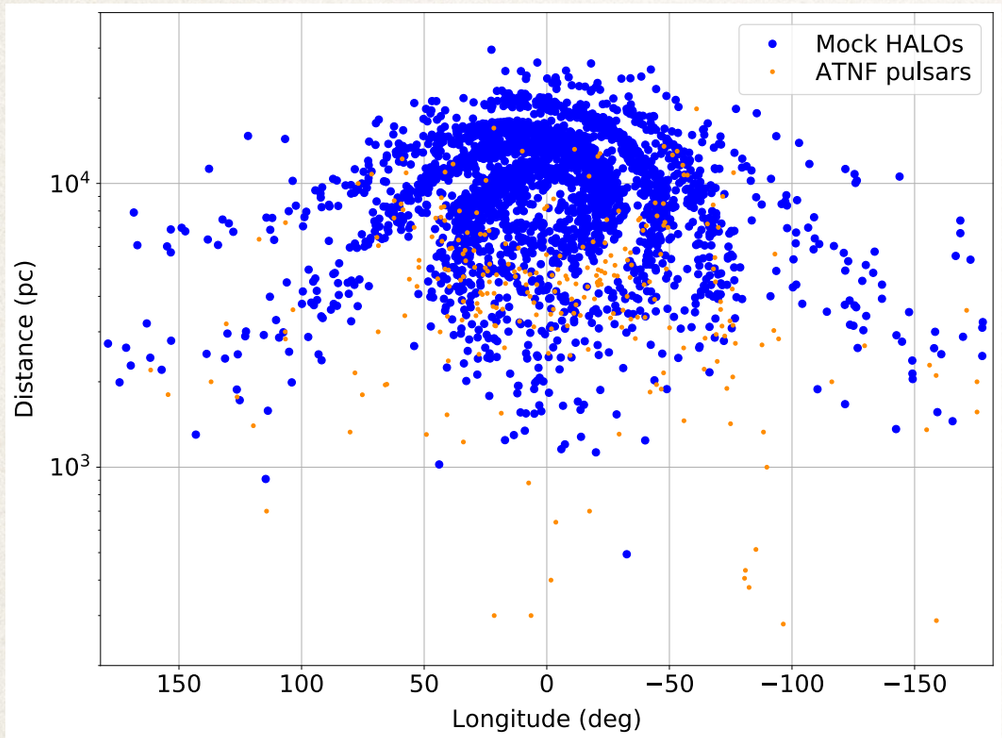
Can we go further from the existing census of Galactic VHE sources ?

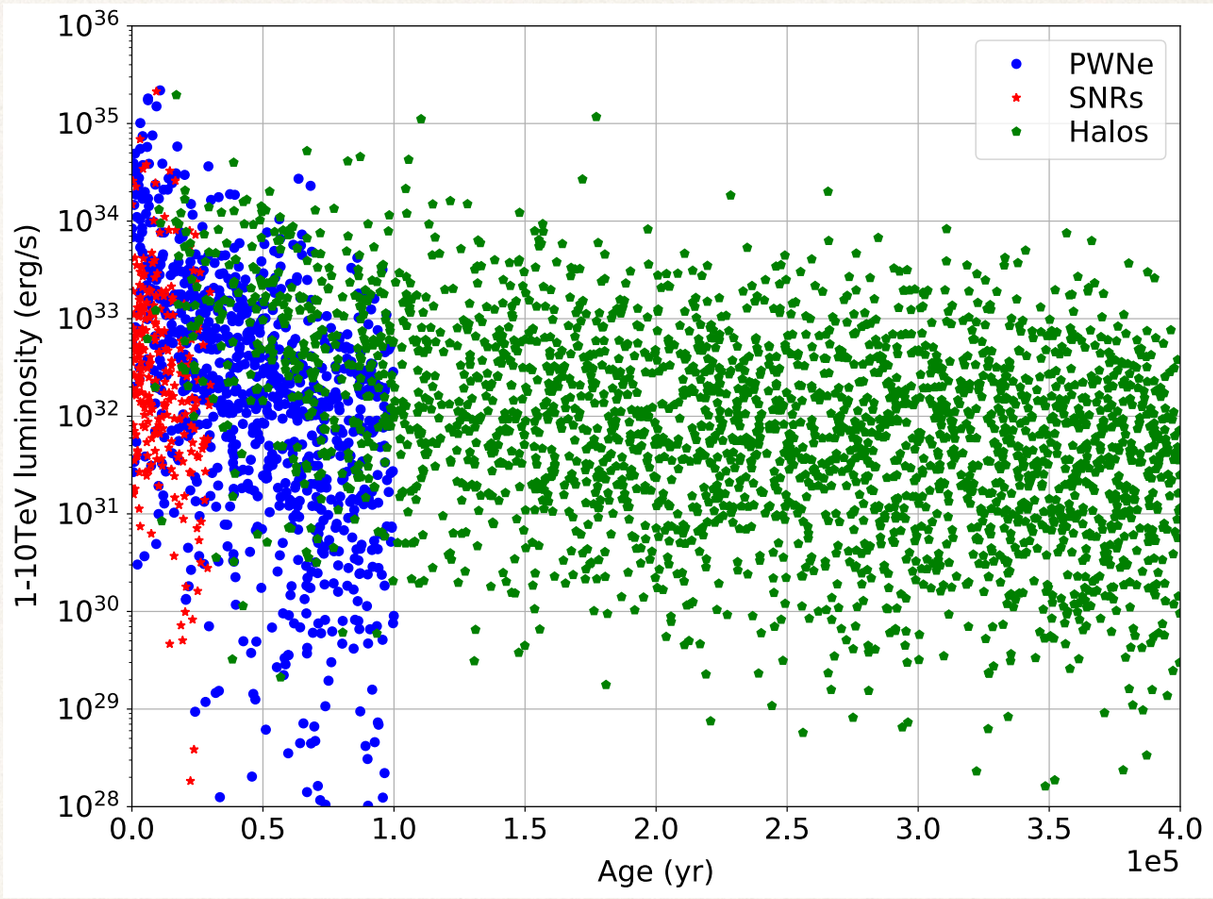
Model

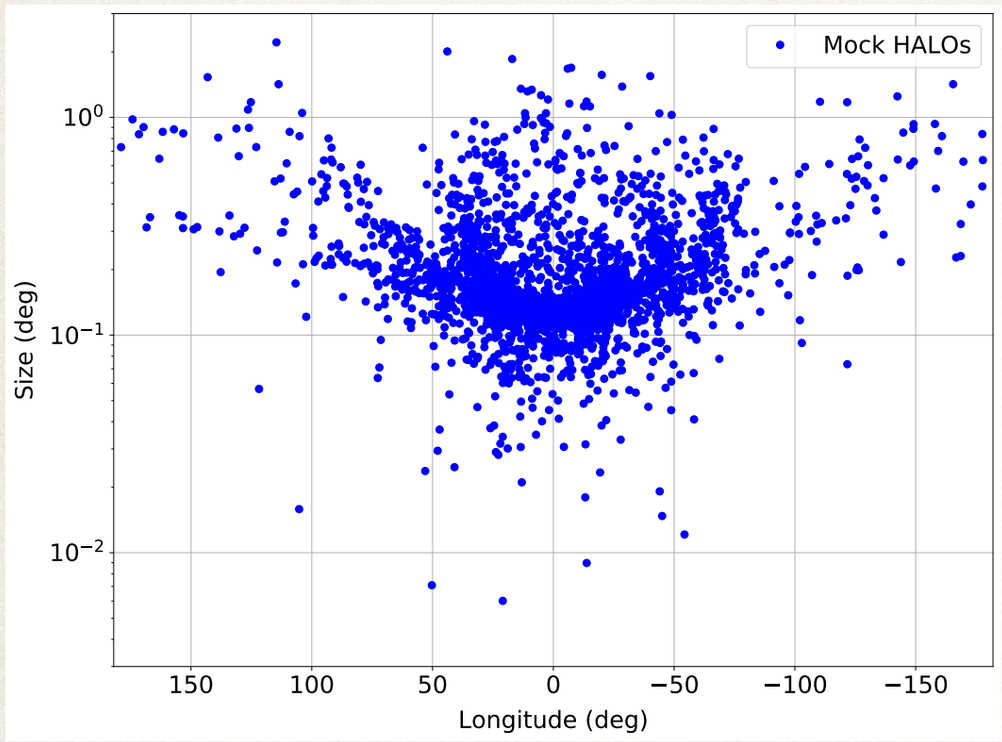
- Individual objects
  - SNRs from Cristofari et al. 2013
  - PWNe from Abdalla et al. 2018
  - Halos around all middle-aged pulsars with different options
    - J0633-like halos with 30,50,80pc sizes and B0656-like halos with 50pc size
    - Injection in halos starts when pulsar exits initial nebula (at 20-80kyr)
    - PWNe then proceeds as relic (no more injection, only ageing)

- Galaxy
  - Magnetic field from Strong et al. 2000
  - Radiation field from Popescu et al. 2017
  - Density distribution at SNRs from Leahy et al. 2020
  - Pulsar spatial distribution from Faucher-Giguere et al. 2006
  - Supernova properties: r_{SN}=2/100yr and $r_{CC/Ia}$=2 and r_{PSR}=1/100yr

Population properties

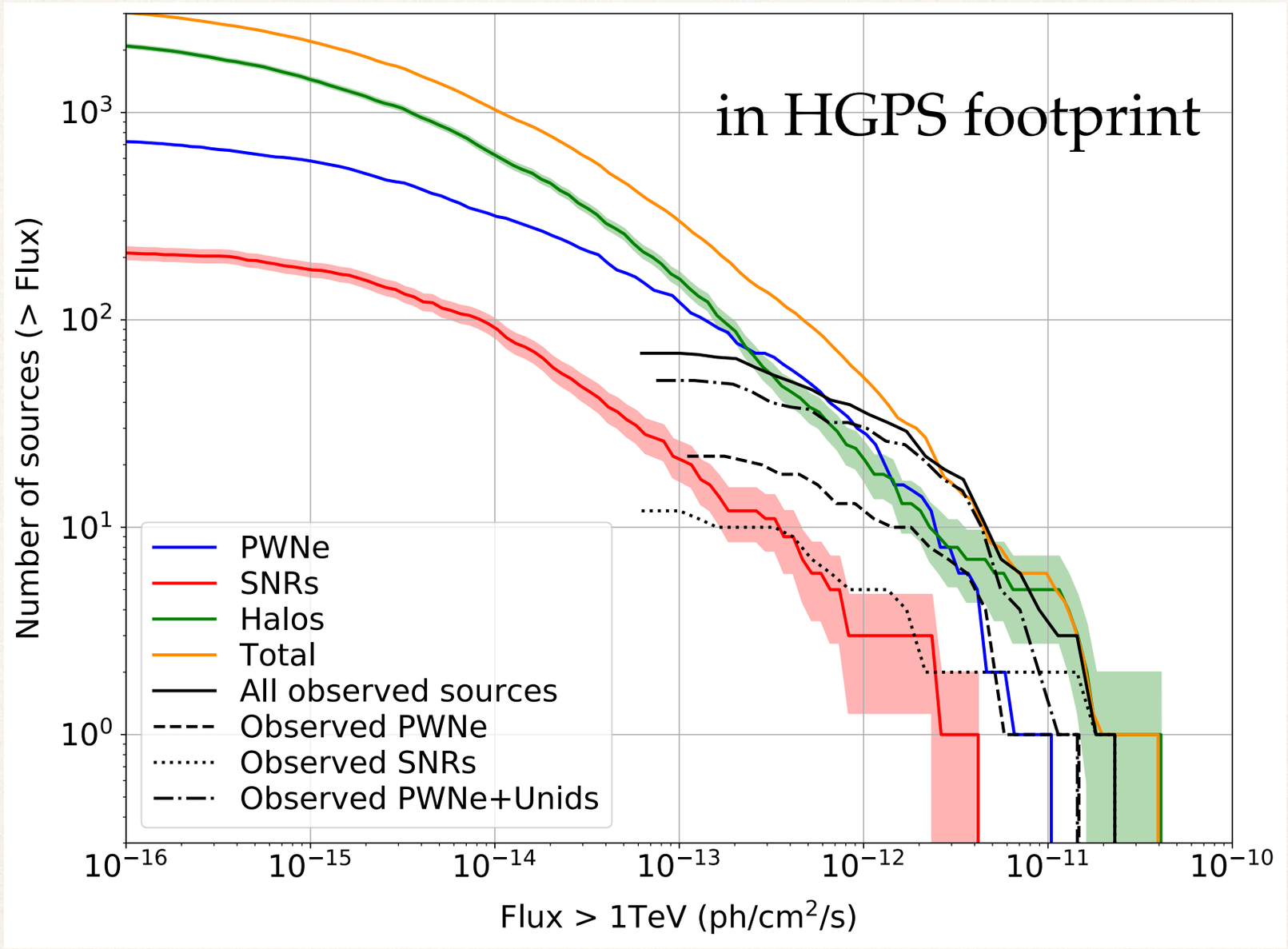






Caveat: deficit of <1kpc objects (no local arm in model)

Flux distributions



Mock PWNe marginally consistent with observed PWNe + UnIDs

Halos seem viable counterparts to some UnIDs

Detection prospects

Geminga-like halos

Survey	SNRs	PWNe	Halos (30 pc)	Halos (50 pc)	Halos (80 pc)	Total
Total in population	266	945	2613	2613	2613	3824
H.E.S.S. (HGPS)	8	54	17	23	23	79/85/85
HAWC (3HWC)	2	19	10	15	16	31/36/37
CTA (GPS)	30	171	43	74	103	244/275/304
CTA (GPS+)	44	261	103	166	217	408/471/522

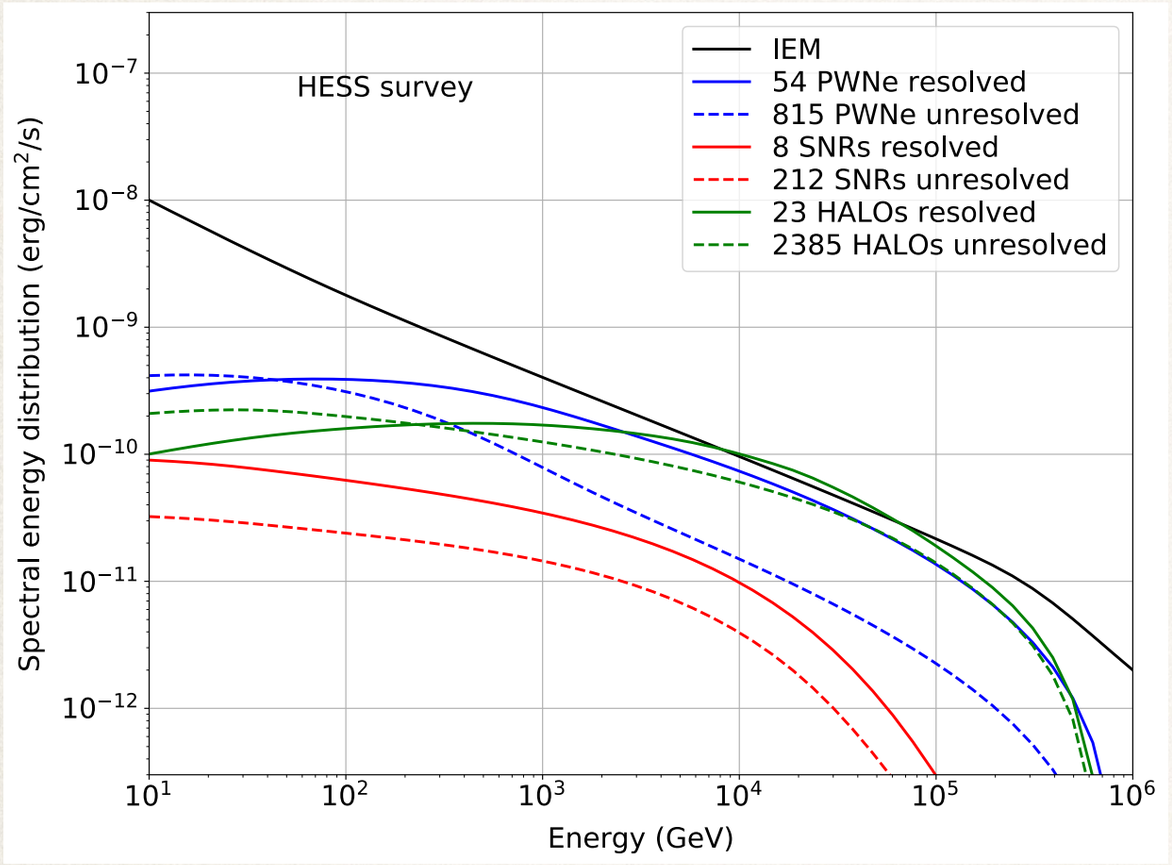
Nice match to HGPS results with ~50 PWNe and ~20 halos
Underestimate for HAWC 1523-day survey with ~35 objects versus 48-65

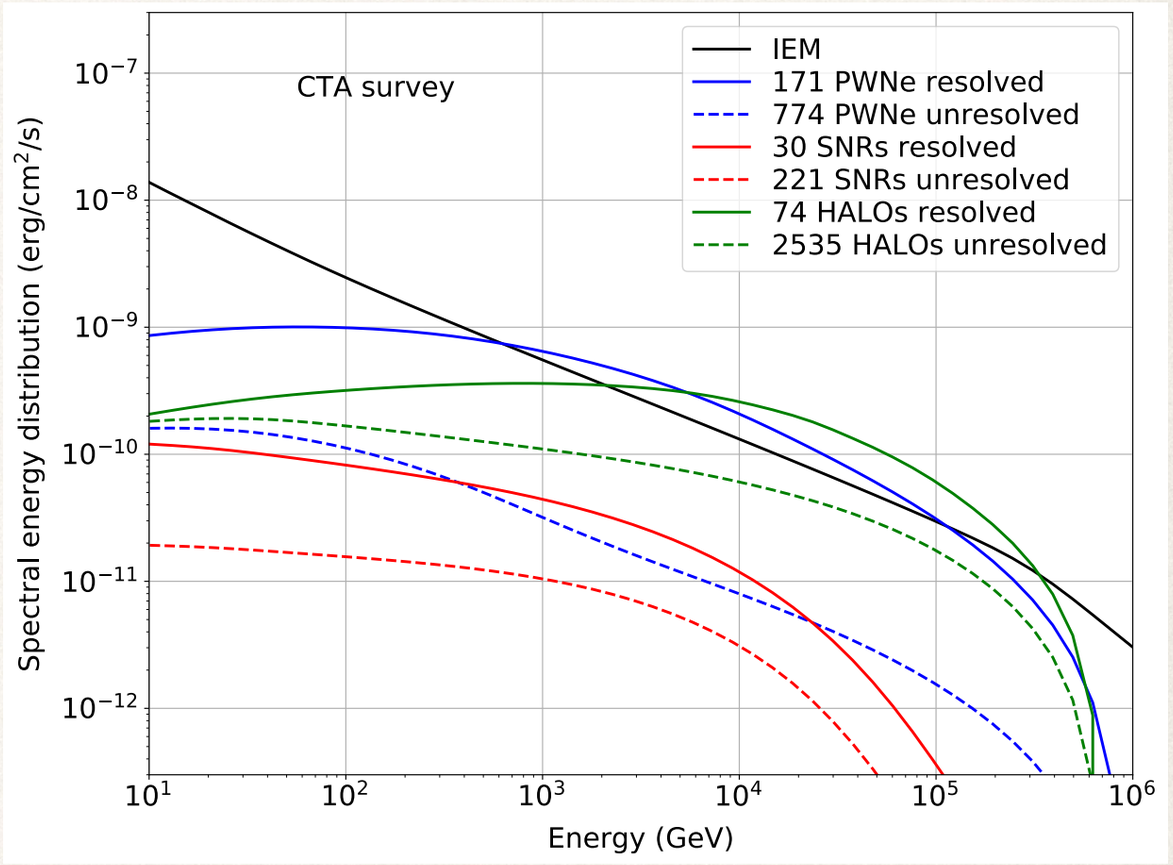
Prospects for CTA: 150-250 PWNe and 50-200 halos
Sensitive to halo extent and rising fast as sensitivity improves

Caveats: simple flux criterion for detectability
+ single characteristic size for each object (at TeV energies)

See poster #428 by Vodeb et al. for more refined prospects for CTA

Contribution to diffuse emission





HESS survey: unresolved halos comparable to interstellar emission

CTA survey: widens the gap between resolved/unresolved

(using De La Torre Luque et al. 2022 ``Base Max'' model as reference)

If only 5-10% of pulsars do develop halos,

unresolved emission is subdominant

Summary for goal 3

- Widespread halo consistent with current TeV obs.
  - (Geminga-like around all middle-aged pulsars)
  - 15-20 sources in each of the HESS and HAWC surveys
  - 50-200 in future CTA survey
  - Subdominant contribution as unresolved diffuse

Conclusions and perspectives

- The commonness of pulsar halos is still unclear
  - Rare scenario suggested by local positron flux constraint+ATNF
  - Widespread scenario consistent with Galactic TeV observations

- The occurrence rate could be as low as 5-10%

- Going beyond static phenomenological diffusion model
  - Dynamical effects *(Evoli et al. 2018, Mukhopadhyay et al. 2021)*
  - Early stages: PWN-halo transition (after reverse-shock crushing ?)
  - Late stages: Halo dissolution into ISM ?