Voyage to the Centre of the Milky Way

a.k.a.

The High Energy Astrophysics of the Galactic Centre

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MARIE CURIE ACTIONS

Some Background

Units/scales

- 1 TeV = 10^{12} eV ~ 1 erg

- Distance to the Galactic centre is ~8 kpc

- 8 kpc ~ 26 000 light years

  ⇒1°~140 pc

  ⇒1´~2.3 pc

  ⇒1´´~ 7900 AU

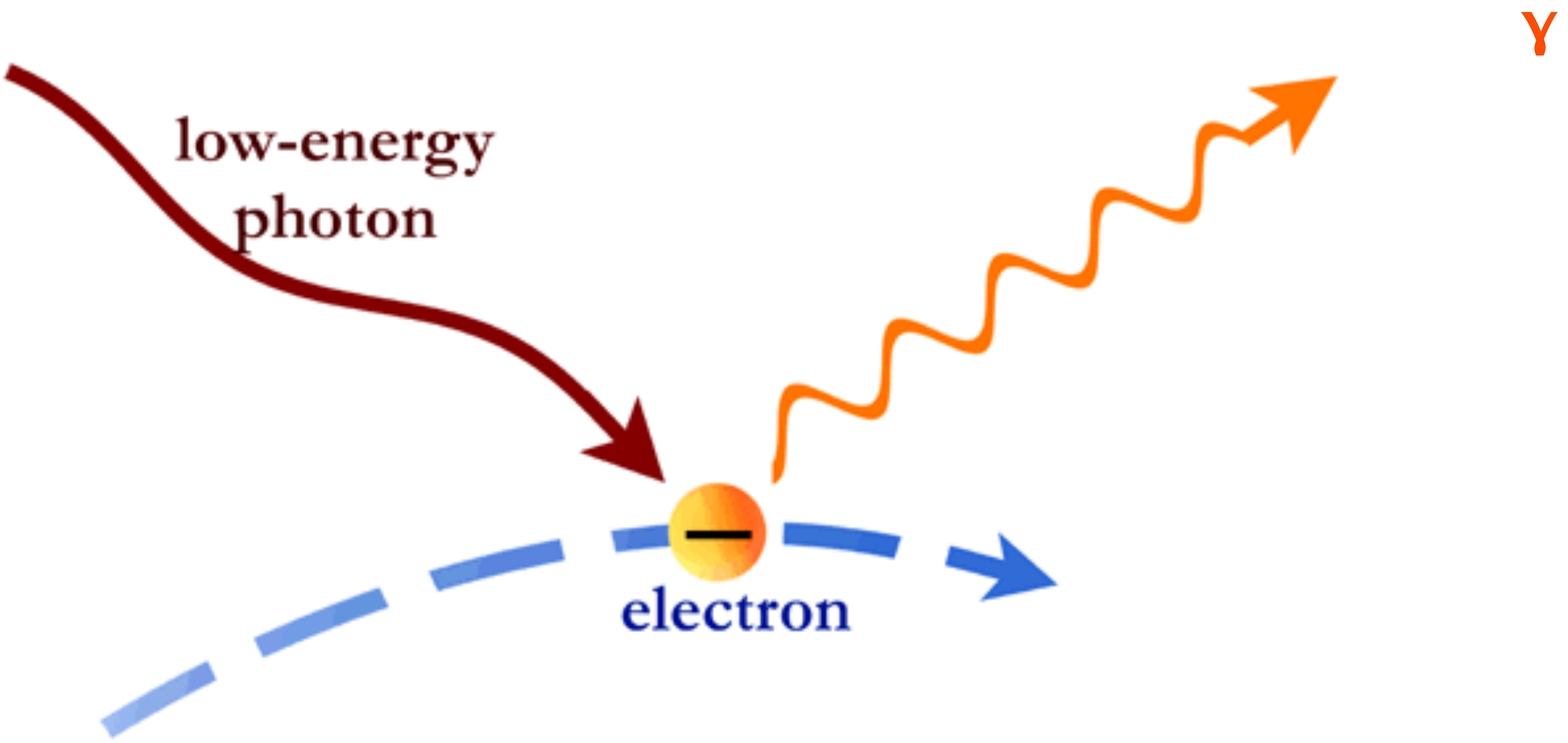
- For me "Galactic centre" = "GC" = inner ~200 pc (diameter)

Relevant Radiative Processes

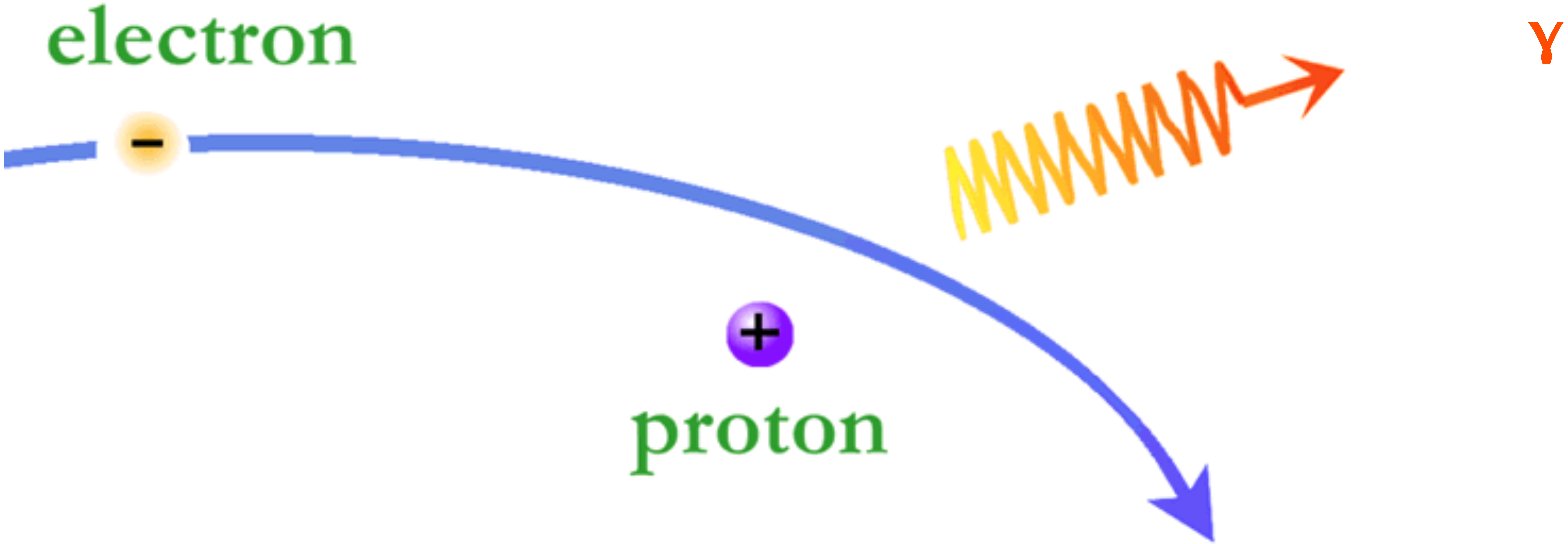
Synchrotron

γ

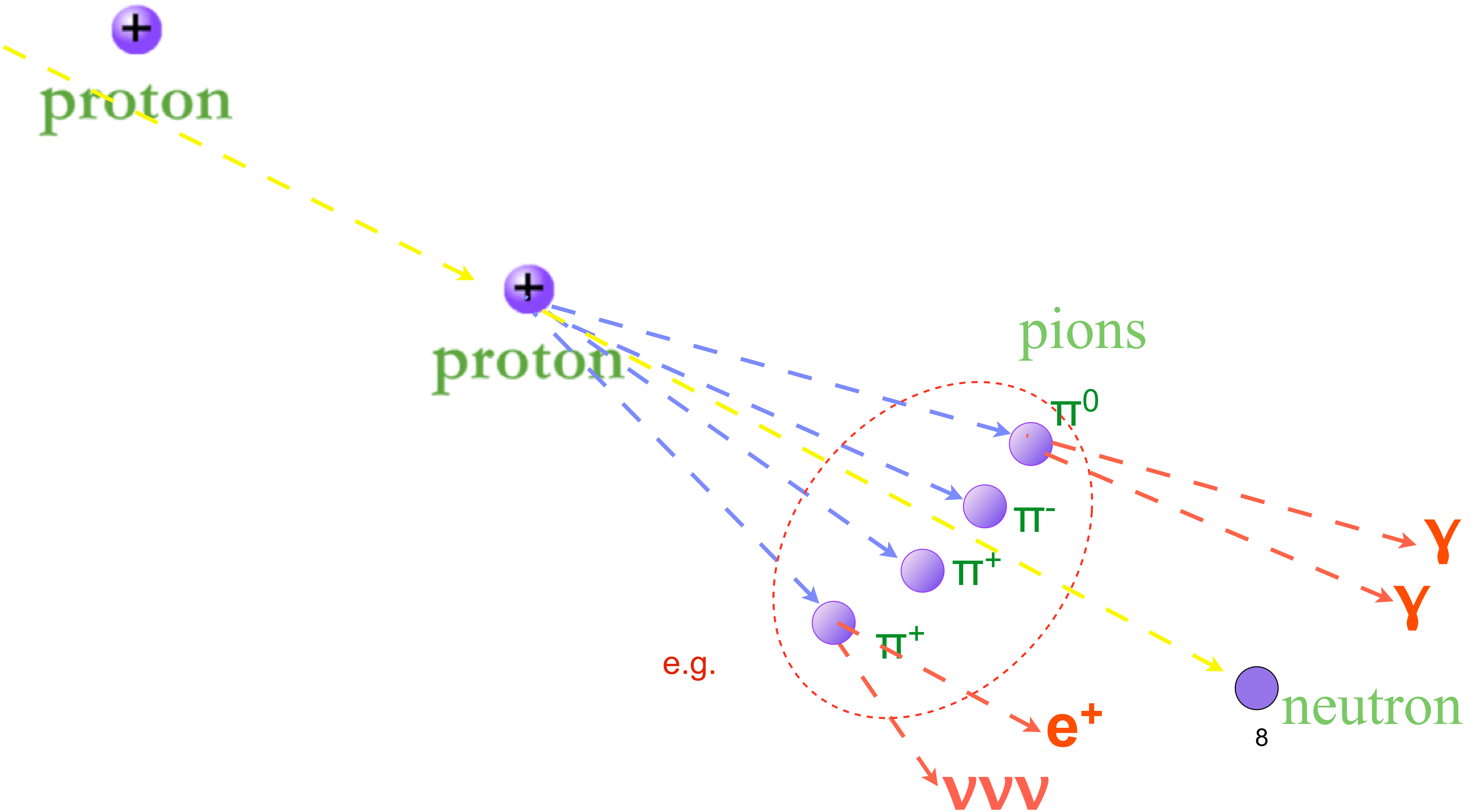
Inverse Compton Scattering



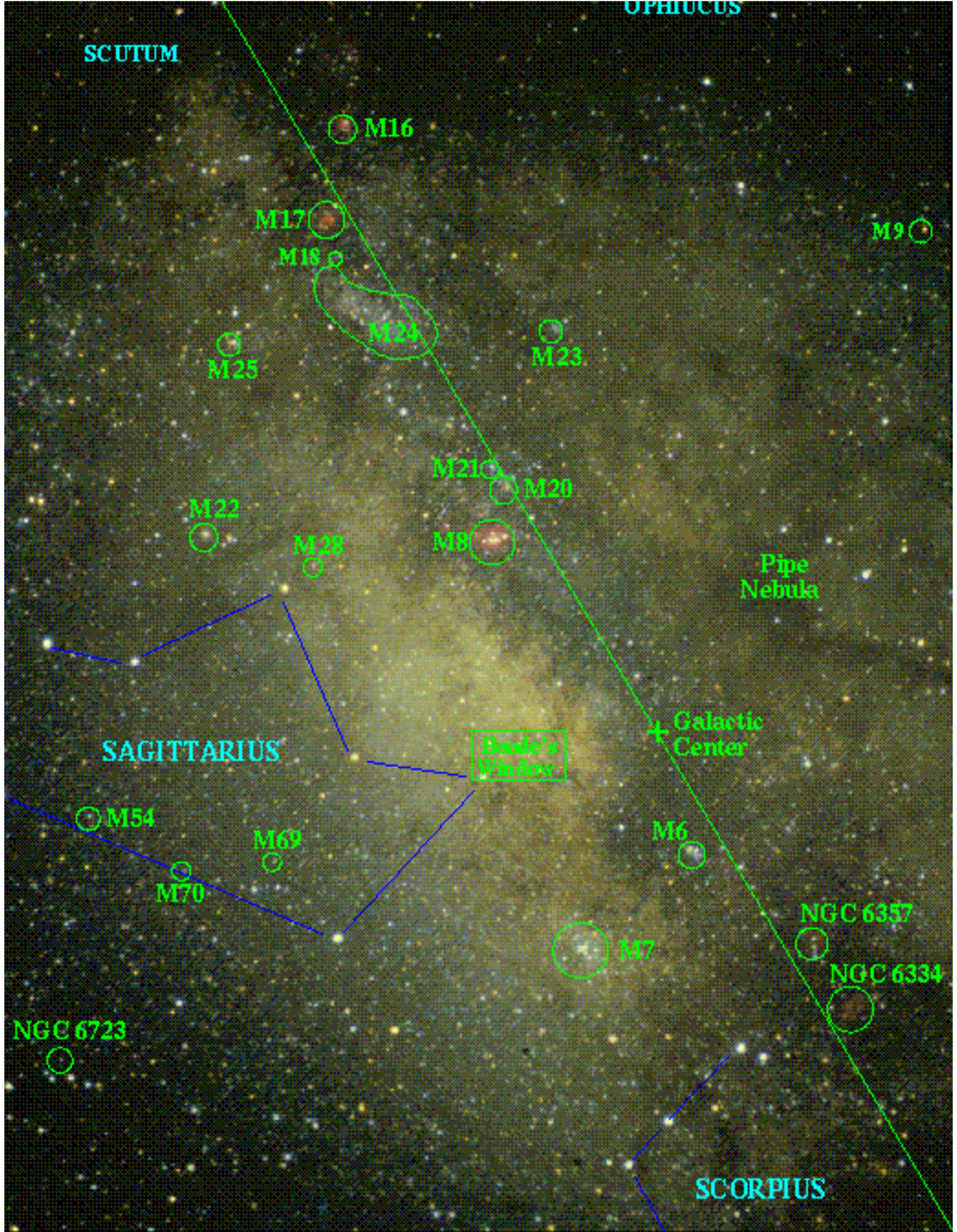
Bremsstrahlung



pp → Pion Decay → secondaries



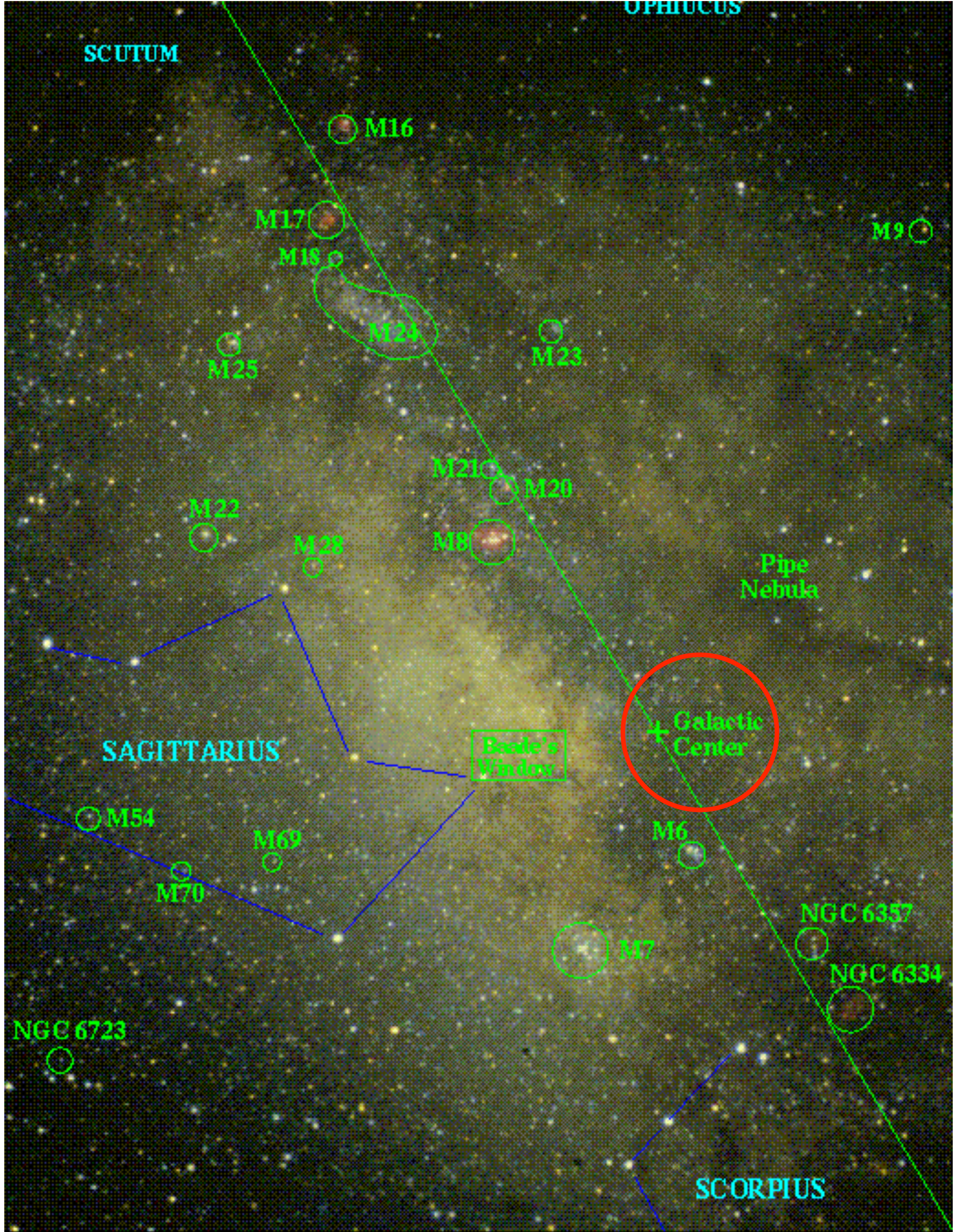
Galactic Centre Phenomenology



GC at Optical Wavelengths - 30 magntiudes of extinction at optical wavelengths!

- Spectral windows: we can observe the GC at radio, sub-millimeter, infrared, X-ray and γ-ray wavelengths

Credit: UCLA Galactic Center Group



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Credit: UCLA Galactic Center Group


purple: 20 cm radio continuum
orange: 1.1 mm (cold dust)
cyan: IR (PAHs)
EAST
Galactic
Plane
Image courtesy of NRAO/AUI


purple: 20 cm radio continuum
orange: 1.1 mm (cold dust)
cyan: IR (PAHs)
EAST
~100
pc
Galactic
Plane
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purple: 20 cm radio continuum
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SNR
Image courtesy of NRAO/AUI


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SNR
NTF
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SNR
radio arc
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NTF
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HII (free free)
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SNR
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20 cm (Yusef-Zadeh)


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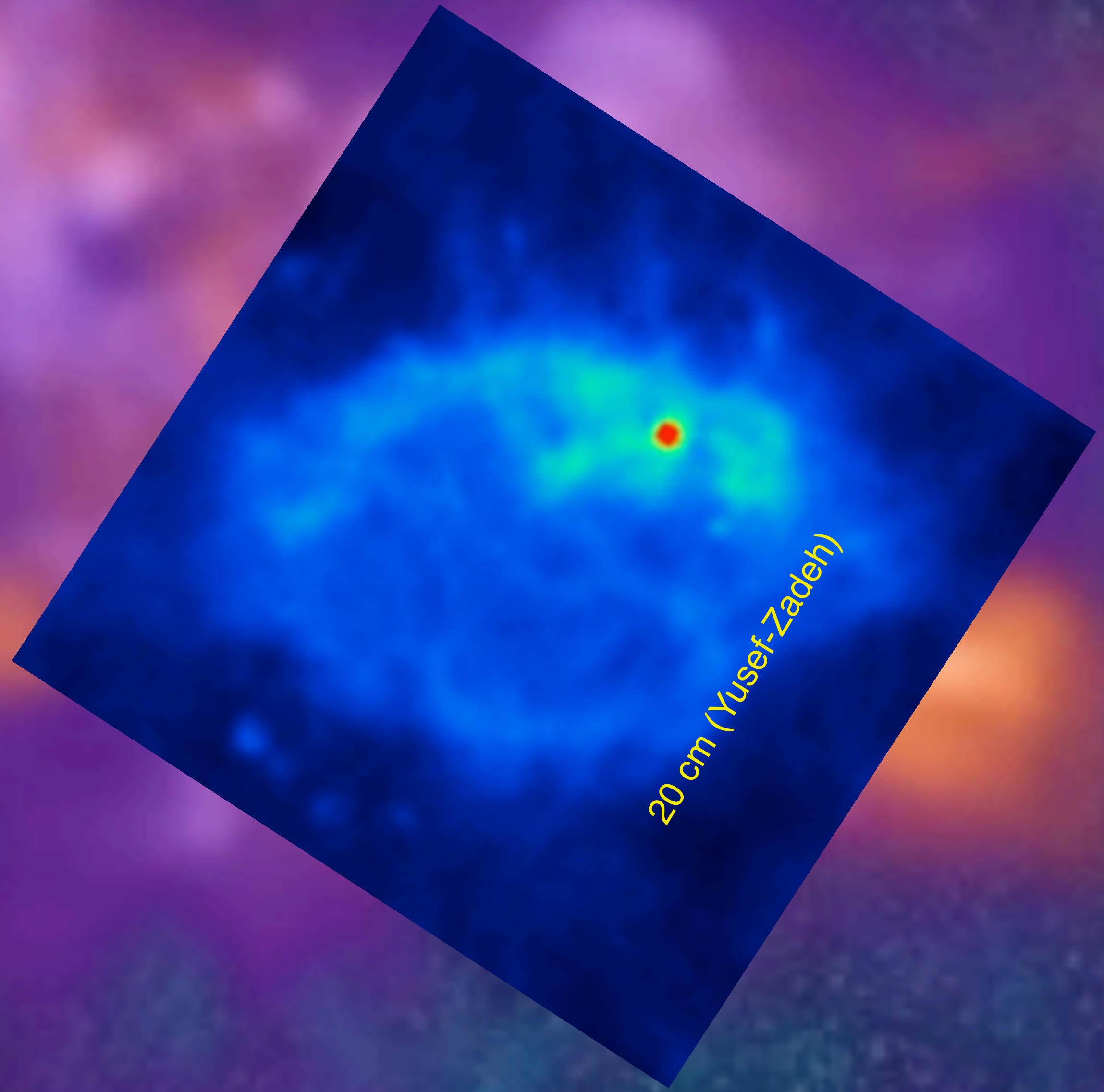
Bright radio point source (~ 1 Jy) "Sgr A*" first identified in the 1970s and coincident with dynamical centre of Galaxy. Variable over tens of days.



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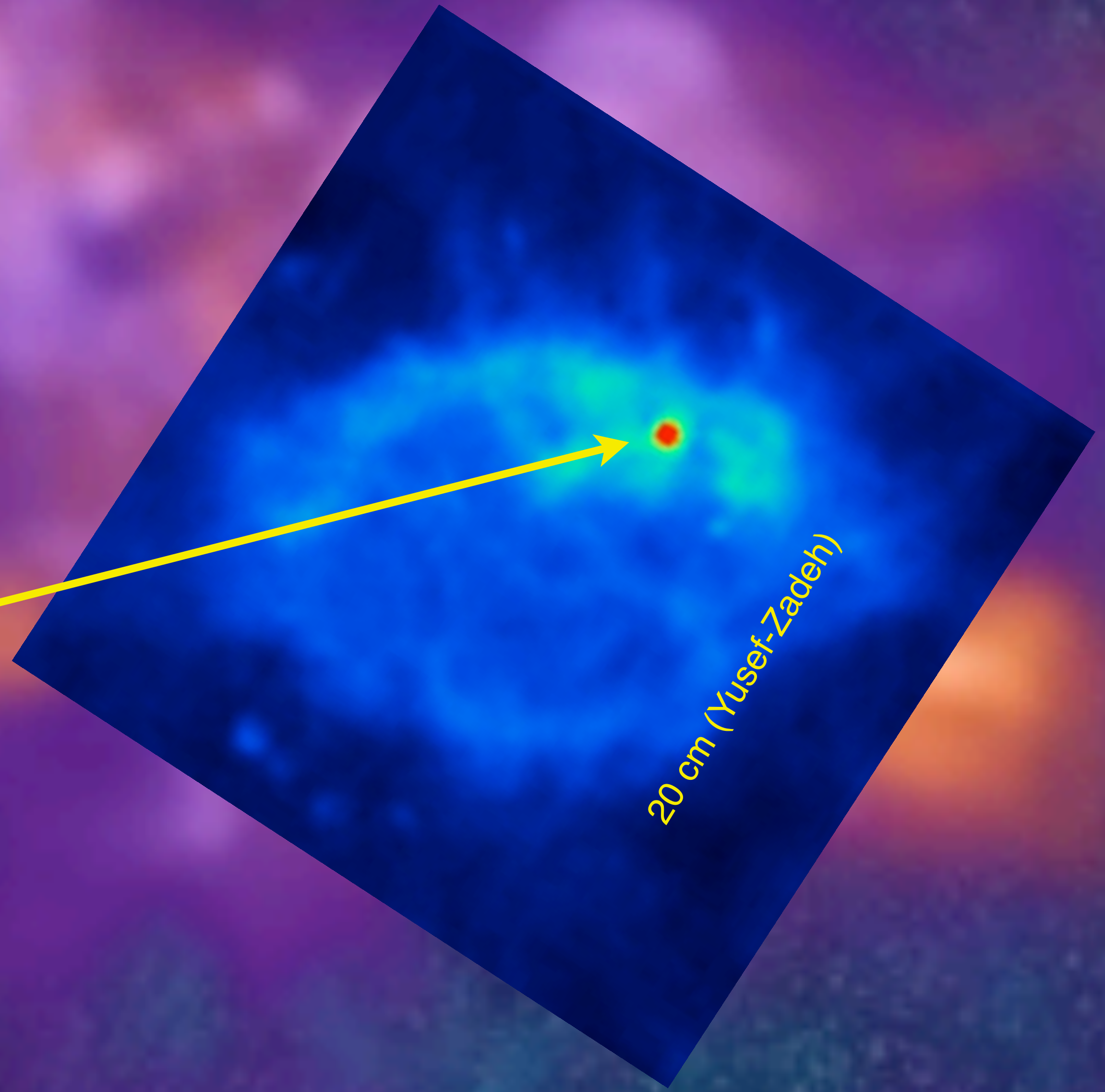
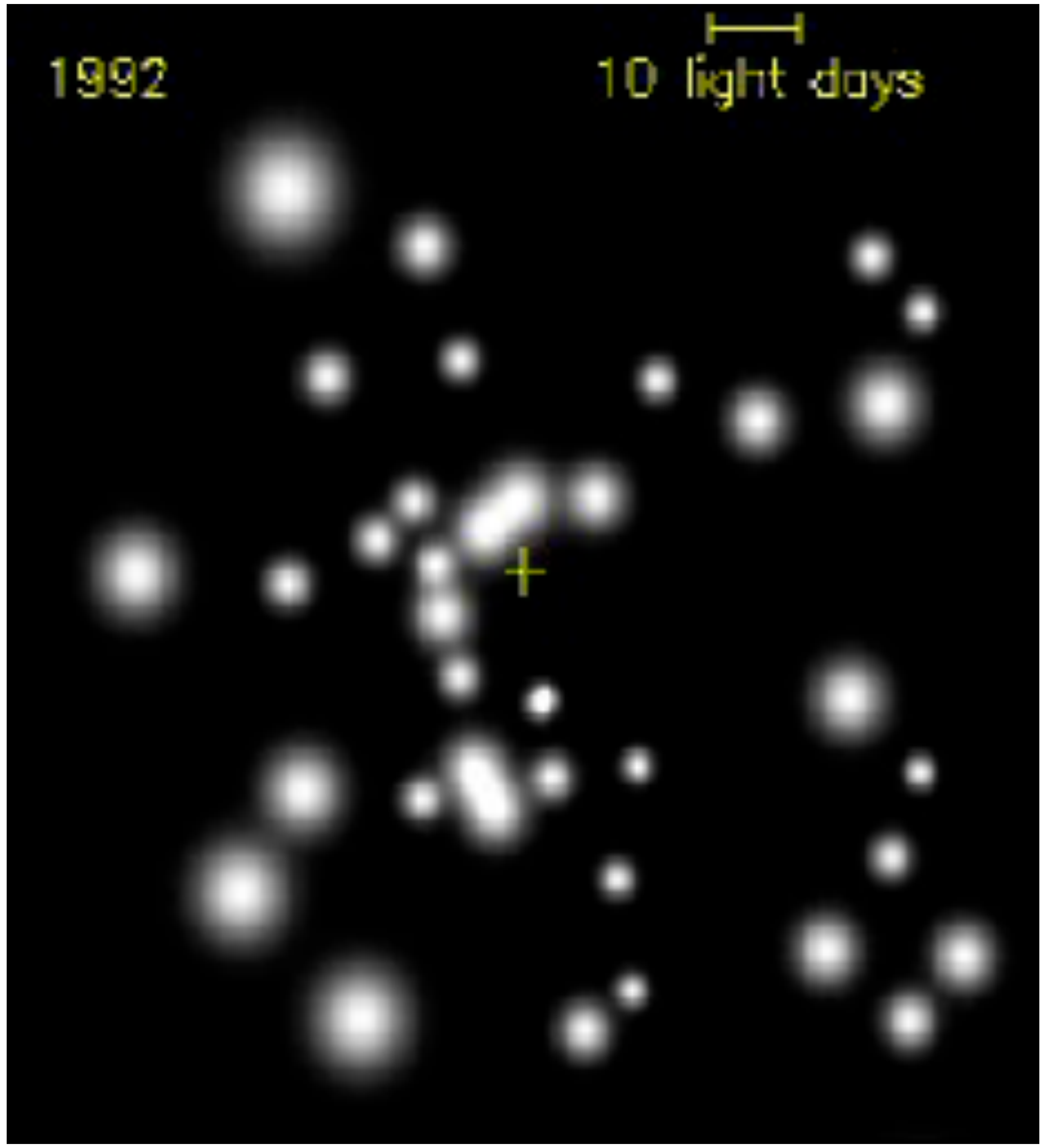


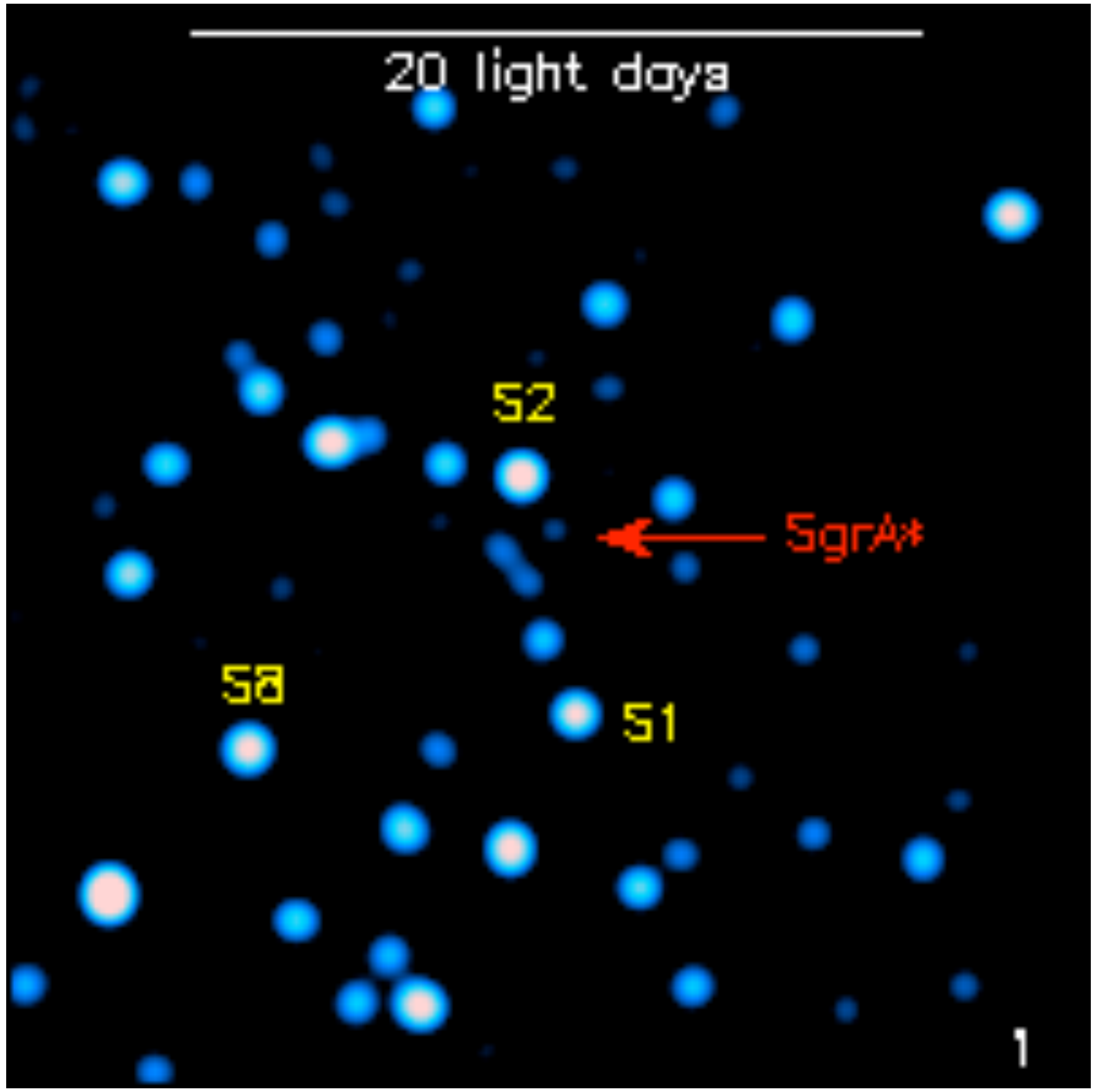
Infra-Red

- Near-infrared high-resolution observations of the GC became possible in the beginning of the 1990s with advances in adaptive optics.
- Analysis of orbits implies **4 million solar masses** inside a region of radius the same as the orbit of Pluto ⟹super-massive black hole



R. Genzel, et al. (2004) - VLT

IR Counterpart of Sgr A*



Movie from Max-Planck-Institut für extraterrestrische Physik : http://www.mpe.mpg.de/ir/GC/index.php

- 0.5 hour flaring is observed in IR
- The largest possible size for the region from which this emission originates is

$$c \times 0.5 \text{ hour} \simeq 4 \times 10^{12} \text{ cm}$$

$$\simeq 10\, r_g$$

- i.e. the radiation probably originates from a region within ~ 10 Schwarzschild radii of the SMBH

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Tsuboi (1999)
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cyan: IR (PAHs)
Tsuboi (1999)
CS J=1-0 -200<V<200 km/s
1.50
1.25
1.00
0.75
0.50
0.25
0.00
-0.25
-0.50
galactic longitude (deg.)
Image courtesy of NRAO/AUI

Gas Density Through GC

Tsuboi (1999)

Gas Density Through GC

Tsuboi (1999)

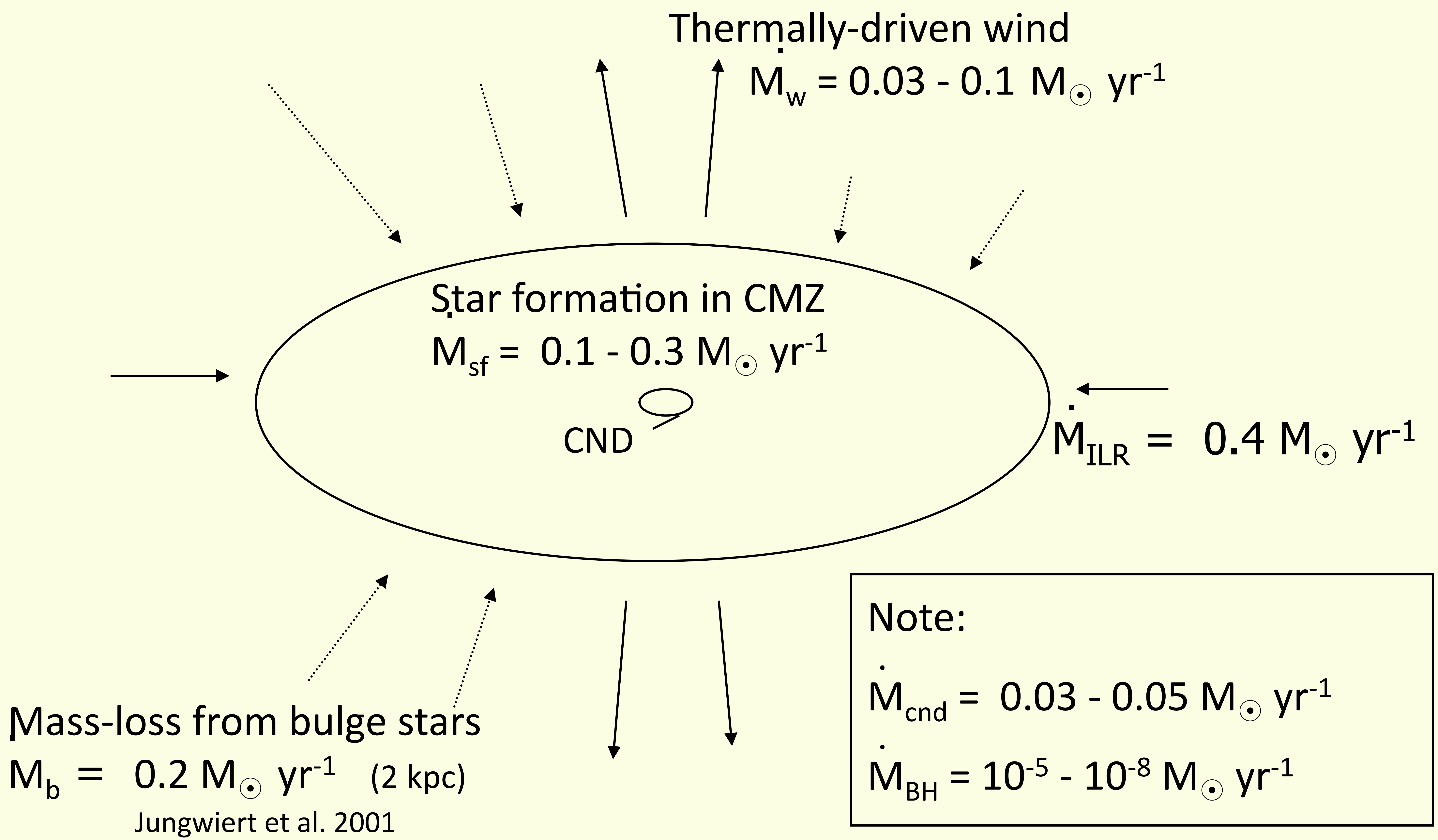
- Molecular line observations trace gas density and show up **Central Molecular Zone** of giant molecular cloud complexes bound in tight orbits (~100 pc) around GC - these contain ~ 5% of the Galaxy's molecular gas (3-8 10^7 solar mass) and at *volumetric-average* number densities of n_{H2} ~ 10^4 cm^{-3}

GC molecular clouds are unusually

- dense (~10^4 cm^{-3}),
- turbulent (velocity dispersion > 15 km/s)
- warm (10's K)

...when compared with Galactic Disk clouds

The Mass Budget



Mark Morris

High gas density implies high SFR

- SFR density over central ~200 pc ≳ 3 orders of magnitude larger than in disk ($\partial_t \Sigma_* \sim 2\ M_\odot\ yr^{-1}\ kpc^{-2}$)
- ⇒ young, hot and massive OB stars and Wolf-Rayets
- 3 known clusters (Arches, Quintuplet, Nuclear) of young, massive stars a few million years old...BUT also population of old (>Gyr) stars
- NB mass[Nuclear Stellar Cluster] ~ 10 x mass[SMBH]
- cf. empirical correlations between Bulge mass and "Central Massive Object" (Ferrarese et al. 2006) mass and Bulge velocity dispersion and CMO mass

A peculiar region of the Galaxy...

- Many enigmatic phenomena peak over the inner 200 pc of the Galaxy, presumably driven by the star-formation occurring there (or the SMBH):

— NTFs ⇒ large scale and strong magnetic fields and relativistic electrons

— "diffuse, very hot" (8 keV) X-ray-emitting plasma (or is it really unresolved, faint source? ...*continuing debate!*)

— diffuse TeV emission (see later)

In General: *Extreme ISM in GC...*

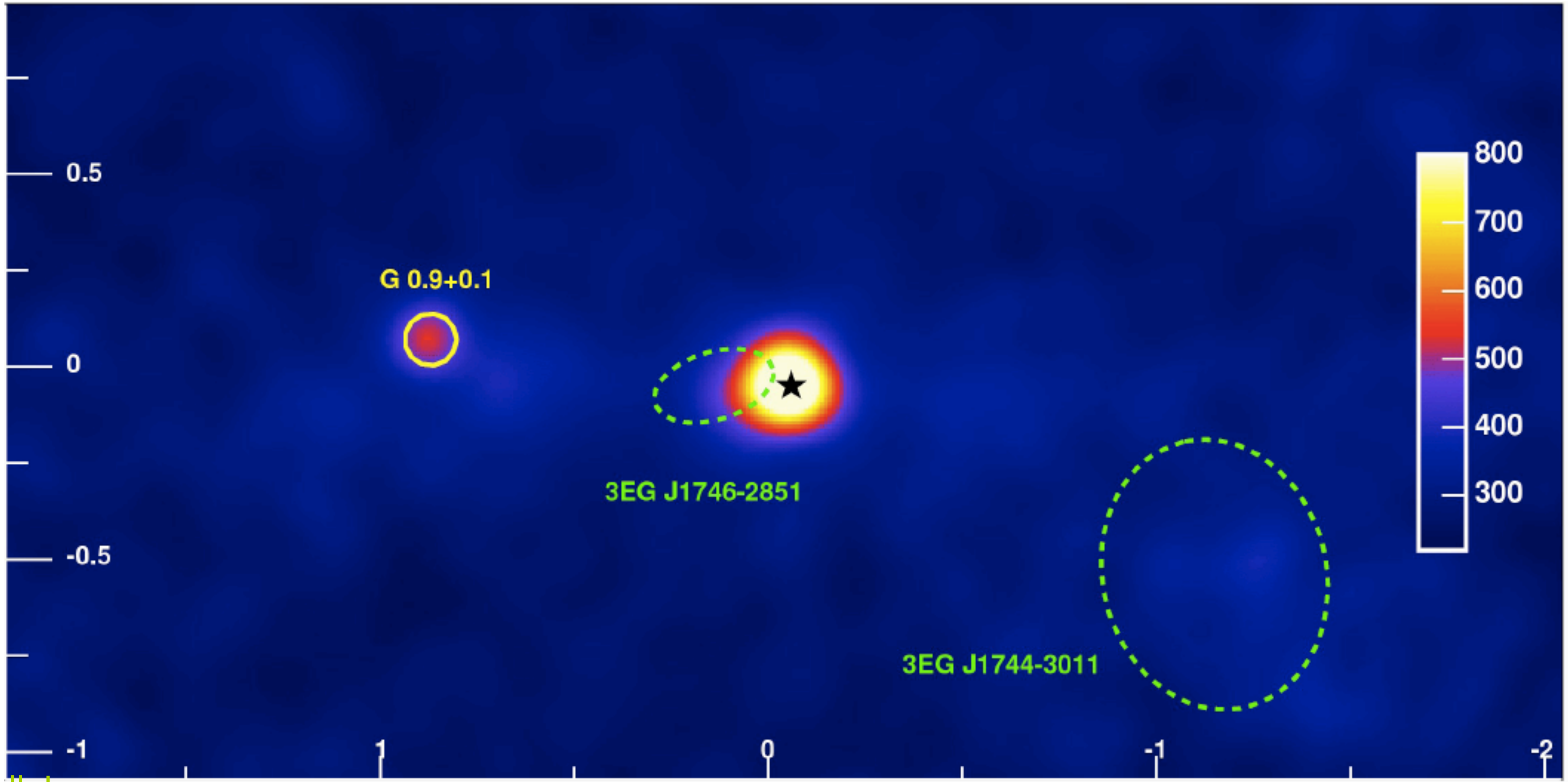
- GC ISM params extreme wrt Gal disk - arguably *more akin to a star-burst*: energy densities/pressures of ISM comps ~2 orders of magnitude larger than in disk (~100's eV cm^{-3})
- **Strong B fields**, high H_2 densities and turbulence, very hot plasma, inter-stellar radiation field

High-energy photons from the GC

High-energy photons from the GC

- 1 keV - 100 TeV
- below ~1 keV optical depth to GC due to photoionization on metals in ISM becomes significant
- above ~40 TeV optical depth to GC due to pair production on IR background and CMB becomes significant
- angular resolution of instruments varies considerably over this range

HESS (TeV) GC Data (2005) - 50 hours



Credit: HESS Collab

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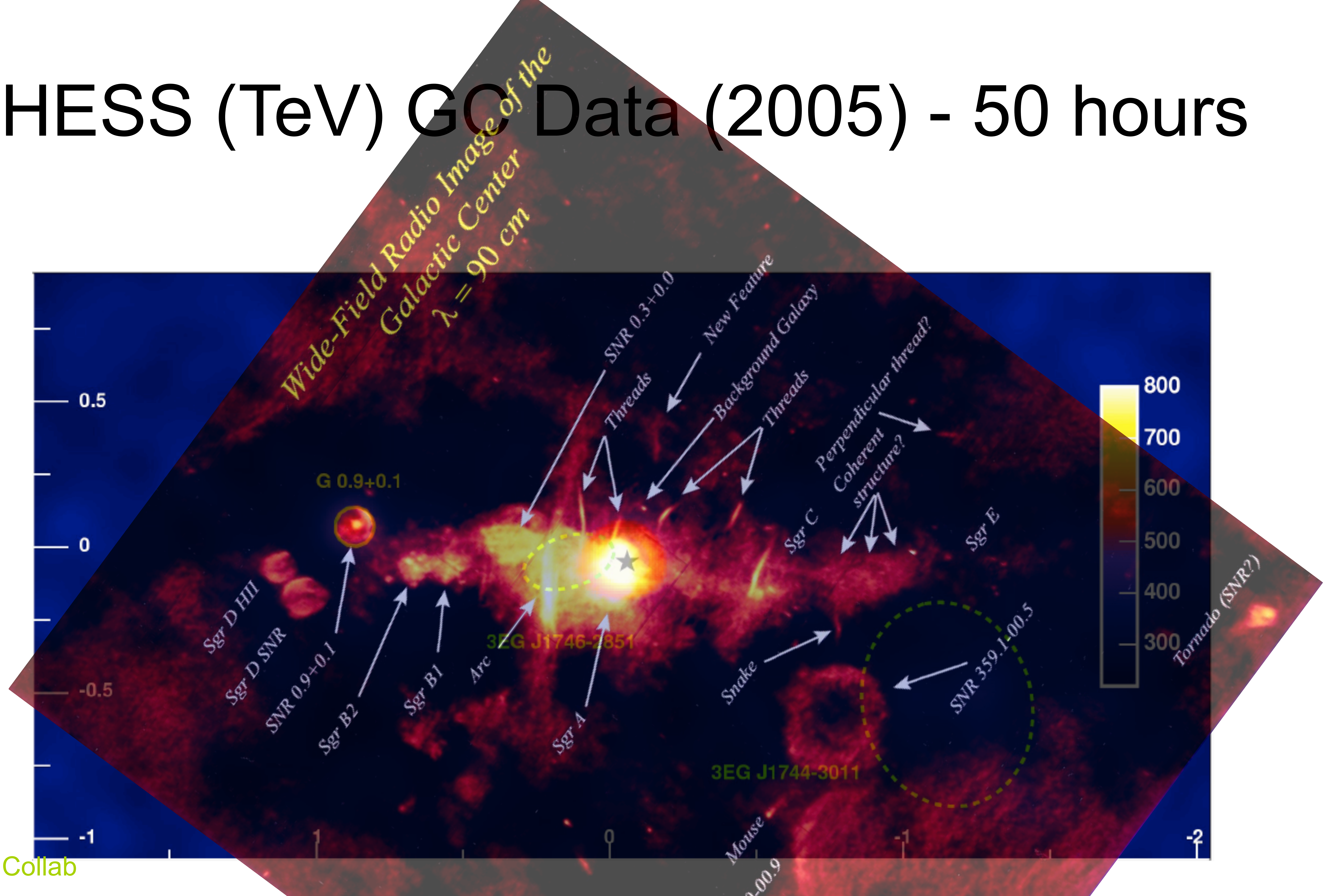

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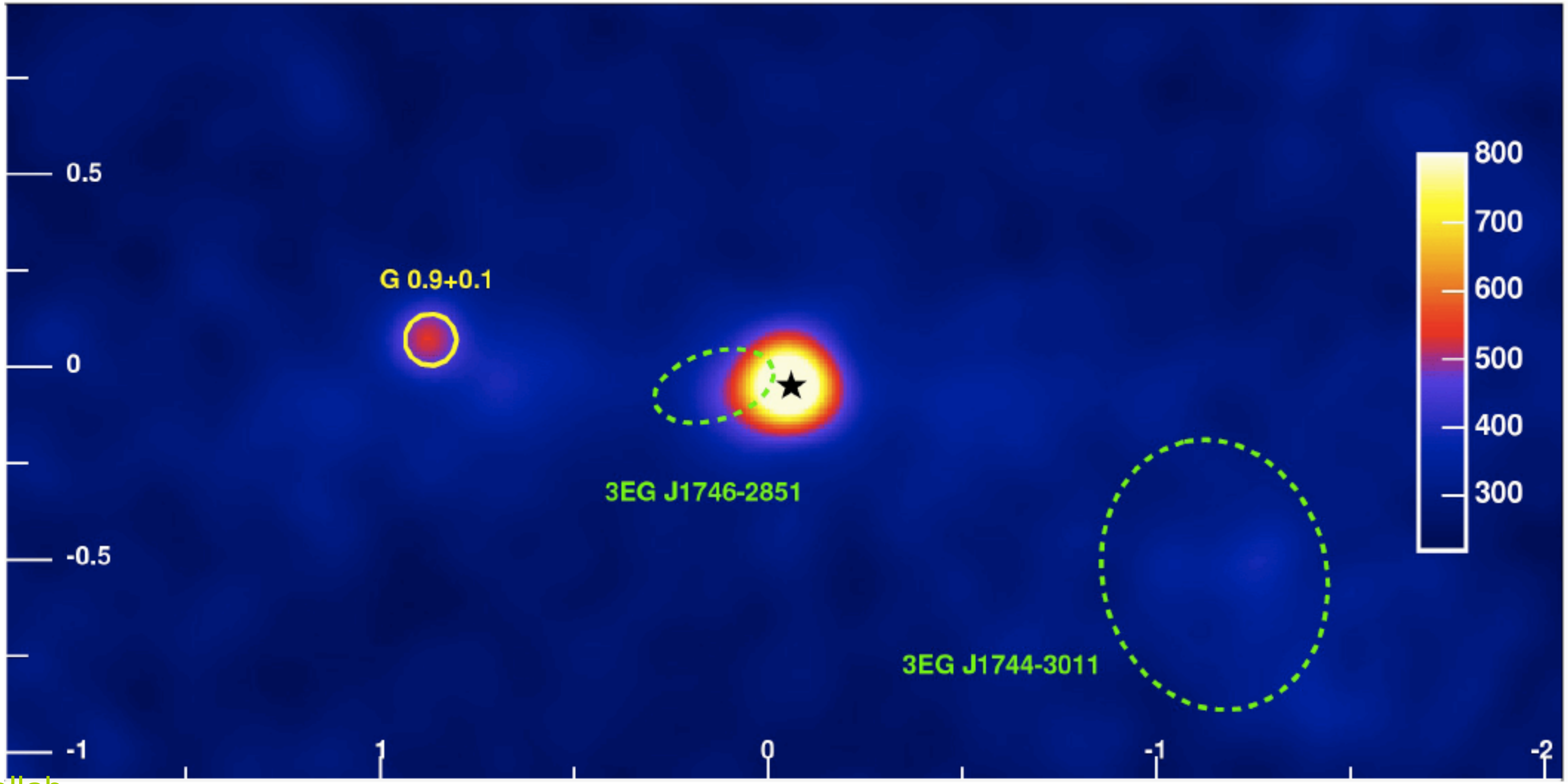


Credit: HESS Collab

HESS ~TeV Observation of Sgr A

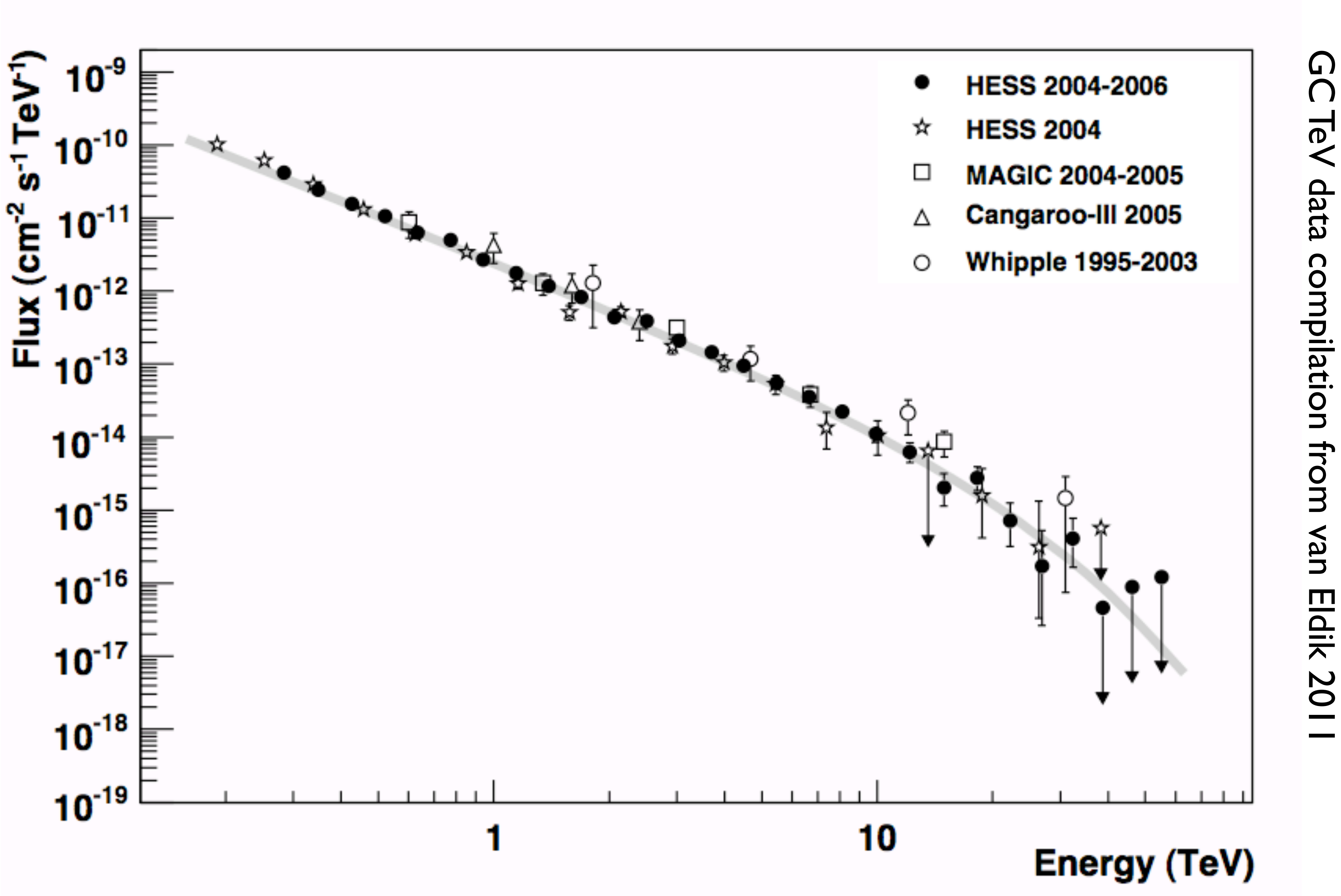
- Hard spectrum:

  Γ = -2.1 ± 0.04 (stat. + syst)

with exponetial cutoff at ~15 TeV

(or broken power law)

- Data consistent with steady source



GC TeV data compilation from van Eldik 2011

What is the mechanism for γ-ray production?

1. *Leptonic models* - high-energy electrons (10 TeV+) inverse-Compton scatter ambient light to TeV energies
2. *Hadronic models* - protons (and heavier ions) collide with ambient gas (H_2) and produce neutral pions
3. Dark matter annihilation?

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Hadronic Models

- protons might be accelerated in/at

1. Sgr A*:
   i. shocks in the accretion disk
   ii. stochastically accelerated (2nd order Fermi) in MHD turbulence (Liu et al. 2004)
   iii. in jet from tidally-disrupted star (Lu et al. 2006)
2. shocks associated with Sgr A East SNR (Crocker et al. 2005)

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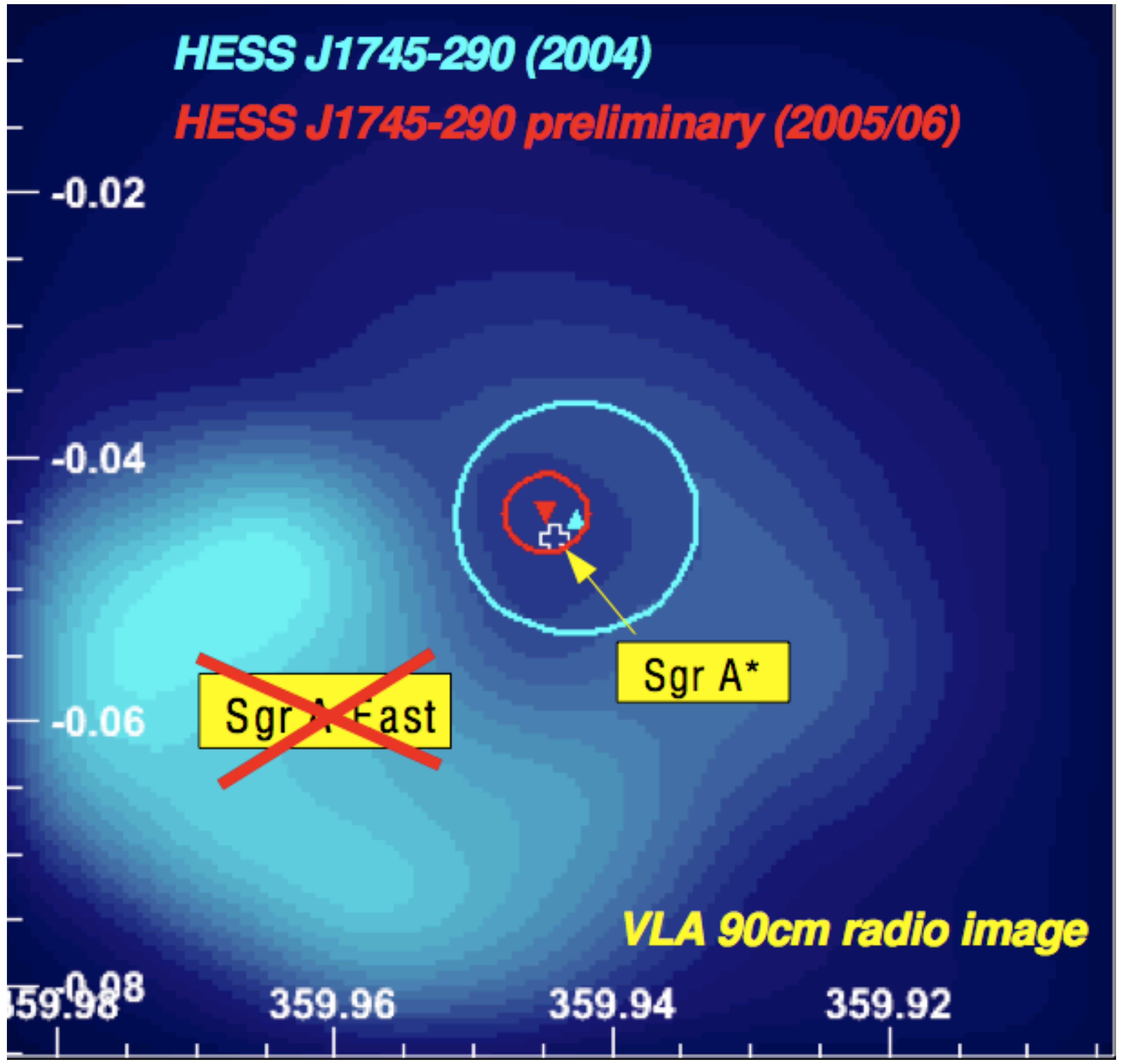
HESS Observation of Sgr A after 100+ hours (2005/06)

- Sgr A TeV source detected by HESS at > 40σ
- Centroid of emission within 8” ± 9” ± 9” coincident with Sgr A* and inconsistent with Sgr A East
- Point-source

  ⇒ emission region < 1.2’ ~3 pc

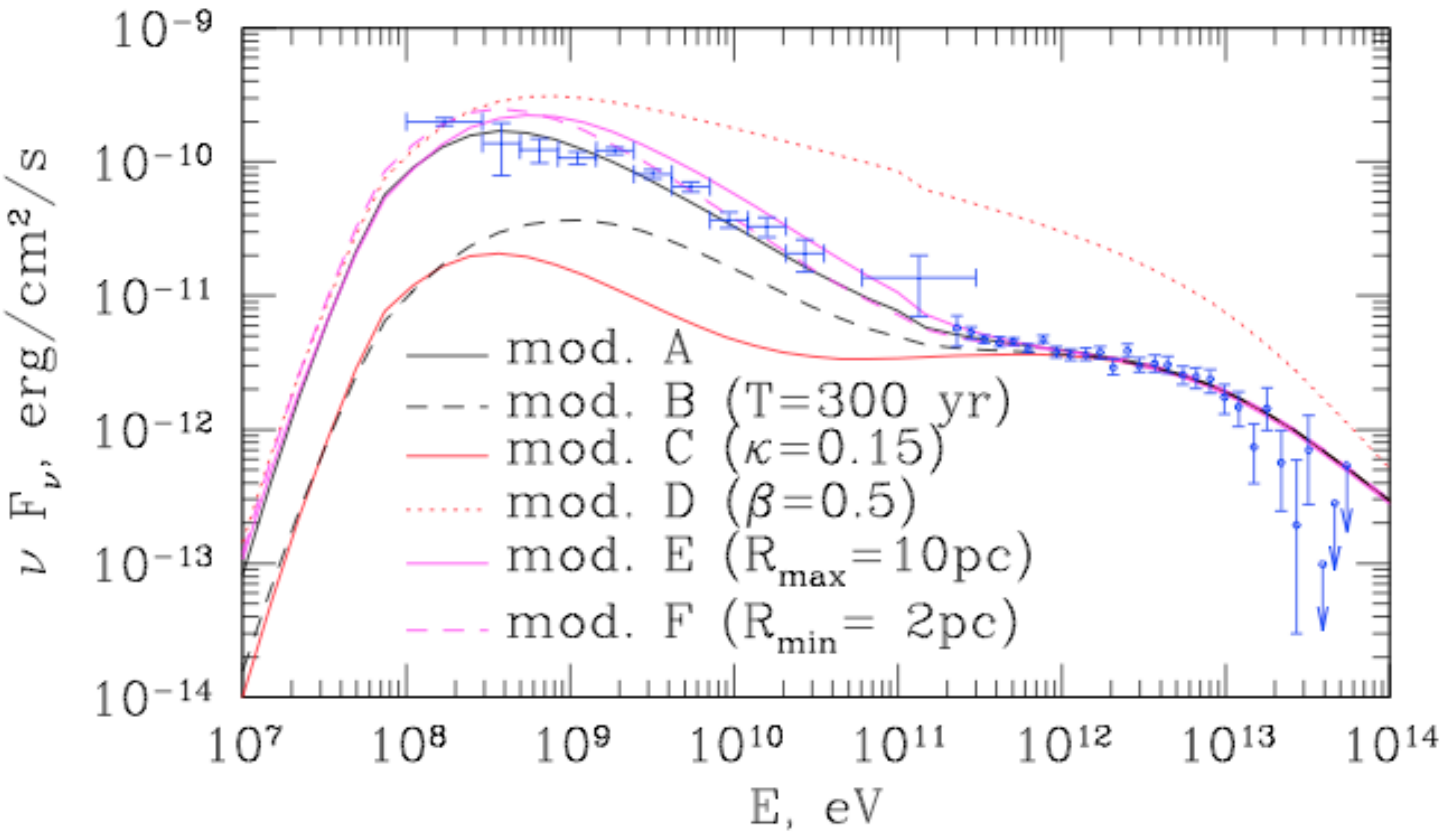


Gamma-rays from pp Collisions

p's might interact

1. close to the BH horizon (inefficient: Aharonian & Neronov 2005)
2. in dense gas at larger radii (Aharonian & Neronov 2005, Ballantyne et al. 2007, Crocker et al. 2007, Chernyakova et al. 2010) – out to a few pc

GeV (Fermi) to TeV (HESS) Spectrum



Chernyakova et al. (2010)

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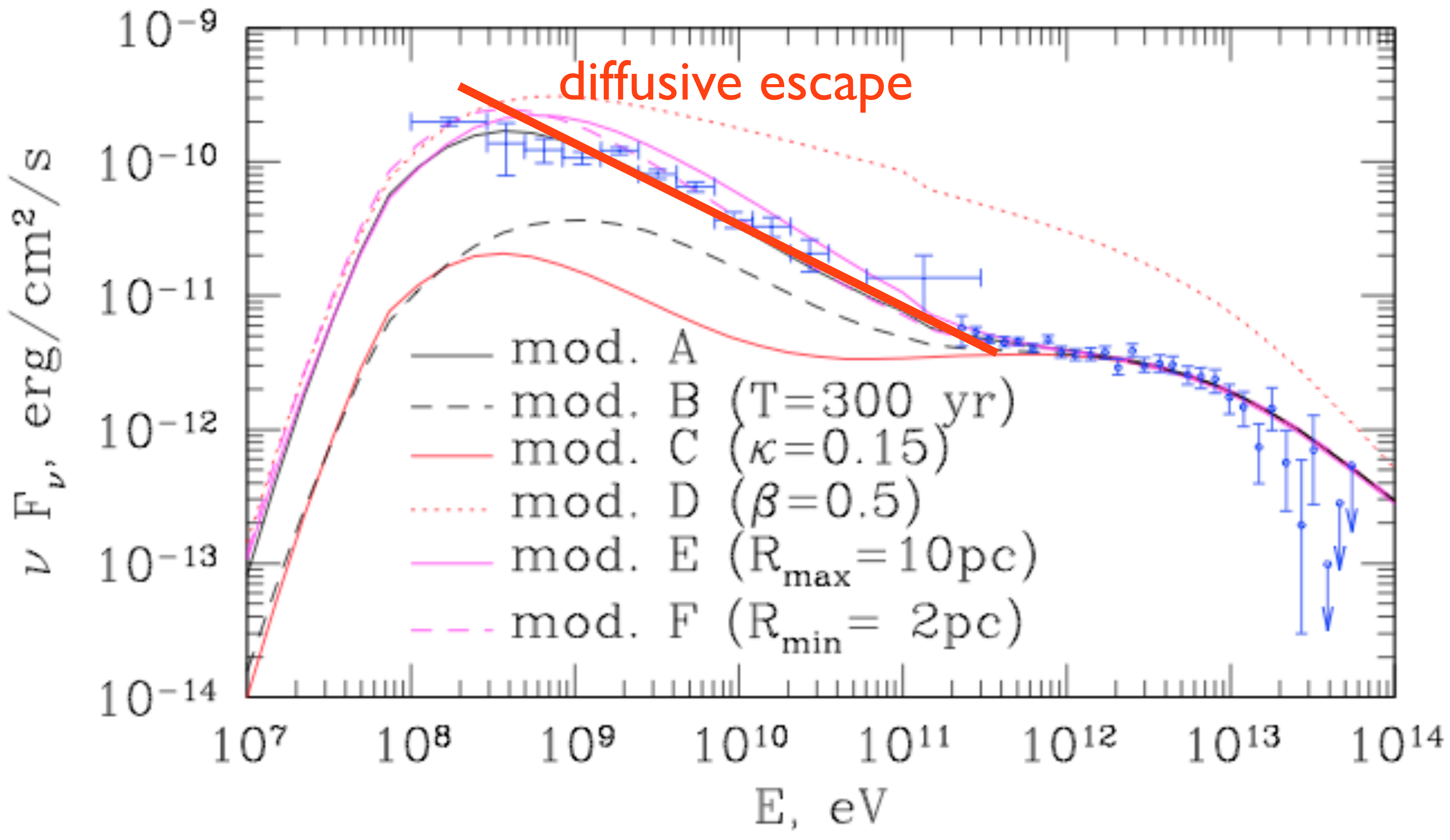

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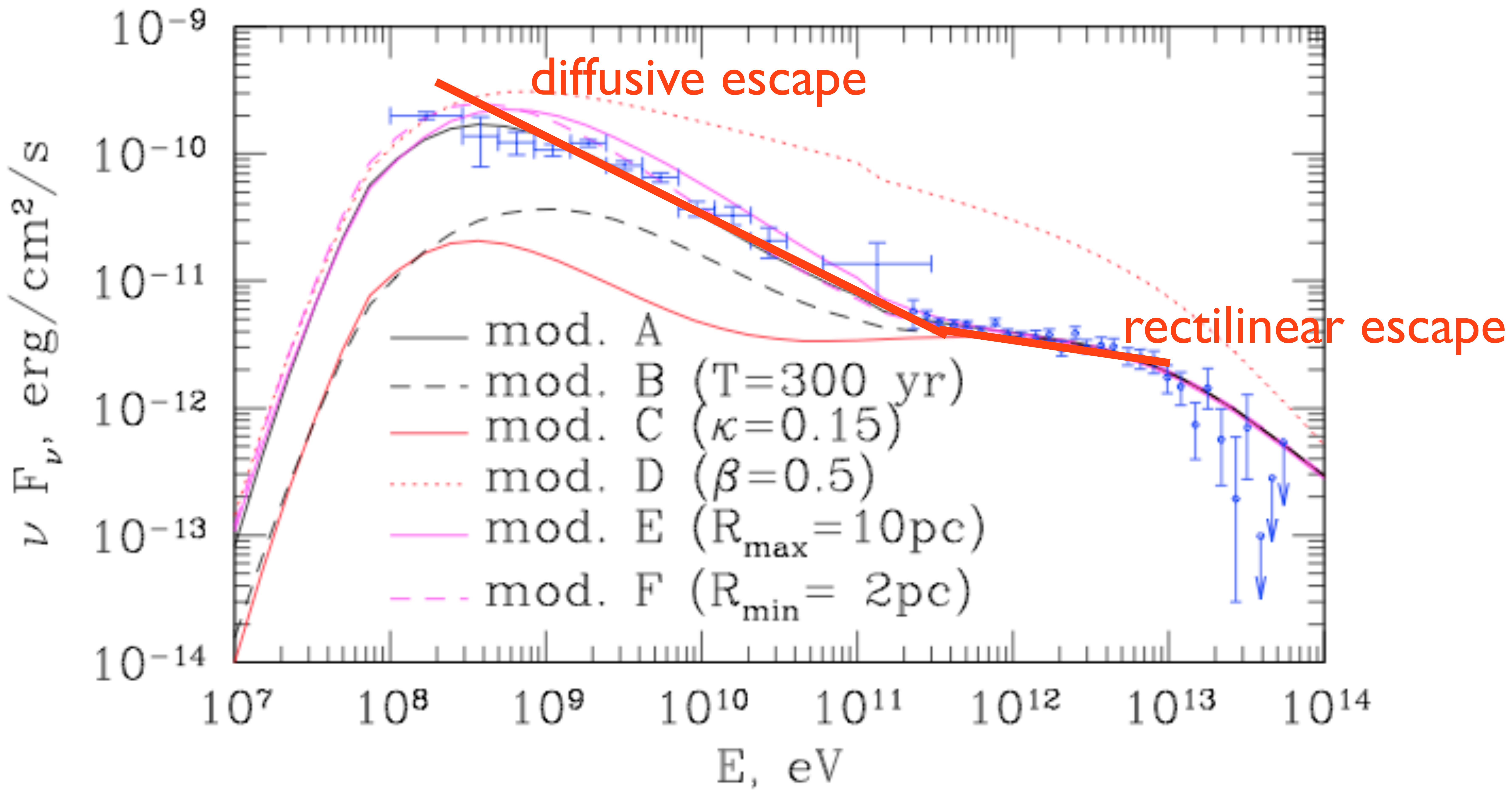

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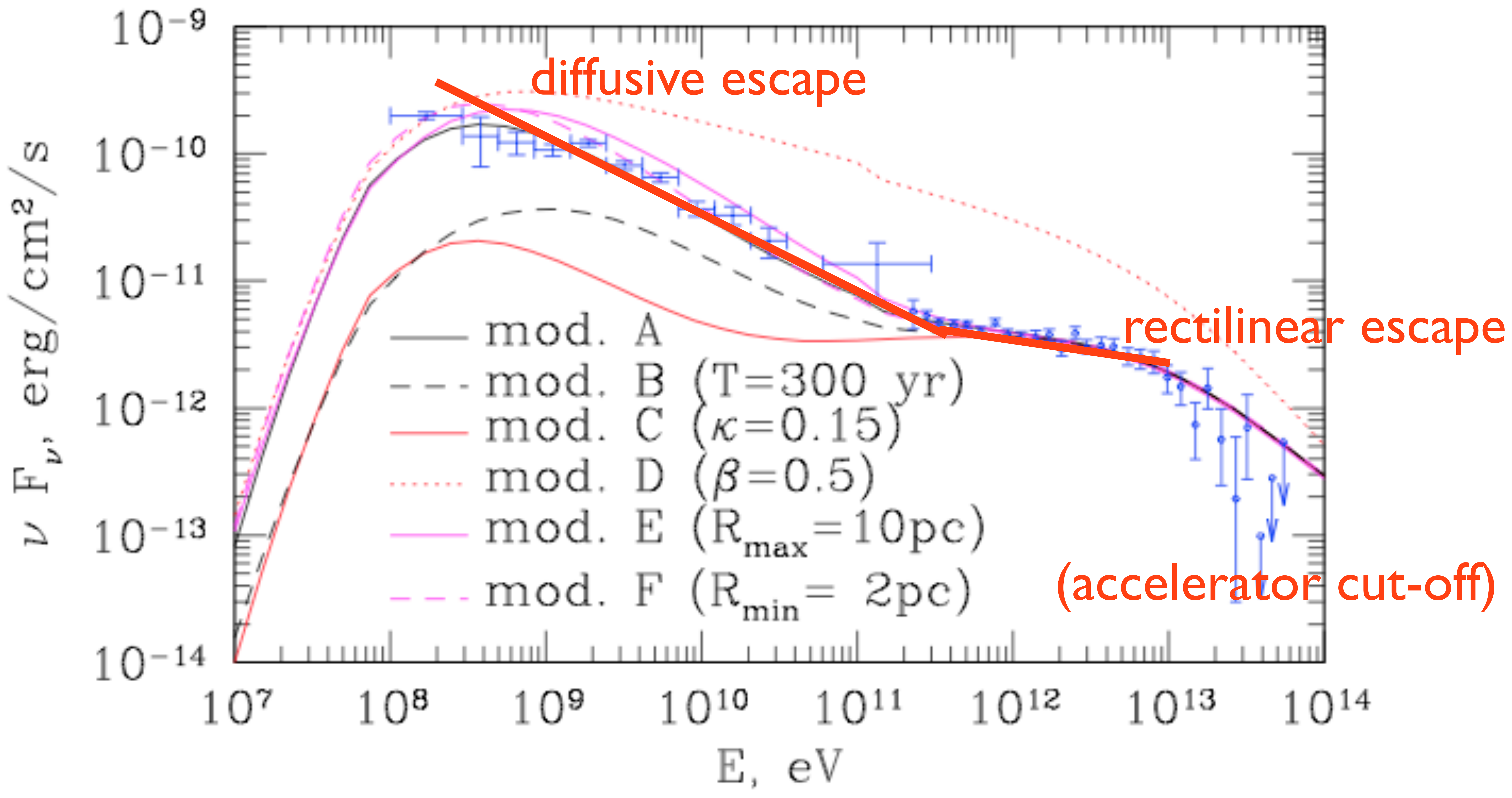

Chernyakova et al. (2010)

Sample of Leptonic Scenarios

- Generically invoke HE e's IC scattering IR γ's with e's accelerated by/at
- strong, ordered **E**/**B** fields close to BH horizon (Aharonian & Neronov 2005)
- stellar winds associated with in situ massive stars (Quataert & Loeb 2005)
- the termination shock of the subrelativistic wind from the central part of the advection-dominated accretion flow on to the GC black hole – cf. pulsar wind nebulae (Atoyan & Dermer 2005)

Lack of Variability…

- Note that lack of variability within observing runs (HESS, MAGIC) and between different instruments' measurements (HESS – MAGIC) would *tend* to disfavour models where the emission comes from a very compact region
- No correlated variability with X-ray flaring seen

Diffuse γs in H.E.S.S. data?

- 50 hour H.E.S.S. Observation of GC in 2005
- Need to subtract the two bright sources

Credit: HESS Collab

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Credit: HESS Collab

CS contours over H.E.S.S. map

Credit: HESS Collab

CS contours from Tsuboi et al. (1999)

GC Diffuse TeV Emission

- Correlated with gas column
- *Hard spectrum:* $F_\gamma \propto E_\gamma^{-2.3}$
- $F_\gamma \sim 10^{35}$ erg/s

Current Research

Refs and collaborators

Wild at Heart:-The Particle Astrophysics of the Galactic Centre,
Roland M. Crocker, David I. Jones, Felix Aharonian, Casey J. Law, Fulvio Melia, Tomoharu Oka, Juergen Ott MNRAS 2011 (**arXiv:1011.0206**)

Gamma-Rays and the Far-Infrared-Radio Continuum Correlation Reveal a Powerful Galactic Center Wind,
Roland M. Crocker, David I. Jones, Felix Aharonian, Casey J. Law, Fulvio Melia, Juergen Ott
MNRAS Letters 2011 (**arXiv:1009.4340**)

The Fermi Bubbles: Giant, Multi-Billion-Year-Old Reservoirs of Galactic Center Cosmic Rays
Roland M. Crocker, Felix Aharonian PRL 2011 (**arXiv:1008.2658**)

A lower limit of 50 microgauss for the magnetic field near the Galactic Centre
Roland M. Crocker, David Jones, Fulvio Melia, Jürgen Ott, Raymond J. Protheroe
Nature 2010

Big picture

- GC magnetic field is > 10 x disk field (> 100 x energy density)
- GC star-formation drives a super-wind → CR transport in GC is advective not diffusive (cf. Galactic Disk)
- The GC wind advects plasma and cosmic ray ions to large distances from the plane and the γ-ray and microwave signatures of these have recently been detected as the *Fermi Bubbles*
- Despite similarity to starburst conditions GC SF proceeding in more-or-less steady state for ≳ Gyrs

Current Research 1
The GC magnetic field is very strong

Diffuse, non-thermal RC

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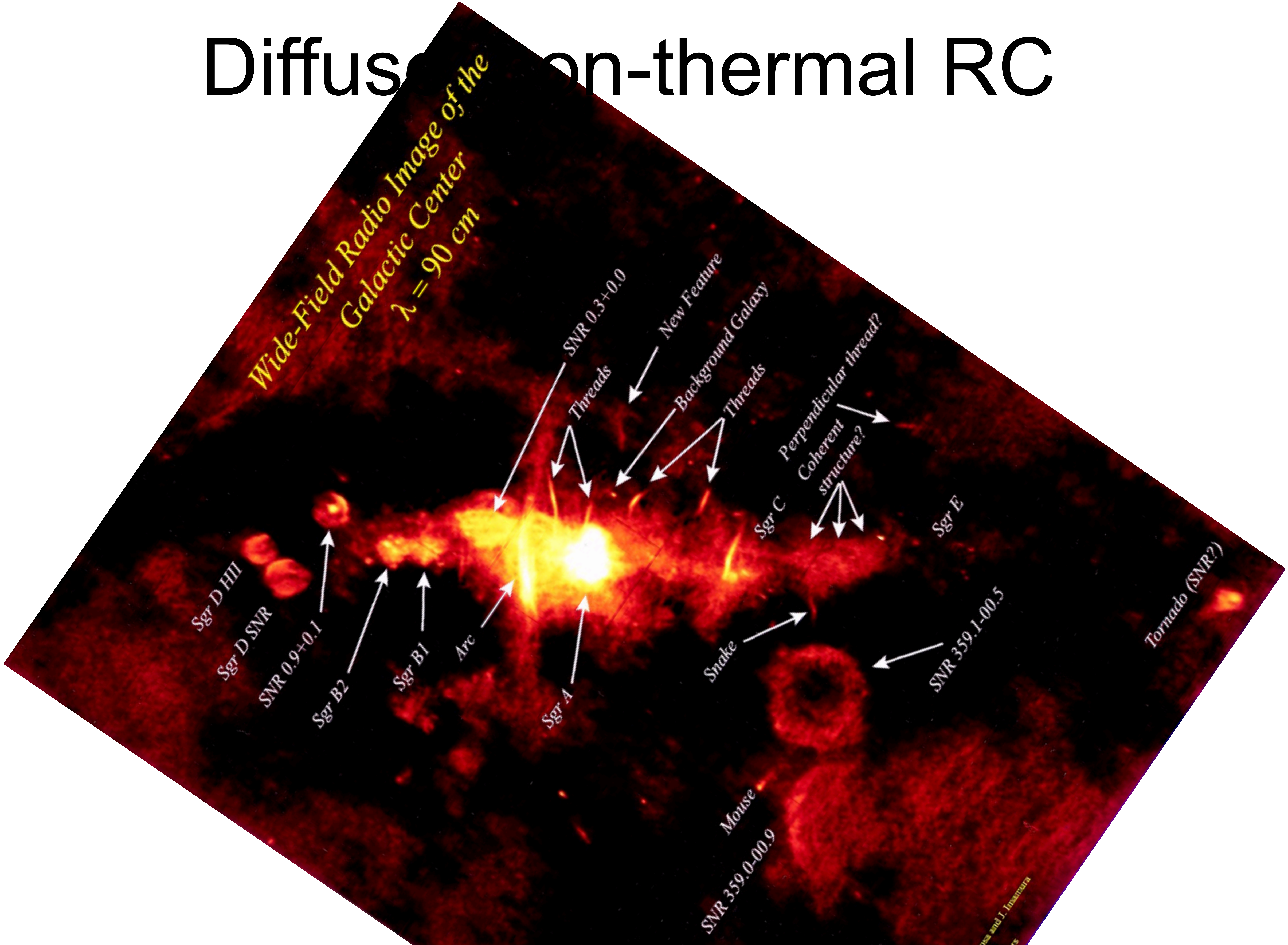
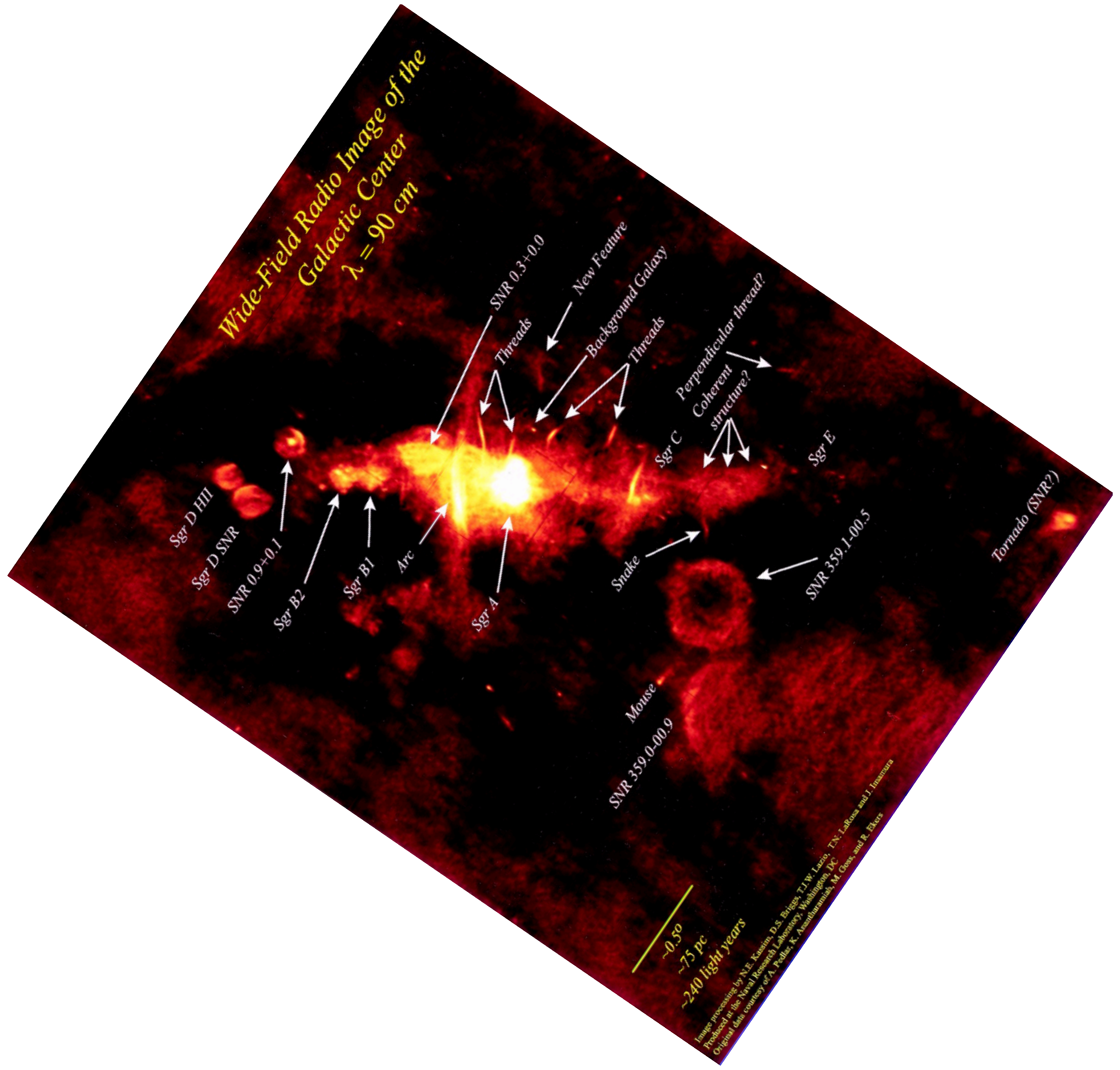


Diffuse, non-thermal RC



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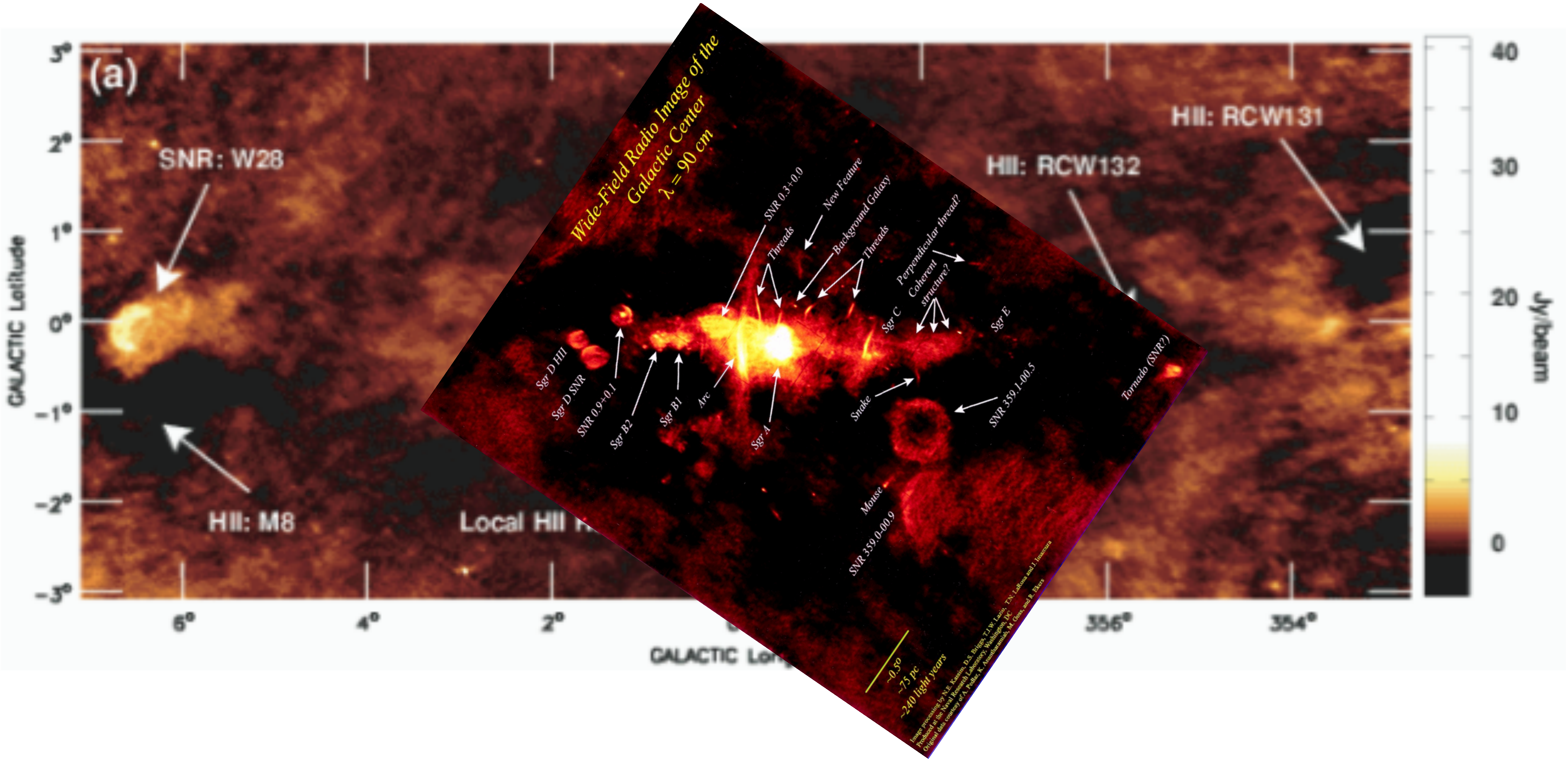

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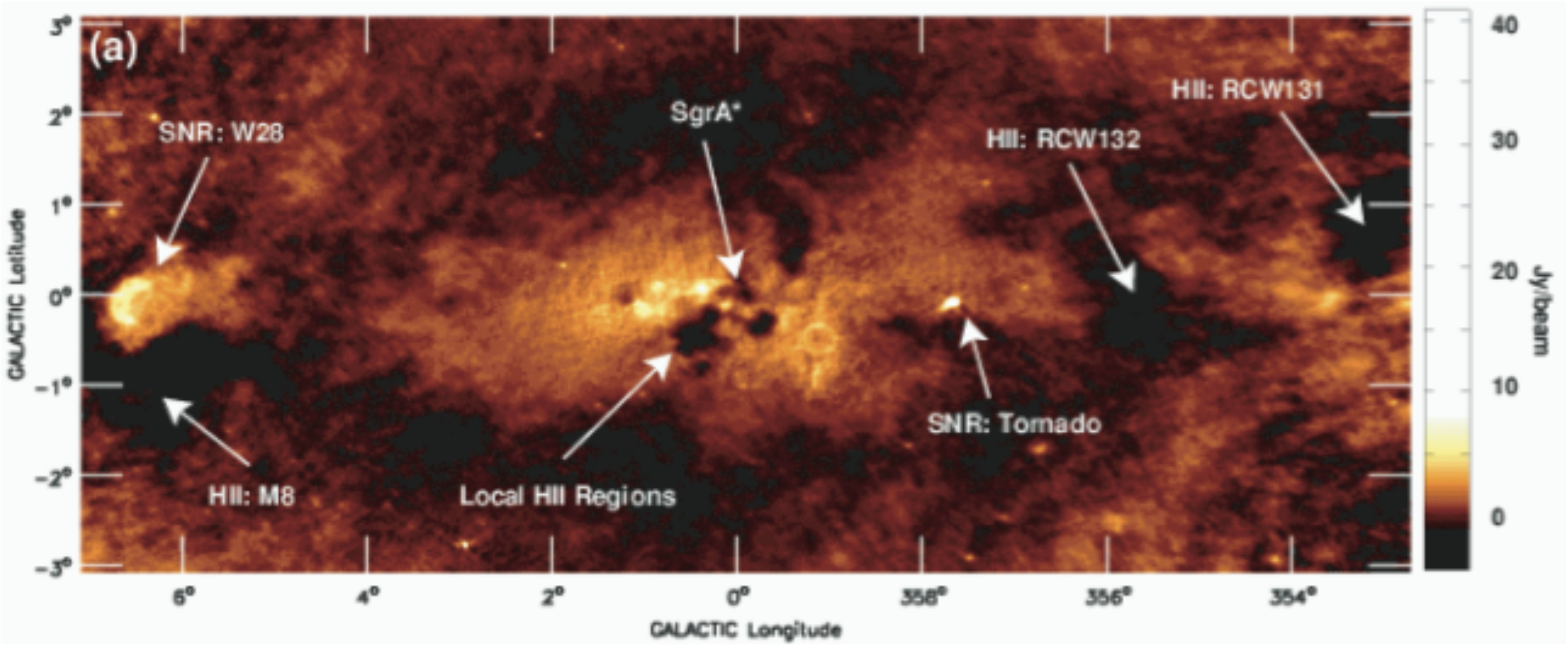
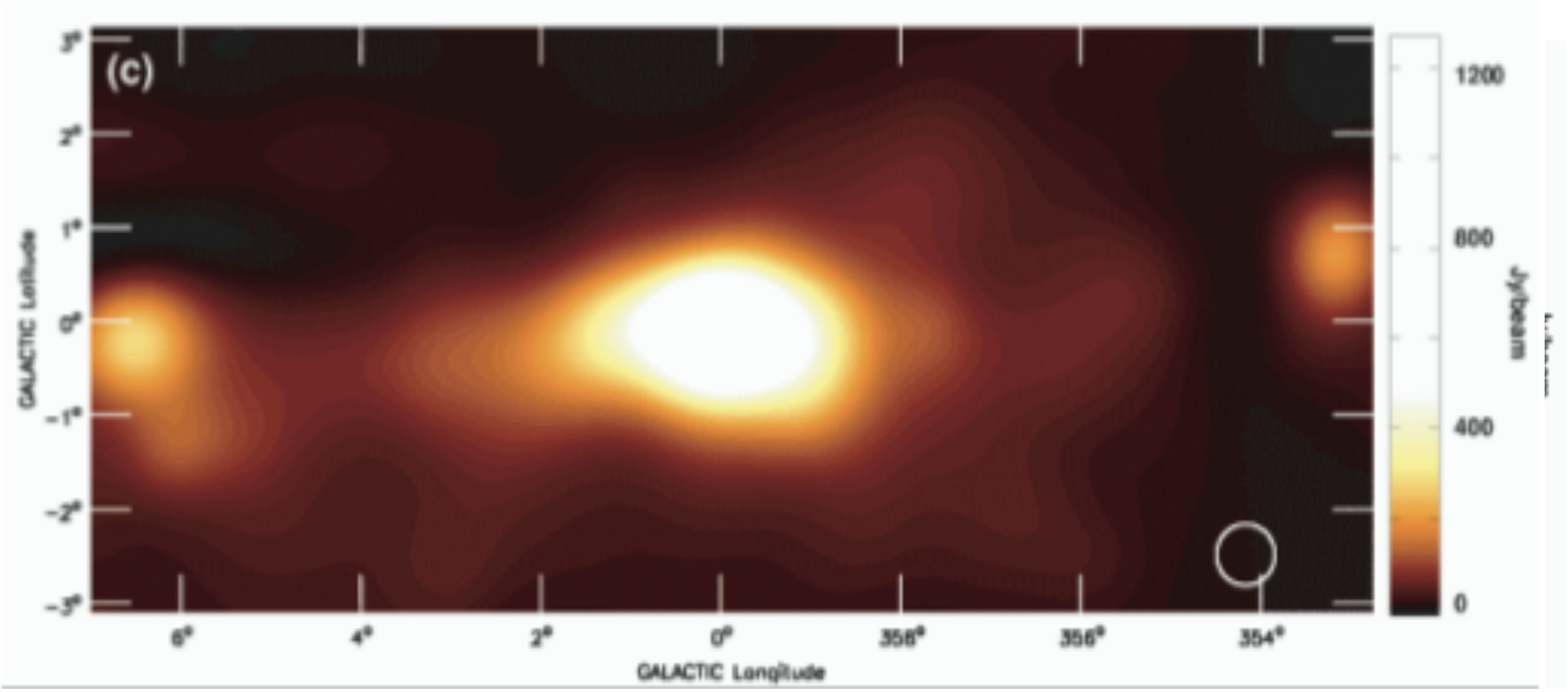


Diffuse, non-thermal RC



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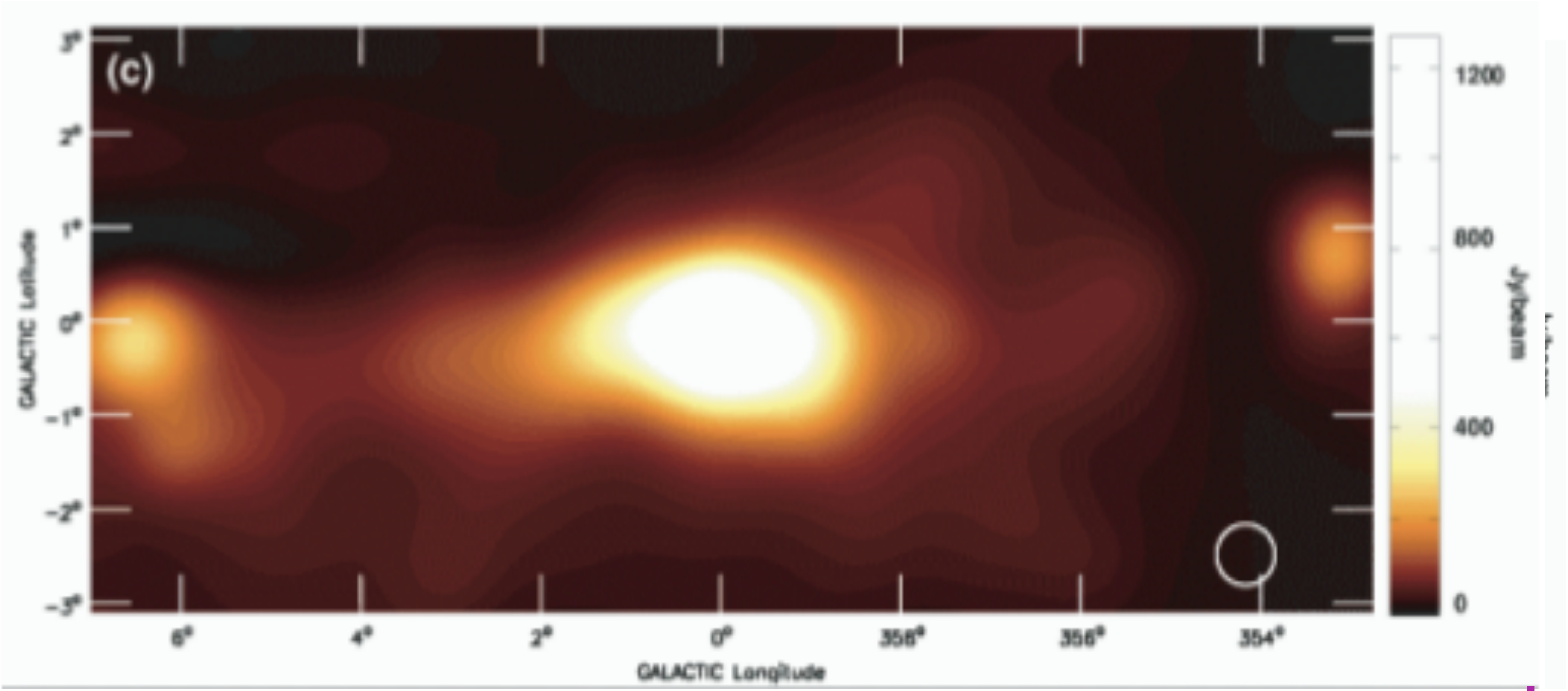
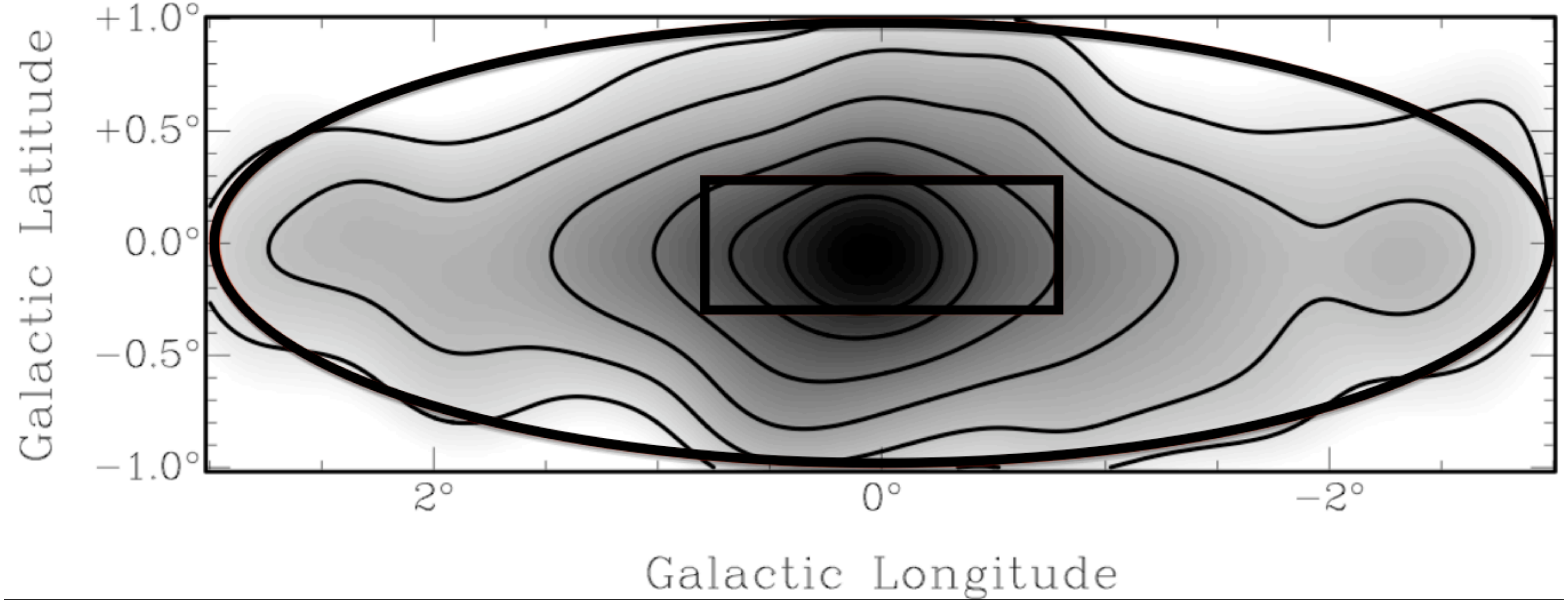


LaRosa et al. 2005

‘DNS’



10 GHz Nobeyama data - spectrum is non-thermal up to 10 GHz

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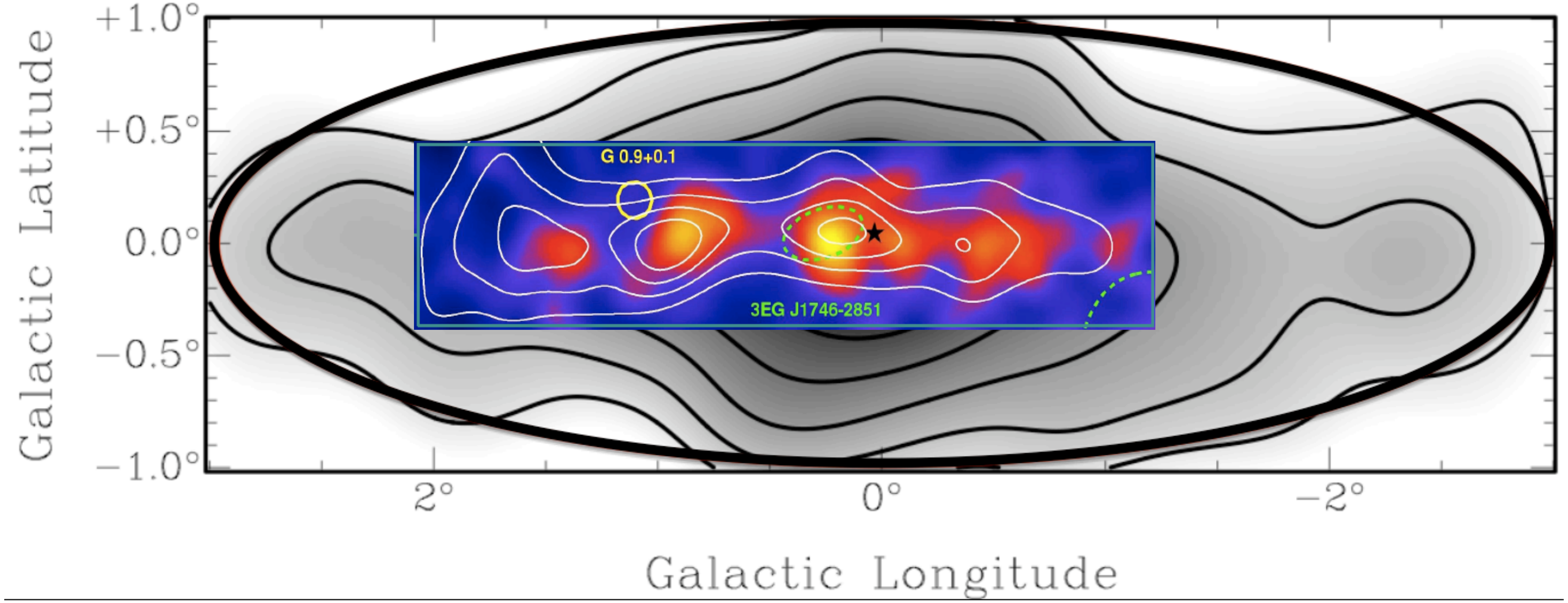

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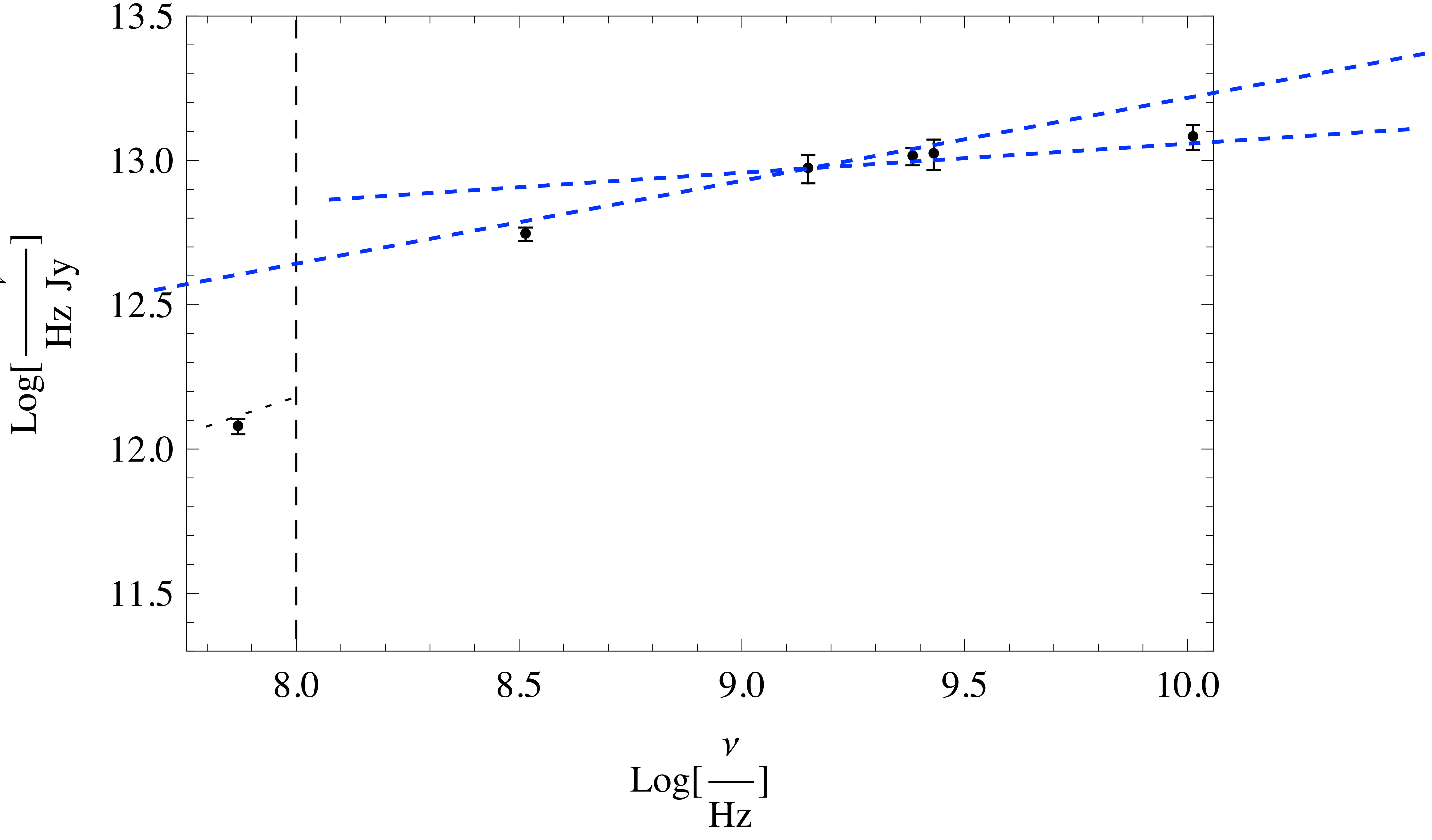

13.5
13.0
12.5
12.0
11.5
8.0
8.5
9.0
9.5
10.0
$\mathrm{Log}[\frac{\nu F_\nu}{\mathrm{Hz\ Jy}}]$
$\mathrm{Log}[\frac{\nu}{\mathrm{Hz}}]$

Δγ ~ -0.5

Electron Cooling

- Given a "thick target", a population of electrons will cool via synchrotron, bremsstrahlung and ionization, with cooling rates:

$$\frac{dE}{dt}_{\rm ioniz} = -5.5\times 10^{-17}\left(\frac{n_{H_2}}{1\ {\rm cm}^{-3}}\right)\times(\ln\gamma + 6.85),$$

$$\frac{dE}{dt}_{\rm bremss} = -1.5\times 10^{-15}\left(\frac{E}{1\ {\rm GeV}}\right)\times\left(\frac{n_{H_2}}{1\ {\rm cm}^{-3}}\right).$$

$$\frac{dE}{dt}_{\rm synch} = -1.0\times 10^{-12}\times\left(\frac{B_\perp}{1\ {\rm gauss}}\right)^2\times\gamma^2,$$

Resultant steady-state population

$$\frac{dn_e}{dE_e}(E_e,\vec{r}) = \frac{\int_{E_e}^{m_\chi c^2} dE'_e Q(E'_e,\vec{r})}{-dE_e(E_e)/dt}$$

slide courtesy David Jones

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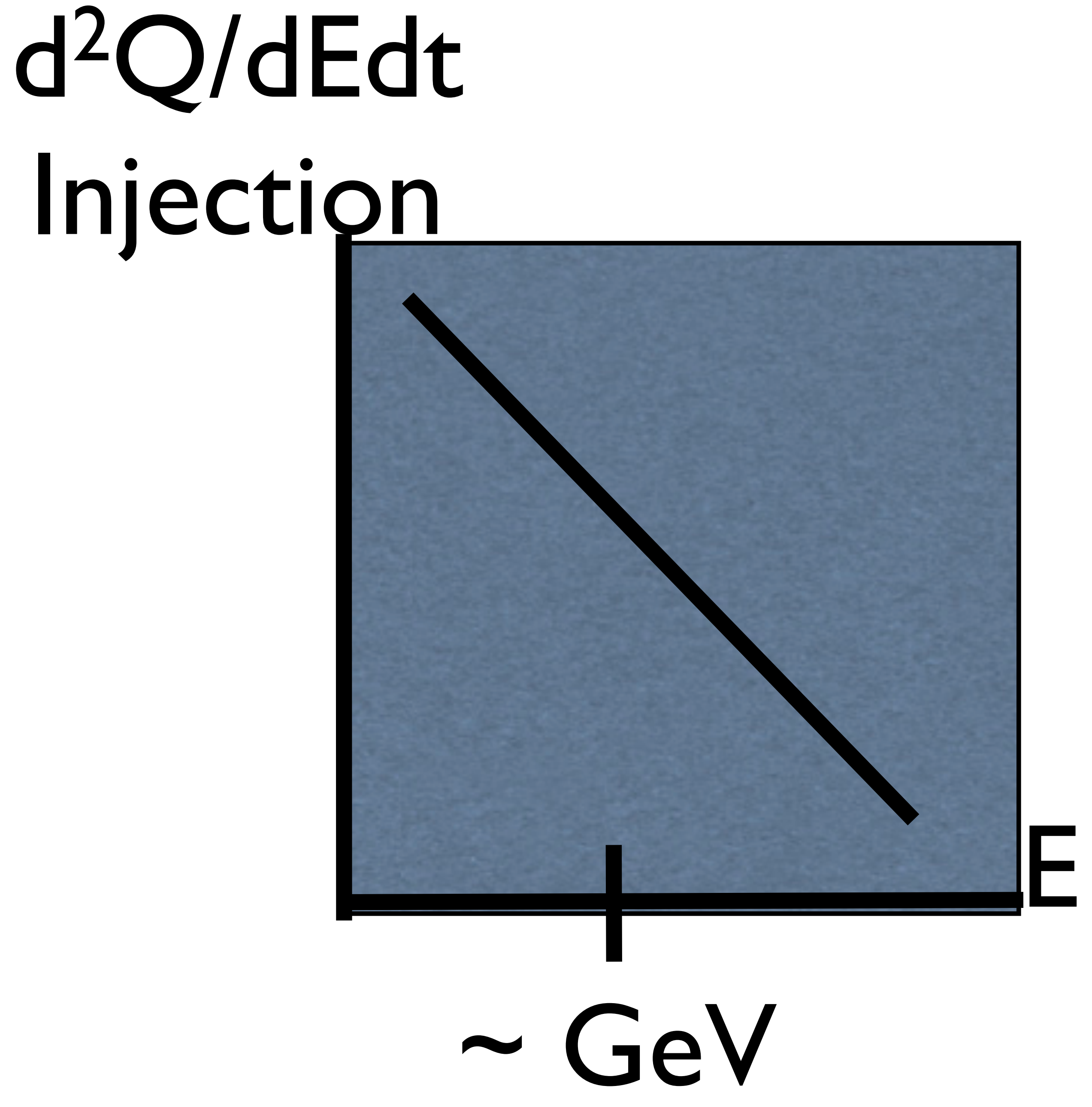
slide courtesy David Jones

Electron Cooling



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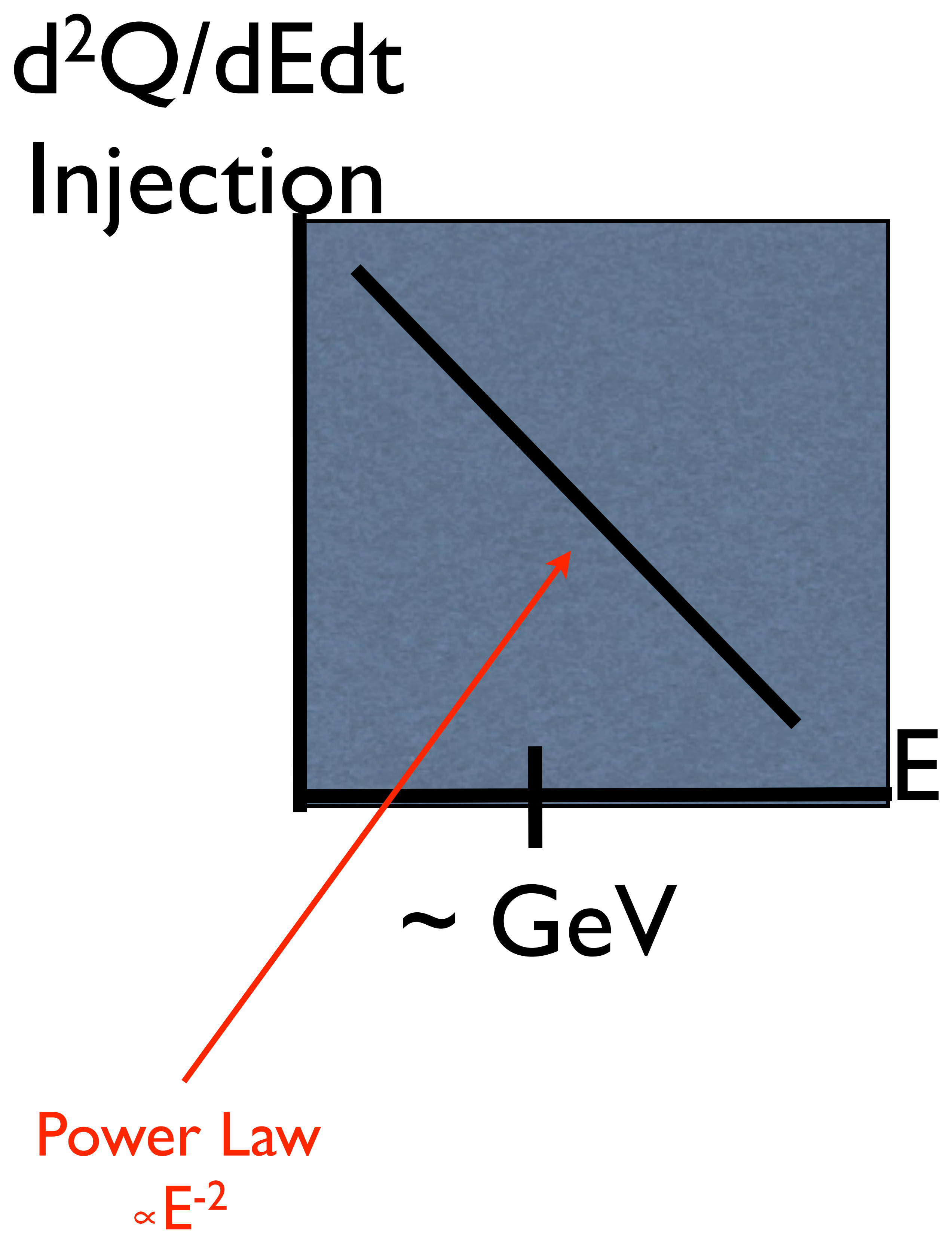

slide courtesy David Jones

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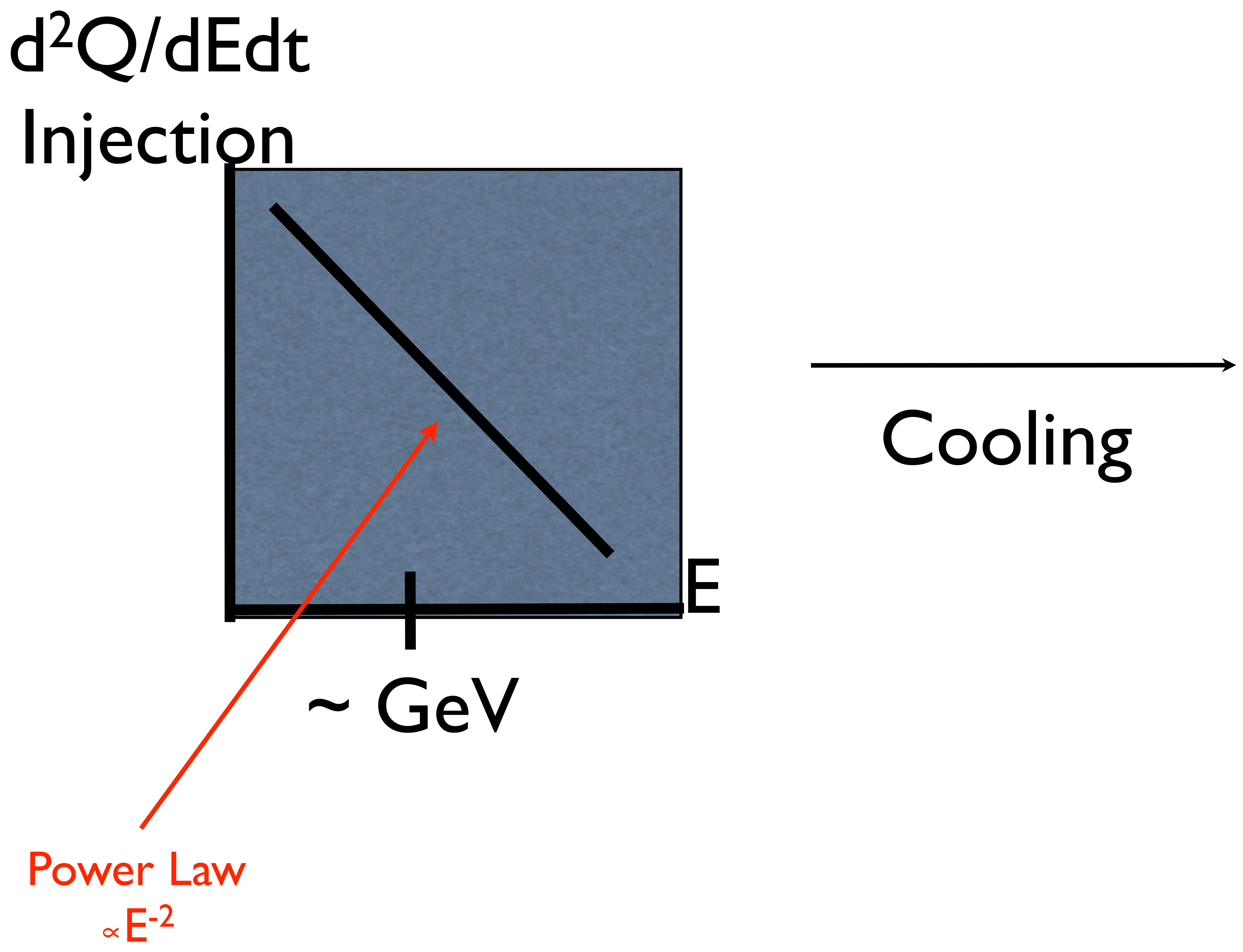

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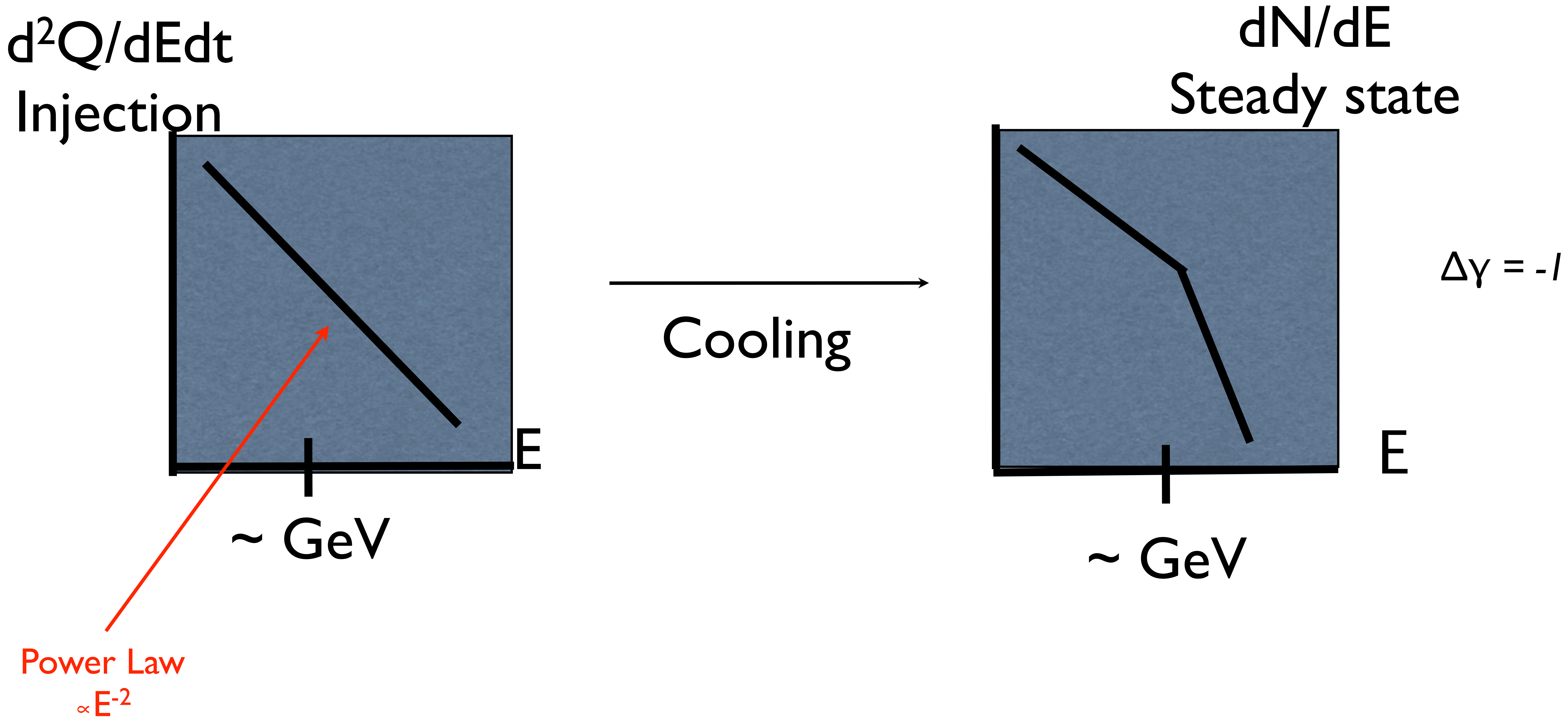

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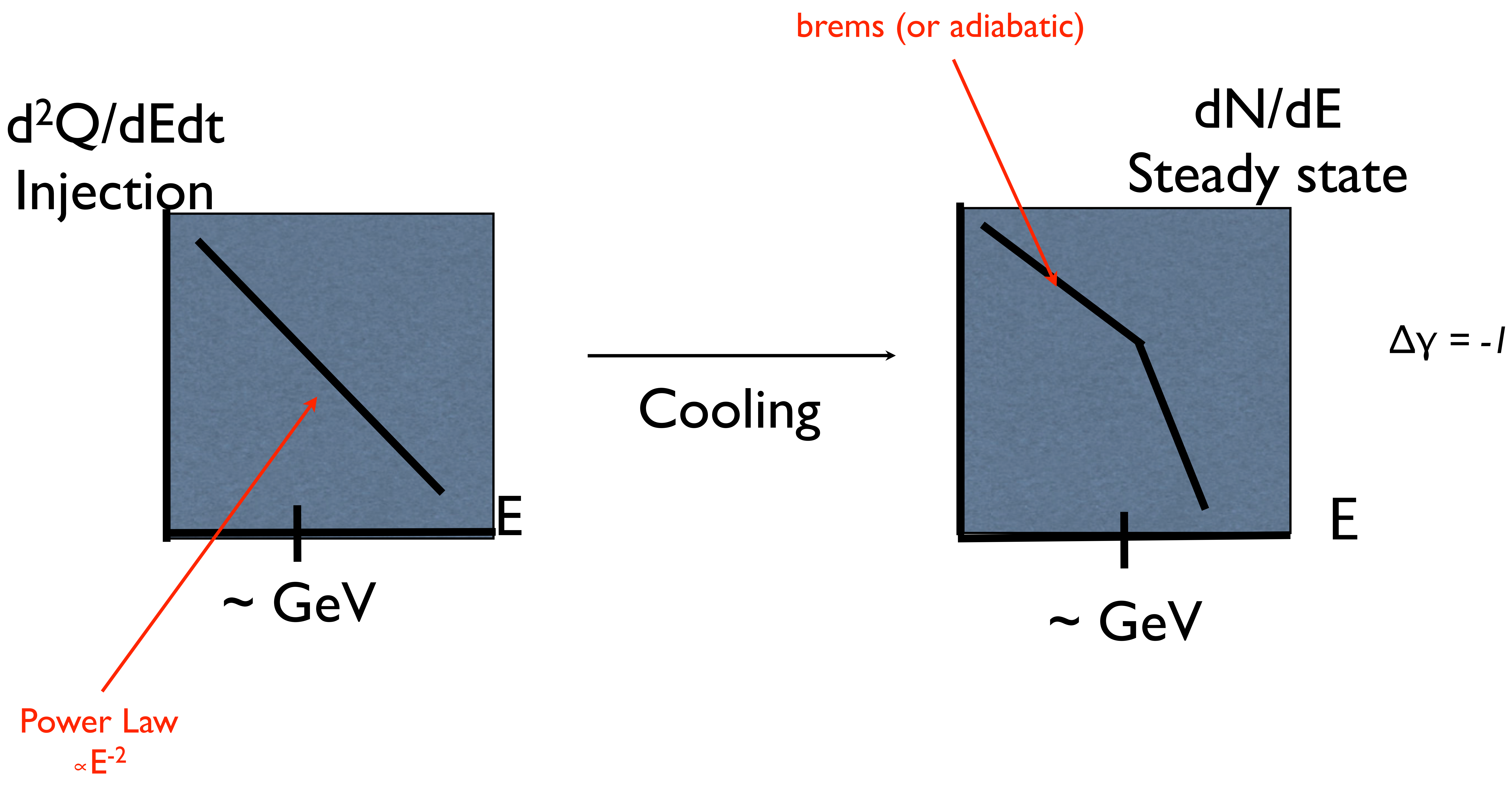

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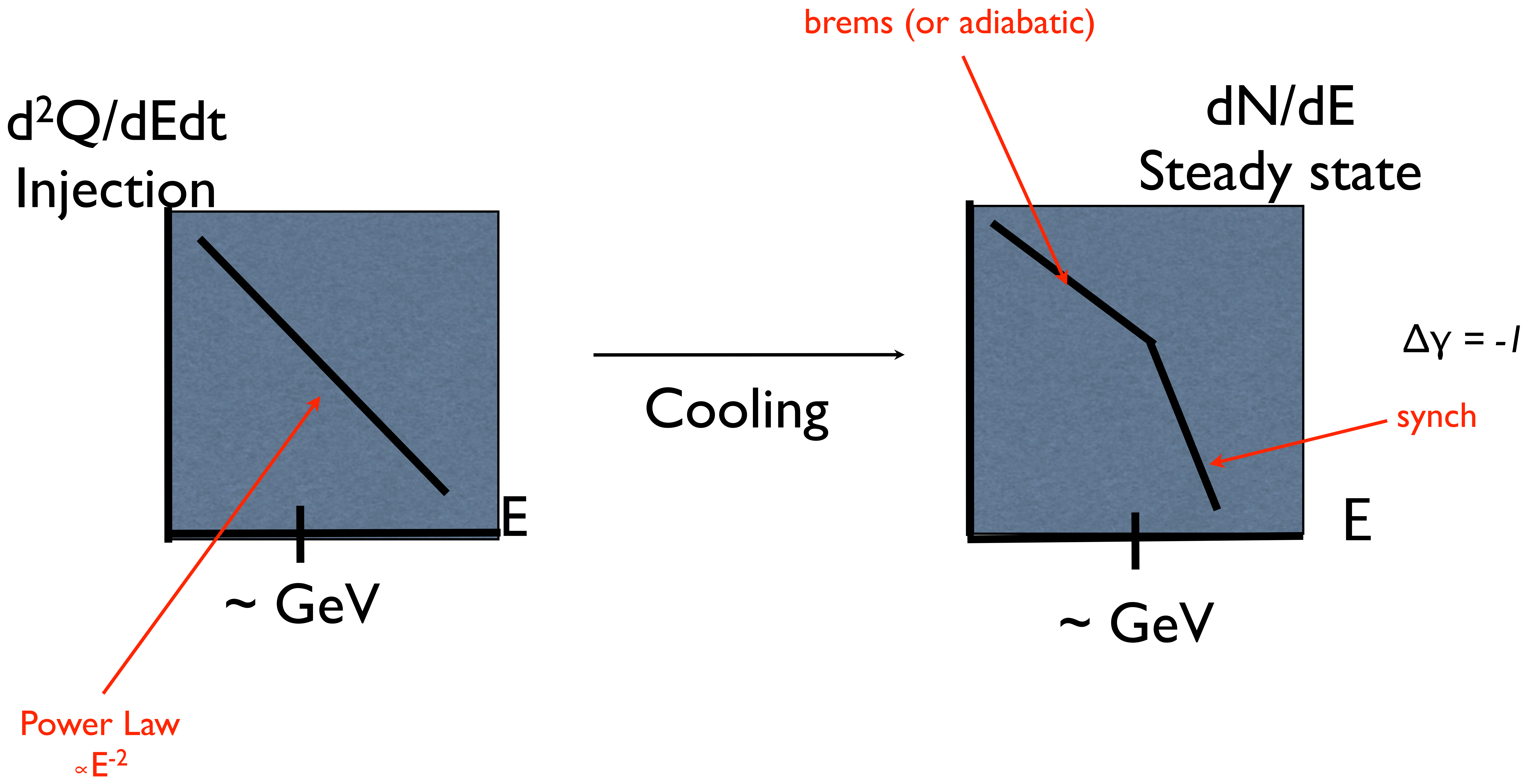

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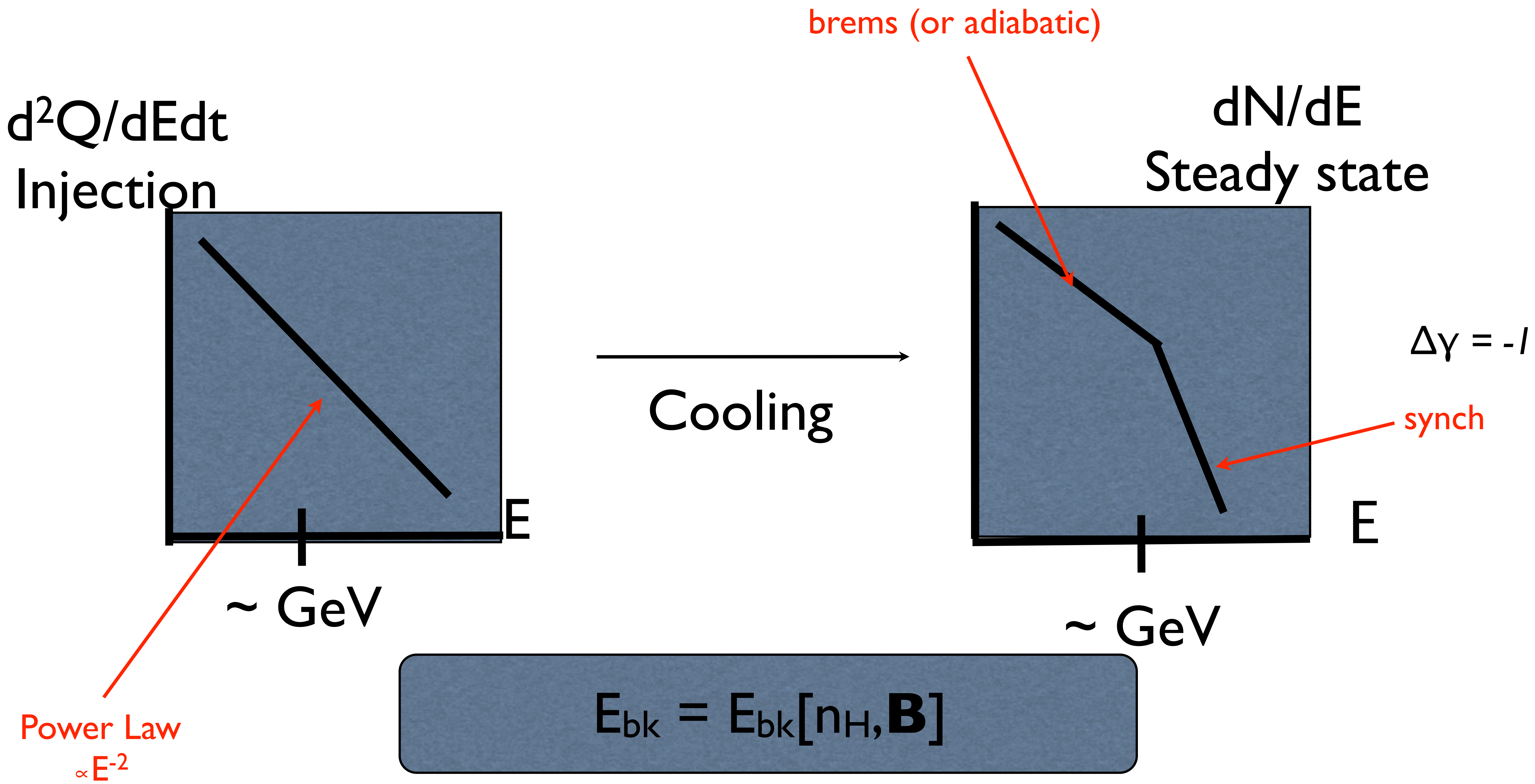
Electron Cooling



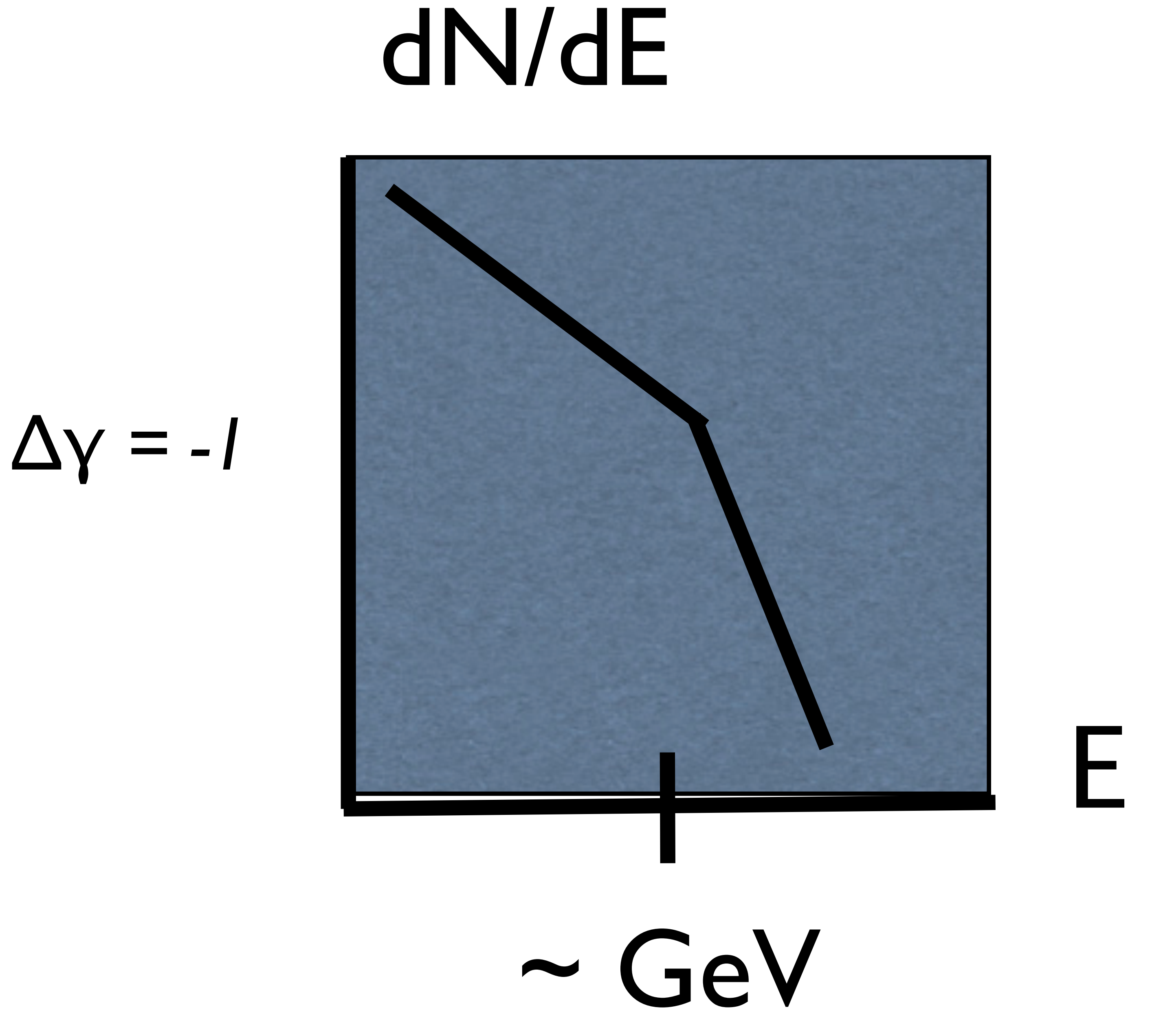
$E_{bk} = E_{bk}[n_H, \mathbf{B}]$

slide courtesy David Jones

Synchrotron Spectrum of Cooled Electrons

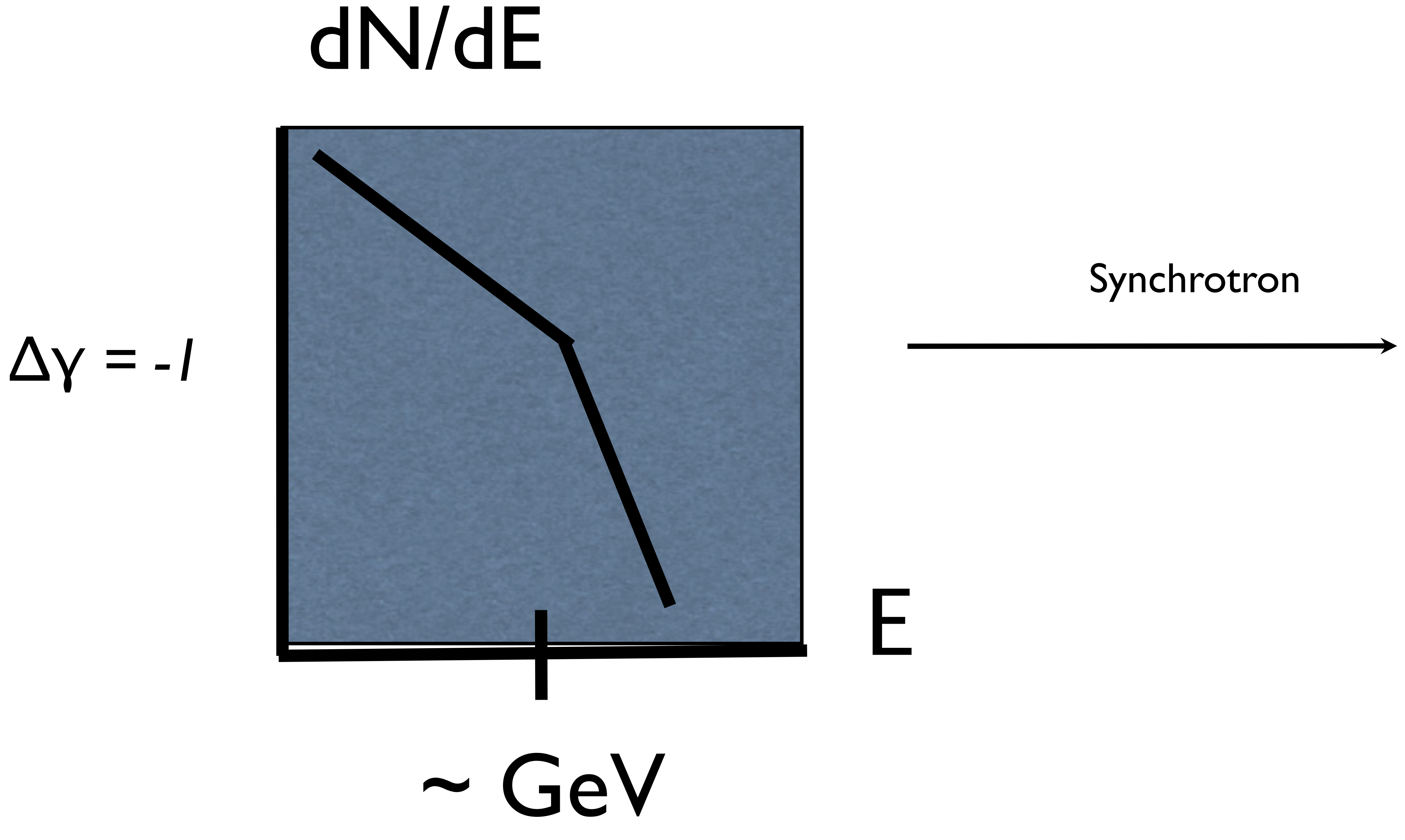
slide courtesy David Jones

Synchrotron Spectrum of Cooled Electrons



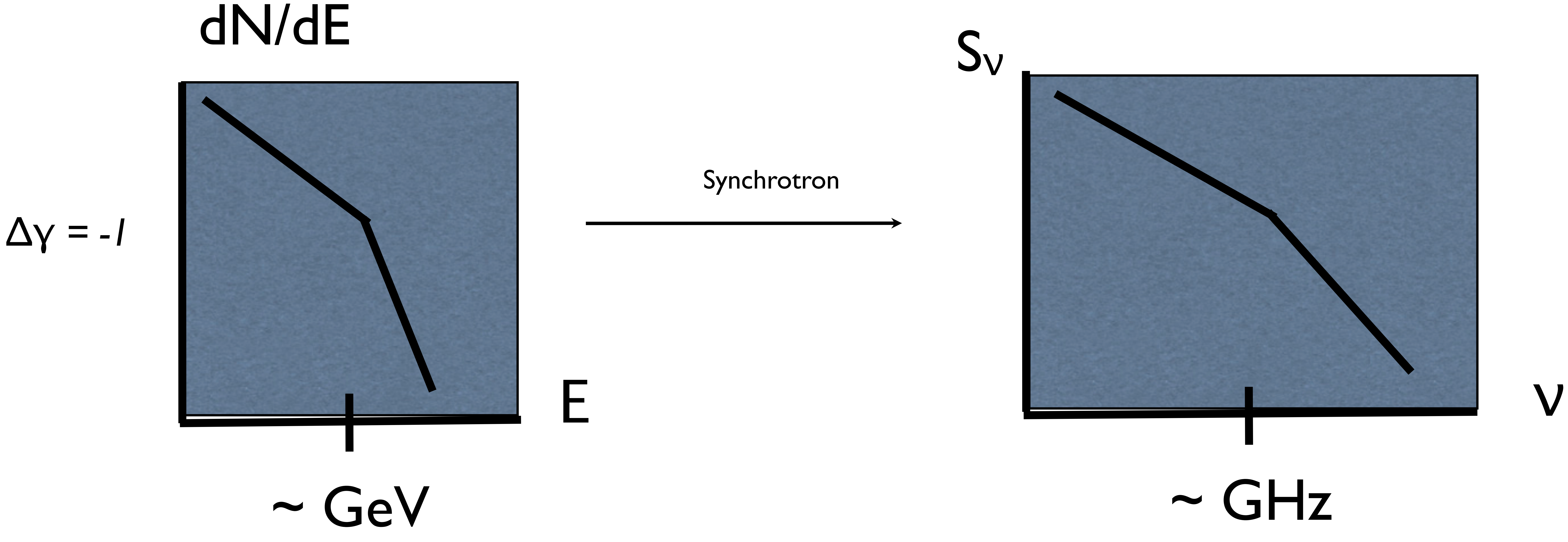
slide courtesy David Jones

Synchrotron Spectrum of Cooled Electrons



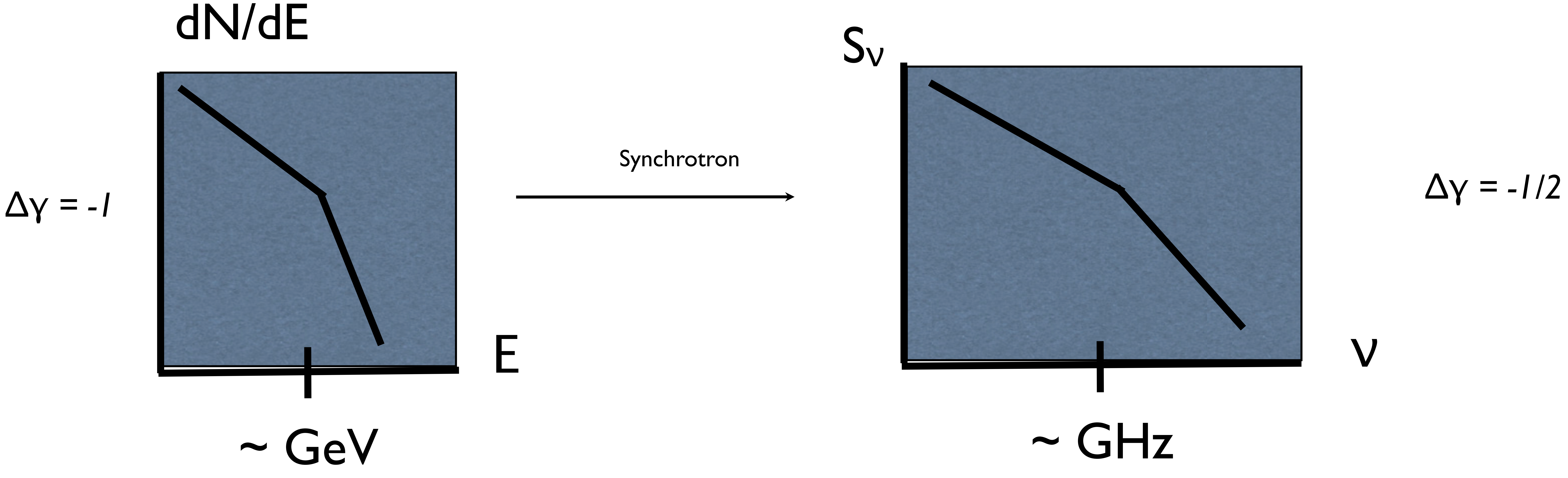
slide courtesy David Jones

Synchrotron Spectrum of Cooled Electrons



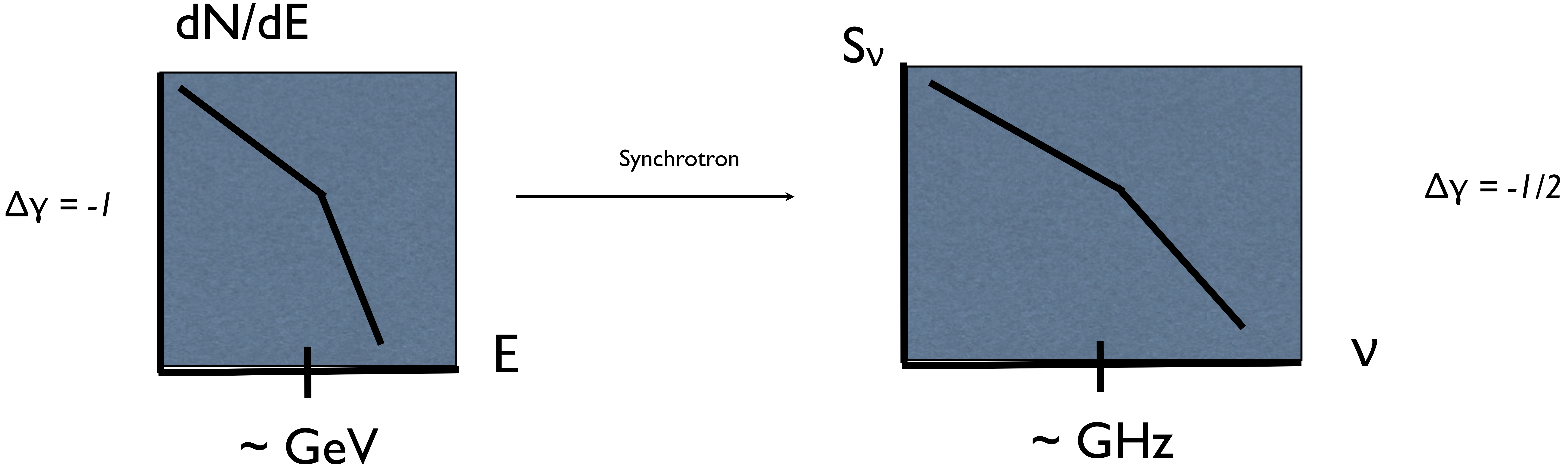
slide courtesy David Jones

Synchrotron Spectrum of Cooled Electrons



slide courtesy David Jones

Synchrotron Spectrum of Cooled Electrons



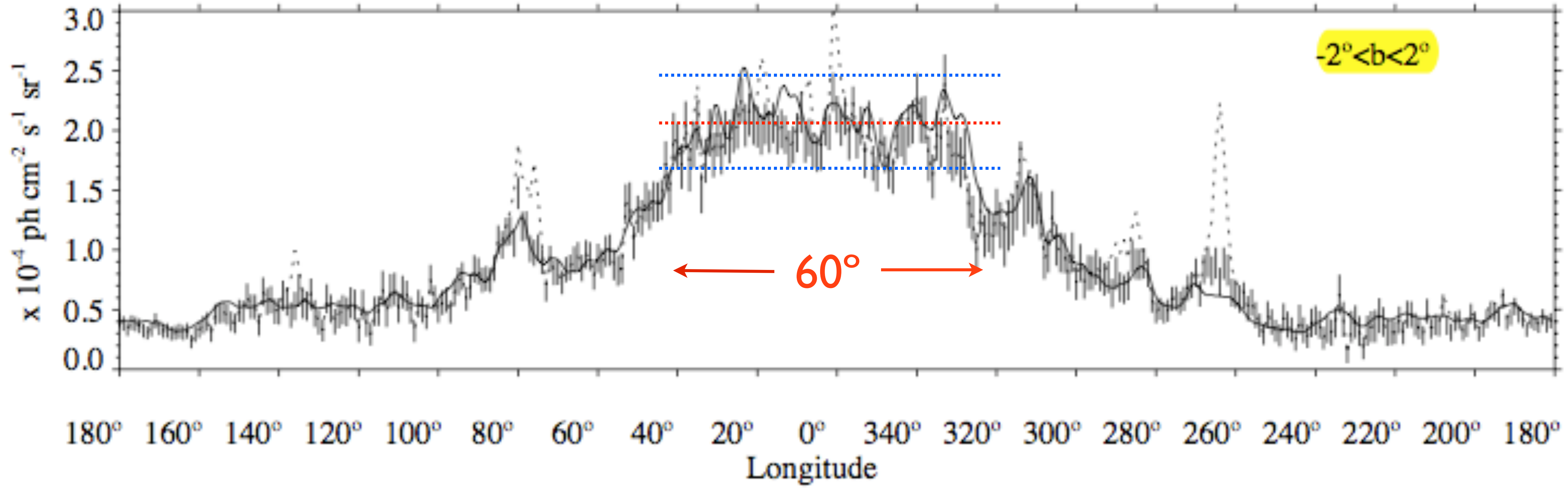
$\nu_{bk} = \nu_{bk}[n_H, \mathbf{B}]$

slide courtesy David Jones

- know n_H
- know steady-state (cooled) electron population
- ➡can predict bremsstrahlung emission by same electron population
- electrons synchrotron radiating at ~GHz frequencies are bremsstrahlung radiating at ~GeV energies
- sub-dominant contribution from IC too

EGRET (GeV) Data

imply upper limit on the integral γ-ray intensity of
E > 300 MeV, | l | < 30.0° and | b | < 2.0° of 1 x 10^4 cm^{-2} s^{-1} sr^{-1}



300 MeV - GeV

Hunter et al. 1997

Bottom Line...

Bottom Line...

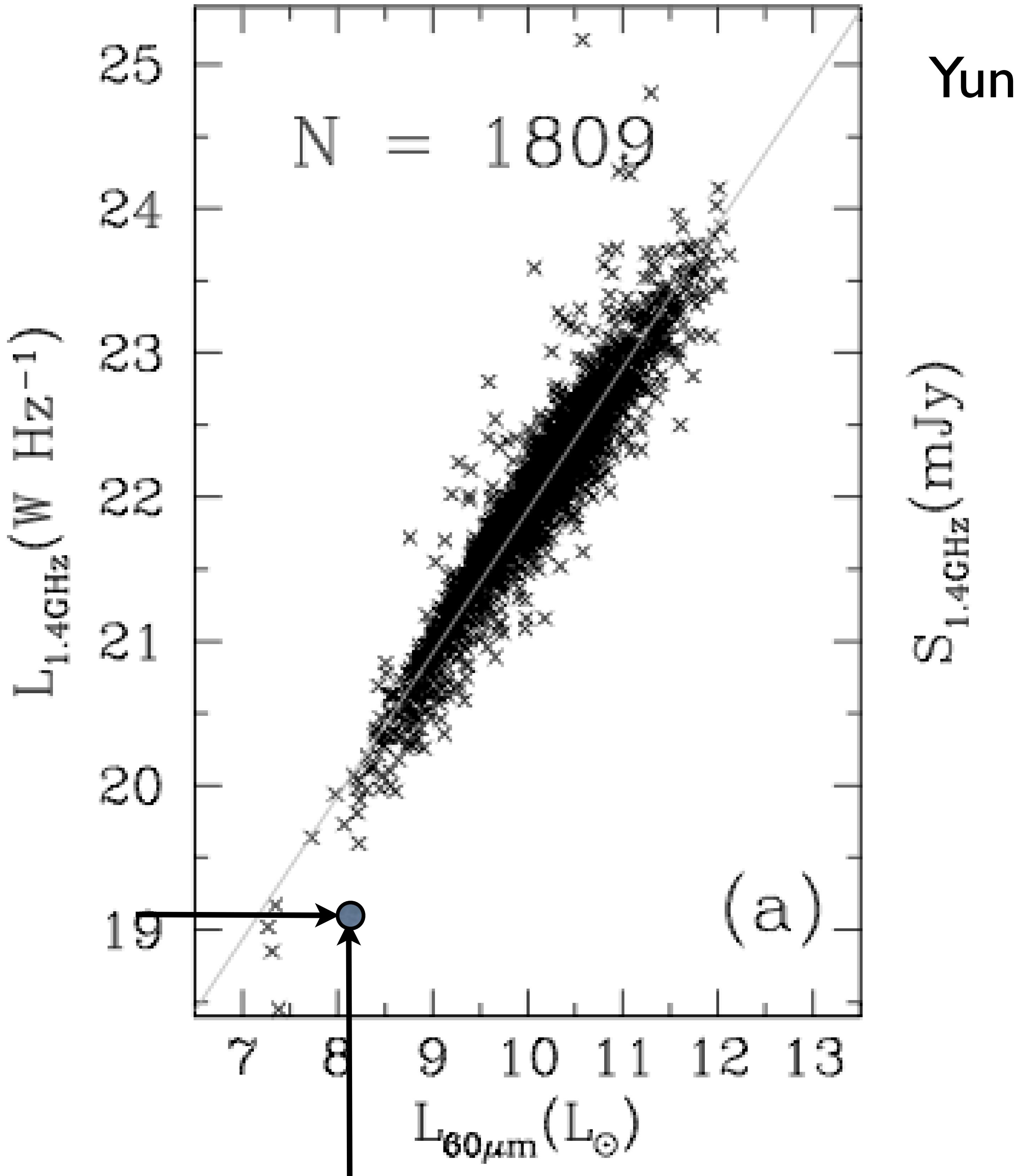
...GC magnetic field is > 50 μG at 2σ confidence

Current Research 2

There is a 'super-wind' outflow from the GC

Far Infrared-Radio Continuum Correlation

$L_{1.4\,GHz} = 1.2 \times 10^{19}$ Watt/Hz



$L_{60\mu m} = 1.3 \times 10^{8}\ L_\odot$

Yun et al. 2001 ApJ 554, 803 fig 5

RC in deficit wrt expectation from FIR

GC is 1 dex (~4σ) off correlation

i.e. **GHz RC emission of HESS region only ~10% expected**

Sidebar: origin of FIR-RC?

- correlation between FRC and RC ultimately tied back to massive star formation (Voelk 1989)
- massive stars → UV → (dust) → IR
- massive stars → supernovae → SNRs → acceleration of CR e's → (B field) → synchrotron

FIR-γ-ray Scaling?

- SNR also accelerate CR p's (and heavier ions)
- there should exist a global scaling b/w FIR and gamma-ray emission from region (Thompson et al. 2007): $L_{GeV} \sim 10^{-5} L_{TIR}$ (assuming 10^{50} erg per SN in CRs)
- Given scaling (or SN rate), **TeV emission of GC only about 1% expected**

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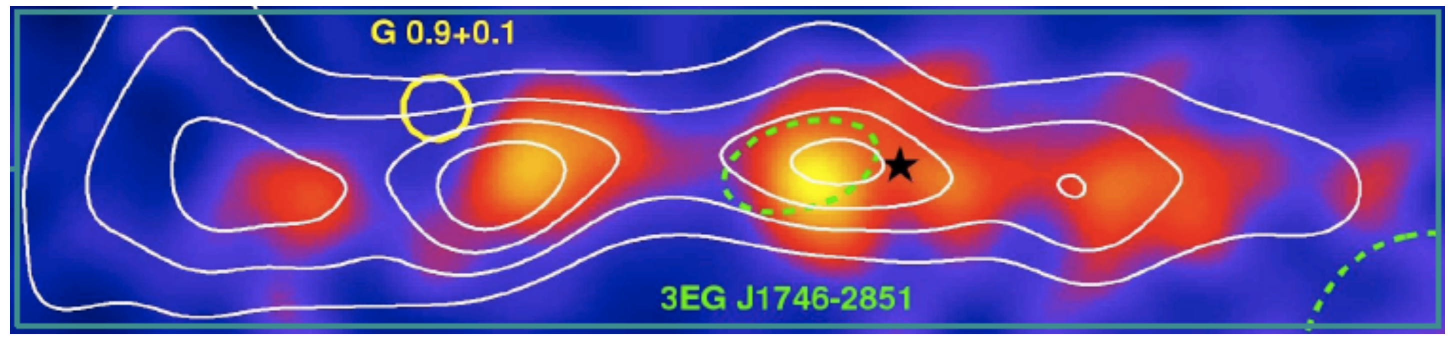


Why is GC's non-thermal emission much less than expected given its FIR?

- Explanation 1: a star-burst occurred more recently than the lifetime (~10^7 years) of the massive stars which produce most UV and whose lives end in supernovae
- Explanation 2: GC SNRs are intrinsically low-efficiency CR-accelerators
- Explanation 3: some transport process removing non-thermal particles from system

Explanation 1: Starburst?

NO:

- Star-formation history of GC is a subject of debate and we expect stochastic variation in SFR at some level
- BUT stellar population studies show GC star-formation has been sustained over long timescales (2 Gyr) at more-or-less current rate (Figer et al 2004)

Explanation 2: Low efficiency of SN as CR accelerators in GC?

- NO: our detailed modelling shows that GC SN act with *at least* typical efficiency as cosmic ray accelerators

Explanation 3: CR Transport

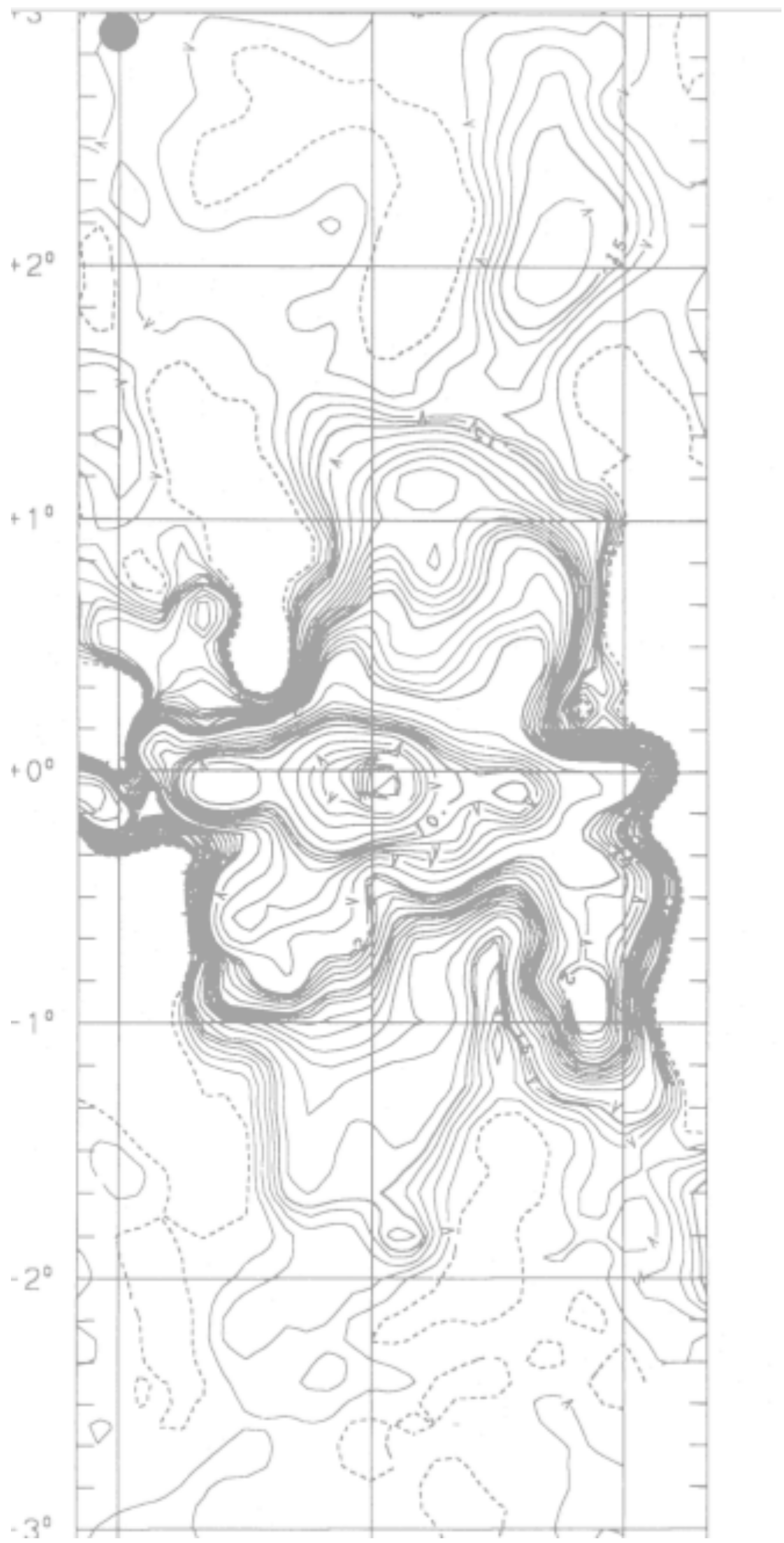
- Flat spectrum of is-situ electron and proton population → transport is advective not diffusive, i.e. via a *wind*
- [contrast situation in Galactic plane]
- there is much prior evidence for such a wind

GC Wind Evidence

- Radio continuum studies show extended, non-thermal emission out to 1.2° north of the plane whose spectrum steepens with distance (Law 2010)
- extended NIR emission mirroring radio continuum (Bland-Hawthorn and Cohen 2003)
- X-rays → apparent, diffuse, very hot plasma in inner ~100 pc ... cf. external star-burst systems
- very extended X-ray emission (10's degrees)

HESS TeV data: Aharonian et al 2006

2.7 GHz radio data (unsharp mask)
Pohl, Reich & Schlickeiser 1992



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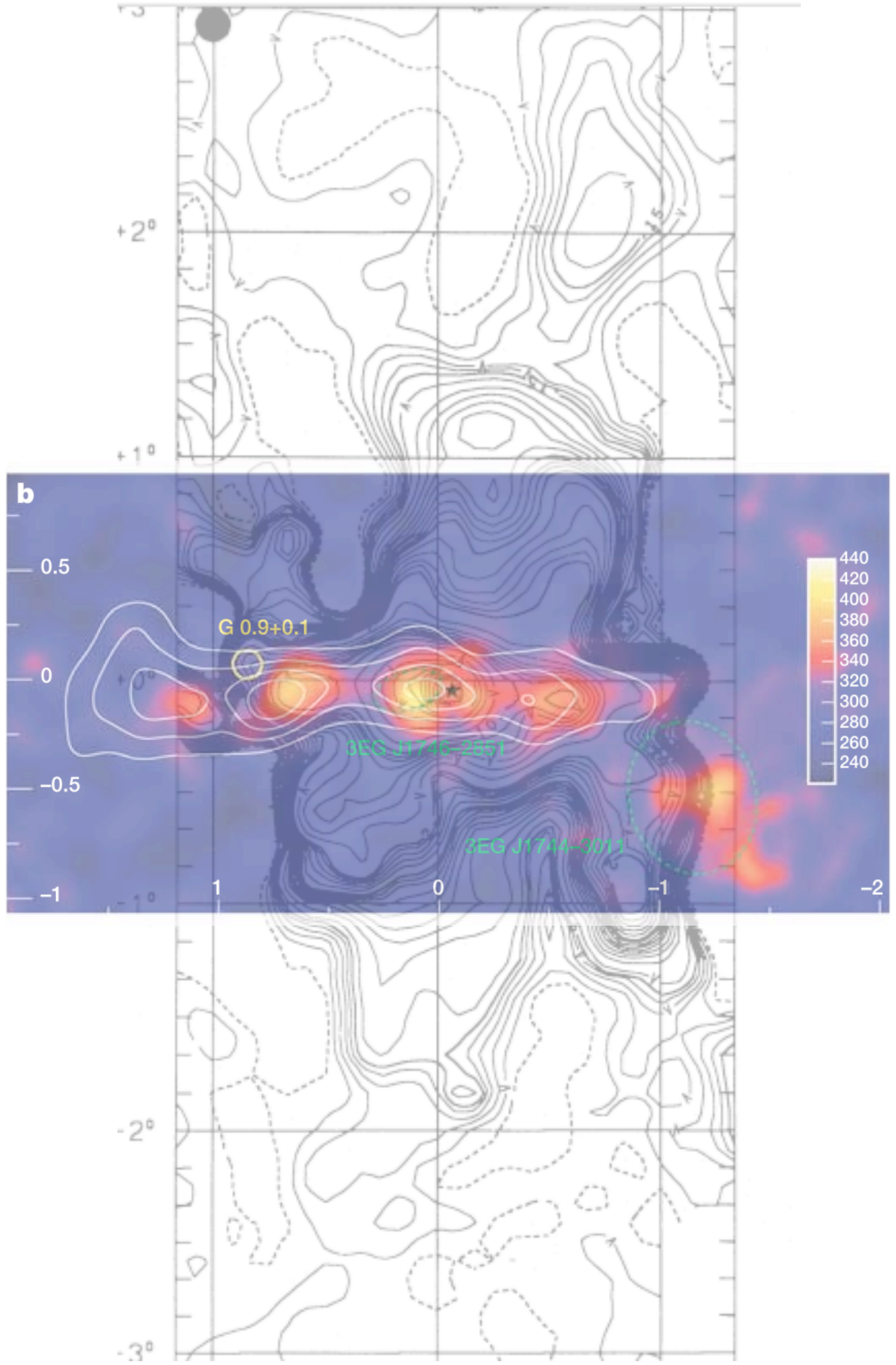

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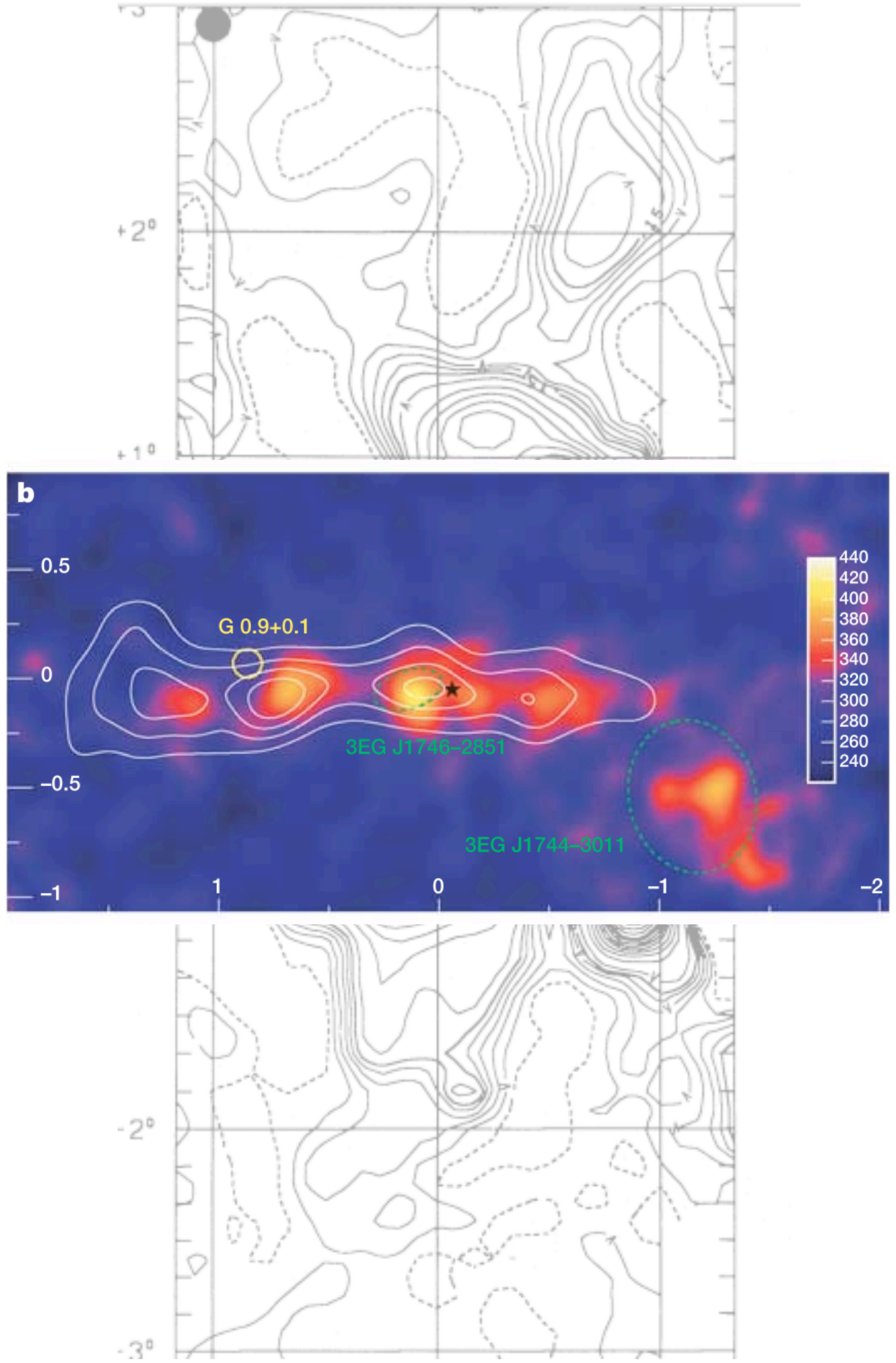

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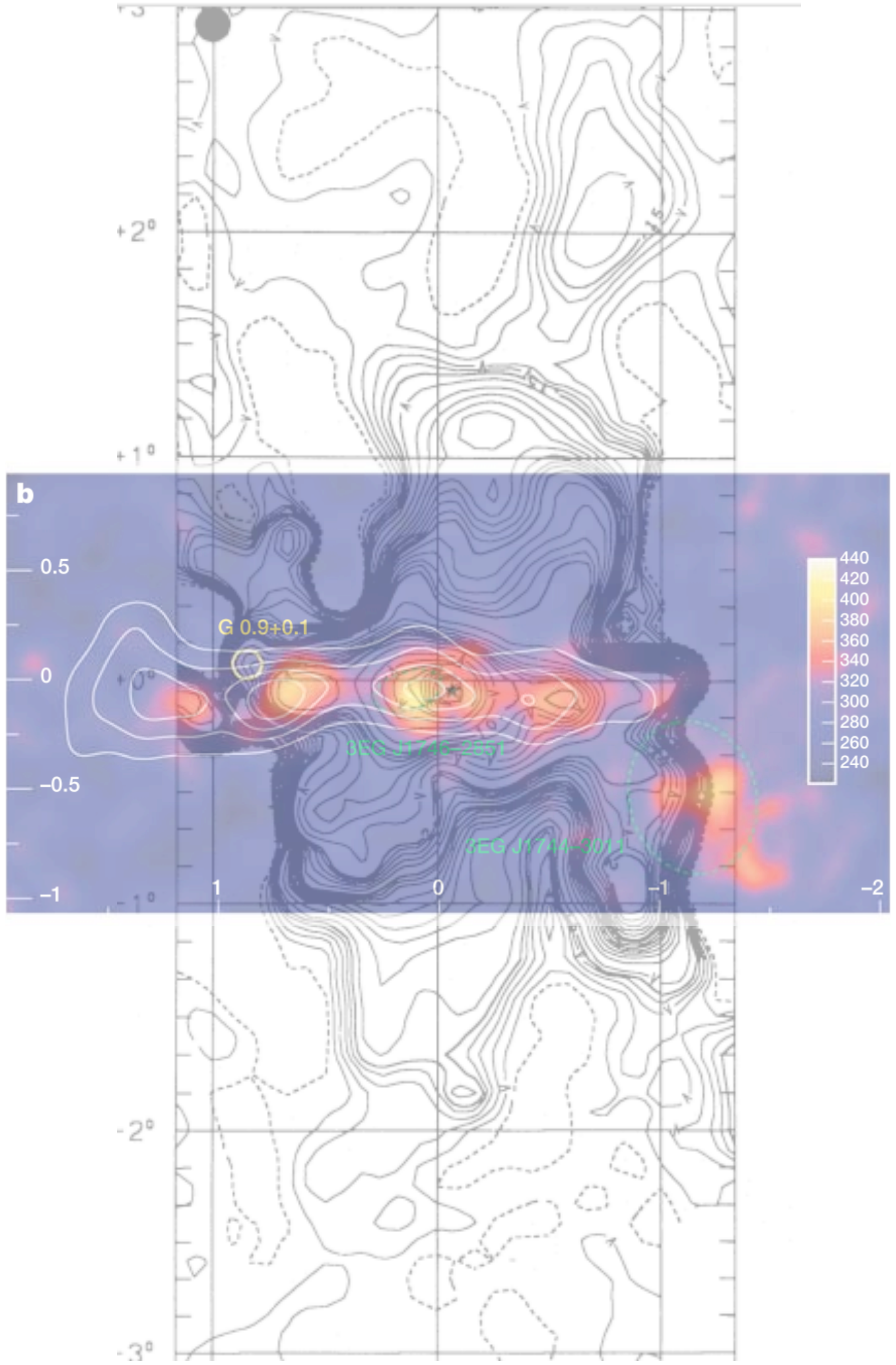
HESS TeV data: Aharonian et al 2006



2.7 GHz radio data (unsharp mask)
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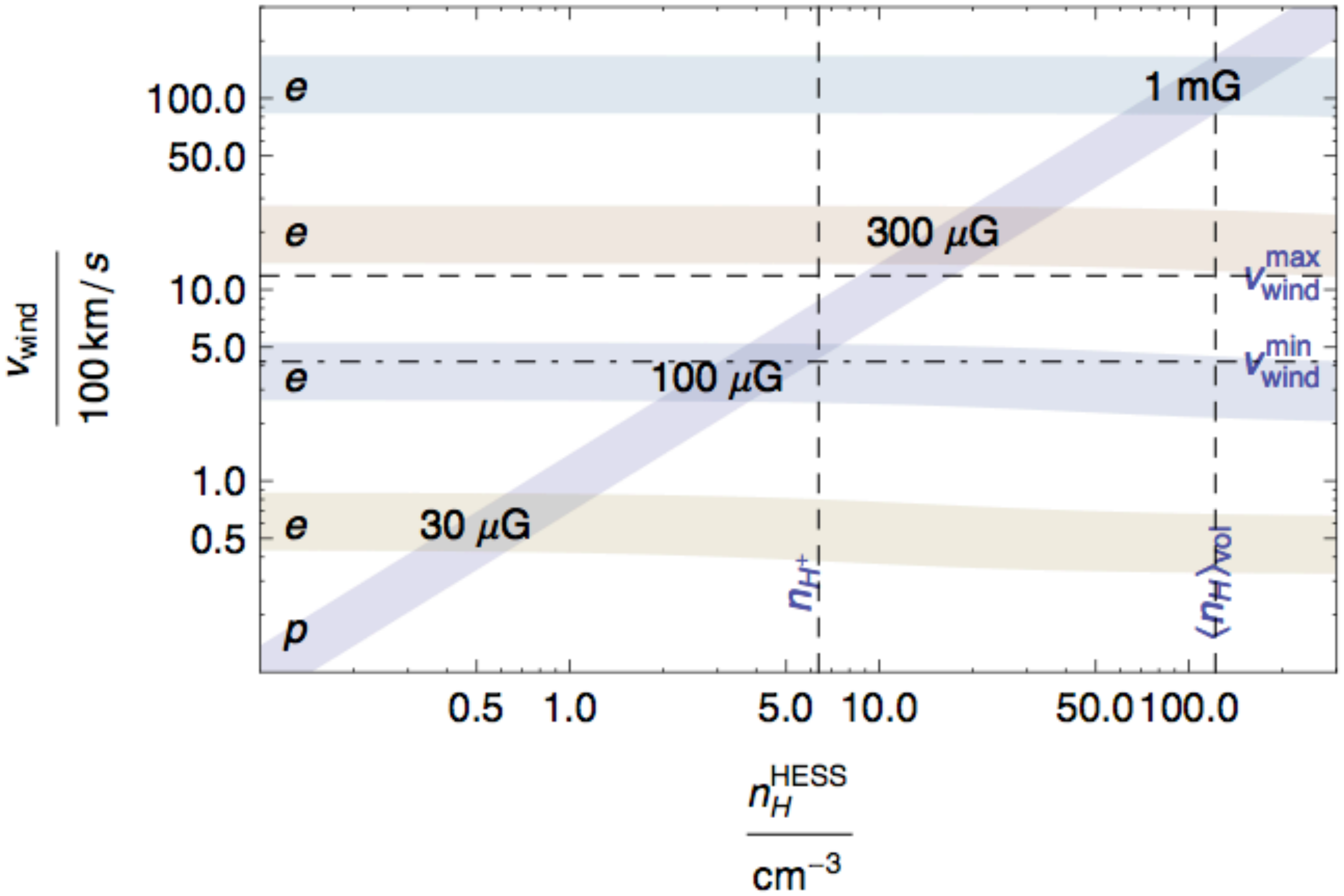
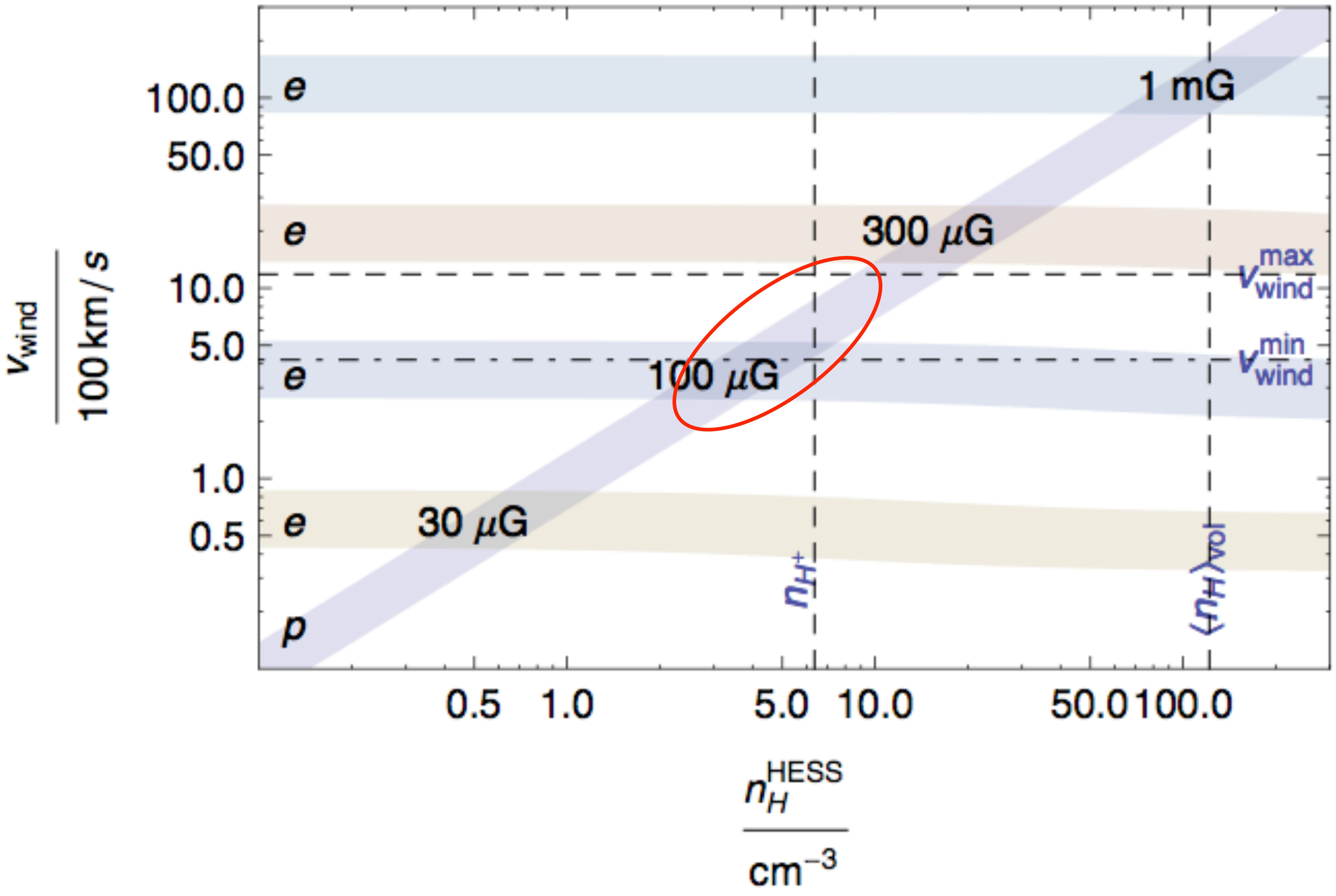
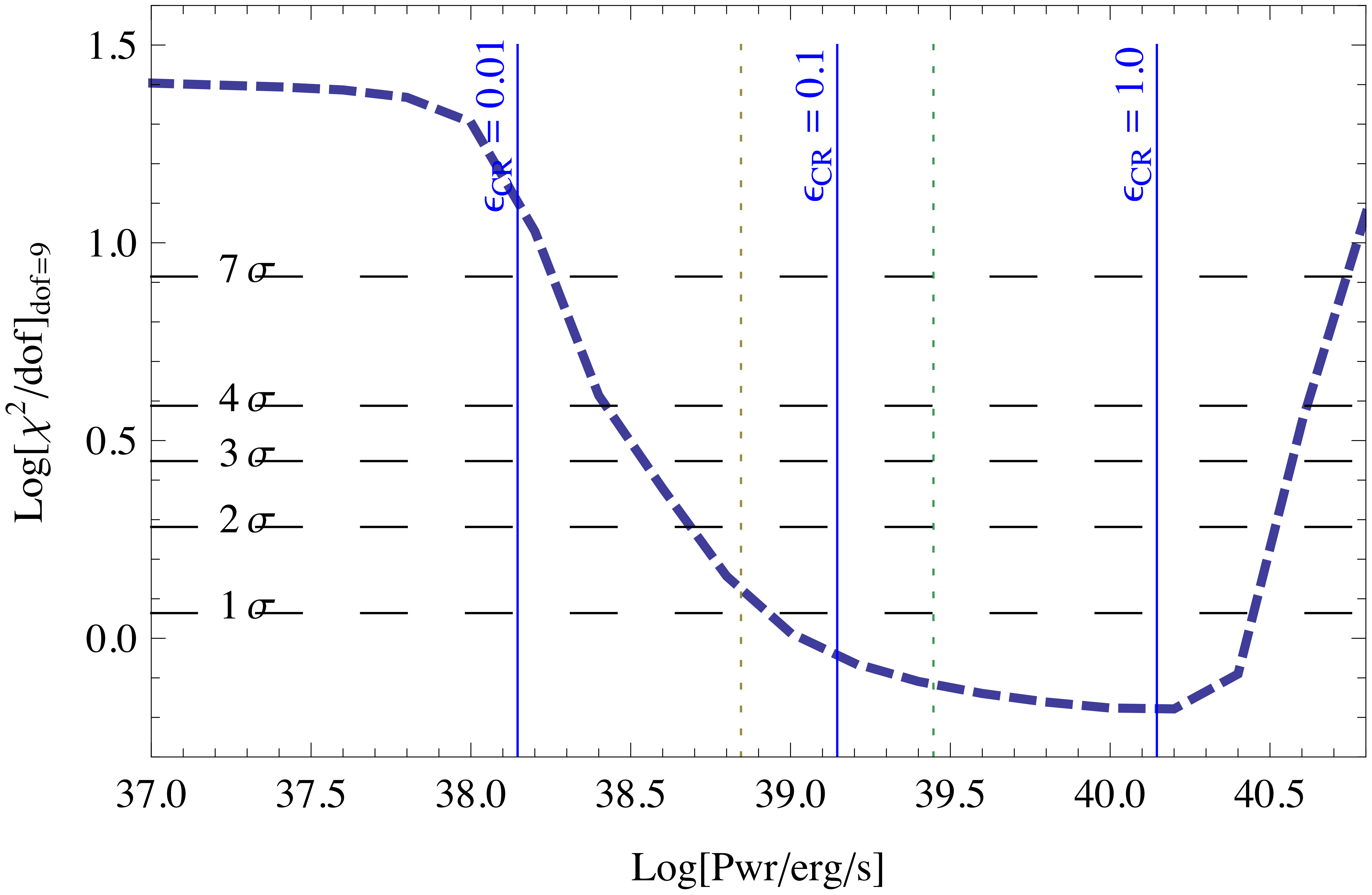
Gas/Wind/Mag. Field



Gas/Wind/Mag. Field



Non-thermal power



Self-consistent modelling confirms ≳10^{39} erg/s *independent* of SN rate estimate

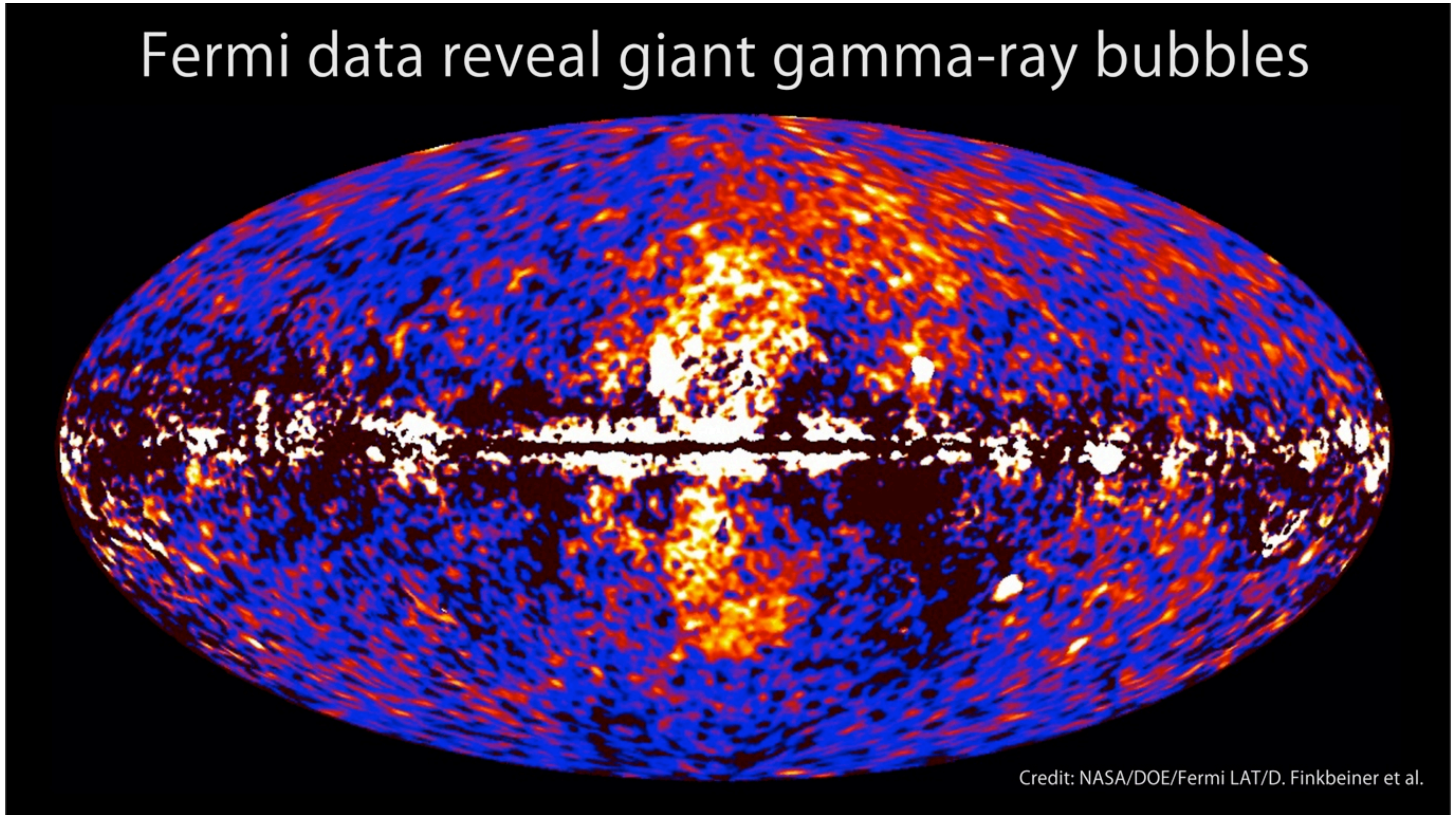
Results of Detailed Modelling

- 'Pure' hadronic scenarios do not work
- 'Pure' leptonic scenarios do not work
- Get good fits for mixed models (GC SNRs are accelerating both ions and electrons)
- Star-formation-related processes launch $\gtrsim 10^{39}$ erg/s in CRs into the Galaxy-at-large on a few 100 km/s wind

...*What are the implications of these CRs?*

Current Research 3
Fermi Bubbles

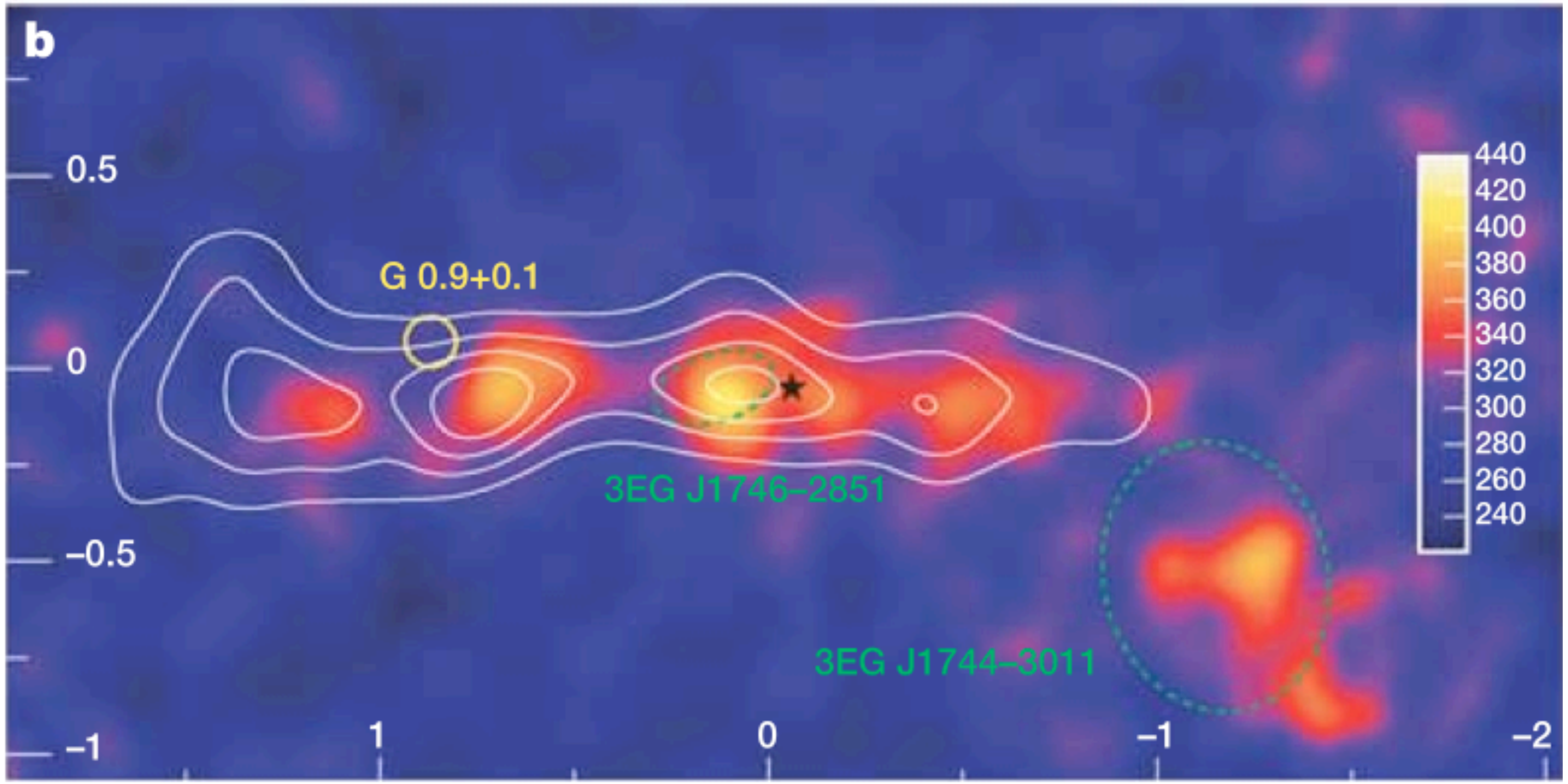
Fermi Bubbles



Su, Slatyer and Finkbeiner 2010 (ApJ)

Fermi Bubbles

[redacted]



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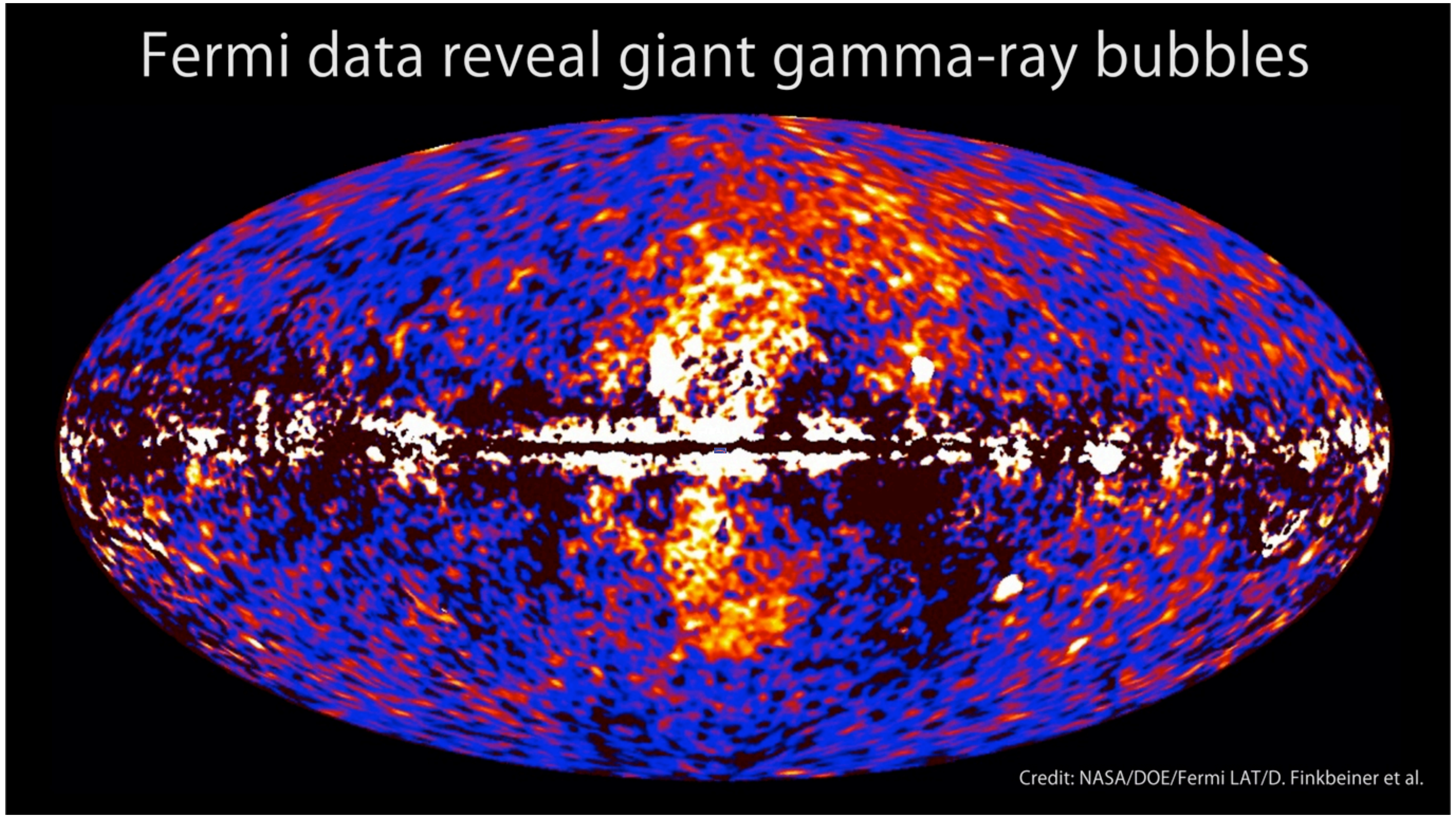


Su, Slatyer and Finkbeiner 2010 (ApJ)

Fermi Bubbles

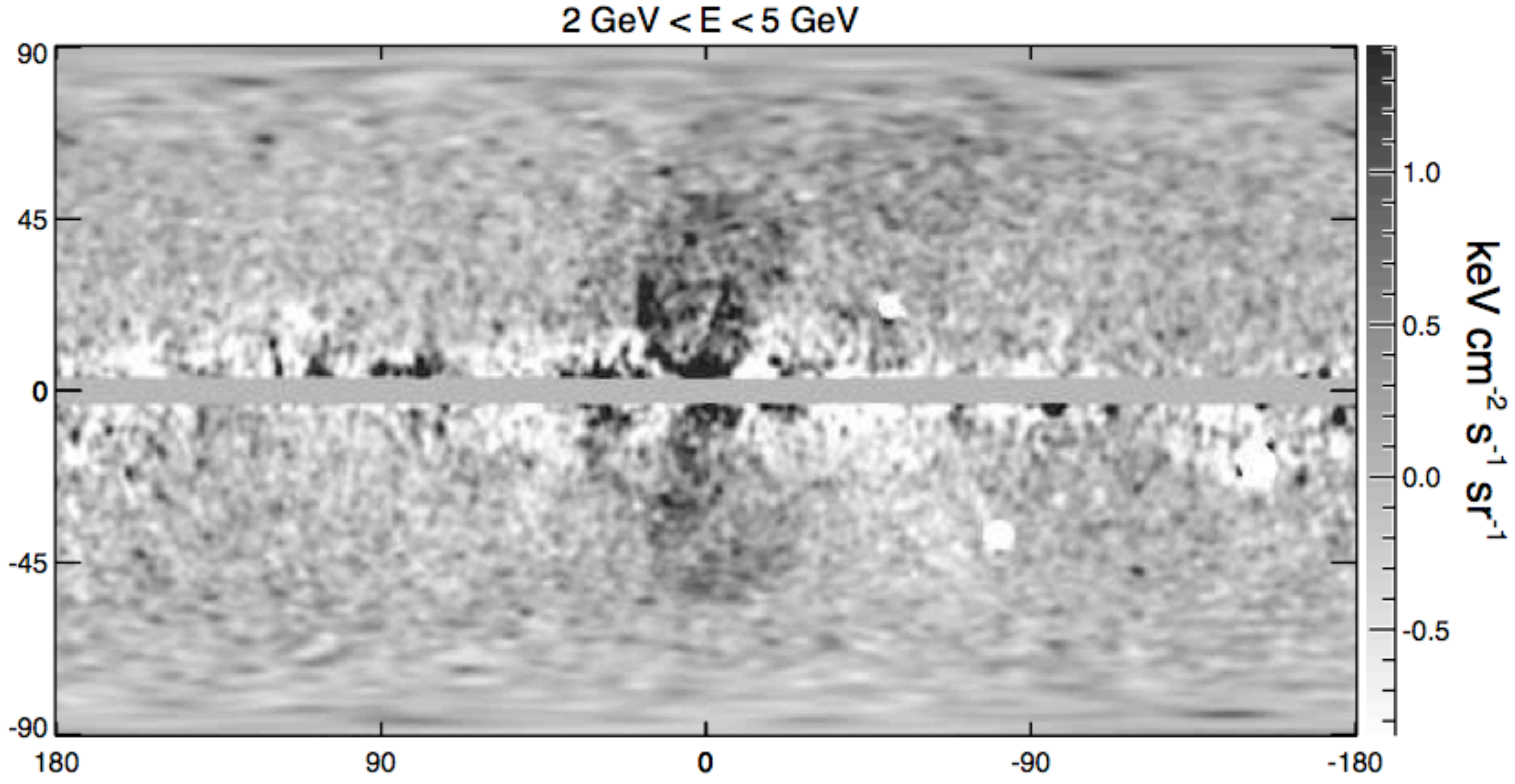
- 4×10^{37} erg/s
- enthalpy $\sim 10^{(56-57)}$ erg
- hard spectrum, but spectral down-break below ~ GeV in SED
- uniform intensity
- sharp edges
- vast extension: ~10 kpc from plane
- something to do with GC

Gamma-ray emissions
X-ray emissions
Milky Way
50,000 light-years
Sun
eye candy credit:
NASA

Mirroring emission at other wavelengths

- in microwaves (WMAP): also hard, non-thermal spectrum, uniform intensity, few x 10^{36} erg/s
- in X-rays (ROSAT): apparently limb-brightened, thermal bremsstrahlung from ~10^7 K, 0.01 cm^{-3} plasma, $\gtrsim 10^{39}$ erg/s

Fermi Bubbles



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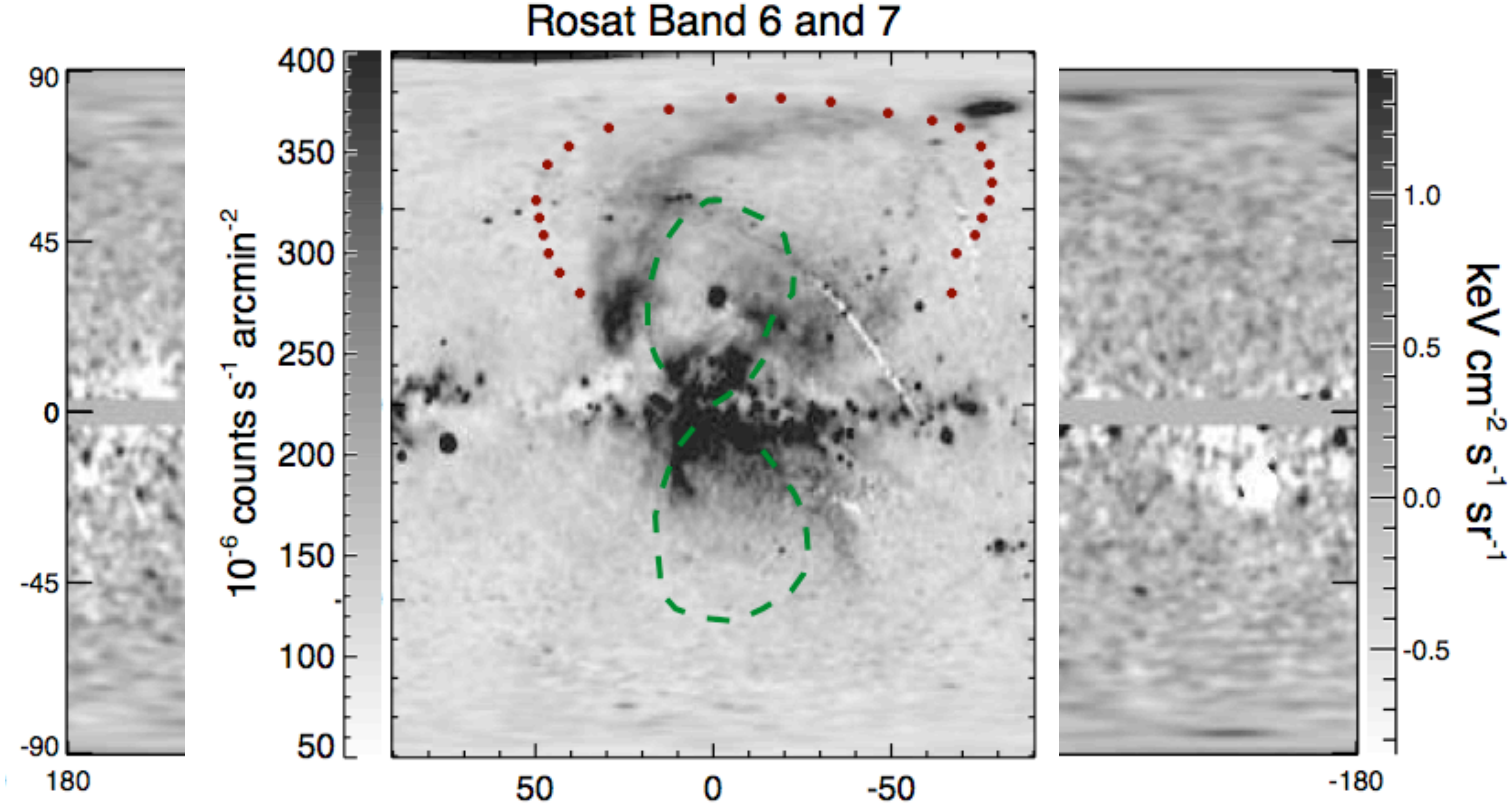

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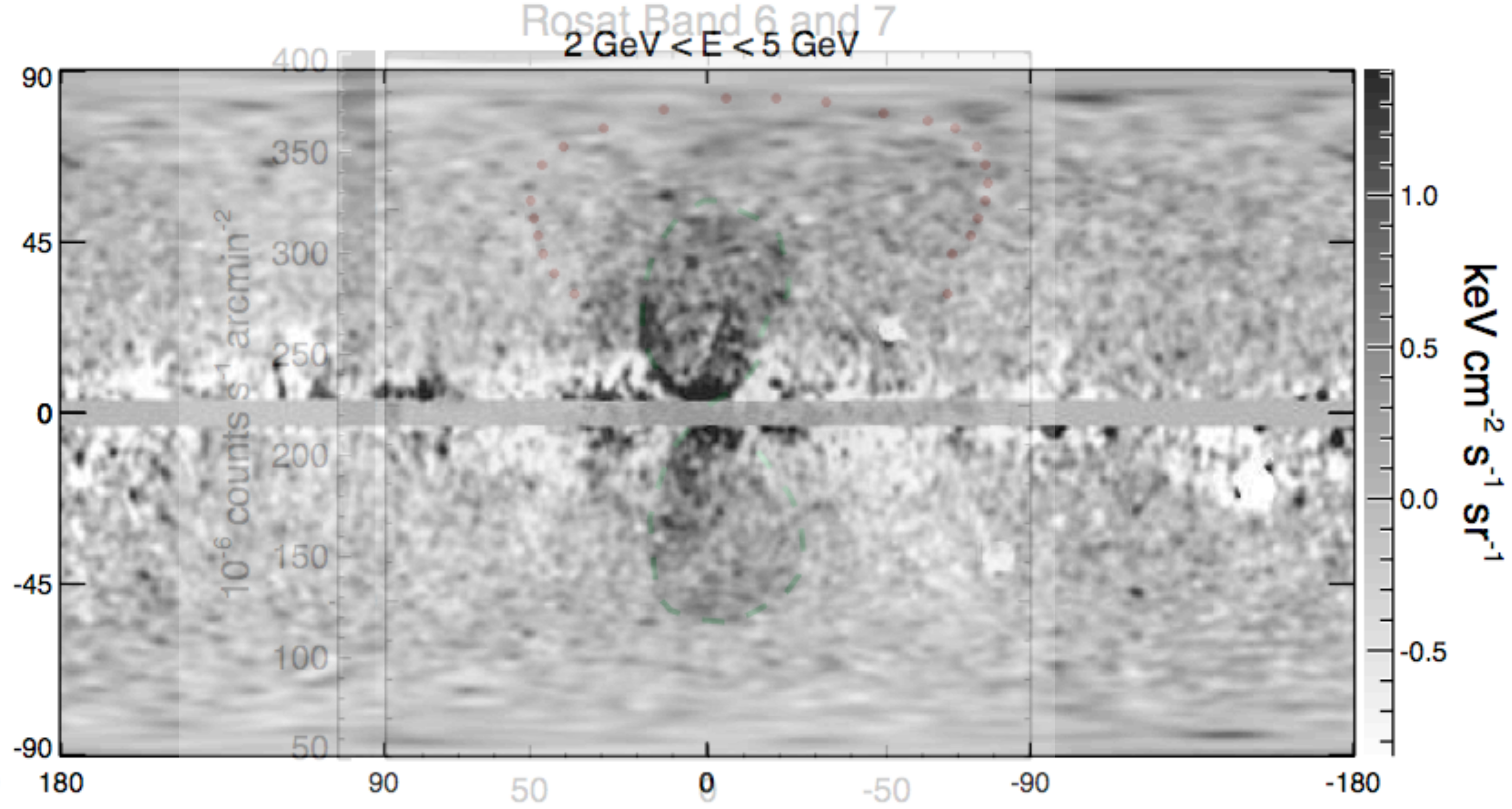

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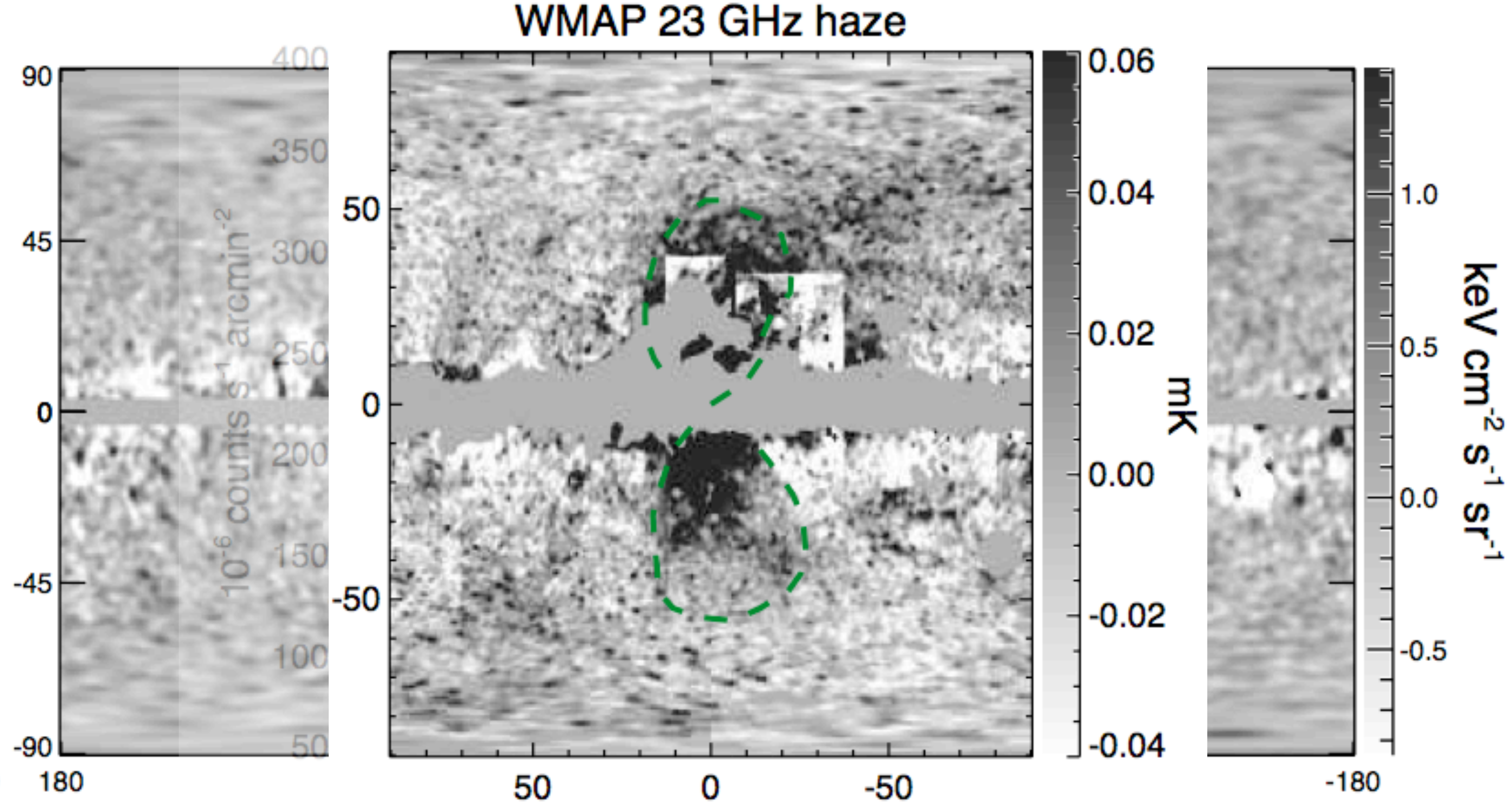

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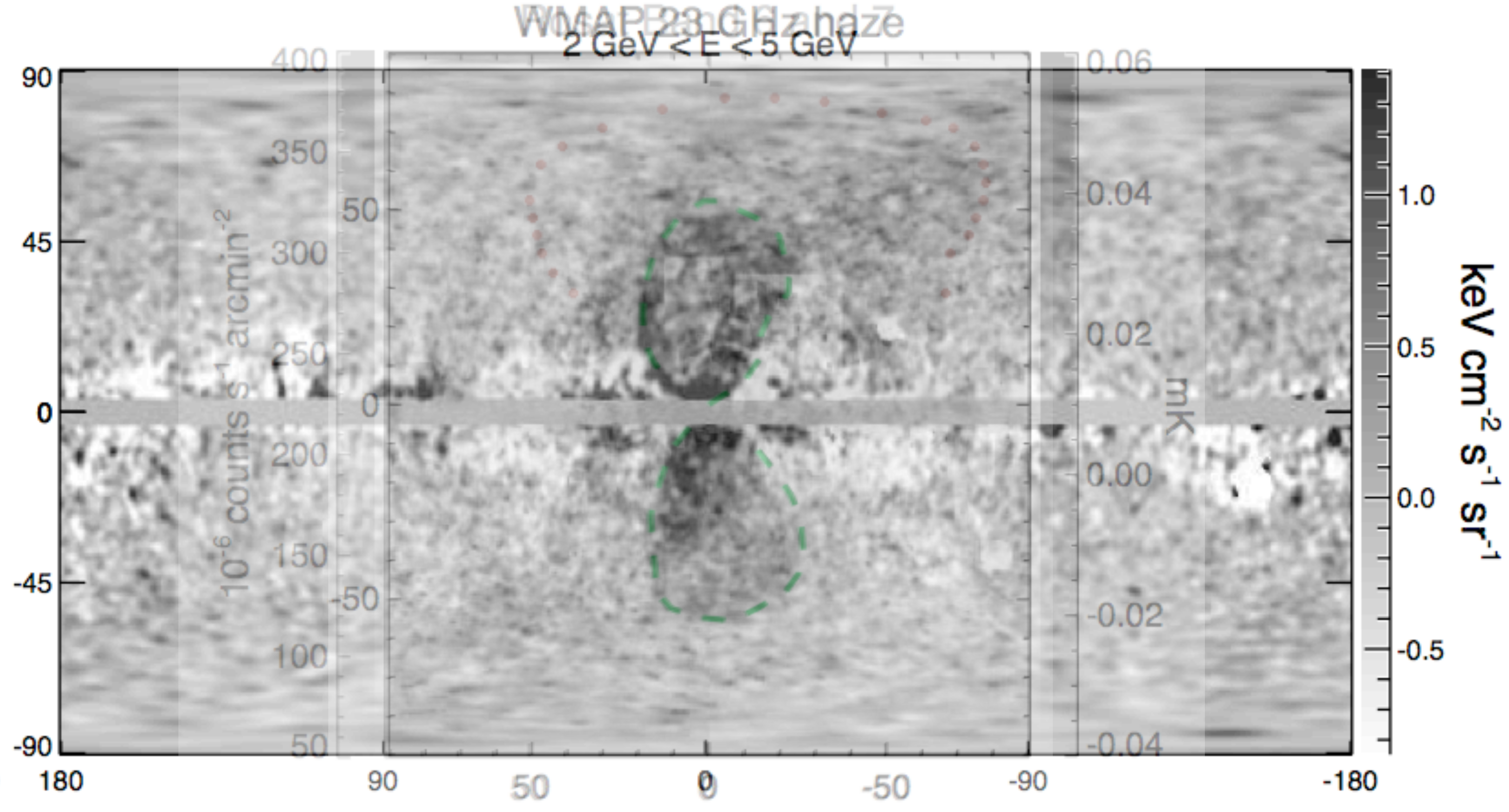

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‘Natural’ explanation: HE, primary electrons

- ~GeV γ-ray emission from IC by hypothesised population of hard-spectrum $\gtrsim$50 GeV electrons
- same population synchrotron-radiates into microwave frequencies

‘Natural’ explanation: HE, primary electrons

- ~GeV γ-ray emission from IC by hypothesised population of hard-spectrum ≳50 GeV electrons ✗
- same population synchrotron-radiates into microwave frequencies

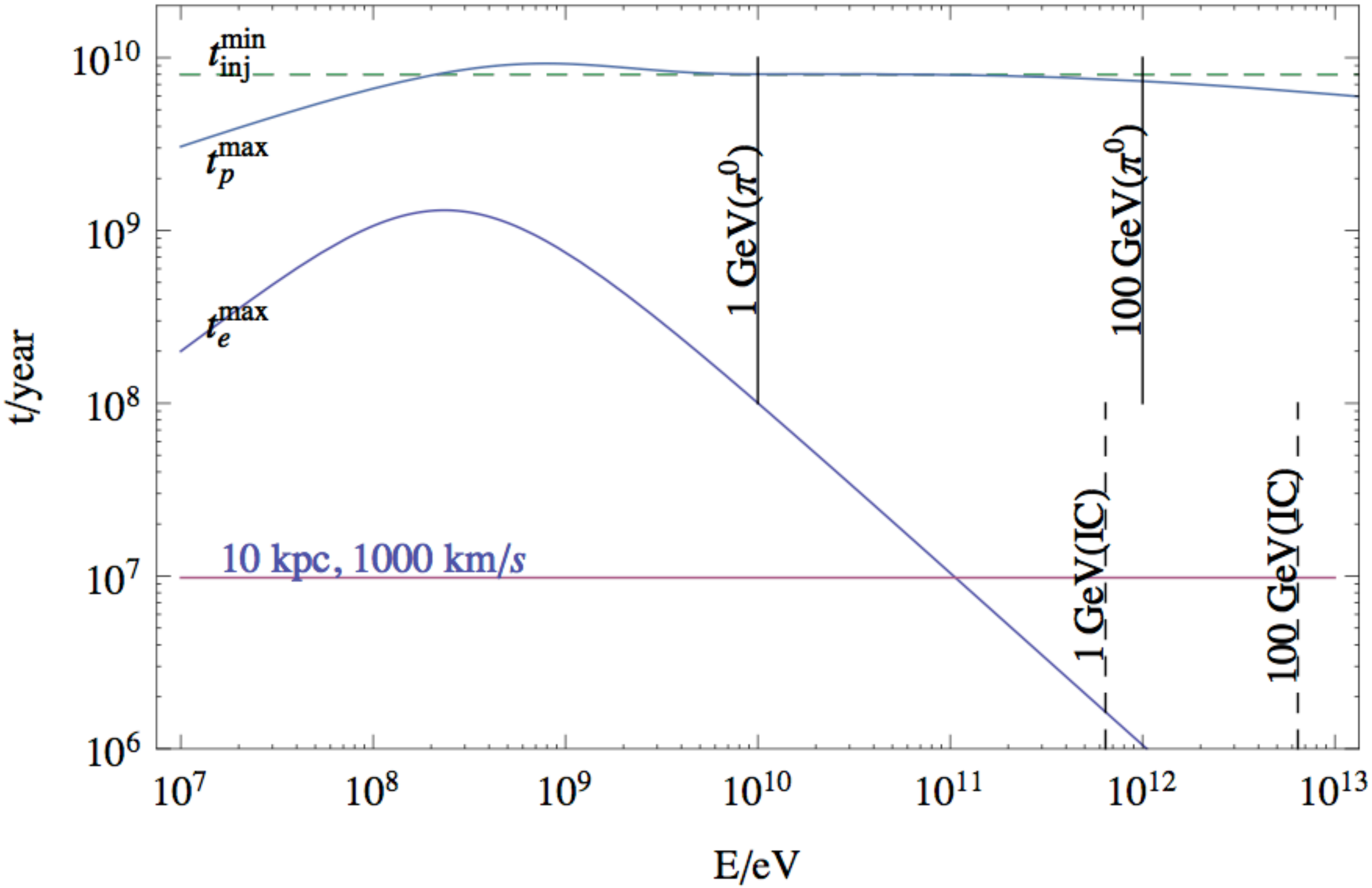
‘Natural’ explanation: HE, primary electrons

- ~GeV γ-ray emission from IC by hypothesised population of hard-spectrum $\gtrsim$50 GeV electrons

  1 TeV

- same population synchrotron-radiates into microwave frequencies

Problem with electrons



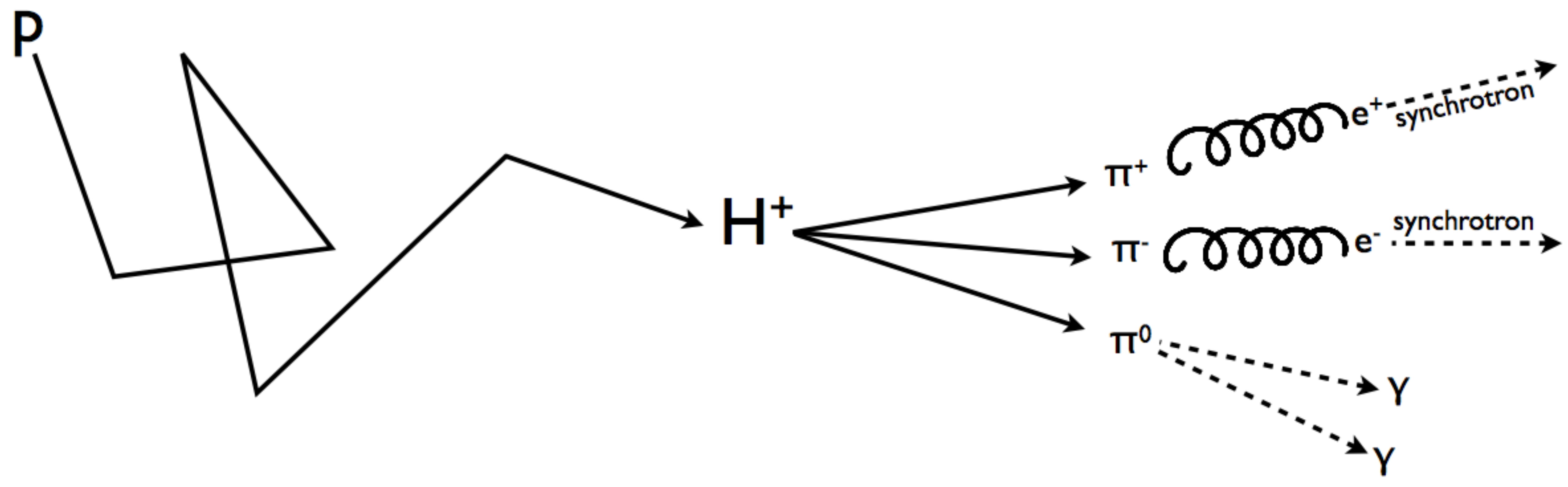
Electron scenarios

- **Very fast transport** (>3% c) ⇒ relativistic outflow ⇒ AGN jet from Sgr A* (Guo and Matthews 2011)
- **In situ acceleration**;
  - 1st order Fermi, e.g. shocks associated with tidal disruptions of stars near Sgr A* (Cheng, Chernyshov et al 2011)
  - 2nd order Fermi on turbulence (stochastic acceleration; Mertsch and Sarkar 2011)

What about protons?

- hard spectrum explained if protons confined in bubbles → the *in situ* spectrum shape = *injection* spectrum shape
- spectral down-turn explained by π^0 decay kinematics
- uniform intensity → saturation scenario
- *secondary* electrons generate microwave emission of correct luminosity

Secondaries from pp collisions



Proton *saturation* scenario

- But shouldn't the π^0 decay γ-rays trace the matter column density?
- Not in *saturation* (= *thick target + steady state)*

$L_\gamma \simeq N_p / t[pp \mapsto \pi^0]$ $\qquad$ $t[pp \mapsto \pi^0] \propto 1/n_H$ $\qquad$ $\pi^0 \mapsto \gamma\,\gamma$

$N_p \simeq \partial_t Q_p \; t[pp]$

$t[pp] \simeq 3 t[pp \mapsto \pi^0]$

$\Rightarrow L_\gamma \simeq \partial_t Q_p / 3$

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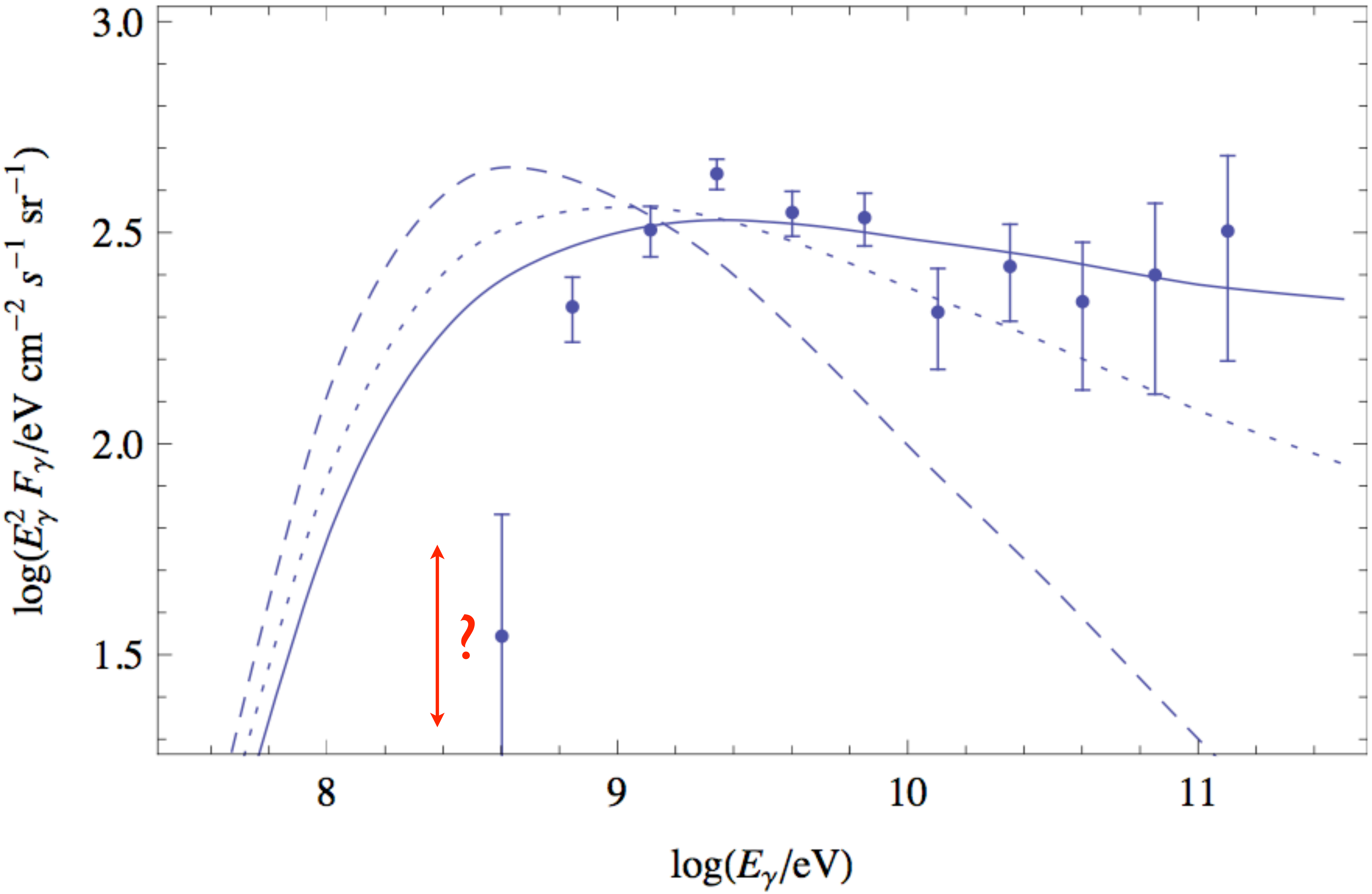
$N_p \simeq \partial_t Q_p\, t[pp]$

$t[pp] \simeq 3t[pp \mapsto \pi^0]$

$\Rightarrow L_\gamma \simeq \partial_t Q_p / 3$

...around 1/3 proton power emerges in γ-rays
over all energies *independent* of n_H

Bubble spectrum



What about protons II?

- BUT gas in bubbles is low-density plasma: nH < 0.01 cm^{-3}
- pp loss time is > 5 Gyr (!)
- need a source hard spectrum CR p's with power ~10^{39} erg/s that has lasted for > 5 Gyr
- CRAZY

...actually not

- the morphology of the bubbles privileges the GC
- the GC has been sustaining a high and approximately constant level of star formation for Gyrs (2% Galactic SFR)
- have independent, *a priori* evidence that the Galactic centre (GC) *currently* accelerates exactly the required CR proton population
- >95% of these CR p’s leave the region on a wind

Discussion points

- Star-formation (and concomitant supernovae) sufficient to drive activity of region
- The SMBH is not a significant actor beyond a few pc radius
- SN in GC seem to act with at least typical efficiency (> 10%) as CR accelerators
- GC mag field v. strong (100-200 μG)

Discussion points II

- GC launches a 'super-wind', v_{wind} > 200 km/s
- the wind stops the GC ISM energy density growing too much
- CRs heat/ionize low density, hot (envelope) H_2
- BUT the wind advects even >TeV CRs before they penetrate into dense H_2 cores → role for CRs in modifying conditions for SF seems to be disfavoured (unless *local* acceleration)
- No evidence for/against biasing of IMF

Discussion points III

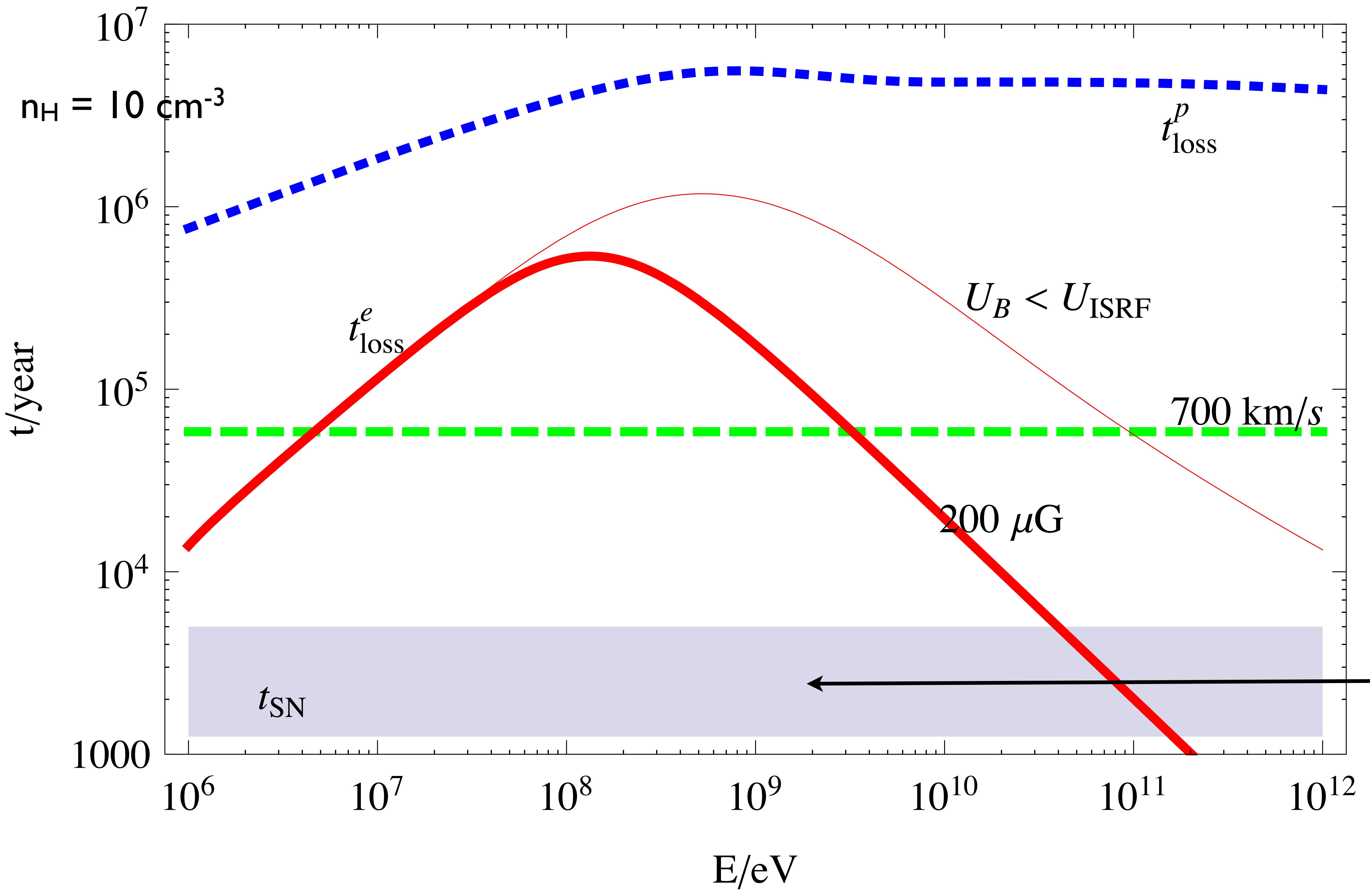
- GC SF seems to be progressing in more-or-less steady state and has been doing so for >Gyr timescales → self-regulation?
- Our scenario implies that the bubbles are a calorimetric recording of GC activity over the lifetime of the Galaxy
- Bubbles should be good neutrino and TeV γ-ray sources

Extra Slides

Modelling

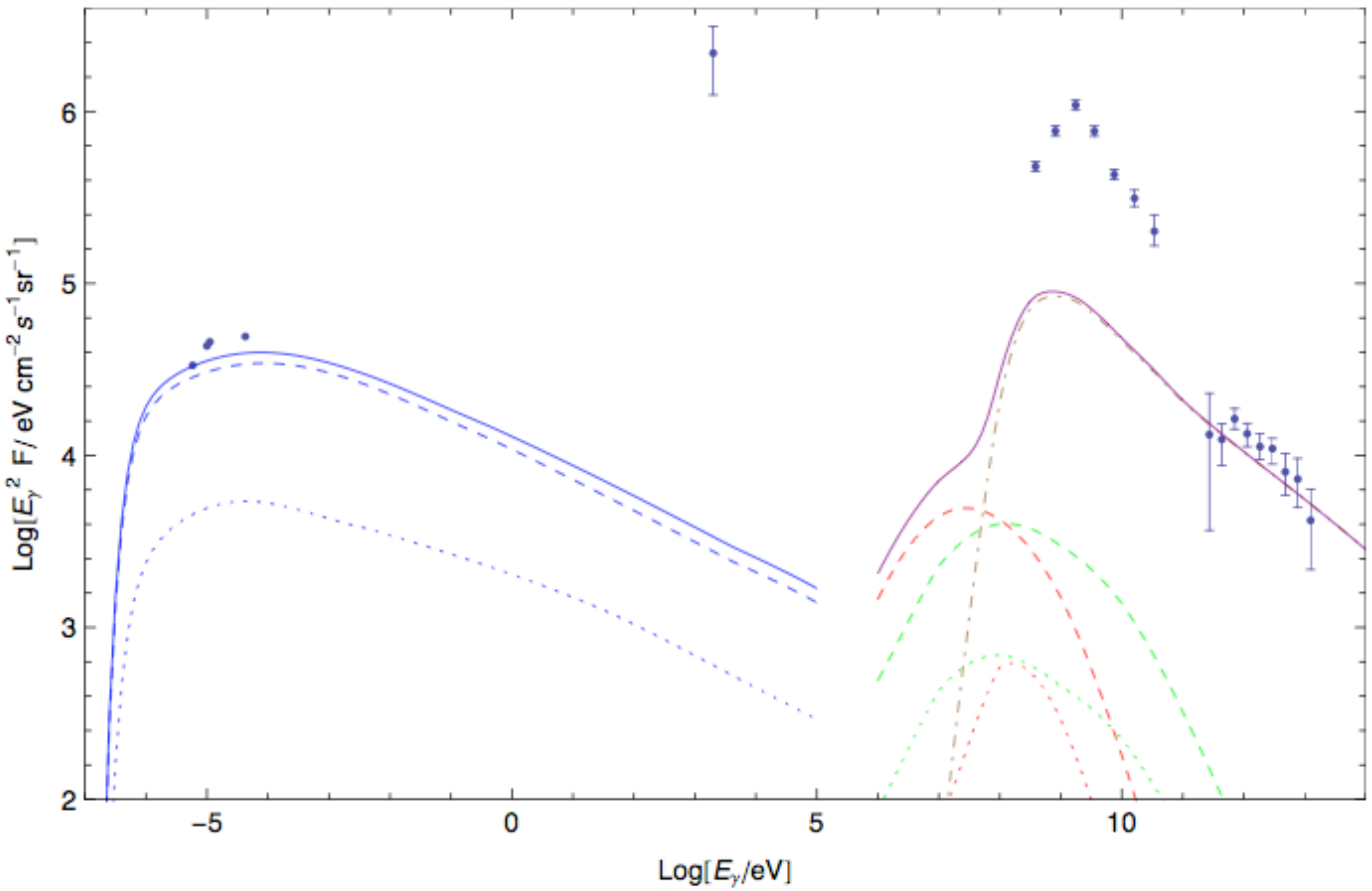
- One-zone, steady-state modelling of in-situ electron and proton population
- Particle transport advective (wind)
- Try to reproduce observed, broad-band (non-thermal) emission from the region

Timescales: steady state justified



1 SN per ~2500 years

Best-fit broadband spectrum



dashed: primary electron emission

dotted: secondary electron (and positron) emission

solid: total emission

Emission processes are:

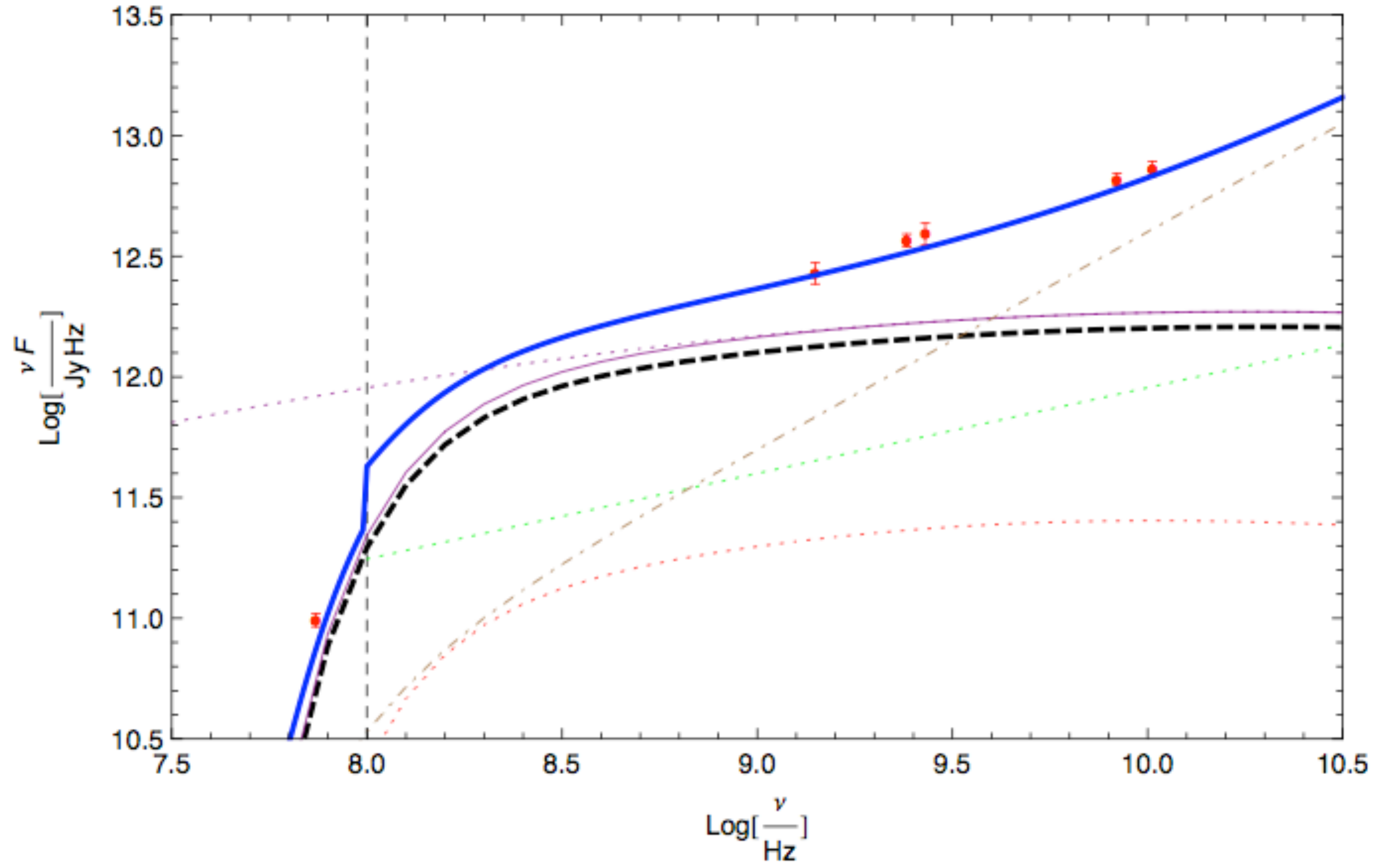
blue: synchrotron

red: bremsstrahlung

green: inverse Compton

brown, dot-dashed: neutral meson decay

Best-fit radio spectrum



solid blue curve: total emission curve

solid, purple: total synchrotron

dotted, purple: total synchrotron in absence of free-free absorption

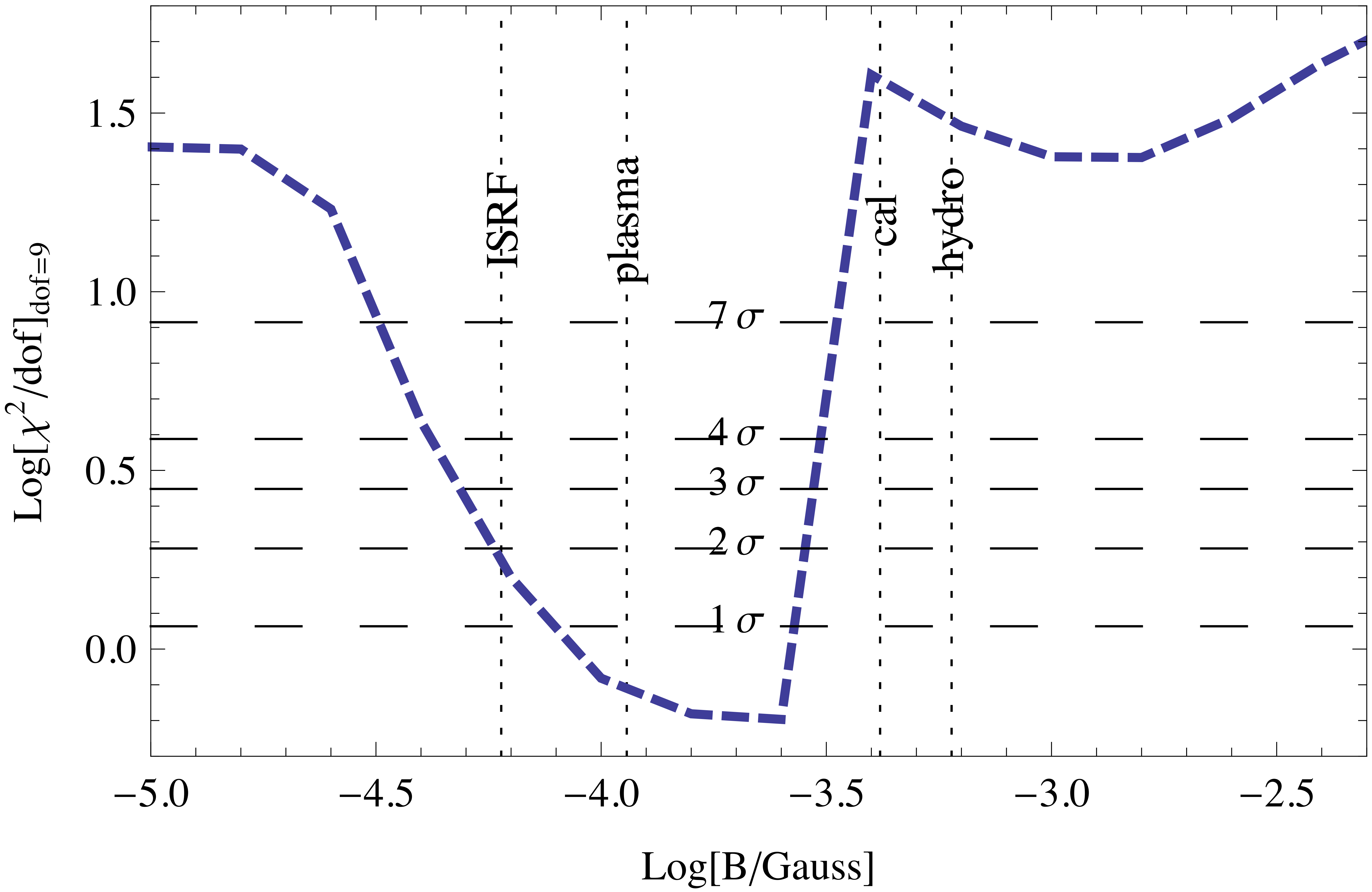
dashed, black: primary electron synchrotron

dotted, red: secondary electron synchrotron

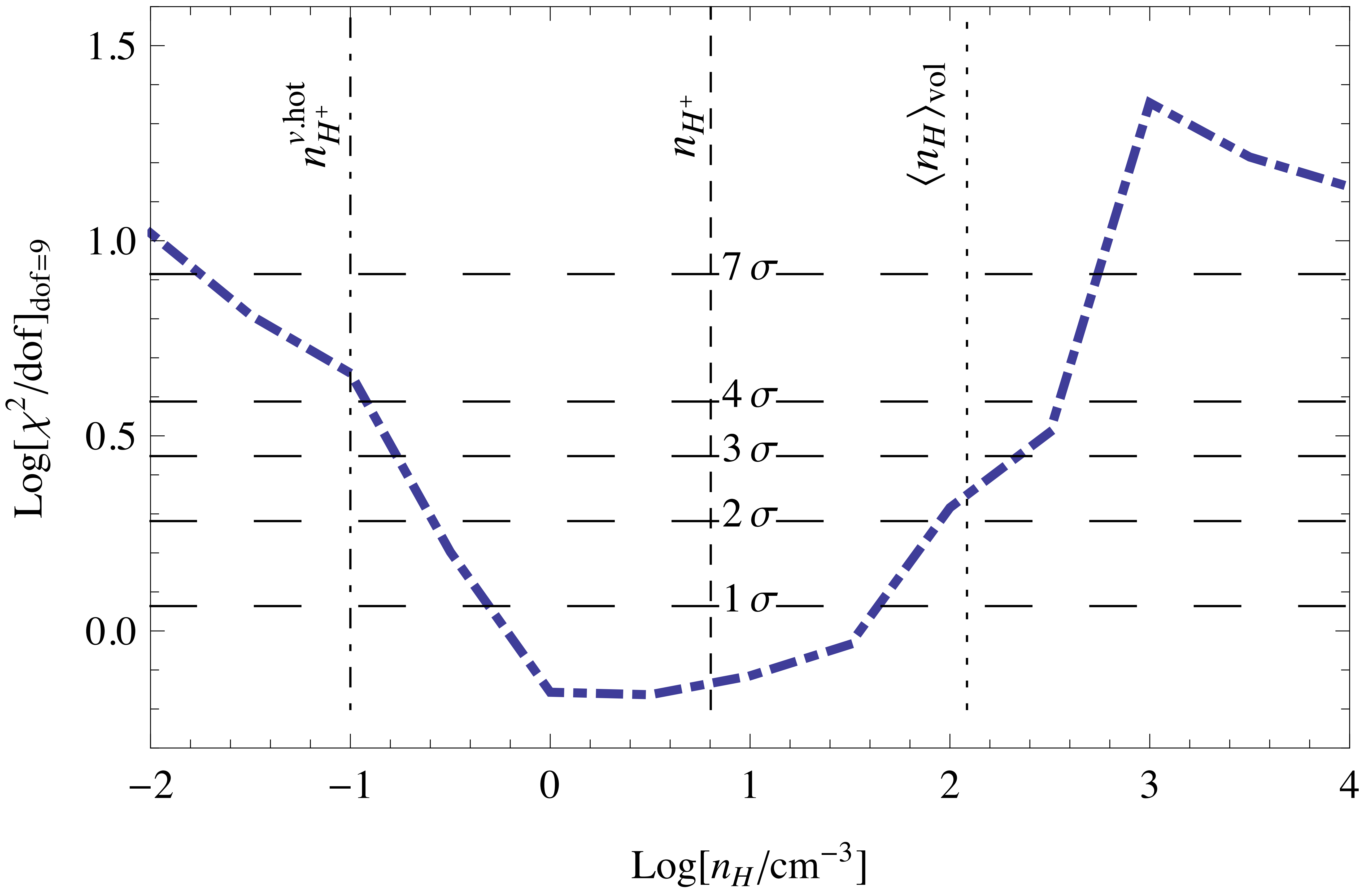
dotted, green: GSB

dot-dashed, brown: free-free emission.

Magnetic field



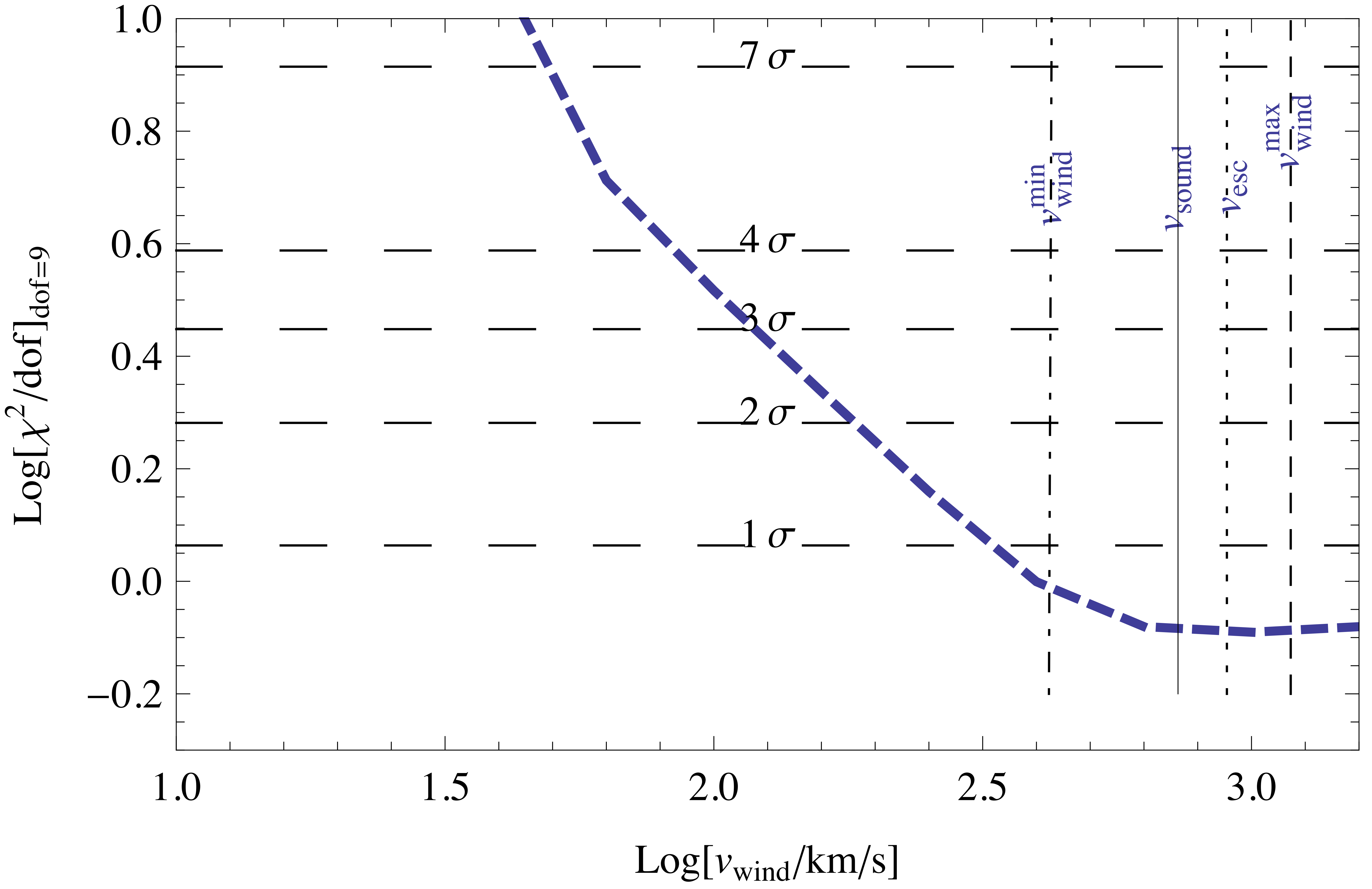
Gas density



CRs do not penetrate into densest gas

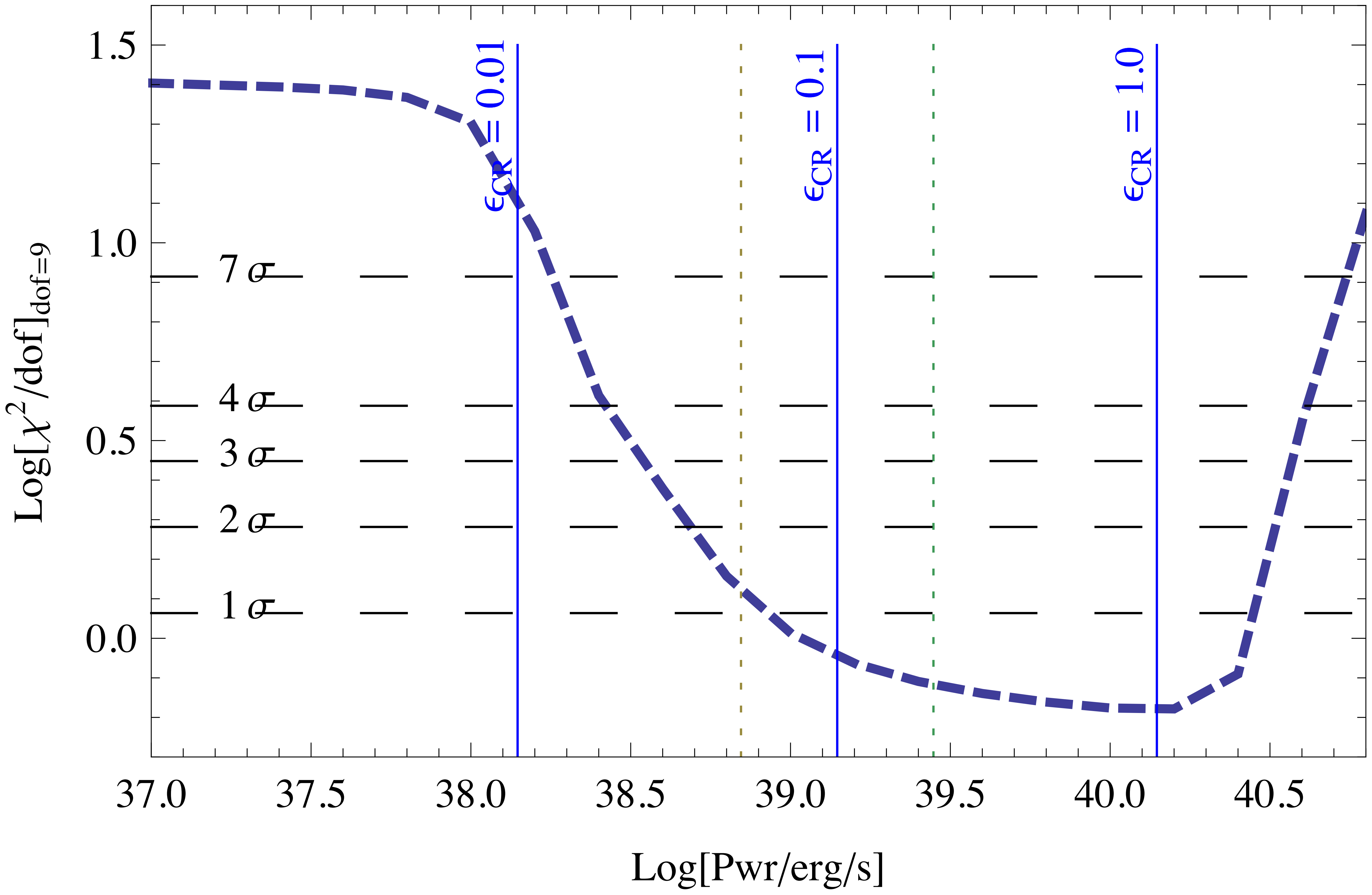
BUT they can heat/ ionize the low-density (warm) H2

Wind speed



1.0
0.8
0.6
0.4
0.2
0.0
−0.2
1.0
1.5
2.0
2.5
3.0
7 σ
4 σ
3 σ
2 σ
1 σ
v_{wind}^{min}
v_{sound}
v_{esc}
v_{wind}^{max}
$Log[\chi^2/dof]_{dof=9}$
$Log[v_{wind}/km/s]$

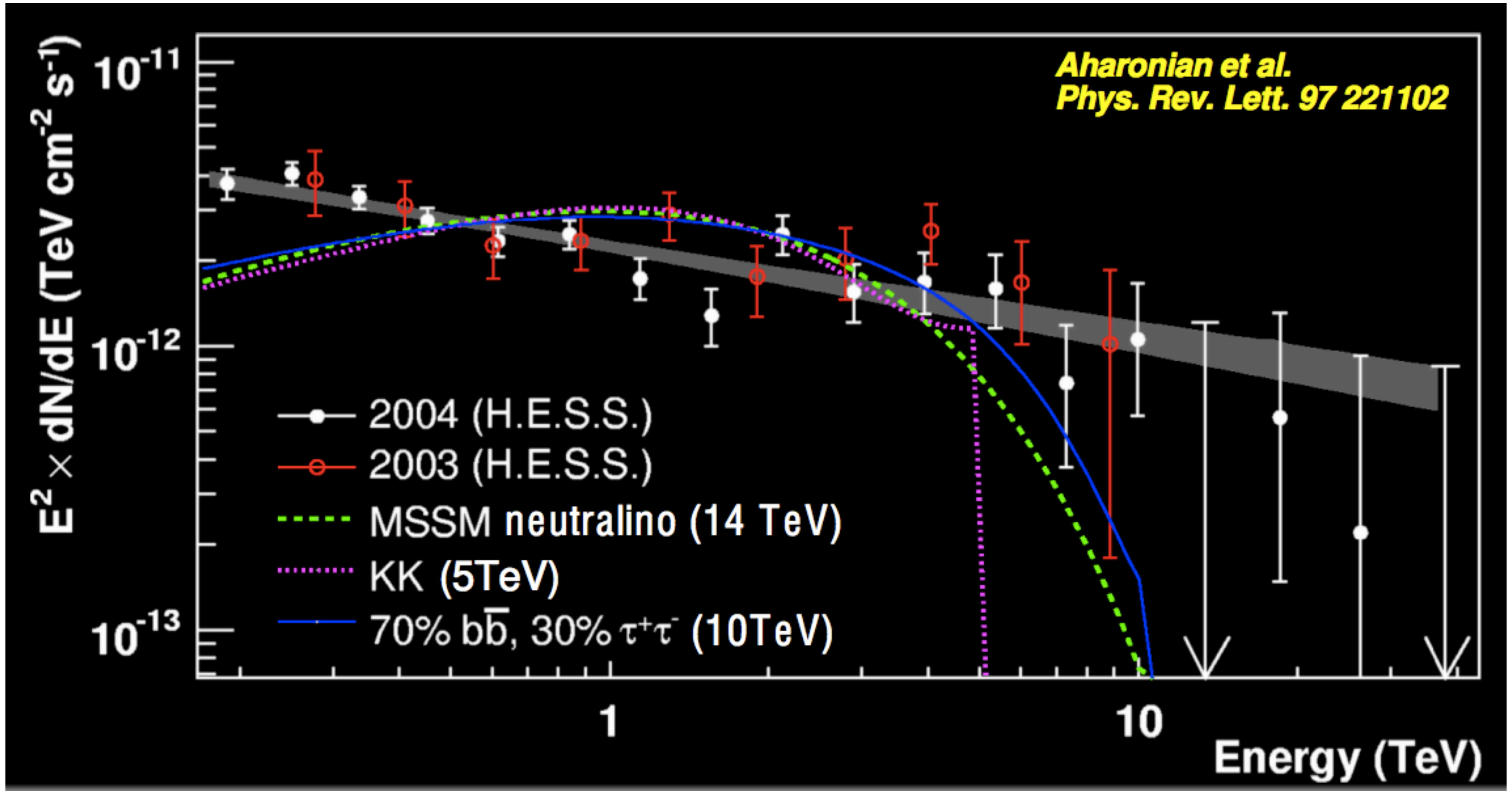
Non-thermal power



Self-consistent modelling confirms $\gtrsim 10^{39}$ erg/s *independent* of SN rate estimate

Gamma Rays from Dark Matter Annihilation?

No: disfavoured by very hard spectrum up to (at least) 20 TeV

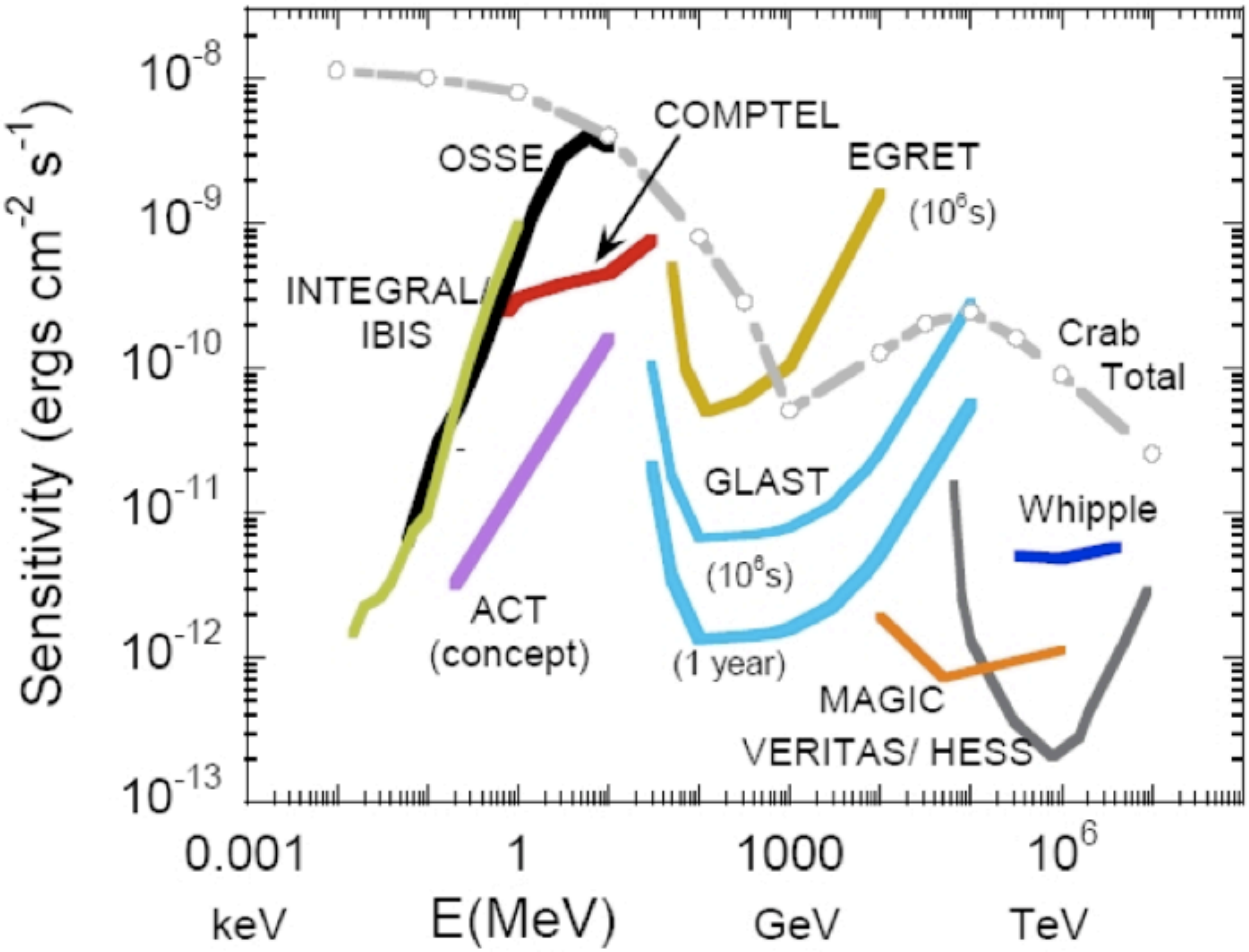


Dark Matter Annihilation

- Disfavoured: a flat spectrum (as observed) extending up to 20 TeV is difficult to reconcile with DM models which tend to turn-over below 10 TeV (given masses of DM candidates)
- A sub-dominant (< 10%) contribution cannot be ruled out however

X-ray/γ-ray Instruments

energy band	instrument	angular resolution	FOV	collecting area
0.5 - 8 keV 0.2 - 12 keV 0.2 - 12 keV	Chandra XMM SUZAKU	0.5 arcsec 5 arcsec 30 arcsec	17’ x 17’ 30’ x 30’ 18’ x 18’	400 cm^2 @ 1 keV 4300 cm^2 @ 1.5 keV 1000 cm^2 @ 2 keV
15 keV - 10 MeV	INTEGRAL (IBIS)	12 arcmin	9° x 9°	100 cm^2
30 MeV - 30 GeV	EGRET Fermi	5°.5 (100 MeV) - 0°.5 (5 GeV+) 3°(100 MeV) - ~few arcmin (>10 GeV)	80° 20°	1000 cm^2 (100 MeV - 3 GeV)
100 GeV - 30 TeV	HESS	~5 arcmin	5°	~2 x 10^9 cm^2 (TeV)



credit: G. Rowell

Space-based: typically ≥5σ after 1 Ms or 1 yr

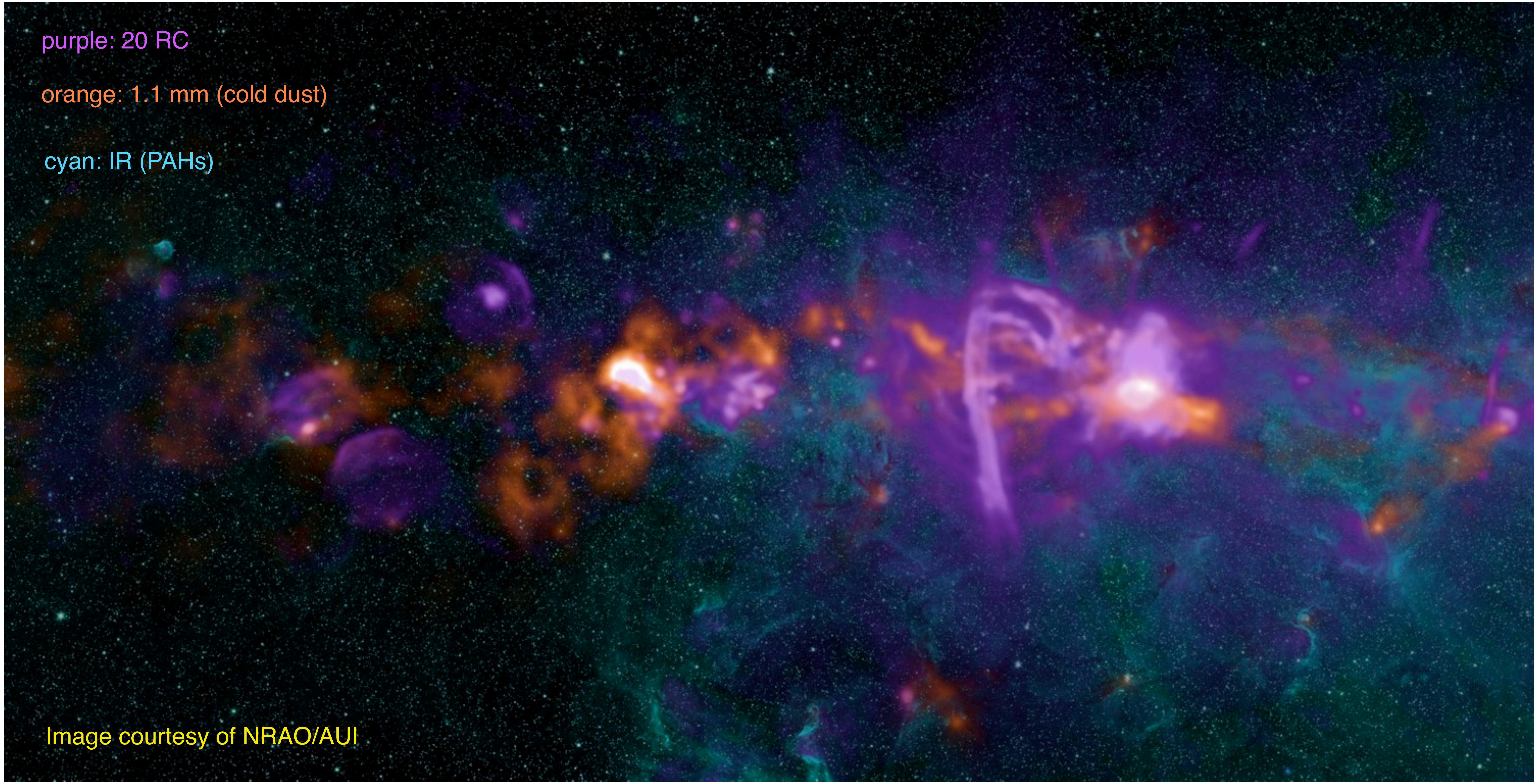
H.E.S.S. et al.:
≥5σ detection after 50 h observation

Distance Scales

object/structure	pc	AU
r. Galaxy	$\sim 1.5 \times 10^4$	3×10^9
dist. to GC	$\sim 8 \times 10^3$	2×10^9
r. Gal. bulge	$\sim 3 \times 10^3$	6×10^8
r. Gal. bar	$\sim 2 \times 10^3$	4×10^8
r. Nuc. bulge	~300	6×10^7
diam. CMZ	~400	8×10^7
ht. CMZ H_2	~40	8×10^6

Distance Scales cont^{d}

object/structure	pc	AU
r. CND	~6	1×10^6
r. typ. cloud	~3	6×10^5
r_{min} star SO-16	$\sim 3 \times 10^{-4}$	60
r. accrtn disk	$\sim 8 \times 10^{-6}$	2
$r_{Scwarzschild}$ (4×10^6 $M_\odot$)	$\sim 4 \times 10^{-7}$	0.08



The Galactic Center and the surrounding Central Molecular Zone comprise the most active star formation region in the Milky Way. This 2 x 1 degree field was imaged at 20 cm (purple) with the NRAO Very Large Array, tracing H II regions that are illuminated by hot, massive stars, supernova remnants, and synchrotron emission. Emission at 1.1 mm (orange) was observed with the Caltech Submillimeter Observatory and highlights cold (20-30 K) dust associated with molecular gas. Some of this material will form stars within in the next few million years; the remainder will be blown away. The diffuse cyan and colored star images are from the Spitzer Space Observatory's Infrared Array Camera. The cyan is primarily emission from stars, the point sources, and from polycyclic aromatic hydrocarbons (PAHs), the diffuse component.

Investigator(s): Adam Ginsburg and John Bally (Univ of Colorado - Boulder), Farhad Yusef-Zadeh (Northwestern), Bolocam Galactic Plane Survey team; GLIMPSE II team

GC Dark Matter Constraints

DM Constraints: Strategy

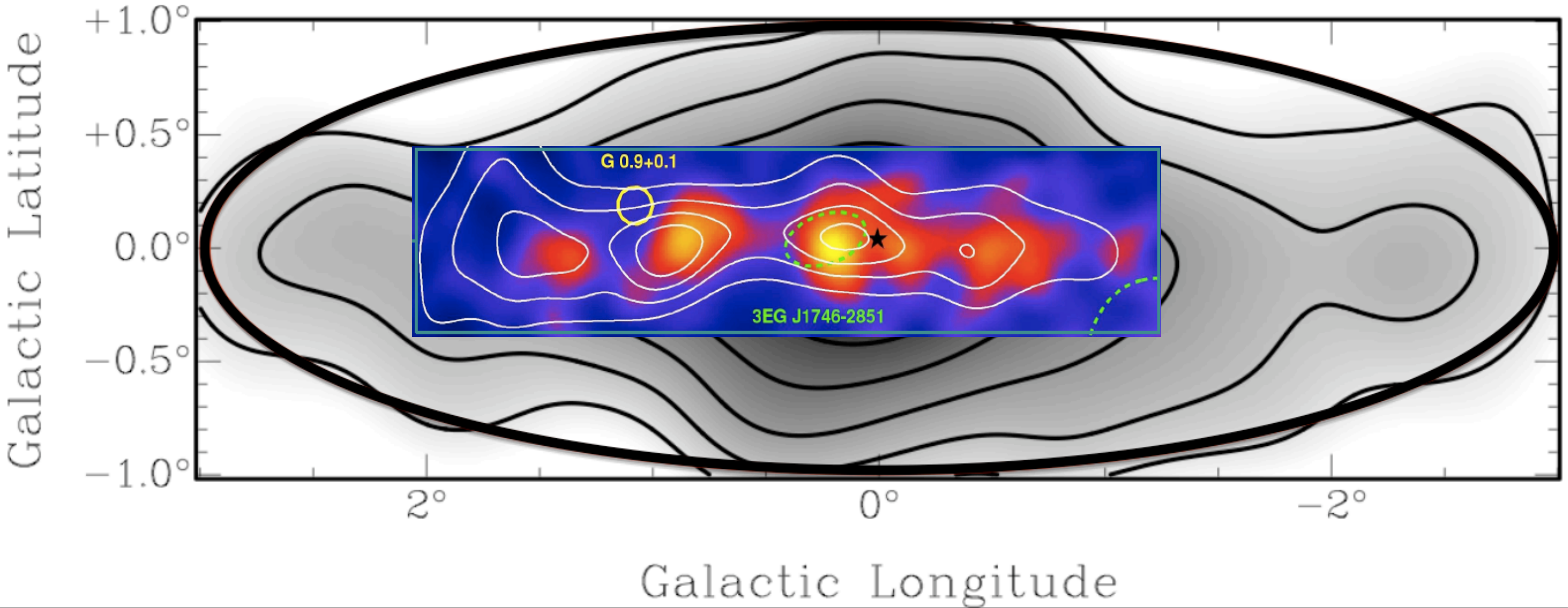
- DM annihilation produces e^- e^+ pairs in the GC
- e^-s & e^+s cool by
  - ionization
  - bremsstrahlung
  - synchrotron
  - inverse Compton scattering
- radio and γ-ray data from the GC should constrain $<\sigma_{ann} v>$ and M_{DM}

Radio Data

- Diffuse, non-thermal radio signal over freq range:
  - 74 MHz & 330 MHz (LaRosa et al. 2005)
  - 1.4 GHz → 10 GHz (assembled by us)
- 2 regions:
  - ellipse around the Galactic center (DNS) 3° semi-major axis & 1° semi-minor axis
  - smaller region around the Galactic center measured by HESS $| l | < 0.8^\circ$ and $| b | < 0.3^\circ$

HESS (TeV) Data

HESS data: $| l | < 0.8°$ and $| b | < 0.3°$
imply limit on the differential γ-ray intensity at 1 TeV of
1.4×10^{-20} cm^{-2} eV^{-2} s^{-1} sr^{-1}
(Aharonian et al., Nature 439, 695, 2006)



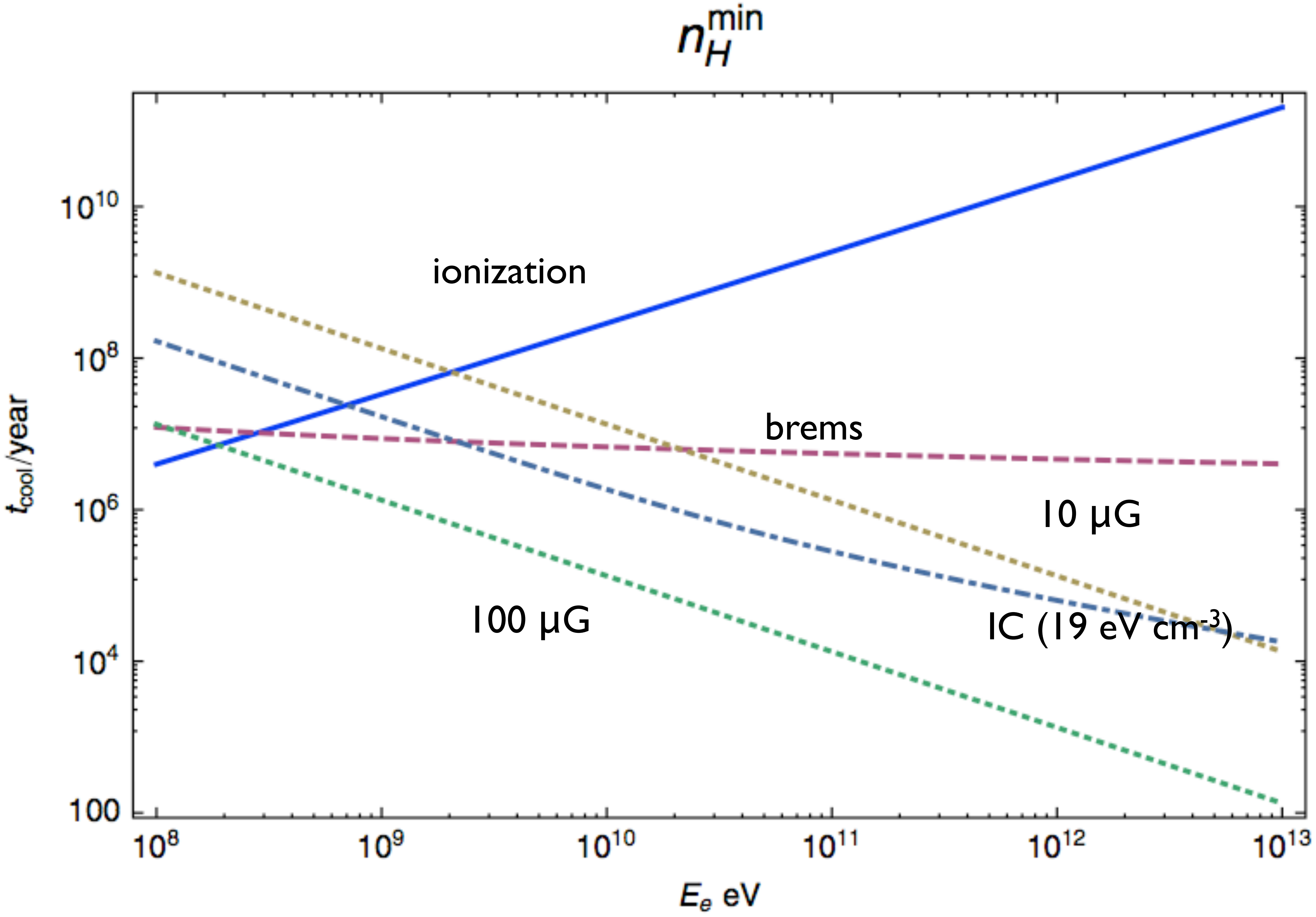
Dark matter annihilation and primary e^+e^- spectrum

- Free parameters: $<\sigma_{ann} v>$ and M_{DM}
- Assume two annihilation processes:
  - $\chi\chi \longrightarrow e^+e^-$ $\longrightarrow$ monochromatic
  - $\chi\chi \longrightarrow$ qbar q $\longrightarrow$ . . . hadronization . . . $\longrightarrow e^+e^-$

$\longrightarrow$ polynomial in (E_e/m_χ) a la Borriello et al. 2008

- annihilation channels $\chi\chi \longrightarrow$ ZZ, WW lead to very similar e^+e^- spectrum as the $\chi\chi \longrightarrow$ qq channel

Cooling Timescales



Steady-State Electron Population

Injection spectrum from DM annihilation:

$$Q(E_e, r) = \frac{1}{2}\left(\frac{\rho(r)}{m_\chi}\right)^2 \langle\sigma_A v\rangle \frac{dN_e}{dE_e}$$

Cooled spectrum from DM annihilation:

$$\frac{dn_e}{dE_e}(E_e, \vec{r}) = \frac{\int_{E_e}^{m_\chi c^2} dE'_e Q(E'_e, \vec{r})}{-dE_e(E_e)/dt}$$

"thick target"

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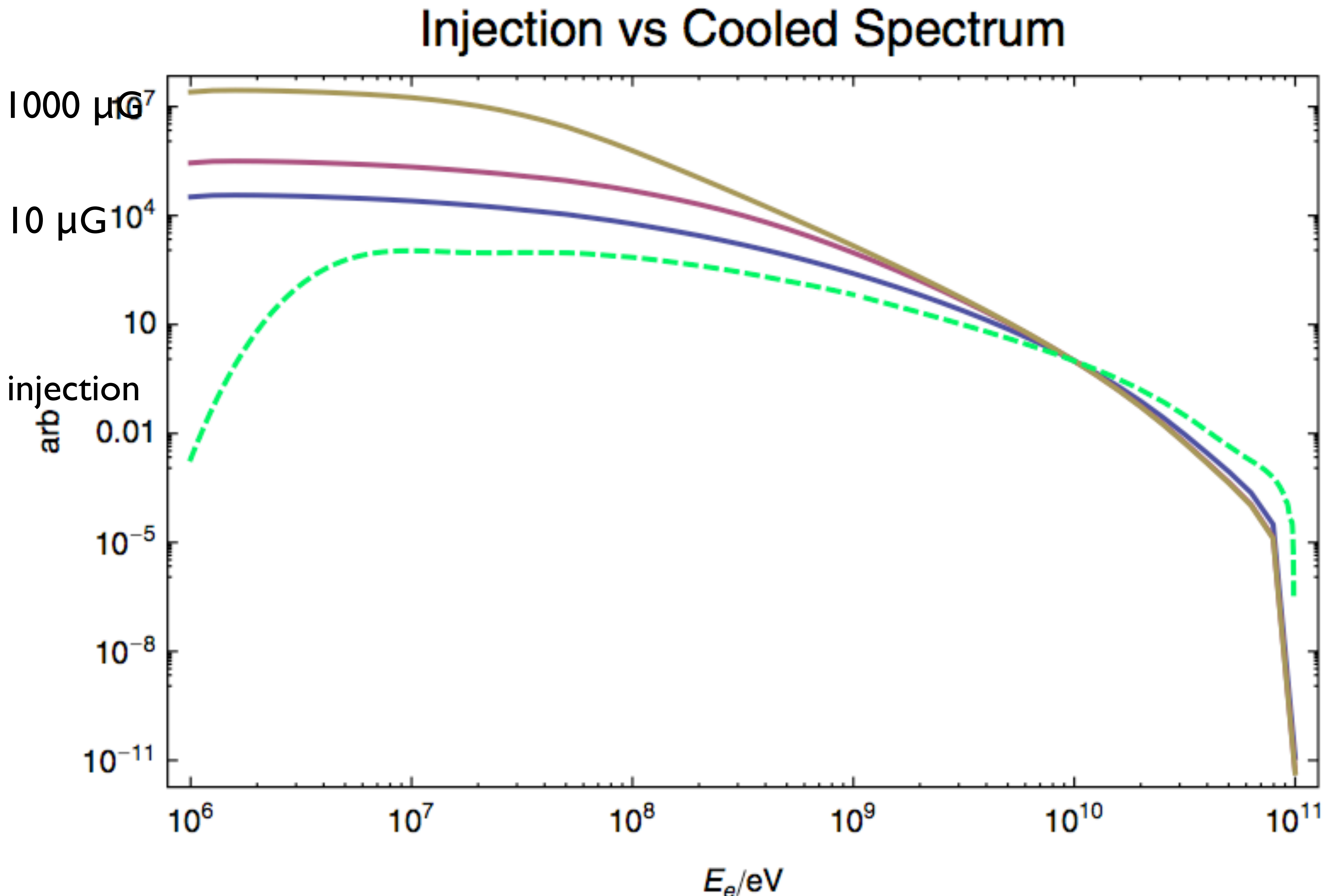
Injection and Cooled Spectra



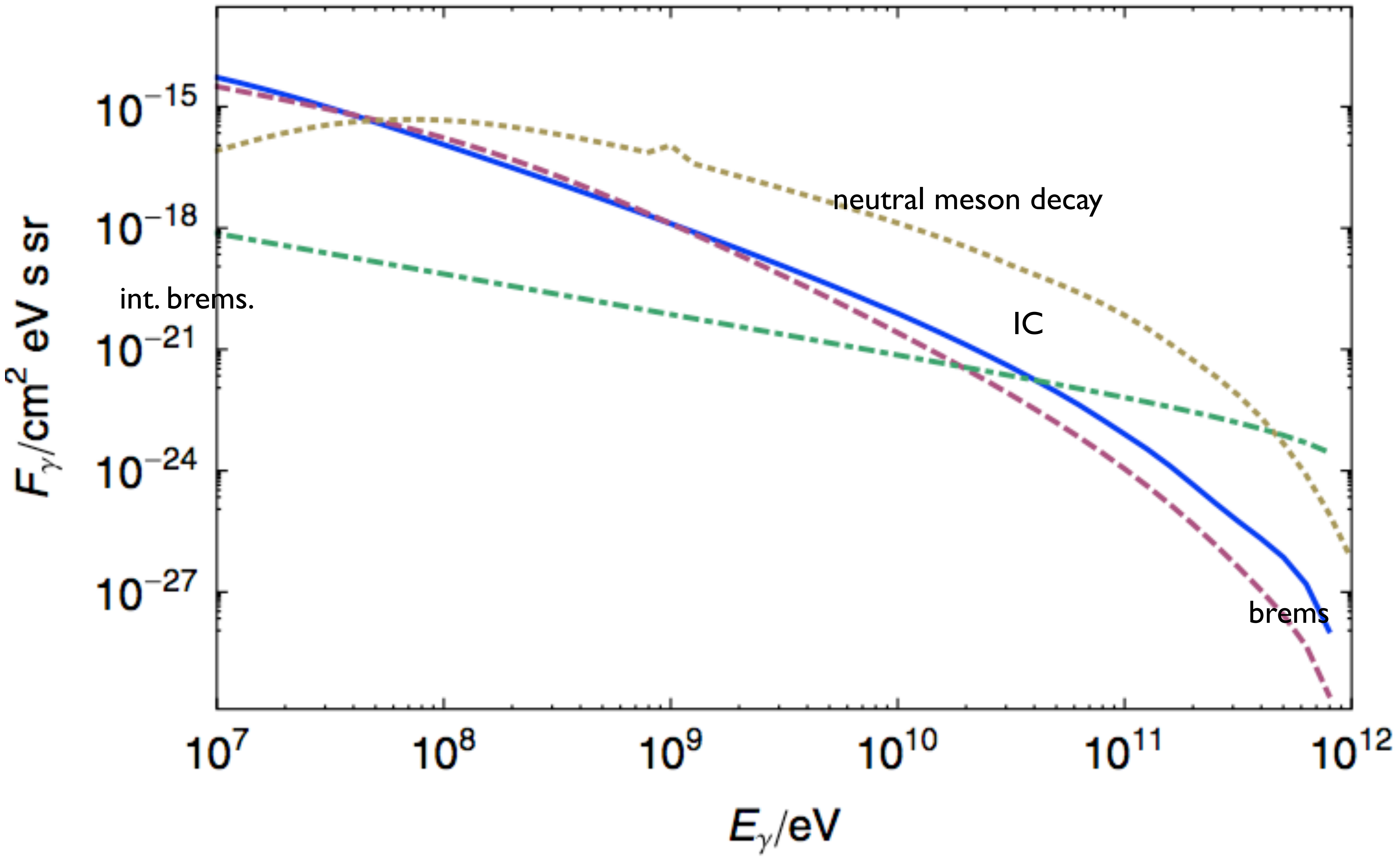
E.g.:

XX⟶qbar q

m_X = 100 GeV

n_H = 3 cm^{-3}

Radiative Processes



E.g. Spectrum:

$\chi\chi \to$ qbar q

m_χ = 1 TeV

$\langle \sigma_{ann} v \rangle = 10^{-26}$ cm^3 s^{-1}

B = 100 μG

n_H = 3 cm^{-3}

DM Constraints

e.g. NFW & χχ⟶qbar q

(a) $\chi\chi \to \bar{q}q$; NFW profile; $B = 10\mu$G. (b) $\chi\chi \to \bar{q}q$; NFW profile; $B = 30\mu$G. (c) $\chi\chi \to \bar{q}q$; NFW profile; $B = 100\mu$G.

...relative insensitivity to magnetic field

Eddington Luminosity

• This limit presents an upper bound to the luminosity of an object driven by **accretion**.

The limit is determined by setting the inward pull of gravity to be equal to the outward pressure of radiation.

Inward gravitational pull on an electron-positron pair in the accreting plasma:

$$F_{grav} = \frac{GM(m_p + me)}{r^2} \simeq \frac{GMm_p}{r^2}$$

Eddington Luminosity cont^{d}

- The radial force from light pressure acts upon the electron; because the accreting plasma must remain electrically neutral, this pressure is communicated to the protons by electrostatic force between electron and positron pairs.
- The force on the electron is just the momentum per unit time communicated to it by the incident flux of photons:

$$F_{light} \simeq \frac{\sigma_T L}{4\pi r^2}$$

- Setting

$$F_{grav} = F_{light}$$

Eddington Luminosity cont^{d}

$$L_{Edd} = \frac{4\pi G M m_p c}{\sigma_T}$$

Eddington luminosity of 4 x 10^6 $M_\odot$ object (Sgr A*):

$$L_{Edd}^{Sgr A*} = 5 \times 10^{44}\, erg/s\, \frac{M_{BH}}{4 \times 10^6 M_\odot}$$

In fact, at all wavelengths Sgr A* is sub-Eddington by a factor 10^{-9} or less