Tracing the propagation of cosmic rays in the Milky Way halo with *Fermi*-LAT observations of high- and intermediate-velocity clouds

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on behalf of
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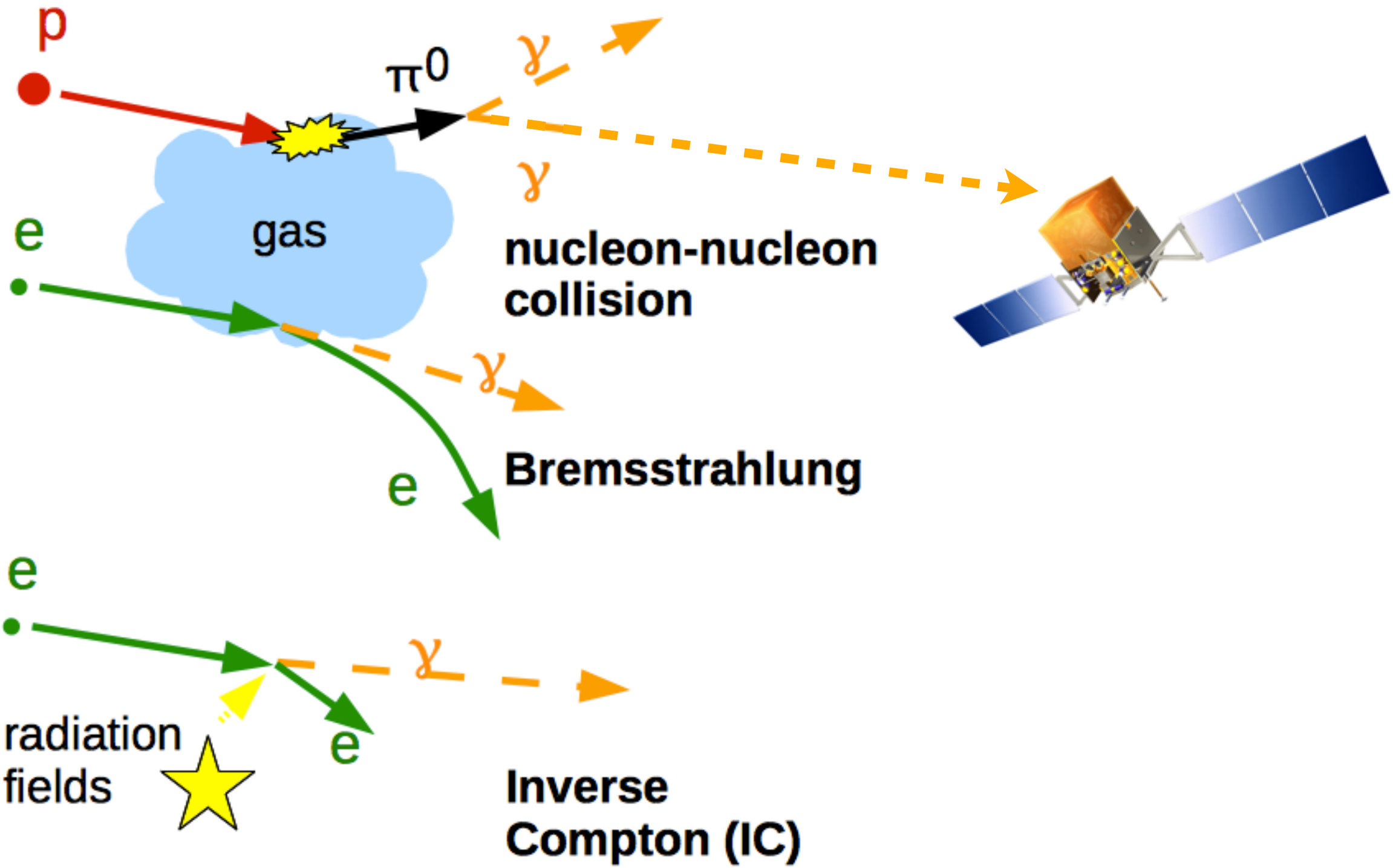
The Galactic cosmic-ray paradigm

below 10^{15} eV

- origin in the disk of the Milky Way
- propagate in > kpc halo (indirect evidence)

γ rays as a charged particle tracer



High- and intermediate-velocity clouds

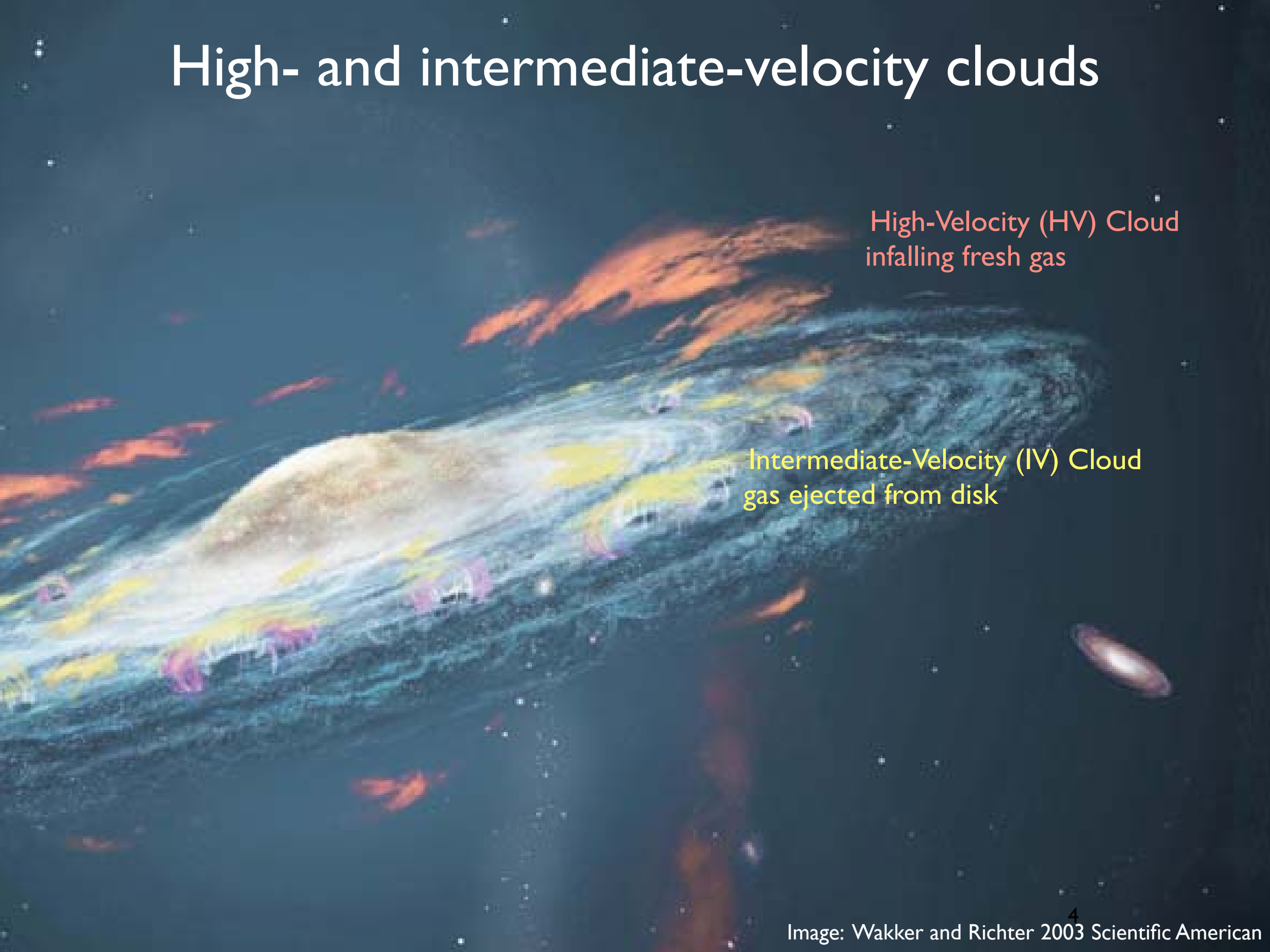
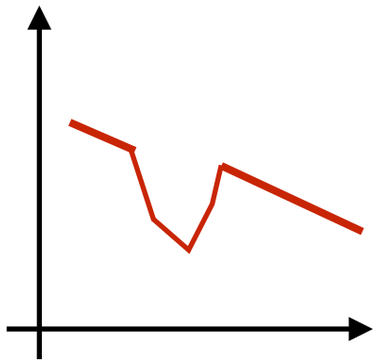
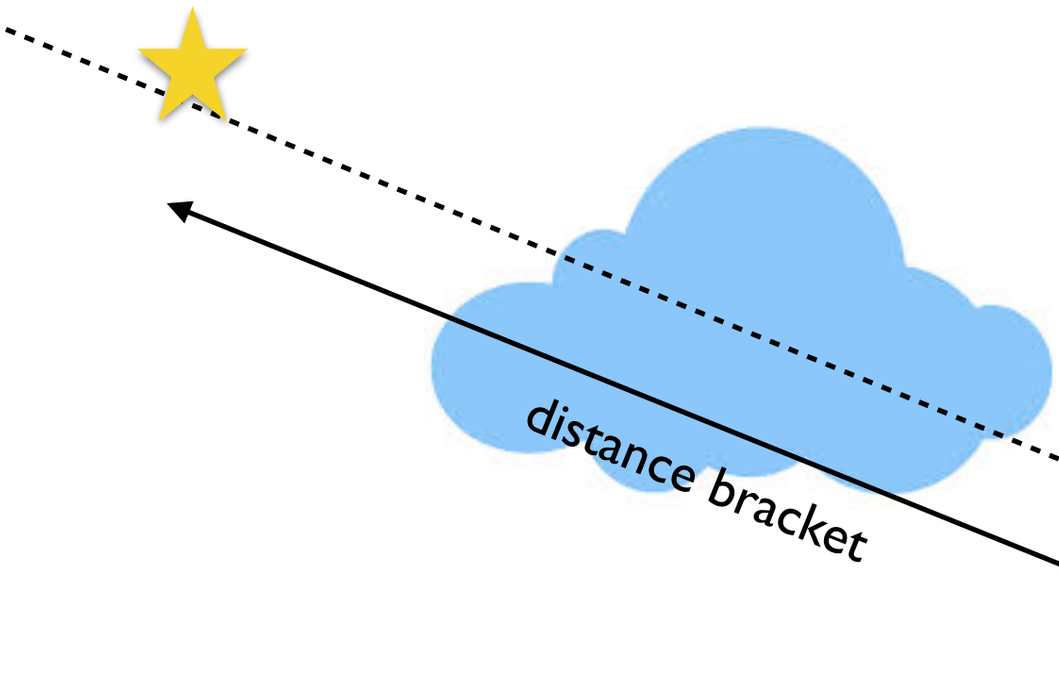


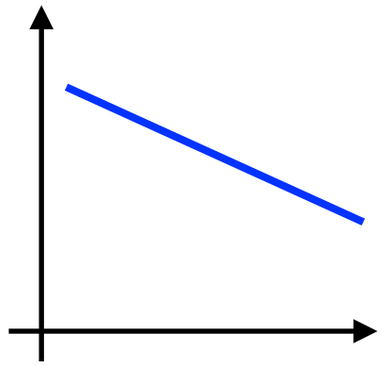
Image: Wakker and Richter 2003 Scientific American

Distances to HVCs/IVCs

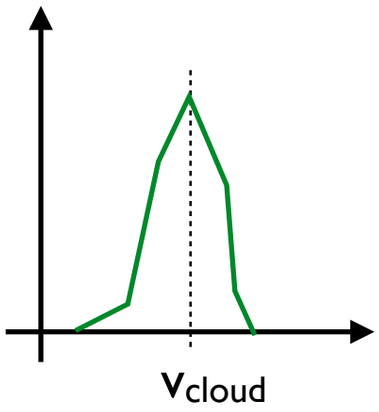


absorption line
→ upper limit on distance

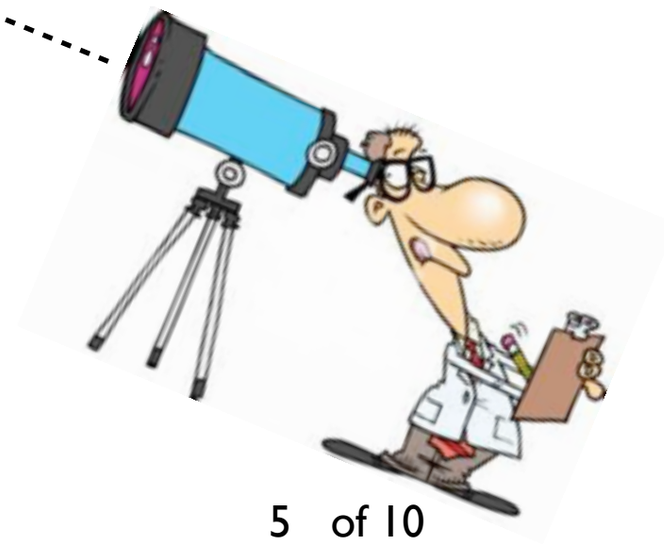




no absorption line
→ lower limit on distance



H I emission intensity
→ gas column density

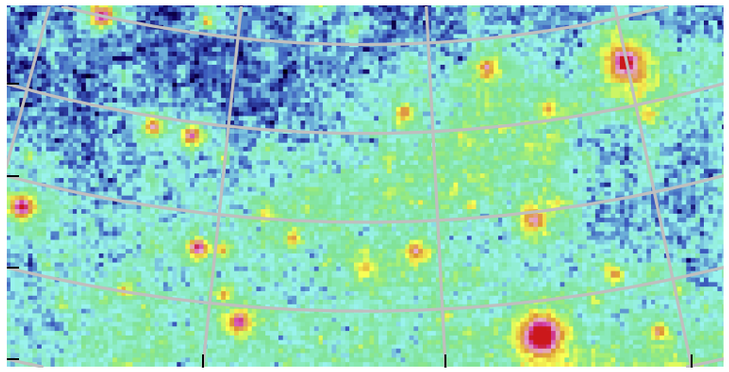


Analysis method

interstellar medium tracer data
LAB HI survey
CfA CO survey
Planck dust thermal emission model

LAT data: 73 months P7REP Clean

γ rays



$$= \text{LAT PSF} \otimes \text{exp} \cdot$$

scaling factor
γ-ray emissivity
cosmic rays

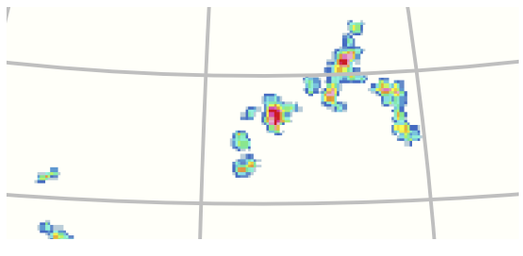
local HI

HI Low-Latitude IV Arch

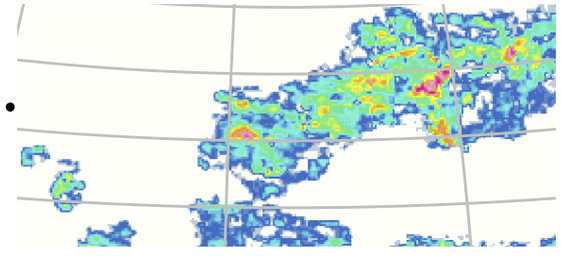
HI Complex A

$$[\, x_{HI,1} \cdot \quad + x_{HI,2} \cdot \quad + x_{HI,3} \cdot$$

CO (traces local H_2)



dust excess
(traces dark neutral medium)

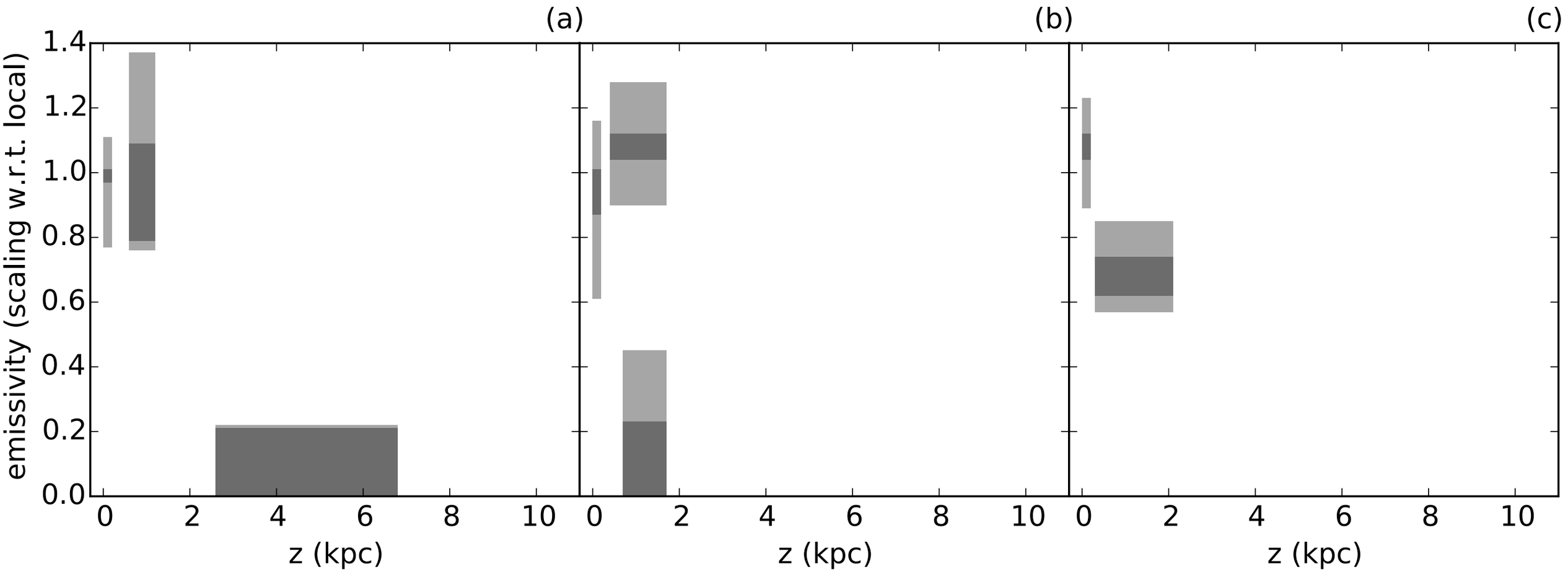


$$+ x_{CO} \cdot \quad + x_{DNM} \cdot \quad] \cdot q_{LIS}(E) +$$

γ-ray emission rate
(emissivity)
per H atom per sr per dE
in Local Interstellar Space
Casandjian (2015)

$$+ \text{IC(l,b,E)} + \text{Isotropic(E)} + \text{3FGL}$$

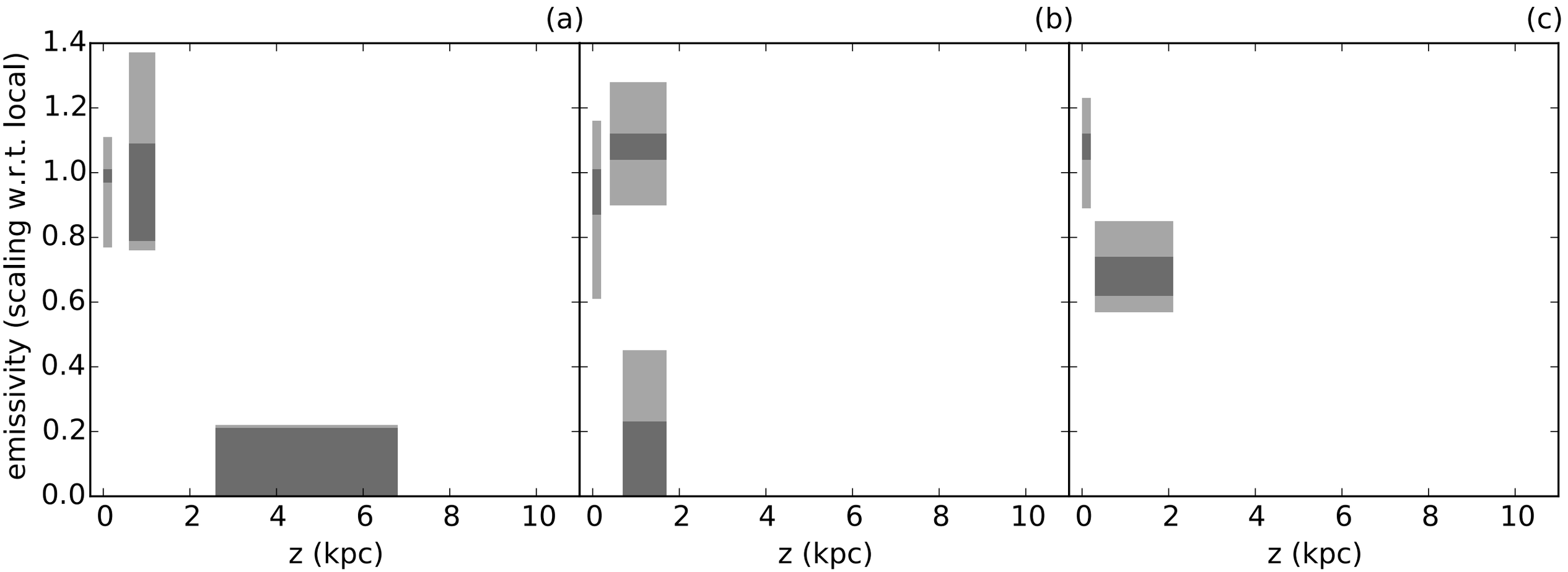
Results



- a: Low-Latitude Intermediate Velocity Arch and Complex A
- b: Lower and Upper Intermediate Velocity Arch
- c: Intermediate Velocity Spur

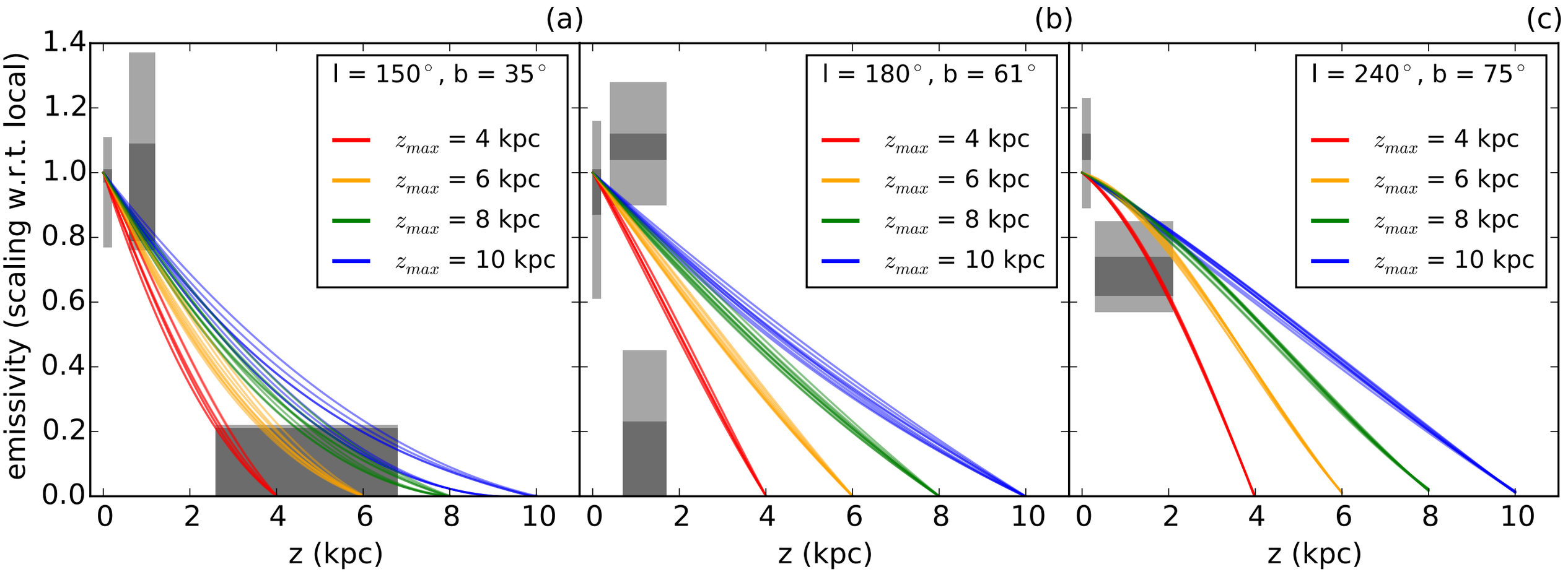
clouds definition and distance brackets from
Wakker 2001 ApJS 136 463

Do CRs originate from the Galactic disk?



- CR densities decrease with distance from the disk at 97.5% c.l.

Comparison to propagation model



models from Ackermann et al 2012 ApJ 750 3

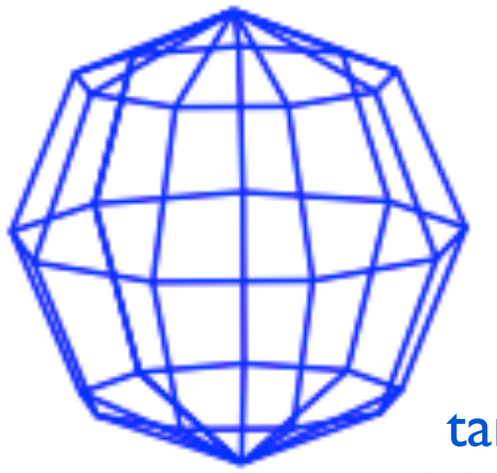
- broad agreement with propagation model
- hint at 50% decrease within 2 kpc from the disk ⟷ large halos

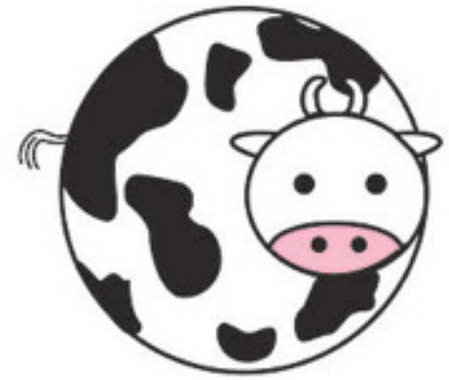
Final remarks

- first direct estimate of cosmic-ray nuclei densities in the Milky Way halo
  - model-independent constraints on halo structure, propagation, and escape
  - constraints tighter from distance brackets for more clouds, or made more stringent (Gaia)
- direct evidence for the origin of cosmic rays in the Milky Way disk
- hint at 50% decline in cosmic-ray densities within 2 kpc from the disk
- full description of method and results in:
  Tibaldo et al. 2015 ApJ 807 161

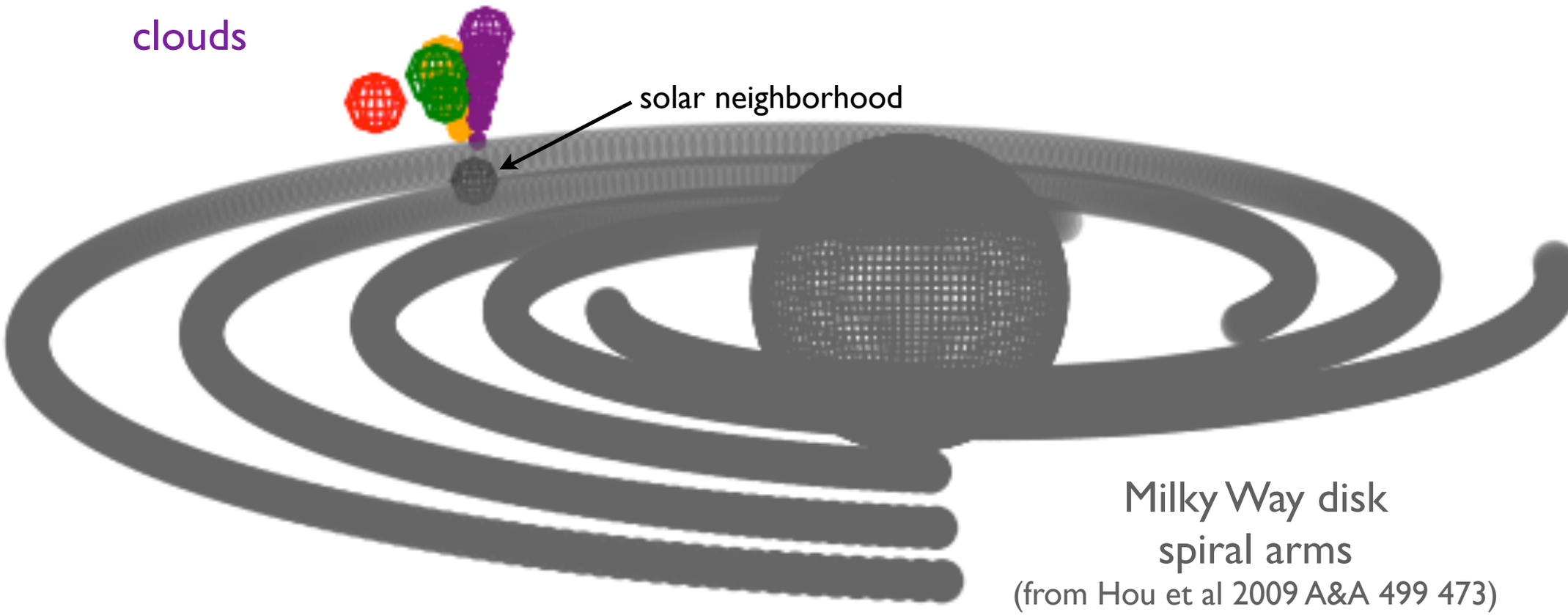
Backup

Target selection





target
HV and IV
clouds



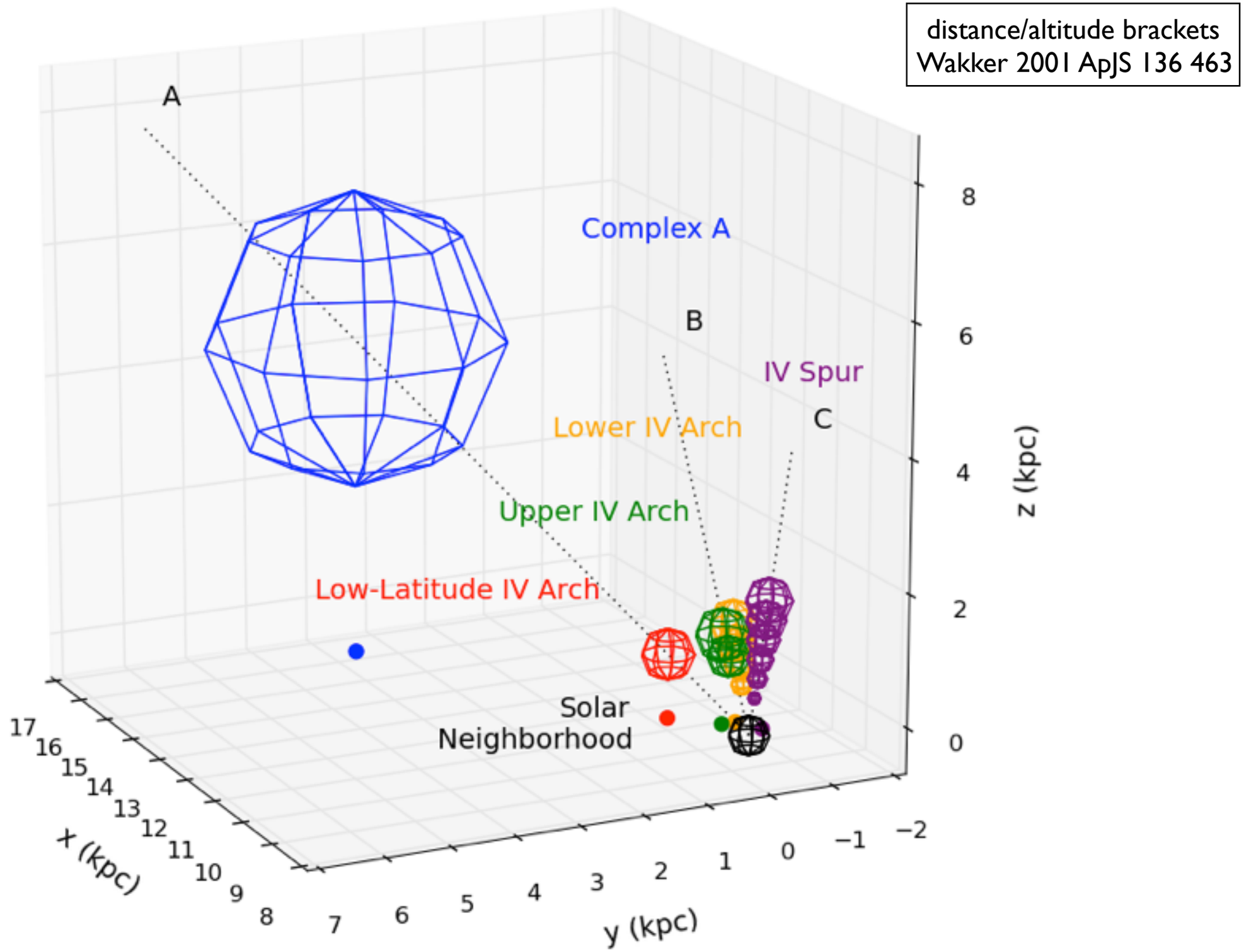
Milky Way disk
spiral arms
(from Hou et al 2009 A&A 499 473)

selection criteria

- distance/altitude bracket
- mass - distance detectable by the LAT

Targets and analysis regions

distance/altitude brackets
Wakker 2001 ApJS 136 463



Spectra of detected clouds