MARCO PADOVANI
ASTROFIT2-MARIE SKŁODOWSKA CURIE FELLOW
INAF-OSSERVATORIO ASTROFISICO DI ARCETRI, ITALY

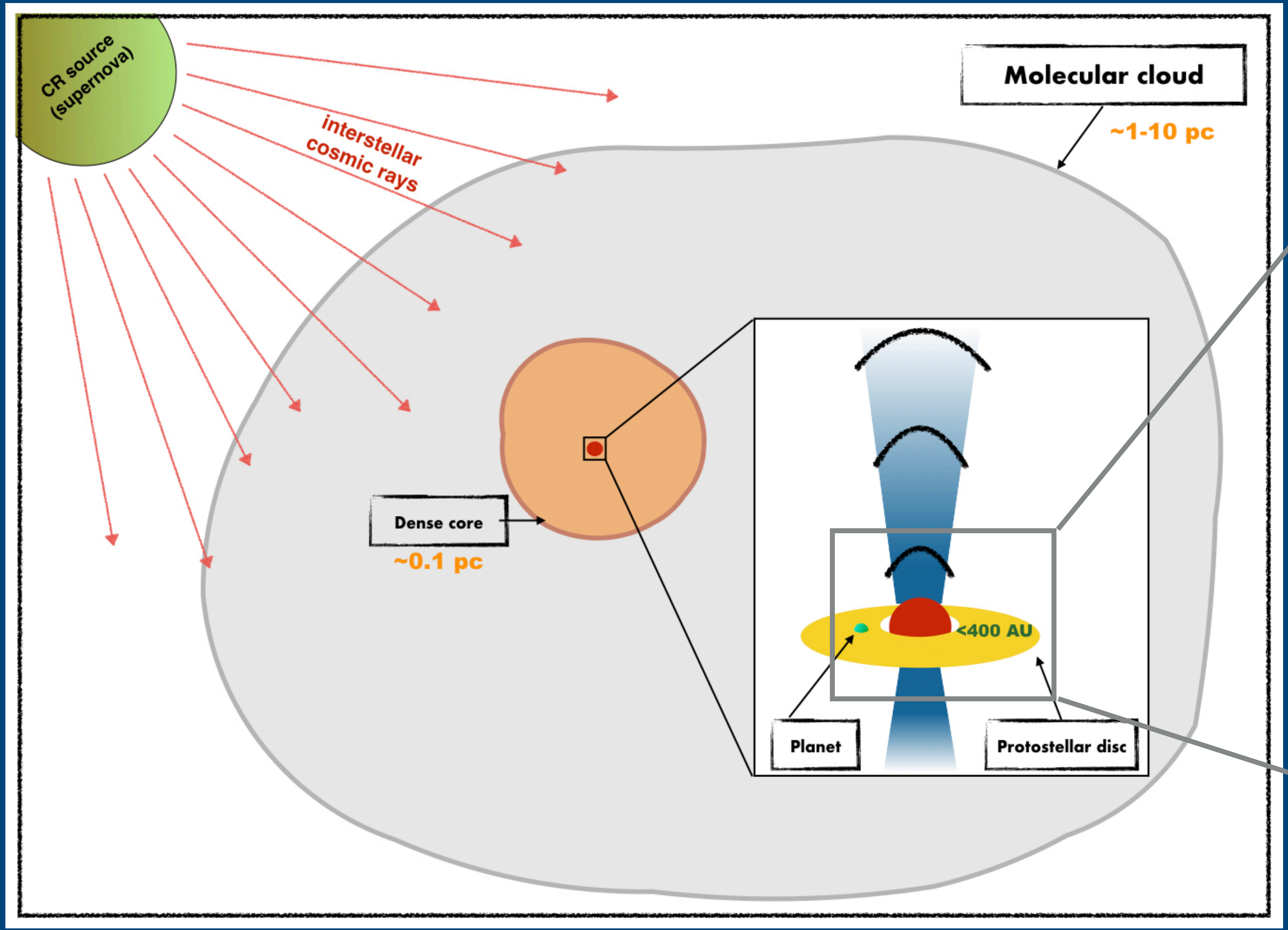
ORIGIN

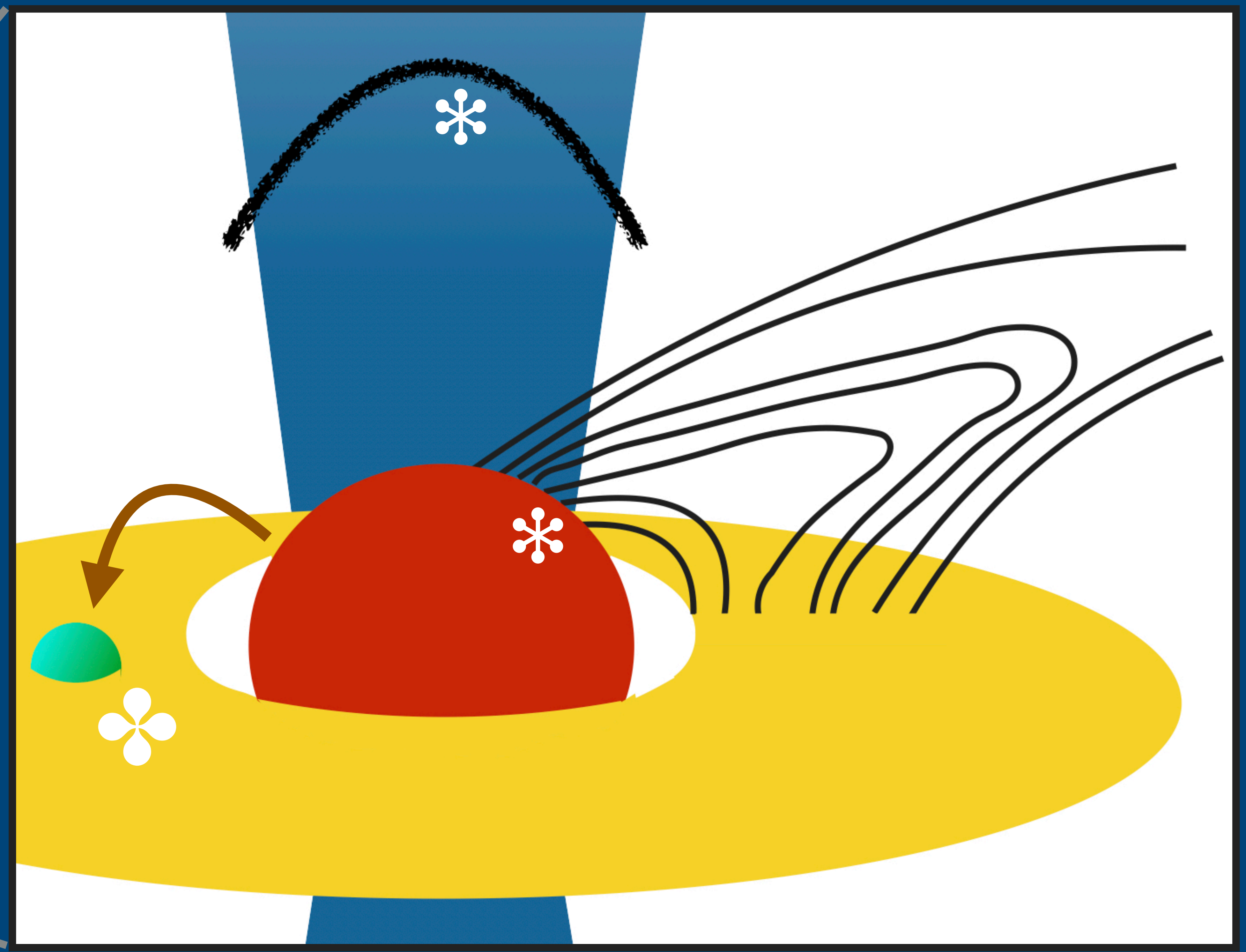
cOsmic Rays, trIGgers of prebIotic chemistry in the iNterstellar medium

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 664931

GOAL

To reach a comprehensive understanding of the impact of cosmic rays on the interstellar environment at large, including diffuse clouds, dense cores, protostellar discs, and protoplanetary habitats, to make a major advance on both the observational and theoretical side.





✻ local acceleration of cosmic rays (accretion shocks, jet shocks)

✤ effects of local cosmic rays on the chemical composition of exoplanetary atmospheres

PUBLICATIONS

16 papers + 1 book chapter (5 as first author, 2 as second author, 5 as third author)

Stellar energetic particle ionization in protoplanetary disks around T Tauri stars (Rab+ 2017 A&A);
The onset of energetic particle irradiation in Class 0 protostars (Favre+ 2017 A&A);
Protostars as cosmic-ray factories (Padovani+ 2017 Mem. S.A.It.);
Resolving the polarized dust emission of the disk around the massive star powering the HH 80-81 radio jet (Girart+ 2018 ApJ);
Cosmic-ray ionisation in circumstellar discs (Padovani+ 2018 A&A);
Magnetic Mirroring and Focusing of Cosmic Rays (Silsbee+ 2018 ApJ);
Magnetic field in a young circumbinary disk (Alves+ 2018 A&A);
Protonated CO_2 in massive star-forming clumps (Fontani+ 2018 A&A);
ALMA observations of polarized emission toward the CW Tau and DG Tau protoplanetary disks (Bacciotti+ 2018 ApJ);
Production of atomic hydrogen by cosmic rays in dark clouds (Padovani+ 2018 A&A);
Synchrotron emission in molecular cloud cores: the SKA view (Padovani+ 2018 A&A);
The challenges of modelling microphysics: ambipolar diffusion, chemistry, and cosmic rays in MHD shocks (Grassi+ 2019 MNRAS)
Protostellar Outflows at the EarliesT Stages (POETS). II. A possible radio synchrotron jet associated with the EGO G035.02+0.35 (Sanna+ 2019 A&A);
The central 1000 AU of a pre-stellar core revealed with ALMA. I. 1.3 mm continuum observations (Caselli+ 2019 A&A);
ALMA resolves the hourglass magnetic field in G31.41+0.31 (Beltrán+ 2019 A&A);
Non-thermal emission from cosmic rays accelerated in HII regions (Padovani+ 2019 A&A);
The physical and chemical structure of Sagittarius B2 V. Non-thermal emission in the envelope of Sgr B2 (Meng+ 2019 A&A).
Book chapter: *Impact of low-energy cosmic rays on star formation* (Padovani+ 2019 - Space Science Series of ISSI, Springer)

Publicly available on-line tool: http://synchrotron-hiiregions.herokuapp.com

Interstellar cosmic rays (effects on physics and chemistry of molecular clouds at different scales)
Cosmic rays locally accelerated in protostars and HII regions
Magnetic fields and polarisation (modelling and observations)

COSMIC RAYS IN GALACTIC STAR FORMATION

COSMIC RAYS
E<10 GeV

chemistry of molecular clouds
Caselli & Ceccarelli (2012)
Padovani+ (2009,2011)
Indriolo+ (2012,2015)
Padovani+ (2013,2018a)

collapse timescale
Nakano+ (2002)
Padovani+ (2013,2014)

gas temperature
Glassgold & Langer (1973)
Cravens & Dalgarno (1978)
Dalgarno+ (1999)
Glassgold+ (2012)
Galli & **Padovani** (2015)

dust grain charge
Prasad & Tarafdar (1983)
Cecchi-Pestellini & Aiello (1992)
Shen+ (2004)
Ivlev, **Padovani**+ (2015)

protostars as cosmic-ray sources
Araudo+ (2007)
Bosch-Ramon+ (2010)
Munar-Adrover+ (2011)
Padovani+ (2015,2016,2017)

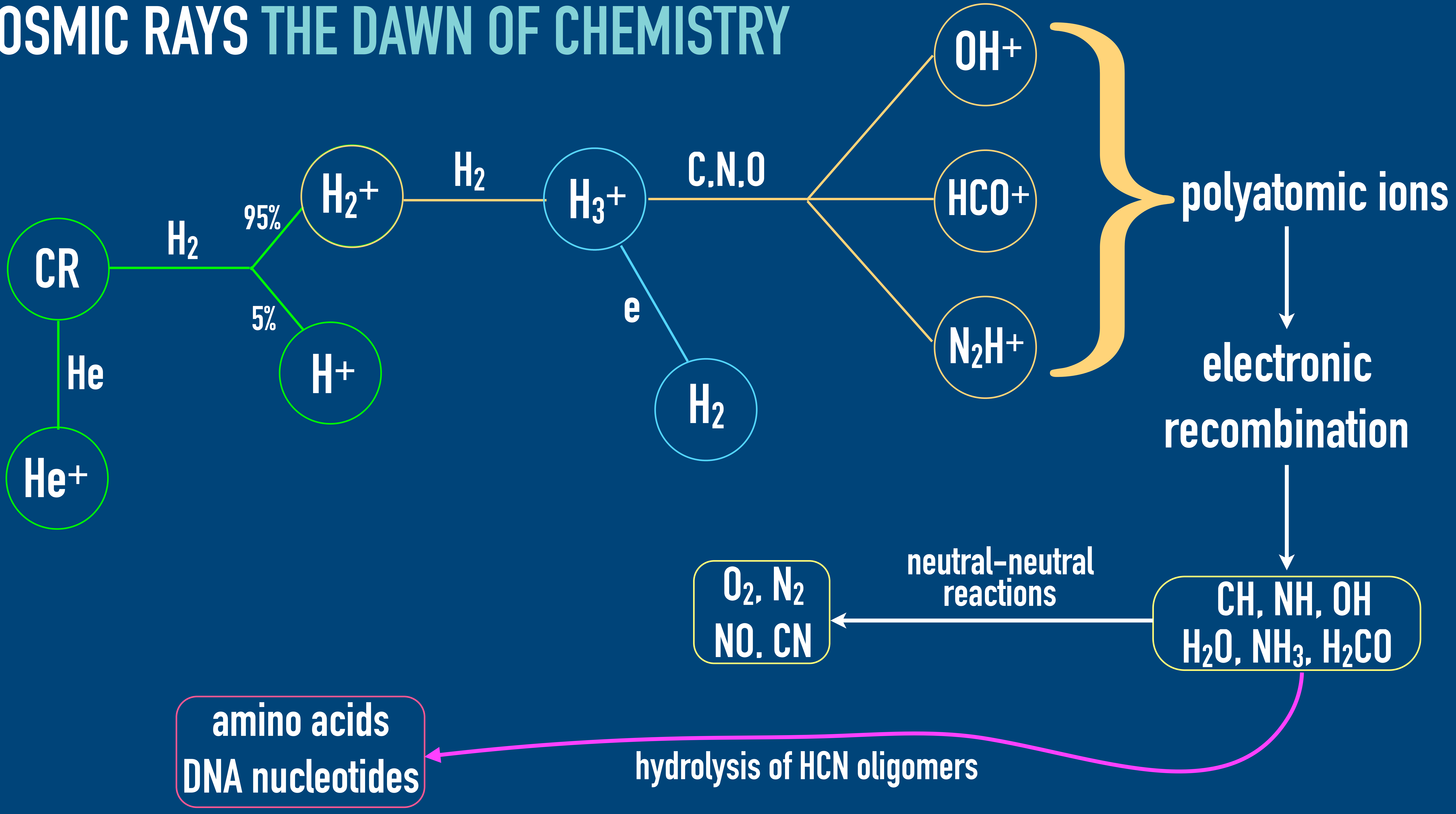
atomic hydrogen in dark clouds
Li & Goldsmith (2003)
Goldsmith+ (2005, 2007)
Padovani+ (2018b)

synchrotron emission in star forming regions (SKA)
Dickinson+ (2015)
Padovani+ (2018c)
Padovani+ (2019)

(production of light elements, gamma-ray emission…)

UV γ
CRs
H
[H]
≈
[H2]
H2
photodissociation region (PDR)
diffuse cloud
dense cloud

COSMIC RAYS THE DAWN OF CHEMISTRY



COSMIC-RAY PROPAGATION: FROM LARGE TO SMALL SCALES

Padovani+ (2009, 2011, 2013a, 2013b)
Padovani+ (2018a)

THE PROBLEM OF THE COLLAPSE TIMESCALE

free-fall time: $t_{\rm ff} = \sqrt{\dfrac{3\pi}{32 G \mu m_p n}} \simeq \dfrac{4 \times 10^7}{\sqrt{n}}$ yr   typically n $\gtrsim$ 50 cm^{-3}, then $t_{\rm ff} \lesssim 5 \times 10^6$ yr

Mass of the Milky Way: $M_{\rm MW} \simeq 10^9\ M_\odot$ then the star formation rate is $\mathrm{SFR} = M_{\rm MW}/t_{\rm ff} \simeq 200\ M_\odot\ \mathrm{yr}^{-1}$

BUT, from observations: $\mathrm{SFR} \simeq 3\ M_\odot\ \mathrm{yr}^{-1}$

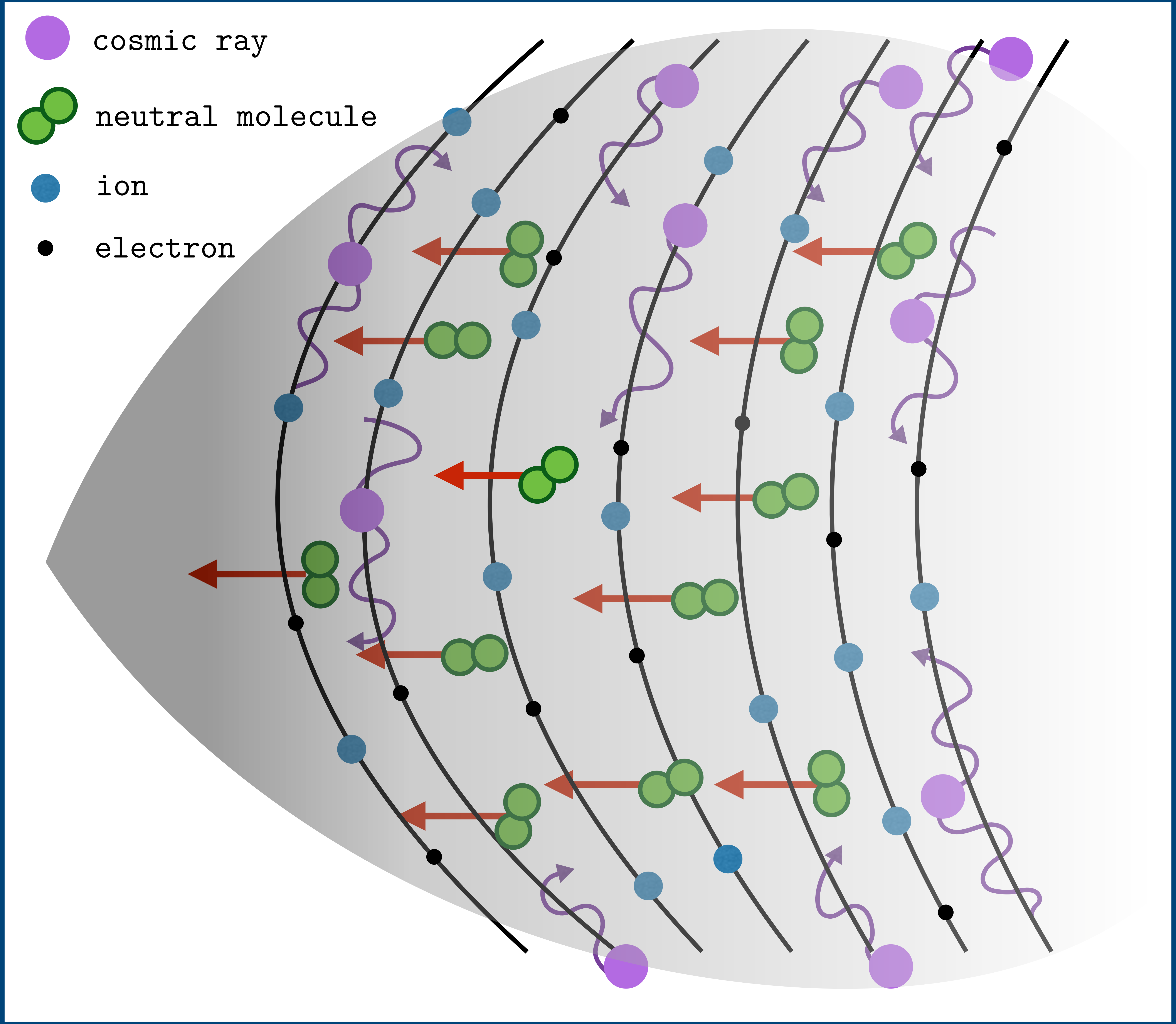
On the scale of prestellar cores, turbulent motions and thermal pressure are negligible.

MAGNETIC FIELD IS THE SOLUTION!

THE PROBLEM OF THE COLLAPSE TIMESCALE

adapted from Machida+ (2007)

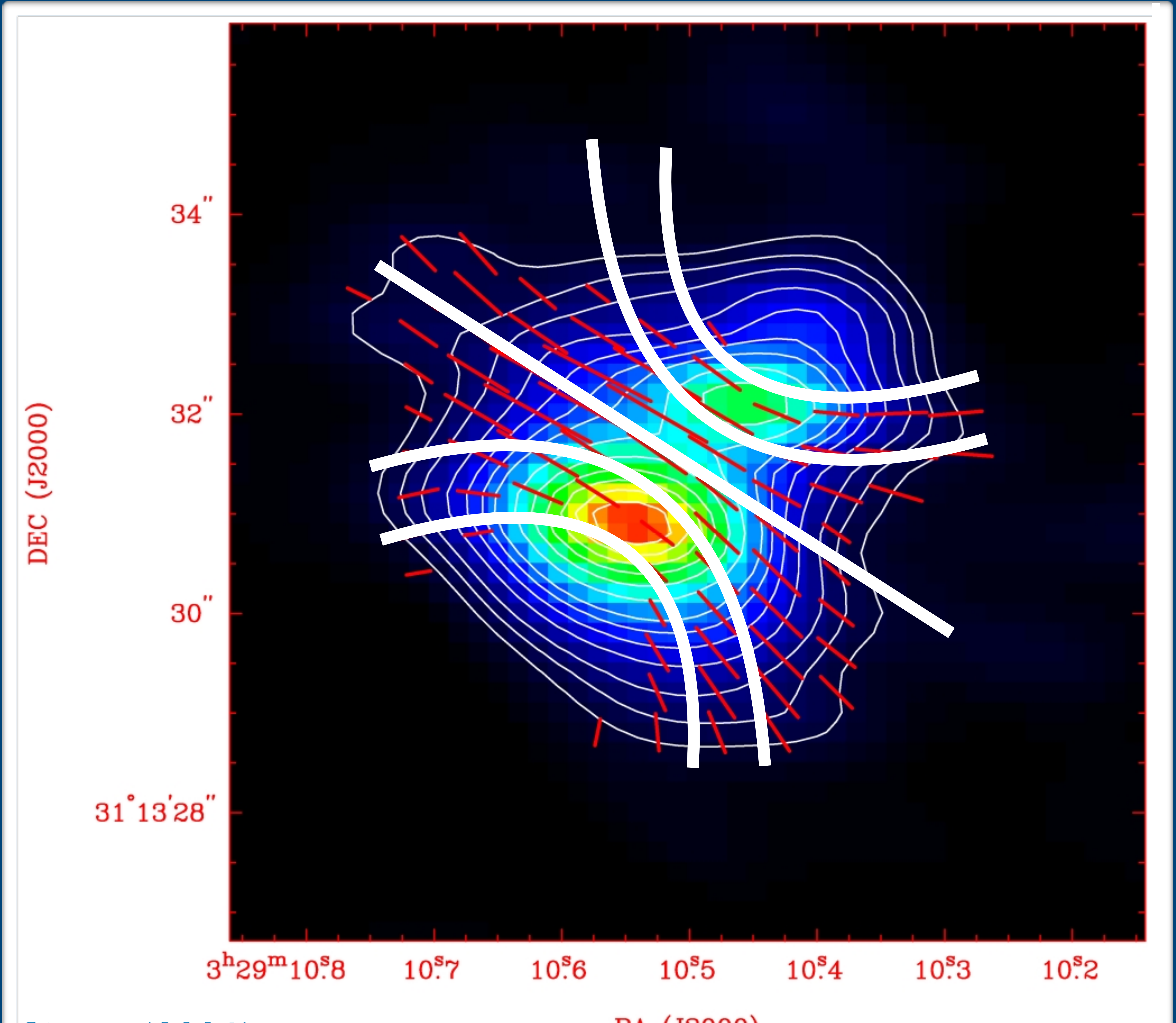
COSMIC RAYS SET THE COLLAPSE TIMESCALE



- ions and electrons are frozen into magnetic field;
- neutrals drift reaching the central part of the core.

A frictional force couples charged particles and neutrals

COSMIC RAYS SET THE COLLAPSE TIMESCALE



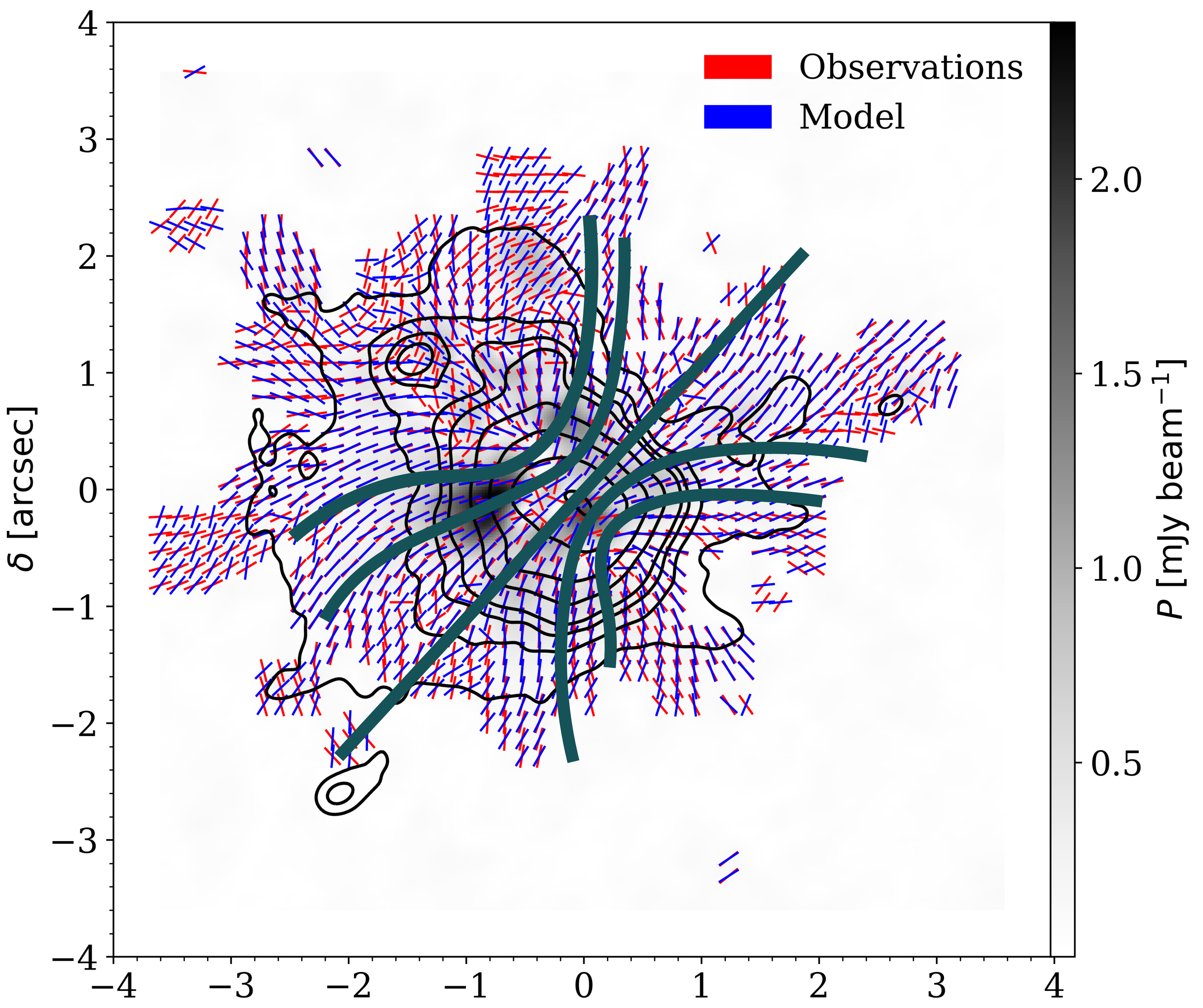
Girart+ (2006)

- ions and electrons are frozen into magnetic field;
- neutrals drift reaching the central part of the core.

A frictional force couples charged particles and neutrals

1. typical "hourglass" shape of the magnetic field configuration (polarised thermal dust emission observations)

COSMIC RAYS SET THE COLLAPSE TIMESCALE



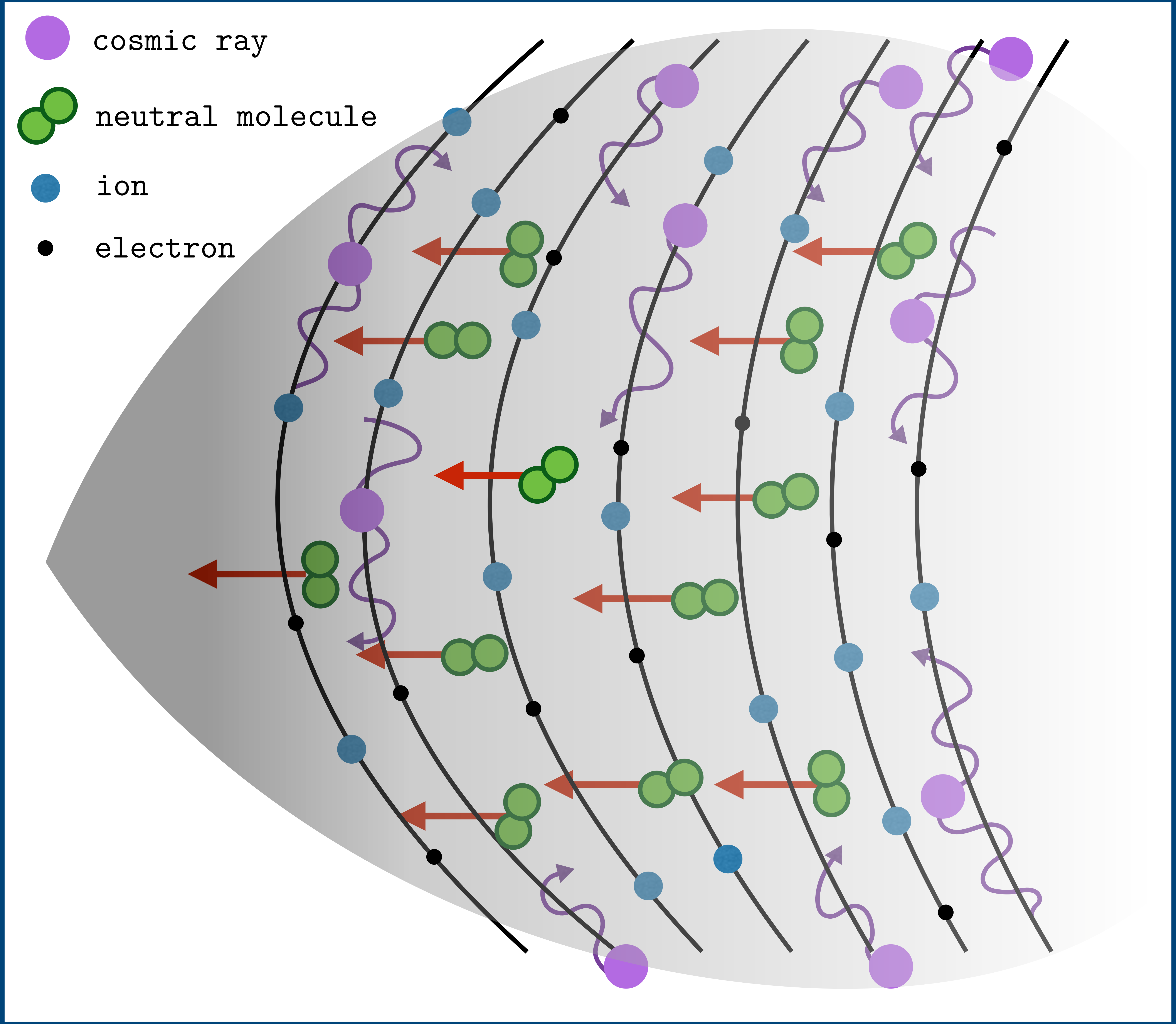
Beltrán, Padovani+ (2019)

- ions and electrons are frozen into magnetic field;
- neutrals drift reaching the central part of the core.

A frictional force couples charged particles and neutrals

1. typical “hourglass” shape of the magnetic field configuration (polarised thermal dust emission observations)

COSMIC RAYS SET THE COLLAPSE TIMESCALE

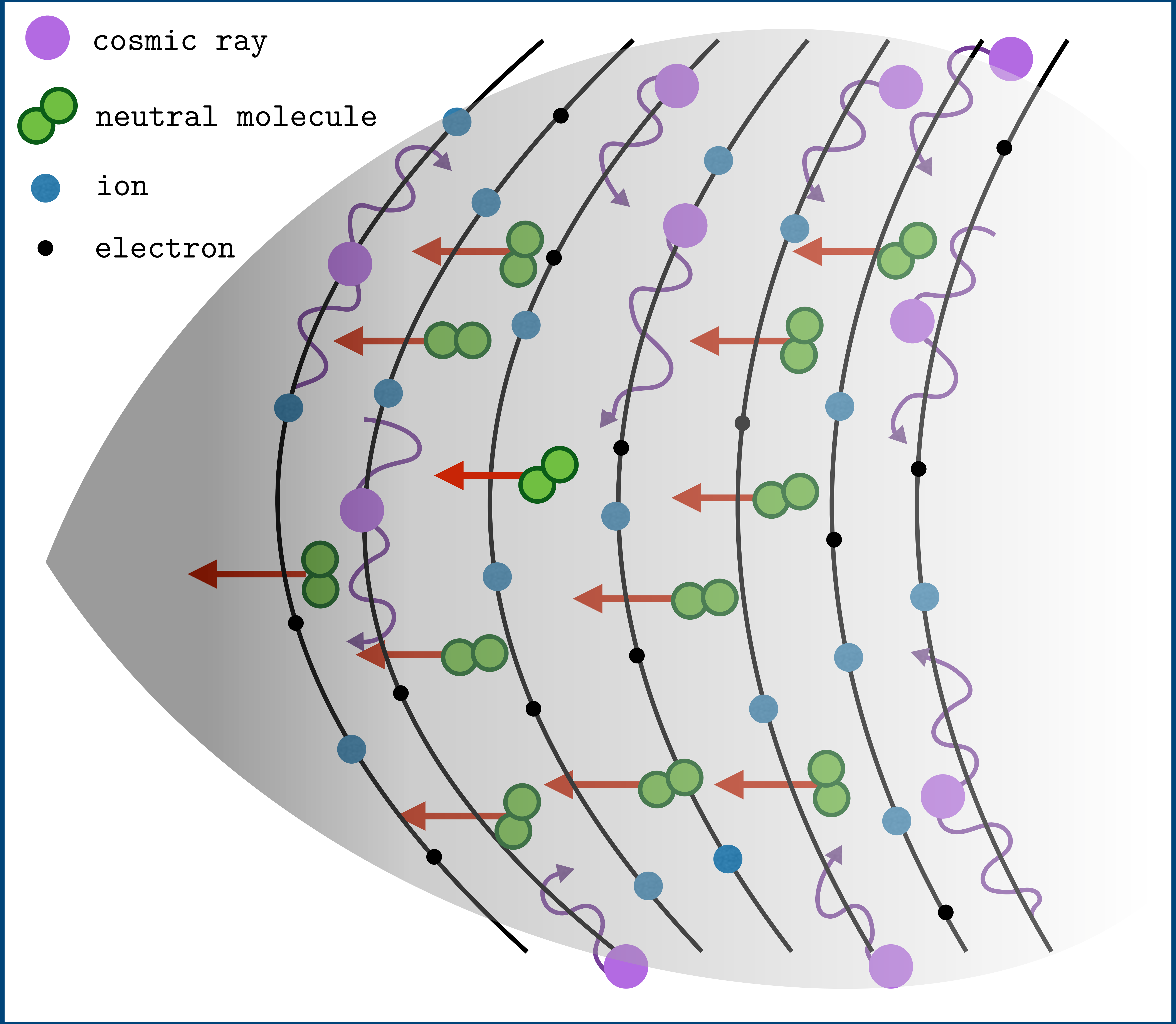


- ions and electrons are frozen into magnetic field;
- neutrals drift reaching the central part of the core.

A frictional force couples charged particles and neutrals

2. magnetic tension prevents the distortion of the field lines, so the collapse of neutrals slows down because of collisions with charges (i.e. the collapse is braked).

COSMIC RAYS SET THE COLLAPSE TIMESCALE



The efficiency of the collapse braking depends on the degree of coupling between gas and the magnetic field, i.e. on the ionisation fraction: $x = n_e/n$

$$\mathrm{CR} + \mathrm{H_2} \rightarrow \mathrm{CR} + \mathrm{H_2^+} + \mathrm{e}$$

H_2 ionisation H_2 recombination

$$\zeta n = k n_e n_i \simeq k n_e^2 = k x_e^2 n^2$$

$$x \propto \sqrt{\zeta / n}$$

$$\zeta(N) \propto \int j_{\mathrm{CR}}(E, N)\, \sigma_{\mathrm{ion}}(E)\, \mathrm{d}E$$

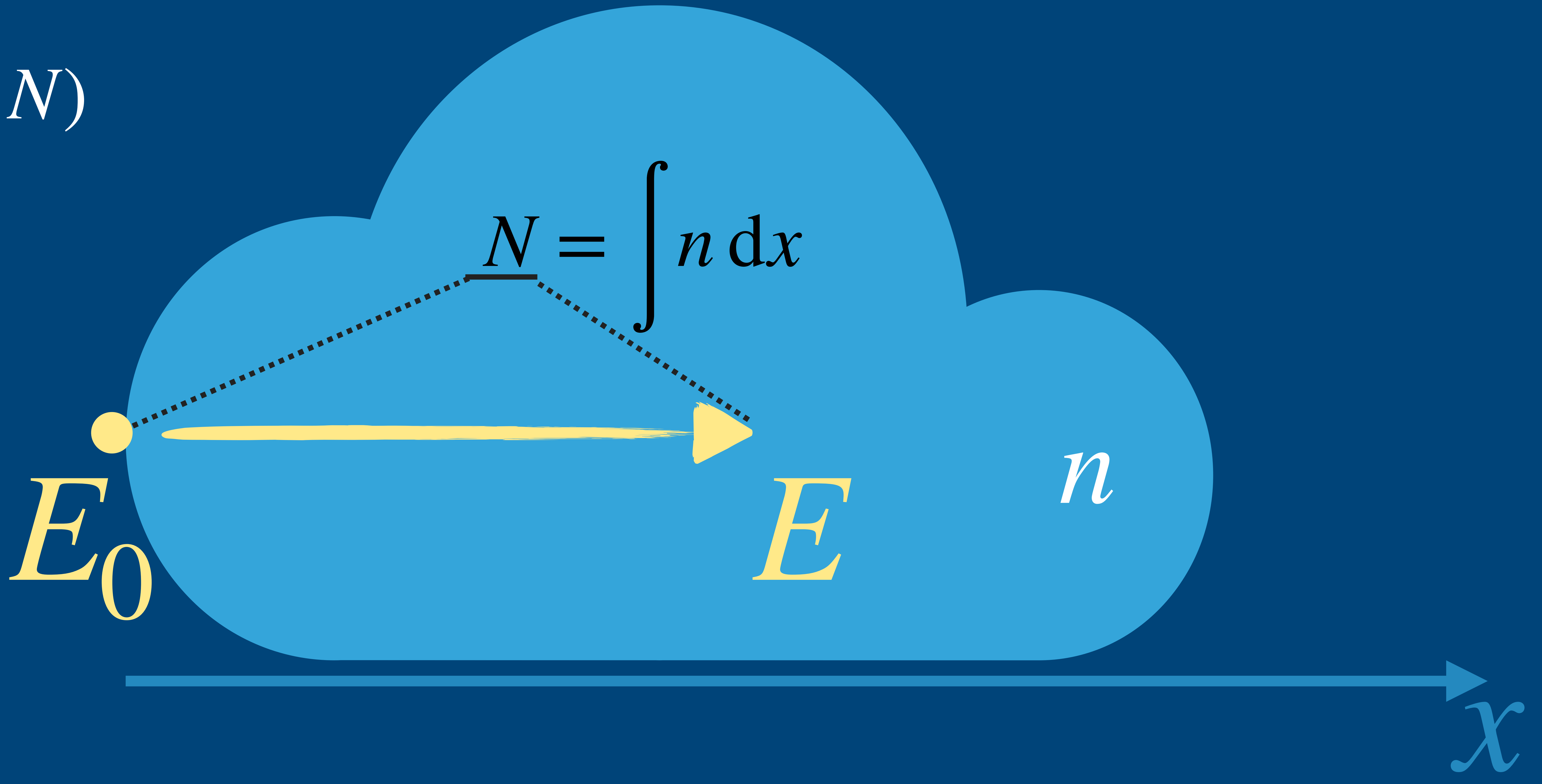
COSMIC-RAY INTERACTION WITH THE INTERSTELLAR MEDIUM

Energy loss function

$$L(E) = -\frac{1}{n}\frac{\mathrm{d}E}{\mathrm{d}x} = -\frac{1}{n\beta c}\frac{\mathrm{d}E}{\mathrm{d}t}$$

COSMIC-RAY PROPAGATION INSIDE A MOLECULAR CLOUD

$$j(E_0, N=0) = j^{\rm IS}(E_0) \longrightarrow j(E,N)$$



Continuous Slowing-Down Approximation

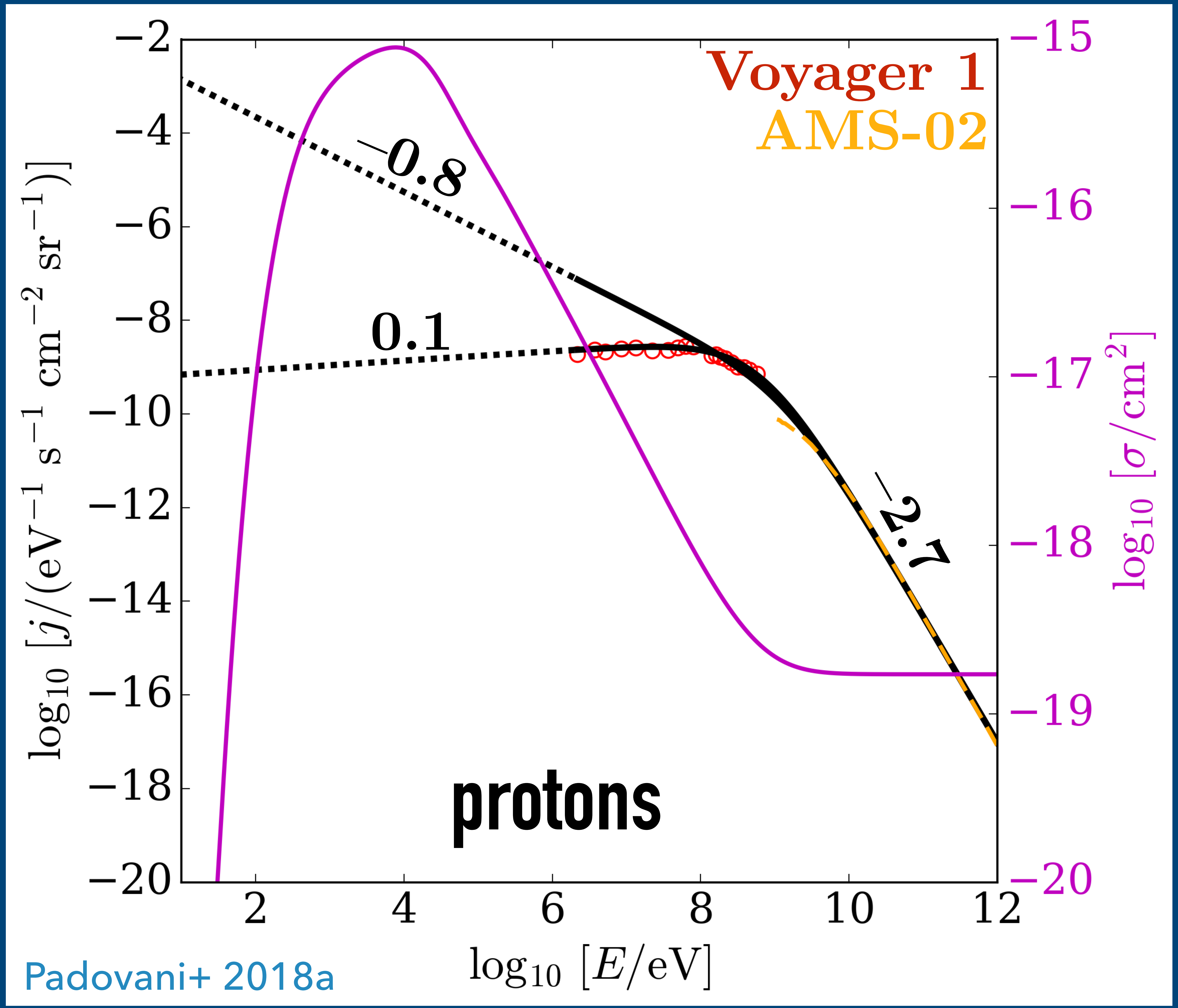
1. straight-line propagation;
2. ΔE≪E.

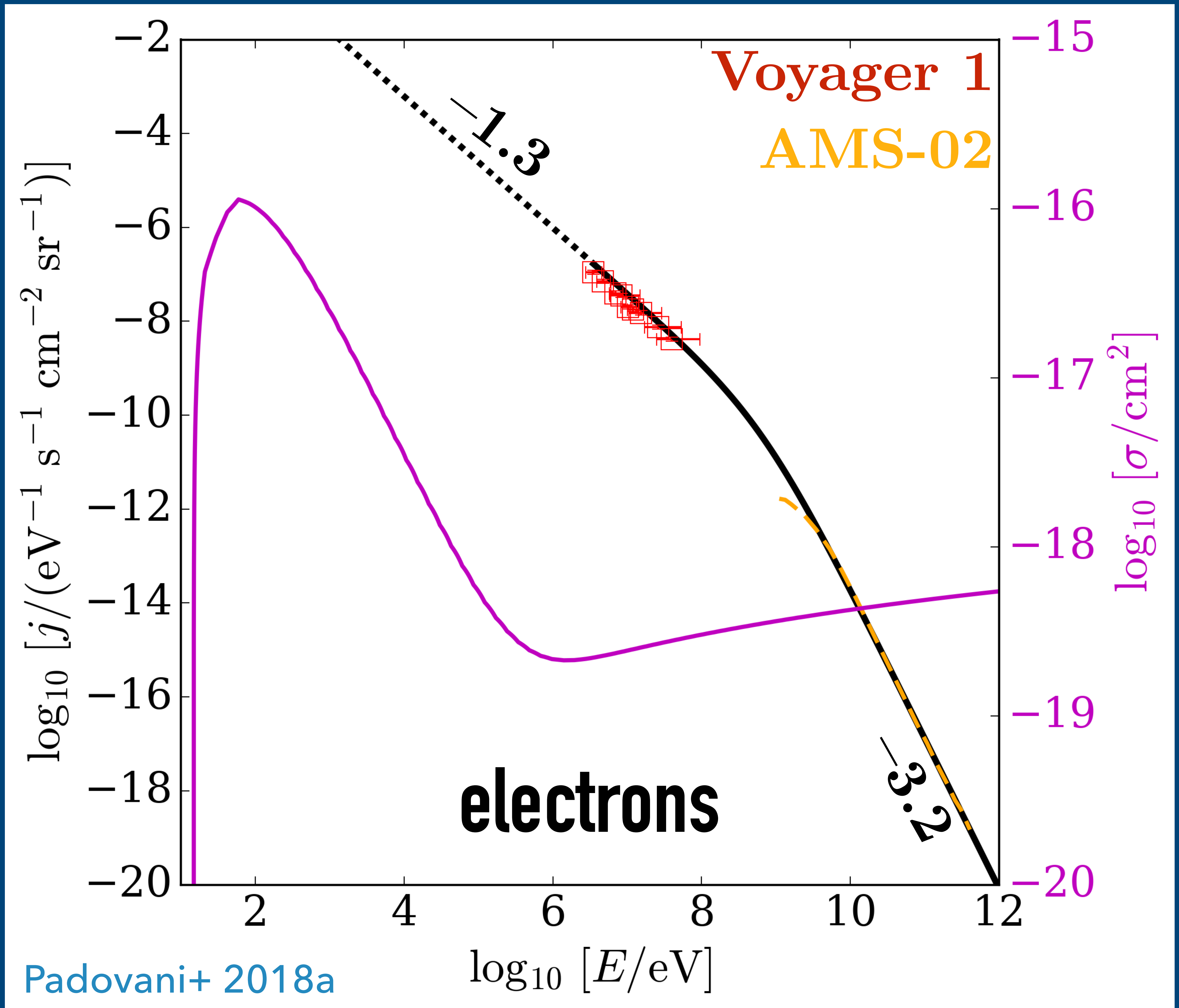
$$L(E) = -\frac{1}{n}\frac{\mathrm{d}E}{\mathrm{d}x} = -\frac{\mathrm{d}E}{\mathrm{d}N}$$

$$N = \int_E^{E_0} \frac{\mathrm{d}E}{L(E)} \qquad \frac{\mathrm{d}E}{L(E)} = \frac{\mathrm{d}E_0}{L(E_0)} \qquad j(E,N)\,\mathrm{d}E = j^{\rm IS}(E_0)\,\mathrm{d}E_0$$

$$j(E,N) = j^{\rm IS}(E_0)\frac{\mathrm{d}E}{\mathrm{d}E_0} = j^{\rm IS}(E_0)\frac{L(E_0)}{L(E)} \longrightarrow \zeta(N) \propto \int j(E,N)\sigma(E)\,\mathrm{d}E$$

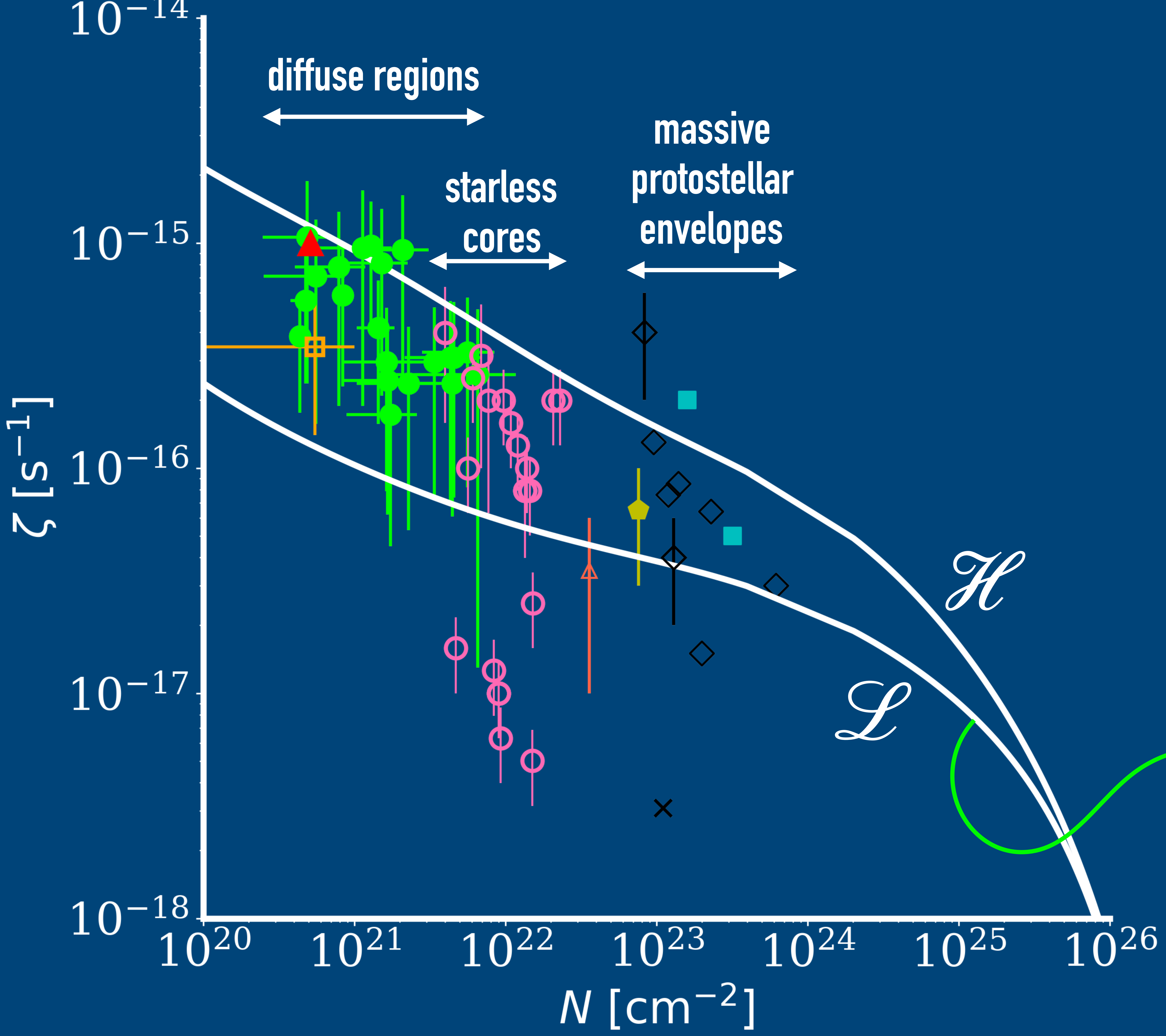
ASSUMPTIONS ON INTERSTELLAR COSMIC-RAY SPECTRA

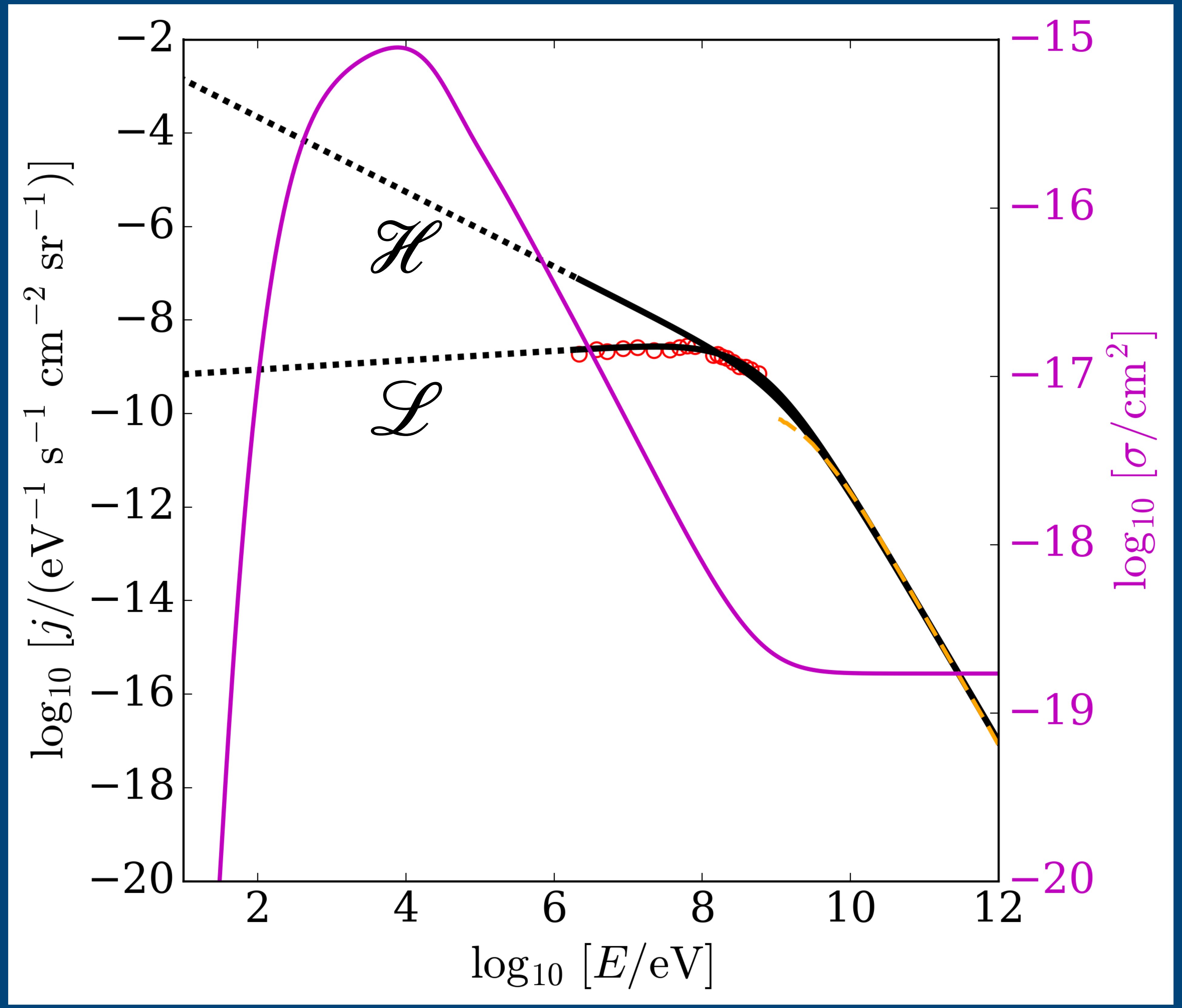




$$\zeta(N) \propto \int j(E,N)\sigma(E)\,\mathrm{d}E$$

COSMIC-RAY IONISATION IN CIRCUMSTELLAR DISCS

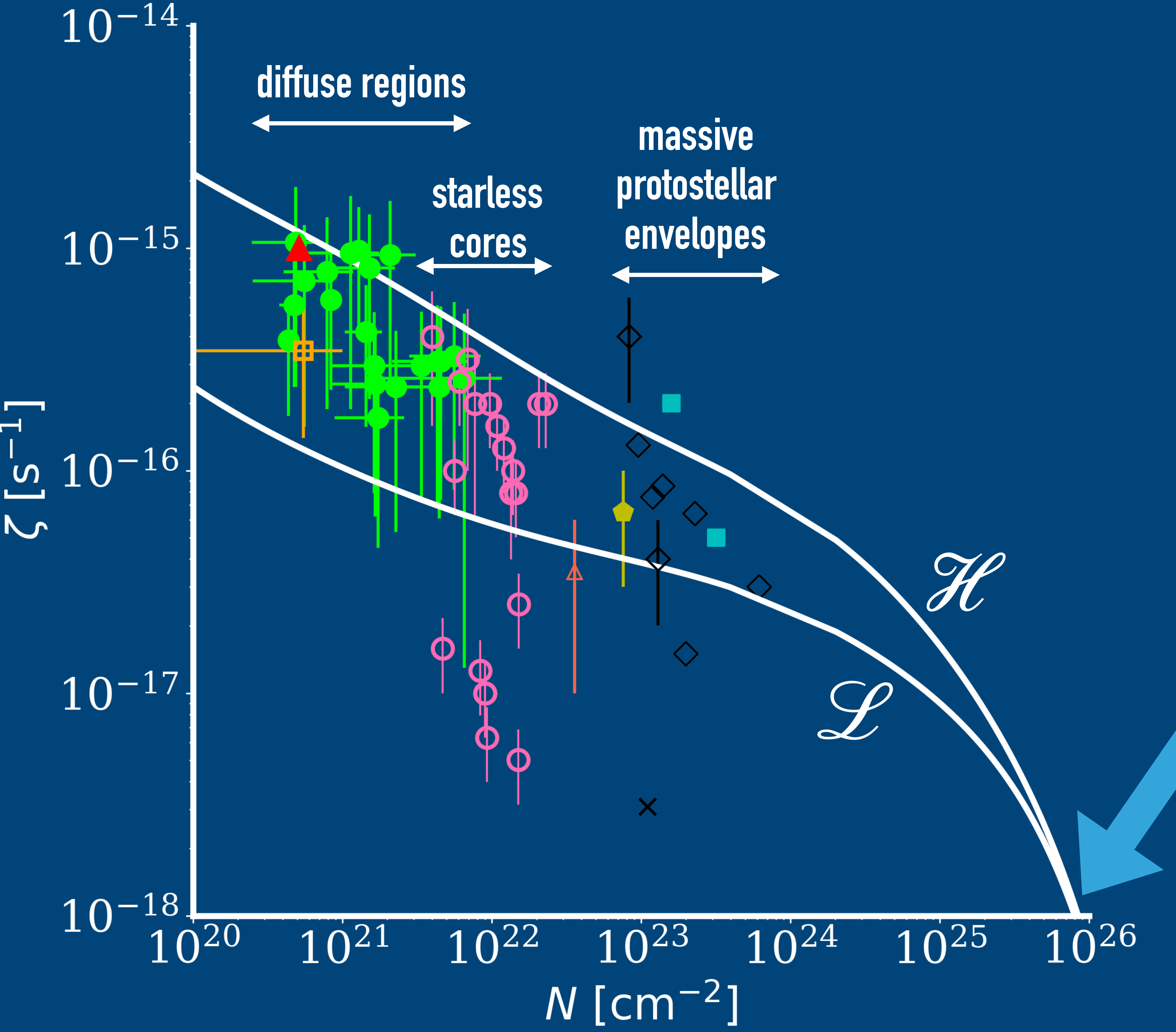




Voyager-like spectrum

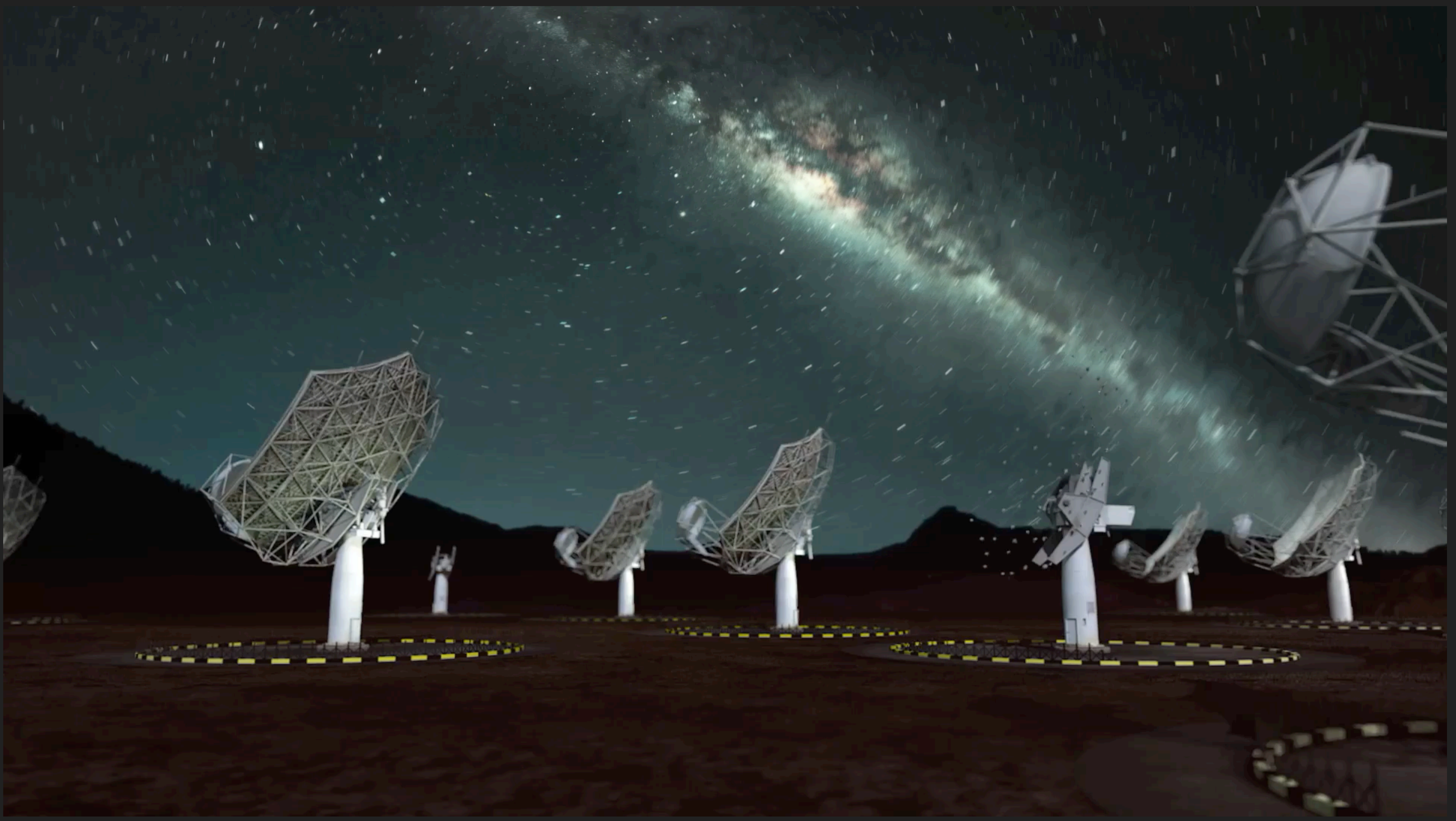
Padovani+ (2018a)

COSMIC-RAY IONISATION IN CIRCUMSTELLAR DISCS



At high column densities, the ionisation rate becomes so low that gas decouples from magnetic fields and the collapse can proceed.

Padovani+ (2018a)



SYNCHROTRON EMISSION IN MOLECULAR CLOUDS

(STARLESS CORES, PROTOSTELLAR JETS, AND HII REGIONS)

Padovani+ (2018c, 2019)

INFERRING THE STRENGTH AND THE MORPHOLOGY OF MAGNETIC FIELDS IN A STAR-FORMING REGION

- Zeeman splitting of hyperfine molecular transitions (e.g. Crutcher+ 1996);
- optical and near-infrared polarisation of starlight (e.g. Alves+ 2008,2011);
- polarisation of sub-millimetre thermal dust emission (e.g. Girart+ 2009; Alves+ 2018);
- maser emission polarisation (e.g. Vlemmings+ 2011);
- Goldreich-Kylafis effect (Goldreich & Kylafis 1981);
- Faraday rotation (e.g. Wolleben & Reich 2004).

HOW TO INFER THE MAGNETIC FIELD STRENGTH IN A STAR-FORMING REGION

An additional method

via synchrotron radiation produced by relativistic electrons braked by the cloud's magnetic fields
(e.g. Brown & Marscher 1977)

technique so far quite disregarded because:
(i) poor knowledge of the IS flux of CR electrons;
(ii) limited sensitivity of current radiotelescopes.

Voyager spacecrafts + SKA = the turning point

… when past meets future!

SYNCHROTRON EMISSION IN MOLECULAR CLOUDS

$$\epsilon_\nu \rightarrow I_\nu \rightarrow S_\nu$$

specific emissivity

specific intensity (brightness)

flux density

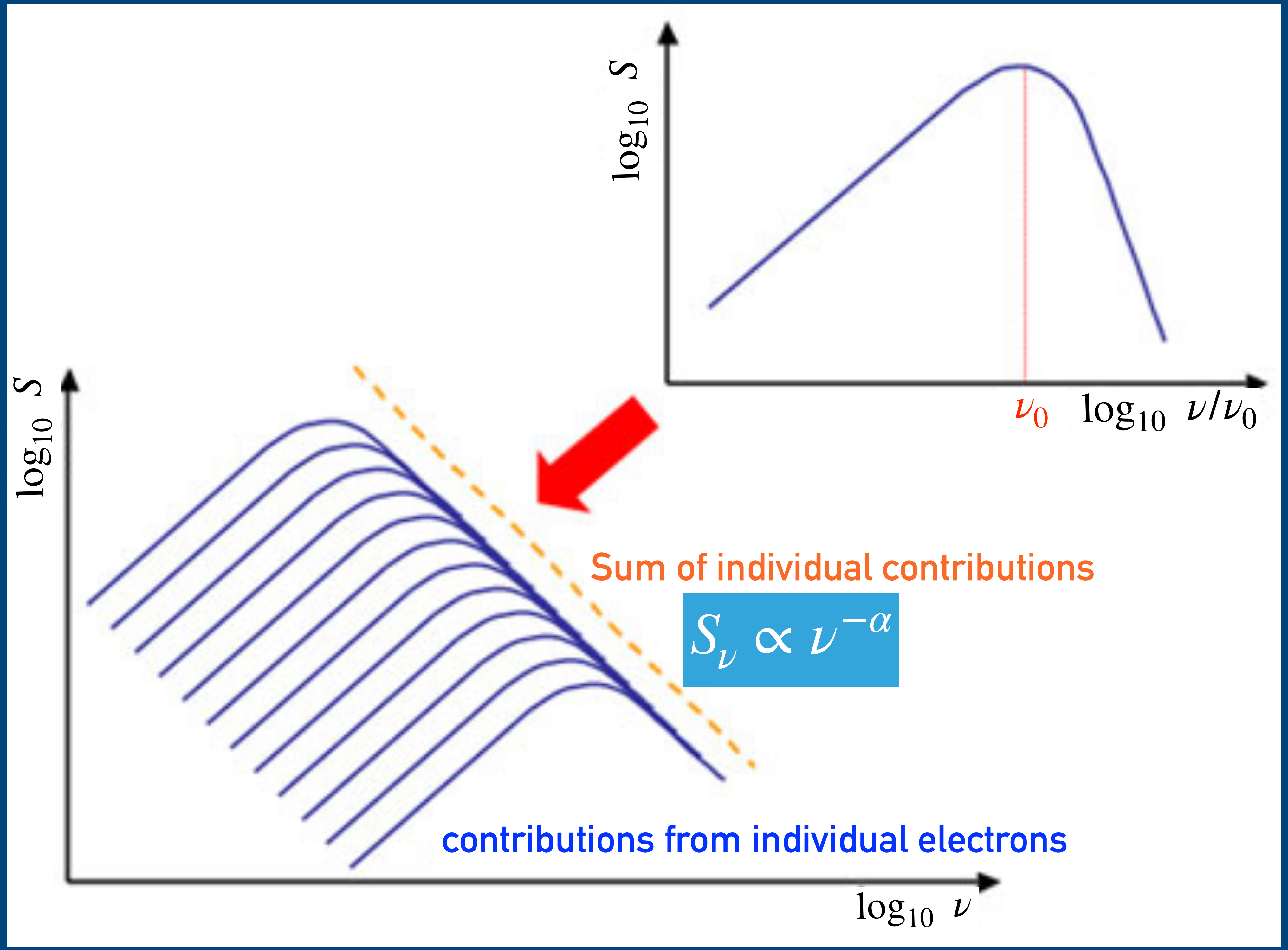
$$S_\nu = \frac{\pi}{4 \ln 2} I_\nu \theta_b^2$$

$$I_\nu = \int \epsilon_\nu \, \mathrm{d}\ell$$

$$\epsilon_\nu(r) = \int_{m_e c^2}^{\infty} \frac{j_e(E,r)}{v_e(E)} P_\nu^{\mathrm{em}}(E,r)\,\mathrm{d}E$$

$$P_\nu^{\mathrm{em}}(E,r) = \frac{\sqrt{3}e^3}{m_e c^2} B_\perp(r) F\left[\frac{\nu}{\nu_c(B_\perp, E)}\right]$$

Total power per unit frequency



see e.g. Longair (2011), Padovani+ (2018c)

SYNCHROTRON EMISSION IN MOLECULAR CLOUDS

$$\epsilon_\nu \rightarrow I_\nu \rightarrow S_\nu$$

specific emissivity

specific intensity (brightness)

flux density

$$S_\nu = \frac{\pi}{4\ln 2} I_\nu \theta_b^2 \qquad I_\nu = \int \epsilon_\nu \, \mathrm{d}\ell$$

$$\epsilon_\nu(r) = \int_{m_e c^2}^{\infty} \frac{j_e(E,r)}{v_e(E)} P_\nu^{\mathrm{em}}(E,r)\,\mathrm{d}E$$

cosmic-ray electron flux → **well-constrained thanks to Voyager-1 observations**

$$P_\nu^{\mathrm{em}}(E,r) = \frac{\sqrt{3}e^3}{m_e c^2} B_\perp(r) F\left[\frac{\nu}{\nu_c(B_\perp, E)}\right]$$

Total power per unit frequency

see e.g. Longair (2011), Padovani+ (2018c)

SYNCHROTRON EMISSION IN MOLECULAR CLOUD CORES: THE SKA VIEW

softened power-law density profile (Tafalla+ 2002)

$$n(r) = \frac{n_0}{1 + (r/r_0)^\alpha}$$

magnetic field strength profile (Crutcher 2012)

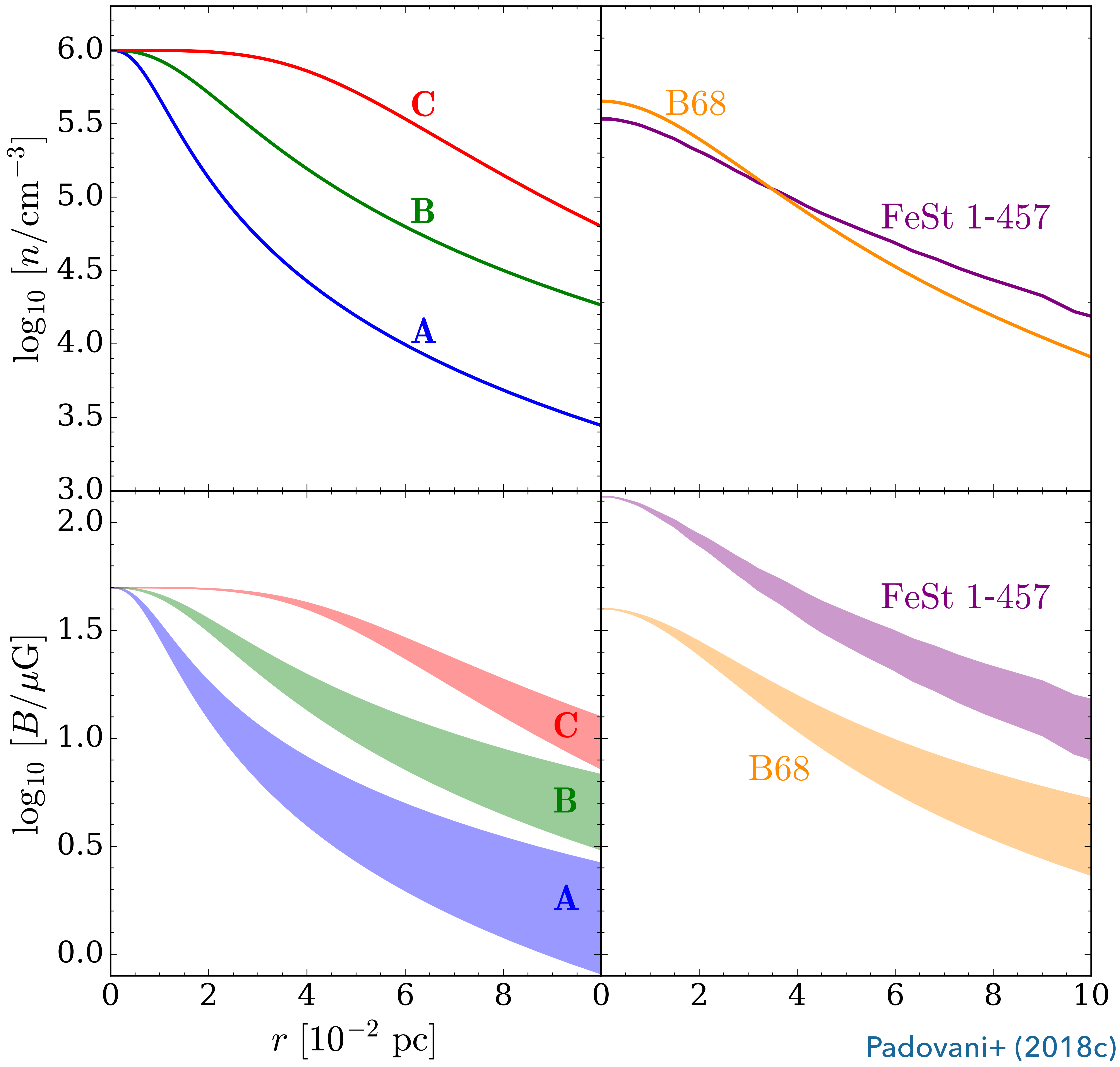
$$B(n) = B_0 \left(\frac{n}{n_0}\right)^\kappa$$

FeSt 1-457, a.k.a. core109 [Pipe Nebula]

- density (Juárez+ 2017)
- B≈132 μG (Kandori+ 2017)

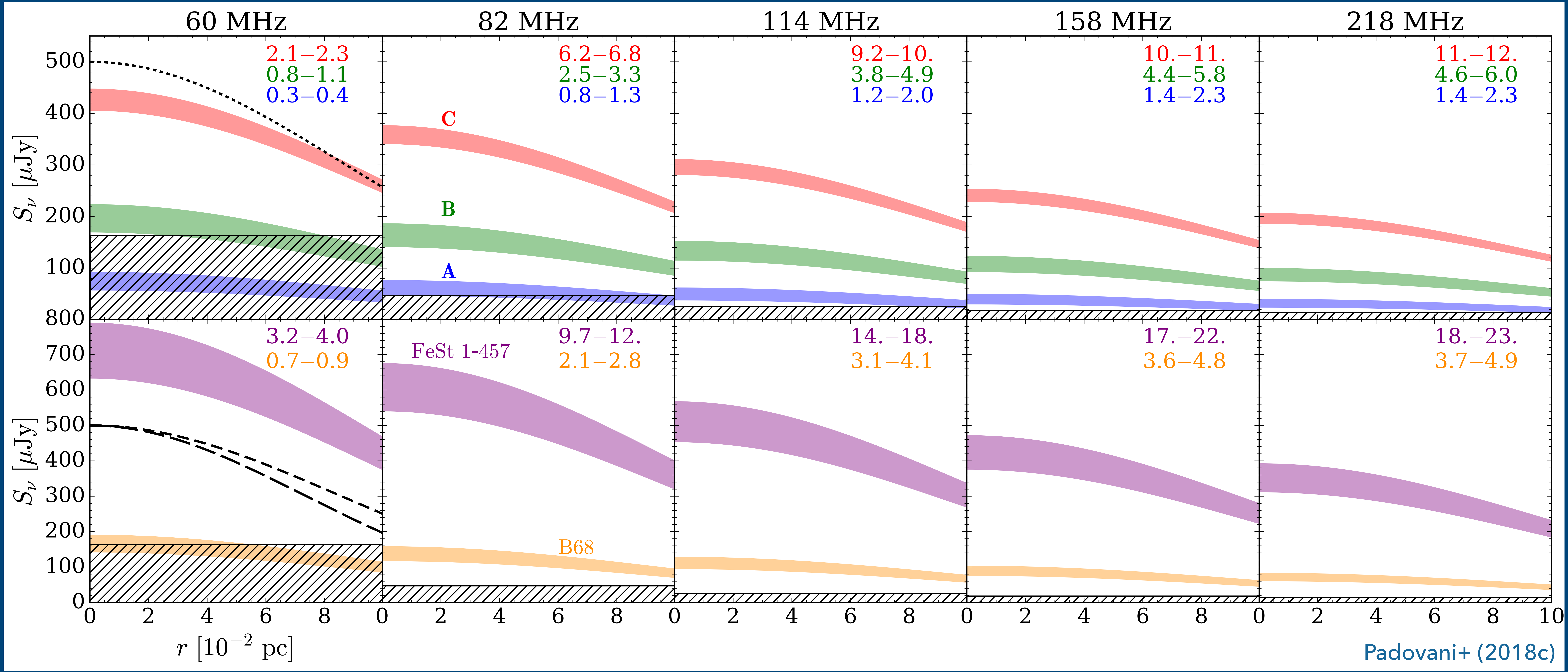
Barnard 68 (B68)

- density (Galli+ 2002)
- B_{pos}≈20 μG (Kandori+ 2009)



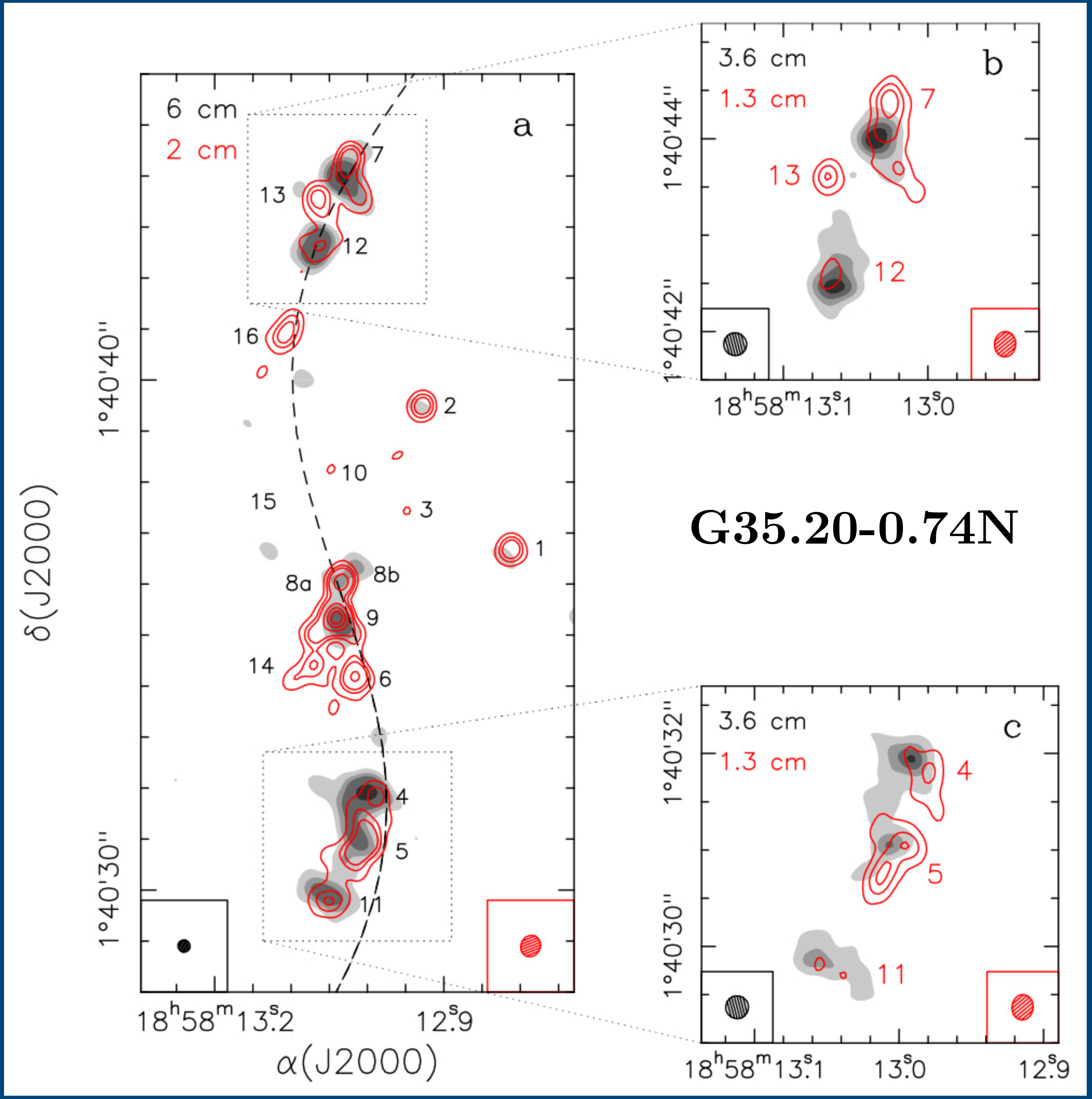
Padovani+ (2018c)

SYNCHROTRON EMISSION IN MOLECULAR CLOUD CORES: THE SKA VIEW



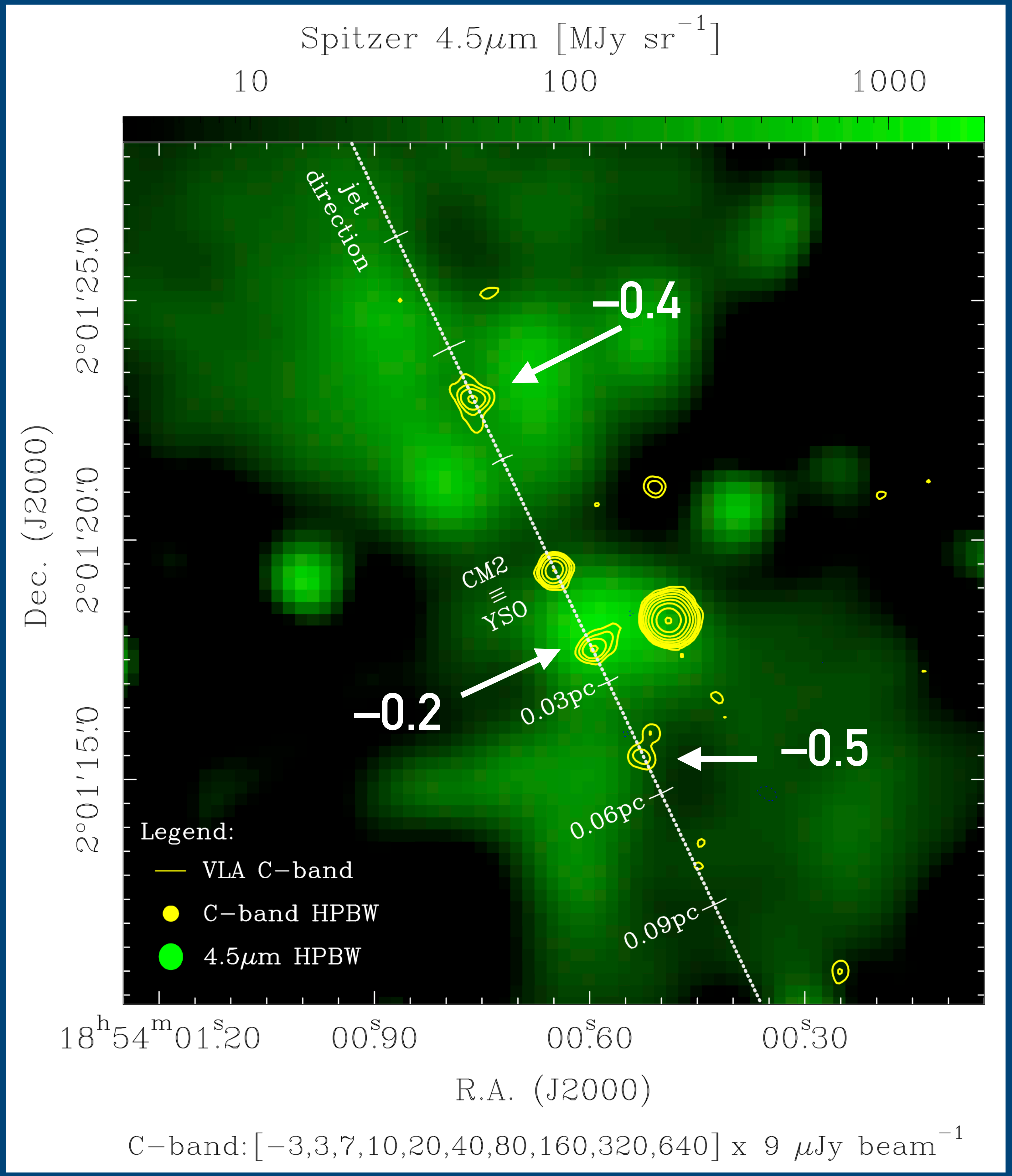
- molecular cloud cores with flattened density profile show higher flux density ($B \propto n^k$, k=0.55-0.65) ;
- S_ν is *not* set by the maximum value of B, but rather by the its integrated value along the line of sight;
- SKA will be able to detect synchrotron emission from starless cores (e.g. B68 and FeSt 1-457) in the range $\nu \in [60, 218]$ MHz with S/N=2–23 in one hour of integration.

SYNCHROTRON EMISSION IN PROTOSTELLAR JETS



Beltrán+ (2016)

G035.02+0.35

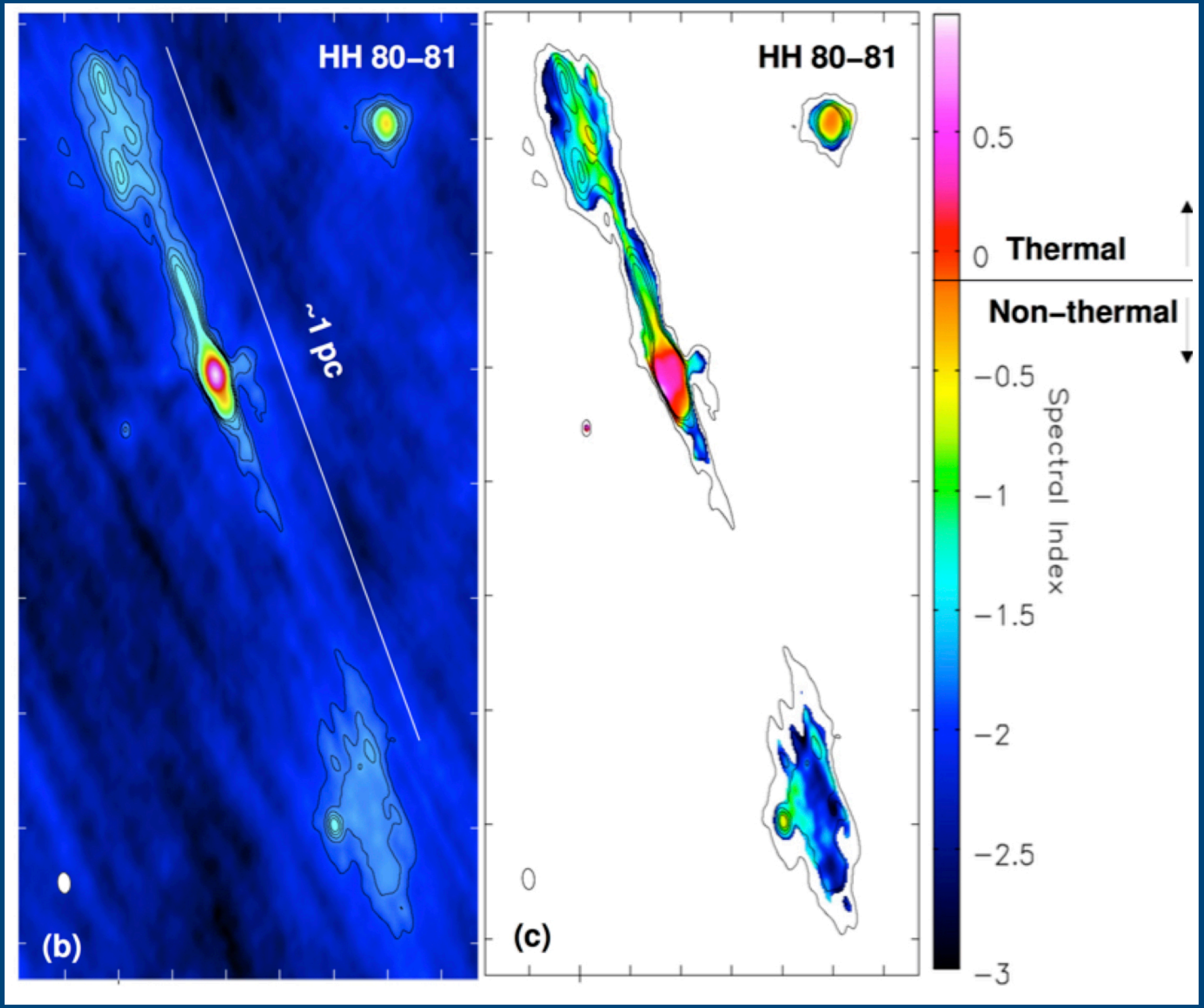


Sanna+ (2019)

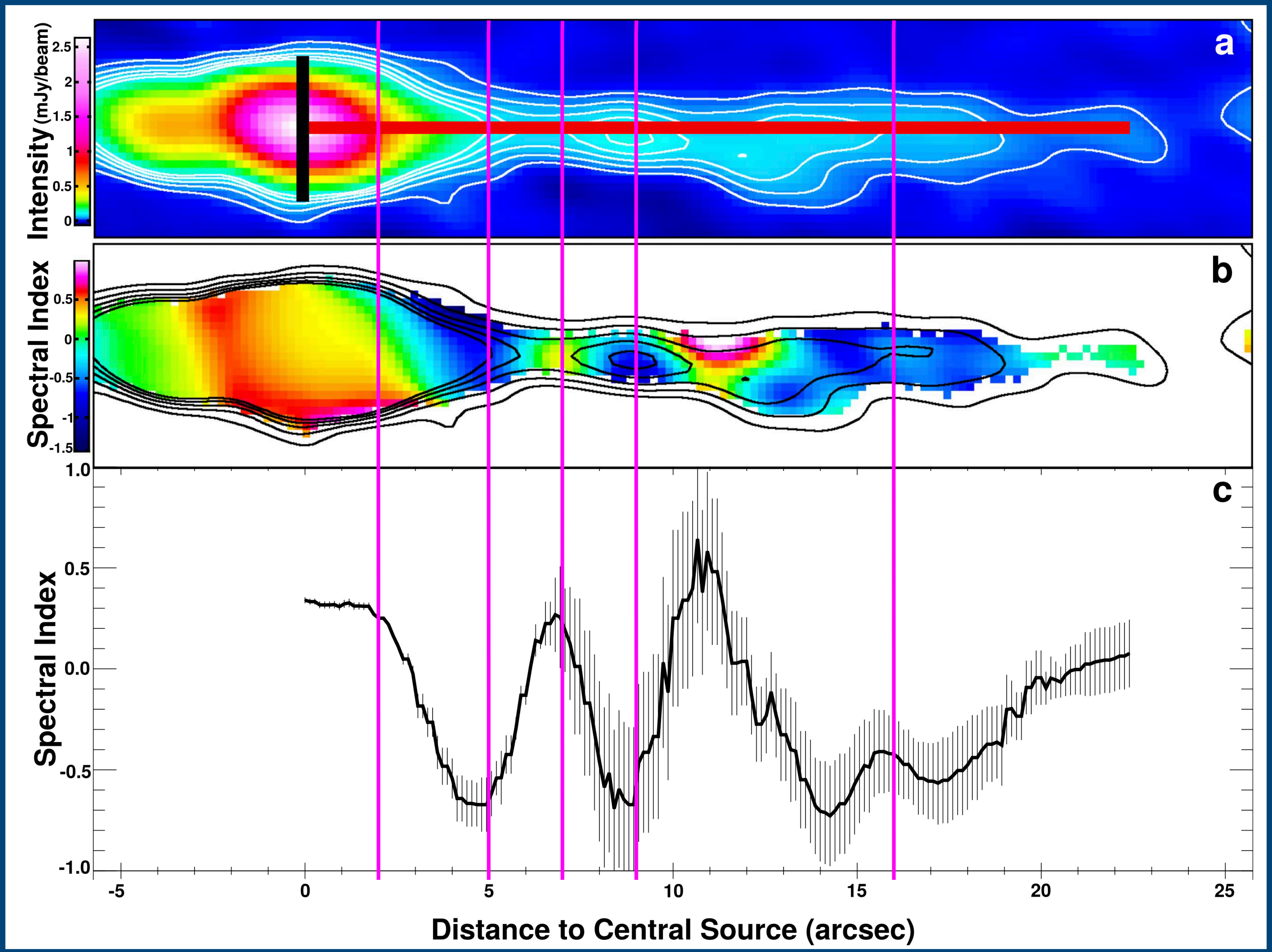
For high-mass protostellar jets see e.g.
Araudo+ (2007), Bosch-Ramon+ (2010), Munar-Adrover+ (2011)

For a recent review, see Anglada+ (2018)

SYNCHROTRON EMISSION IN PROTOSTELLAR JETS



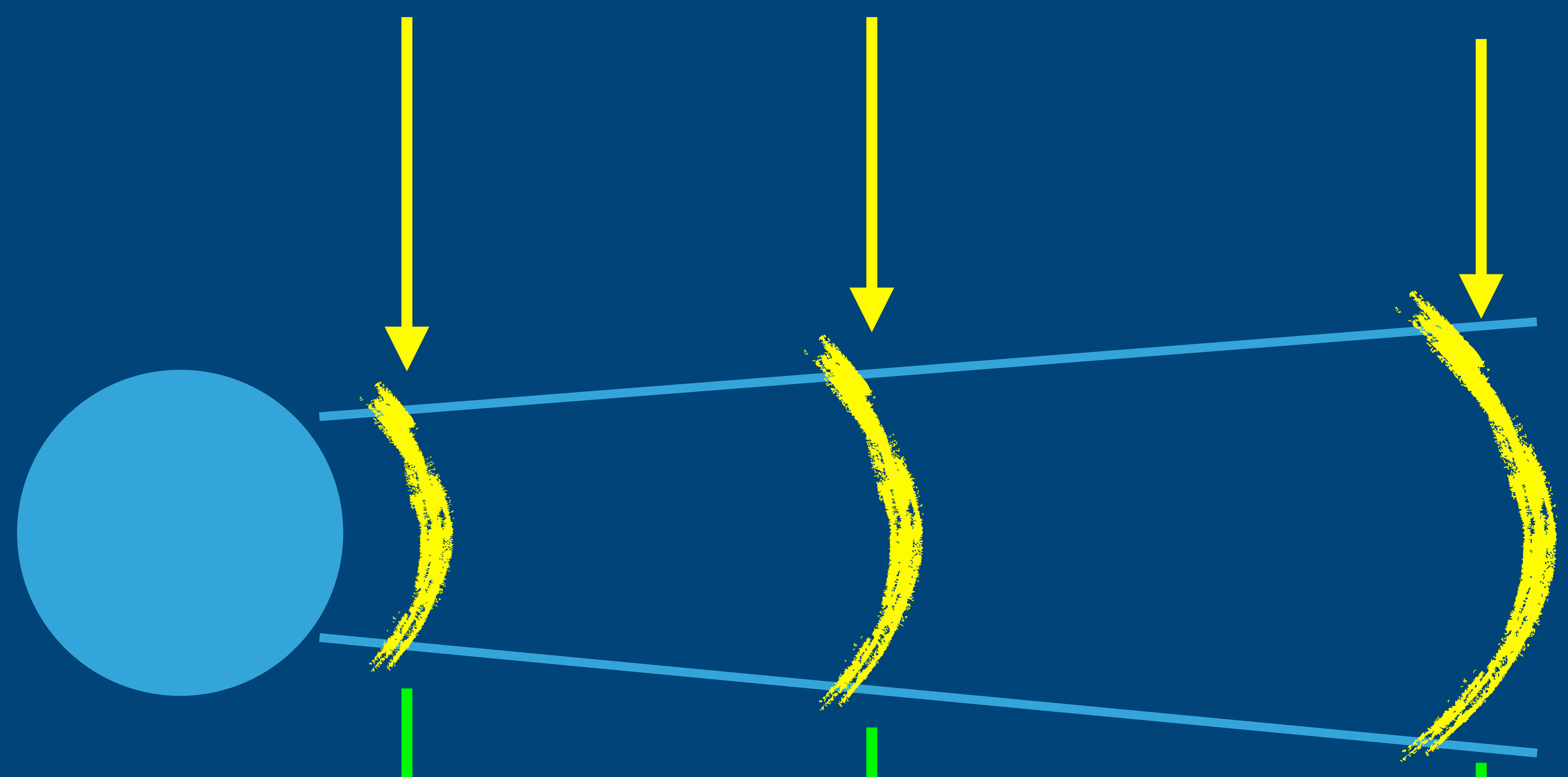
Carrasco-González+ (2013)



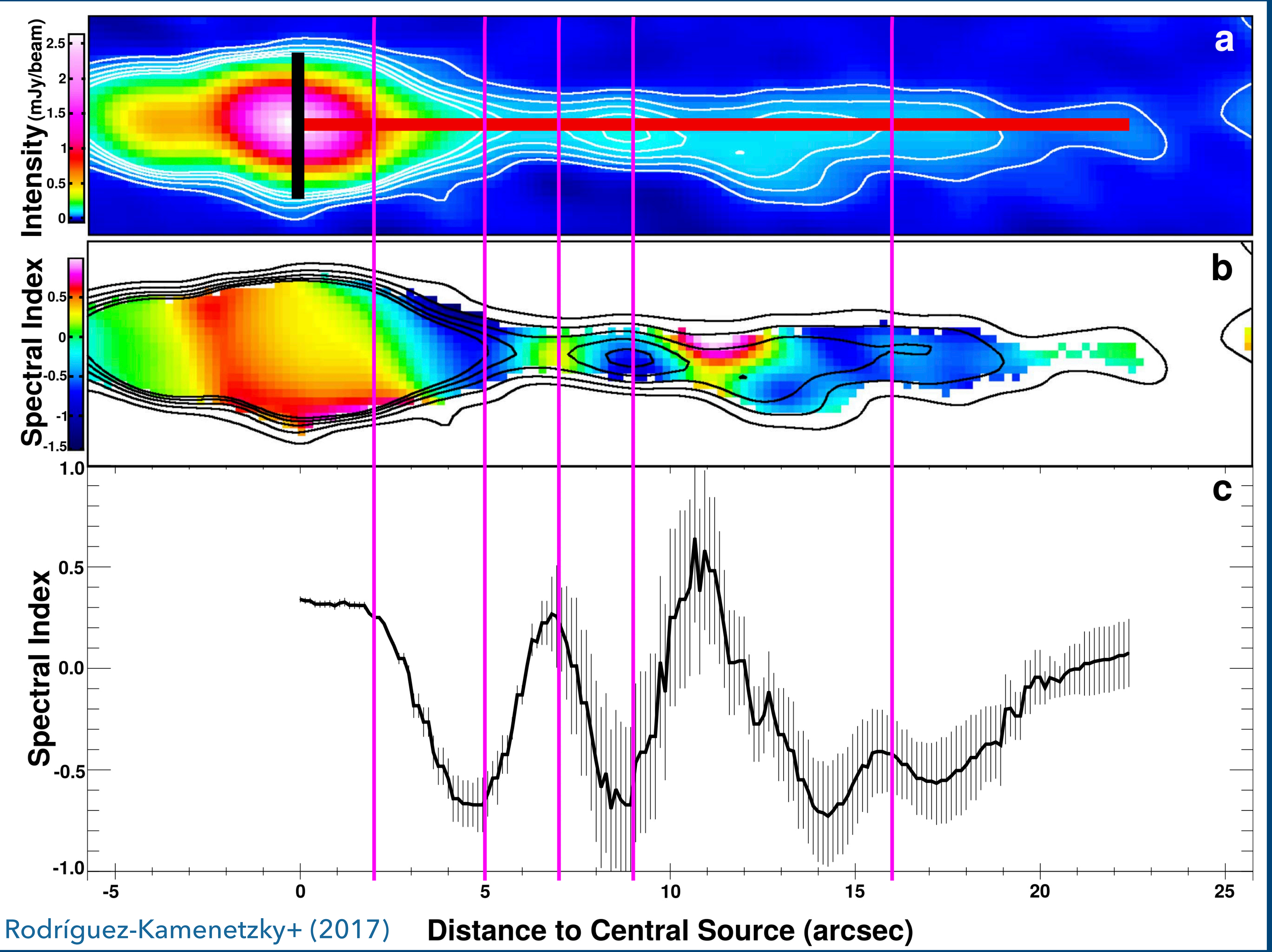
Rodríguez-Kamenetzky+ (2017)

but protostars are embedded in molecular clouds, where the interstellar flux of cosmic rays is strongly attenuated…

PROTOSTELLAR JETS AS PARTICLE ACCELERATORS



LOCALLY ACCELERATED ELECTRONS!

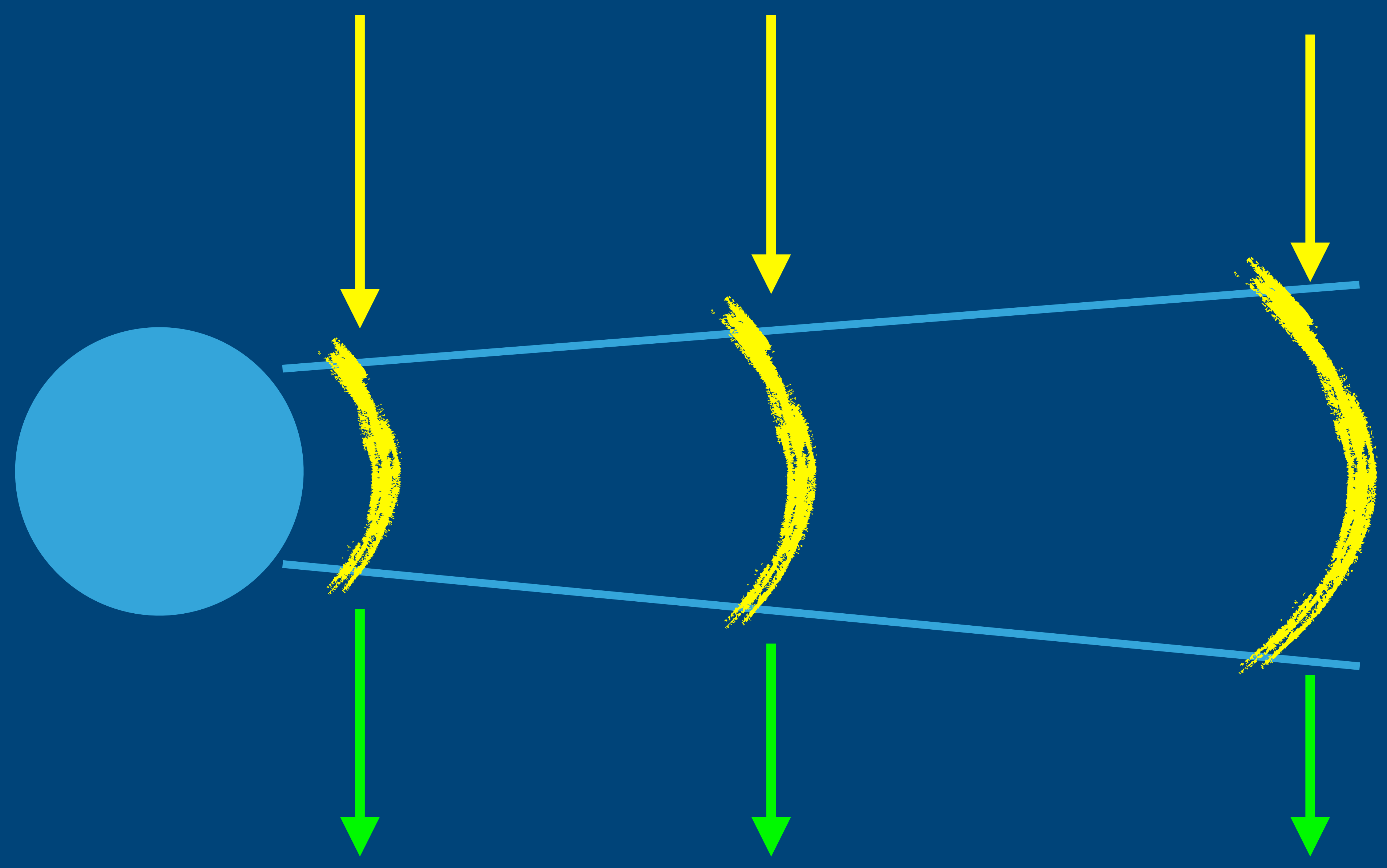


Rodríguez-Kamenetzky+ (2017)

Model described in Padovani+ (2015, 2016)

PROTOSTELLAR JETS AS PARTICLE ACCELERATORS

local acceleration of relativistic electrons

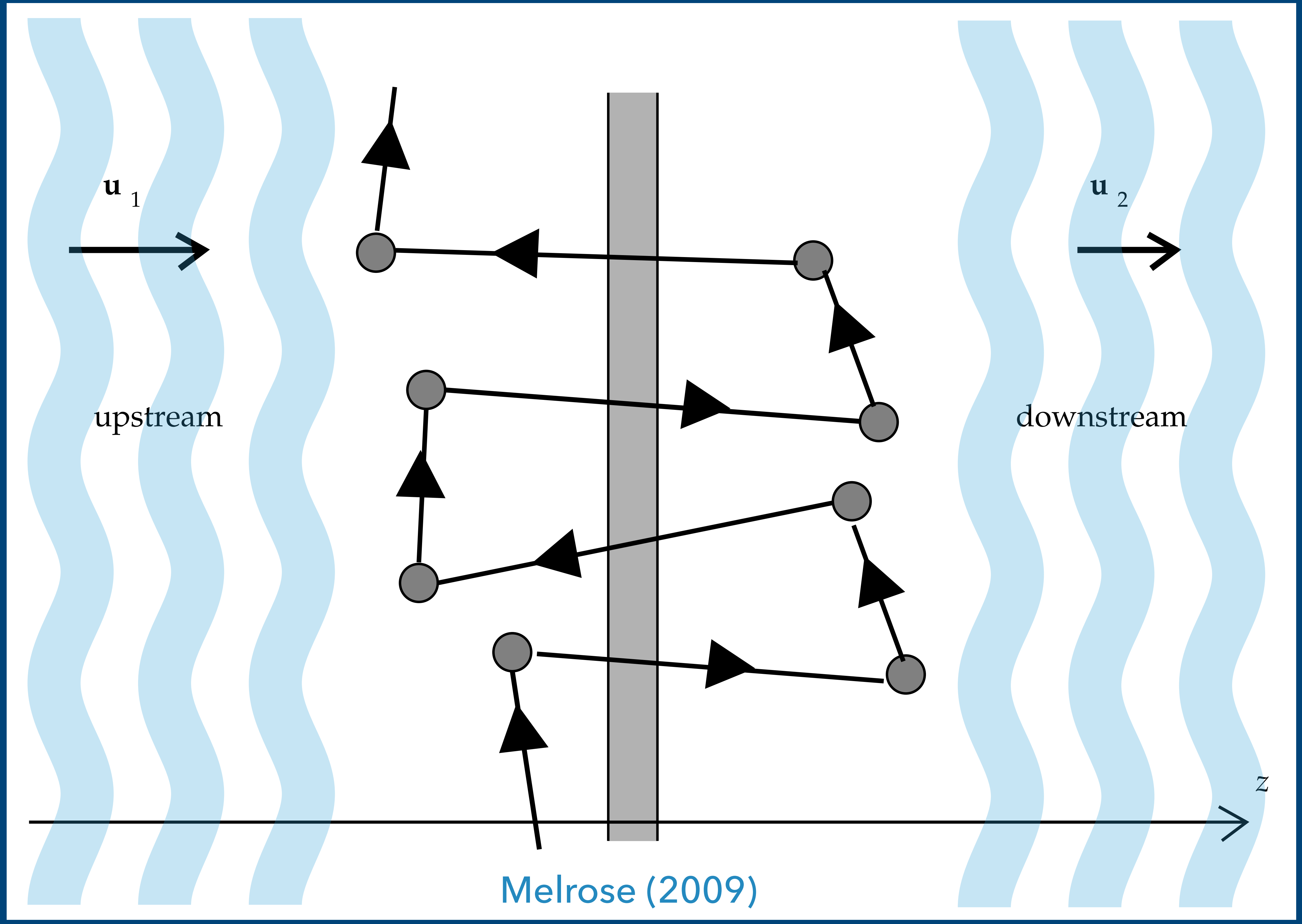


negative spectral index of the flux density $S_\nu \propto \nu^\alpha$

LOCALLY ACCELERATED ELECTRONS!

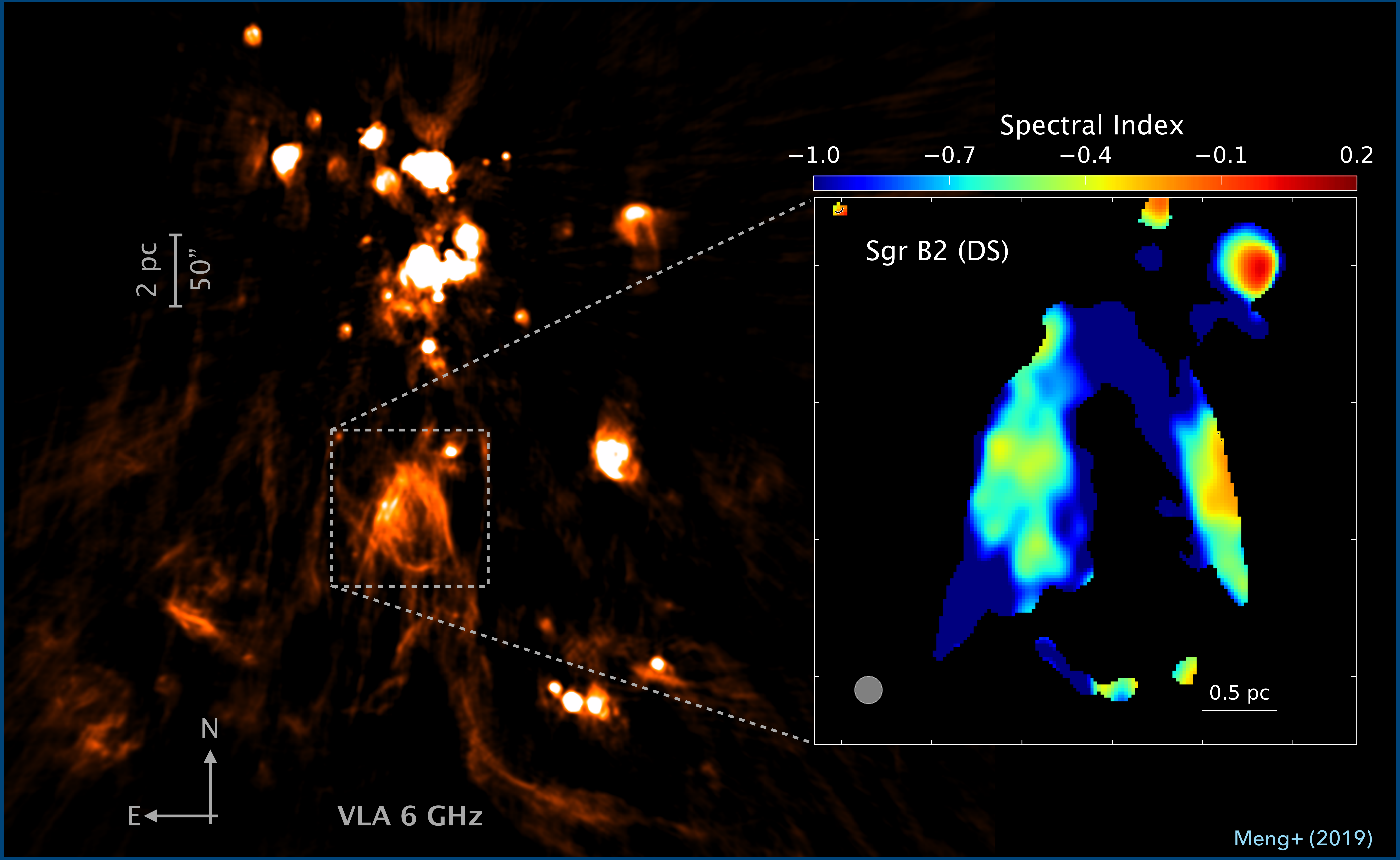
First-order Fermi acceleration

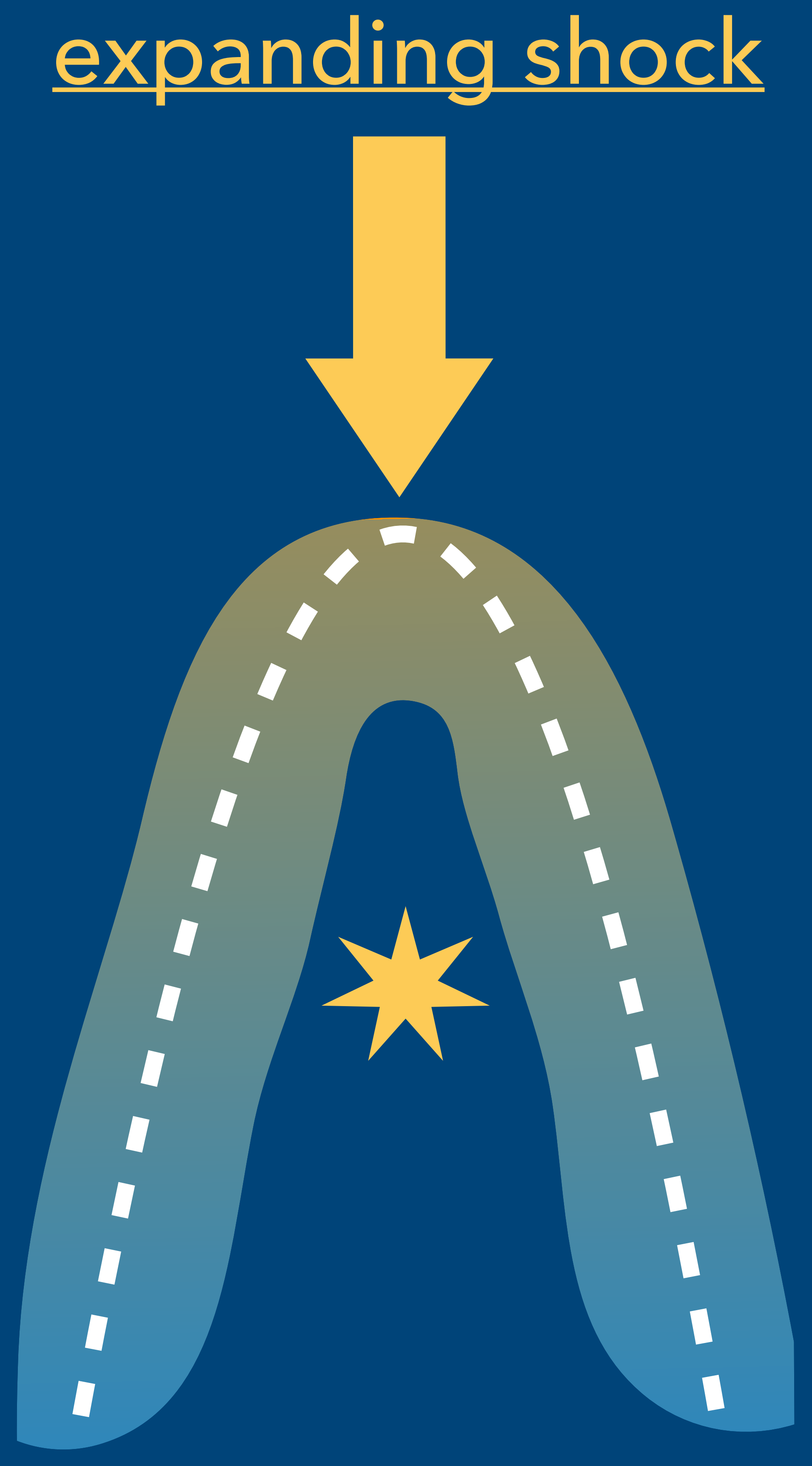
(or Diffusive Shock Acceleration)



Model described in Padovani+ (2015, 2016)

COSMIC-RAY ACCELERATION SITES

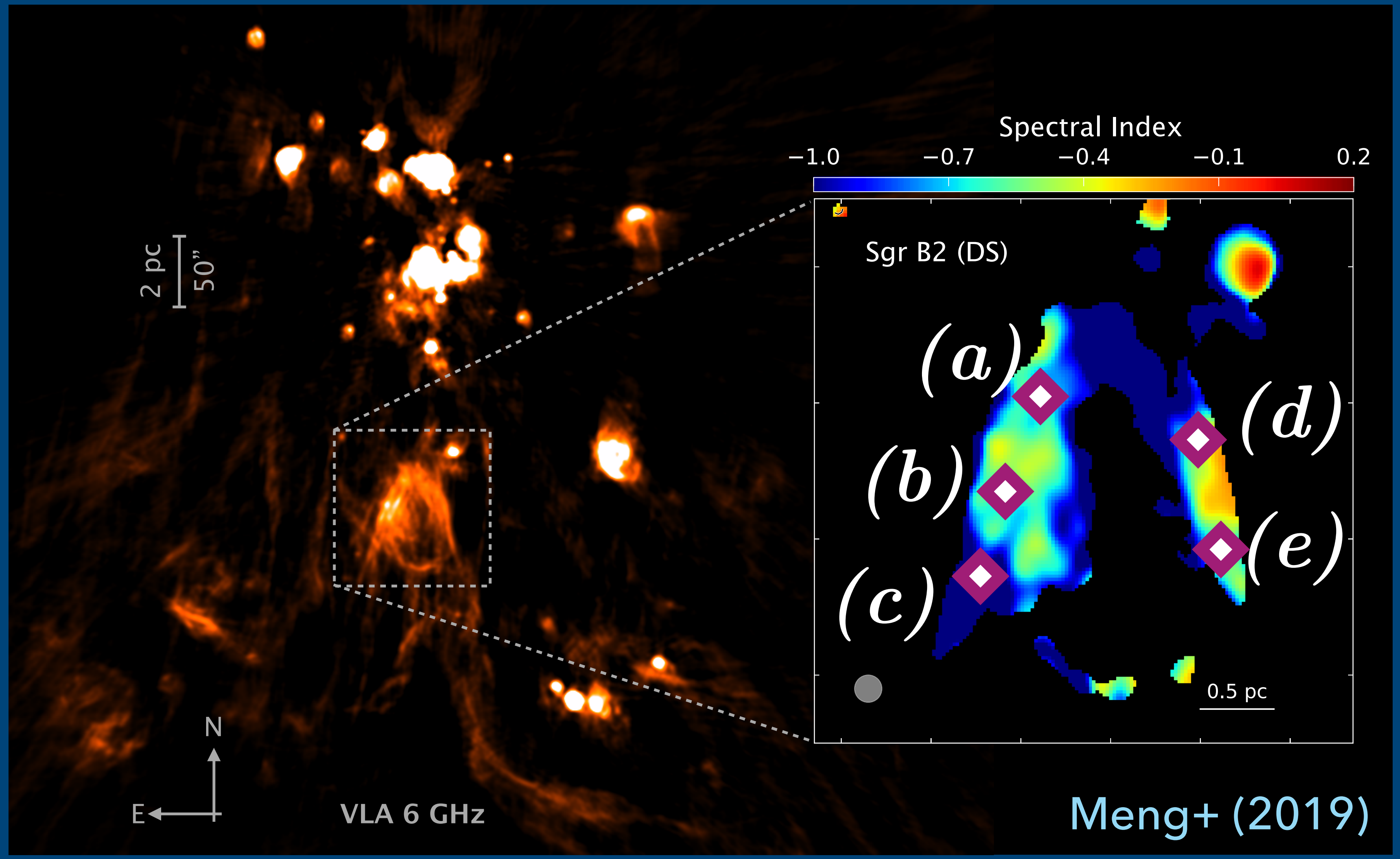


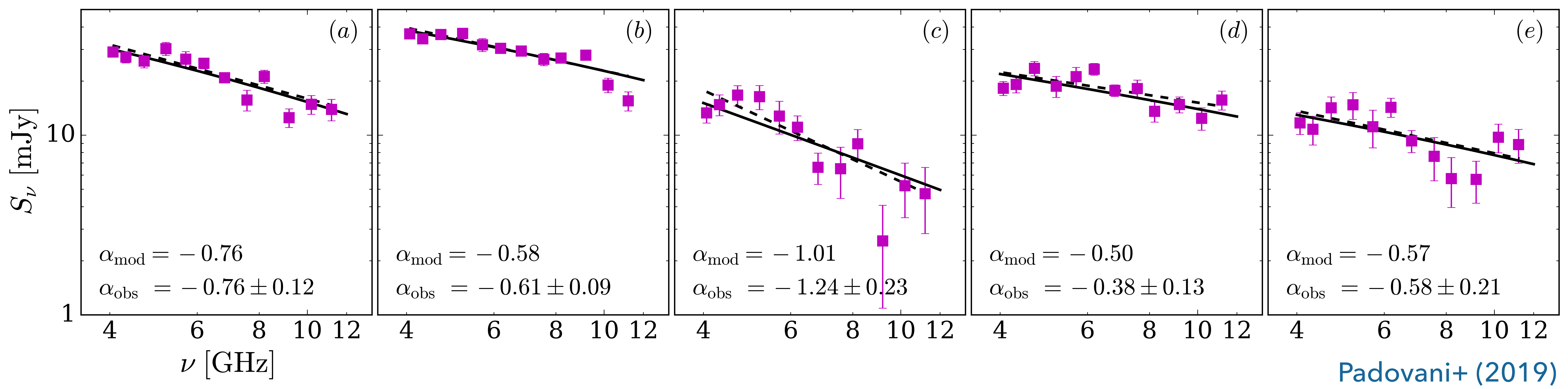


COSMIC-RAY ACCELERATION SITES

fit to observations
Meng+ (2019)

model
Padovani+ (2019)

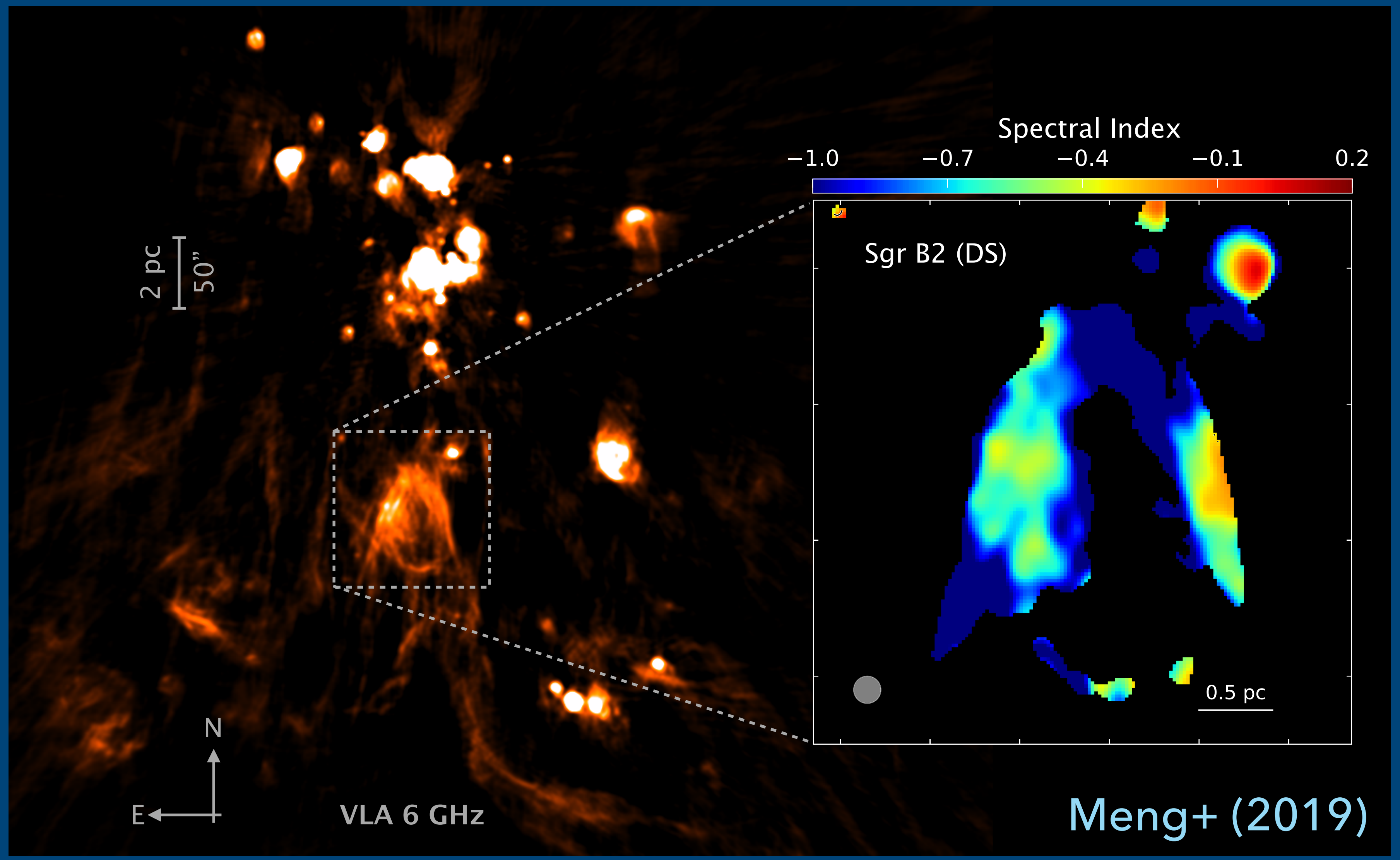


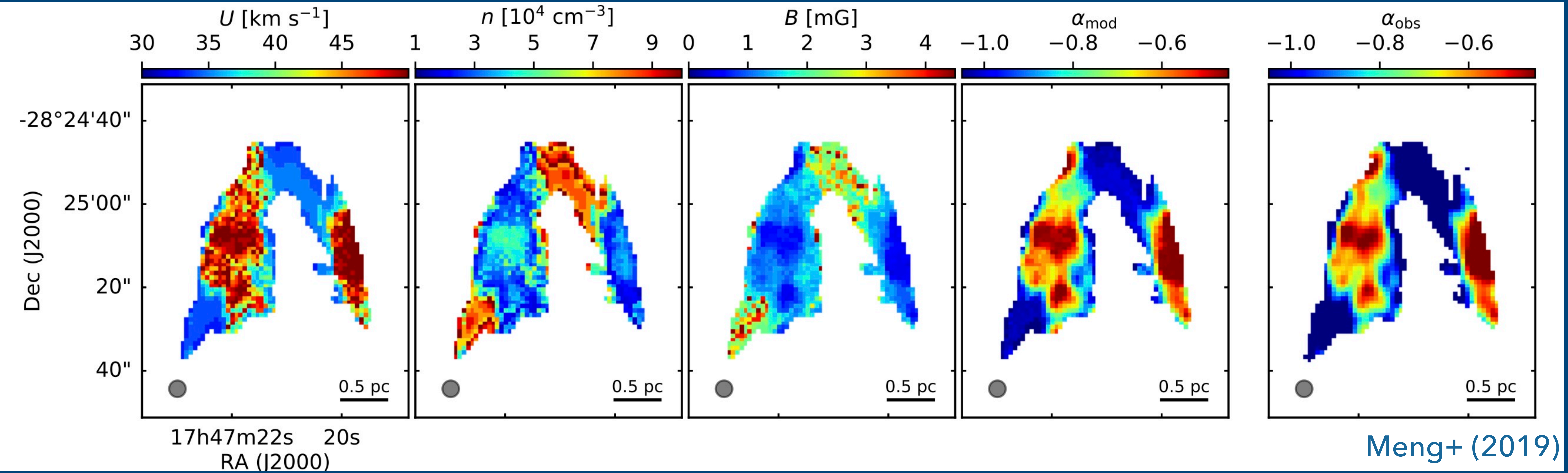


COSMIC-RAY ACCELERATION SITES

fit to observations
Meng+ (2019)

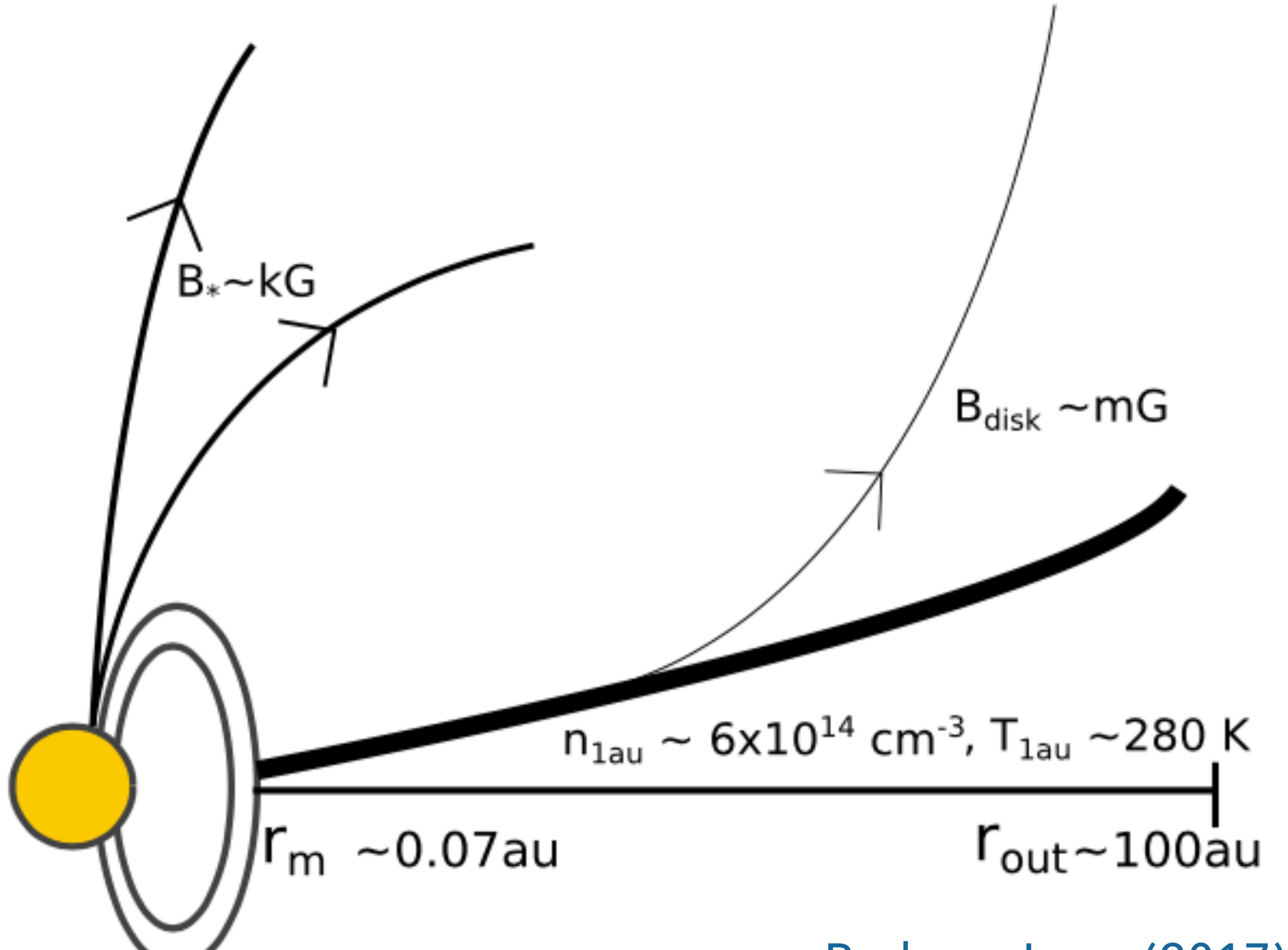
model
Padovani+ (2019)





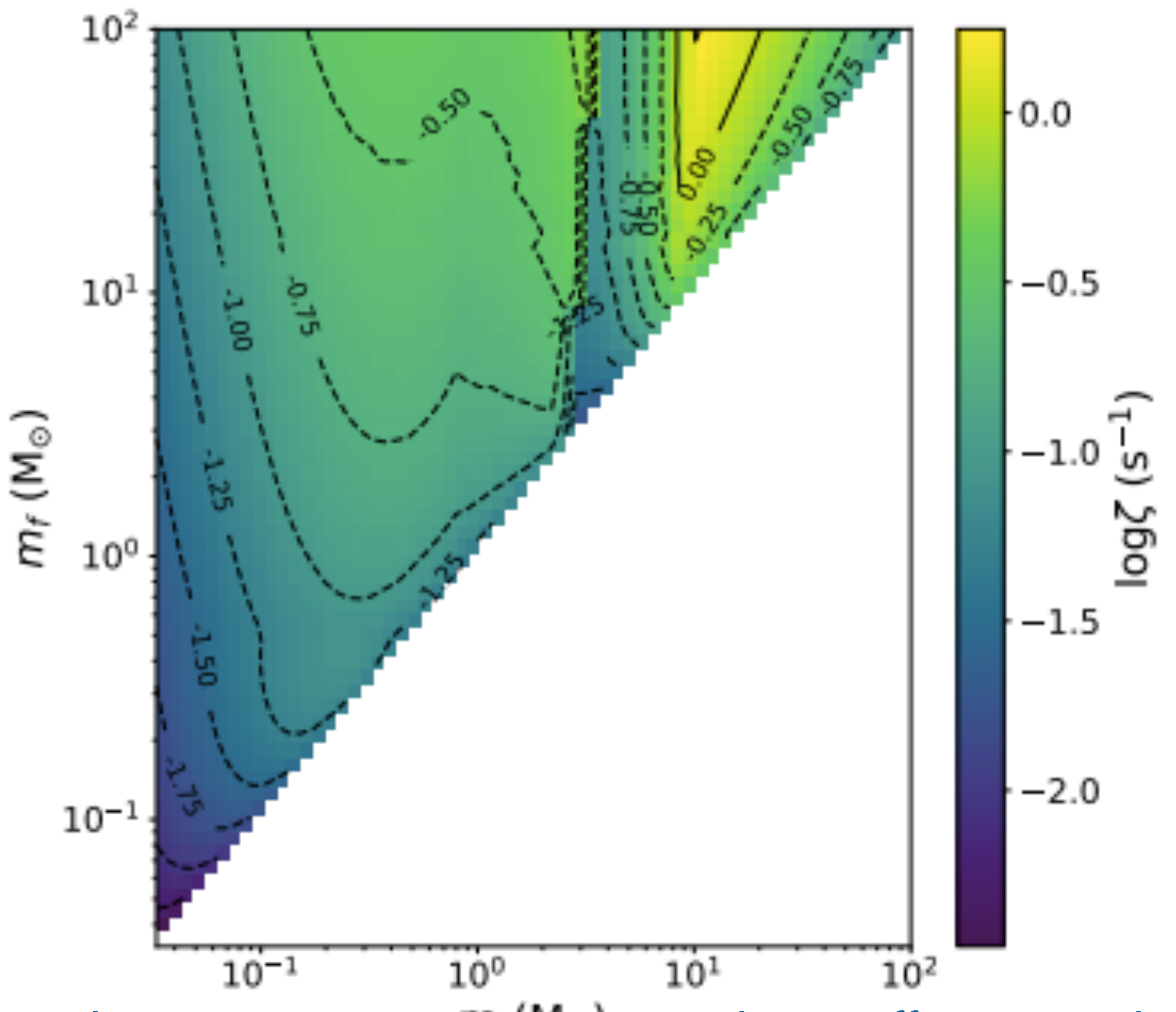
STELLAR PARTICLES : A NEW RESEARCH FIELD

Effect of stellar CRs from TT stars on PPDs



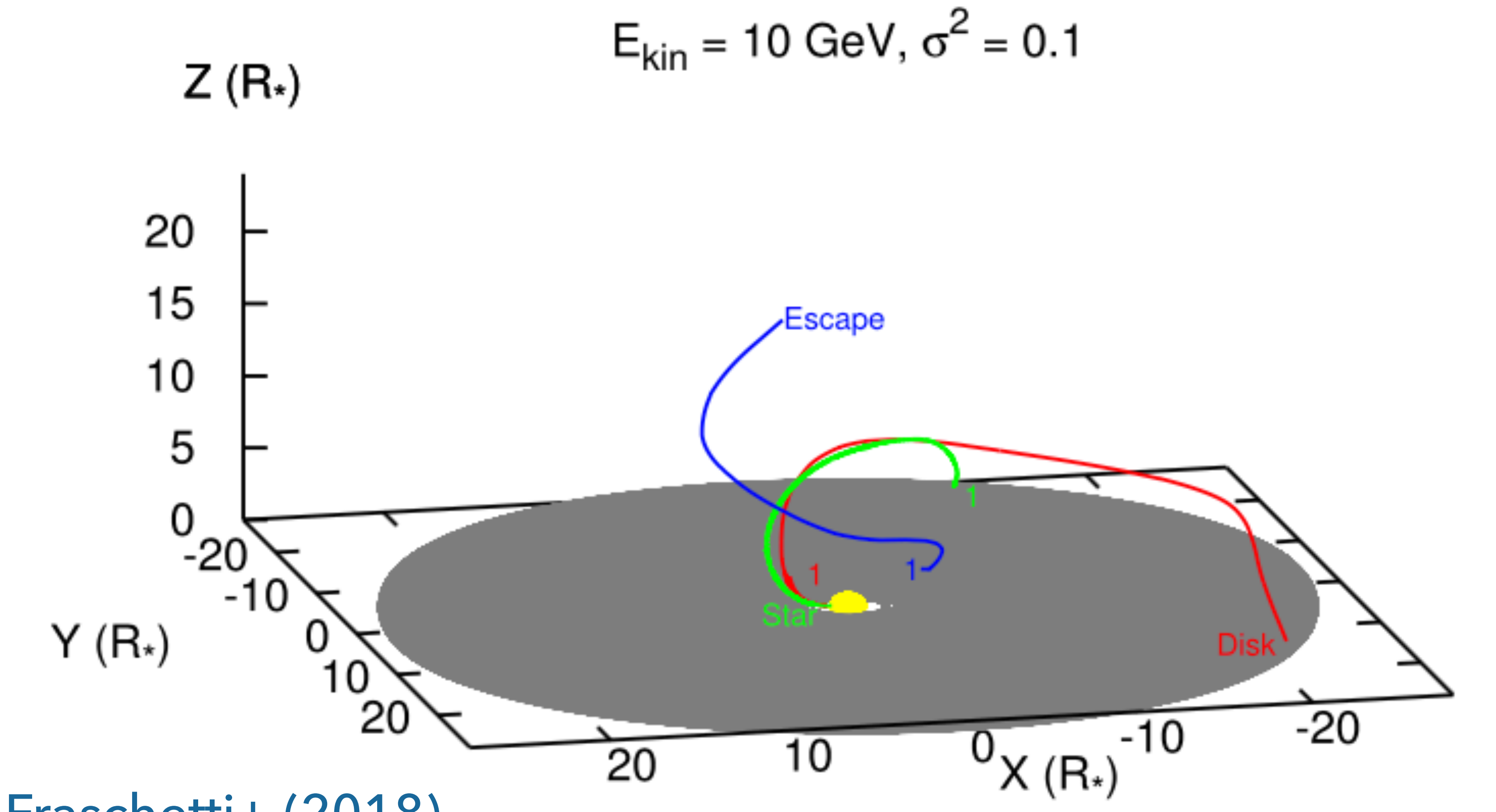
Rodgers-Lee+ (2017)

Impact of local CRs in protoclusters



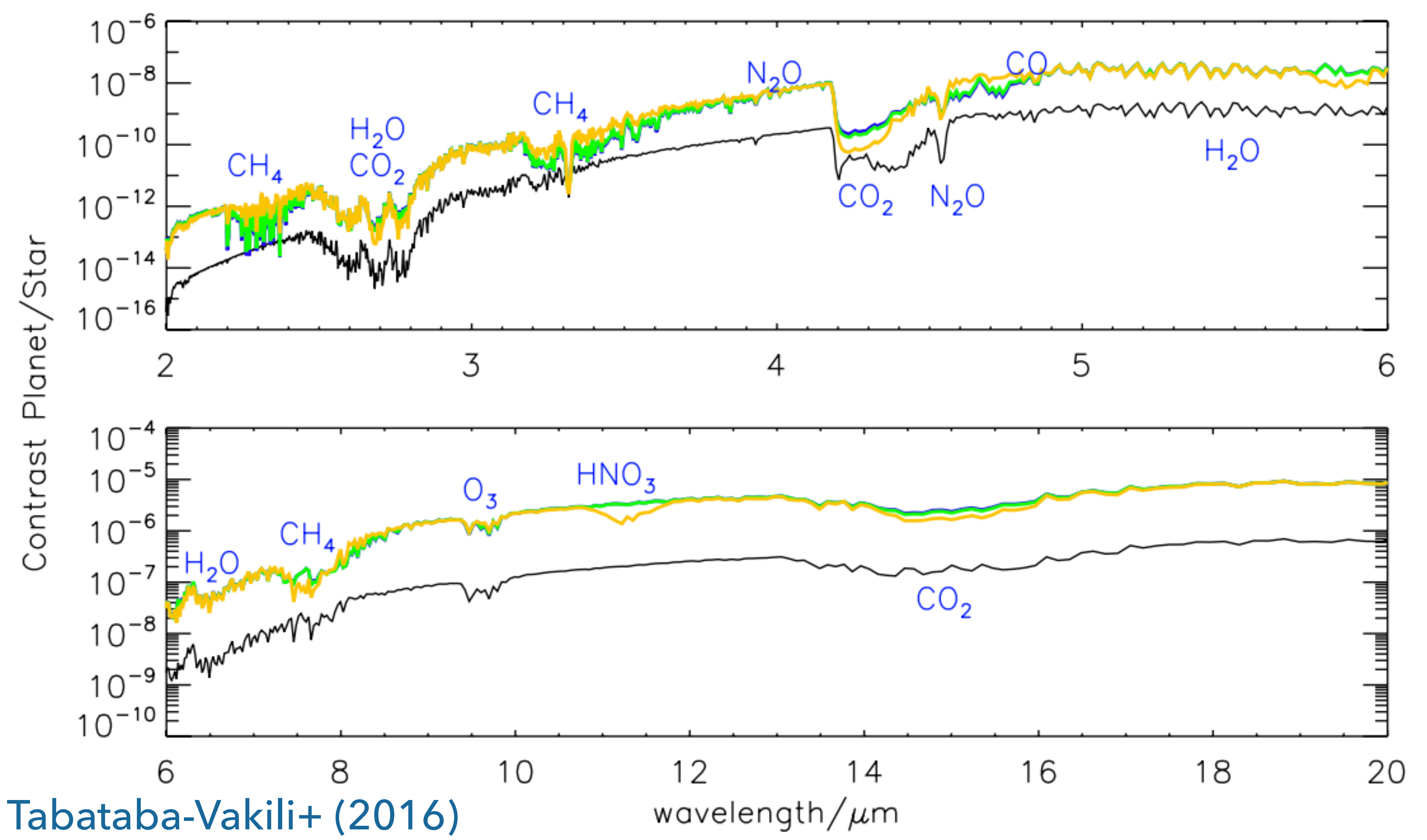
Gaches+ (2019) Gaches&Offner (2018b)

Stellar CRs propagating in TT winds



Fraschetti+ (2018)

Effect of Stellar CRs from M-dwarfs on Earth-like exoplanetary atmospheres



Tabataba-Vakili+ (2016)