A lower limit of 50 μG for the Galactic centre magnetic field

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Magnetic fields: properties & origin: Krakow 2010

Introduction

- Background
  - The Galactic centre (GC)
  - Evidence for a 1 mG field
  - Evidence for a 10 μG field
- The Diffuse Non-thermal Source revisited
  - The DNS spectrum
  - Rejection of the null hypothesis
  - Arguments for a cooling break
  - GC radio and gamma-ray analysis: A lower limit of 50 μG
- Conclusions

Where is the GC?

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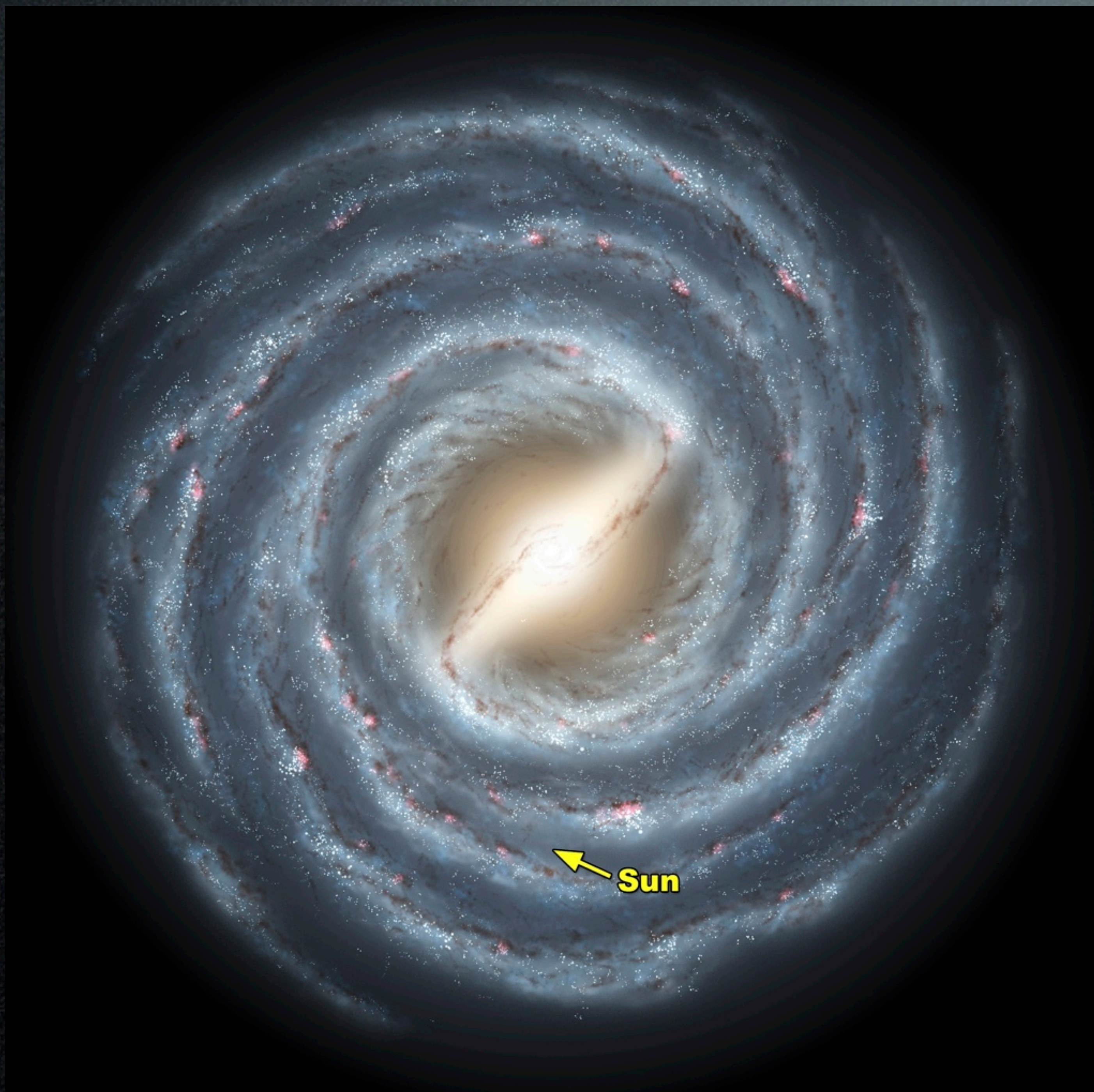

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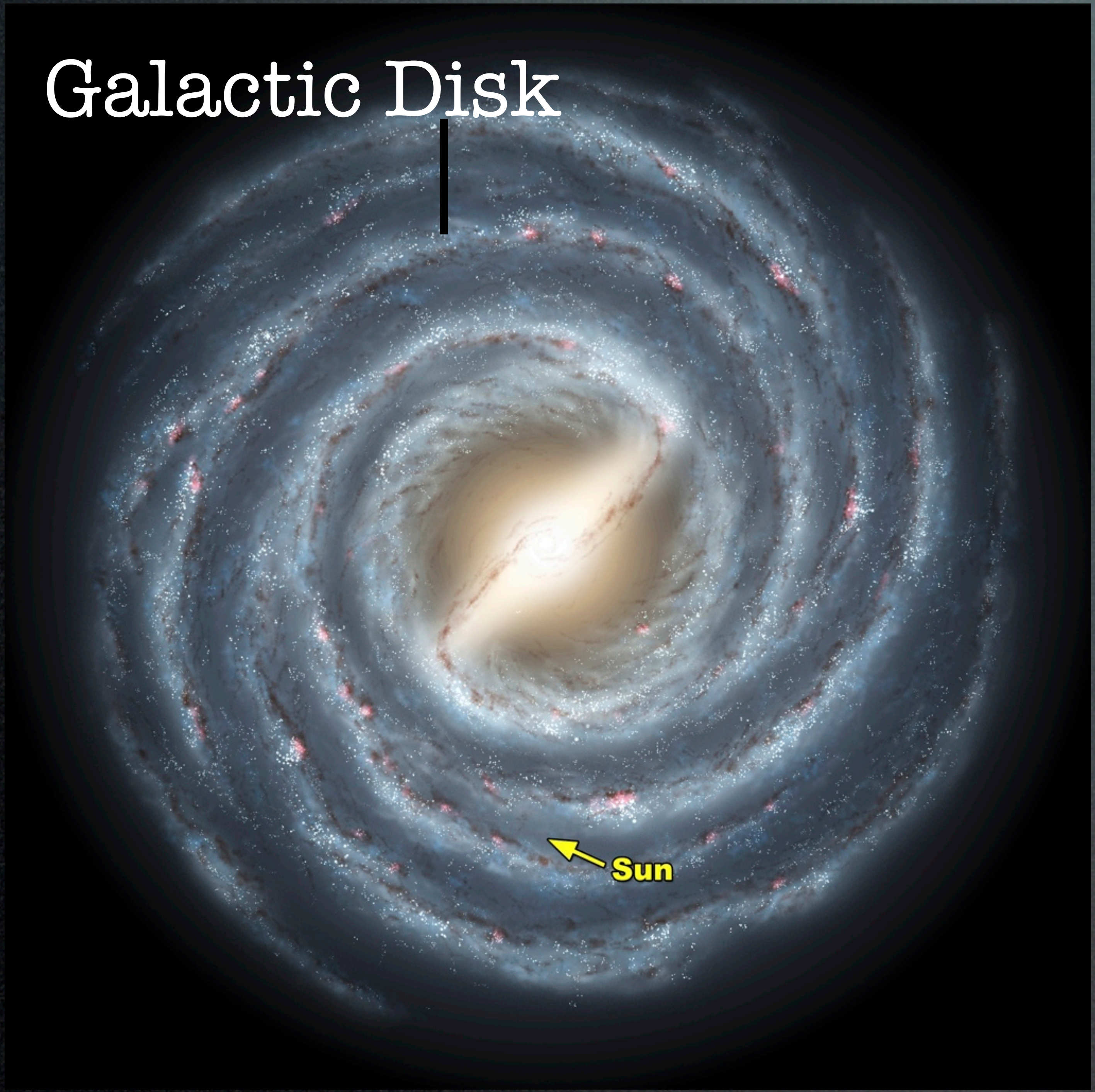

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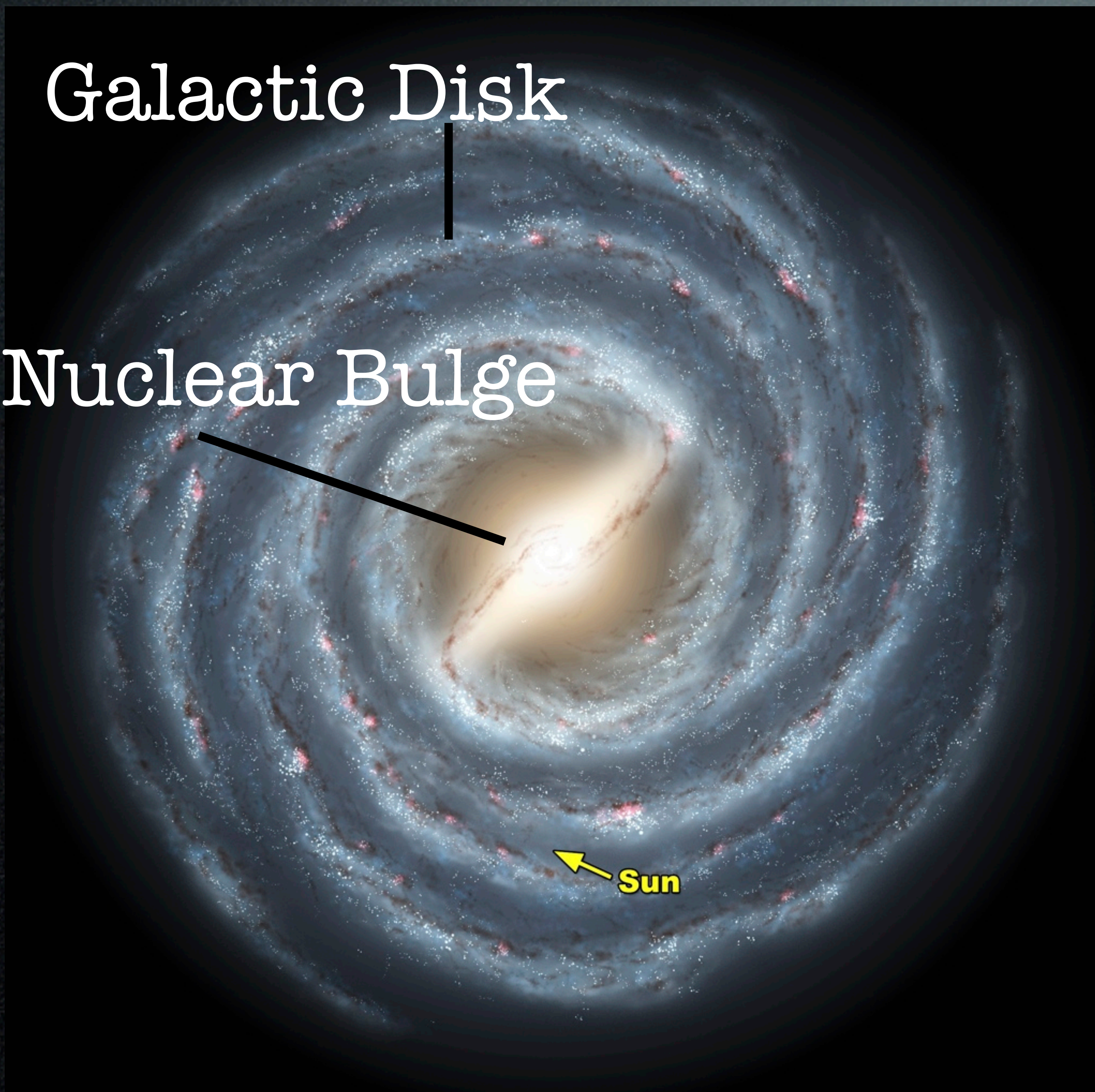

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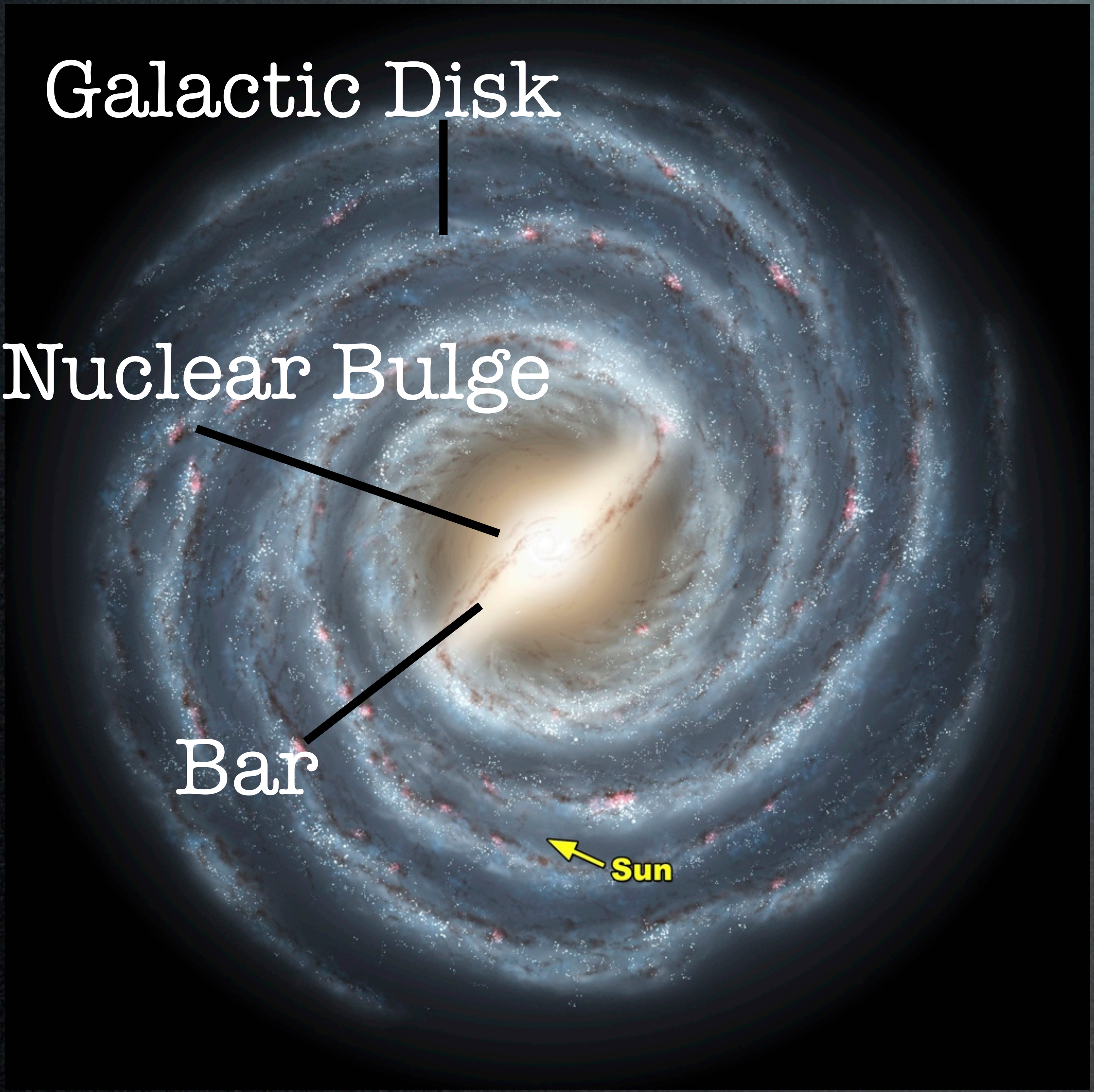

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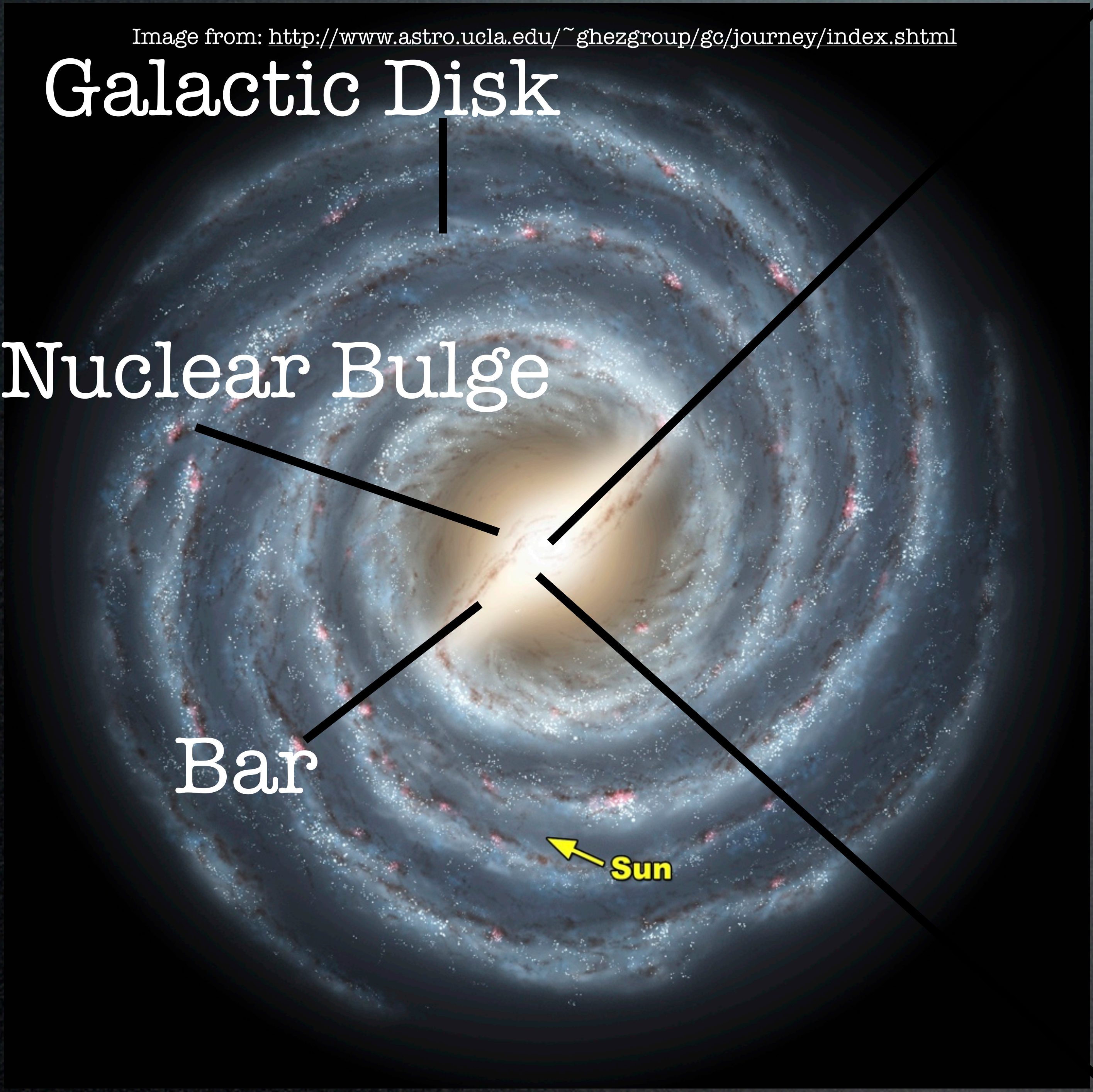

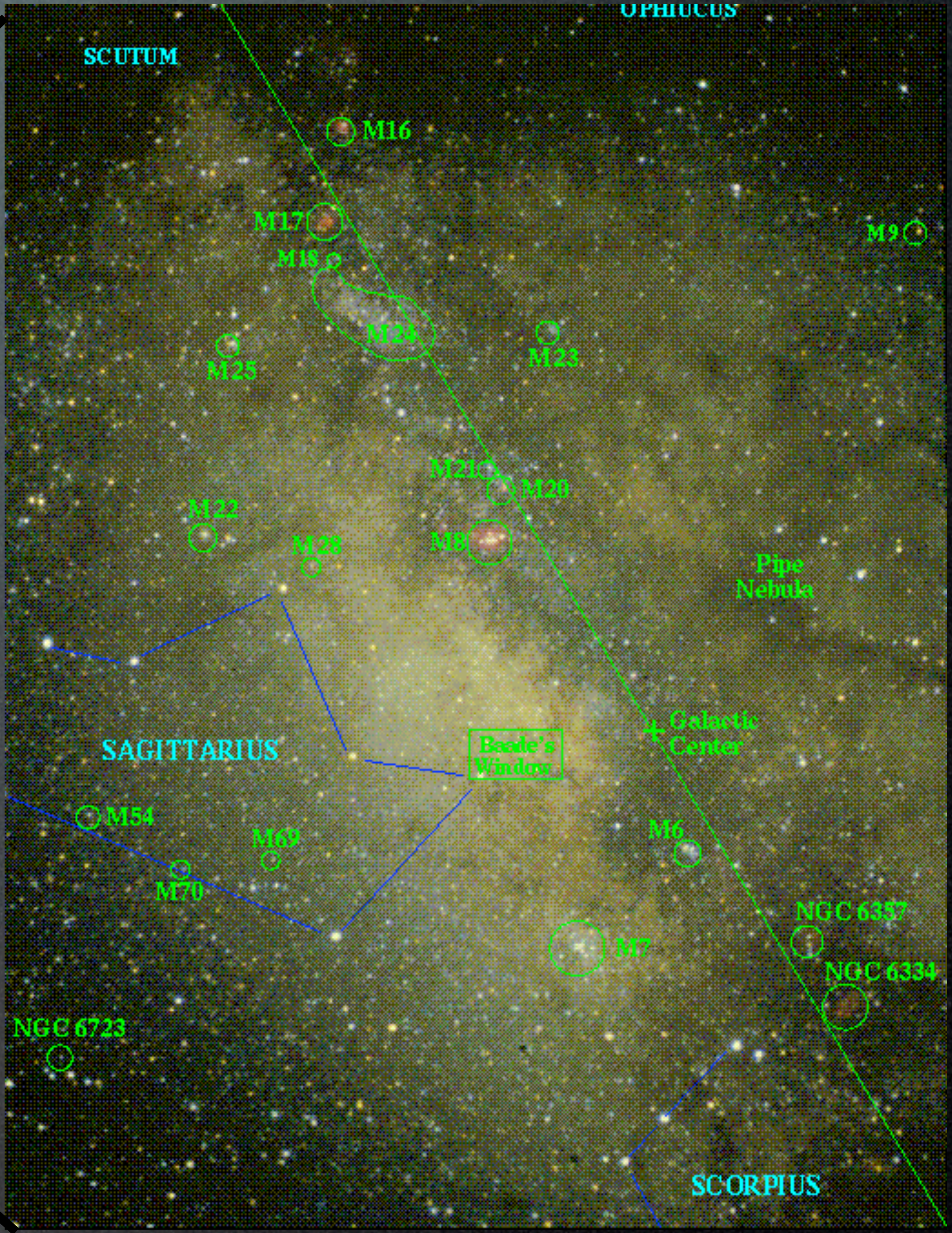

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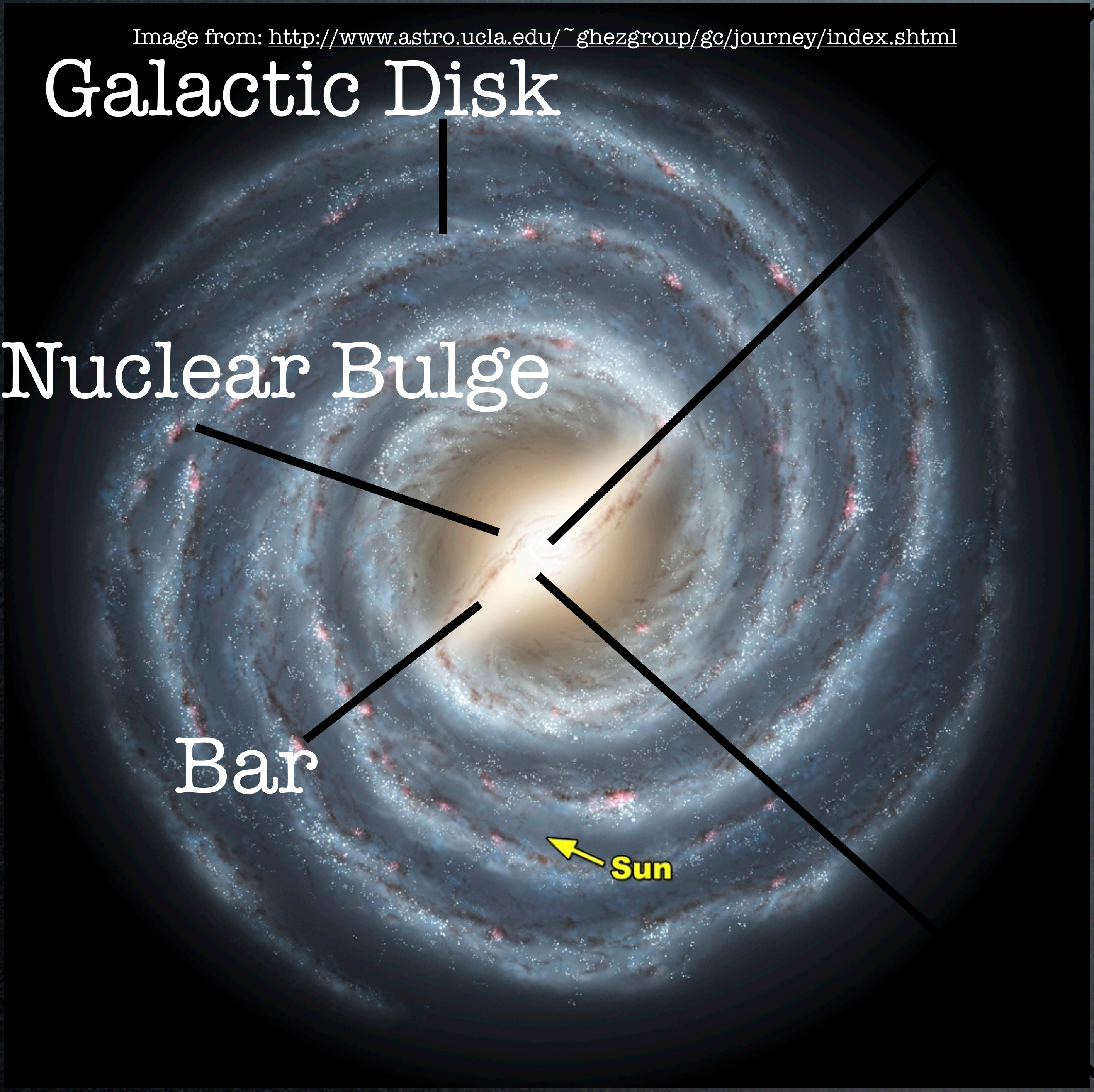

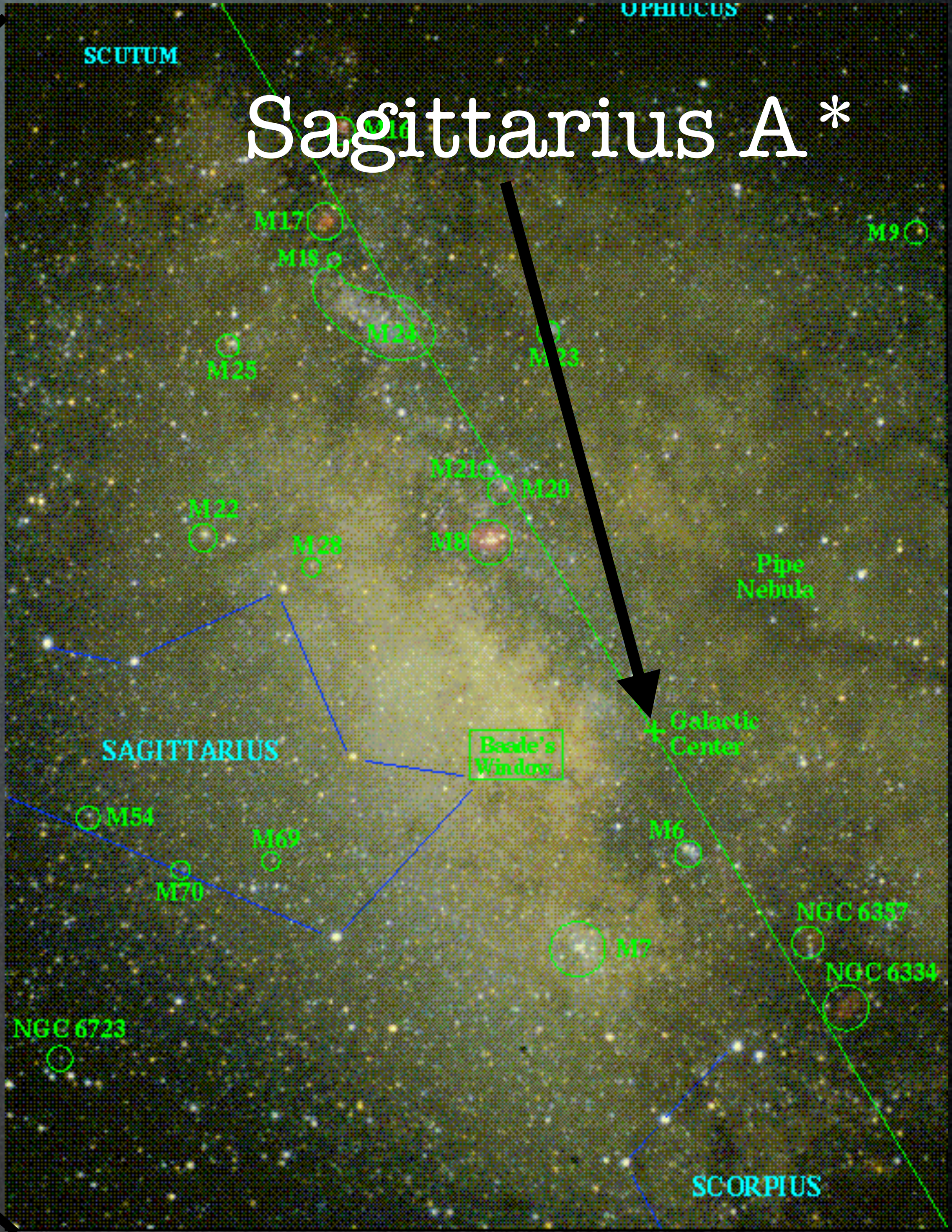

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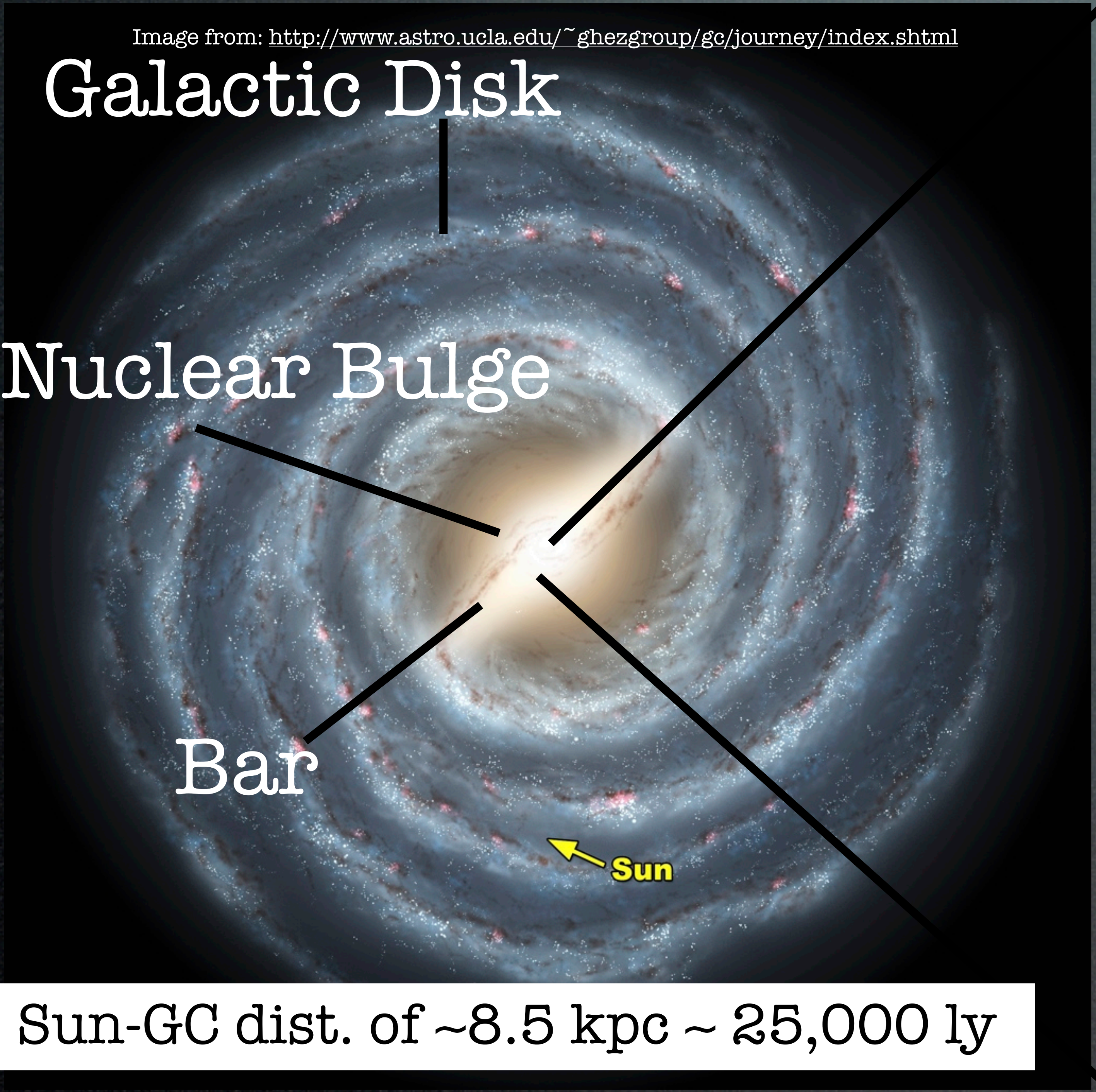

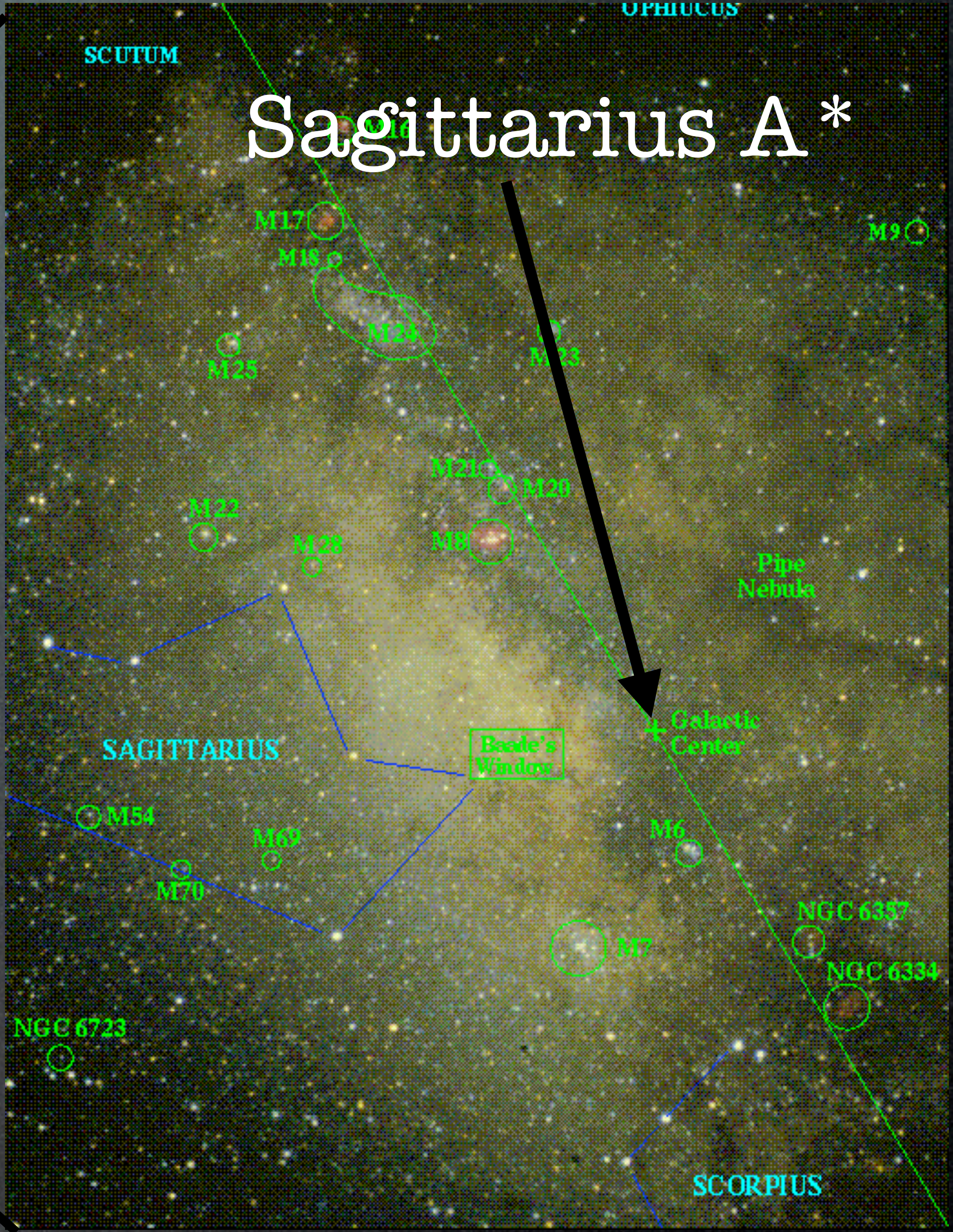

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The GC at radio wavelengths

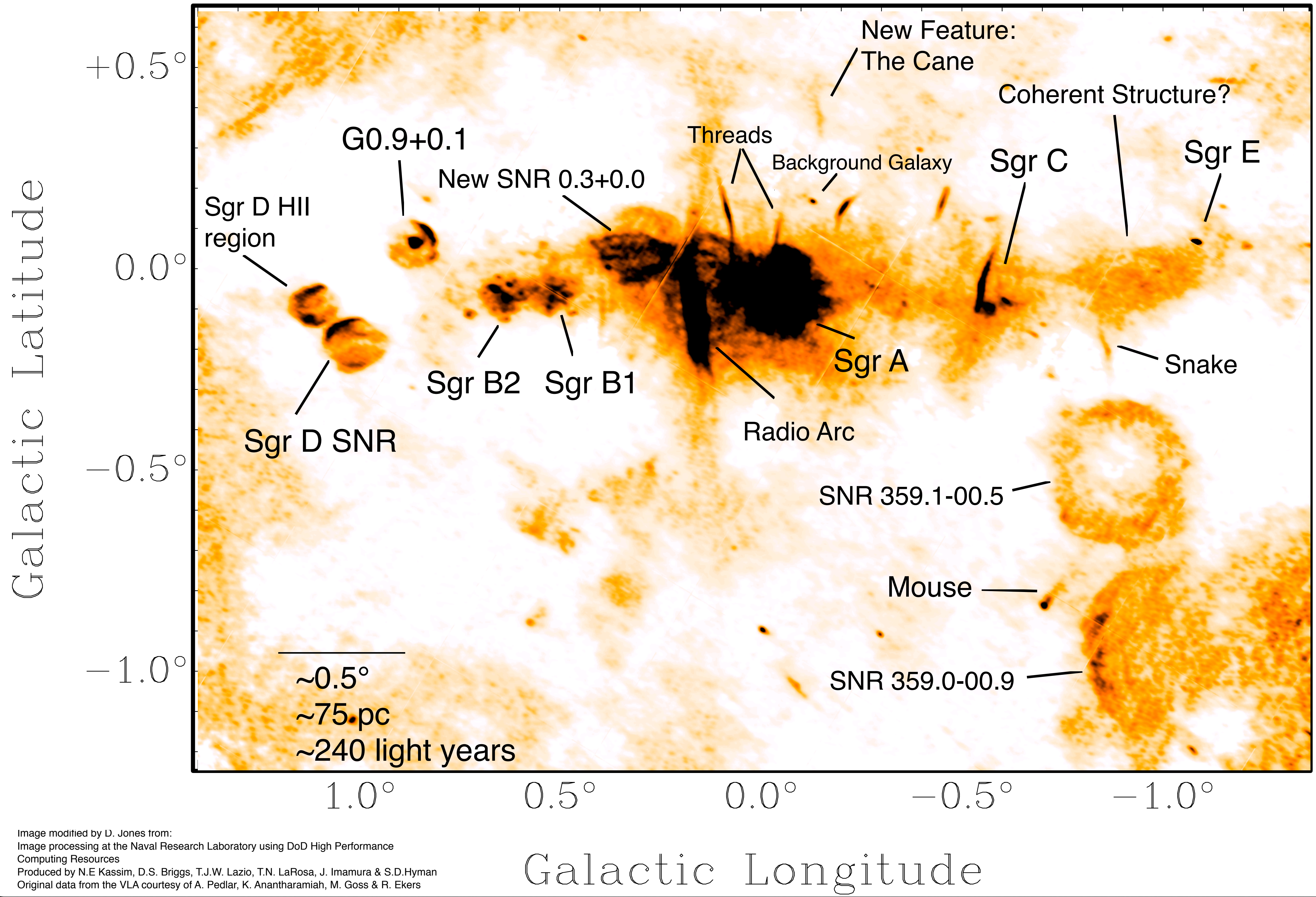
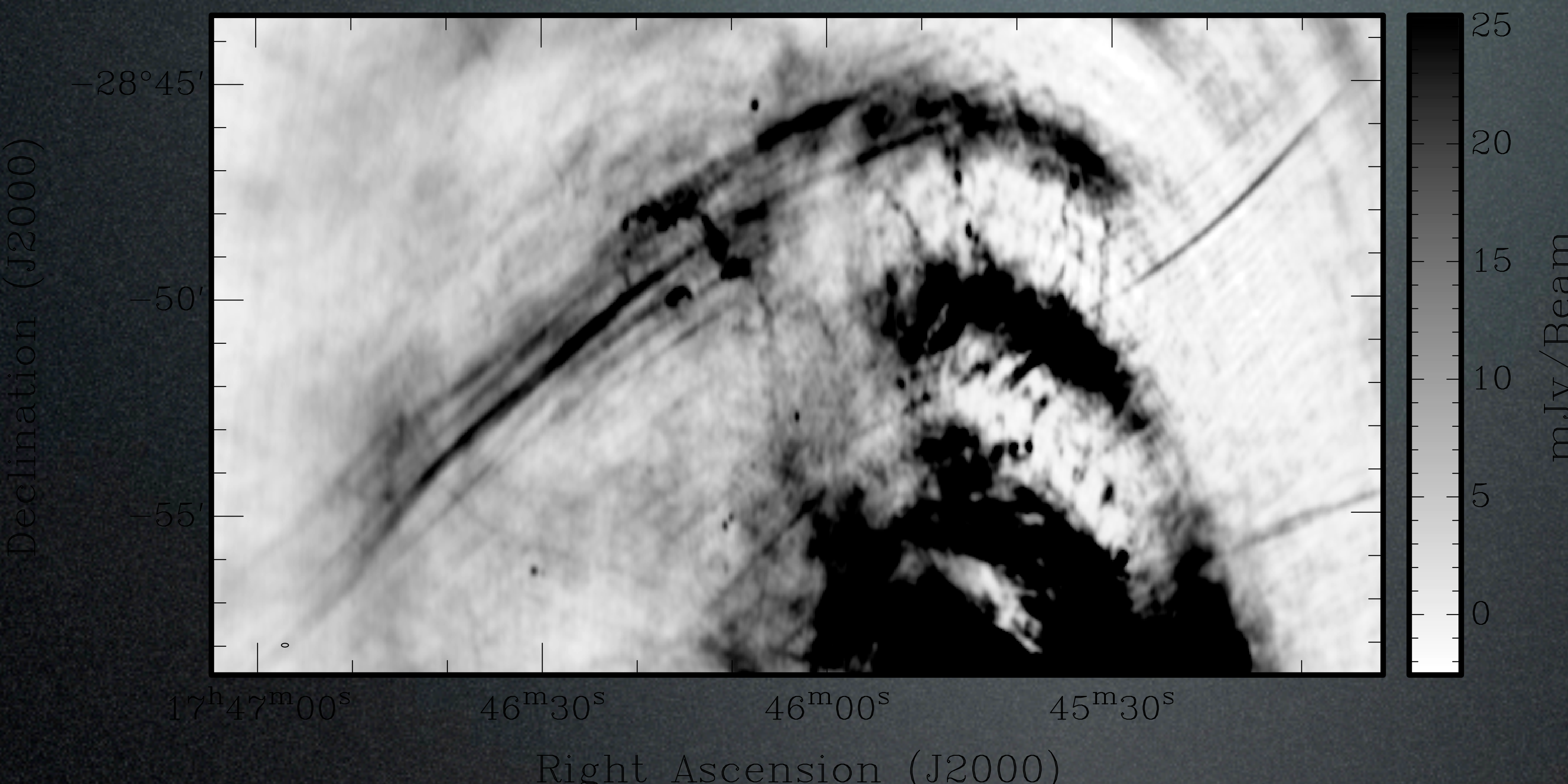


Image modified by D. Jones from:
Image processing at the Naval Research Laboratory using DoD High Performance Computing Resources
Produced by N.E Kassim, D.S. Briggs, T.J.W. Lazio, T.N. LaRosa, J. Imamura & S.D.Hyman
Original data from the VLA courtesy of A. Pedlar, K. Anantharamiah, M. Goss & R. Ekers

Evidence for a 1 mG field

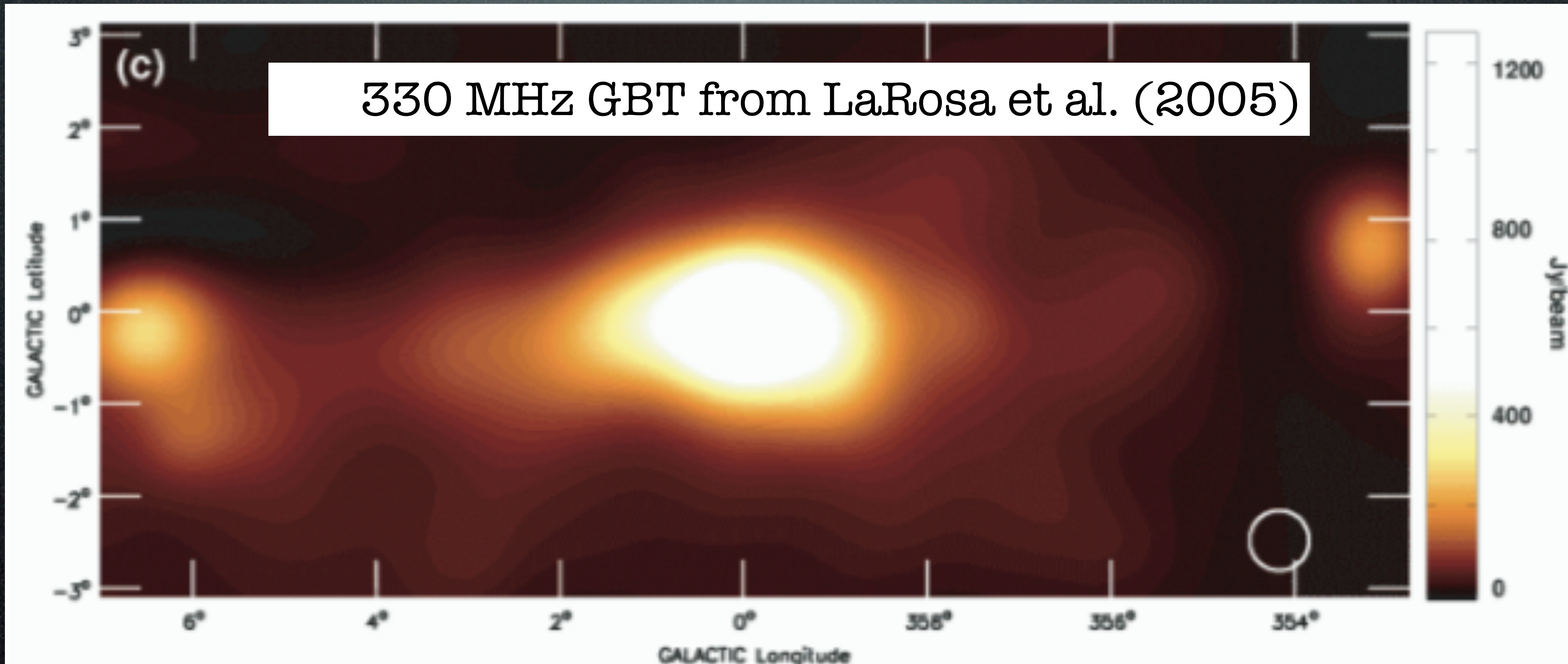


ATCA view of the Radio Arc and non-thermal radio filaments at 1.4 GHz at a resolution of 2"x3"

The GC is home to spectacular non-thermal filaments (NTFs); 2cm polarization obs. show that the B-field is along the NTFs (Tsuboi et al. 1986)

For these to be static & straight a counter-balancing field $\gtrsim$1 mG is required (Yusef-Zadeh & Morris. 1987)

Evidence for a 10 μG field



A large, 6x2 degree discrete GC source with a non-thermal (α=-0.7) spectral index between 74 and 330 MHz.

Assuming **equipartition** (equal energy density in CRs and **B**-field), they argued for a 10 μG field.

This field strength is also implied, using rotation measures of background galaxies (Roy et al. 2008).

10 μG or 1 mG: which one?

- A 1 mG B-field is measured on scales of the order of 100 pc
  - perhaps localised, intense fields? Transient?
  - incredibly high for large scales (given local ISM is 6 μG)
  - i.e. Katia Ferriere's talk
- 10 μG is inferred on scales of 400 pc
  - Inferred on the basis of two frequencies
  - Is equipartition argument valid?
- Definitive evidence of either has been missing for around 30 years

The Diffuse Non-thermal Source revisited

What is the spectral behaviour above 330 MHz of the diffuse non-thermal source (DNS) that LaRosa et al. (2005) discovered?

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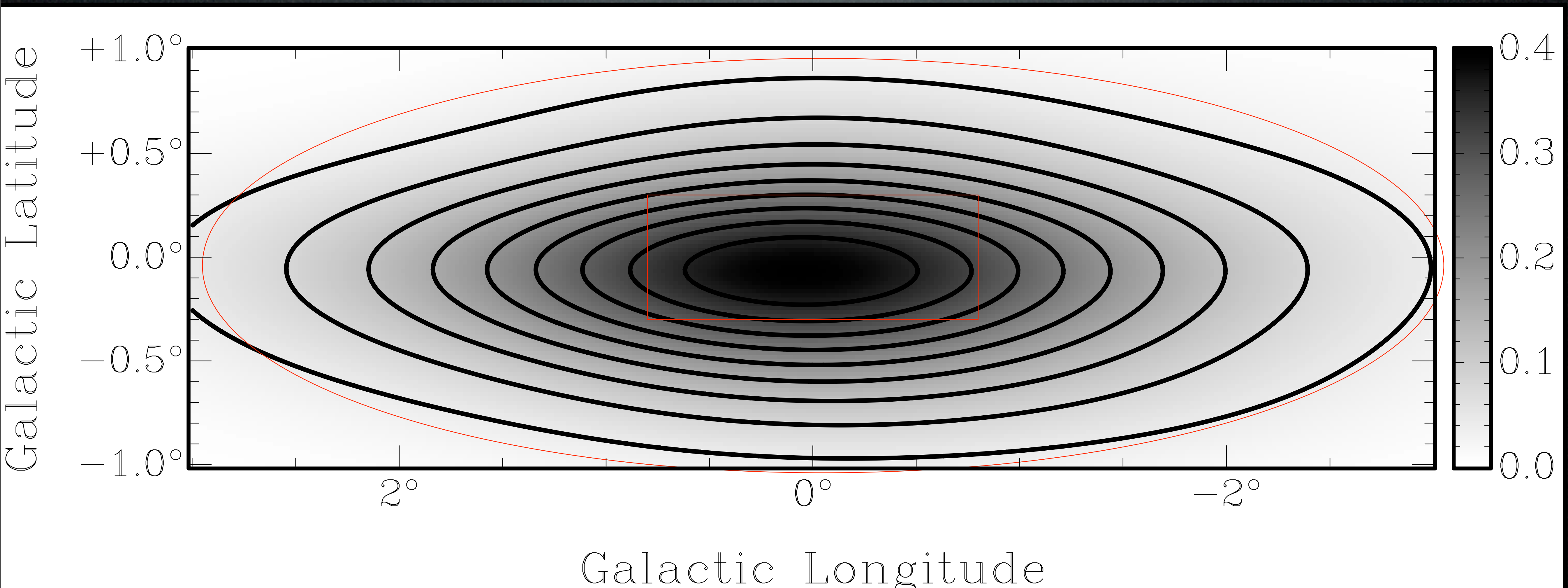

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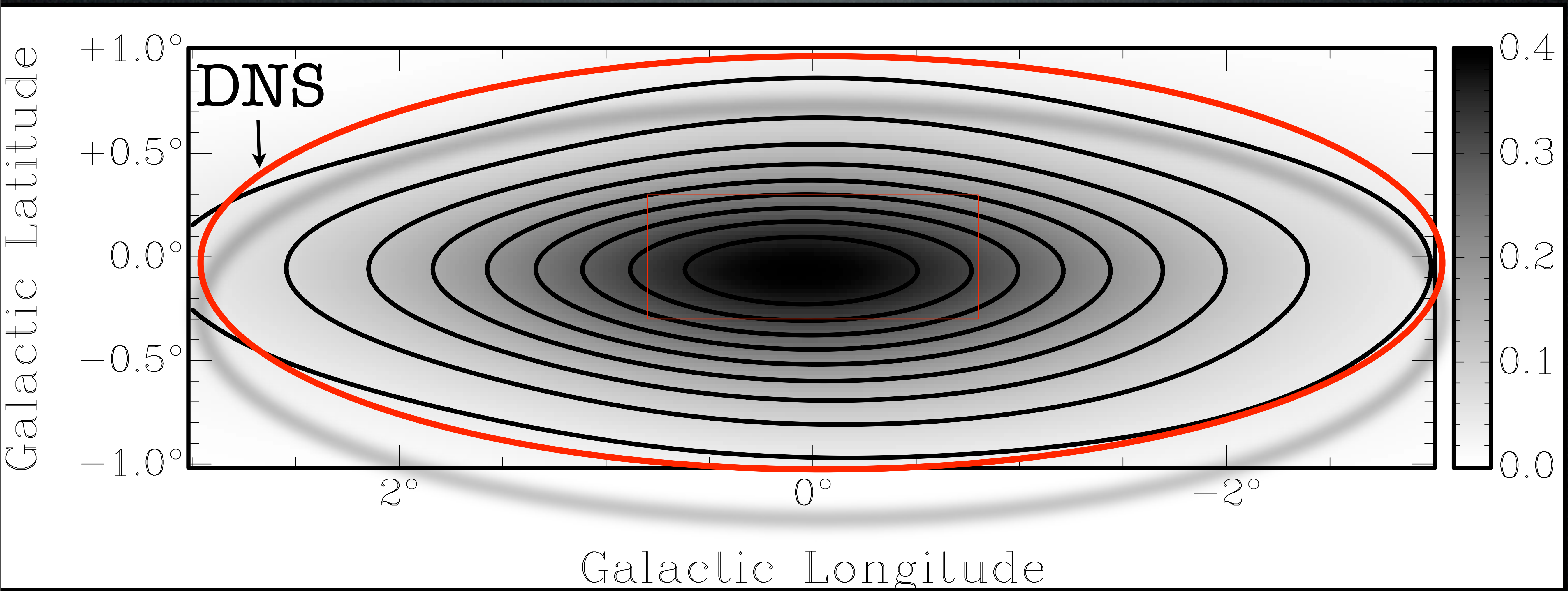

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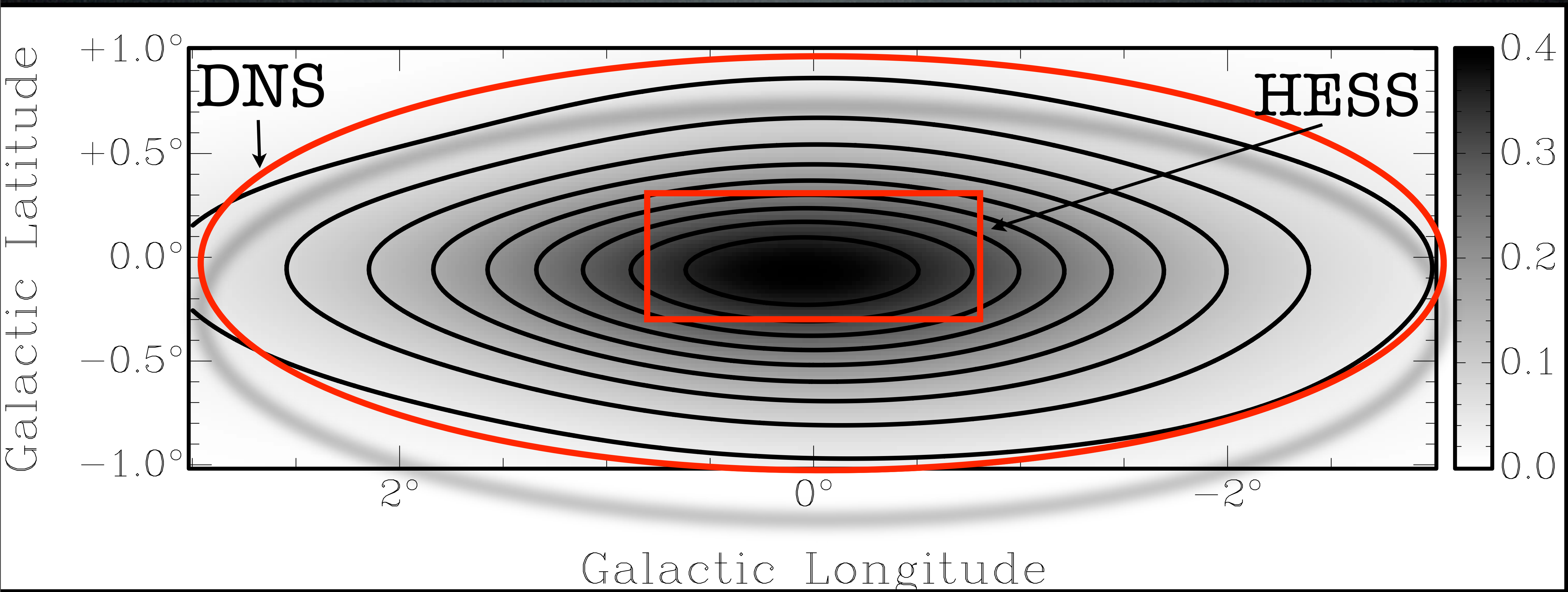

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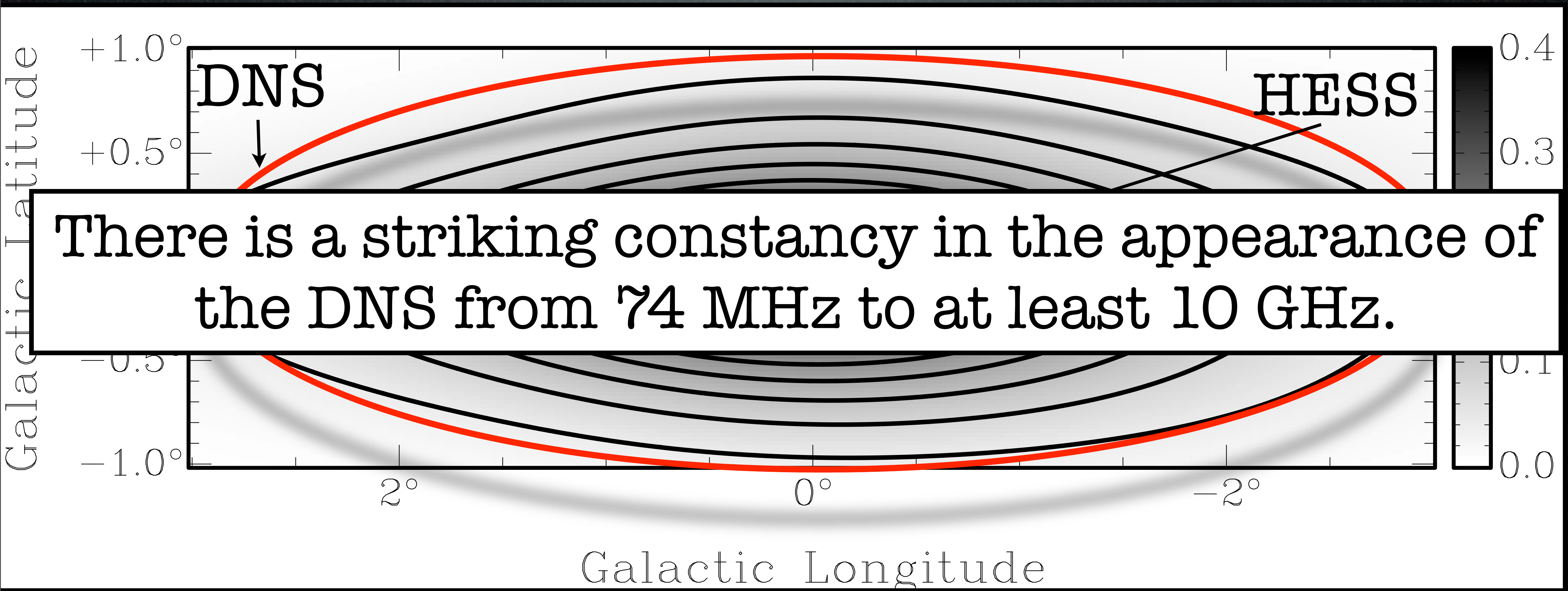

There is a striking constancy in the appearance of the DNS from 74 MHz to at least 10 GHz.

The DNS spectrum

Integrating the total intensity within the DNS ellipse at 1.4, 2.4, 2.7 and 10 GHz using archival single-dish data

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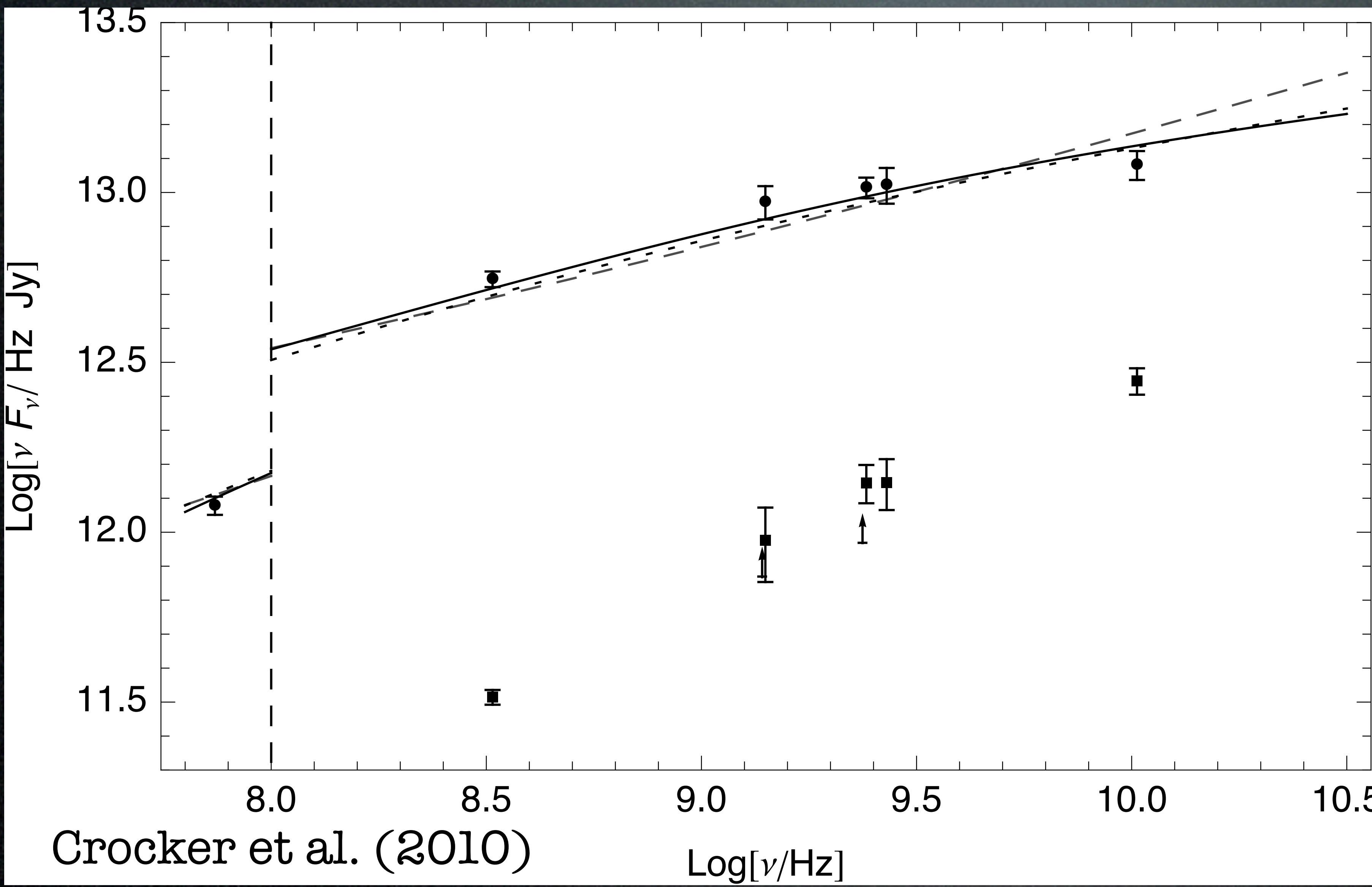

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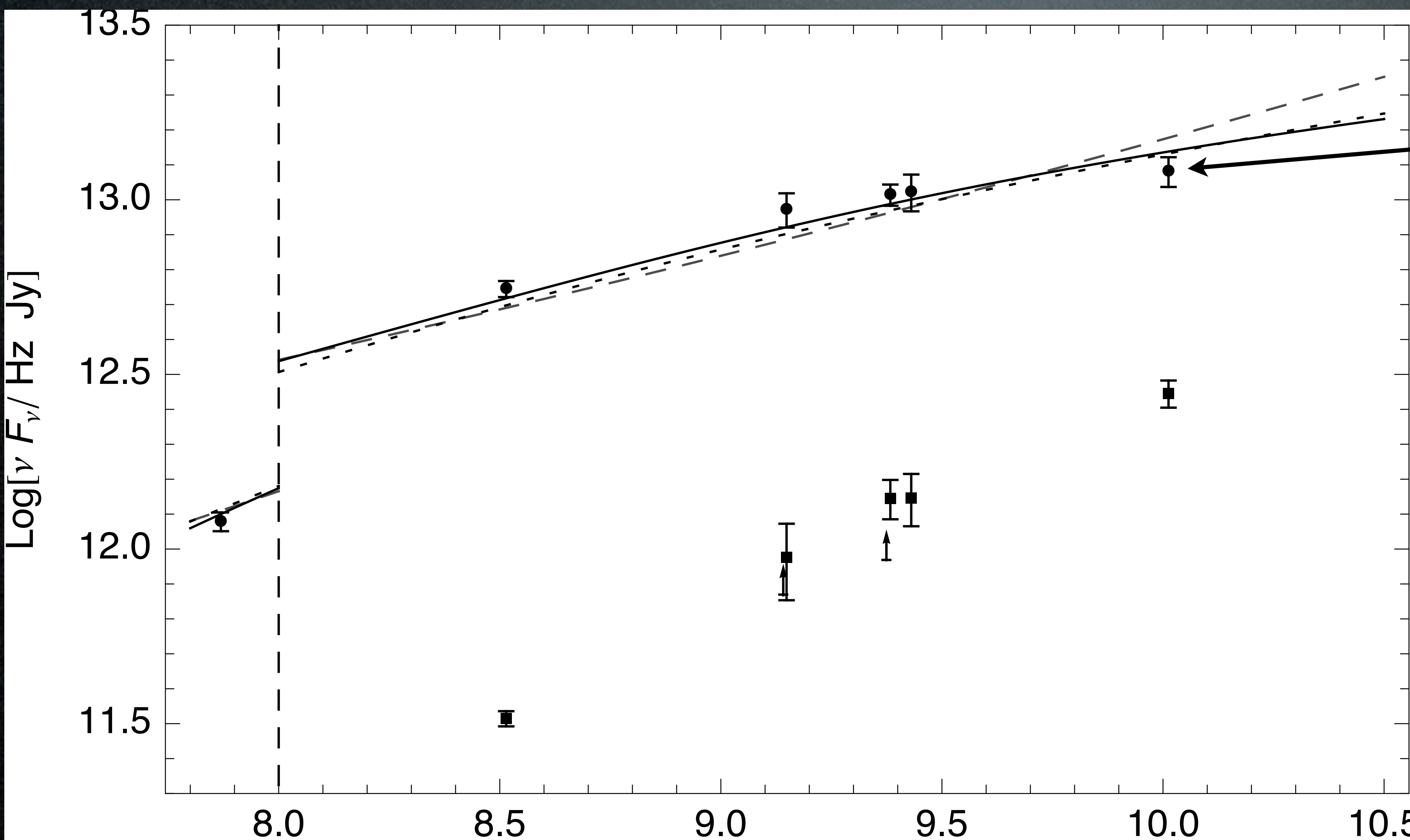

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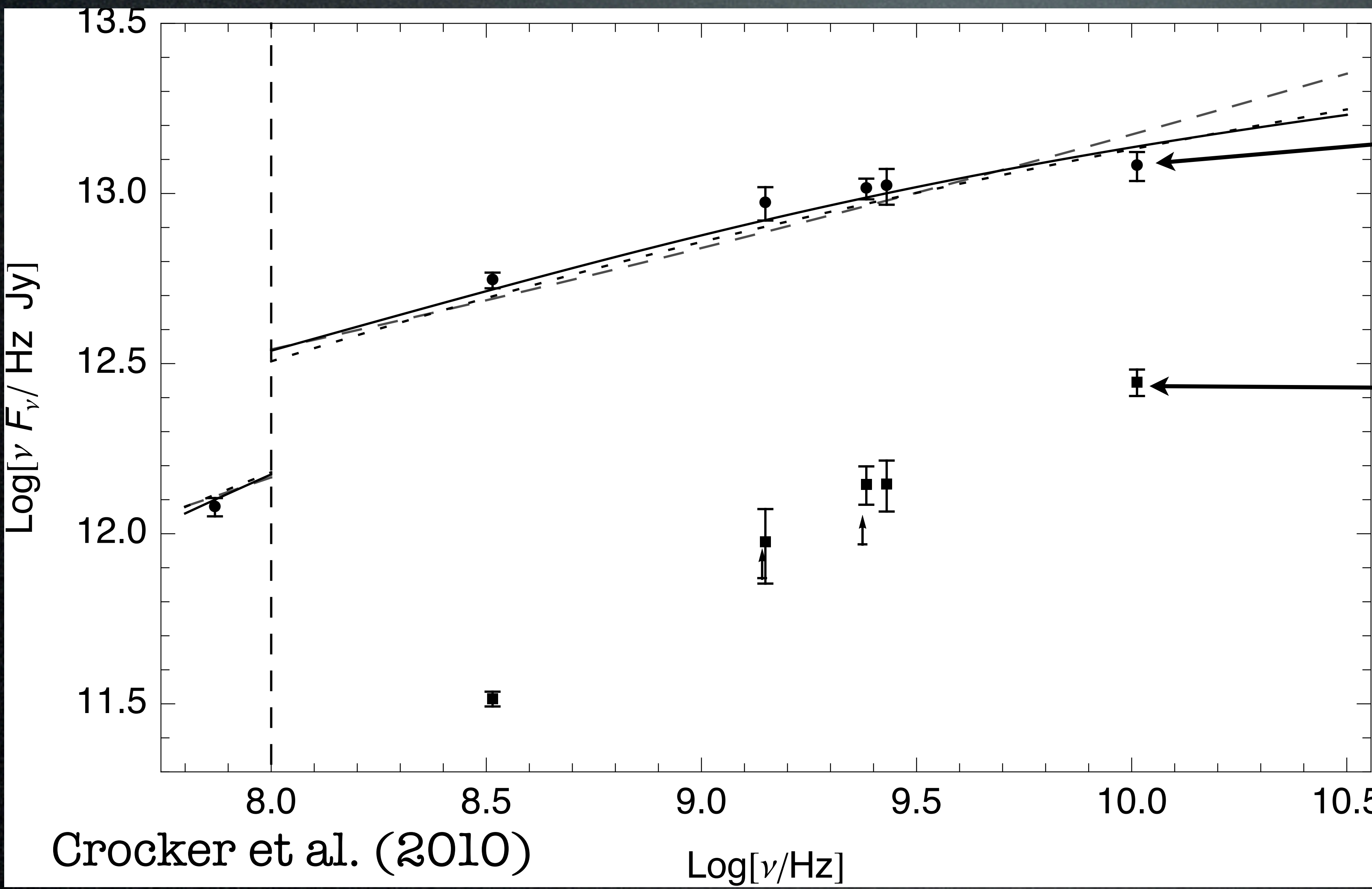

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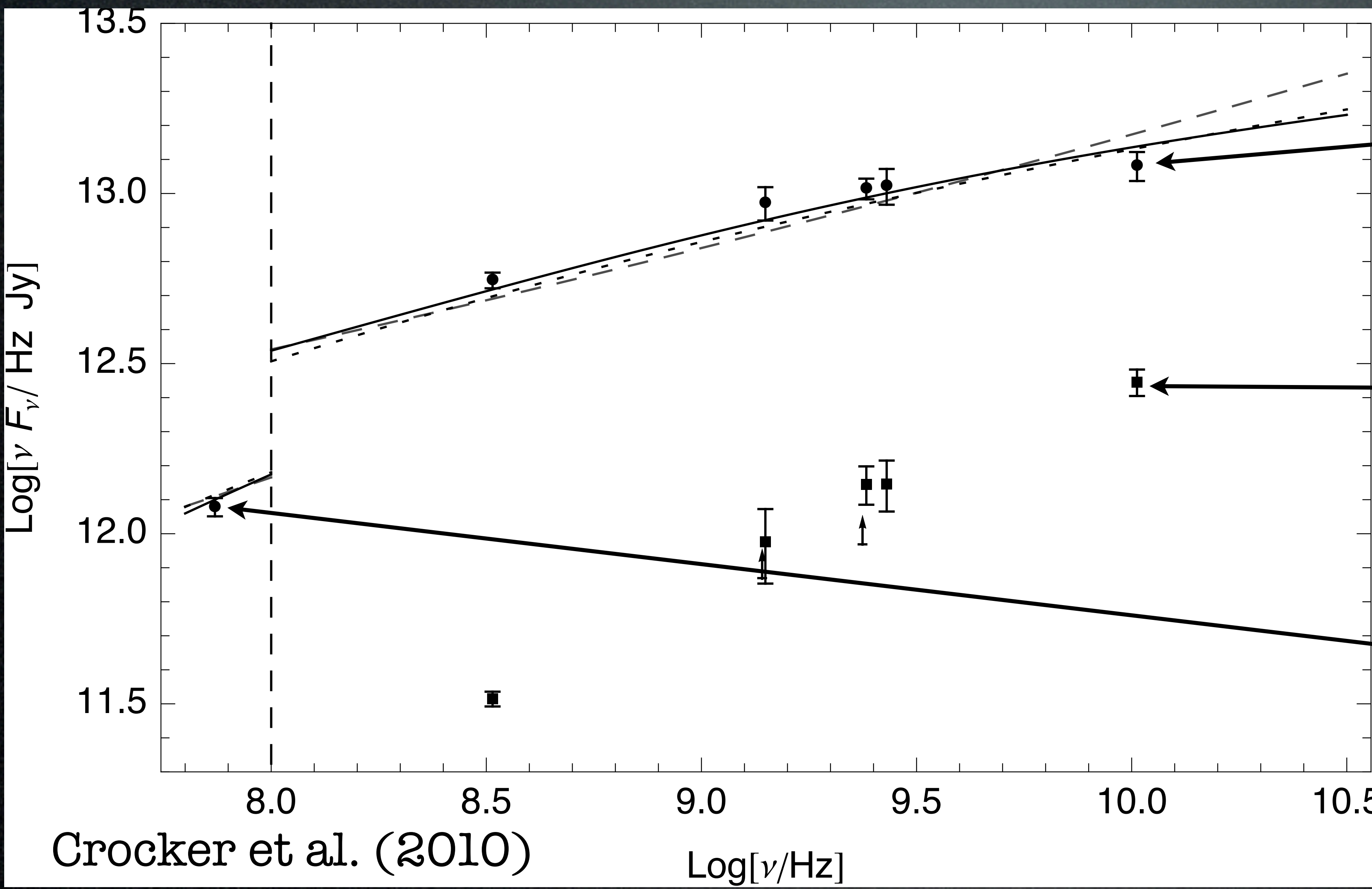

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74 MHz datum (VLA; LaRosa et al., 2005)

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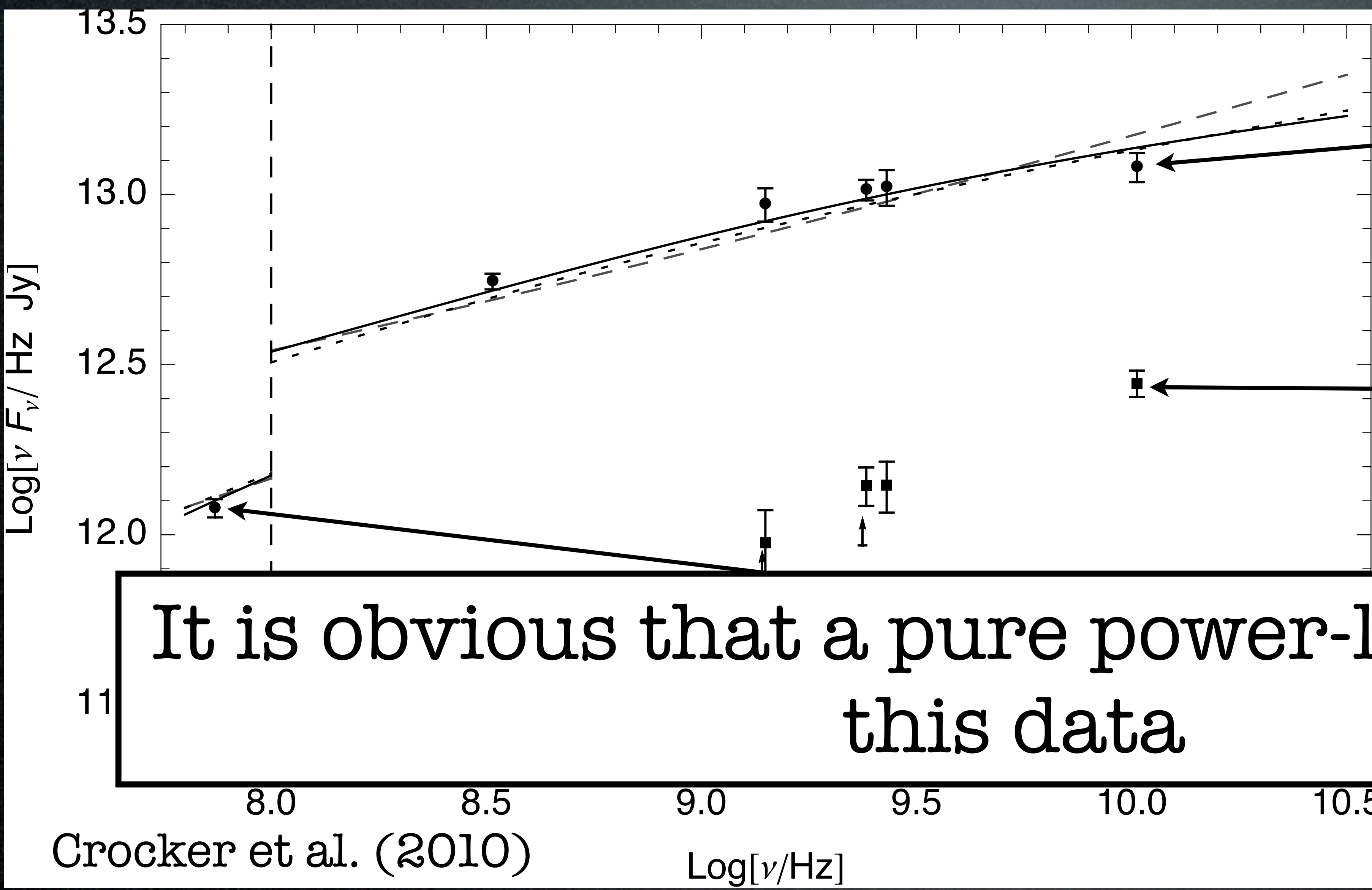

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Spectrum between 74 MHz and 10 GHz

Backgrounds (discrete sources)

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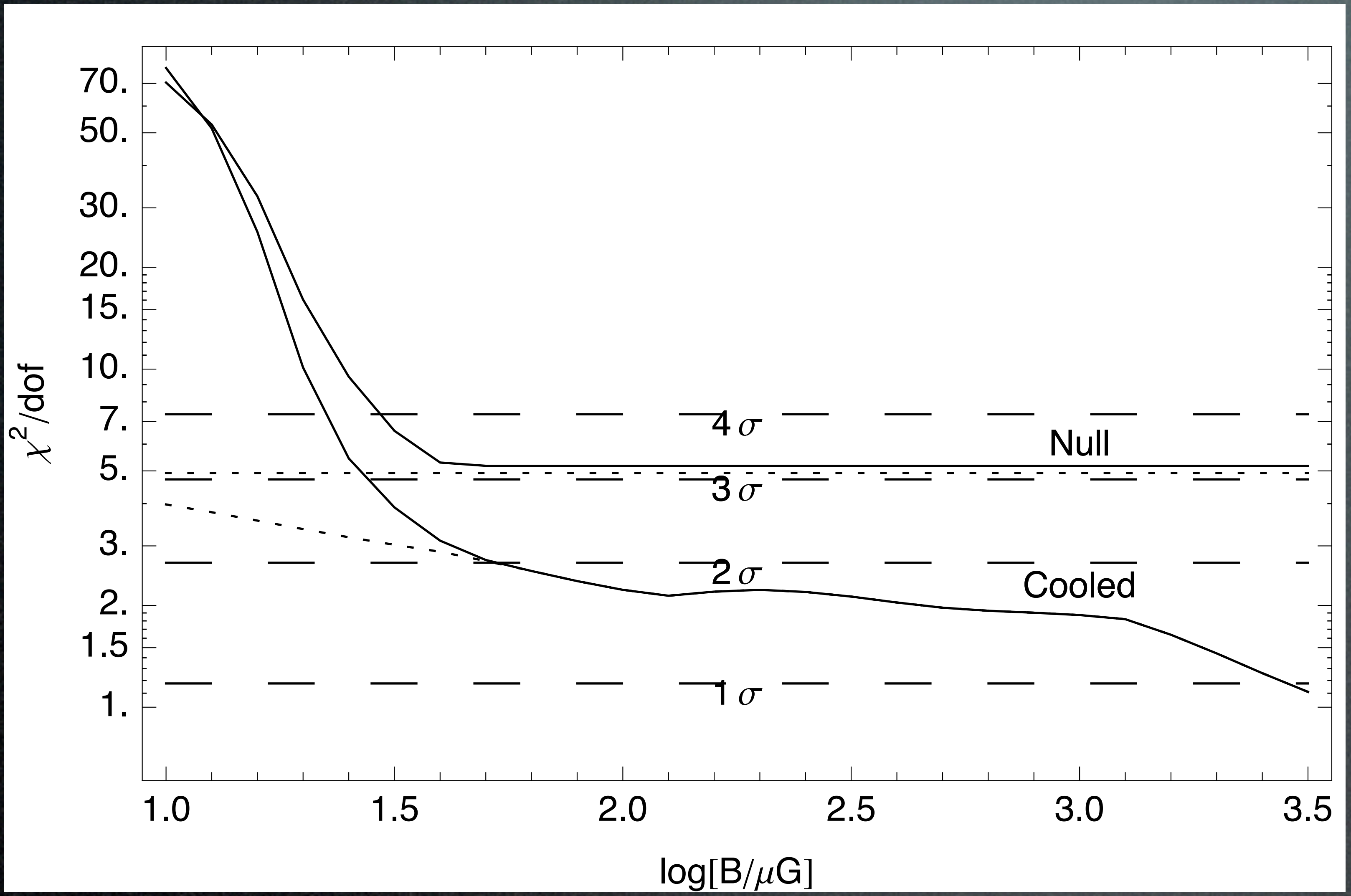
It is obvious that a pure power-law cannot fit this data

Rejection of the Null Hypothesis



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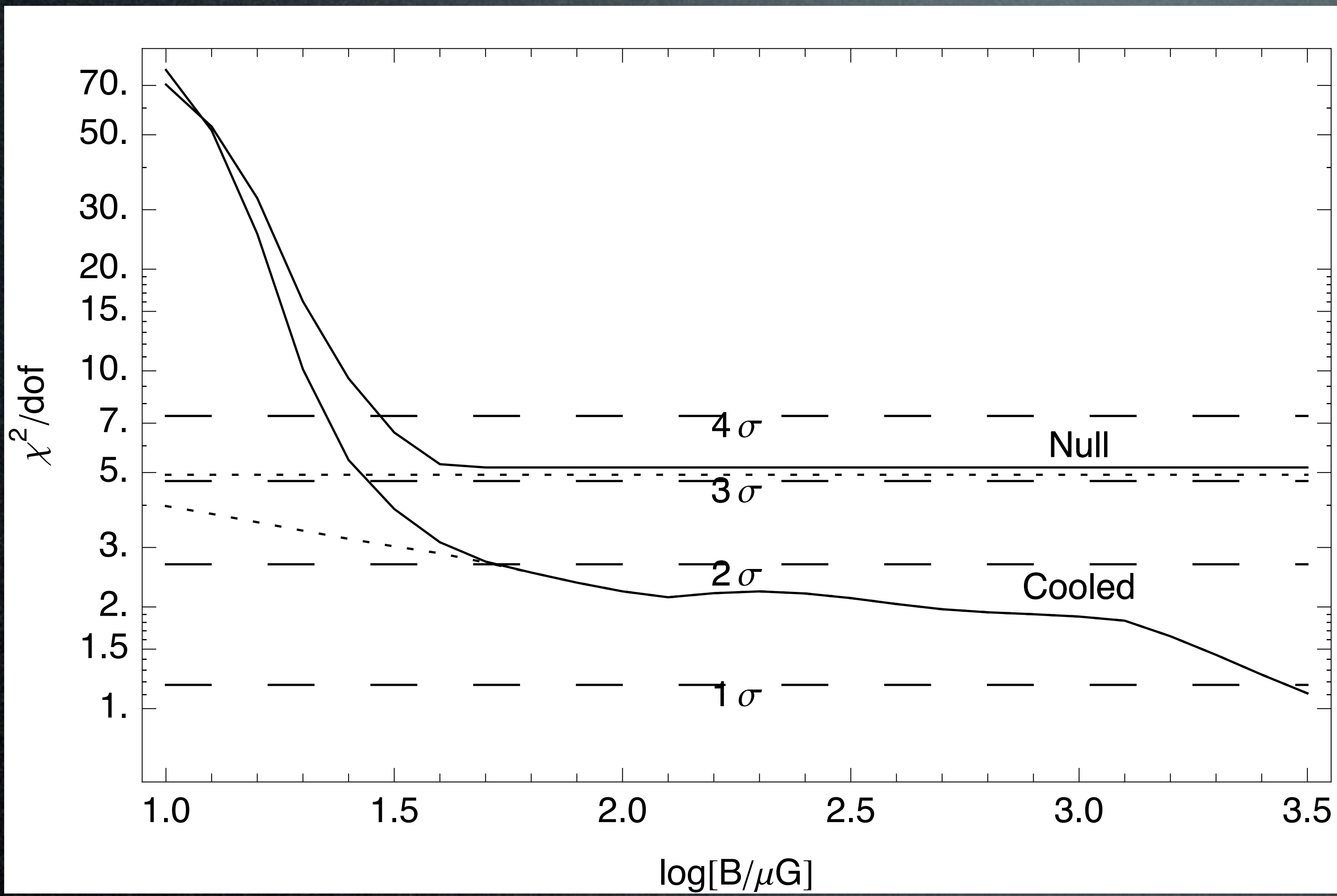

Fitting the spectra, we find that the null hypothesis (single power-law) is only achieves a best fit acceptable at the ~3.4σ level

Question: what is causing the spectrum downturn?
Hypothesis: there is a cooling break due to the increased efficiency of bremsstrahlung cooling at lower energies

Steady-state, synchrotron-radiating electron distributions I

At lower energies, cooling of in-situ electron (1e or 2e) populations is more efficient by bremsstrahlung than synchrotron

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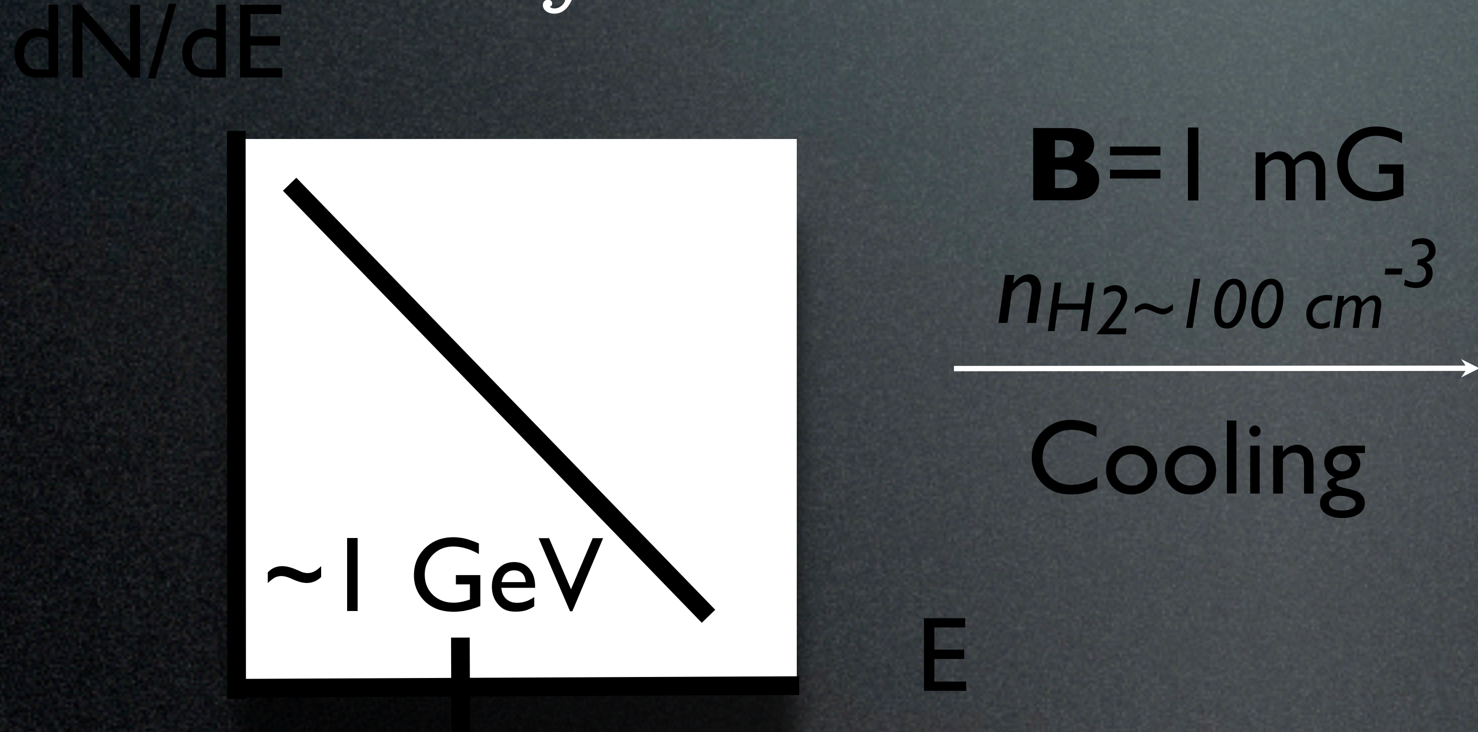

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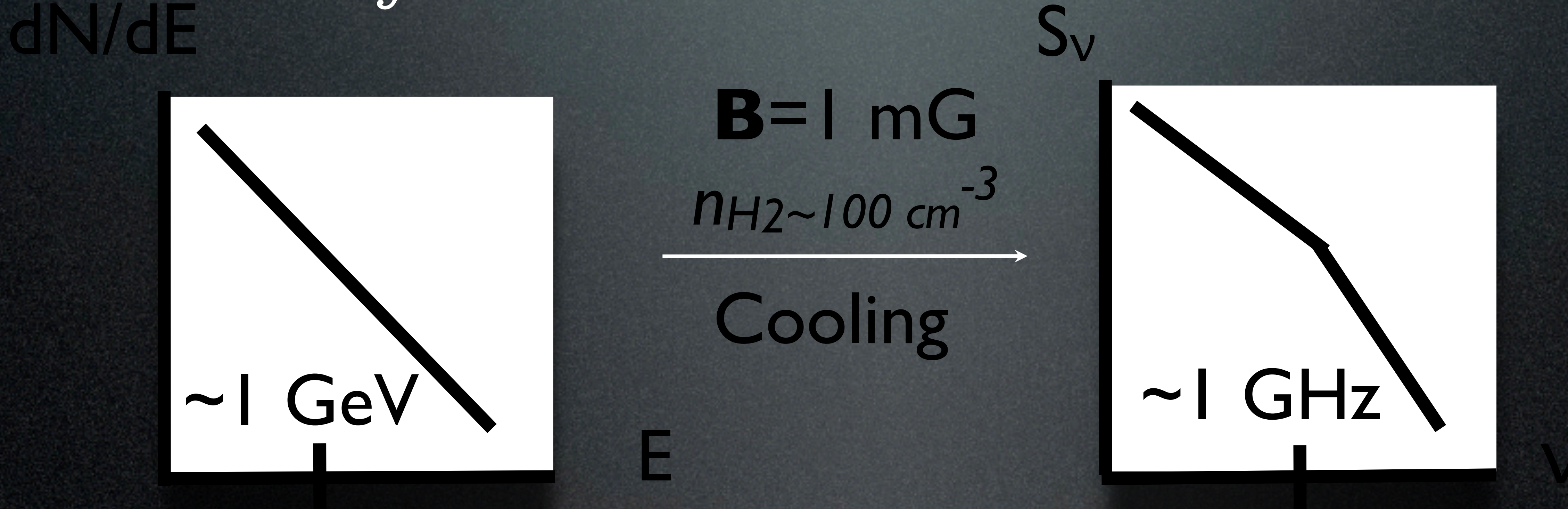

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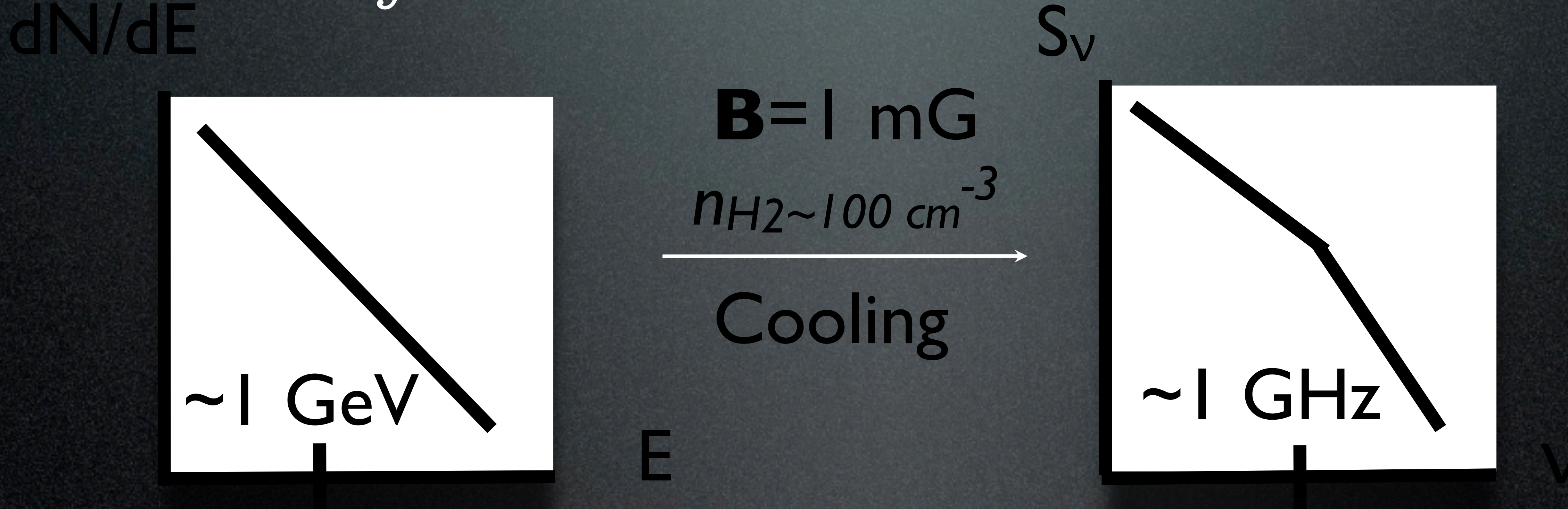

Shows "spectral downturn" of **exactly** 0.5 in spectral index.
The energy at which this occurs is determined by B and n_H.

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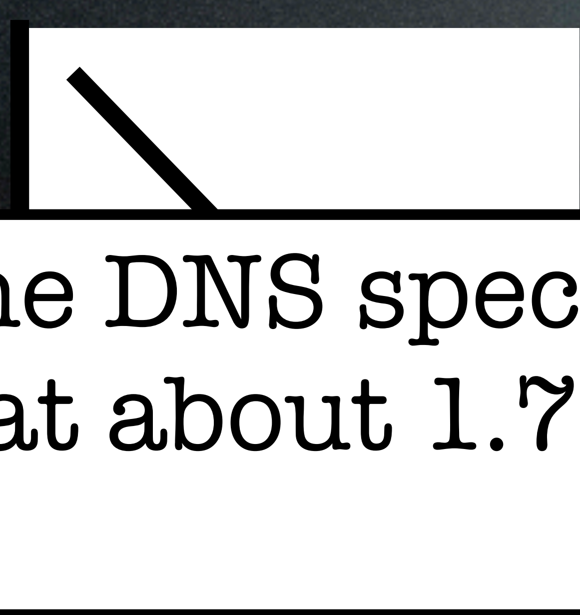
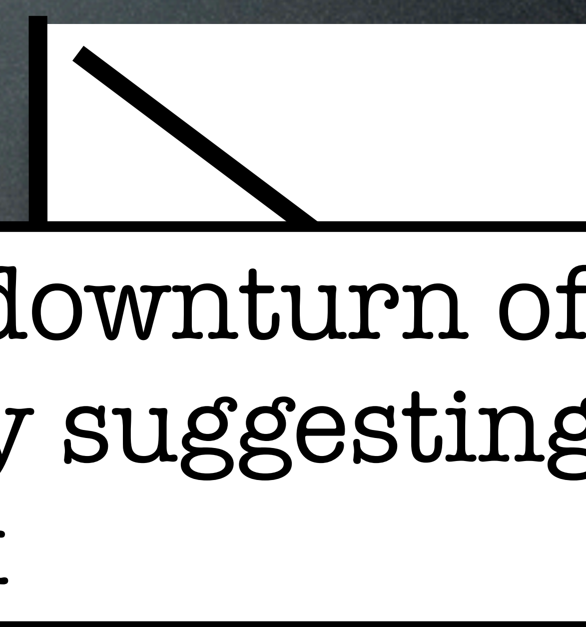


B=1 mG

n_{H2}~100 cm^{-3}

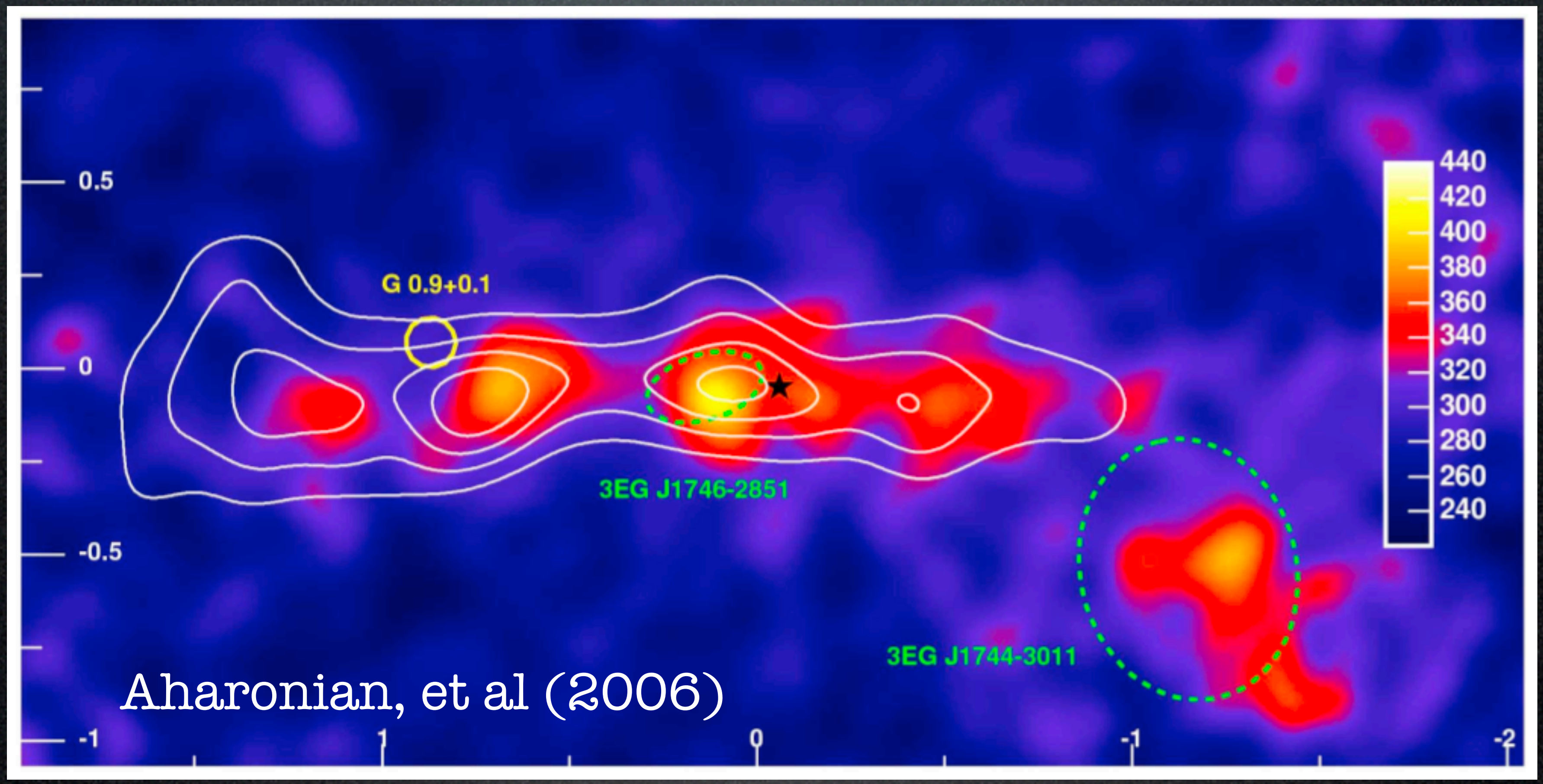


The DNS spectrum shows a downturn of 0.6 at about 1.7 GHz -- strongly suggesting a cooling break

Shows "spectral downturn" of **exactly** 0.5 in spectral index.
The energy at which this occurs is determined by B and n_H.

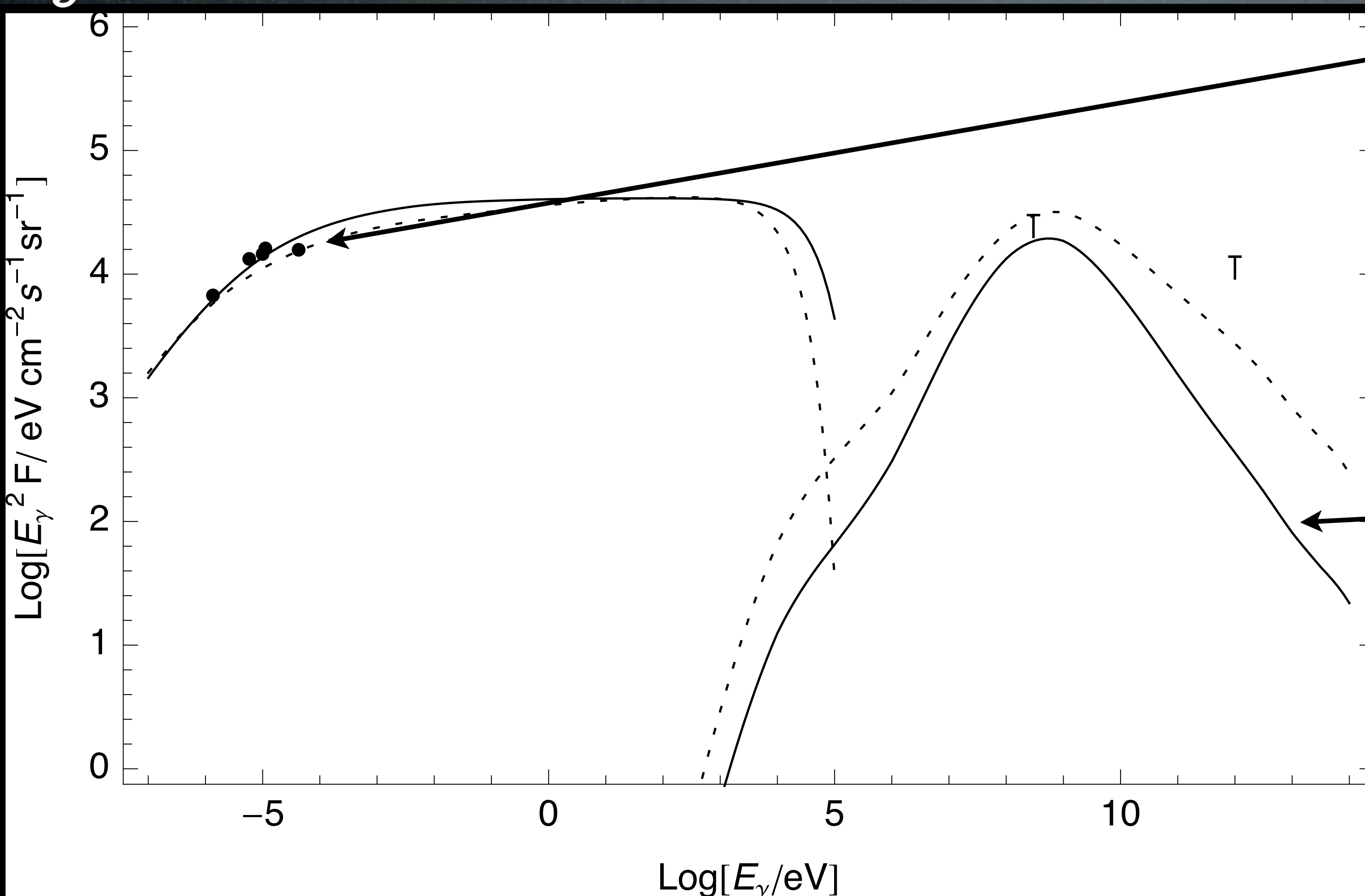
Steady-state, synchrotron-radiating electron distributions II

- These same electrons will then produce (multi-) GeV non-thermal bremsstrahlung and IC emission
- We can use the GHz radio spectrum and the GeV (and TeV) gamma-ray spectrum to select regions of acceptable phase-space



GC radio and gamma-ray analysis: A lower limit of 50 μG

The upper limits are due to observations by EGRET at 300 MeV and HESS at TeV.



Fit to the radio spectrum for synchrotron (1e,2e)+ bremsstrahlung + IC + ioniz.

Predict the GeV--TeV gamma-ray emission from NT bremsstrahlung & IC

Models for **B**-field of 100 μG (solid) and 30 μG (dotted). The lower energy curves are synchrotron emission. The higher are bremsstrahlung plus inverse Compton emission from the same electrons responsible for the synchrotron

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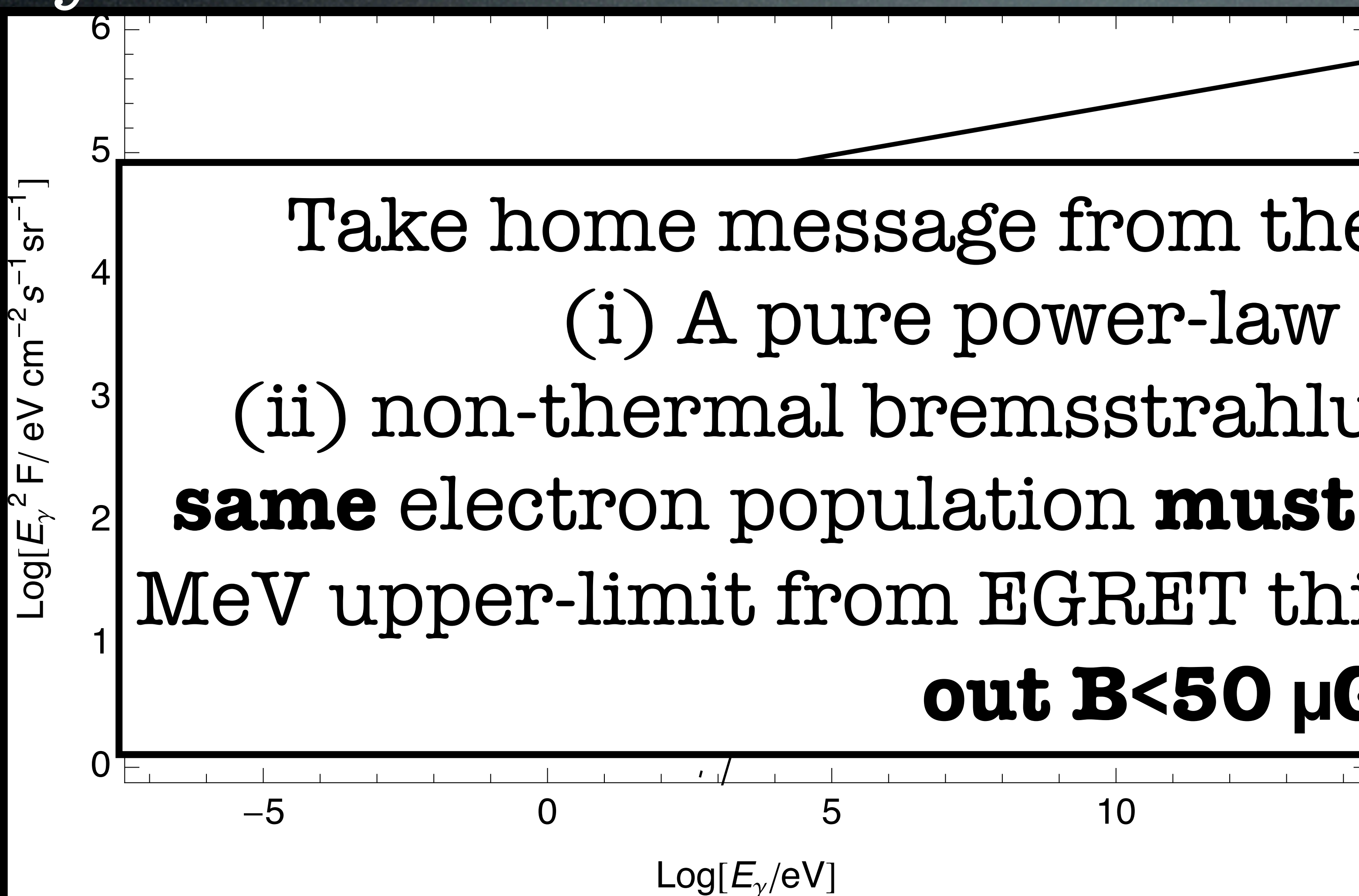


Fit to the radio spectrum for

Take home message from the past two figures:

(i) A pure power-law is rejected

(ii) non-thermal bremsstrahlung and IC from the **same** electron population **must not** surpass the 300 MeV upper-limit from EGRET this consideration **rules out B<50 μG**

Models for **B**-field of 100 μG (solid) and 30 μG (dotted). The lower energy curves are synchrotron emission. The higher are bremsstrahlung plus inverse Compton emission from the same electrons responsible for the synchrotron

Conclusions

- We have shown that **B-**fields below about 50 μG are **ruled out** on size scales of 400 pc in the GC. This can have important consequences for the dynamics of the region.
- In the context of diffuse, ~GeV emission around the GC, we eagerly await results from Fermi whose sensitivity (more than an order of magnitude better than EGRET's) promises, at worst, an increased lower-limit to the large-scale magnetic field (and at best, a direct measurement).
- For now we emphasis that it is a novel analysis – not new data – that has allowed the new constraint on the GC magnetic field

Extra Slides

- Physics of alternate explanations of the break
- Equilibrium agruments
- The GC as a starbust

Why a cooling break?

- A cut-off feature in the injected electron distribution? We can reject explanations of this type for the following reasons:
  - They do not explain the change in spectral index of ~ 1/2 which is predicted by the synchrotron cooling hypothesis and seen in the data,
  - Hypothesising a cut-off in the injection spectrum this is required to be at ~ GeV (B/100 μG)1/2 to reproduce the observed break at ~ GHz.
  - Direct evidence from the TeV observations by the HESS instrument of the Galactic centre that – within the same field – acceleration/injection of electrons beyond a TeV is occurring.
  - The possibility that the radio break is due to electron escape (on a wind):
    - there probably is an outflow but this doesn't change our conclusion about the strength of the magnetic field because, for reasonable outflow speeds (> 100 km/s), one still requires a 100 muG field to get a break

Synchrotron ageing?

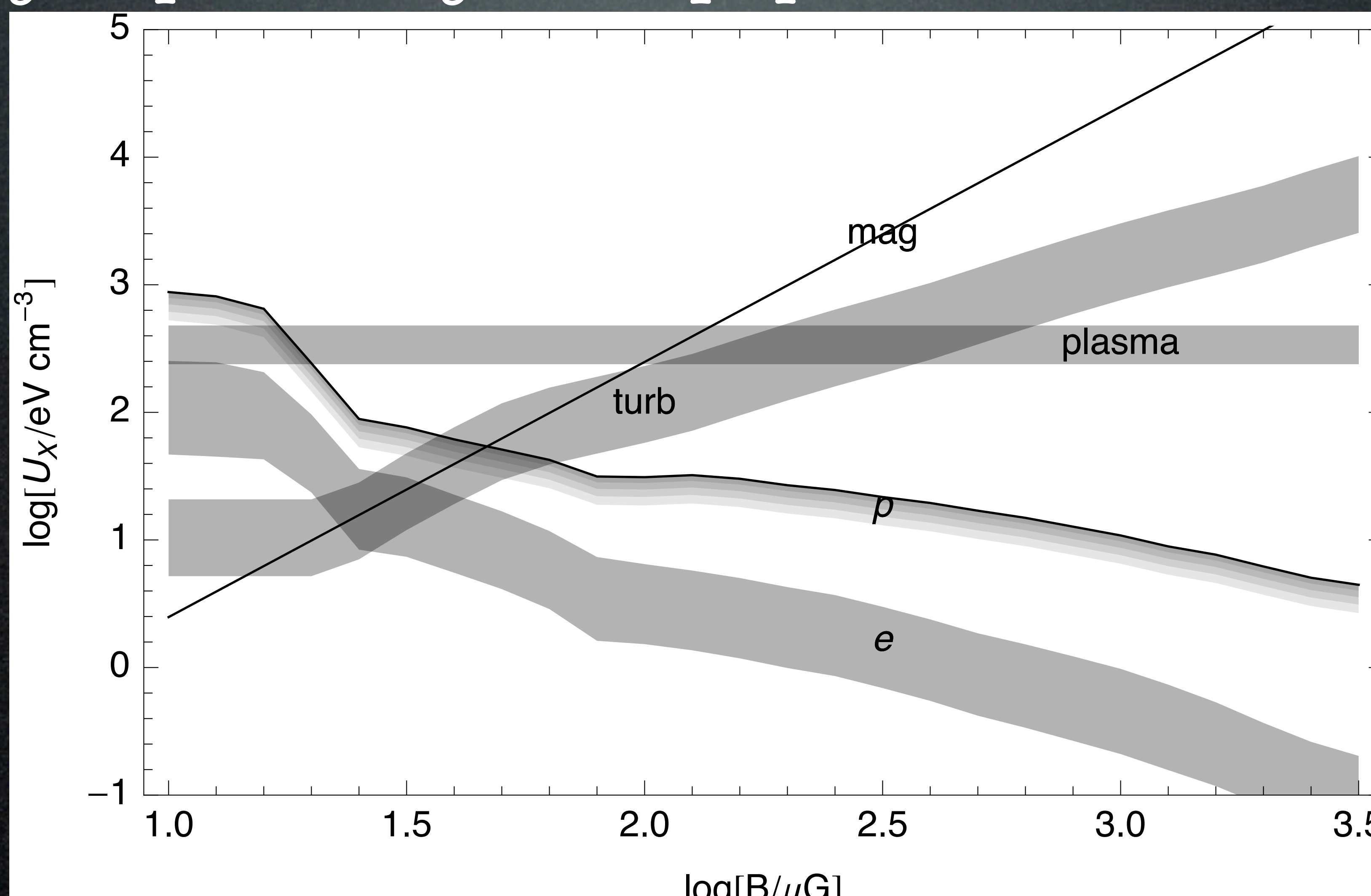
- This can be quickly dismissed: a non steady-state situation implies that the particles ultimately responsible for the radio emission diffuse over the entire diffuse non-thermal source over a timescale shorter than t_wait.

- Conservatively, the ultimate source of energy for the relativistic particles is supernova and, for the GC, we have conservatively, t_wait ~ 10^4 years.

- Thus an un-physically large effective diffusion velocity, v > c/3 is required in order that the system be out of steady state while, at the same time, synchrotron emission be observed emanating from the entire region.

ISM phase and equilibrium

- For acceptable **B**-fields, the GC CR electron pop^n. is sub-equipartition.
- May explain why the equipartition field is too low



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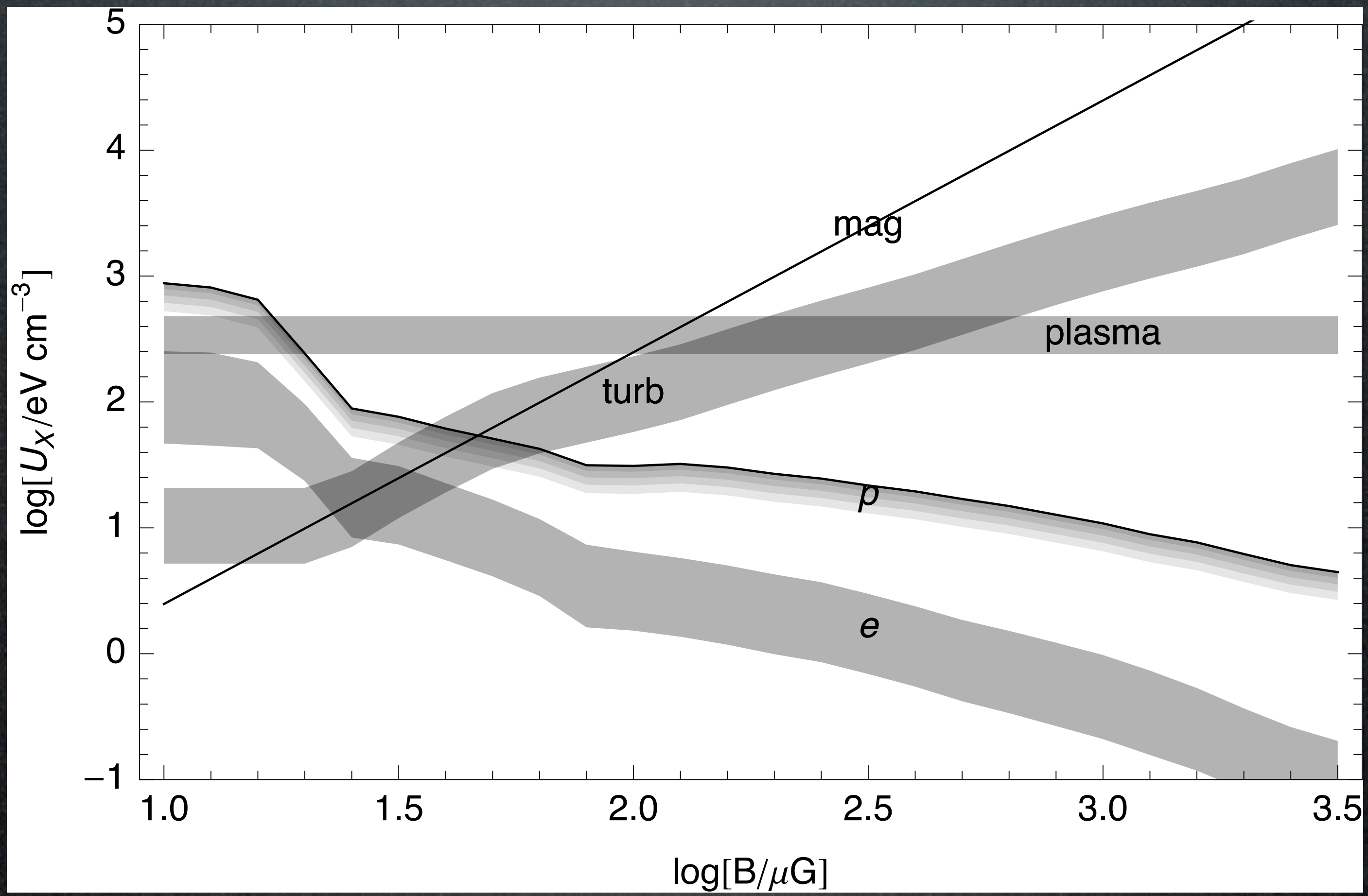
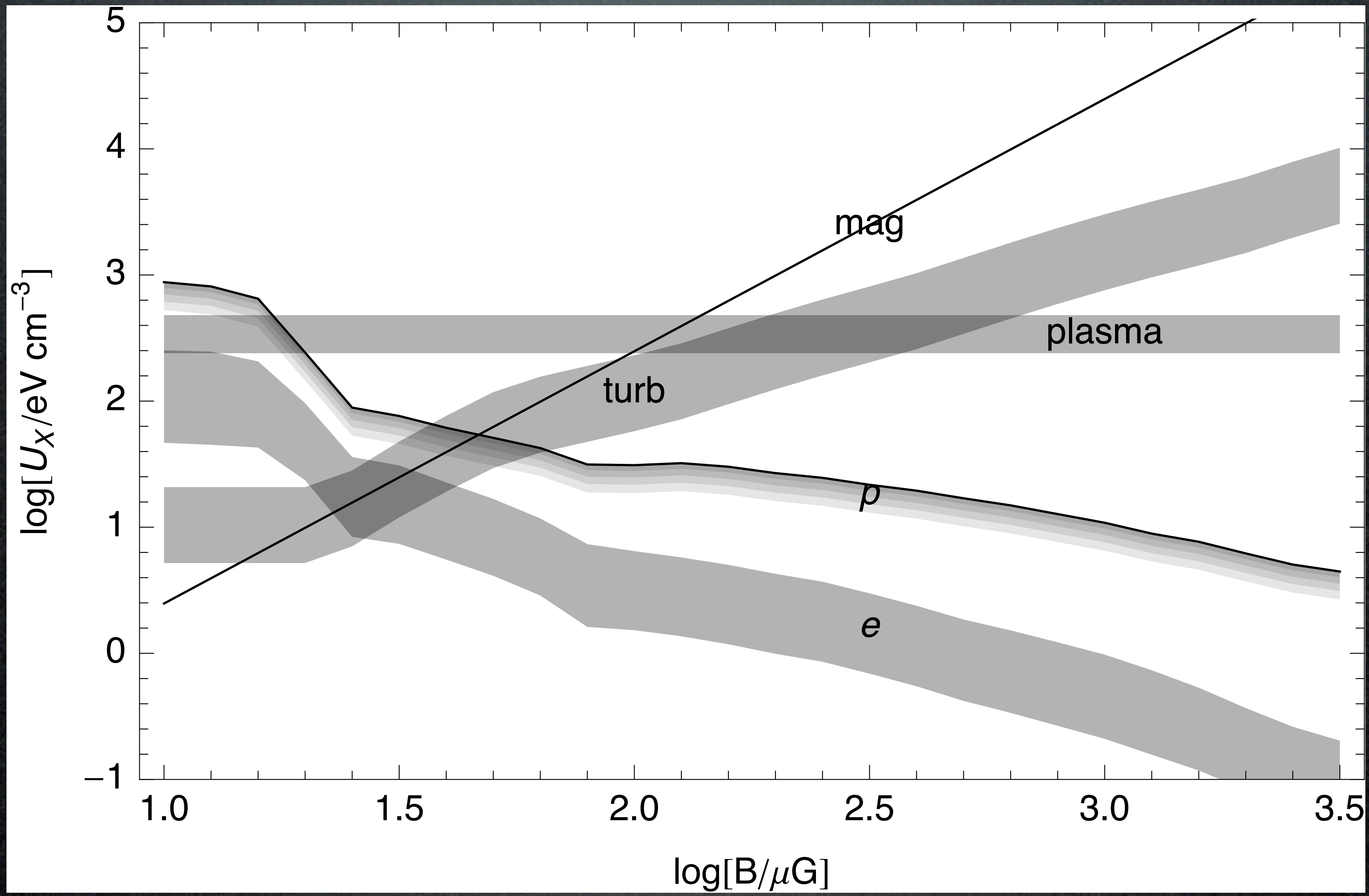
Magnetic field amplitude for equilibrium

- The energy density with other GC ISM implies near pressure equilibrium -- as is the case in the Galactic disk.
- A **B**-field value of 100 μG implies equilibrium of **all** ISM phases -- this field amplitude had been predicted by Spergel & Blitz (1992, Nature, 357, 665).



The GC as a miniature starburst

- The pressure equilibrium mirrors that thought to occur in starburst galaxies (Thompson, et al., 2006 ApJ, 645, 186)



Magnetic pressure support

- Magnetic fields of 100 μG is in the range to establish hydrostatic equilibrium, and can lead to the establishment of the Parker Instability