Constraining the Enigma of Pulsar Halos with eROSITA

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with Manami Sasaki (FAU), Werner Becker (MPE), Alena Khokhriakova (MPE), et al.

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FAU

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eROSITA

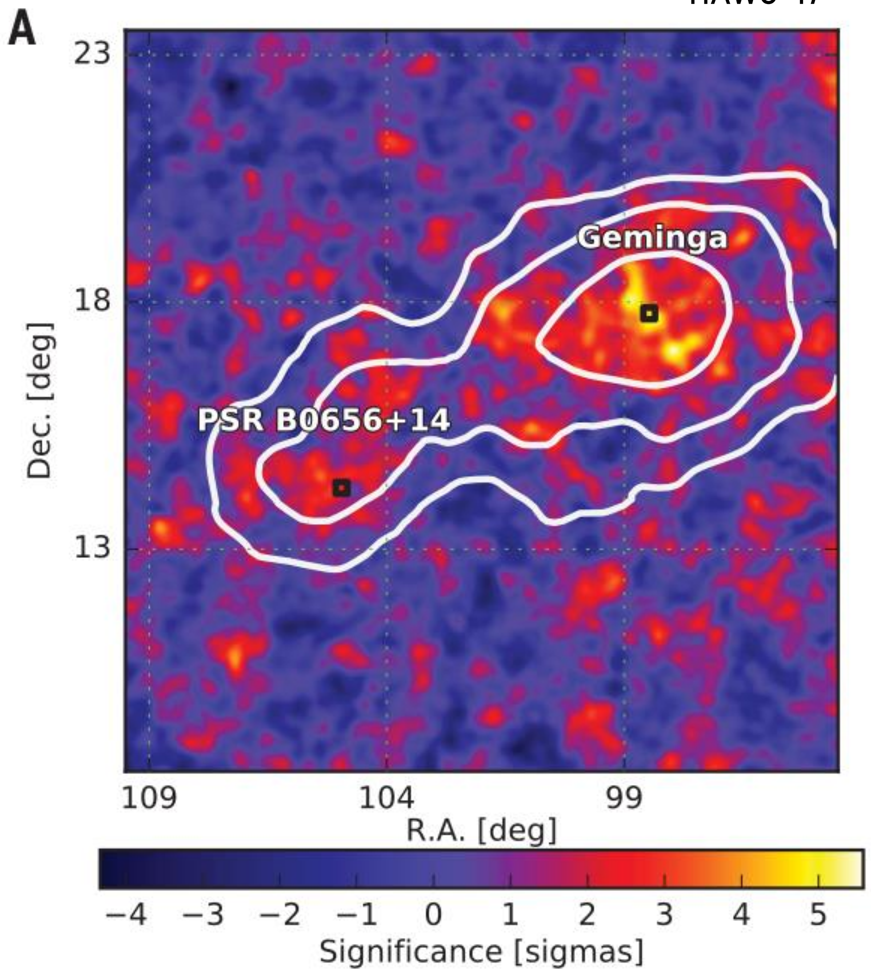
Walter Benjamin-Programm

DFG Deutsche Forschungsgemeinschaft

Pulsar halos and their problems

- Extended γ-ray emission around middle aged pulsars ($\sim 10^5 - 10^6$ yr)
  - ➢ Inverse-Compton emission of TeV electrons (HAWC+17)

TeV significance map of HAWC halos
HAWC+17



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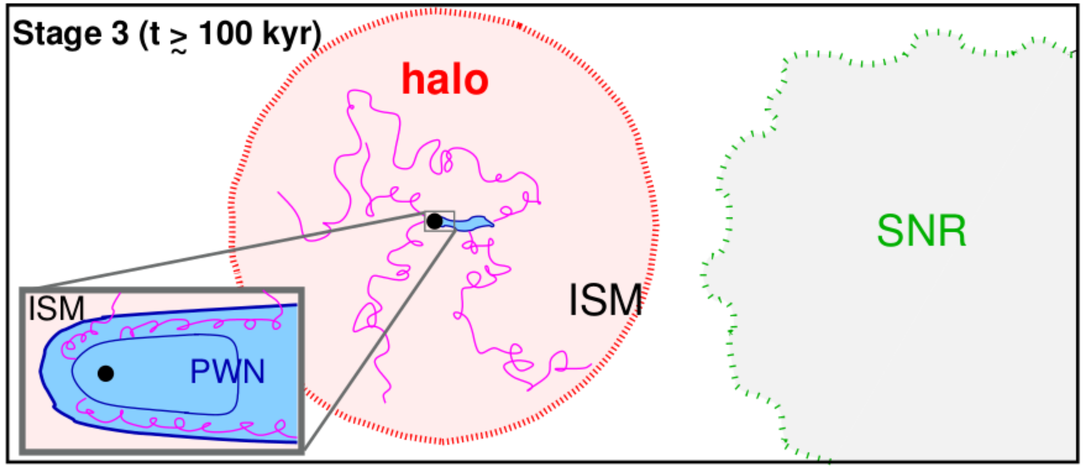
  - ➢ Diffusion much slower than in ISM ($D \sim 10^{27}$ cm²/s)

Halos as late evolutionary stage of PWNe
Giacinti+20



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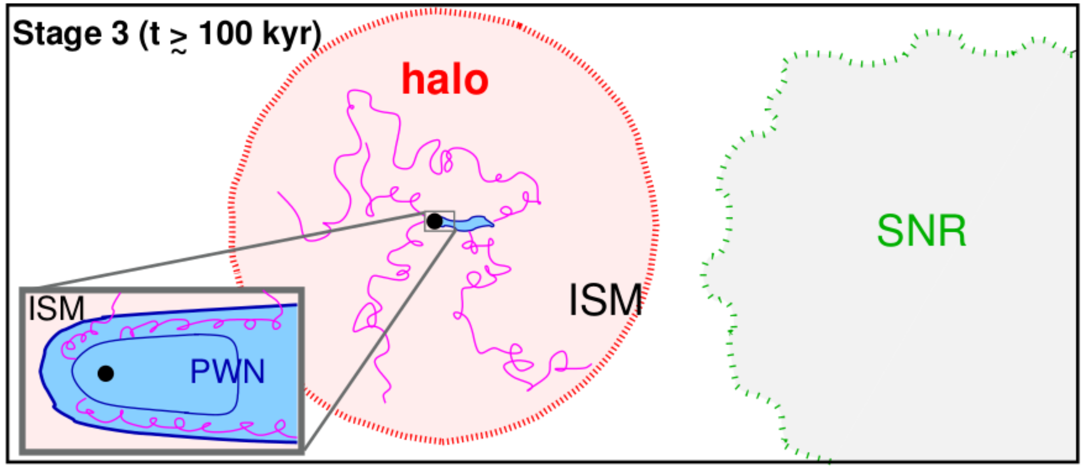

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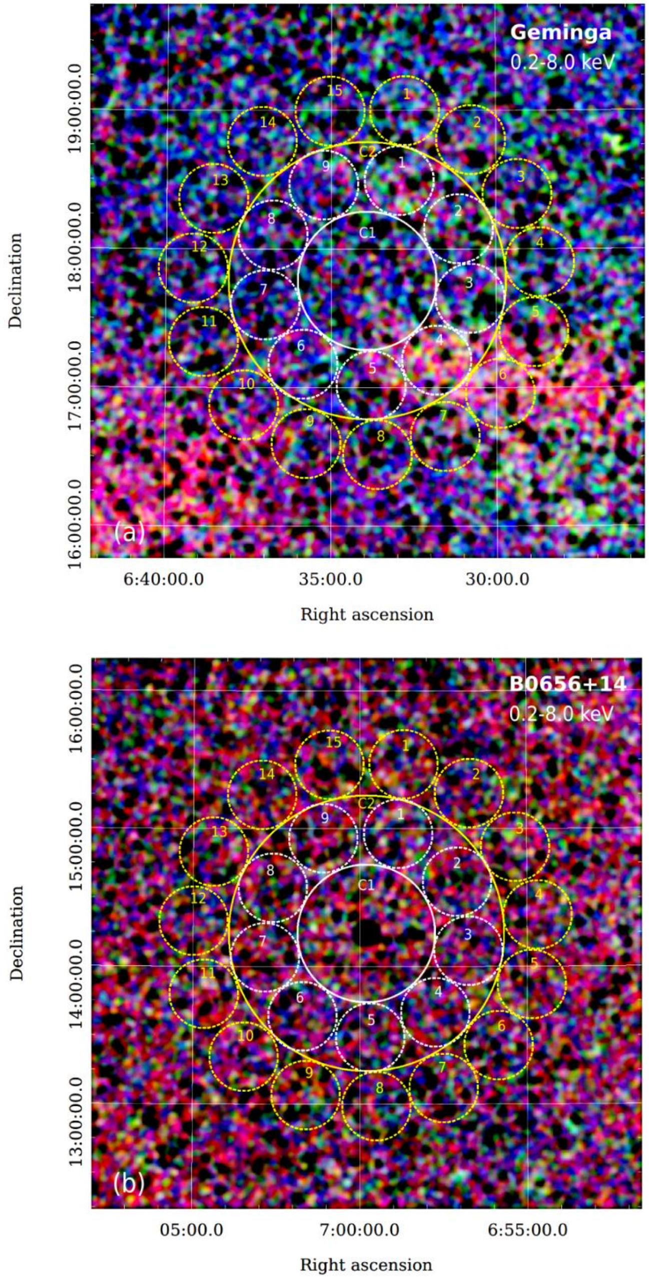
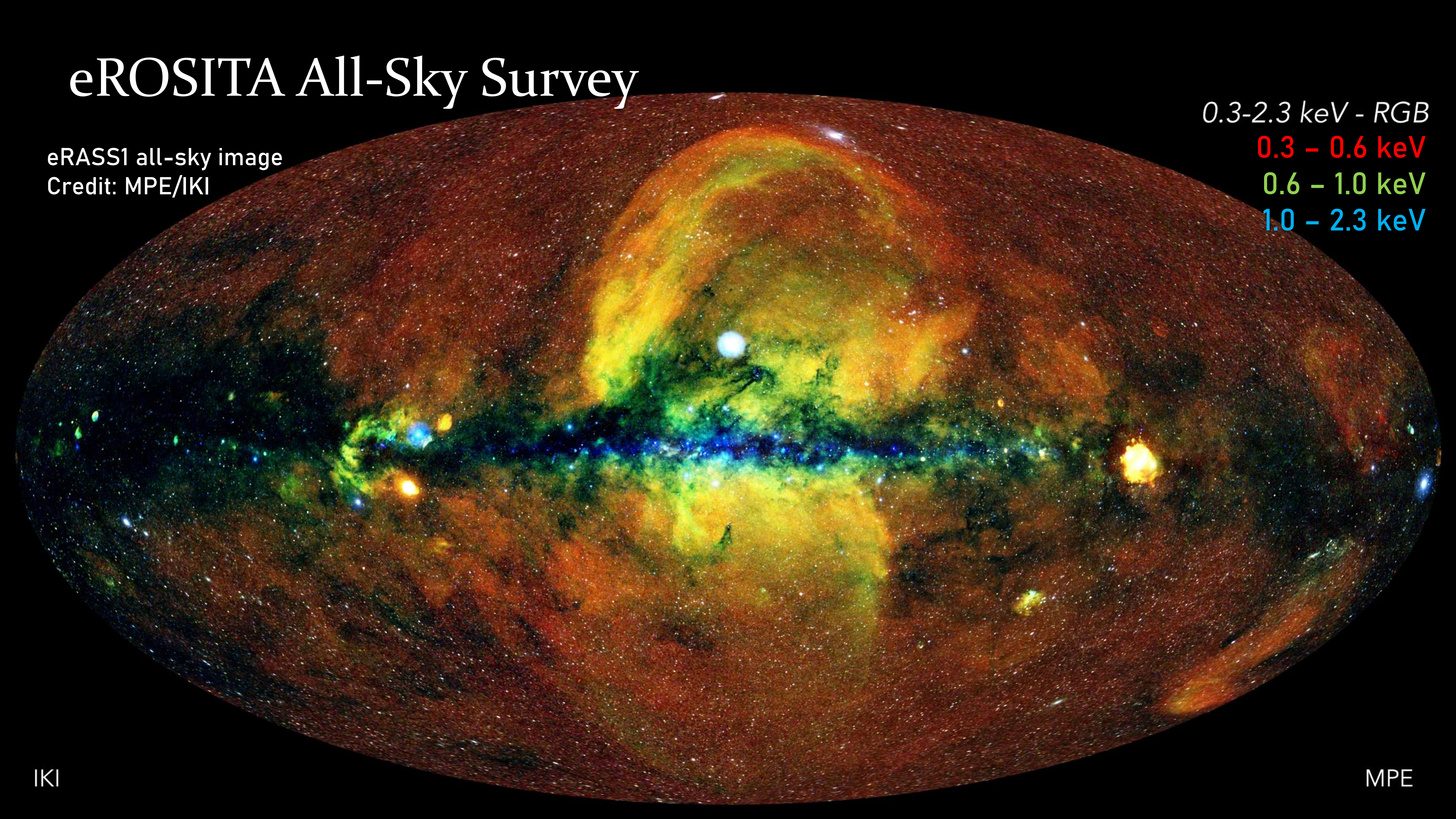
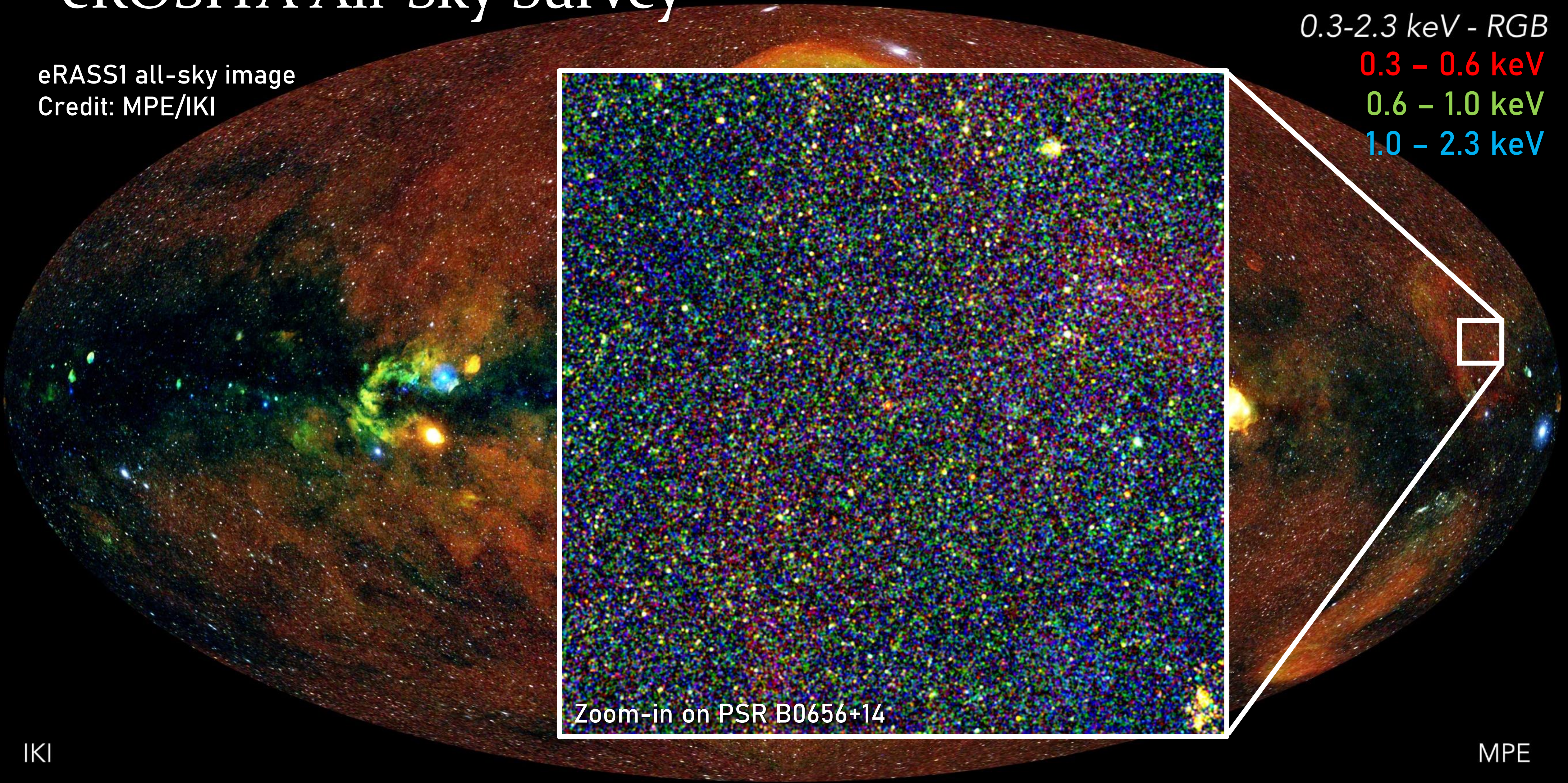
- No X-ray synchrotron emission from pulsar halos (Krivonos+26, Khokhriakova+24, Manconi+24, …)
  - ➢ $B \lesssim 1 - 2$ μG for Geminga pulsar
  - ➢ Anisotropic diffusion, hadronic population, …? (Liu+19a,b, Recchia+21)

eROSITA maps of halos (Khokhriakova+24)




eROSITA All-Sky Survey
eRASS1 all-sky image
Credit: MPE/IKI
0.3-2.3 keV - RGB
0.3 – 0.6 keV
0.6 – 1.0 keV
1.0 – 2.3 keV
IKI
MPE

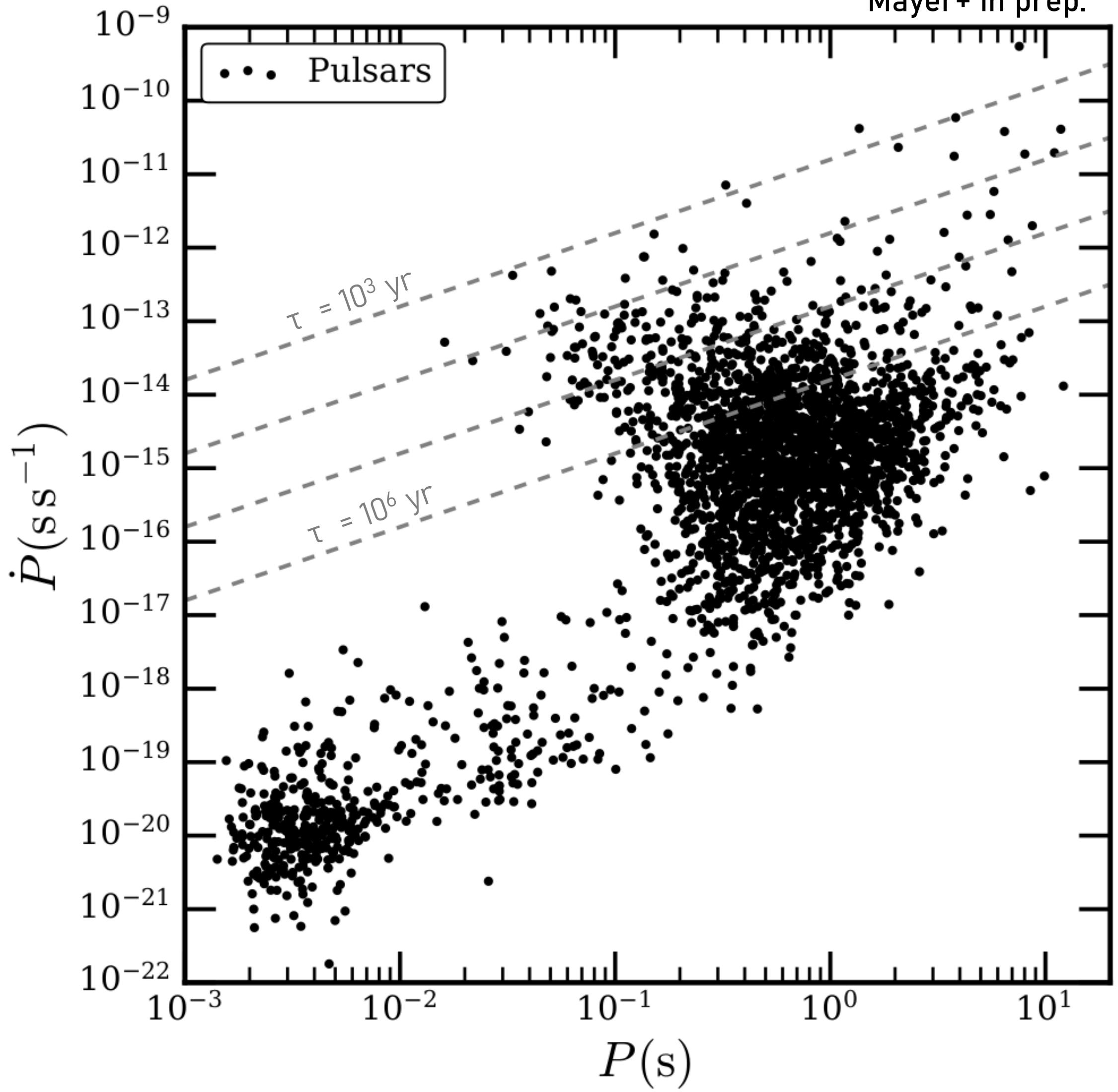
eROSITA All-Sky Survey



A population of middle-aged pulsars

- Build population model of halo-like pulsar environments with eROSITA All-Sky Survey (Predehl+21)
  - Uniform source coverage
  - „Unlimited“ field of view

P-Pdot diagram of ATNF pulsars
Mayer+ in prep.



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➢ Construct target sample of pulsars from ATNF catalog (Manchester+05)
  - Middle-aged ($10^{4.5}$ yr < τ < 10^6 yr)
  - Energetic ($\dot{E} > 10^{33}$ erg/s)
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  - Accessible with eROSITA (180° < l < 360°)

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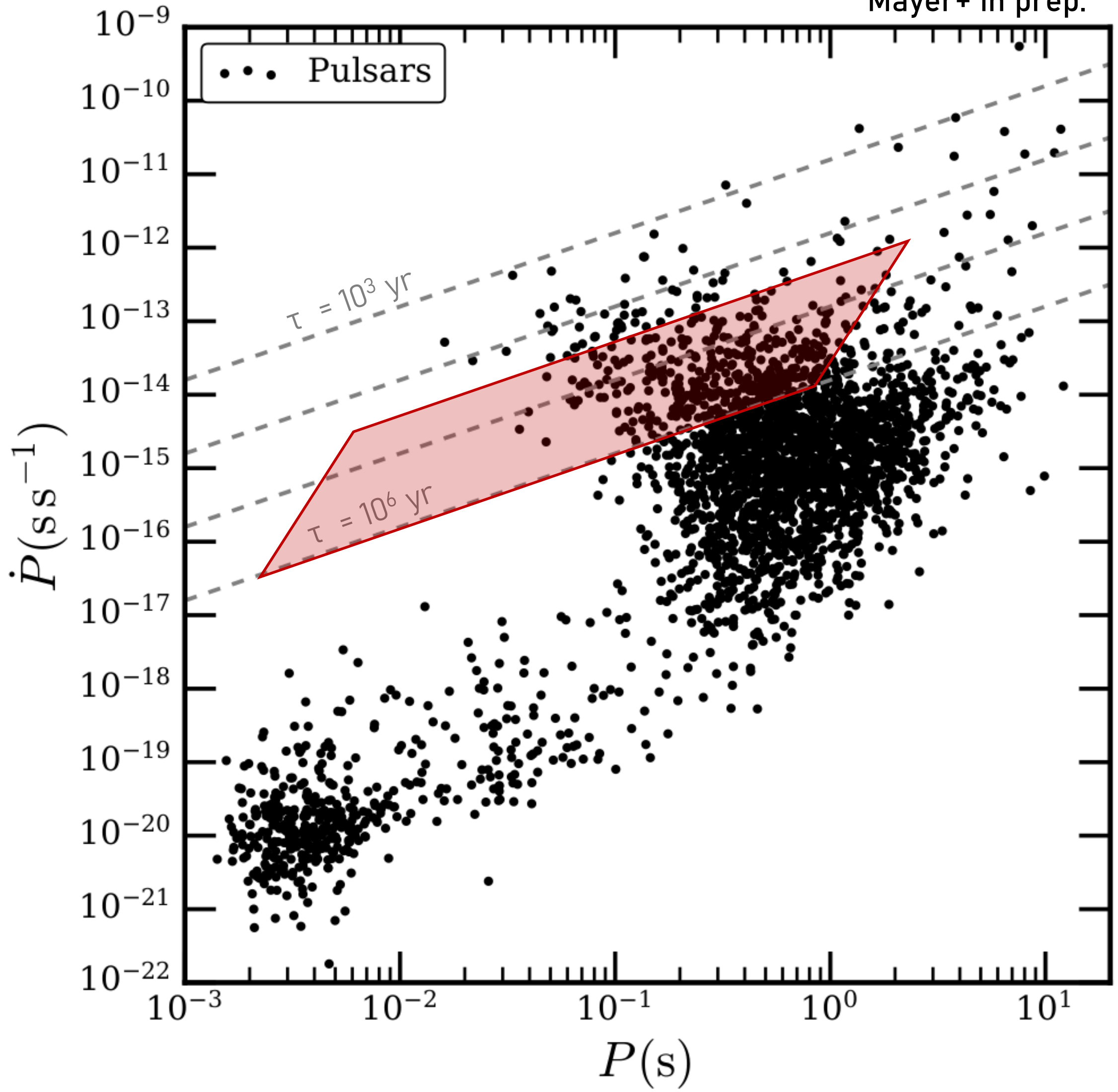

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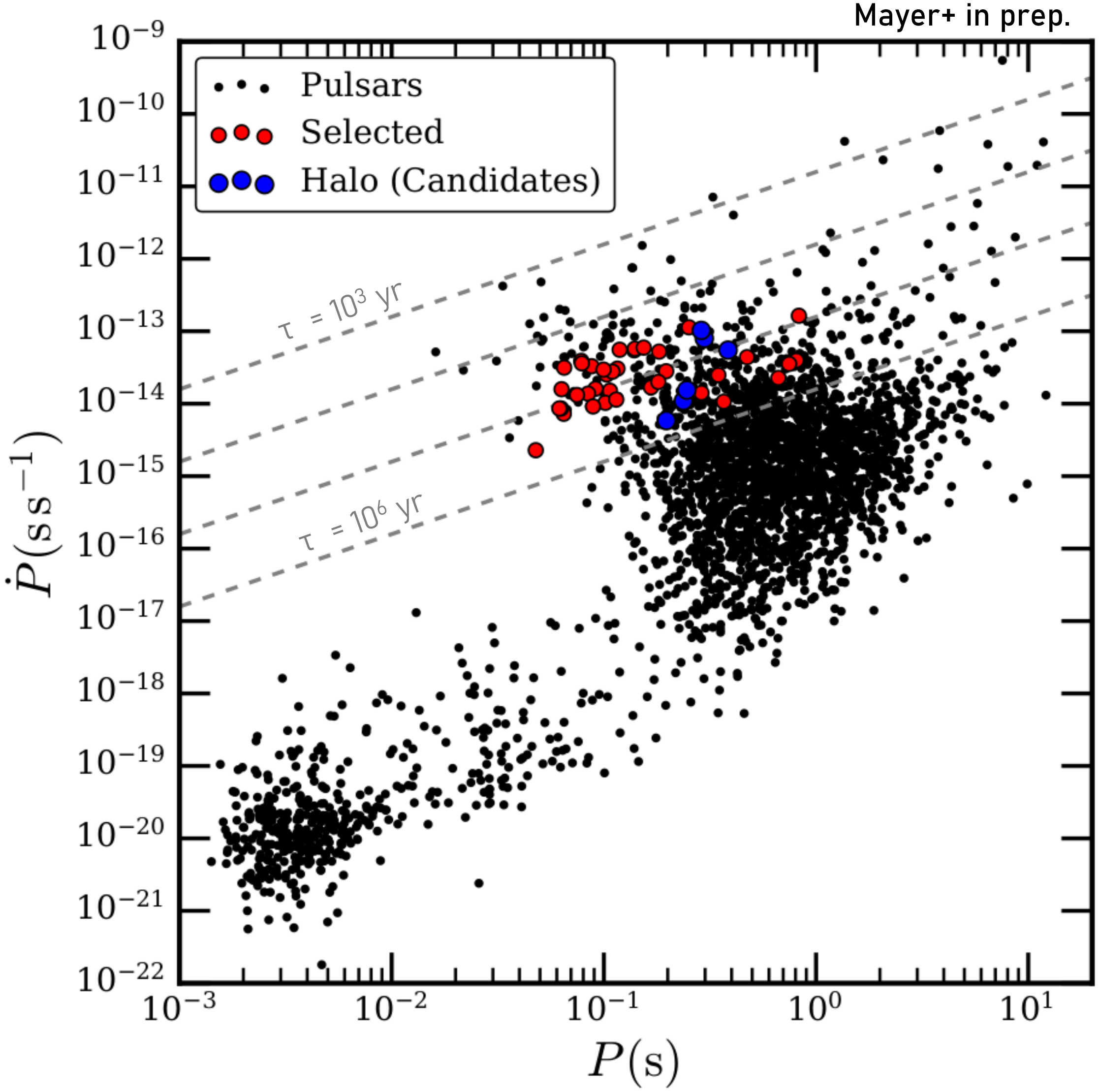
  - ➢ Around 40 targets

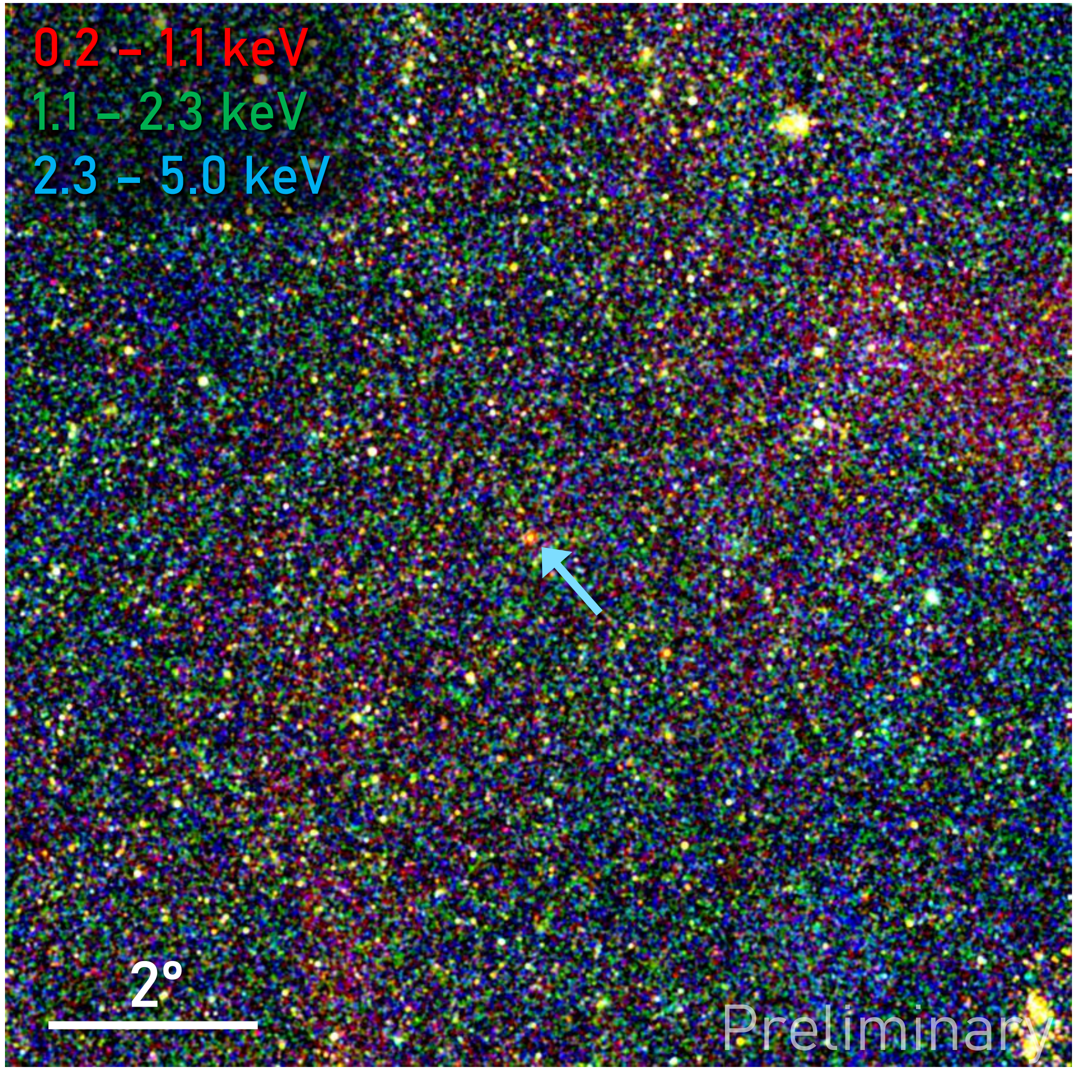
Sample selection in P-Pdot diagram of ATNF pulsars
Mayer+ in prep.



Hunting a faint signal in X-ray images

eRASS view of B0656+14 field
Mayer+ in prep.

- Construct multi-band X-ray images covering ~ 20 pc from pulsar



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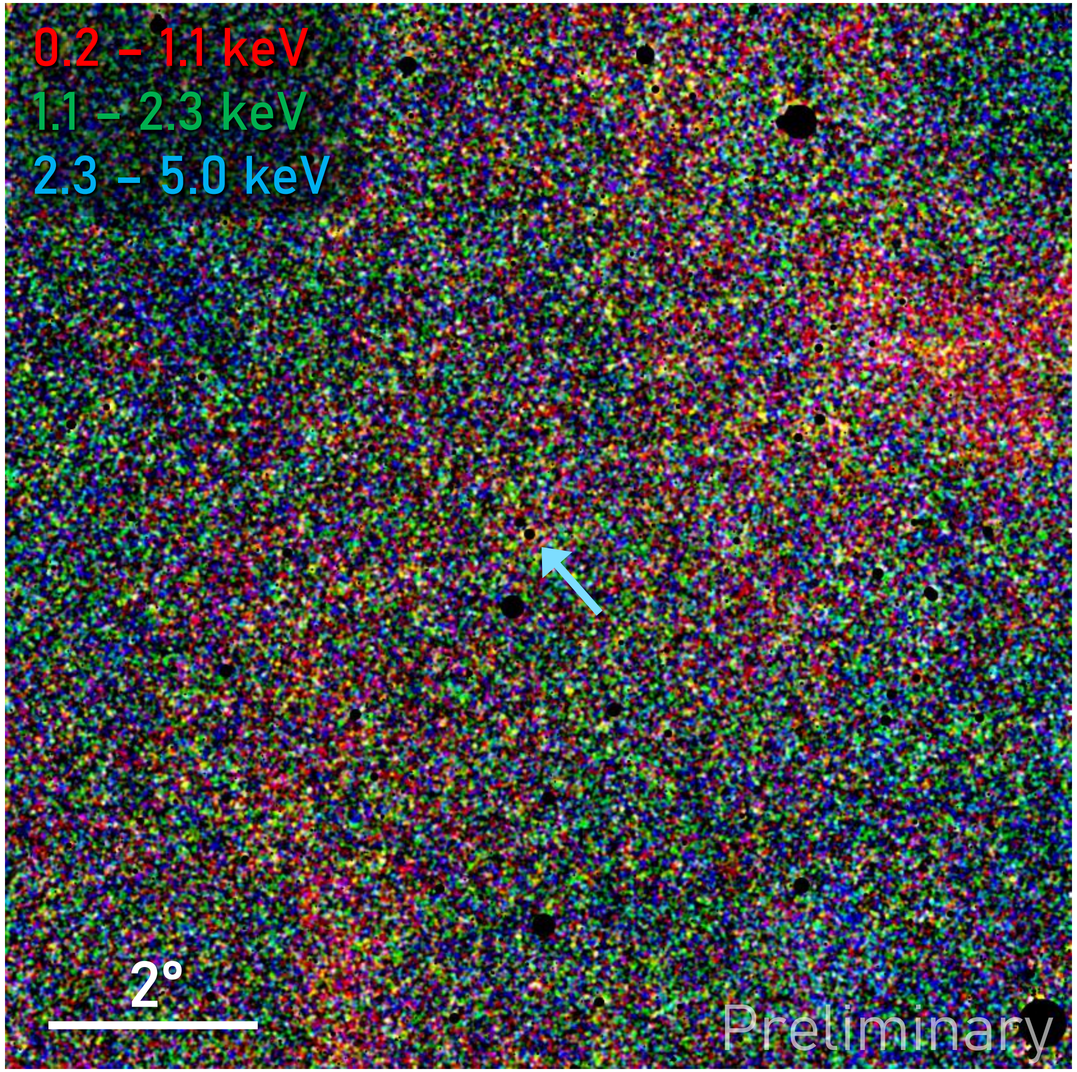

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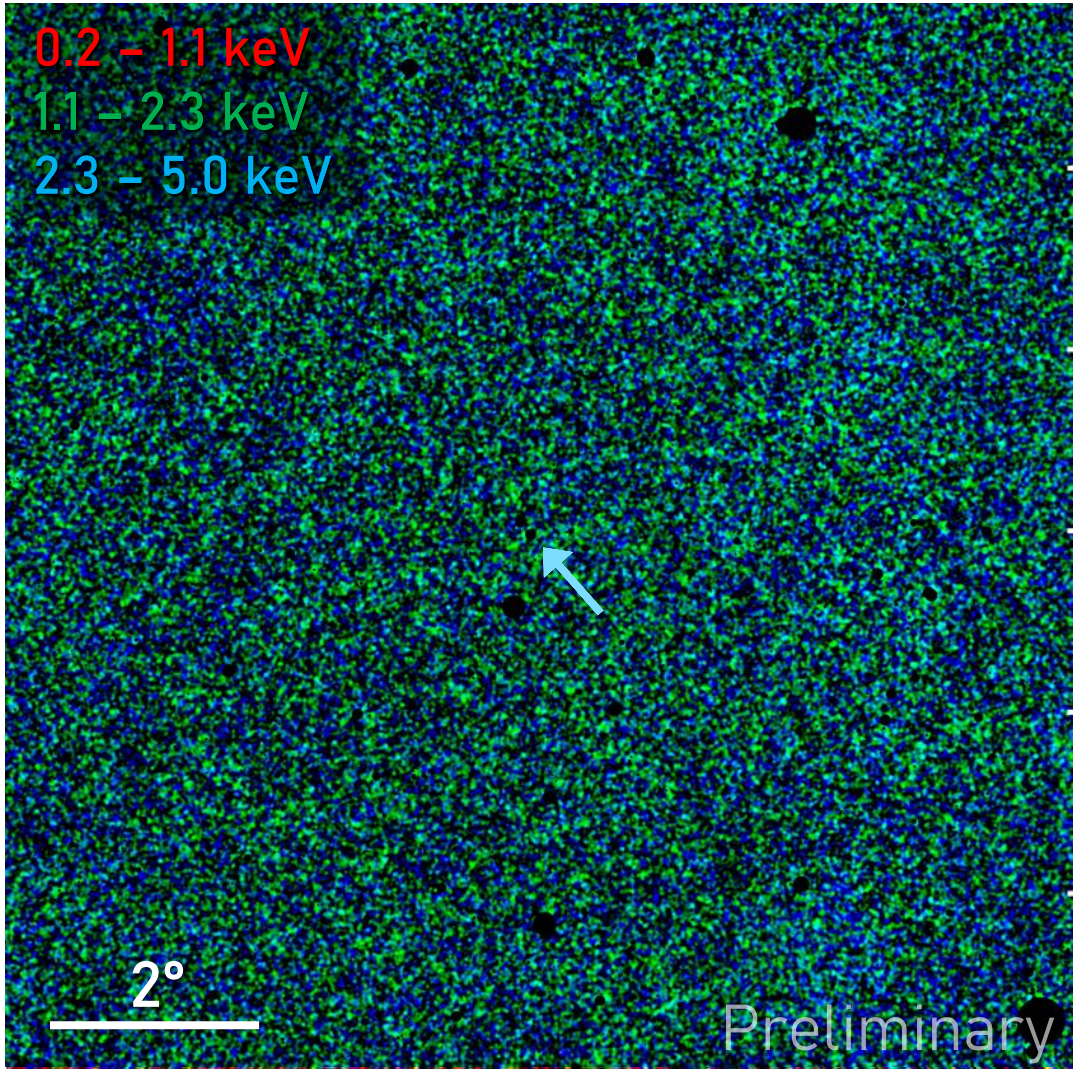

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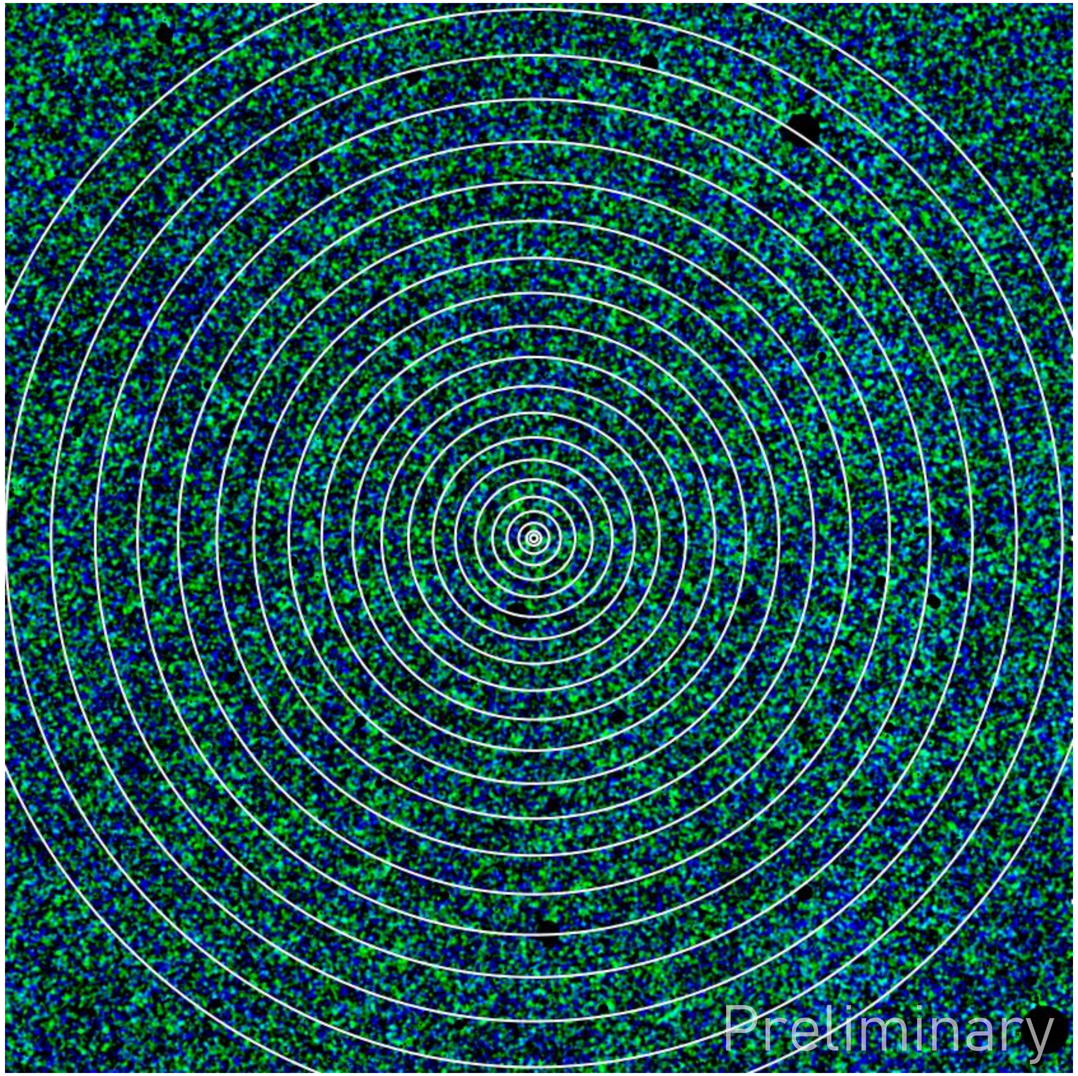

Hunting a faint signal in X-ray images

- Construct multi-band X-ray images covering ~ 20 pc from pulsar

  - ➢Mask bright sources
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  - ➢Background variations via azimuthal division

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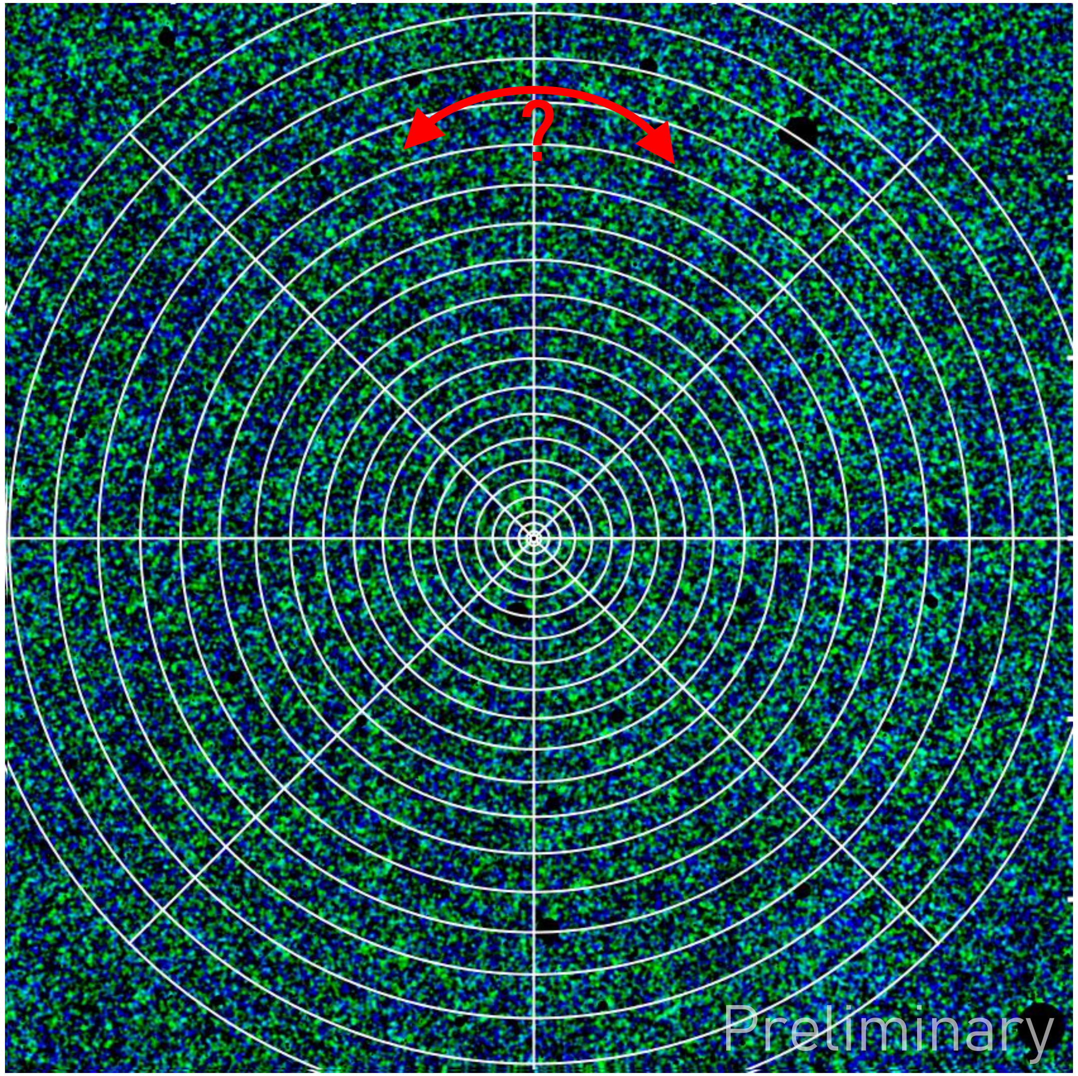

Hunting a faint signal in imaging data

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  - ➢ Mask bright sources
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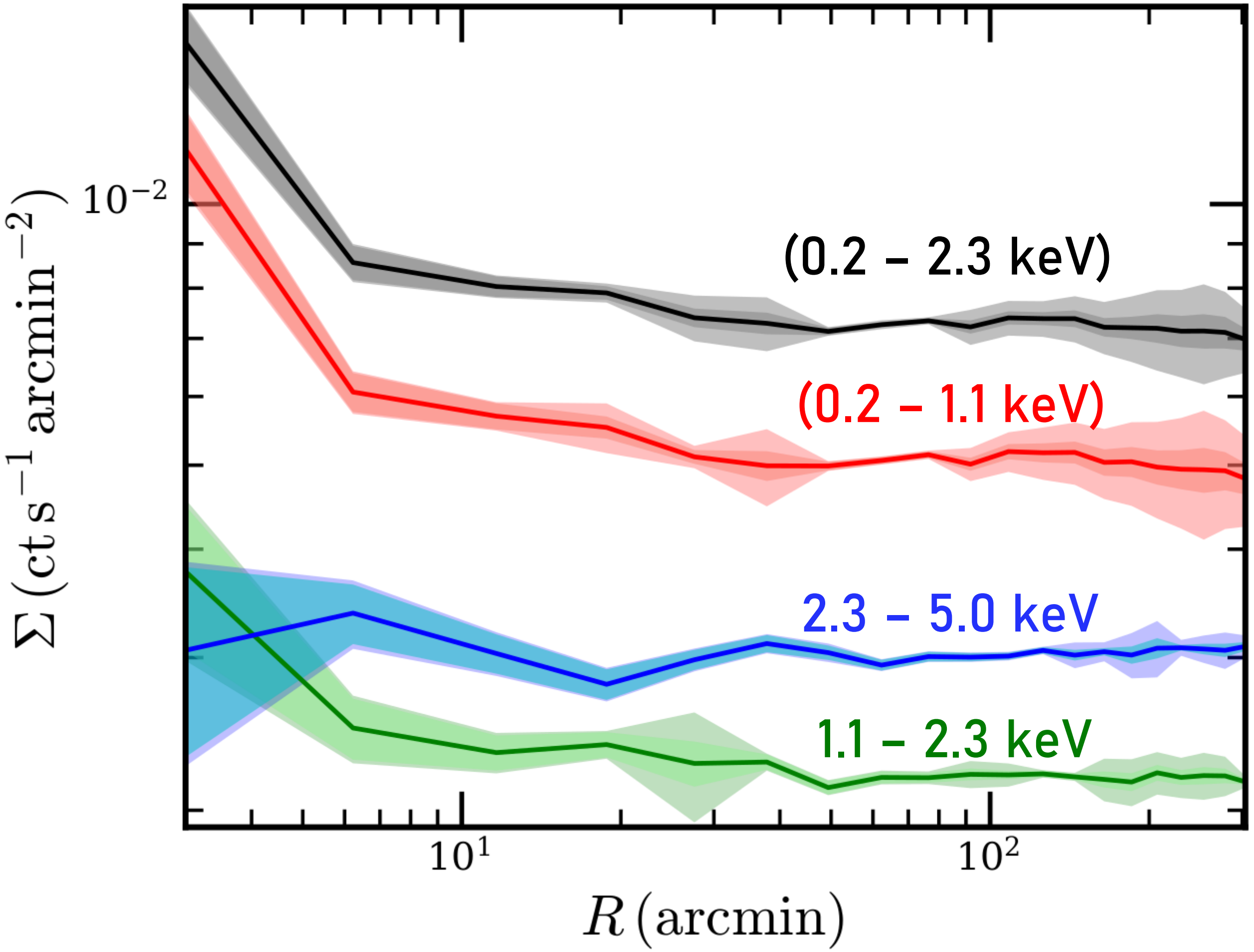
  - ➢ Background variations via azimuthal division

➢ Radial profiles with statistical & systematic errors

Radial emission profile of B0656+14
Mayer+ in prep.



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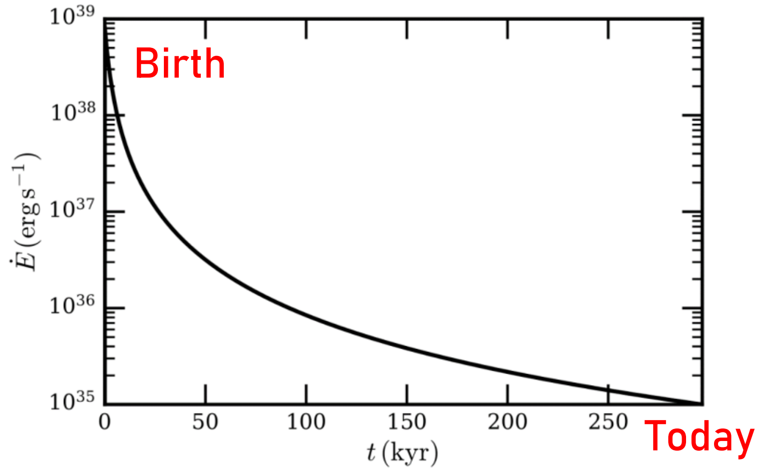

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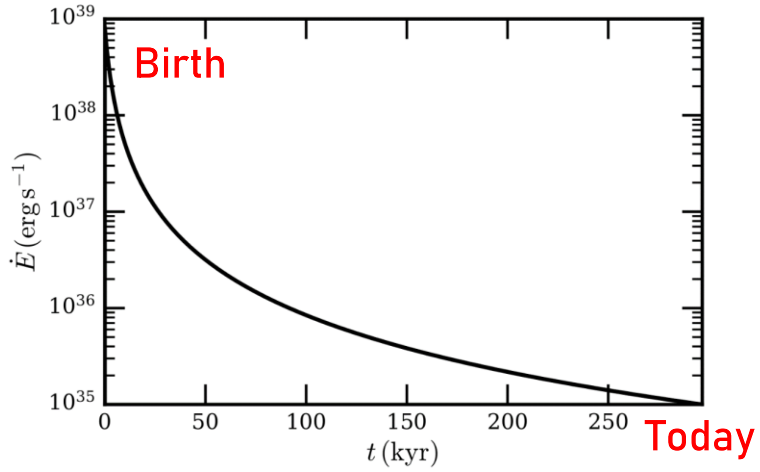

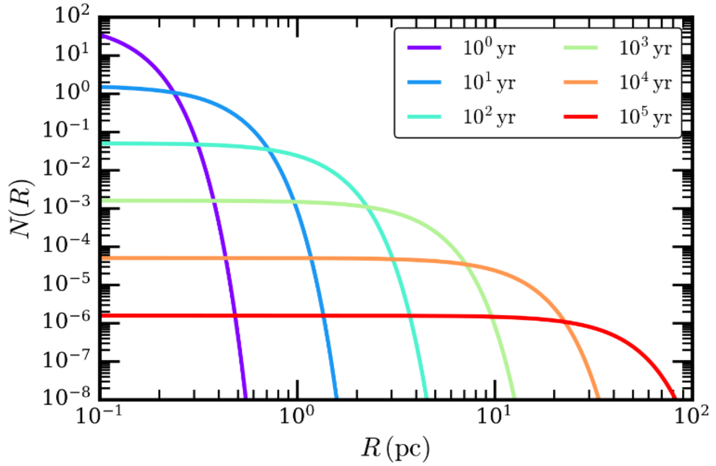

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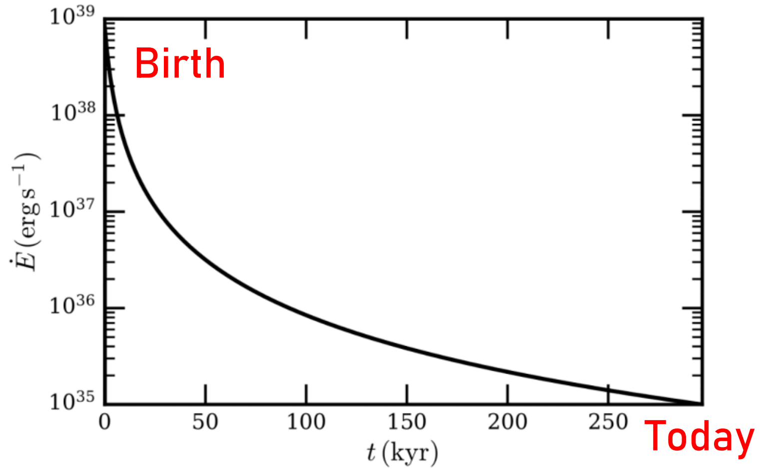

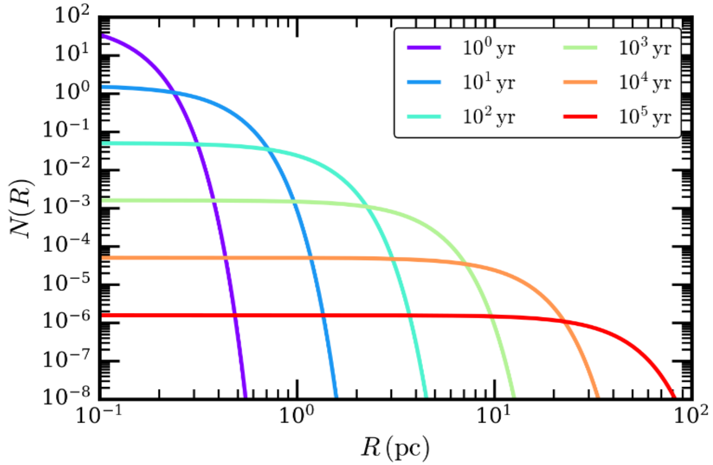

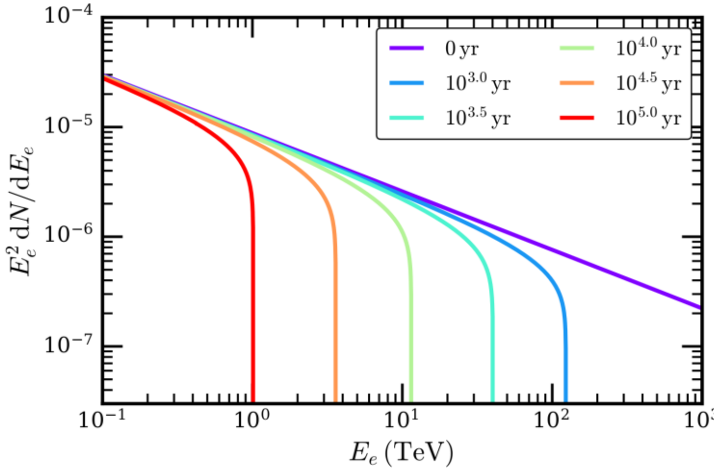

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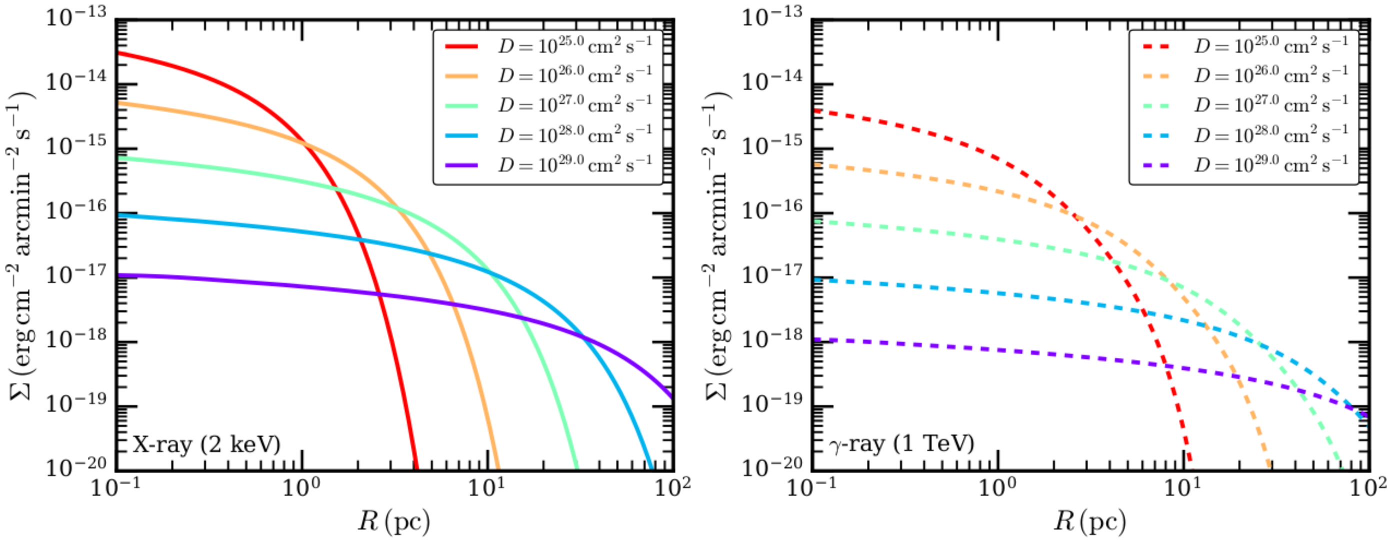

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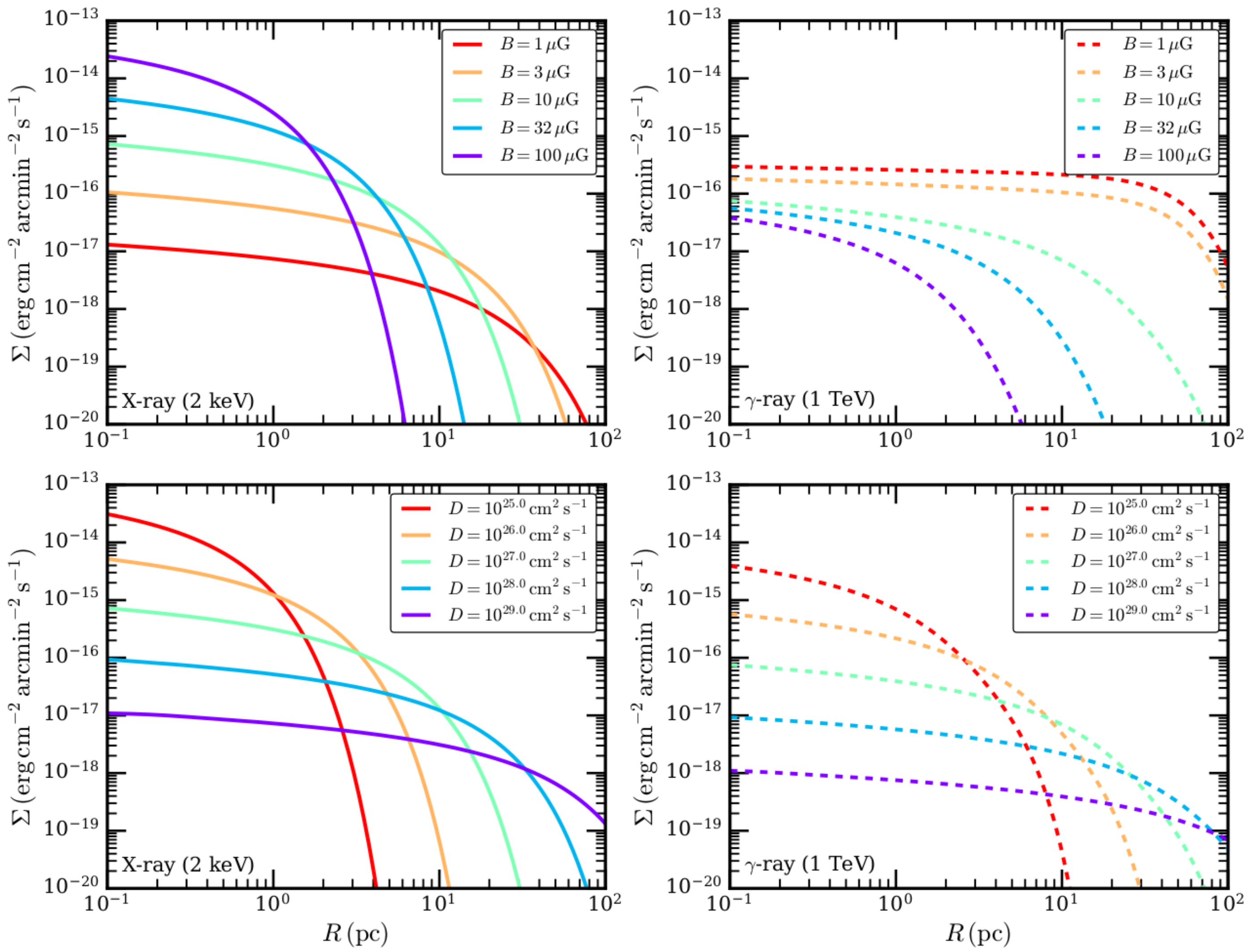

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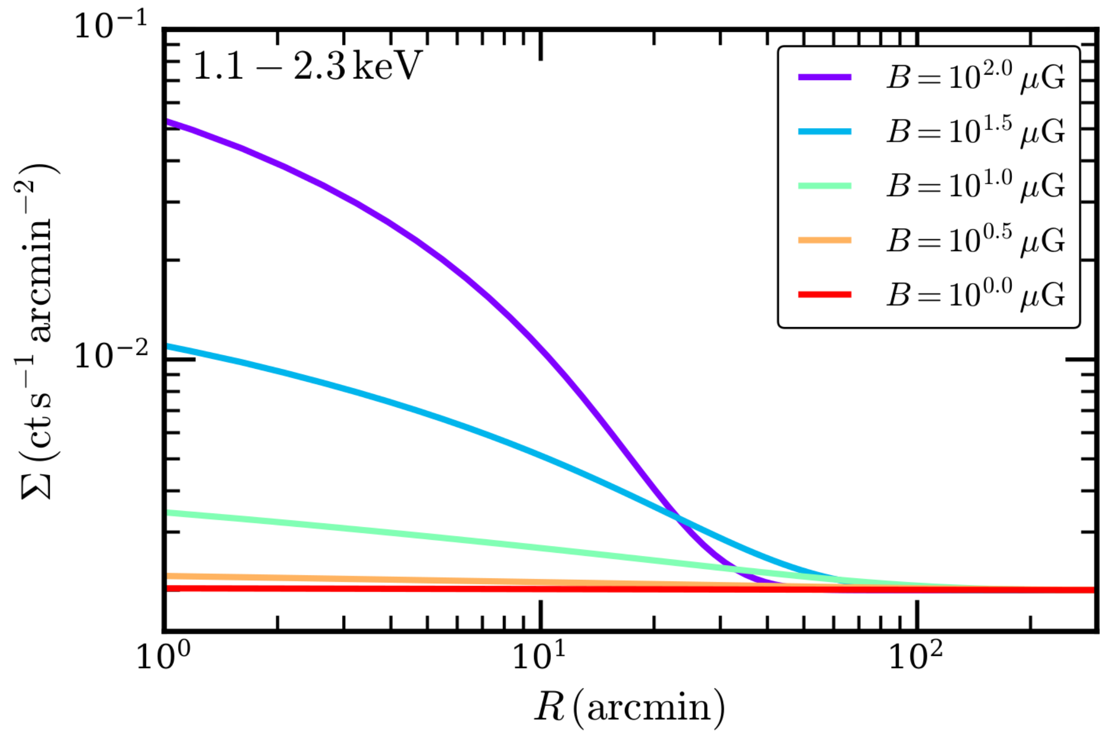
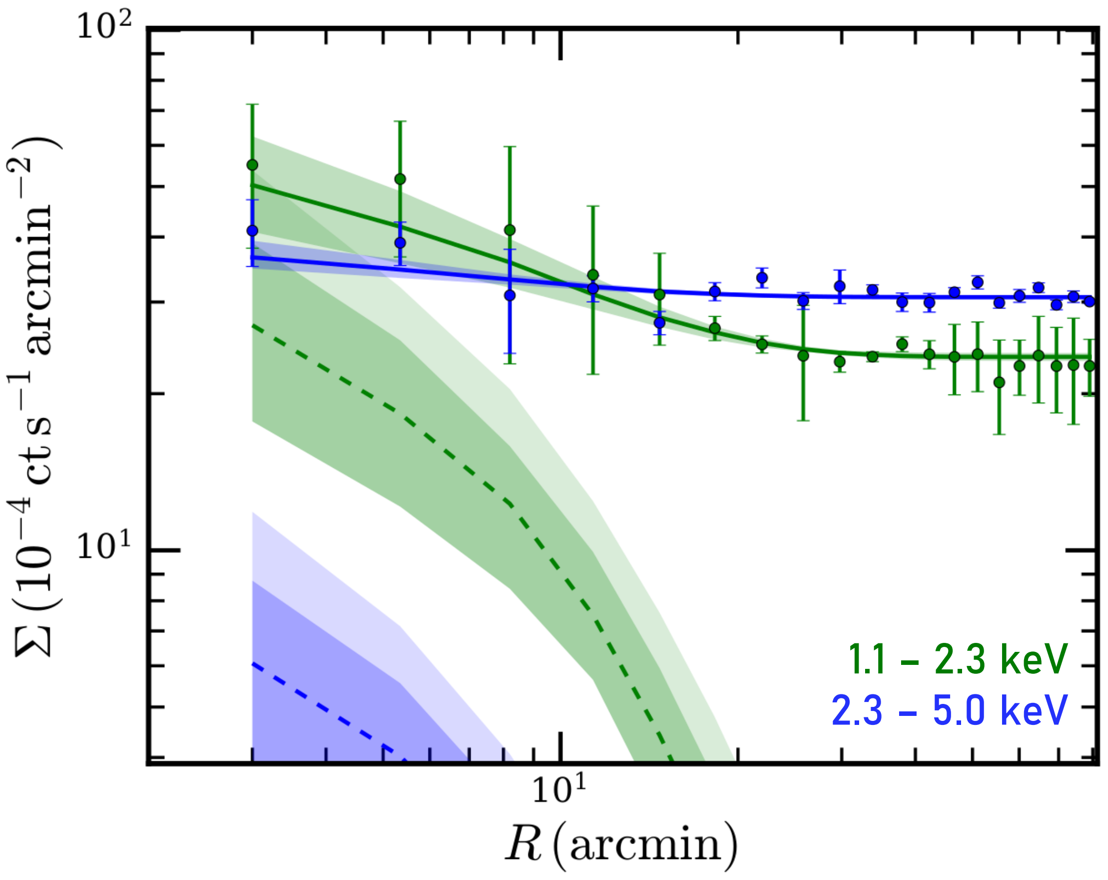
- X-ray absorption, instrumental response, & background



Constraining the signal

- Fit multiple X-ray energy bands + γ-ray properties (if available)

Fitted radial emission profile of J0633+0632
Mayer+ in prep.



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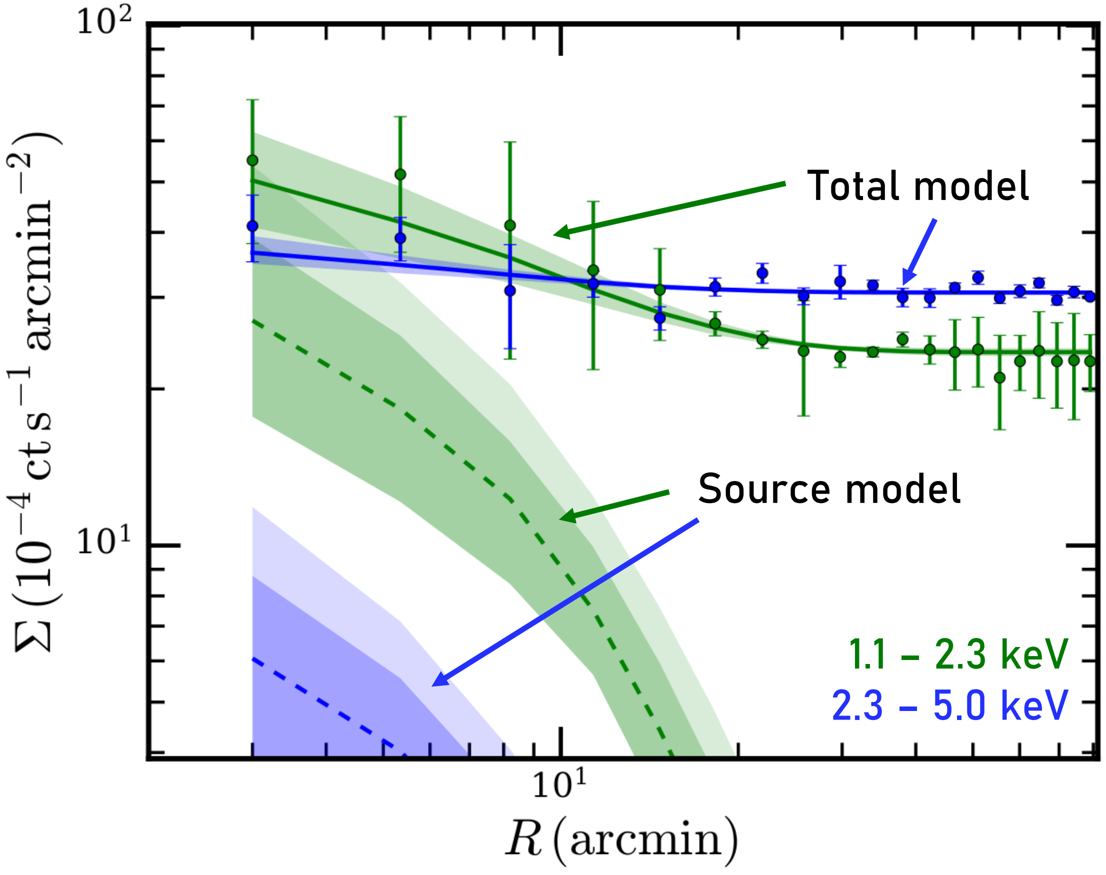

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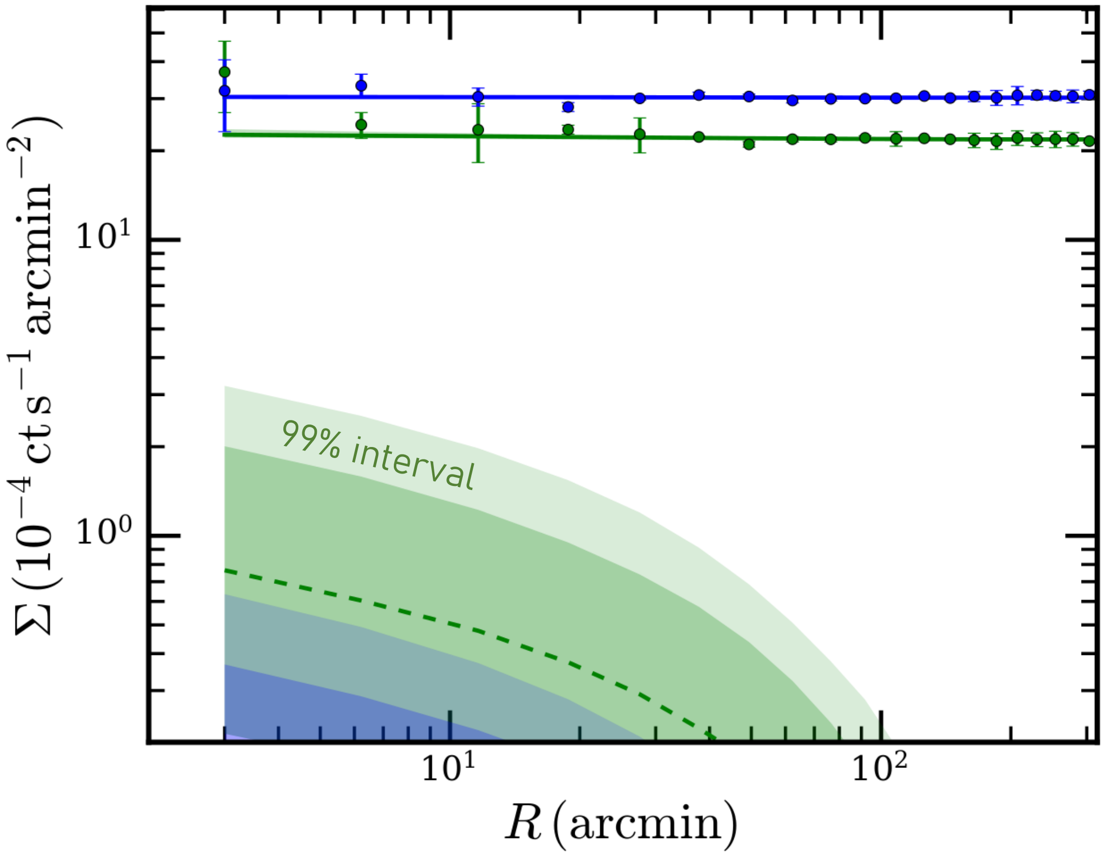

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- *B*: Effective magnetic field
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- *η*: CR injection efficiency
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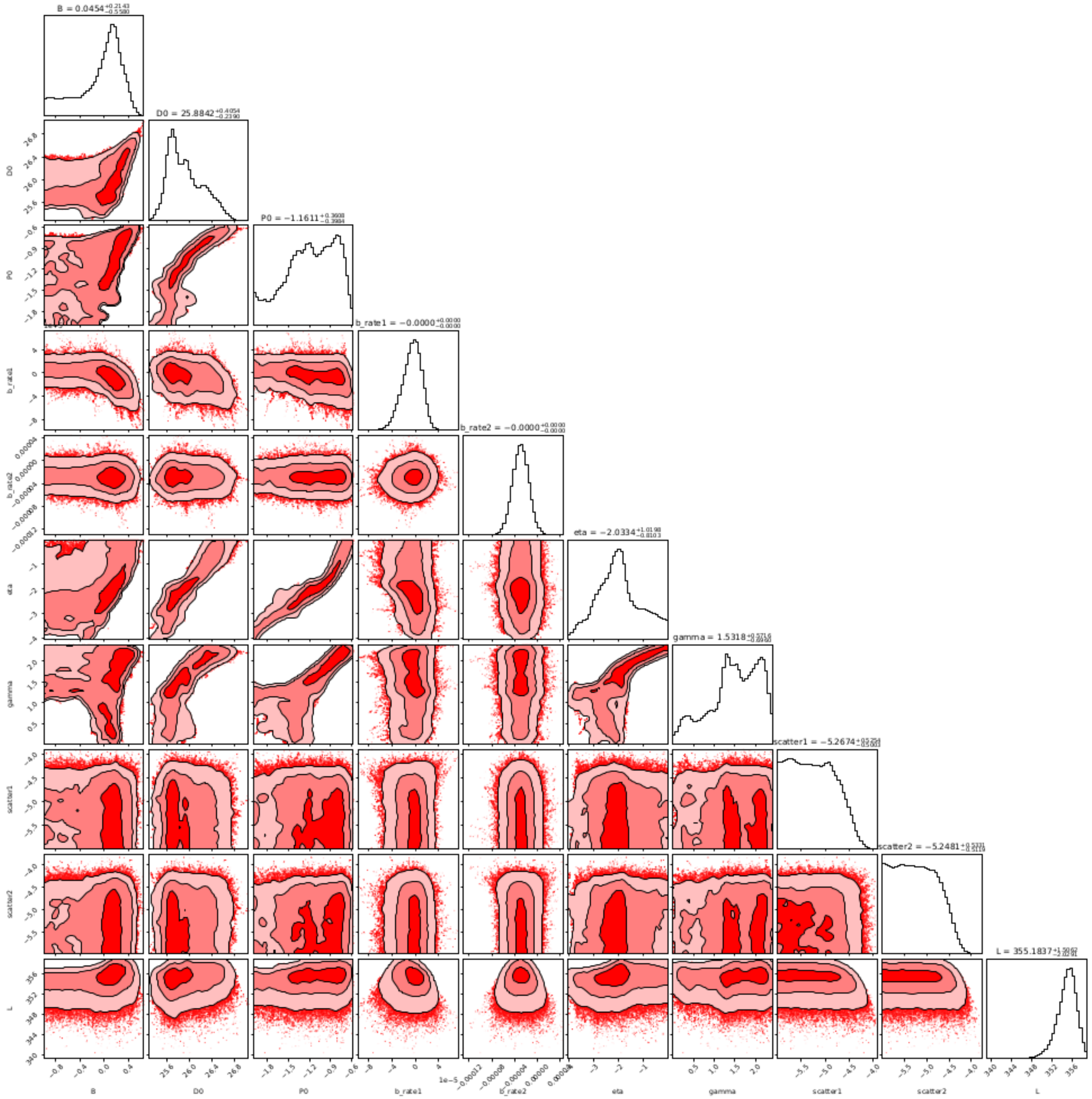

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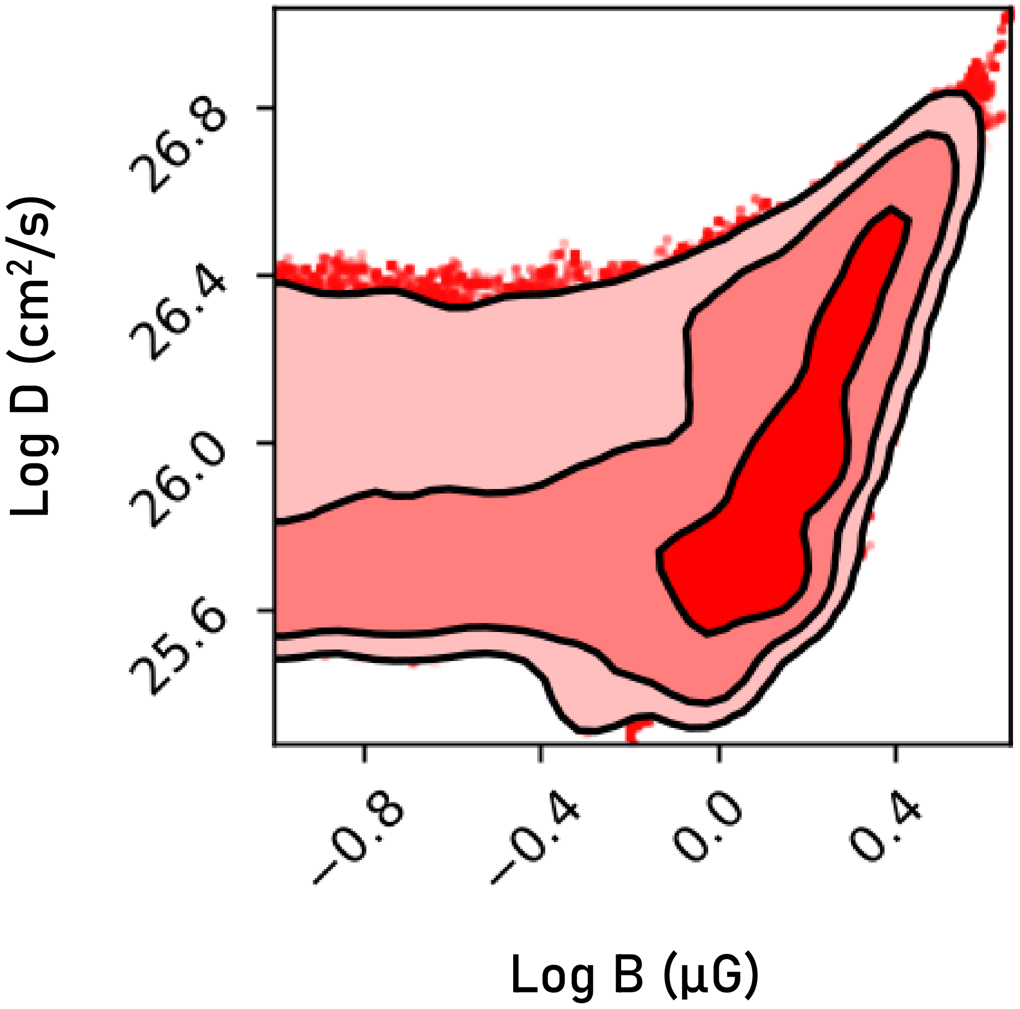
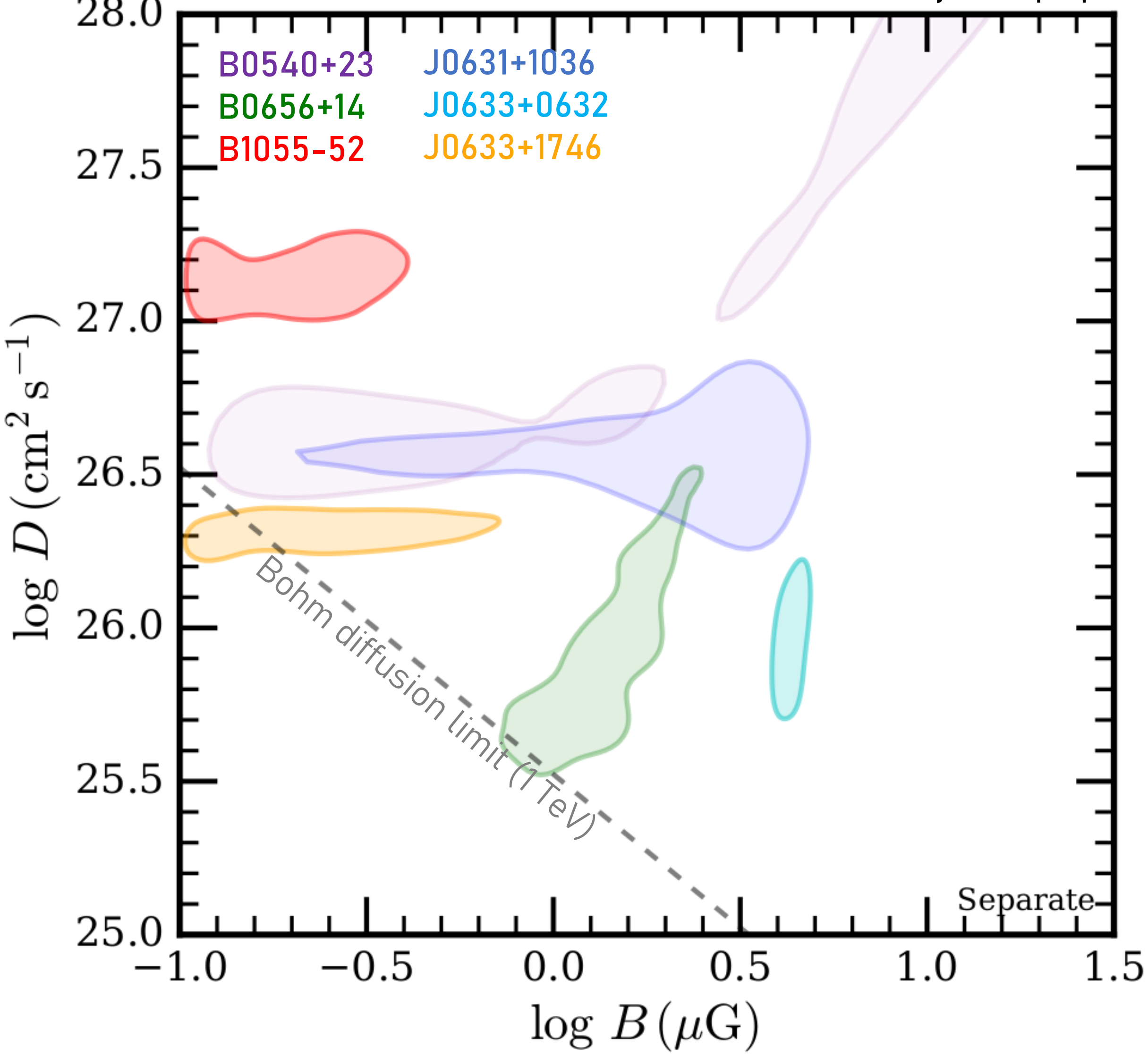
B-D constraints for B0656+14
Mayer+ in prep.



Assembling the population

- Derive constraints on physical properties of pulsar environments

One-sigma constraints for all sources
Mayer+ in prep.



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  - ➢ log B, log D, ... ~ $Norm(\mu_B, \mu_D, ... | \sigma_B, \sigma_D, ...)$

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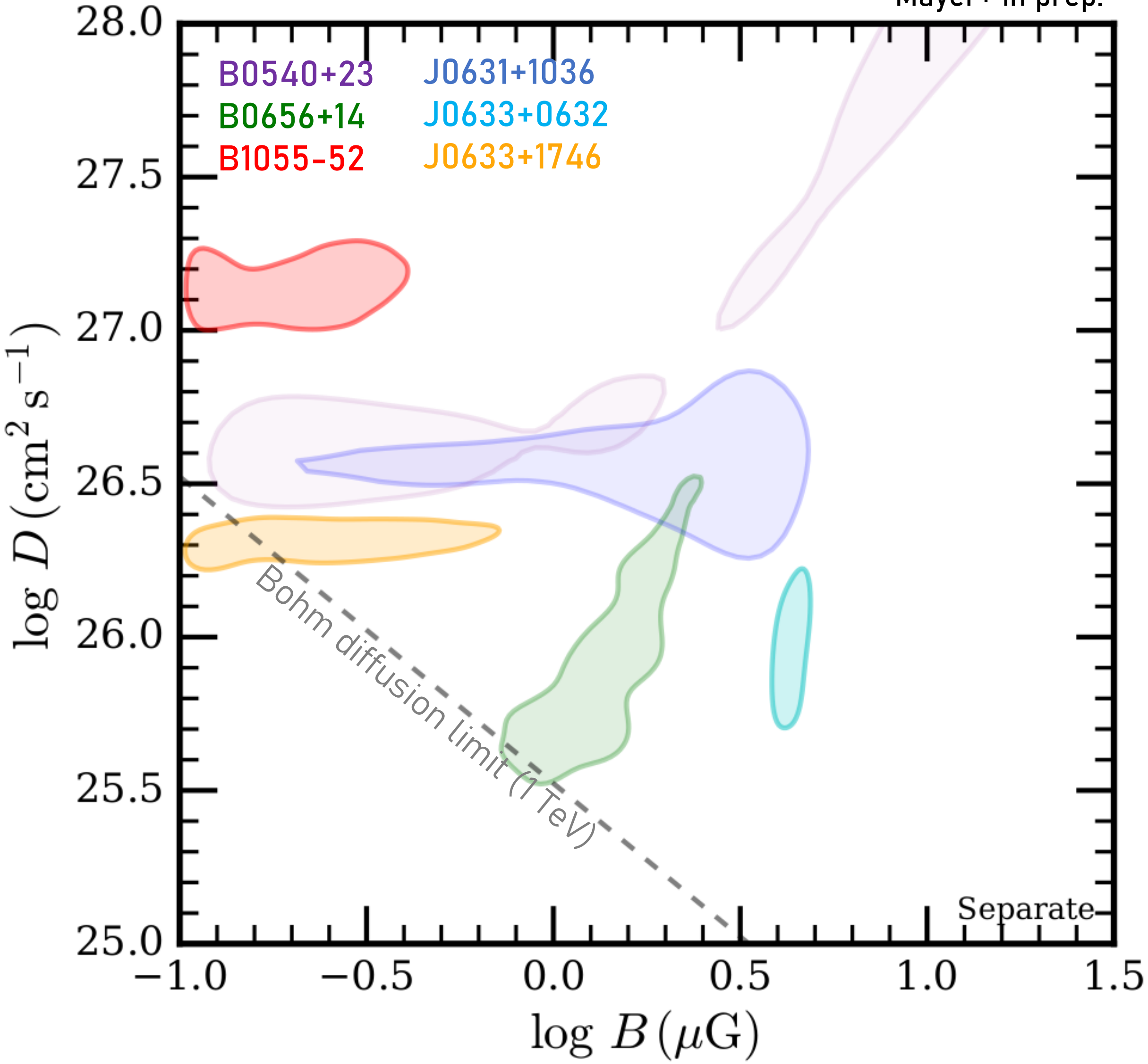

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Joint one-sigma constraints for source population
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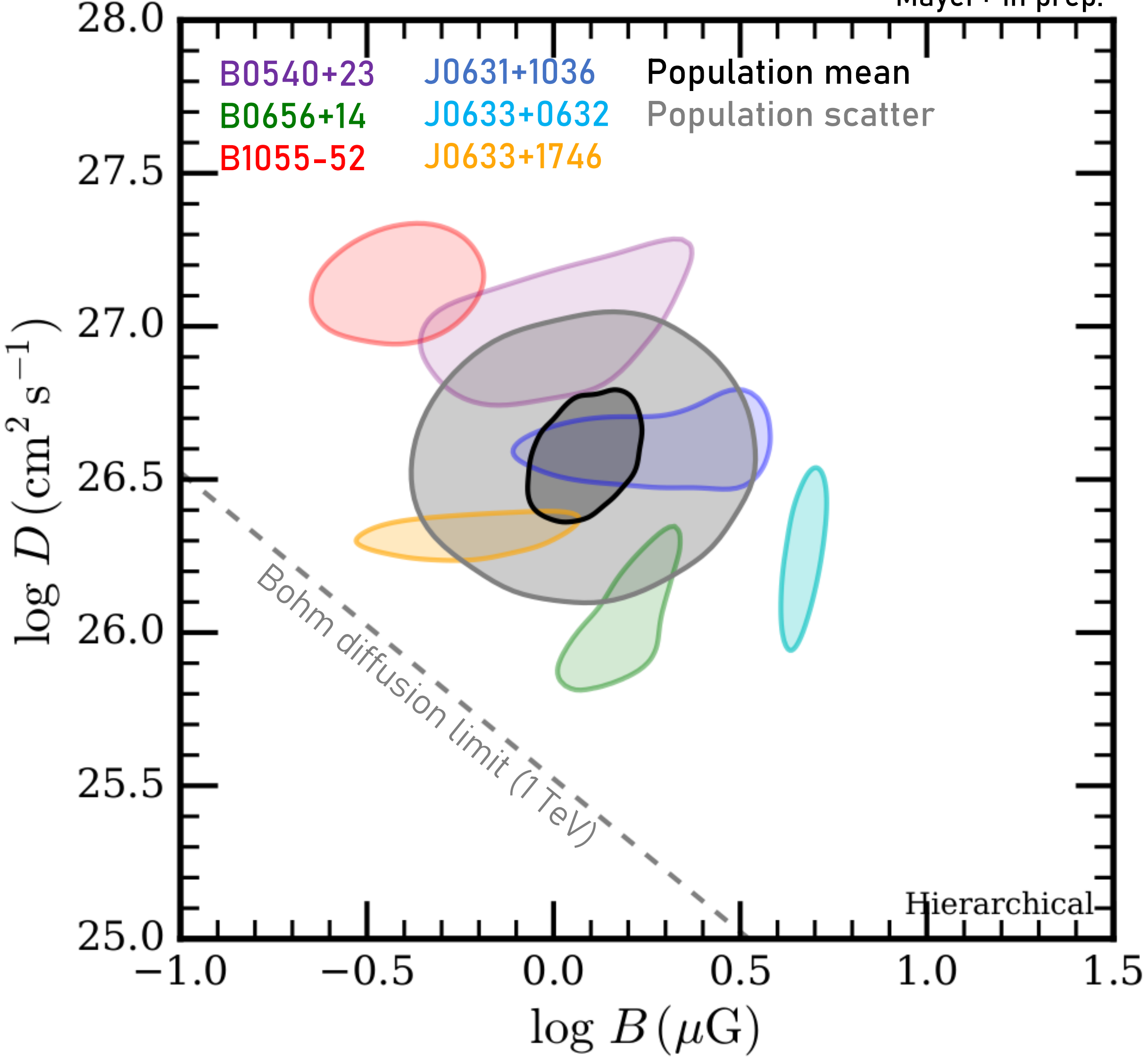

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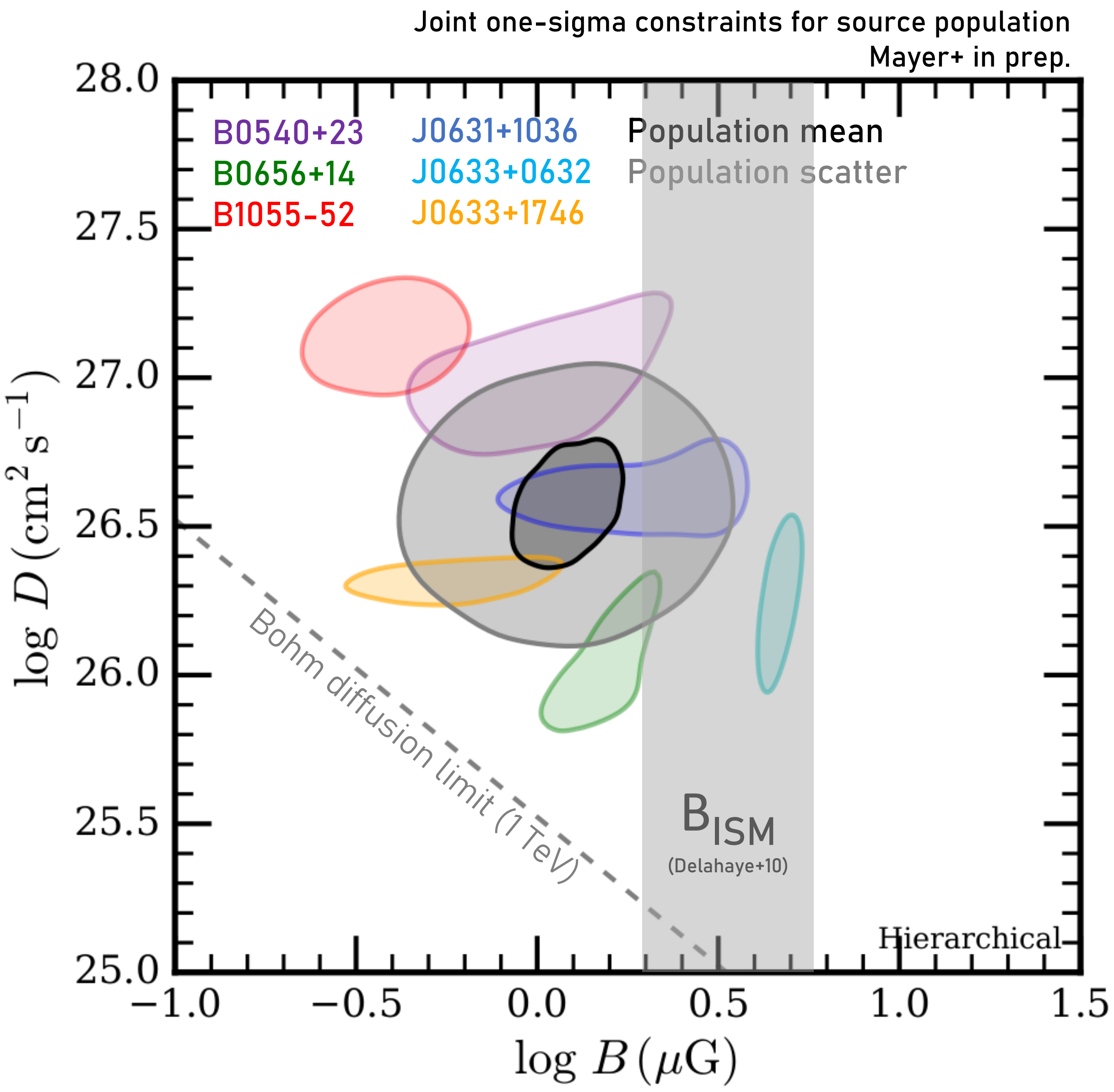

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  - ➢ At 50 TeV: $D_{mean} \sim D_{Bohm}$

Joint one-sigma constraints for source population
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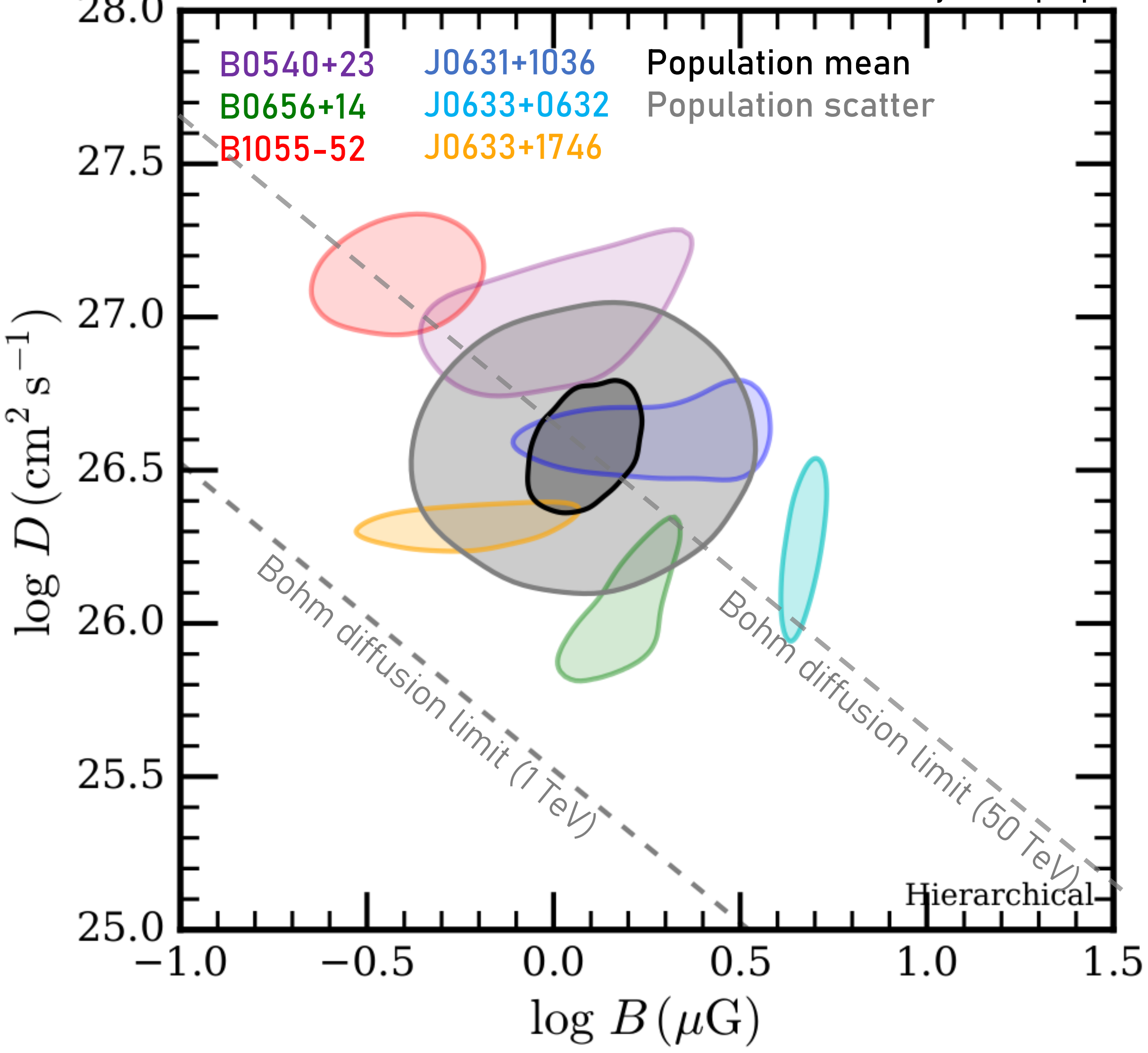

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Systematic study of environments of middle-aged pulsars with eROSITA

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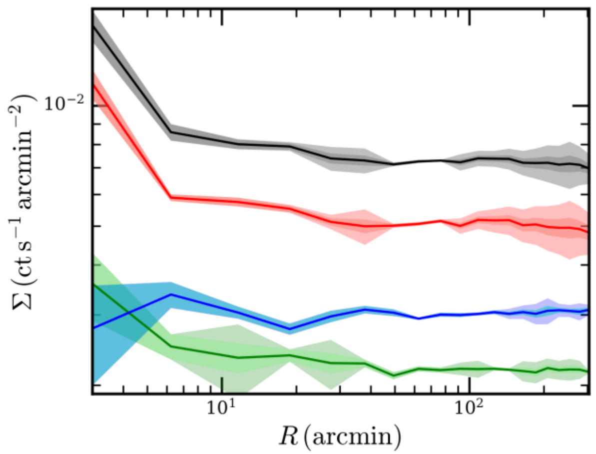

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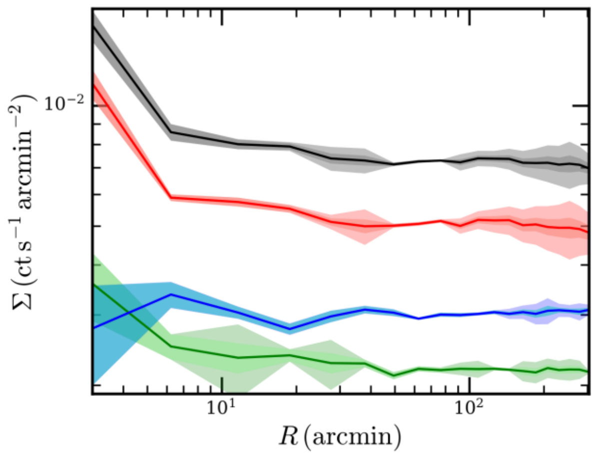

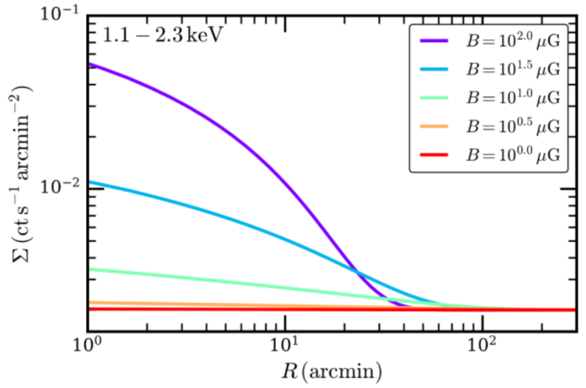

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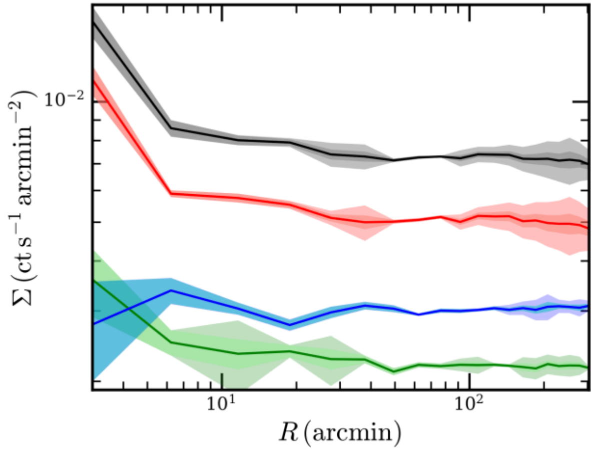
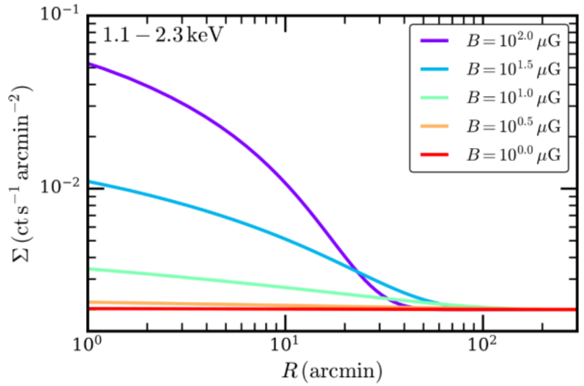
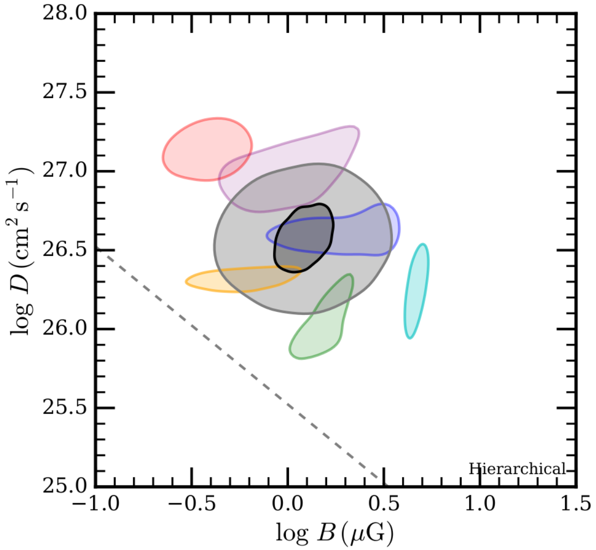
- X-ray morphological analysis for radial profiles

- One-dimensional emission models: particle transport and magnetic fields

- Hierarchical model of pulsar-halo population
    - ➢Mean magnetic field B ~ 1μG < B_{ISM}
    - ➢Extremely slow cosmic-ray diffusion







Extra Slides

Introduction – Pulsar halos in γ-rays

- Extended γ-ray emission around middle aged pulsars (~ 10^5 – 10^6 yr)

  - ➢ Inverse-Compton emission of TeV electrons (HAWC+17)

TeV significance map of HAWC halos
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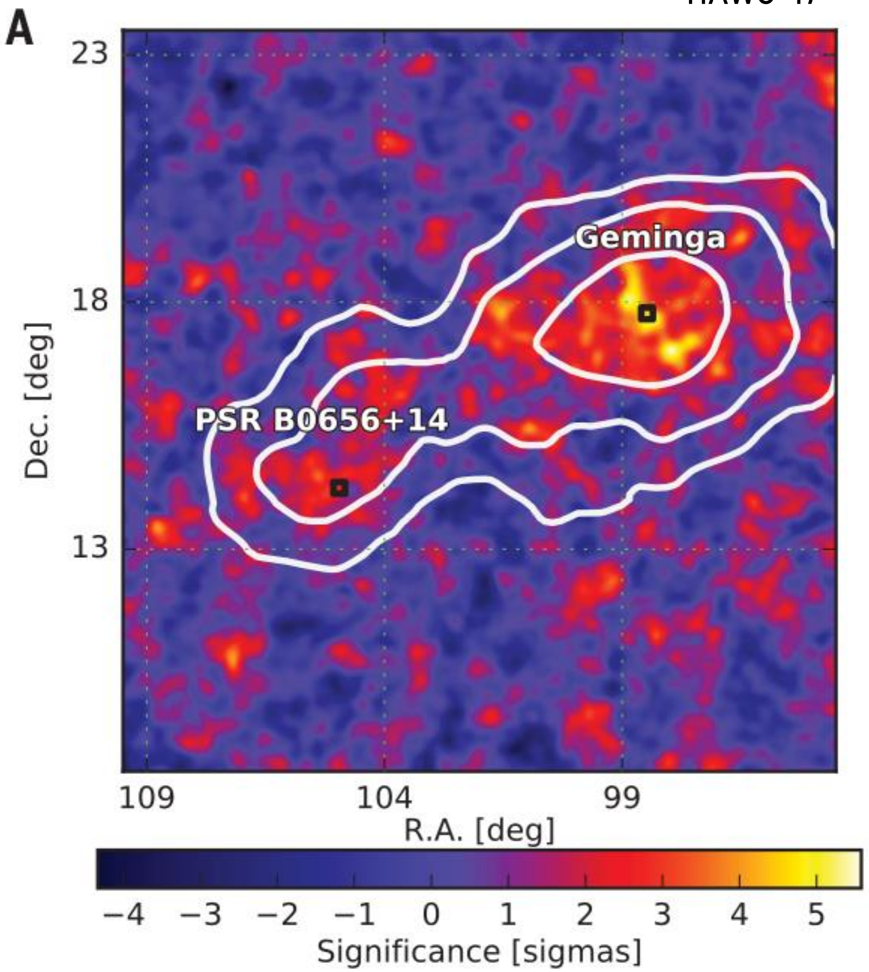

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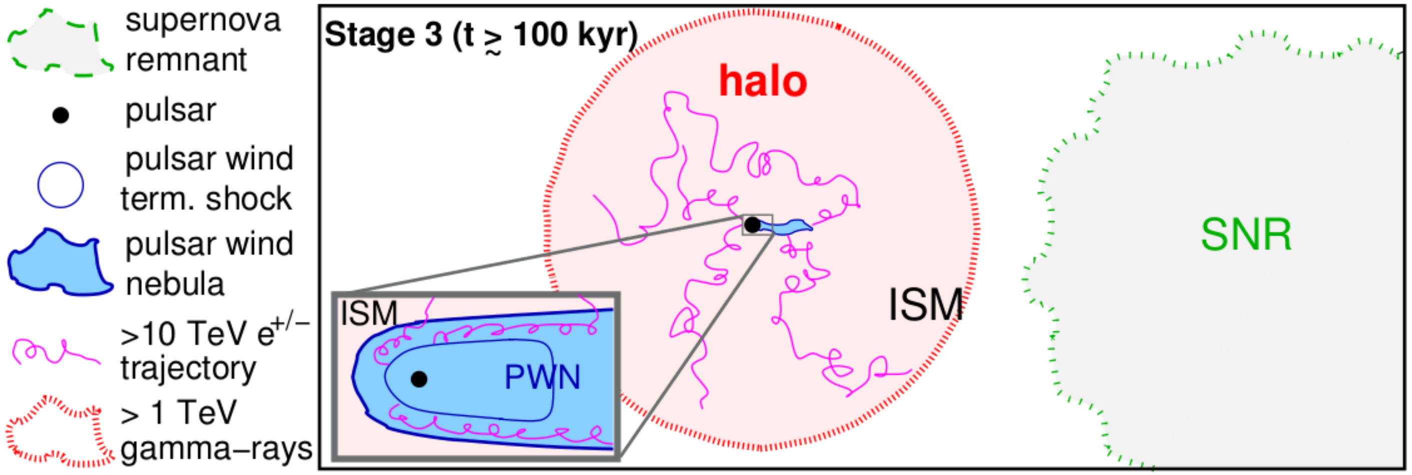

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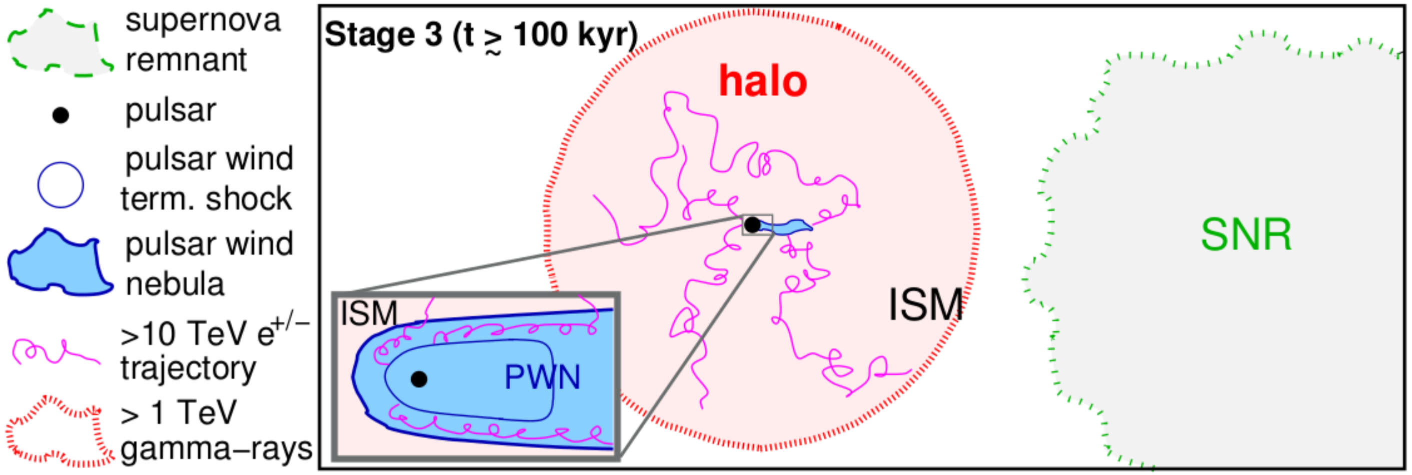
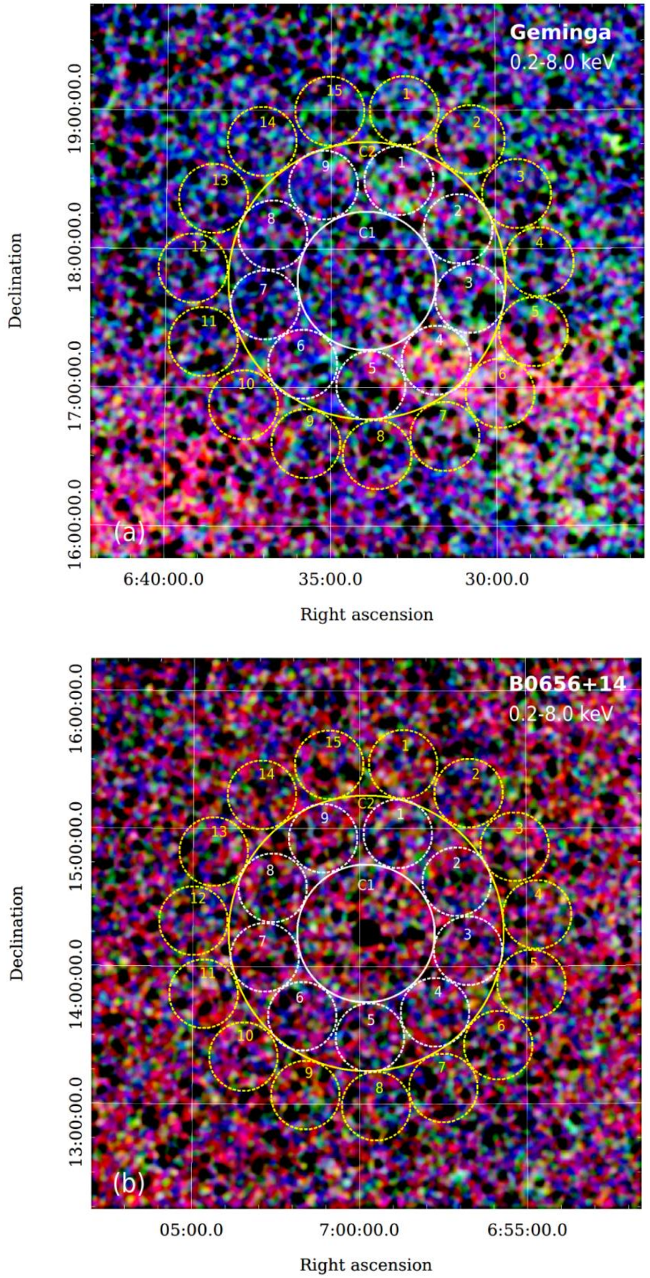


Introduction – Pulsar halos in X-rays

eROSITA maps of halos (Khokhriakova+24)



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- No X-ray synchrotron emission in region of pulsar halos (e.g. Krivonos+26, Khokhriakova+24, Liu+19a)
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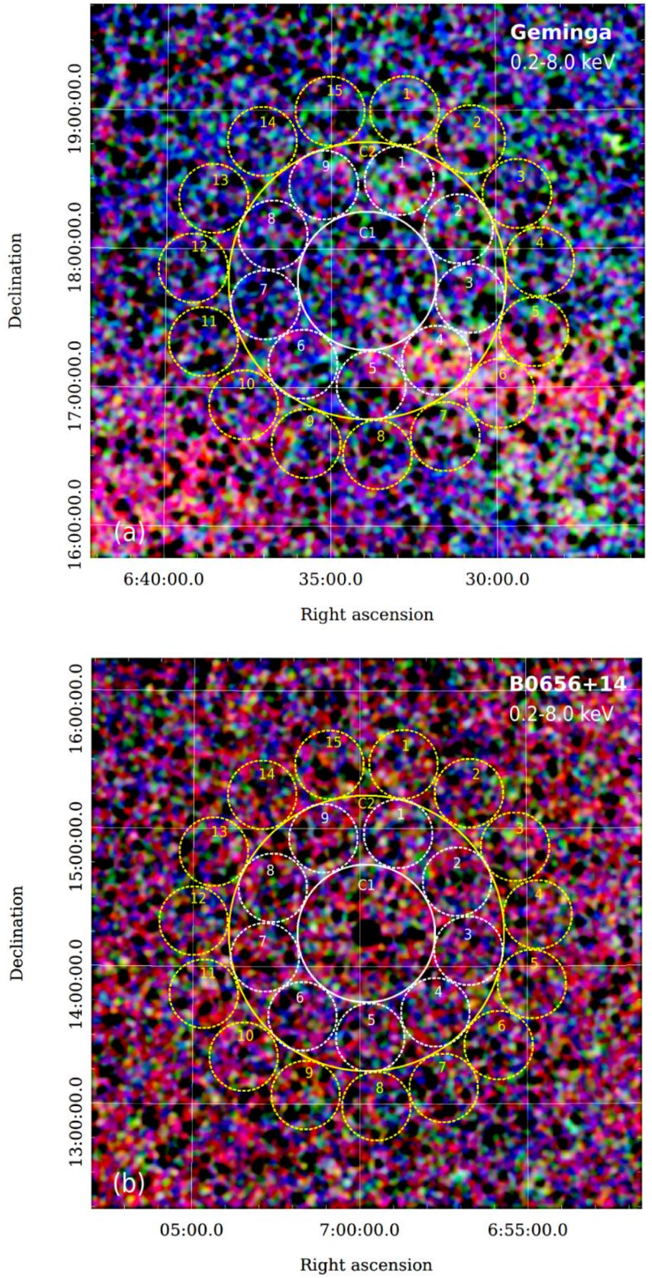

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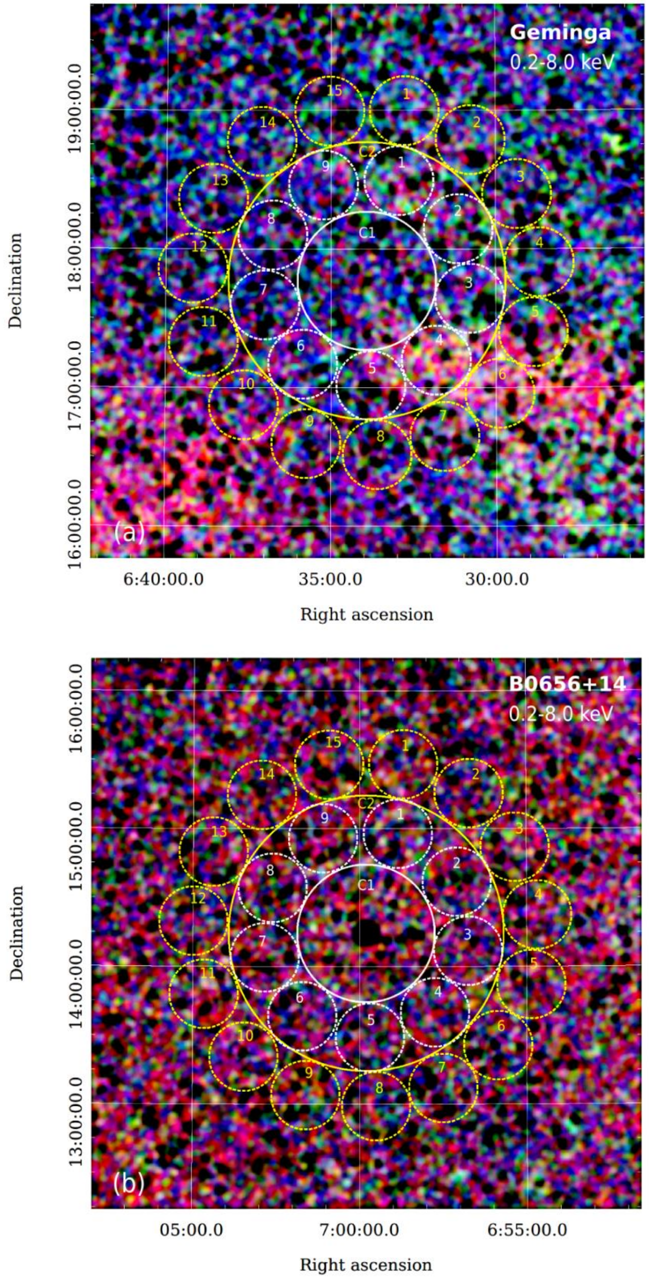

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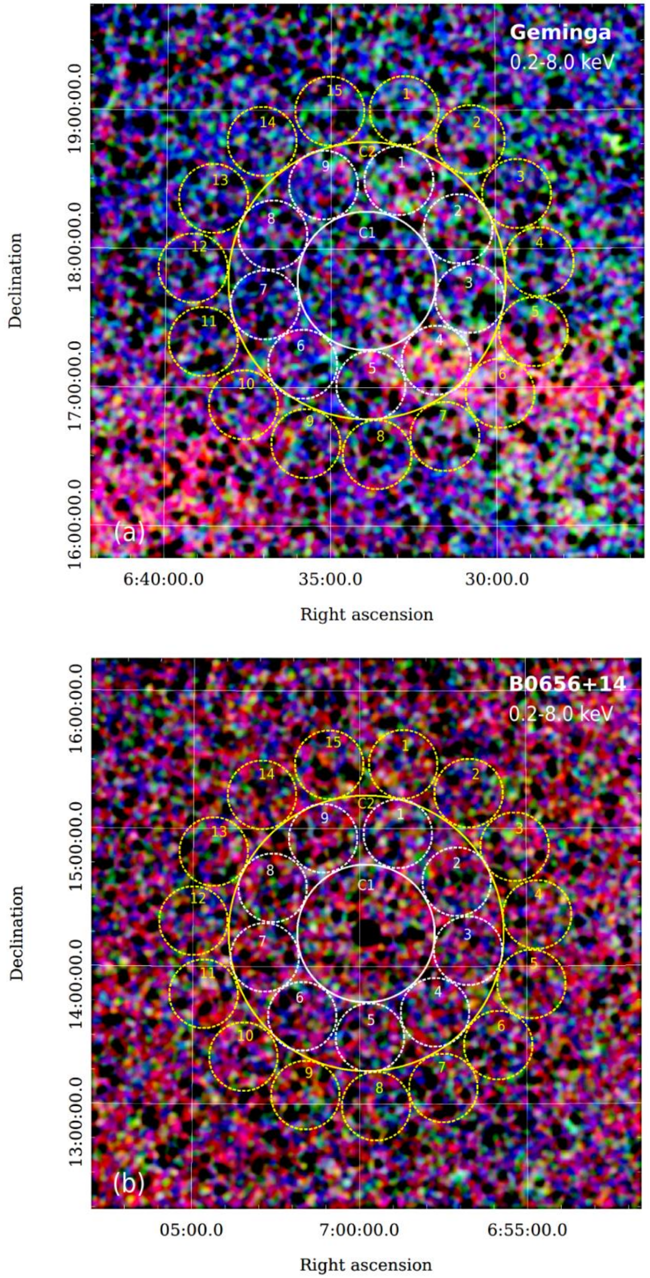
➢Build population-level model of pulsar environments with eROSITA All-Sky Survey (Predehl+21)

- Uniform source coverage
- „Unlimited“ field of view

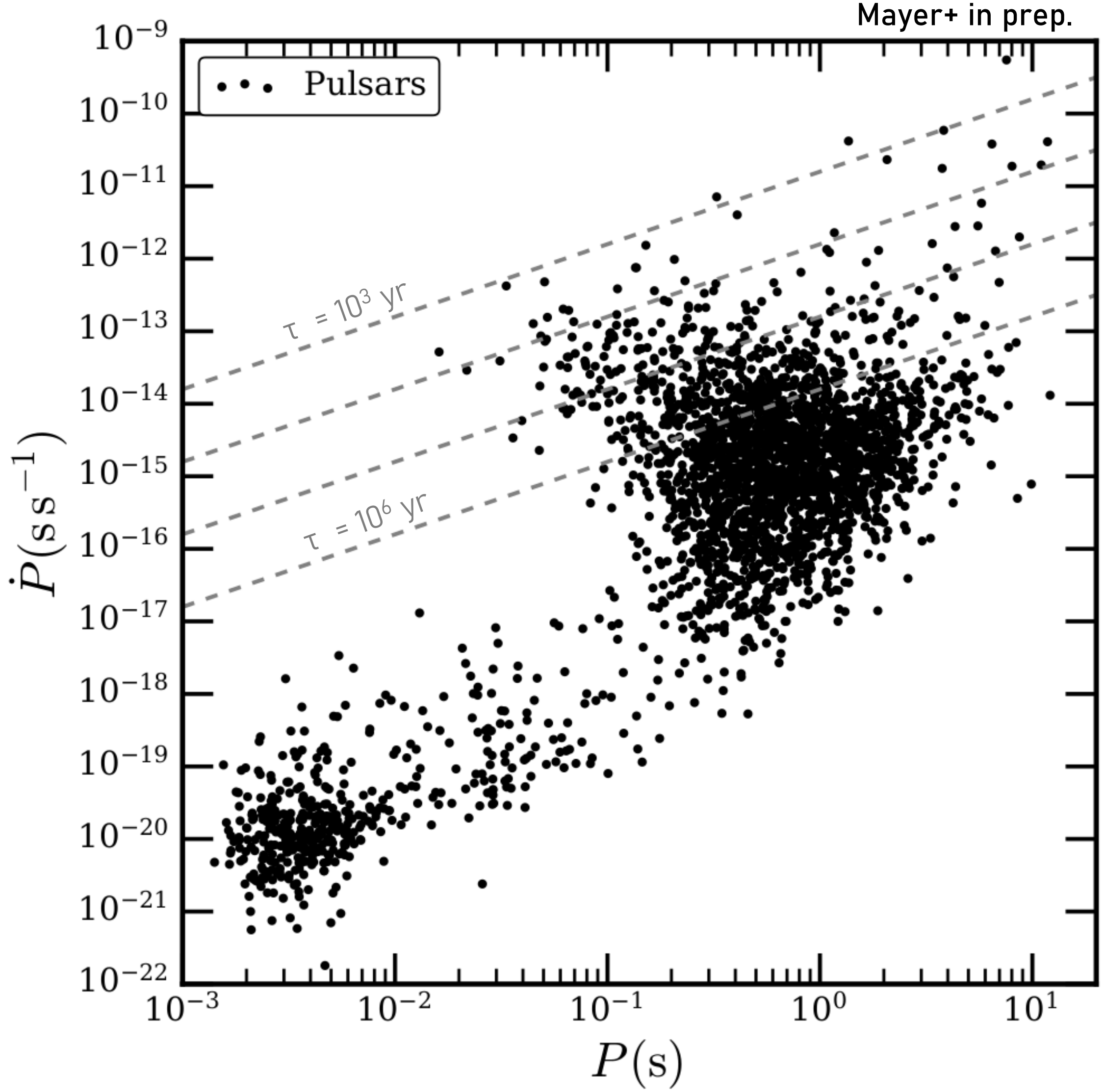
eROSITA maps of halos (Khokhriakova+24)



A population of middle-aged pulsars

- Construct target sample of halo-like pulsars from ATNF catalog (Manchester+05)

P-Pdot diagram of ATNF pulsars
Mayer+ in prep.



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  - Middle-aged ($10^{4.5}$ yr < τ < 10^6 yr)
  - Energetic ($\dot{E} > 10^{33}$ erg/s)
  - Nearby ($\dot{E}/4\pi d^2 > 10^{-10}$ erg/s/cm²)
  - Accessible with eROSITA (180° < l < 360°)

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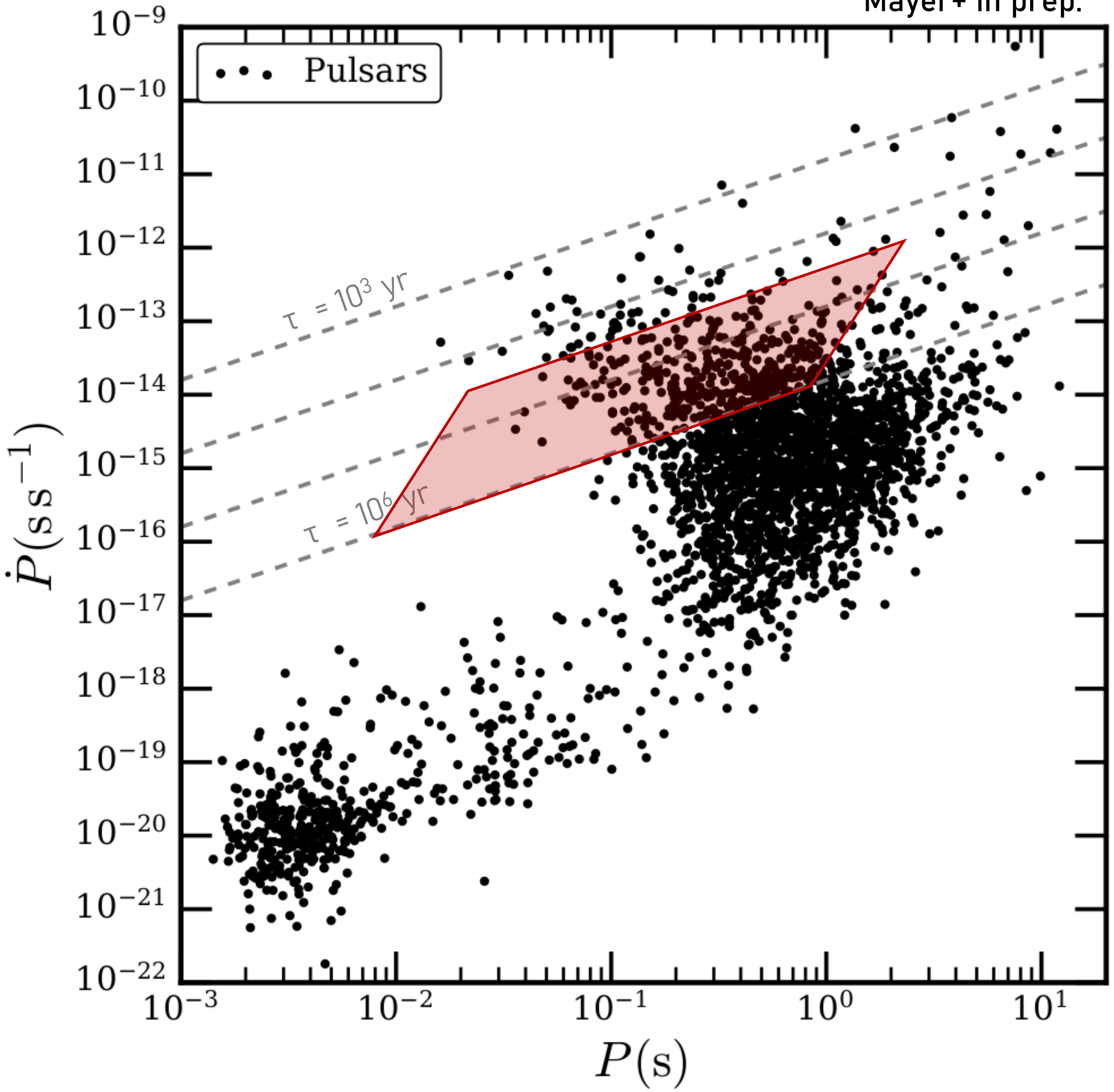

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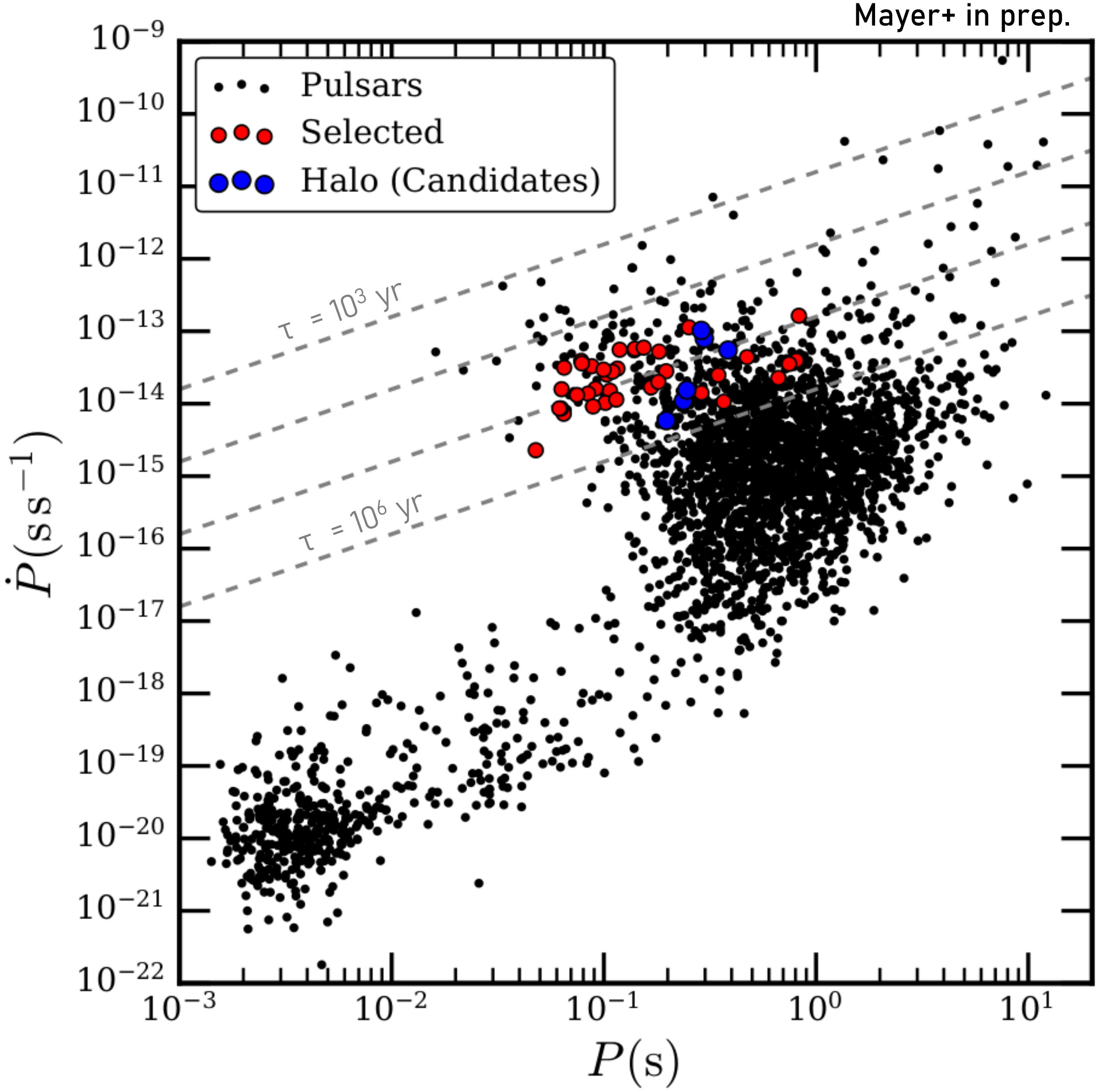
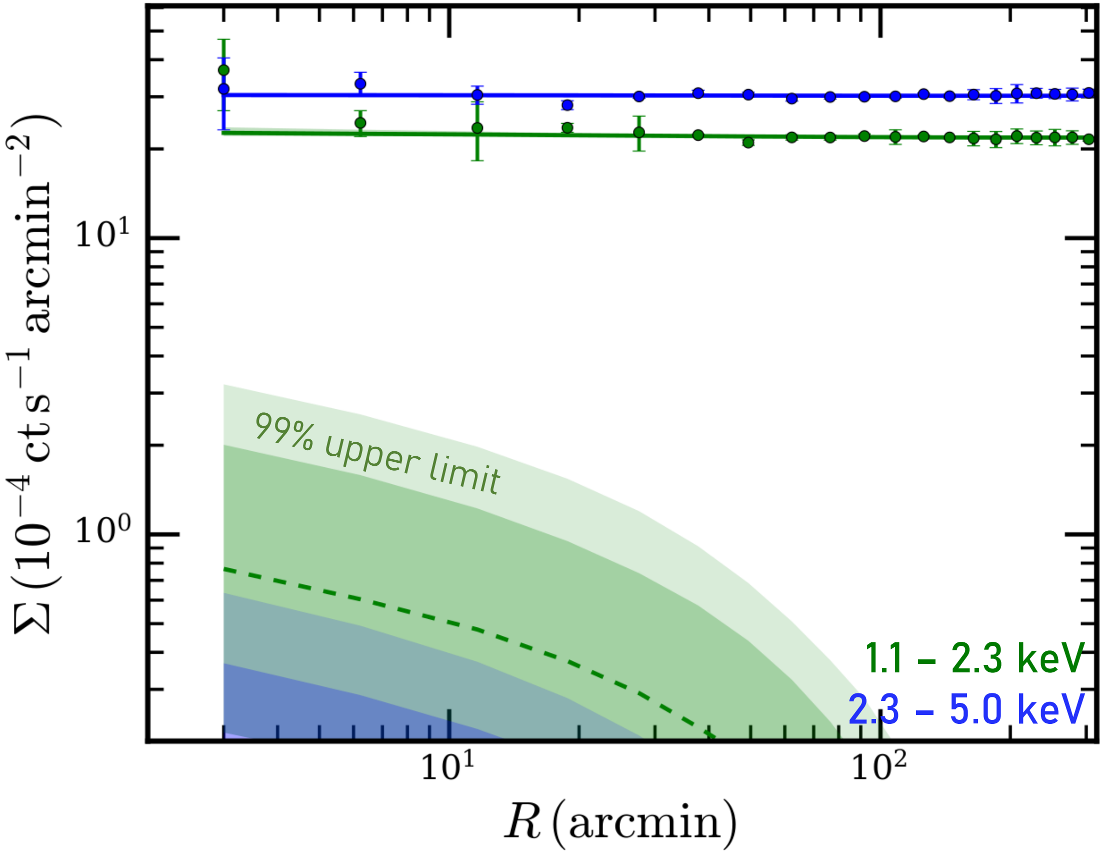
➢ Around 40 pulsar environments

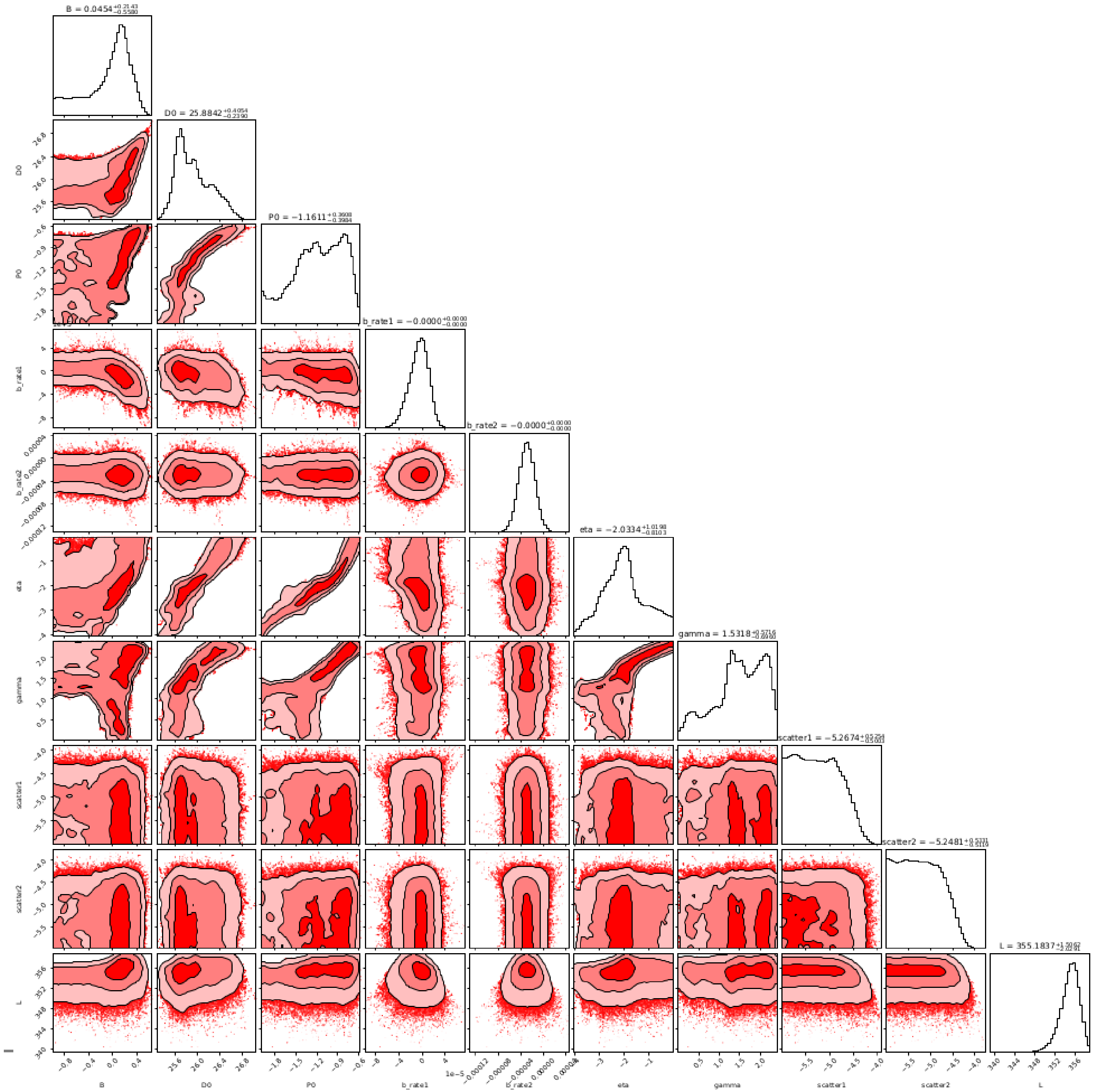
Sample selection in P-Pdot diagram of ATNF pulsars
Mayer+ in prep.



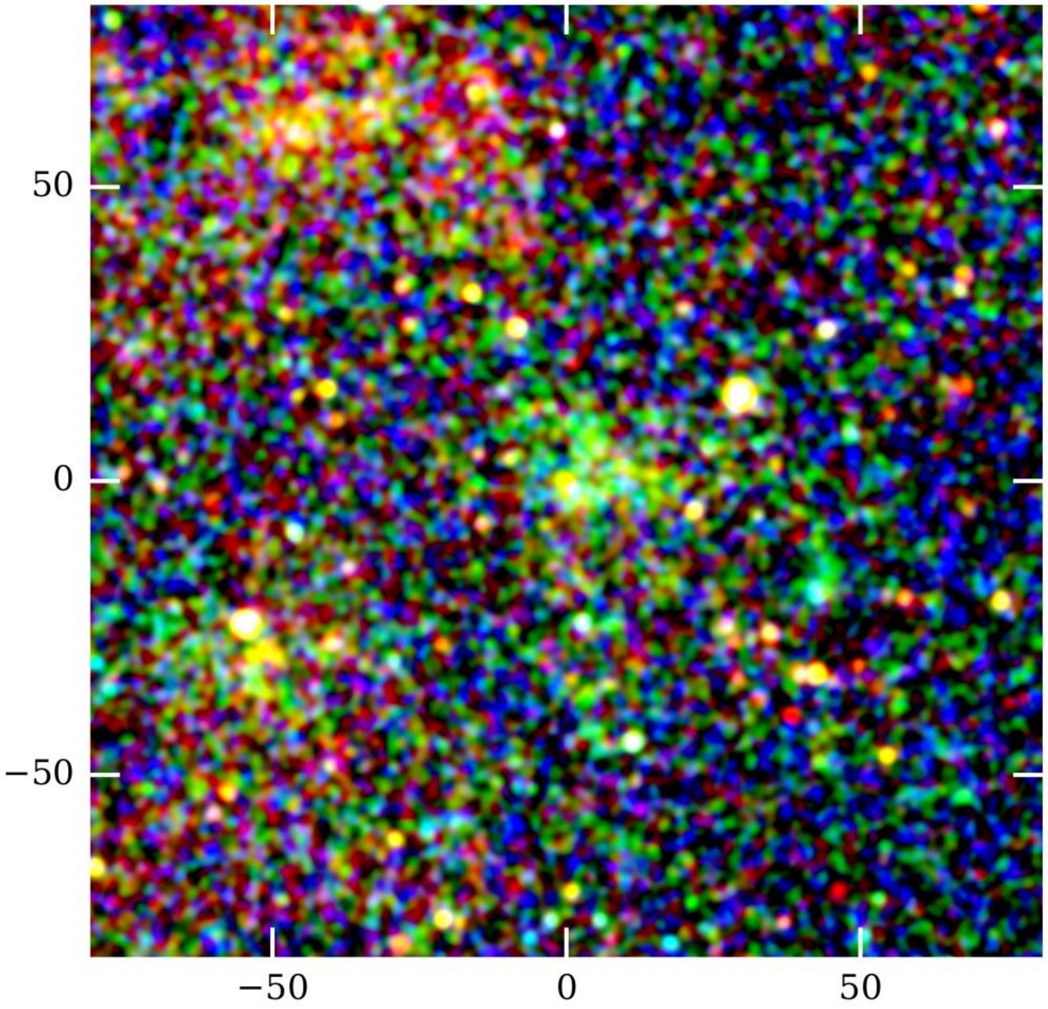
Full constraints for B0656+14

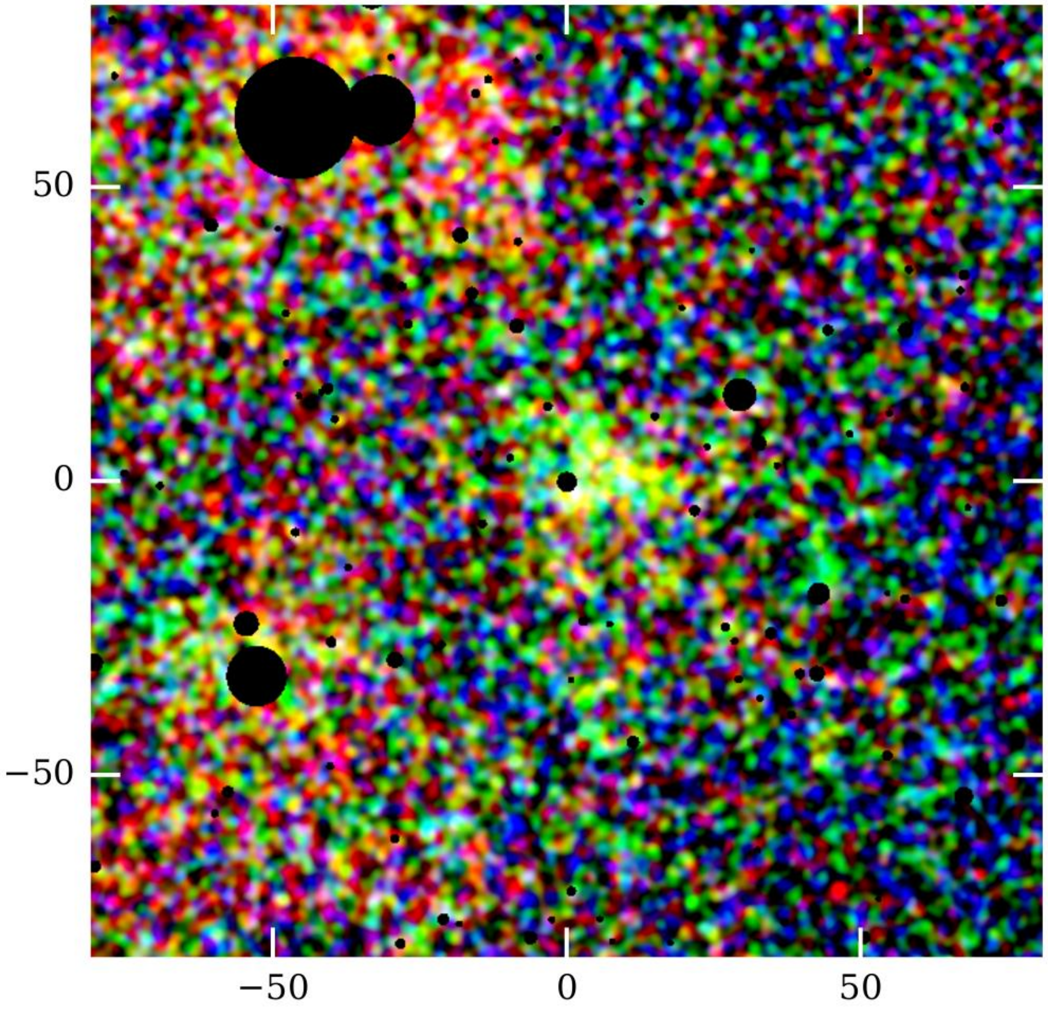
Fitted radial emission profile of B0656+14
Mayer+ in prep.





Images of J0633+0632





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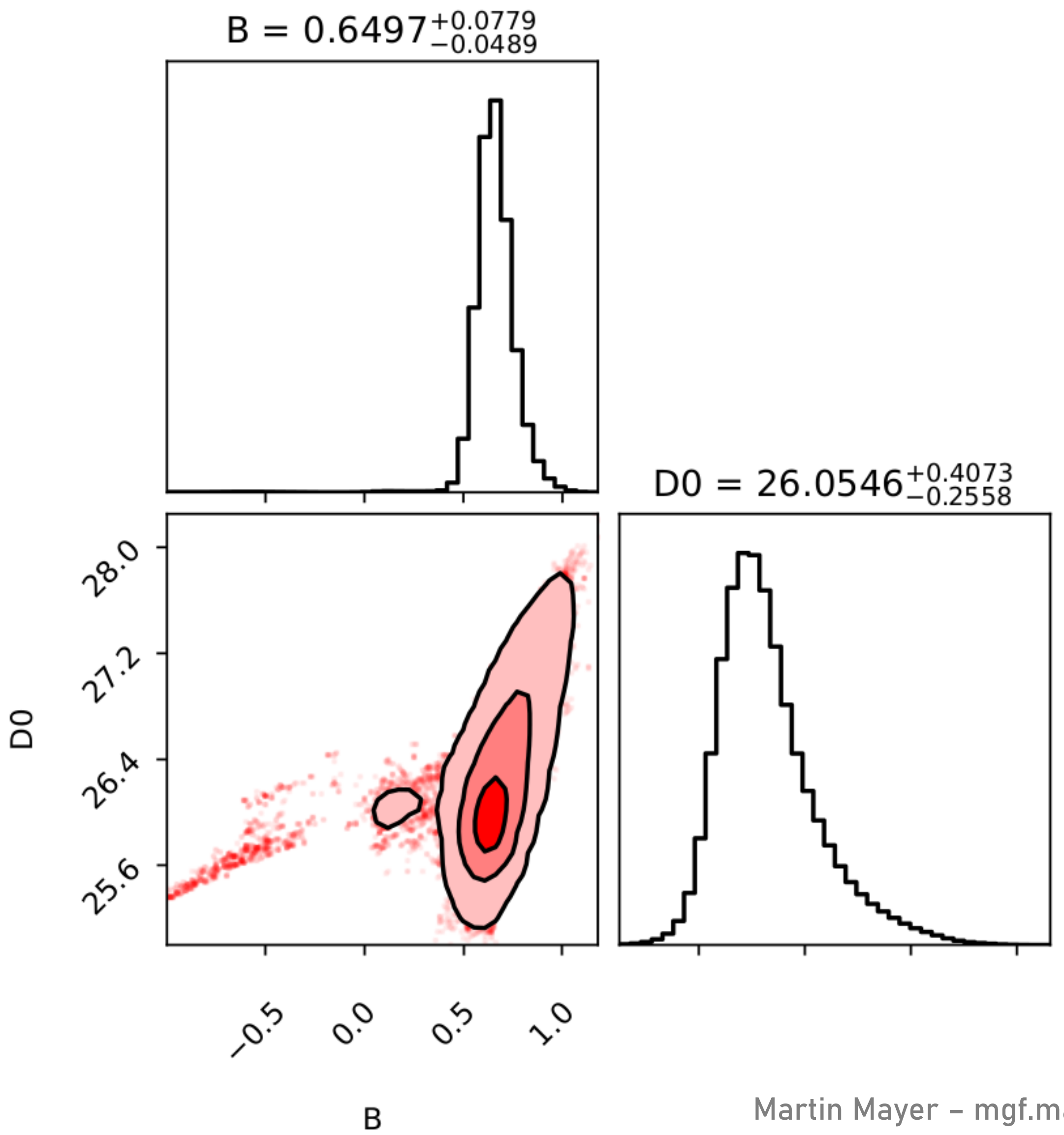

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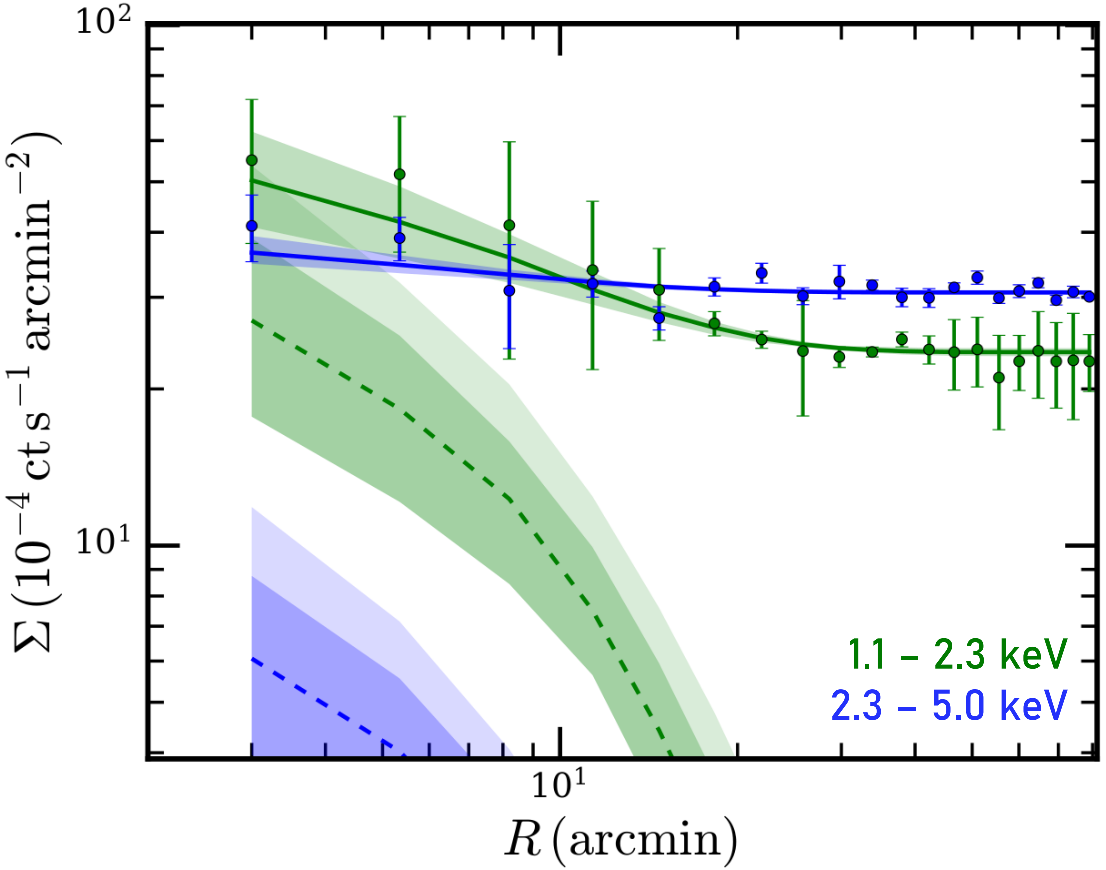
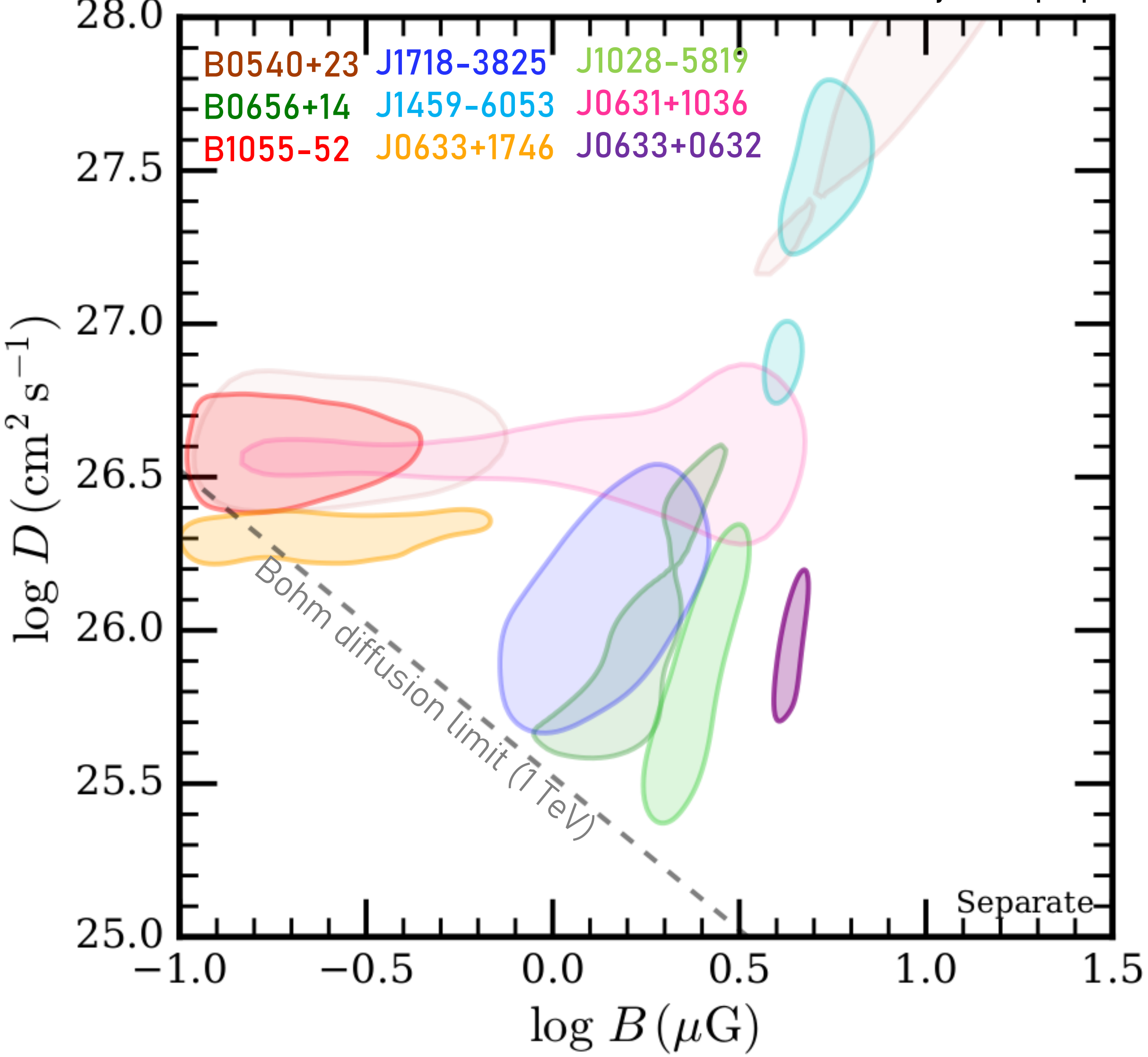


Assembling the population

- Derive constraints on physical properties of pulsar environments

One-sigma constraints for all sources
Mayer+ in prep.



Assembling the population

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  - ➢ $\log B$, $\log D$, …. ~ $Norm(\mu_B, \mu_D, \ldots \mid \sigma_B, \sigma_D, \ldots)$

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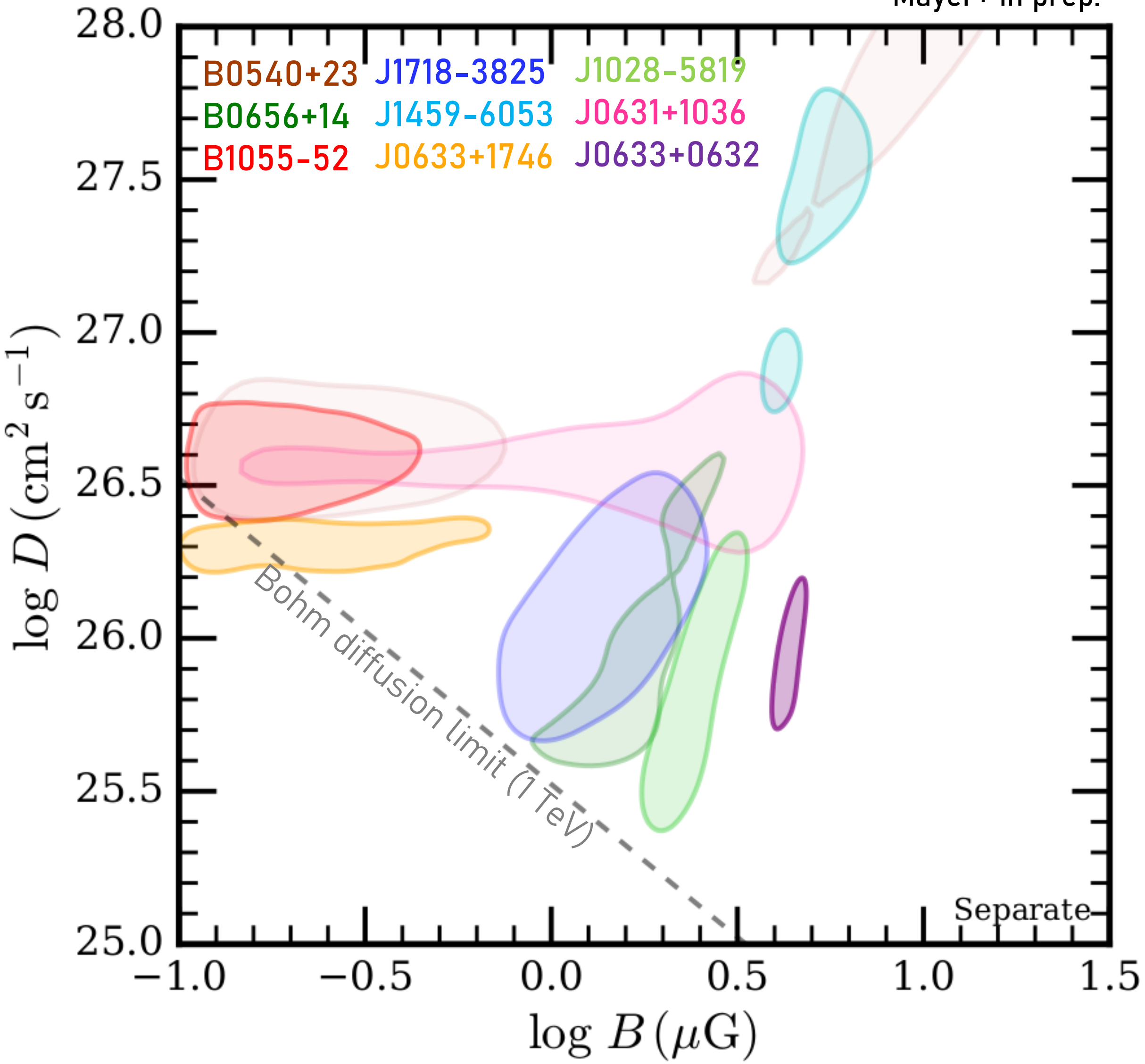

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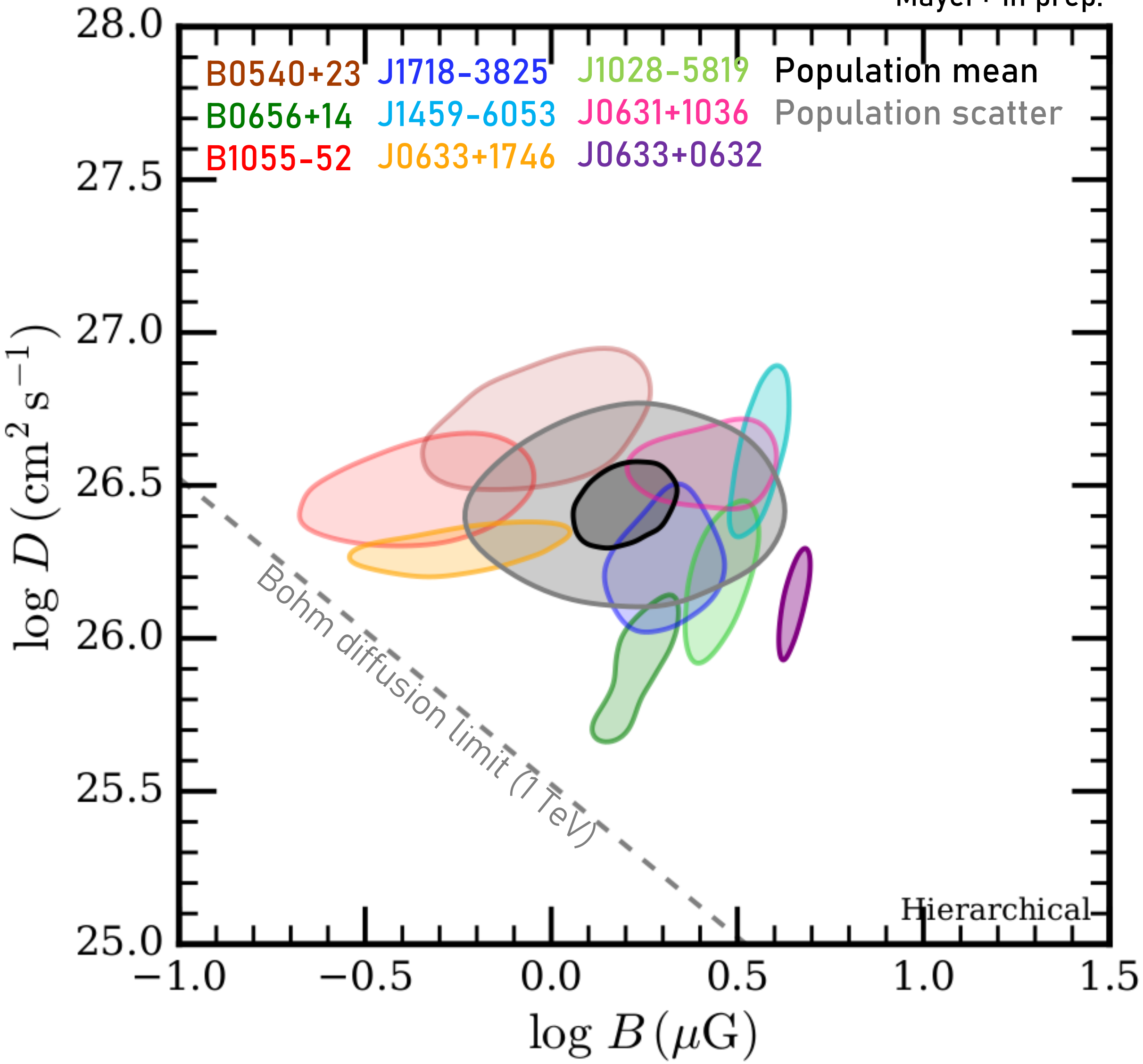

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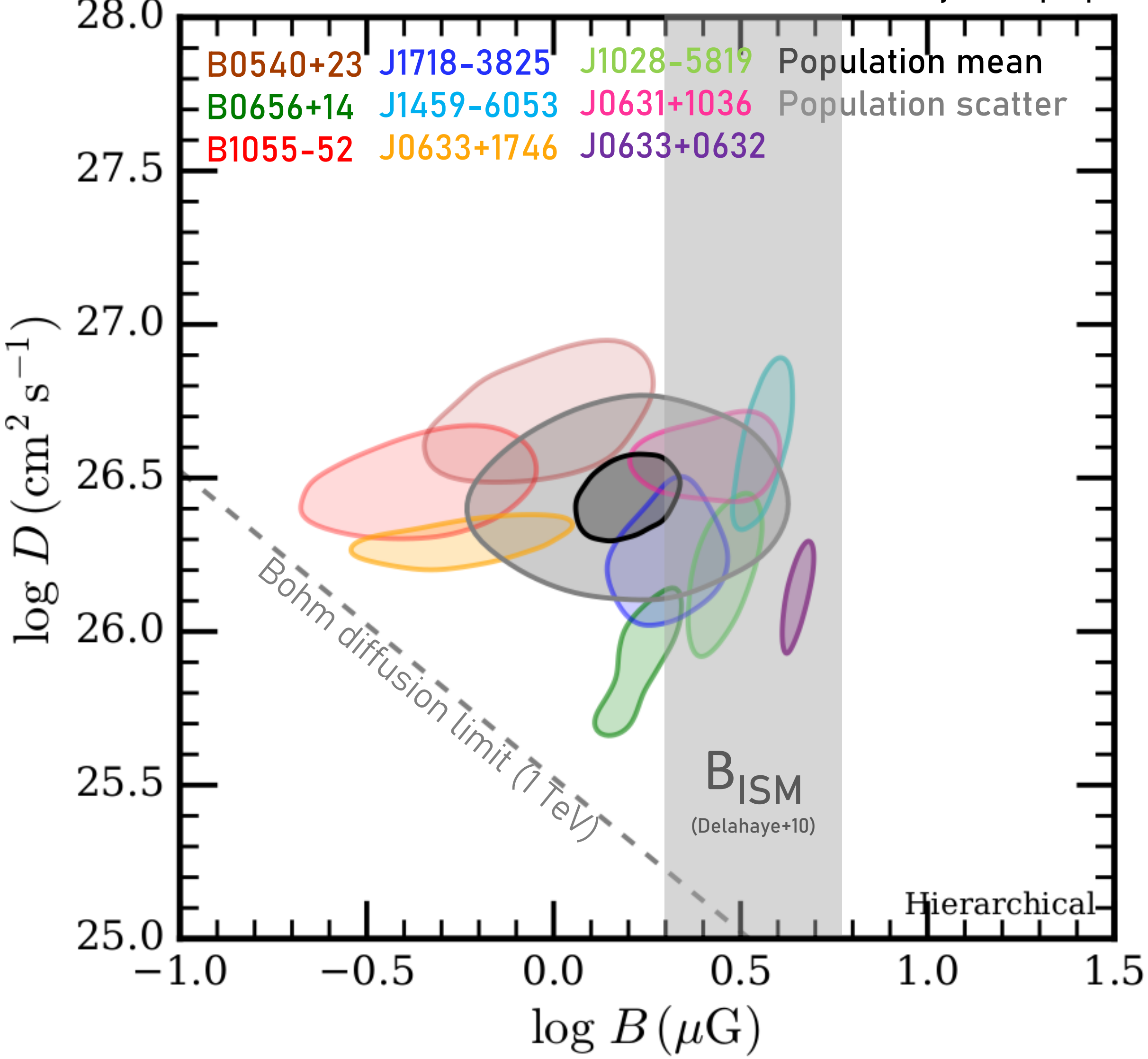

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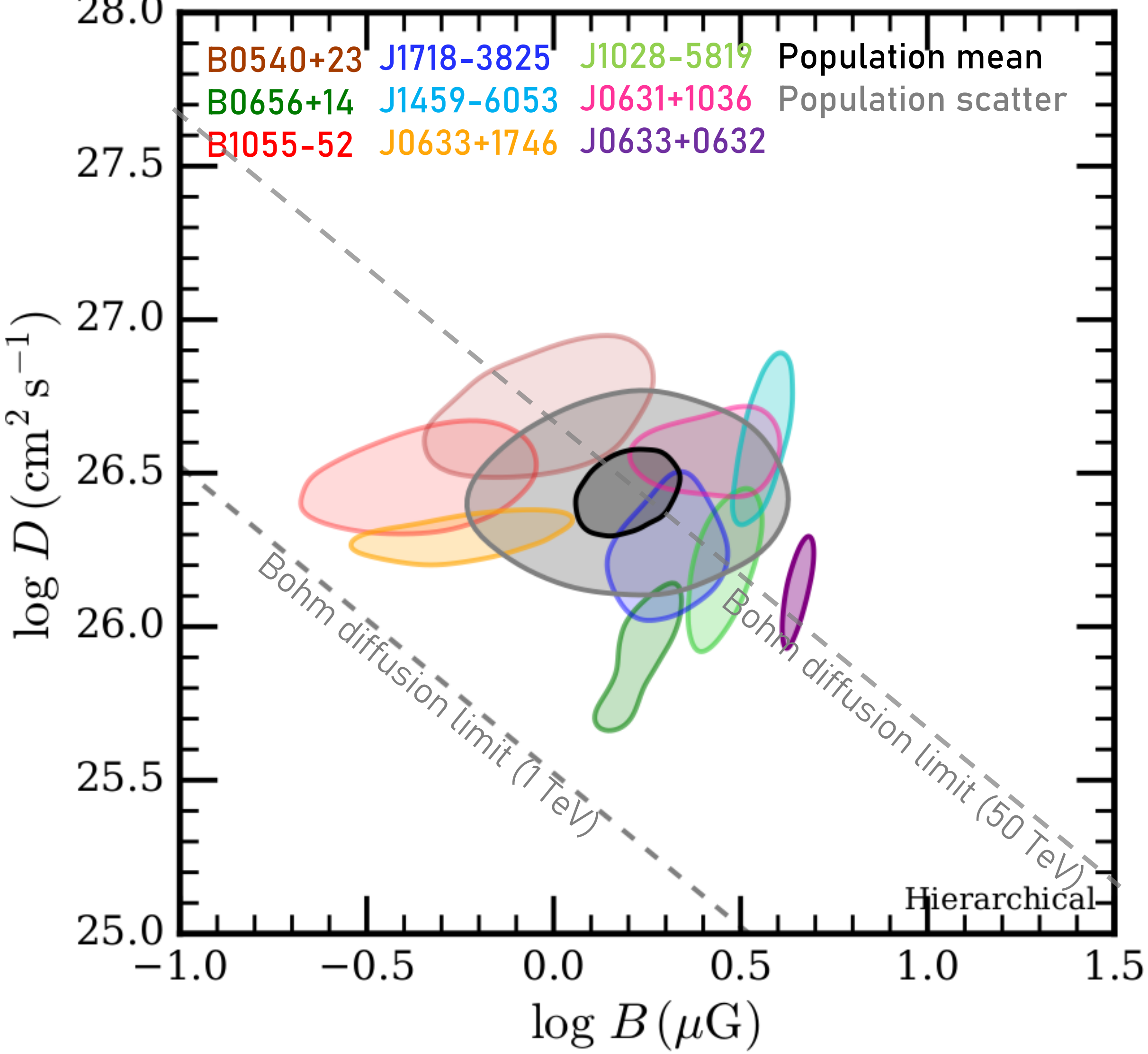

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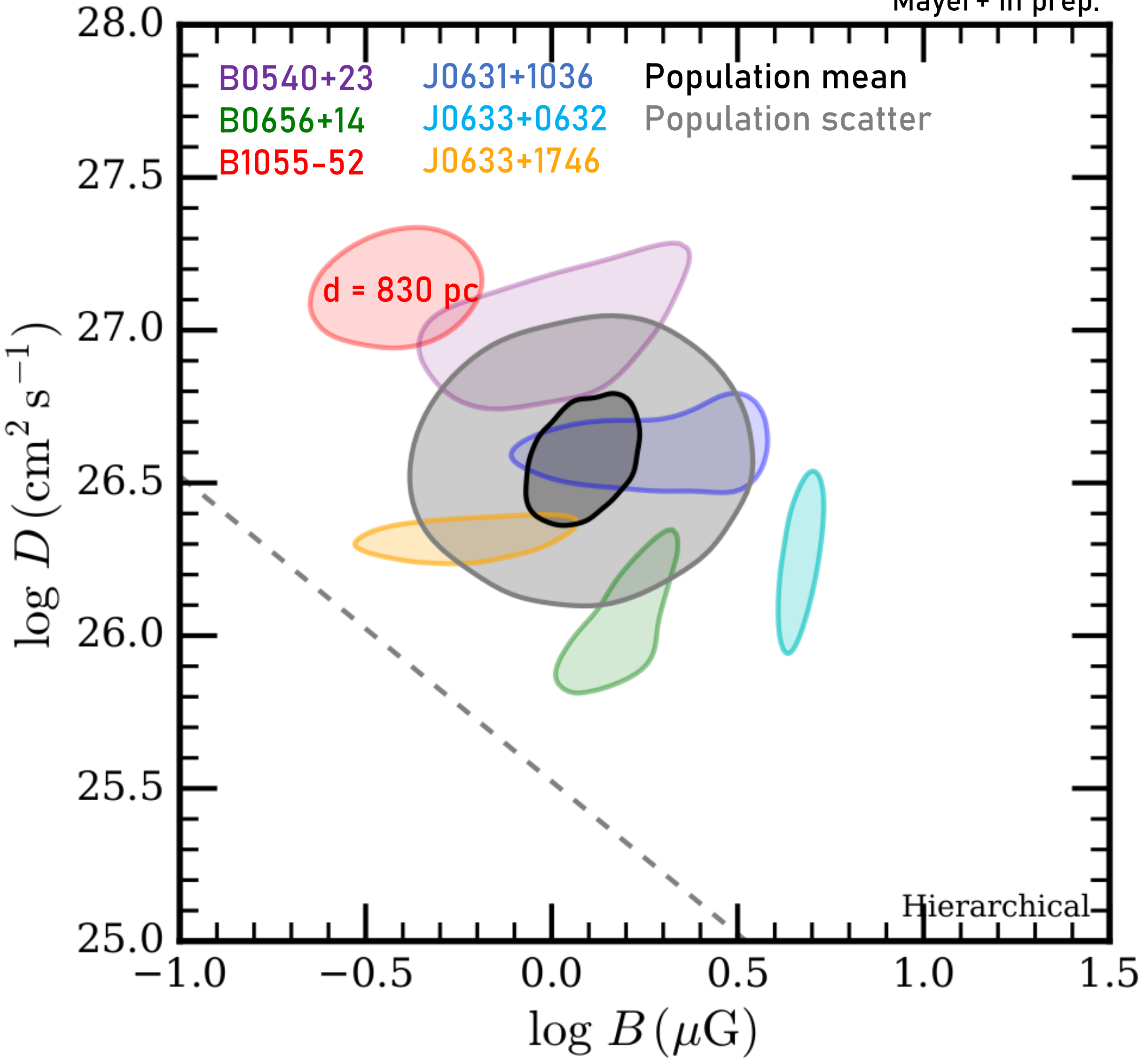

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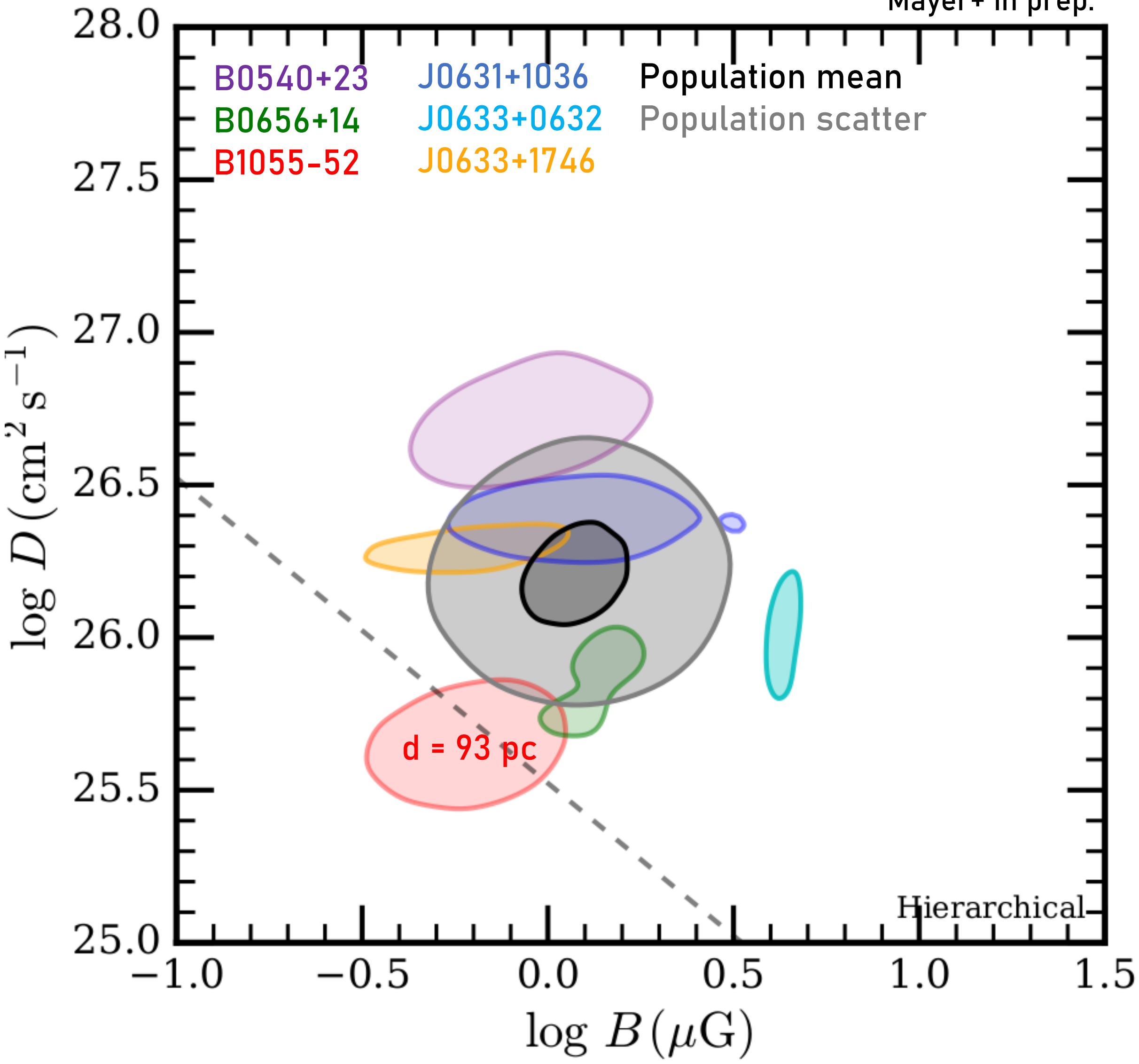

Building a pulsar population

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One-sigma constraints for all sources
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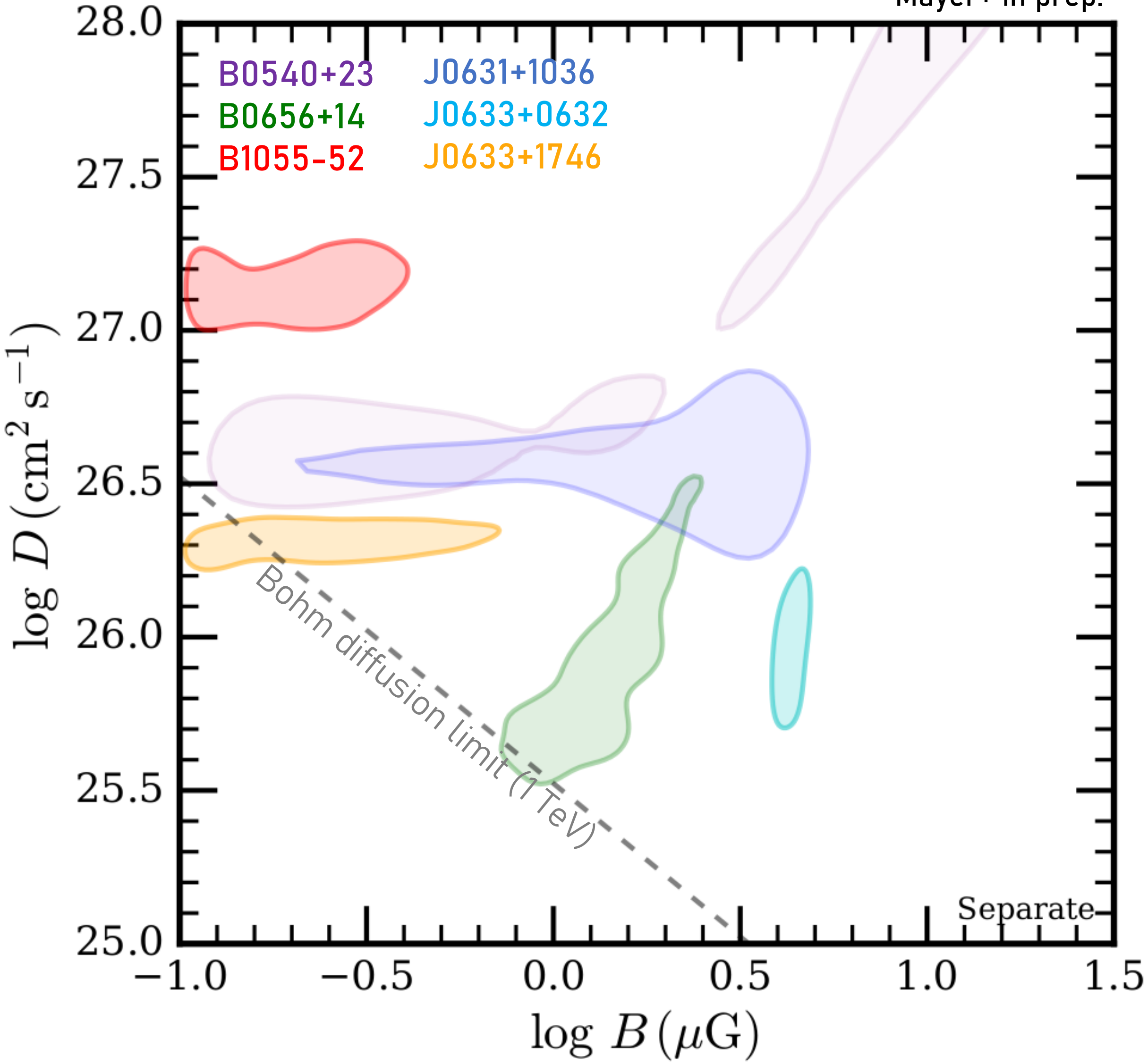

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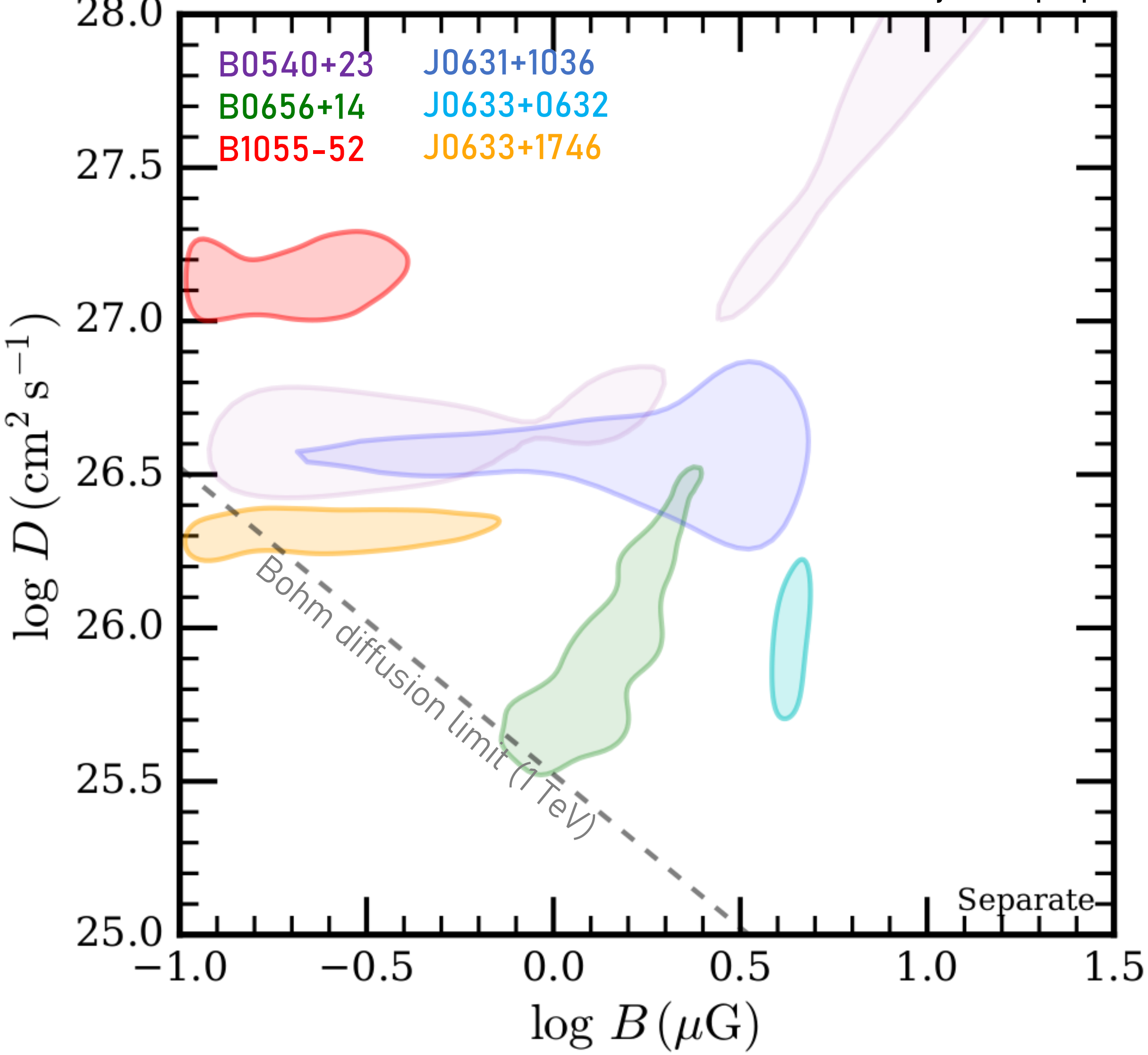

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  - ➢ $\log B$, $\log D$, ... ~ $Norm(\mu_B, \mu_D, \ldots \,|\, \sigma_B, \sigma_D, \ldots)$
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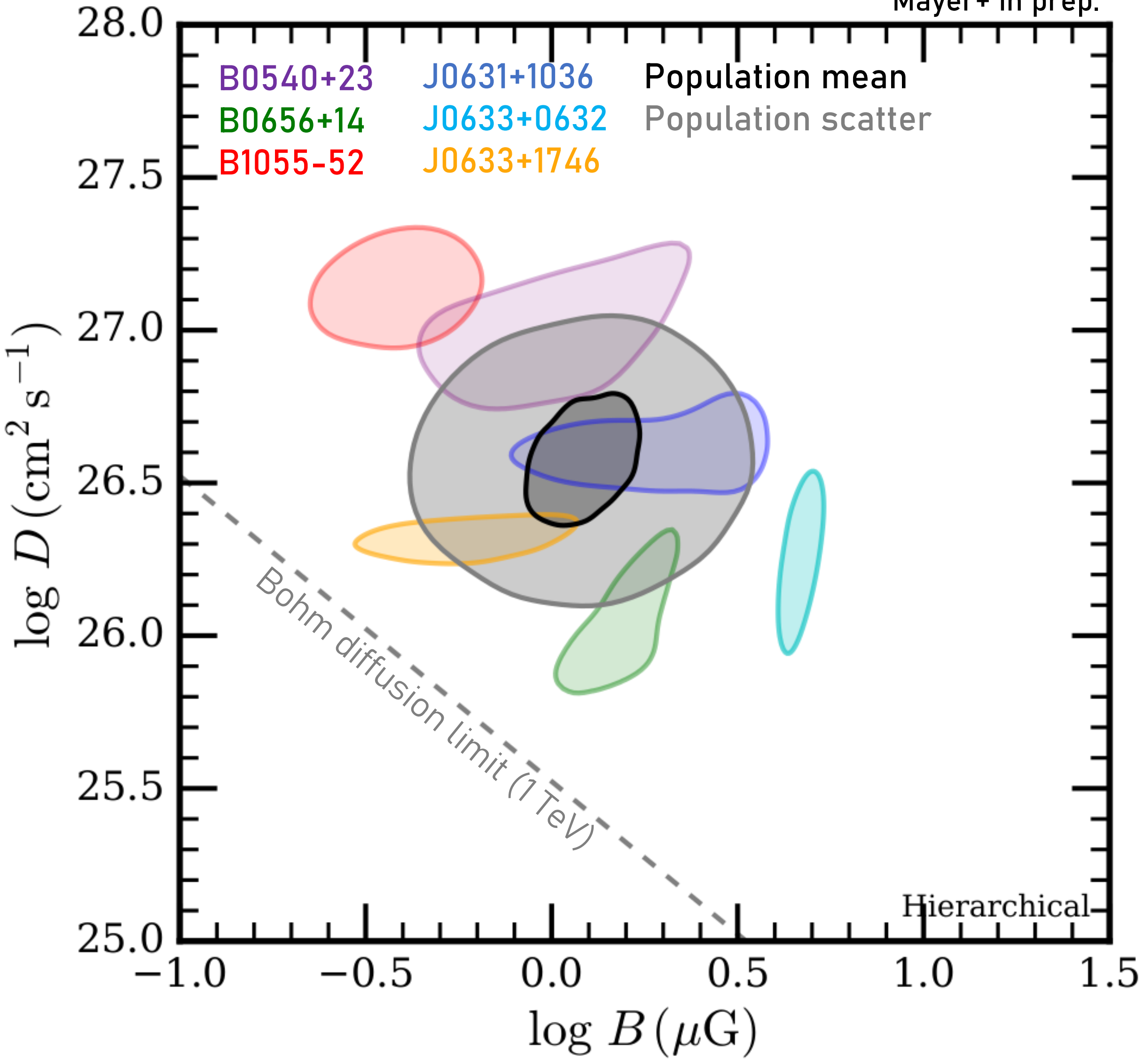

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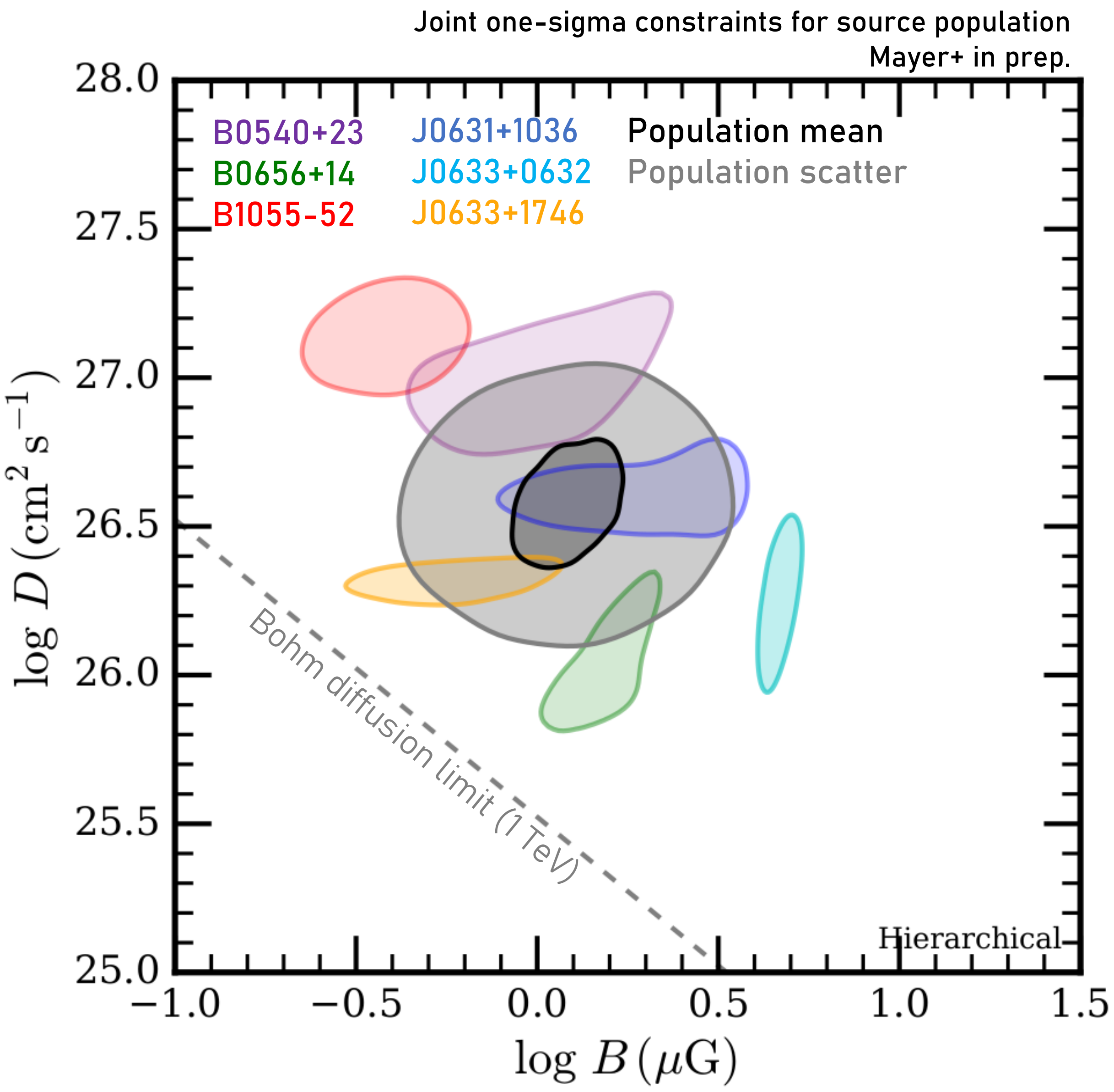

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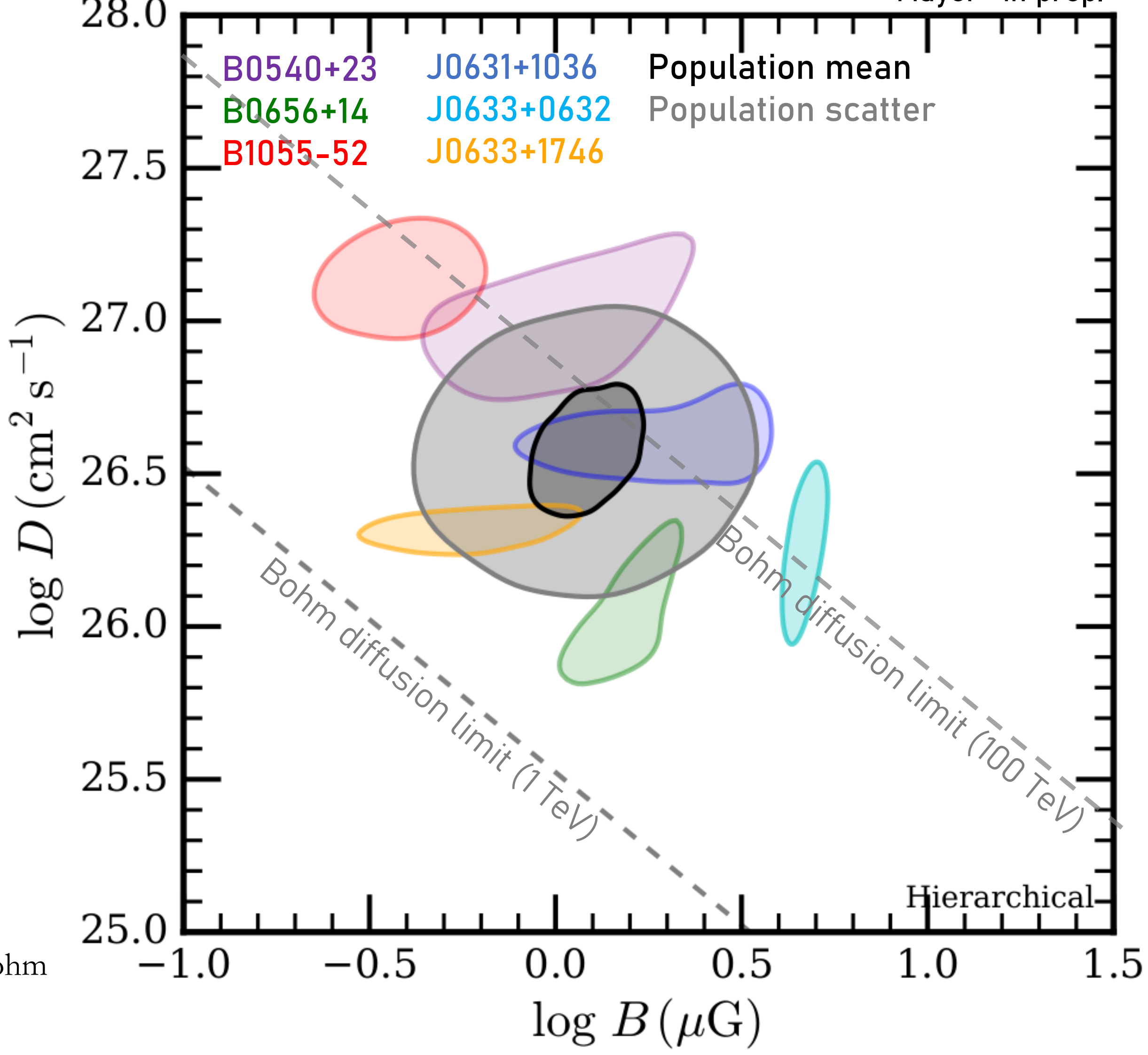

Modelling caveats

- No time evolution in properties (e.g., magnetic field, injection spectrum)
- Isotropic diffusion, uniform magnetic field

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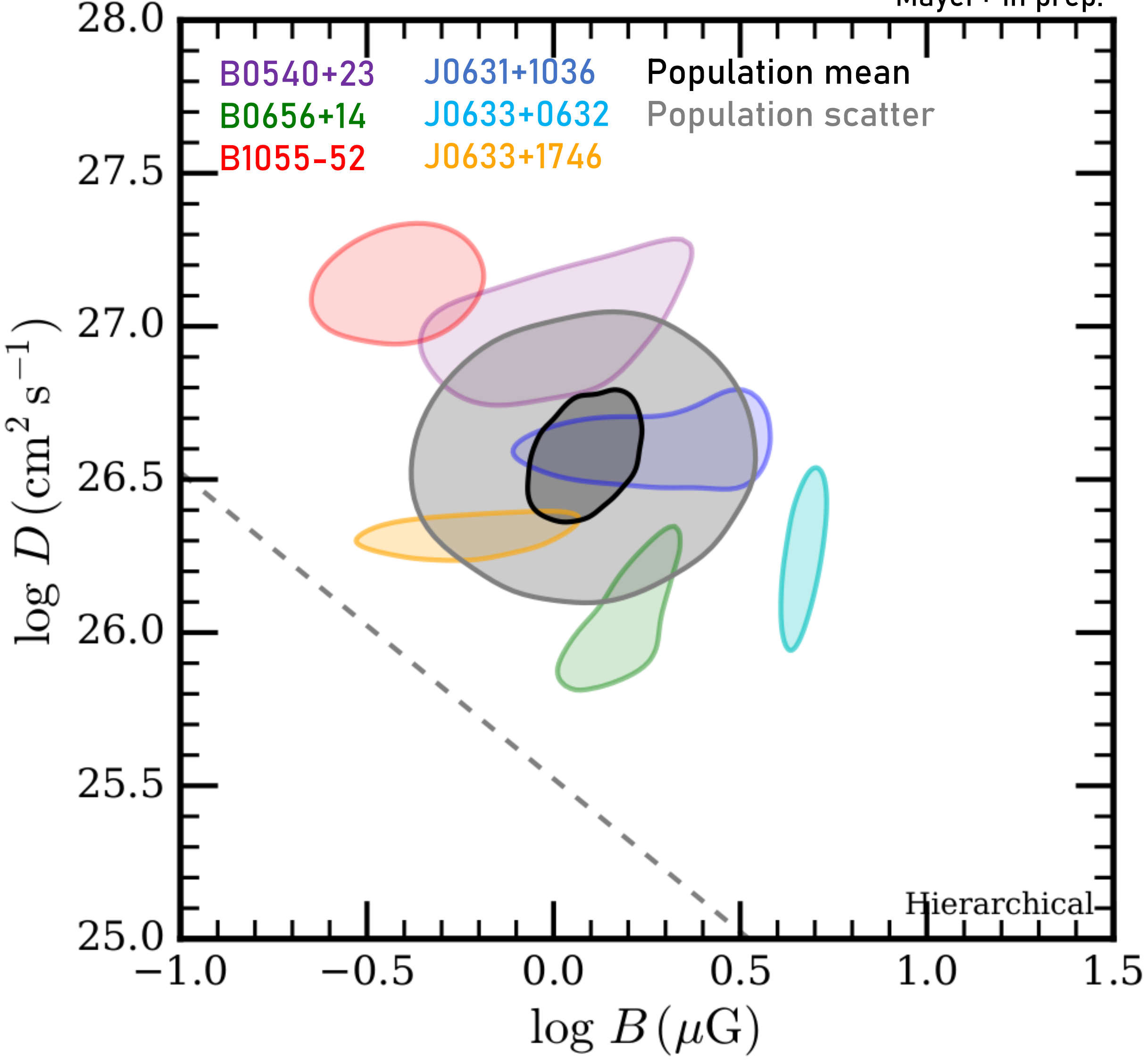

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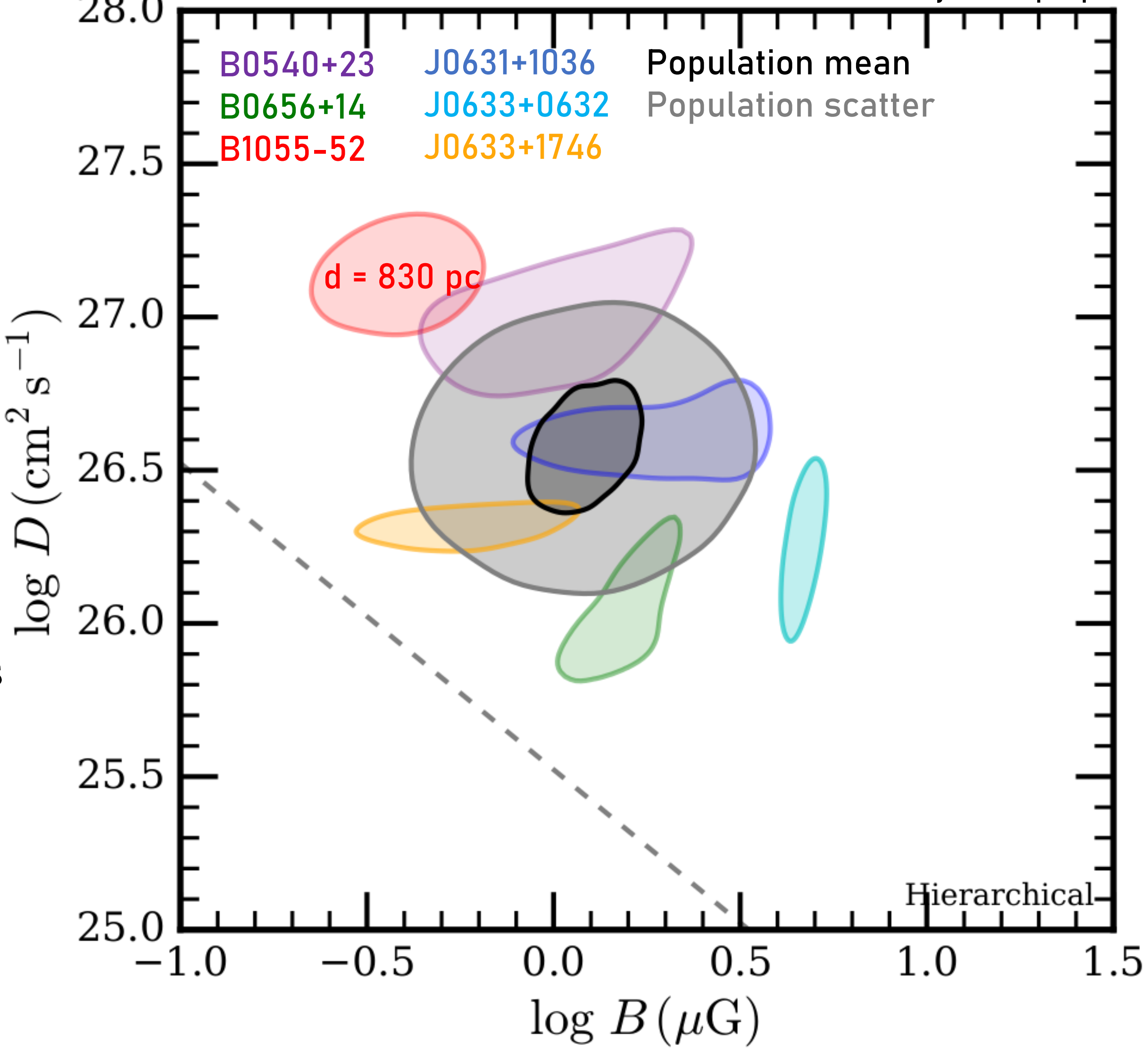

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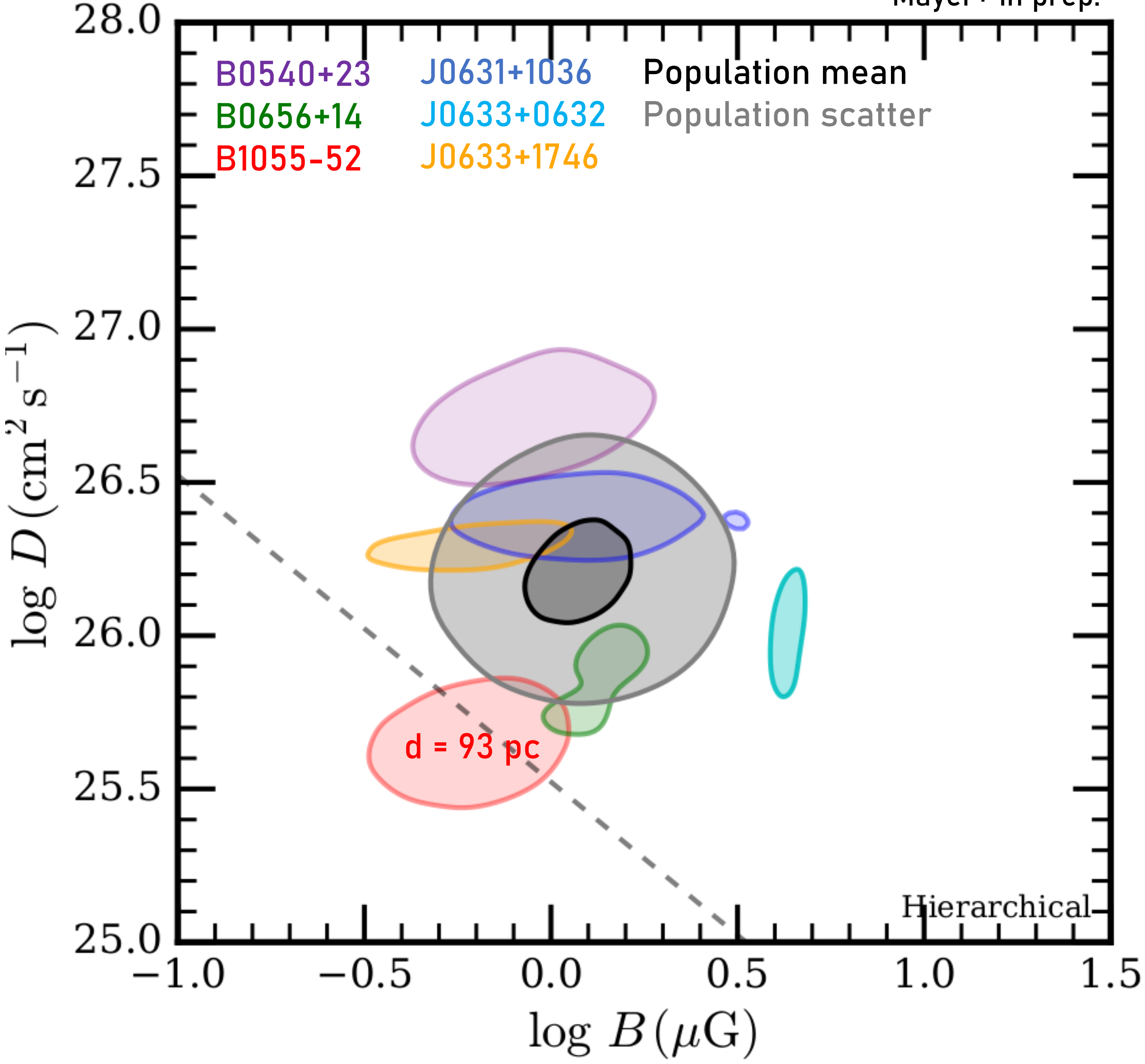
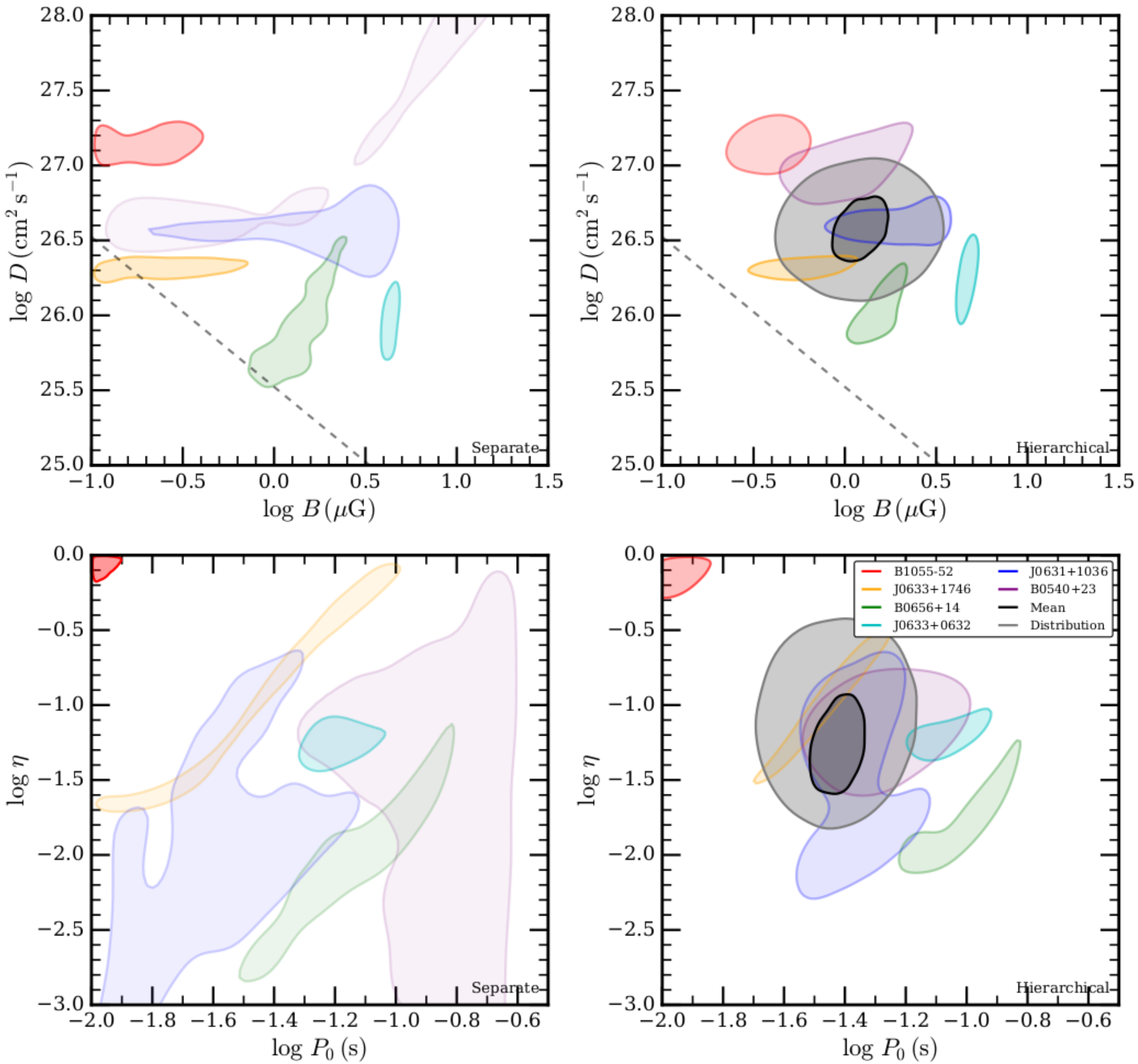
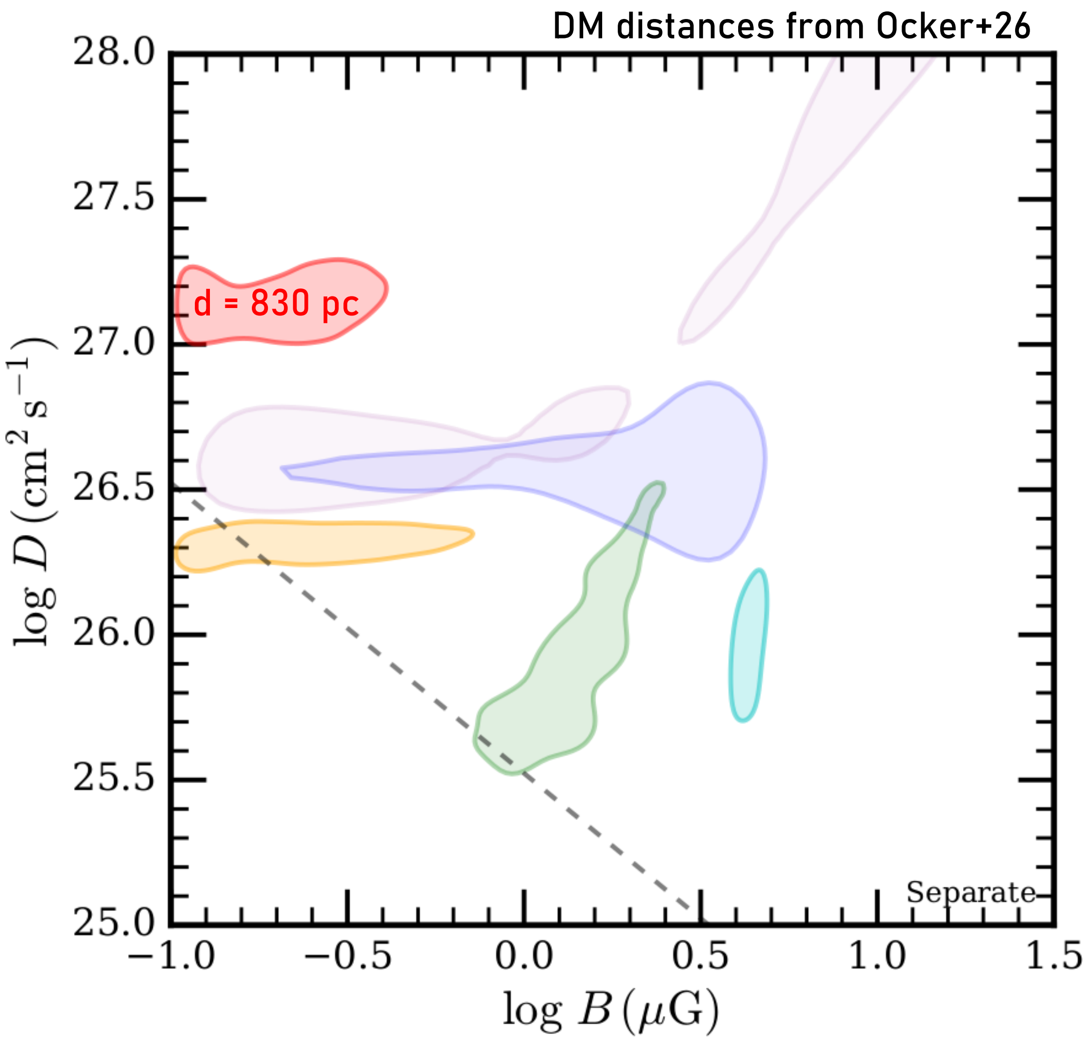
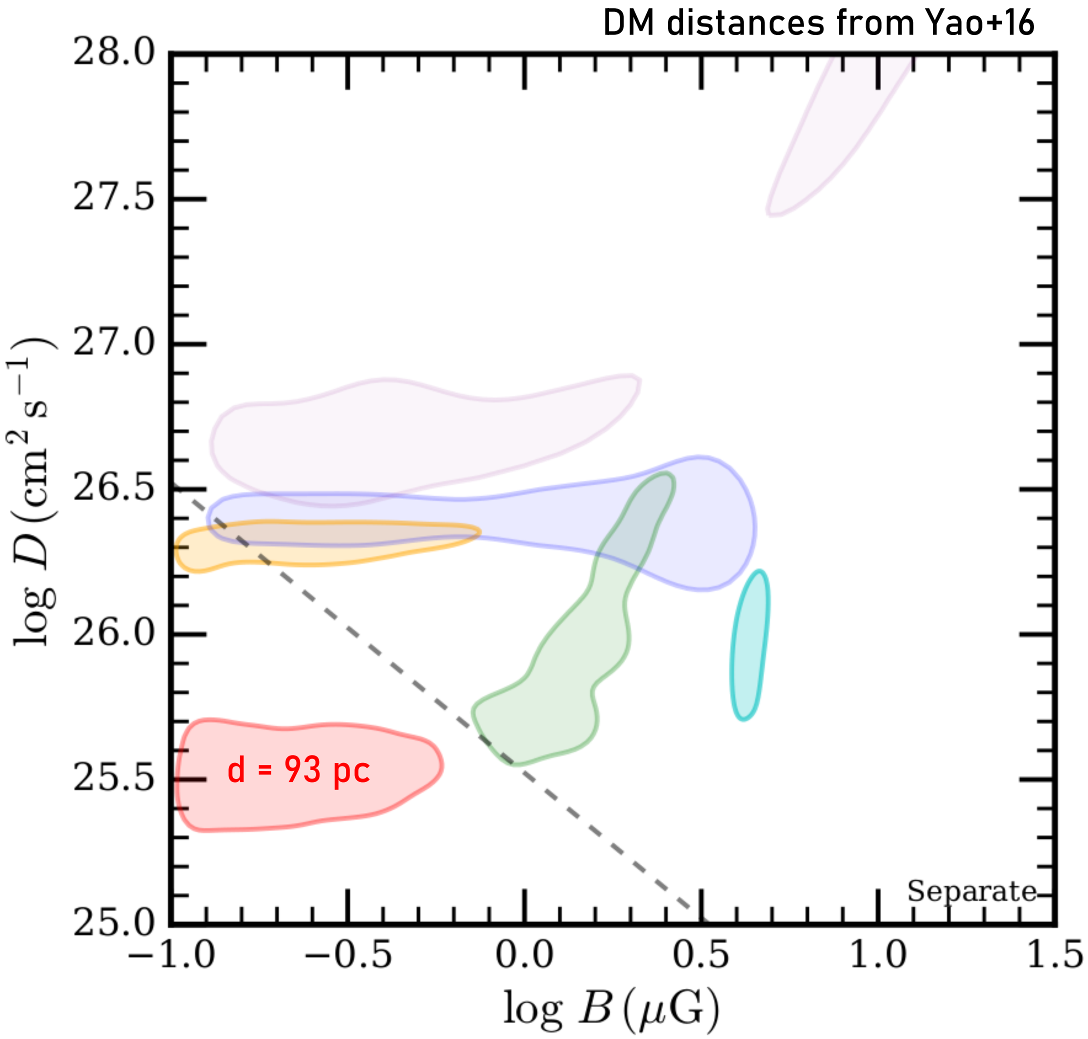


Full Hierarchical Model



Individual fits – distance effect





Summary

Systematic study of environments of middle-aged pulsars with eROSITA

- X-ray morphological analysis to obtain systematic uncertainties

- One-dimensional emission models to constrain particle transport and magnetic fields

- Hierarchical model of source population
  - ➢ Mean magnetic field $B \sim 1\mu G < B_{ISM}$
  - ➢ Strongly suppressed diffusion