Interstellar electron and positron spectra from MeV to TeV energies

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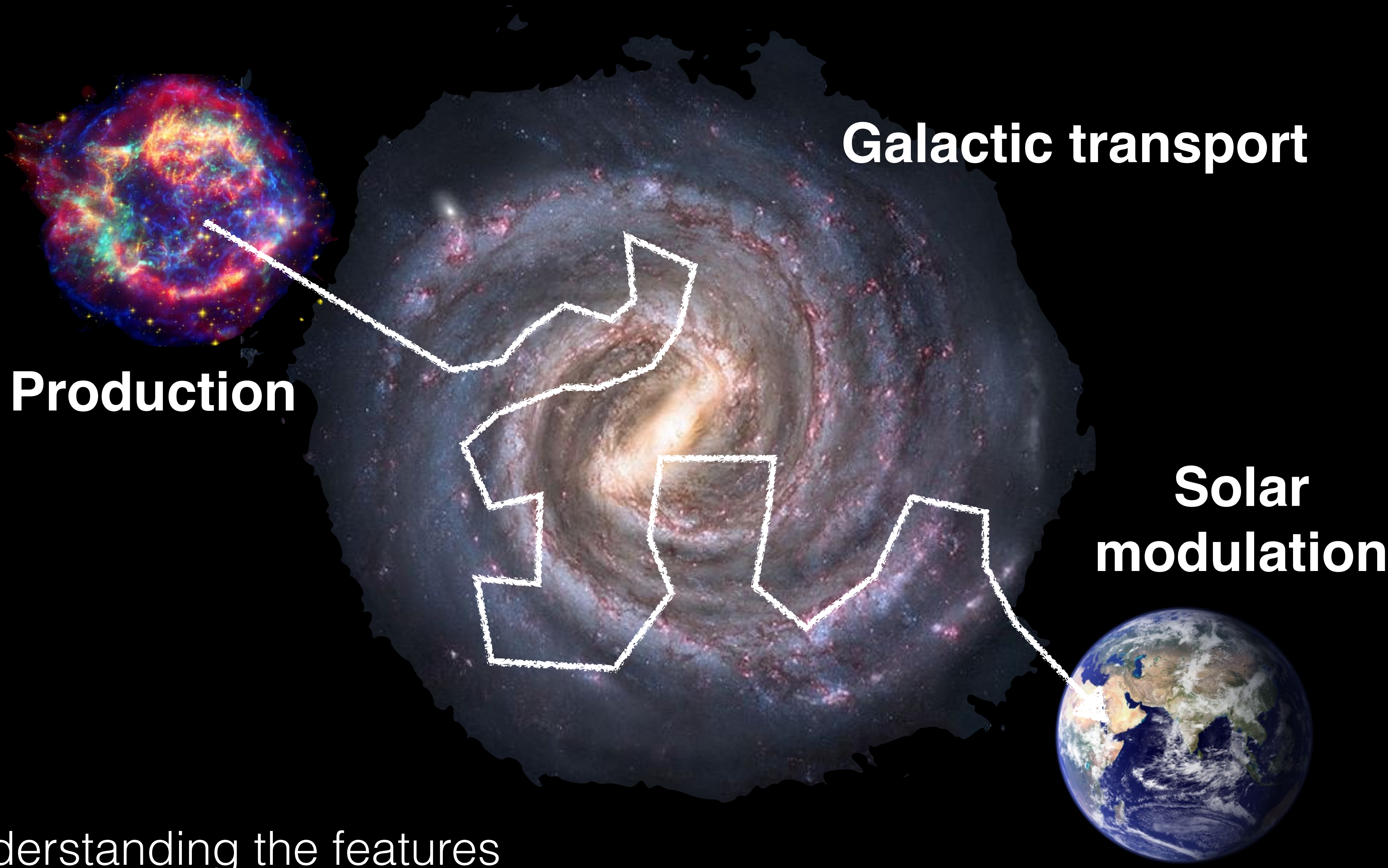
2018 TeV Particle Astrophysics

TeVPA

From sources to Earth



Understanding the features
of the CR electron and positron spectra requires an
accurate modelling of all these processes

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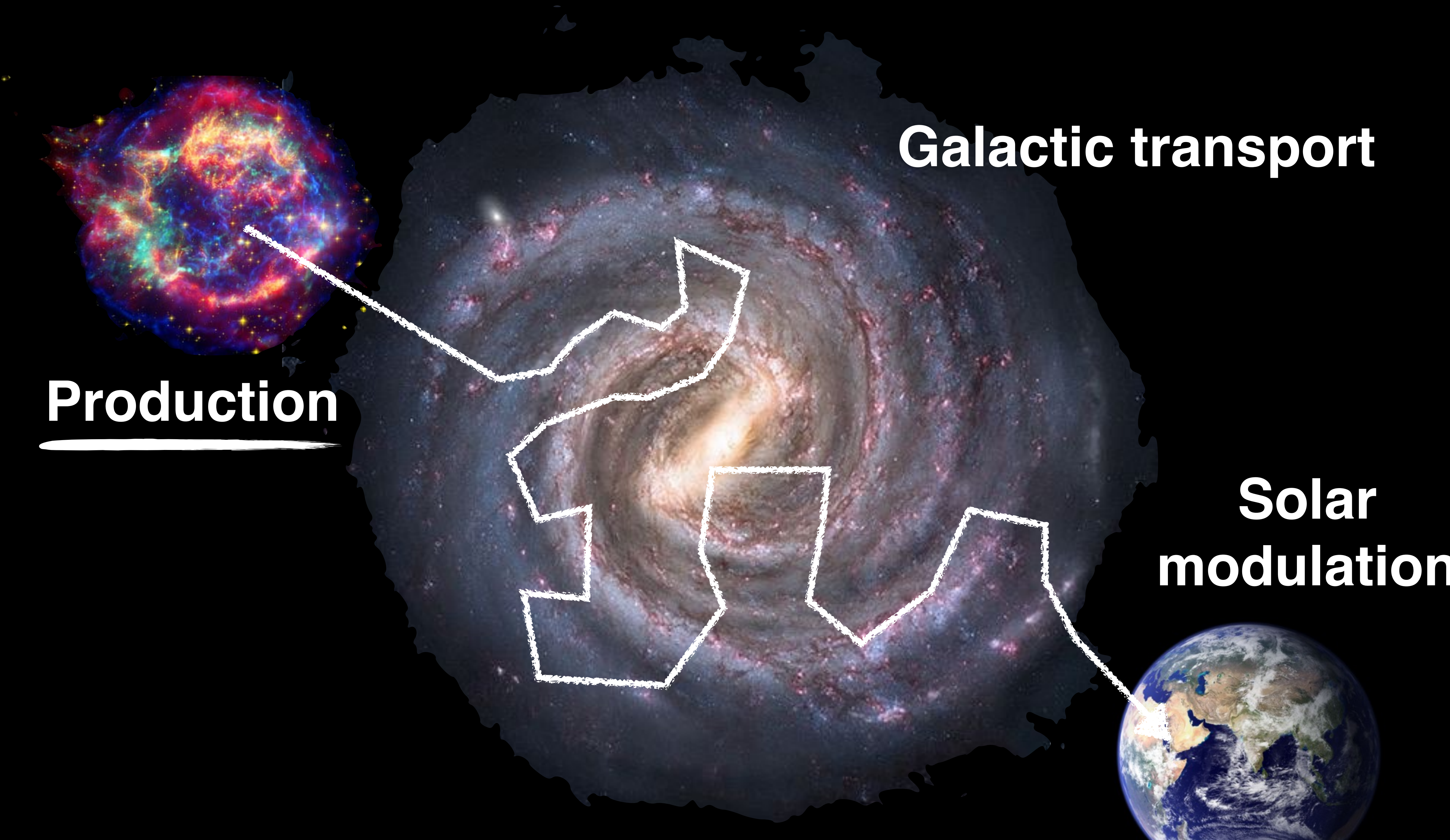

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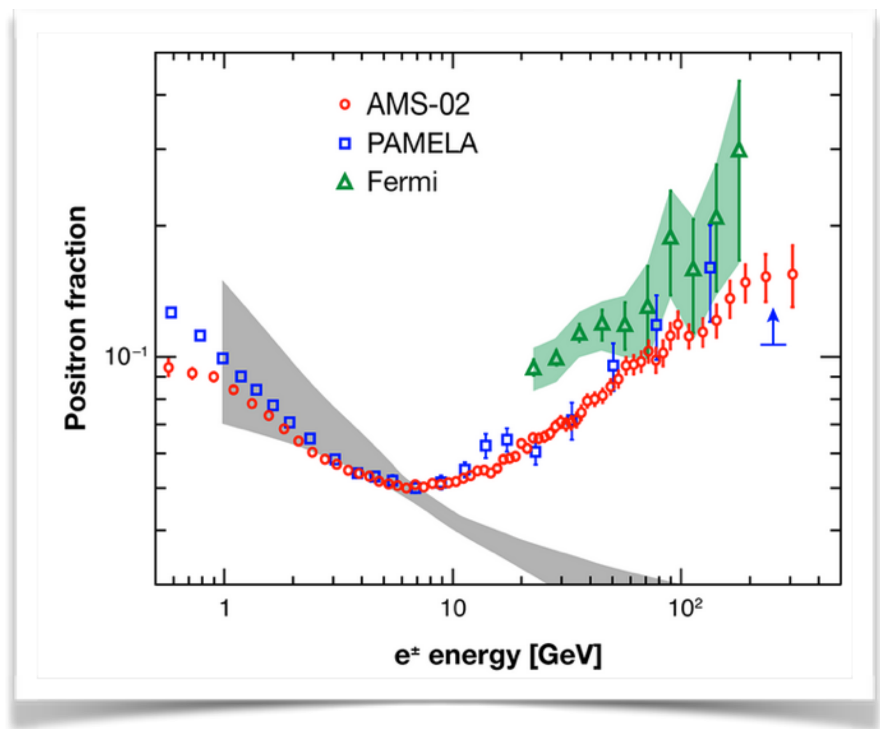
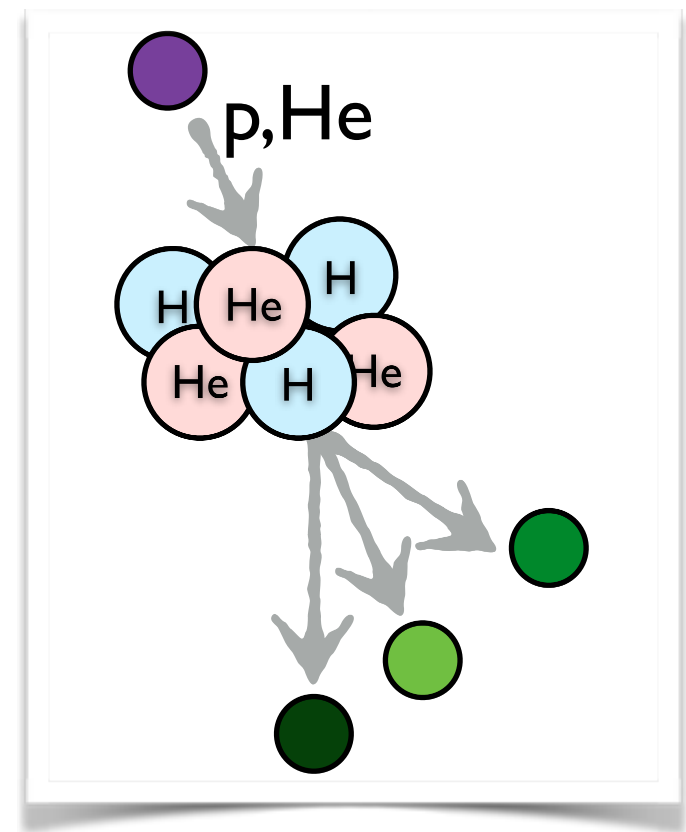
Electron and positron sources

Electrons and positrons are emitted by **several sources**:

Supernova Remnants



Extra source



Secondary emission

Electron and positron sources

Electrons and positrons are emitted by **several sources**:

1. **Supernova Remnants (SNRs)** are the **main source of primary electrons**.

$$Q_{\mathrm{SNR}}(r, z, \mathcal{R}) = Q_0 f(r, z) g(\mathcal{R})$$

$\mathcal{R}$ = rigidity

- $f(r, z)$ is the average distribution of SNRs **Ferriere 2001**

- We assume the spectrum to be a **power law**

$$g(\mathcal{R}) = N_{e^-} \mathcal{R}^{-\Gamma}$$

free parameters

Electron and positron sources

Electrons and positrons are emitted by **several sources**:

2. An **extra source** is required to fit the **rise in the positron fraction** **[PAMELA 2009, AMS-02 2013]**

$$\mathcal{Q}^{e^\pm}_{\mathrm{extra}}(r,z,\mathcal{R}) = f(r,z) N_x \mathcal{R}^{-\Gamma_x} \exp\left(-\frac{\mathcal{R}}{\mathcal{R}_{\mathrm{cut}}}\right)$$

free parameters

- $f(r,z)$ is the **same distribution** adopted for **SNRs**
- The extra source is **charge- symmetric**
- We fix $\mathcal{R}_{\mathrm{cut}} = 600\,\mathrm{GV}$

Electron and positron sources

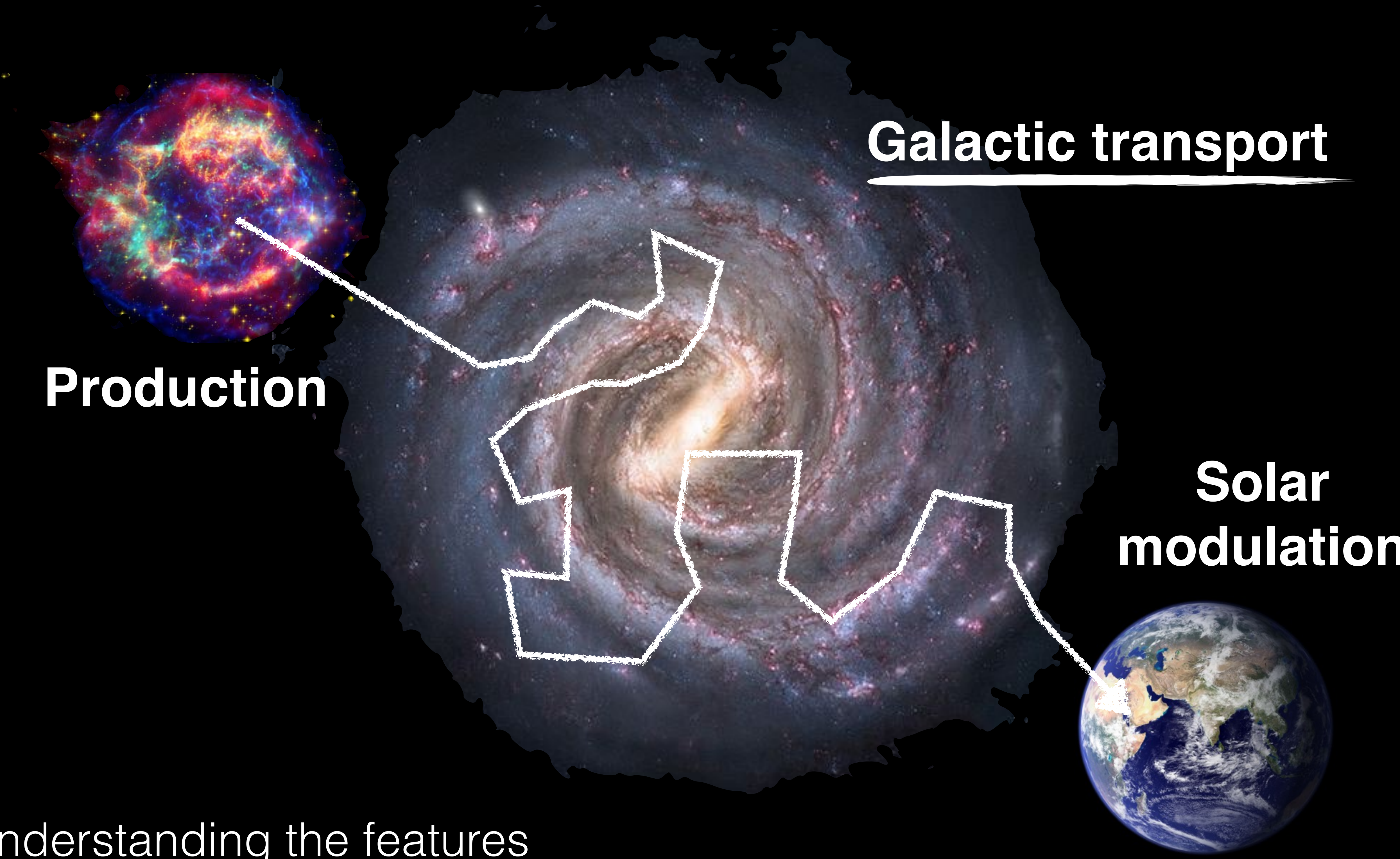
Electrons and positrons are emitted by **several sources**:

3. **Secondary emission**

$$\mathcal{Q}^{e^\pm}_{\rm sec}(r,z,E_{e^\pm}) = 4\pi \sum_{\rm CR=p,He} \sum_{\rm ISM=H,He} n_{\rm ISM} \int dE_{\rm CR} \Phi_{\rm CR}(r,z,E_{\rm CR}) \frac{d\sigma}{dE_{e^\pm}}(E_{\rm CR},E_{e^\pm})$$

- The **primary CR fluxes** $\Phi_{\rm CR}(r,z,E_{\rm CR})$ will be obtained by **fitting experimental measurements**
- Differential cross sections as in the MC- based model by **Kamae et al. 2005,2006**

From sources to Earth



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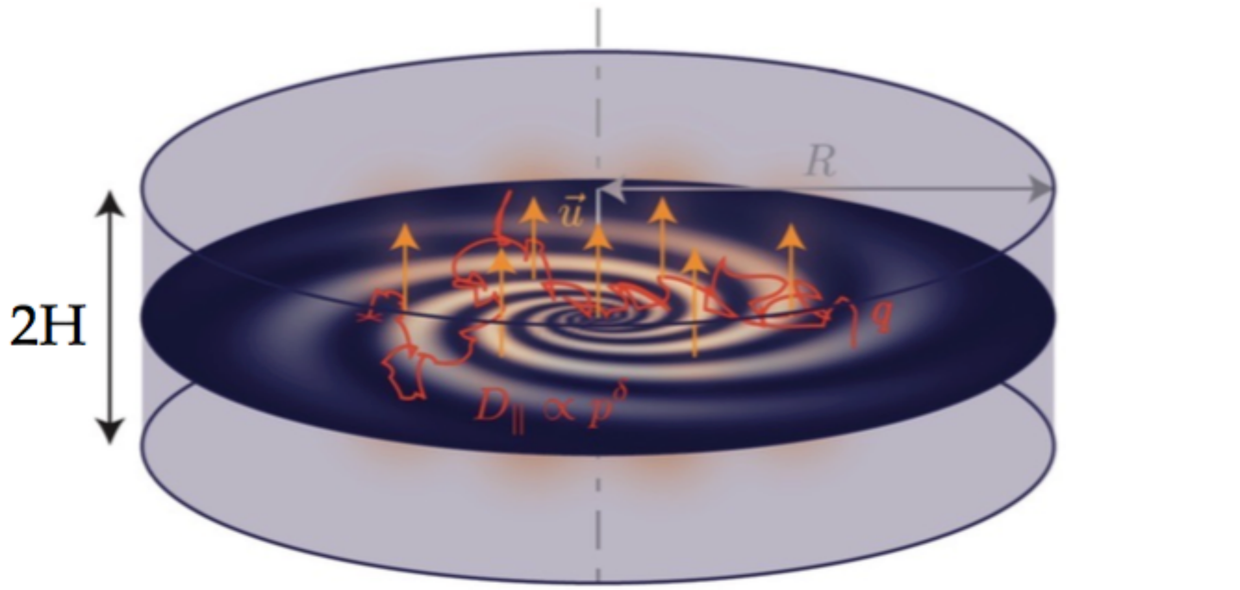
Transport of cosmic rays in the Galaxy



The transport of a generic CR species across the interstellar medium is described by a **transport equation**:

$$\frac{\partial N_i}{\partial t} - \nabla \cdot (D_{xx} \nabla N_i - \vec{v}_w N_i) + \frac{\partial}{\partial p}\left[p^2 D_{pp} \frac{\partial}{\partial p}\left(\frac{N_i}{p^2}\right)\right] - \frac{\partial}{\partial p}\left[\dot{p} N_i - \frac{p}{3}\left(\vec{\nabla} \cdot \vec{v}_w\right) N_i\right] = \mathcal{Q} - \frac{N_i}{\tau_i^f} + \sum_j \Gamma^s_{j\to i}(N_j) - \frac{N_i}{\tau_i^r} + \sum_j \frac{N_j}{\tau^r_{j\to i}}$$

N_i = CR momentum density

can be solved with **analytical** or **numerical** approaches

Transport of cosmic rays in the Galaxy

We consider a **simplified scenario** where **reacceleration and convection are neglected**

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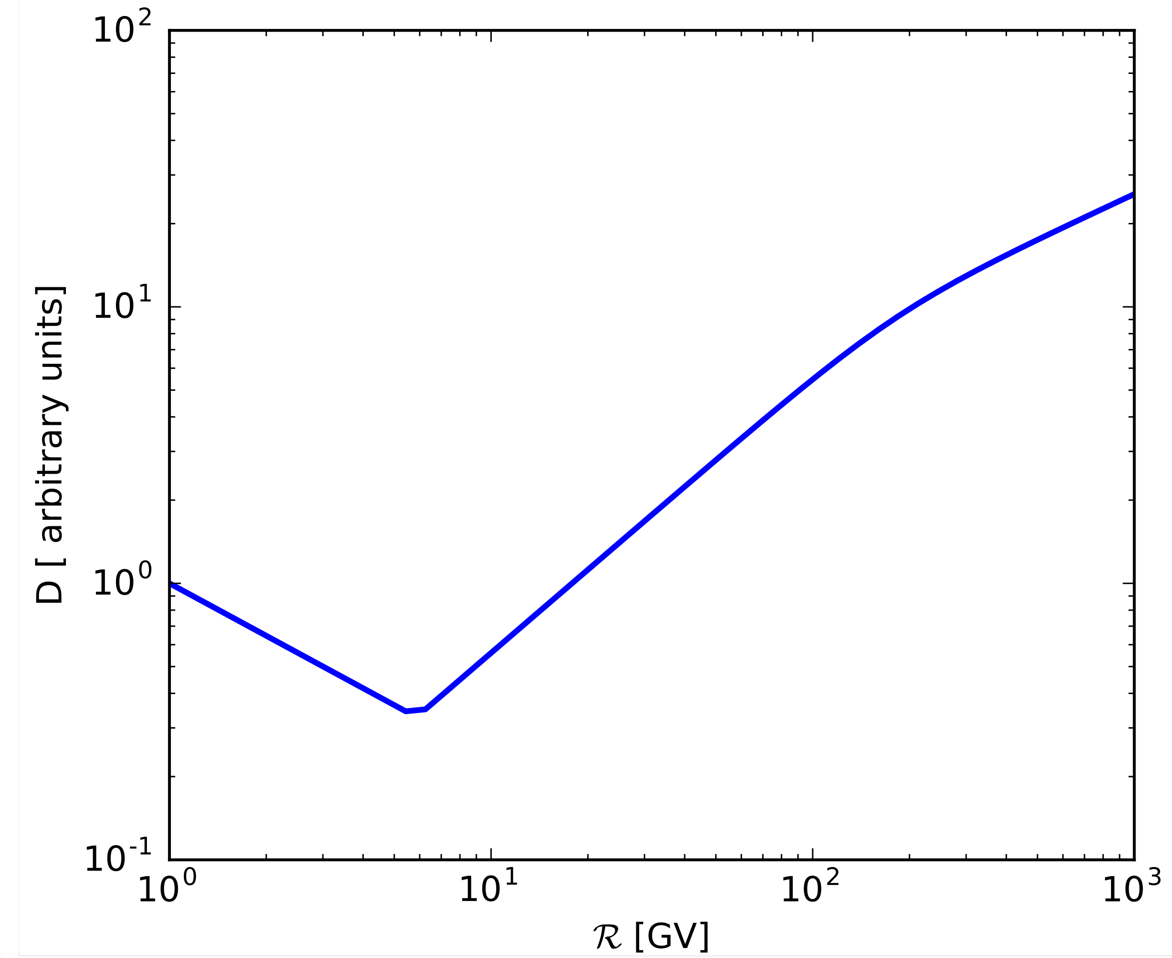
How do we model CR diffusion?

Modelling CR diffusion

$$D_{xx} = D(\mathcal{R})$$

We model the diffusion coefficient as homogenous and **isotropic in space**. The rigidity dependence is in terms of a **doubly broken power law**



$$D(\mathcal{R}) = D_0 \beta \times \begin{cases} \left(\frac{\mathcal{R}}{\mathcal{R}_0}\right)^{\delta_1} & \text{for } \mathcal{R} \leq \mathcal{R}_{b,1}\,, \\ \mathcal{C}\left(\frac{\mathcal{R}}{\mathcal{R}_{b,2}}\right)^{\delta_2} \left\{\frac{1}{2}\left[1 + \left(\frac{\mathcal{R}}{\mathcal{R}_{b,2}}\right)^{1/s}\right]\right\}^{(\delta_3-\delta_2)s} & \text{for } \mathcal{R} \geq \mathcal{R}_{b,1}\,, \end{cases}$$

free parameters

Modelling CR diffusion

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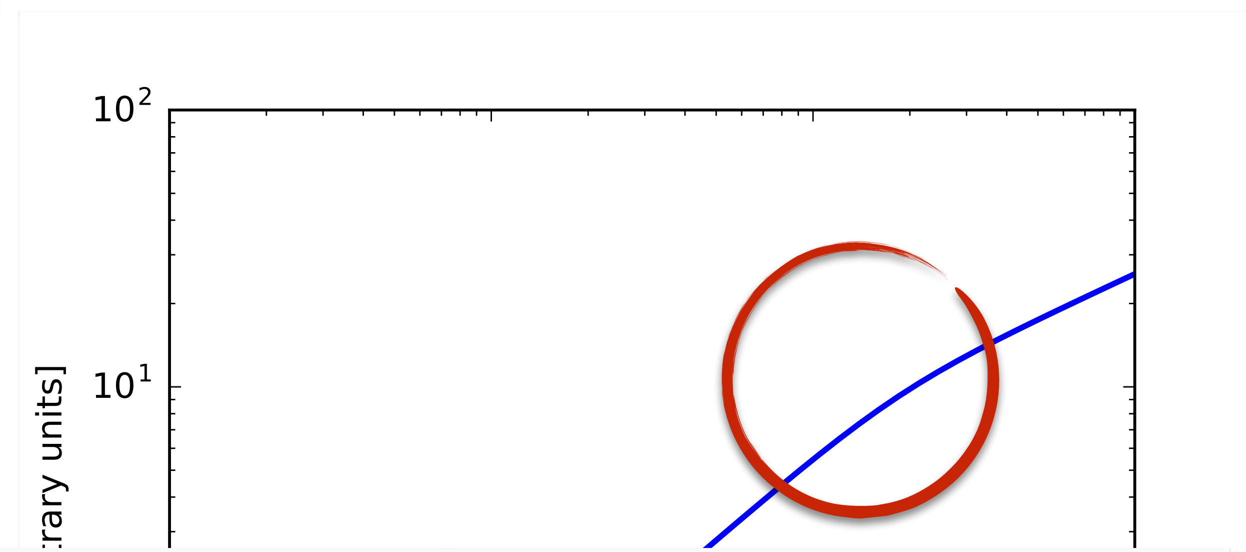

High-rigidity break

Observationally, required to fit the hardening at ~200 GV observed in primary and secondary CRs **[AMS-02 2015, 2018]**.

Theoretically, it can be related to the **transition** between diffusion in **different turbulent regimes** **[Blasi et al. 2012]**

$$D(\mathcal{R}) = D_0\beta \times \begin{cases} \left(\frac{\mathcal{R}}{\mathcal{R}_0}\right) \dots \\ \mathcal{C}\left(\frac{\mathcal{R}}{\mathcal{R}_{b,2}}\right) \dots \end{cases}$$

Modelling CR diffusion

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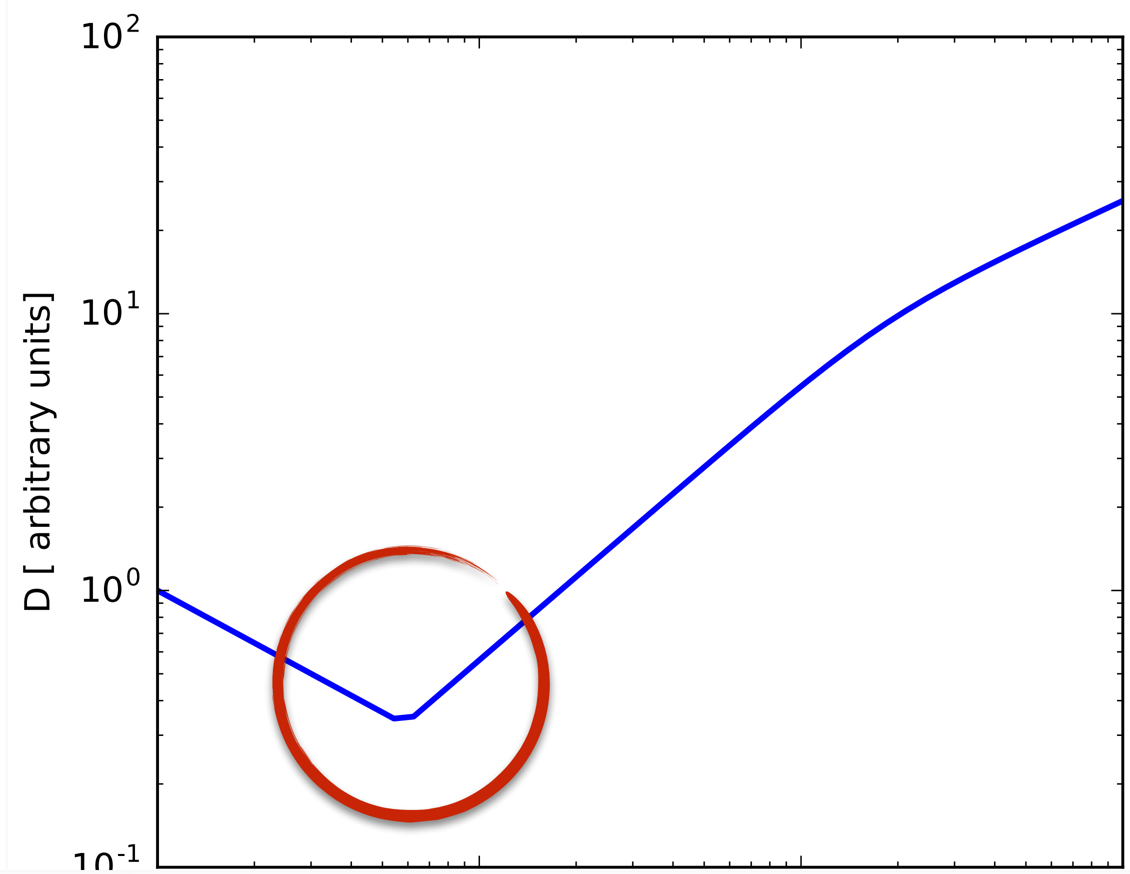

Low-rigidity break

Observationally, it is required to fit the **low-rigidity peak** of the **B/C ratio** in purely diffusive scenarios.

Theoretically, it can be related to the **damping** of turbulence on cosmic rays at low rigidities **[Ptuskin et al., 2006]**.

Fitting CR nuclear data

We constrain the **diffusion parameters** and the **secondary $e^{\pm}$ contribution** by fitting AMS-02 **B/C**, **proton** and **helium** data:

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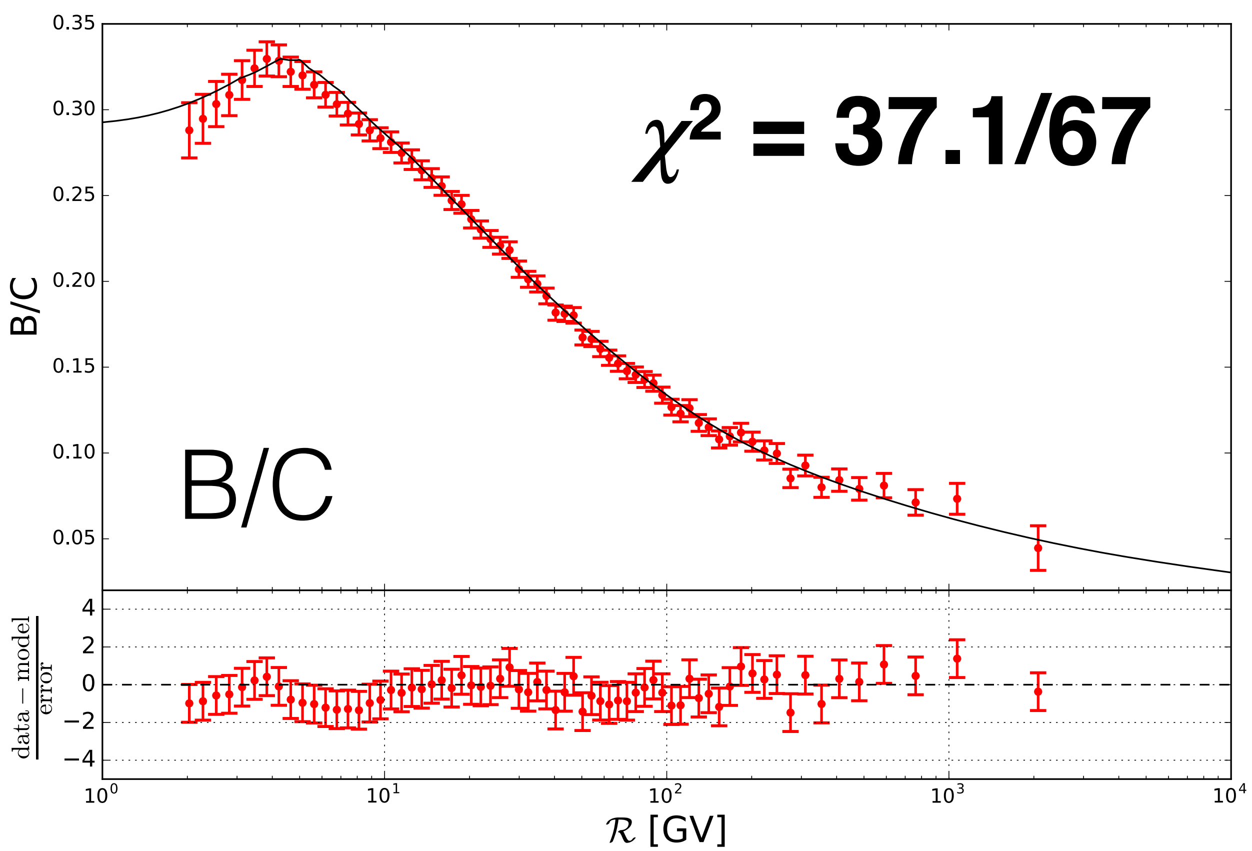

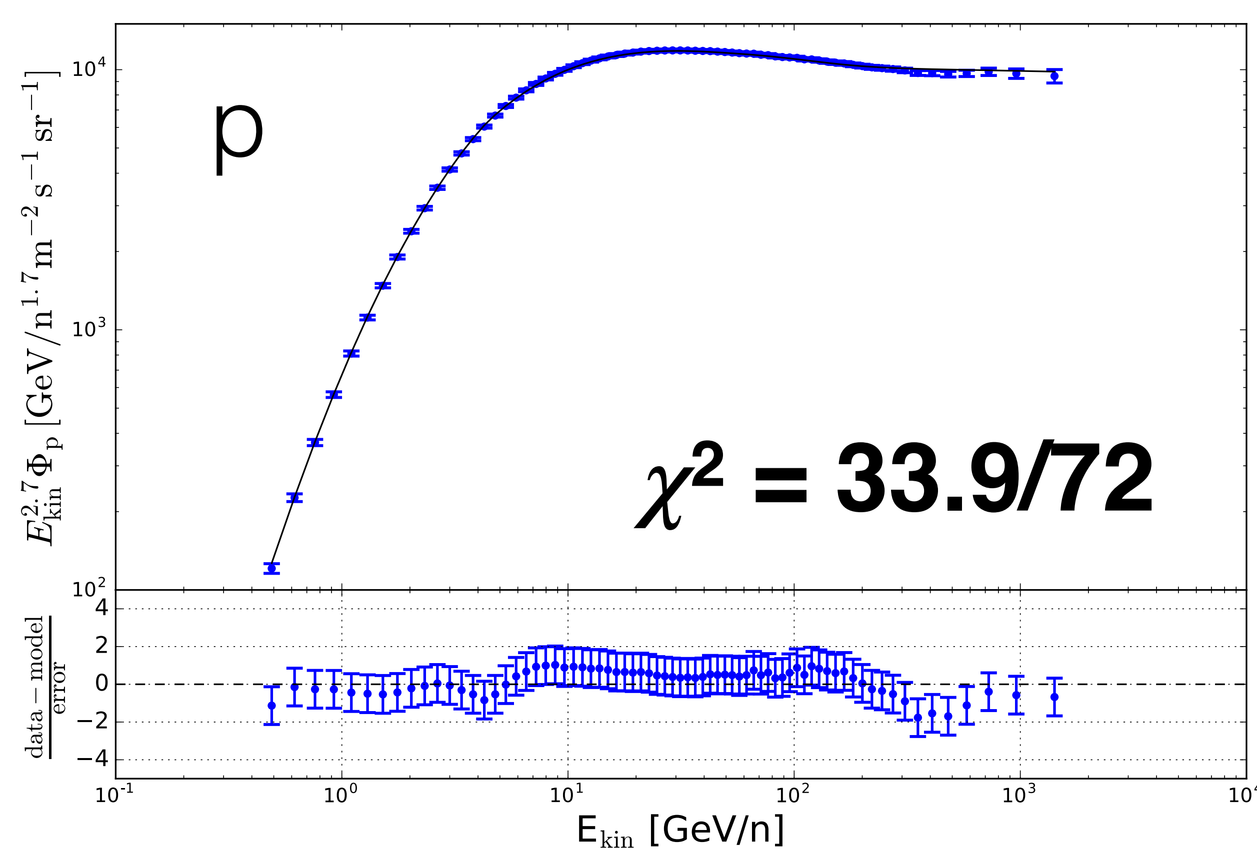

data from **Aguilar et al., PRL 117 (2016)**

solar modulation : standard force field approx

D_0	δ_1	δ_2	δ_3	$\mathcal{R}_{b,1}$	$\mathcal{R}_{b,2}$	s	q_p	$\theta_{p,1}$	$\theta_{p,2}$	$\mathcal{R}_{b,p}$	φ_{nuclei}	φ_p
4.01	-0.63	0.56	0.34	5.86	182.39	0.34	0.002	3.03	2.38	5.90	0.72	0.75

diffusion parameters

p injection

solar mod

Fitting CR nuclear data

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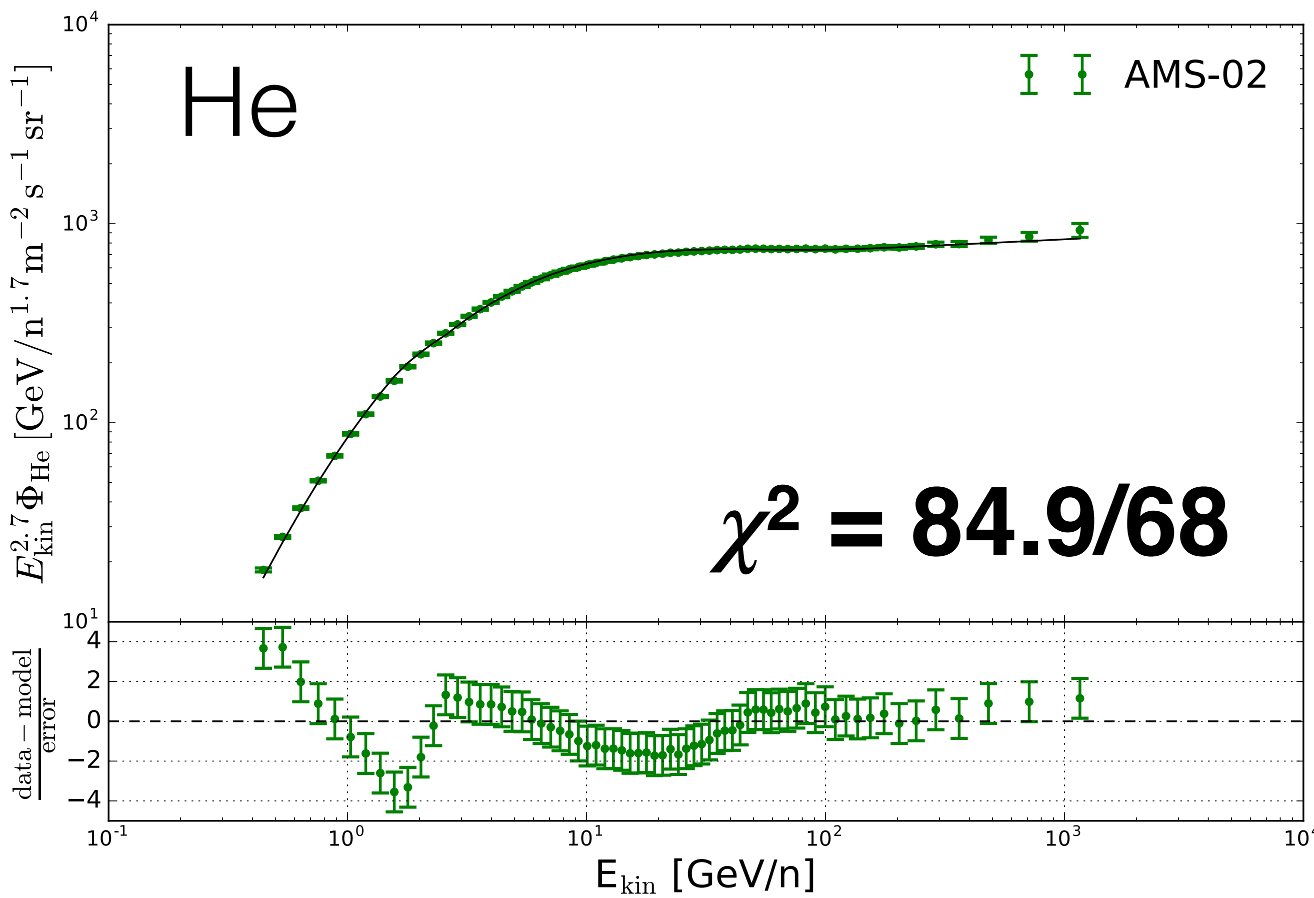

solar modulation : standard force field approx

data from **Aguilar et al., PRL 120 (2018)**

$\theta_{\rm He,1}$	$\theta_{\rm He,2}$	$\mathcal{R}_{b,\rm He}$	$\varphi_{\rm nuclei}$
2.83	2.31	7.48	0.72

He injection   solar mod

Investigating the $e^{\pm}$ spectra

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  - SNRs : N_{e-} , Γ_a "0 breaks" model
  - Extra source : N_x , Γ_x

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- We fit the following **datasets**:

1. **AMS-02 e$^-$ and e$^+$ 2011-2013 spectra**, above **20 GeV** **[Aguilar et al., PRL 113, 121102 (2014)]**
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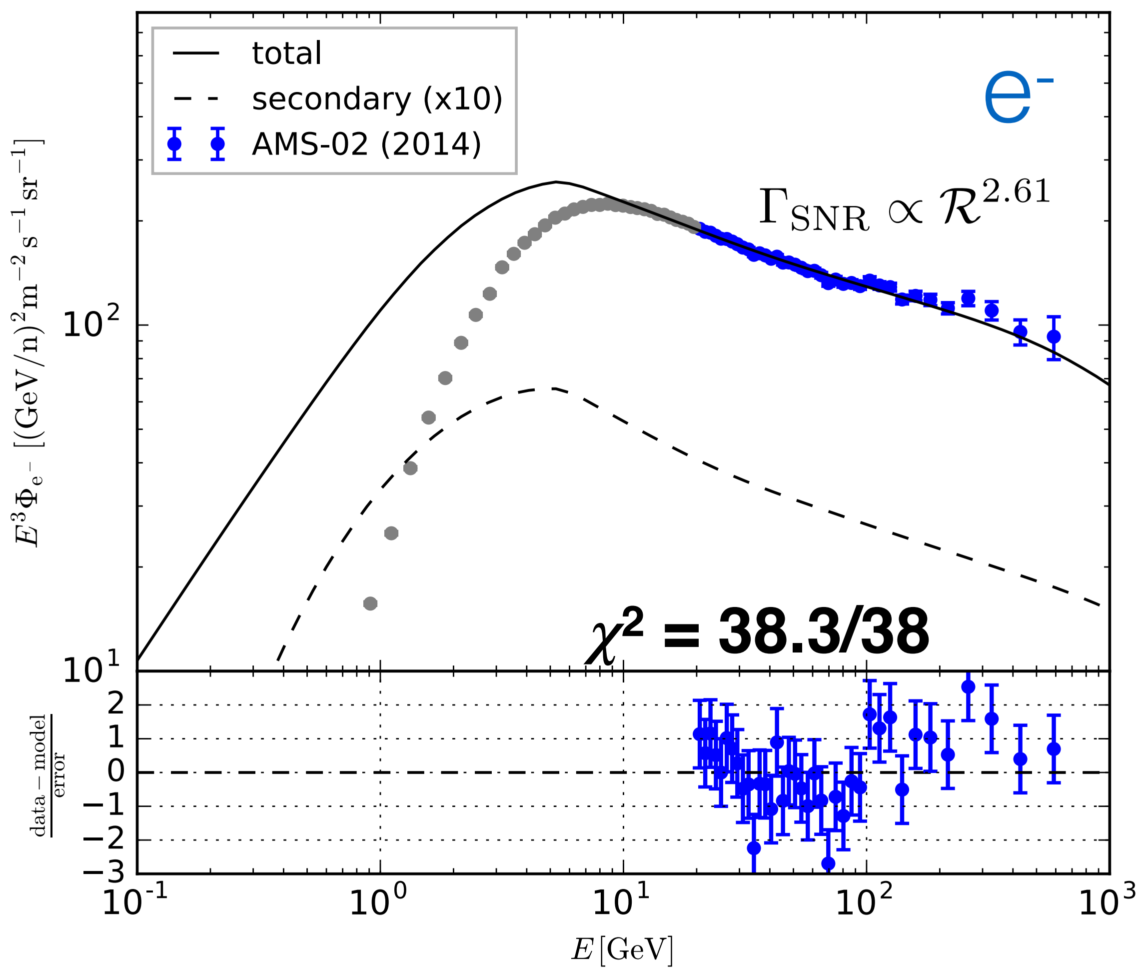
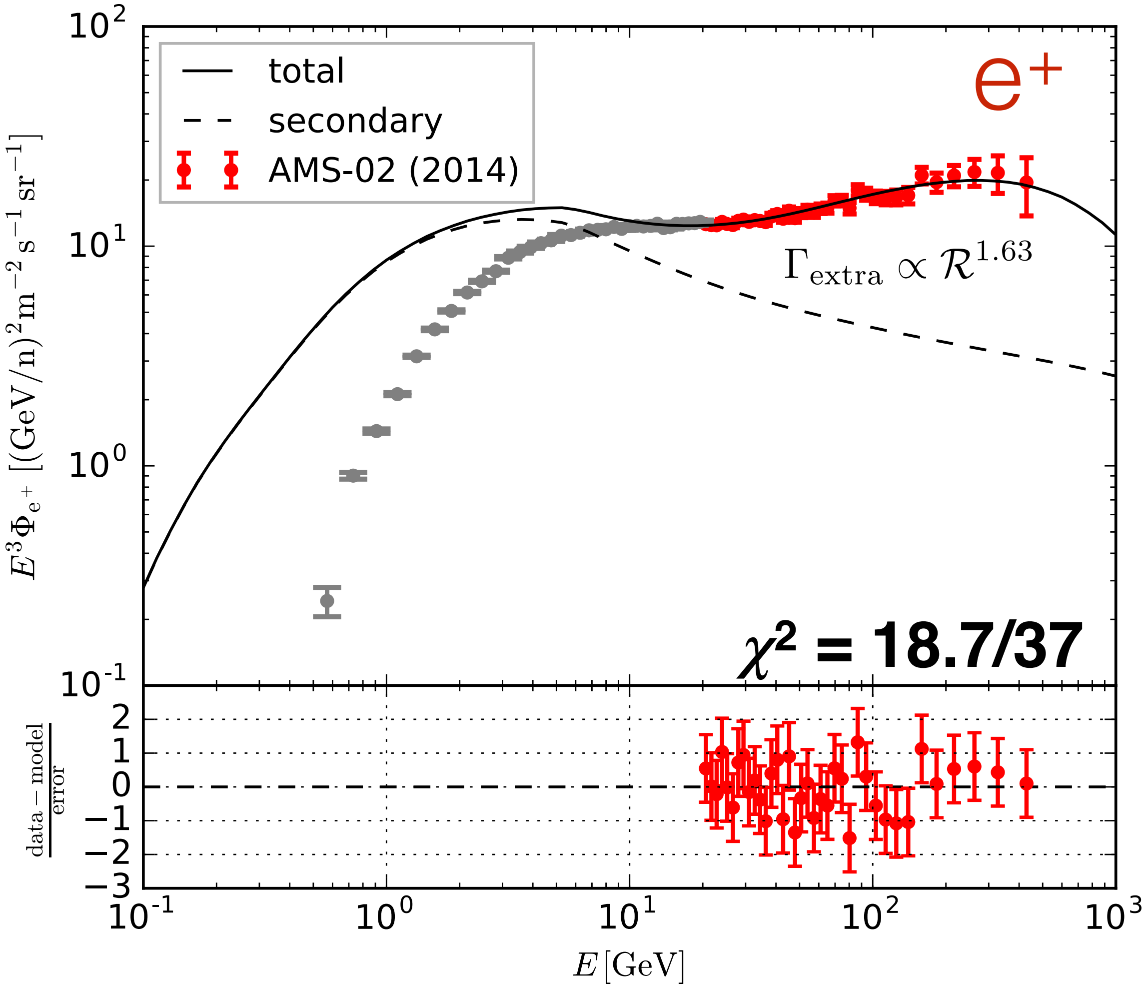
Results of the fit - 0 breaks model





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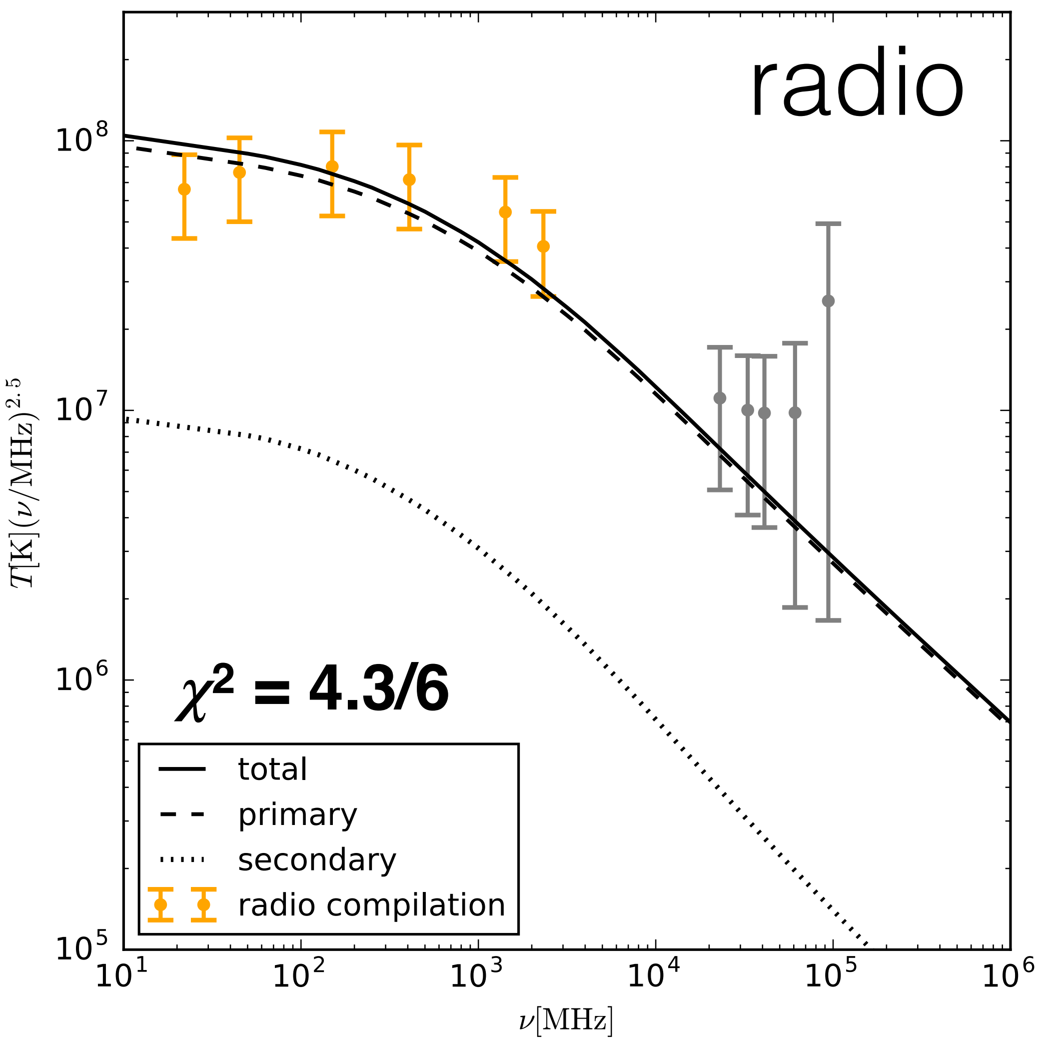

best-fit parameters

N_{e^-}	$4.31^{+0.07}_{-0.07} \times 10^{-3}$	Normalisation of the SNR flux at 30 GV
N_x	$2.56^{+0.08}_{-0.08} \times 10^{-4}$	Normalisation of the extra component flux at 30 GV
Γ_x	$1.630^{+0.04}_{-0.006}$	Slope of the extra component flux
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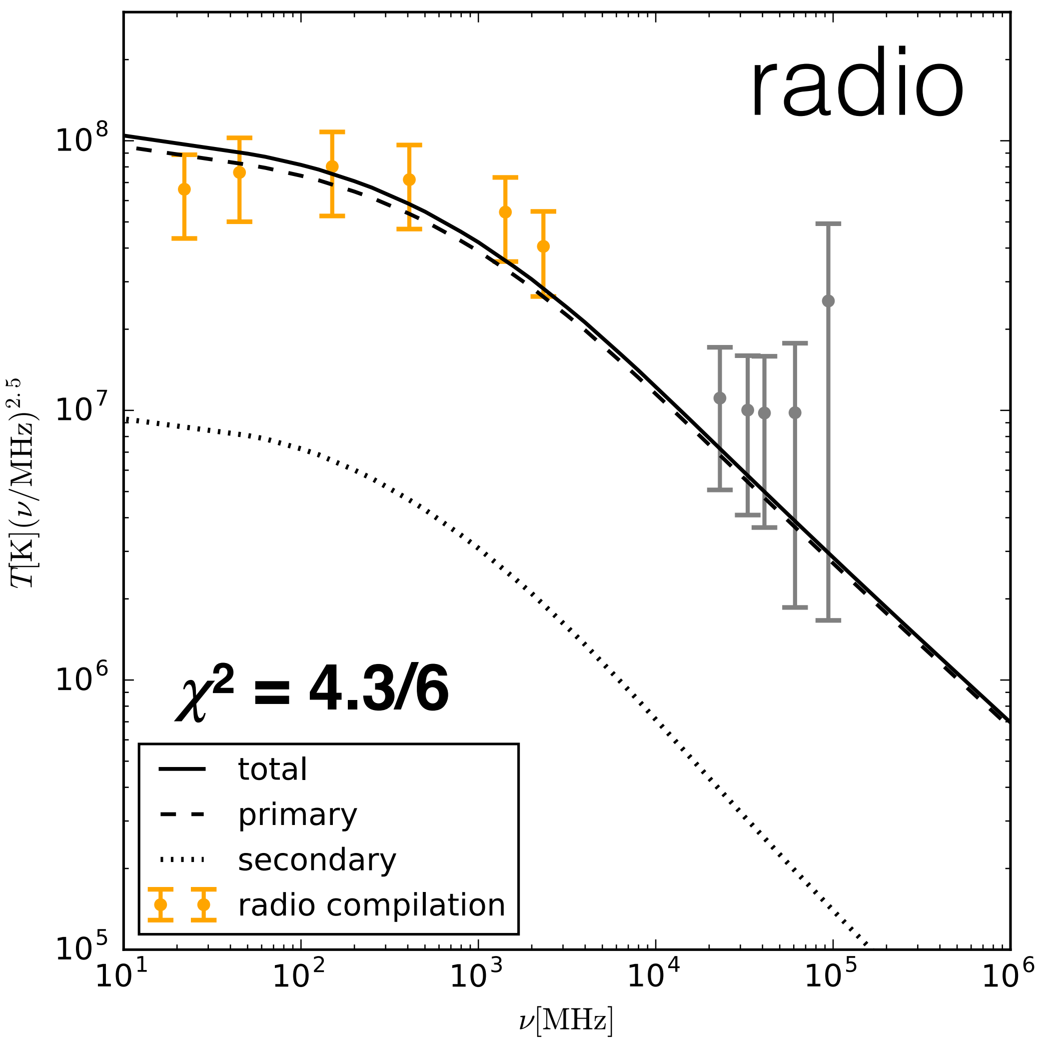

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This very simple model is able to reproduce remarkably well high energy and radio data.

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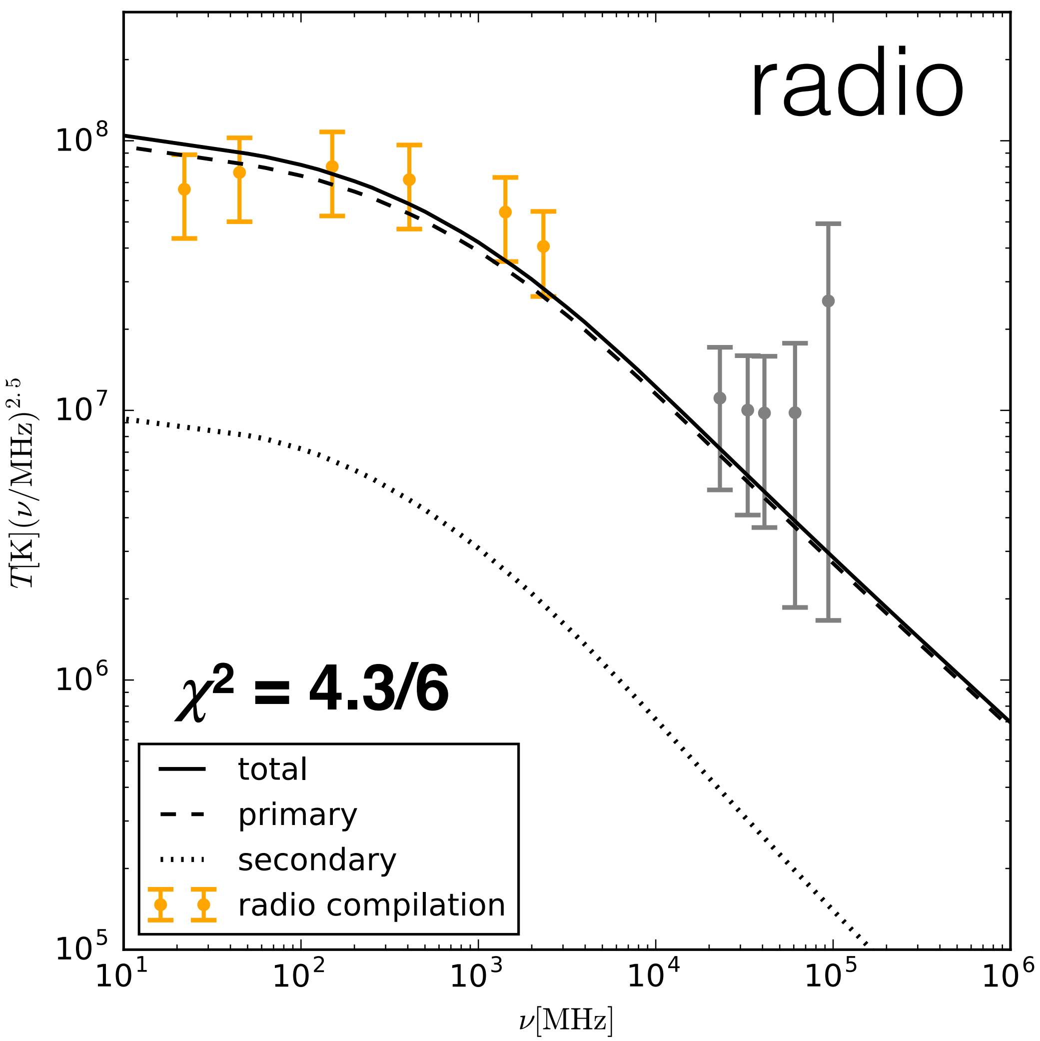

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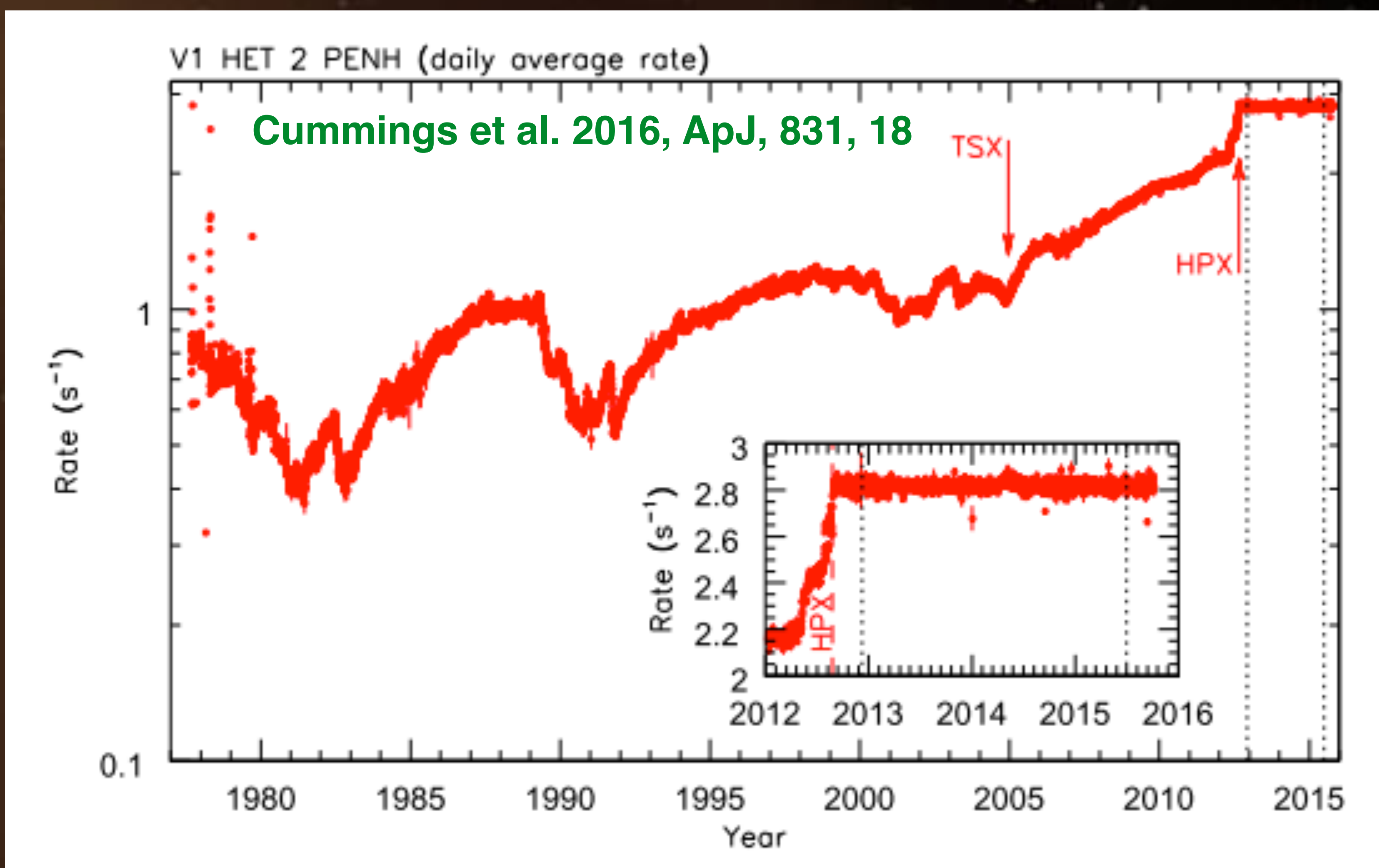
How does this model perform at very low energies?

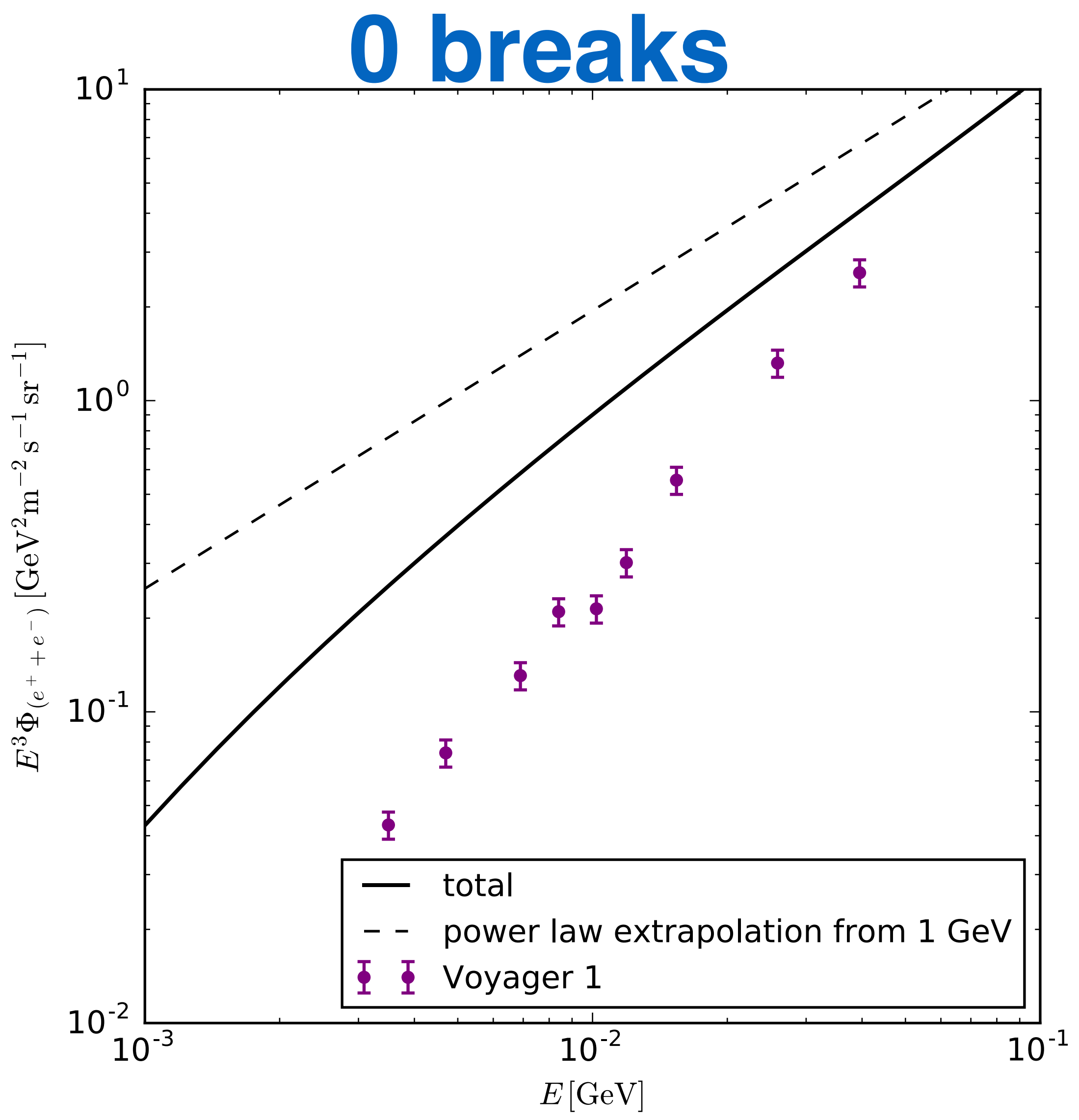
Voyager 1

Launched in 1977, the Voyager I spacecraft has crossed the heliopause in 2012



“0 breaks” model

Voyager data



The “0 breaks” model is **not able** to reproduce Voyager I data

Investigating the $e^{\pm}$ spectra - Adding 1 break

- We repeat the fit assuming that the e^- spectrum injected by SNRs is a **power-law with one break**.

"1 break" model

$$\mathcal{Q}_{\rm SNR}(r,z,\mathcal{R}) = \mathcal{Q}_0 f(r,z) g(\mathcal{R}) \quad \text{with} \quad g(\mathcal{R}) = \begin{cases} \left(\frac{\mathcal{R}}{\mathcal{R}^*}\right)^{-\Gamma_1} & \text{for } \mathcal{R} \leq \mathcal{R}_1 , \\ \left(\frac{\mathcal{R}_1}{\mathcal{R}^*}\right)^{-\Gamma_1} \left(\frac{\mathcal{R}}{\mathcal{R}_1}\right)^{-\Gamma_2} & \text{for } \mathcal{R} > R_1 \end{cases}$$

4 free parameters

- We fit the following **datasets**:

1. **AMS-02 e^- and e^+ 2011-2013 spectra**, above **20 GeV** **[Aguilar et al., PRL 113, 121102 (2014)]**
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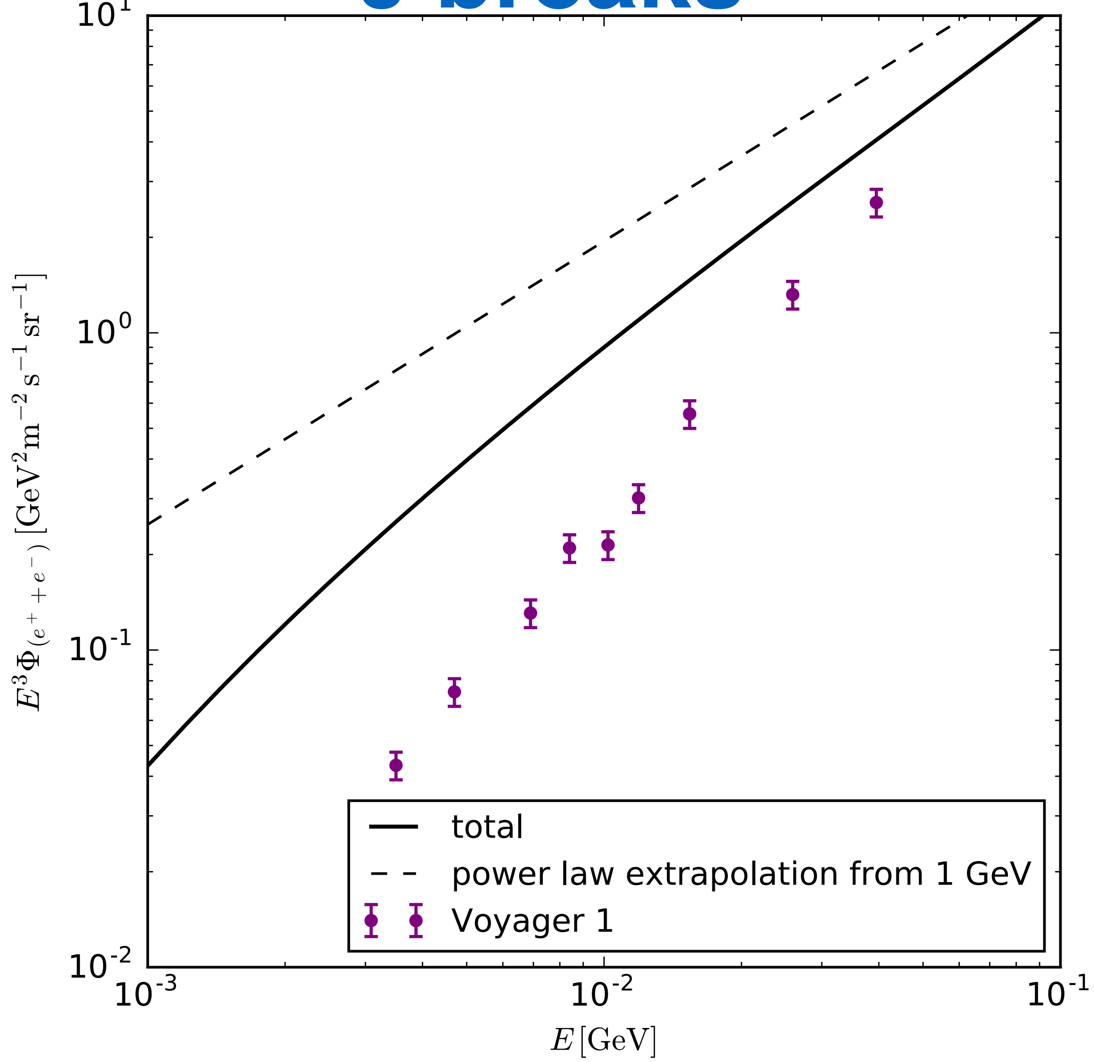
3. **Voyager $e^+ + e^-$ spectrum [Cummings et al. 2016, ApJ, 831, 18]**

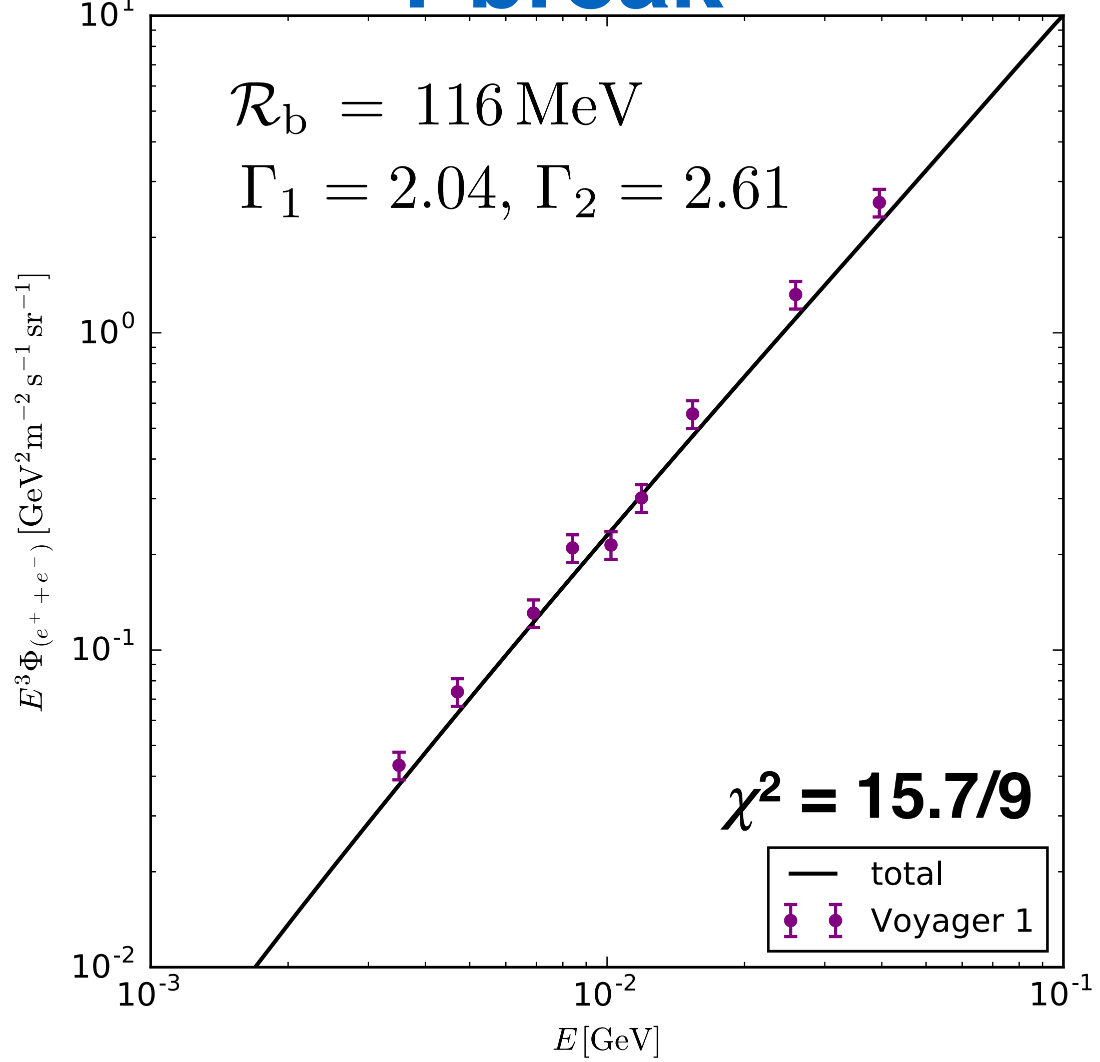
“1 break” vs. “0 breaks”

Voyager data

0 breaks



1 break



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$N_{\rm x}$	$2.56^{+0.07}_{-0.08} \times 10^{-4}$	Normalization of the extra component flux at 30 GV
$\Gamma_{\rm x}$	$1.636^{+0.006}_{-0.005}$	Slope of the extra component flux
$\mathcal{R}_1$	$0.1159^{+0.0002}_{-0.0014}$	rigidity break of the SNR flux [GV]
Γ_1	$2.040^{+0.006}_{-0.013}$	Slope of the SNR flux (below the break)
Γ_2	$2.607^{+0.007}_{-0.006}$	Slope of the SNR flux (above the break)
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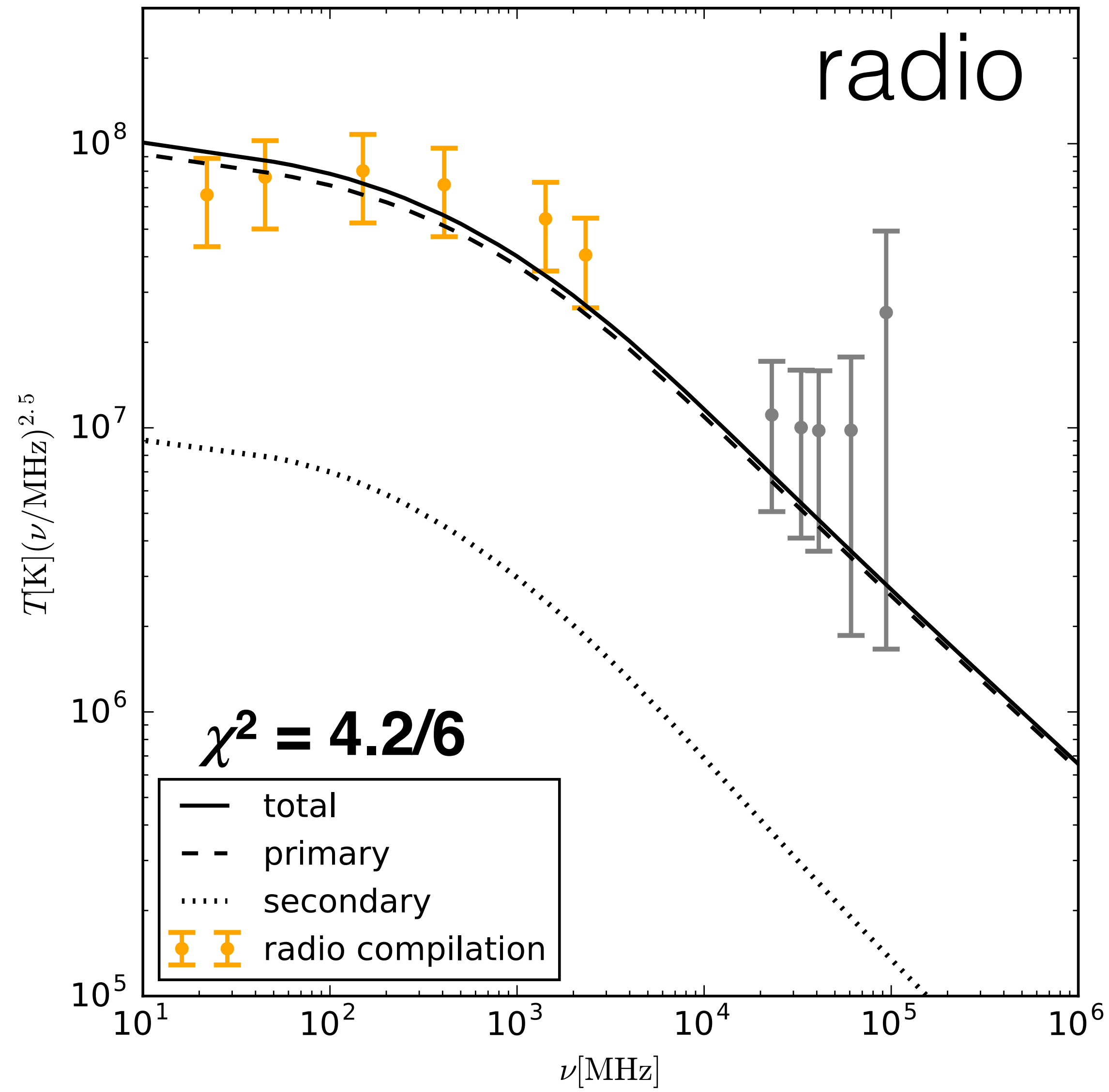

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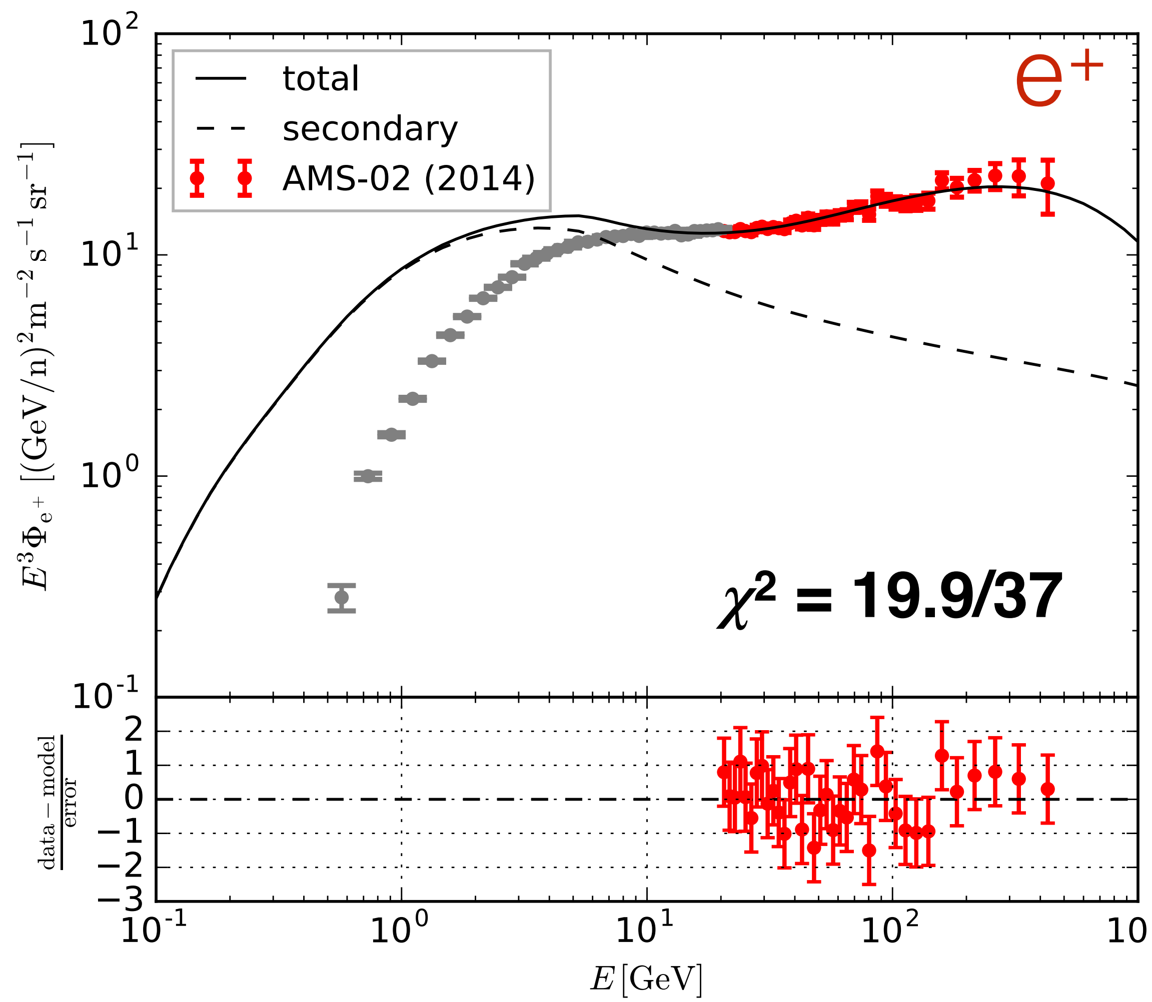

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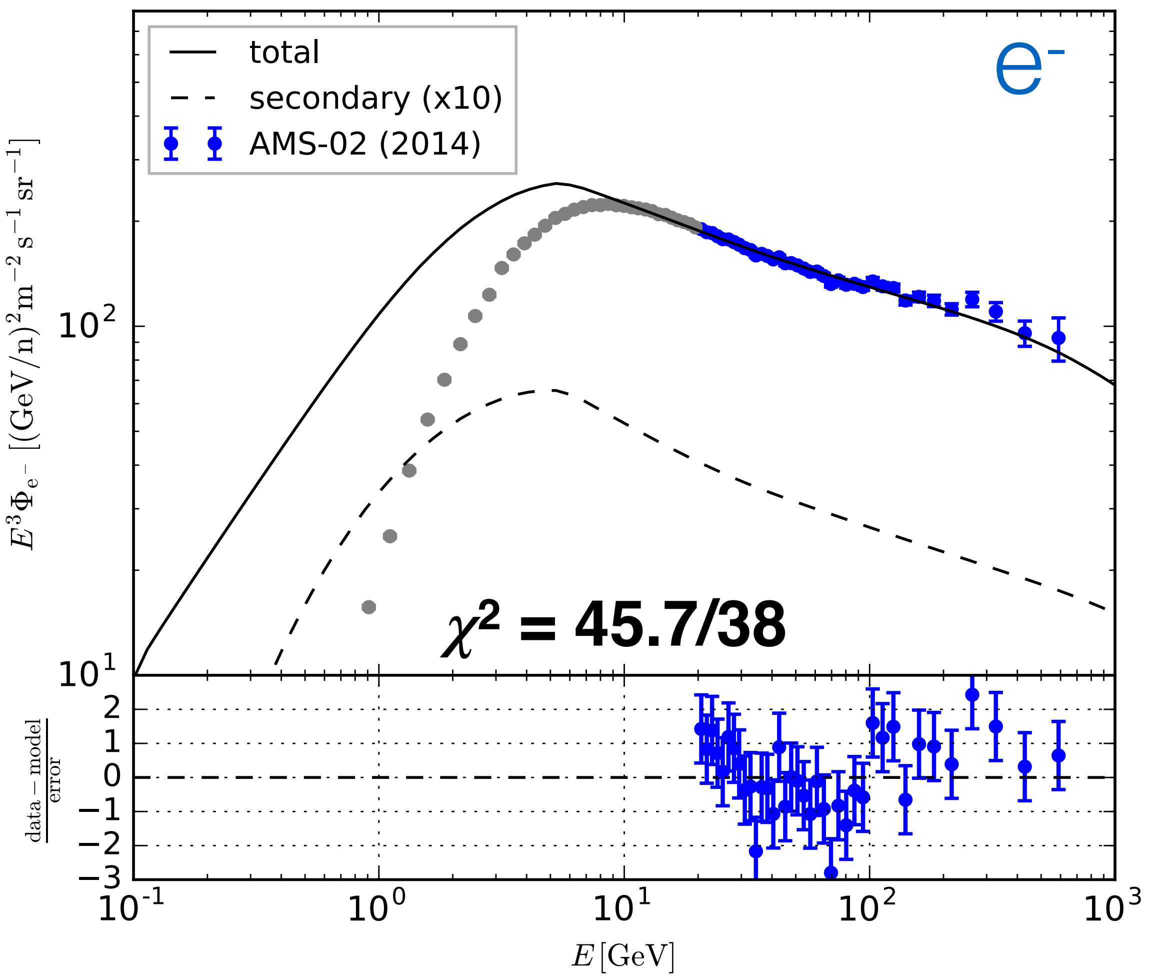

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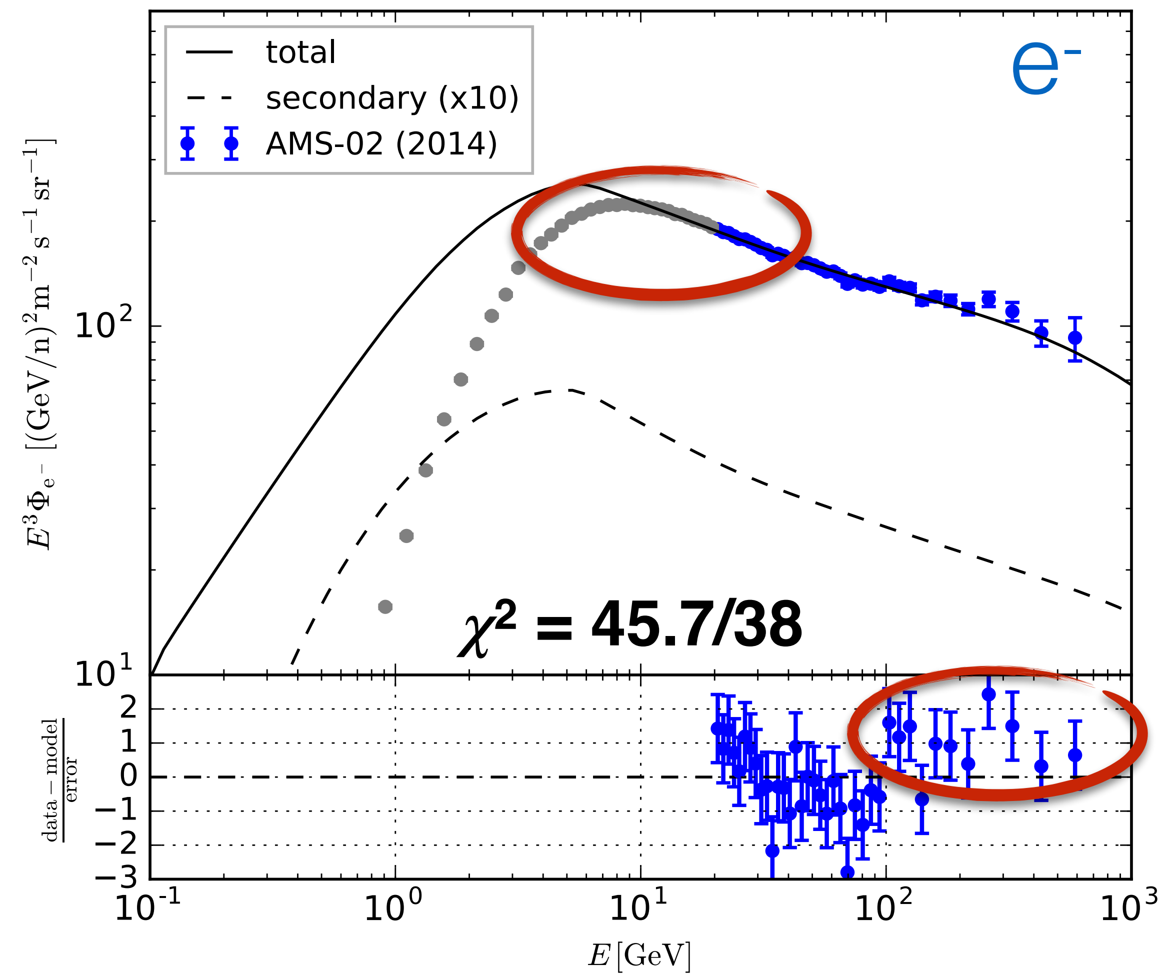


- At **low energies** the electron LIS appears to be **lower than AMS-02 data**. Will there be **enough room** for **solar modulation**?
- The **residuals** are large at **high energies**

Investigating the e$^{\pm}$ spectra - solar modulation

- The e$^-$ spectrum injected by SNRs is a **power-law with two breaks**.

"2 break" model

$$\mathcal{Q}_{\rm SNR}(r,z,\mathcal{R}) = \mathcal{Q}_0 f(r,z) g(\mathcal{R}) \text{ with } g(\mathcal{R}) = \begin{cases} \left(\frac{\mathcal{R}}{\mathcal{R}^*}\right)^{-\Gamma_1} & \text{for } \mathcal{R} \leq \mathcal{R}_1, \\ \left(\frac{\mathcal{R}_1}{\mathcal{R}^*}\right)^{-\Gamma_1} \left(\frac{\mathcal{R}}{\mathcal{R}_1}\right)^{-\Gamma_2} & \text{for } R_1 < \mathcal{R} \leq R_2 \\ \left(\frac{\mathcal{R}_1}{\mathcal{R}^*}\right)^{-\Gamma_1+\Gamma_2} \left(\frac{\mathcal{R}_2}{\mathcal{R}_*}\right)^{-\Gamma_2} \left(\frac{\mathcal{R}}{\mathcal{R}_2}\right)^{-\Gamma_3} & \text{for } \mathcal{R} > \mathcal{R}_2 \end{cases}$$

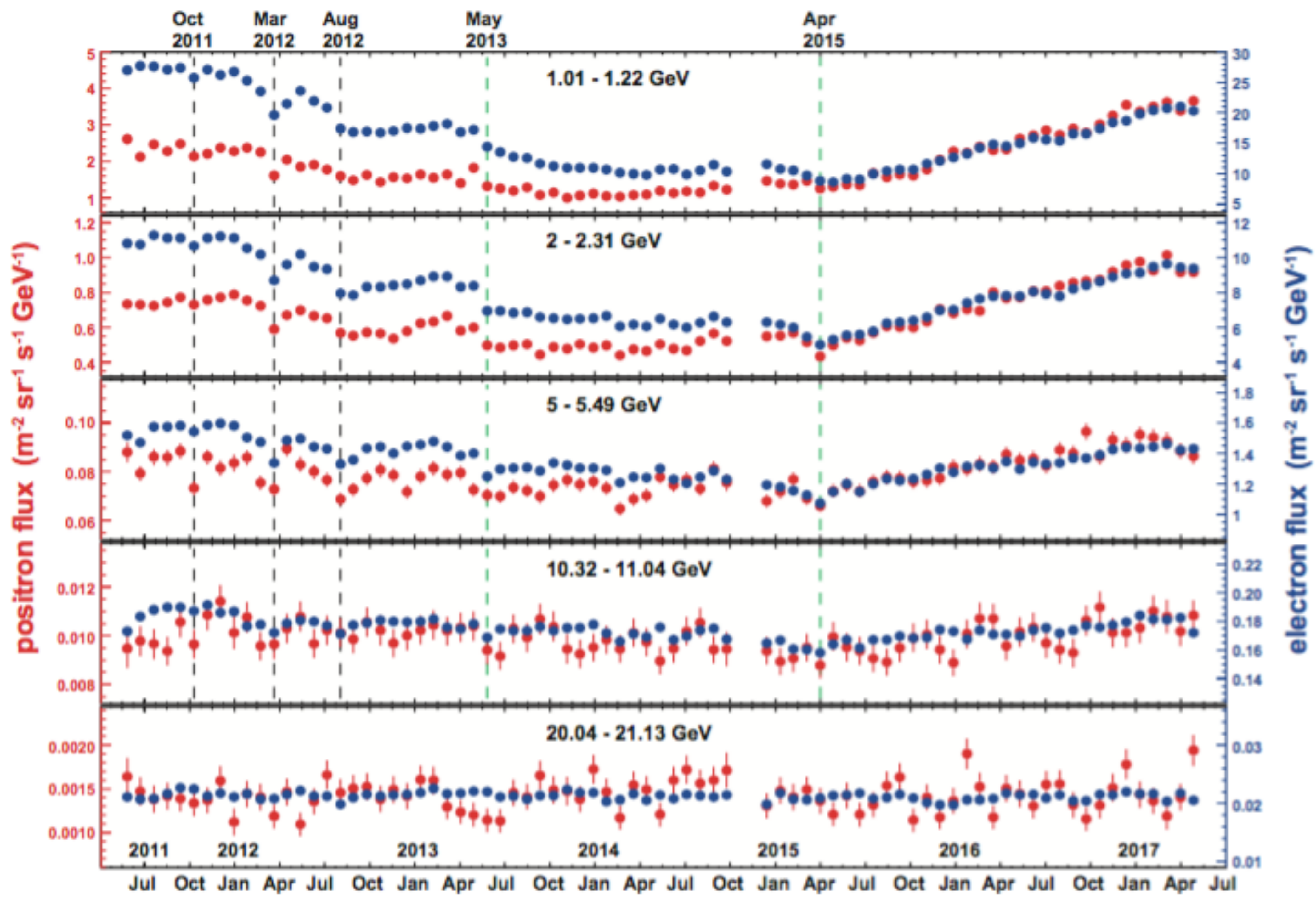
6 free parameters

- **We now consider solar modulation**.

- We fit the following **datasets**:

1. **AMS-02 e$^-$ and e$^+$ 2011-2013 spectra**, above **40 GeV**
   Aguilar et al., PRL 113, 121102 (2014)
2. **Radio data** : diffuse radio emission integrated over the high-latitude sky, in the 22 MHz - 2.3 GHz range
3. **Voyager e+ + e- spectrum**
   Cummings et al. 2016, ApJ, 831, 18
4. **AMS-02 time dependent e+ and e- data** .
   Aguilar et al. Phys. Rev. Lett. 120, 021101 (2018)

AMS-02 time dependent spectra



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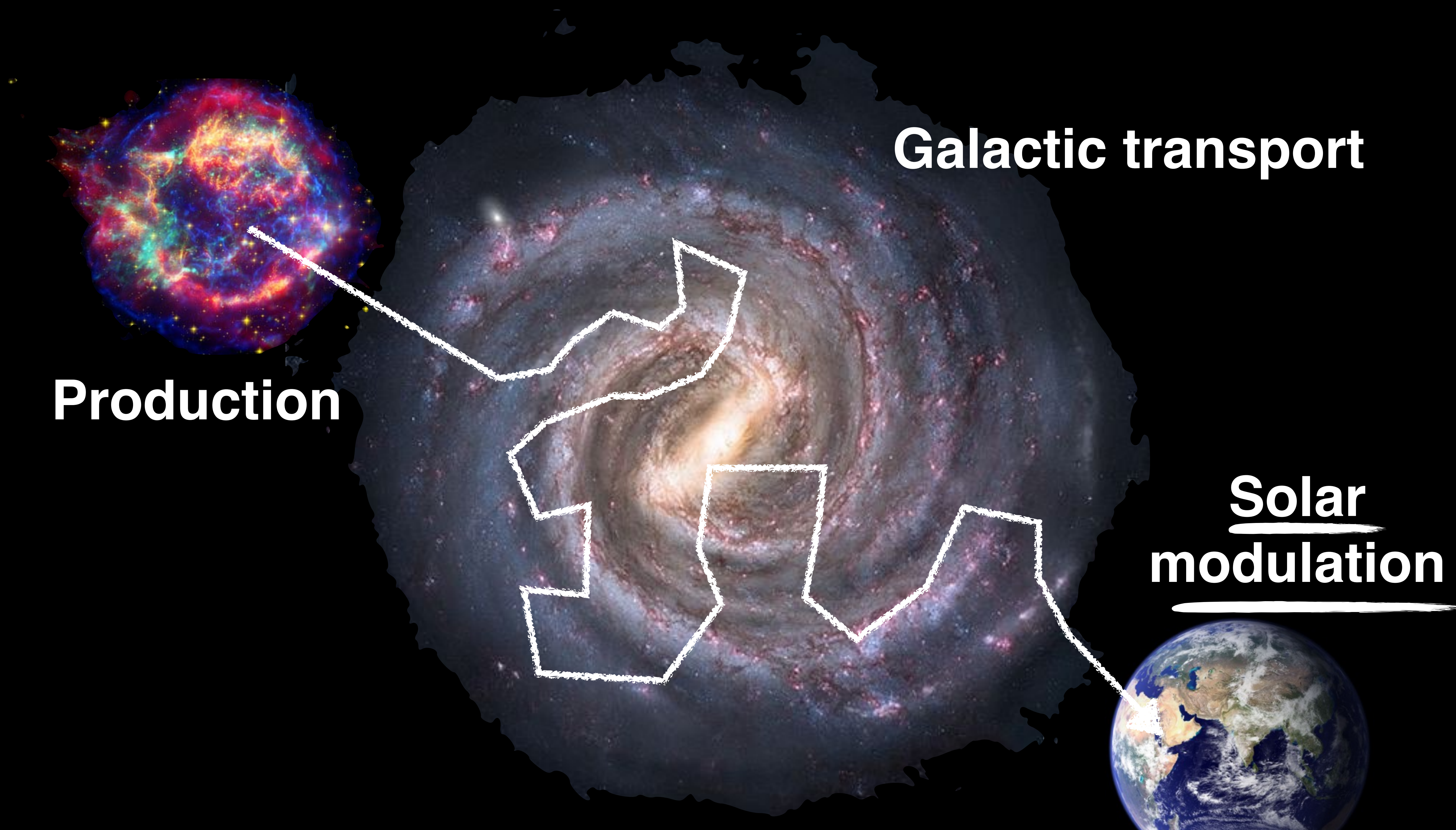
From sources to Earth



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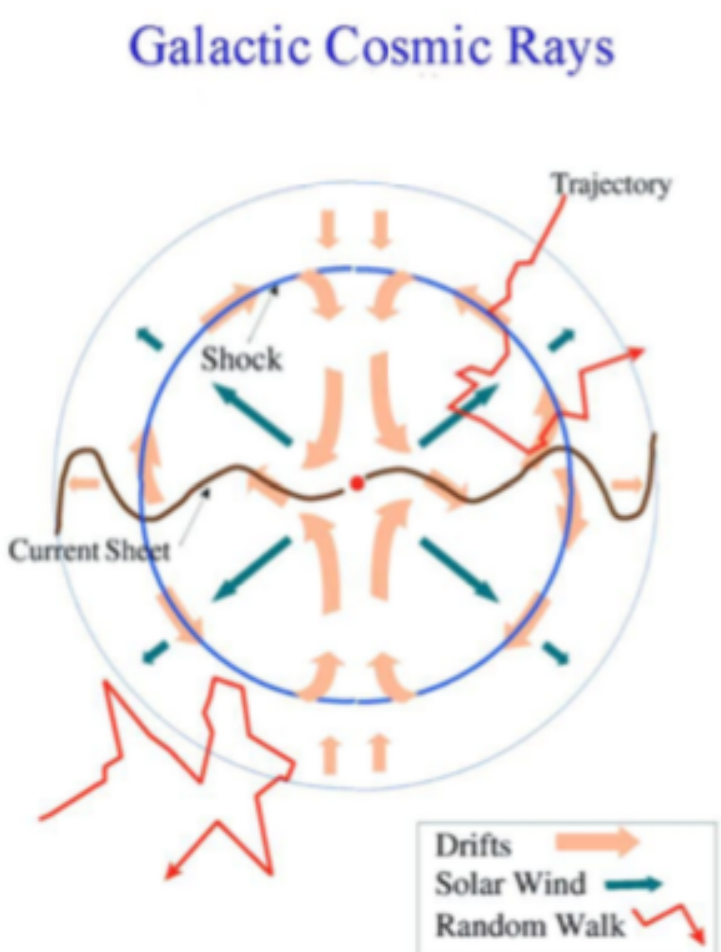
accurate modelling of all these processes

Solar modulation



The **interaction of CRs** with the different elements of the heliosphere is described in terms of a **transport equation**

$$\frac{\partial f}{\partial t} + \vec{V}_{\rm sw} \cdot \nabla f - \nabla K \nabla f - \frac{\mathcal{R}}{3}(\nabla \cdot \vec{V}_{\rm sw})\frac{\partial f}{\partial \mathcal{R}} = Q^{\rm helio}$$

Force field approximation

Gleeson and Axford, 1968

Assumptions:

- Steady state
- Spherical symmetry
- Constant radial solar wind velocity
- The advective and convective fluxes are equal:

$$V_{\rm sw} f - K \frac{\partial f}{\partial r} = 0$$

Under the additional assumption that $K = K_0 \mathcal{R}$ one finds the usual relations:

$$J_{\rm TOA}(\mathcal{R}_{\rm TOA}) = \frac{\mathcal{R}^2_{\rm TOA}}{\mathcal{R}^2_{\rm LIS}} J_{\rm LIS}(\mathcal{R}_{\rm LIS})$$

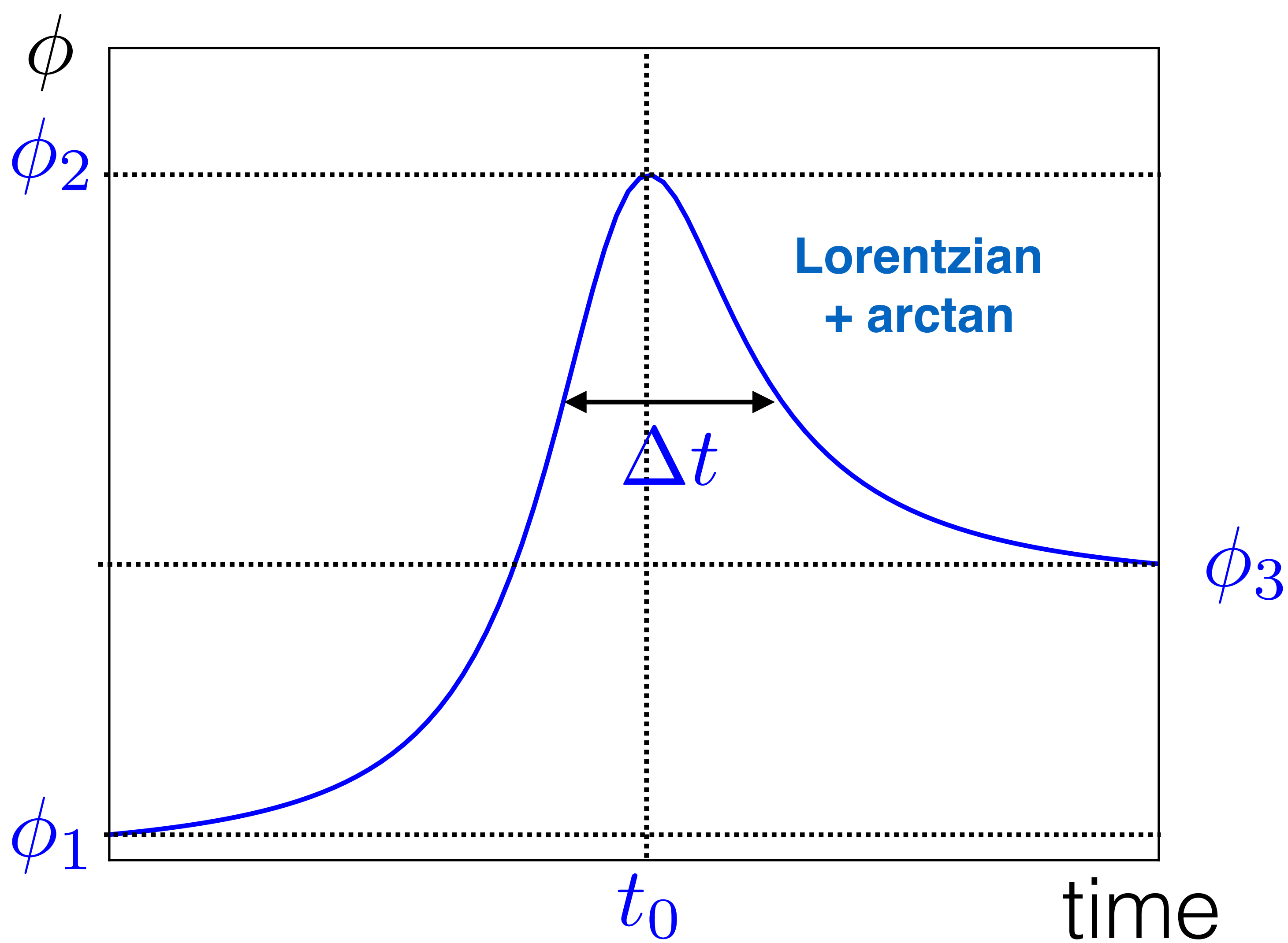
$$\mathcal{R}_{\rm TOA} = \mathcal{R}_{\rm LIS} - \phi$$

$$\phi = \frac{V_{\rm sw} R_{\rm helio}}{3 K_0}$$

Extending the force-field approx

We **extend** the force field approximation:

By taking a time-dependent force field potential (with $\phi_{e^+} \neq \phi_{e^-}$)

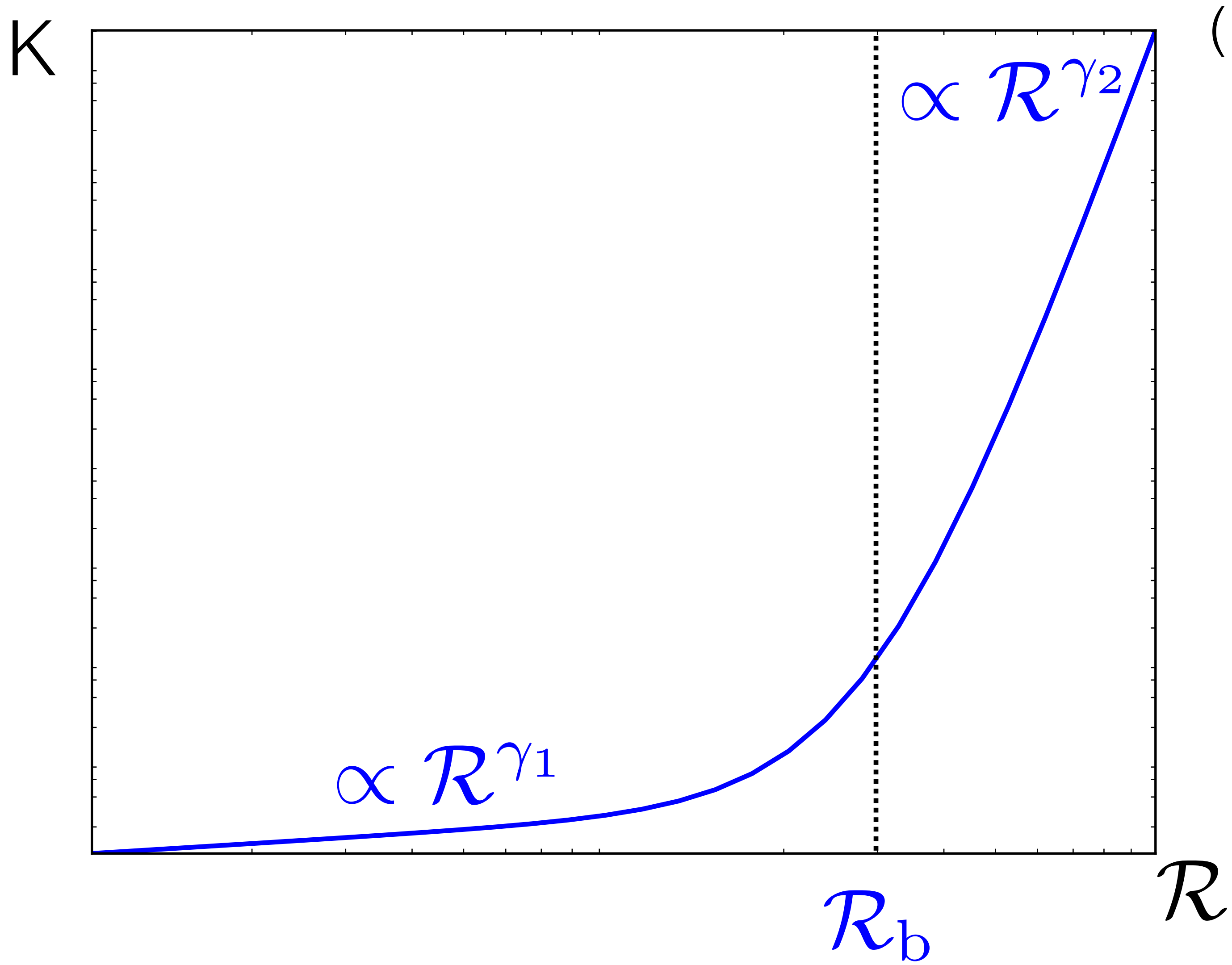


5 free parameters

Extending the force-field approx

We **extend** the force field approximation:

By changing the rigidity dependence of the diffusion coefficient in the heliosphere



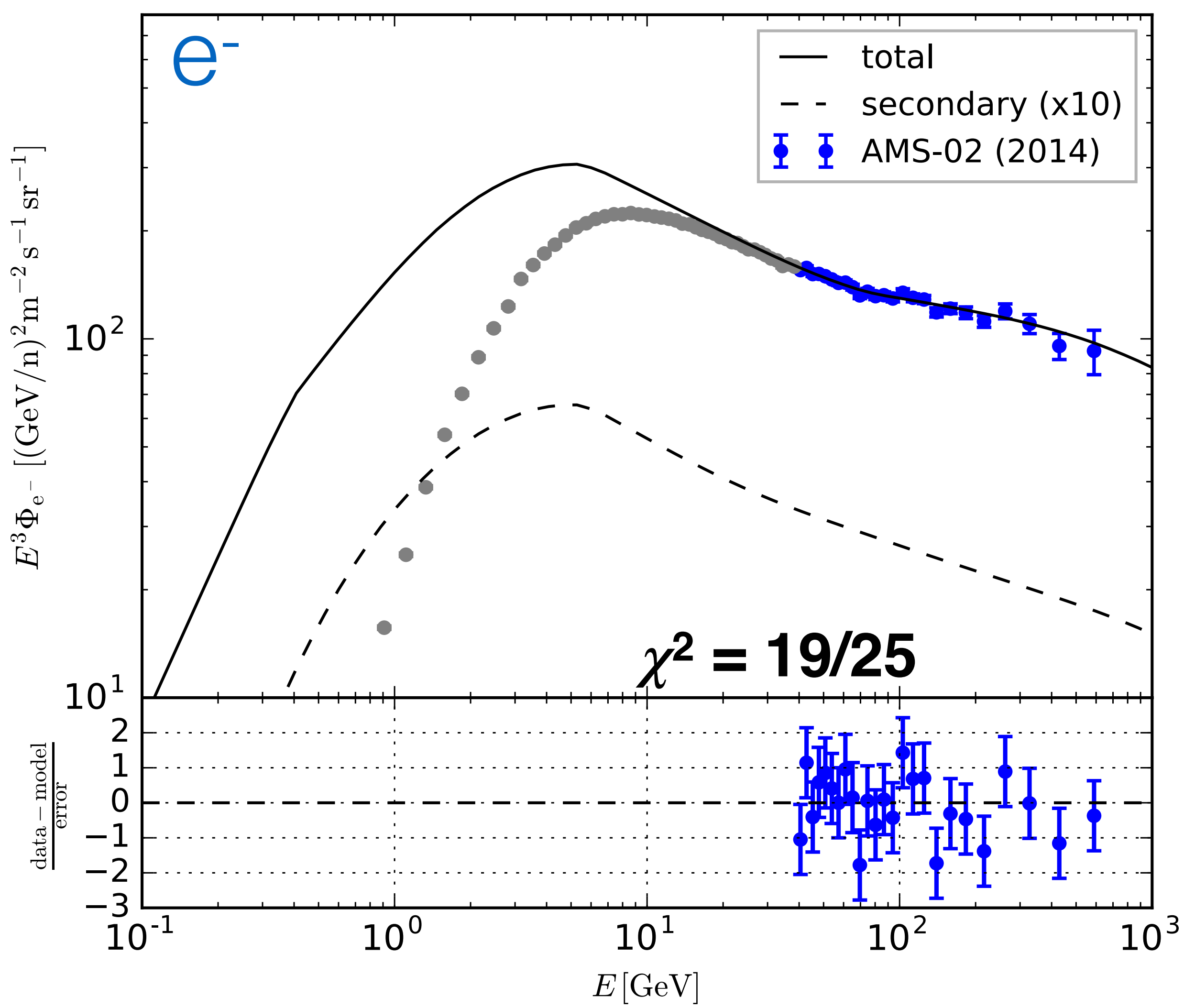
(In the standard force-field approx: $K = K_0 \mathcal{R}$)

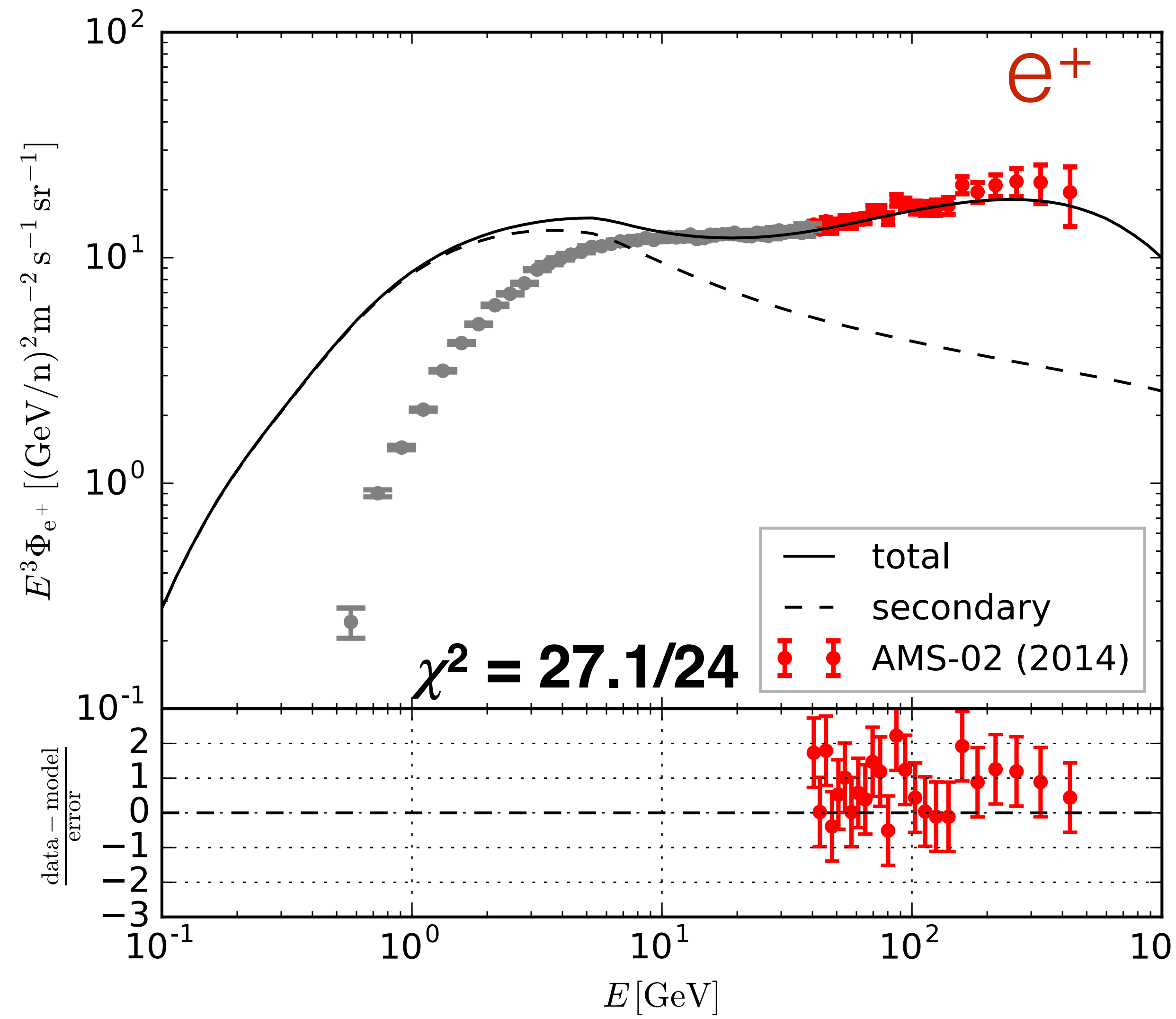
the break is at the **transition** from **resonant** to **non-resonant (small-angle) scattering**

- $\mathcal{R}_b \approx 6\,\mathrm{GV}$ if the outer scale of the turbulence is ~ 0.03 AU (**Wicks et al. 2009, 2010**)
- $\gamma_1 = 2 - q$ with q being the spectral index in the inertial range
- $\gamma_2 = 2$

3 free parameters

“2 breaks” model

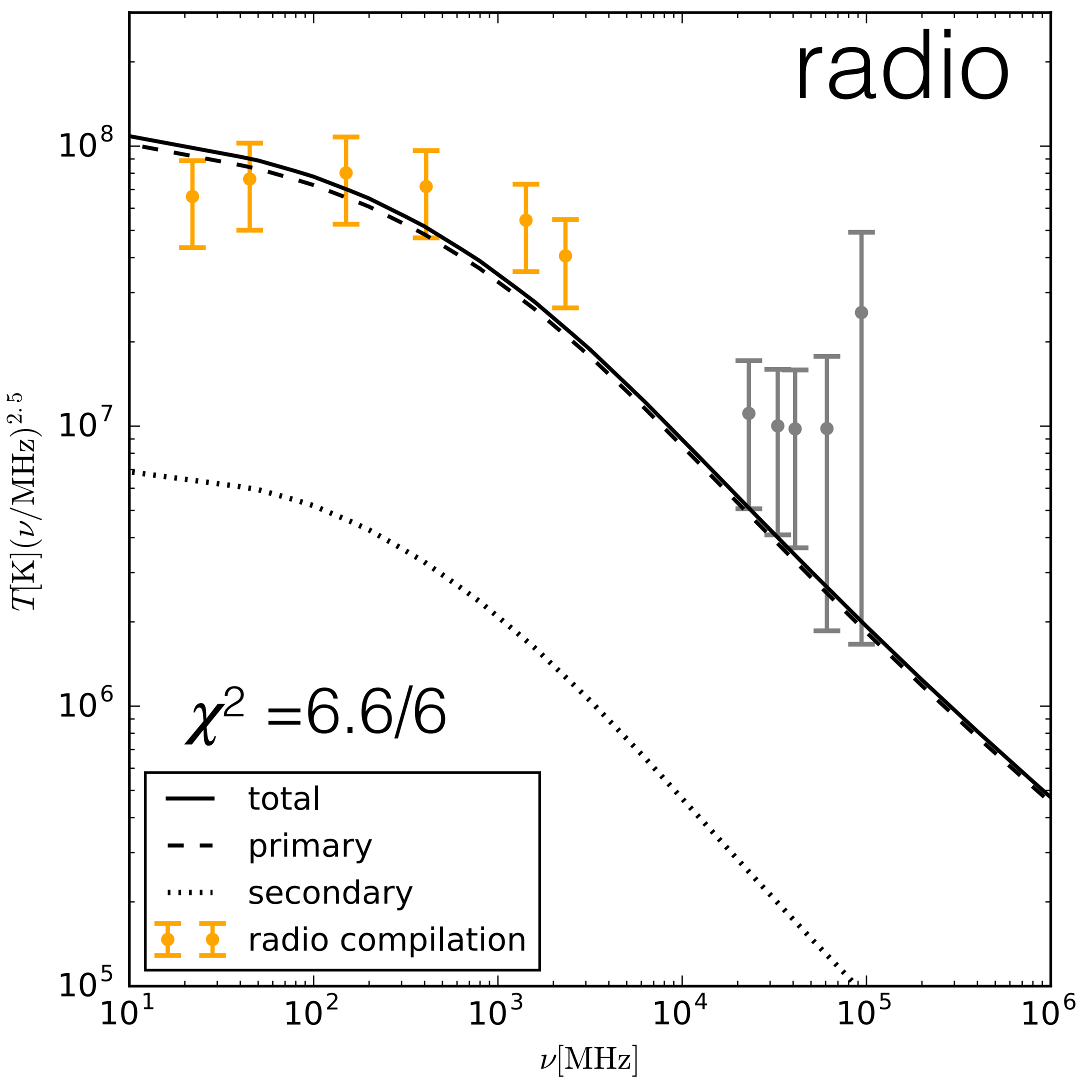




The e- spectrum is now **steeper** at **low energies**

Residuals at high energies are now **smaller**

“2 breaks” model

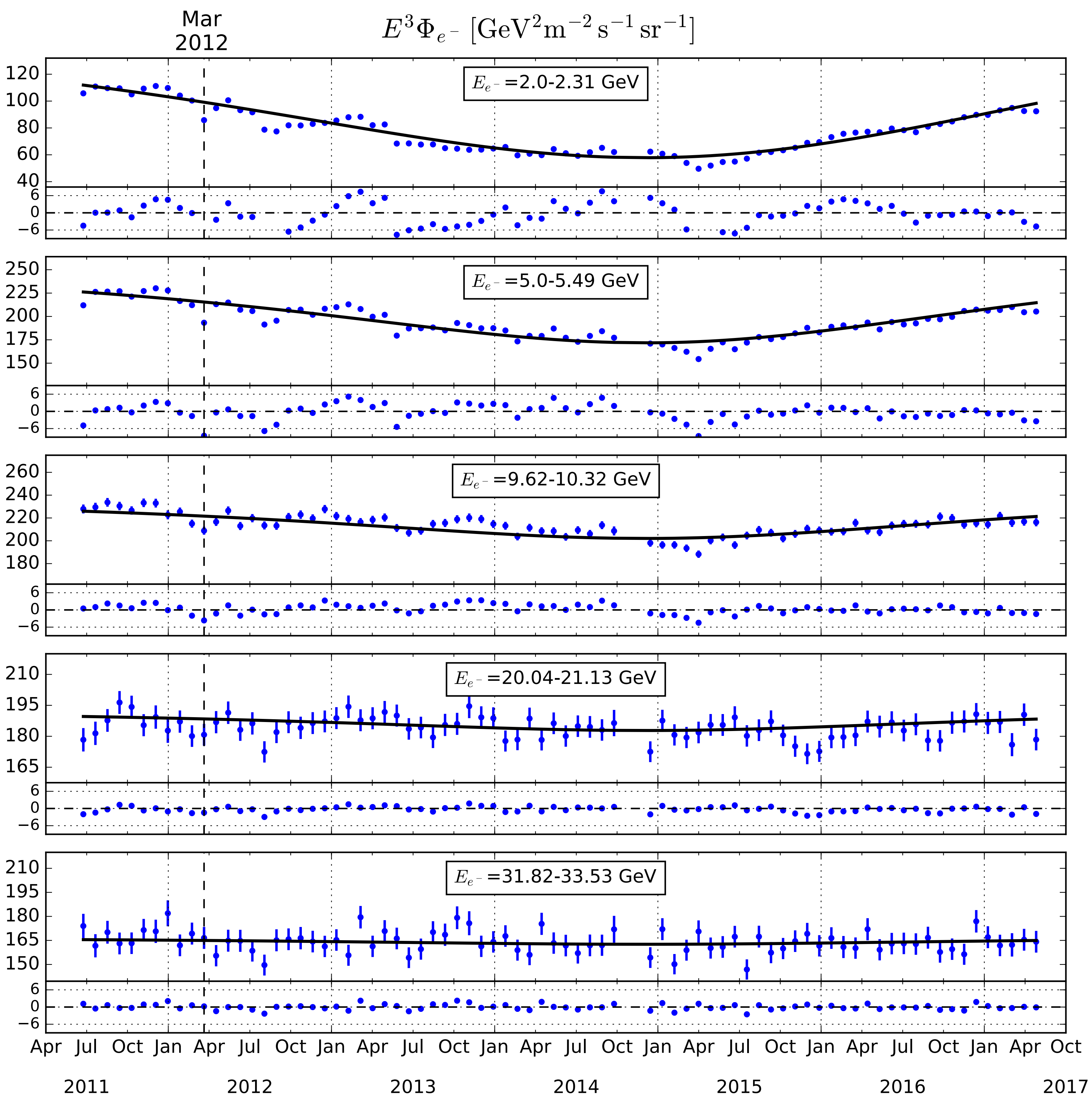


The **radio fit is slightly worse** since the e⁻ spectrum is now steeper at low energies

best-fit parameters (LIS)

N_{e^-}	$4.38^{+0.07}_{-0.08} \times 10^{-3}$	Normalization of the SNR flux
N_x	$2.447^{+0.006}_{-0.012} \times 10^{-4}$	Normalization of the extracomponent flux
Γ_x	$1.67^{+0.01}_{-0.01}$	Spectral index of the extra component
$\mathcal{R}_1$	$0.41^{+0.12}_{-0.06}$	1^{st} break of the SNR spectrum [GV]
$\mathcal{R}_2$	$79.8^{+38.2}_{-48.8}$	2^{nd} break of the SNR spectrum [GV]
Γ_1	$2.111^{+0.009}_{-0.015}$	SNR spectral index below the 1^{st} break
Γ_2	$2.70^{+0.05}_{-0.03}$	SNR spectral index between the 1^{st} and the 2^{nd} break
Γ_3	$2.64^{+0.014}_{-0.03}$	SNR spectral index above the 2^{nd} break
f_b	$2.38^{+0.09}_{-0.68}$	RMS value of the turbulent B field [μG]

“2 breaks” model



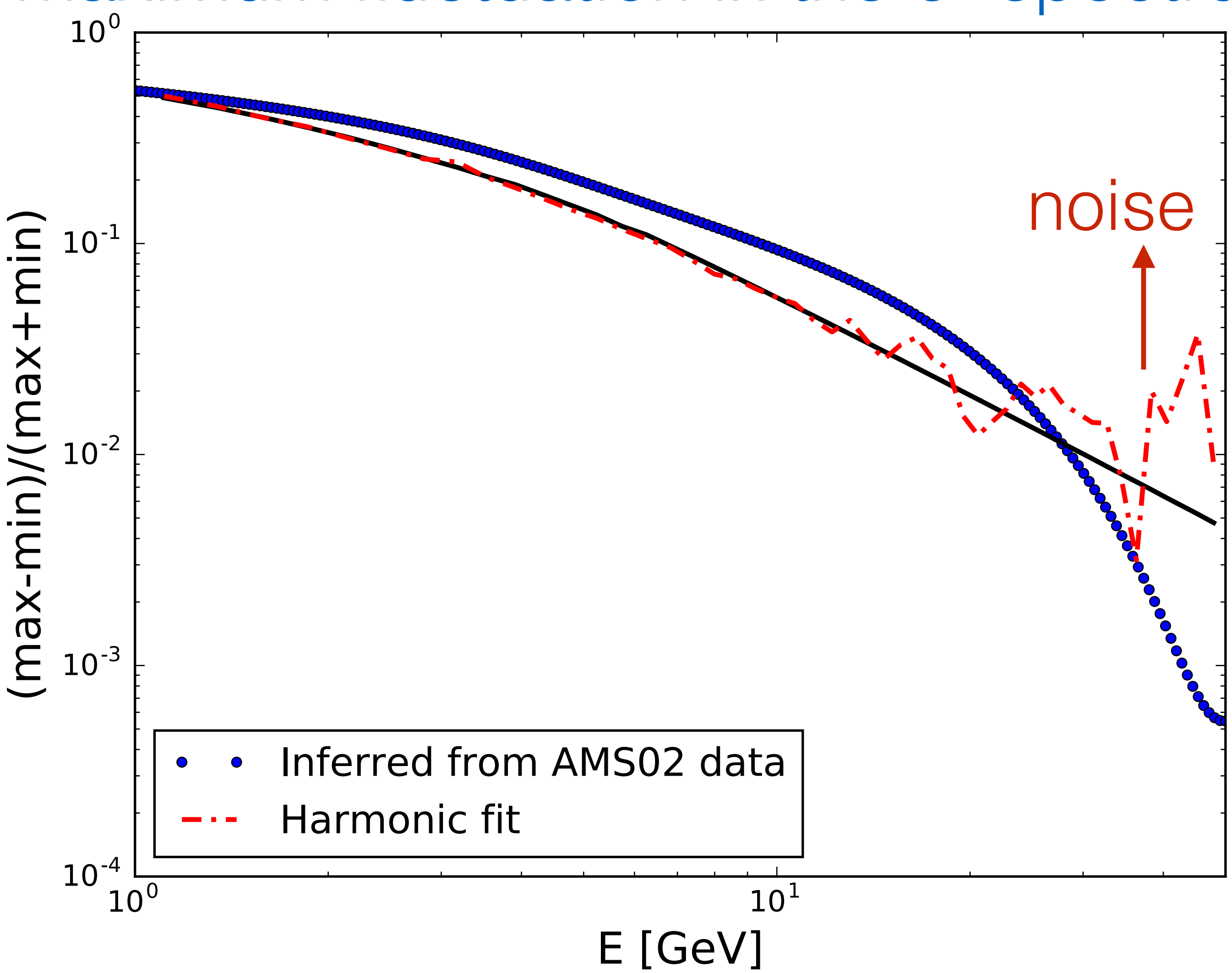
χ^2/dof = 5.4

electrons:

- good description of long-term variations
- short-term variations?
- At all energies

The impact of solar modulation

maximum fluctuation in the e- spectrum



blue: AMS-02 data

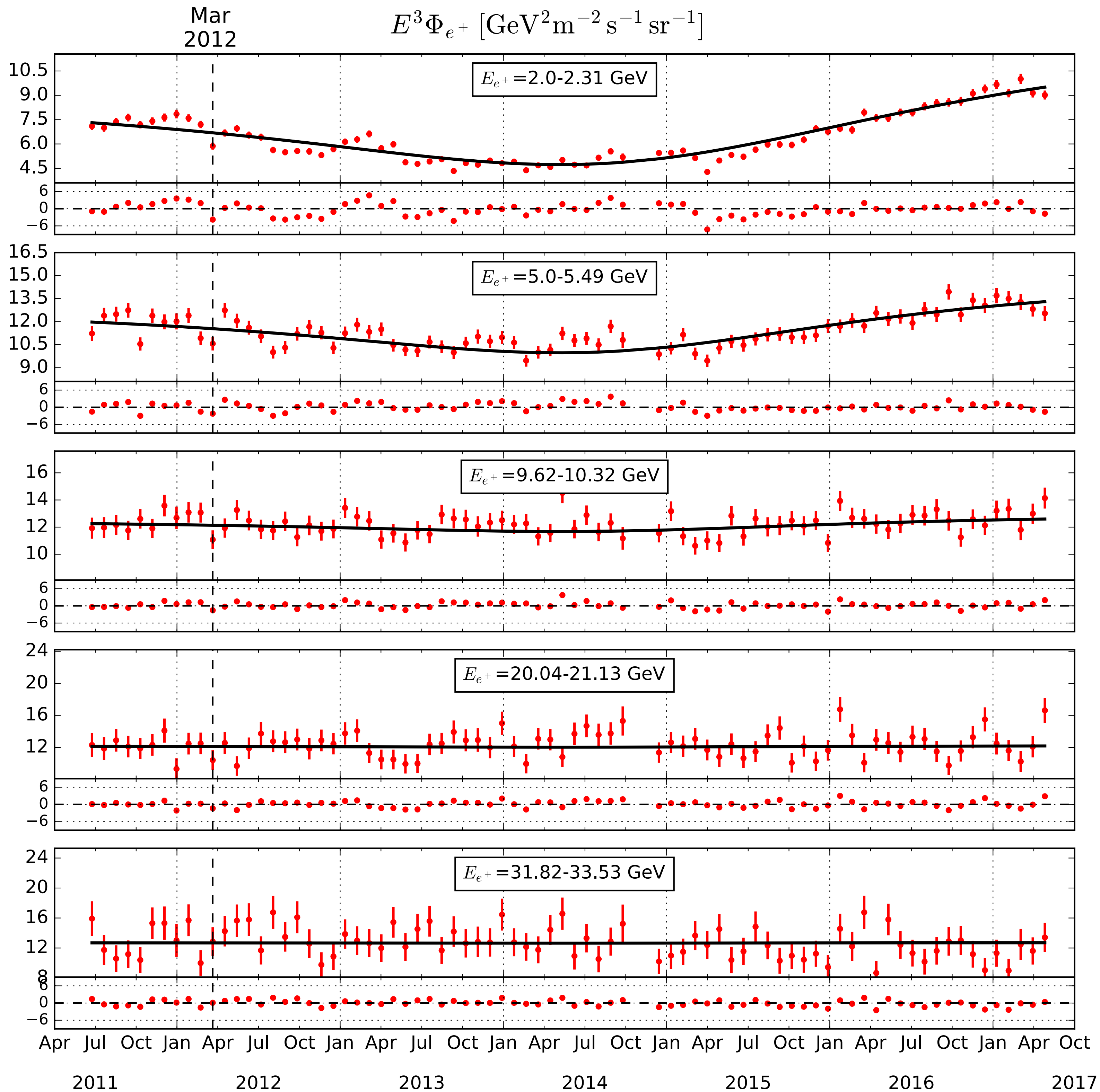
black: the prediction of our model

red: fit of the e- flux with an harmonic function

$$\Phi(t) = A + B \cdot \cos\left(\frac{2\pi(t-t_0)}{P}\right)$$

Even when **short term events are not taken into account**, solar modulation can account for a fluctuation of the e$^-$ flux at the level of **2% at 20 GeV**

“2 breaks” model



χ^2/dof = 1.7

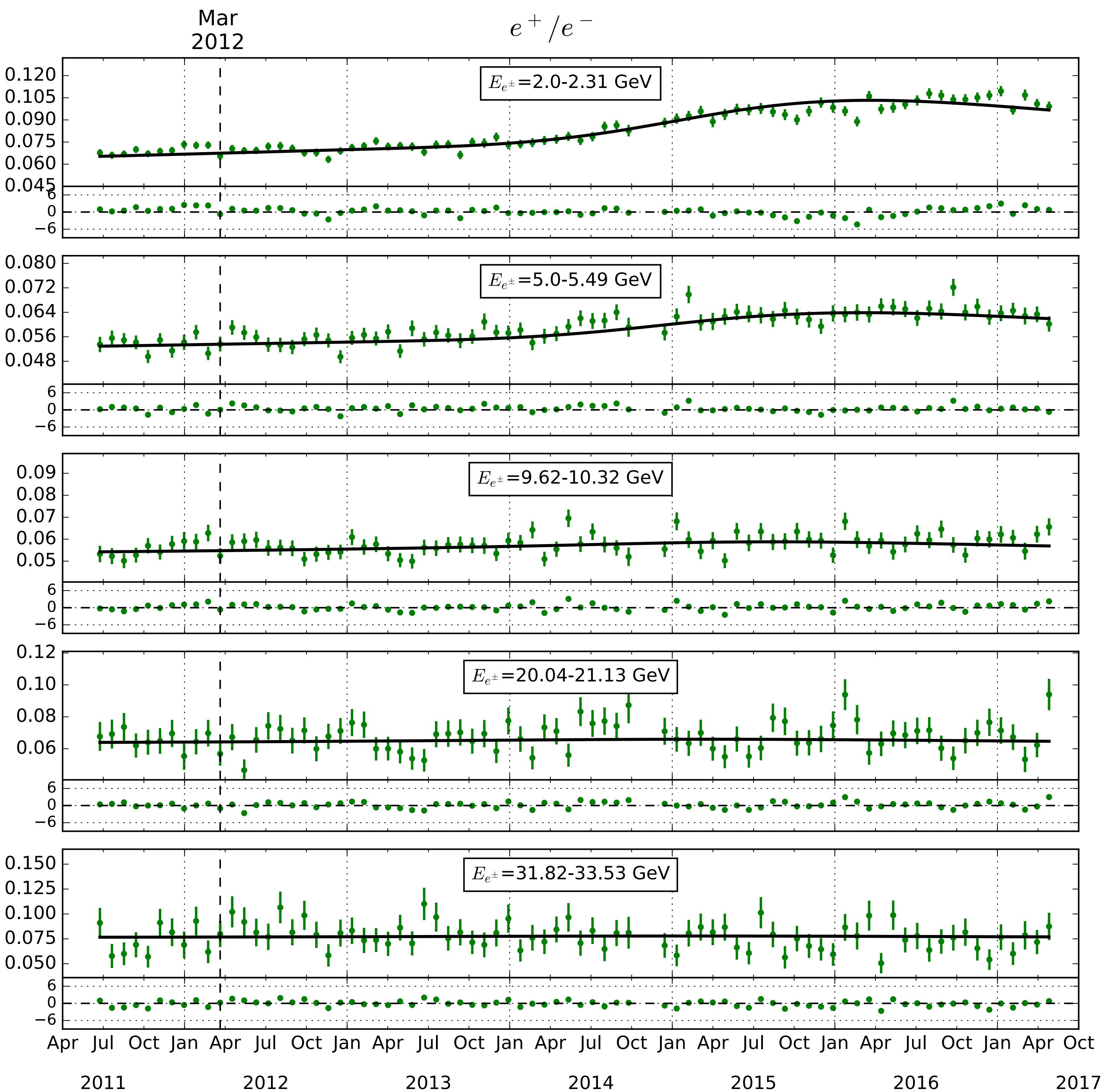
electrons:

- good description of long-term variations
- short-term variations?
- At all energies

positrons:

- good description of long-term variations
- short-term variations?
- At all energies

“2 breaks” model



χ^2/dof = 1.1

electrons:

- good description of long-term variations
- short-term variations?
- At all energies

positrons:

- good description of long-term variations
- short-term variations?
- At all energies

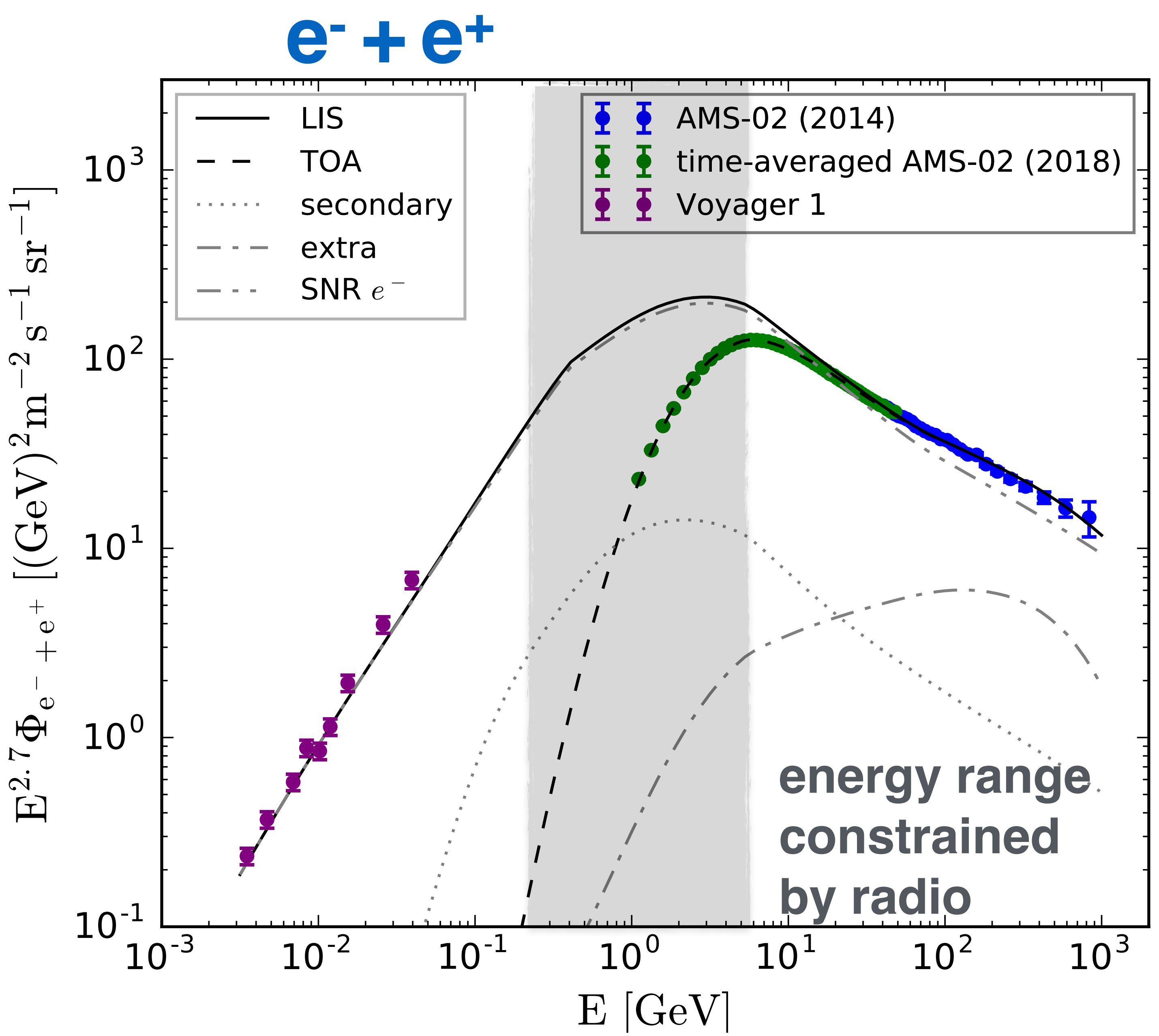
ratio:

- short term variations cancel out
- reasonable description of data

Conclusions

By using **several datasets** we are able to **constrain the properties** of the CR leptonic spectra from the **MeV to TeV energies**

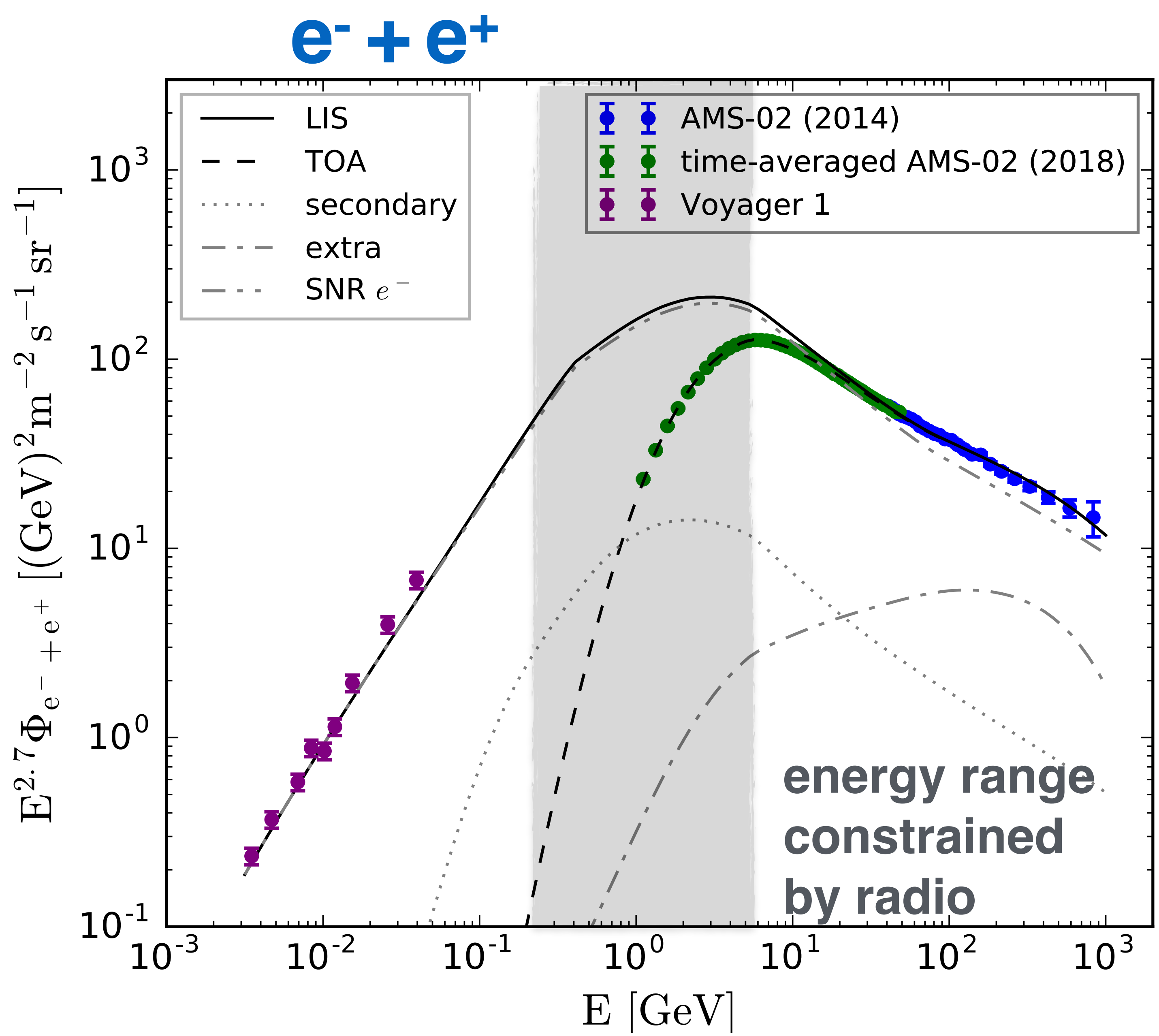
We have shown how the **average properties of solar modulation** can be reproduced **fairly well** by means of a **simple extension of the force-field approximation**



Conclusions

By using **several datasets** we are able to **constrain the properties** of the CR leptonic spectra from the **MeV to TeV energies**

We have shown how the **average properties of solar modulation** can be reproduced **fairly well** by means of a **simple extension of the force-field approximation**



Thank you for your attention!

back-up slides

Conclusions - a recap of the features we added

We have shown how in order **to fit some of the datasets** we have to introduce **new features** in the injected spectra / diffusion coefficients

In particular, we have introduced the following **spectral breaks**:

- **A low-rigidity spectral break in D_{xx}**. It might be associated to MHD wave damping on CRs
- **A high-rigidity break in D_{xx}**. It might be associated to the transition between different regimes of turbulence
- **A break in K**. It should be related to the transition between the resonant scattering and the small-angle scattering regimes
- **A low-rigidity break in the e- primary spectrum.** Where does it come from?
- **A high-rigidity break in the e- primary spectrum**. Is it related to the contribution from local sources?

“2 breaks” model

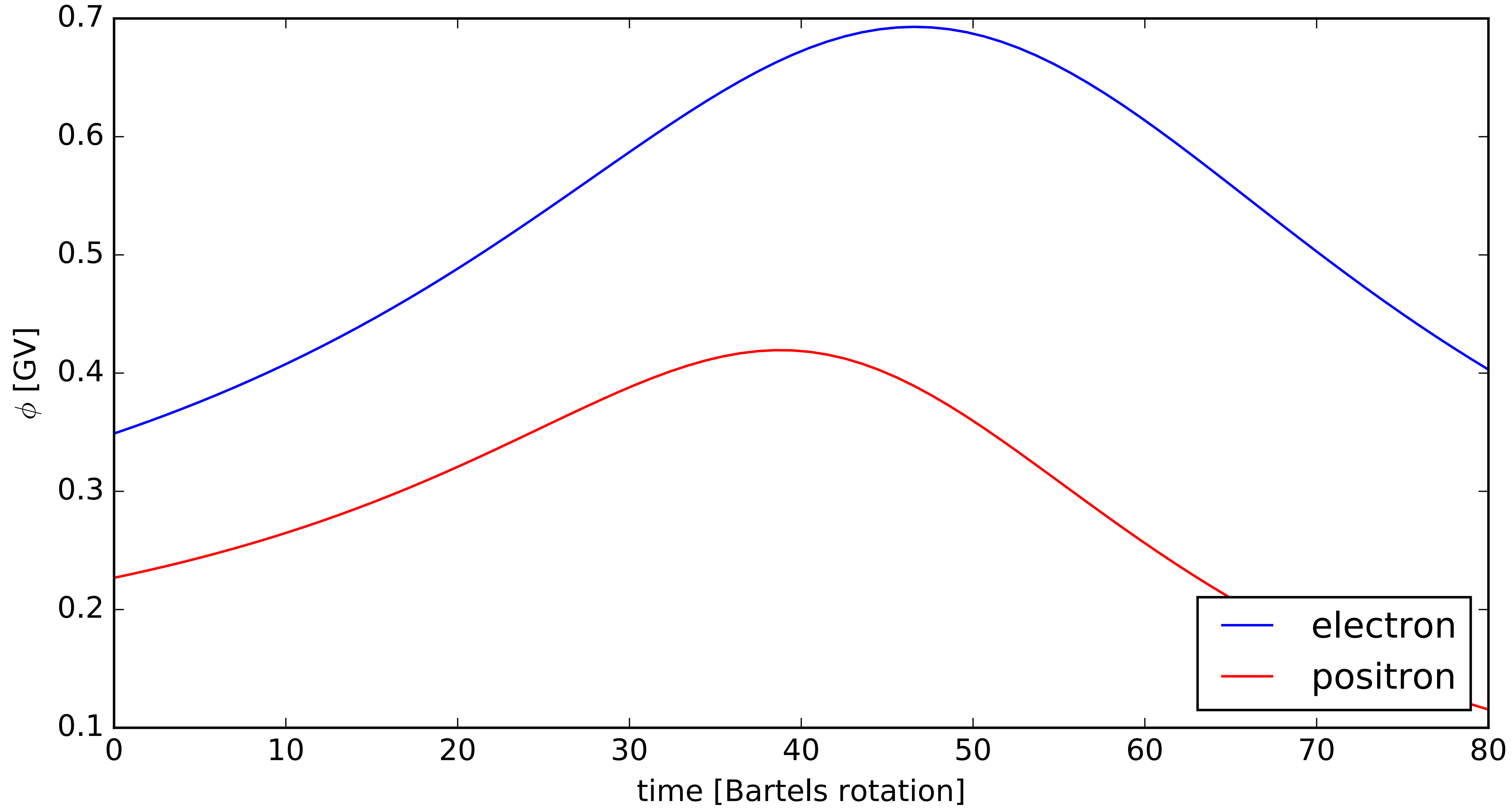
best-fit parameters (solar mod.)

parameter	e^+	e^-
γ_1	$1.218^{+0.004}_{-0.023}$	$1.284^{+0.090}_{-0.041}$
γ_2	$2.22^{+0.14}_{-0.39}$	$1.78^{+0.23}_{-0.10}$
$\mathcal{R}_b$ [GV]	$6.02^{+0.21}_{-0.21}$	$4.80^{+0.41}_{-0.89}$
ϕ_1 [GV]	$0.133^{+0.007}_{-0.001}$	$0.136^{+0.001}_{-0.044}$
ϕ_2 [GV]	$0.418^{+0.014}_{-0.003}$	$0.633^{+0.015}_{-0.060}$
ϕ_3 [GV]	$0.010^{+0.002}_{-0.010}$	$0.086^{+0.003}_{-0.047}$
t_0 [Bartels rot.]	$2468.29^{+0.06}_{-0.01}$ [June 2014]	$2474.373^{+0.08}_{-0.21}$ [December 2014]
Δt [Bartels rot.]	$25.96^{+0.24}_{-0.01}$	$32.87^{+0.263}_{-0.02}$

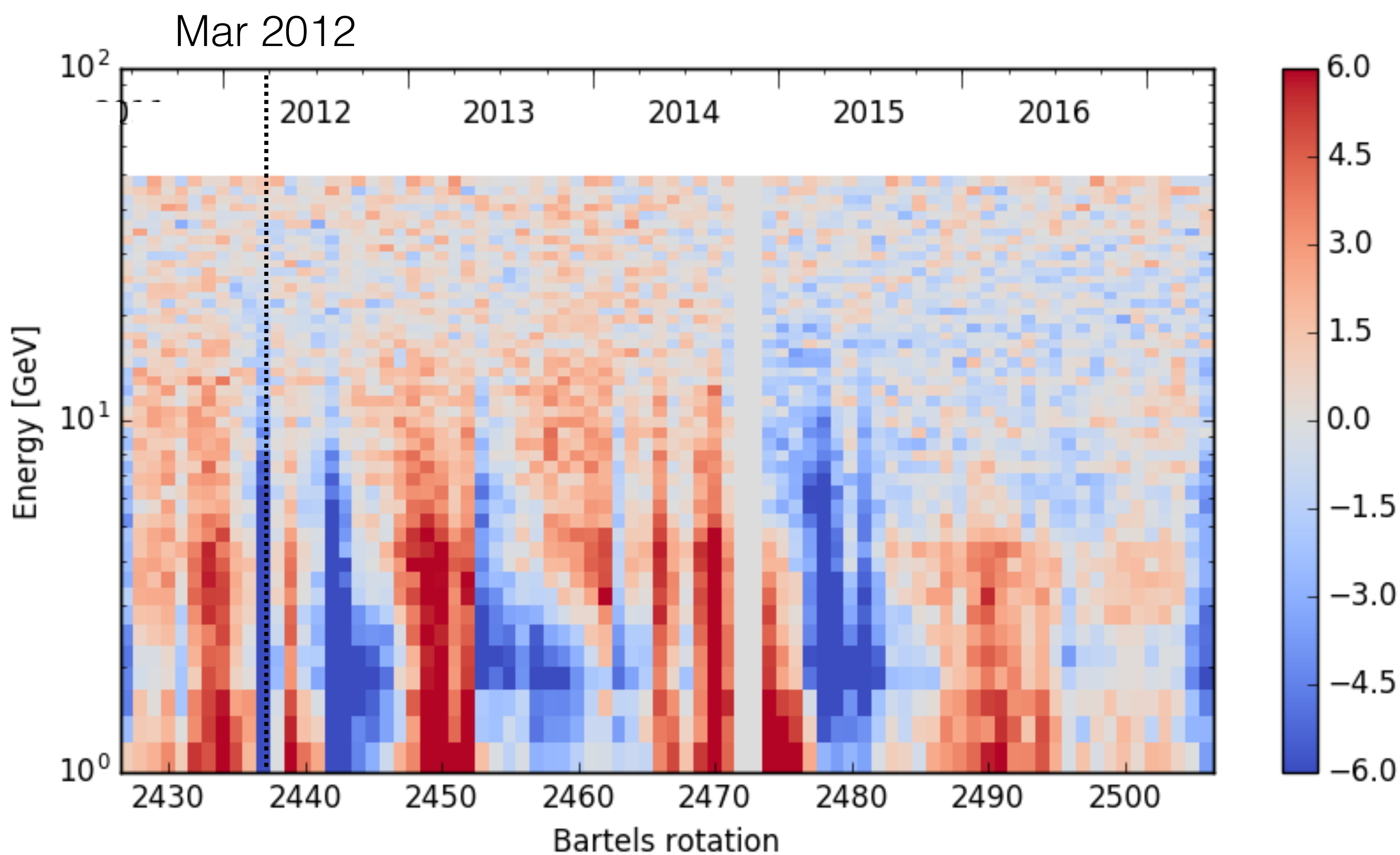
Modelling of the diffusion coefficient

Modelling of the time-dependent force-field potential

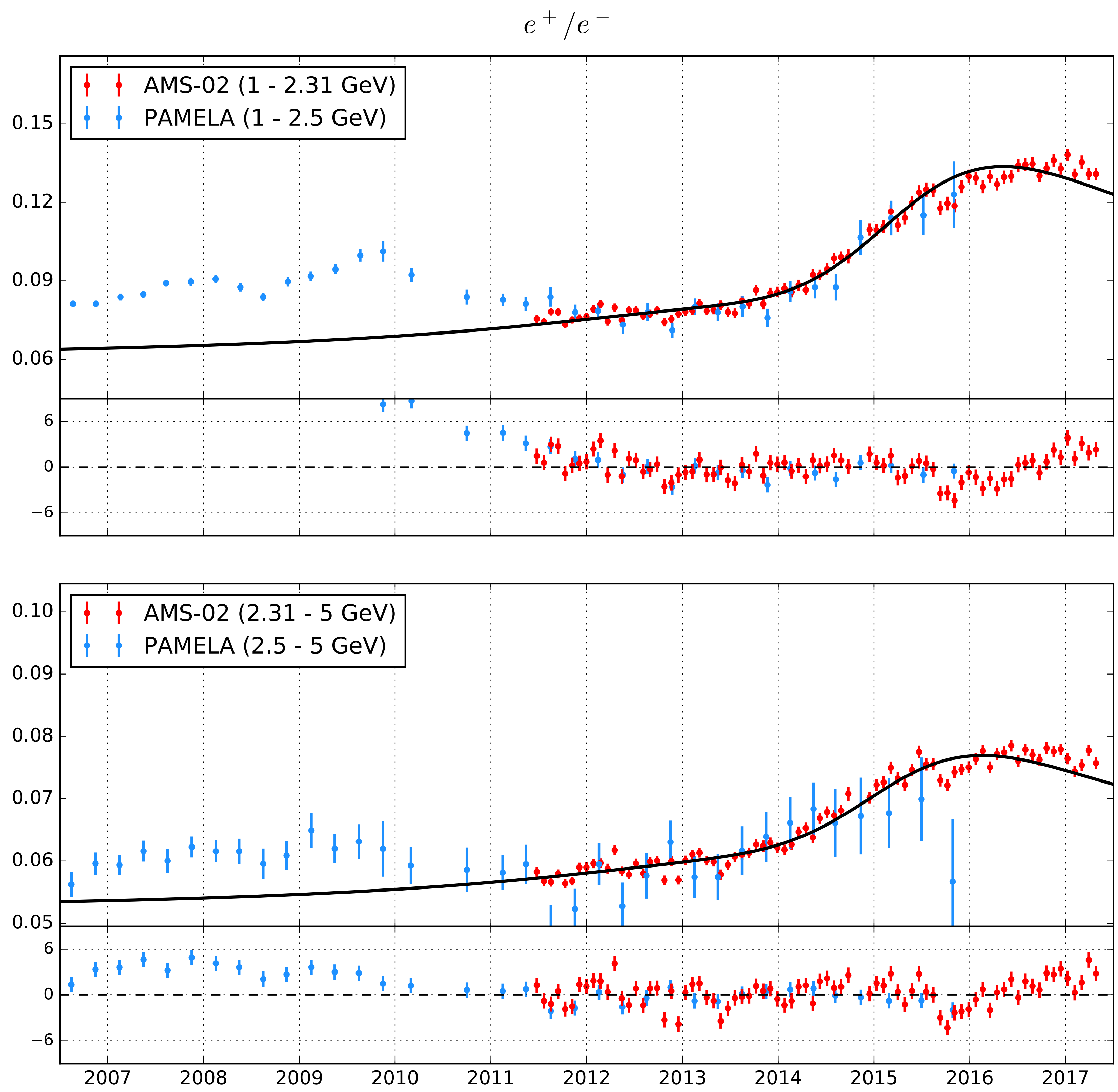
Force-field potentials



short-term variations



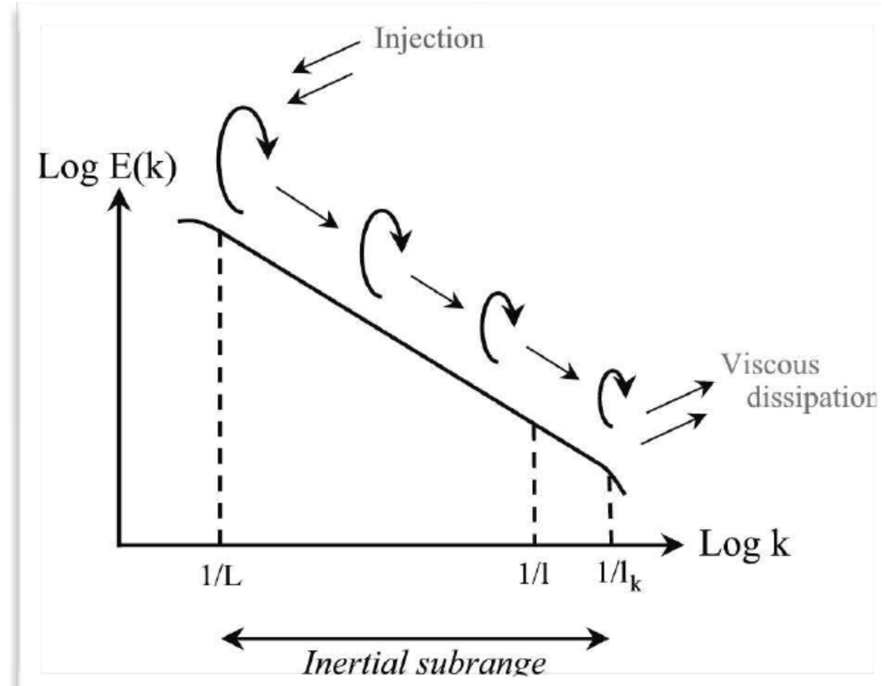
Our model vs. PAMELA data



PAMELA data from ICRC2017

Modelling CR diffusion

CRs diffuse in the turbulent Galactic magnetic field by **pitch-angle scattering** off MHD waves



Starting from the Vlasov equation and working within **quasi-linear theory**, one finds:

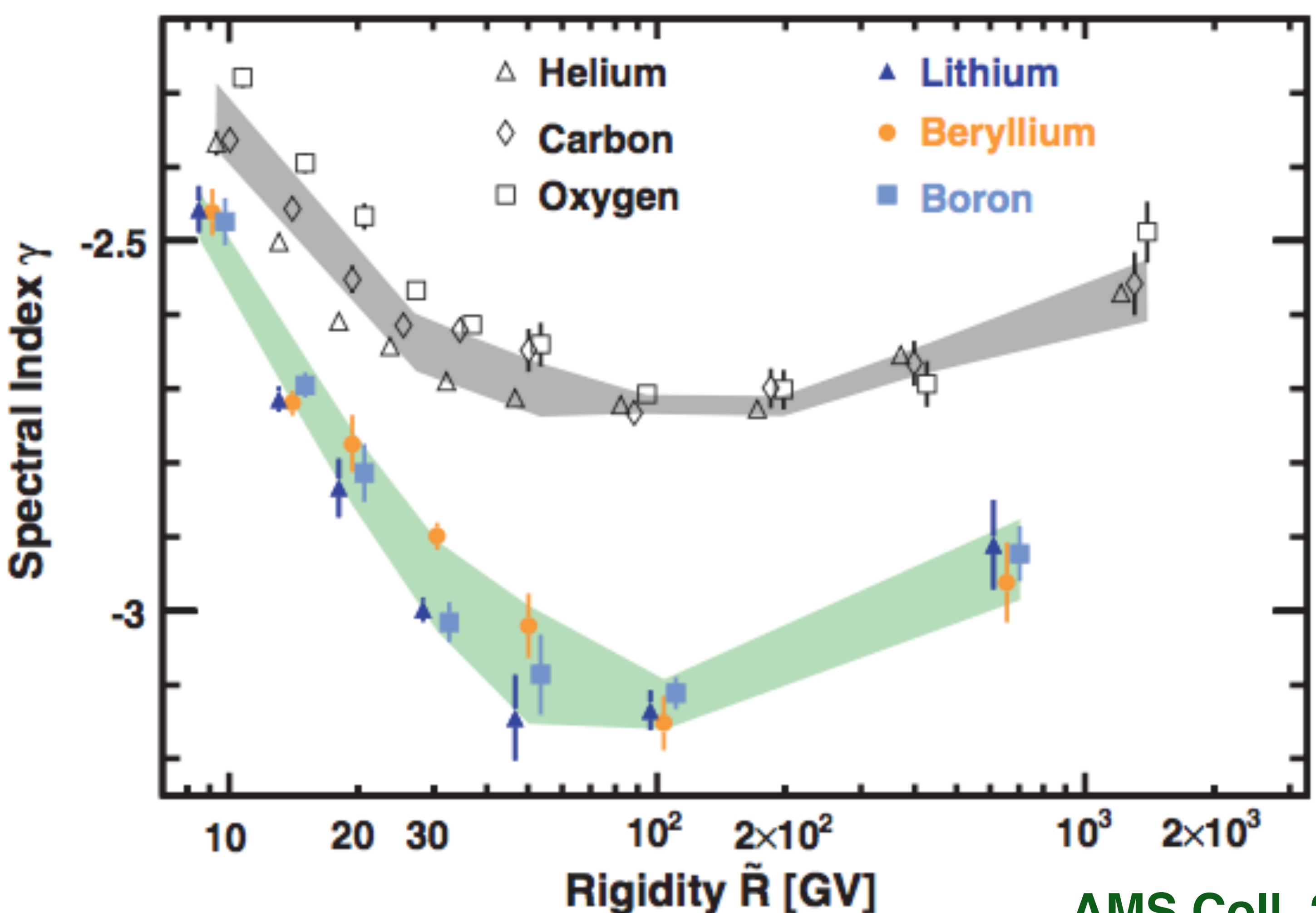
$$D_{\theta\theta} = \frac{\langle \Delta\theta^2 \rangle}{2t} = \frac{\pi}{8}\Omega\frac{\kappa P(\kappa)}{B^2} \Rightarrow D_{\|} = \frac{v^2}{4}\int_{-1}^{1} d\mu \frac{(1-\mu^2)^2}{D_{\mu\mu}} \quad \text{with} \quad \mu = \cos\theta$$

By exploiting the **resonance condition** $\kappa^{-1} \approx r_L$ one gets:

$$D_{\|} = D_0 \mathcal{R}^{\delta} \quad \text{with} \quad \delta = 2 - q$$

Modelling CR diffusion - break at high rigidities

Possible evidence: Both **primary** (p,He,O) and **secondary** (Li, Be, B) CR species show **spectral hardenings** at ~ 200 GV. The **hardening** of the **secondary species** appears to be **stronger**



AMS Coll. 2018

Possible interpretation: **transition** between diffusion in an **external turbulence** (as the one injected from SNRs) and diffusion onto **CR self-generated waves** (through the mechanism of streaming instability)

Modelling CR diffusion - break at low rigidities

Observationally, it is required to fit the **peak** of the **B/C ratio** at low rigidities in purely diffusive transport models.

Possible interpretation: **damping** of turbulence at low rigidities

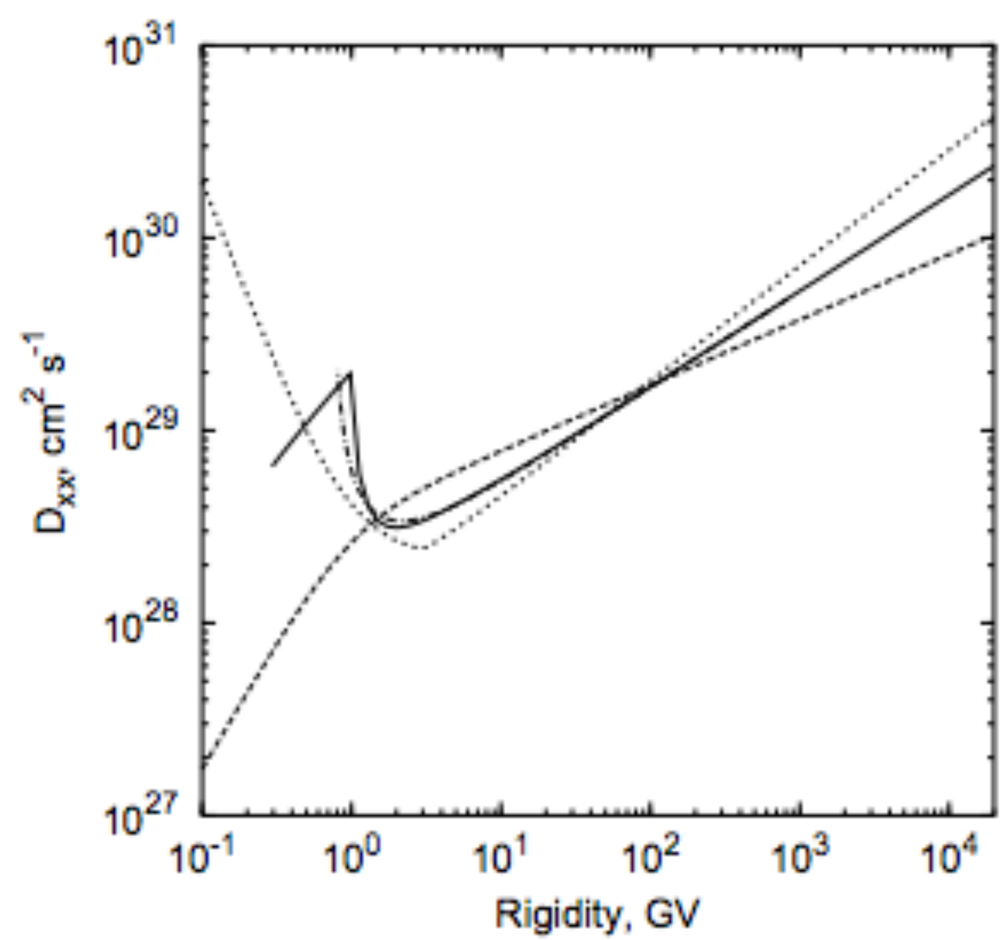
Equation for the **MHD wave spectrum**:

$$\frac{\partial}{\partial \kappa}\left(\frac{C_M}{\rho V_a}\kappa^3 W^2(\kappa)\right) = -2\Gamma W(k) + S\delta(\kappa - \kappa_L)$$

Damping term: $\Gamma = \Gamma_{\rm th} + \Gamma_{\rm CR}$

$$\Gamma_{\rm CR} = \frac{\pi Z^2 e^2 V_a^2}{2\kappa c^2}\int_{p_{\rm res}(\kappa)}^{\infty} N(p)\frac{dp}{p}$$

has to be solved **together** with the CR transport equation



Ptuskin et al., 2006

Fitting AMS-02 data

The **systematic uncertainty** of AMS-02 is in the range 3% - 17%

A significant fraction of such uncertainty is **correlated** between the **different energy bins**. A rigorous treatment of this correlation would require the knowledge of the **correlation matrix**, which is not publicly available.

Simple assumption:

$$\sigma_{\rm syst} = \sigma_{\rm syst,corr} + \sigma_{\rm syst,uncorr}$$ with $\sigma_{\rm syst,uncorr}$ = 1% of measured value

Cavasonza et al. Astrophys.J. 839 (2017) no.1, 36

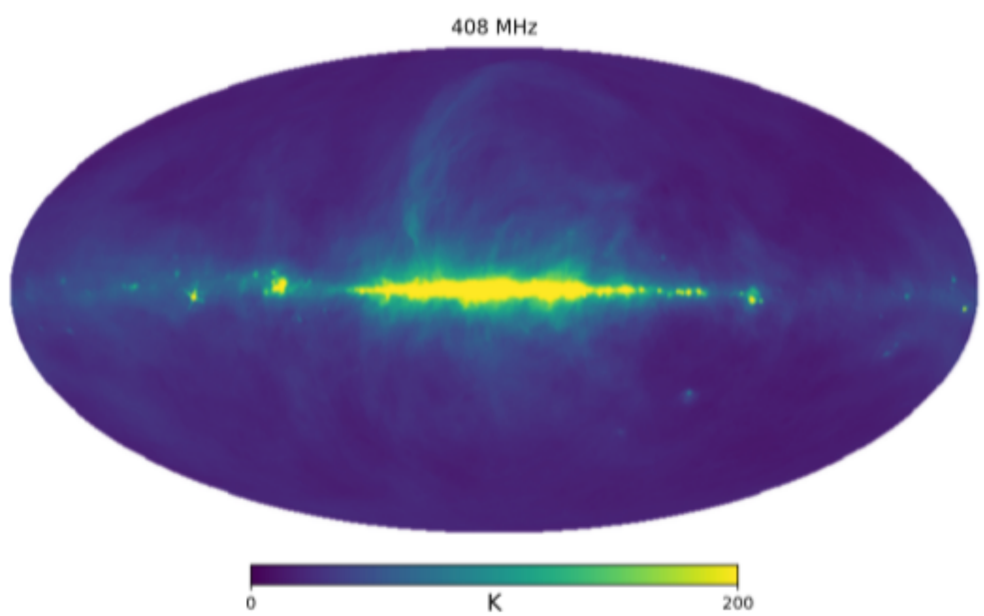
$$\sigma_{\rm tot} = \sqrt{\sigma^2_{\rm stat} + \sigma^2_{\rm syst,uncorr}}$$

$\sigma_{\rm stat,corr}$ is treated as an **overall scale uncertainty** on the acceptance and is used to determine the **errors on the best-fit parameters**

Radio data

Relativistic e± emit diffuse radio signal through **synchrotron emission**

$$\nu_{\rm C}[\rm GHz] \approx 0.016 \left(\frac{B\sin\theta}{\mu G}\right)\left(\frac{E}{\rm GeV}\right)^2$$



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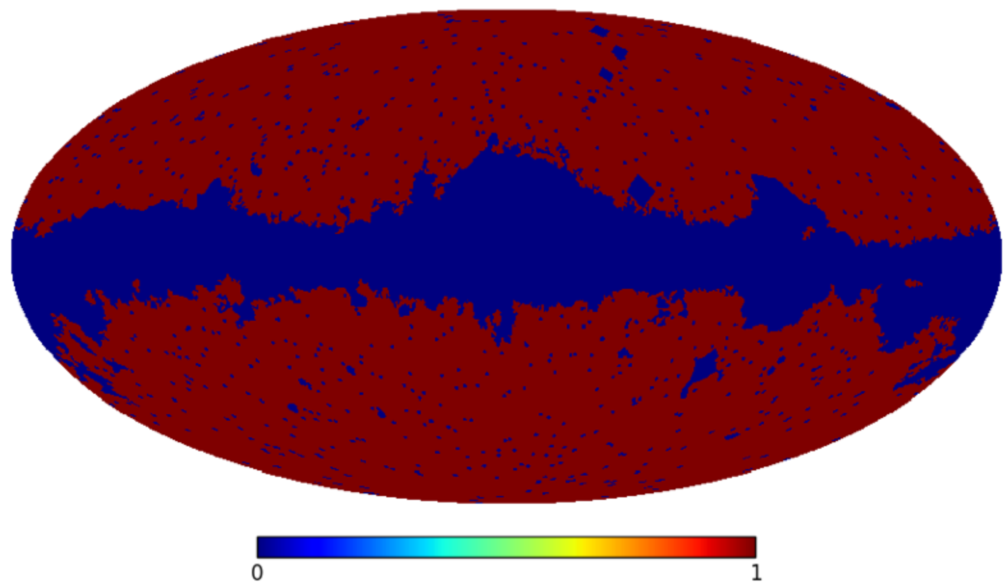


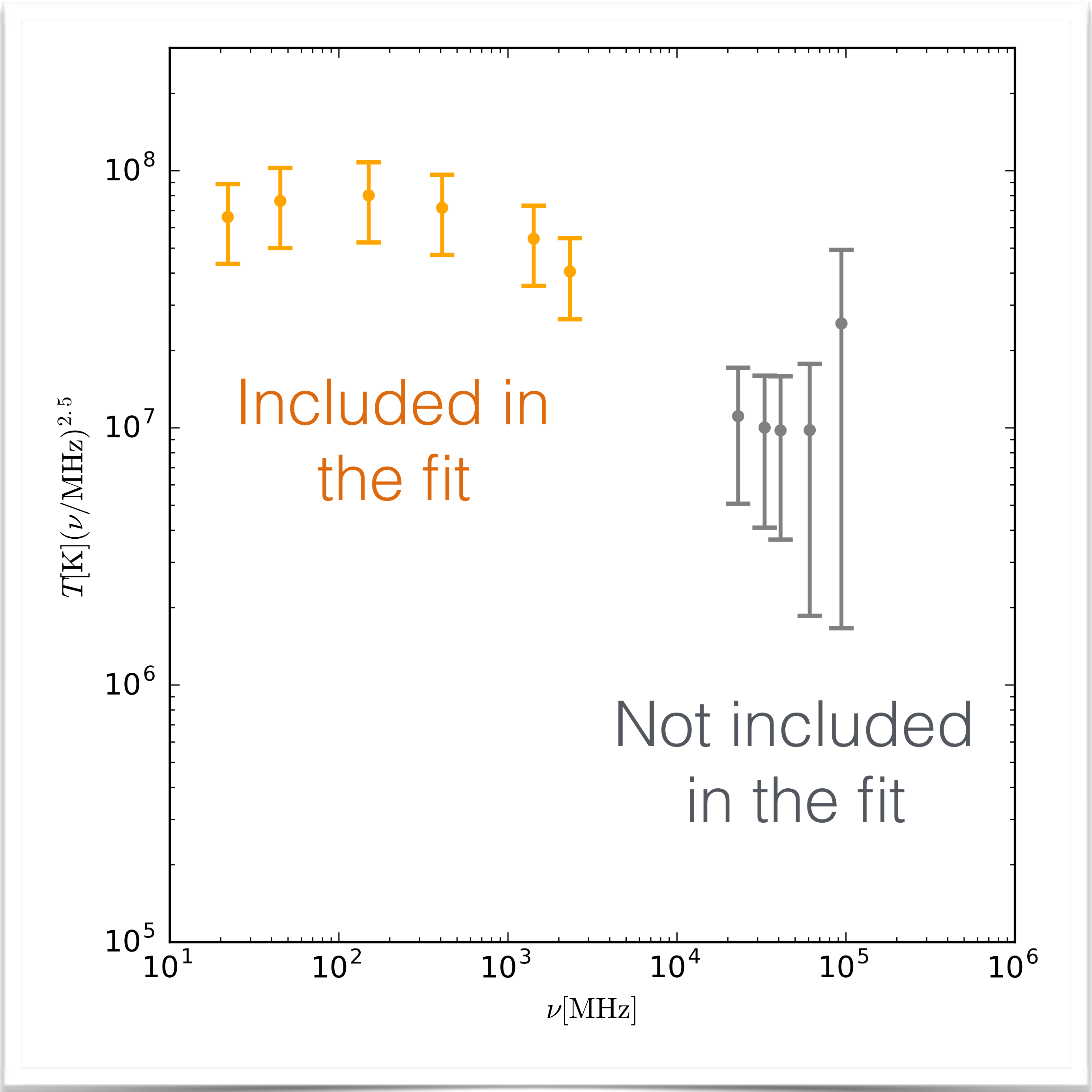
Several **radio surveys** with nearly **complete sky coverage** in the frequency interval [22 MHz, 94GHz]

WMAP temperature analysis **mask**

Strong et al. 2010, Jaffe et al. 2011, Di Bernado et al. 2013, Orlando 2017

Radio data

Relativistic e± emit diffuse radio signal through **synchrotron emission**



- At **high frequencies**, large contributions from **free-free and thermal dust emission** are expected
- **uncertainty** from **variance** across the sky