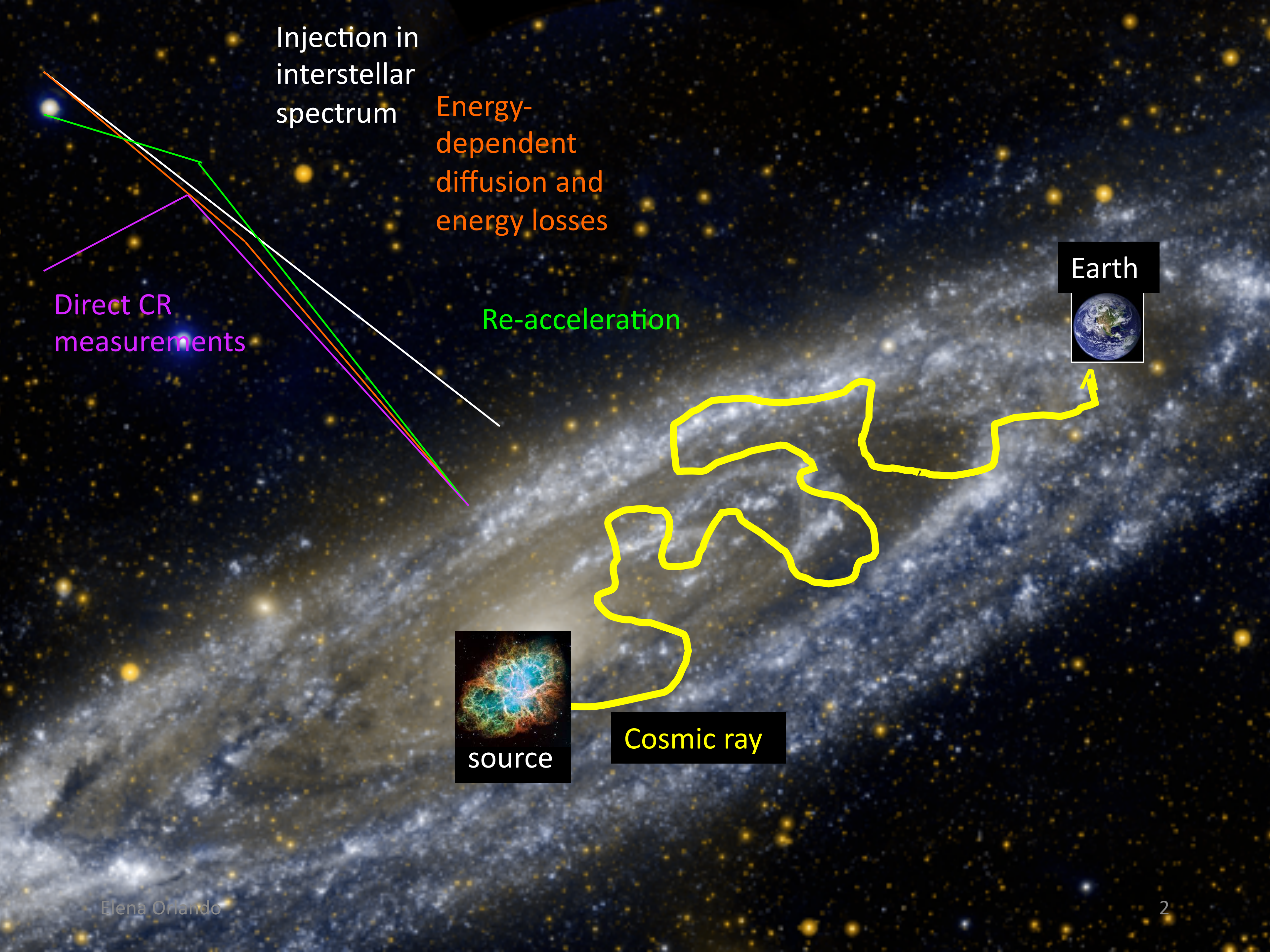
Review on codes of Cosmic Ray Propagation in the Galaxy

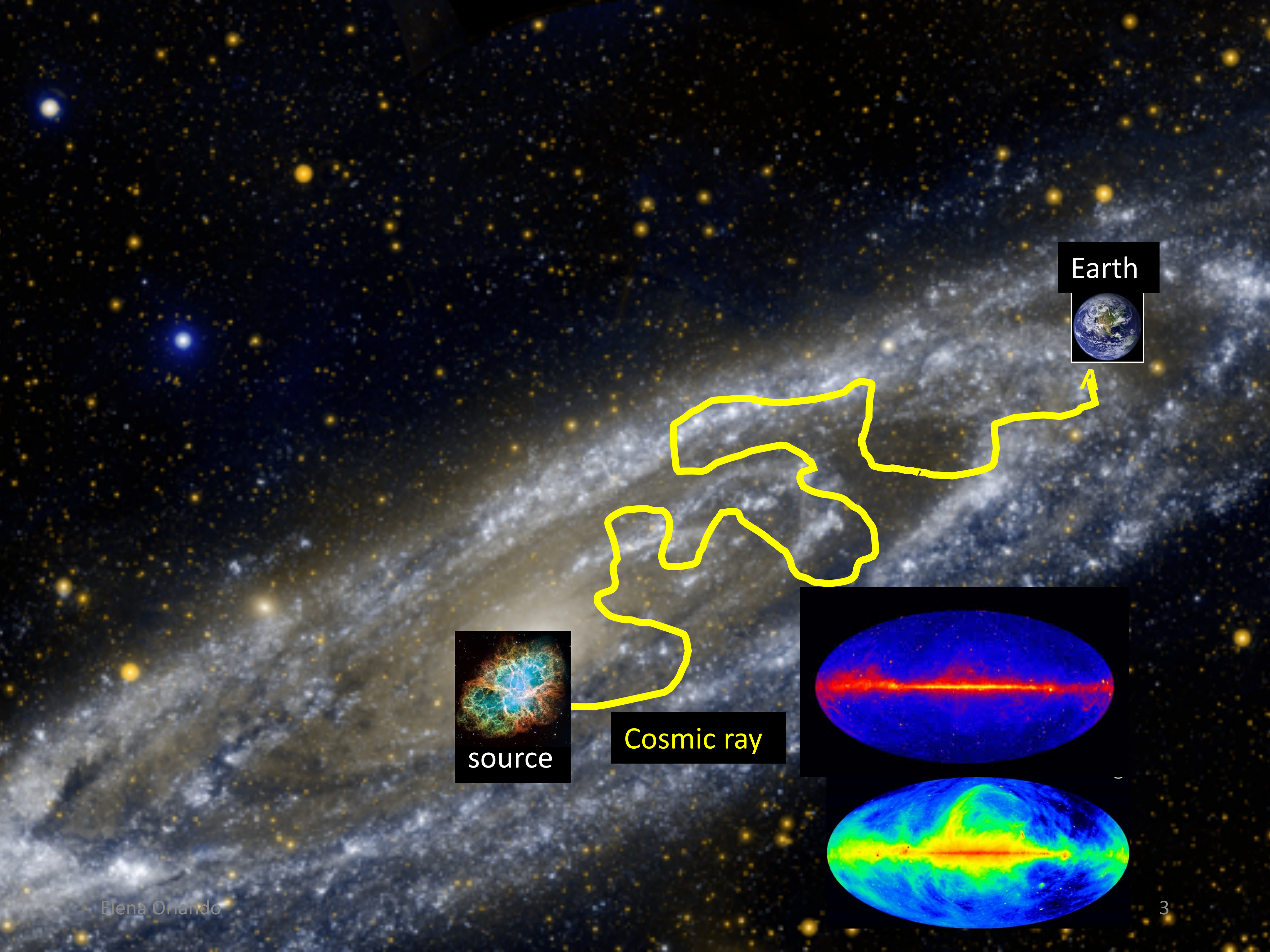
Elena Orlando

(University of Trieste & Stanford University)

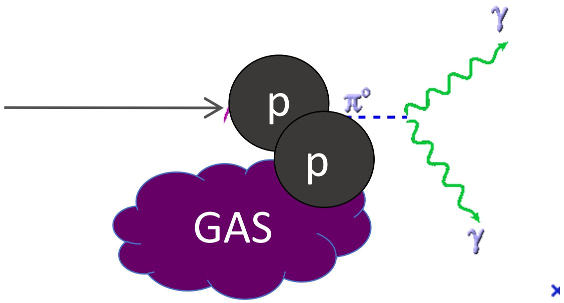
1st Workshop on Gamma-ray Halos around Pulsars
Virtual 1-3 Dec 2020



Injection in interstellar spectrum
Energy-dependent diffusion and energy losses
Direct CR measurements
Re-acceleration
Earth
source
Cosmic ray
Elena Orlando
2

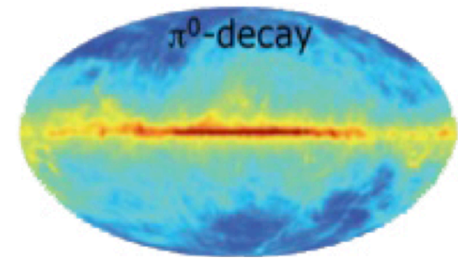

Earth
Cosmic ray
source

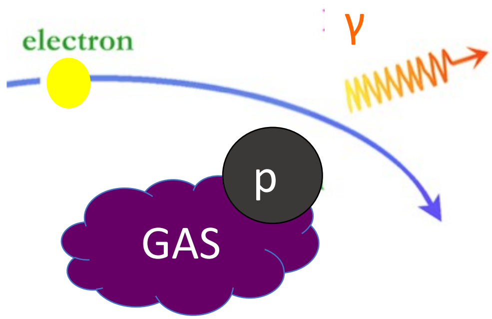
Interstellar Emission Mechanisms



Pion decay

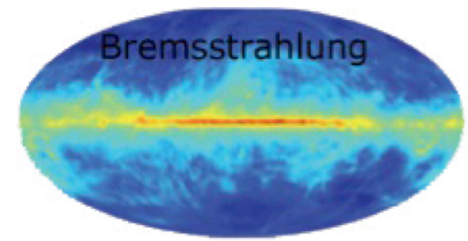
$$p + p \rightarrow p + p + \pi^0 \rightarrow 2\gamma$$

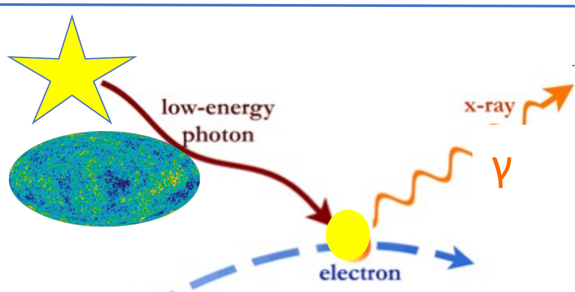




Bremsstrahlung

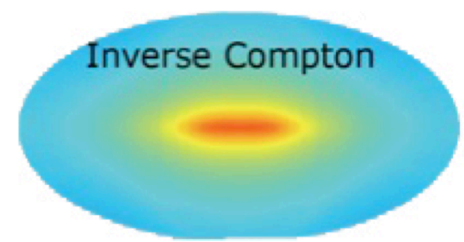
$$e^{\pm} \rightarrow e^{\pm} + \gamma$$

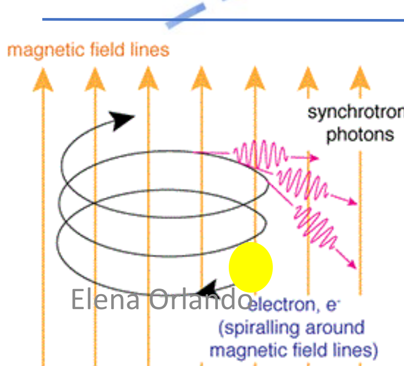




Inverse Compton

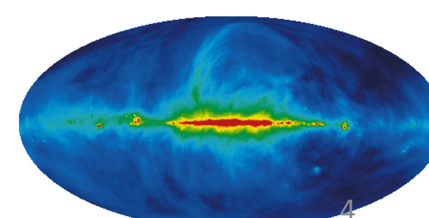
$$e^{\pm} + \gamma \rightarrow \gamma + e^{\pm}$$





Synchrotron

$$e^{\pm} \rightarrow e^{\pm} + \gamma$$



Transport of CR in the Galaxy

e.g.
Strong, Moskalenko, Ptuskin (2007) ARNPS 57, 285
Grenier et al. (2015) ARAA 53, 199
Gabici et al. (2019) IJMPD 1930022
Kachelrieβ & Semikov (2019) PPNP 109, 103710

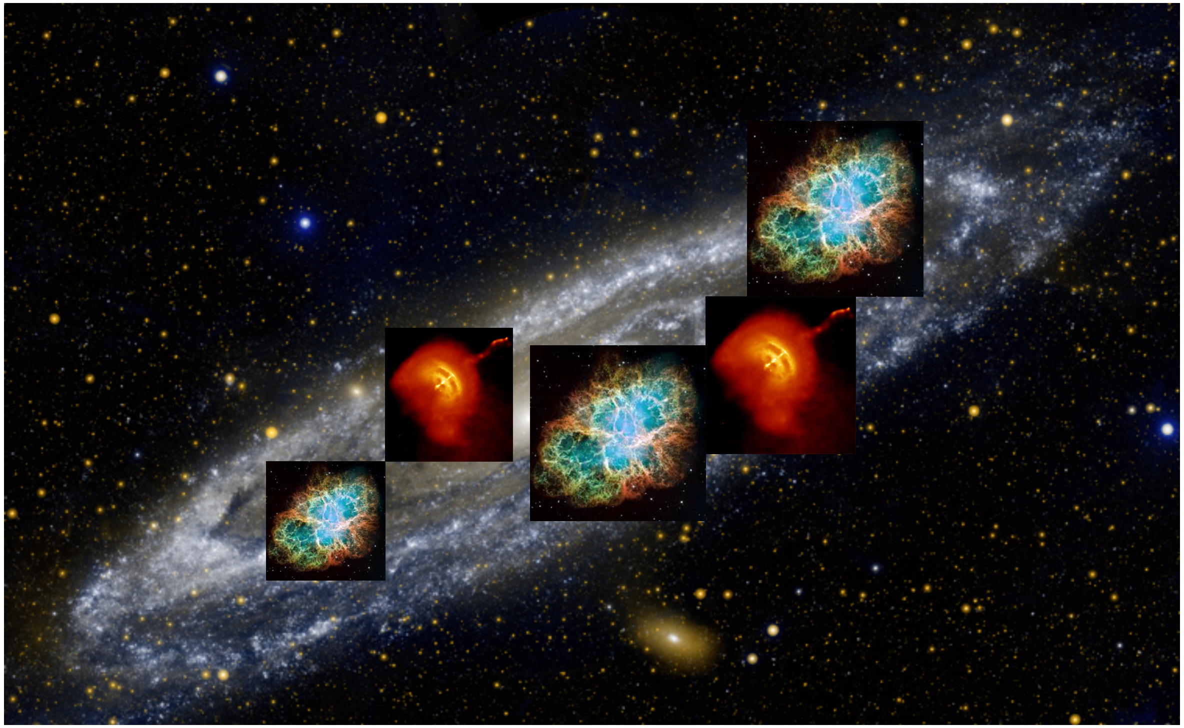
(not an exhaustive list)

The Transport Equation

$$\frac{\partial \psi(\vec{r},p,t)}{\partial t} = q(\vec{r},p,t) + \vec{\nabla} \cdot (D_{xx}\vec{\nabla}\psi - \vec{V}\psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla} \cdot \vec{V})\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi$$

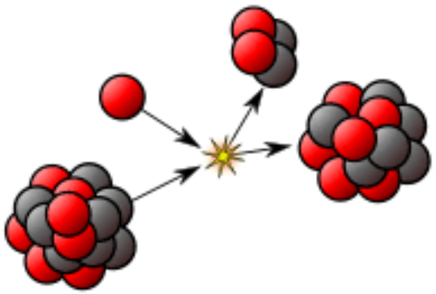
The Transport equation: the source term

$$\frac{\partial \psi(\vec{r},p,t)}{\partial t} = q(\vec{r},p,t) + \vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi - \vec{V}\psi)$$
$$+ \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi$$



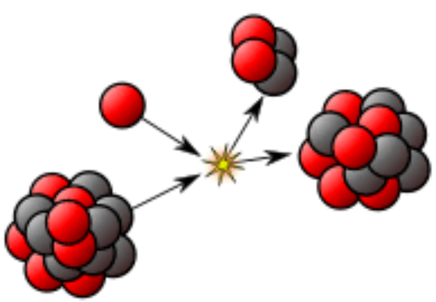
The Transport Equation: spallation/decay

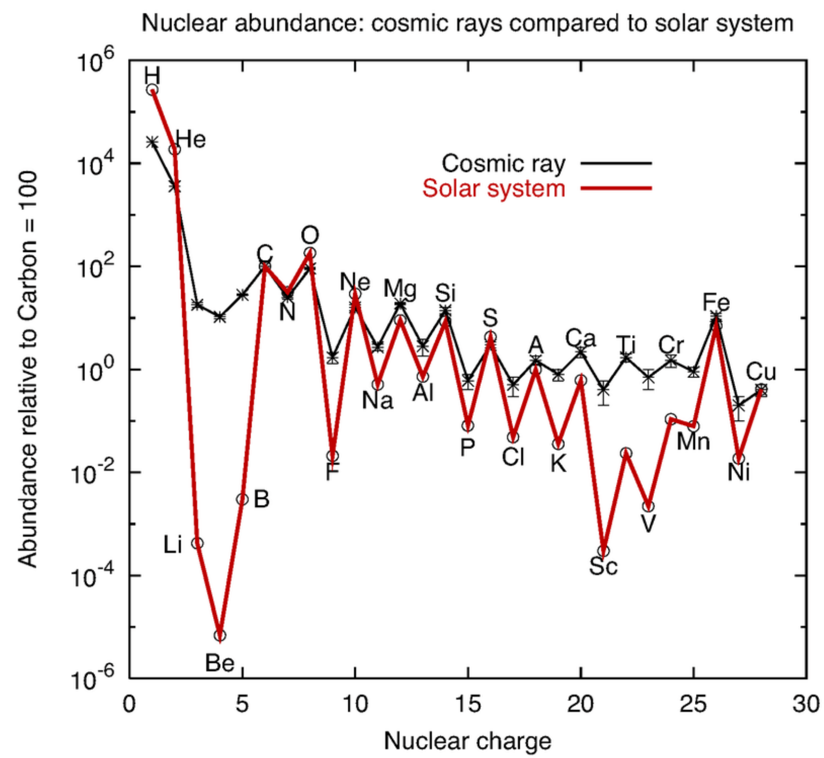
$$\frac{\partial \psi(\vec{r},p,t)}{\partial t} = q(\vec{r},p,t) + \vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi - \vec{V}\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi$$



The Transport Equation: spallation/decay

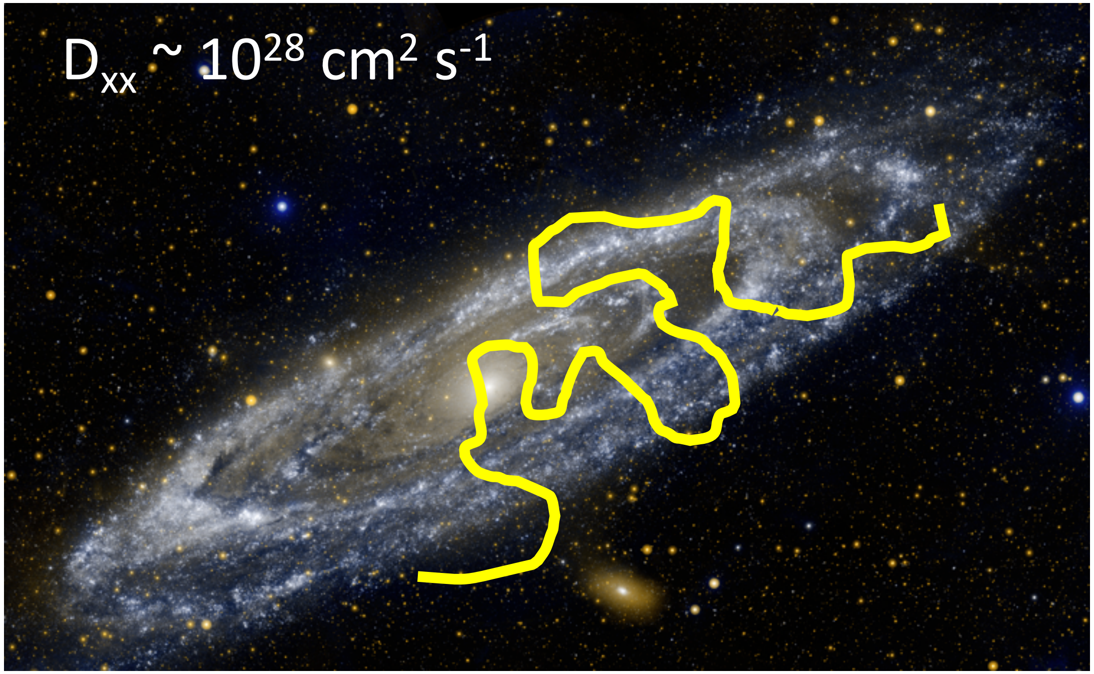
$$\frac{\partial \psi(\vec{r},p,t)}{\partial t} = q(\vec{r},p,t) + \vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi - \vec{V}\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi$$





The Transport Equation: diffusion

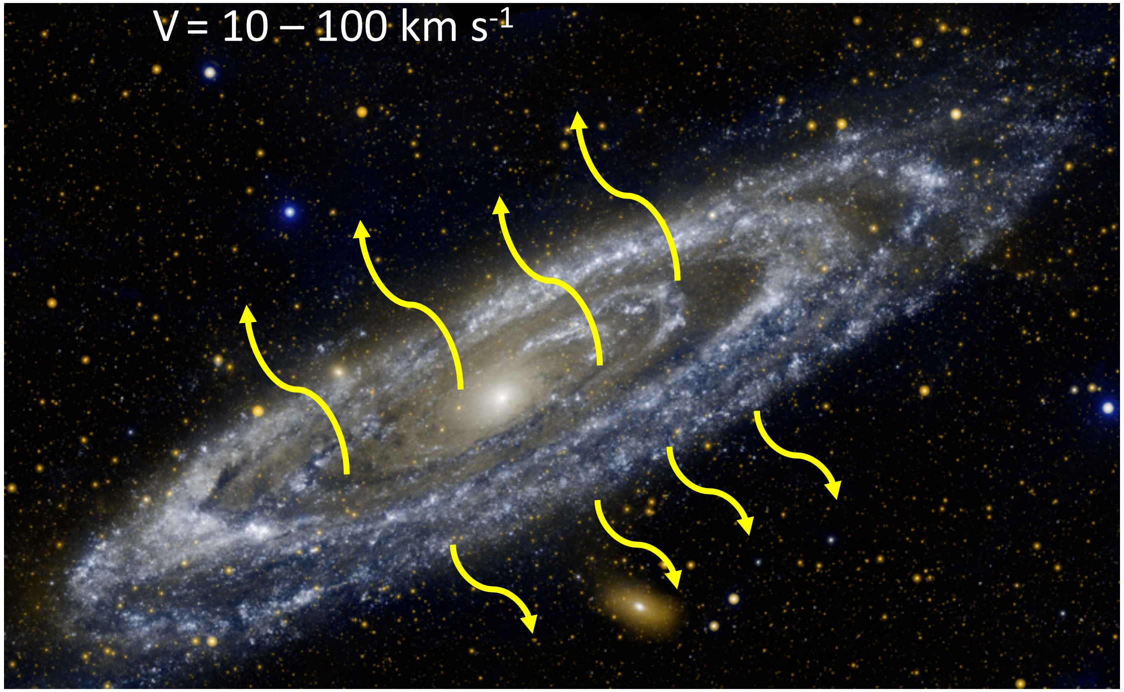
$$\frac{\partial \psi(\vec{r},p,t)}{\partial t} = q(\vec{r},p,t) + \vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi - \vec{V}\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi$$



e.g. Strong et al. (2007) ARNPS 57, 285 and references therein

The Transport Equation: convection

$$\frac{\partial \psi(\vec{r},p,t)}{\partial t} = q(\vec{r},p,t) + \vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi - \vec{V}\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi$$



e.g.

Breitschwerdtet al. 1991, A&A, 245, 79

Hanasz et al. 2009, A&A, 498, 335

Everett et al.2010 ApJ 711 13

Giacinti et al. 2012 PRL 108, 261101

Pakmor et al. 2016, ApJ, 824, L30

Recchia et al. 2017, MNRAS, 470, 865

Pfrommer et al. 2017, MNRAS, 465, 4500

Evoli et a. 2018 Phys. Rev. Lett. 121

Tremblay et al. 2019 BAAS 51c 480 ASTRO2020 white paper

Hopkins et al. MNRAS submitted

The Transport Equation: reacceleration

$$\frac{\partial \psi(\vec{r},p,t)}{\partial t} = q(\vec{r},p,t) + \vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi - \vec{V}\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi$$

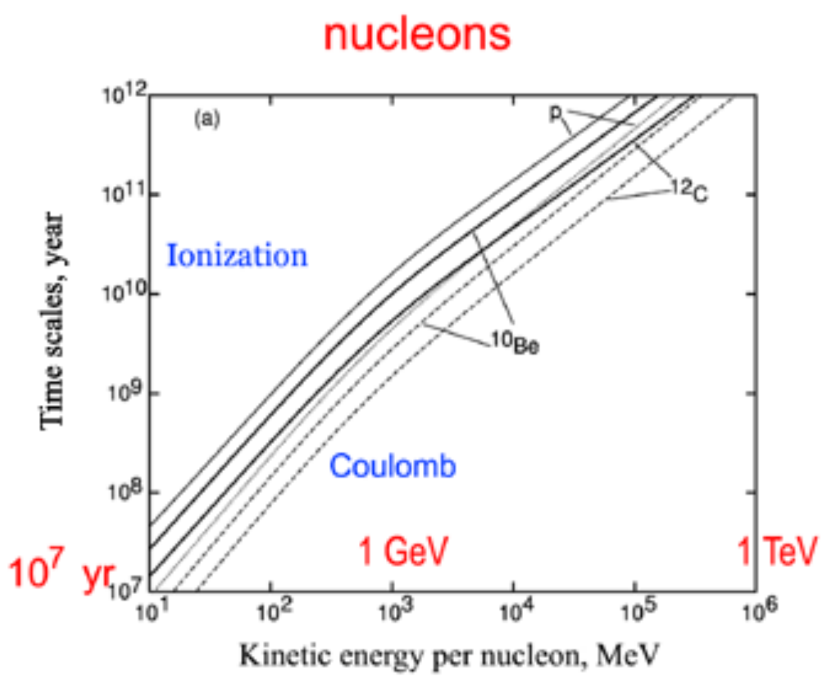
$V_a = 0 - 40$ km s^{-1}

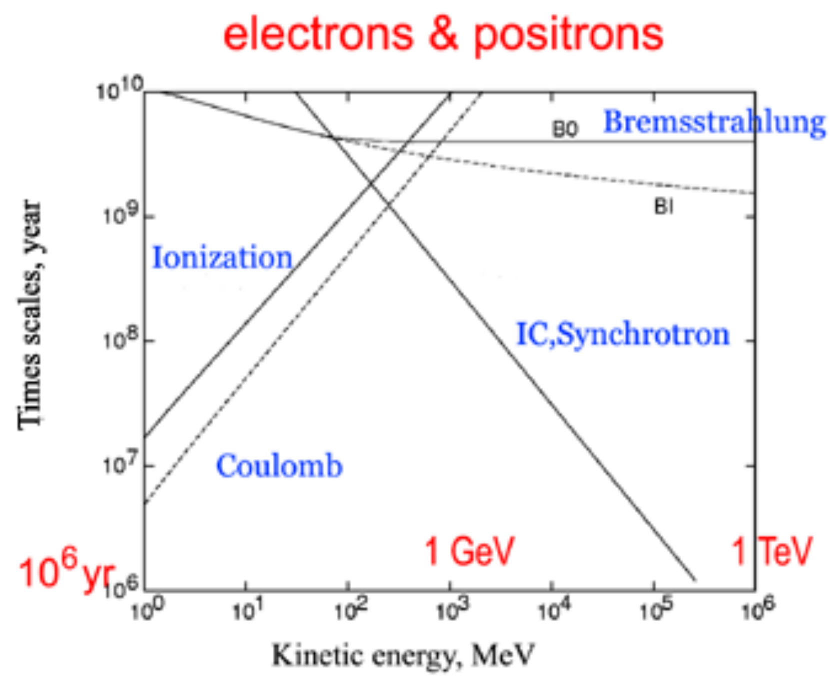
e.g.

Seo & Ptuskin, 1994
Thornbury & Drury, MNRAS 442, 3010 (2014)
Drury & Strong, A&A 597, 117 (2017)
Tomassetti 2015, PhRvD, 92, 081301

The Transport Equation: energy losses

$$\frac{\partial \psi(\vec{r},p,t)}{\partial t} = q(\vec{r},p,t) + \vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi - \vec{V}\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi$$





Strong & Moskalenko 1998, ApJ 509, 212

Solutions to the transport equation

Analytical	**Numerical**
quick estimates	
simple cases	more complex cases
simplified assumptions	more realistic

Approach

Analytical

e.g.
Davis (1960)
Ginzburg & Syrovatskii (1969)
Webber et al. (1992)
Maurin, Donato et al. (2001)
Jones et al. (2001)

Semi-Analytical

Ptuskin (1980)
Schlickeiser (1990)
USINE (Maurin et al. 2000)

Numerical

GALPROP (Strong & Moskalenko 1998)
DRAGON (Evoli *et al.*, 2008)
PICARD (Kissmann *et al.*, 2013)

CR Propagation Codes

Solving the transport equation

GALPROP (public; around since ’98; Strong & Moskalenko as original developers).

It models all CR species, and gamma rays. Recent extensions to synchrotron temperature (Strong et al. 2011) and polarization, free-free absorption and emission (Orlando & Strong 2013).

DRAGON (public; Evoli et al.)

It models all CR species and gamma rays. Inspired by GALPROP, recently rewritten as DRAGON2 with new features (e.g. coefficient diffusion tensor).

PICARD (not public; Kissmann et al.)

It models all CR species. No B-field yet. It allows fine 3d spatial resolution with reasonable CPU time.

USINE (public; Maurin)

Semi-analytical. It models hadronic CRs. Plan to include also CR electrons in future

(Additional Related Codes and Scenarios)

Girichidis et al.: MHD with CR as a fluid, CR-driven wind from SNa, small scale.

Hanasz et al. **PIERNIK** code**,** MHD with CR as a fluid, large-scale CR-driven outflows in galaxies; full galaxy.

Pakmor & Pfrommer et al.: feedback, e.g. CR driven galactic winds.

Uhlig et al 2012, Salem et al. 2014, Jacob et al. 2017, Simpson et al. 2016, Booth 2013, etc... (incomplete reference)

For CR propagation in the Galaxy with self-generated turbulence see also

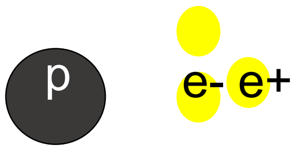
Aloisio & Blasi (2013) JCAP 1307

Blasi, Amato, Serpico (2015) 583 A95

Evoli's talk this conference

Ingredients (& Uncertainties) in CR Propagation Codes

CR direct measurements to constrain injected spectra and **propagation parameters**



But

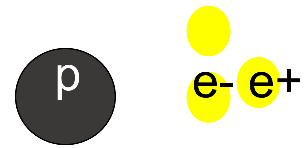
Primary B? (e.g. Genolini+2015)

Different diffusion for CR heavier than He? (e.g. Jóhannesson+2016)

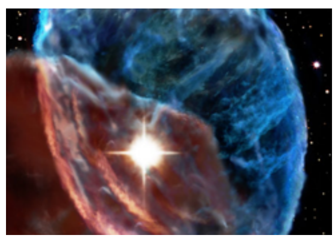
Anisotropic diffusion coefficient? (e.g. De Marco+ 2007, Blasi+ 2012, Aloisio+ 2015, Gaggero+ 2015, Tomassetti 2015, Fend+ 2016 , Cerri+ 2017)

Ingredients (& Uncertainties) in CR Propagation Codes

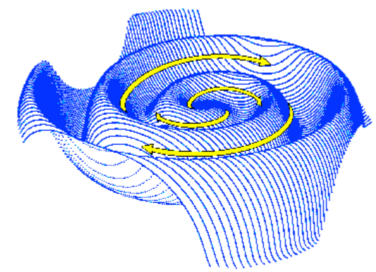
CR direct measurements to constrain injected spectra and **propagation parameters**



CR source distribution

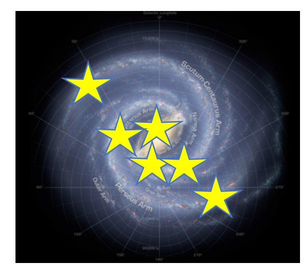


Magnetic field



Gas distribution

Interstellar photon distribution

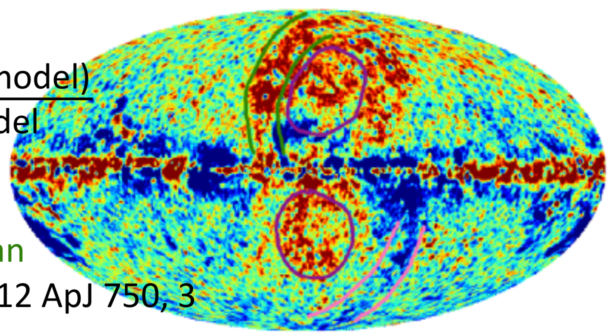


Cross-sections

Challenges with present CR propagation models

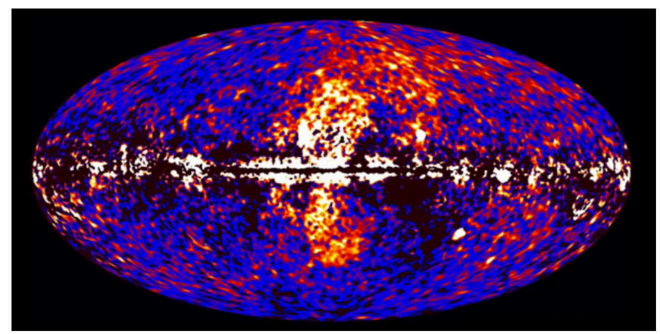
- Disagreement with some precise CR measurements
- Excesses and deficiencies in gamma rays data at a large and at small scales.

(data-model) / model

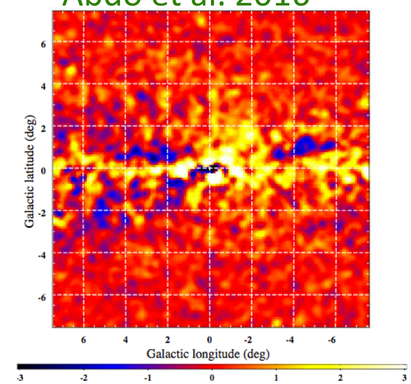


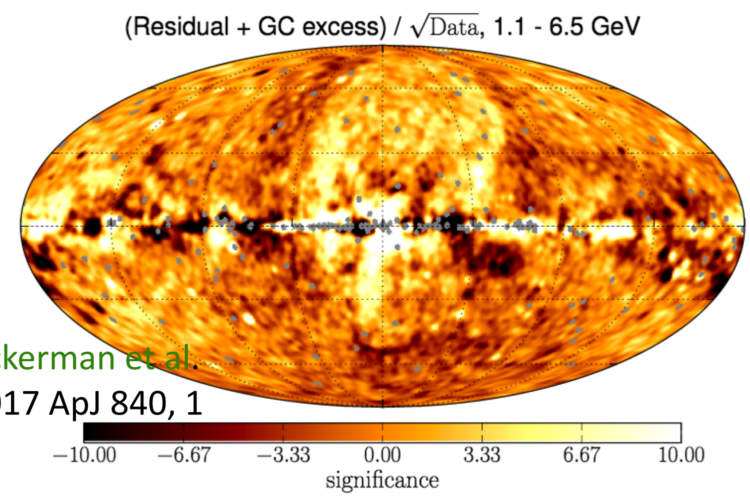
Ackerman et al. 2012 ApJ 750, 3

NASA/DOE/Fermi LAT/Finkbeiner et al.
Su et al. 2010



Abdo et al. 2016





Ackerman et al. 2017 ApJ 840, 1

Confirmed by many authors!

(e.g. Dobler+ 2010; Calore+ 2015, Hooper+ 2010,2013, Acero+ 2016, Goodenough+ 2011, Abazajian+ 2012, Gordon+ 2013, Daylan+ 2014, Cholis+ 2015, Bartels+ 2016, Herold & Malyshev 2019, ...)

A modified source term in the center absorbs the GC excess (Gaggero+ 2015; Carson & Profumo 2016)

Challenges with present CR propagation models

- Disagreement with some precise CR measurements
- Excesses and deficiencies in gamma rays data at a large and at small scales.

International Journal of Modern Physics D | VOL. 28, NO. 15

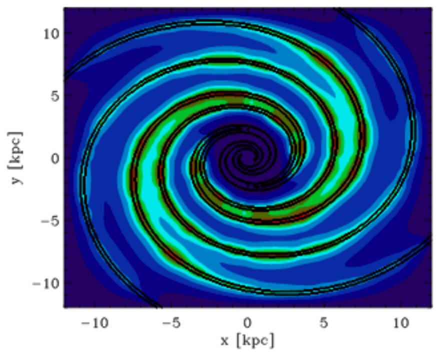
The origin of Galactic cosmic rays: Challenges to the standard paradigm

Stefano Gabici, Carmelo Evoli, Daniele Gaggero, Paolo Lipari, Philipp Mertsch, Elena Orlando, Andrew Strong and Andrea Vittino

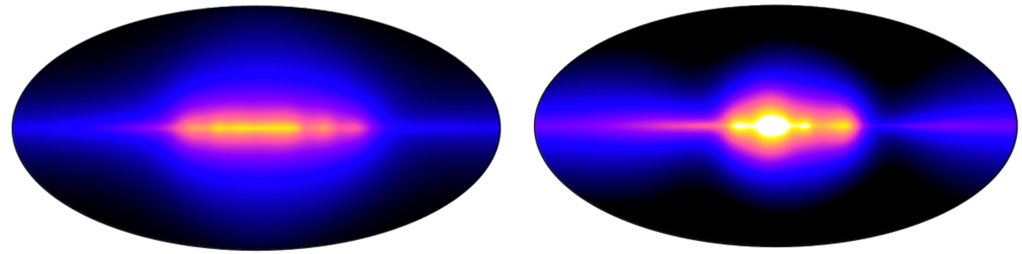
https://doi.org/10.1142/S0218271819300222

A critical review of the standard paradigm for the origin of Galactic cosmic rays (CRs) is presented. Recent measurements of local and far-away CRs reveal unexpected behaviors, which challenge the commonly accepted scenario. These recent findings are discussed, together with long-standing open issues. Despite the progress made thanks to ever-improving observational techniques and theoretical investigations, at present our understanding of the origin and of the behavior of CRs remains incomplete. We believe it is still unclear whether a modification of the standard paradigm, or rather a radical change of the paradigm itself is needed in order to interpret all the available data on CRs within a self-consistent scenario.

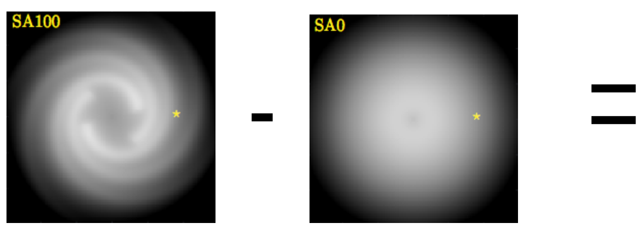
Effects of 3D CR distributions

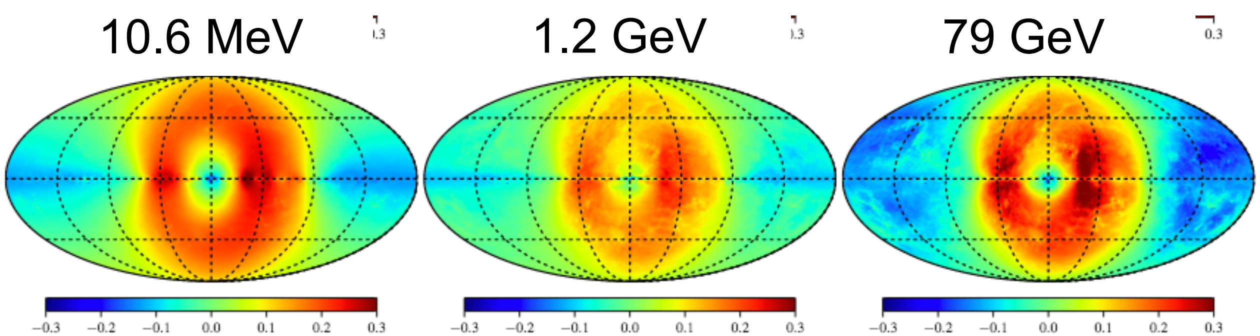


Electron density at 100 GeV with **DRAGON** (Gaggero et al. 2013 PRL 111, 021102)



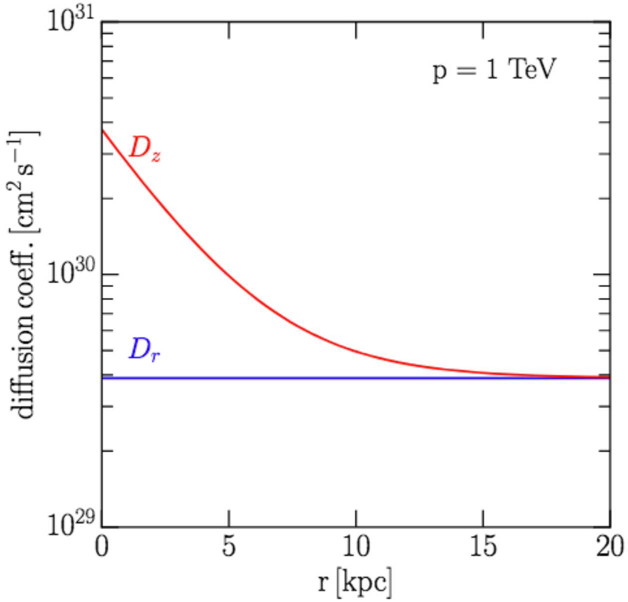
Inverse Compton: with Galactic bar and 4 spiral arms implemented in **PICARD** (Werner, M. et al. 2015, APh 64, 18; Kissmann, R. et al. 2015, APh 70, 39; Kissmann's talk at CRATER2018)



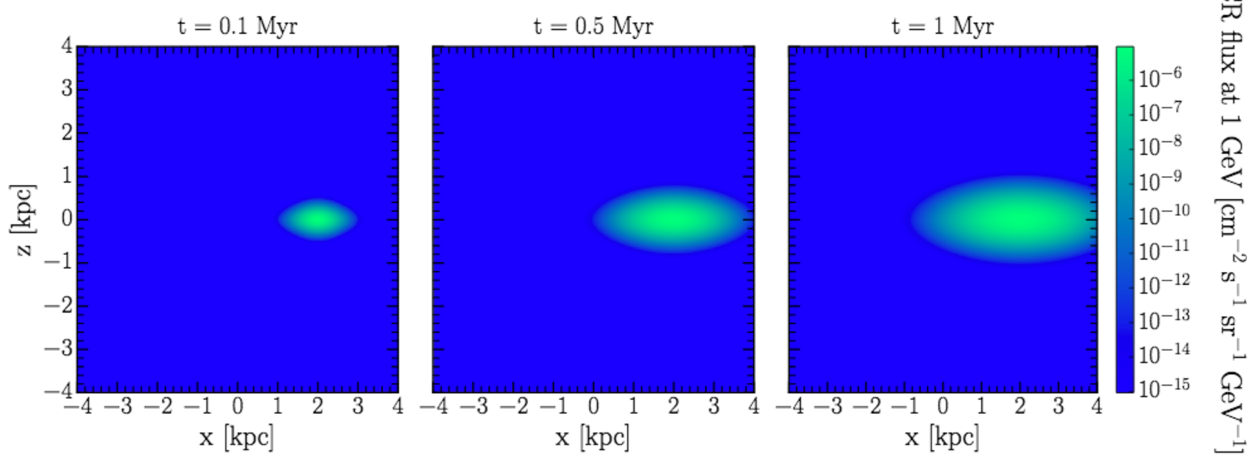


Gamma residuals between spirals arms and non-spiral CR source distribution with **GALPROP** (Porter et al. 2017 ApJ 846, 67; Johannesson et al. 2018 ApJ 856, 45)

An example of anisotropic diffusion in DRAGON2



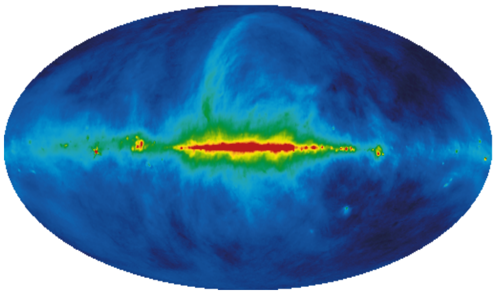
Evoli et al. (2017) JCAP 02, 015 (see also Gaggero et a. 2015)



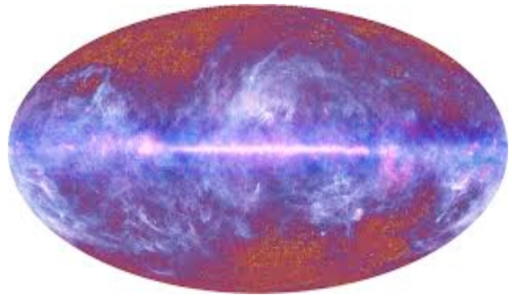
Also diffusion coefficient tensor implementation in DRAGON2 (Cerri+ 2017)

Inclusion of synchrotron modeling and 3D Bfield in GALPROP & Effects in gamma

Modeling temperature & polarization with 3D magnetic fields in a consistent way with gammas



Radio surveys

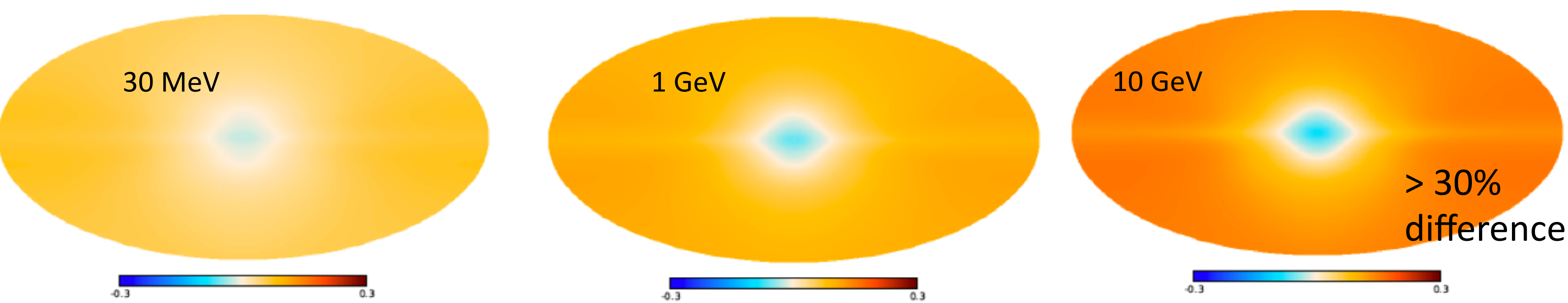


Planck - microwaves

Strong, Orlando, Jaffe (2011) A&A 534, 54
Orlando & Strong (2013) MNRAS 436, 2127
Orlando (2018) PRD 436, 2127

Inverse Compton residuals (Orlando 2019, Phy.Rev.D 99, 043007)

(IC old – IC new) / IC old



Updated B-fields produces brighter IC in the inner Galaxy than predicted by previous models used for Fermi LAT analyses

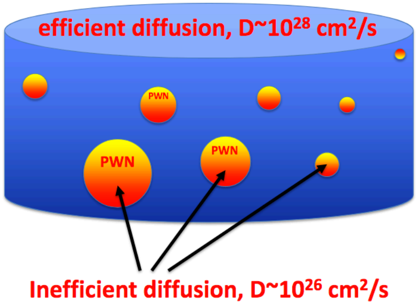
CR propagation codes for halos?

As large-scale back-/fore-ground

- many model uncertainties (gas, ISRF, CR distribution, B-field, cross-sections)
- challenges in describing very precise recent data (review by Gabici+ 2019)

Including regions of inefficient diffusion around sources

- “Swiss cheese” (Profumo’s talk)



- Same uncertainties as for the large-scale modeling
- Need of non-equidistant binning (Evoli et al. (2017) JCAP 02, 015; Jóhannesson et al. (2019) ApJ 879, 91)
- need to reduce the Galaxy, very high computational costs and memory (Jóhannesson et al. 2019 ApJ 879, 91)

Thank you for your attention