Astrophysics of the Galactic Center Part I: Giant Shocks in the Fermi Bubbles and the Origin of the Microwave Haze

Roland Crocker
ARC Future Fellow
Australian National University

image credit: NASA

Collaborators

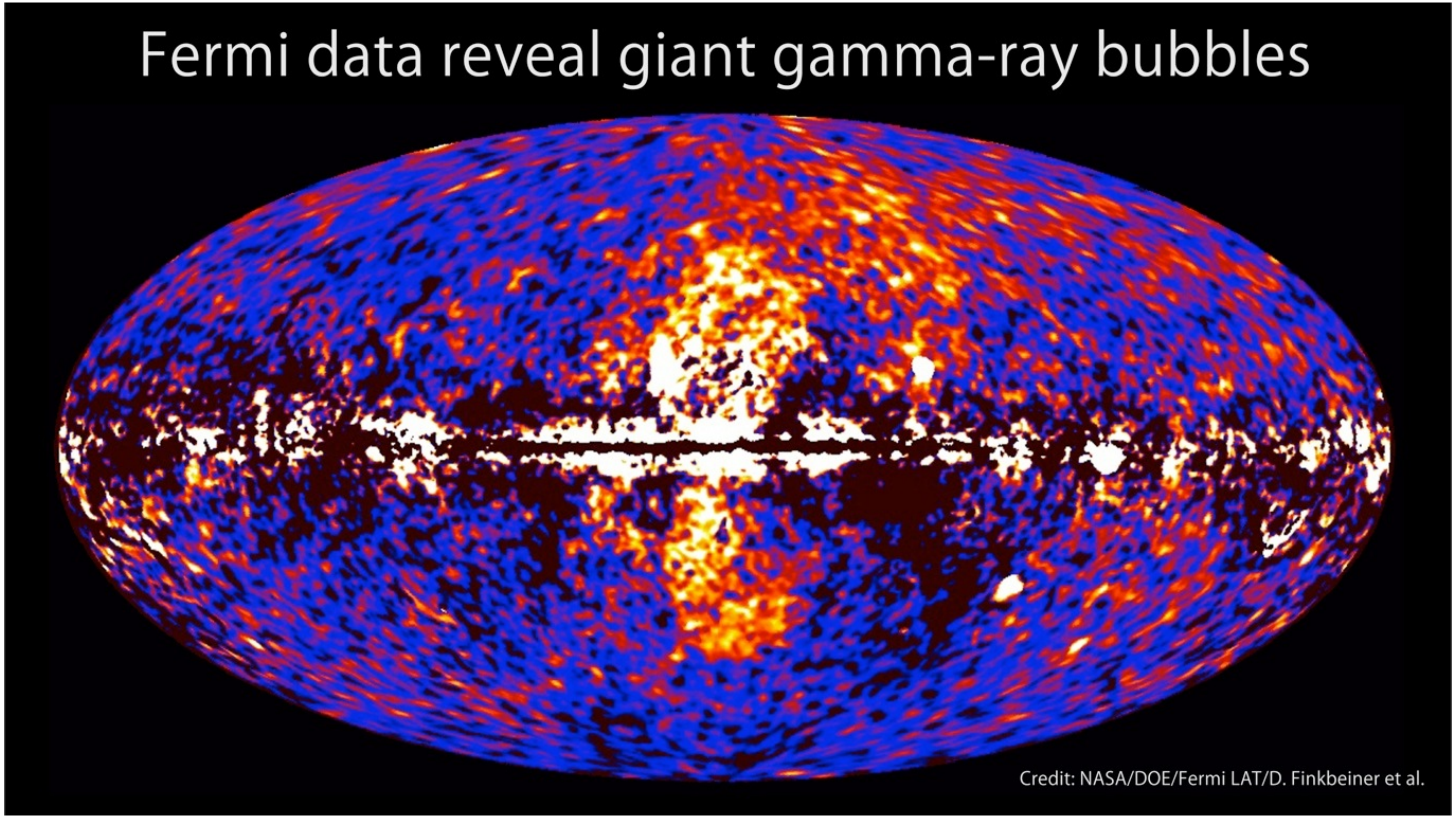
- Geoff Bicknell, RSAA

- Ettore Carretti, Cagliari Observatory

- Andrew Taylor, Dublin Institute for Advanced Studies

Details: Crocker et al. 2015 ApJ, 808, 107; Crocker et al. 2014 ApJL, 791, L20

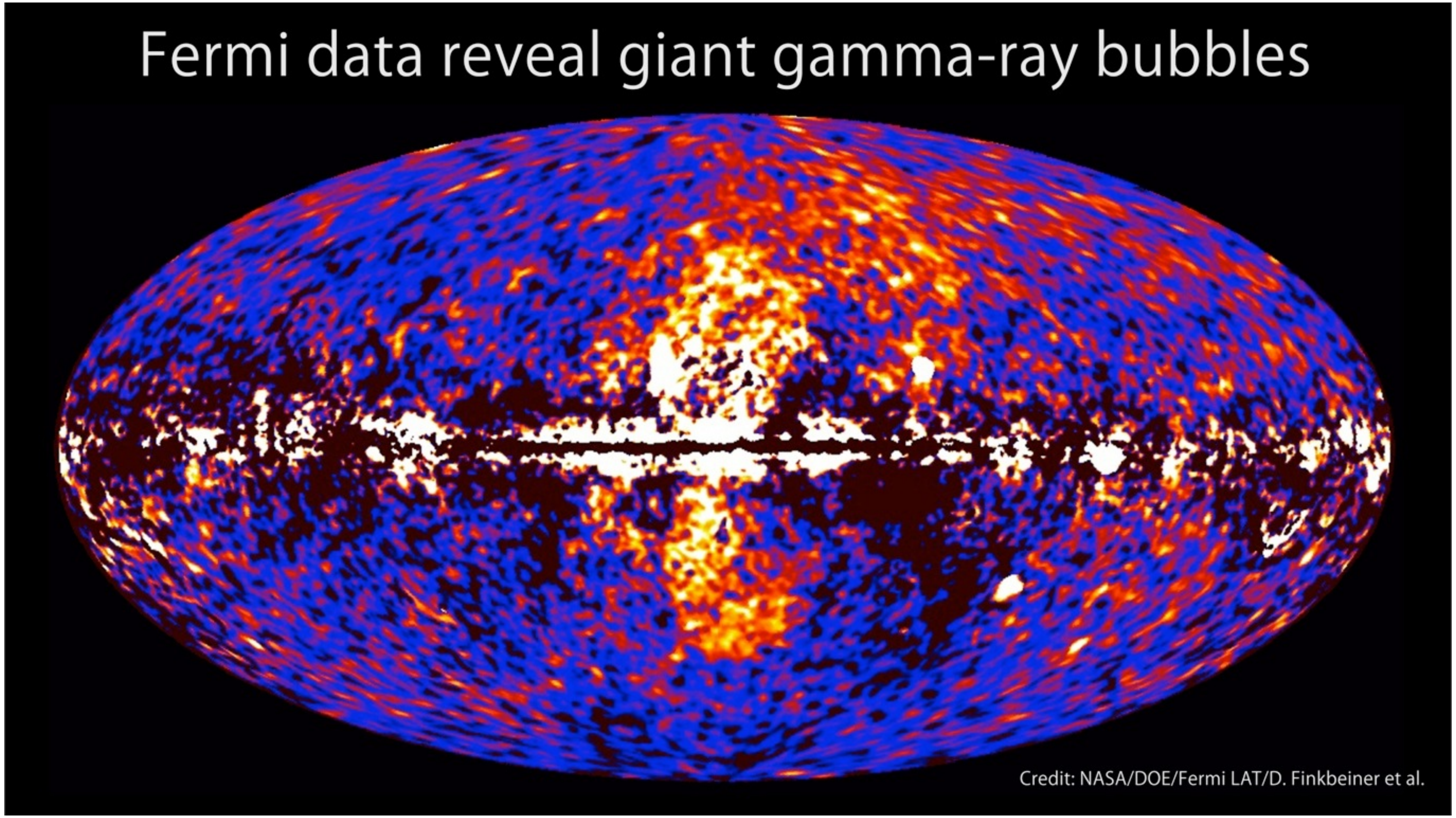
Fermi Bubbles



Su, Slatyer and Finkbeiner 2010 (ApJ)

Fermi Bubbles

- 2 x 10^{37} erg/s [1-100 GeV]
- hard spectrum, but spectral down-break below ~ GeV in SED, cut-off (?) ~100 GeV
- uniform projected intensity
- sharp edges
- vast extension: ~7 kpc from plane
- $\gtrsim$ few 10^{55} erg
- coincident emission at other wavelengths



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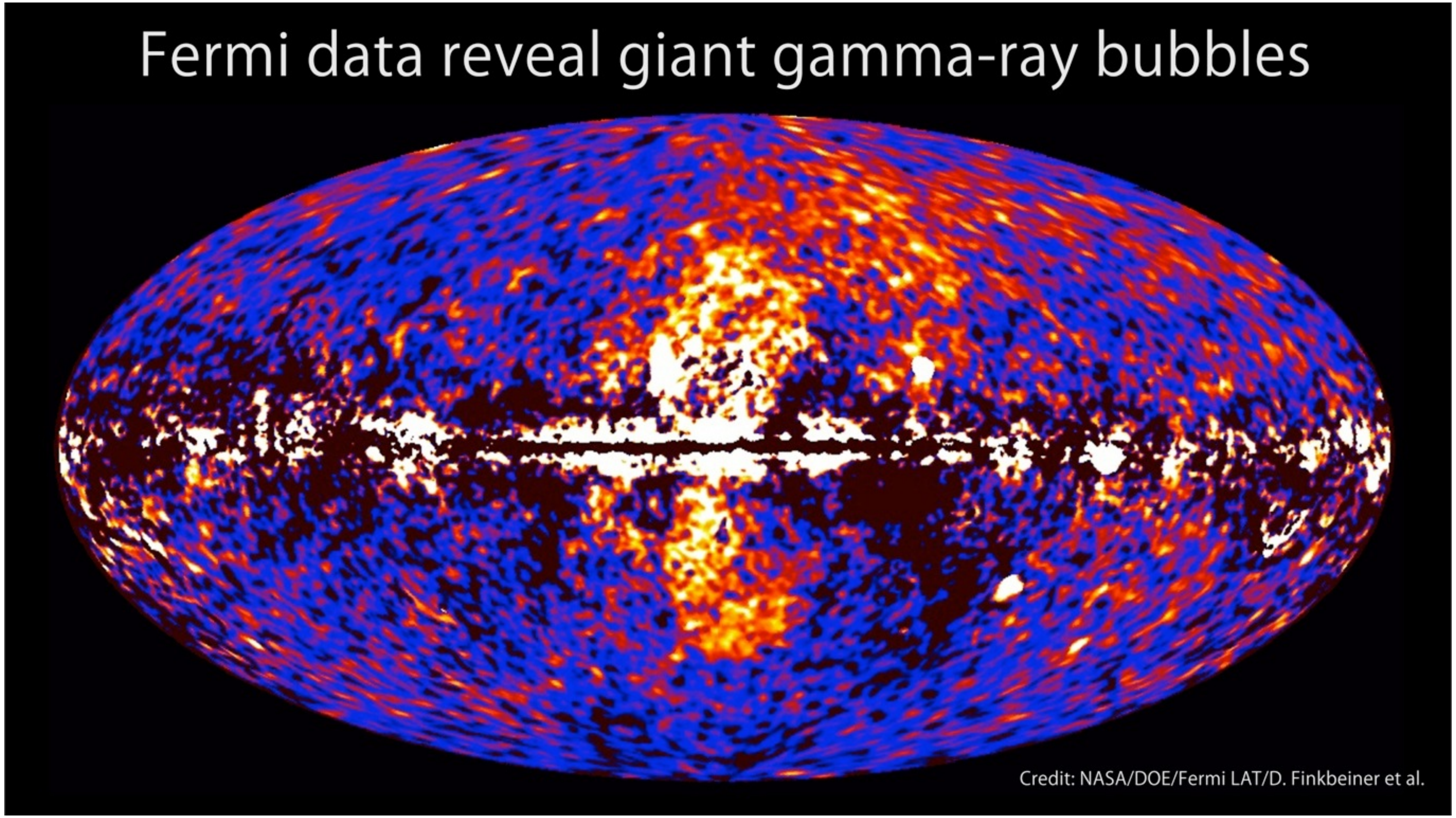
WMAP Haze



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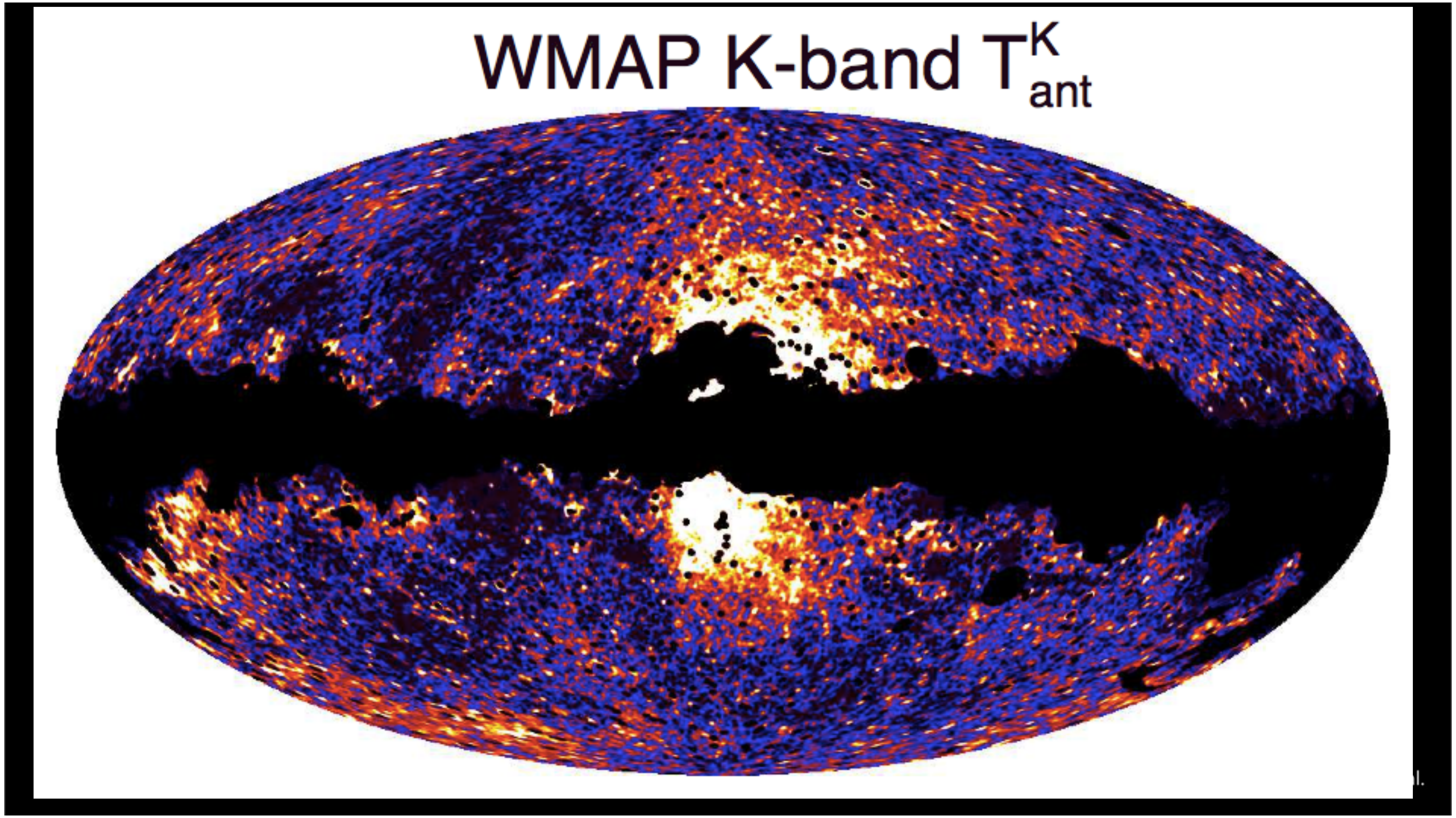
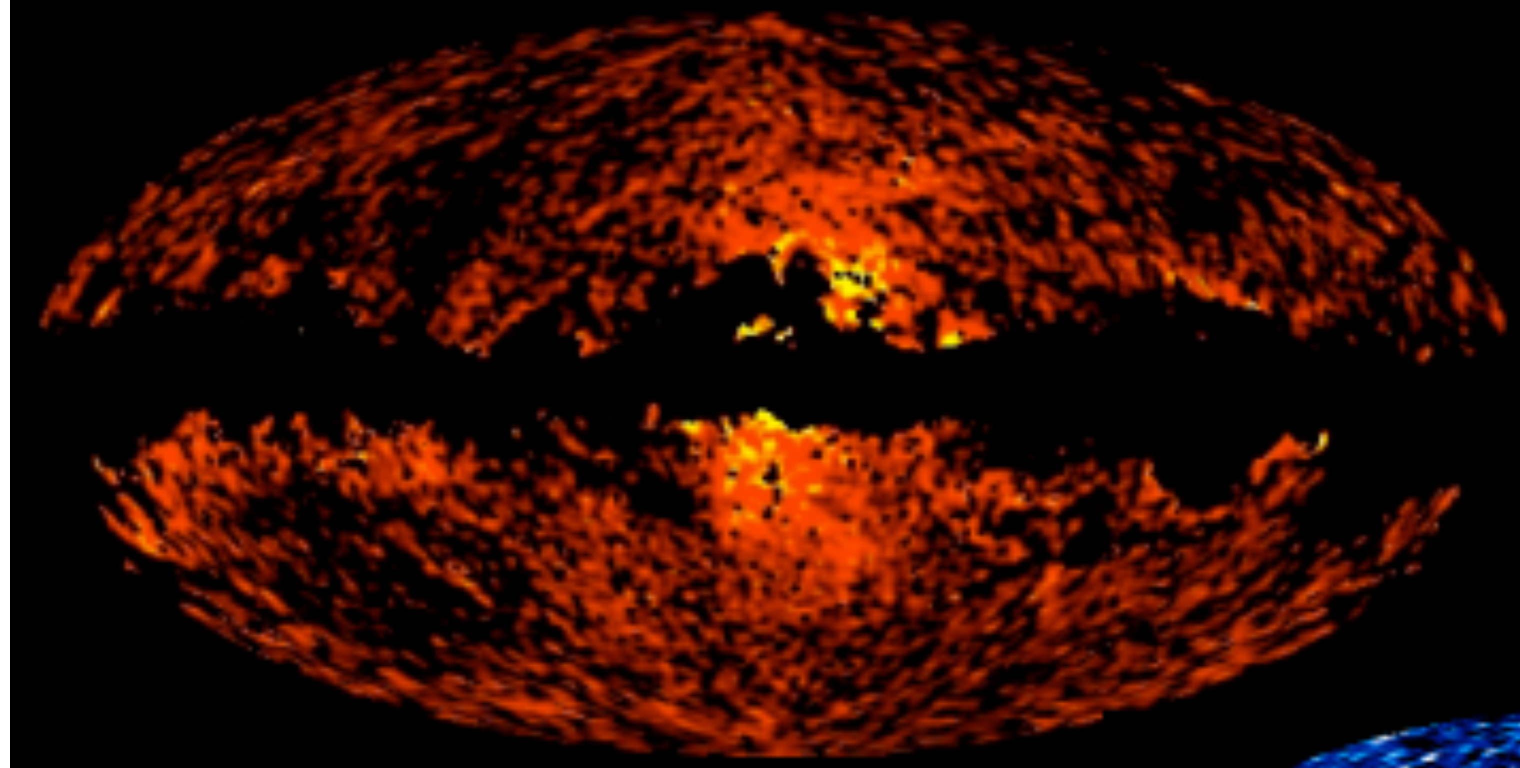
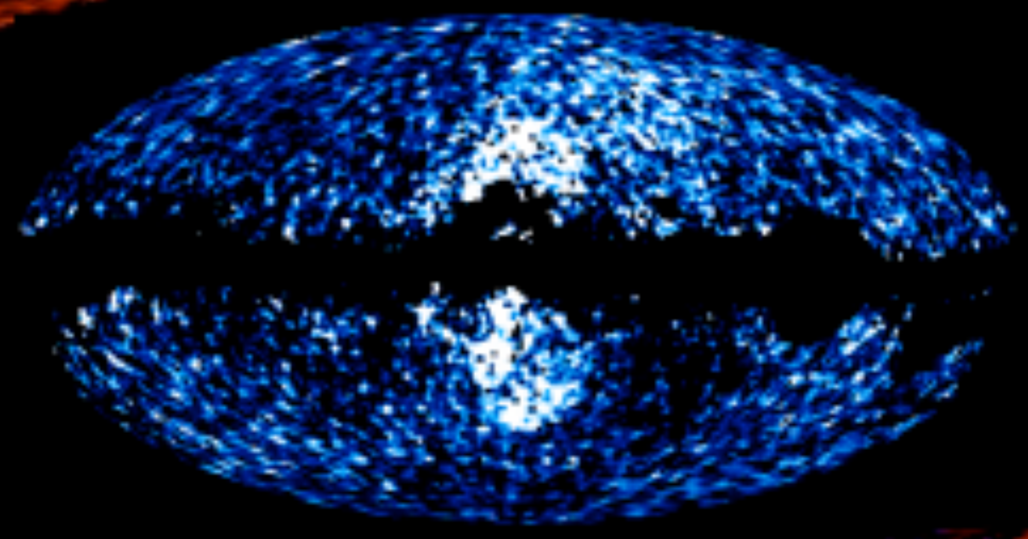


Dobler (2012)

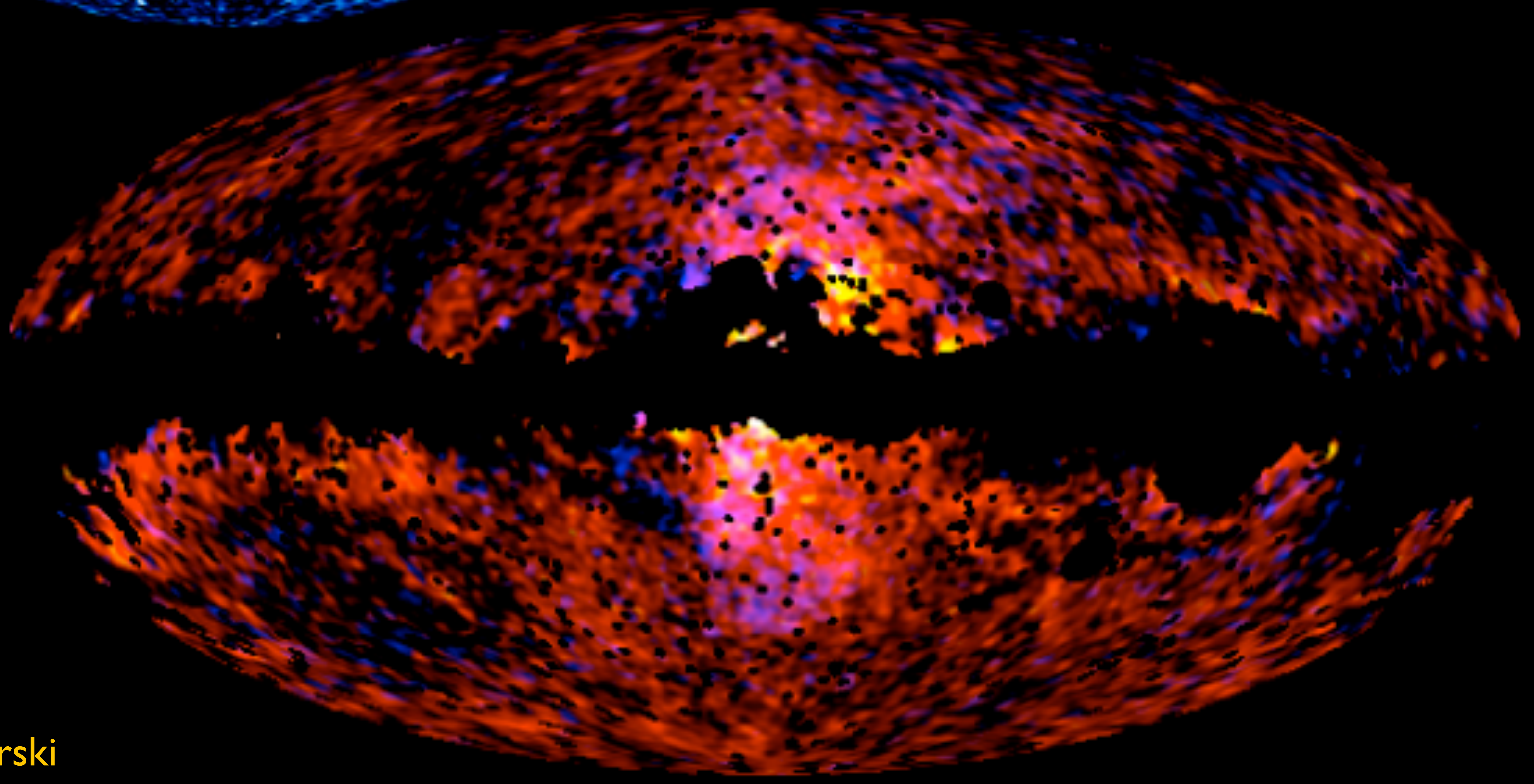
PLANCK images a giant eruption from the heart of the Milky Way



The Galactic haze/bubbles is shown here in *PLANCK* data from *30-44* GHz

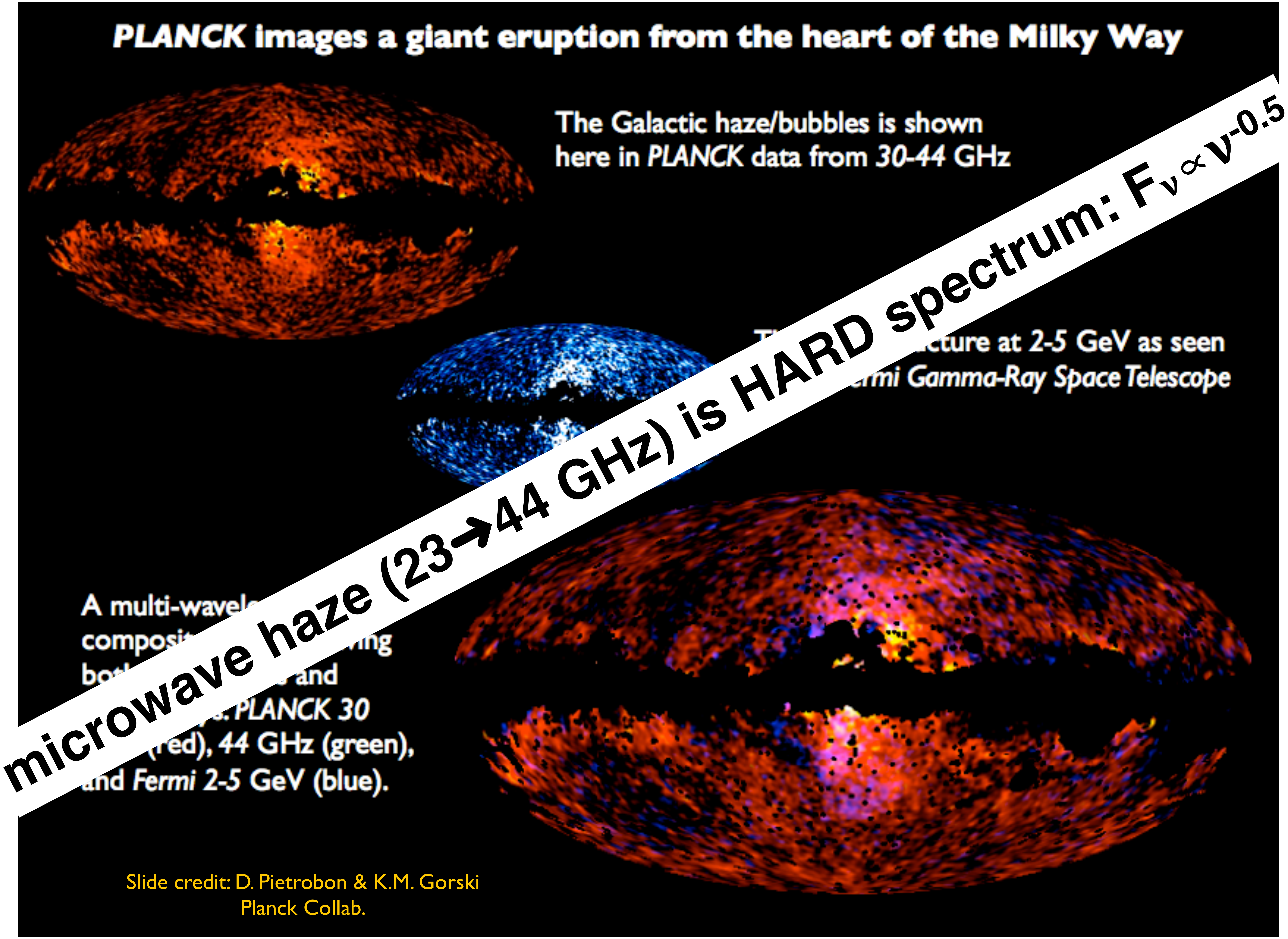


The same structure at 2-5 GeV as seen by the *Fermi Gamma-Ray Space Telescope*



A multi-wavelength composite image showing both microwaves and gamma-rays: *PLANCK 30* GHz (red), 44 GHz (green), and *Fermi* 2-5 GeV (blue).

Slide credit: D. Pietrobon & K.M. Gorski
Planck Collab.



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microwave haze (23→44 GHz) is HARD spectrum: $F_\nu \propto \nu^{-0.5}$
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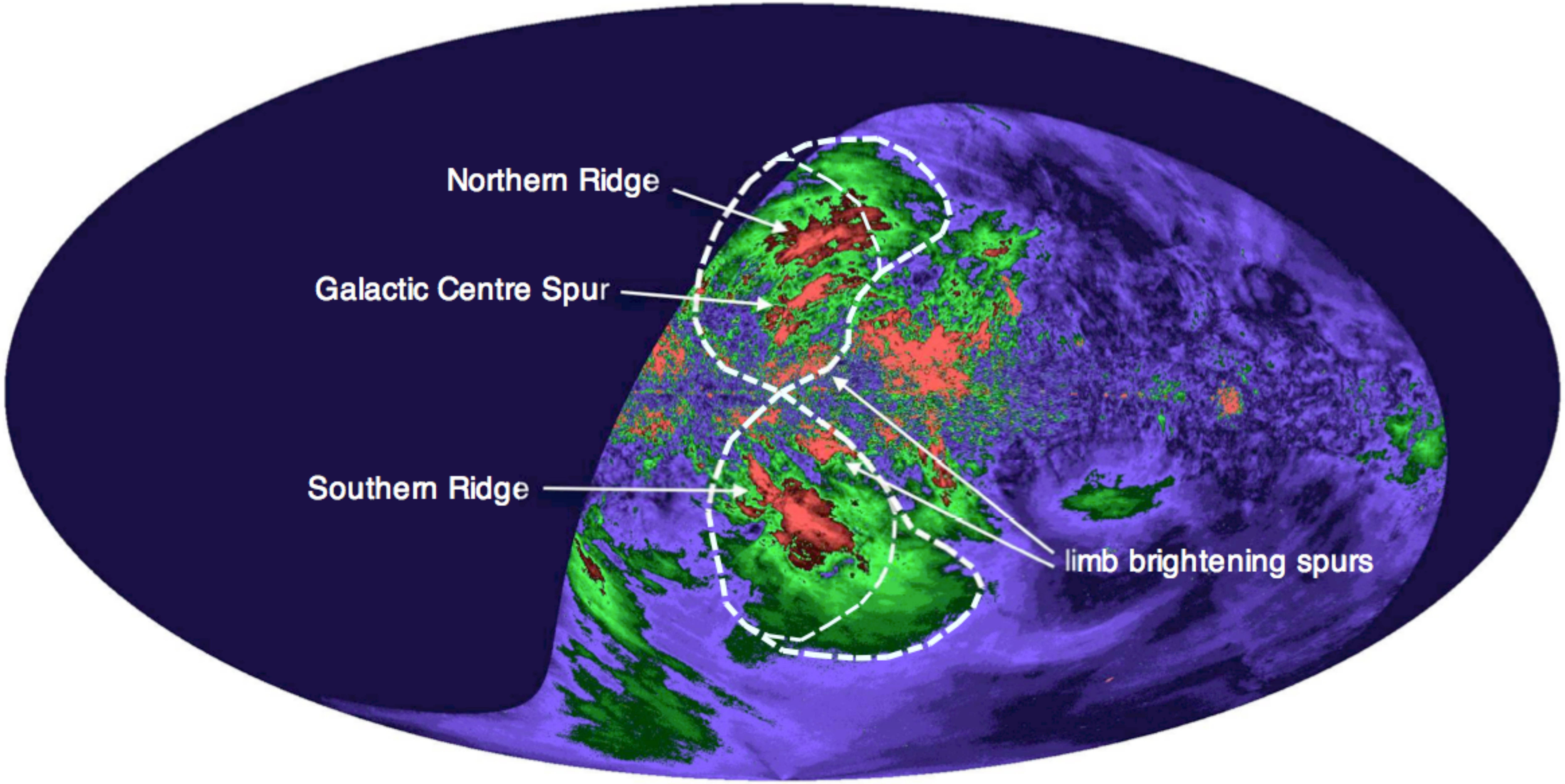
Giant Radio Lobes



Carretti et al. 2013

2.3 GHz **polarized** intensity

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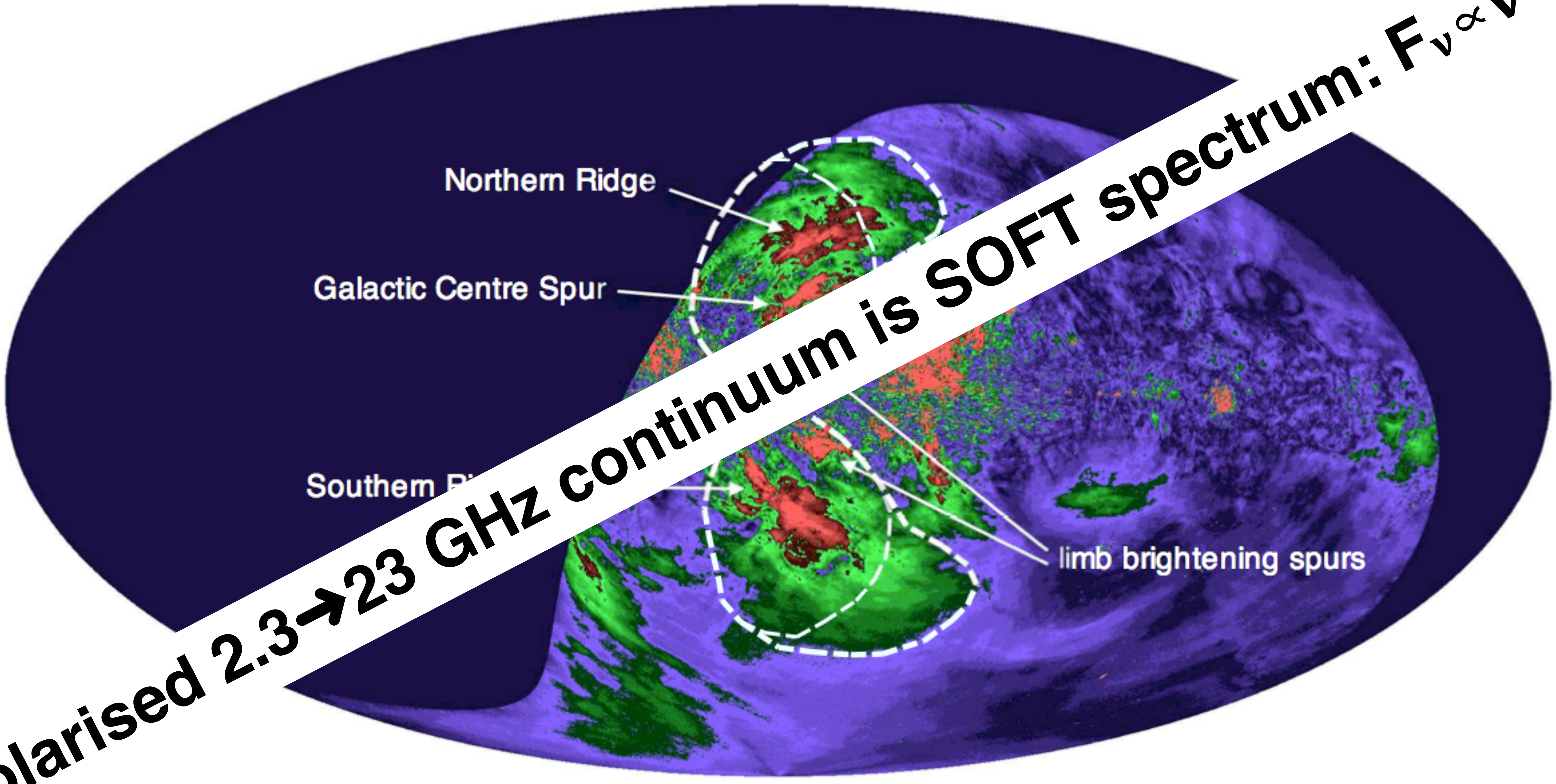

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Fermi Bubbles: Two Interlocking Questions

Q1. What energizes the outflow?

OR

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SMBH at Sgr A*

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…nuclear star-formation

Energetics

- The (photon) Eddington luminosity of Sgr A* ($4 \times 10^6\ M_{Sun}$): 5×10^{44} erg/s
- Star formation in the Galactic Centre at a rate ~0.08 M_{Sun}/yr (Crocker at al. 2011) …*the Galactic Centre is not a Starburst*
- This injects mechanical power (supernova explosions, stellar winds) of

$$P_{mech} \sim 0.08\ M_{Sun}/yr \times 1\ SN/(90\ M_{Sun}) \times 10^{51}\ erg/SN$$

$$= 3 \times 10^{40}\ erg/s$$

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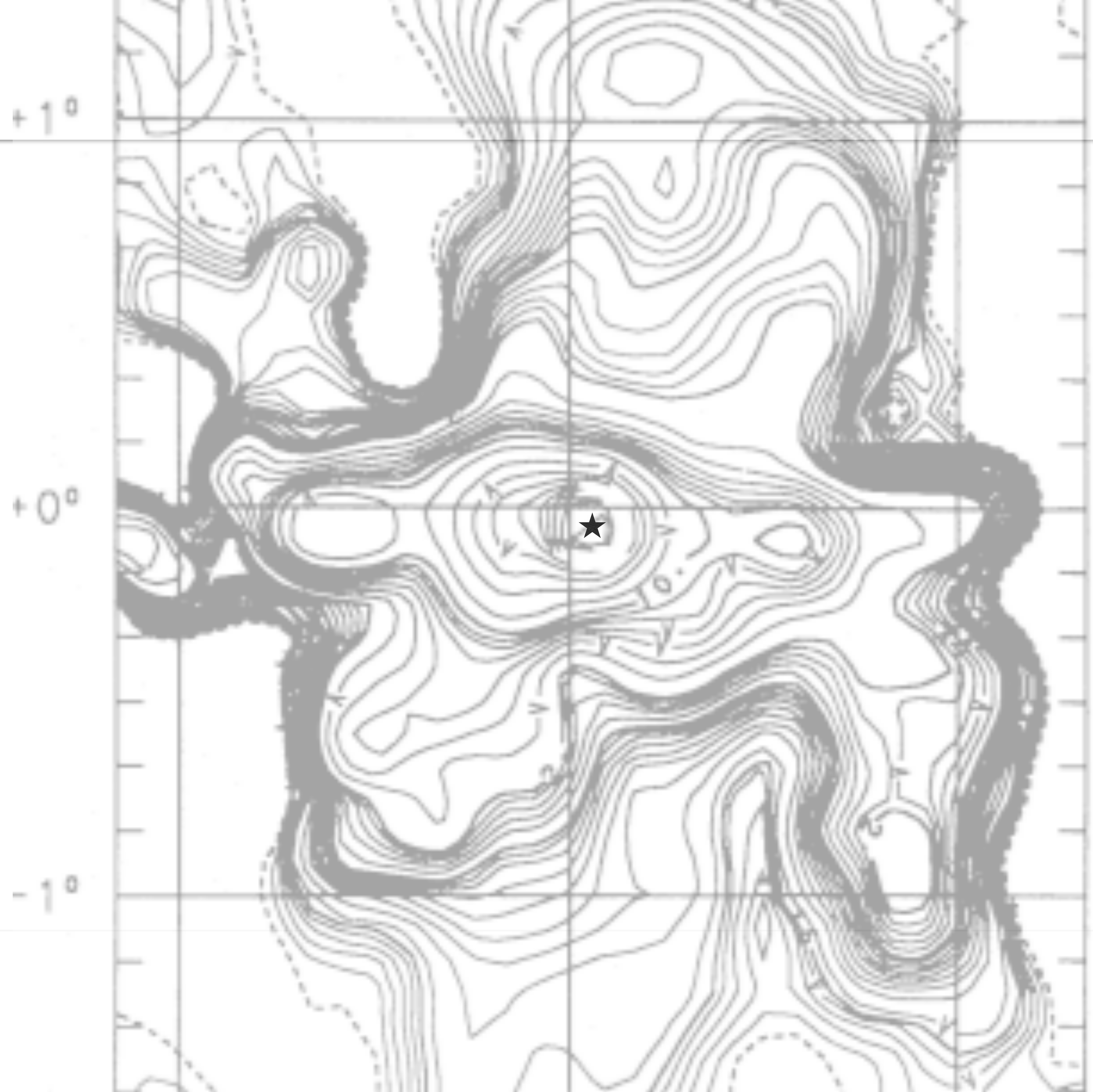
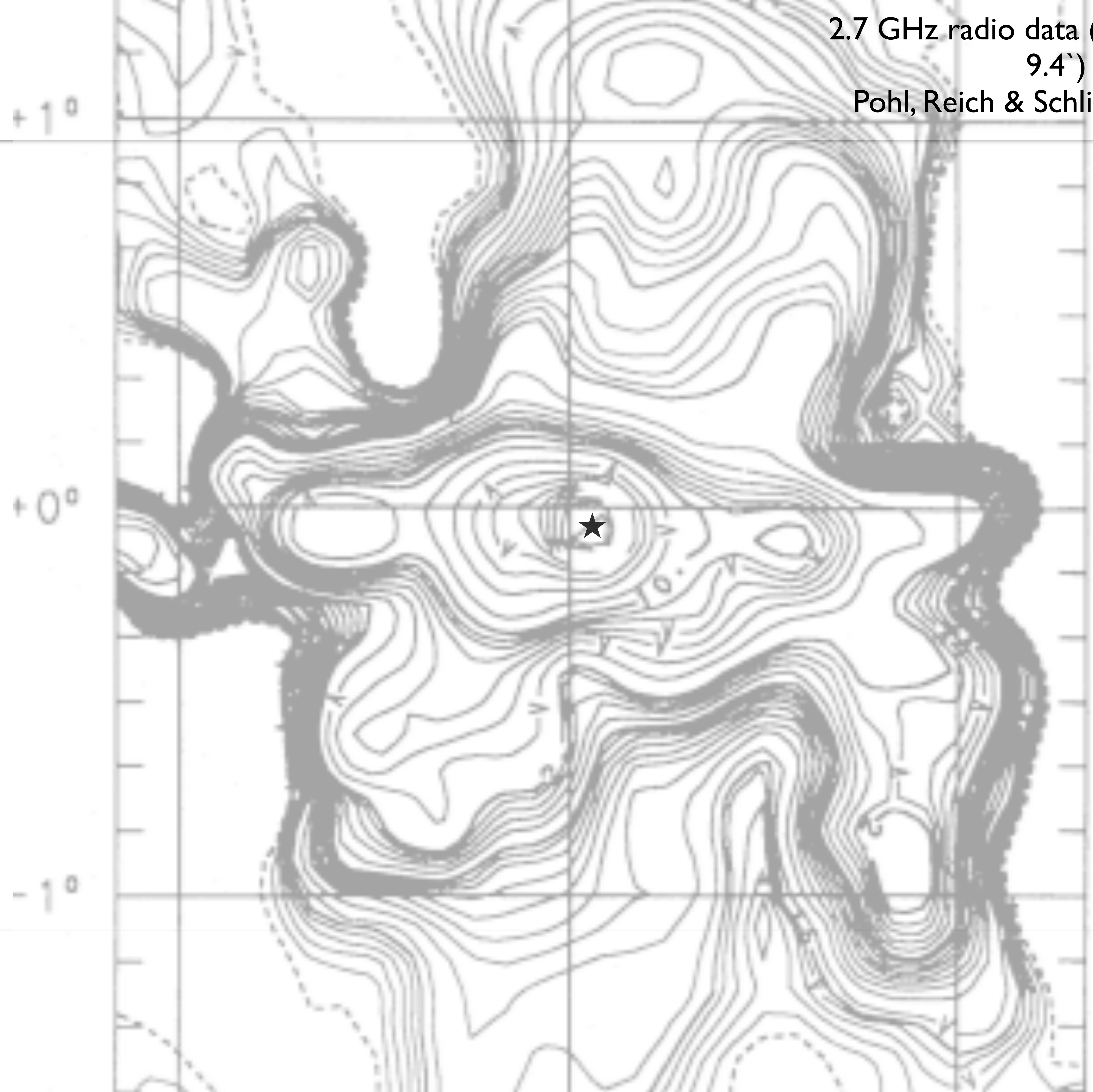
A few words about the Central Molecular Zone…



+1°
+0°
-1°

2.7 GHz radio data (unsharp mask, 9.4`)
Pohl, Reich & Schlickeiser 1992



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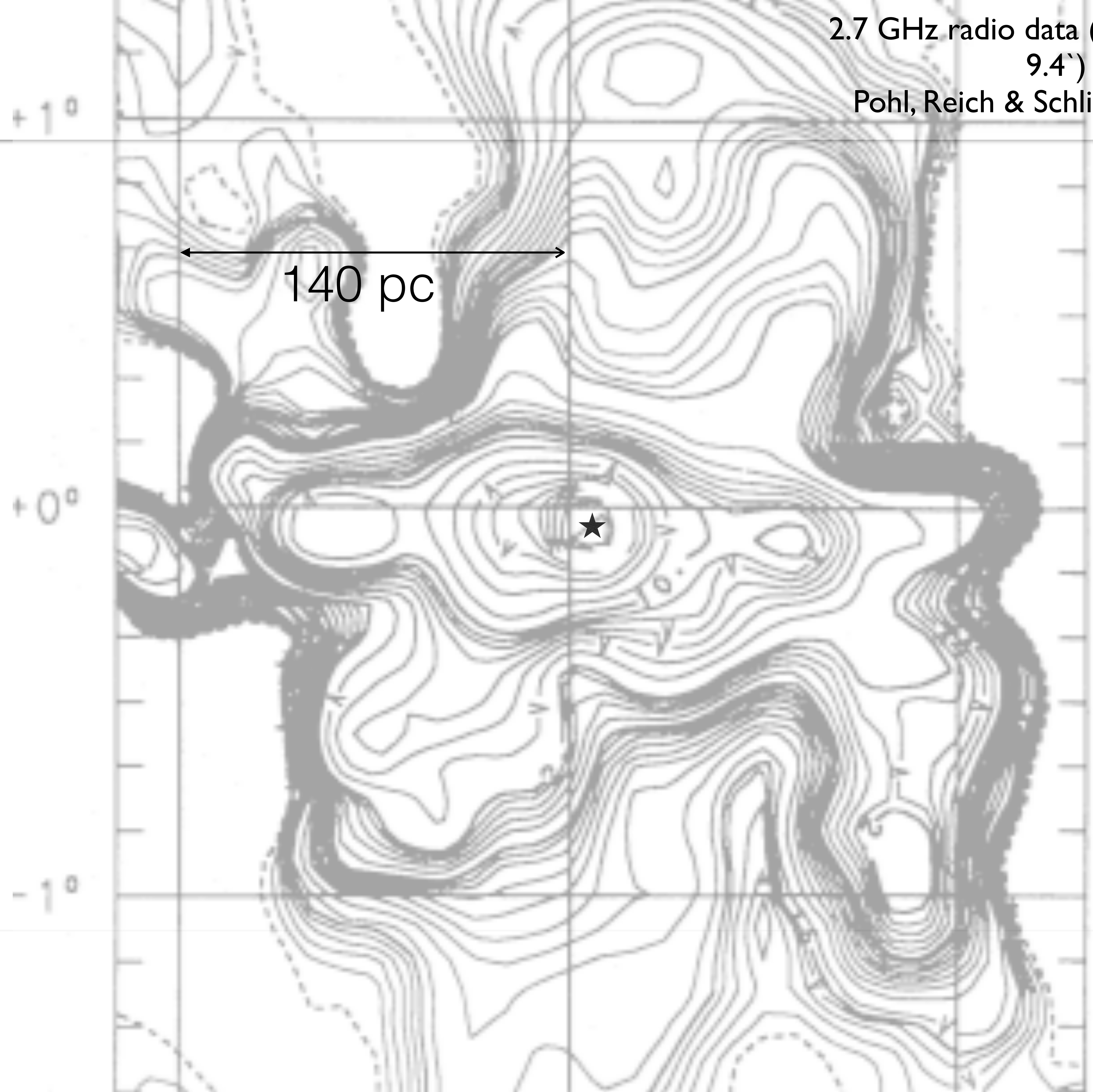

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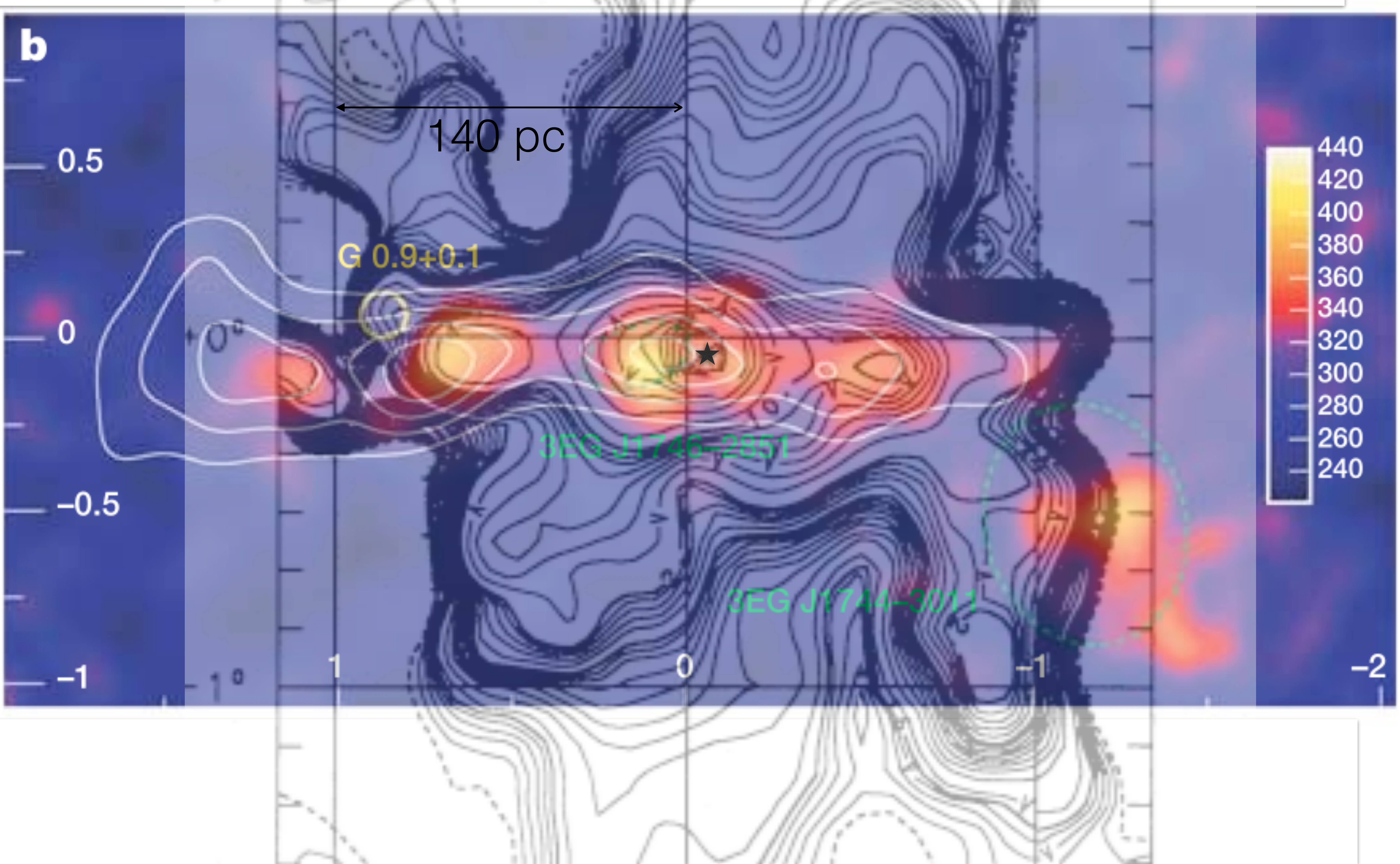

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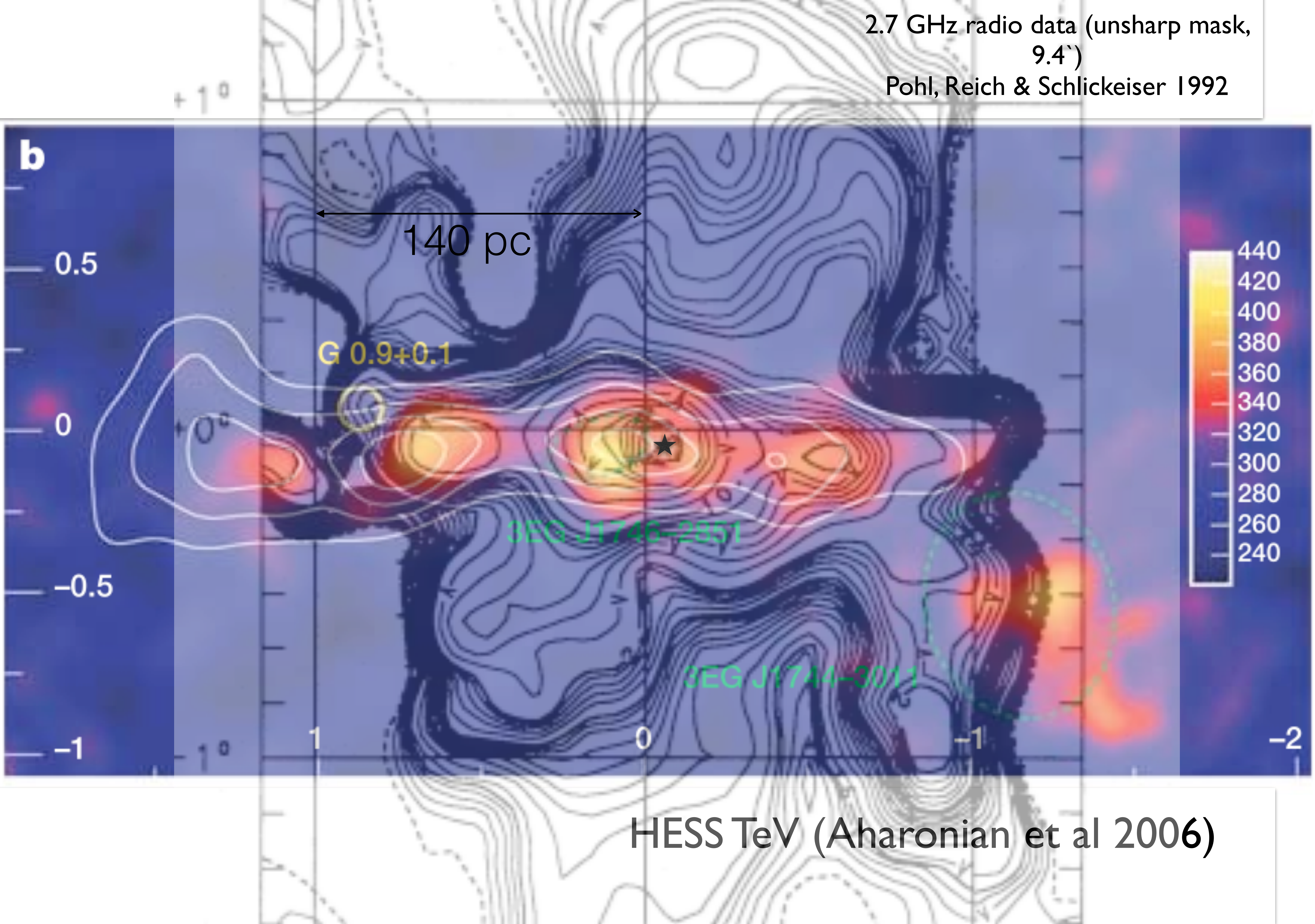

HESS TeV (Aharonian et al 2006)

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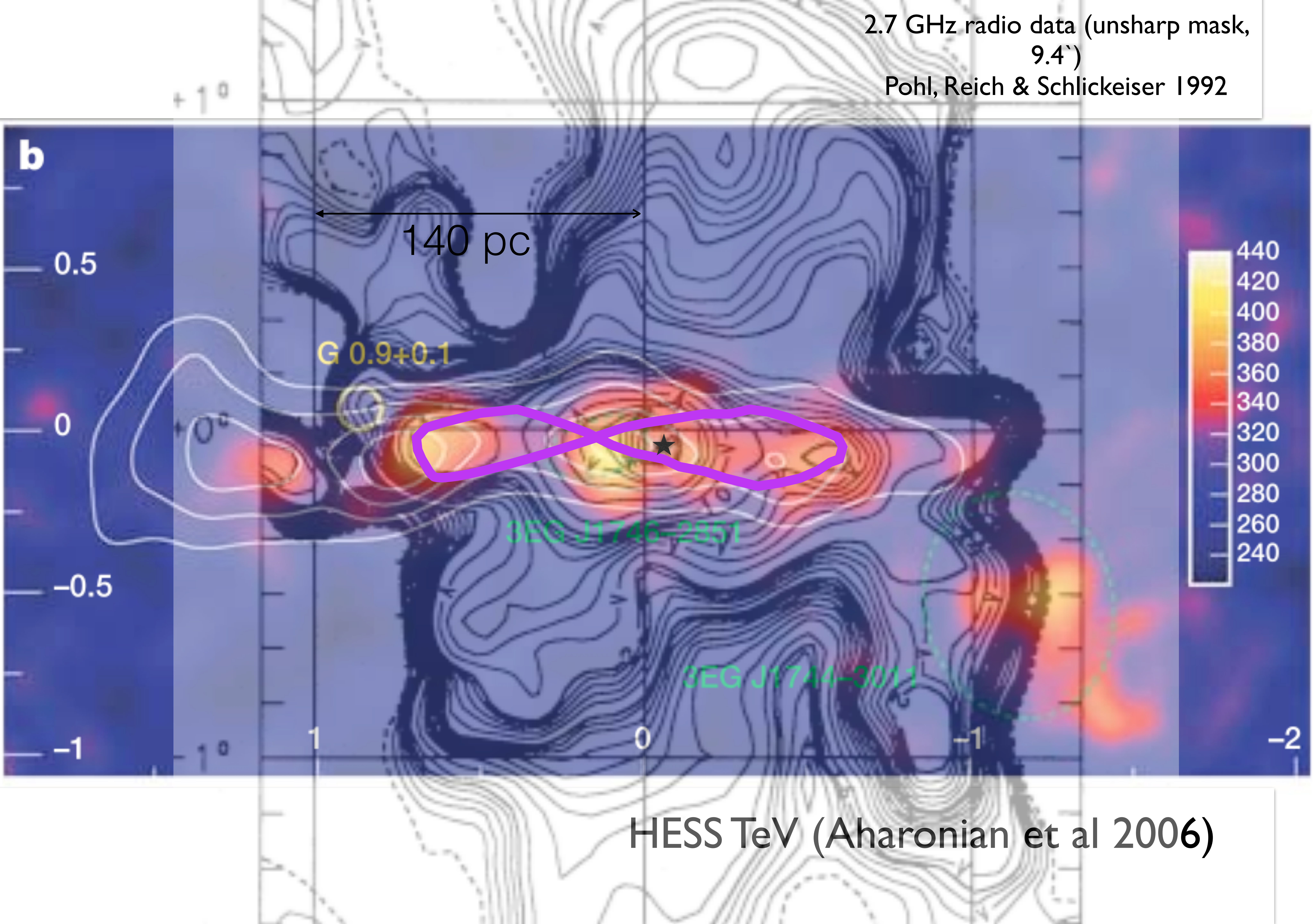

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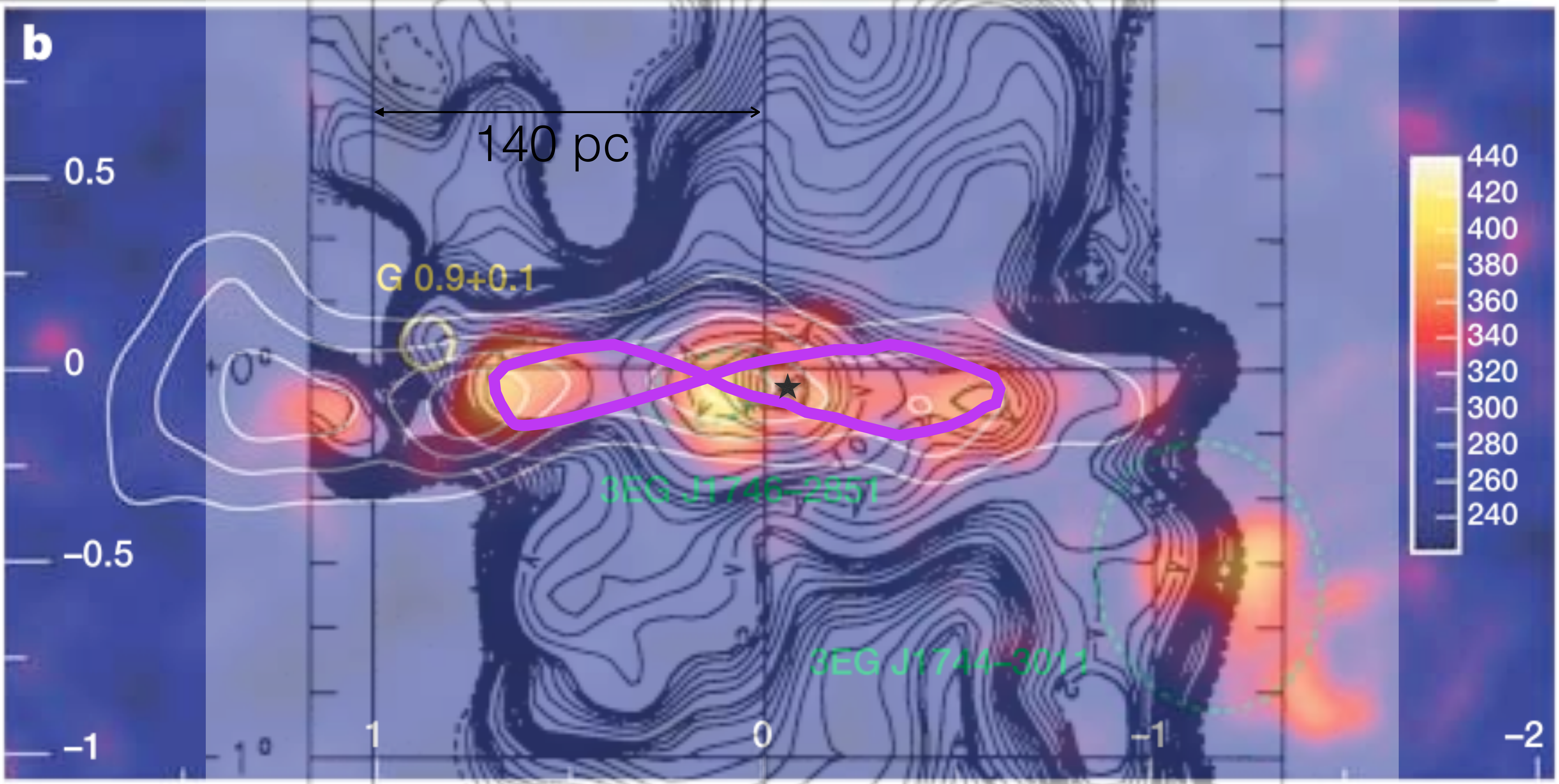

Ring collimates outflow - outflow ablates cold gas

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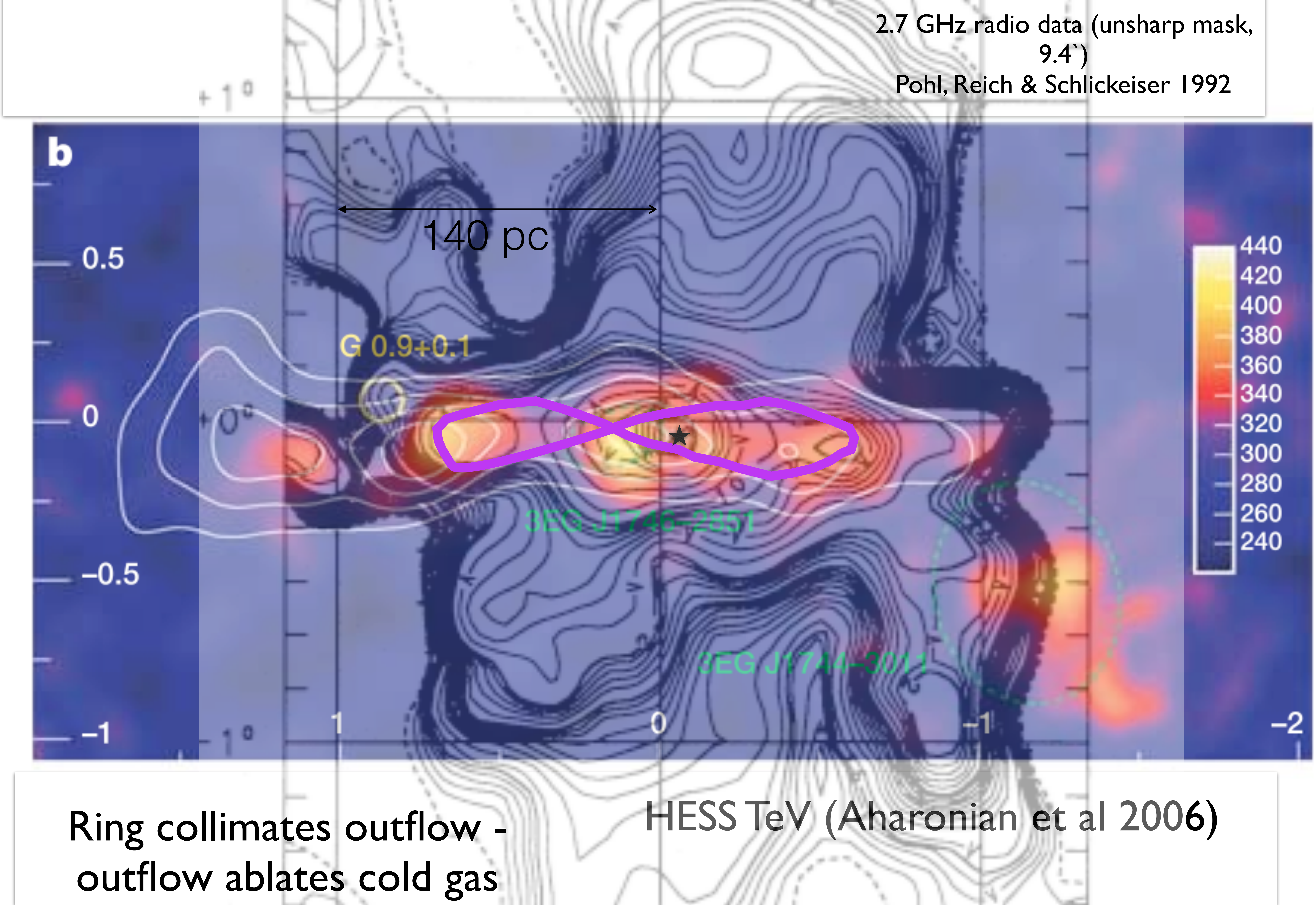

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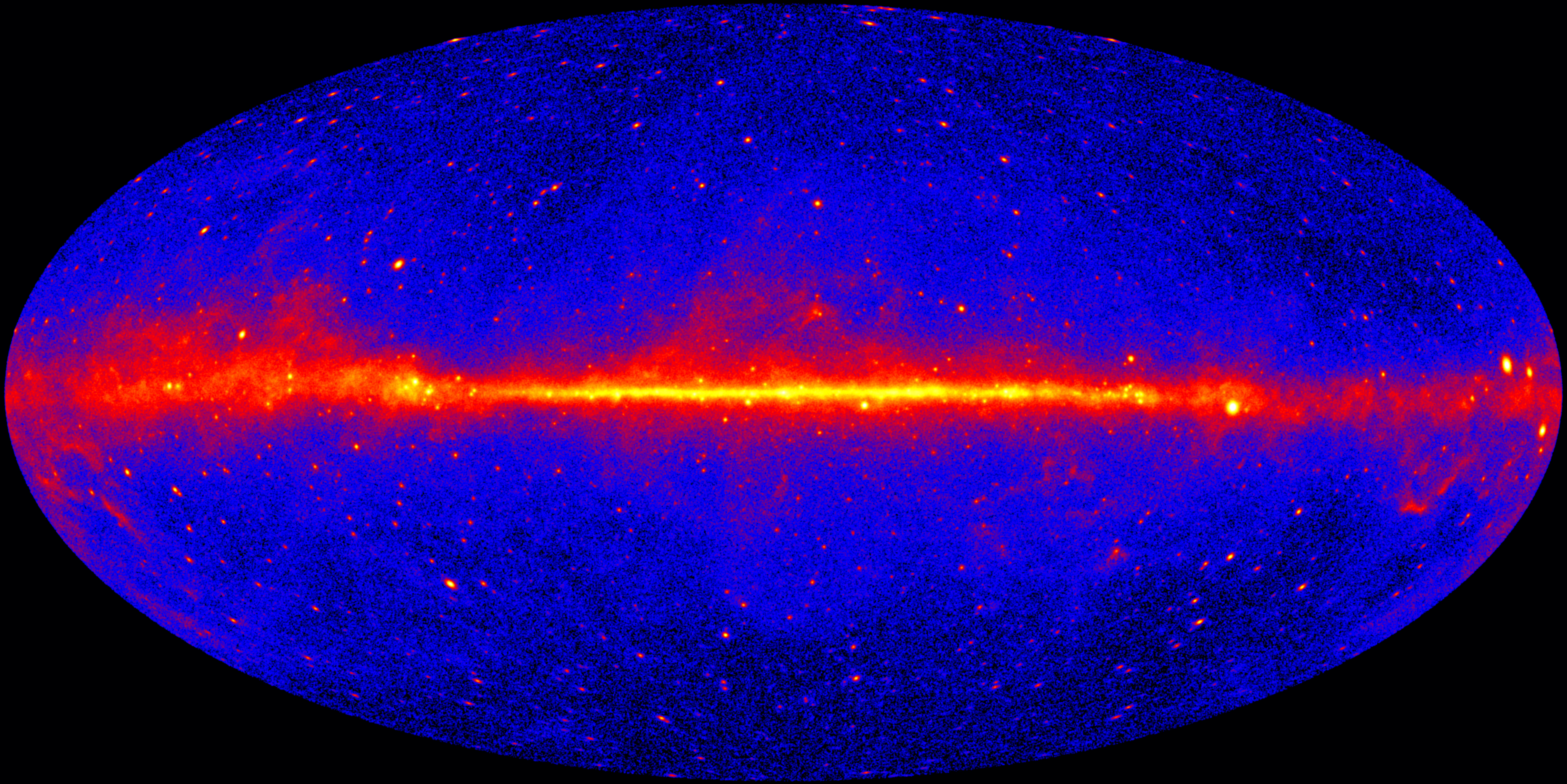


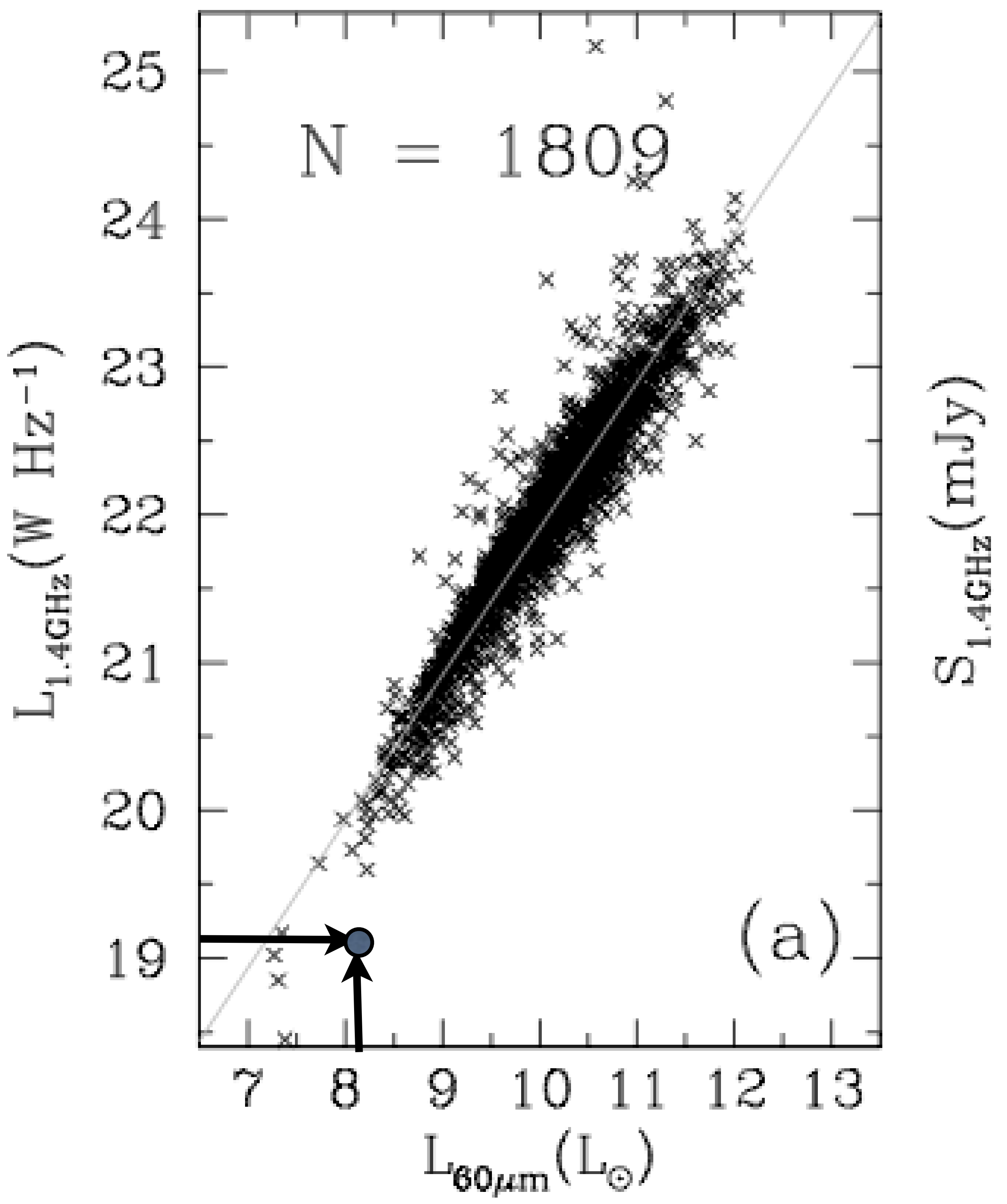
Fermi 5 year >1 GeV


Where is the Galactic Centre?
Fermi 5 year >1 GeV

FIR-RC

Yun et al. 2001 ApJ 554, 803 fig 5

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



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

radio in deficit wrt expectation from FIR

system is 1 dex (> 4σ) off correlation

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

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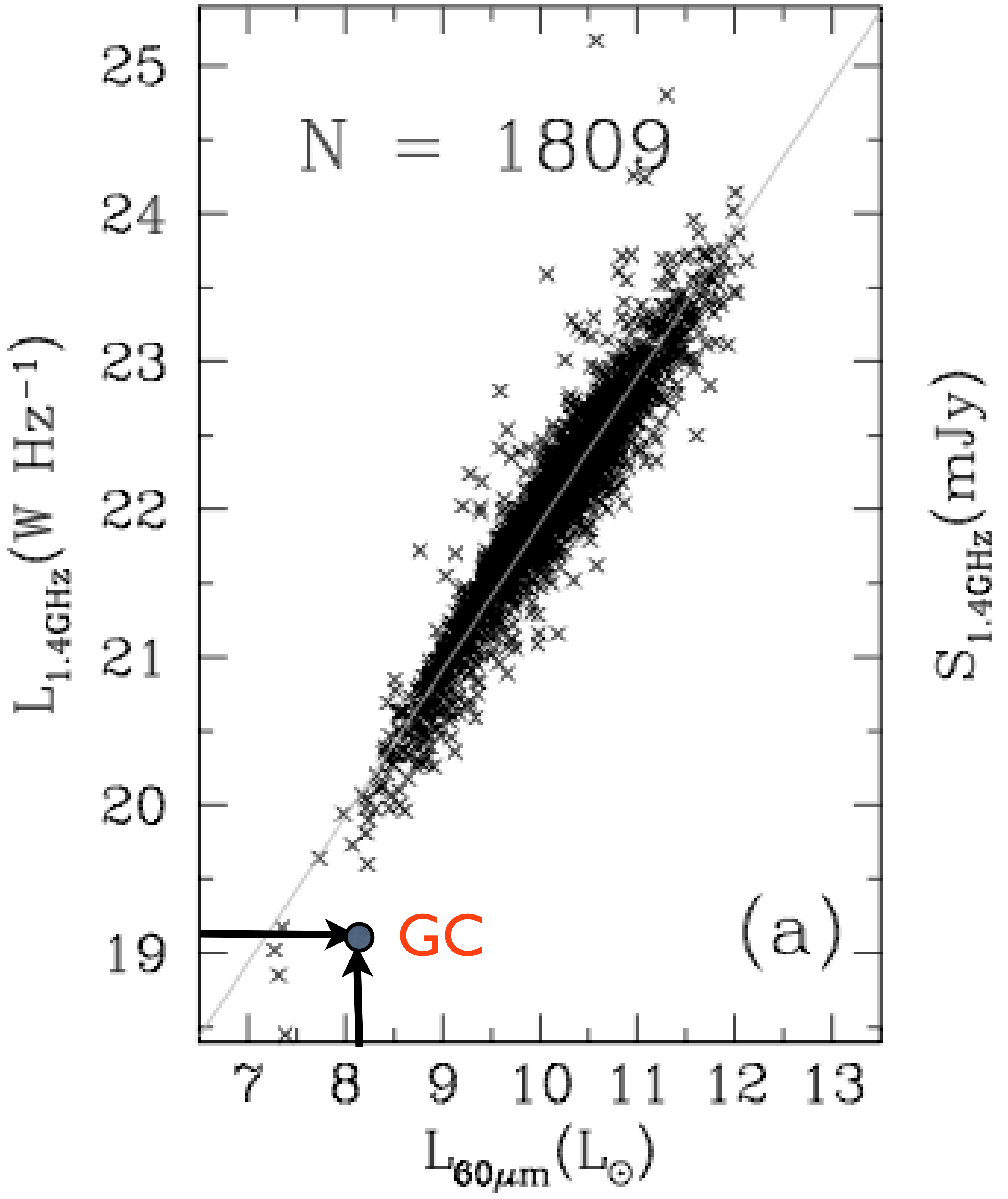

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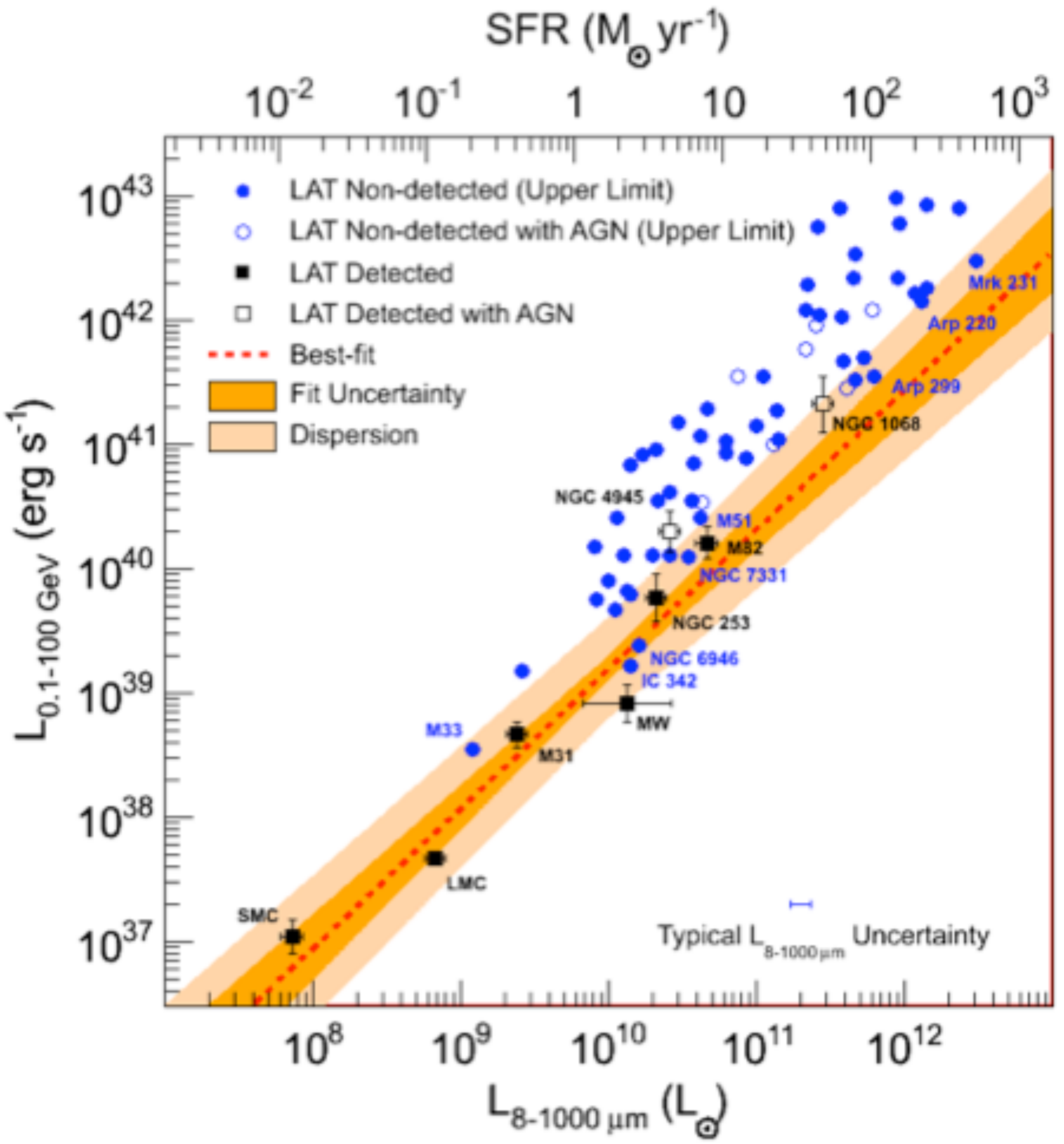
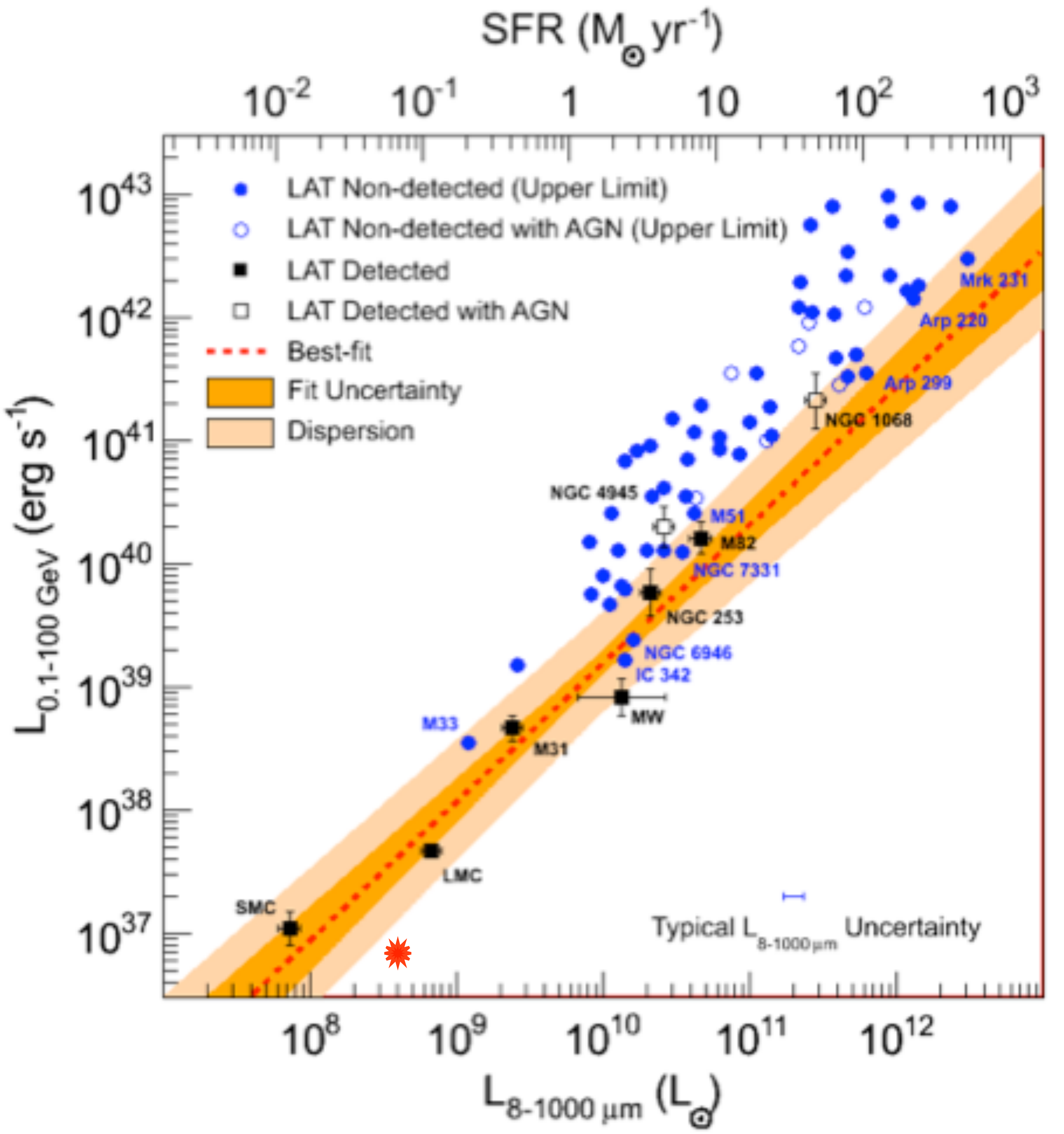


Ackermann et al. 2012 (*Fermi collab*)

Fig. 1. Gamma-ray luminosity (0.1-100 GeV) versus total IR luminosity (8-1000μm).



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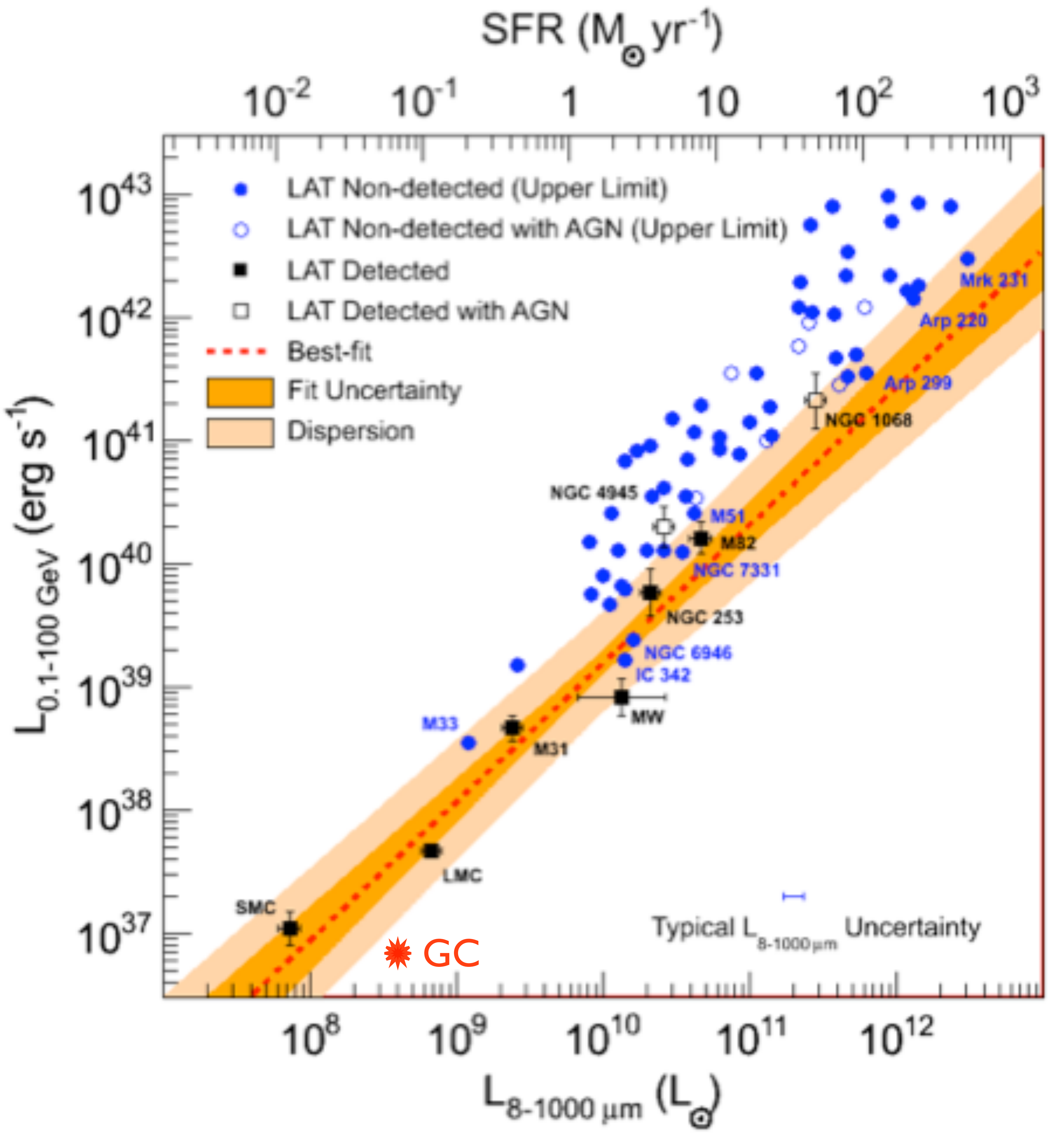

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Fermi Bubbles: Two Interlocking Questions

Q2. What is the radiation mechanism?

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‘**leptonic**’: Cosmic ray electrons/Inverse Compton emission

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‘**leptonic**’: Cosmic ray electrons/Inverse Compton emission

OR

‘**hadronic**’: Cosmic ray protons/gas collisions

Points for/against AGN/IC scenarios

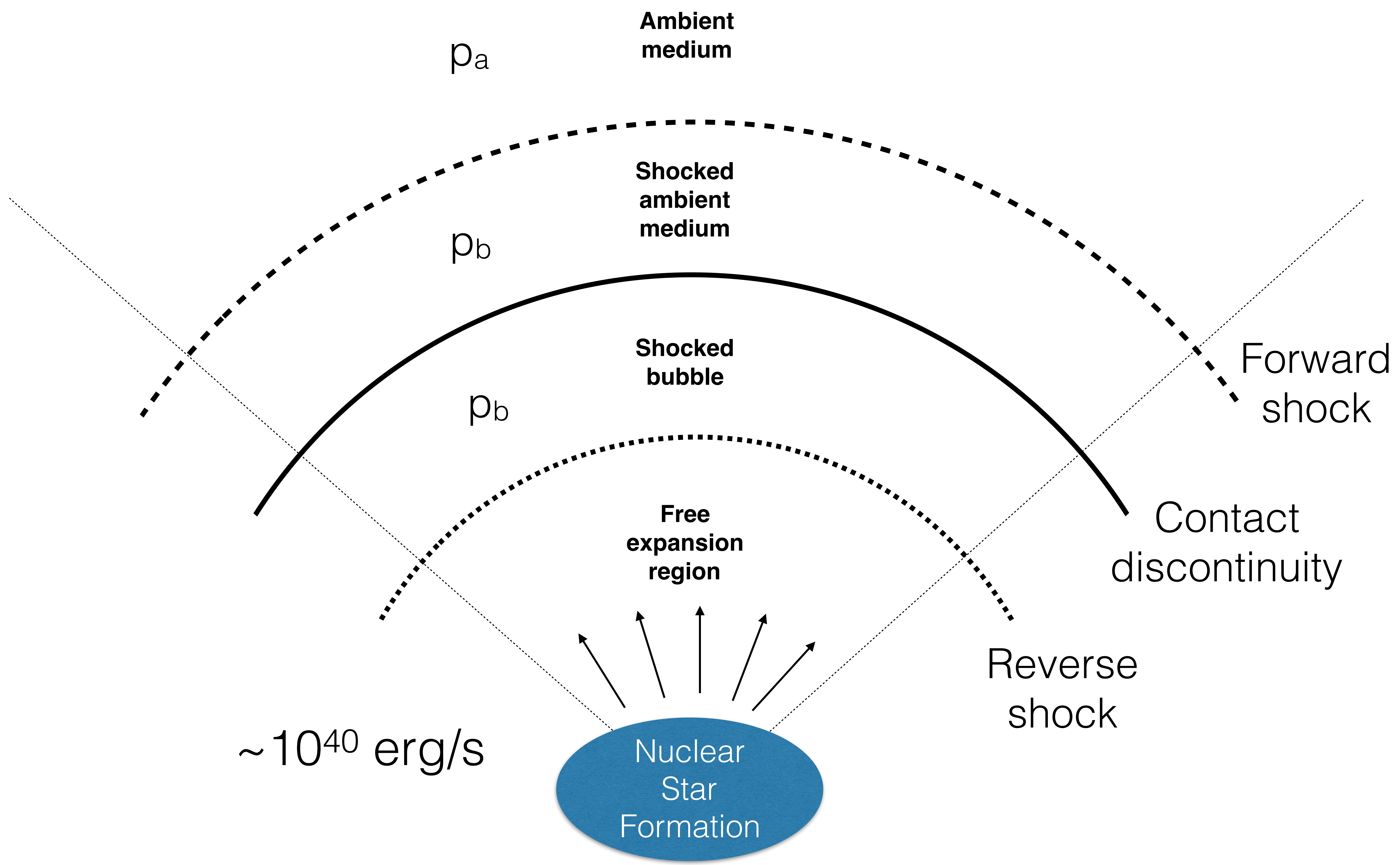
- **PRO**: single electron population can explain both the Bubbles' gamma-ray emission (as IC) and the microwave haze (as synchrotron)
- **PRO**: Hα measurements suggest a hard UV "flash" may have irradiated the Magellanic Stream above the nucleus 1-3 Myr ago (Bland-Hawthorn et al. 2013) [but the Hα emission might also be explained by shocks: Bland-Hawthorn et al. 2007]
- **CON**: we are required to be seeing the Bubbles at a privileged time
- **CON**: Lack of a bright/hot X-ray edge suggests that Bubbles are expanding, at most, at the sound speed 300 km/s (Tahara et al. 2015, Karaoke et al. 2015)
- **CON:** ***Steep***-spectrum polarized radio lobes coincident with Bubbles imply an electron population with age > 3 10^7 year
- **CON:** Difficult to understand why gamma-ray spectrum does not evolve strongly (may even harden) with latitude in an IC model

Points for/against SF/hadronic scenarios

- **PRO**: Bubbles' gamma-ray luminosity requires a source of protons of power ~10^{39} erg/s *in saturation*…this *is* the approximate power supplied by nuclear SF to cosmic rays that escape the GC
- **CON:** *Secondary* electrons can supply microwave synchrotron radiation but predict a too-steep spectrum to explain the haze
- **CON**: Structures have to maintain coherence for very long timescales

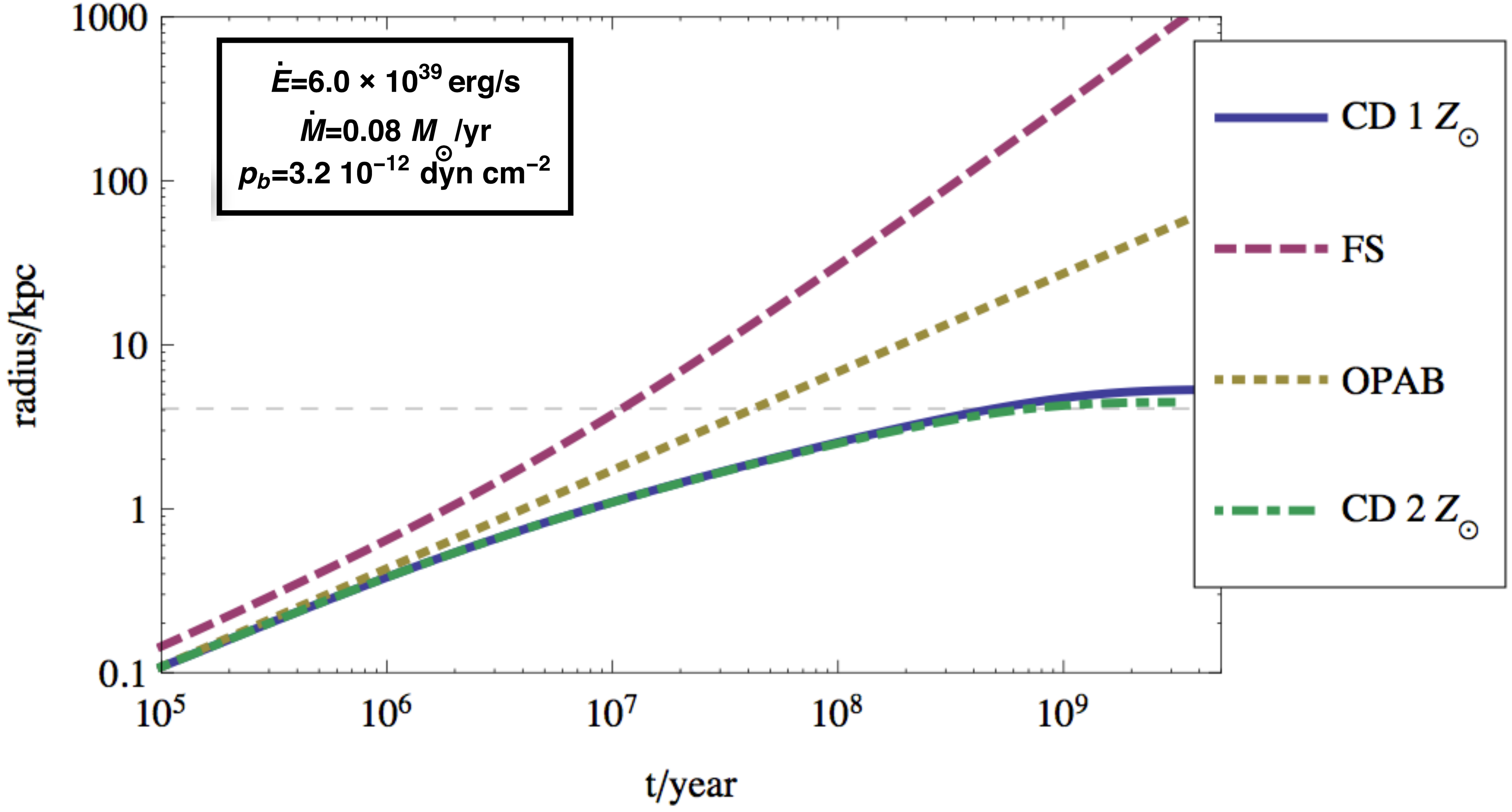
The Fermi Bubbles *as Bubbles*

Crocker, Bicknell, Taylor & Carretti 2015, ApJ *808, 107*



Ambient medium
p_a
Shocked ambient medium
p_b
Shocked bubble
p_b
Forward shock
Contact discontinuity
Free expansion region
Reverse shock
$\sim 10^{40}$ erg/s
Nuclear Star Formation

Expansion of a radiative bubble into finite (const) pressure medium



$$V_{\rm f} \simeq \frac{\dot{E}}{n_{\rm tot}^2 \Lambda[T]} = \frac{5/2\ \dot{M}/(\mu {\rm m})\ k_B T_{\rm FB}}{n_{\rm tot}^2 \Lambda[T]}$$

Crocker et al. 2015

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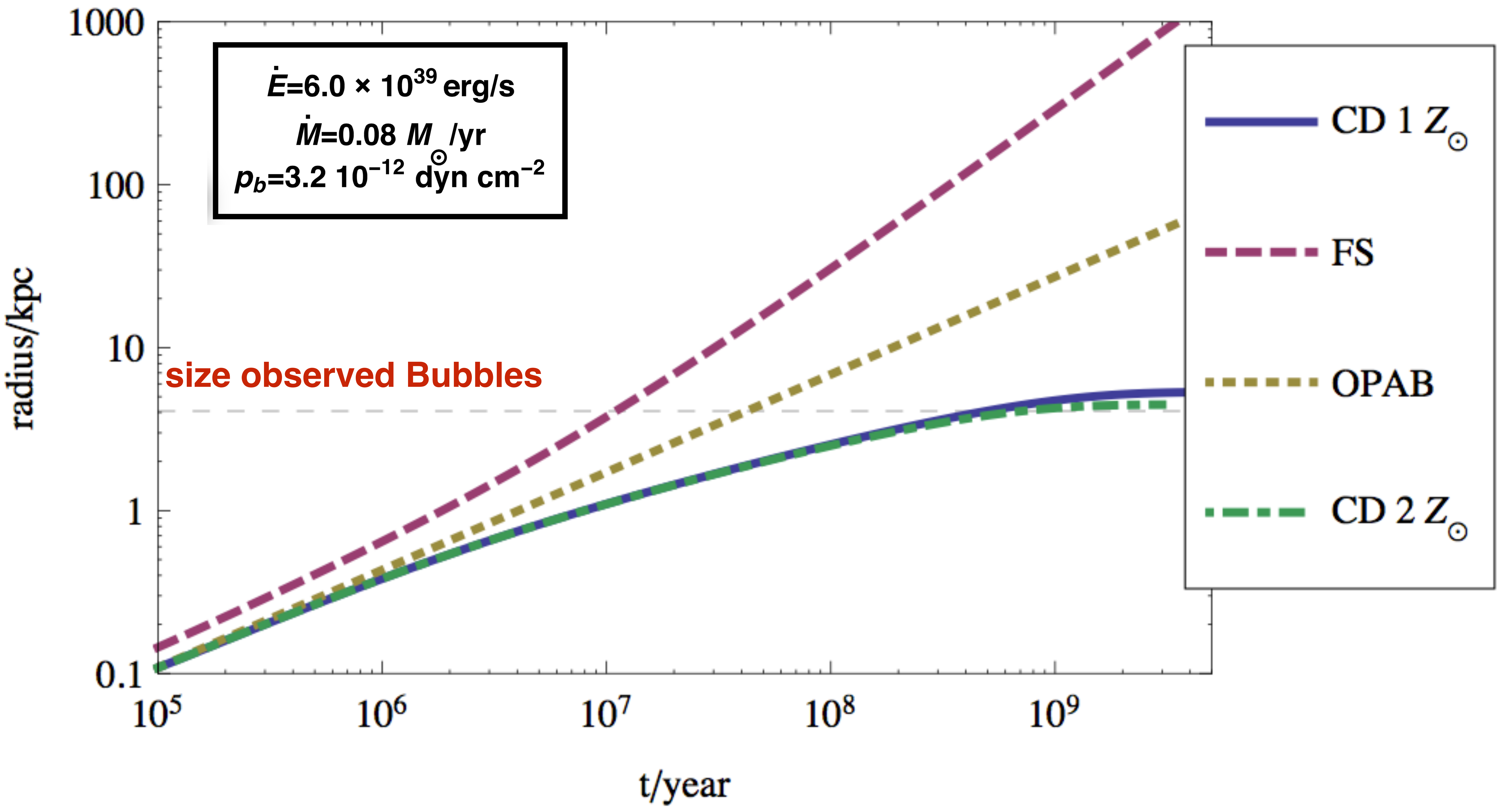

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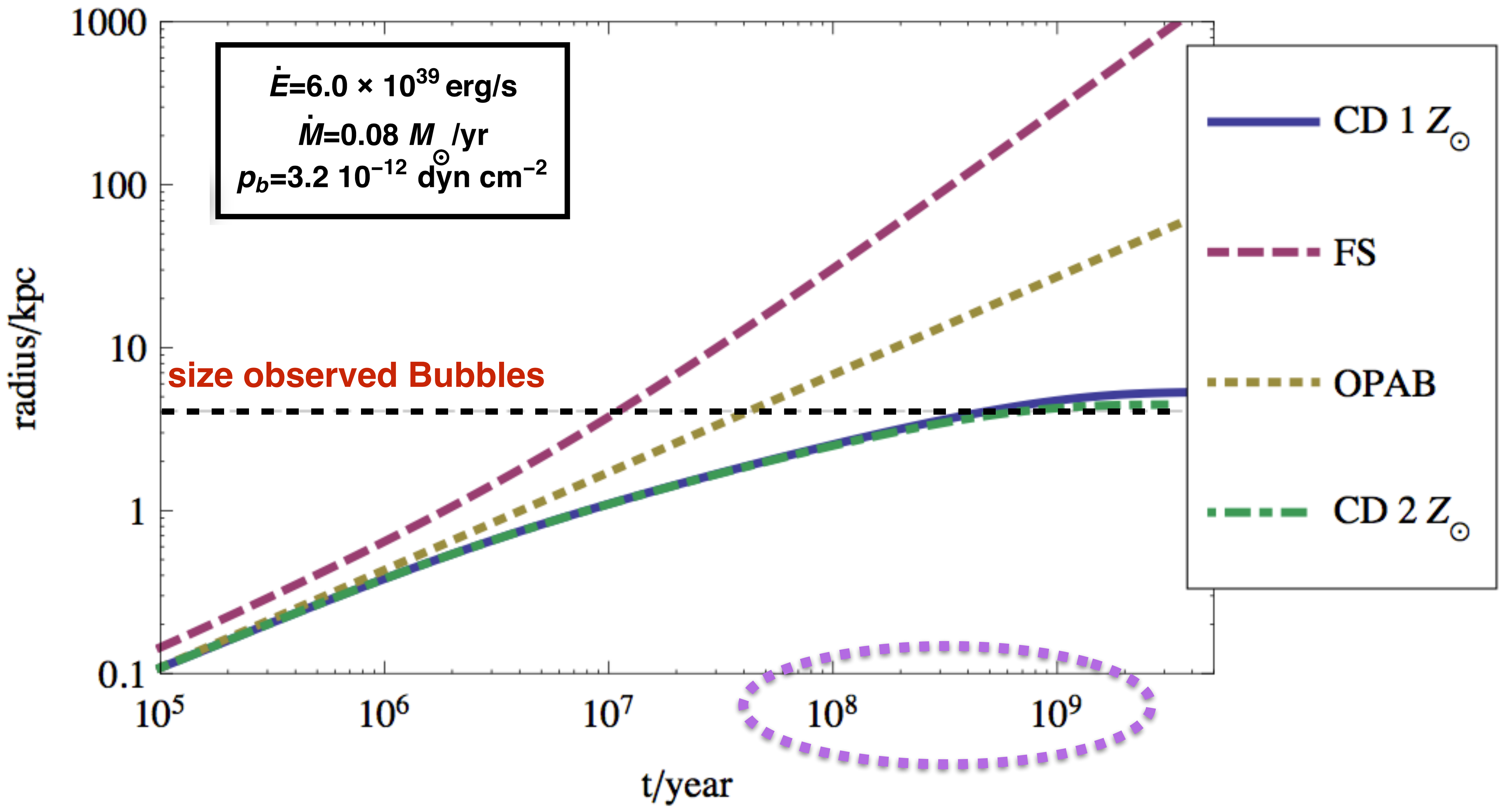

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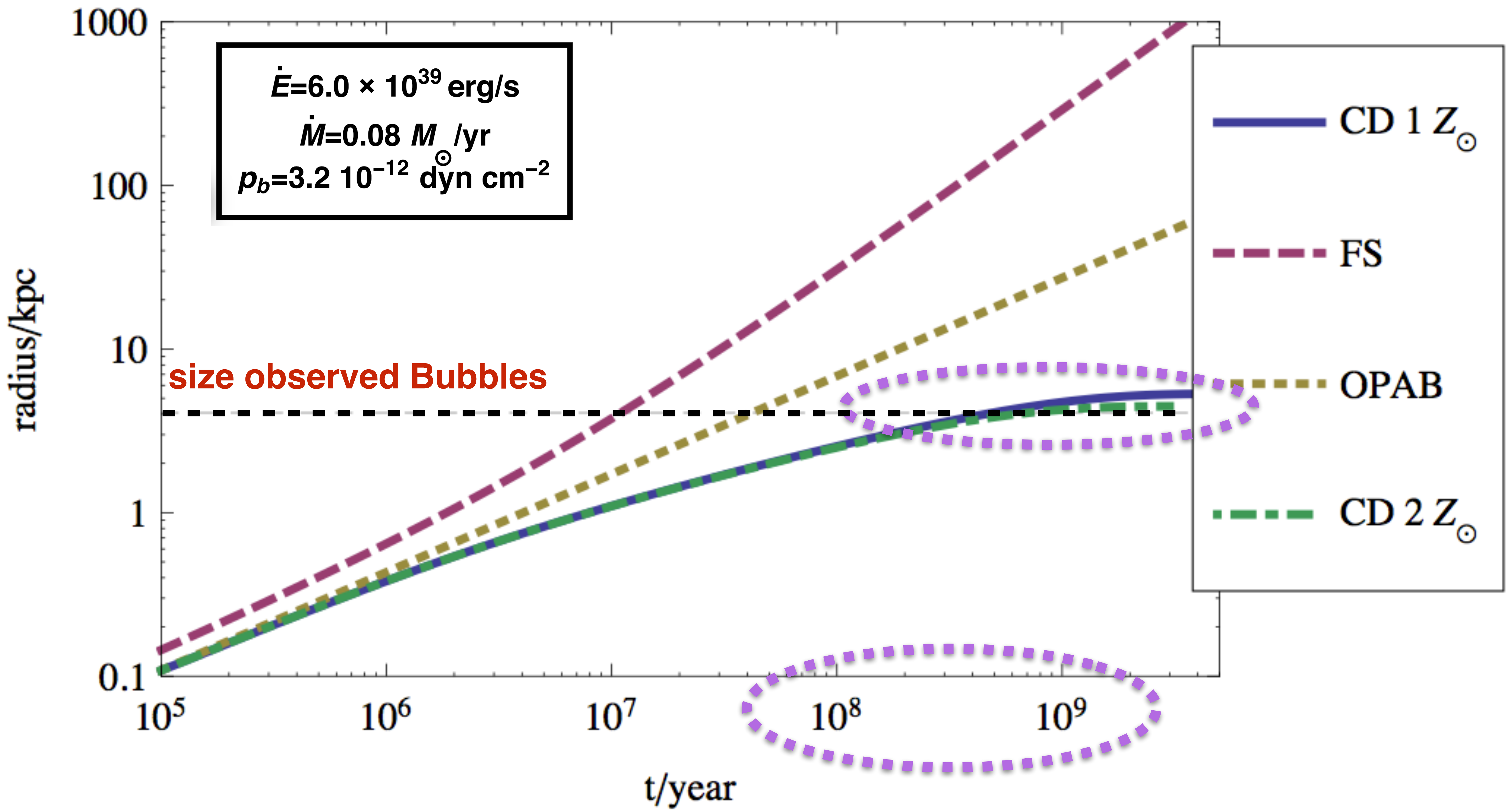

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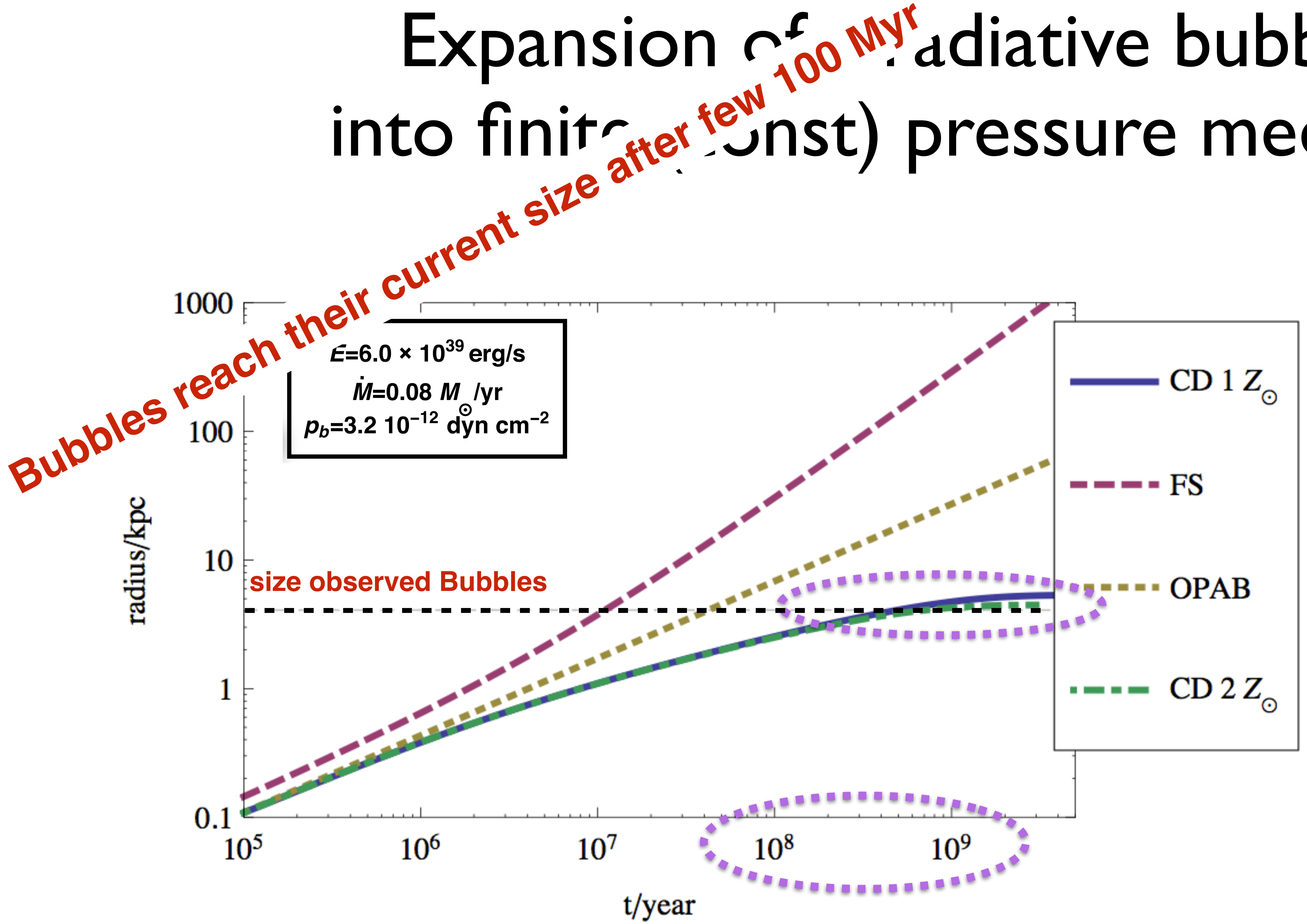

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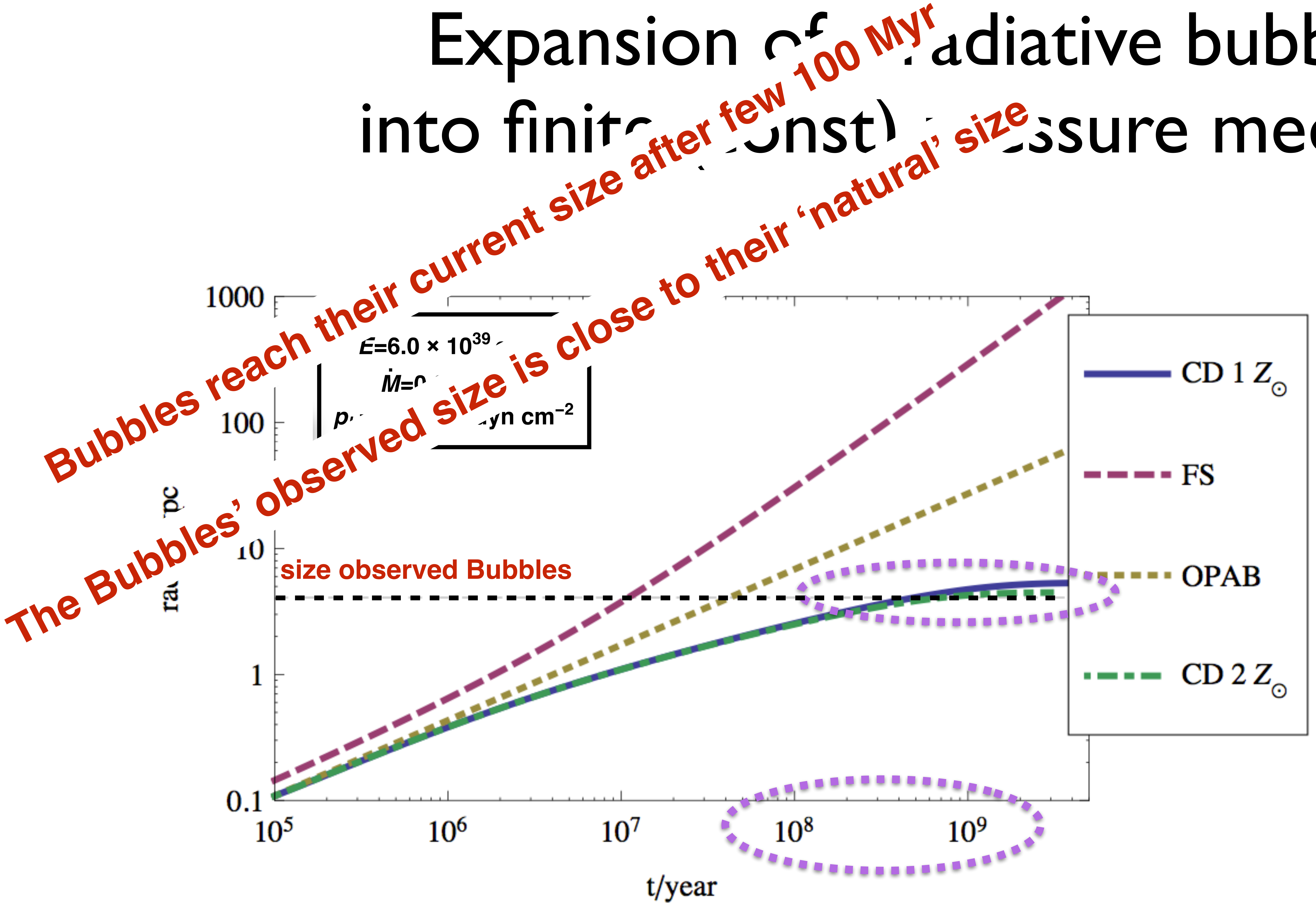

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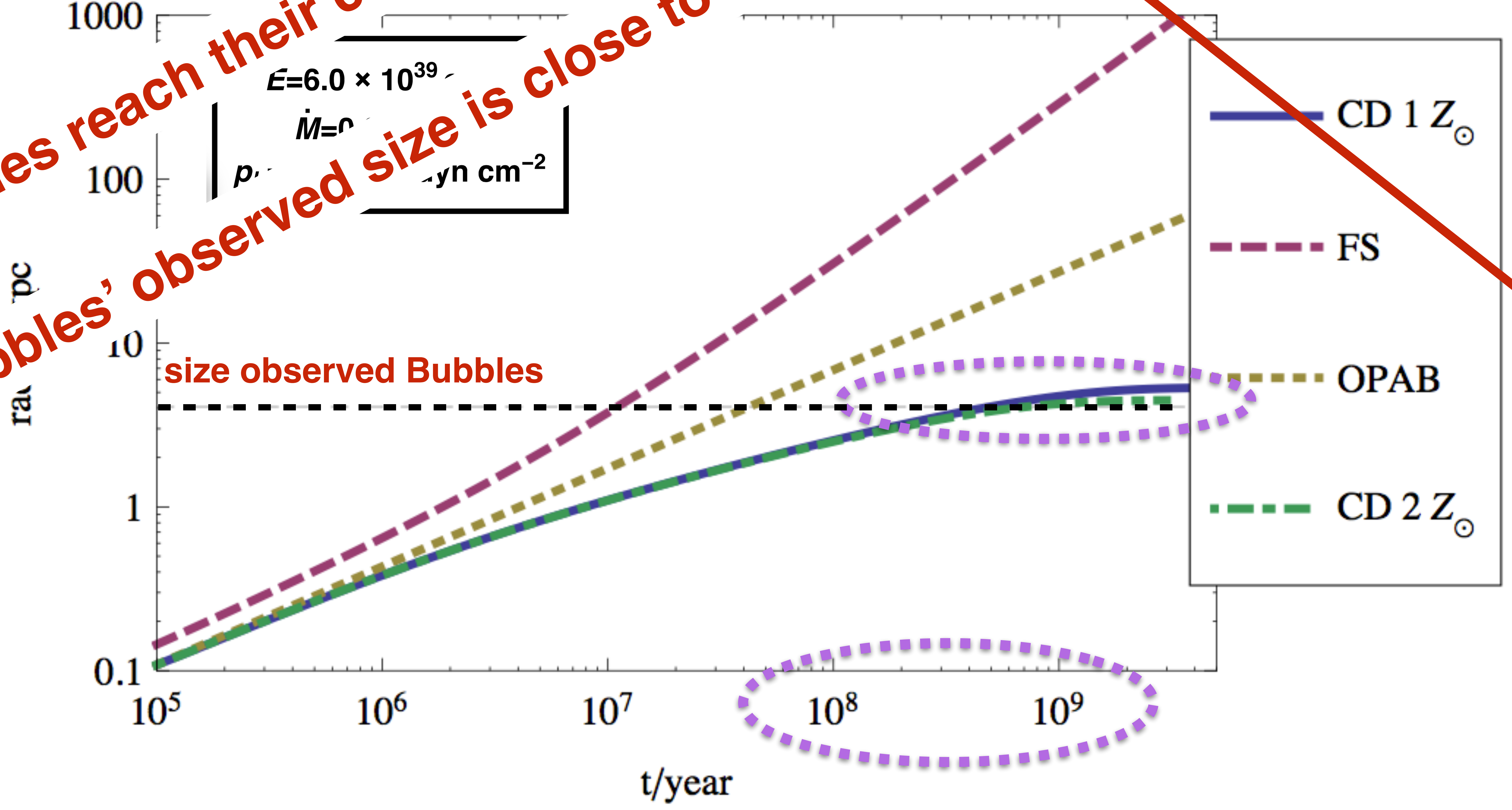
Crocker et al. 2015

Expansion of radiative bubble into finite (const) pressure medium

Bubbles reach their current size after few 100 Myr

The Bubbles' observed size is close to their 'natural' size



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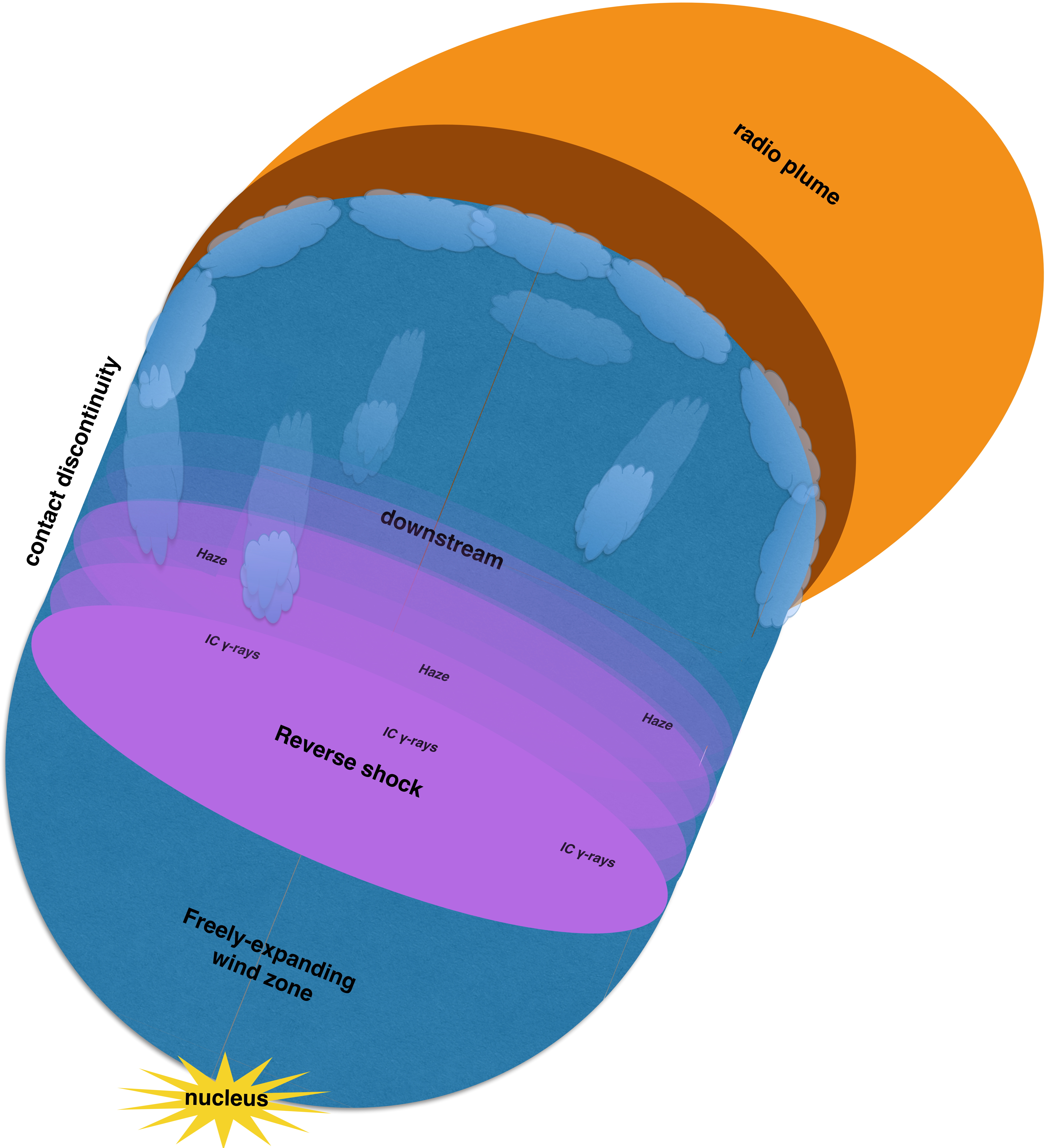
Crocker et al. 2015

Mass Drop-Out

Crocker et al. 2015


radio plume
contact discontinuity
downstream
Haze
Haze
Haze
IC γ-rays
IC γ-rays
IC γ-rays
Reverse shock
Freely-expanding
wind zone
nucleus

Giant Shocks in the Fermi Bubbles

- General scenario: adiabatically-expanding nuclear wind…
- Reverse shock where $P_{ram} = P_{pls}$
- Have to incorporate gravity, halo pressure & cooling

Crocker et al. 2015

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height ~ 1 kpc

Mach num ~ 6-9

Crocker et al. 2015

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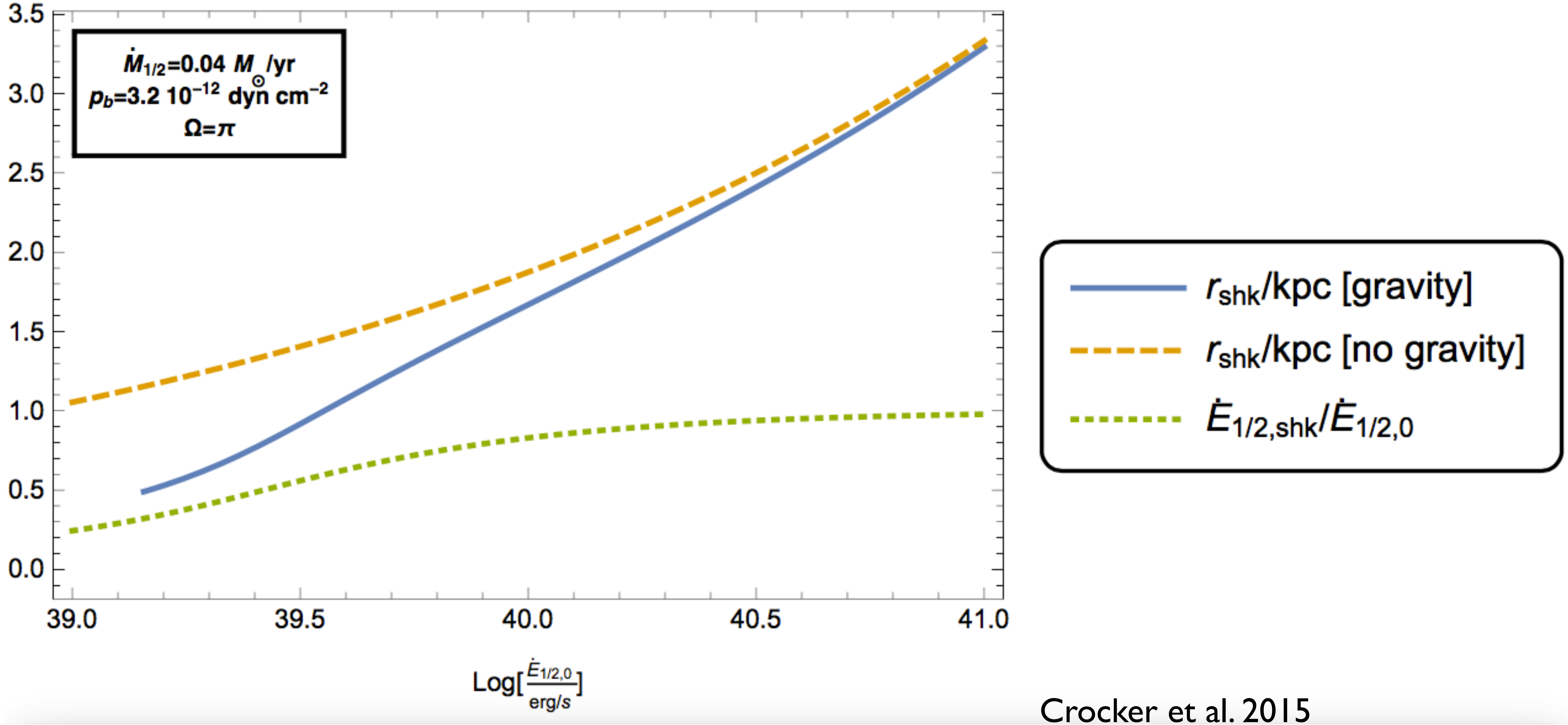

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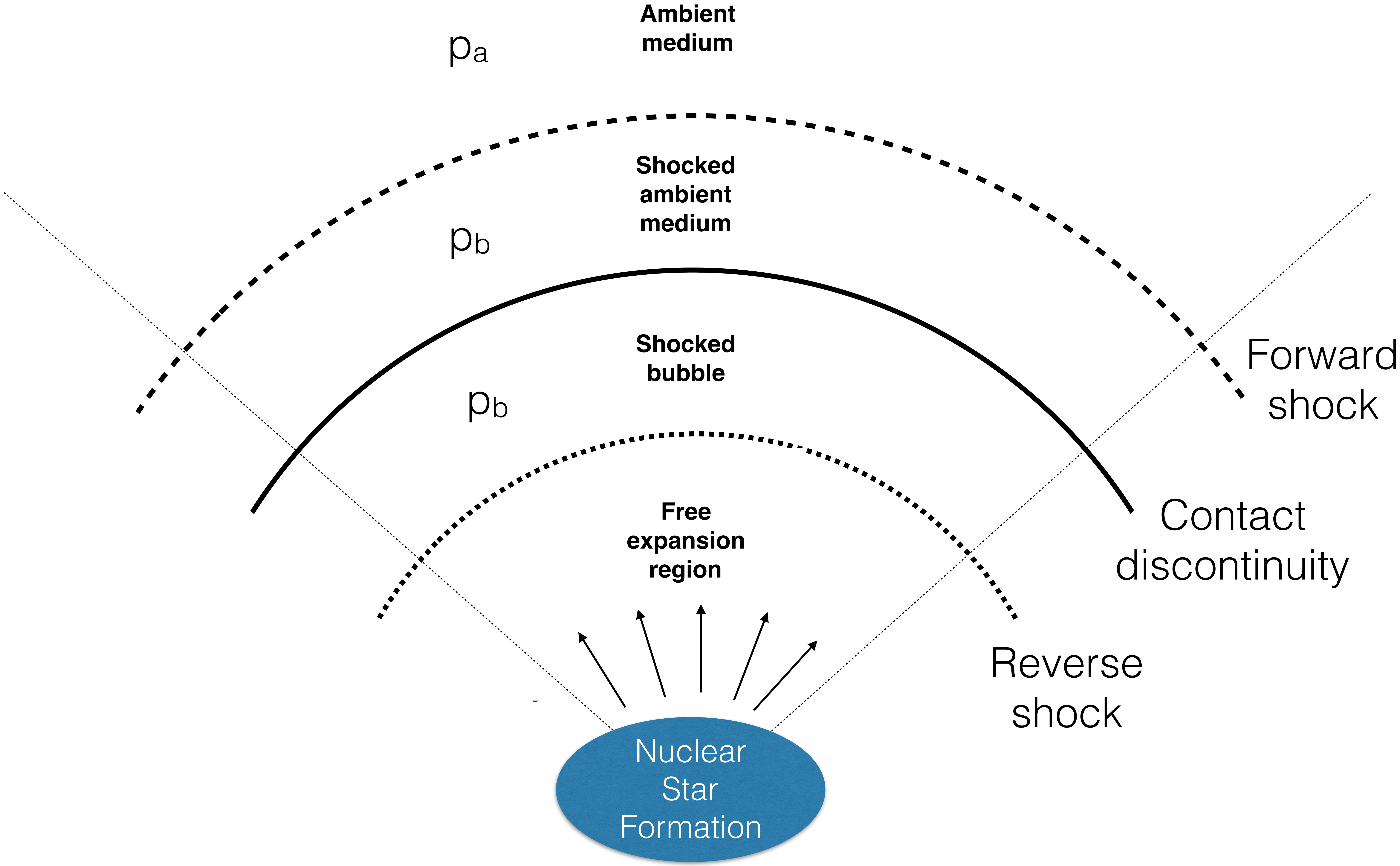
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p_a
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bubble
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Forward
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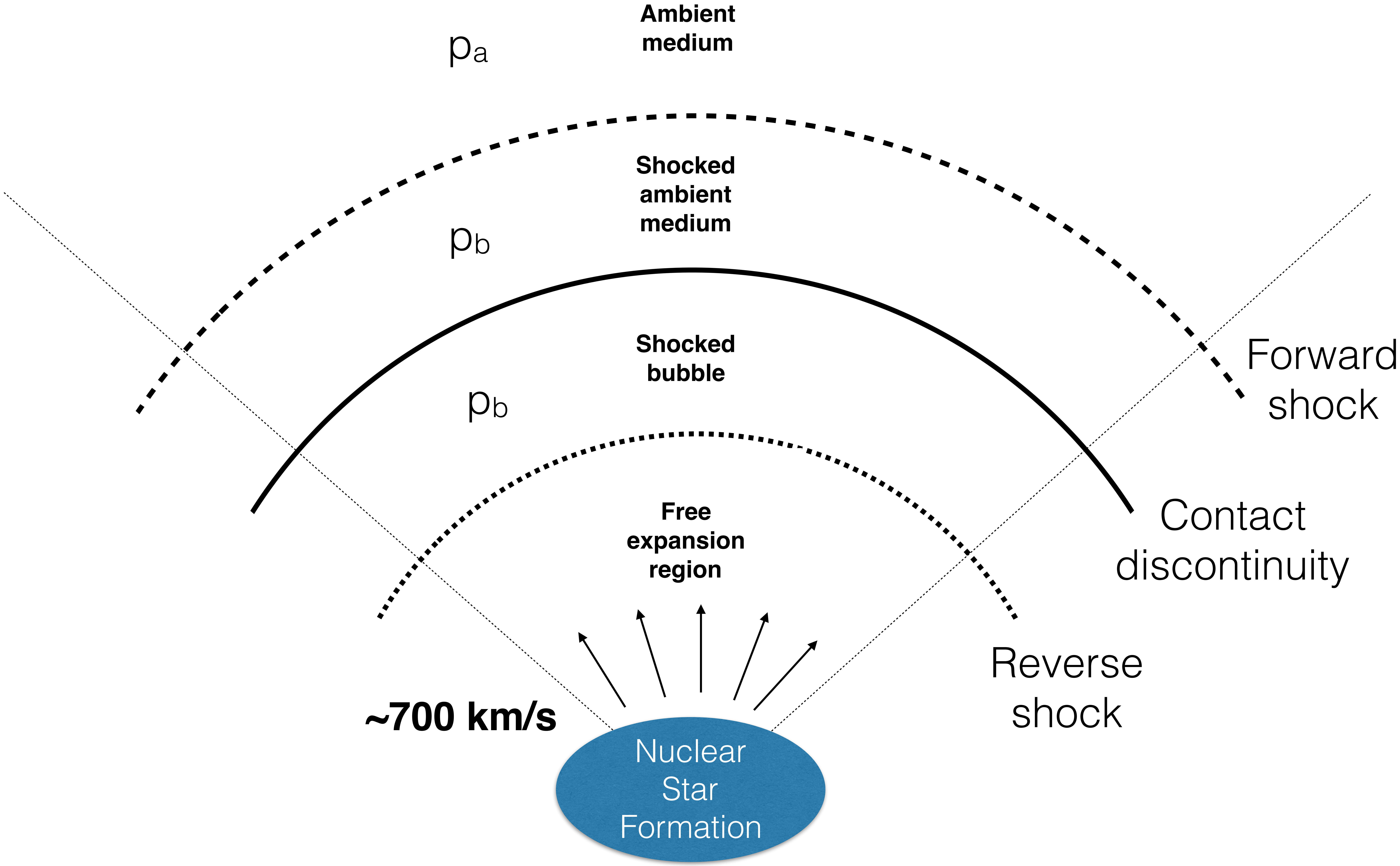
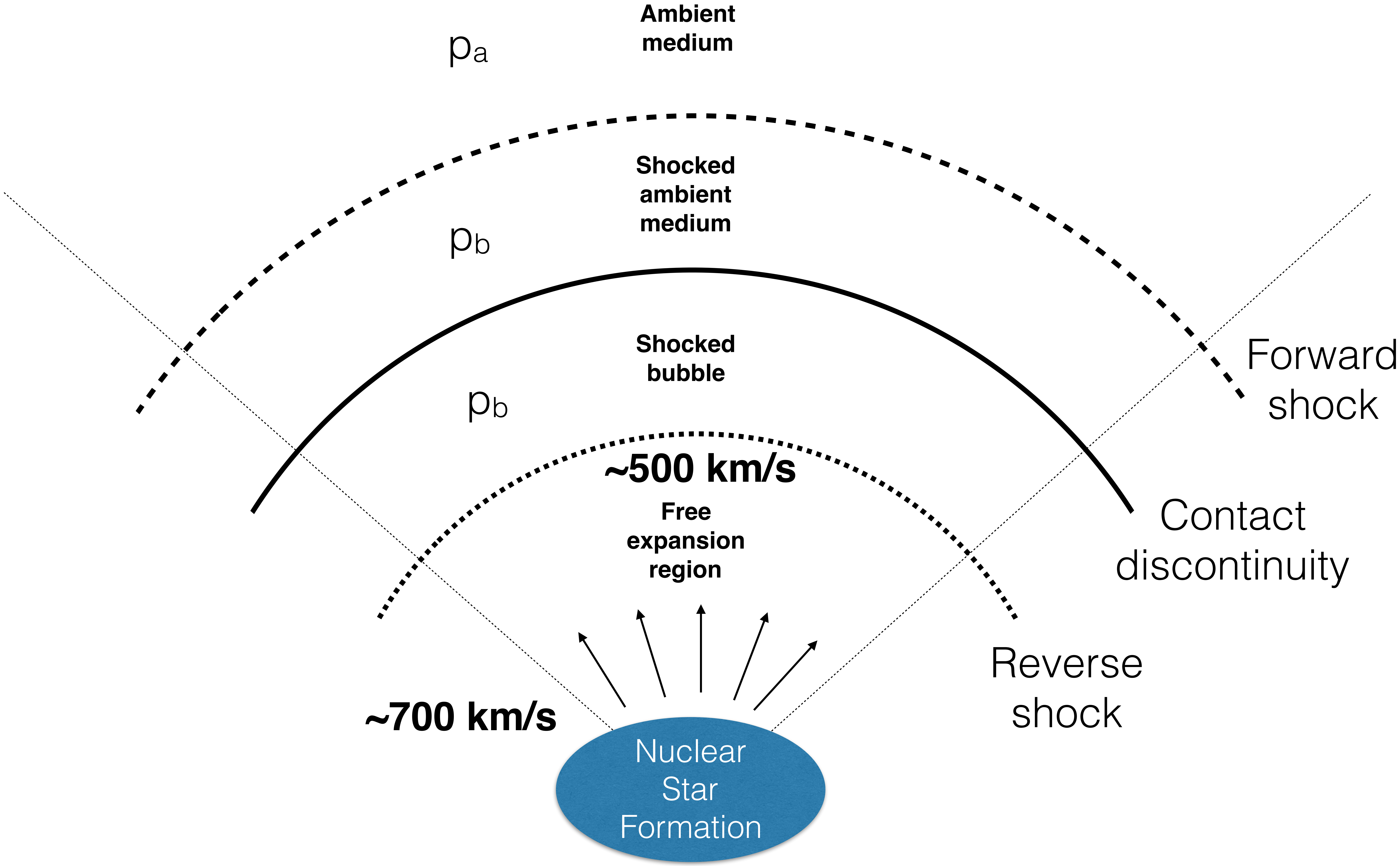
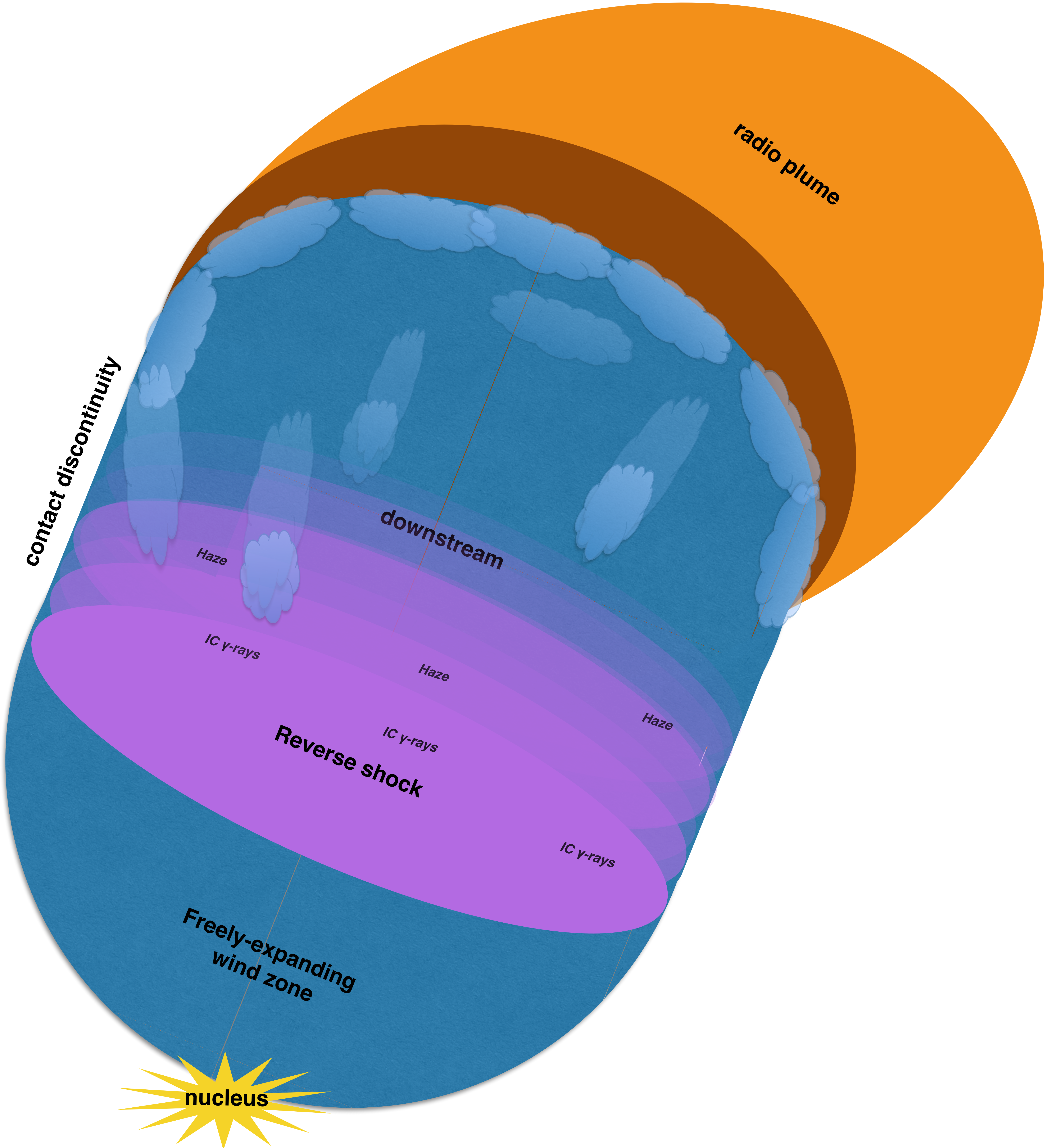
Nuclear
Star
Formation

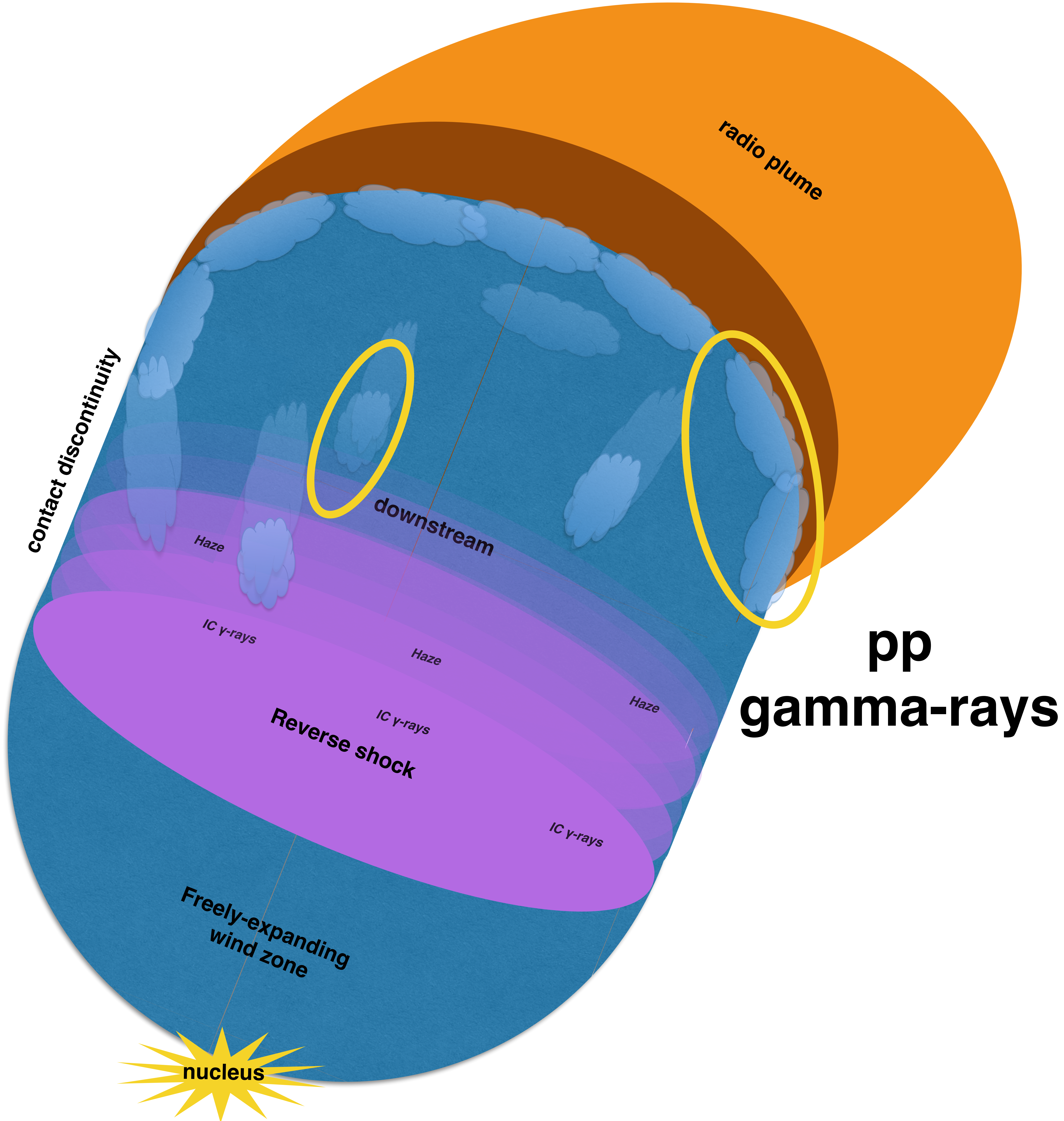


Ambient medium
pa
Shocked ambient medium
pb
Shocked bubble
pb
Forward shock
Contact discontinuity
Free expansion region
Reverse shock
~700 km/s
Nuclear Star Formation



Ambient medium
p_a
Shocked ambient medium
p_b
Shocked bubble
p_b
~500 km/s
Free expansion region
~700 km/s
Nuclear Star Formation
Forward shock
Contact discontinuity
Reverse shock


radio plume
contact discontinuity
downstream
Haze
Haze
Haze
IC γ-rays
IC γ-rays
IC γ-rays
Reverse shock
Freely-expanding
wind zone
nucleus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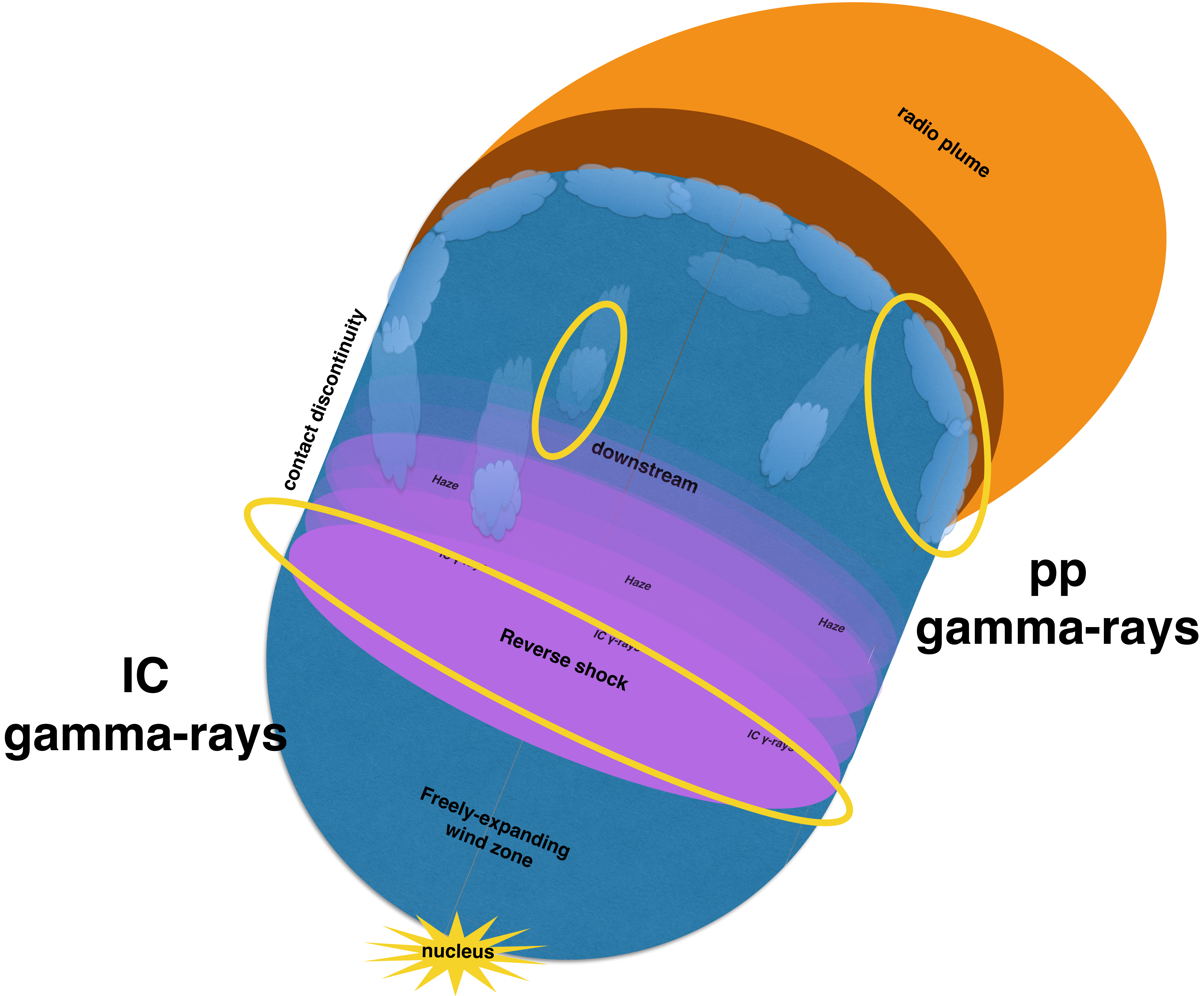
Reverse shock
IC γ-rays
Freely-expanding
wind zone
nucleus
pp
gamma-rays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Reverse shock
IC γ-rays
Freely-expanding
wind zone
nucleus
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gamma-rays
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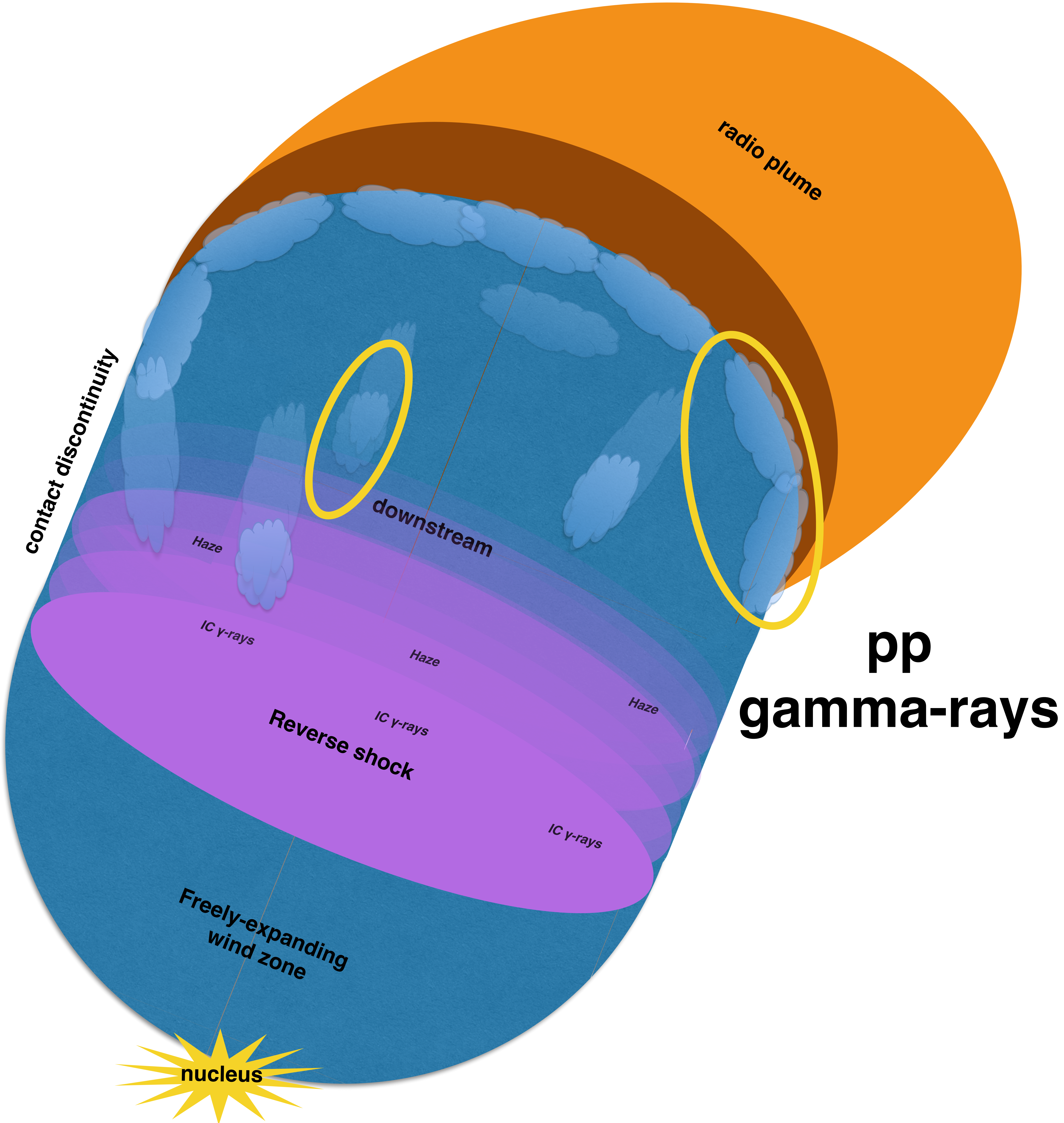
gamma-rays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Reverse shock
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Freely-expanding
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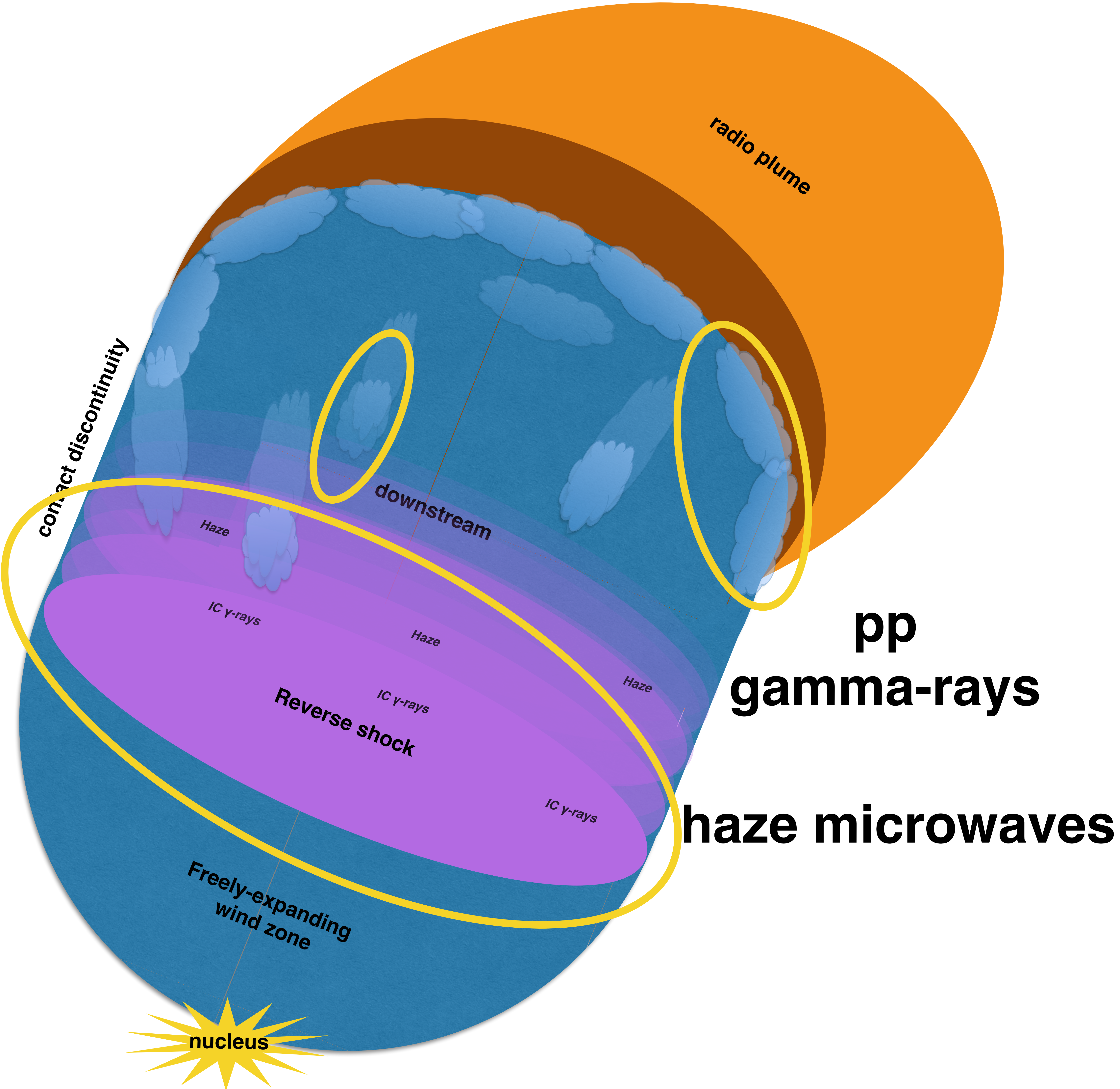
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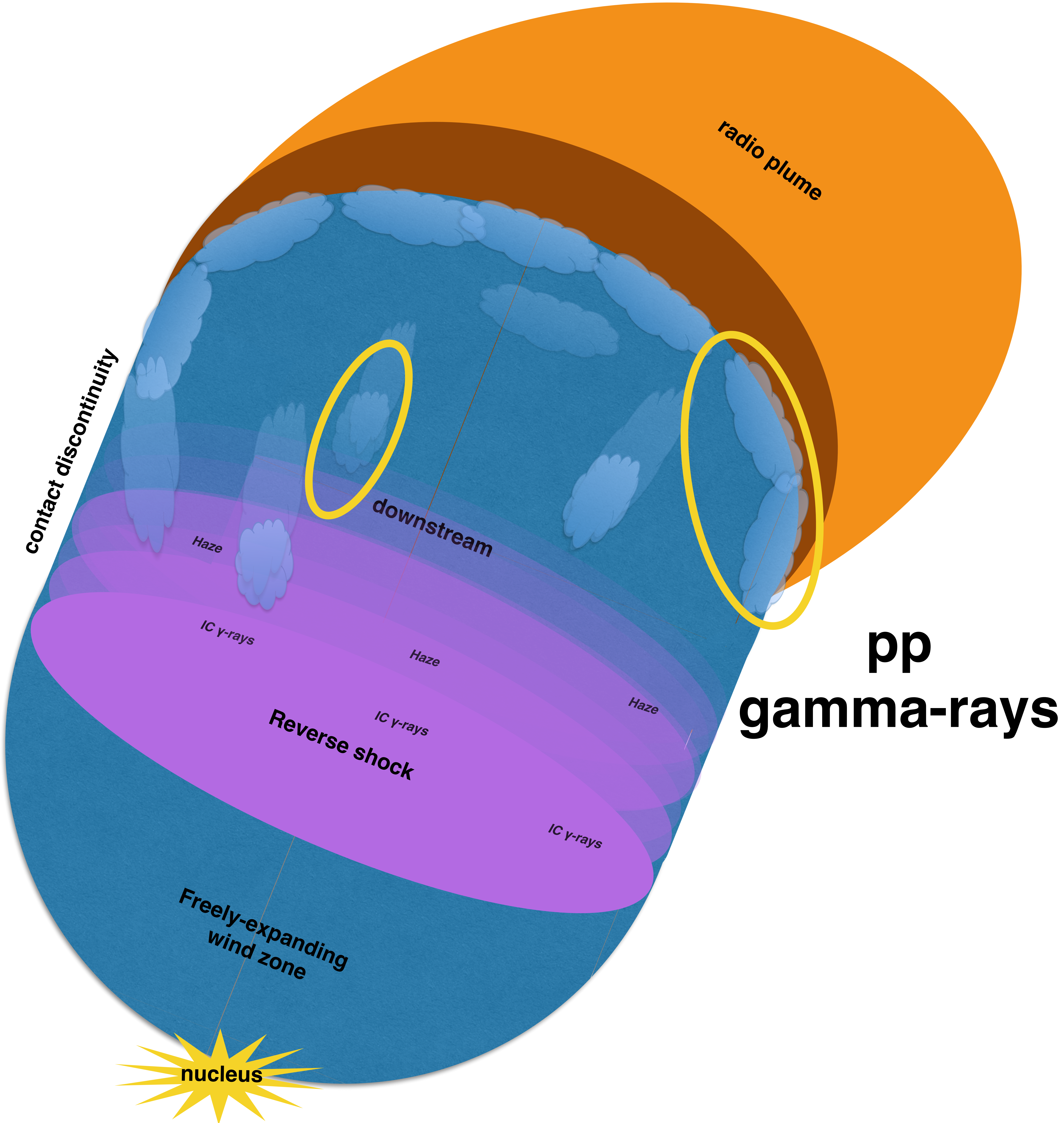
Reverse shock
IC γ-rays
Freely-expanding
wind zone
nucleus
pp
gamma-rays
haze microwaves



radio plume
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Reverse shock
IC γ-rays
Freely-expanding
wind zone
nucleus
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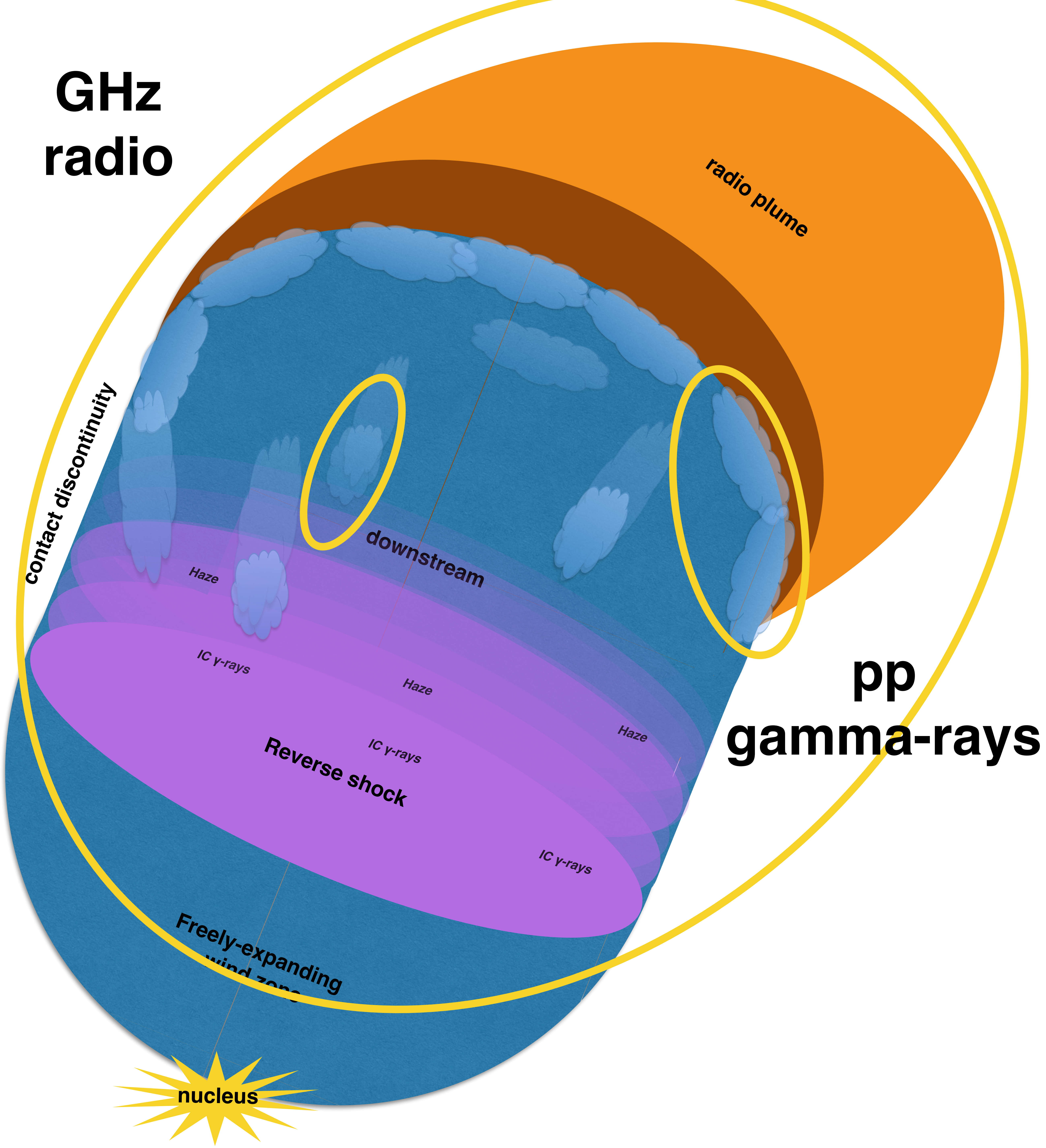
gamma-rays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Reverse shock
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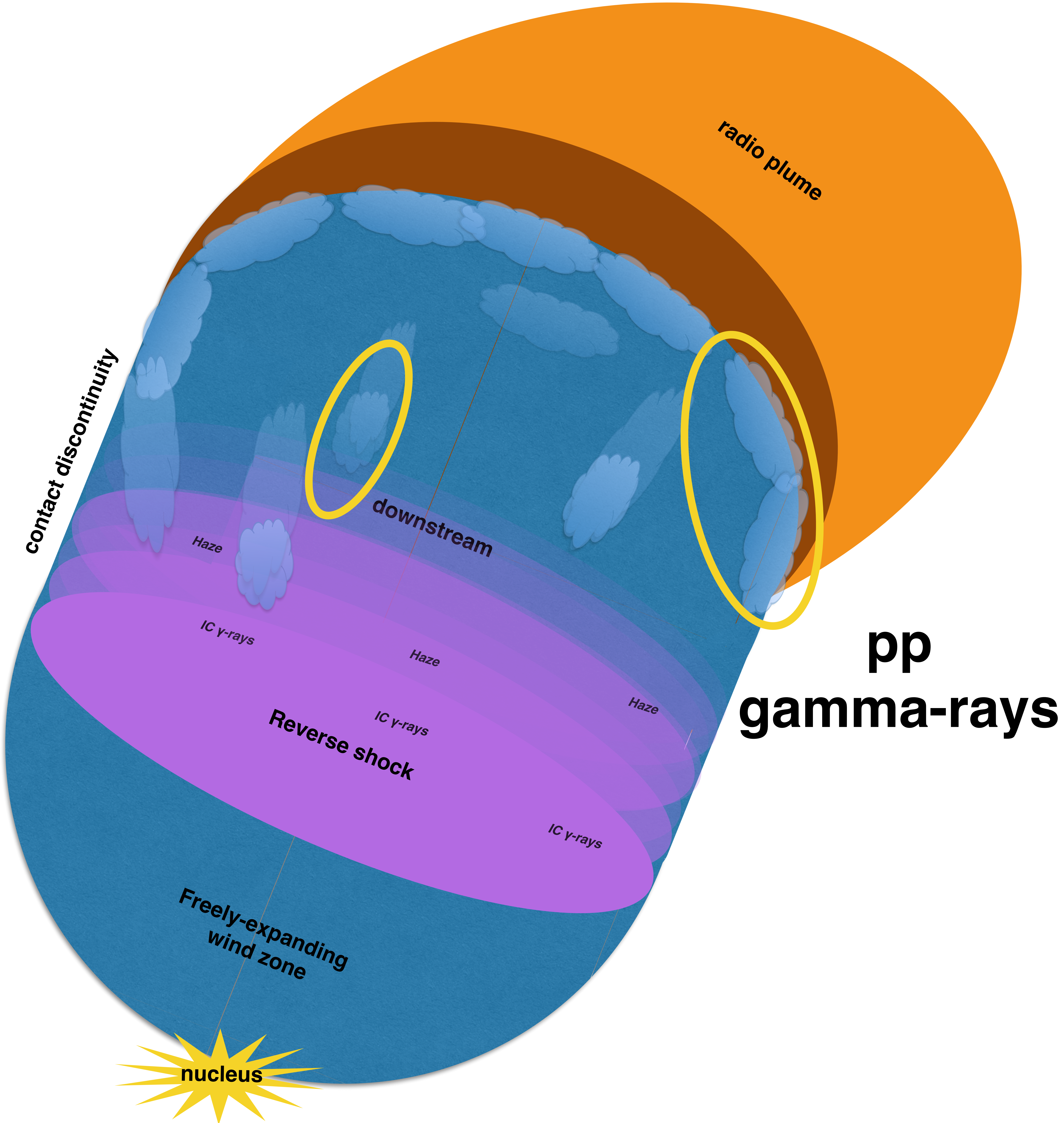
gamma-rays
Freely-expanding
nucleus


radio plume
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Haze
IC γ-rays
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Reverse shock
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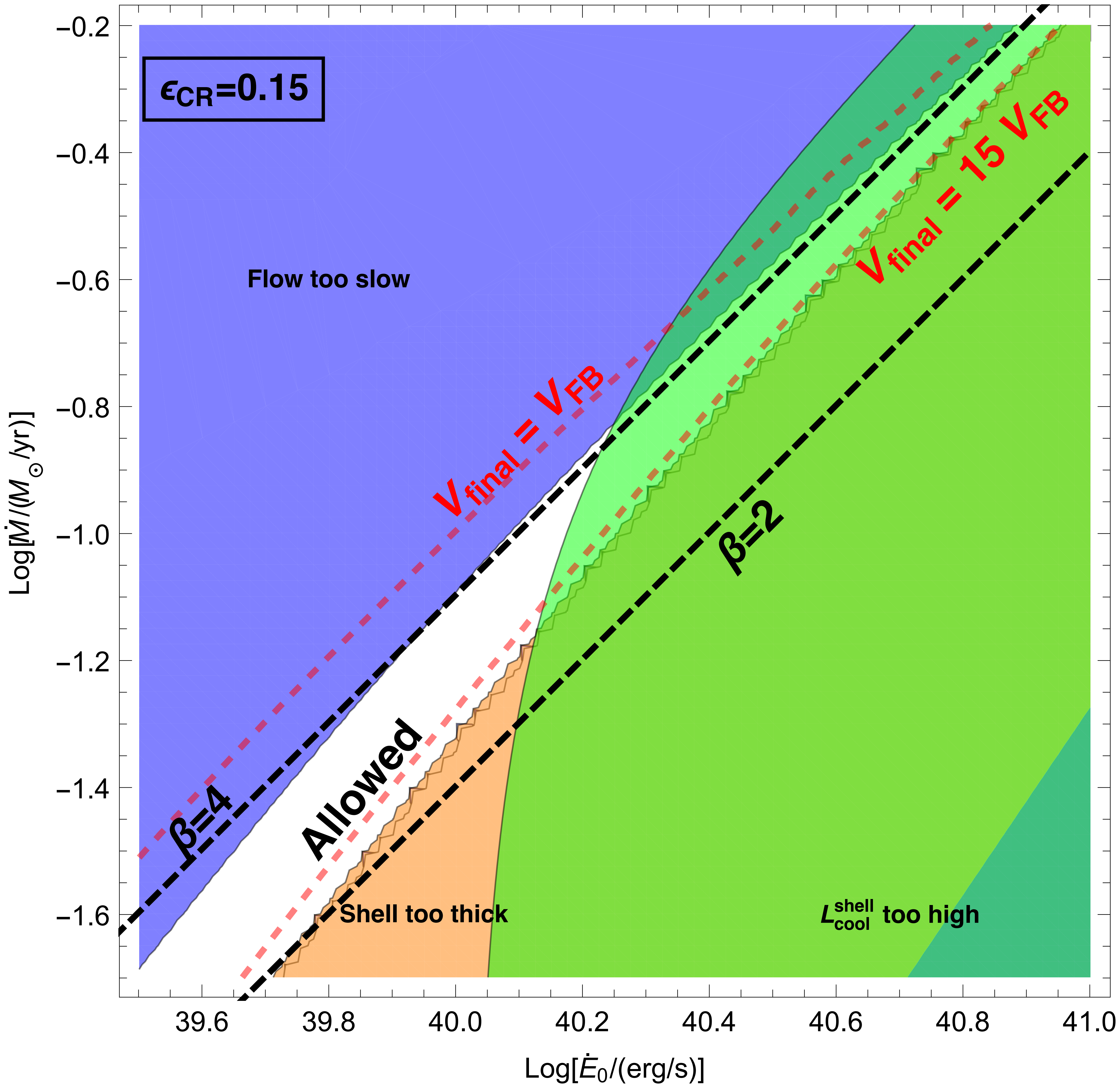
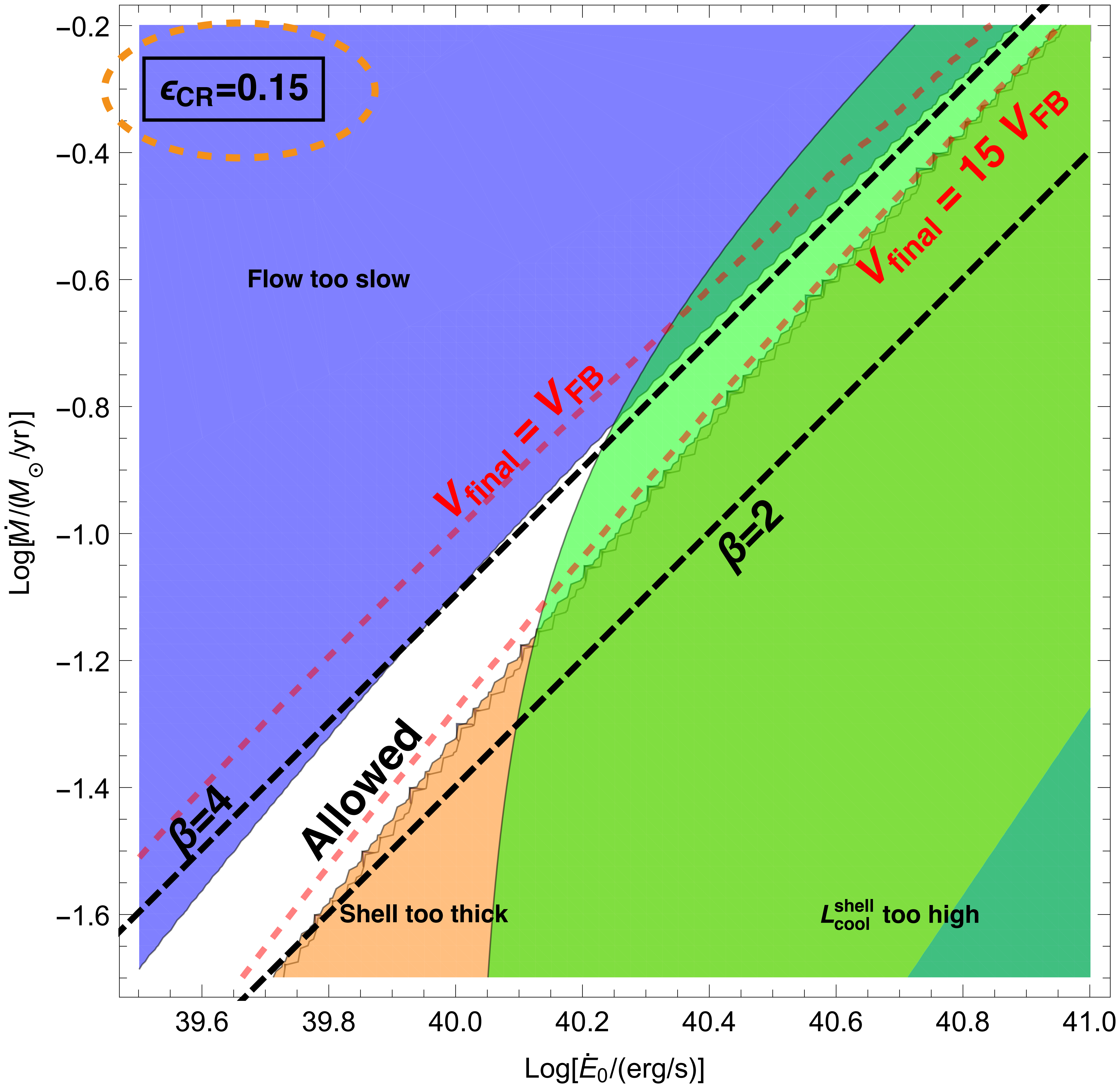
Freely-expanding
wind zone
nucleus
pp
gamma-rays

Parameter Space



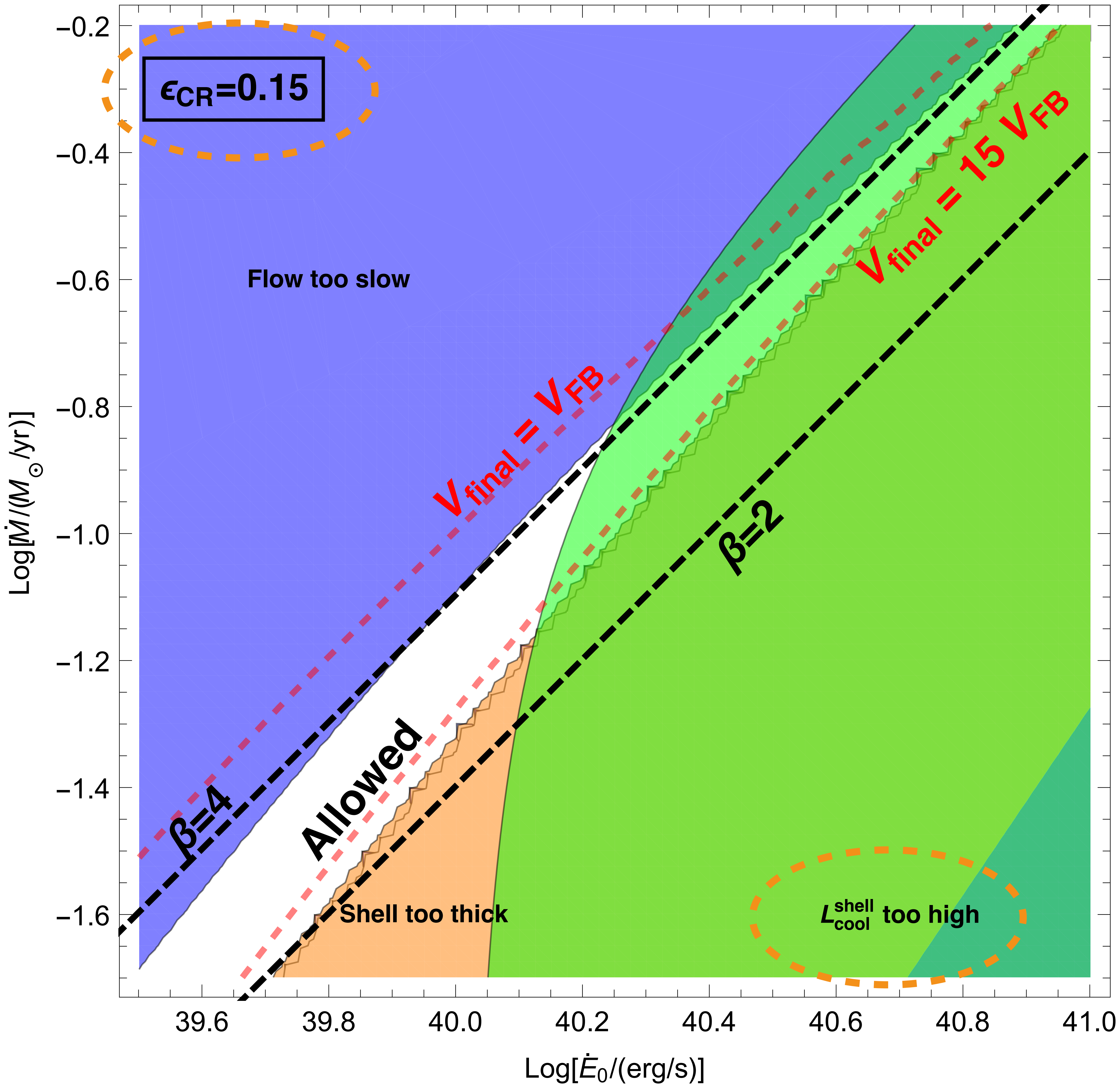
Crocker et al. 2015

Parameter Space



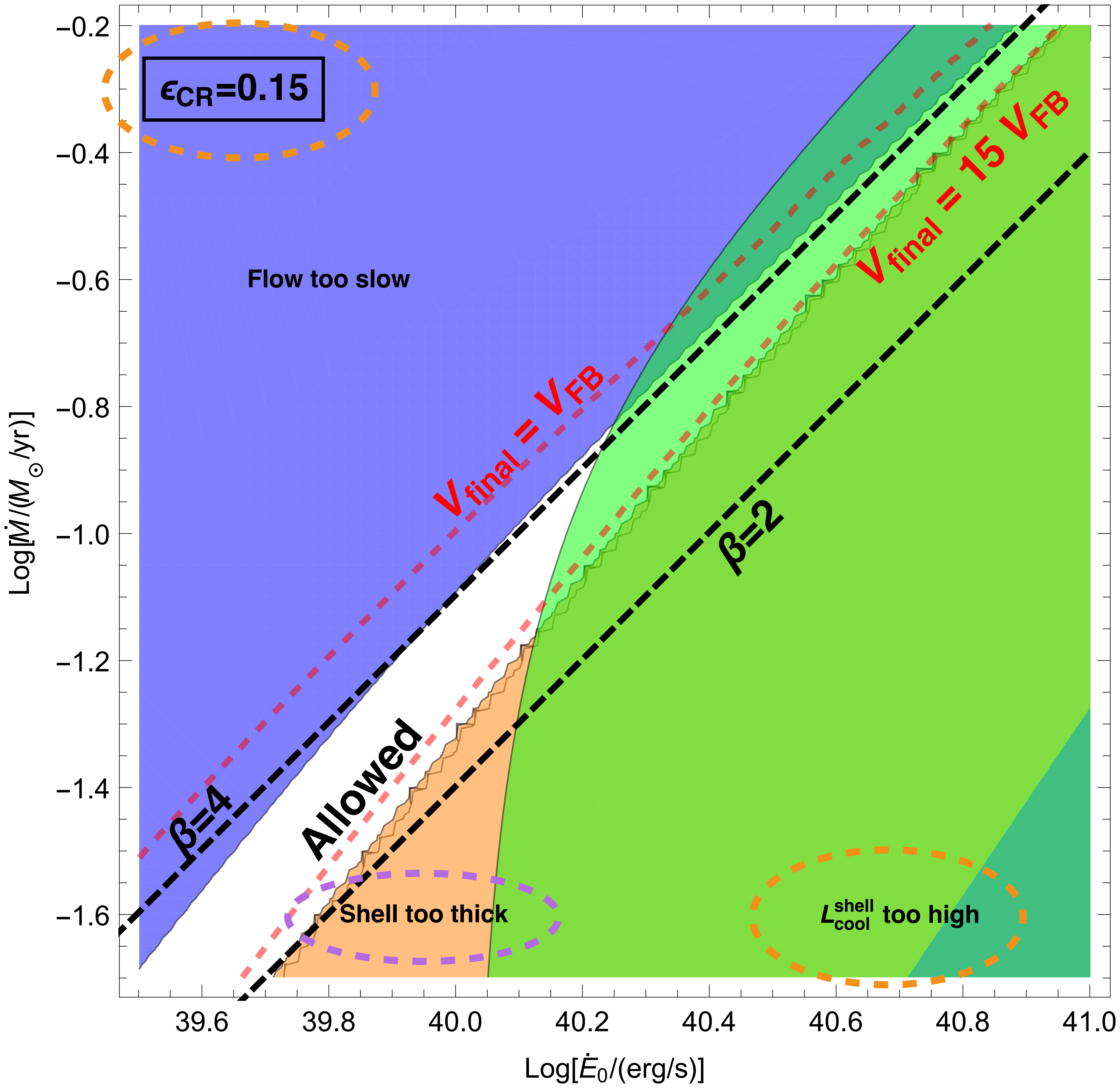
Crocker et al. 2015

Parameter Space



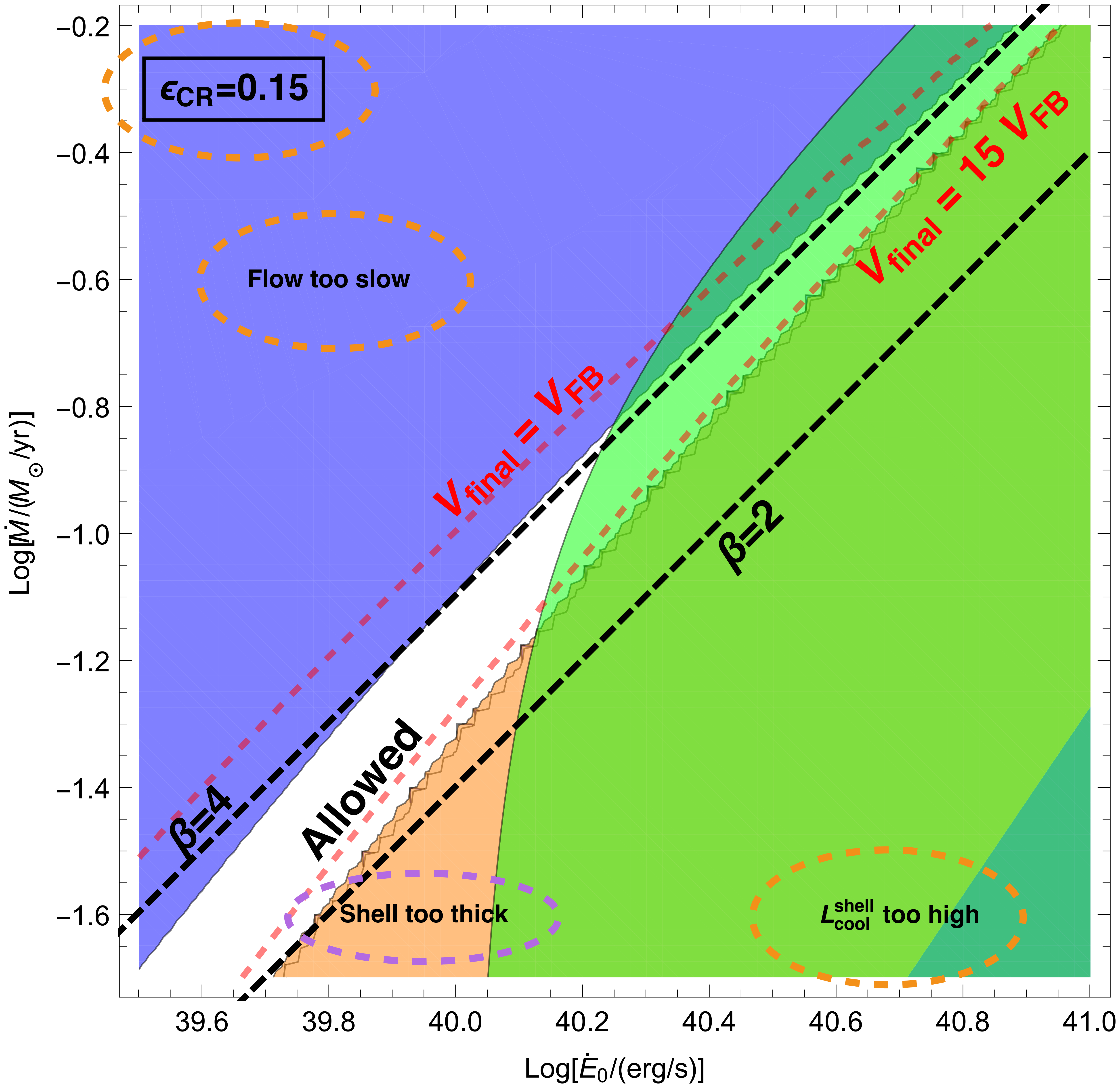
Crocker et al. 2015

Parameter Space



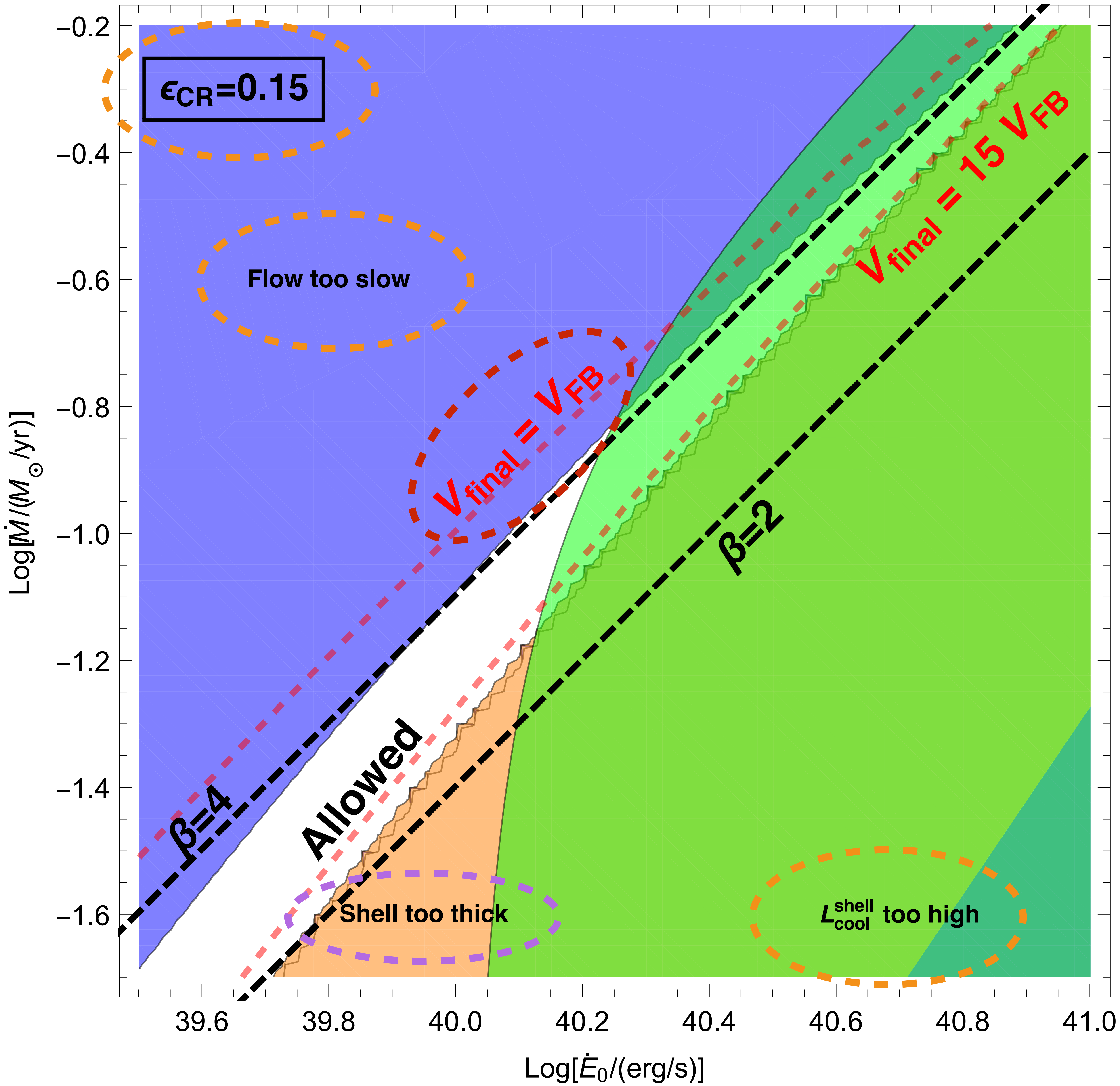
Crocker et al. 2015

Parameter Space



Crocker et al. 2015

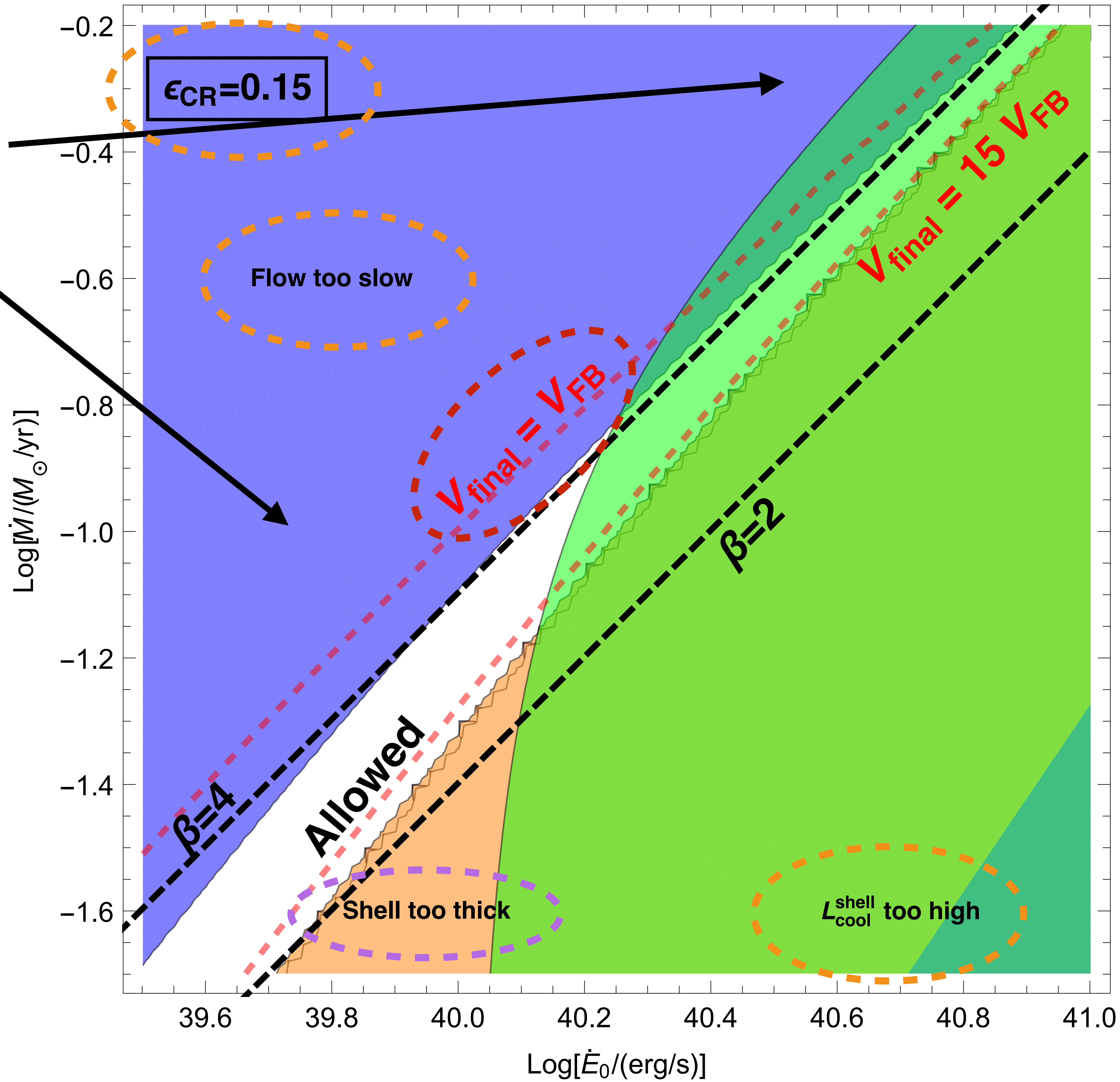
Parameter Space



Crocker et al. 2015

Parameter Space

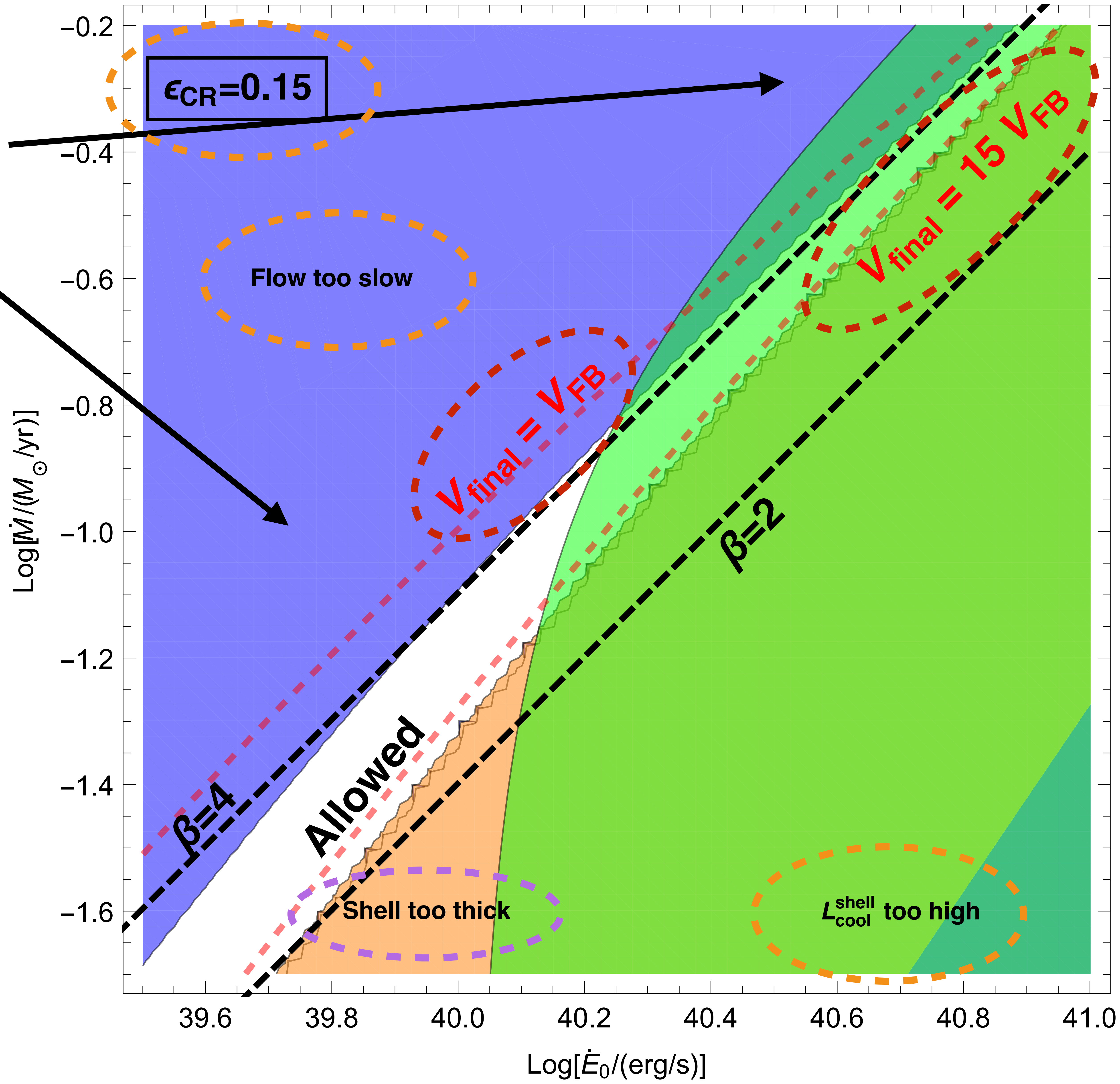
Bubbles never reach observed size



Crocker et al. 2015

Parameter Space

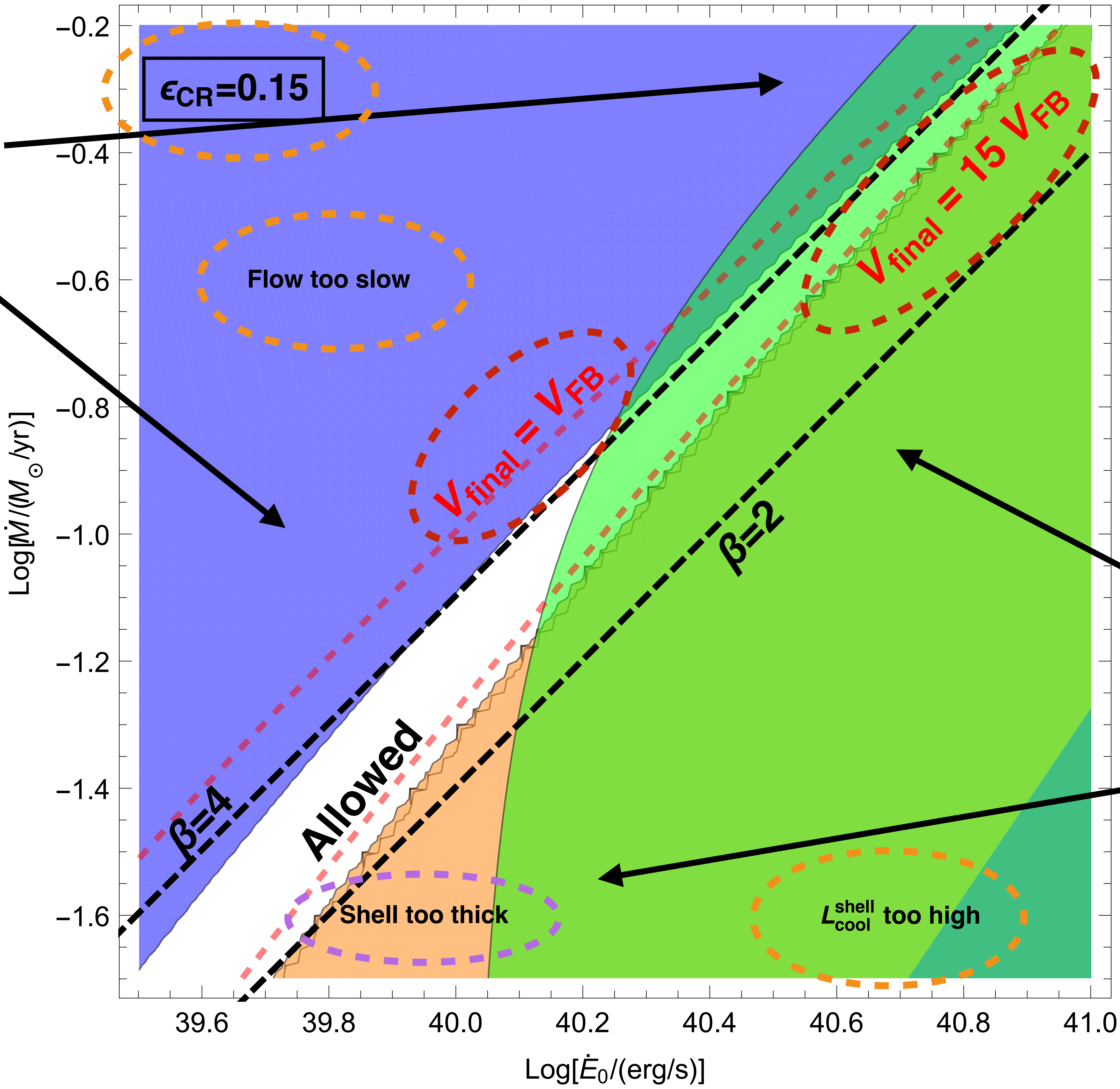
Bubbles never reach observed size



Crocker et al. 2015

Parameter Space

Bubbles never reach observed size

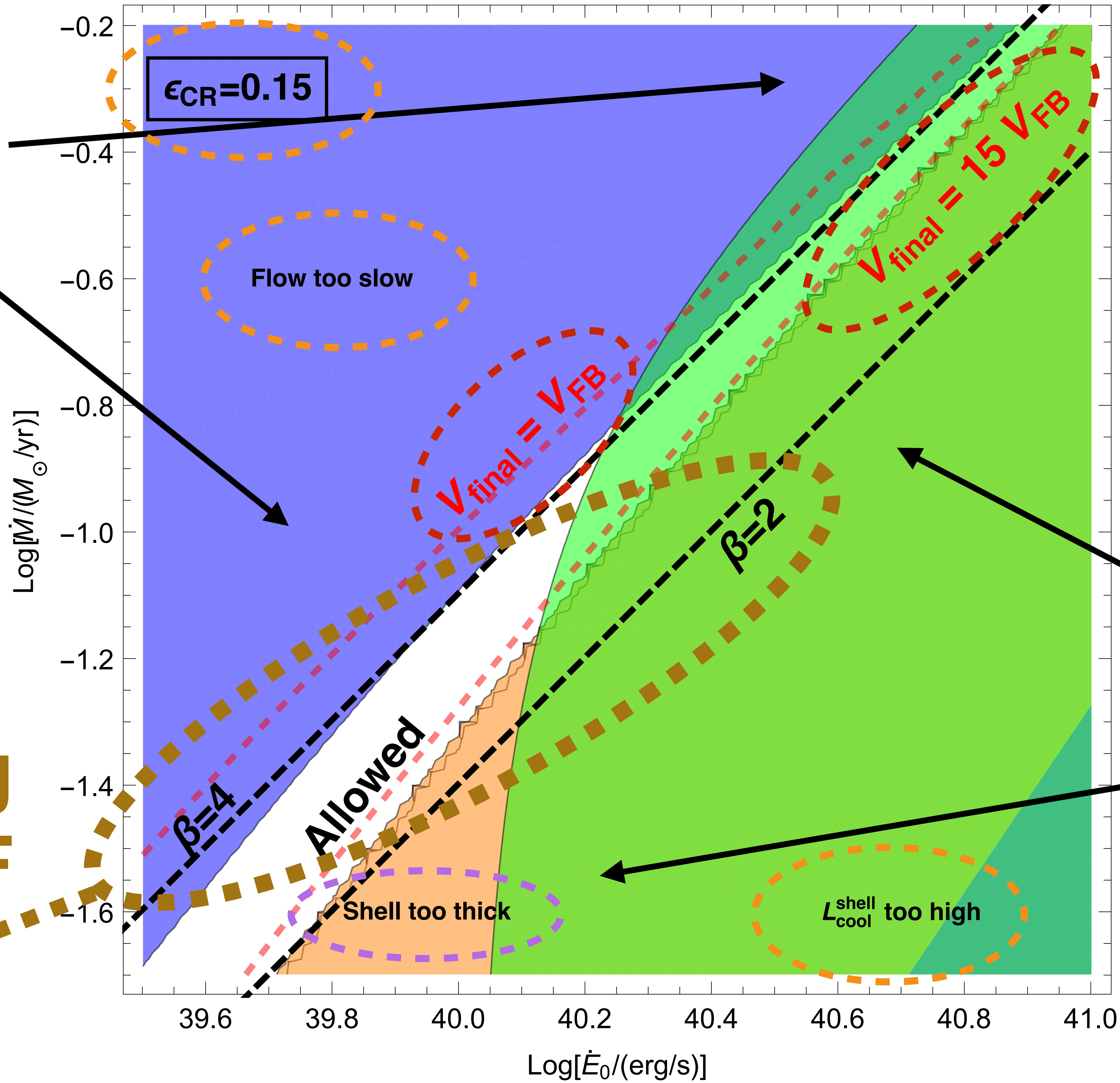


Bubbles quickly shoot past observed size

Crocker et al. 2015

Parameter Space

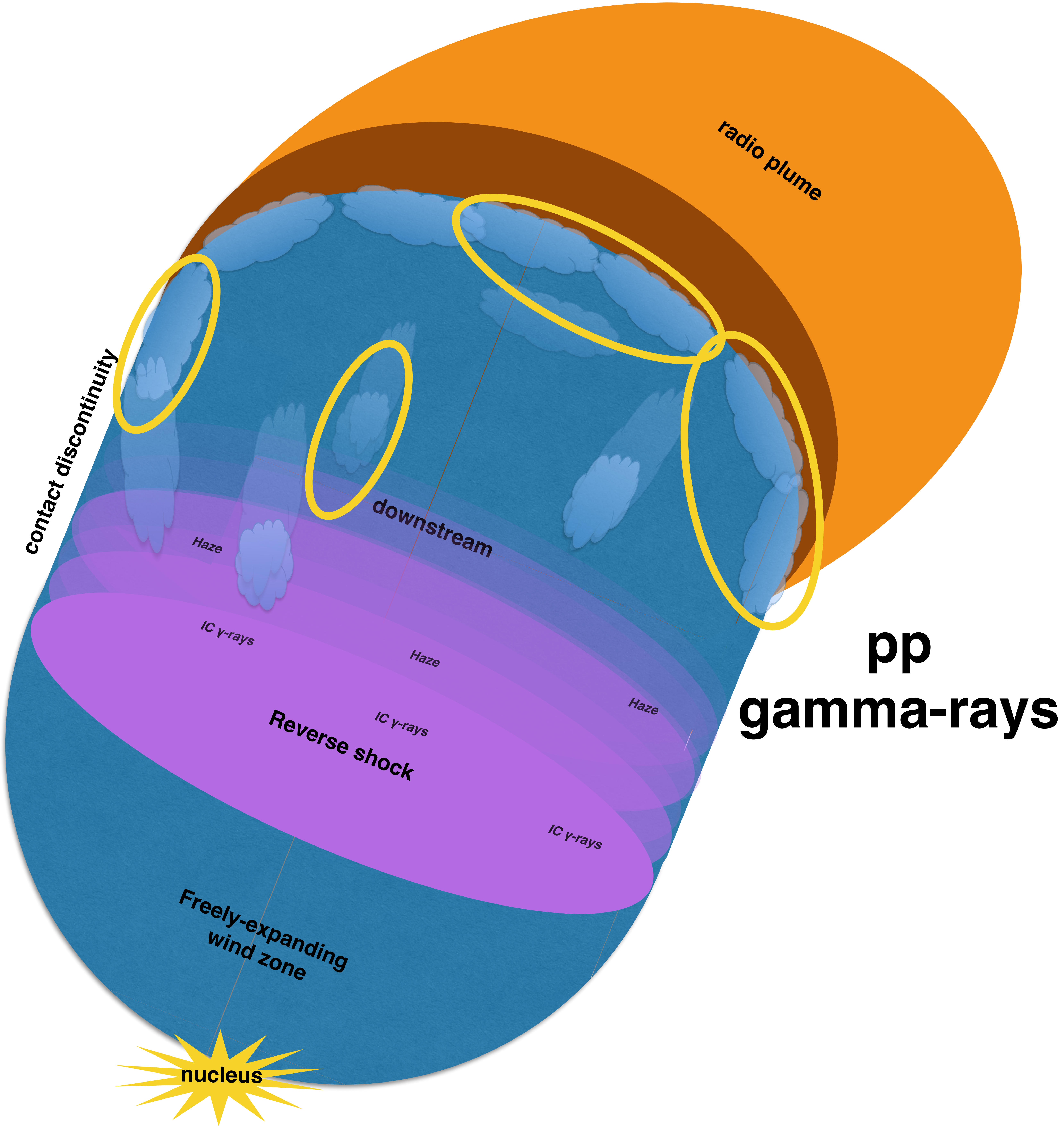
Bubbles never reach observed size



Bubbles quickly shoot past observed size

Mass loading typical for SF outflow

Crocker et al. 2015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IC γ-rays
Haze
Haze
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Reverse shock
IC γ-rays
Freely-expanding
wind zone
nucleus
pp
gamma-rays

Hadronic Gamma-Rays from Cooling Shell

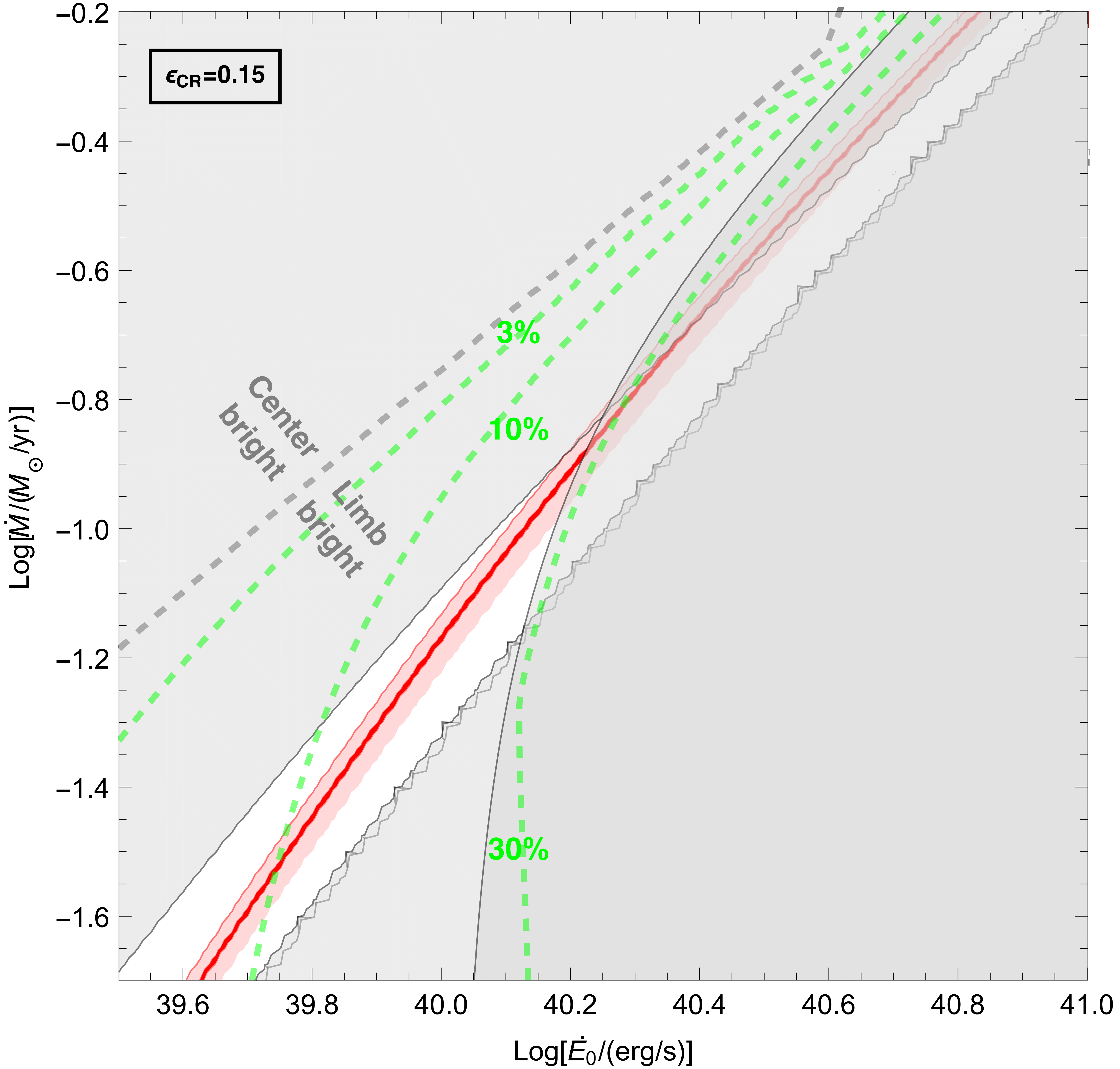
- Shell dissipates incoming enthalpy flux radiatively
- Cosmic rays and magnetic fields adiabatically amplified in cooling shell/filaments
- Cooling shell/filaments supported by non-thermal pressure

…these assumptions are sufficient to predict the hadronic gamma-ray luminosity:

$$L_\gamma^{\rm pp} \simeq 2.4 \times 10^{37}\ {\rm erg\ s^{-1}} \left(\frac{T_{\rm FB}}{6.0 \times 10^6\ {\rm K}}\right)^2 \left(\frac{\dot{M}}{0.1\ M_\odot\ {\rm yr}^{-1}}\right) \times \left(\frac{L_{\rm CR}^{\rm FB}}{\dot{E}_{\rm therm}^{\rm FB}} \Big/ 0.1\right)^{3/4}$$

Crocker et al. 2015

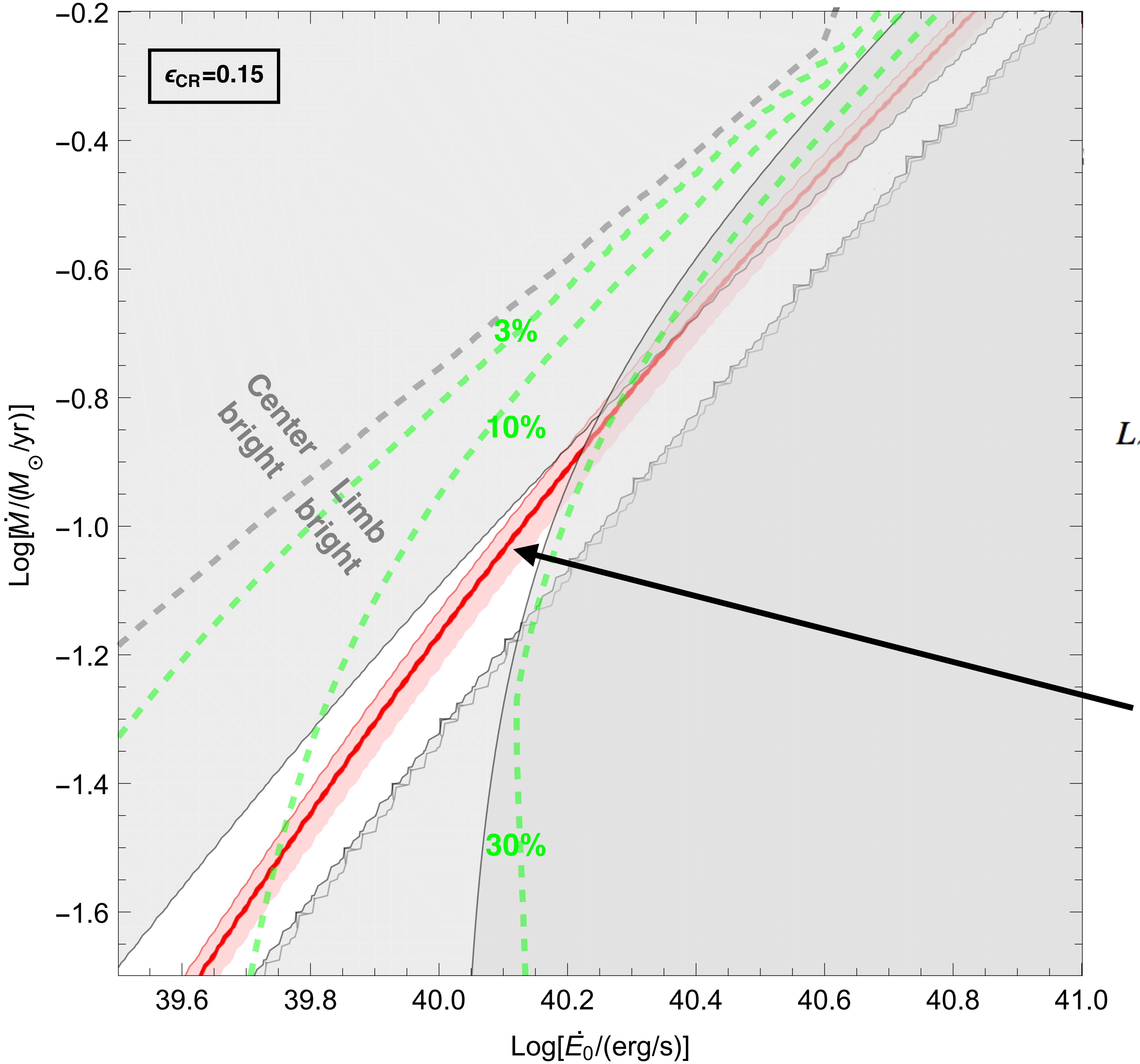
Gamma-ray Luminosity



$$L_\gamma^{pp} \simeq 2.4 \times 10^{37}\ \mathrm{erg\ s^{-1}} \left(\frac{T_{FB}}{6.0 \times 10^6\ \mathrm{K}}\right)^2 \left(\frac{\dot{M}}{0.1\ M_\odot\ \mathrm{yr}^{-1}}\right) \times \left(\frac{L_{CR}^{FB}}{\dot{E}_{therm}^{FB}} \Big/ 0.1\right)^{3/4}$$

Crocker et al. 2015

Gamma-ray Luminosity

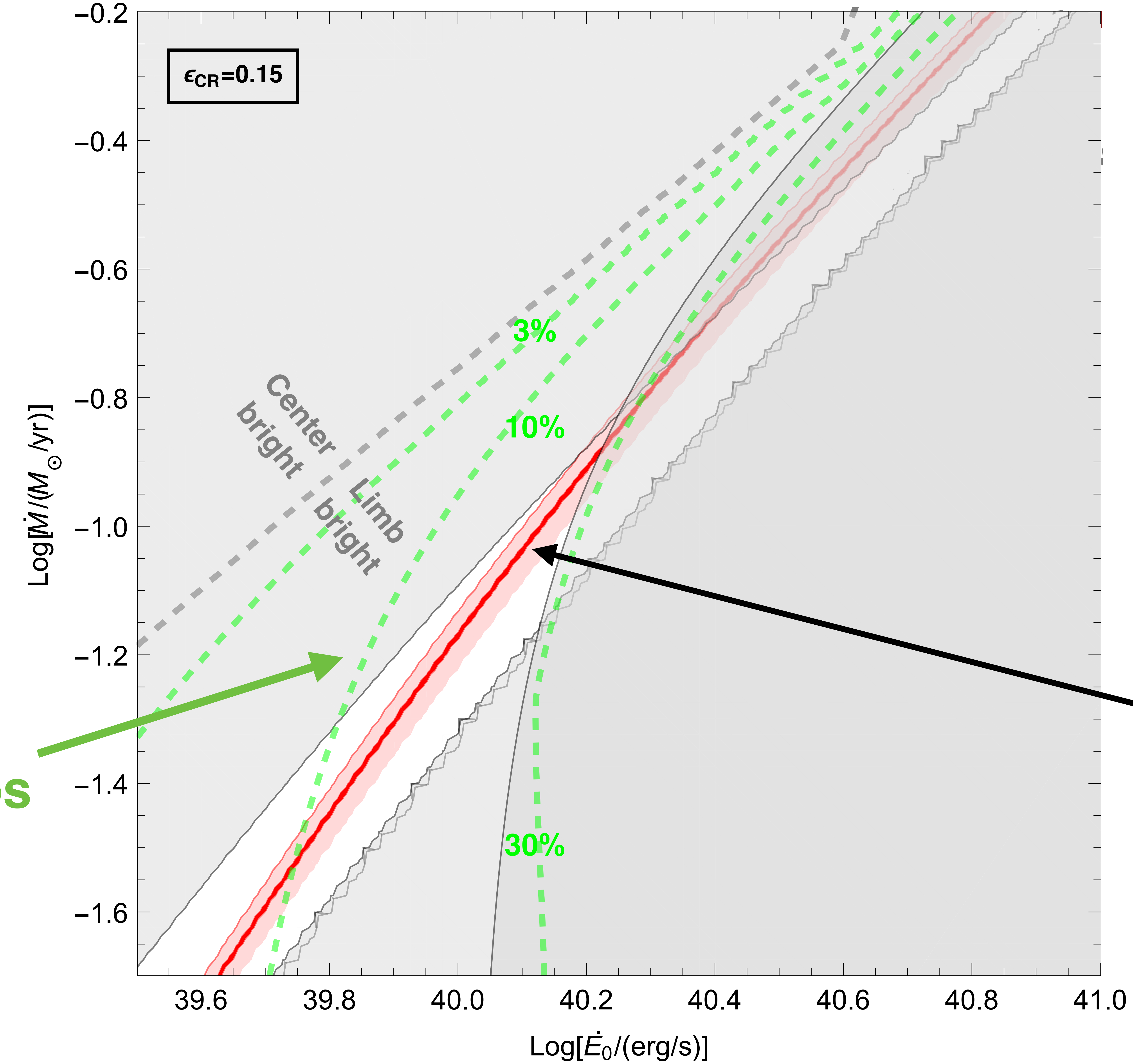


$$L_\gamma^{pp} \simeq 2.4 \times 10^{37}\ \mathrm{erg\ s^{-1}} \left(\frac{T_{FB}}{6.0 \times 10^6\ \mathrm{K}}\right)^2 \left(\frac{\dot{M}}{0.1\ M_\odot\ \mathrm{yr}^{-1}}\right) \times \left(\frac{L_{CR}^{FB}}{\dot{E}_{therm}^{FB}} \Big/ 0.1\right)^{3/4}$$

$$\mathbf{L_\gamma^{pp} = L_\gamma^{obs}}$$

Crocker et al. 2015

Gamma-ray Luminosity



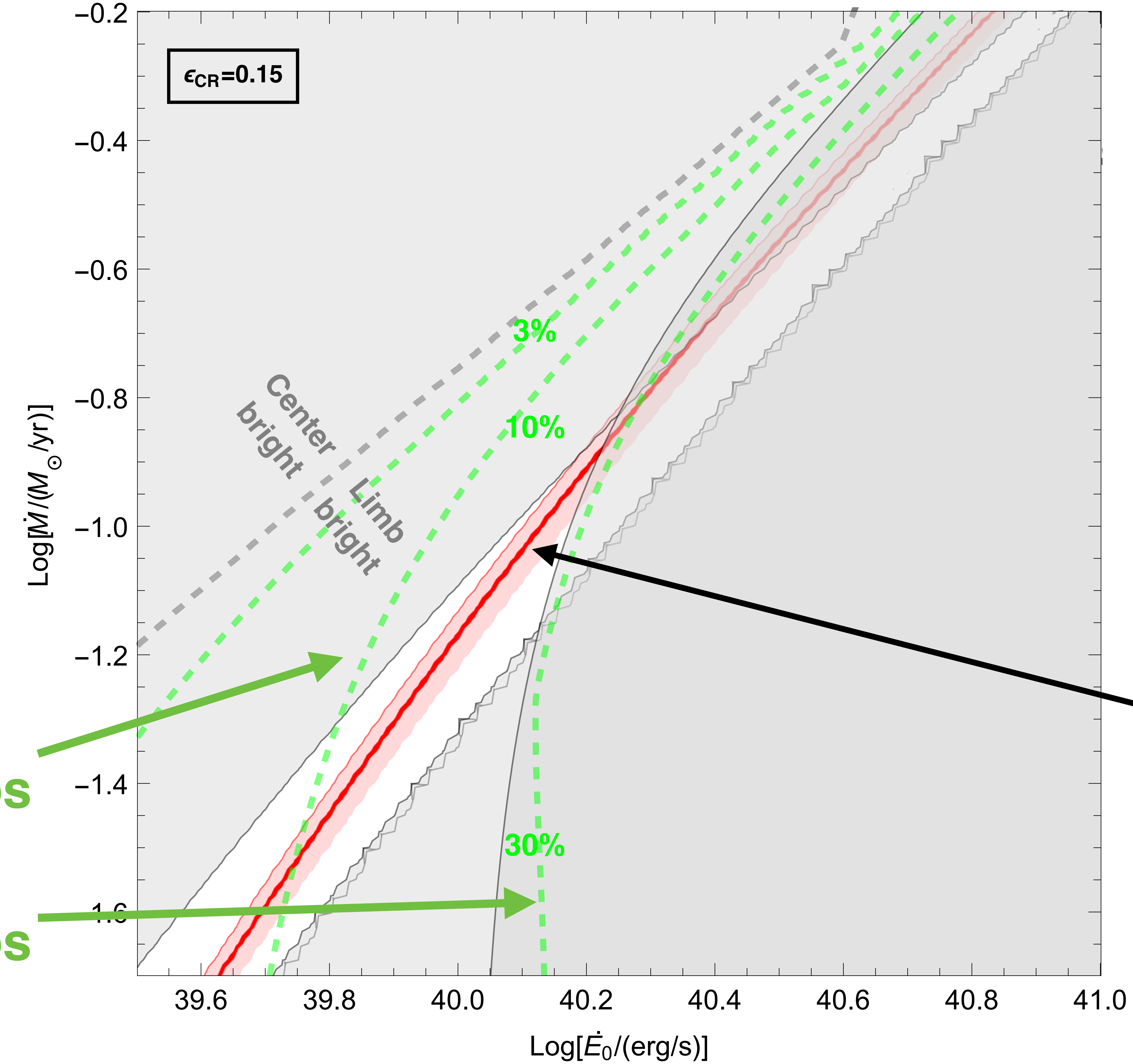
$$L_\gamma^{pp} \simeq 2.4 \times 10^{37}\ \mathrm{erg\ s^{-1}} \left(\frac{T_{FB}}{6.0 \times 10^6\ \mathrm{K}}\right)^2 \left(\frac{\dot{M}}{0.1\ M_\odot\ \mathrm{yr}^{-1}}\right) \times \left(\frac{L_{CR}^{FB}}{\dot{E}_{therm}^{FB}} \Big/ 0.1\right)^{3/4}$$

$L_{IC} = 10\%\ L_\gamma^{obs}$

$L_\gamma^{pp} = L_\gamma^{obs}$

Crocker et al. 2015

Gamma-ray Luminosity



$$L_\gamma^{pp} \simeq 2.4 \times 10^{37} \text{ erg s}^{-1} \left(\frac{T_{FB}}{6.0 \times 10^6 \text{ K}}\right)^2 \left(\frac{\dot{M}}{0.1 \, M_\odot \text{ yr}^{-1}}\right) \times \left(\frac{L_{CR}^{FB}}{\dot{E}_{therm}^{FB}} \Big/ 0.1\right)^{3/4}$$

$L_\gamma^{pp} = L_\gamma^{obs}$

$L_{IC} = 10\% \; L_\gamma^{obs}$

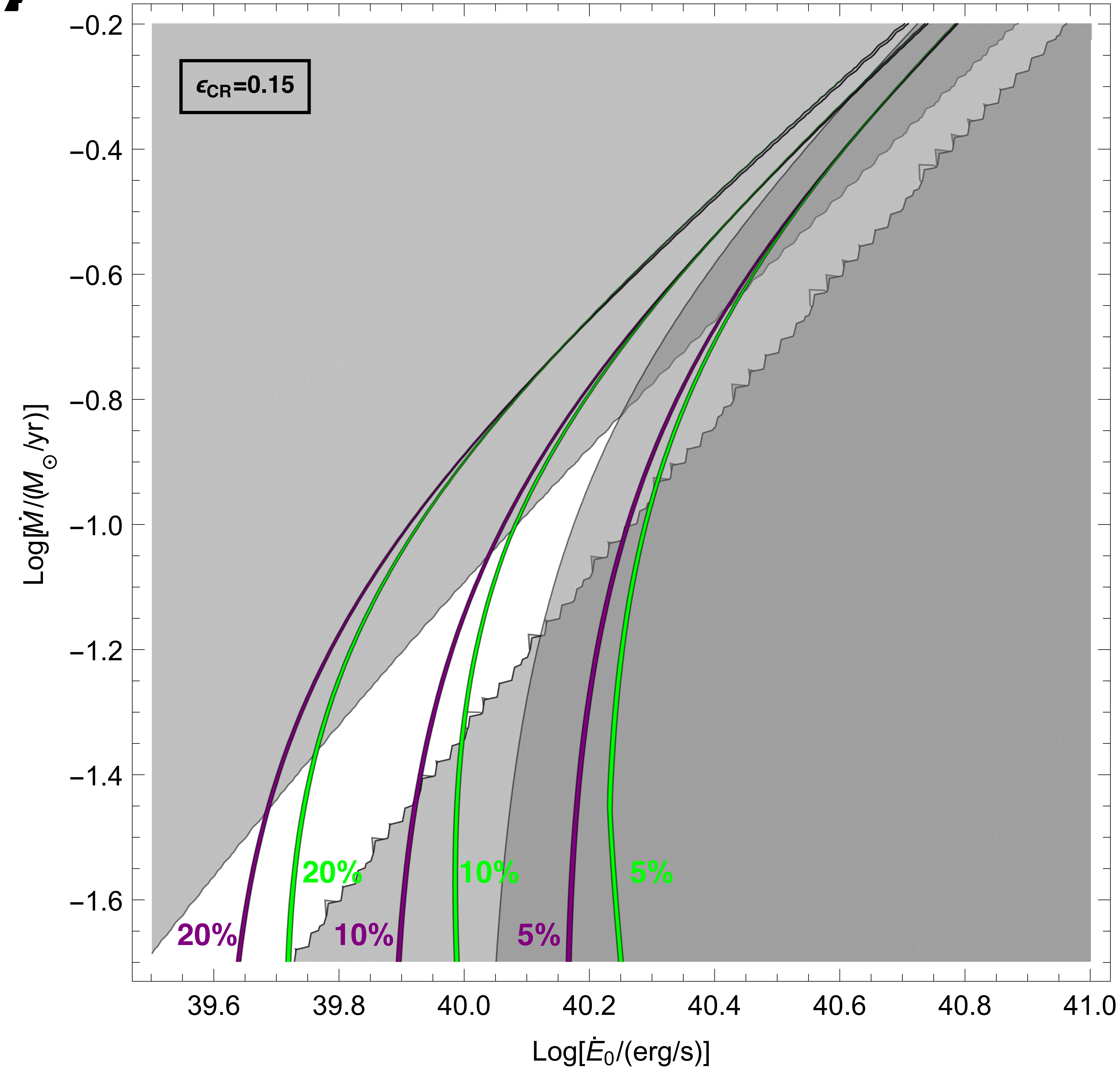
$L_{IC} = 30\% \; L_\gamma^{obs}$

Crocker et al. 2015

Synchrotron radiation I: Microwave Haze

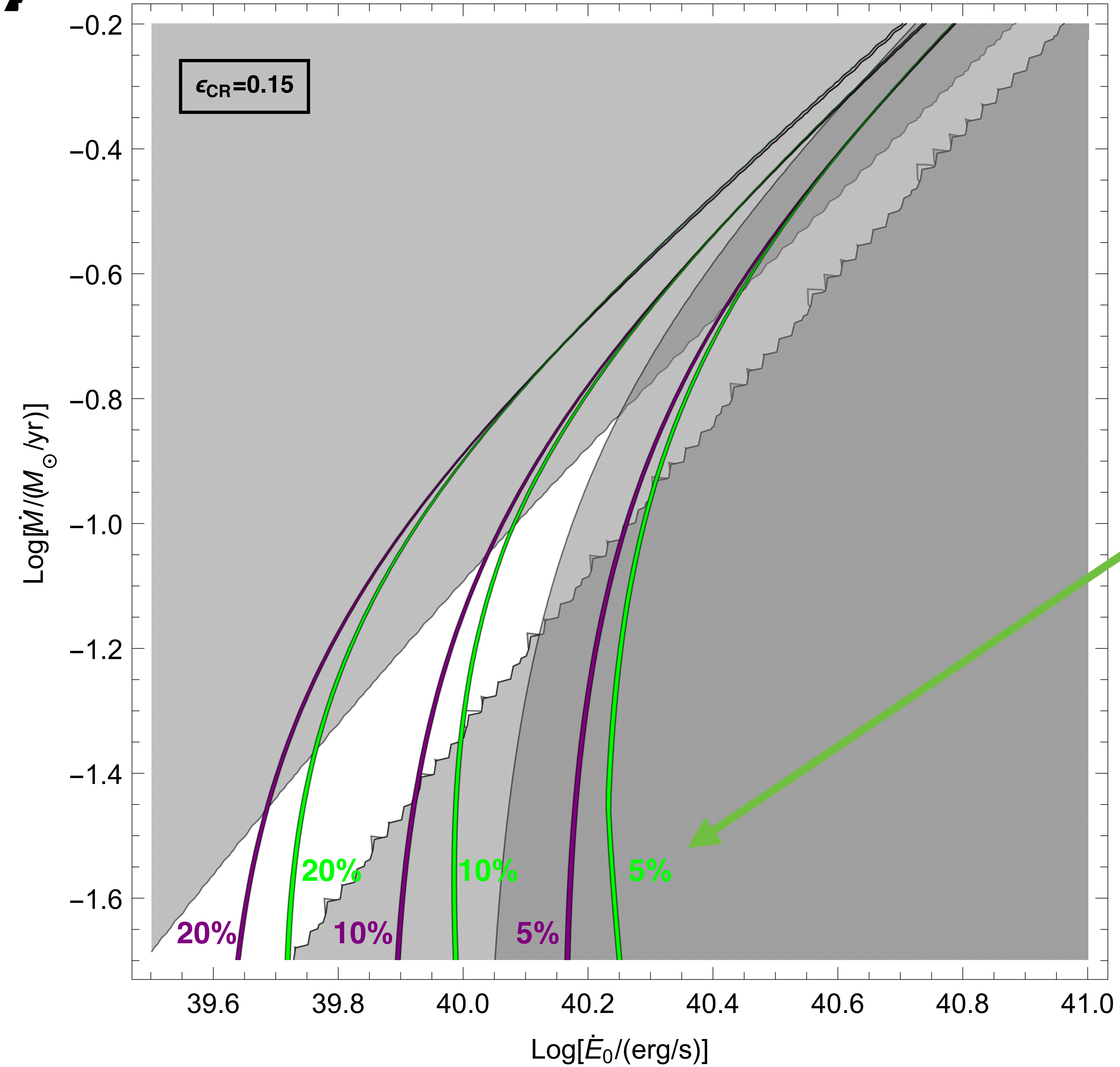
Crocker, Bicknell, Taylor & Carretti 2015, ApJ *808, 107*

Synchrotron Luminosity



Crocker et al. 2015

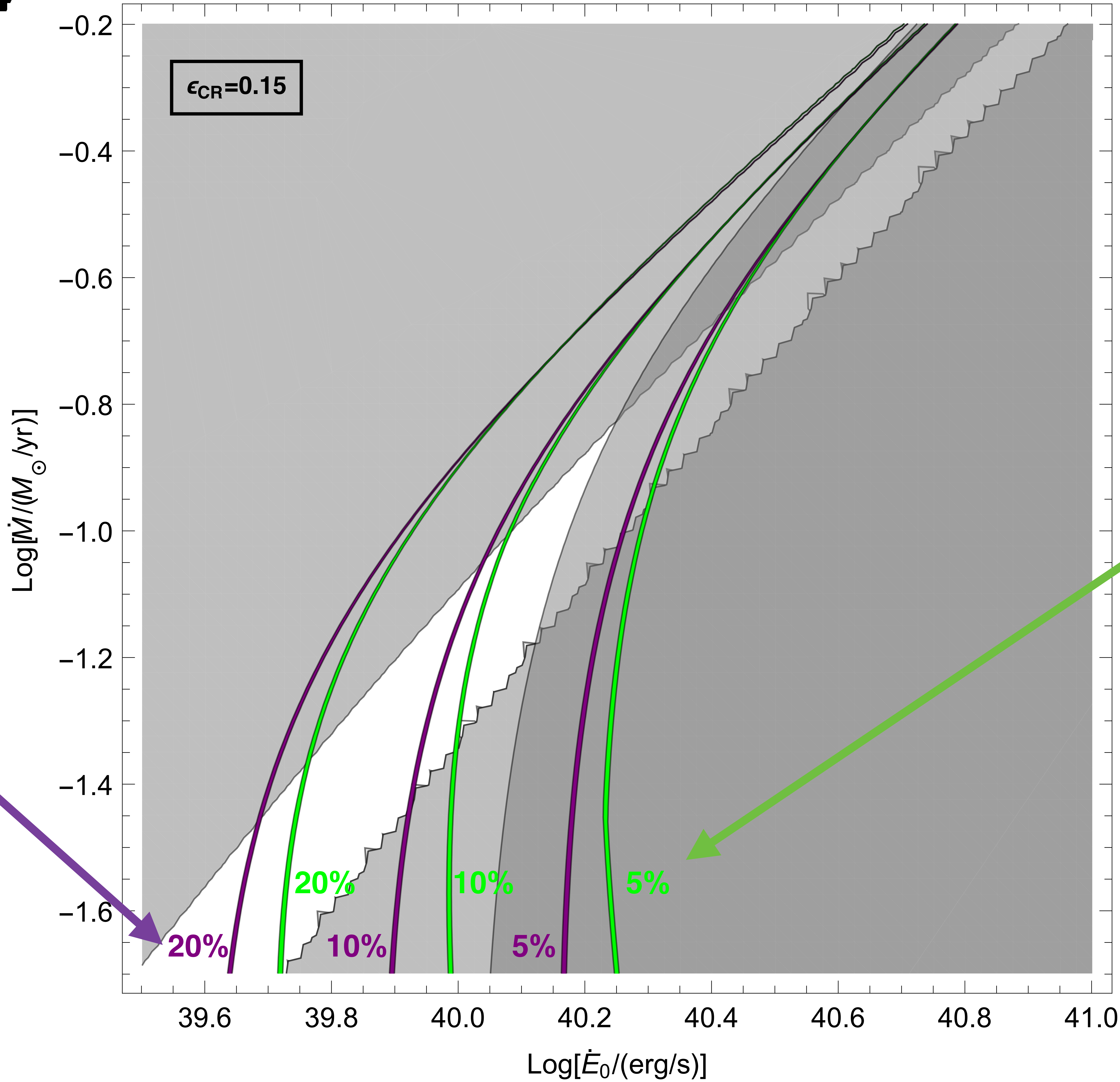
Synchrotron Luminosity



2.3 GHz luminosity supplied with 5% of CR power going to electrons

Crocker et al. 2015

Synchrotron Luminosity

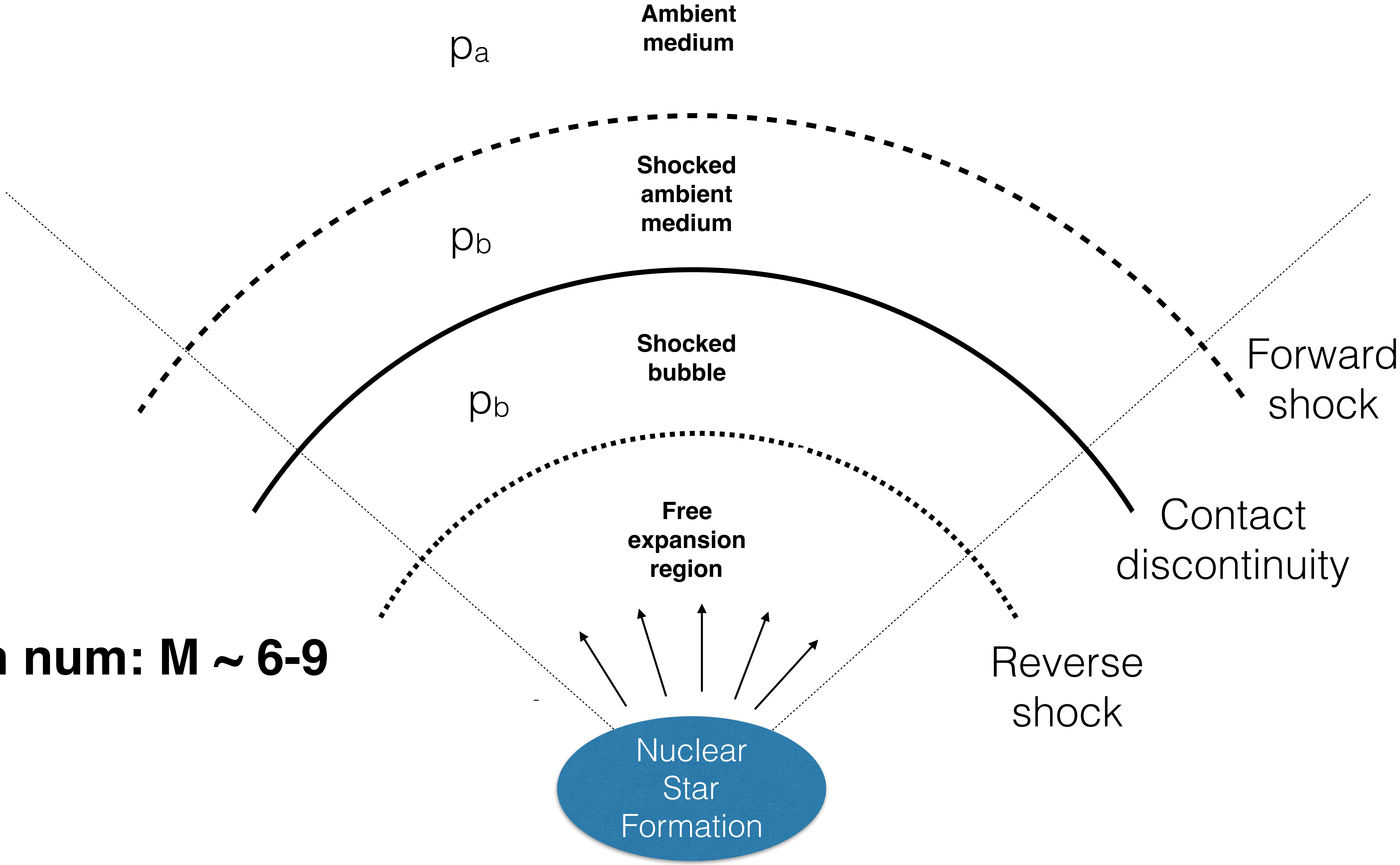


2.3 GHz luminosity supplied with 20% of CR power going to electrons

2.3 GHz luminosity supplied with 5% of CR power going to electrons

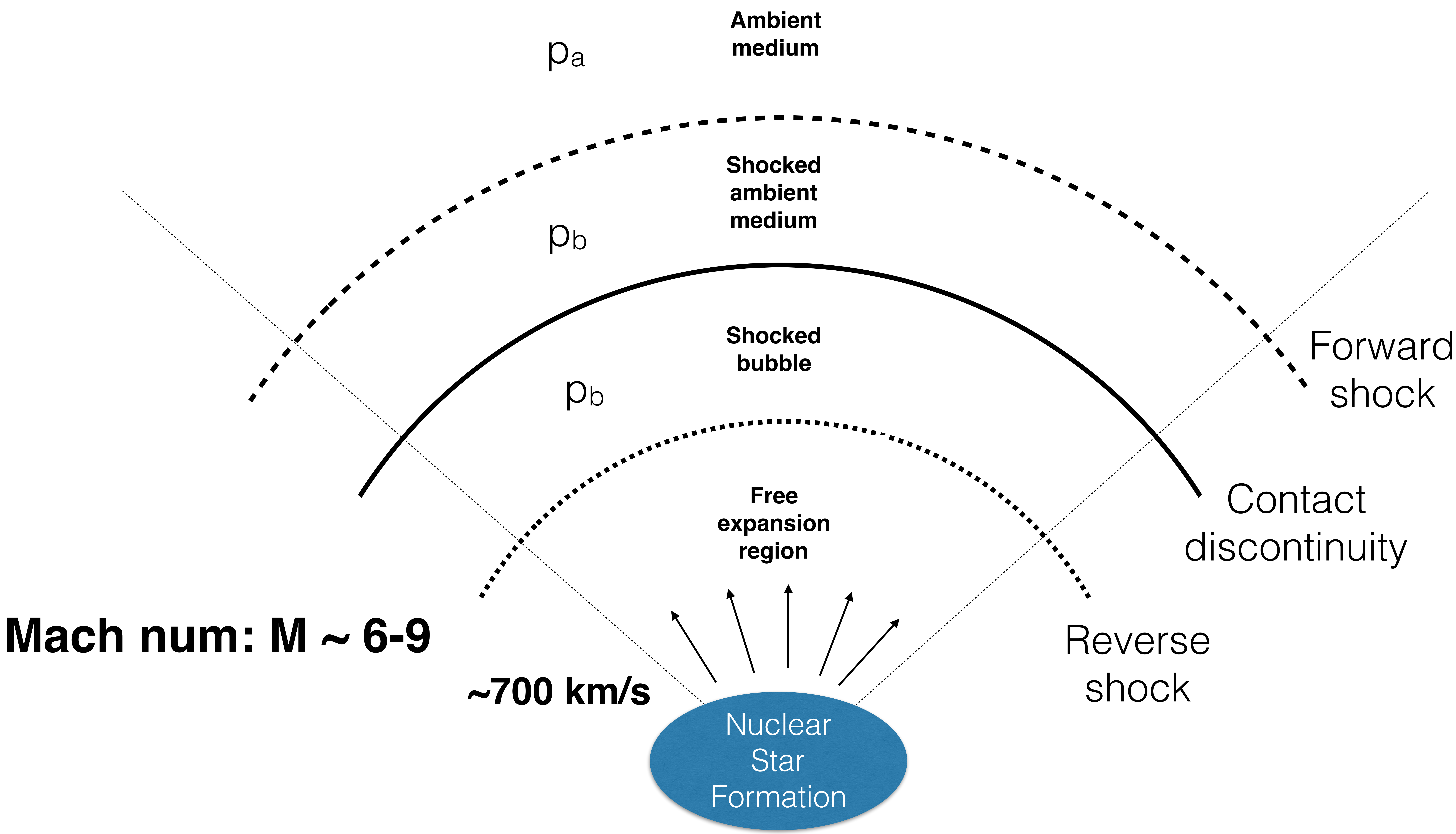
Crocker et al. 2015

Explaining hard haze spectrum

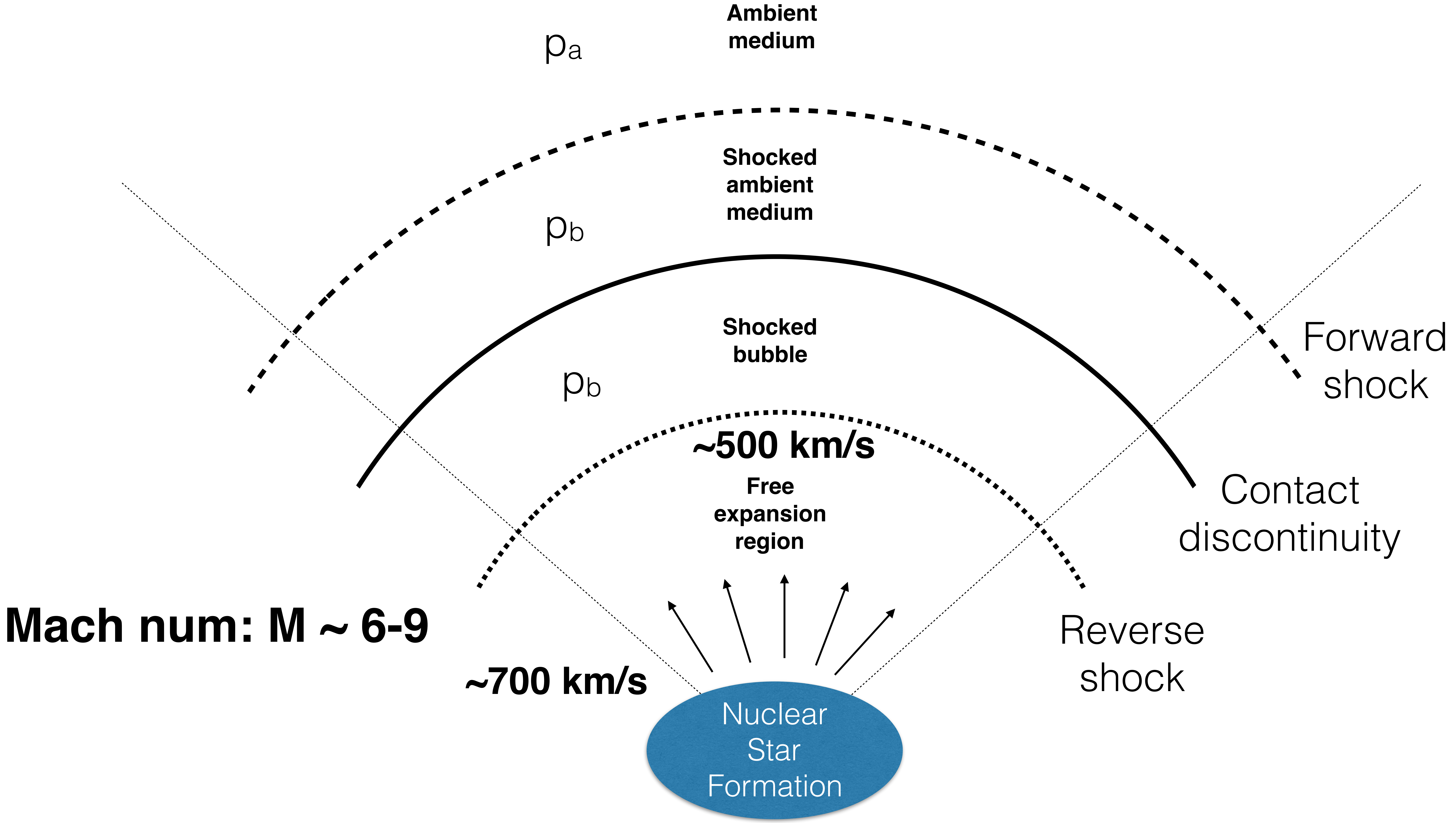


Mach num: M ~ 6-9

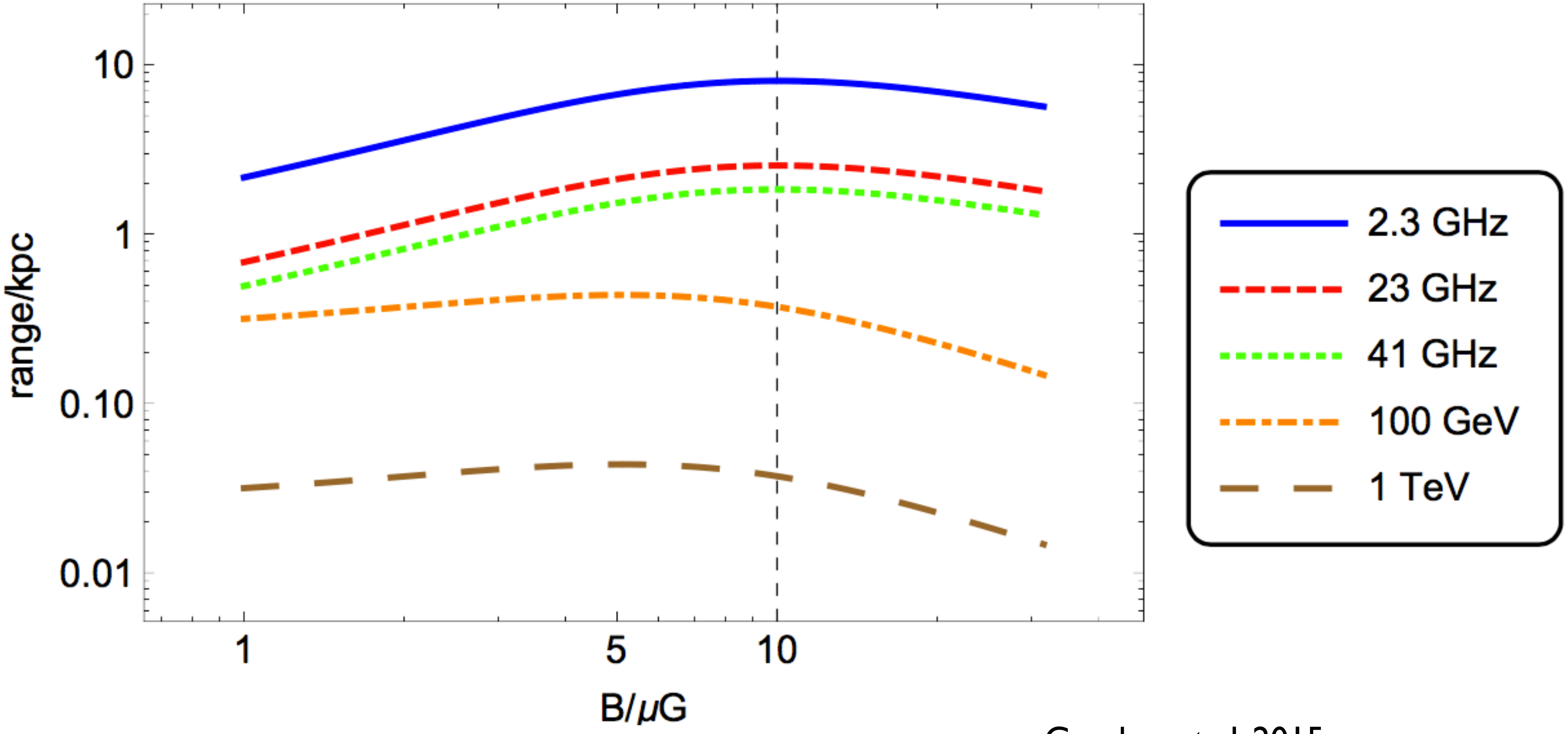
Explaining hard haze spectrum



Explaining hard haze spectrum

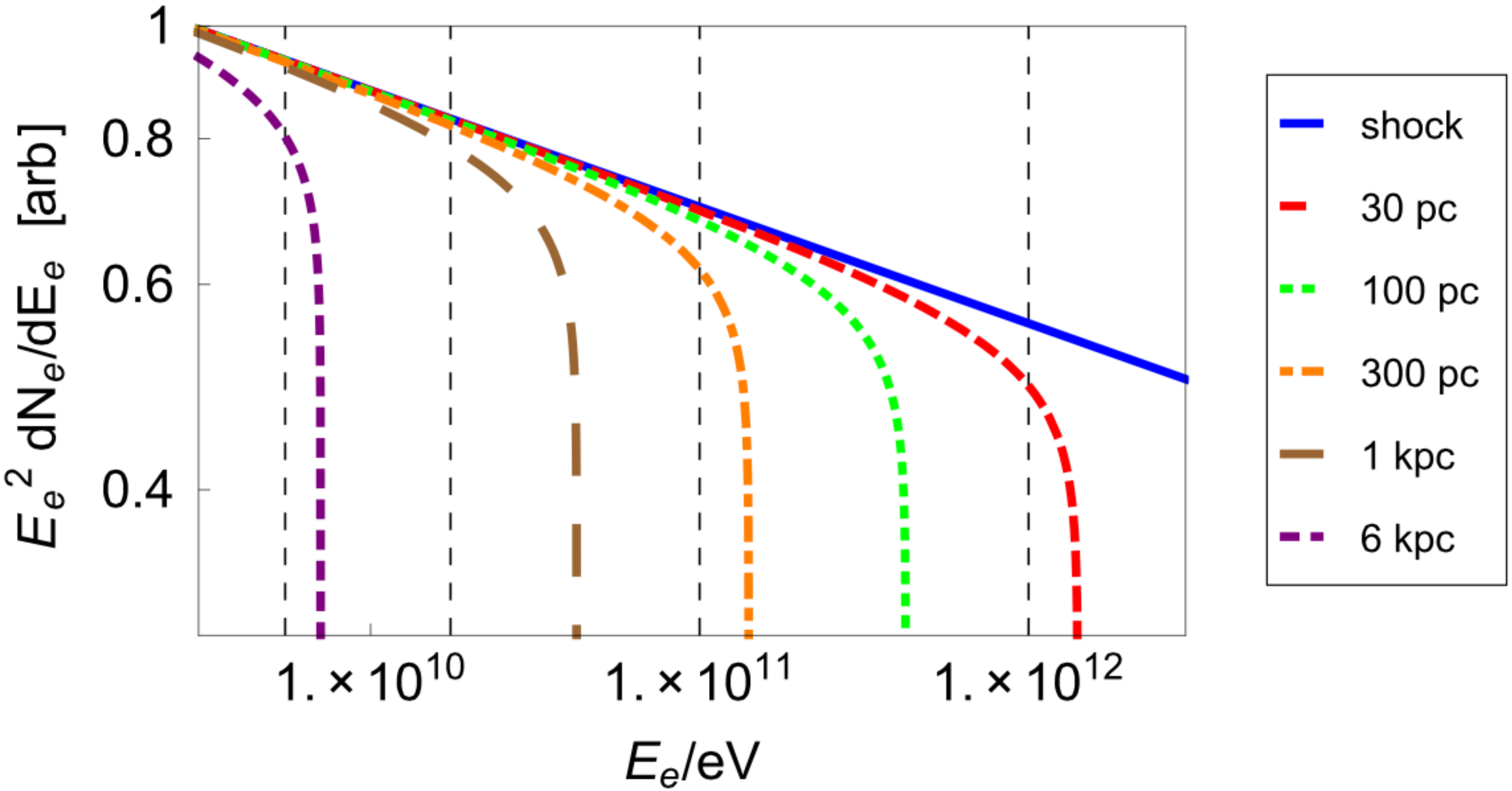


Range of CR electrons downstream of shock



Crocker et al. 2015

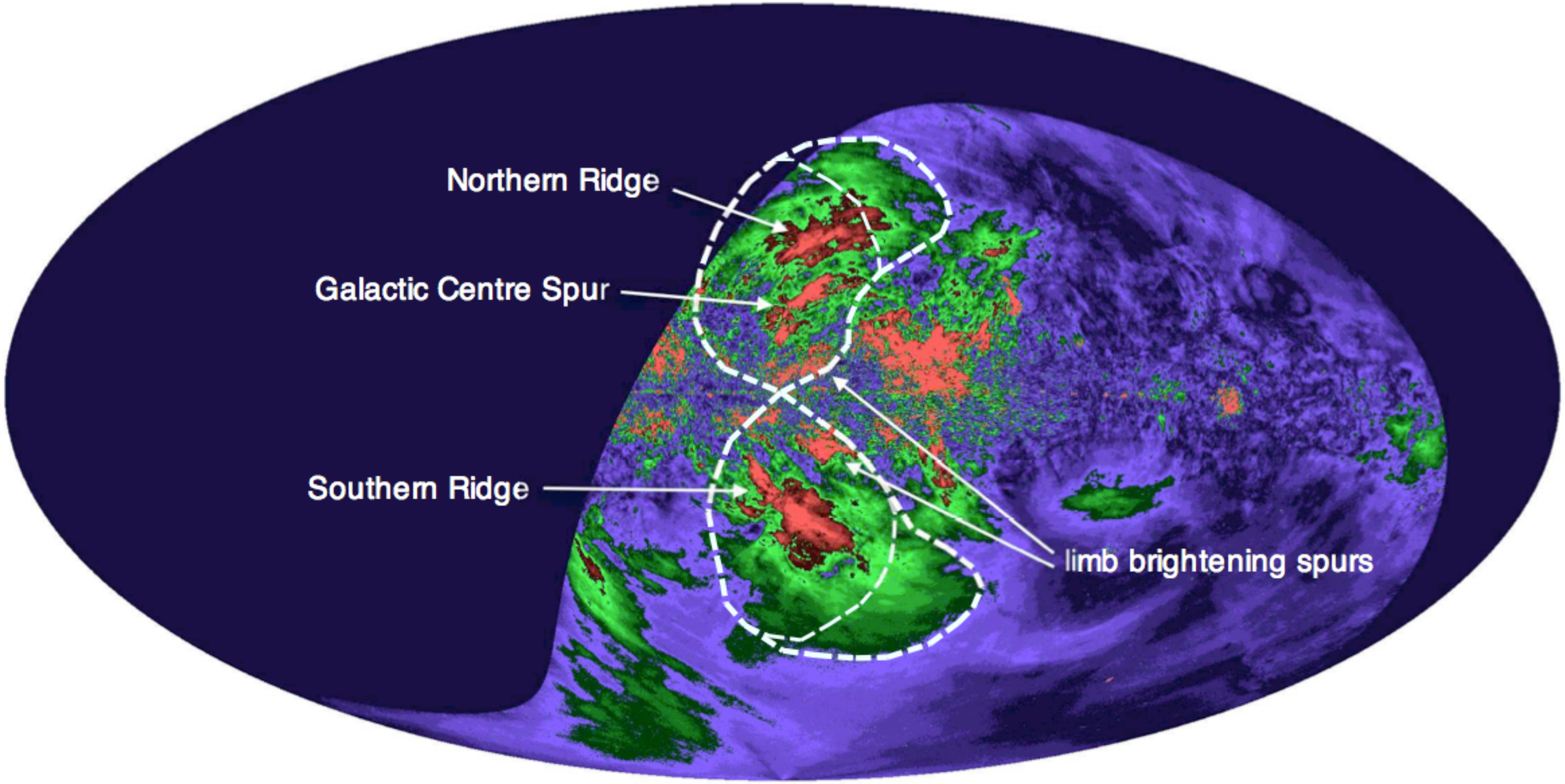
Explaining hard haze spectrum



Synchrotron radiation II: Polarized, steep-spectrum radio continuum

Crocker, Bicknell, Taylor & Carretti 2015, ApJ *808, 107*

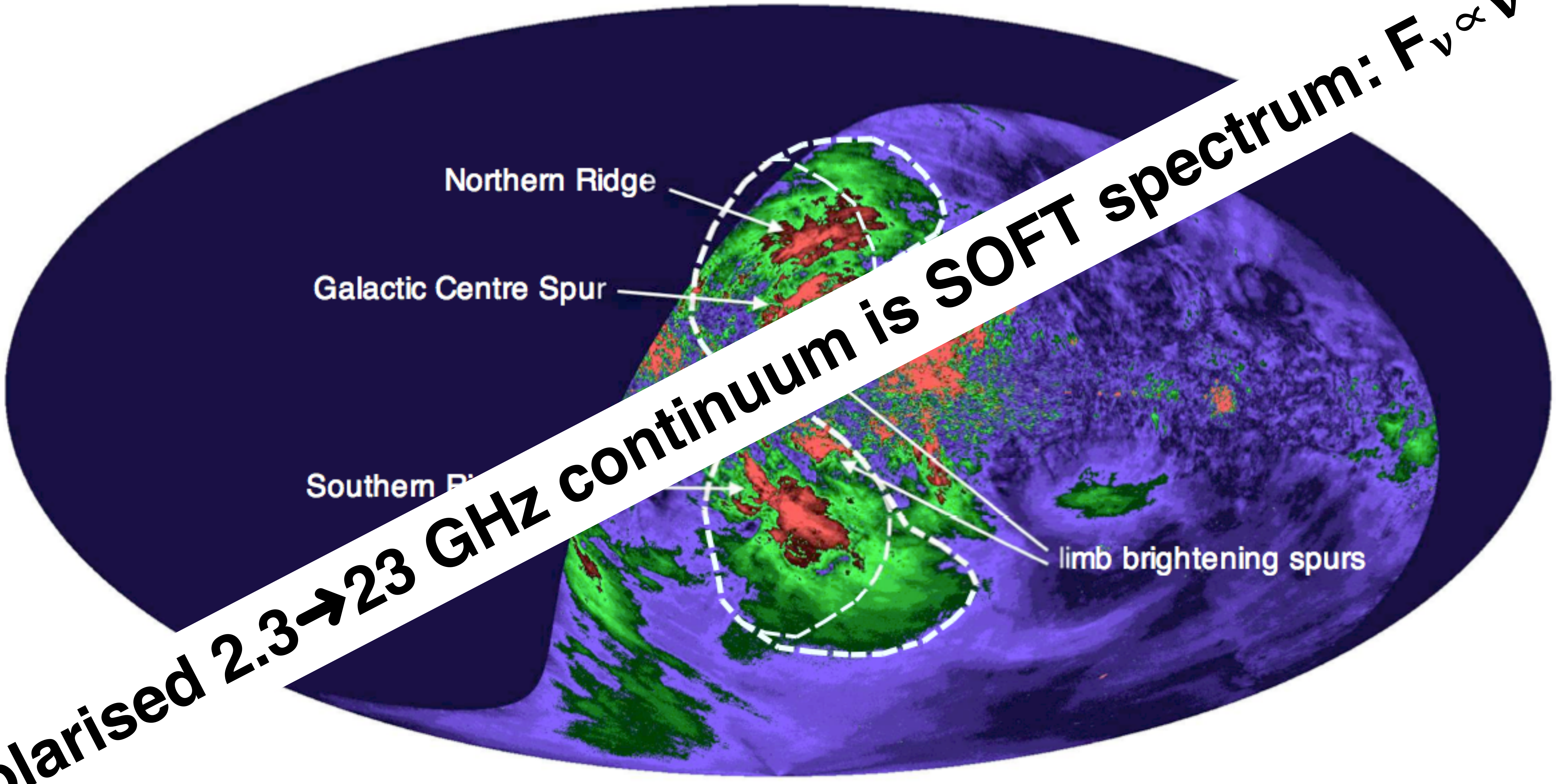
Giant Radio Lobes



Carretti et al. 2013

2.3 GHz **polarized** intensity

Giant Radio Lobes

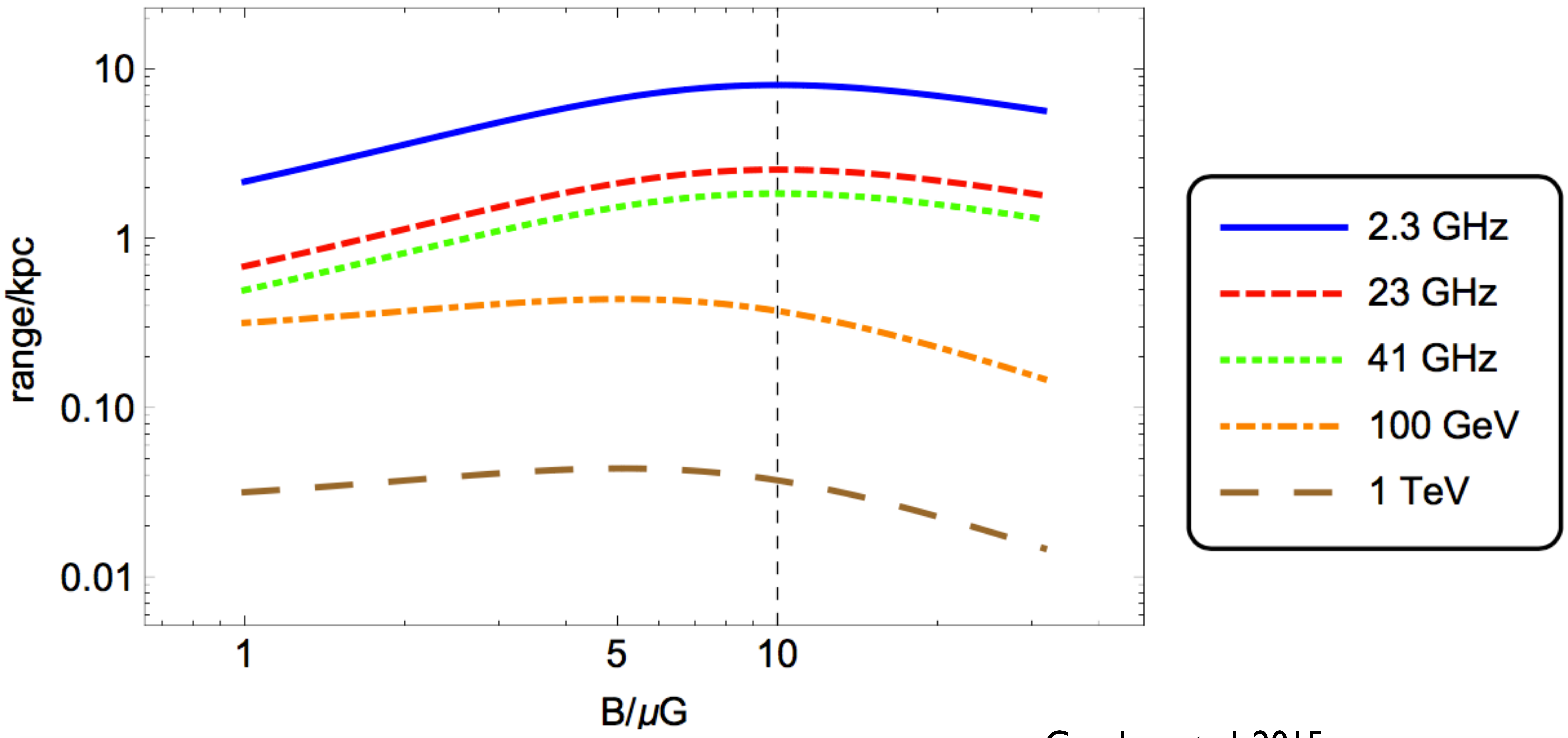


polarised 2.3→23 GHz continuum is SOFT spectrum: $F_\nu \propto \nu^{-1.0}$

Carretti et al. 2013

2.3 GHz **polarized** intensity

Range of CR electrons downstream of shock



Crocker et al. 2015

Polarized, steep-spectrum emission

- lower-energy electrons that reach the magnetised shell synchrotron cool in situ
- there is then a mixture of electron populations with different 'ages' resulting in $\propto E_e^{-3}$ overall electron spectrum (Karadashev)
- explanation for the $F_\nu \propto \nu^{-1}$, polarised radio emission

Conclusions

With ***few free parameters*** our nuclear SF-driven model addresses or explains:

- the size of the Bubbles
- the luminosity, spectrum and morphology of the Bubbles' gamma-ray emission
- the luminosity, spectrum and extent of the microwave haze
- the luminosity, spectrum and extent of the microwave haze of the polarised radio lobes
- the power dissipated in the Bubbles is a good match to the mechanical power injected by nuclear SF
- the total energy content of the Bubbles is a good match to (nuclear SF power) x (few 100 Myr expansion timescale)

Advertisement:

IAU Symposium 322: *The Multi-Messenger Astrophysics of the Galactic Centre*

“The meeting aims to combine results, not just from astrophysics, but also astroparticle physics for the first time.”

Palm Cove, Australia, July 18-22 2016

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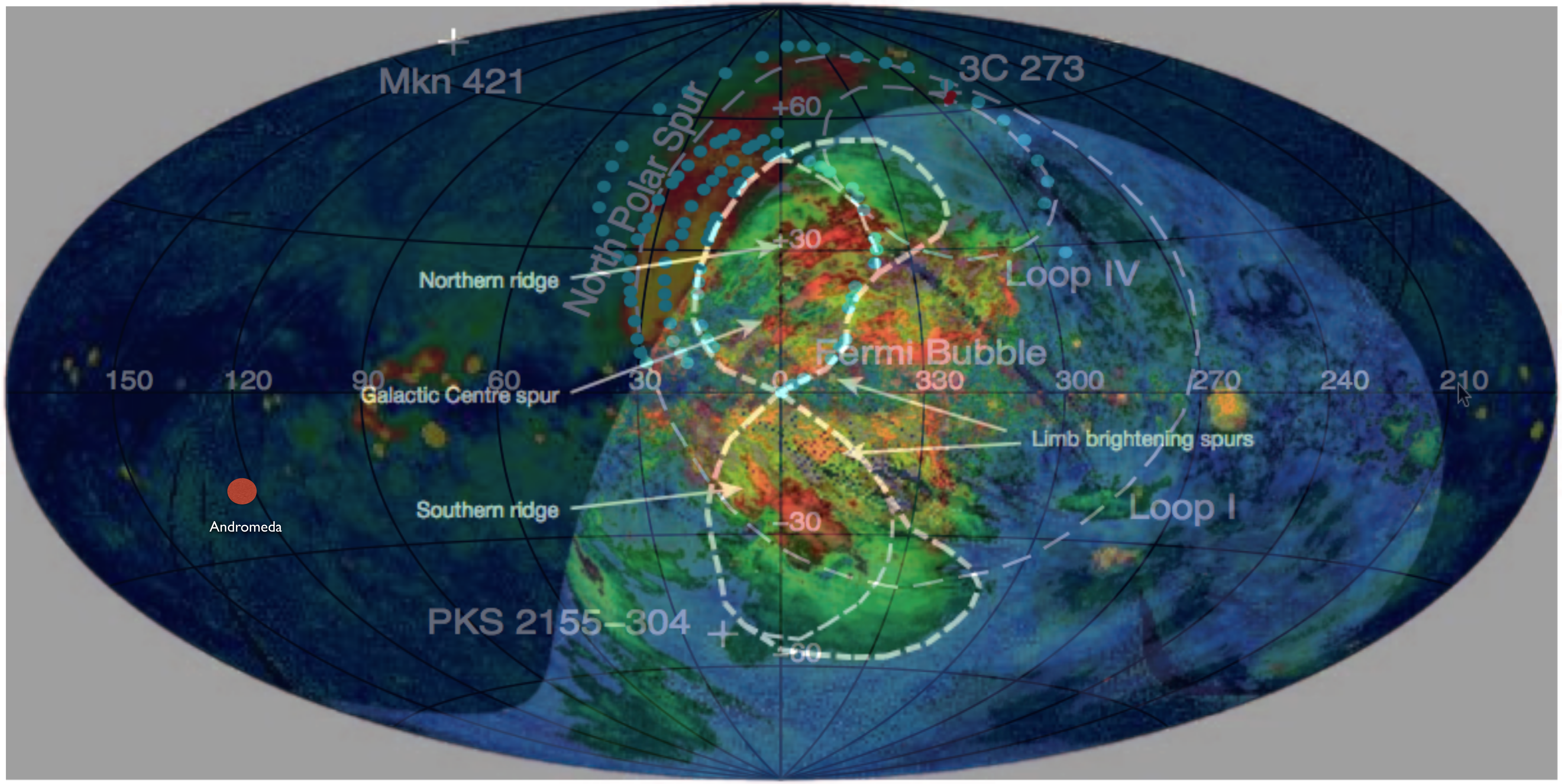
Extra Slides

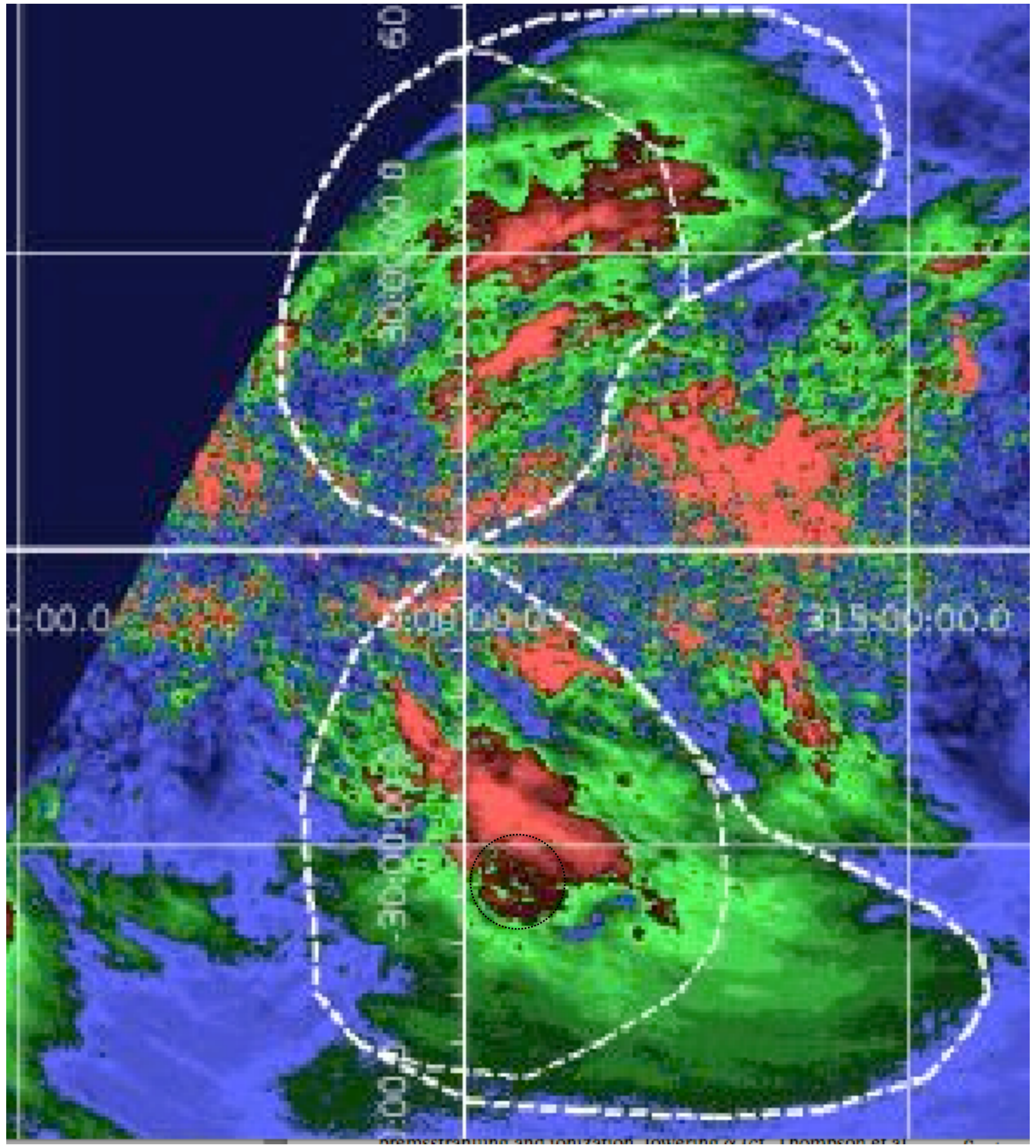
Adjustable Parameters

- ‘Atmospheric’ pressure ~ 3 x 10^{-12} dyn/cm^2
- solid angle each conical outflow $\Omega = \pi$
- shock mechanical power going into cosmic rays ε_{CR} ~ 0.15
- fraction of cosmic ray power going into electrons L_e/L_{CR} ~ 0.1

$\dot{E}$=6.0 × 10^{39} erg/s
$\dot{M}$=0.08 $M_\odot$/yr
p_b=3.2 10^{-12} dyn cm^{-2}
1000
100
10
1
0.1
radius/kpc
10^5
10^6
10^7
10^8
10^9
t/year
CD 1 $Z_\odot$
CD 2 $Z_\odot$
CD 1.2 × 10^{40}
CD 3.0 × 10^{39}
FS
OPAB

A breeze from Andromeda?

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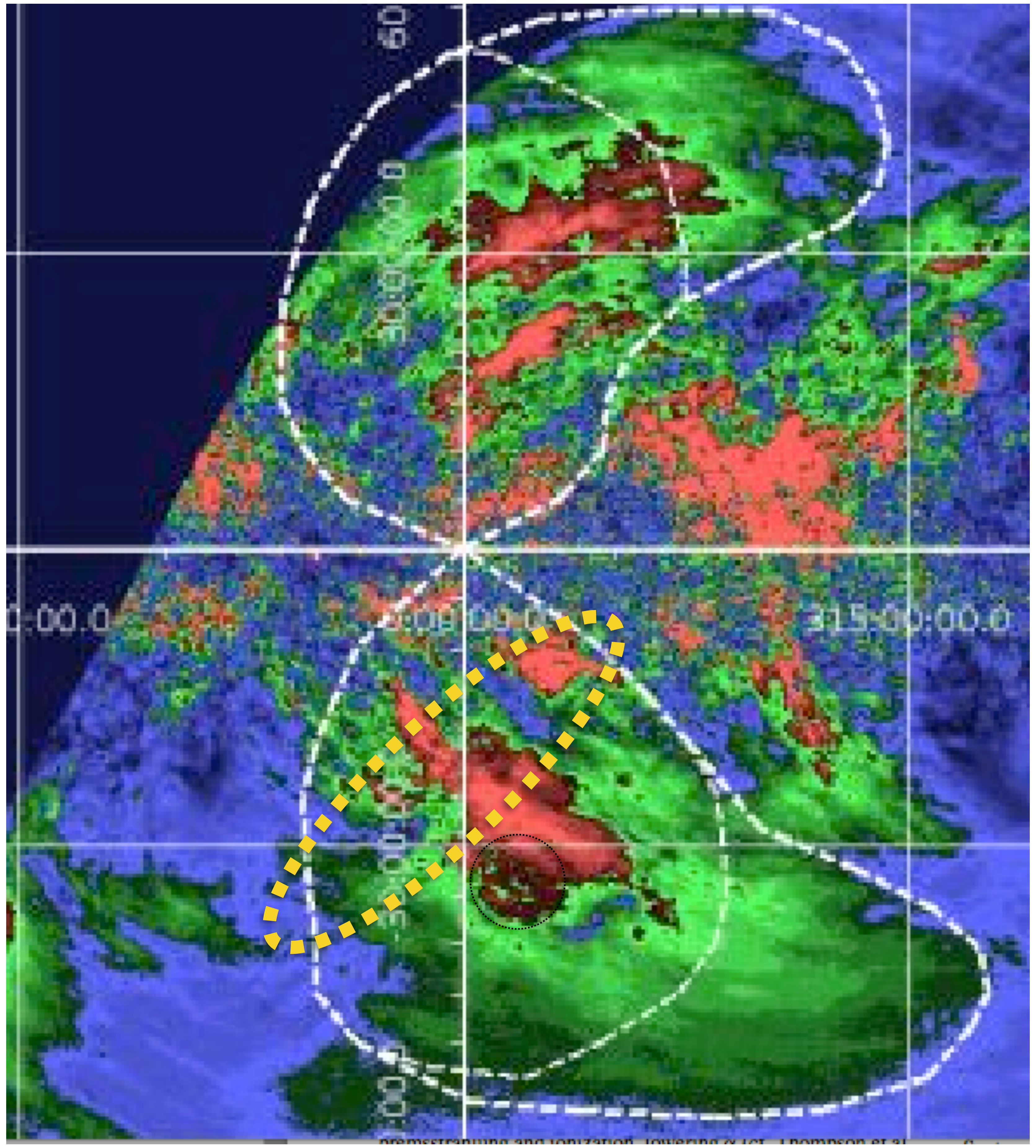
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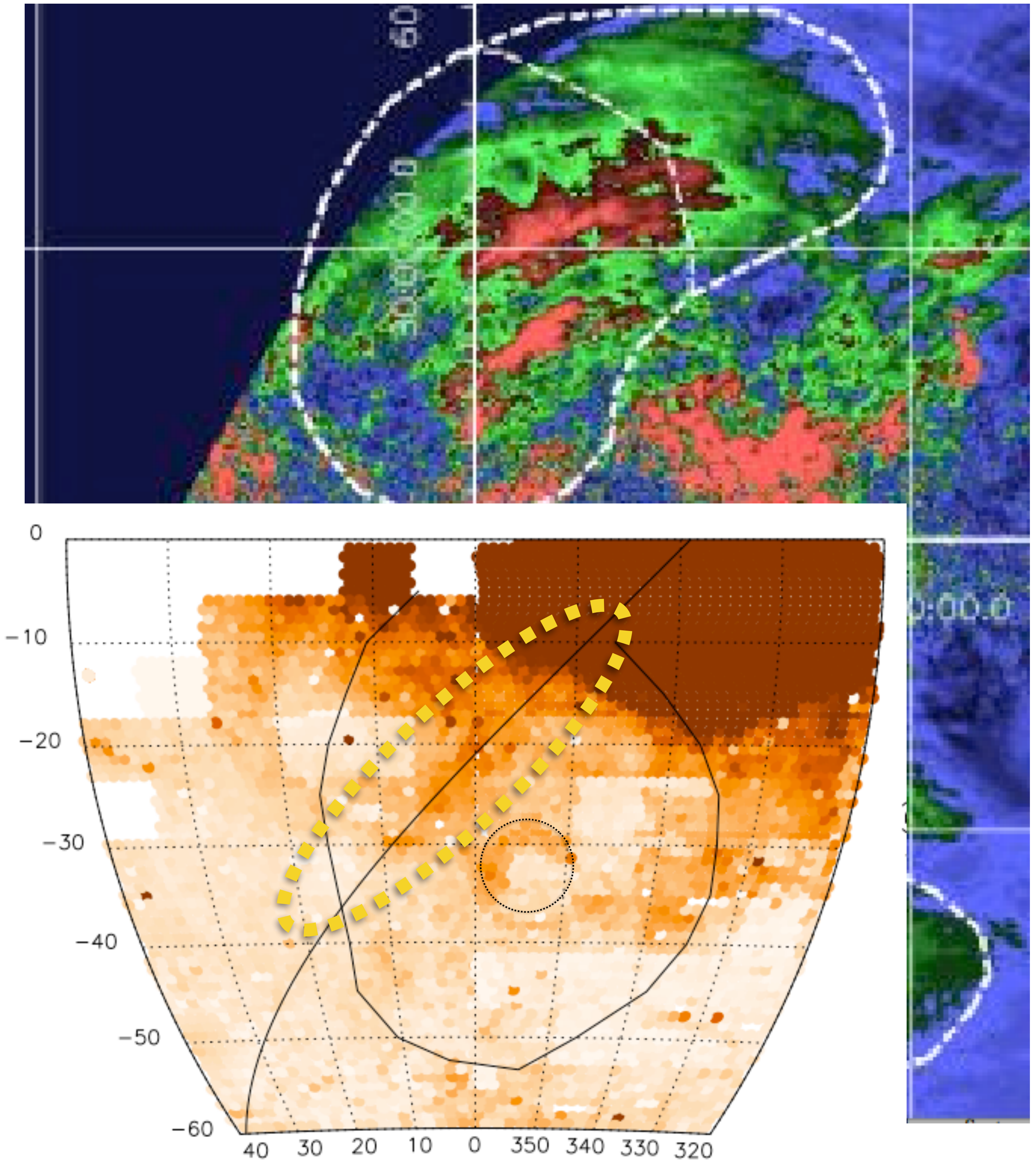

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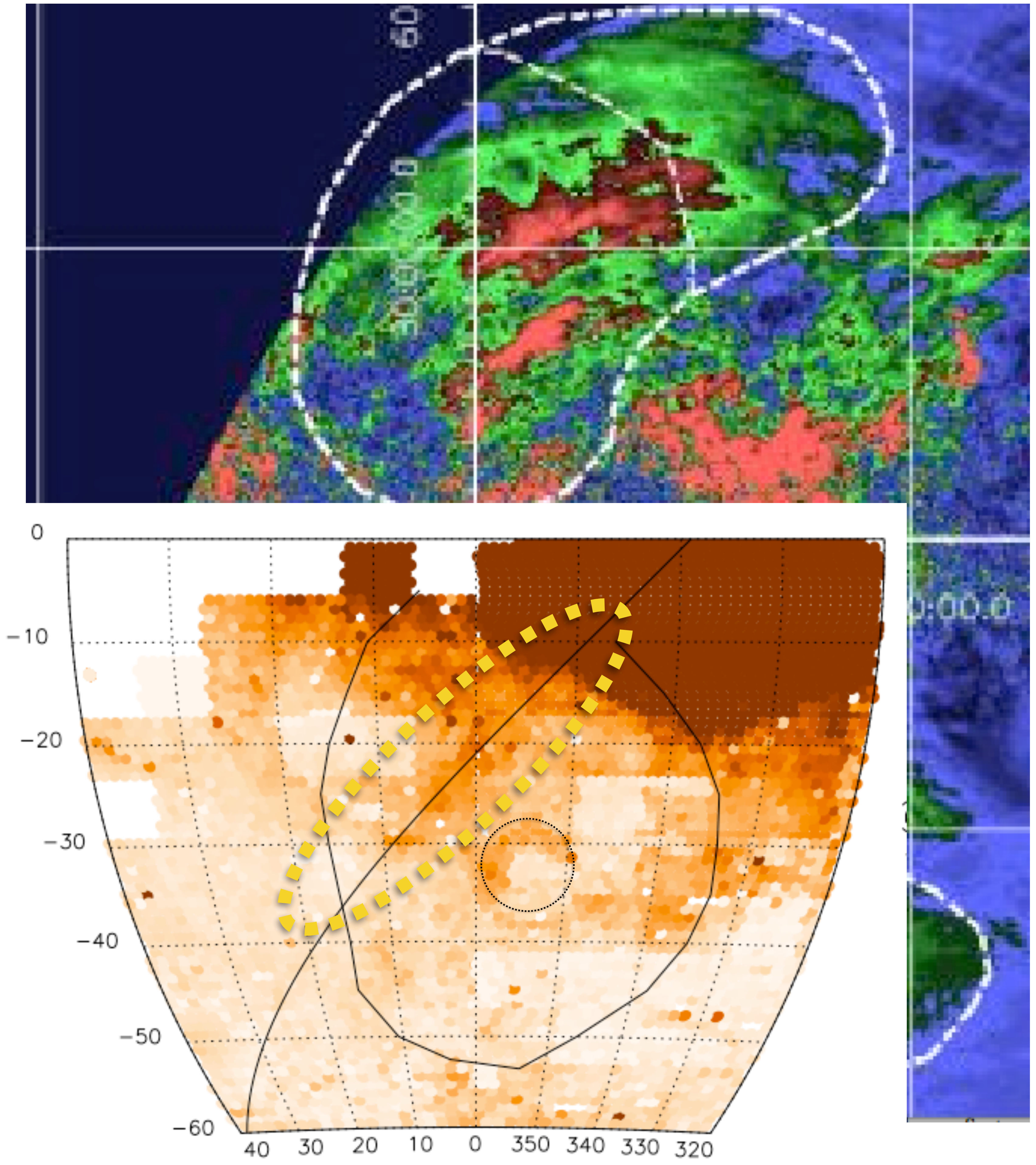
H-alpha



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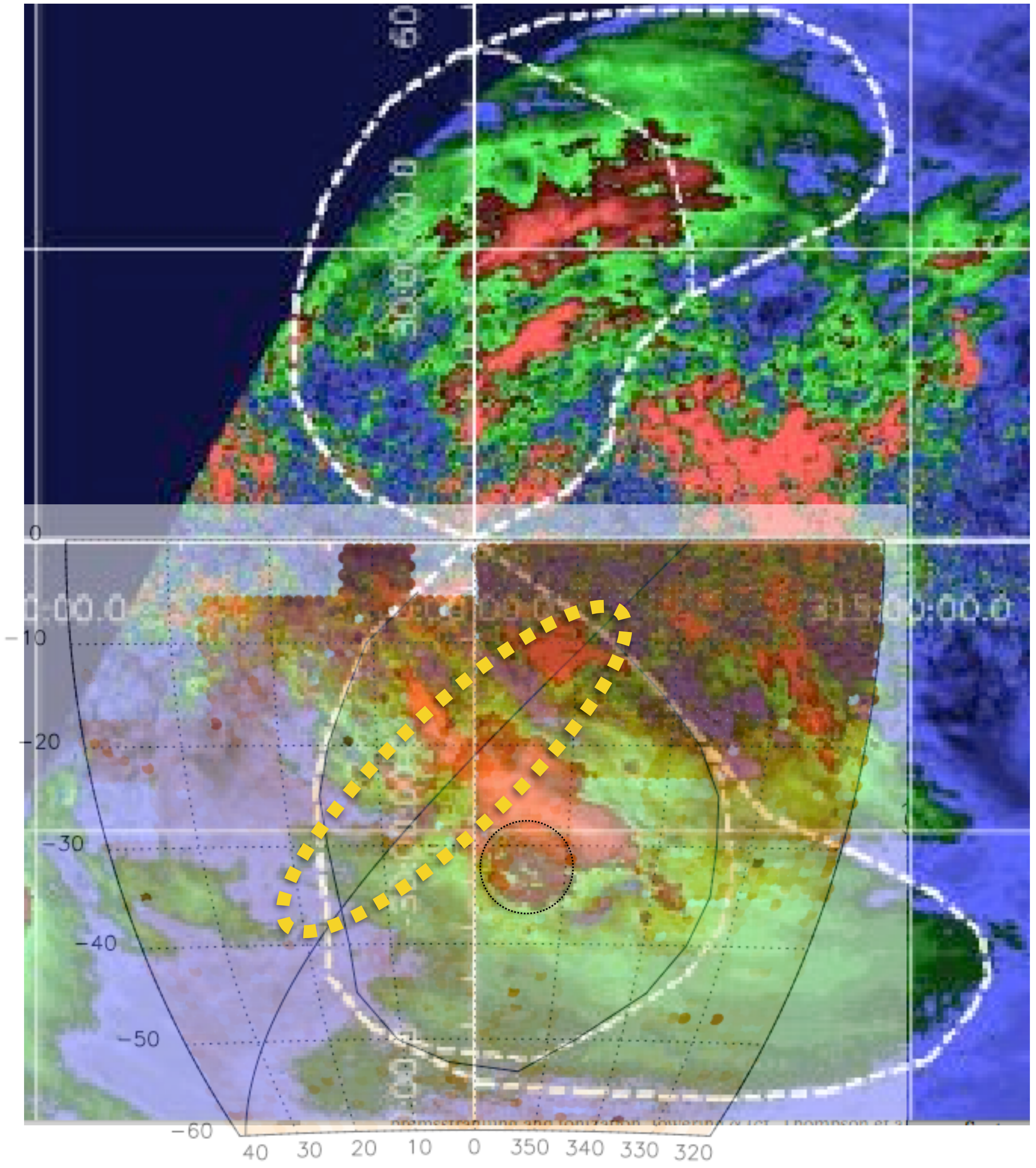
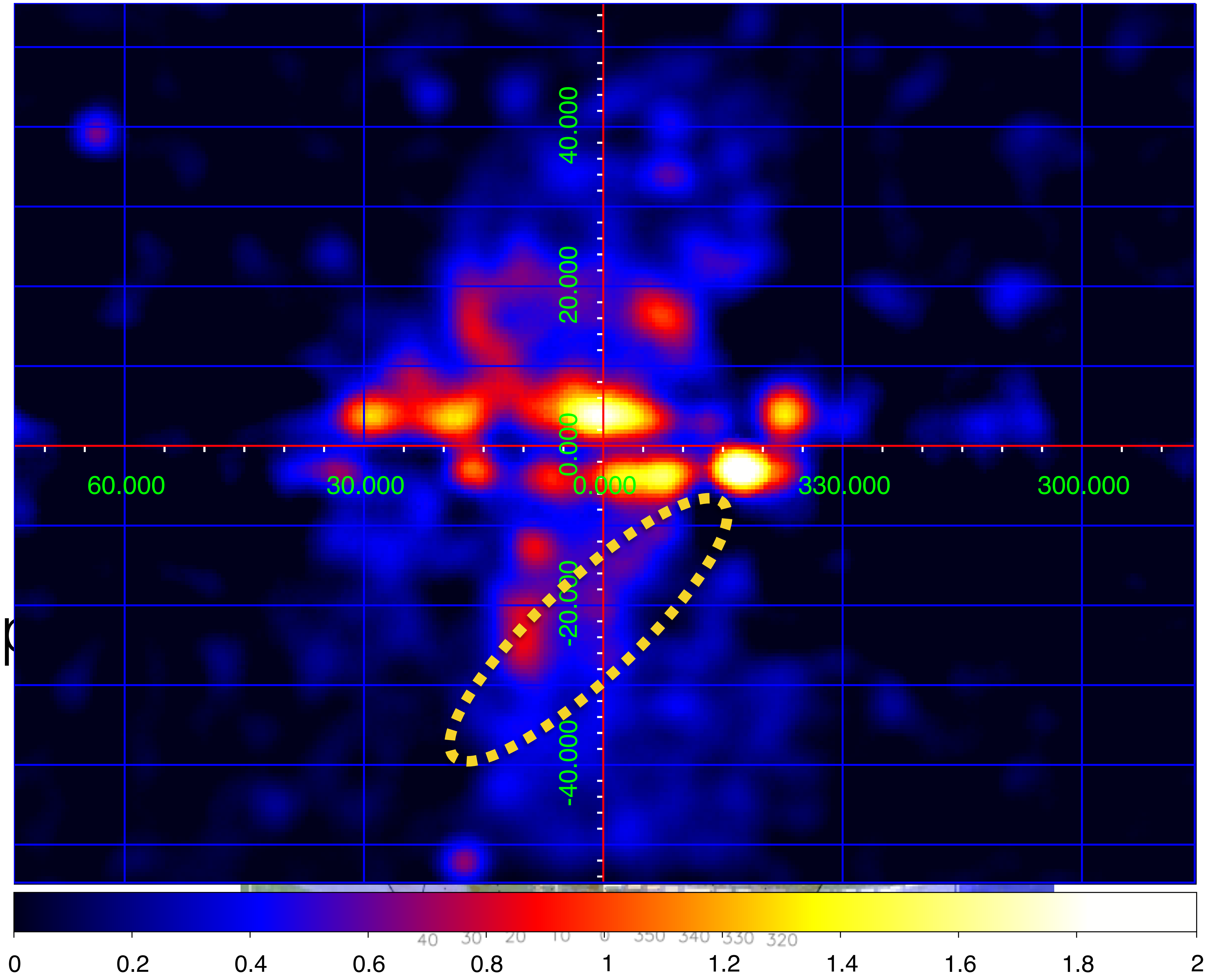


H-alp



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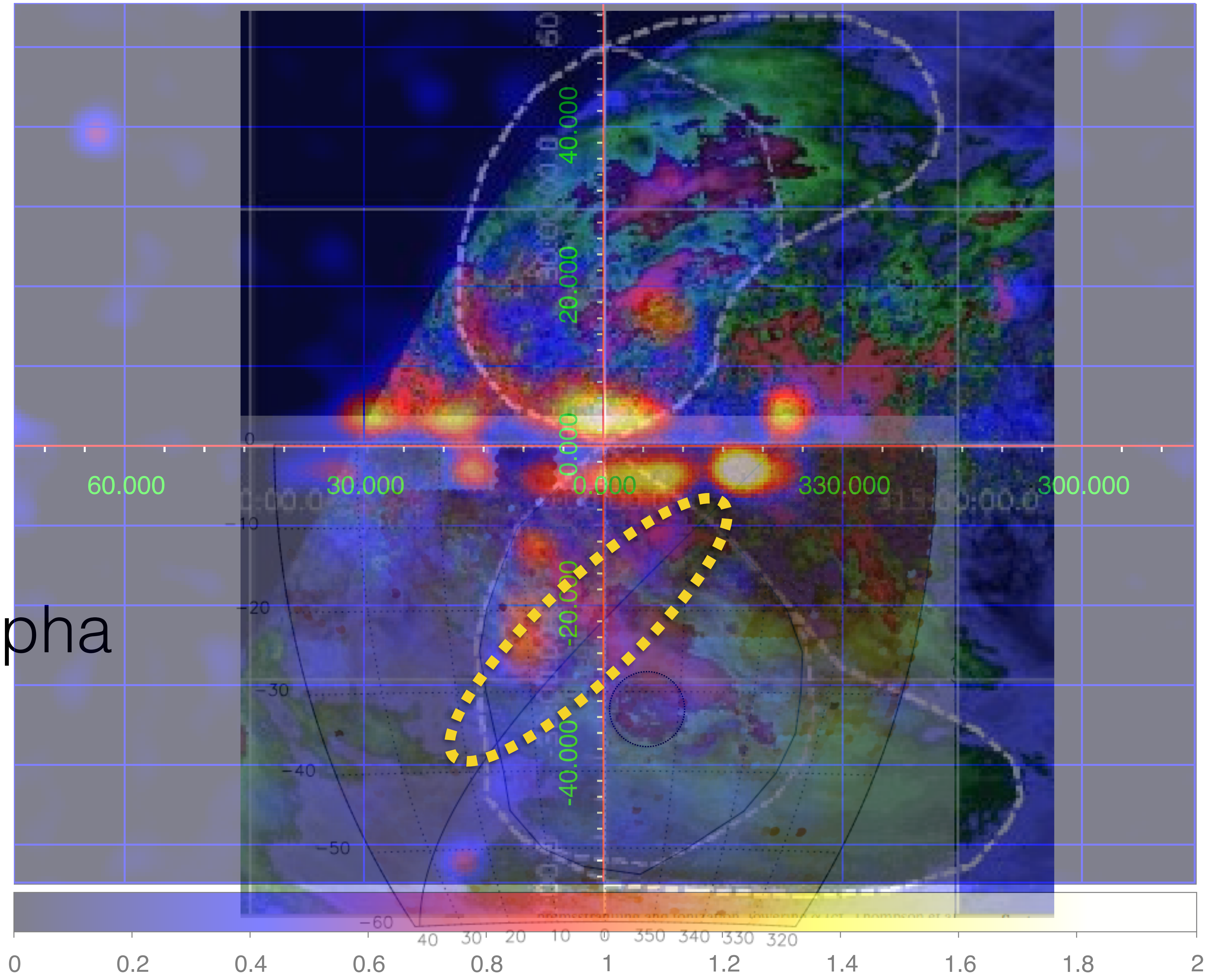
H-alpha



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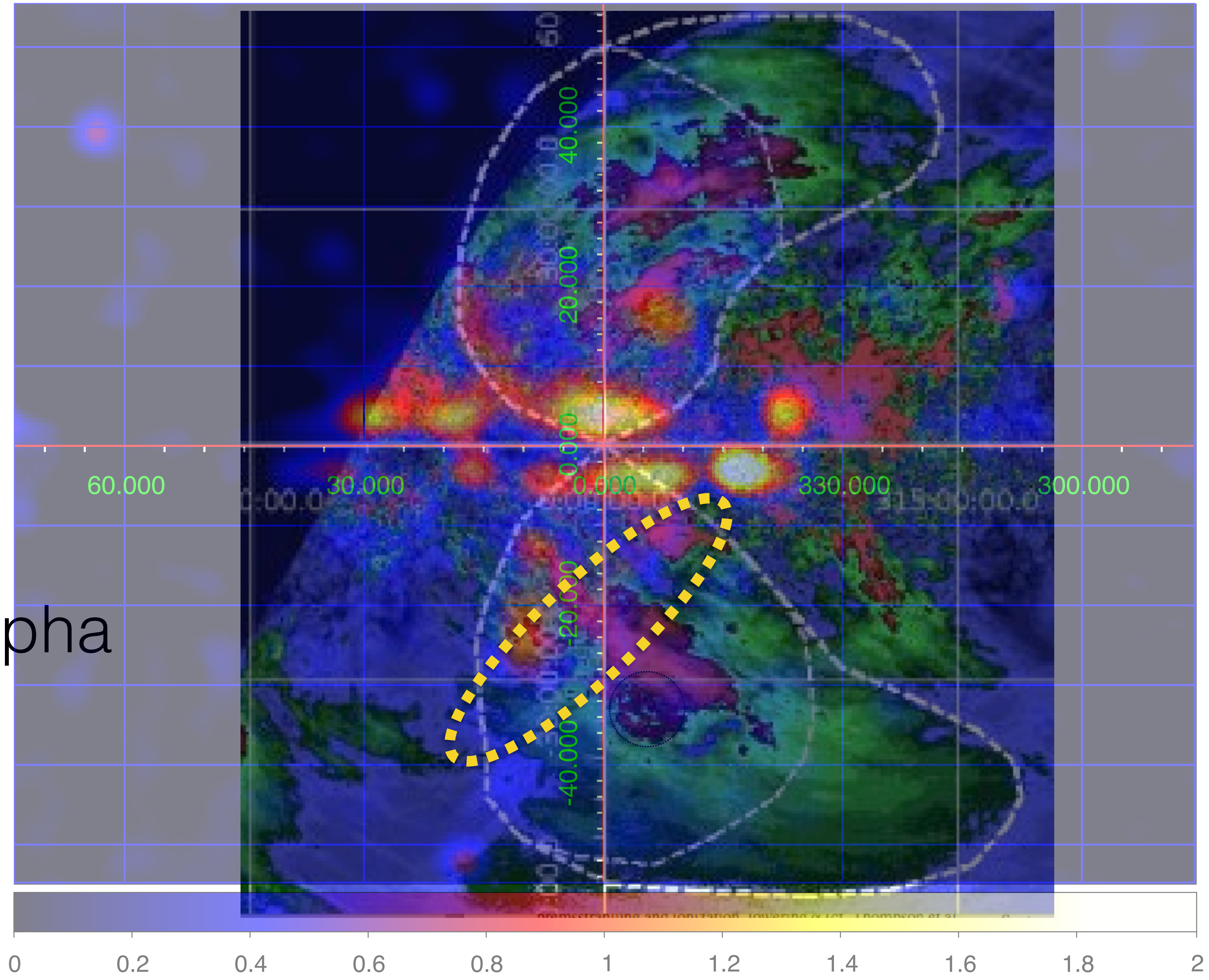

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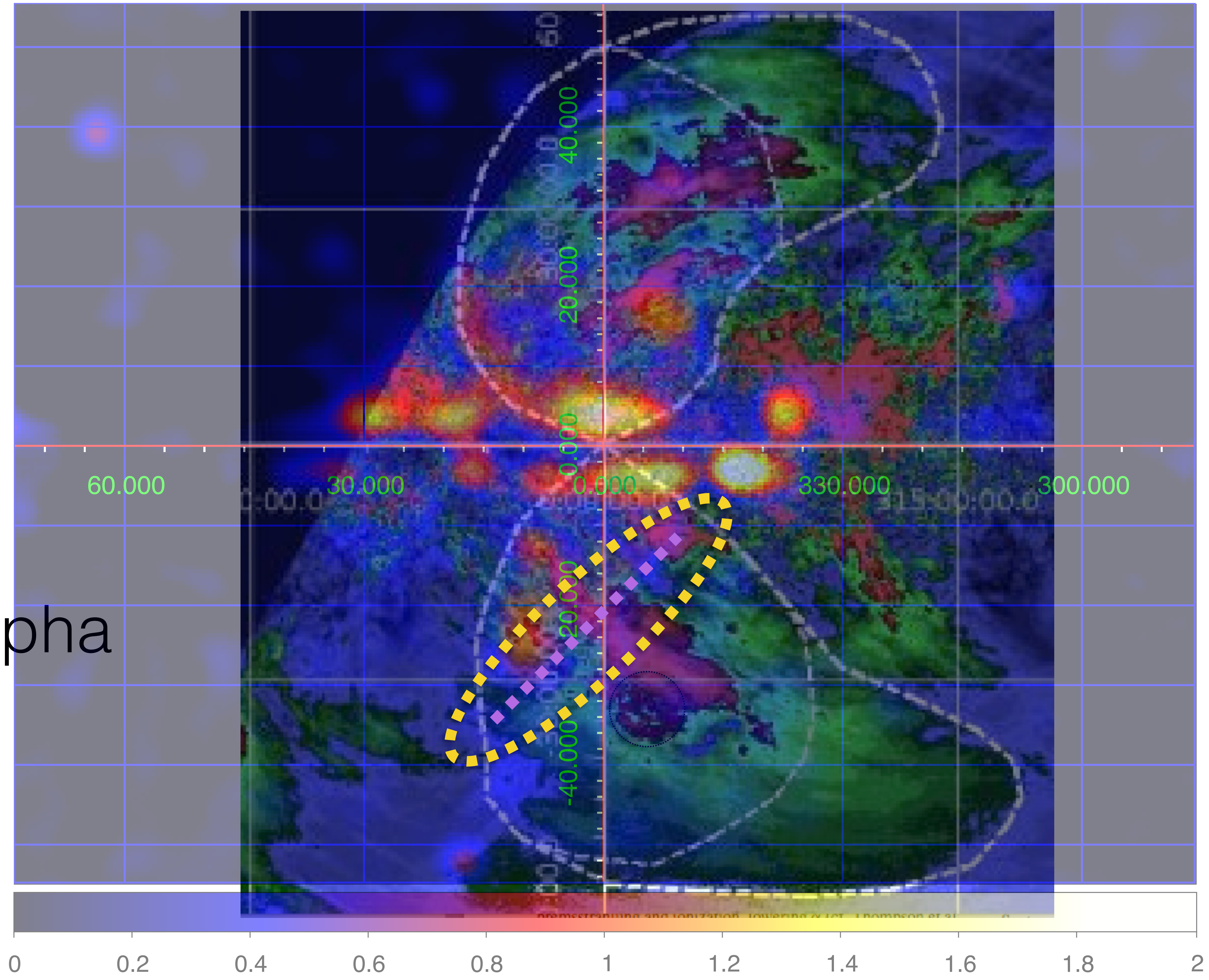

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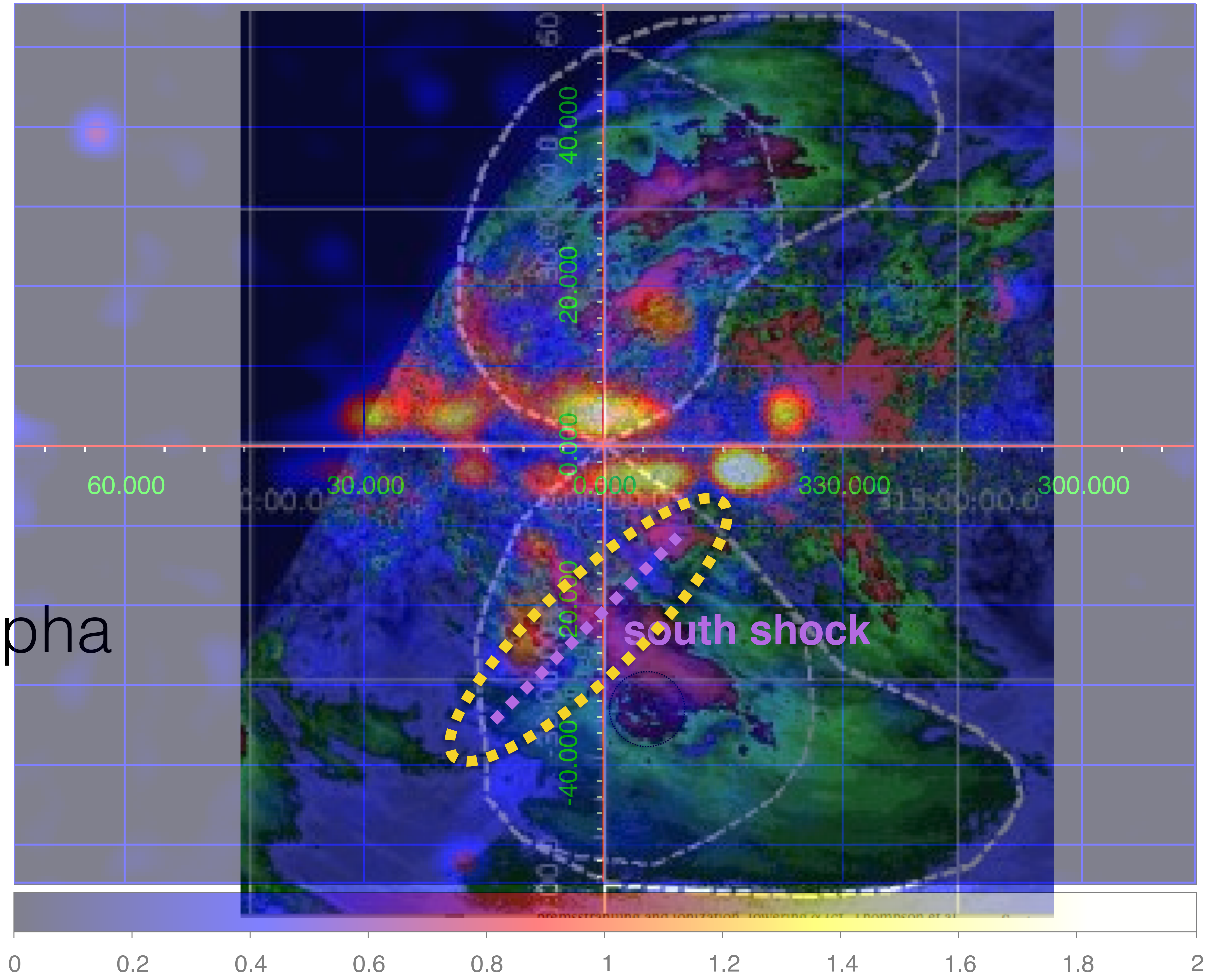

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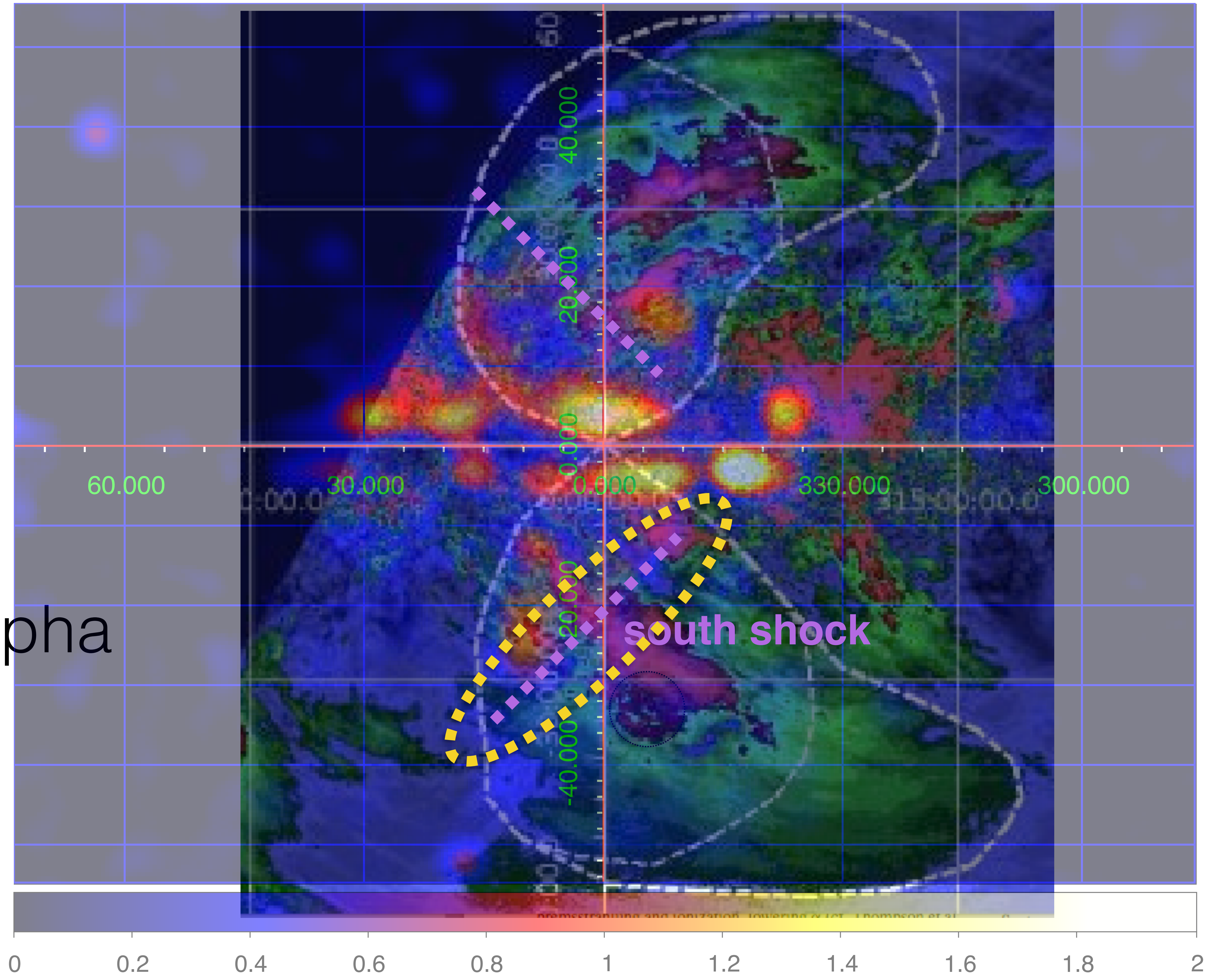
H-alpha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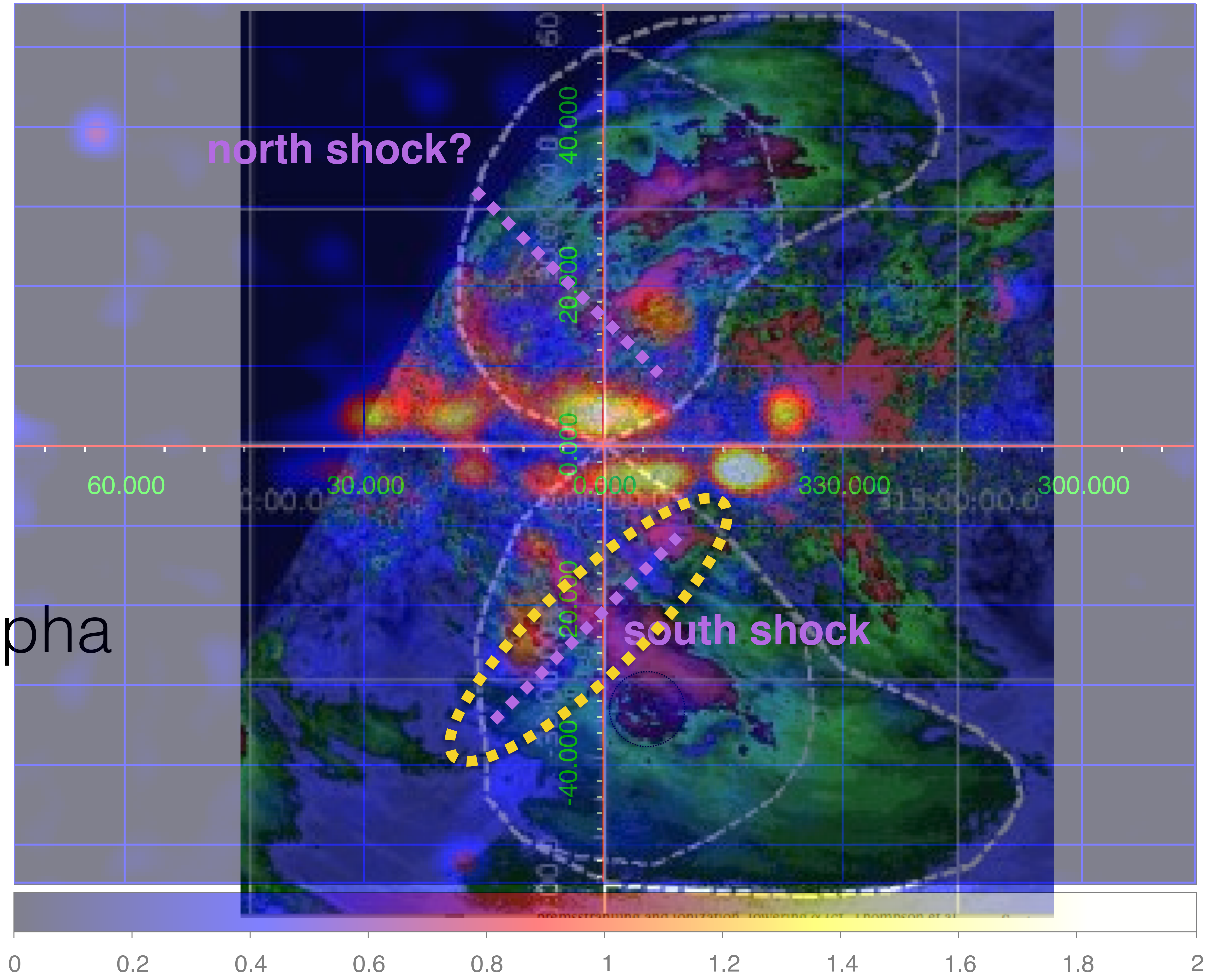
H-alpha



north shock?
south shock
60.000
30.000
0.000
330.000
300.000
40.000
20.000
-20.000
-40.000
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2