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ISTITUTO NAZIONALE
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OSSERVATORIO ASTROFISICO DI ARCETRI

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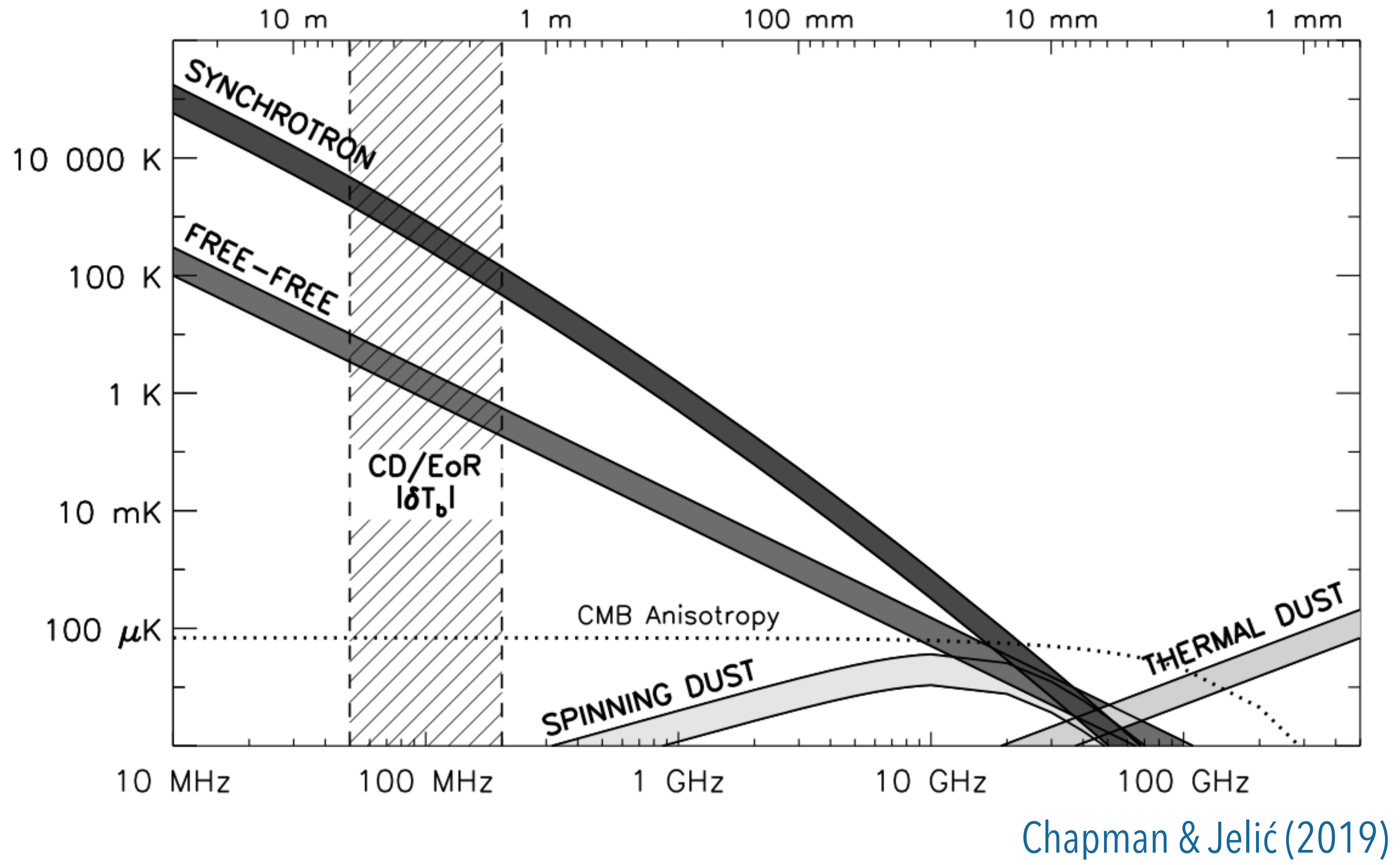
SPECTRAL INDEX OF SYNCHROTRON EMISSION: INSIGHTS FROM THE DIFFUSE AND MAGNETISED INTERSTELLAR MEDIUM

M. Padovani, A. Bracco, V. Jelić, D. Galli & E. Bellomi, A&A 651, A116 (2021)

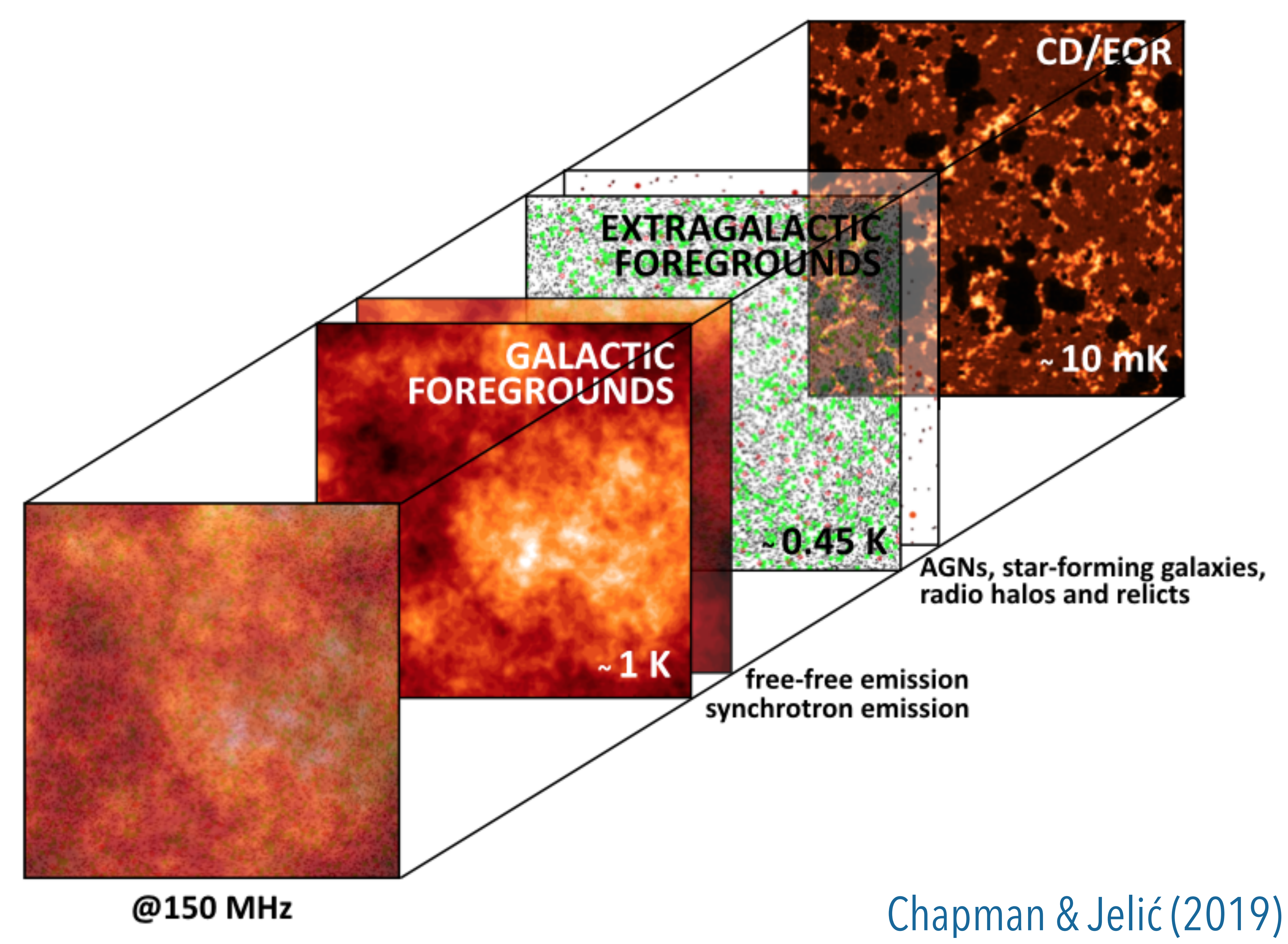
OUTLINE

- WHY STUDY THE GALACTIC SYNCHROTRON EMISSION (GSE)?
- FUNDAMENTALS OF SYNCHROTRON EMISSION
- UPDATES ON THE GALACTIC COSMIC-RAY ELECTRON FLUX
- A CAREFUL MODELLING OF GSE
- A METHOD TO ESTIMATE $B_\perp$

FOREGROUND CONTAMINANTS



Chapman & Jelić (2019)



Chapman & Jelić (2019)

Galactic synchrotron emission (GSE) is one of the main foreground contaminants in cosmological experiments and its emission dominates the radio sky at frequencies below about 10 GHz.

It is therefore of great importance to obtain a detailed understanding of the spectral and spatial variations of GSE in order to mitigate their effects on cosmological observations.

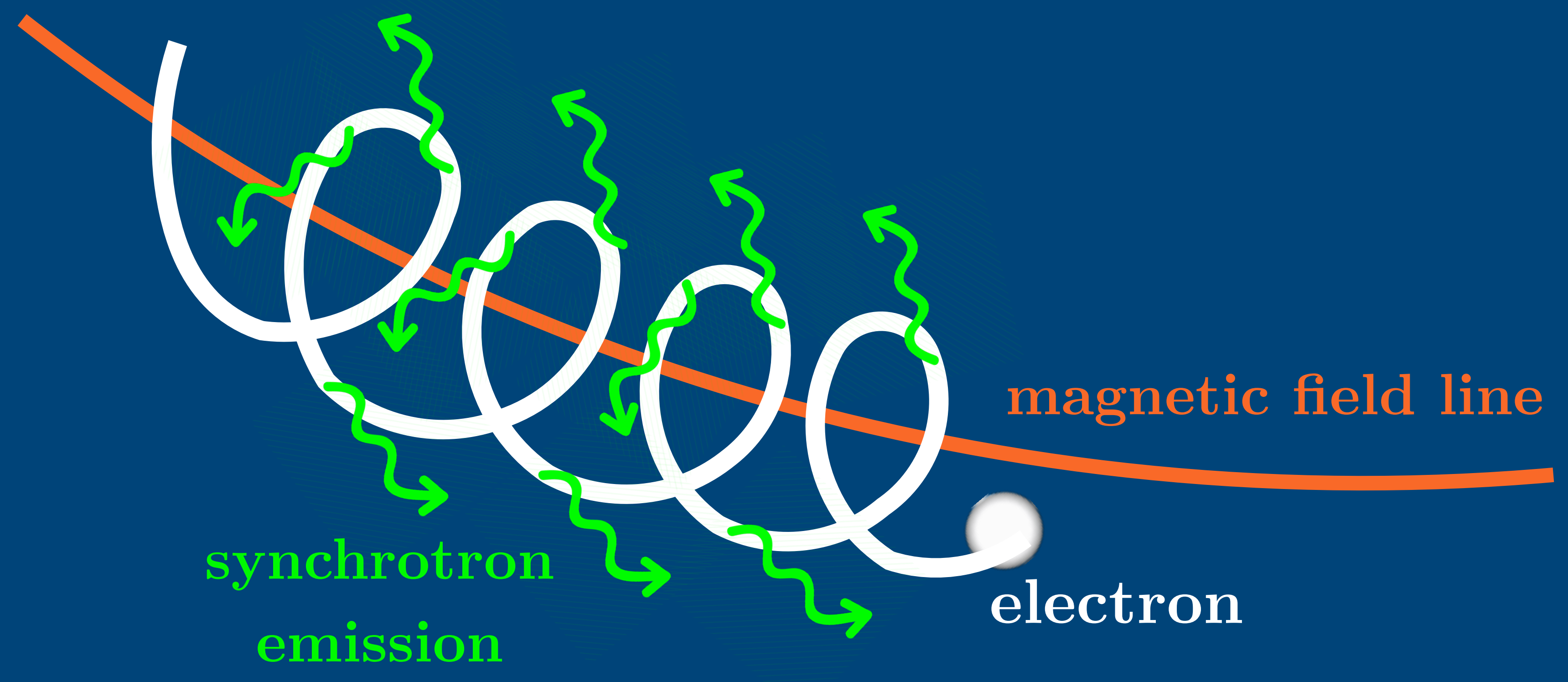
FUNDAMENTALS OF SYNCHROTRON EMISSION

$$\epsilon_\nu \rightarrow I_\nu \rightarrow T_\nu$$

specific emissivity

specific intensity
(brightness)

brightness
temperature



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

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

$$I_\nu = \int \epsilon_\nu\,\mathrm{d}\ell \xrightarrow{\text{beam convolution}} S_\nu$$

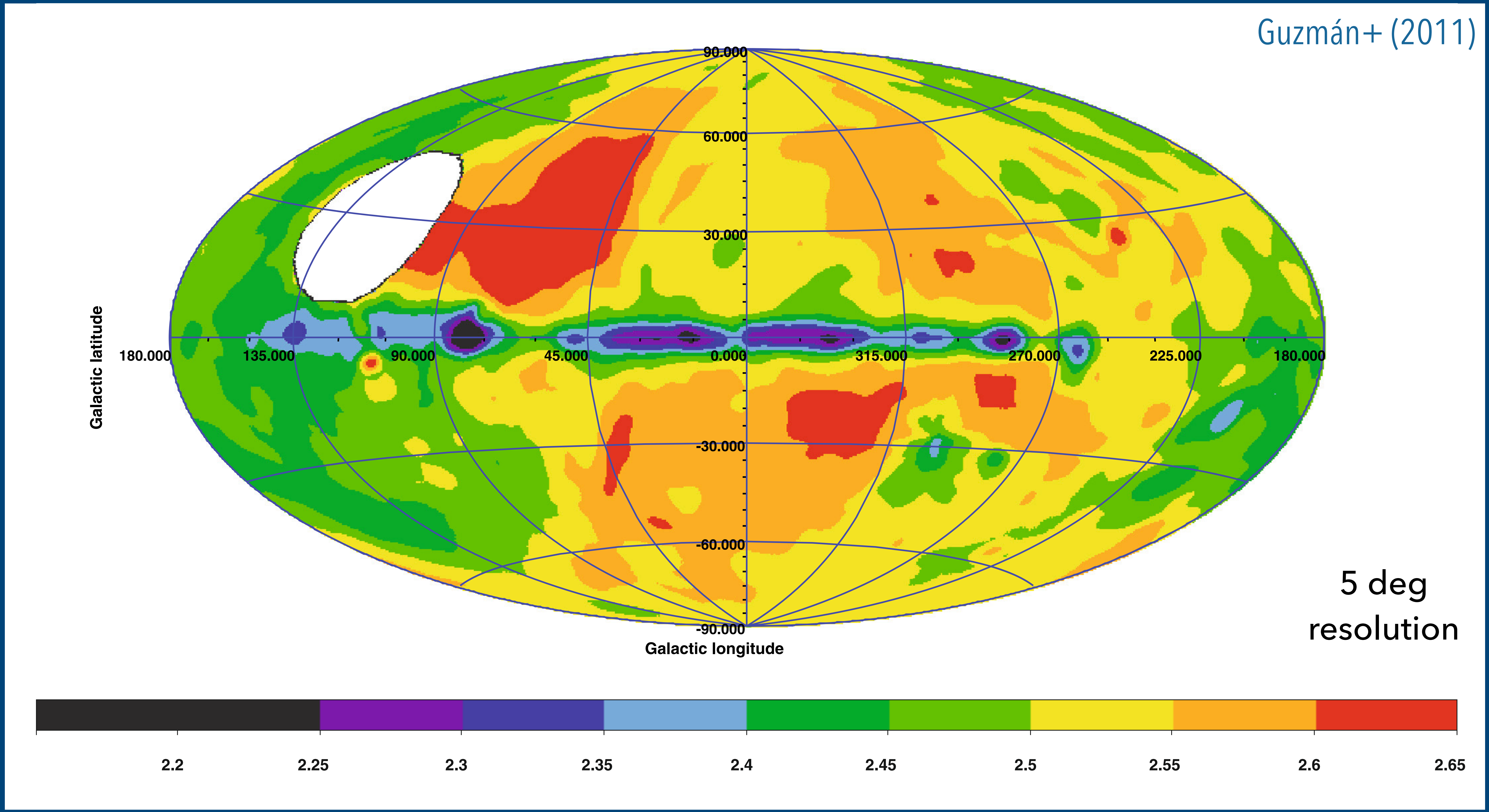
$$T_\nu = 10^{-23}\frac{S_\nu c^2}{2k_{\rm B}\Omega\nu^2}\ \mathrm{K}$$

$$\beta_\nu = \frac{\mathrm{d}\log T_\nu}{\mathrm{d}\log\nu} = \mathscr{F}(j_e, B_\perp)$$

SPECTRAL INDEX MAPS

$$\beta_\nu = \frac{\mathrm{d}\log T_\nu}{\mathrm{d}\log \nu} = \mathscr{F}(j_e, B_\perp)$$

Spatial variations of the spectral index β_ν reflects spatial variations of the CR electron flux and the magnetic field properties of the ISM along the LOS.



Guzmán+ (2011)

5 deg resolution

Full sky maps of GSE show spatial variations of β already at the (low) angular resolution of 5 deg.

LOFAR and SKA, with at least three times this angular resolution, will be able to investigate even finer variations of β.

SPECTRAL INDEX MAPS

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Spatial variations of the spectral index β_ν reflects spatial variations of the CR electron flux and the magnetic field properties of the ISM along the LOS.

Mozdzen+ (2017,2019)

$50 < \nu/\mathrm{MHz} < 100 : -2.59 < \beta < -2.54 \pm 0.01$

$90 < \nu/\mathrm{MHz} < 190 : -2.62 \pm 0.02 < \beta < -2.60$

Platania+ (1998)

$1.4 < \nu/\mathrm{GHz} < 7.5 : \beta = -2.81 \pm 0.16$

General oversimplification

Depending on the observing frequency, it is usually assumed that the CR electron spectrum contributing to the GSE is characterised by a single energy slope, *s*.

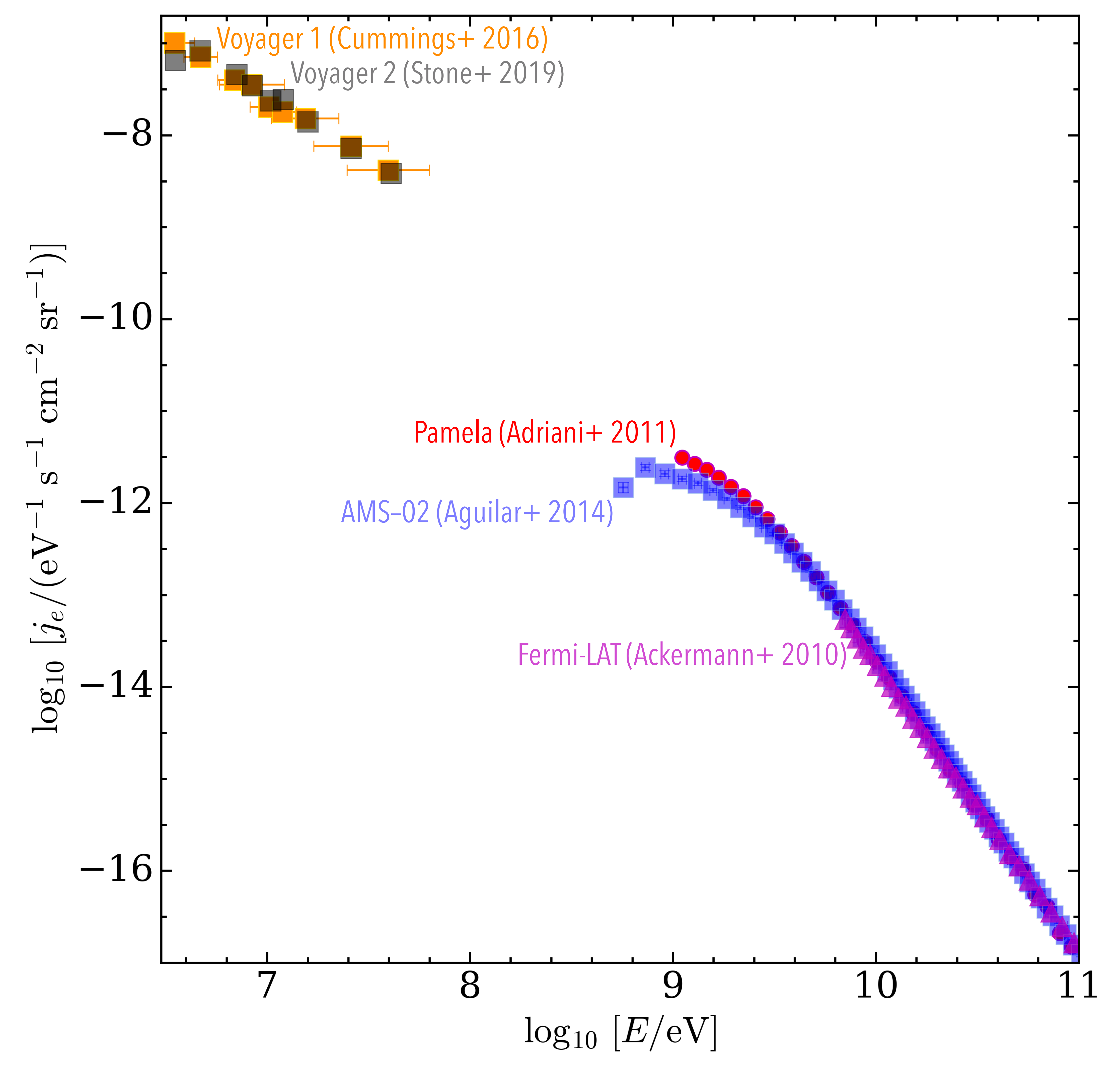
$$j_e(E) \propto E^s$$

$\nu < 408\ \mathrm{MHz} \longrightarrow s = -2$

$\nu > 408\ \mathrm{MHz} \longrightarrow s = -3$

This assumption avoids time-consuming calculations.

GALACTIC COSMIC-RAY ELECTRON FLUX



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misinterpretation of GSE!

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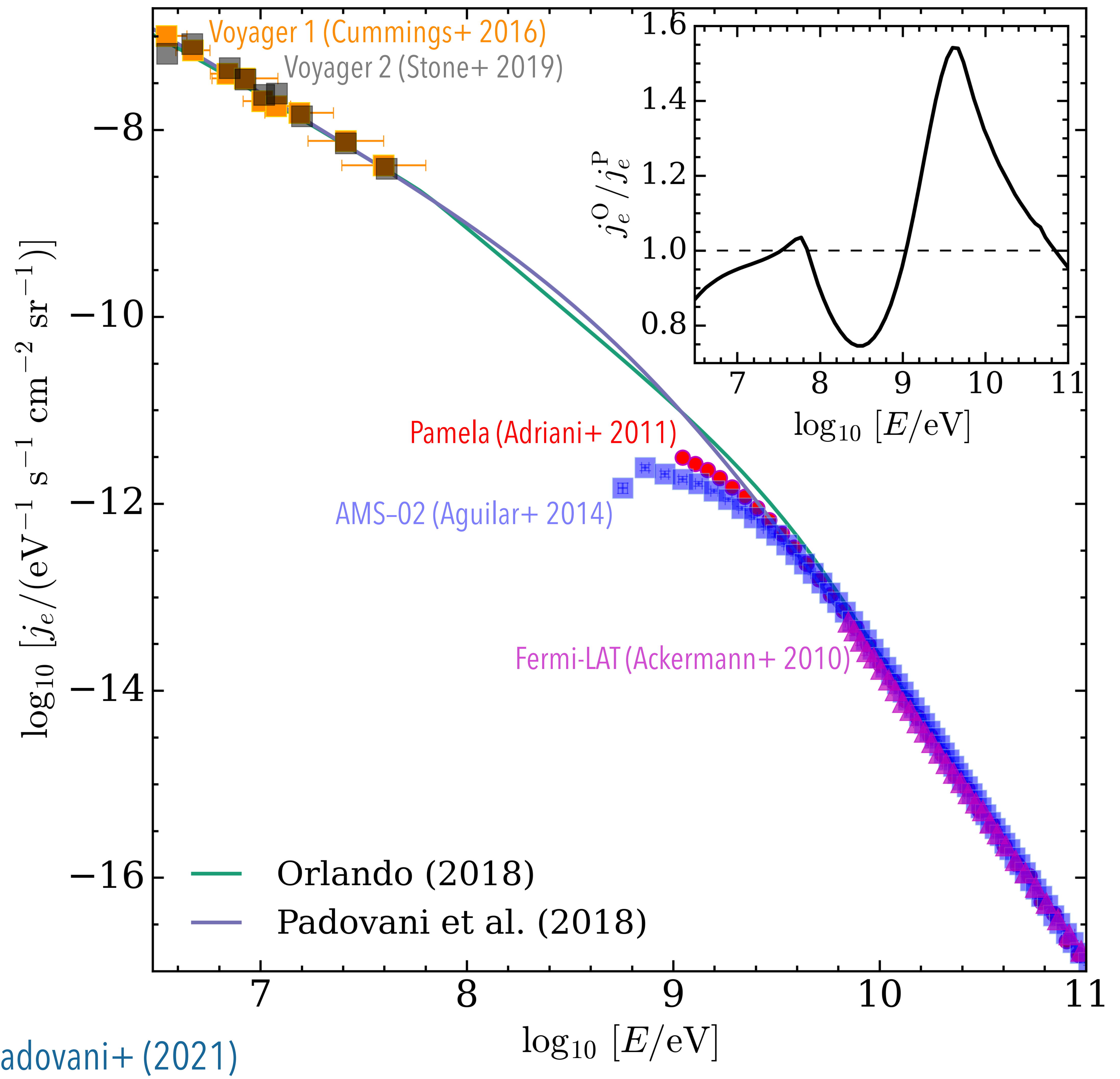

Padovani+ (2021)

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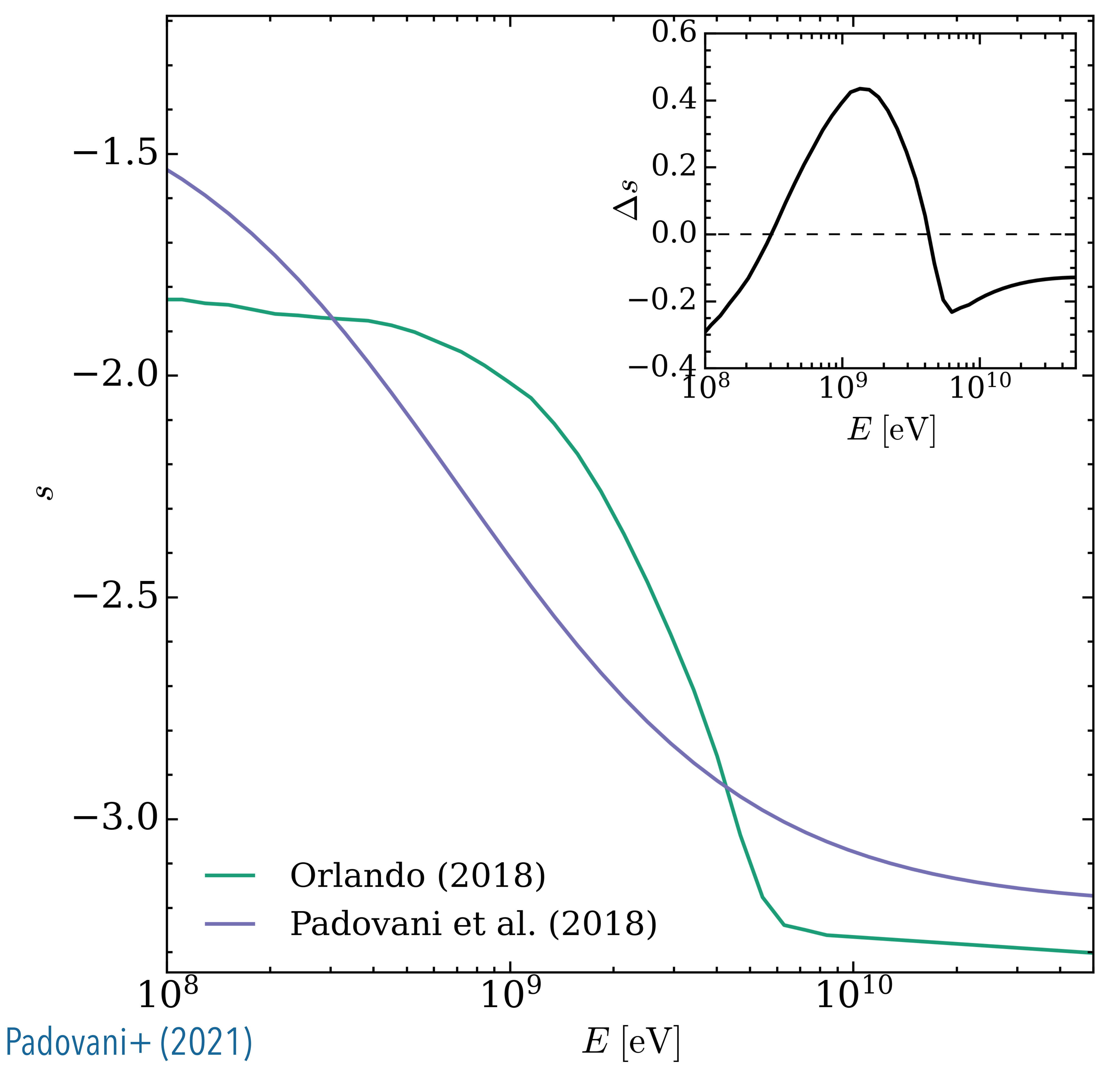
misinterpretation of GSE!

Orlando (2018): multifrequency observations (radio,γ) plus V1, representative of intermediate Galactic latitudes ($10^\circ < |b| < 20^\circ$), including most of the local radio synchrotron emission within a radius of ~1 kpc around the Sun.

Padovani+ (2018): analytical four-parameter fitting formula that perfectly reproduces the power-law behaviour at low and high energies;

Below 50 GeV (energy range of interest) these two realisations differ on average by less than 25%.

GALACTIC COSMIC-RAY ELECTRON FLUX



Padovani+ (2021)

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misinterpretation of GSE!

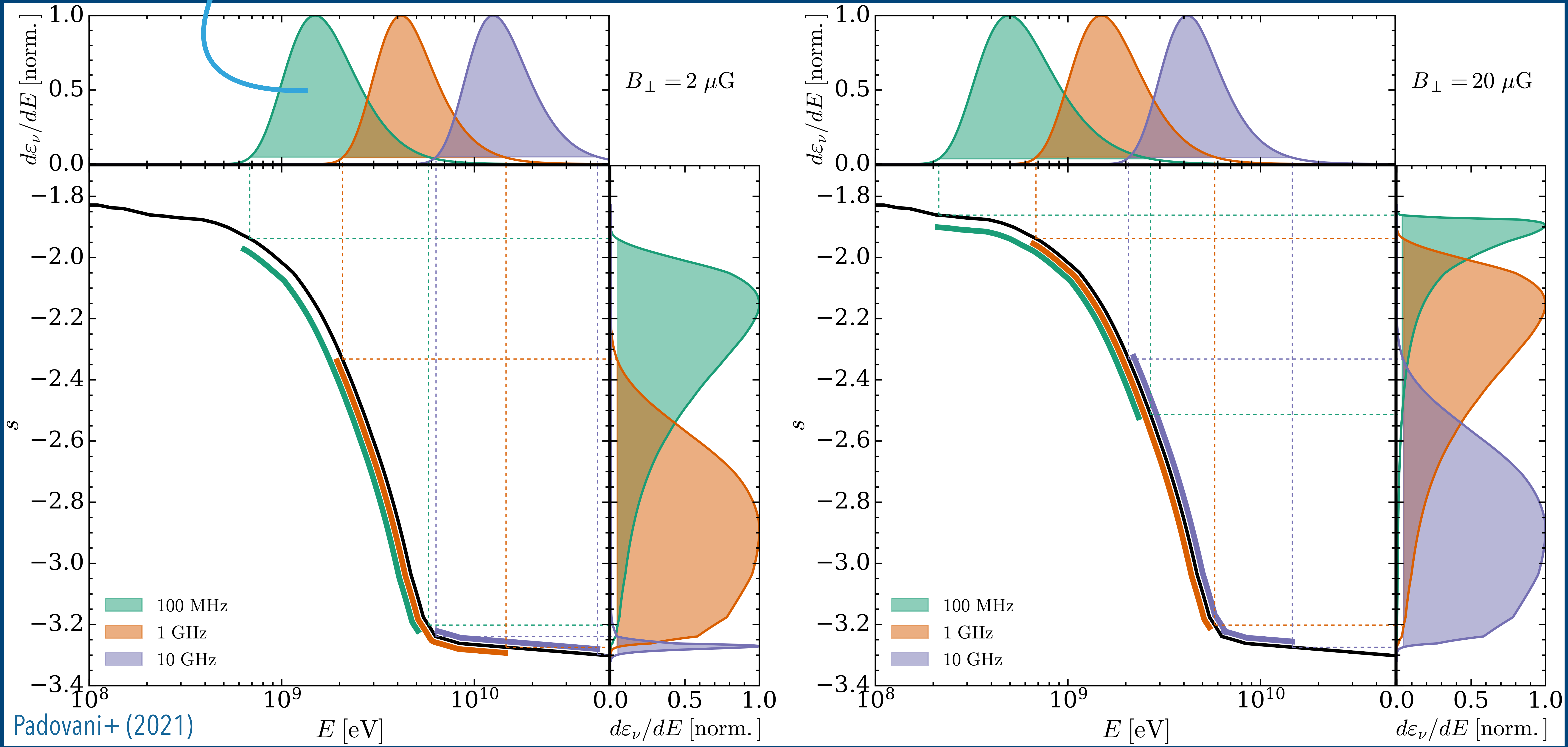
The spectral energy slope *s* has large and continuous variations with energy

MODELLING SYNCHROTRON EMISSION

$$\frac{\mathrm{d}\epsilon_\nu}{\mathrm{d}\nu} \propto \mathscr{F}(j_e, B_\perp)$$

The electron energy range determining the synchrotron emission is *broad*.

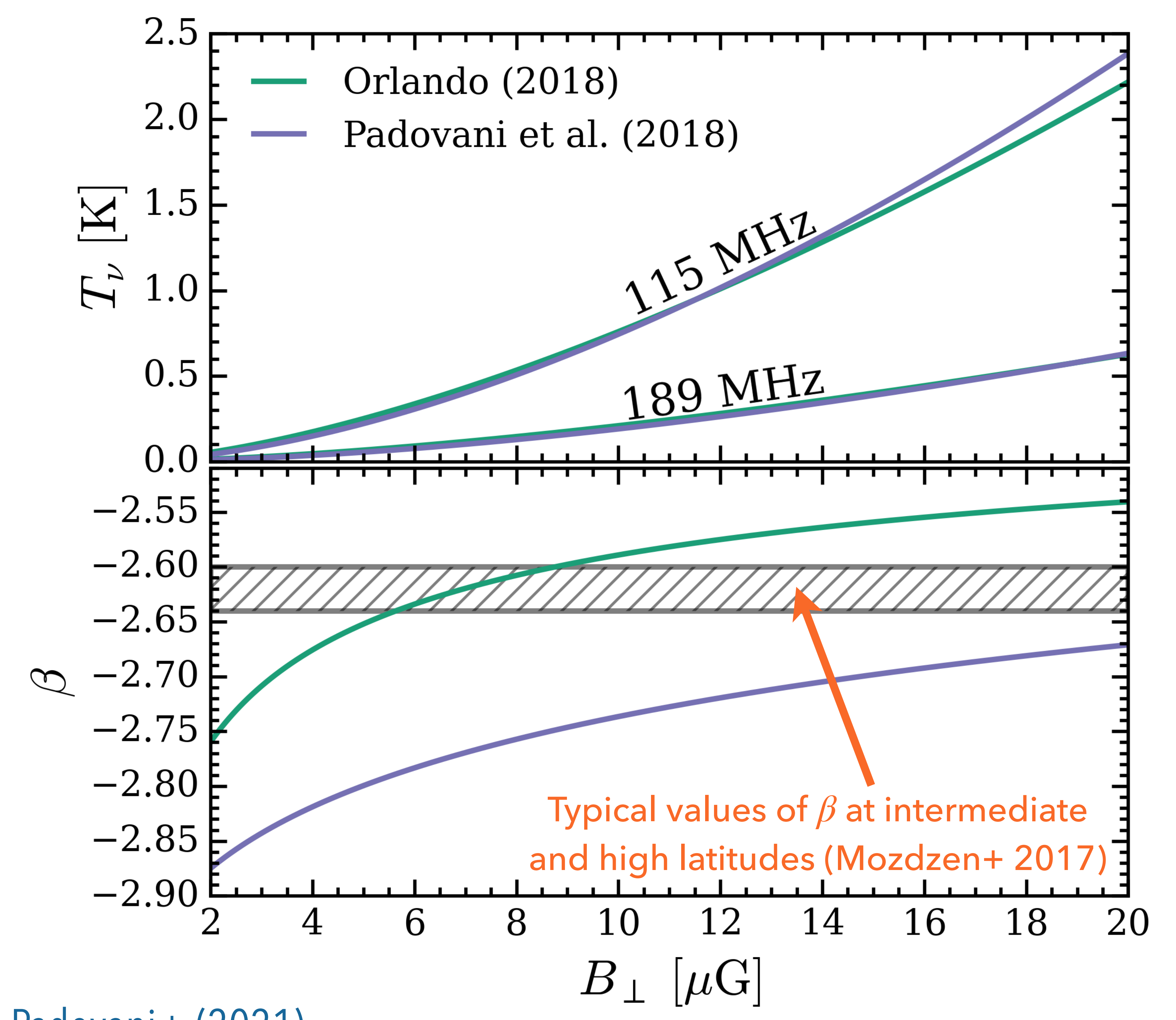
$B_\perp = 2 - 20\ \mu$G (Heiles & Troland 2005; Beck 2005; Ferrière 2010)



Padovani+ (2021)

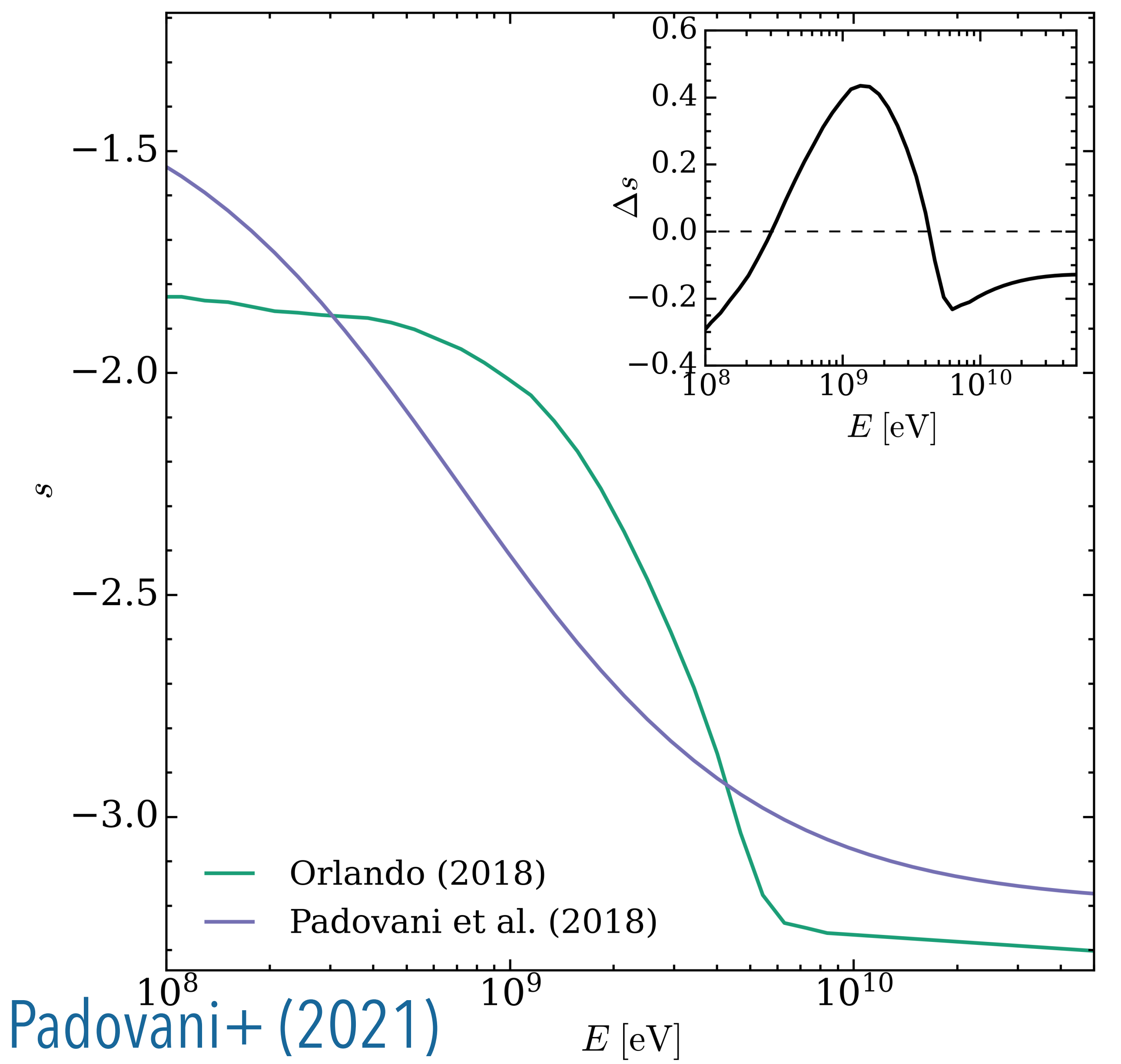
MODELLING SYNCHROTRON EMISSION: UNIFORM SLAB

Brightness temperature for a 1 pc slab with a fixed, spatially uniform, component of the magnetic field $B_\perp$ varying from 2 to 20 μG exposed to the CR electron flux. Frequency range $\nu = 115 - 189$ MHz; frequency resolution $\Delta\nu = 183$ MHz; angular resolution $\theta_b = 4'$ (representative of LOFAR HBA observations by Jelić+ 2015).



Typical values of β at intermediate and high latitudes (Mozdzen+ 2017)

Padovani+ (2021)



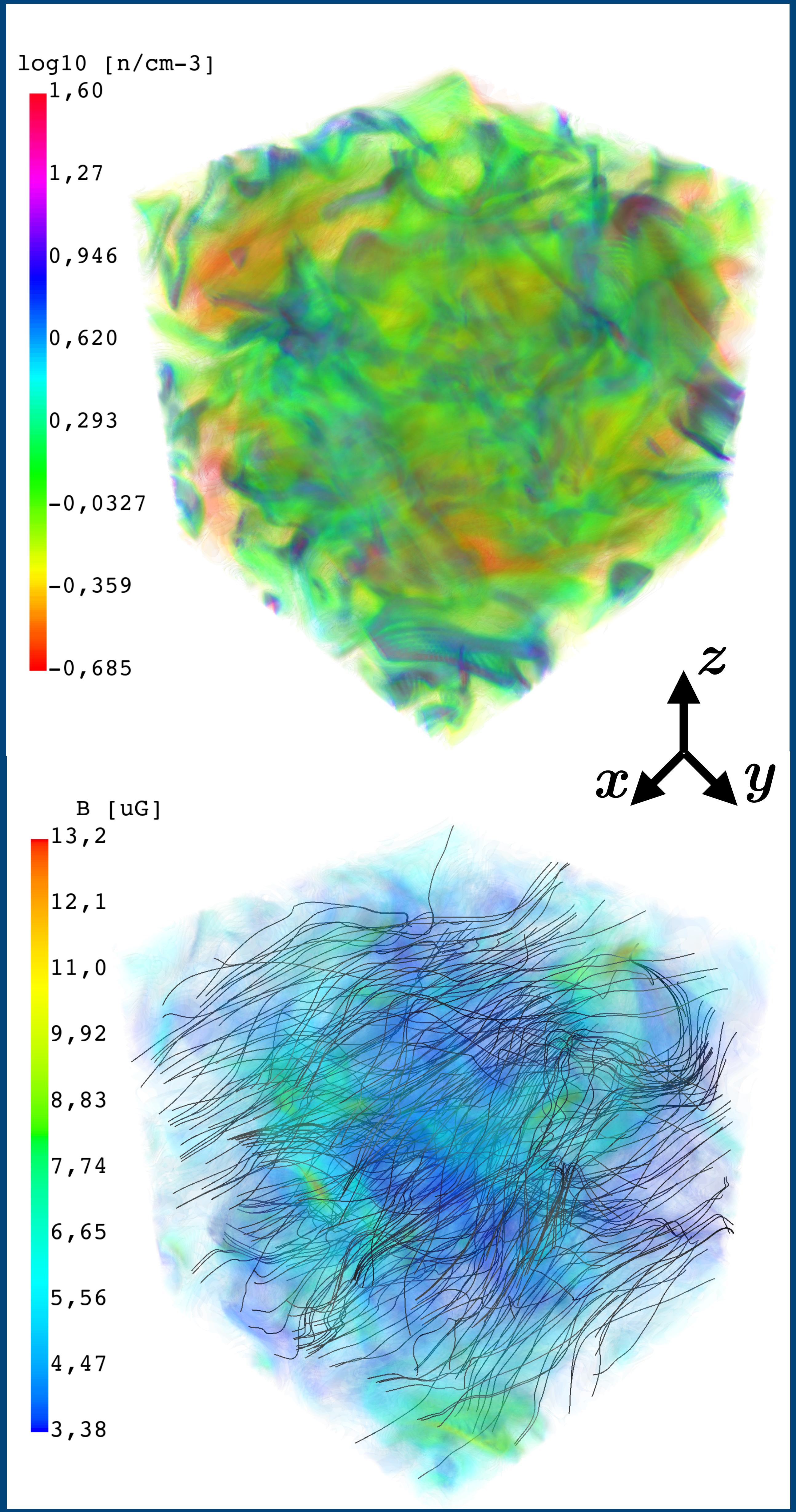
Padovani+ (2021)

1st take-home message:
s cannot be assumed as constant to interpret GSE;

2nd take-home message:
the choice of the CR electron spectrum is crucial.

The highly accurate determination of β allowed by current (e.g. LOFAR) and future (e.g. SKA) instruments is a strong motivation for modelling GSE, avoiding oversimplifications.

MODELLING SYNCHROTRON EMISSION: NUMERICAL SIMULATIONS



Snapshots of the Galactic diffuse matter (Bellomi+ 2020) over a box of 50 pc, 128^3 pixels, effective resolution of 0.39 pc; initial homogeneous density $n_{\rm H} = 1.5\ {\rm cm}^{-3}$, $T = 8000\ {\rm K}$, uniform magnetic field $\mathbf{B_0} = B_0 \hat{e}_x$.

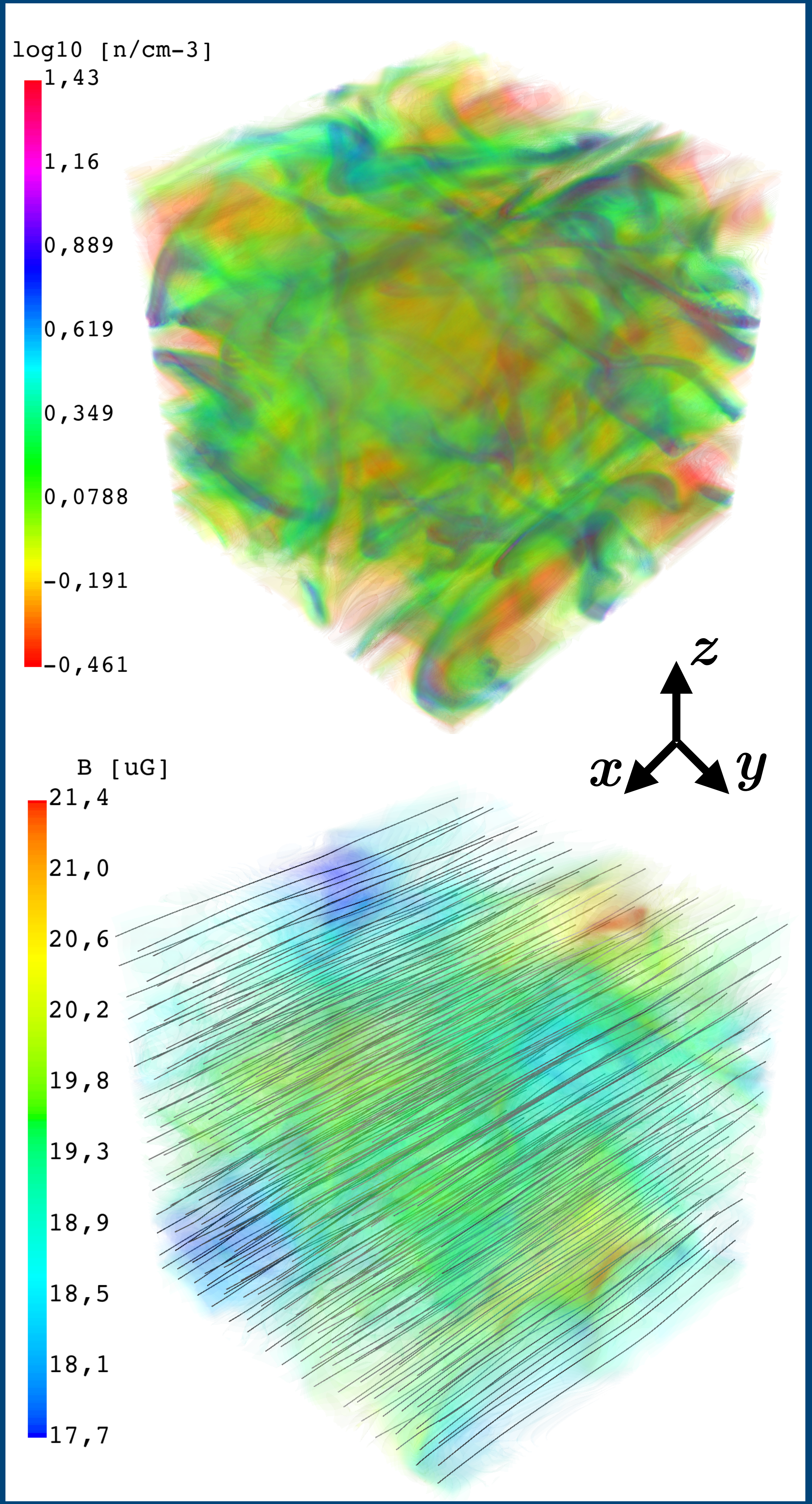
The gas evolves under the joint influence of turbulence, magnetic fields, and thermal instabilities, and separates into three different phases: CNM, WNM, and unstable.

"weak-field" case

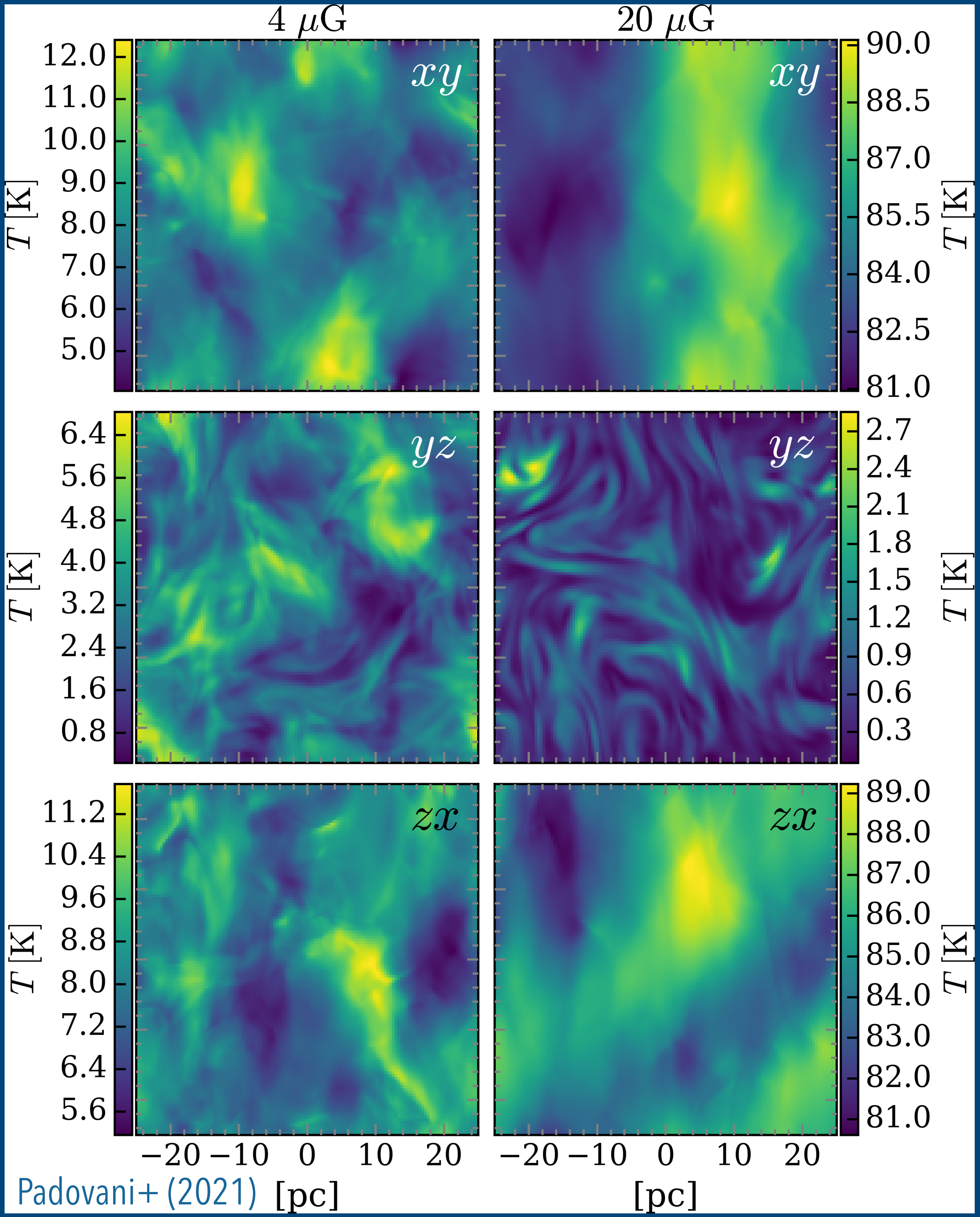
$\langle B \rangle = 4\ \mu{\rm G}$

"strong-field" case

$\langle B \rangle = 20\ \mu{\rm G}$



TEMPERATURE MAPS



Padovani+ (2021)

$$\nu = 130\ \mathrm{MHz}, \theta_b = 6.7', \ L = 50\ \mathrm{pc}$$

- T is higher where $B_\perp$ is larger;
- strong field case: highest T in the POSs containing B_x ;
- T maps more inhomogeneous in the POS yz of both snaphots, since in this POS, $B_\perp$ has a significant turbulent component.

$$\mu = \sigma_{B_\perp} / \tilde{B}_\perp$$

to quantify the relative turbulent component of $B_\perp$

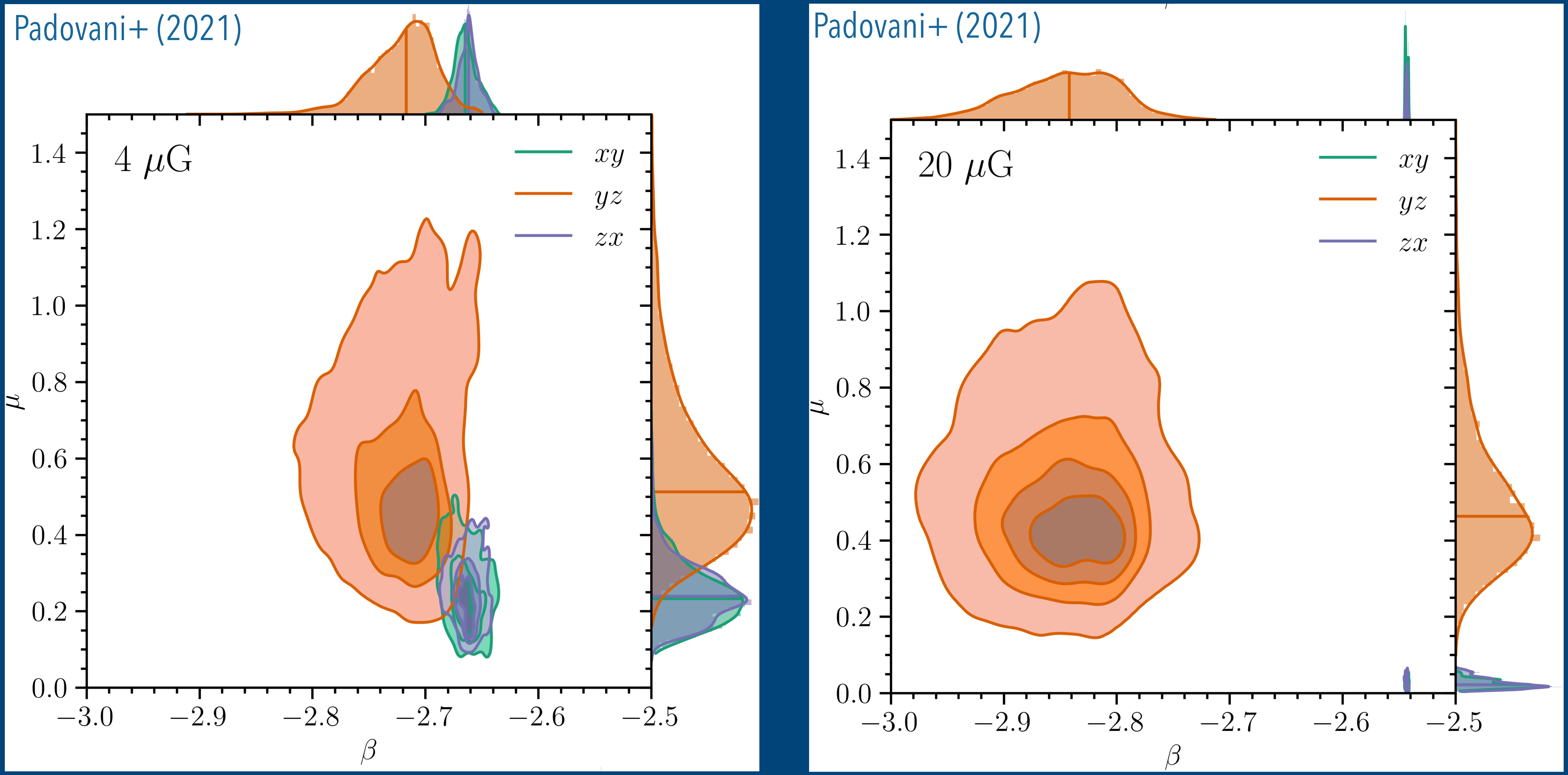
SPECTRAL INDEX β ($\nu = 115 - 189$ MHz)

$$j_e(E) \propto E^s$$

$$\nu < 408 \text{ MHz} \longrightarrow s = -2$$
$$\nu > 408 \text{ MHz} \longrightarrow s = -3$$

→ $$\beta = \frac{s-3}{2} = -2.5$$

Bivariate distributions



3rd take-home message:
β variations can only be explained by accounting for a non-constant energy spectral slope s.

Same considerations holds in the high-frequency regime ($\nu \gtrsim 408$ MHz), where the assumption $s = -3$, then $\beta = -3$, turns out to be incorrect.

Only in the case of almost no turbulence ($\mu \simeq 0$), i.e. constant $B_\perp$ along the LOS, β can be assumed constant. Still a very unlikely case.

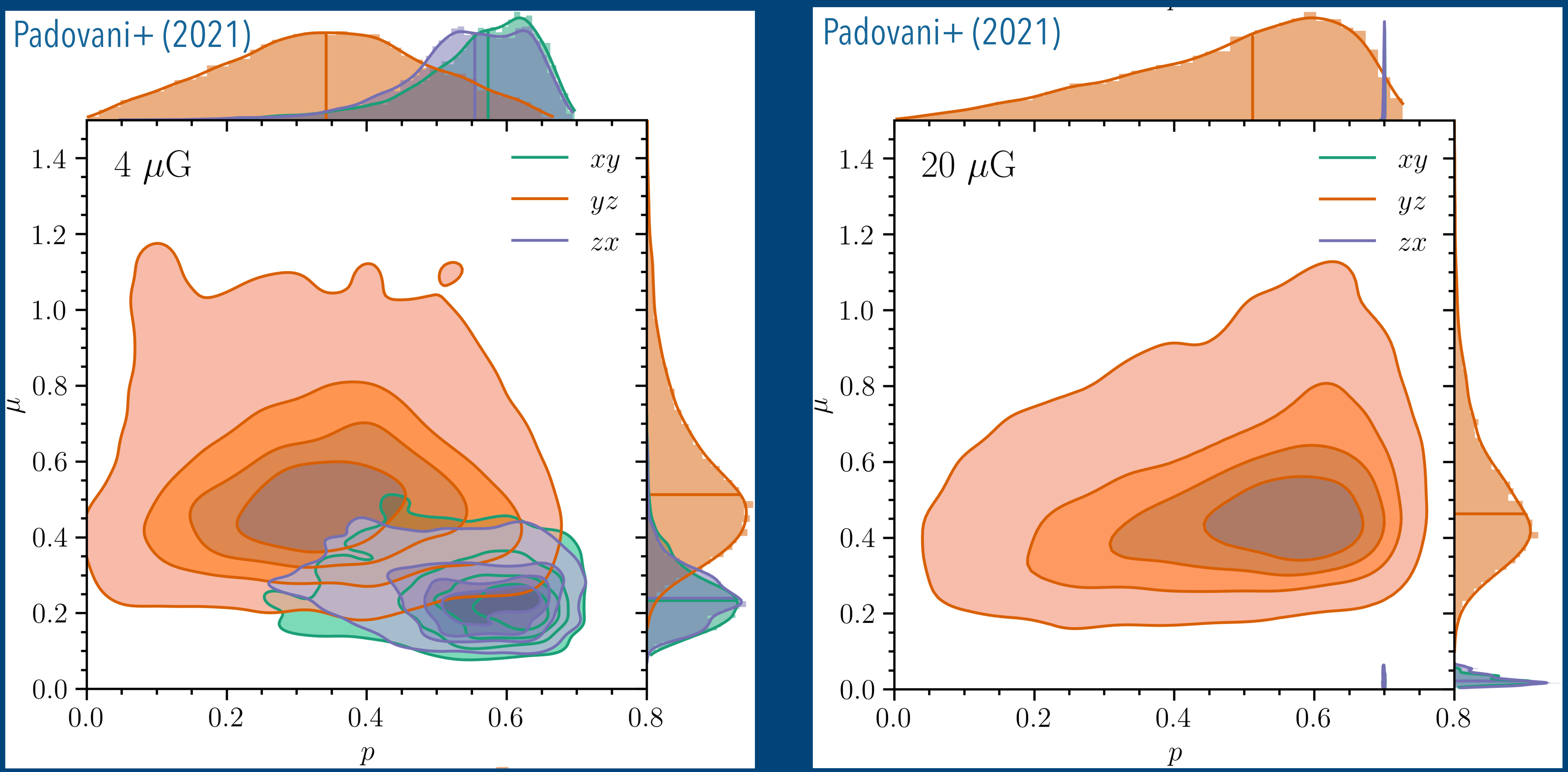
POLARISATION FRACTION p $(\nu = 115 - 189\ \mathrm{MHz})$

$$j_e(E) \propto E^s$$

$$\nu < 408\ \mathrm{MHz} \longrightarrow s = -2$$
$$\nu > 408\ \mathrm{MHz} \longrightarrow s = -3$$

$$\longrightarrow \quad p = \frac{3-3s}{7-3s} = \frac{3+3\beta}{1+\beta} = 69\,\%$$

Bivariate distributions



Depolarisation effects are here mainly caused by the tangling of the turbulent component of the magnetic field along the LOS (see POSs yz). This effect has been already reported in the literature in both the radio (e.g. Gaensler+ 2011) and in the submillimetre domain (Planck Coll. Int. XX 2015).

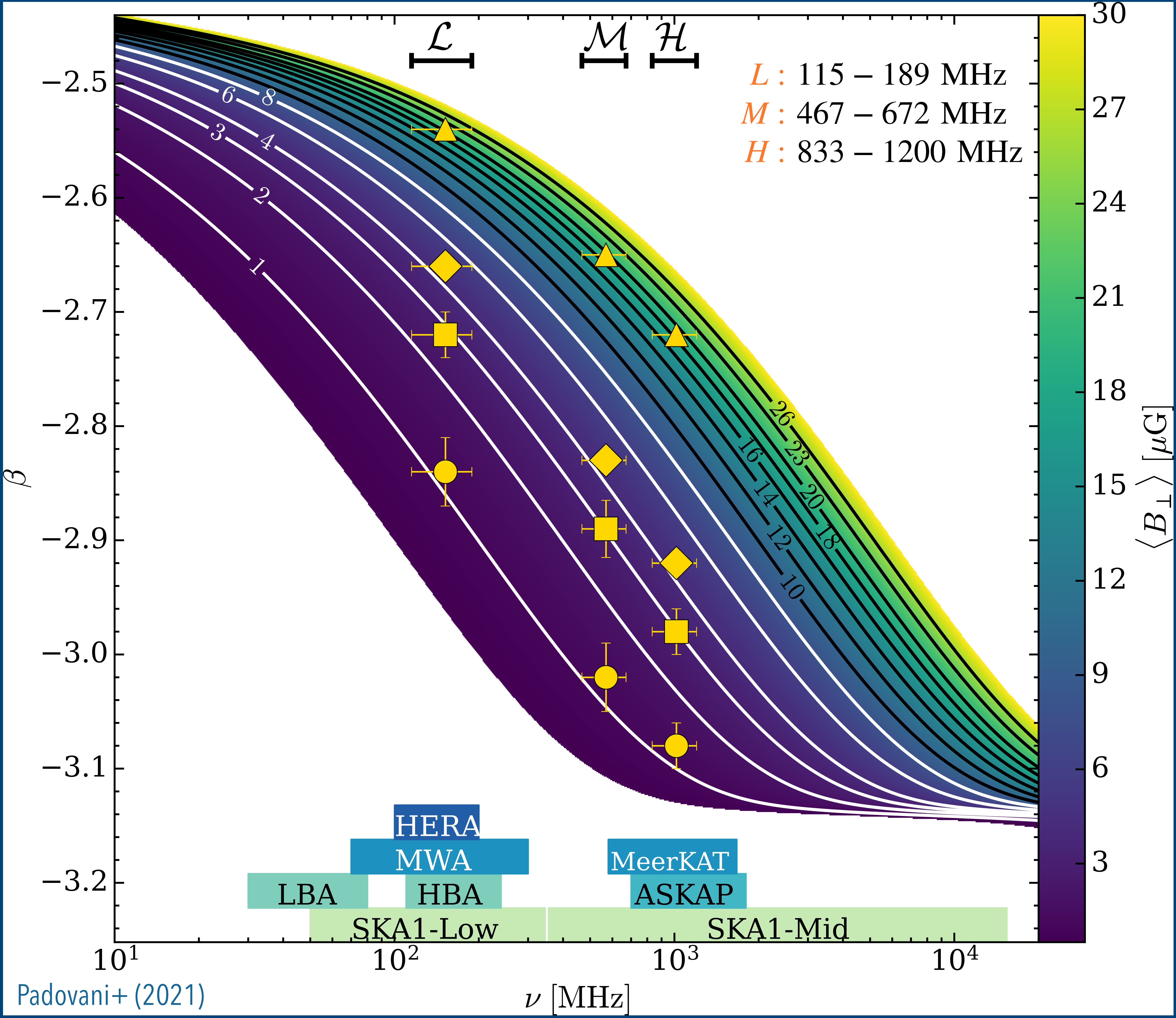
Bracco et al. (in prep.): synchrotron polarisation can be severely affected by Faraday rotation, especially at a few hundred of MHz (rot. angle $\propto \lambda^2 \int n_e B_\parallel \, d\ell$).

A LOOK-UP PLOT FOR $B_\perp$

A method to estimate $\langle B_\perp \rangle$ for a given j_e .

$$\beta(\nu, \langle B_\perp \rangle) = \frac{\mathrm{d}\log T_\nu(\langle B_\perp \rangle)}{\mathrm{d}\log \nu}$$

- for each POS, the estimates of $\tilde{\beta}$ in the three frequency intervals correspond to the same $\langle B_\perp \rangle$;
- there is a preferred ν range ($\simeq 0.1 - 5$ GHz), where s, then β, varies the most (isocontours of $\langle B_\perp \rangle$ are more separated).



Padovani+ (2021)

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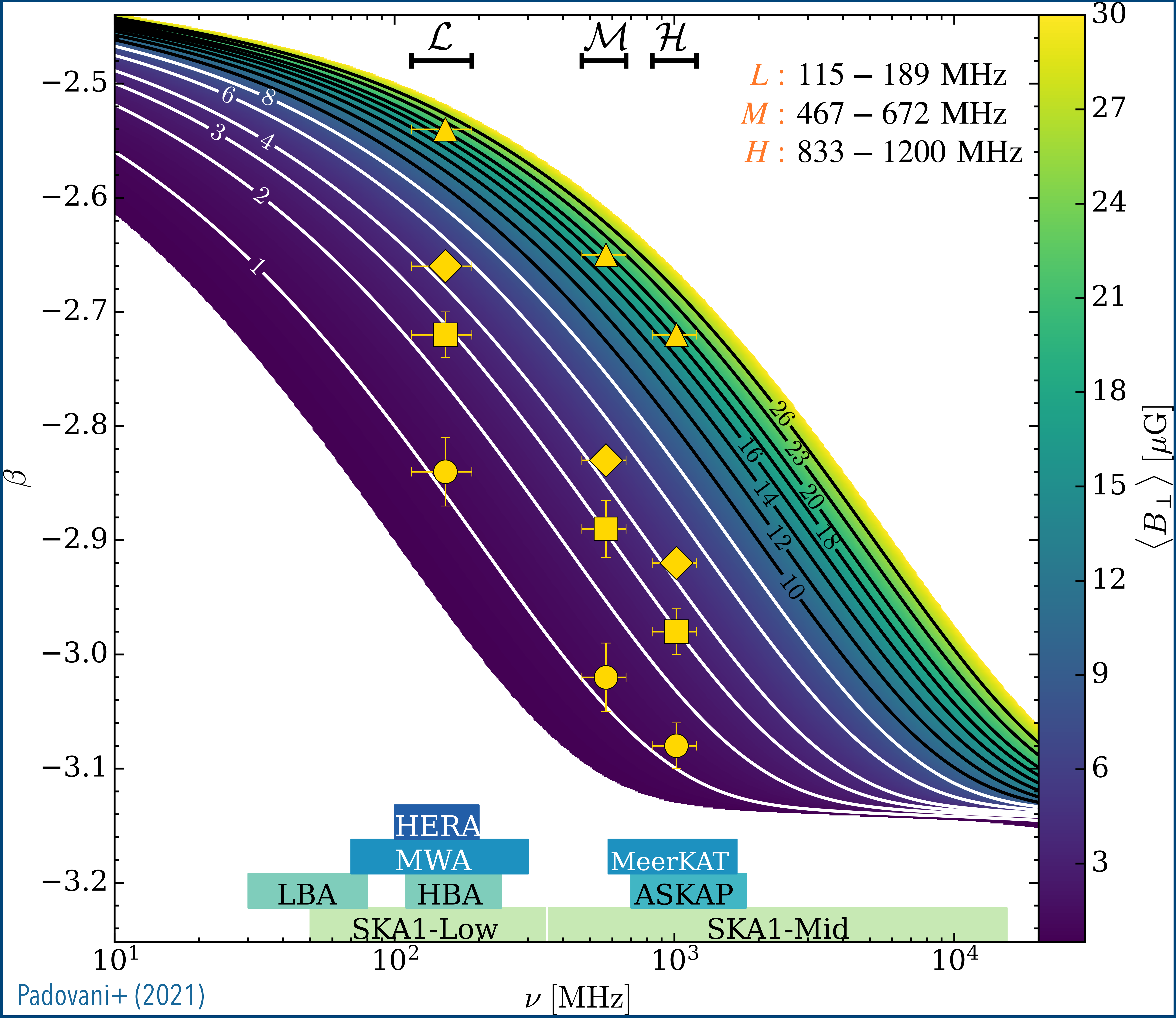
4th take-home message:

it is advisable to simultaneously observe in narrow frequency ranges with high spectral resolution (as the *L*, *M*, and *H* intervals) in order to have independent β estimates that should follow a specific isocontour of $B_\perp$.

Frequency ranges of the main current and future facilities



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