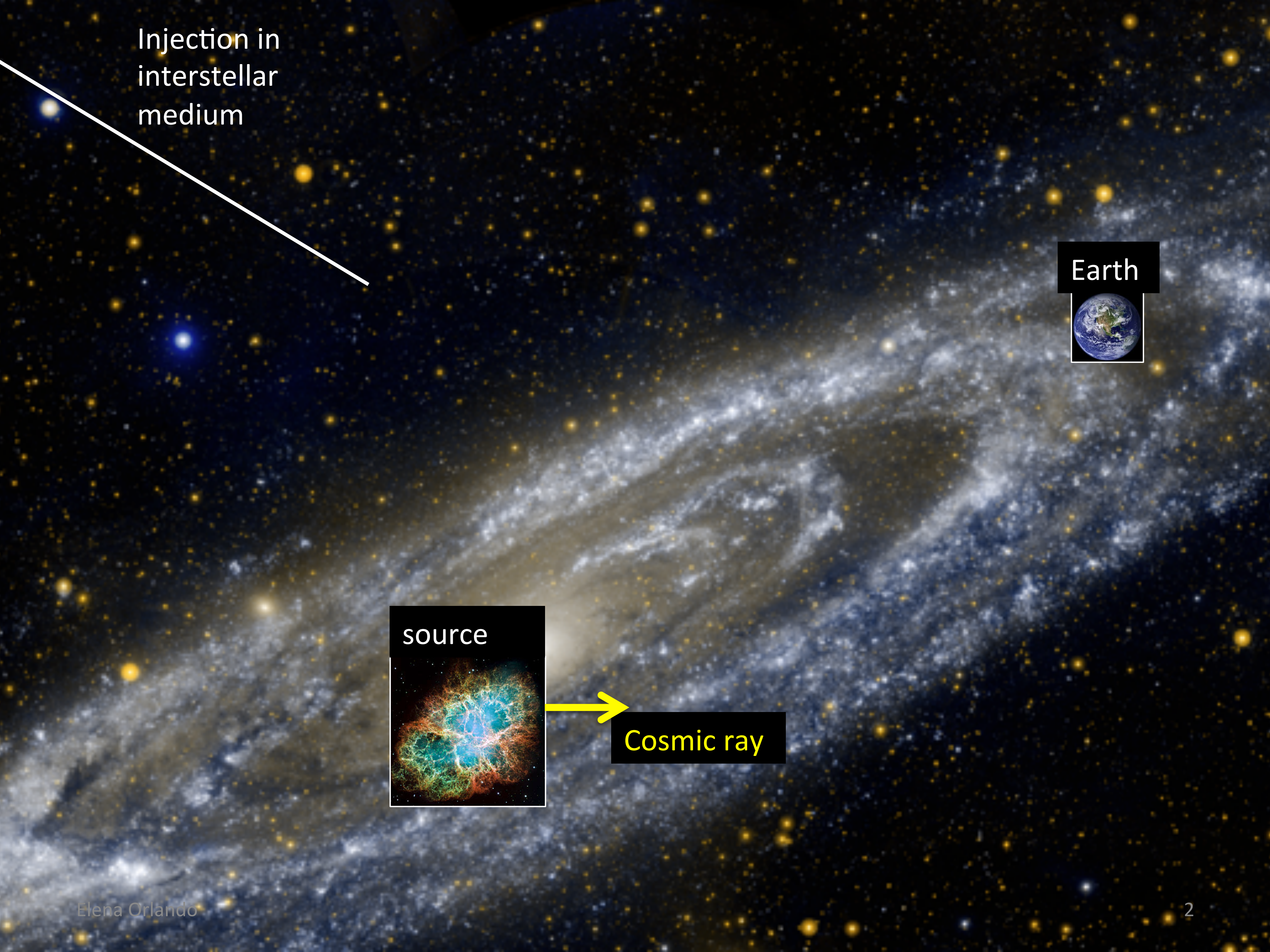
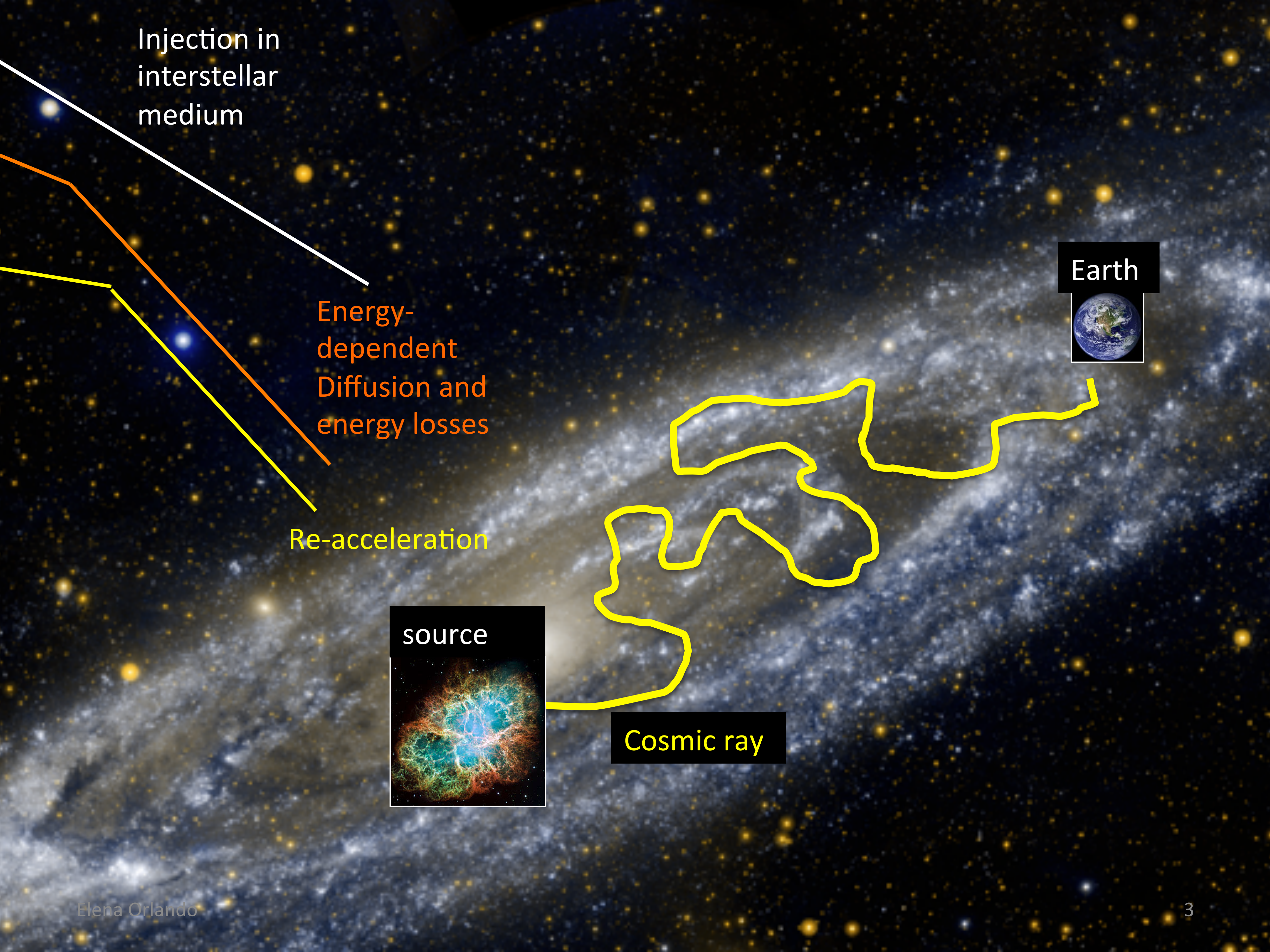
Recent results and coming improvements of the GALPROP cosmic-ray propagation code

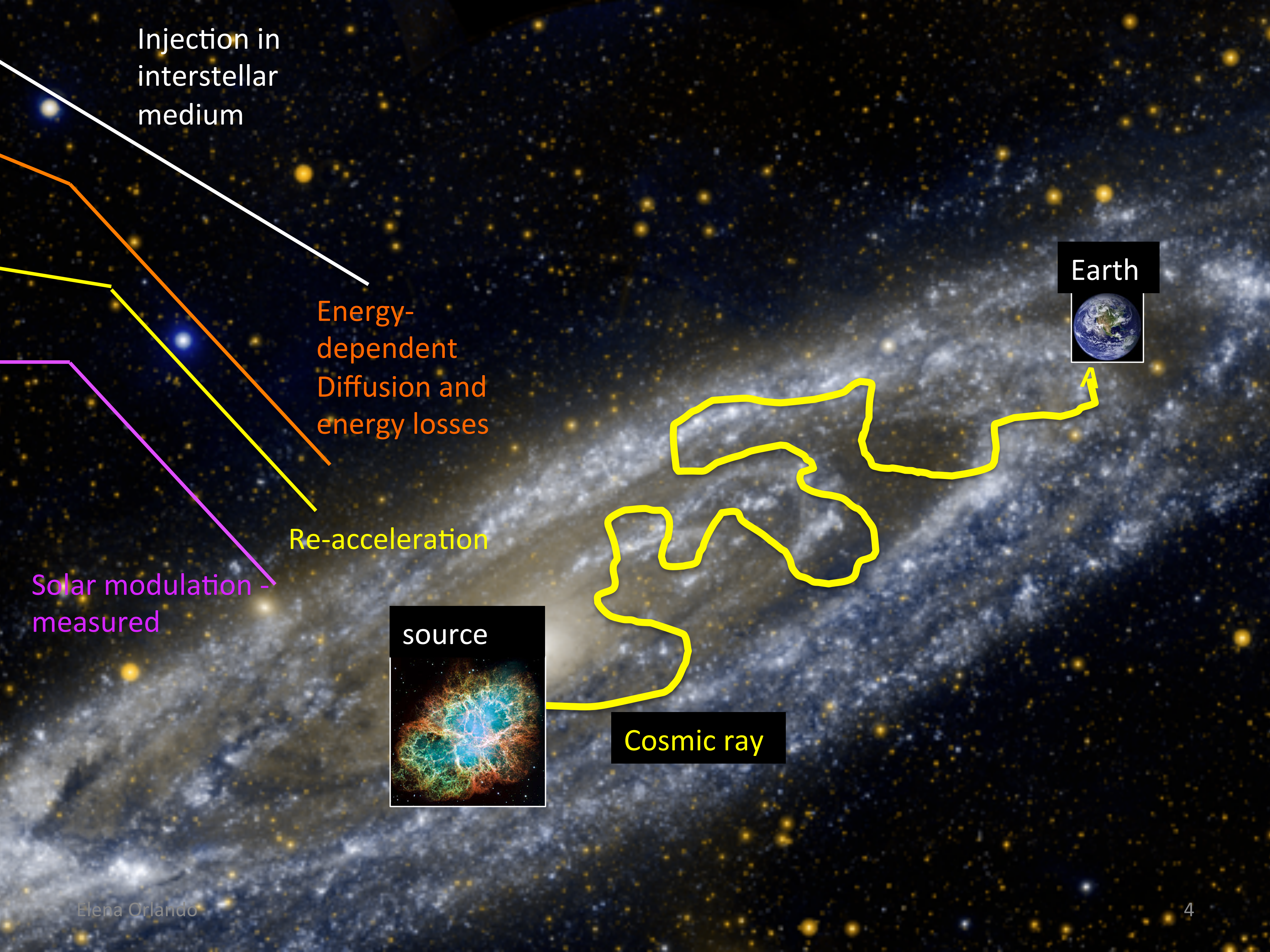
Elena Orlando
(Stanford University)
& the GALPROP team

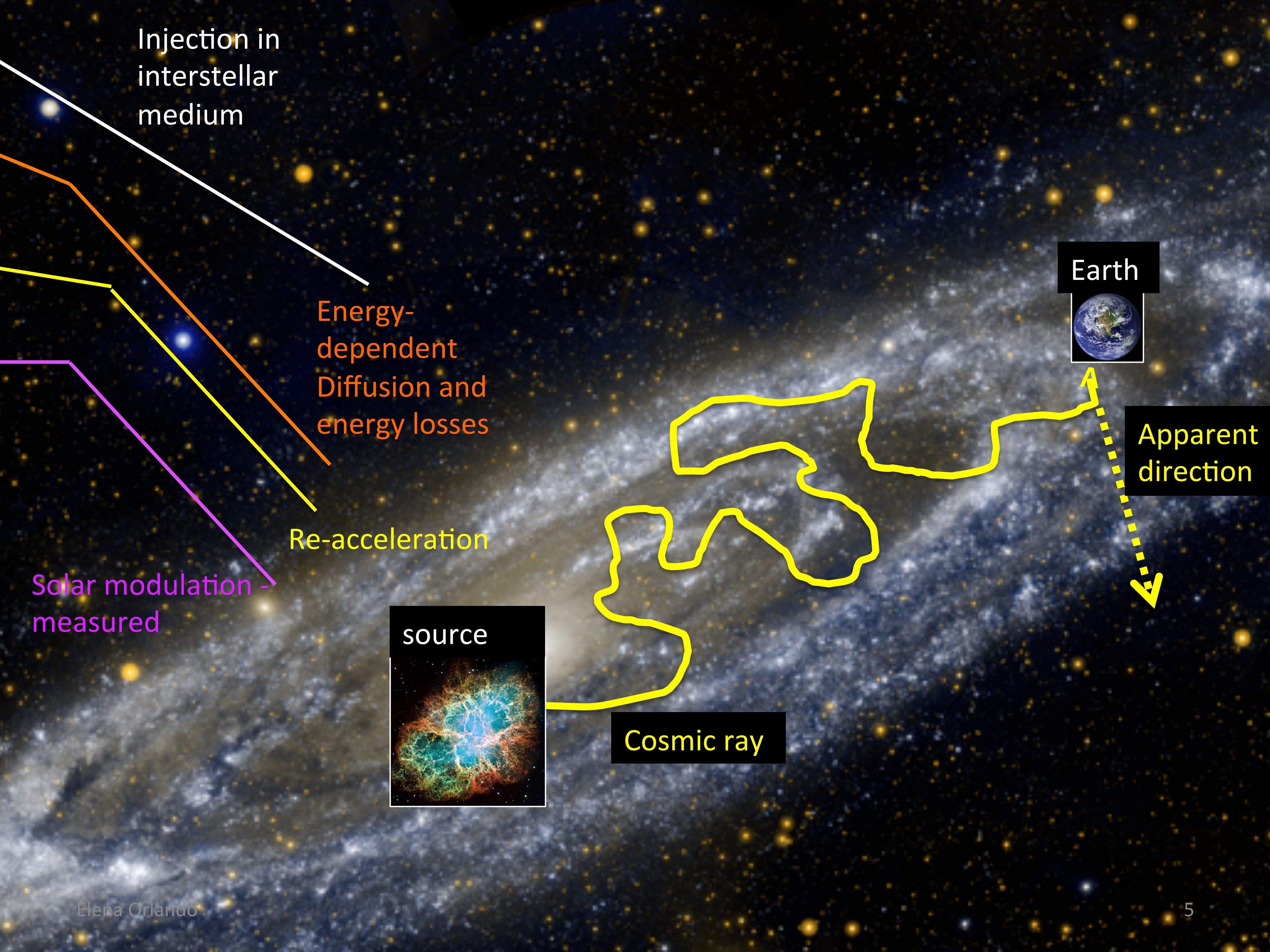
CRBTSM 2016 – San Vito di Cadore



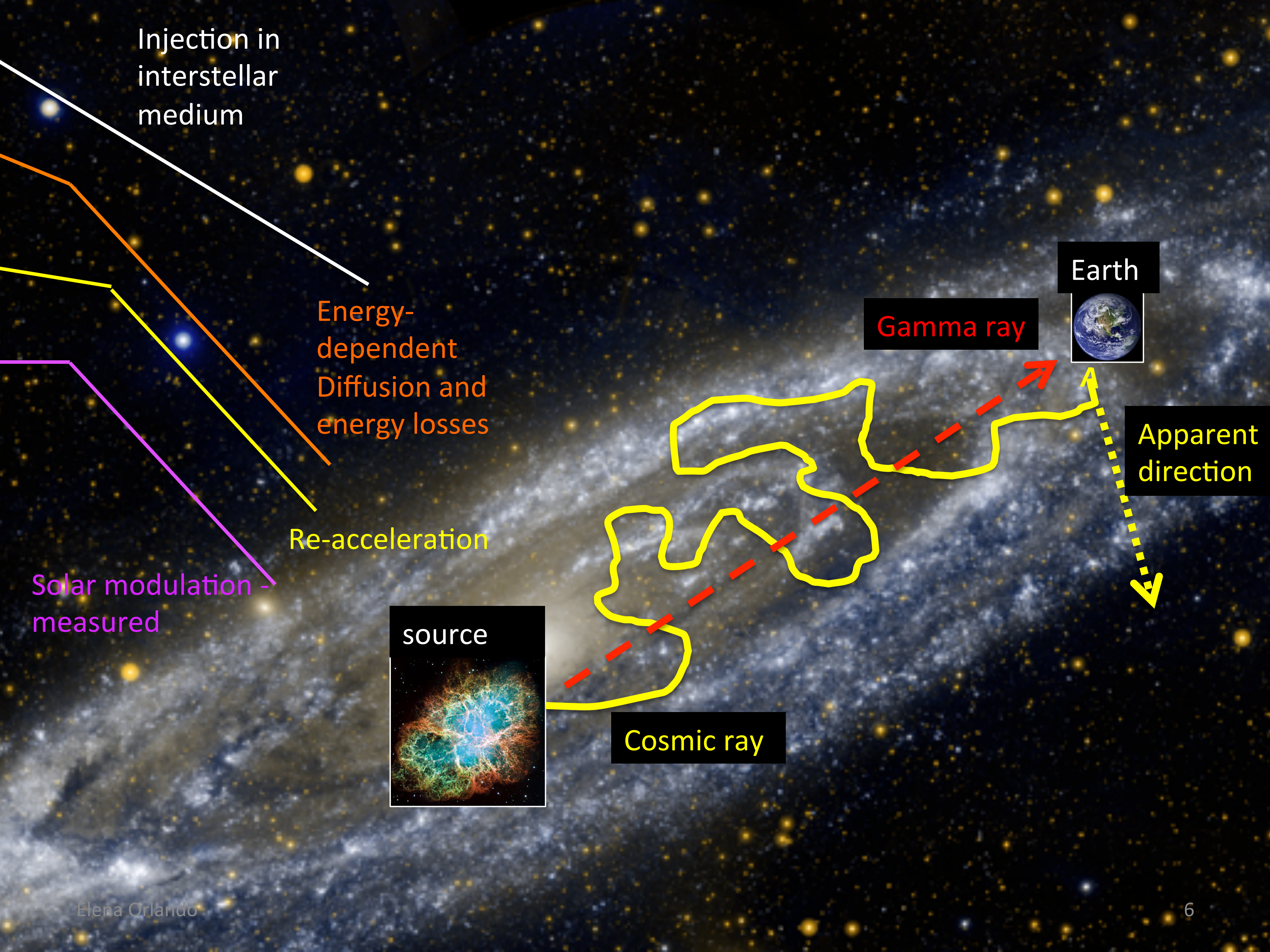
Injection in interstellar medium
Earth
source
Cosmic ray

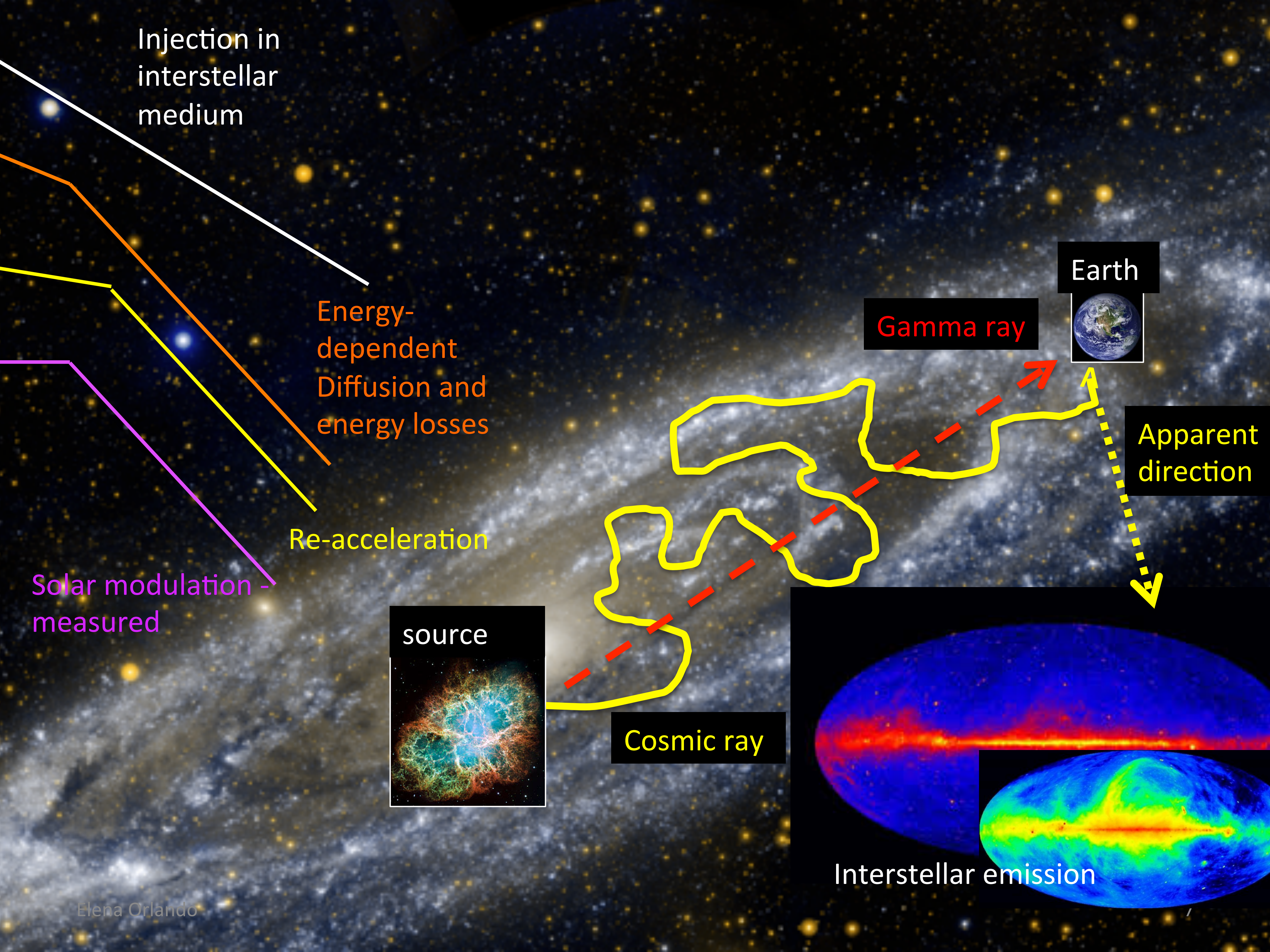

Injection in interstellar medium
Energy-dependent Diffusion and energy losses
Re-acceleration
Earth
source
Cosmic ray


Injection in interstellar medium
Energy-dependent Diffusion and energy losses
Re-acceleration
Solar modulation - measured
Earth
source
Cosmic ray



Injection in interstellar medium
Energy-dependent Diffusion and energy losses
Re-acceleration
Solar modulation - measured
Earth
Apparent direction
source
Cosmic ray


Injection in interstellar medium
Energy-dependent Diffusion and energy losses
Re-acceleration
Solar modulation - measured
Earth
Gamma ray
Apparent direction
source
Cosmic ray
Elena Orlando


Injection in interstellar medium
Energy-dependent Diffusion and energy losses
Re-acceleration
Solar modulation - measured
source
Cosmic ray
Gamma ray
Earth
Apparent direction
Interstellar emission

CR Propagation: GALPROP

THE GALPROP TEAM:
I. Moskalenko and A. Strong (original developers),
G. Johannesson, E. Orlando, T. Porter, (A. Vladimirov)

http://*galprop.stanford.edu*

AROUND SINCE '98 WHEN USED
FOR COMPTEL AND EGRET!

It solves the transport equation (energy losses, diffusion, acceleration, convection, fragmentation, radioactive decay) for all CR species

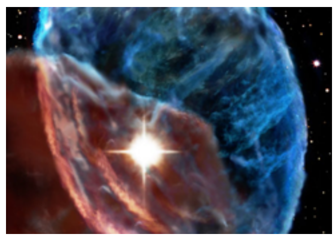
Ingredients (and sources of uncertainty)

Injected spectra and **propagation parameters** (adjusted to fit CR measurements)

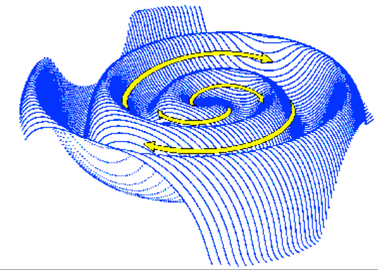
p

e- e+

CR source distribution

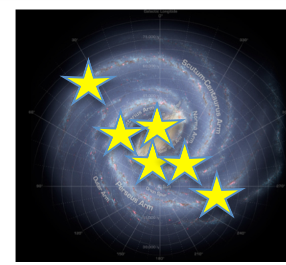


Magnetic field



Gas distribution (atomic HI; molecular H2; ionized HII)

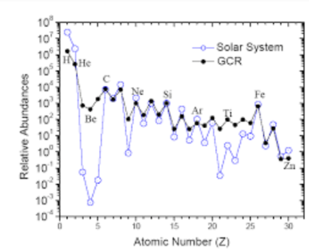
ISRF



Cross sections

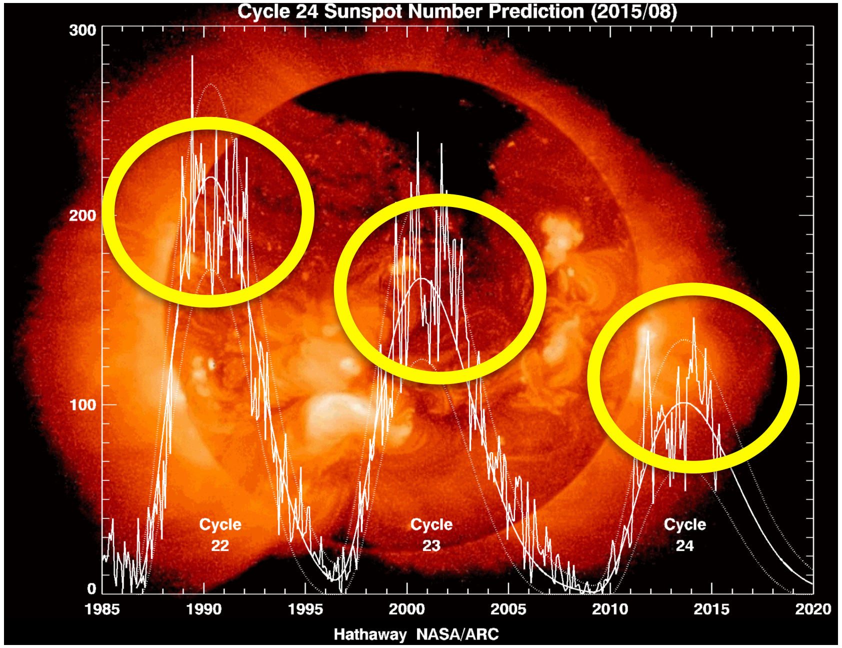
σ

CR abundances



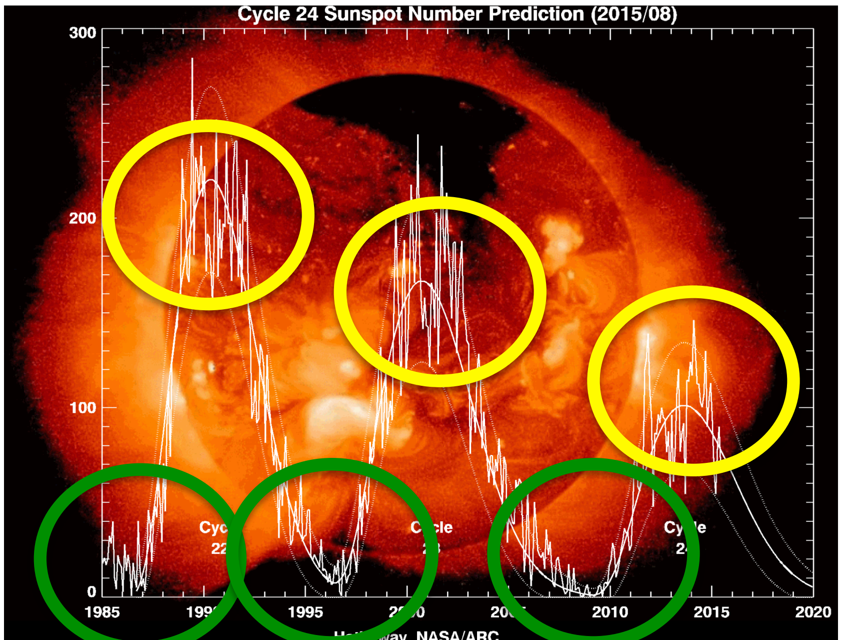
Latest results:
Interpretation of CR measurements

Solar modulation



CR

Solar modulation

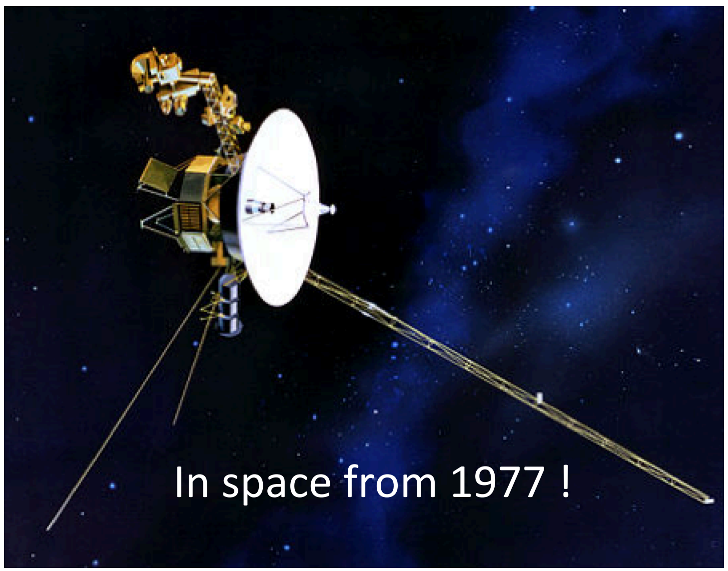


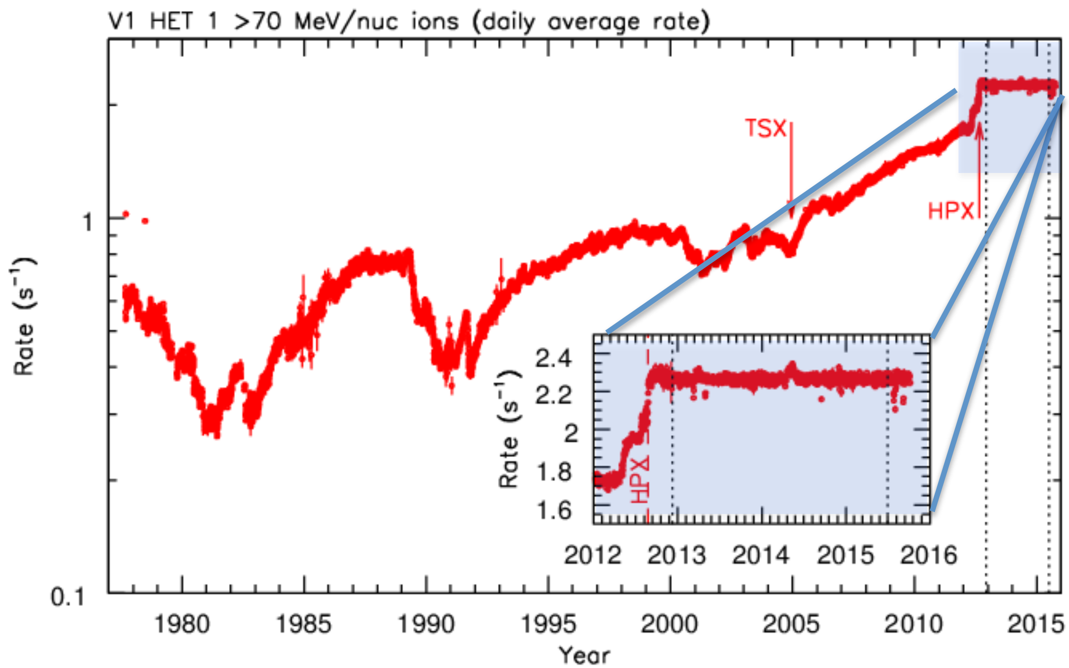
CR

CR

Voyager 1

In the interstellar space!

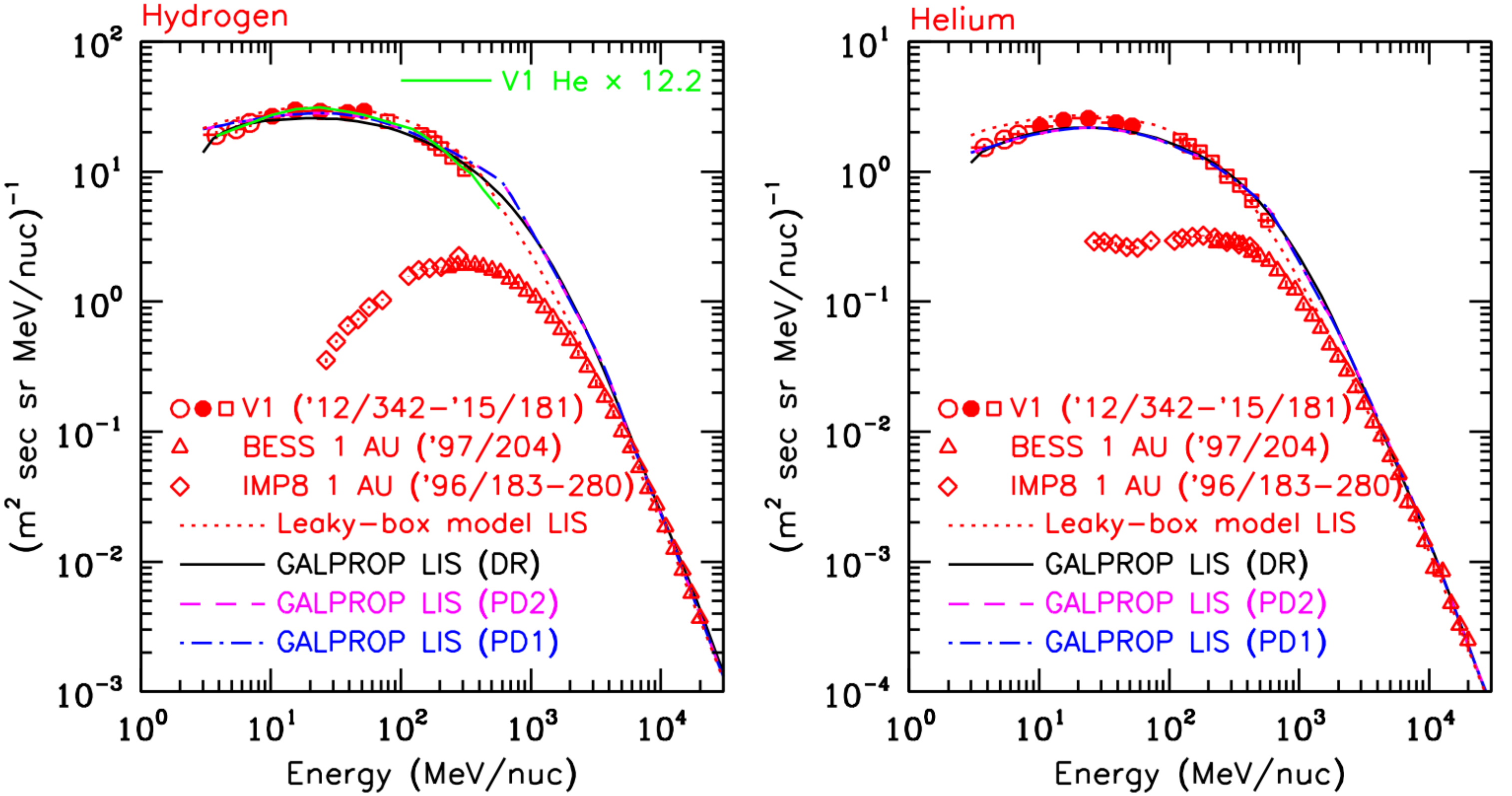




Cummings, Stone, Heikkila, Lal, Webber, Jóhannesson, Moskalenko, Orlando, and Porter, 2015 Fall AGU, ApJ accepted

Voyager 1

GALPROP models were fit to data to obtain the energy density (0.83-1.02 eV cm^{-3}) and elemental abundances



Cummings, Stone, Heikkila, Lal, Webber, Jóhannesson, Moskalenko, Orlando, and Porter, ApJ accepted

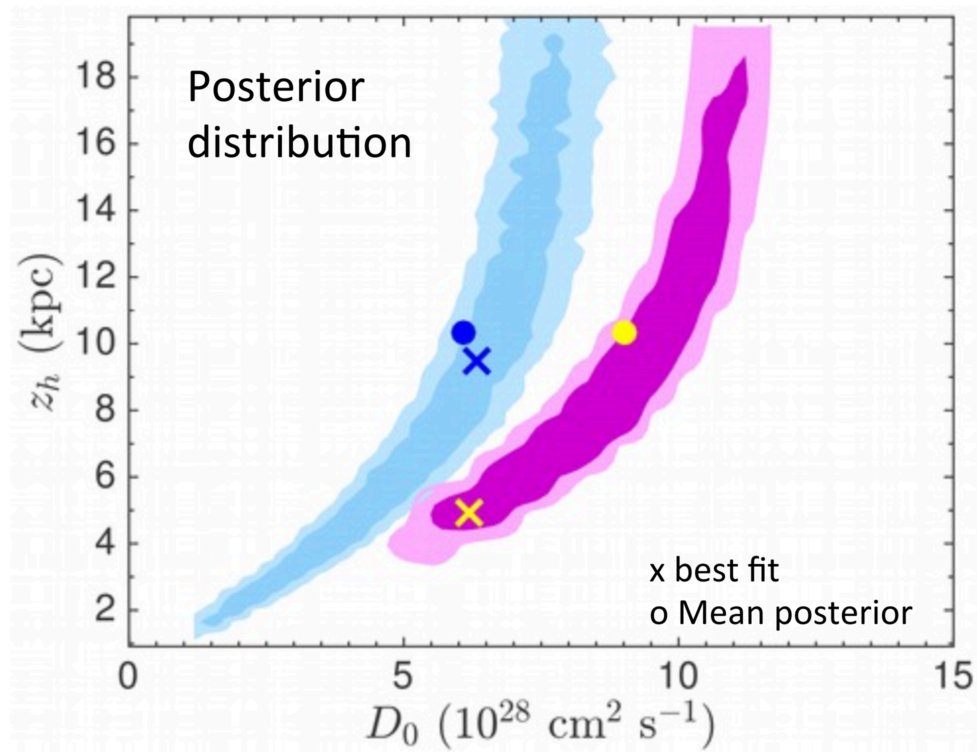
Bayesian analysis of CR propagation

The Galbayes collaboration

Bayesian analysis of CR propagation

G. Jóhannesson, R. Ruiz de Austri, A. C. Vincent, I. V. Moskalenko, E. Orlando, T. A. Porter, A. W. Strong, R. Trotta, F. Feroz, P. Graff, M. P., 2016 ApJ 824...16J Hobson, 2016 ApJ 824, 16

Two different scans:
- p, pbar, He
- Light elements

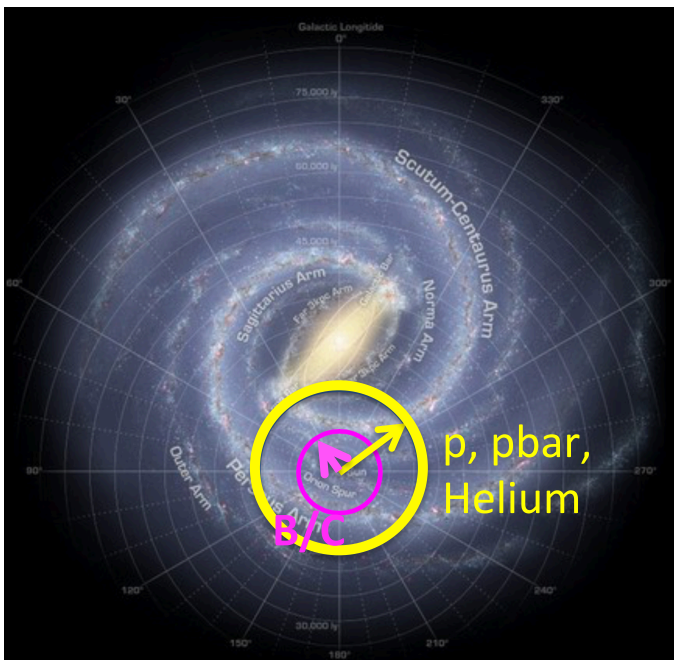


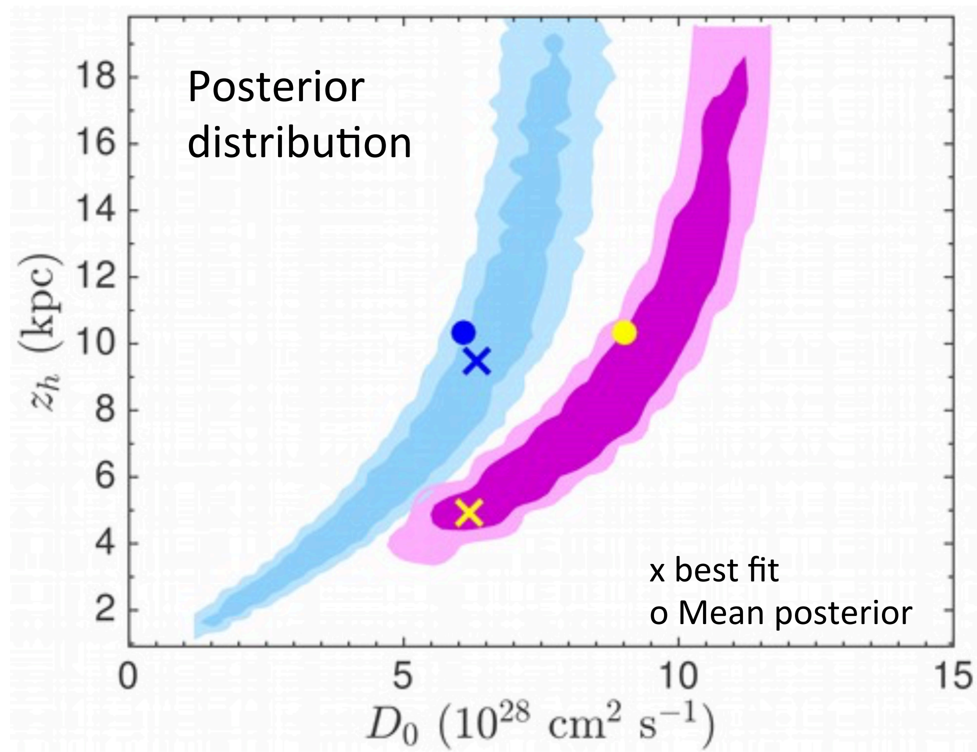
No homogeneous diffusion !

Bayesian analysis of CR propagation

G. Jóhannesson, R. Ruiz de Austri, A. C. Vincent, I. V. Moskalenko, E. Orlando, T. A. Porter, A. W. Strong, R. Trotta, F. Feroz, P. Graff, M. P., 2016 ApJ 824...16J Hobson, 2016 ApJ 824, 16

Two different scans:
– p, pbar, He
– Light elements



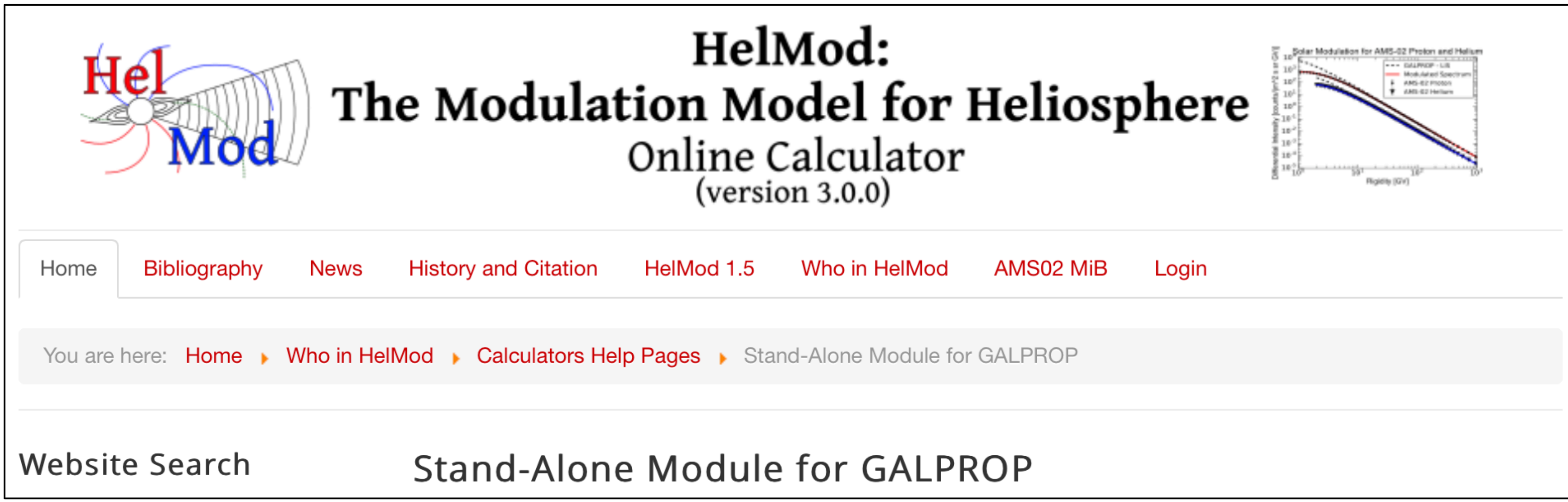


Different propagation parameters !

HelMod

2D Monte Carlo model

http://www.helmod.org



Grandi et al. ECRS Torino '16

HelMod + Galprop

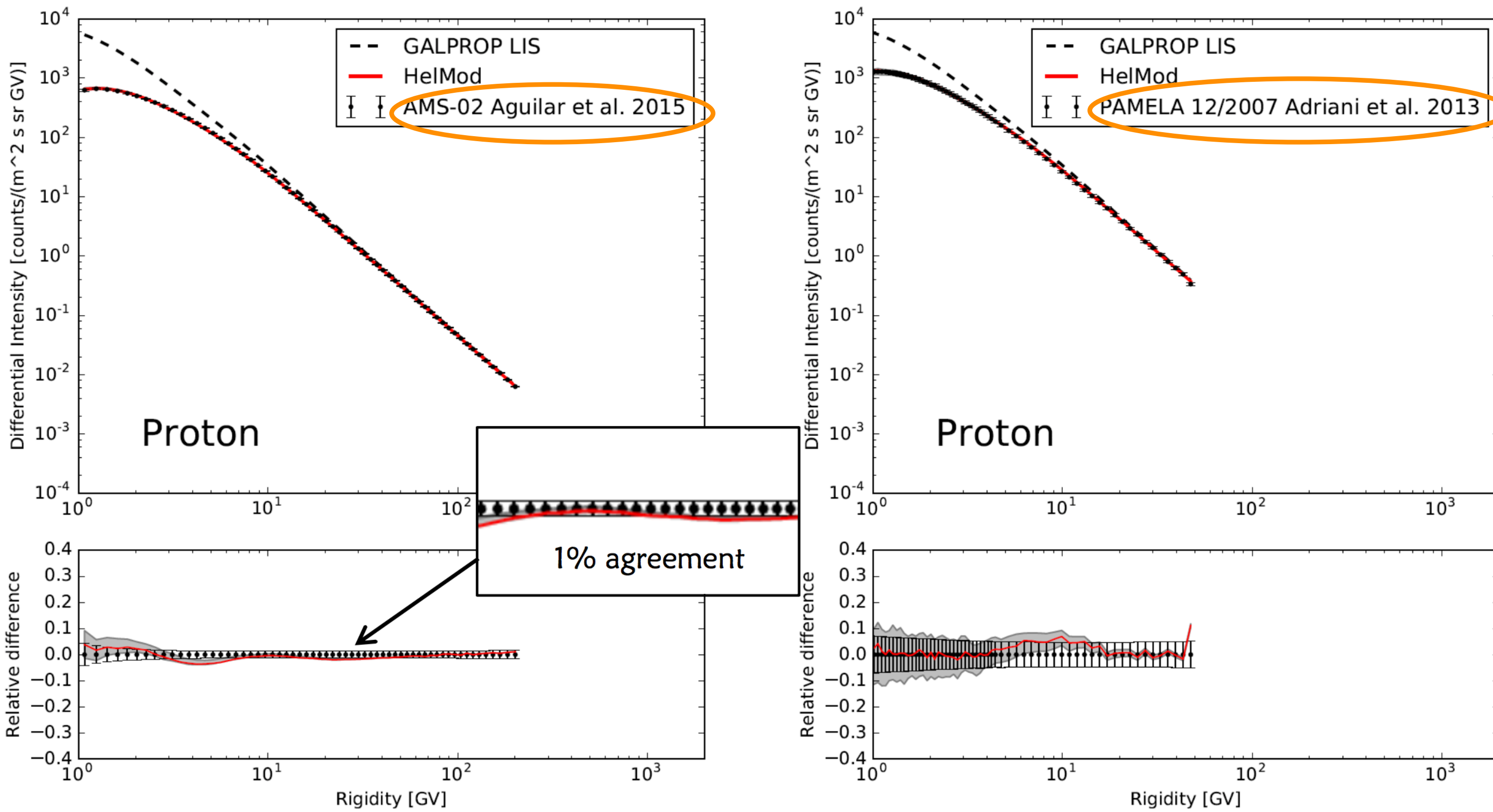
Tuning LIS to reproduce CR data during Solar Cycle 23 and 24

1. Solar modulation with HelMod

2. GALPROP framework into the Monte-Carlo-Markov-Chain interface: propagation parameters using **AMS-02** data as observational constraints, exploring a very large parameter space (*Masi et al. ECRS Torino '16*)

Della Torre, Grandi, La Vacca, Gervasi, Johannesson, Masi, Moskalenko, Orlando, Porter, Quadrani, Rancoita, Rozza, in prep.

HelMod + Galprop



- Found the best LIS that agrees with data at low- and high- solar activity for AMS-01, Pamela and AMS-02
- Simultaneous inclusion of diffusion, convection and reacceleration is required

Della Torre et al, in prep. (*Masi et al. and Della Torre et al. ECRS Torino '16*)

Recent results:

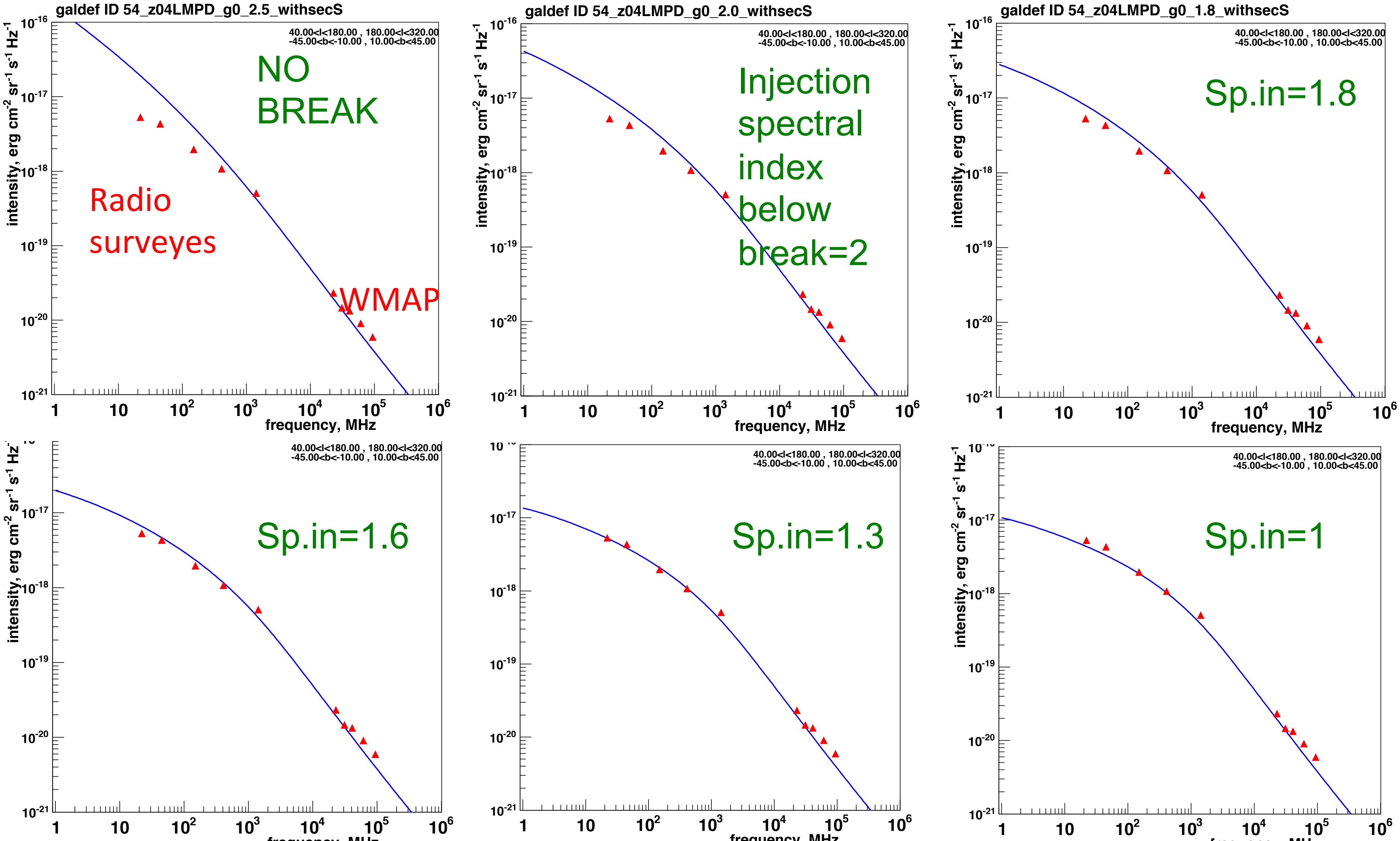
Interpretation of CR-induced interstellar emission

from radio to gamma rays

Radio and microwave modeling

Injection e- break < 4GeV

Strong, Orlando and Jaffe 2011 A&A, 534, 54



injection spectral index above 4 GeV = 2.5

Radio and microwave modeling

Strong, Orlando and Jaffe 2011 A&A, 534, 54

→ Break in local interstellar electron spectrum from <2 to ~3 @ few GeV

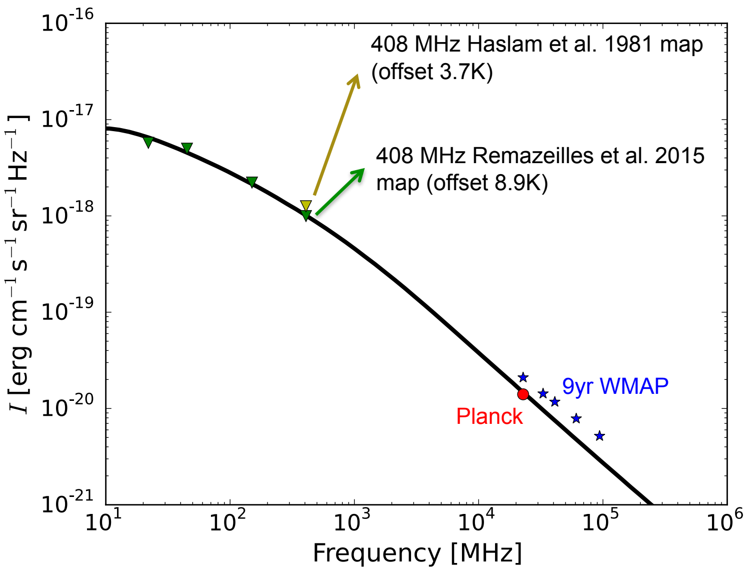
→ Injection spectrum < few GeV is harder than 1.6

→ Standard reacceleration models hard to reconcile with synchrotron.

UPDATES

- Planck data
- Reprocessed 408MHz map
- AMS-02 data

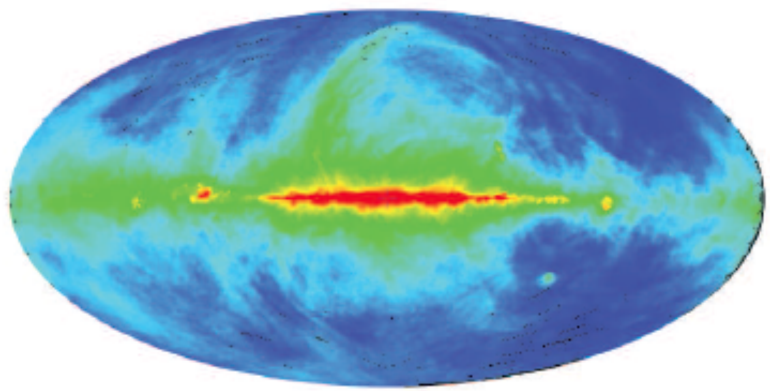
Orlando, Strong, Moskalenko, Dickinson, Digel, Jaffe, Jóhannesson, Leahy, et al. ICRC 2015; JPhCS 2016

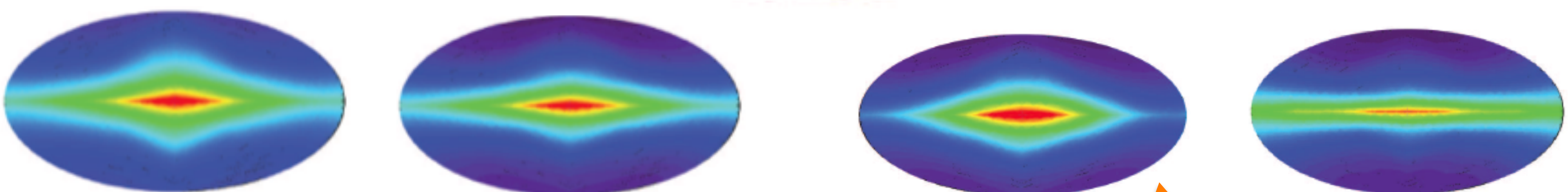


Radio and microwave modeling

Orlando & Strong 2013 MNRAS 436, 2127

I @ 408 MHz





Z=10 kpc

Z=4 kpc

Different propagation halo size

Different CR electron distribution

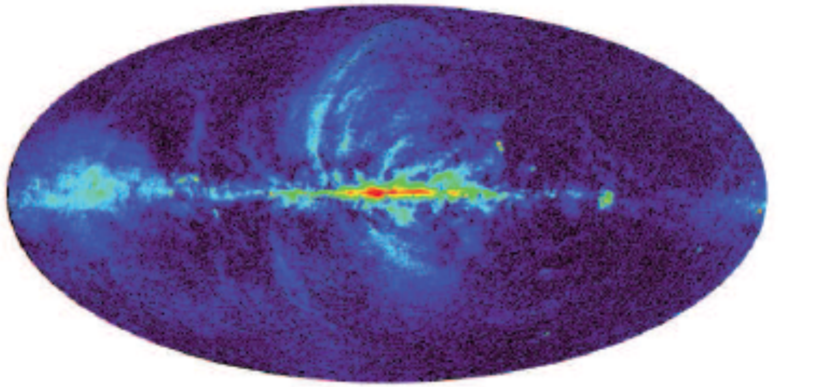
Different CR source distribution

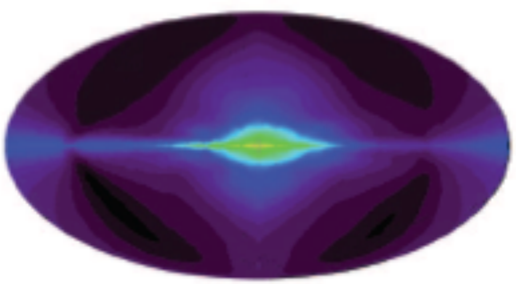
Radio and microwave modeling

Orlando & Strong 2013 MNRAS 436, 2127

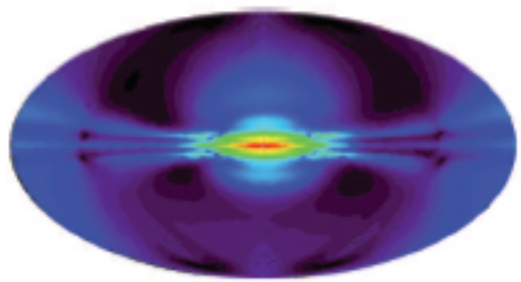
P @ 23 GHz

WMAP

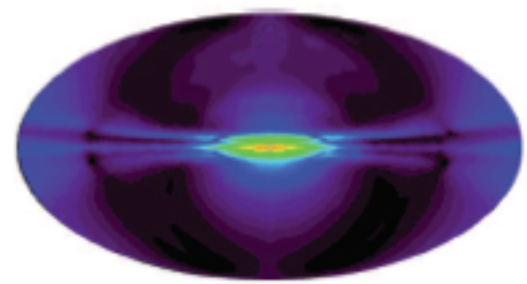




Sun 2008, 2010



Pshirkov, 2011 (ASS)



Pshirkov, 2011 (BSS)

Different B-fields

Radio and microwave modeling

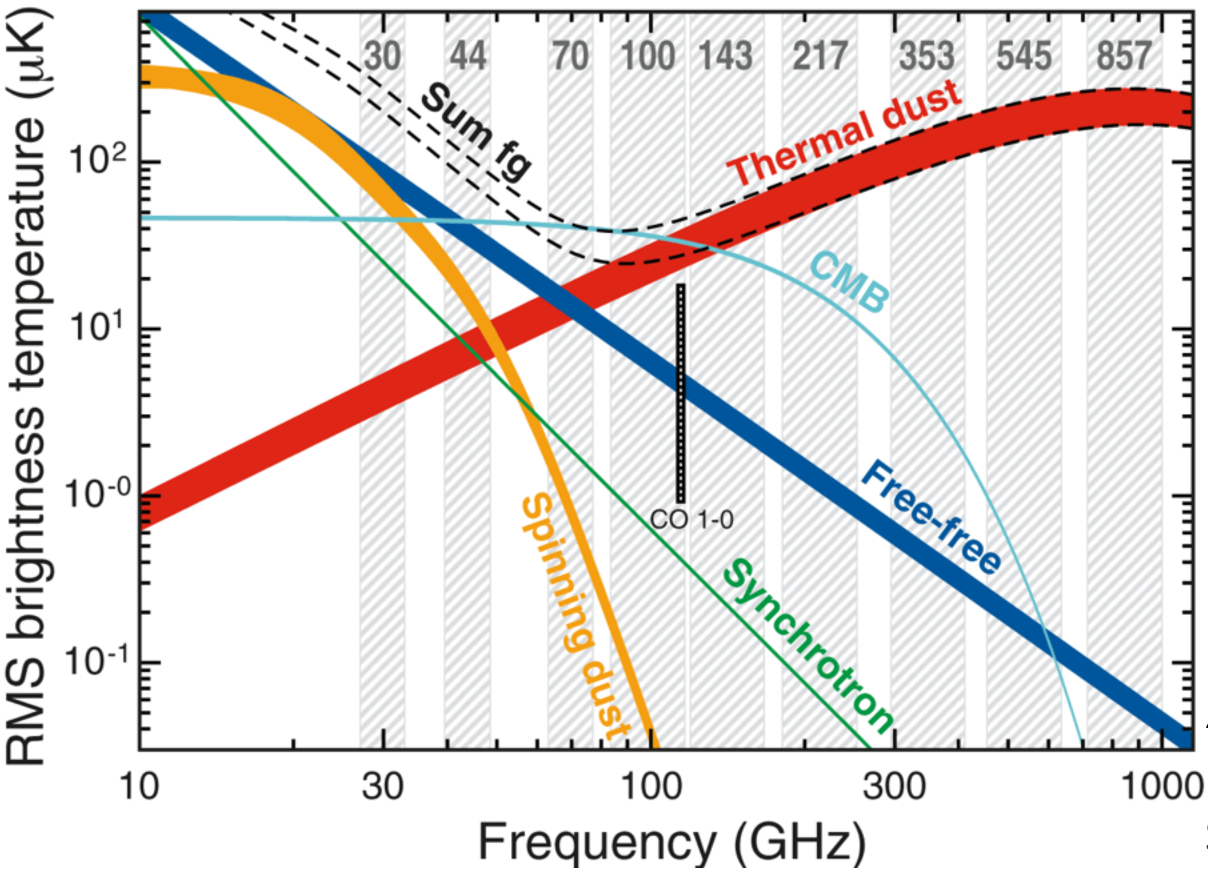
Based on Orlando & Strong 2013 MNRAS 436,2127

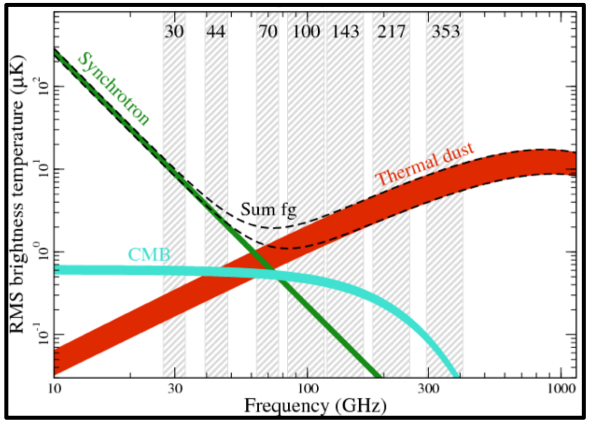
Main results:

- Flat CR source distribution in the outer Galaxy preferres
- Halo height > 4 kpc preferred
- Best fit magnetic field obtained

-- Residual structures not modeled

The microwave sky





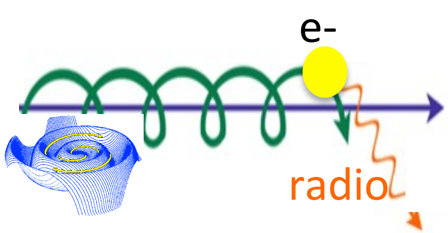
Planck coll. 2015 arXiv150201588
A&A accepted

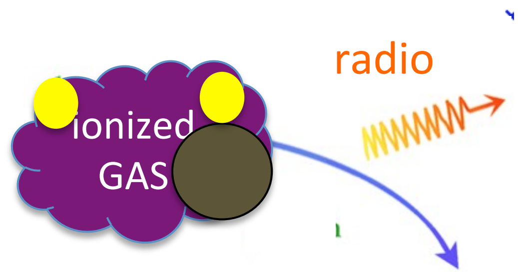
Synchrotron spectrum depends on CRe spectrum !

Difficulty on separating components: help from ancillary data and models !

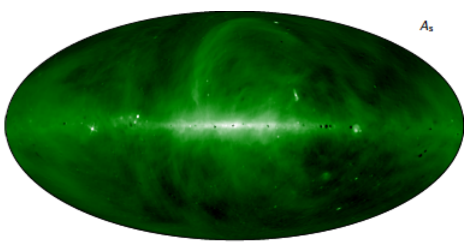
Galprop models & Planck data

- We used the synchrotron Model* for Planck low-frequency component separation to generate the maps officially released (Planck 2015 results. XXV & Planck 2015 results. X A&A accepted)

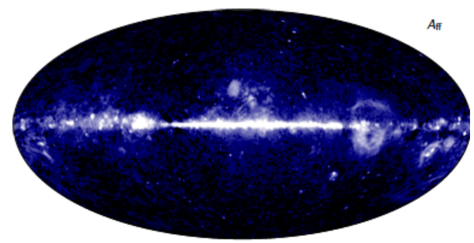




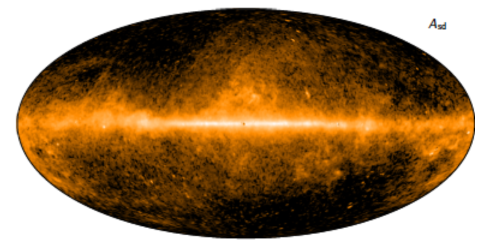
Interstellar synchrotron



free-free



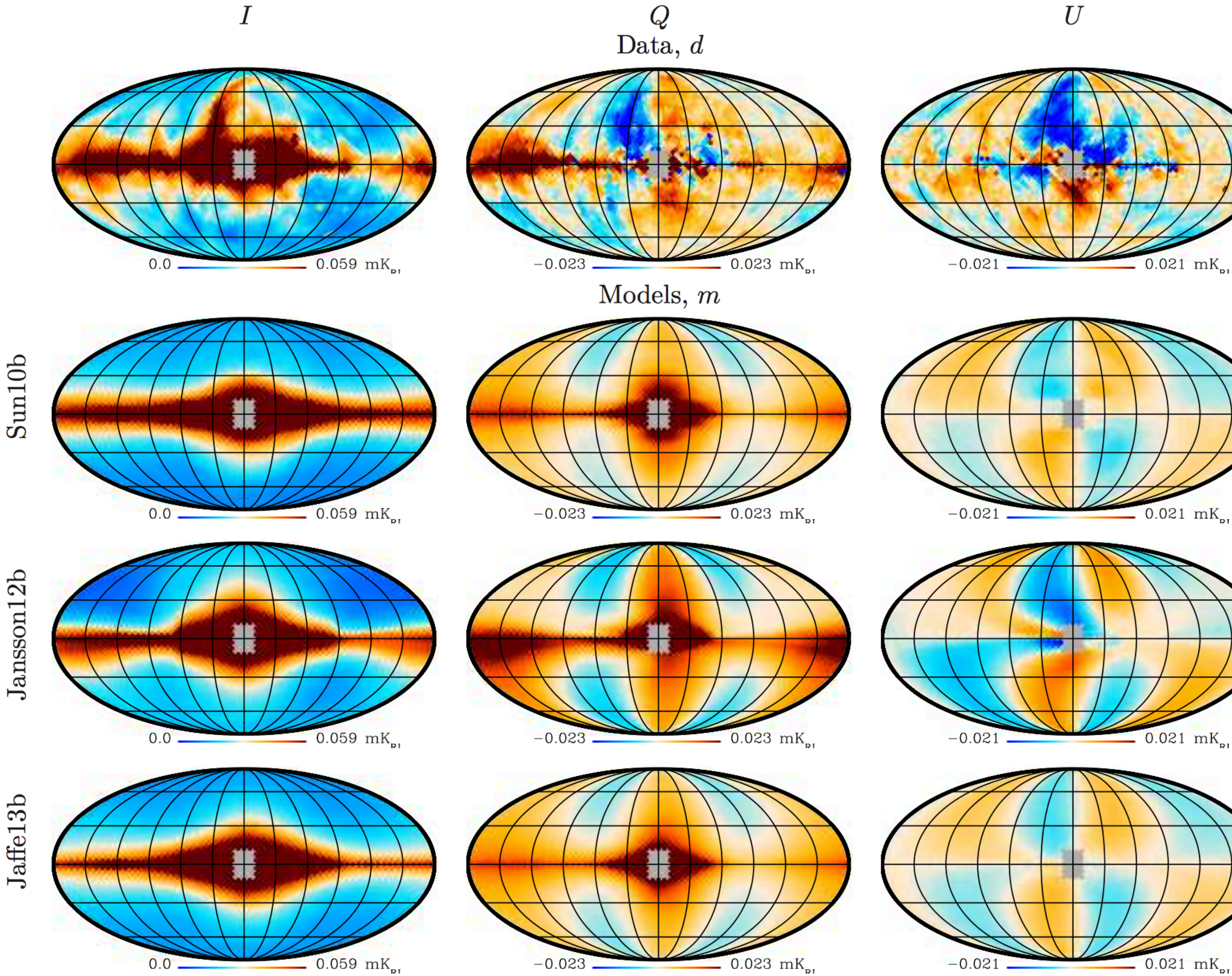
Spinning dust



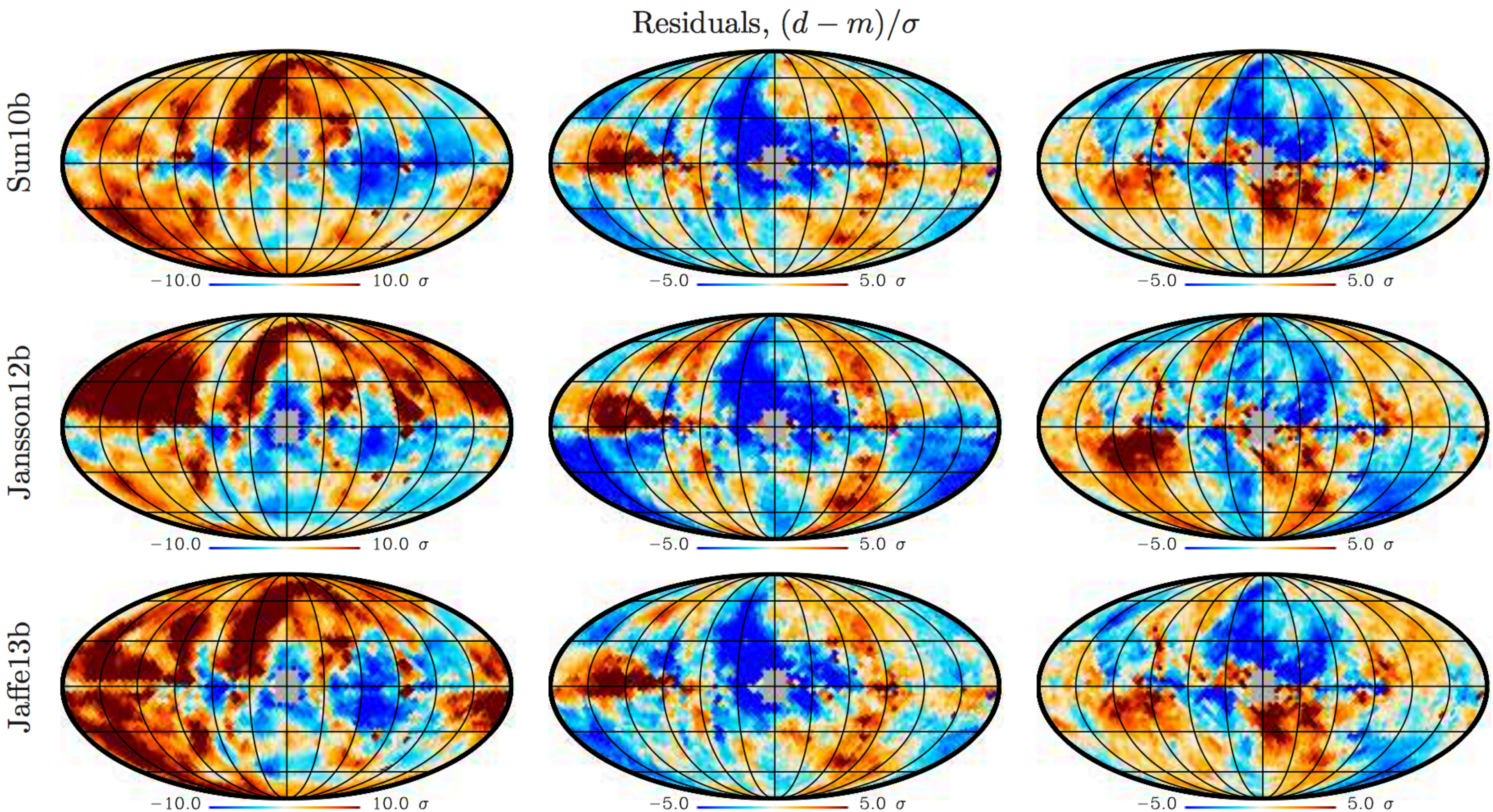
- The Model* was also used for obtaining the Galactic magnetic field (*Planck intermediate results. XLII A&A accepted*)

**Best fit from Orlando & Strong 2013 MNRAS 436,2127*

Planck intermediate results. XLII



Planck intermediate results. XLII

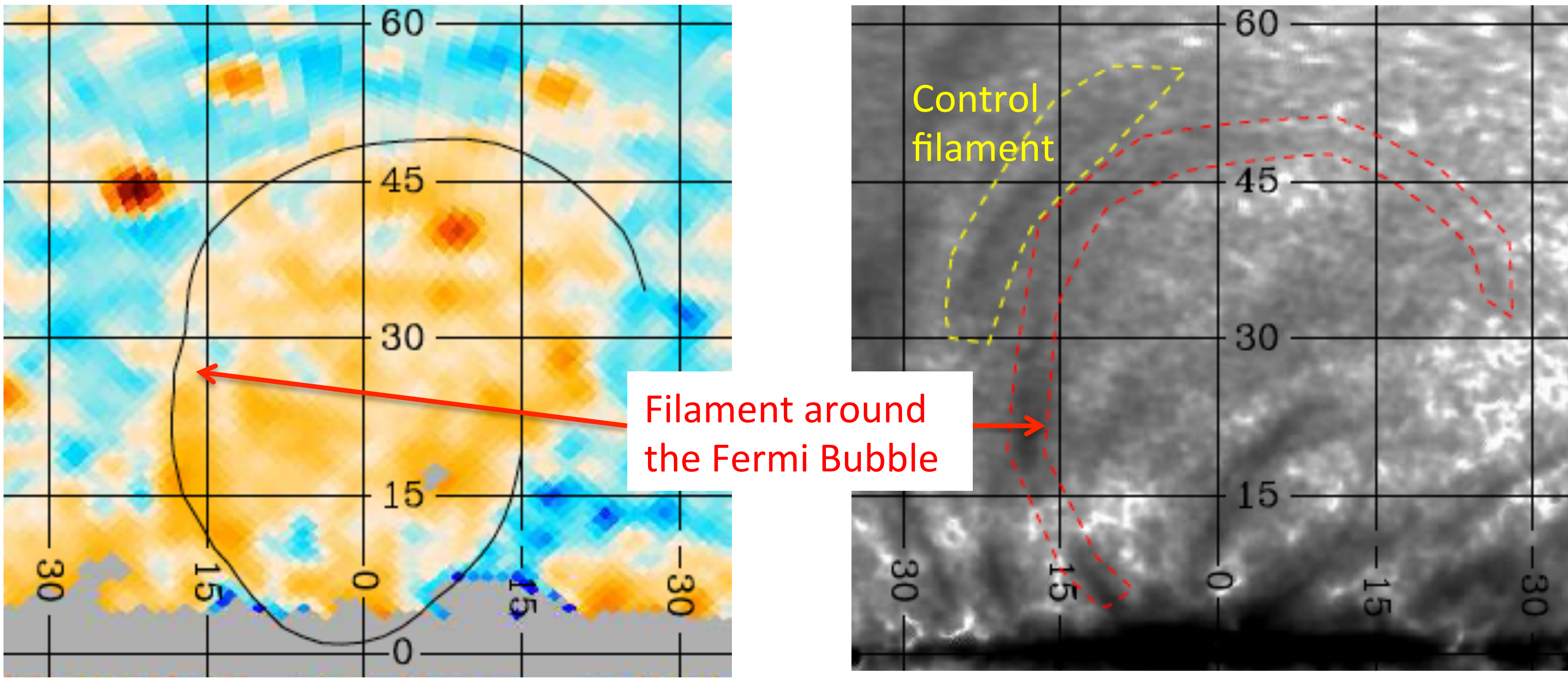


Planck polarization and Fermi Bubbles

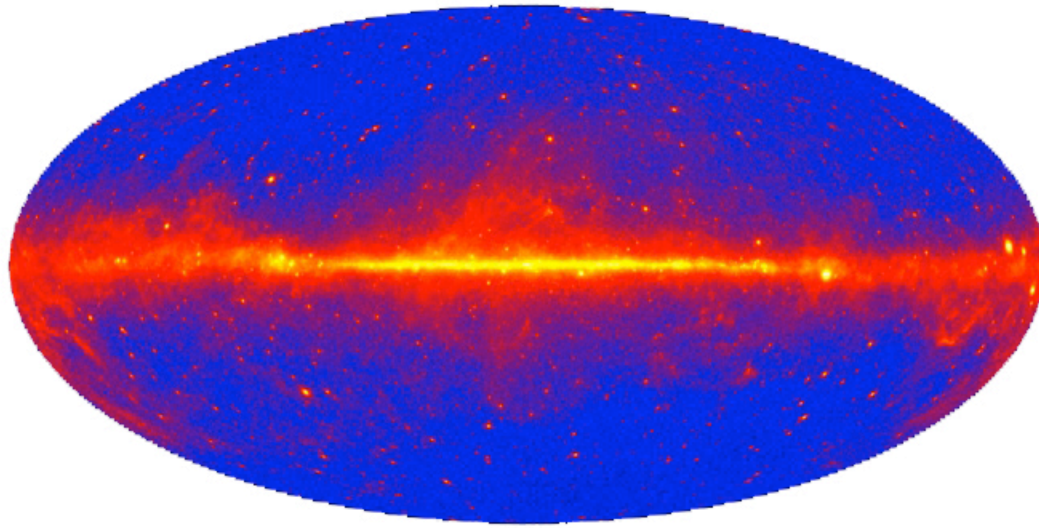
Planck coll. 2015 ArXiv: 1506.06660

Fermi-LAT > 10 GeV from
Ackermann et al 2014 ApJ,793,64 (dust subtracted)

Planck polarization map

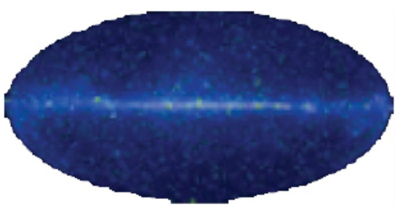


The gamma-ray sky

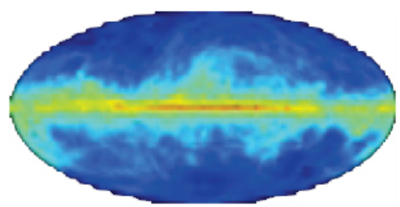


Fermi-LAT
>1 GeV

DETECTED SOURCES



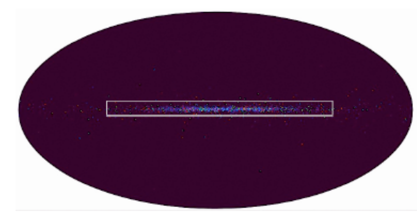
INTERSTELLAR



> 60%

EXTRAGALACTIC

UNDETECTED SOURCES

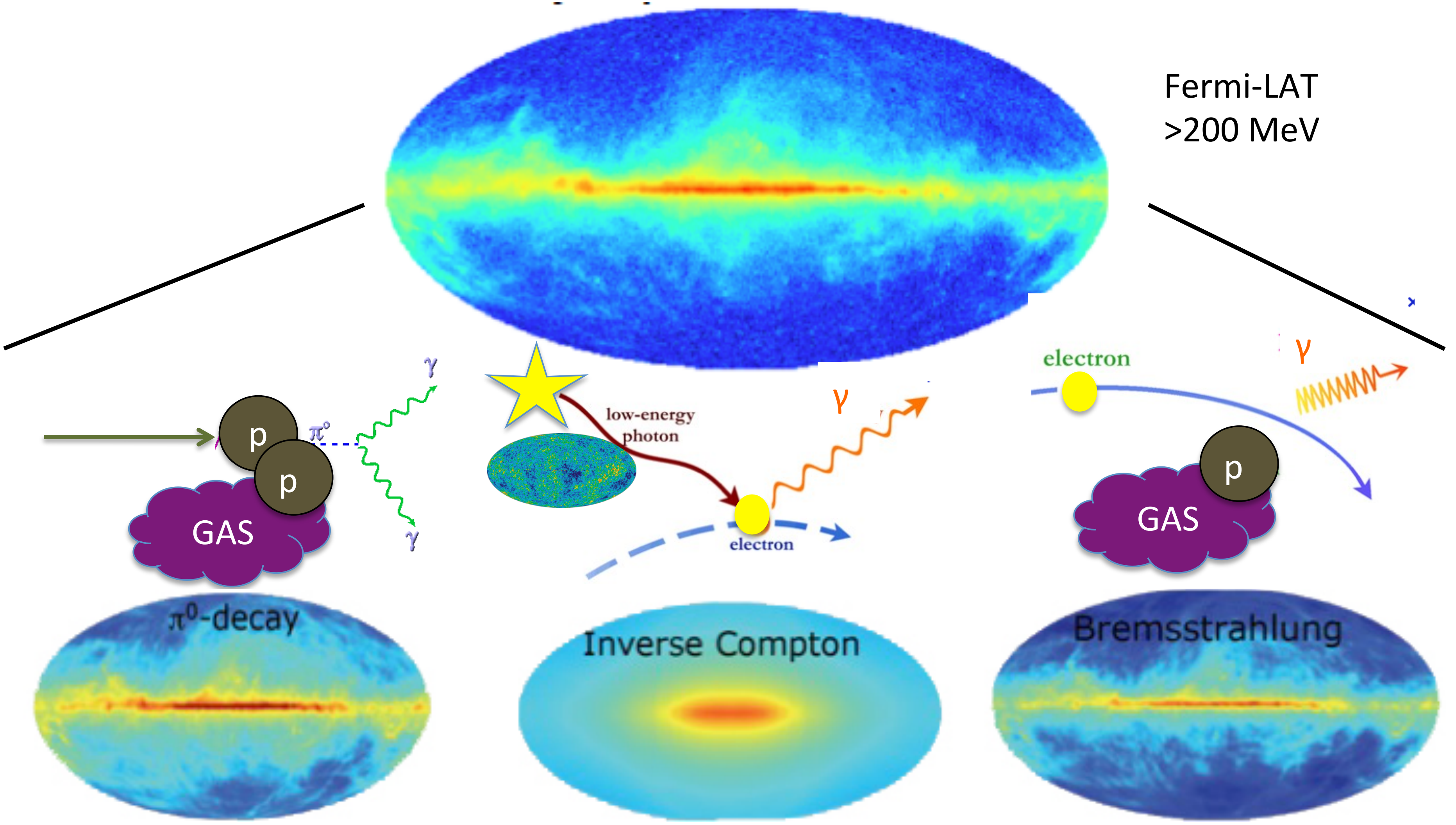


+ background + Dark Matter?

Interstellar emission needs to be accurately modeled

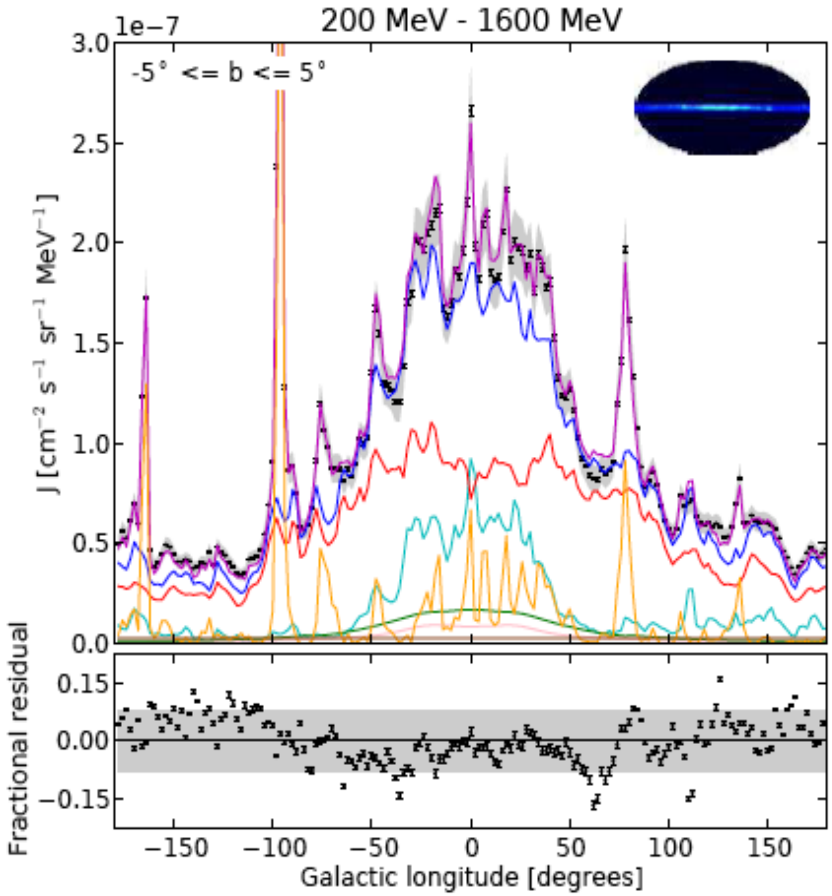
The gamma-ray interstellar emission

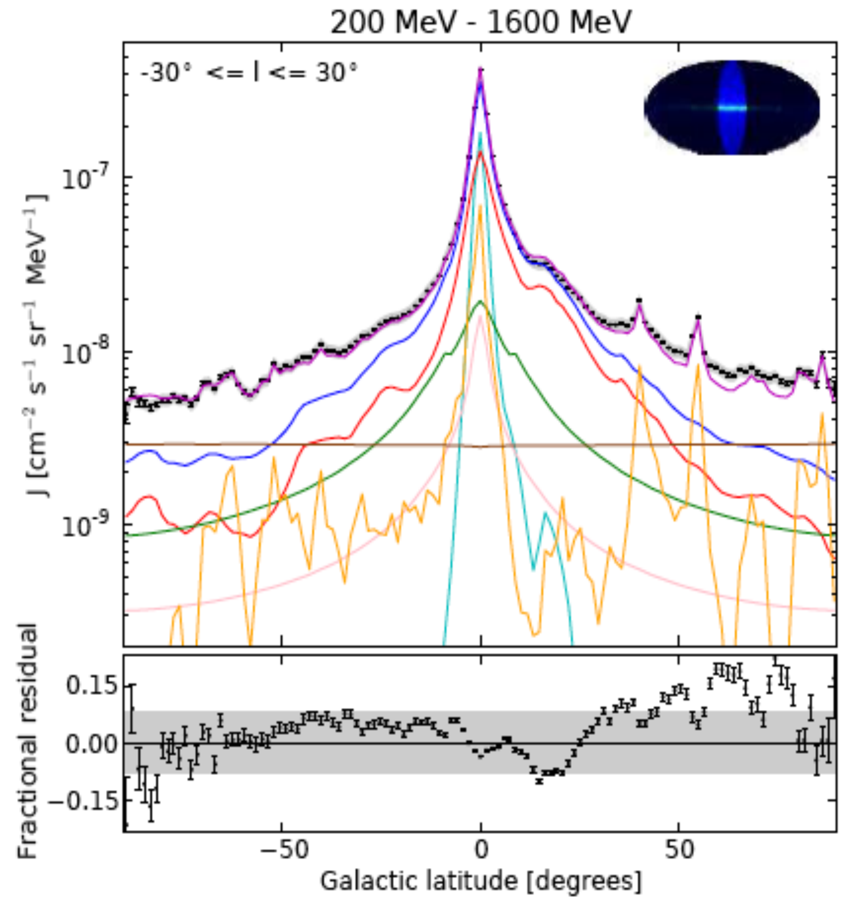
FROM INTERACTIONS OF COSMIC RAYS IN THE INTERSTELLAR MEDIUM



Gamma rays with Fermi-LAT

Ackerman et al.2012 ApJ 750,3

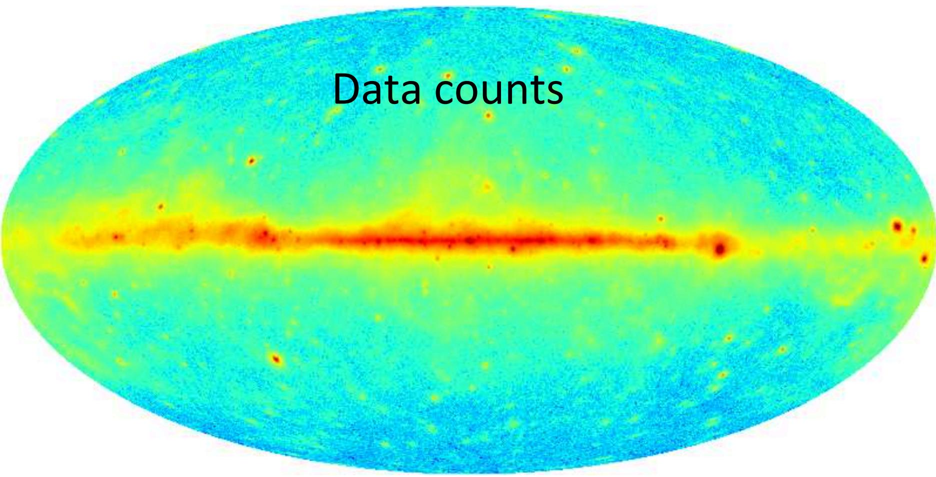


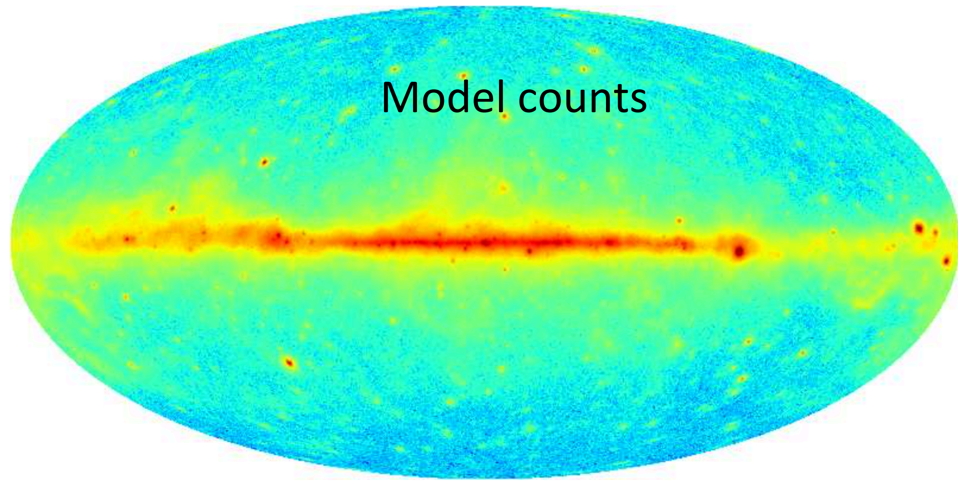


The physics of the interstellar emissions well understood and described.

Gamma rays with Fermi-LAT

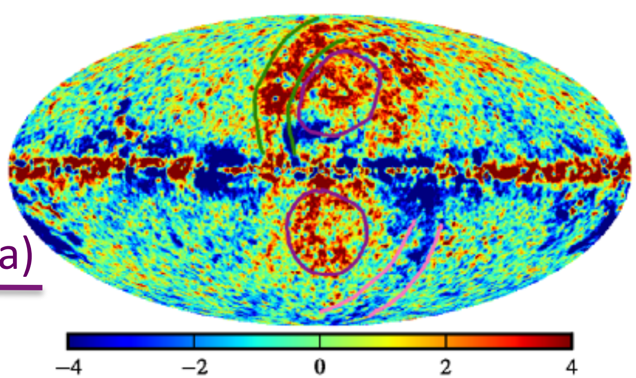
Ackerman et al.2012 ApJ 750,3





→ With CRs consistent with CR local measurements

(model-data) / model



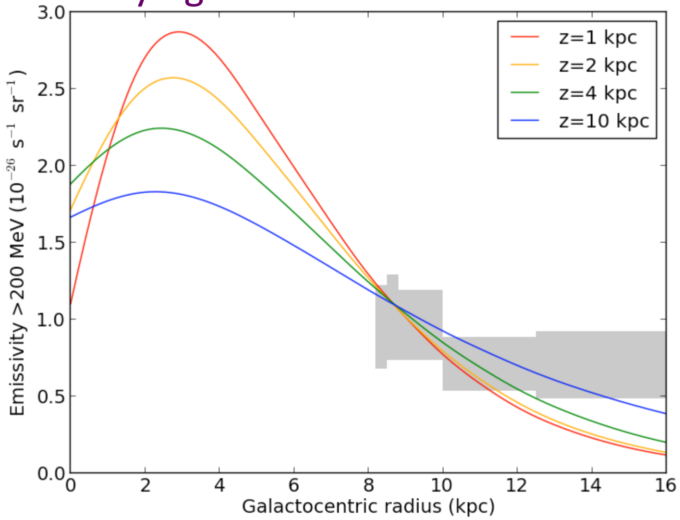
Excess:
- Outer Galaxy
- Fermi Bubbles?
- Inner Galaxy

CRs and the outer Galaxy

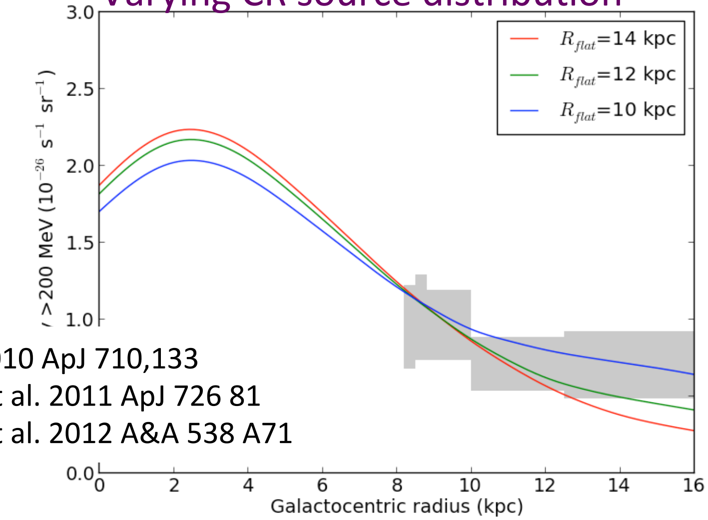
Emissivity in molecular clouds

(Gamma-ray emission rate per H atom)

Varying halo size



Varying CR source distribution



Abdo et al. 2010 ApJ 710,133
Ackermann et al. 2011 ApJ 726 81
Ackermann et al. 2012 A&A 538 A71

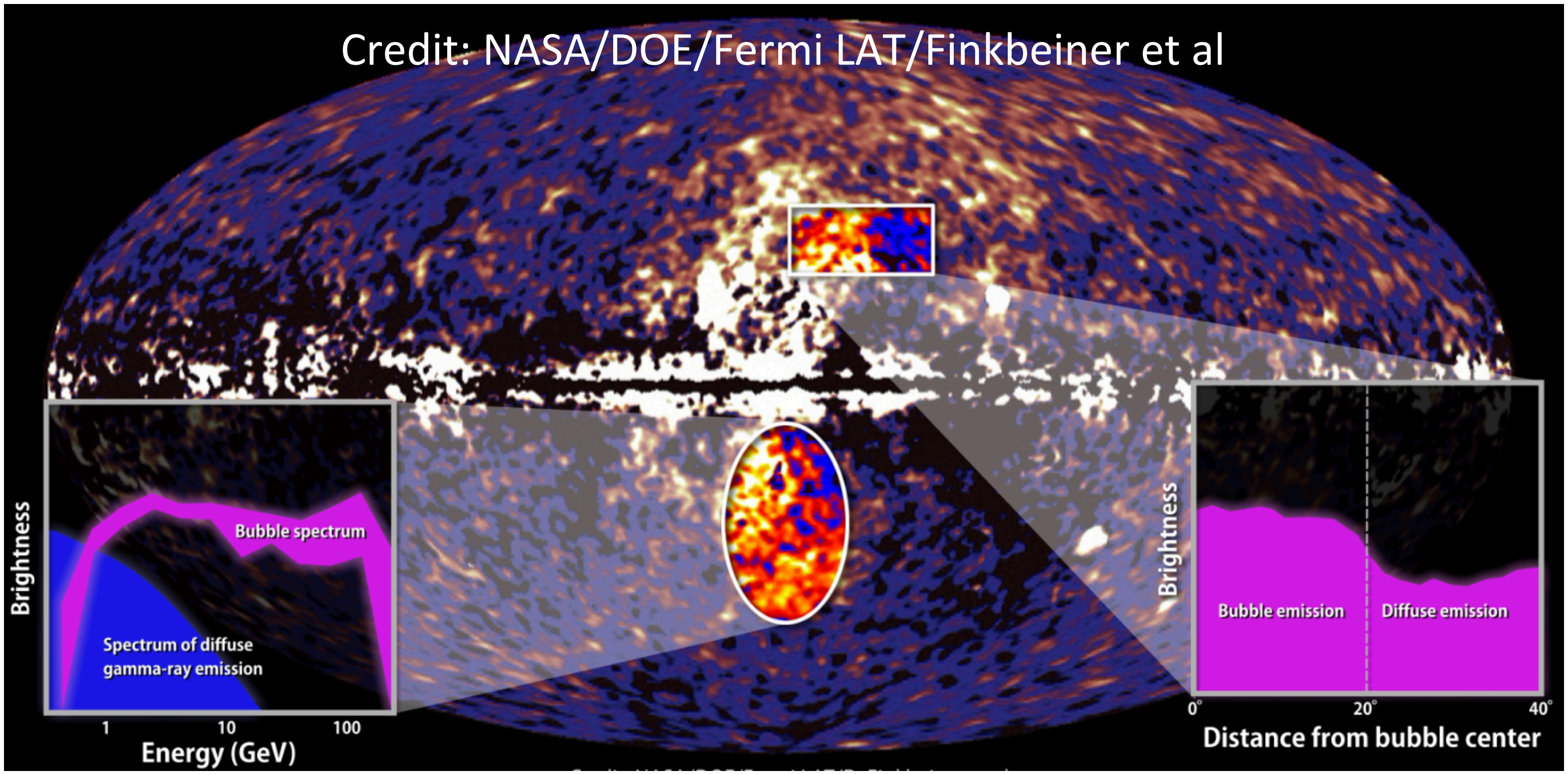
Hints for:

- Larger z (~10 kpc)*
- Additional gas in the outer Galaxy
- Flat CR source distribution*

Same hints as in Ackerman et al. 2012.

* Also found in the study comparing the synchrotron emission models with radio and microwave data (Orlando & Strong 2013)

Some residuals: Fermi Bubbles



References: Dobler et al. 2010; Su et al 2010, 2012; ..; since then many studies including different wavelength (e.g. Carretti 2013, S-PASS; Dobler 2012, WMAP; Snowden 1997, Su 2012 ROSAT; Kataoka 2013, Tahara 2015, Suzaku, Planck coll 2013; …)

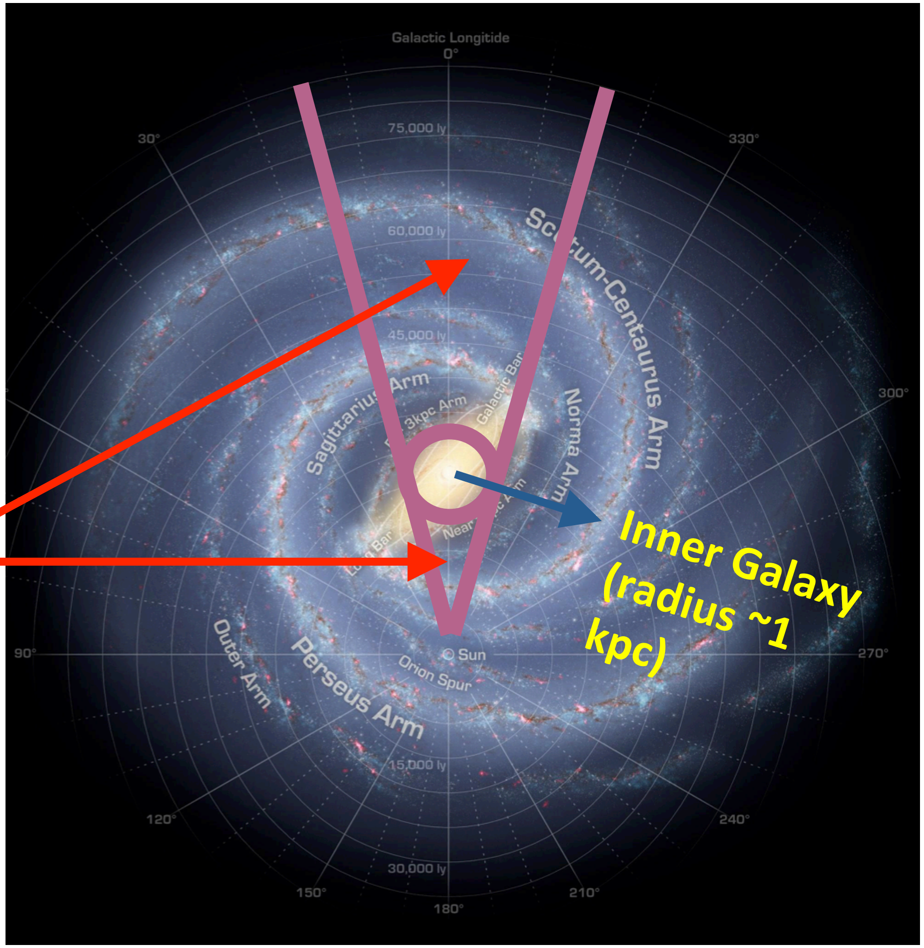
→ Both leptonic and hadronic models represent Fermi spectral data well

(Ackermann et al., 2014)

Some residuals: the inner Galaxy

- CRs? - Unresoved sources? - Dark Matter?

Fore/background interstellar modeling is critical



Ref:Hooper et all 2010, Goodenough et al. 2011, Abazajian et al. 2012, Hooper et al 2013, Gordon et al. 2013, Daylan eta al. 2014, Calore et al 2015; Mirabal (2013), Petrovic et al (2015), Cholis et al. (2015), Lee et al. 2016, Bartels et al. 2016, Brandt & Kocsis 2015, Carlson et al. 2016 etc

Ajello et al. 2016

- GeV excess with respect to usual interstellar models
- Inverse Comton dominant and enhanced (ISRF or CR electrons?)

What's cooking?

$D_{xx} \neq D_{zz}$

3D ISRF

Updated 3D B-field

3D CR sources

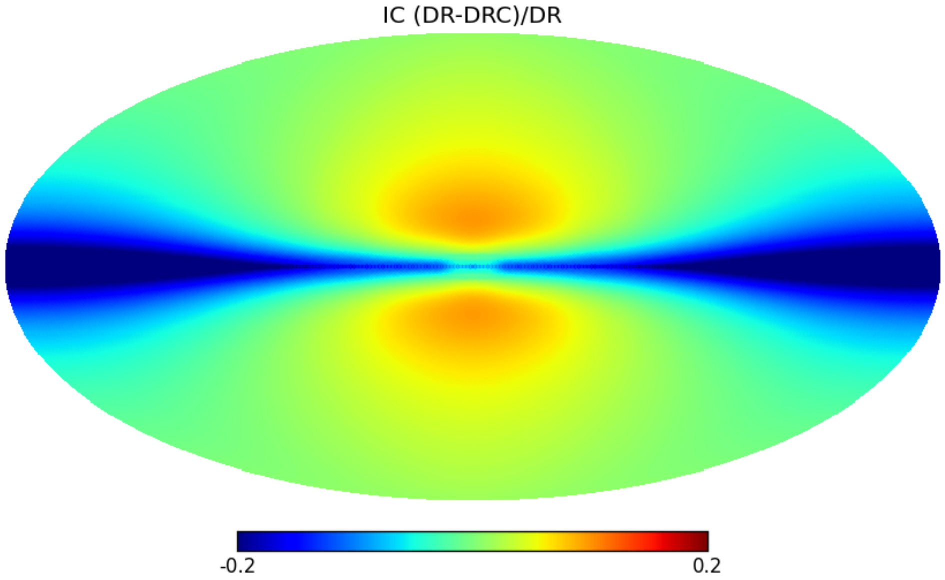
Anisotropic IC

"non-standard" propagation models

Stay tuned !

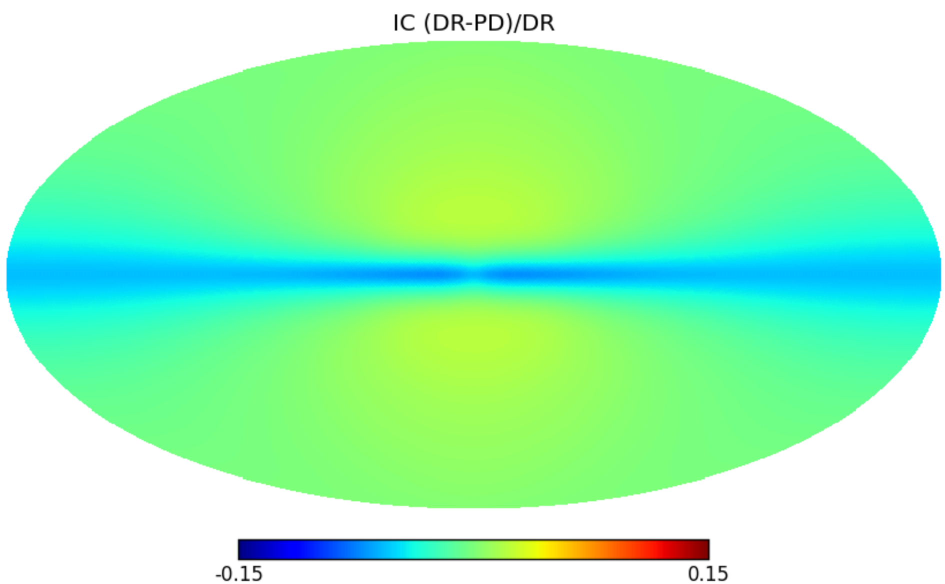
Investigations on the spatial effects in gamma rays of some interstellar models beyond the standard ones used in LAT analyses so far.

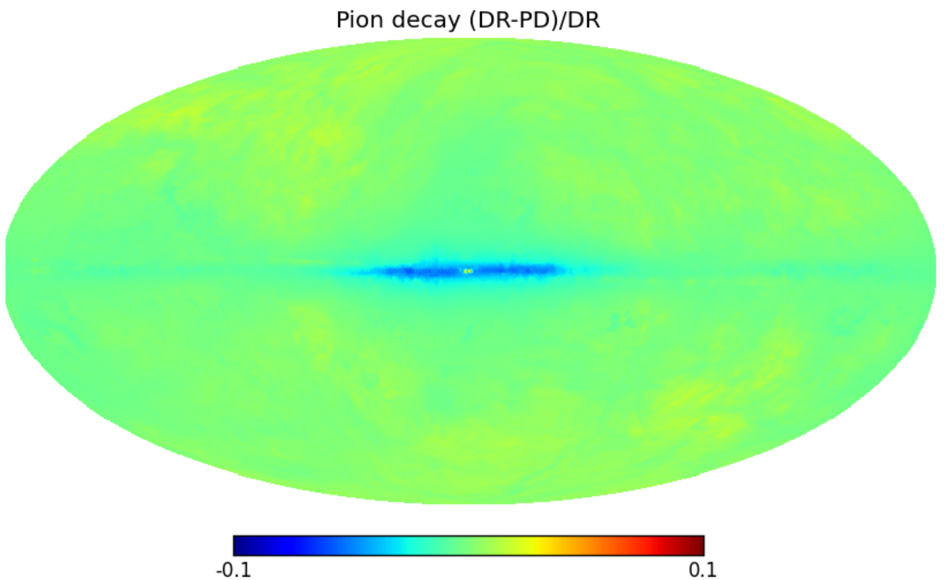
Effect of convection



Up to 30% variation in inverse Compton emission

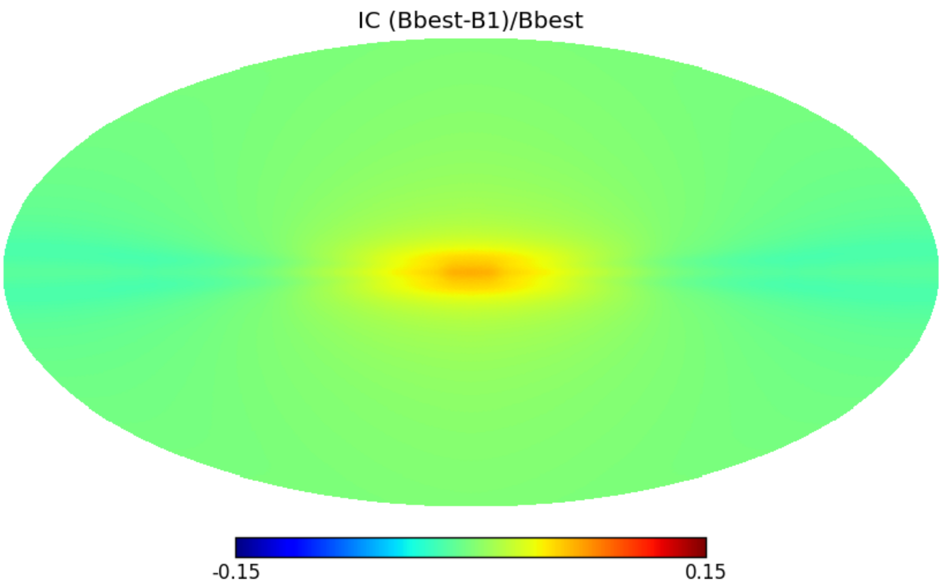
Effect of no reacceleration



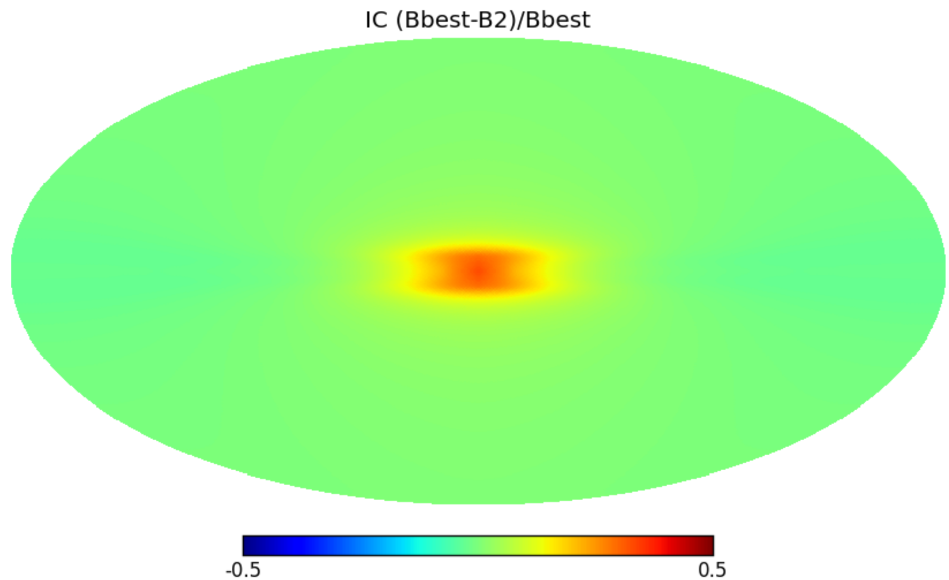


Up to 15% variation in inverse Compton emission
More than 10% variation in the pion decay emission in Galactic center

Effect of different B-field models on the Inverse Compton emission



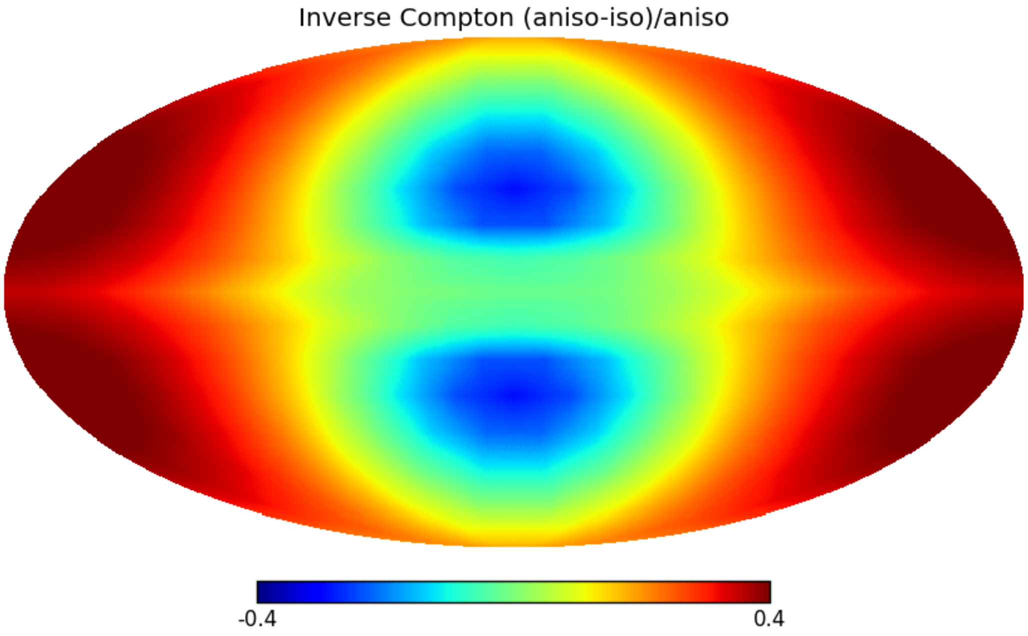
B-field as in present gamma-ray models



B-field strongly peaked at the Galactic center

B-field is very uncertain, if no spatial constraints from synchrotron are accounted for it can affect the IC in the GC even of a factor of 2.

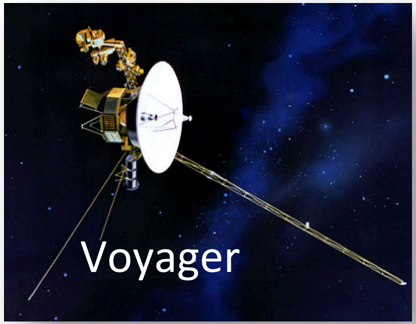
Effect of anisotropic IC cross-section

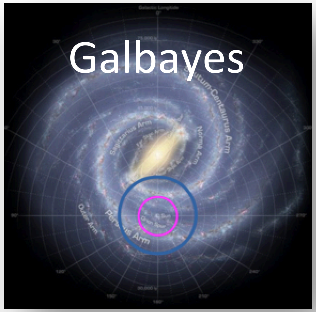


Variation of a factor of 2

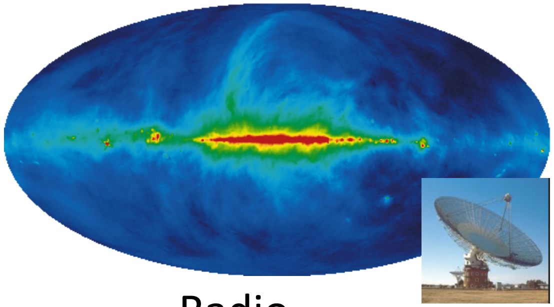
Summary

- CR measurements:

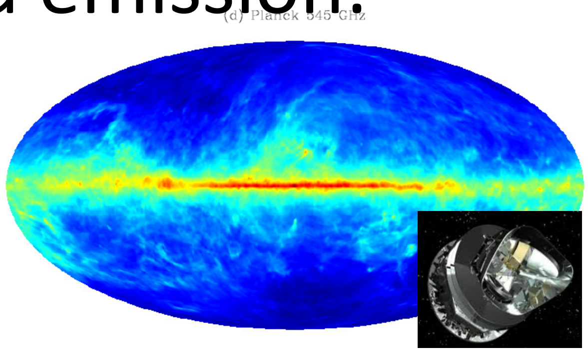




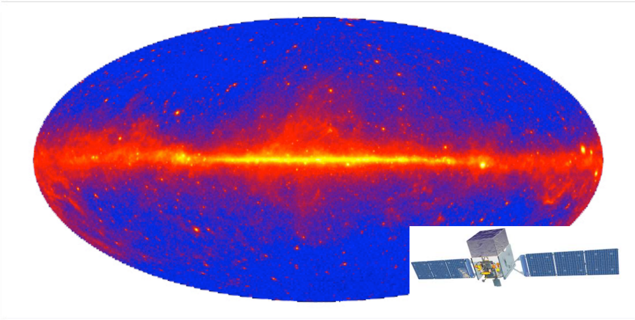
- CR associated emission:



Radio



Microwave



Gamma rays

- Work in progress