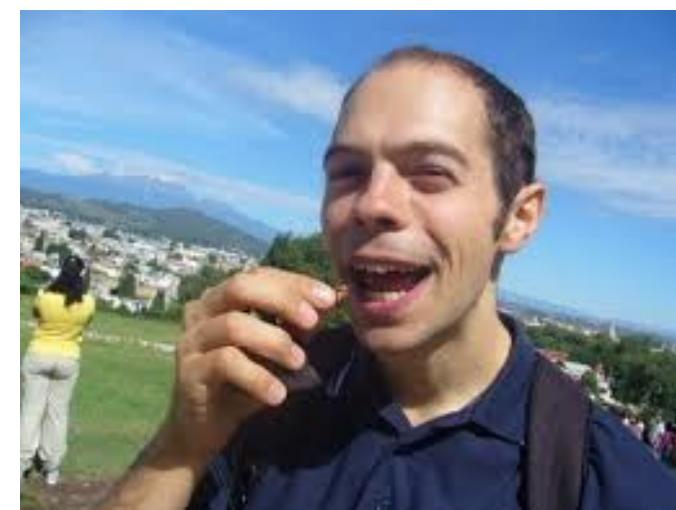


Roland Crocker
ARC Future Fellow
Australian National University

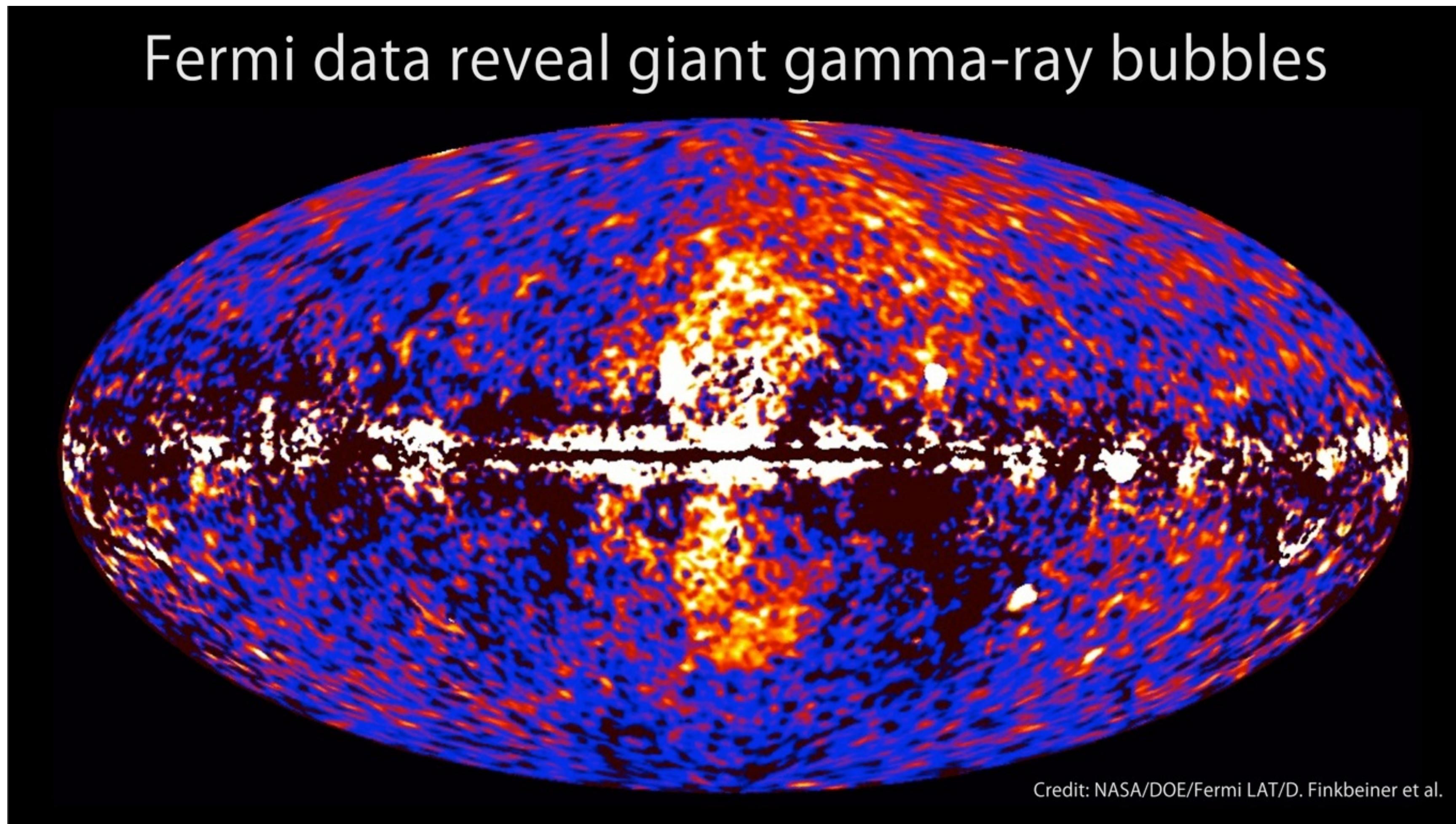
Collaborators

- 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

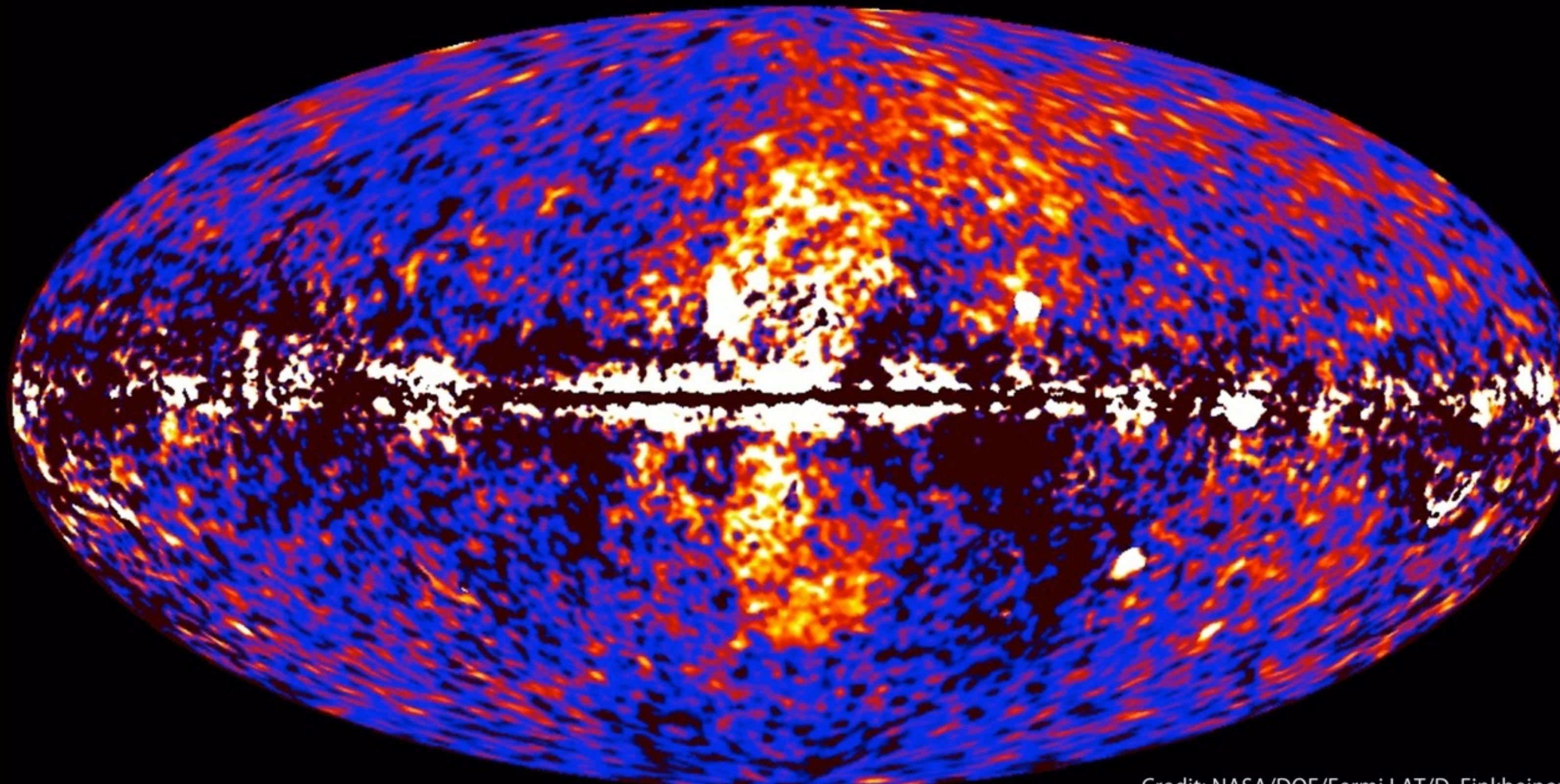


Su, Slatyer and Finkbeiner 2010 (ApJ)

Fermi Bubbles

- 2×10^{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

Fermi data reveal giant gamma-ray bubbles

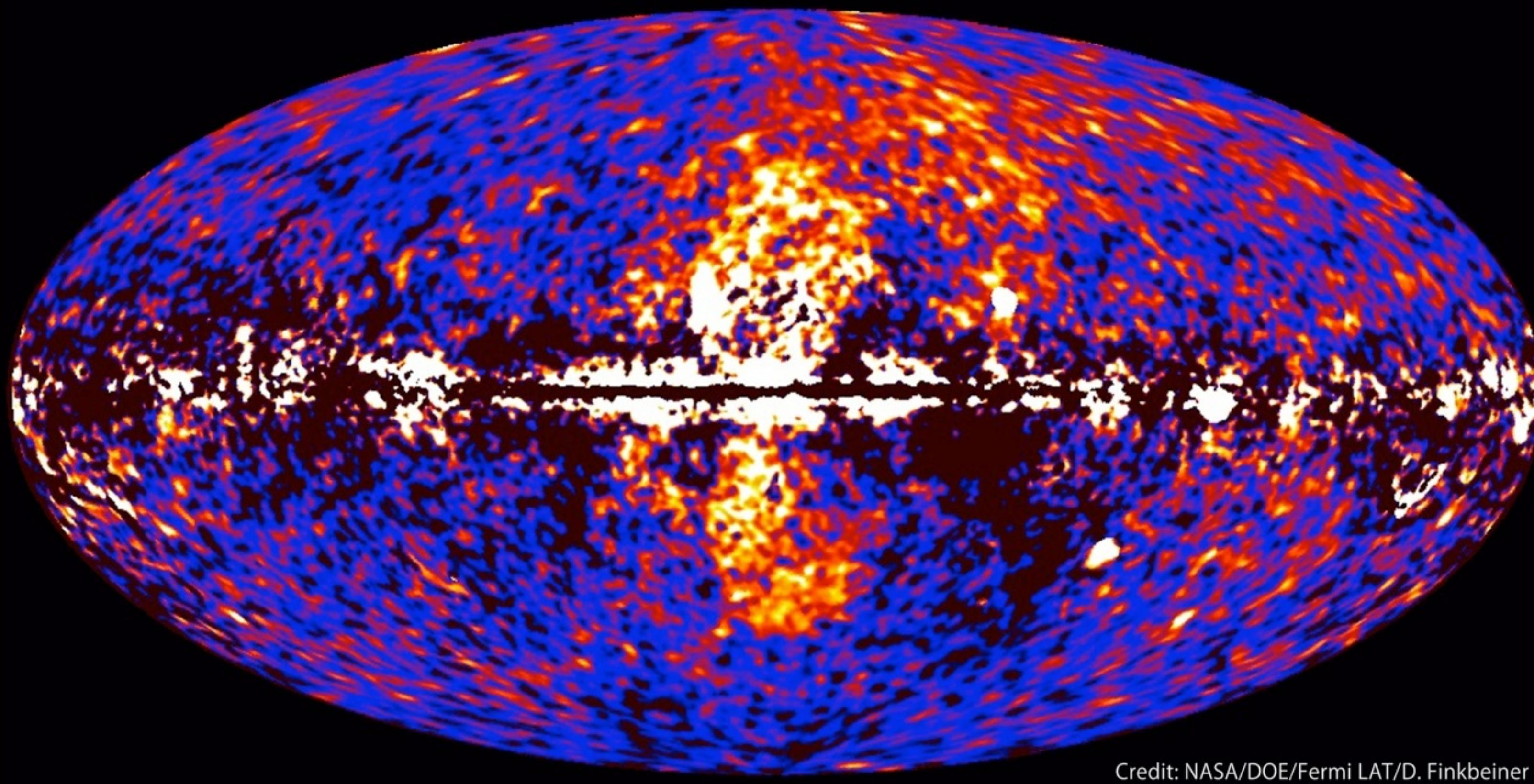


Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.

Su, Slatyer and Finkbeiner 2010 (ApJ)

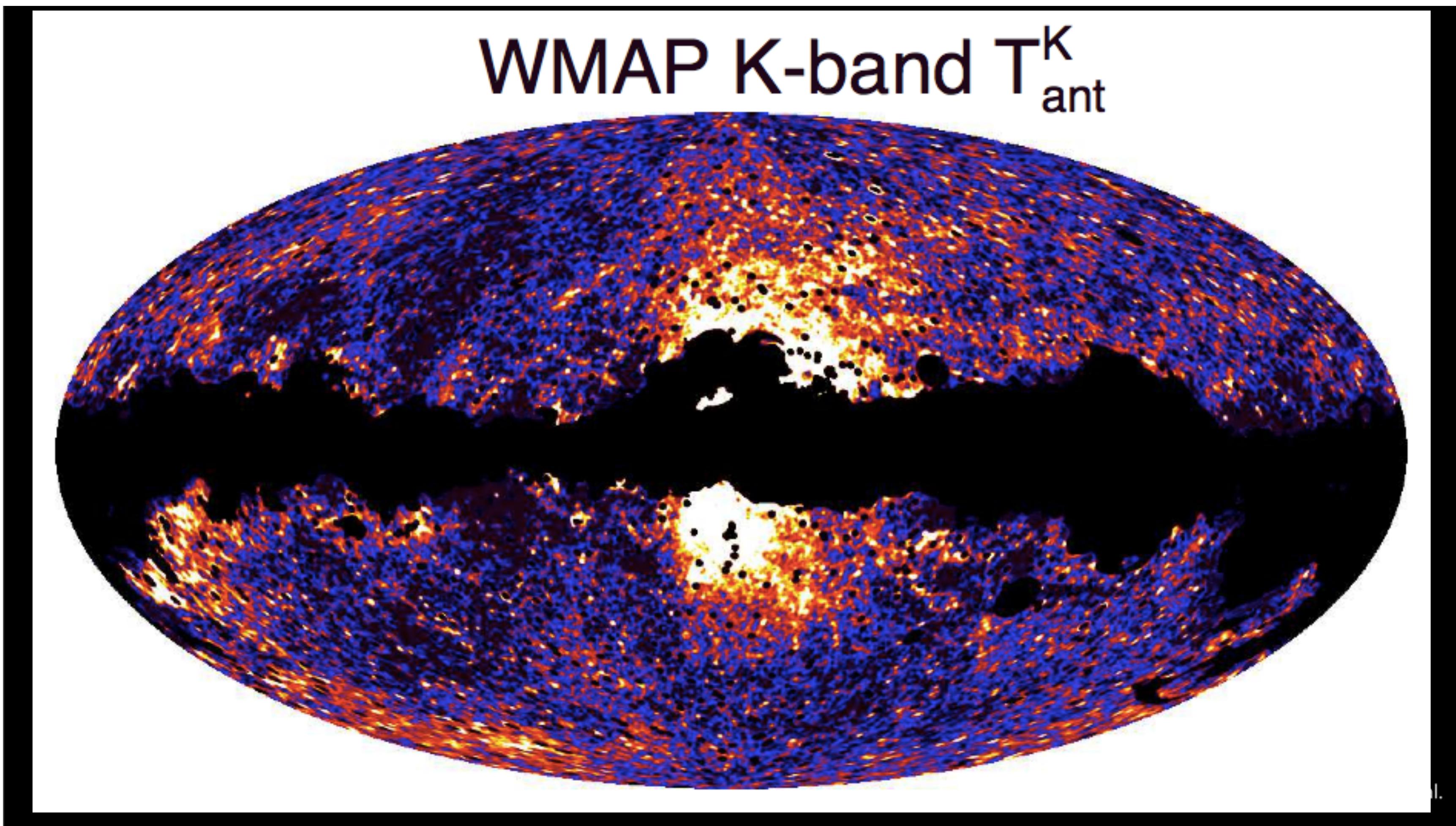
WMAP Haze

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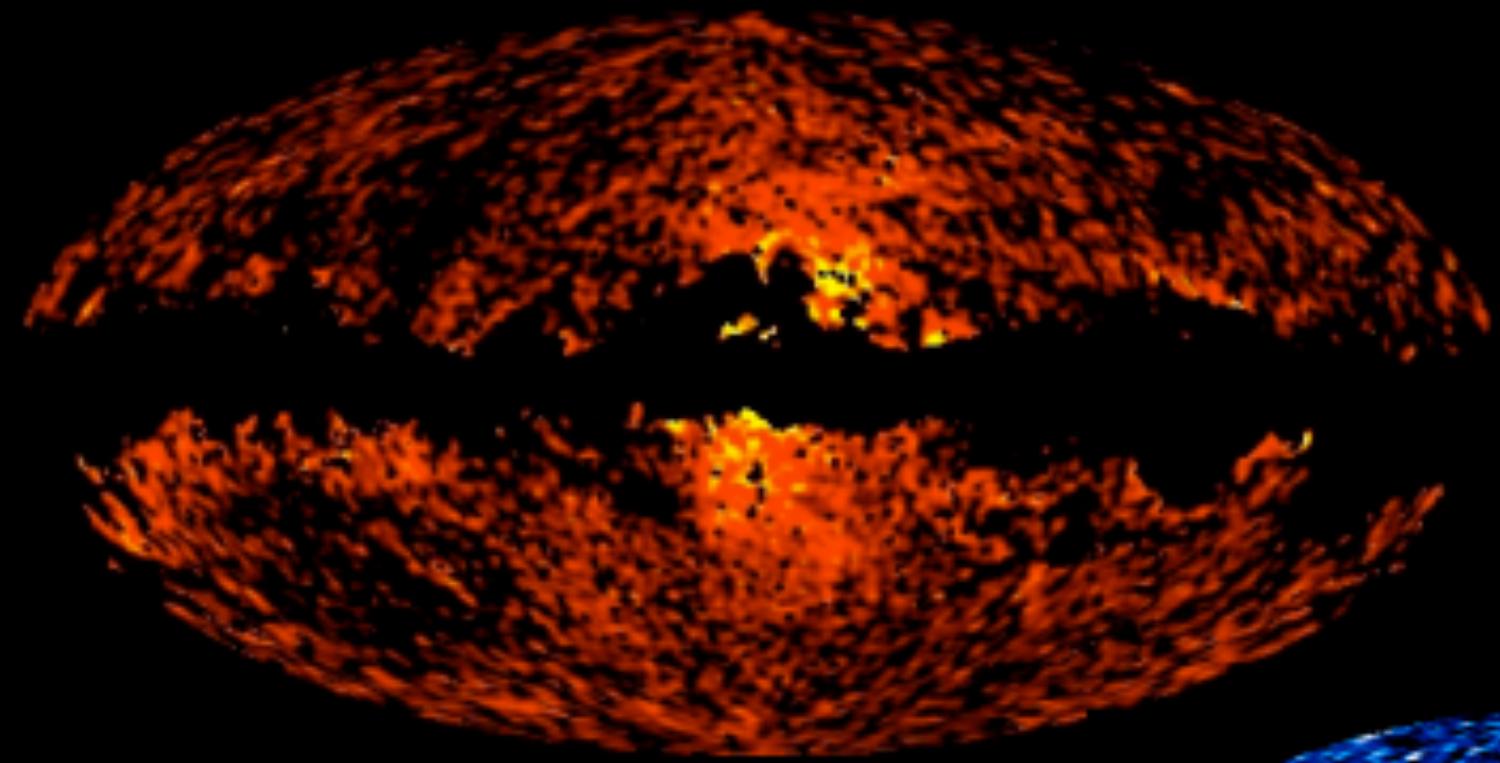
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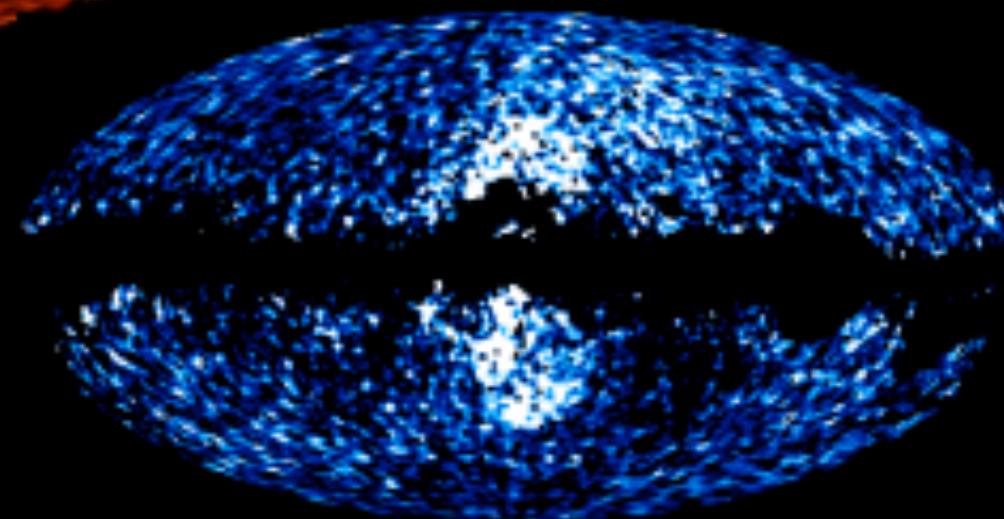


Dobler (2012)

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

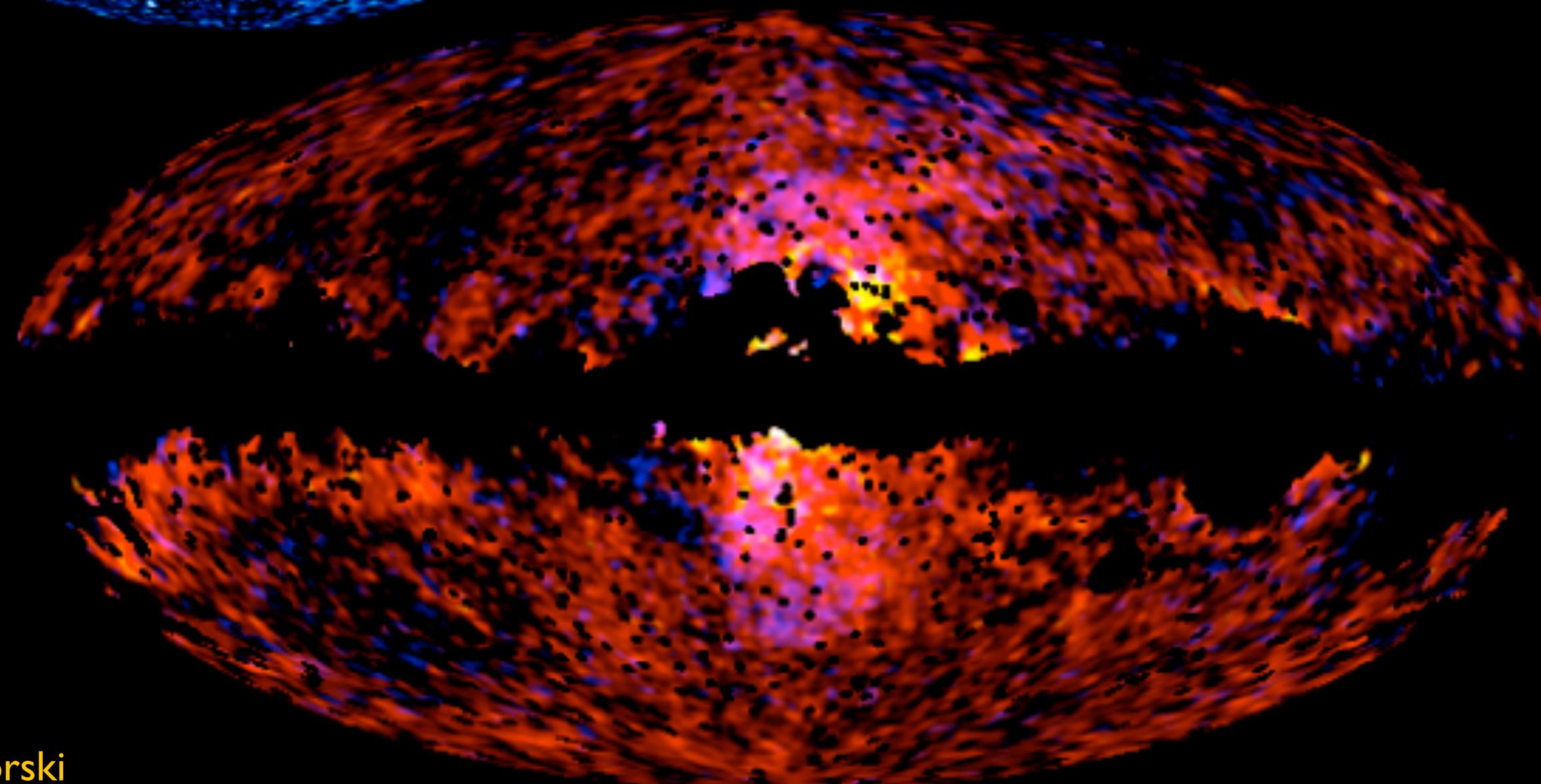


The Galactic haze/bubbles is shown here in *PLANCK* data from 30-44 GHz

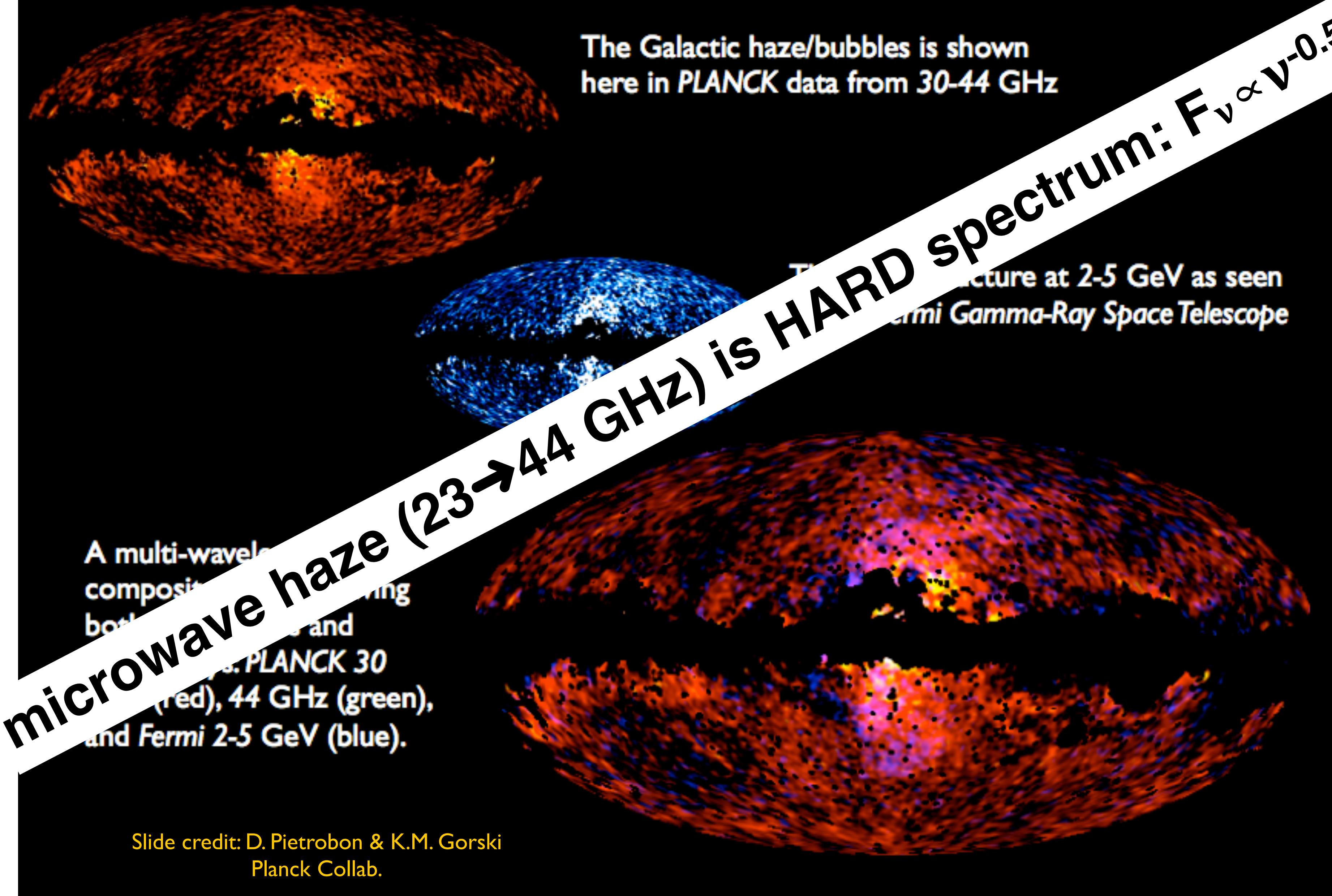


The same structure at 2-5 GeV as seen by the *Fermi Gamma-Ray Space Telescope*

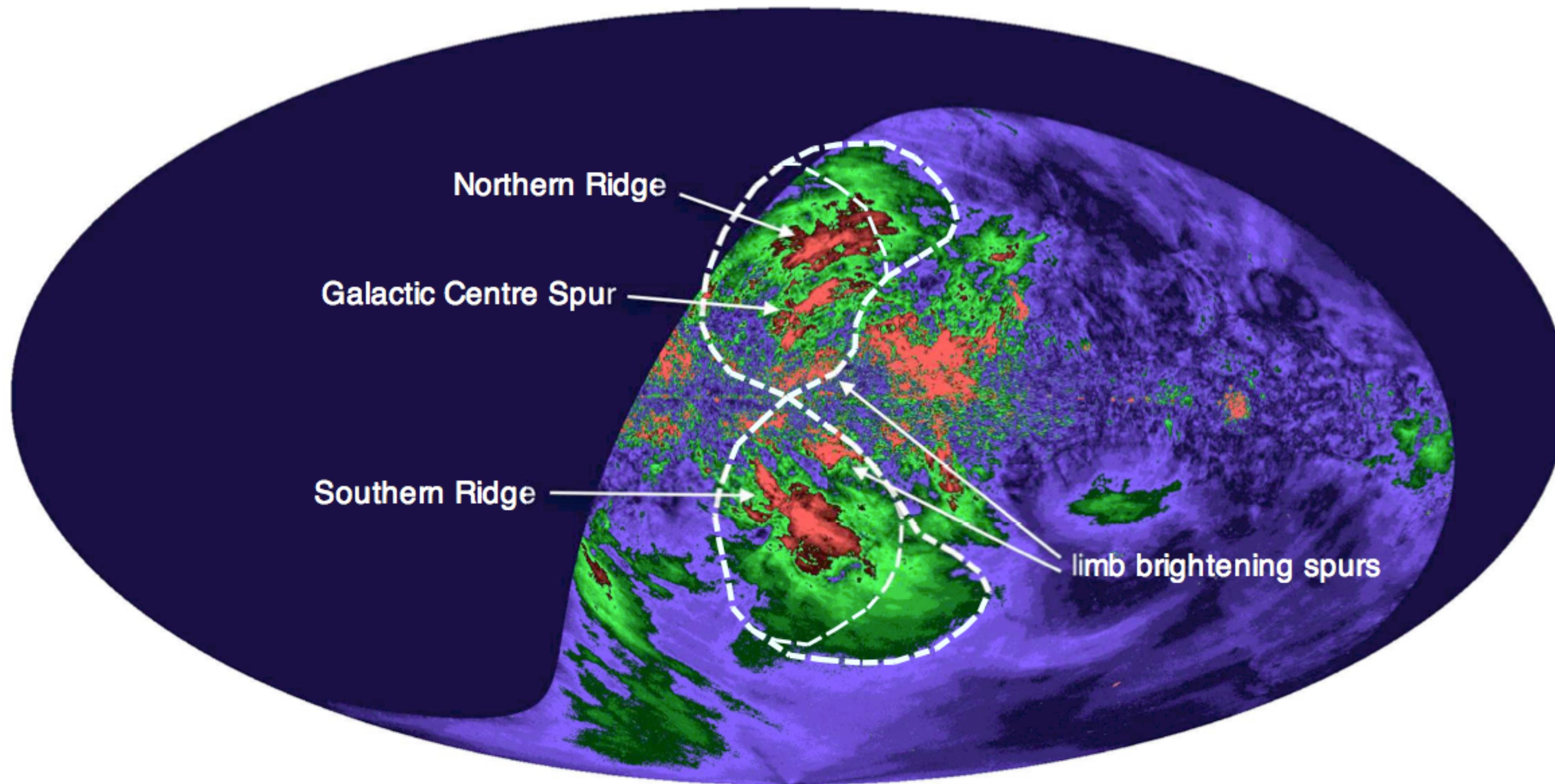
A multi-wavelength composite image showing both microwaves and gamma-rays: *PLANCK* 30 GHz (red), 44 GHz (green), and *Fermi* 2-5 GeV (blue).



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



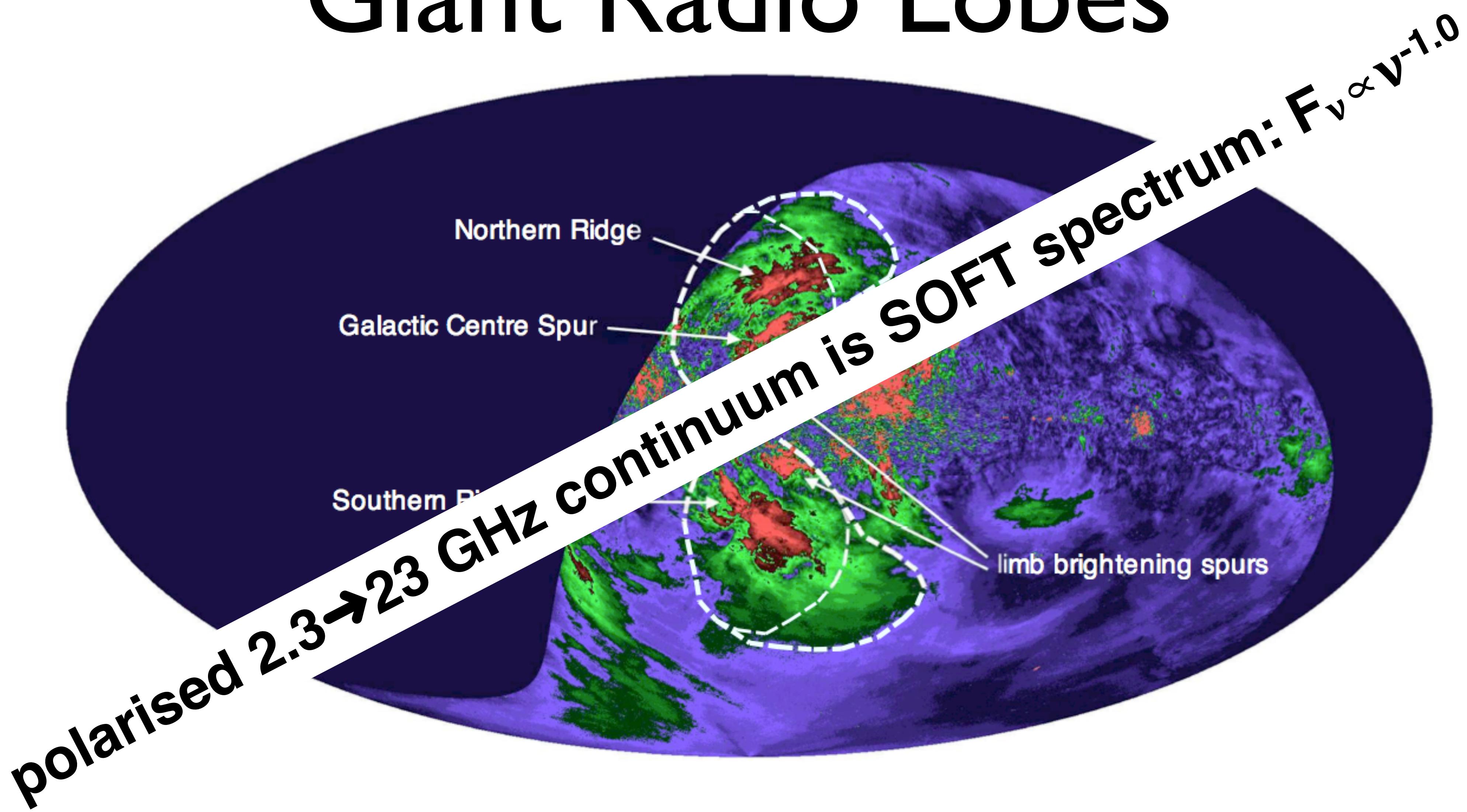
Giant Radio Lobes



Carretti et al. 2013

2.3 GHz **polarized** intensity

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Fermi Bubbles: Two Interlocking Questions

Q1. What energizes the outflow?

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...nuclear star-formation

Energetics

- The (photon) Eddington luminosity of Sgr A* ($4 \times 10^6 M_{\text{Sun}}$): $5 \times 10^{44} \text{ erg/s}$
- Star formation in the Galactic Centre at a rate $\sim 0.05 M_{\text{Sun}}/\text{yr}$
...the Galactic Centre is not a Starburst
- This injects mechanical power (supernova explosions, stellar winds) of

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

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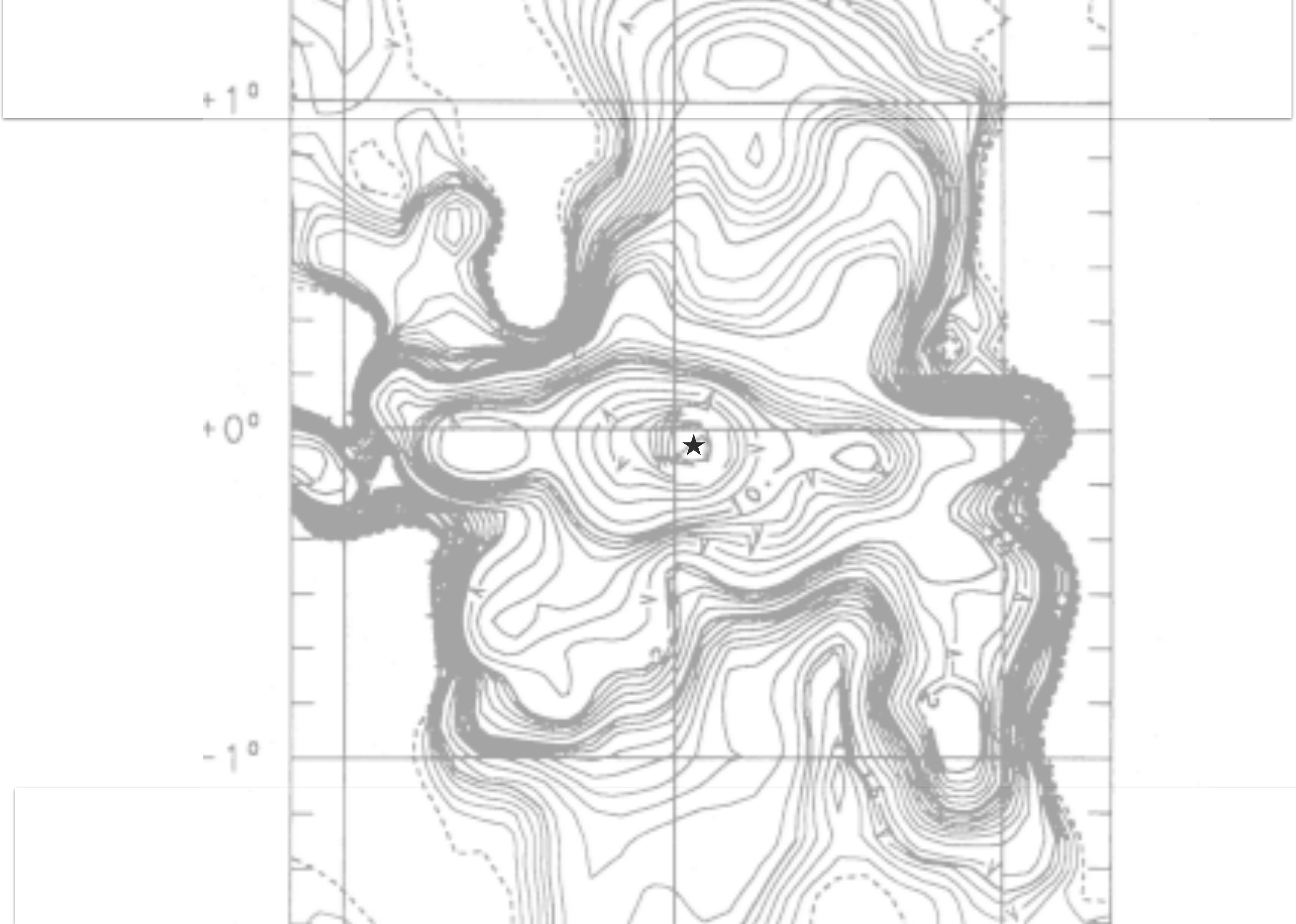


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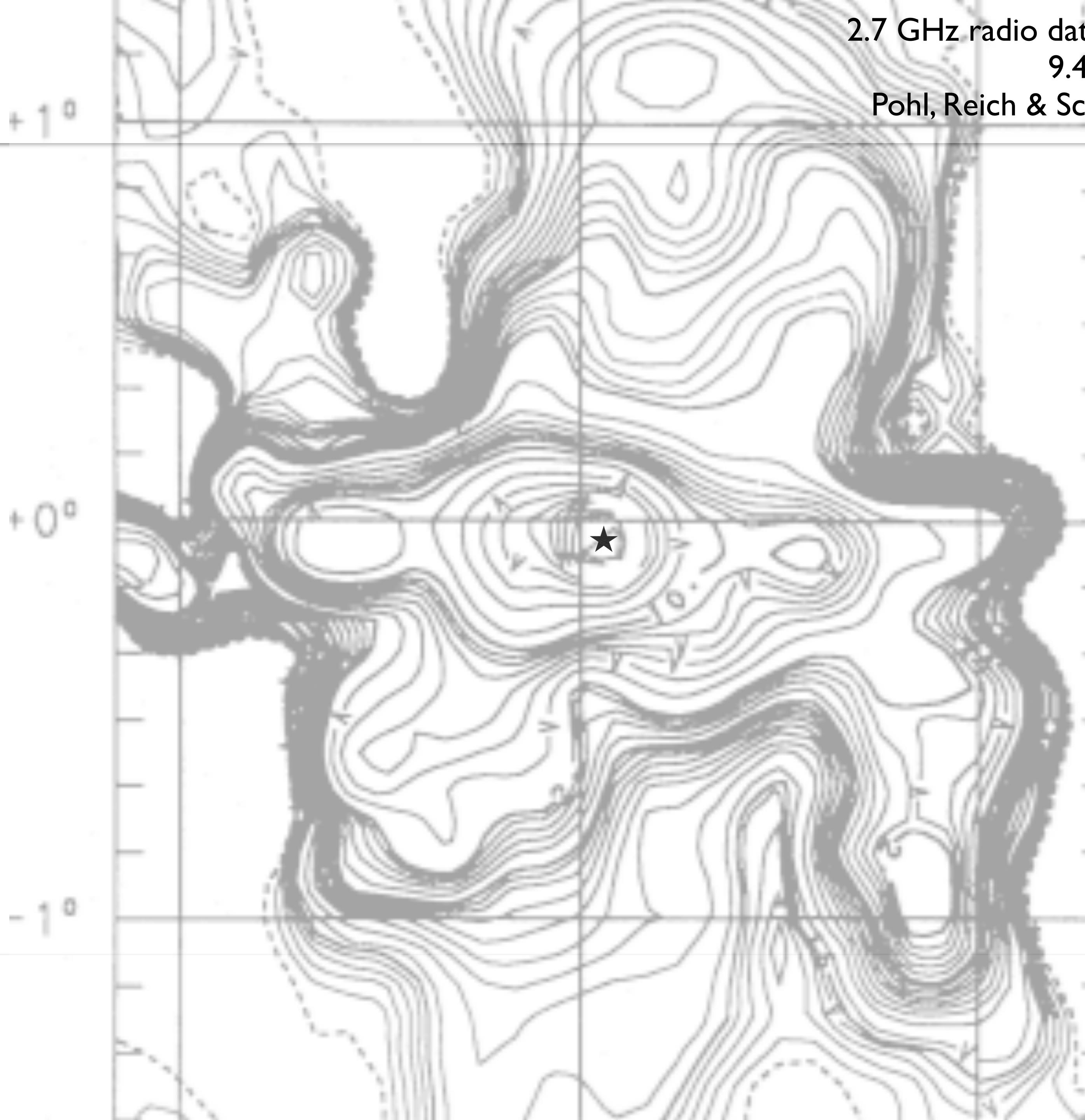
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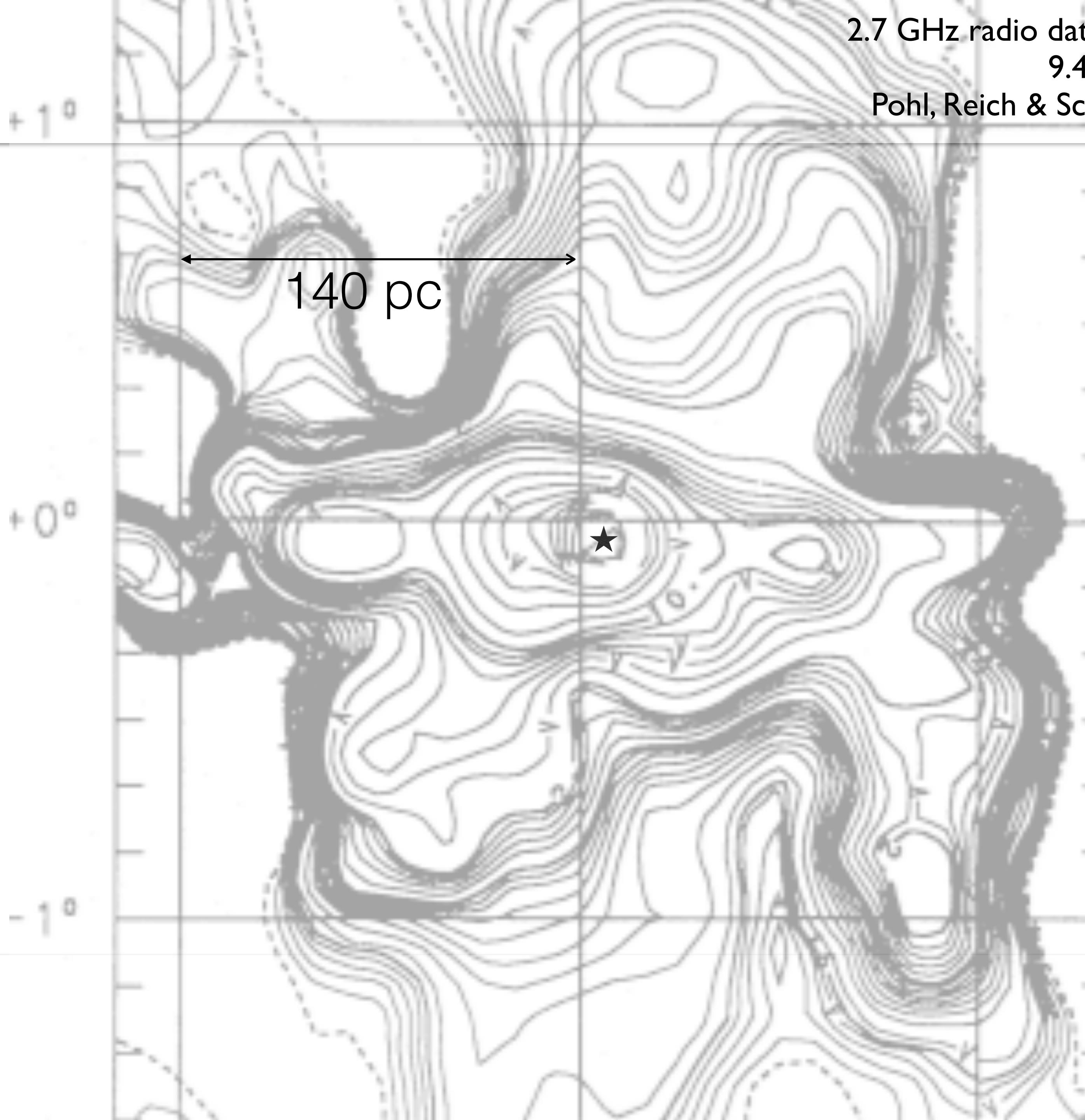




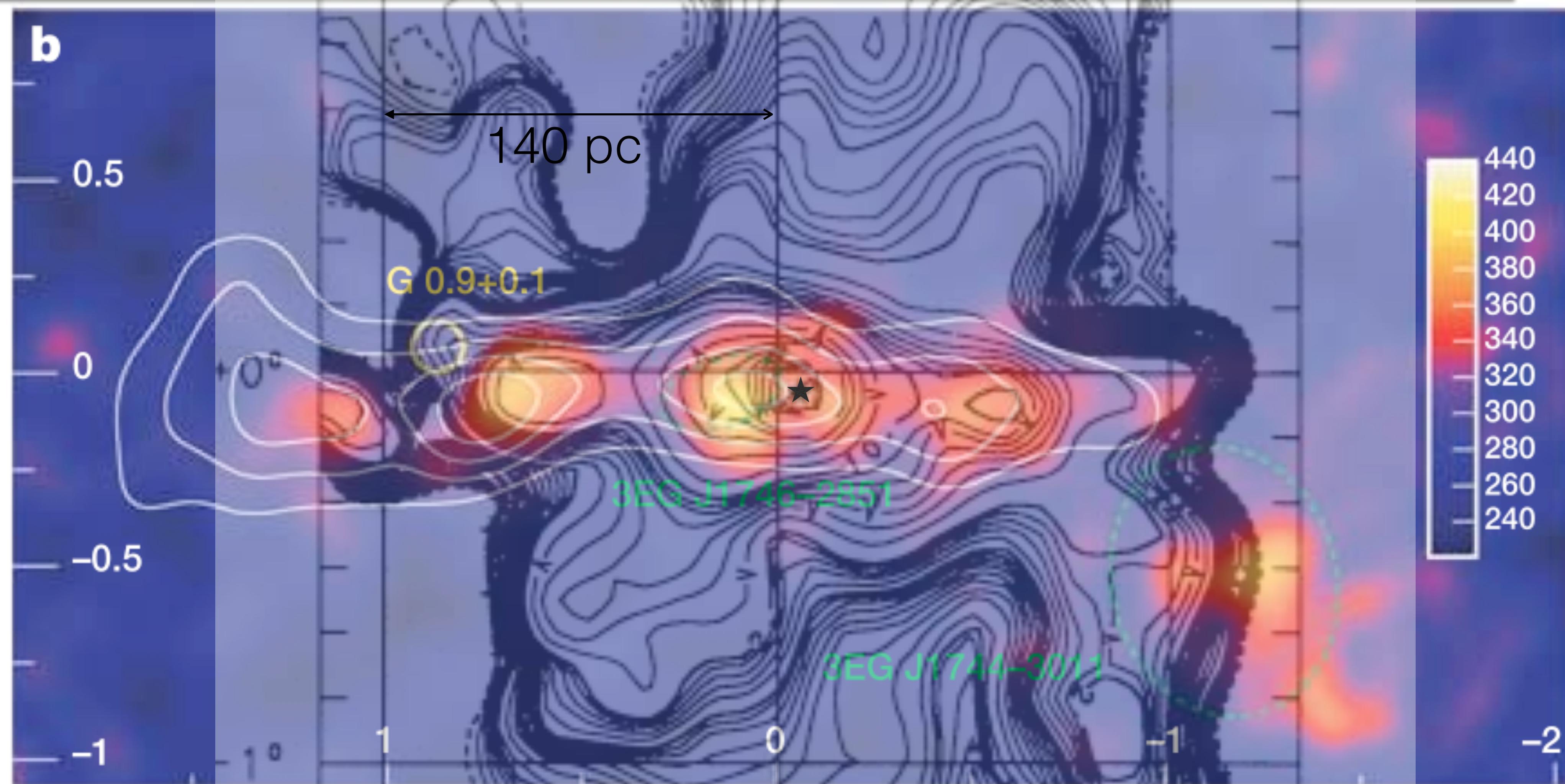
2.7 GHz radio data (unsharp mask,
9.4 $''$)
Pohl, Reich & Schlickeiser 1992



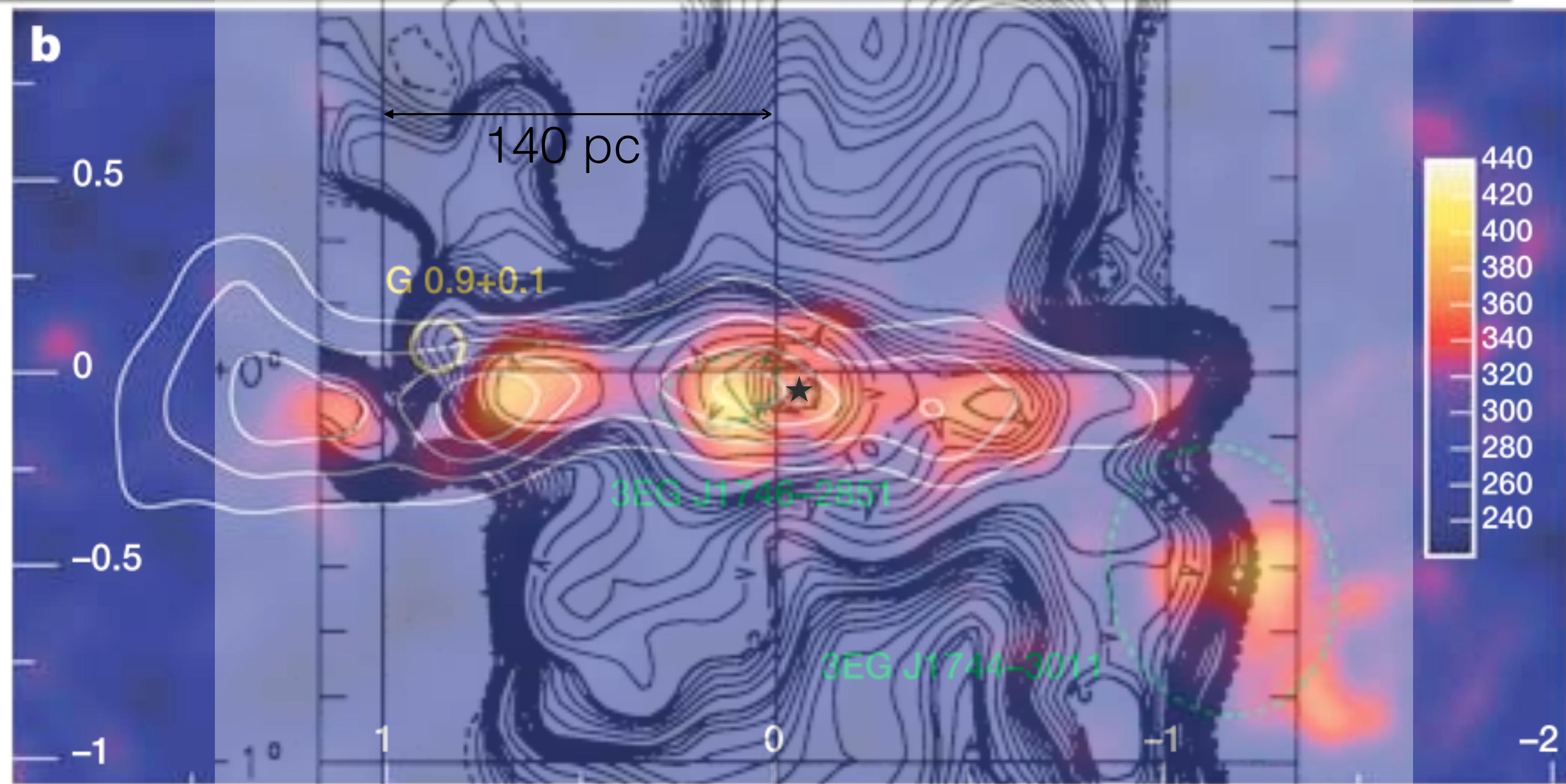
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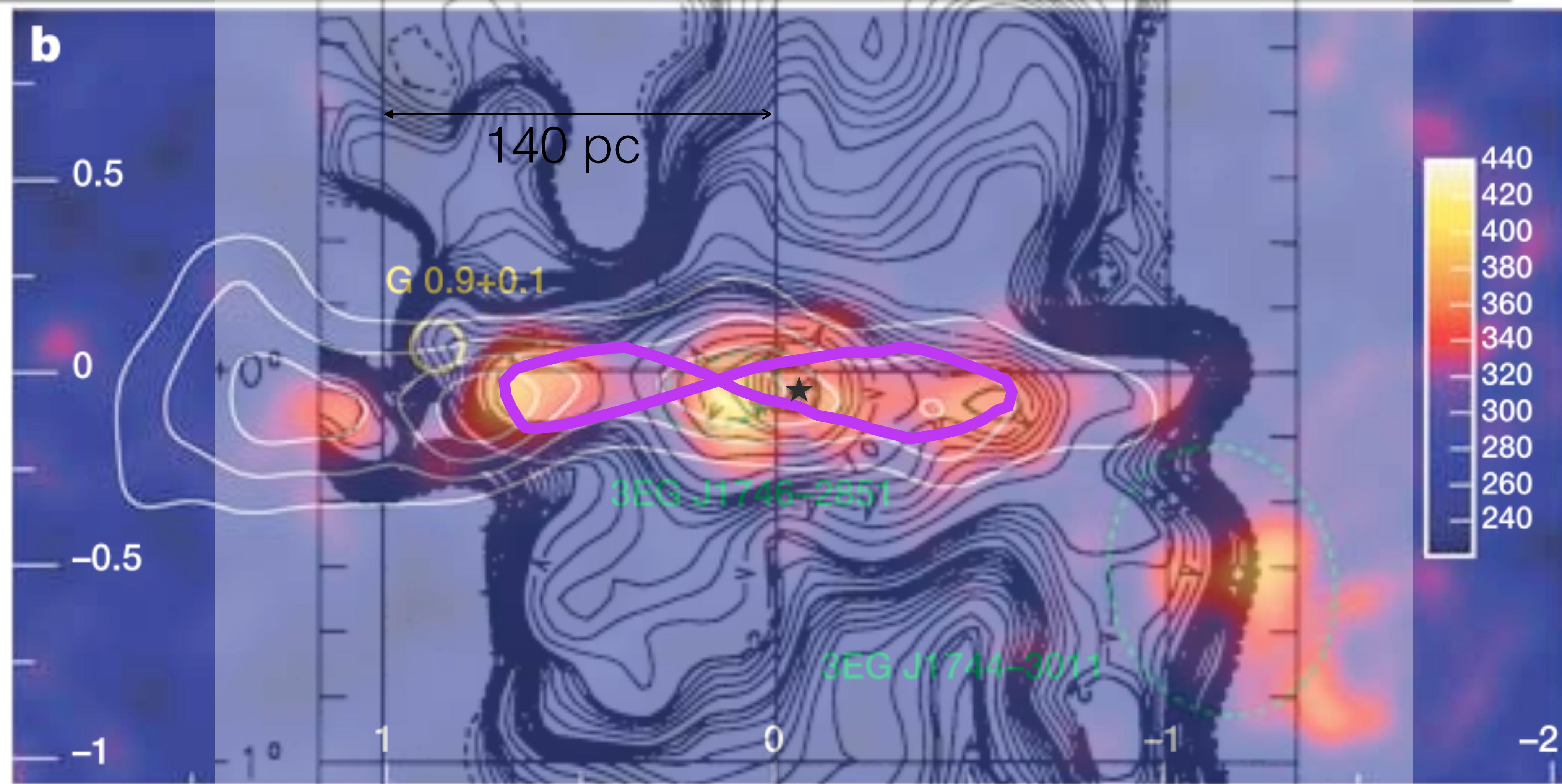


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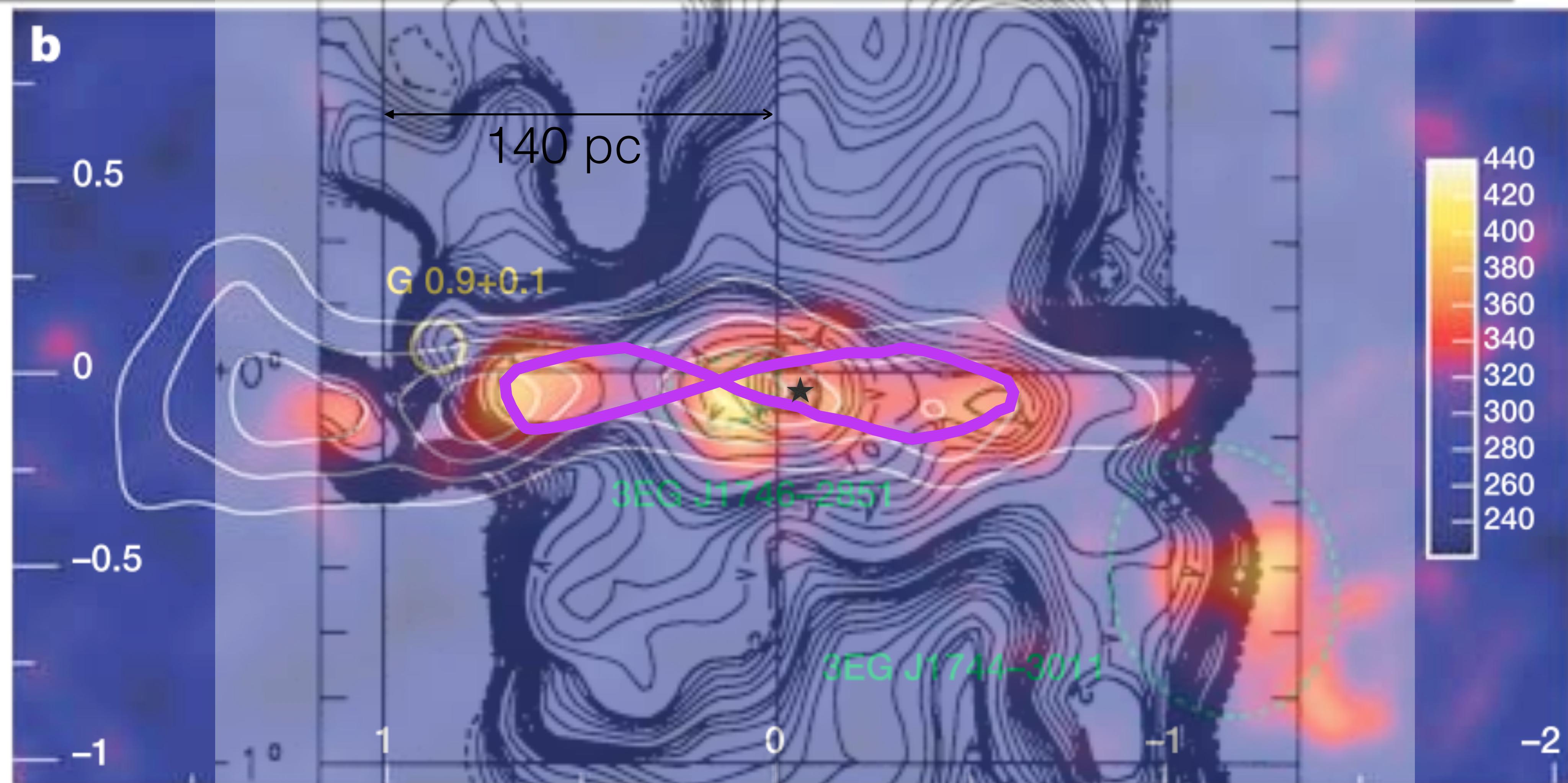
HESS TeV (Aharonian et al 2006)

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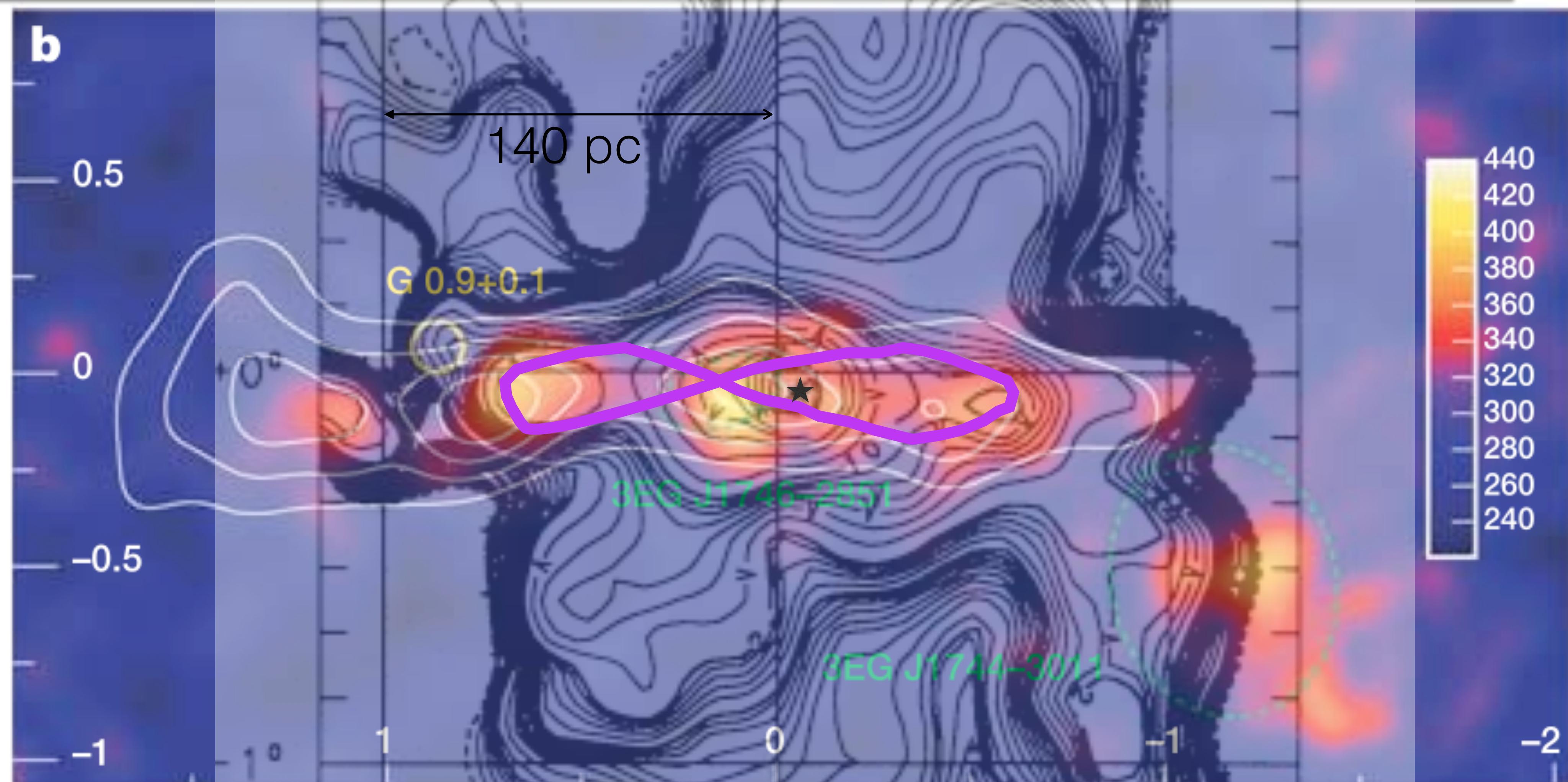
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Ring collimates outflow -
outflow ablates cold gas

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Fermi Bubbles: Two Interlocking Questions

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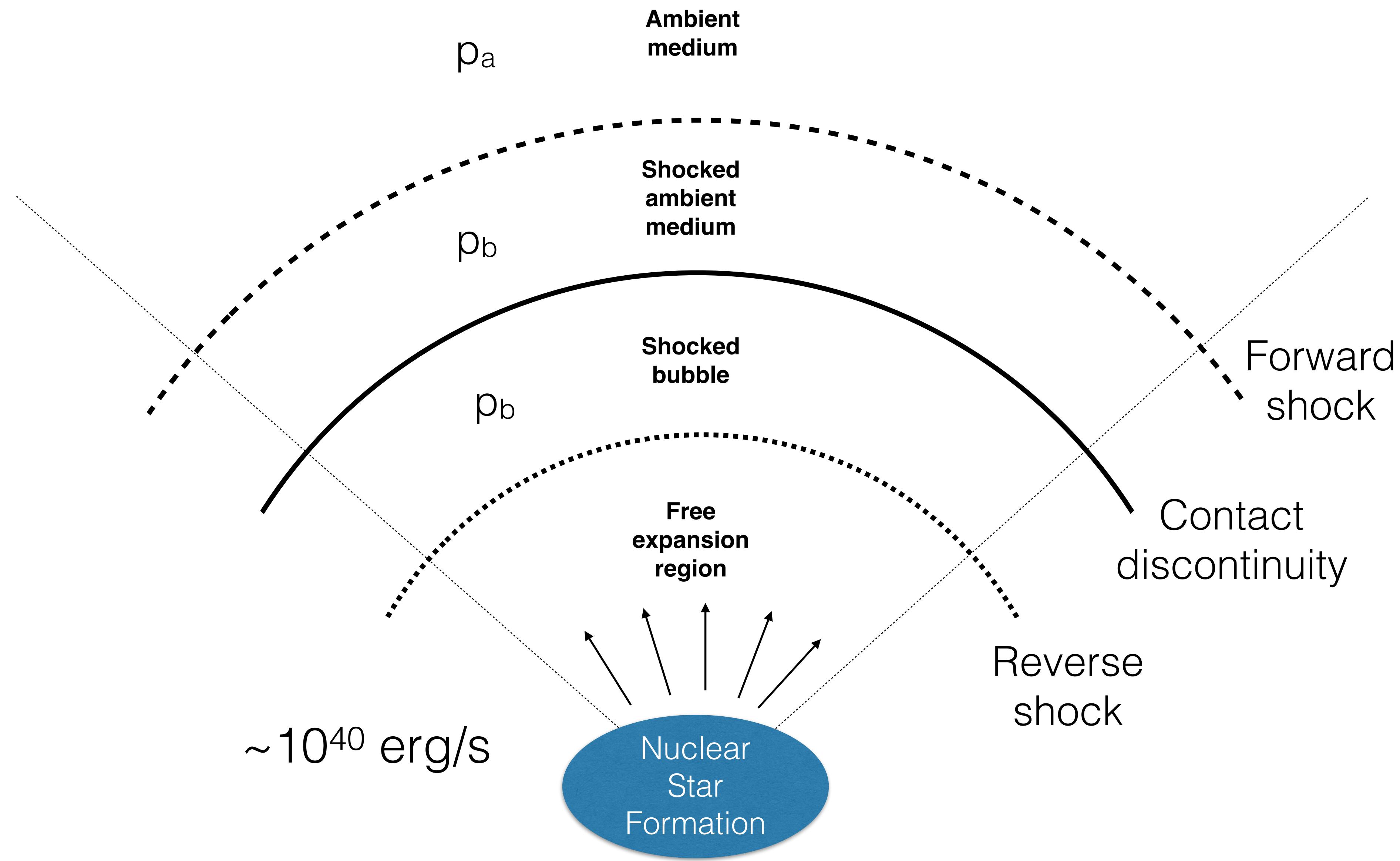
‘hadronic’: Cosmic ray protons/gas collisions

Hadronic Scenario

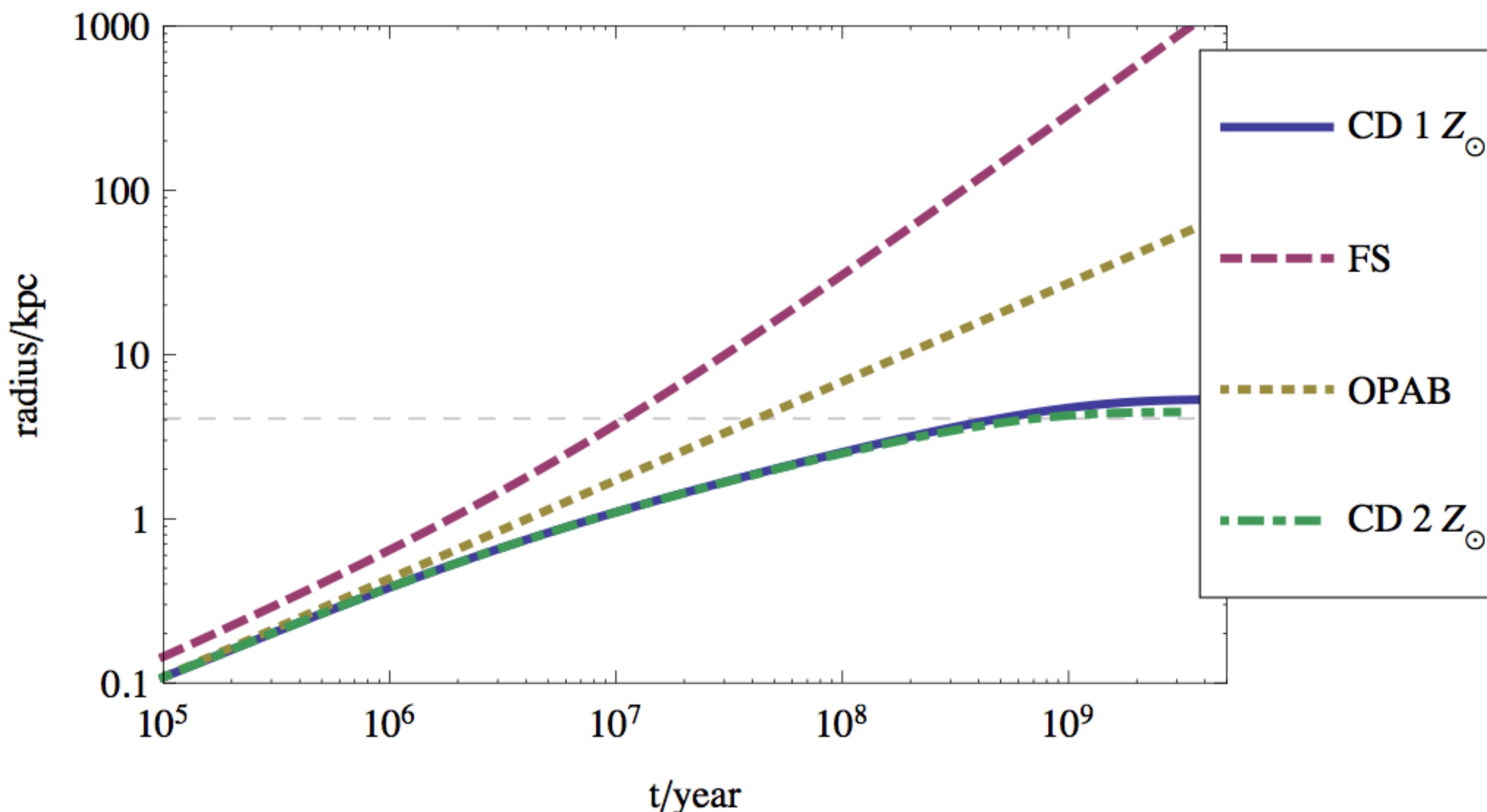
Crocker & Aharonian PRL 2011

- Bubbles' gamma-ray luminosity requires a source of protons of power $\sim 10^{39}$ erg/s *in saturation*
- This **is** the power supplied by nuclear SF to cosmic rays that escape the GC

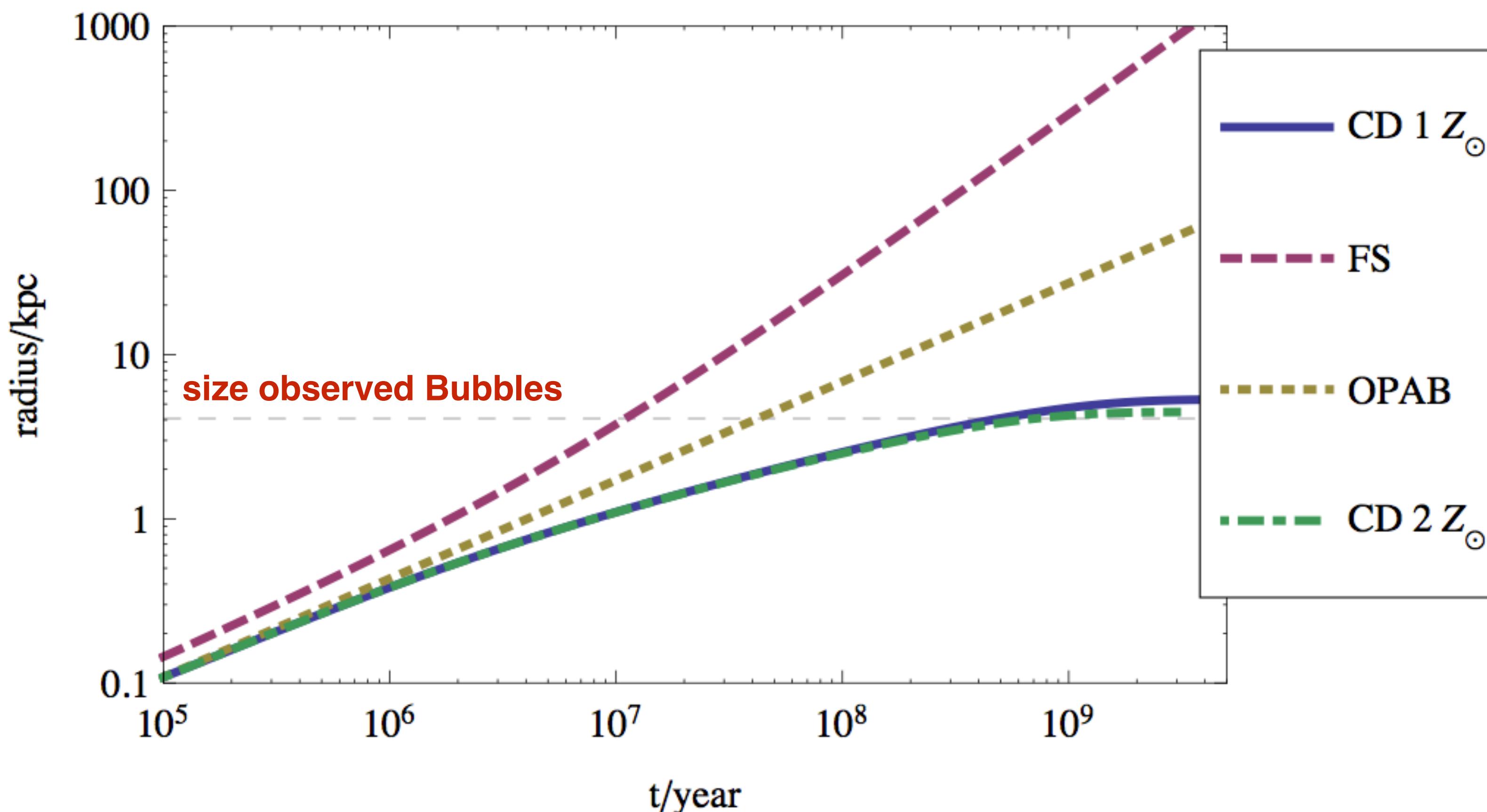
The Fermi Bubbles *as Bubbles*



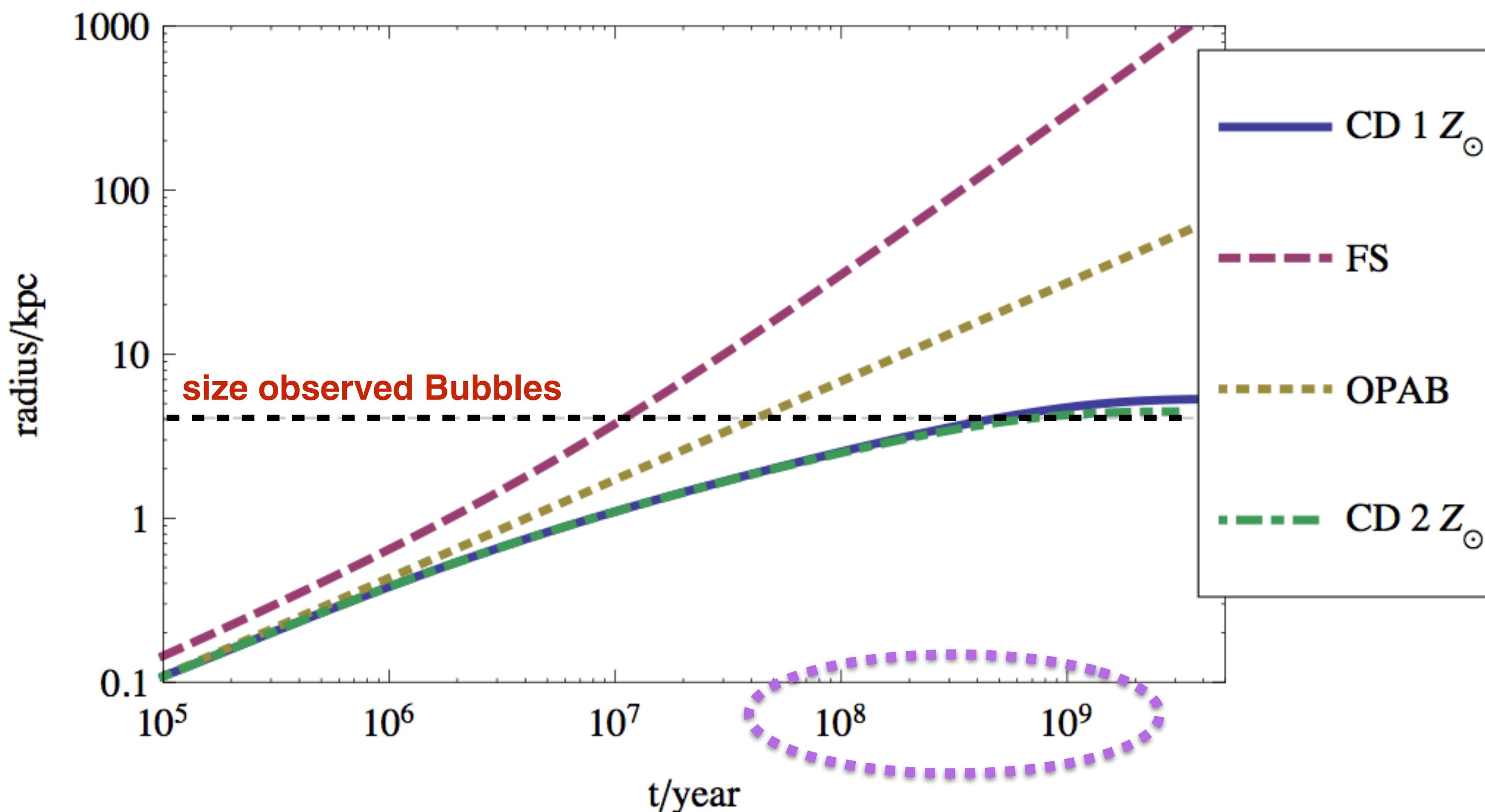
Expansion of a radiative bubble into finite (const) pressure medium



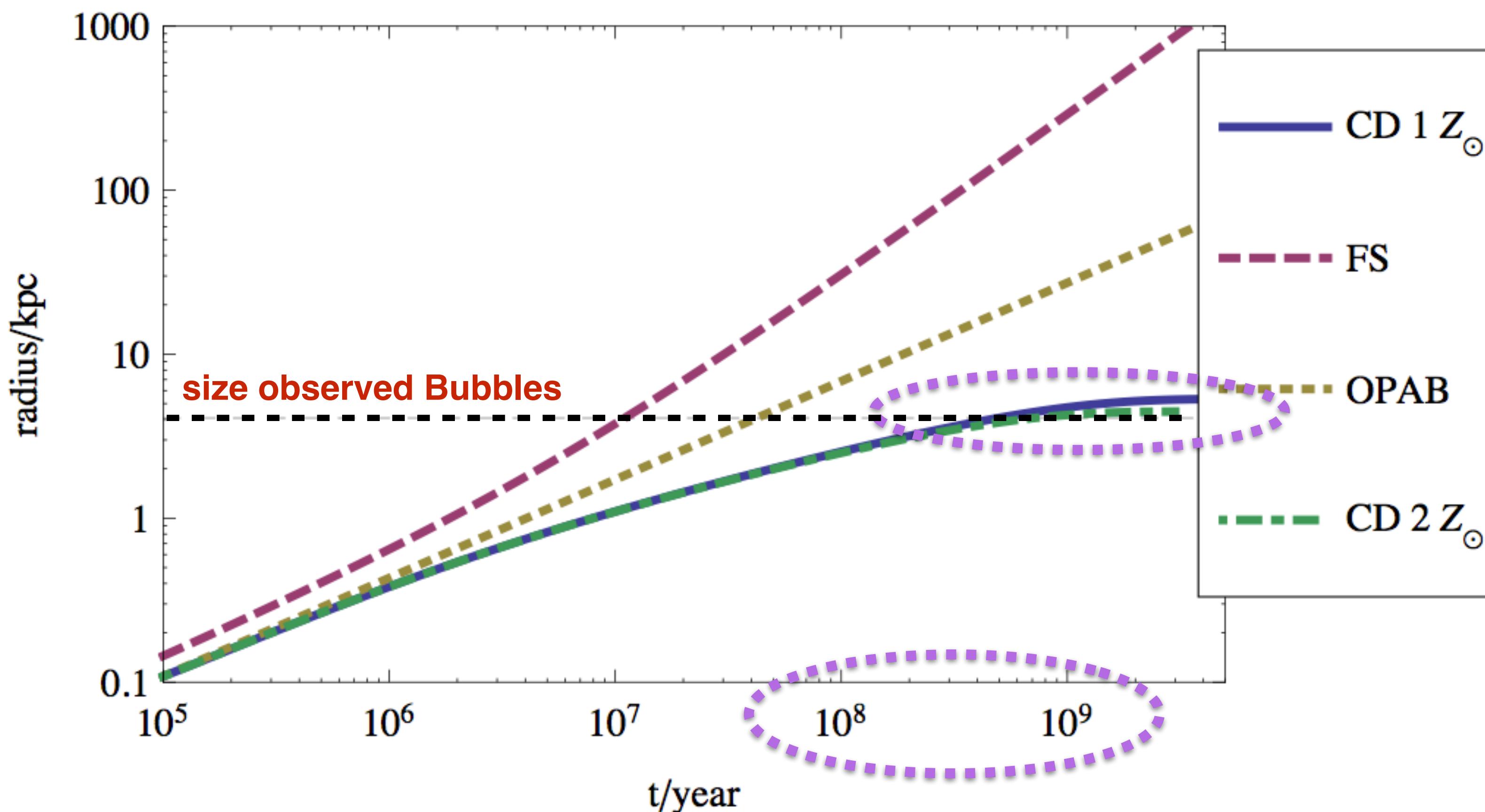
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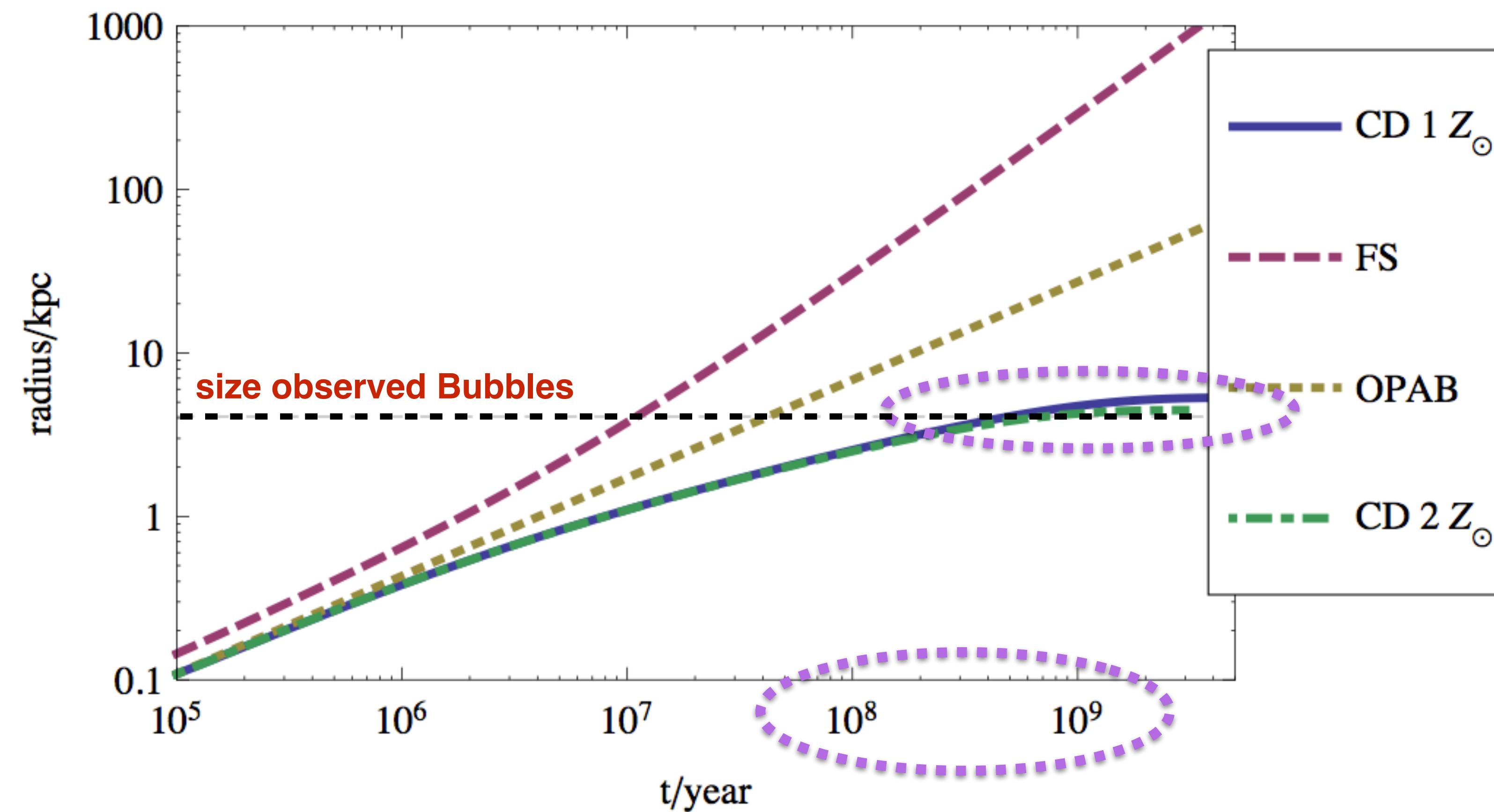
Expansion of a radiative bubble into finite (const) pressure medium



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



Bubbles are close to their ‘natural’
size in a finite (const) pressure medium



Giant Shocks in the Fermi Bubbles

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

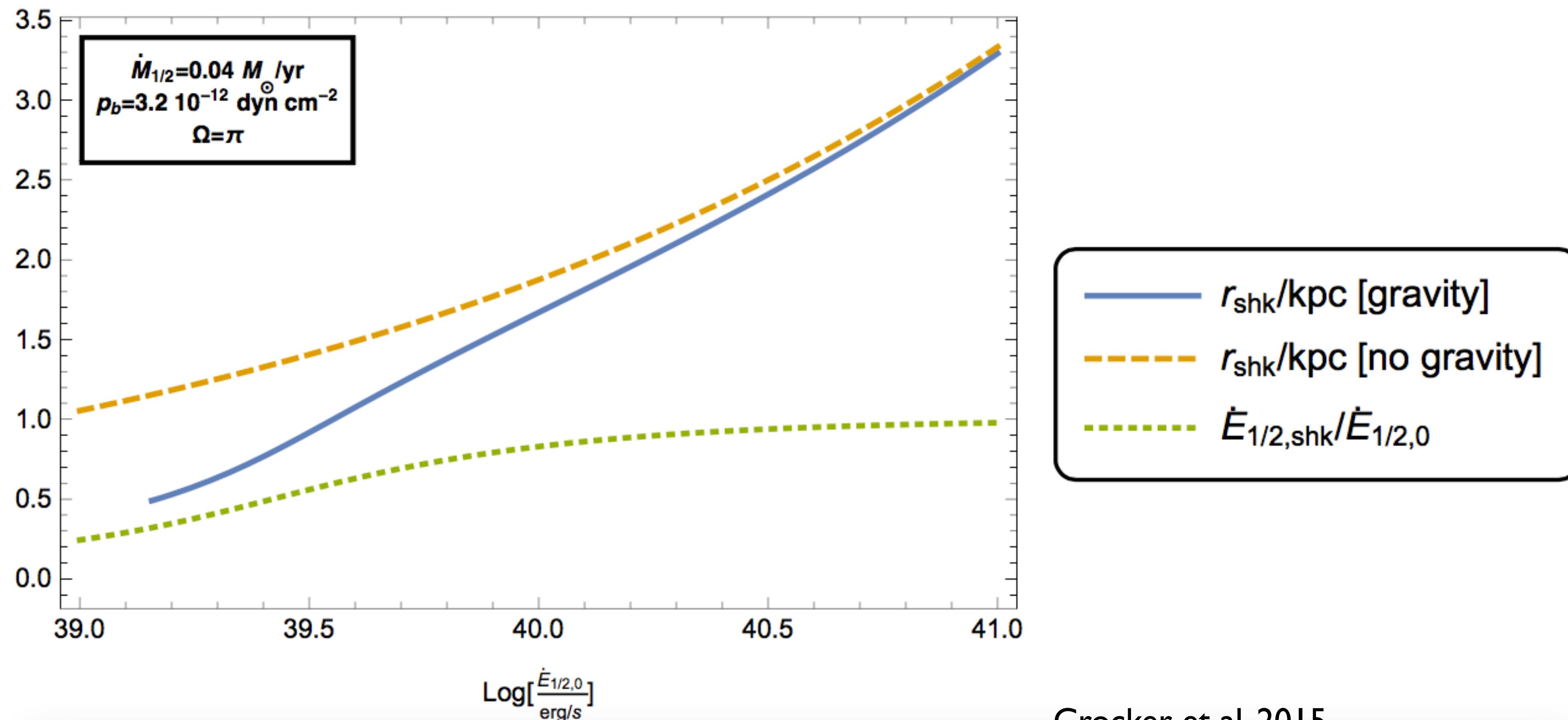
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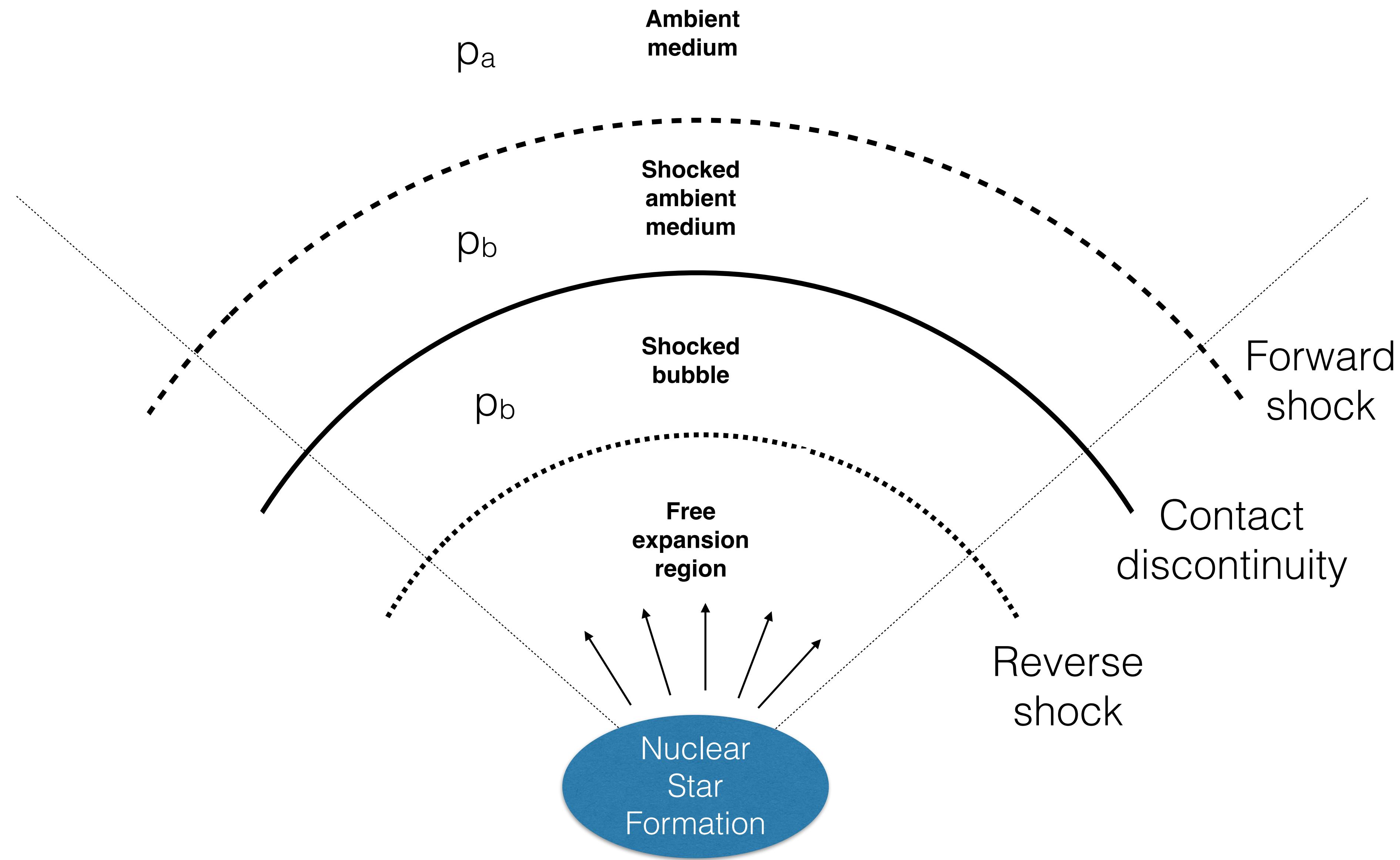
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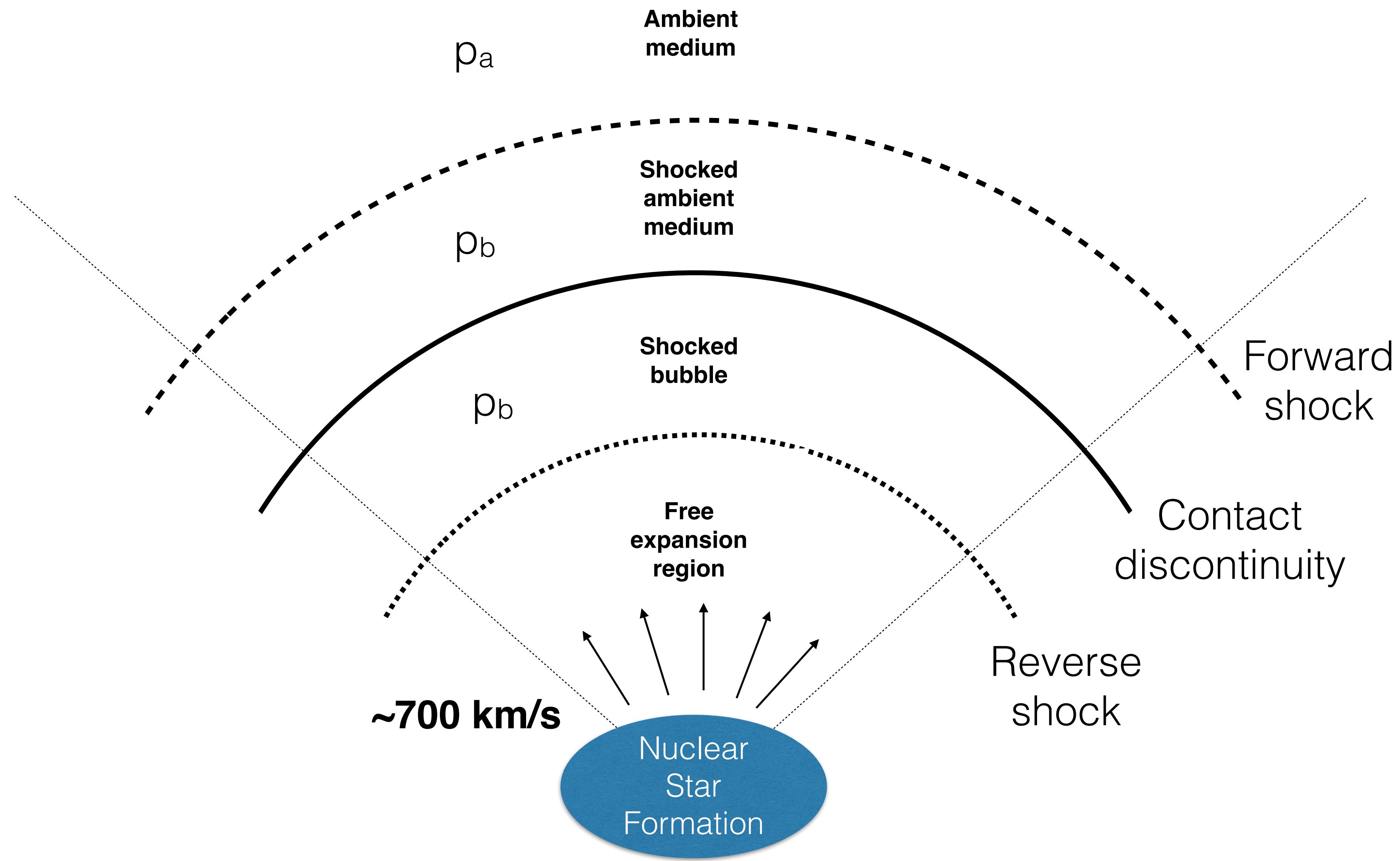
height $\sim 1 \text{ kpc}$

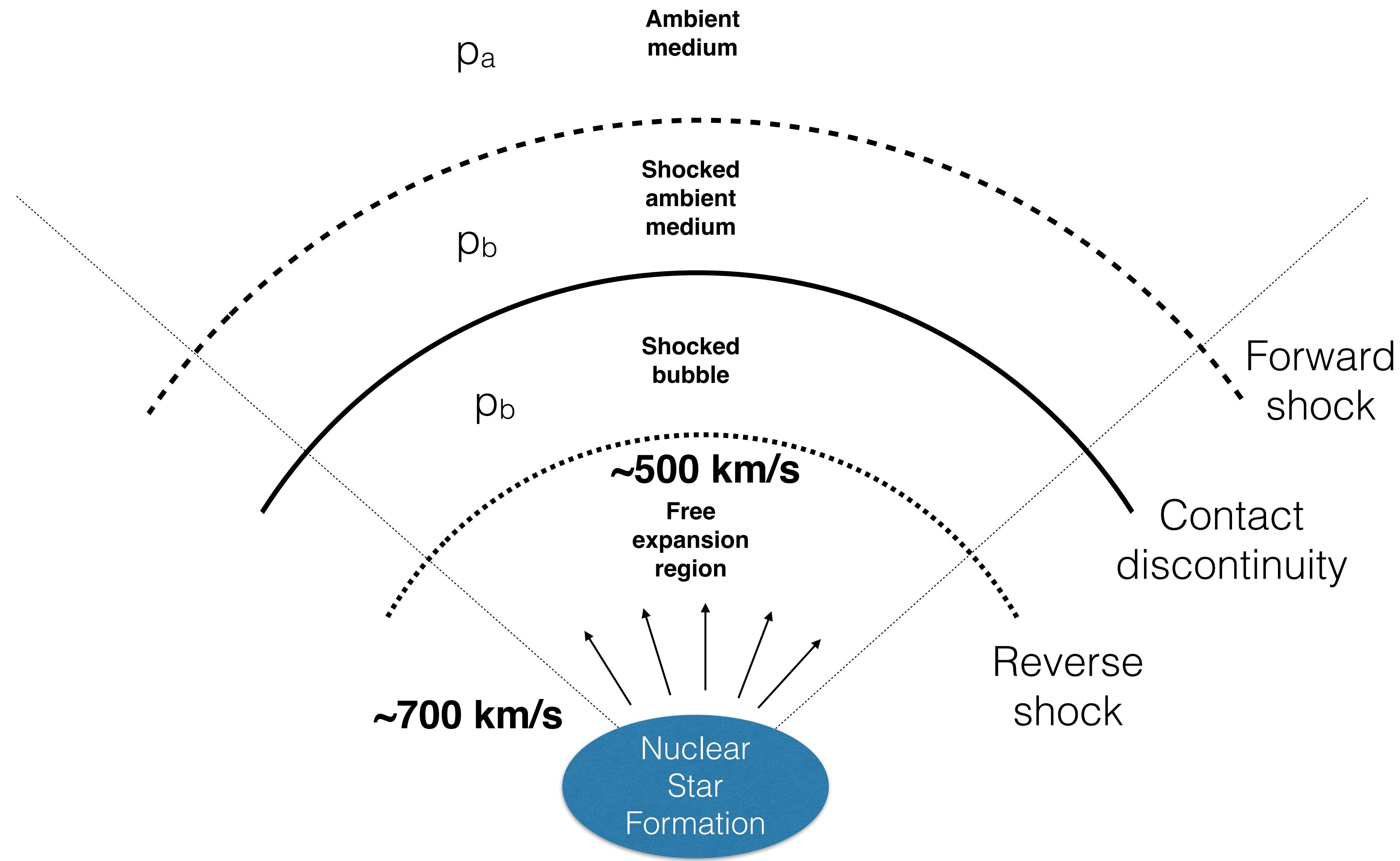
Mach num ~ 6

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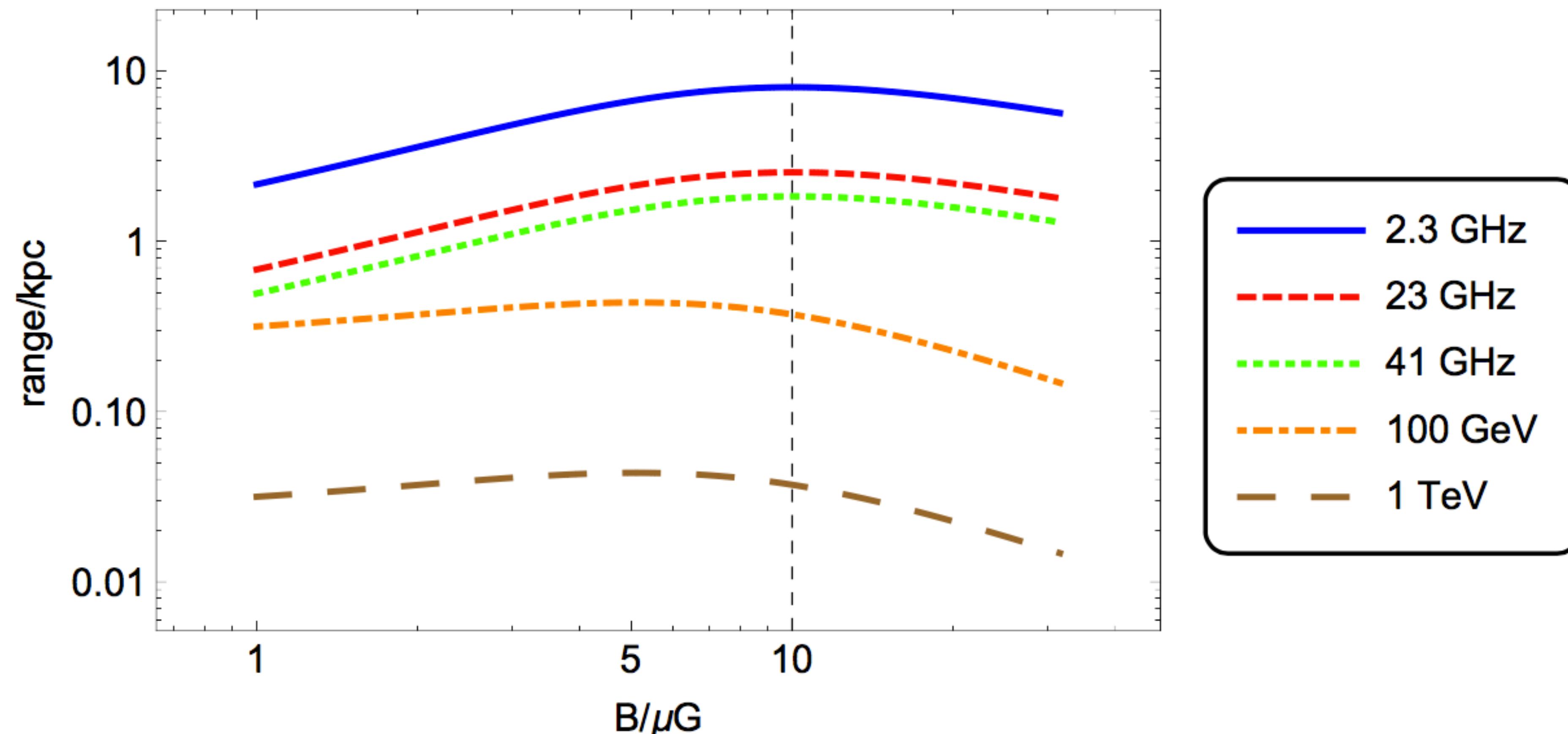


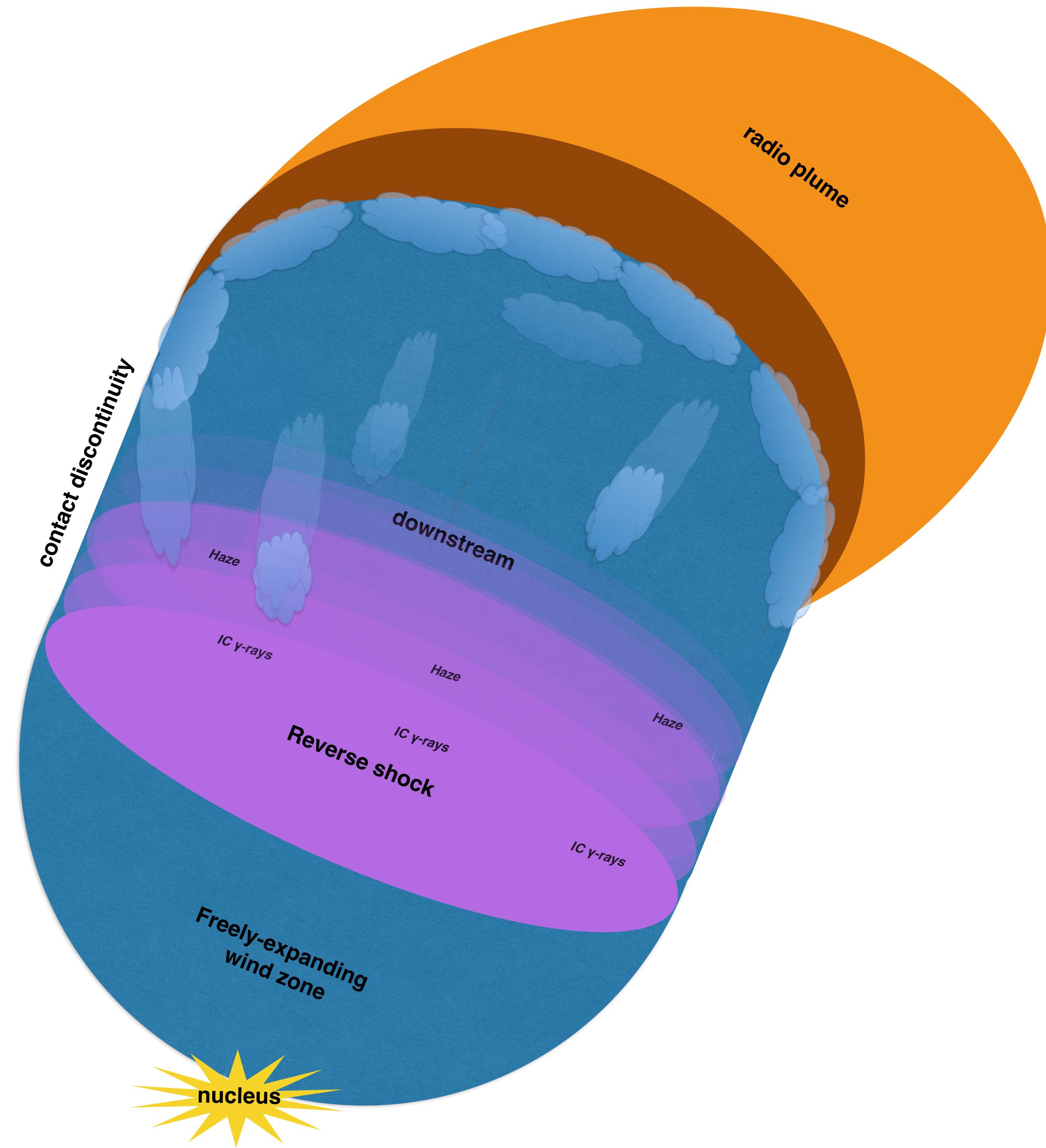


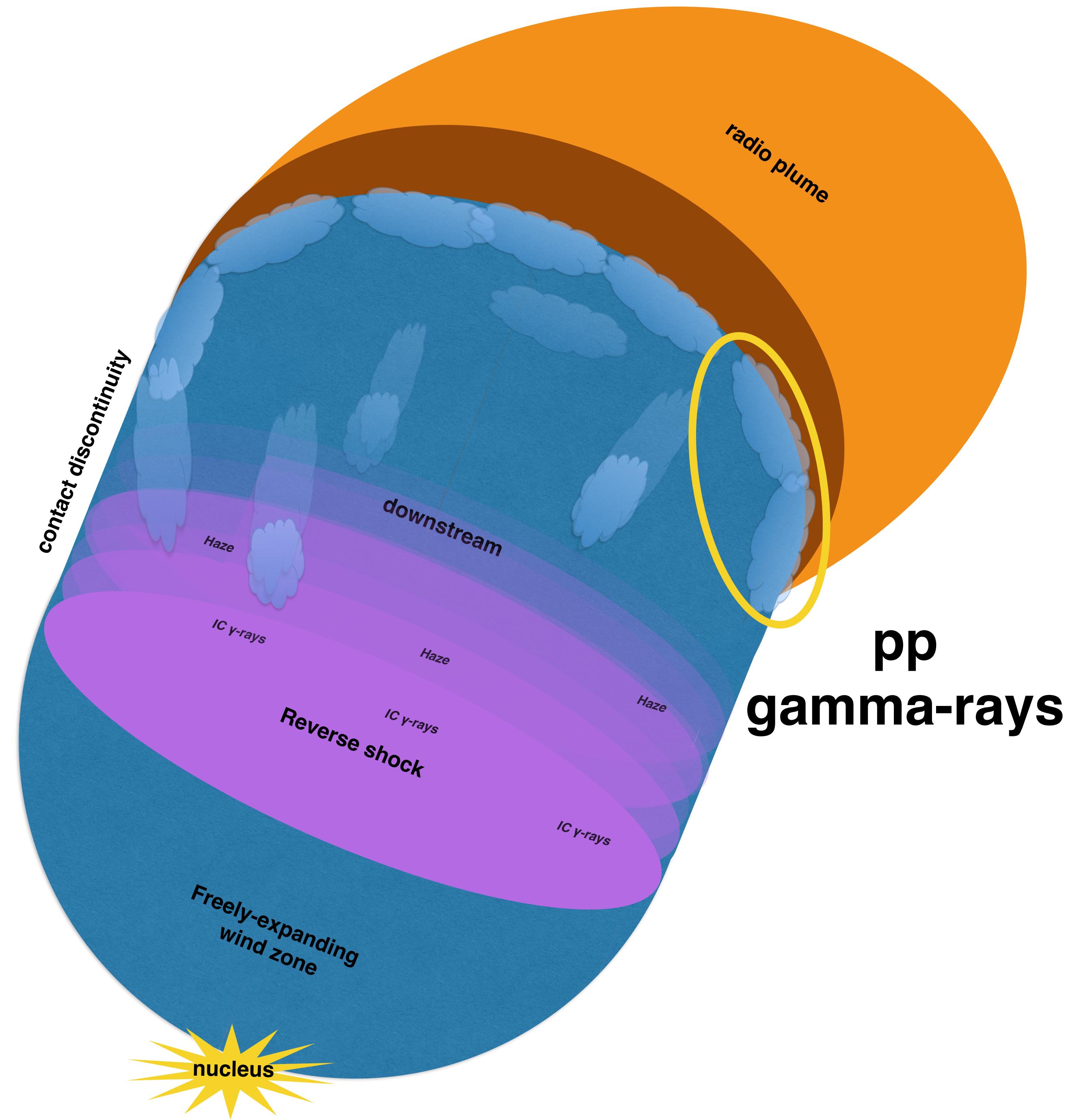


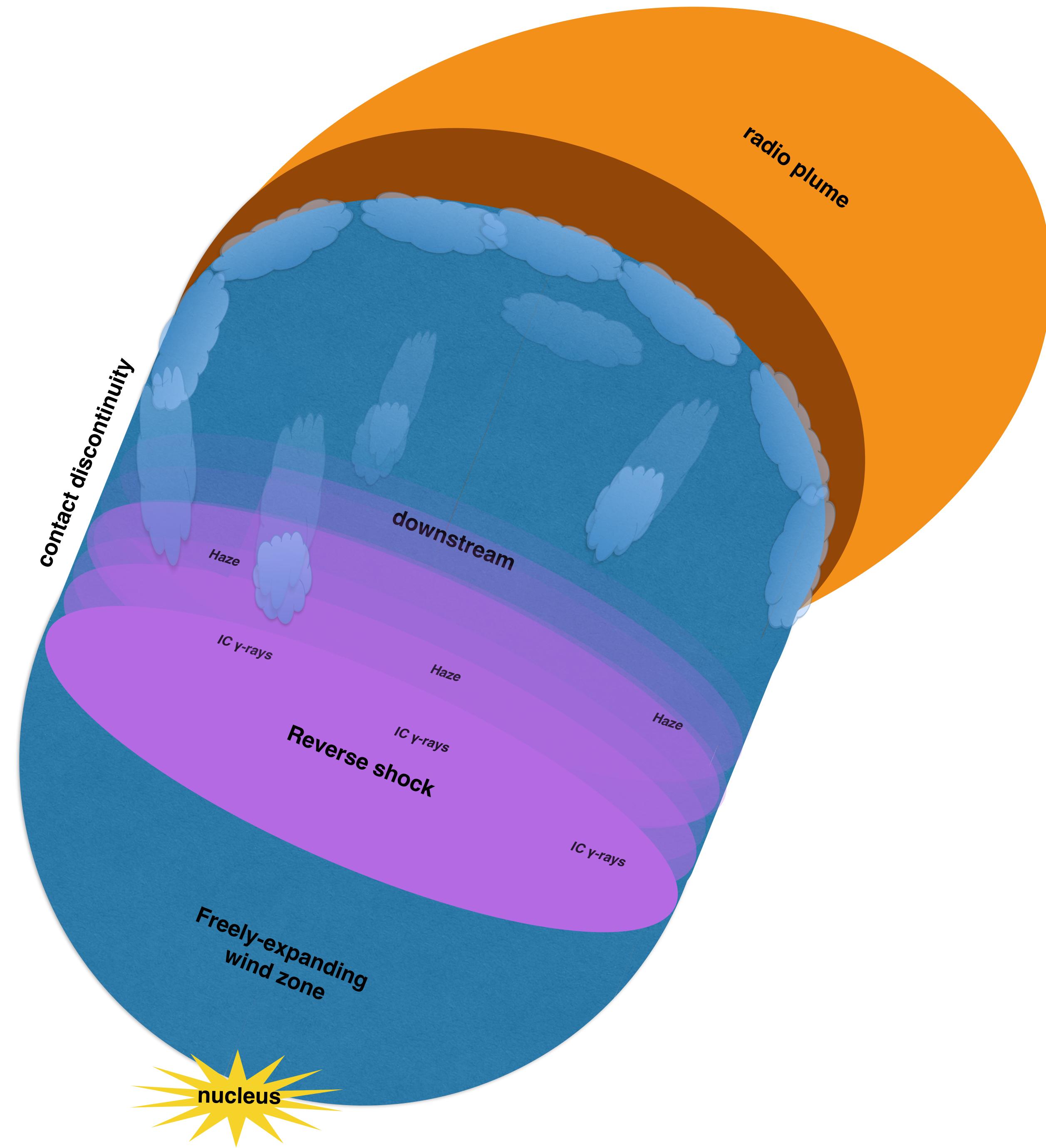


Range of CR electrons downstream of shock

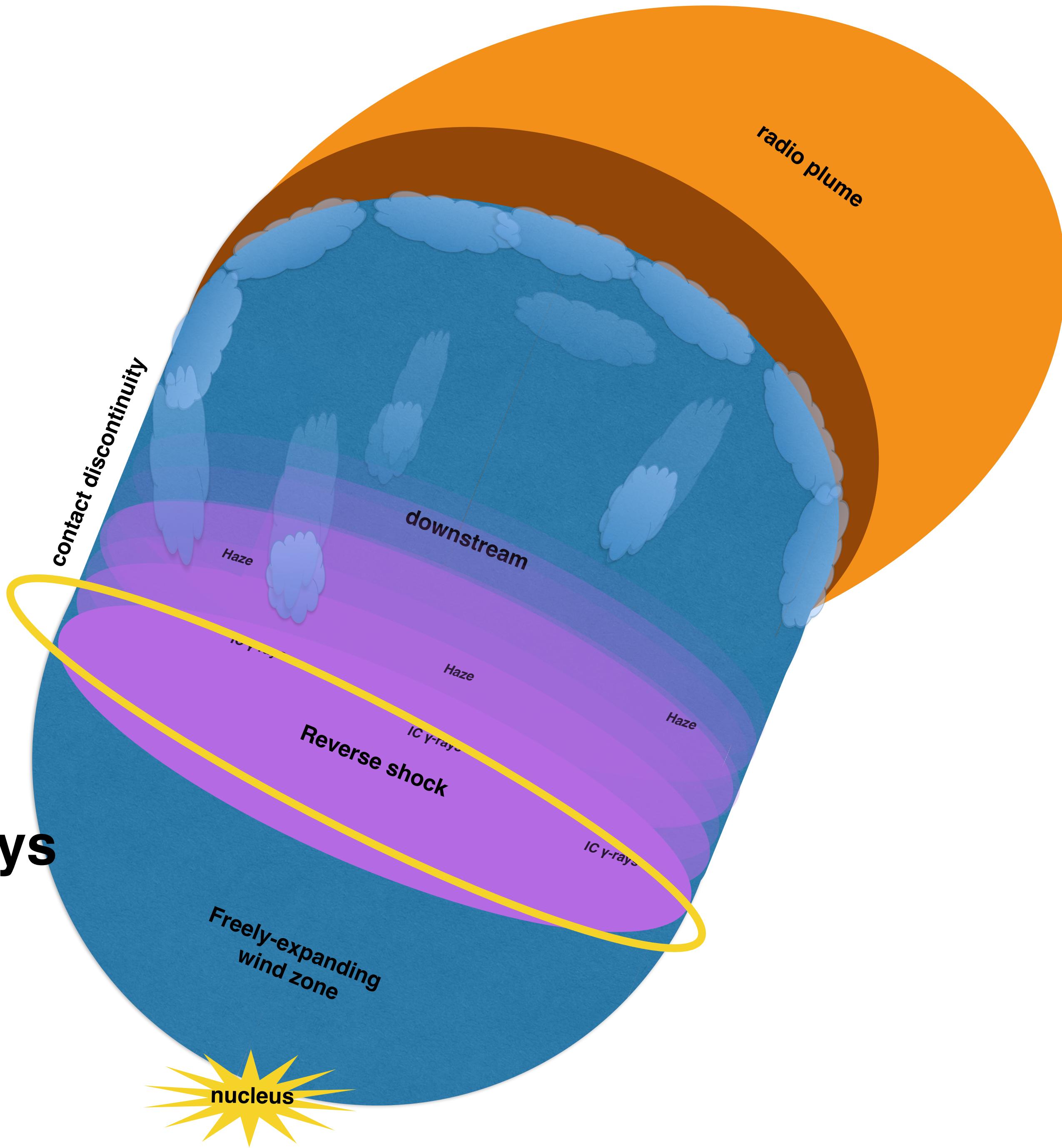


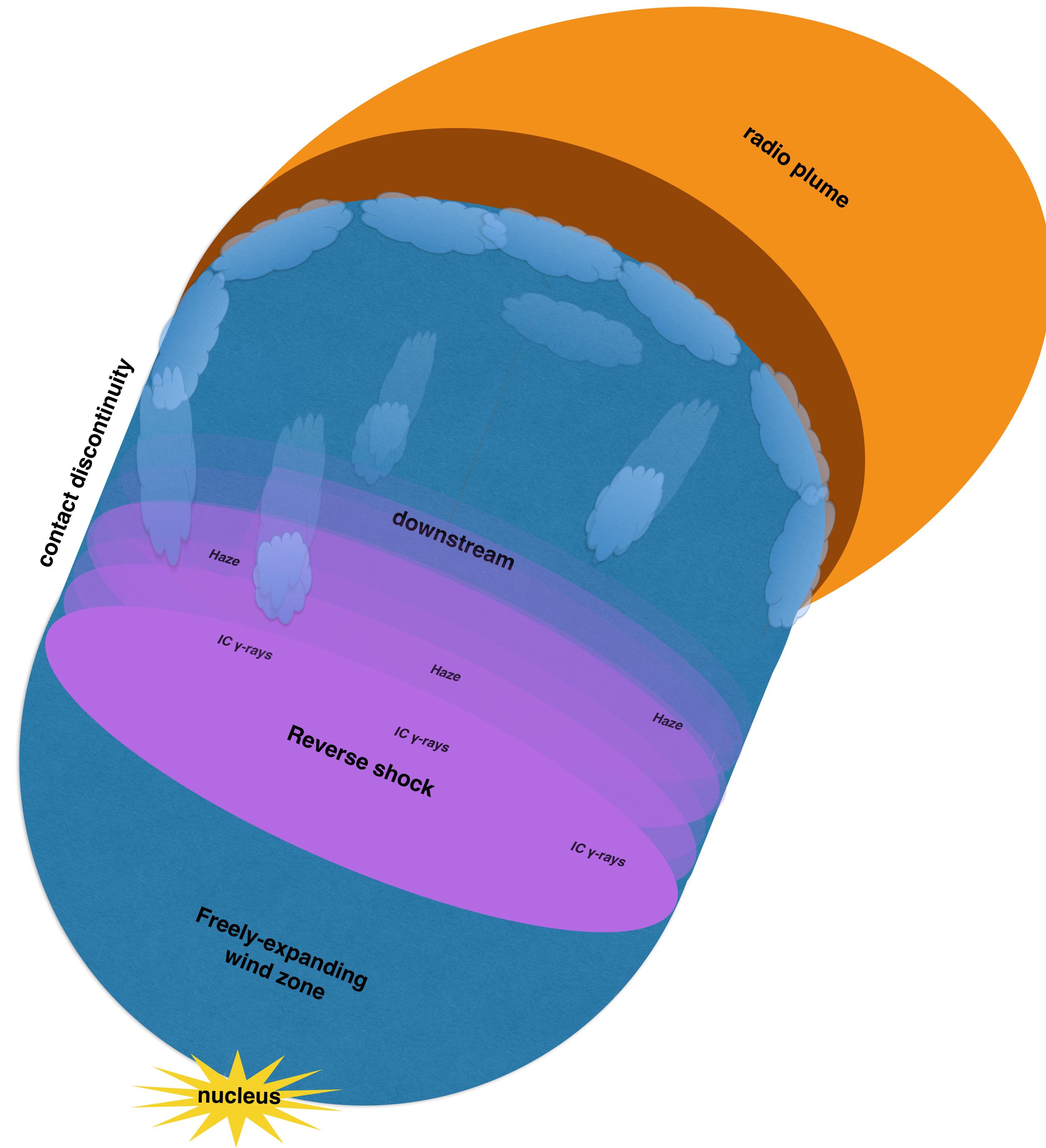


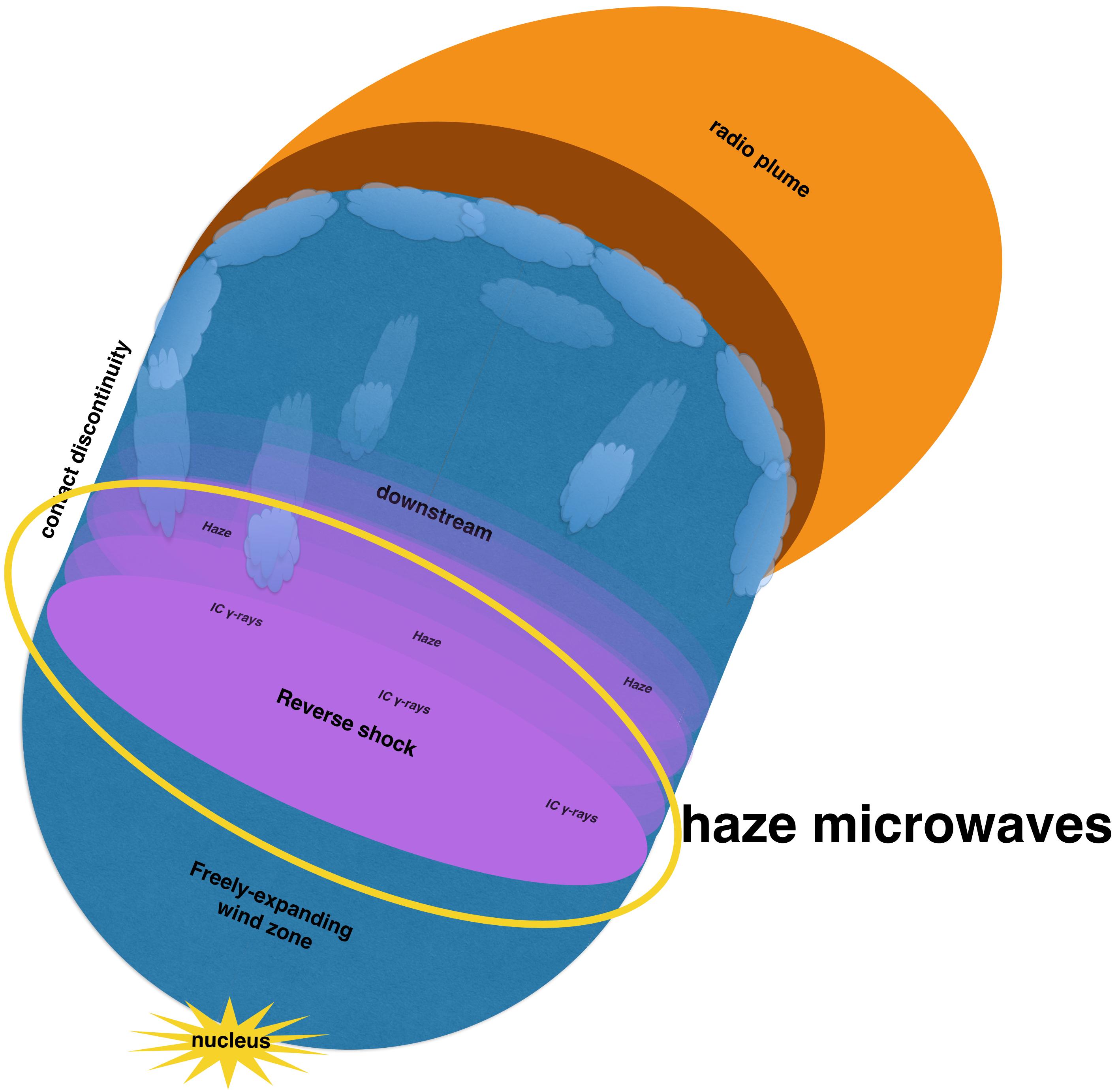


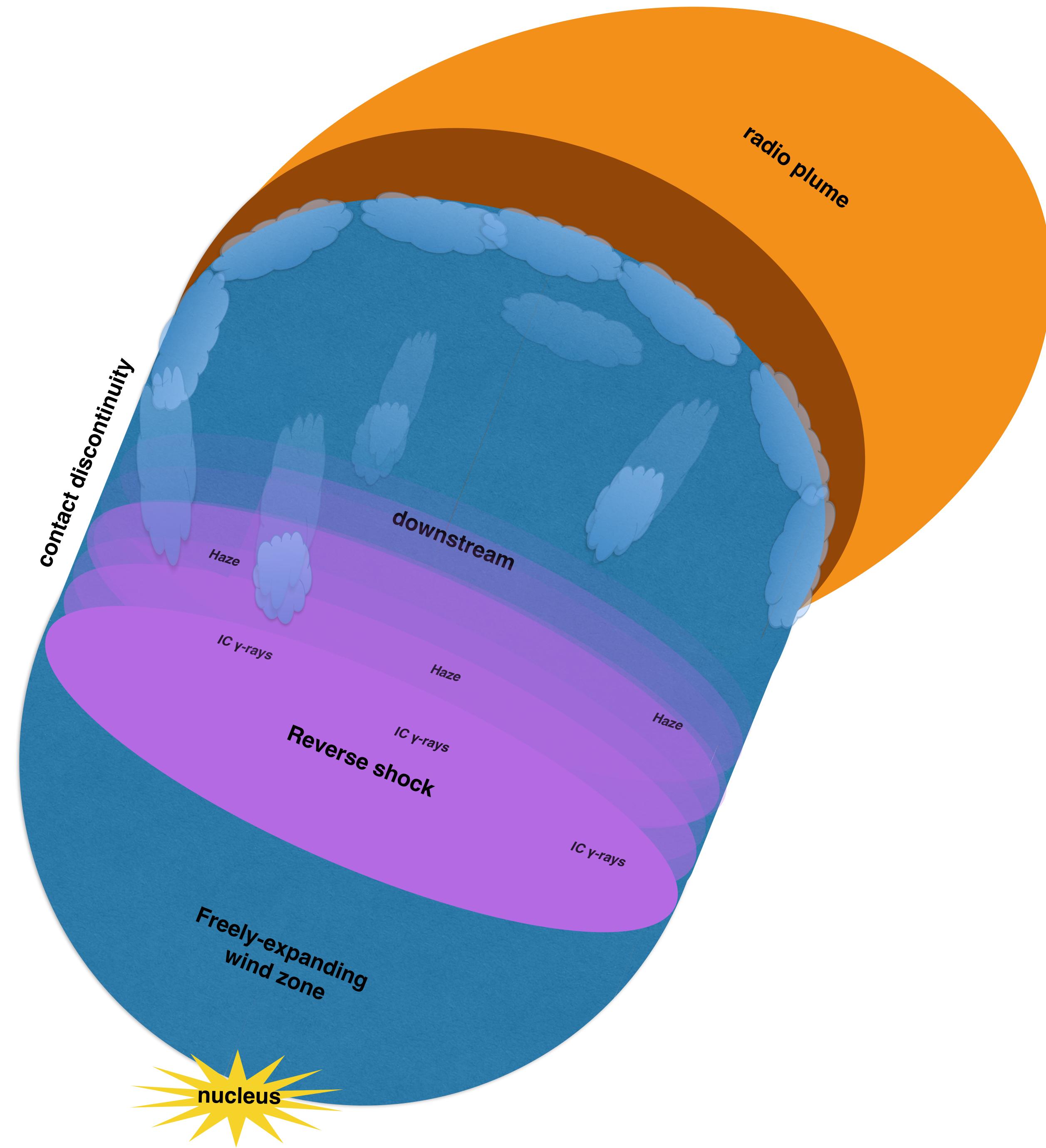


IC gamma-rays

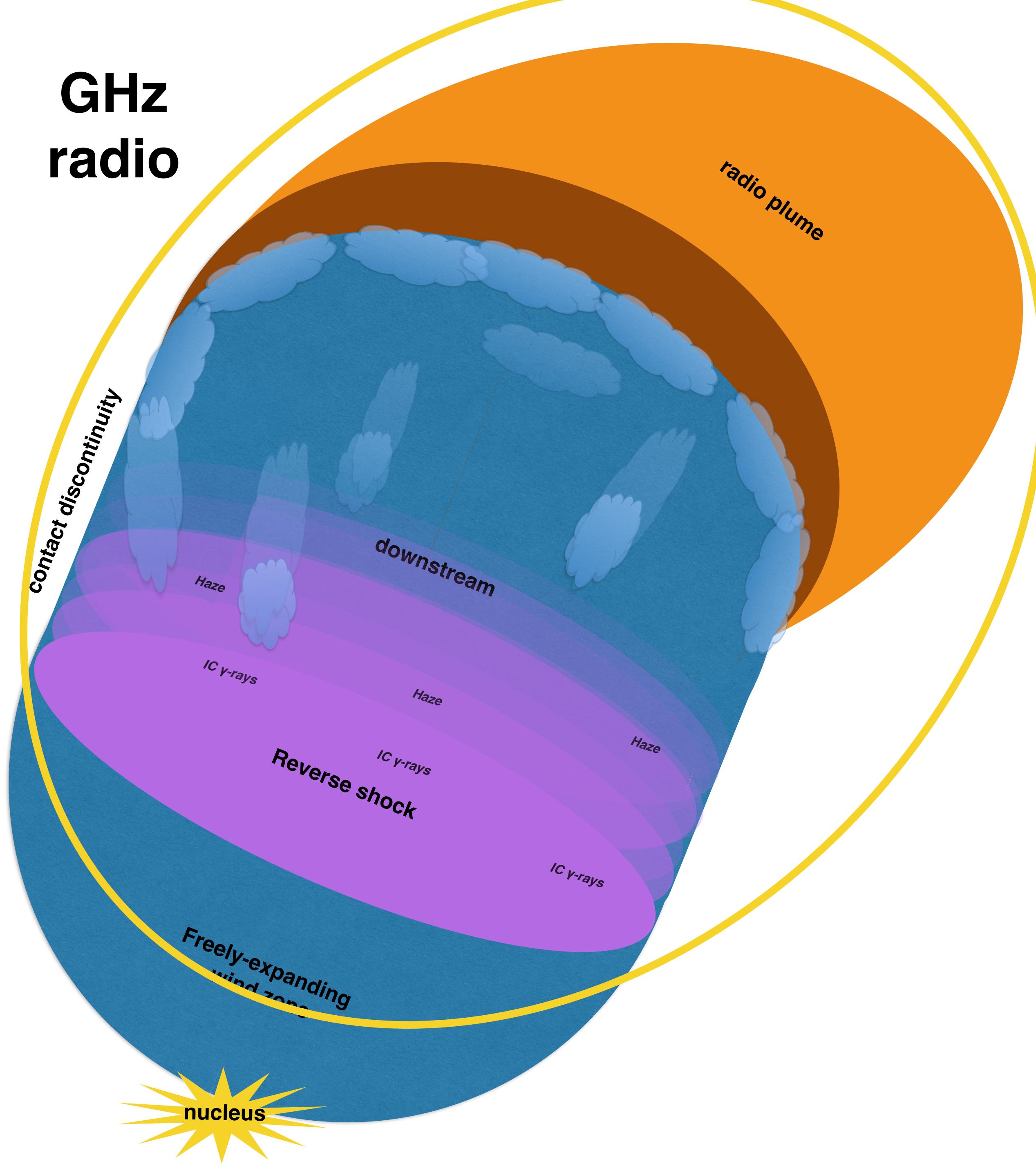


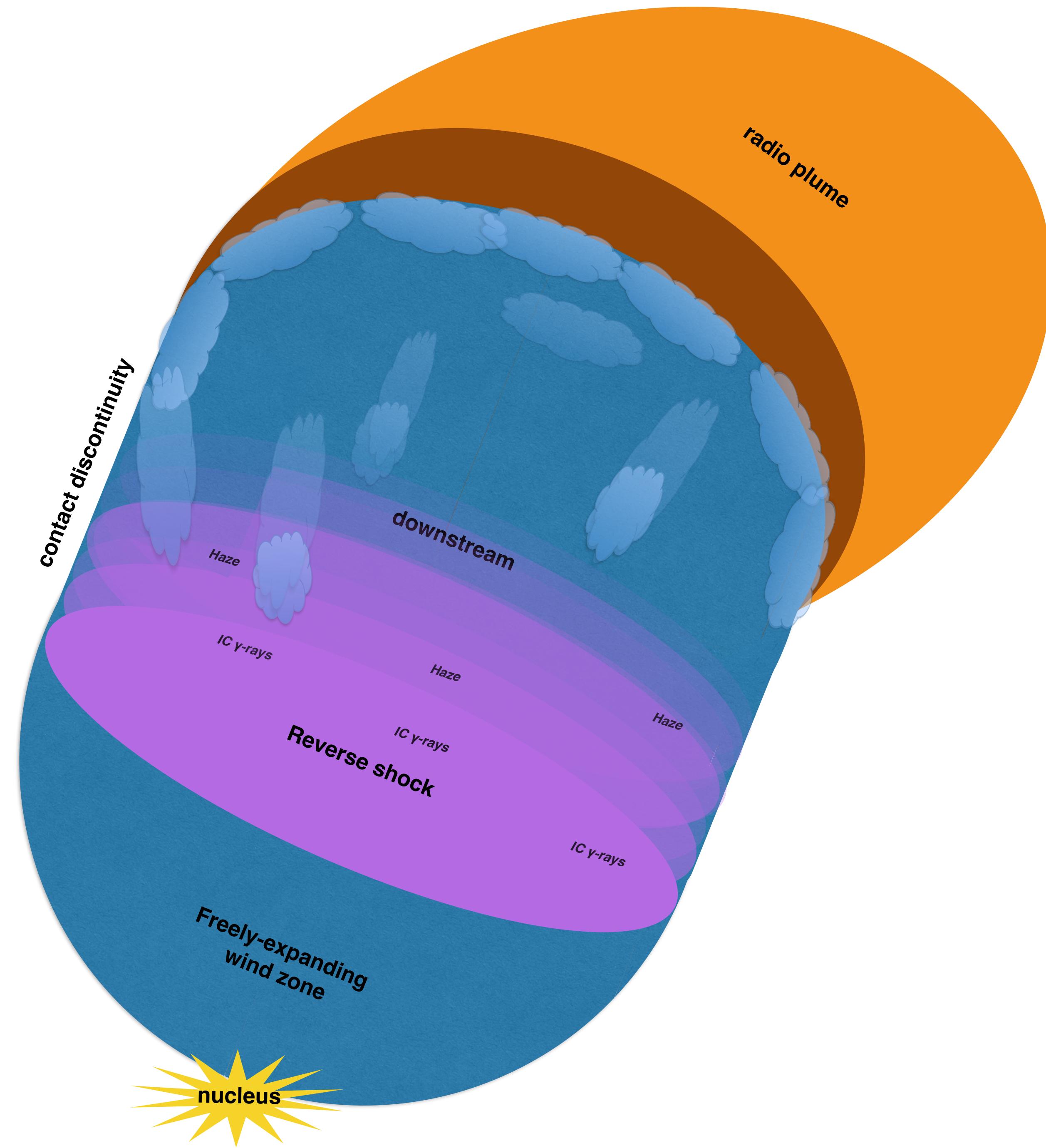






GHz radio





Conclusions

With few free parameters our model 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