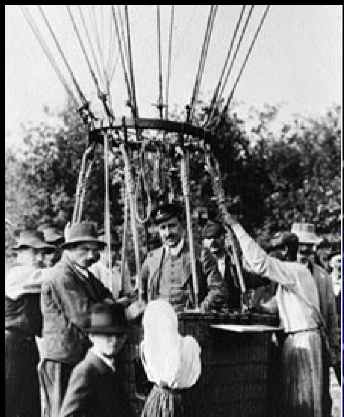
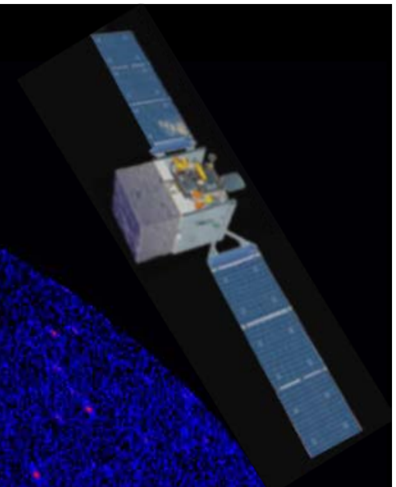




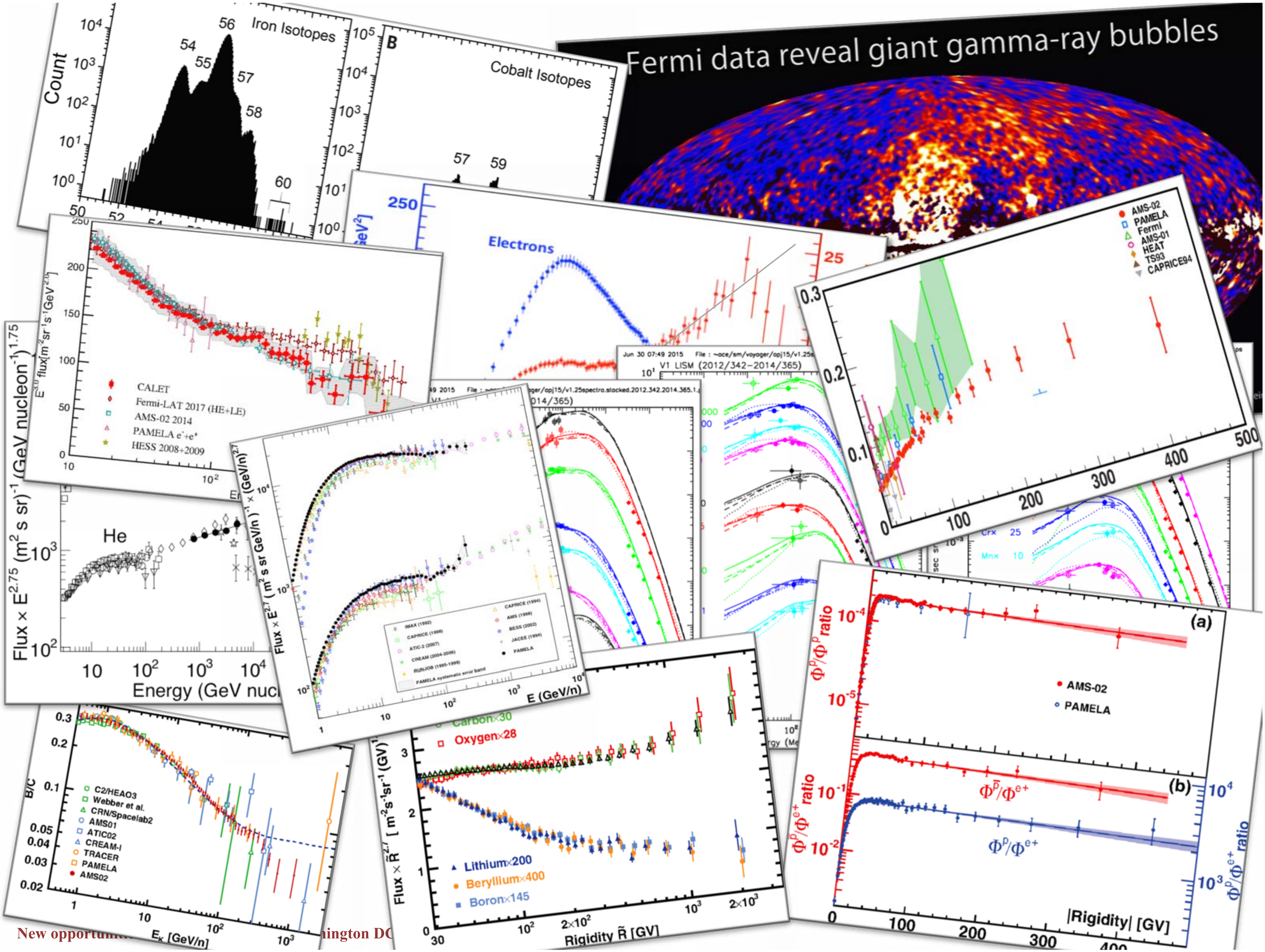
GALPROP CODE FOR GALACTIC COSMIC RAY PROPAGATION AND ASSOCIATED PHOTON EMISSIONS

IGOR V MOSKALENKO – STANFORD

New Opportunities in the AMS-02 Era

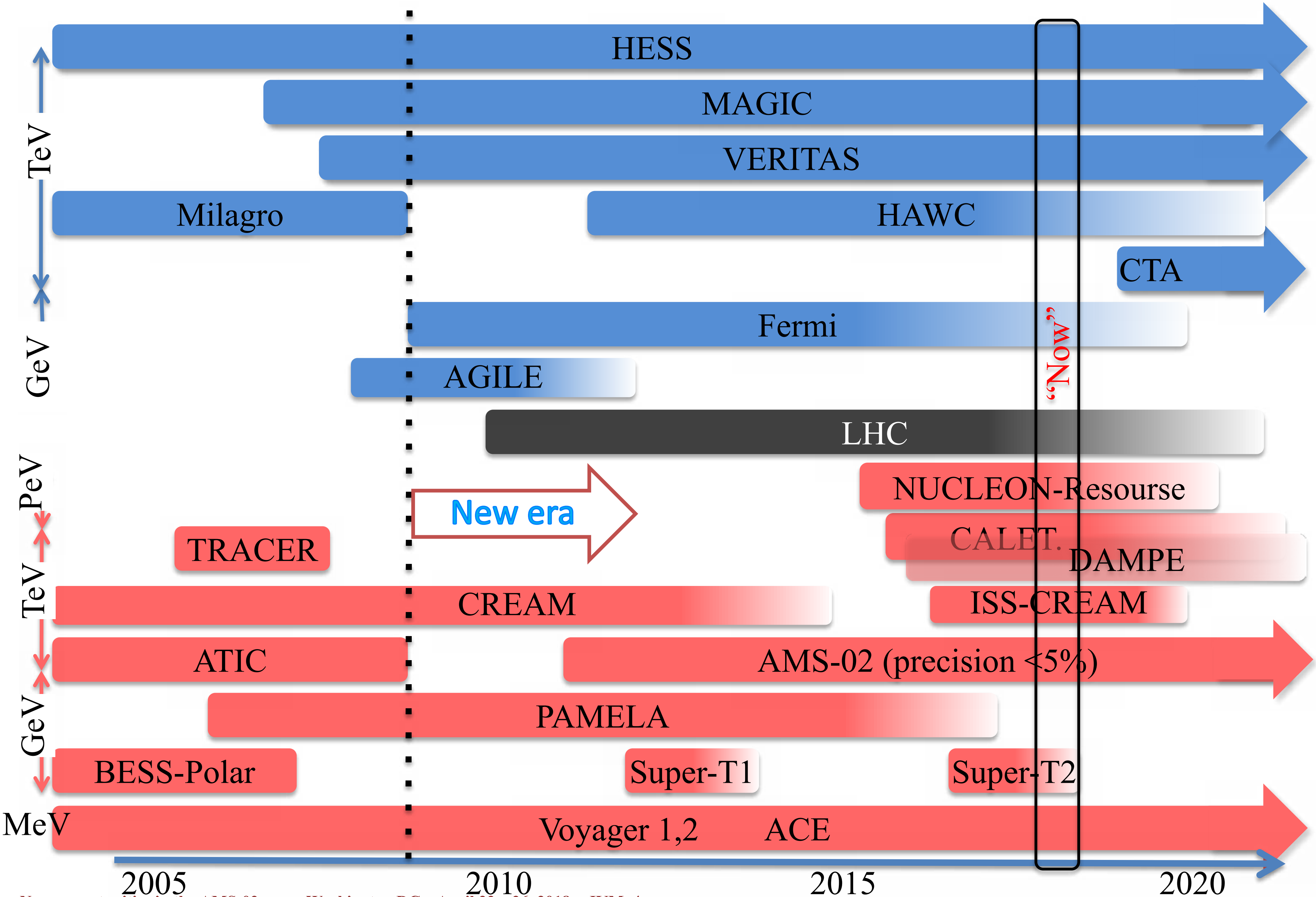
Decade of discoveries in astrophysics of CRs

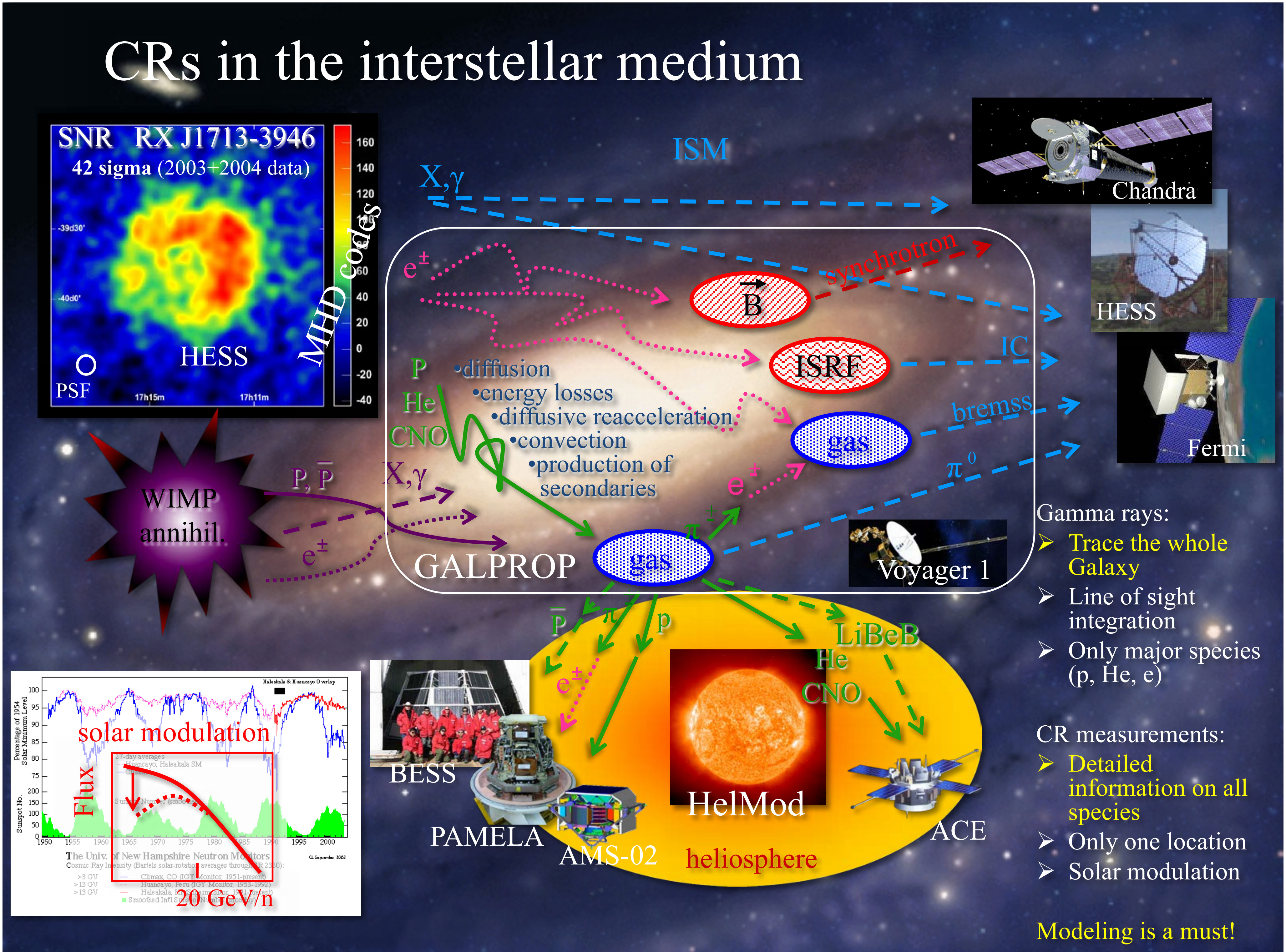
- High Statistics Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5-500 GeV
- Electron and Positron Fluxes in Primary Cosmic Rays
- Precision Measurement of the ($e^{+}+e^{-}$) Flux in Primary Cosmic Rays from 0.5 GeV to 1 TeV and above
- Discovery of breaks in spectra of p and He and their precision measurements up to 3 TV
- Antiproton Flux, Antiproton-to-Proton Flux Ratio, and Properties of Elementary Particle Fluxes in Primary Cosmic Rays
- Precision Measurement of the Boron to Carbon Flux Ratio in Cosmic Rays from 1.9 GV to 3 TV
- Observation of the Identical Rigidity Dependence of He, C, and O Cosmic Rays at High Rigidities
- Observation of New Properties of Secondary Cosmic Rays Lithium, Beryllium, and Boron
- Measurements of spectra of CR species in the interstellar medium (Voyager 1)
- Observation of ^{60}Fe in CRs
- Observation of Fermi Bubbles
- Observation of gamma-ray emission from normal starforming galaxies
- Many of these CR discoveries were made by AMS-02 Collaboration



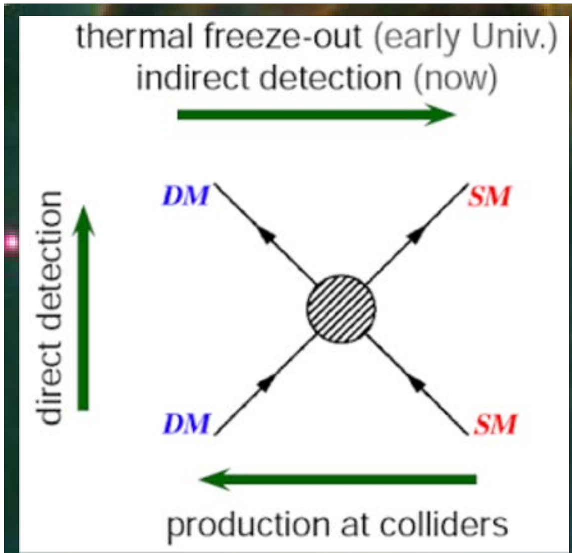
Iron Isotopes
Count
Cobalt Isotopes
Fermi data reveal giant gamma-ray bubbles
Electrons
CALET
Fermi-LAT 2017 (HE+LE)
AMS-02 2014
PAMELA e⁻+e⁺
HESS 2008+2009
AMS-02
PAMELA
Fermi
AMS-01
HEAT
TS93
CAPRICE94
V1 LISM (2012/342–2014/365)
He
Flux × E^2.75 (m^2 s sr)^-1 (GeV nucleon^-1)^1.75
Energy (GeV nuc
E (GeV/n)
IMAX (1992)
CAPRICE (1998)
ATIC-2 (2007)
CREAM (2004-2006)
RUNJOB (1995-1999)
PAMELA systematic error band
CAPRICE (1994)
AMS (1998)
BESS (2002)
JACEE (1994)
PAMELA
B/C
C2/HEAO3
Webber et al.
CRN/Spacelab2
AMS01
ATIC02
CREAM-I
TRACER
PAMELA
AMS02
E_K [GeV/n]
Carbon×30
Oxygen×28
Lithium×200
Beryllium×400
Boron×145
Rigidity R̃ [GV]
AMS-02
PAMELA
(a)
(b)
|Rigidity| [GV]

Timeline of γ-ray, CR, and particle experiments

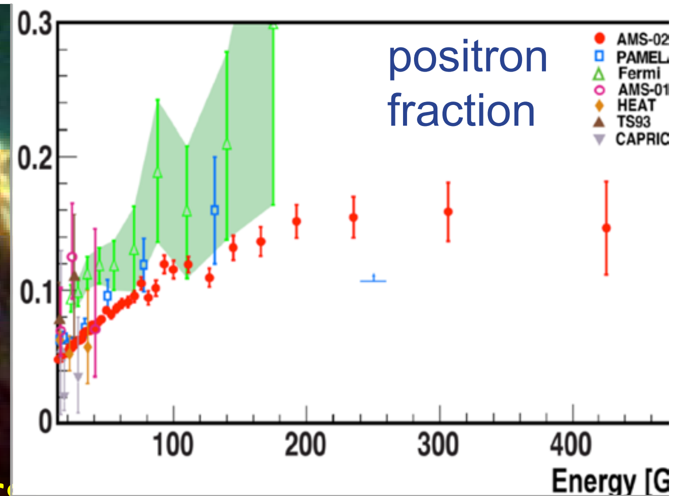




CRs in the interstellar medium
SNR RX J1713-3946
42 sigma (2003+2004 data)
HESS
PSF
MHD codes
ISM
X,γ
e±
synchrotron
B
ISRF
IC
gas
bremss
π0
P
He
CNO
•diffusion
•energy losses
•diffusive reacceleration
•convection
•production of secondaries
WIMP annihil.
P, P̄
X,γ
e±
GALPROP
Voyager 1
Chandra
HESS
Fermi
P̄
π
p
e±
LiBeB
He
CNO
solar modulation
Flux
20 GeV/n
BESS
PAMELA
AMS-02
HelMod
heliosphere
ACE
Gamma rays:
➢ Trace the whole Galaxy
➢ Line of sight integration
➢ Only major species (p, He, e)
CR measurements:
➢ Detailed information on all species
➢ Only one location
➢ Solar modulation
Modeling is a must!



Interpretations



✧ Dark matter annihilation/ signatures(>1500 papers)

Astrophysical origin (~200 papers):

✧ Pulsars & Pulsar Wind Nebulae

✧ Pulsar bow shocks

✧ SNR shocks:

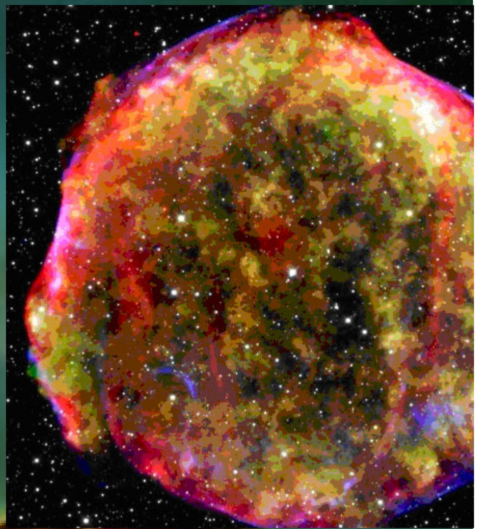
- ✦ Galactic SNRs
- ✦ Local SNR(s)

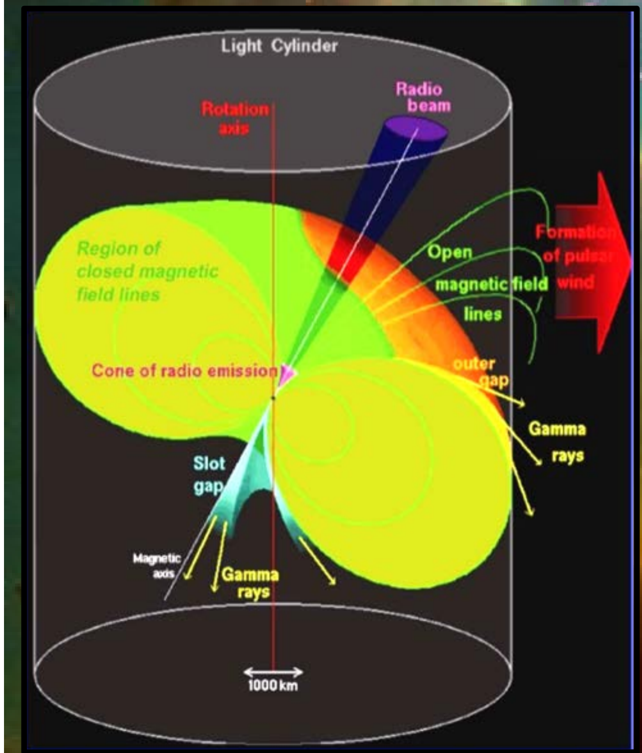
✧ “Nested Leaky-Box” (SNRs)

✧ Inhomogeneity of CR sources (SNRs)

✧ SNR shocks interacting with clouds

✧ “Model-independent estimates”

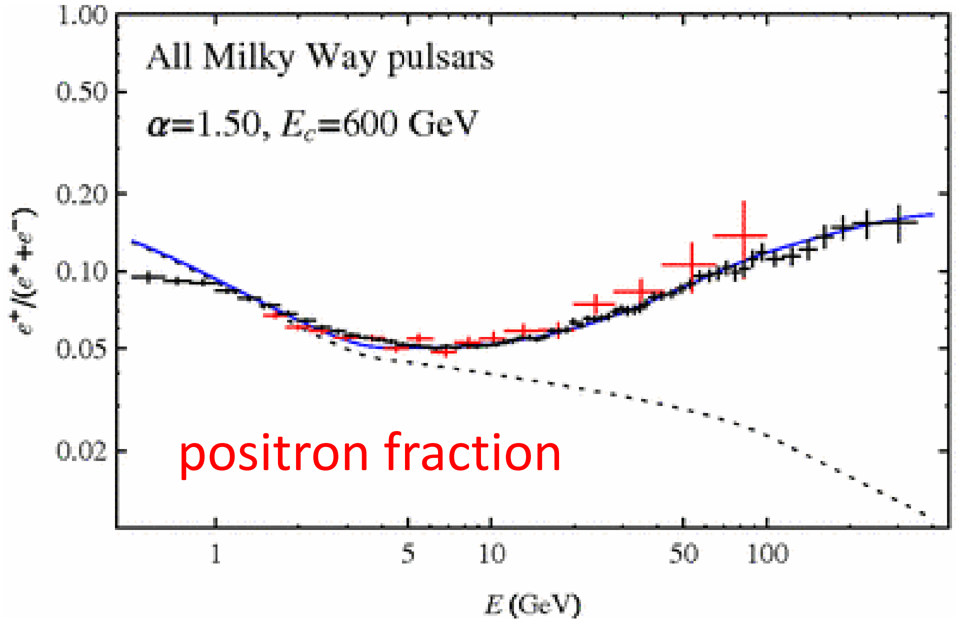


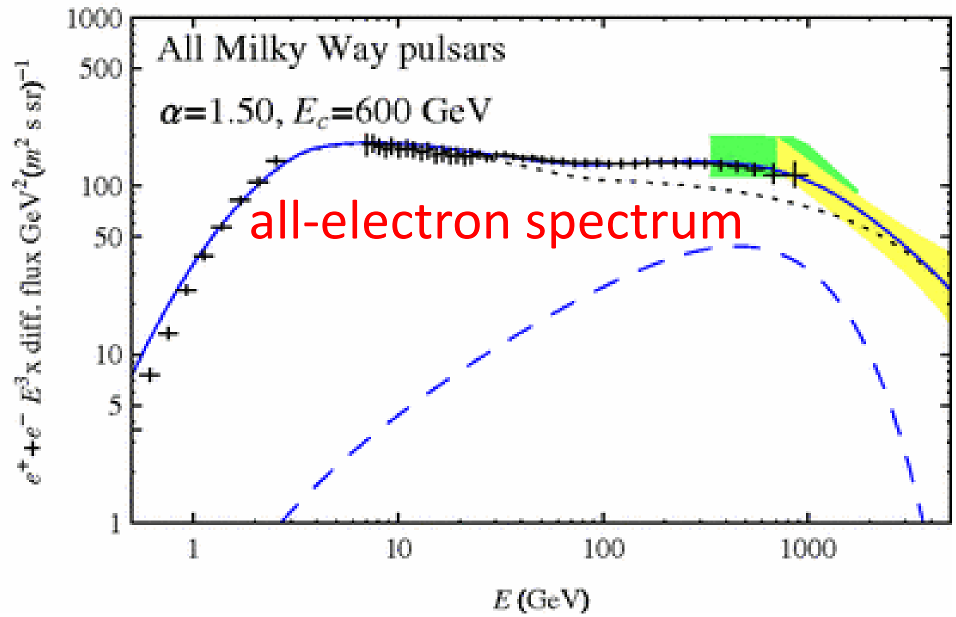


ISM

Pulsars as sources of CR positrons (& electrons)

Recent example: Cholis & Hooper '13





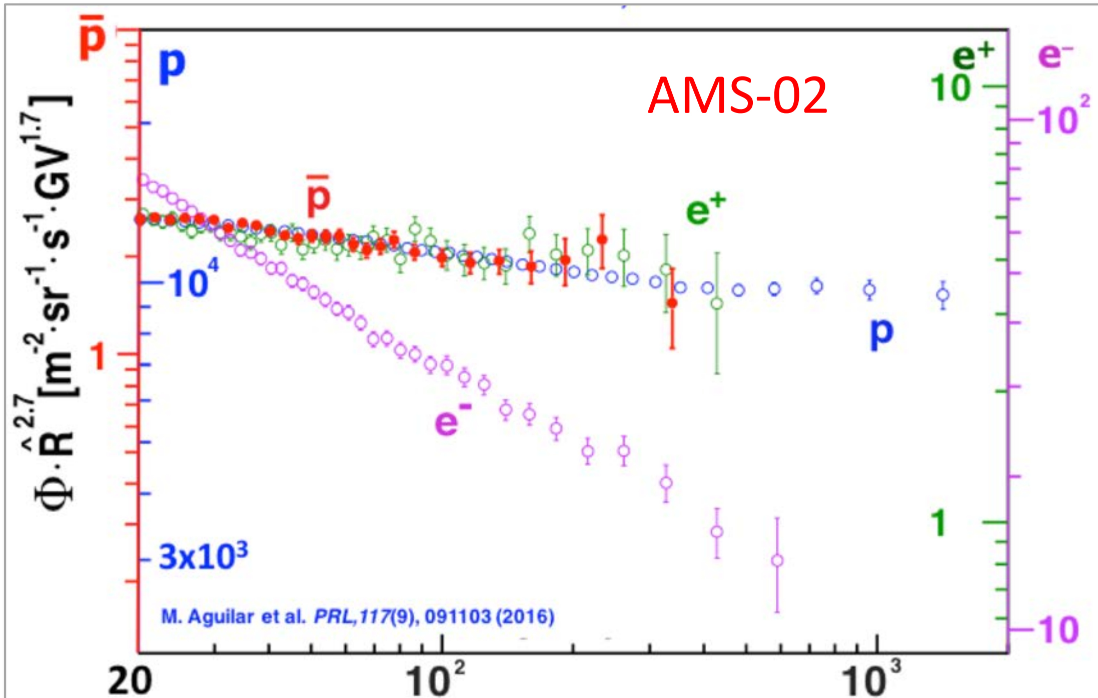
Pulsar spectrum is parametrized as: $\frac{dN}{dE} \sim E^{-\alpha} e^{\left(-\frac{E}{E_c}\right)}$

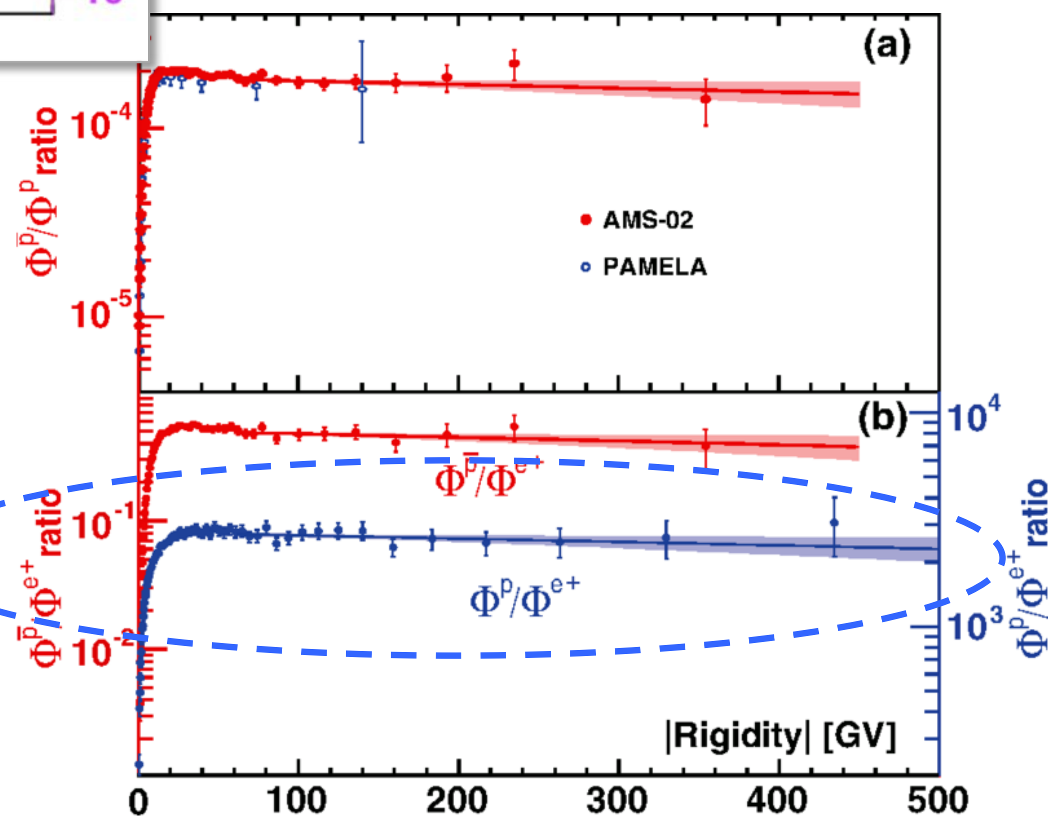
- ✧ α, E_c – free parameters
- ✧ Free injection spectrum of electrons from SNRs

Good:

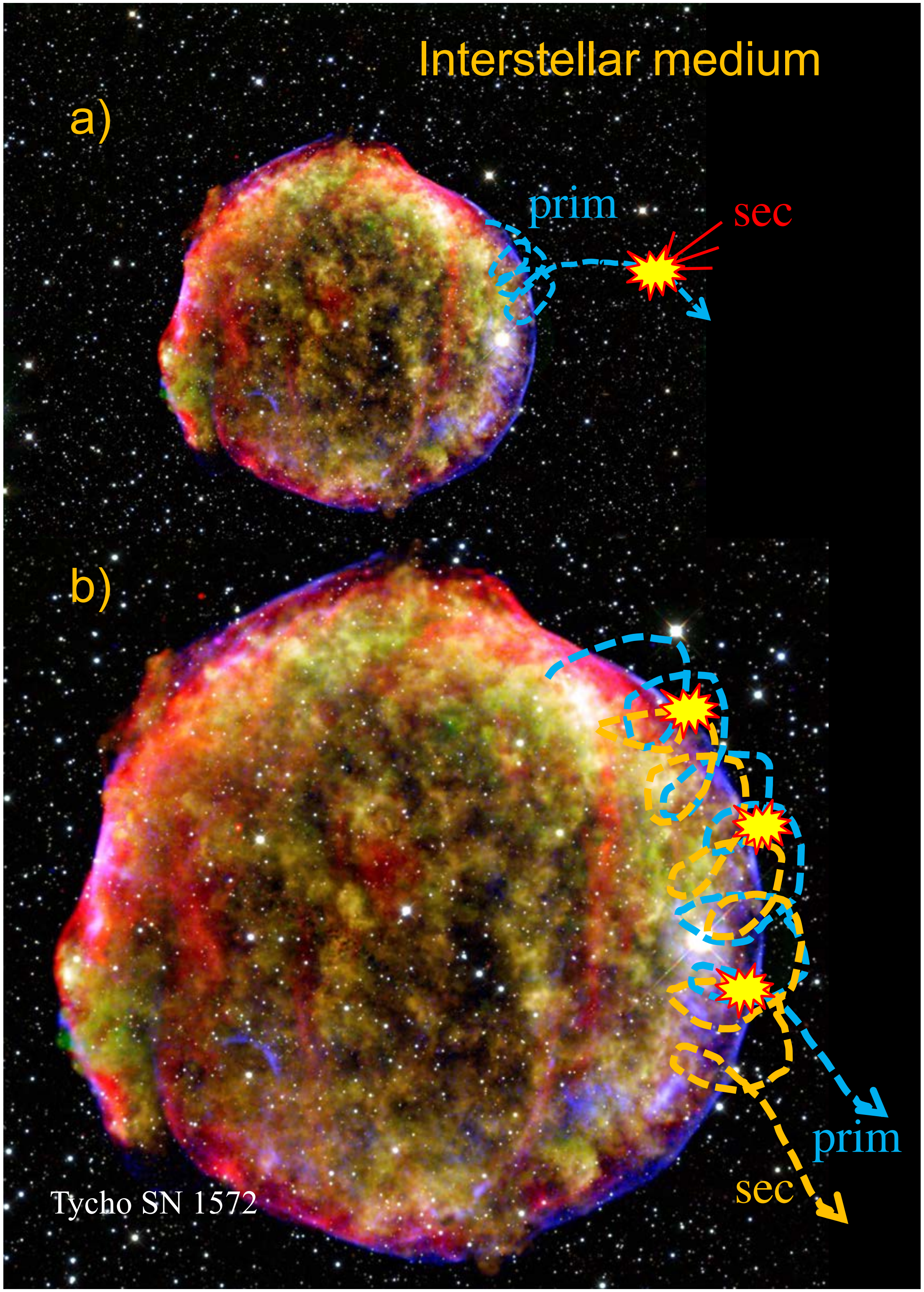
- ✓ Affects only electrons and positrons, does not affect other CR species
- ✓ Given enough free parameters, it is possible to fit the positron fraction and all-electron spectrum

Killing pulsar hypothesis or what do pulsars know about CR protons?





- ✧ If excess positrons are produced in pulsars or DM decays why the p/e$^+$ ratio is flat?
- ✧ The flat p/e$^+$ ratio perhaps indicates a common origin of p and e$^+$!



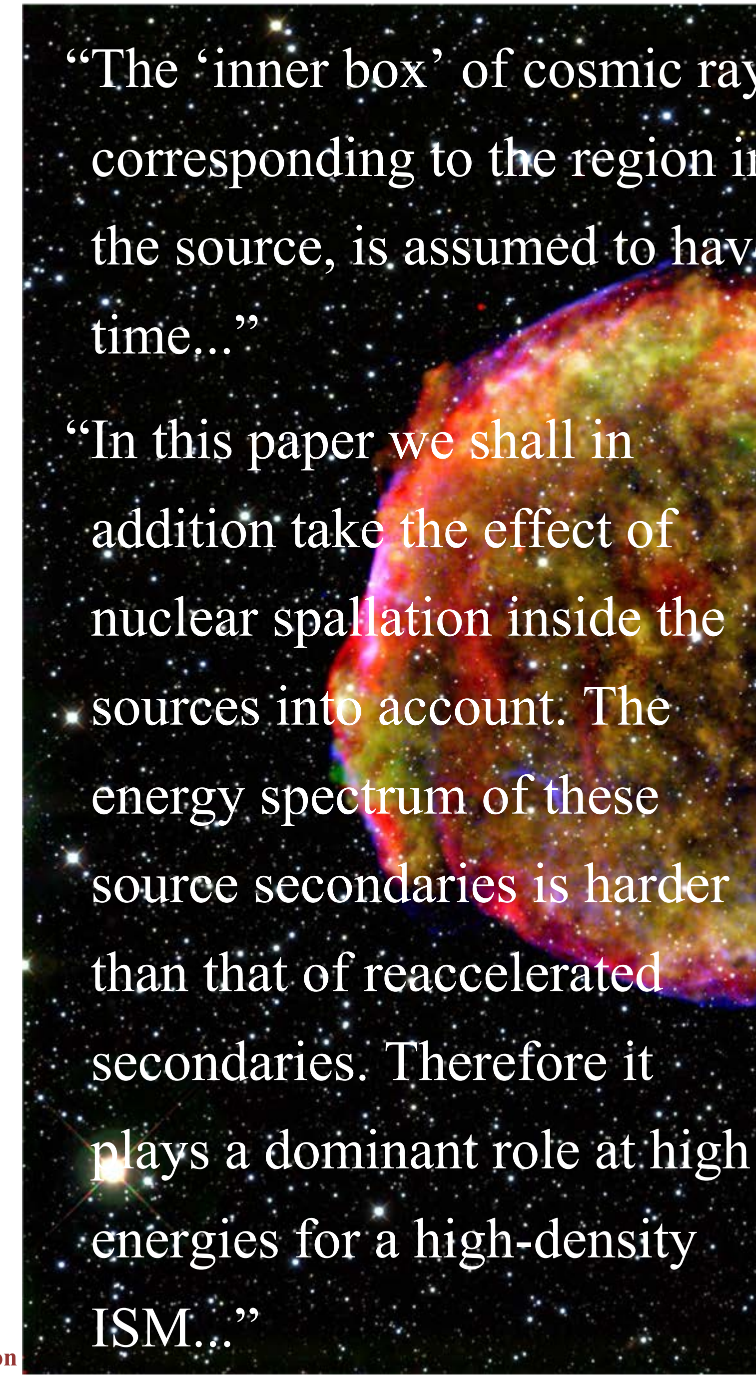
Production of secondaries in SNR shock

- In the “standard” scenario, secondary species are produced in the interstellar medium – softer spectrum at all energies
- In the SNR scenario, some proportion of secondary species is produced in the shock and then accelerated together with primary species – harder spectrum at high energies

Reinvention of the Nested Leaky-Box – SNRs

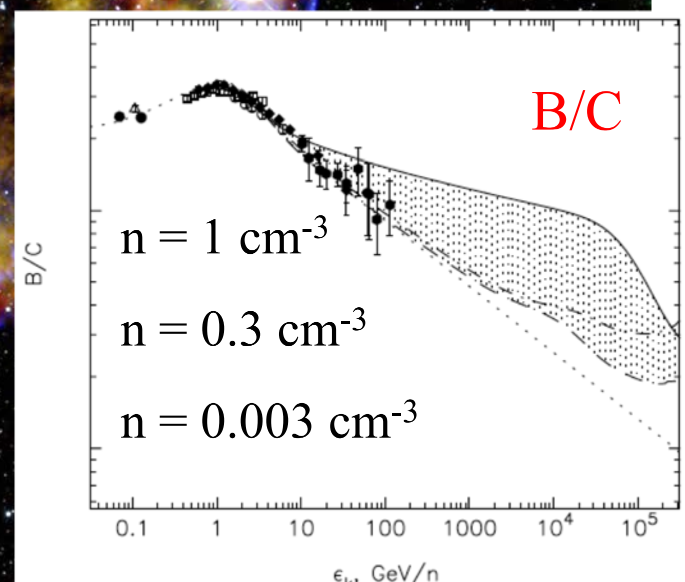
- Cowsik & Wilson 1974 “The nested Leaky-Box model for Galactic cosmic rays”
- Berezkho+’2003 “Cosmic ray production in supernova remnants including reacceleration: The secondary to primary ratio”
- Blasi’2009 “Origin of the Positron Excess in Cosmic Rays”

and other authors



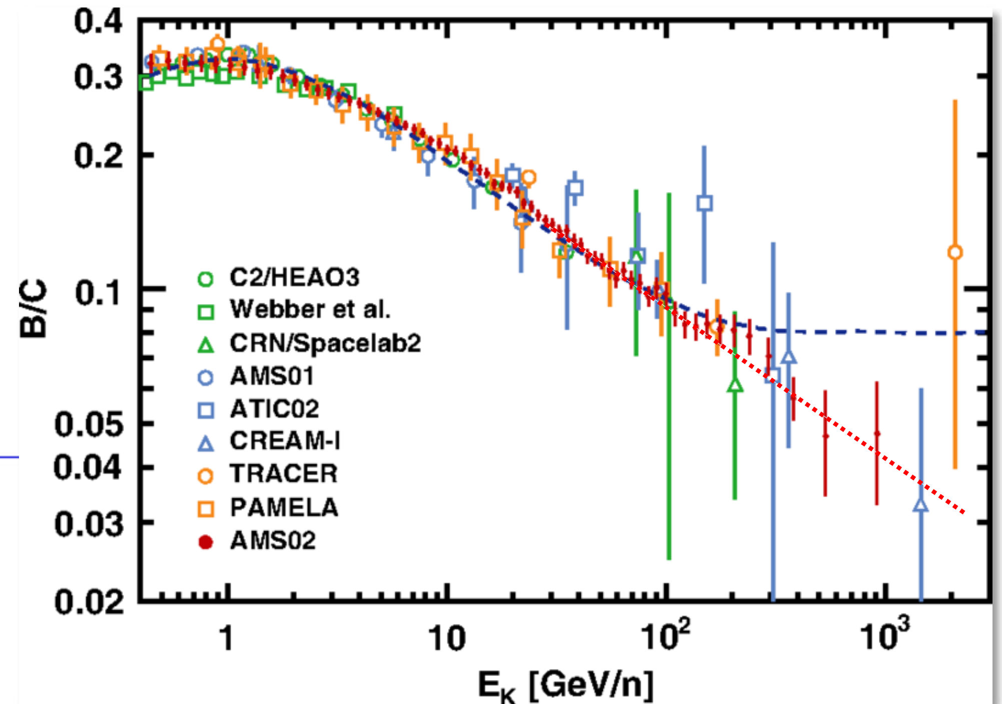
“The ‘inner box’ of cosmic ray confinement, corresponding to the region immediately surrounding the source, is assumed to have energy-dependent life time...”

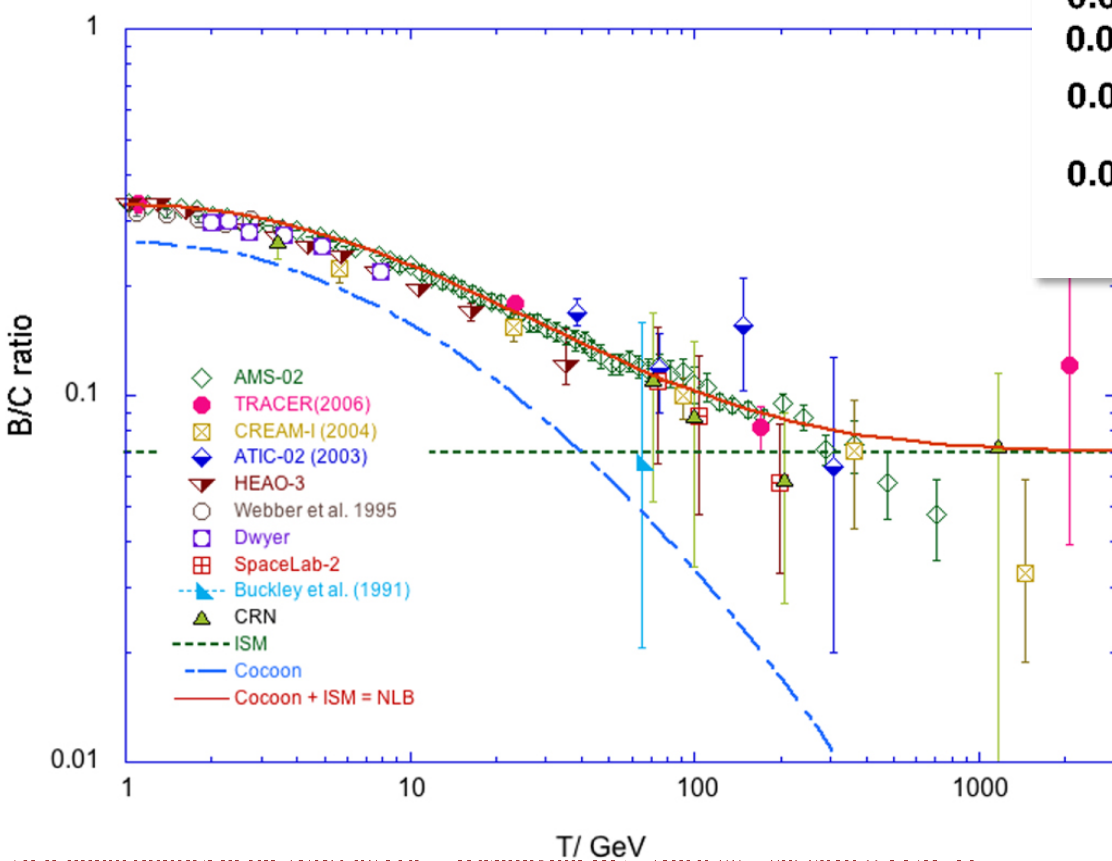
“In this paper we shall in addition take the effect of nuclear spallation inside the sources into account. The energy spectrum of these source secondaries is harder than that of reaccelerated secondaries. Therefore it plays a dominant role at high energies for a high-density ISM...”



Nested Leaky-Box – Cowsik et al. model

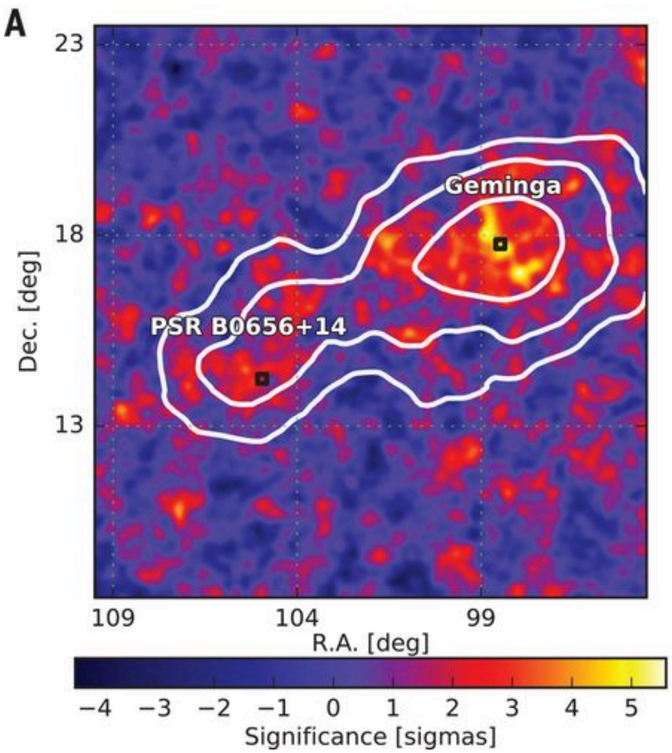
- The model includes a cocoon around SNR with most of the grammage
- Secondaries are produced in cocoons
- ISM - small energy independent grammage

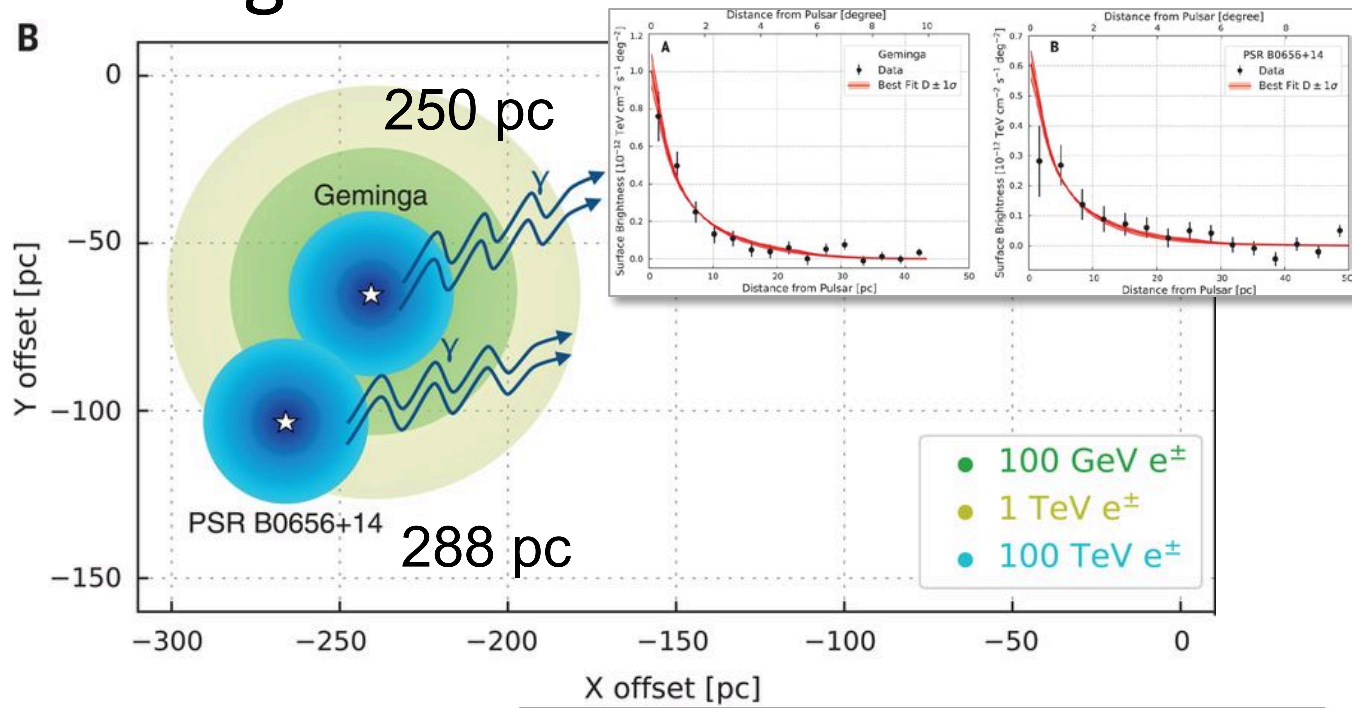




- ✧ The diffuse gamma-ray emission predicted by the model would be very faint
- ✧ The model also contradicts to the most recent B/C data
- ✧ Hypothesis rejected ?

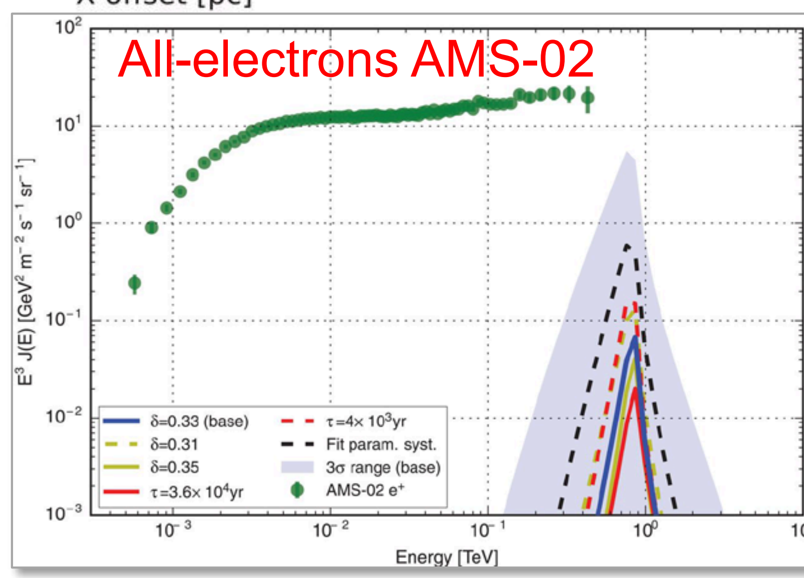
HAWC observations of the extended emission from Geminga & PSR B0656



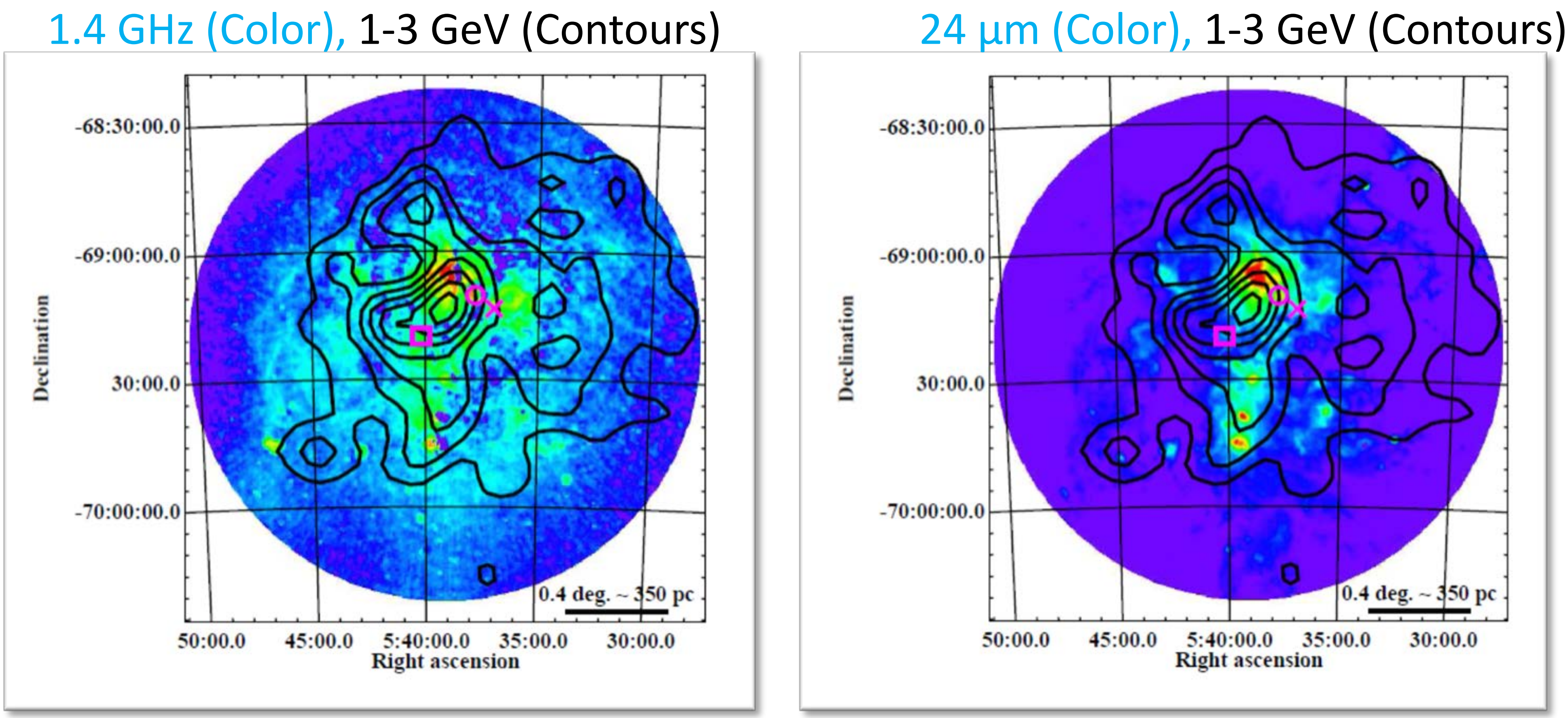


Abeysekara+’2017

- ✧ Evidence of a non-uniform diffusion near the sources of CRs
- ✧ The local value ~4.5×10^{27} cm^2 s^{-1} @100 TeV is much less than the average derived from the B/C ratio
- ✧ Proper motion ~60 pc since SN (Geminga)



Spatially Resolved CR diffusion in LMC: 30 Doradus

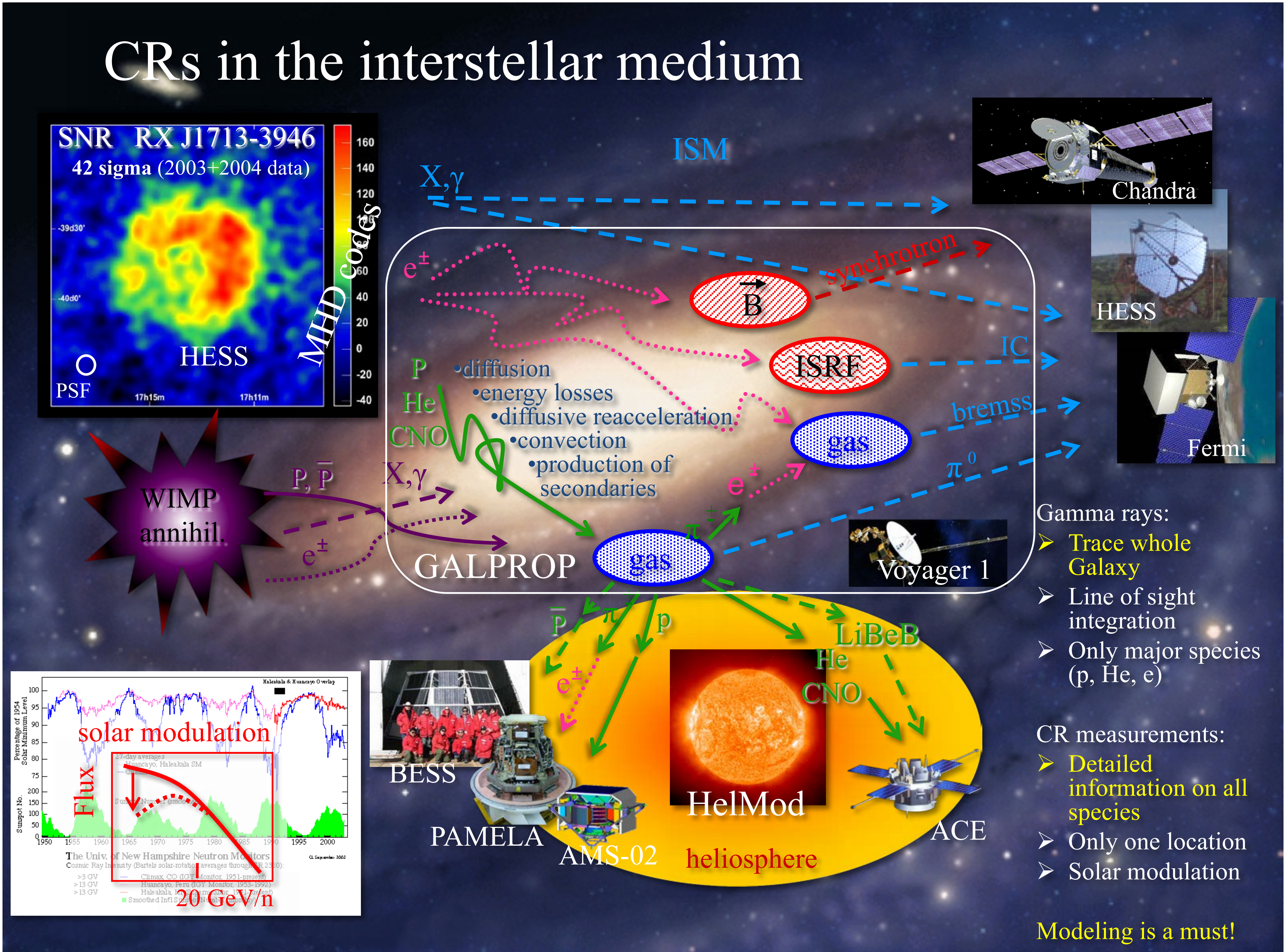


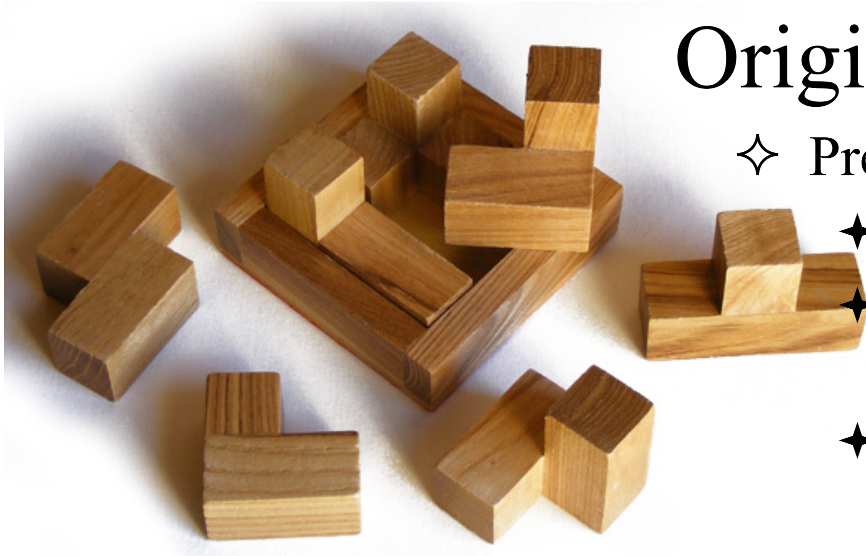
Murphy+'2012

- ✧ IR – proxy for the star forming region (SNR)
- ✧ Radio – synchrotron emission from electrons (100-140 pc at ~3 GeV)
- ✧ Gamma rays – emission from π^0-decay (CR protons, 200-320 pc at ~20 GeV)
- ✧ Diffusion coefficient ~$10^{27}(R/GV)^{0.7}$ cm^2 s^{-1} (~20 times lower than average in the MW)

GALPROP: a universal tool for interpretation

- Billions of $$ spent on CR & gamma-ray experiments
- Nature's communications are always encrypted; decoding them requires an intelligence and sophistication
- The proper interpretation of the precise data delivered by many different CR-related experiments over several decades requires a well-developed propagation code
- The most advanced numerical propagation model GALPROP celebrates its 22nd anniversary this year – it does exactly that!


CRs in the interstellar medium
SNR RX J1713-3946
42 sigma (2003+2004 data)
HESS
PSF
MHD codes
WIMP annihil.
P, $\bar{P}$
X,γ
e±
ISM
X,γ
synchrotron
B
ISRF
gas
IC
bremss
π0
e±
P
He
CNO
•diffusion
•energy losses
•diffusive reacceleration
•convection
•production of secondaries
GALPROP
gas
π±
Chandra
HESS
Fermi
Voyager 1
$\bar{P}$
π−
p
e±
LiBeB
He
CNO
BESS
PAMELA
AMS-02
HelMod
ACE
heliosphere
solar modulation
Flux
20 GeV/n
Gamma rays:
Trace whole Galaxy
Line of sight integration
Only major species (p, He, e)
CR measurements:
Detailed information on all species
Only one location
Solar modulation
Modeling is a must!



Original motivation

- ✧ Pre-GALPROP (before ~1997)
  - ✦ Leaky-box type models: simple, but not physical
  - ✦ Many different simplifying assumptions – hard to compare
  - ✦ Many models, each with a purpose to reproduce data of a single instrument
  - ✦ No or few attempts to make a self-consistent model

✧ Two key concepts are forming the basis of GALPROP

I. One Galaxy – a self-consistent modeling:

Various kinds of data, such as direct CR measurements including primary and secondary nuclei, electrons and positrons, γ-rays, synchrotron radiation, and so forth, are all related to the same astrophysical components of the Galaxy and, therefore, have to be modeled self-consistently

II. As realistic as possible:

The goal for GALPROP-based models is to be as realistic as possible and to make use of all available astronomical and astrophysical information, nuclear and particle data, with a minimum of simplifying assumptions

Components of GALPROP

- Numerically solves time-dependent transport equations for all cosmic ray species (stable + long-lived isotopes + pbars + leptons ~90) in 2D or 3D
- Propagation, diffusive acceleration, convection, energy losses…
- Derives the propagation parameters corresponding to the assumed transport phenomenology and source distribution
- Detailed gas distribution from HI and CO gas surveys (energy losses from ionization, bremsstrahlung; secondary production; γ-rays from π^0-decay, bremsstrahlung)
- Interstellar radiation field (inverse Compton losses/γ-rays for $e^{\pm}$)
- B-field models
- Nuclear & particle production cross sections + the reaction network (cross section database + LANL nuclear codes + phenomenological codes)

GALPROP development team

Troy A Porter
Stanford University

Igor V Moskalenko
Stanford University

Gudlaugur Jóhannesson
University of Iceland & NORDITA

And many others who contributed over many years of development;
Special thanks to: Stepan Mashnik (cross sections), Seth Digel (initial gas maps),
Roberto Trotta…

<u>Our former colleagues:</u>

Andrew W Strong (retired)
Max-Planck-Institut
für extraterrestrishe Physik

Elena Orlando
Stanford University

Andrey Vladimirov
Colfax International

New GALPROP features (v.56)

- ✧ Options for 2D/3D gas distributions (Jóhannesson et al., 2018)
- ✧ Options for 2D/3D interstellar radiation field (Porter et al., 2017)
- ✧ Options for 2D/3D source density distributions
- ✧ Allows spatial variations in the diffusion coefficient and Alfvèn speed
- ✧ Wave damping: to speed up, an approximate solution is now used
- ✧ Observer can now be anywhere in (*x, y, z*); gamma-ray skymaps!
- ✧ Injection spectrum allows it to be set independently for each isotope
- ✧ A new skymap integrator with a variable step size
- ✧ Can be used for arbitrary galaxy
- ✧ Single external dependency on the GALTOOLSLIB library
- ✧ Numerous generalizations, improvements, and optimizations
- ✧ Other large and small upgrades

Computing cluster: http://galprop.stanford.edu

Provides the latest version of GALPROP and WebRun service (online version)

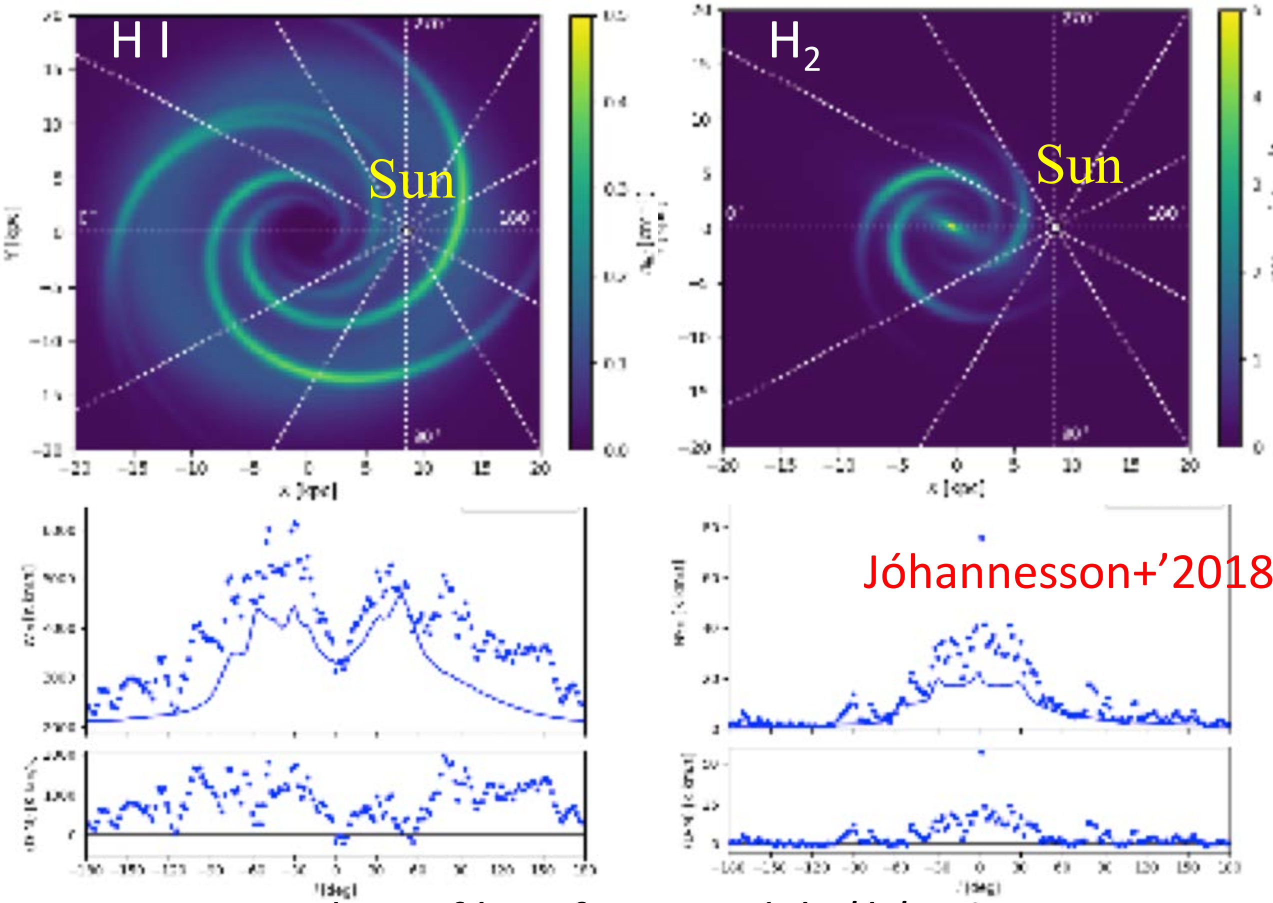
<u>Now: 500+ cores (Xeon & Opteron)</u>

Upgrade will nearly double the capacity

- Intel Xeon 4 × 32 cores
  - 384 GB shared memory each
- Intel Xeon Phi coprocessor 4 × 2 cards
- AMD Opteron 3 × 64 cores
  - 256 GB shared memory each
- 6174 AMD Opteron 4 × 48 cores
  - 128 GB shared memory each
- Web server
- Data storage (12 TB RAID0)
- Infiniband link (10 Gbit/s)

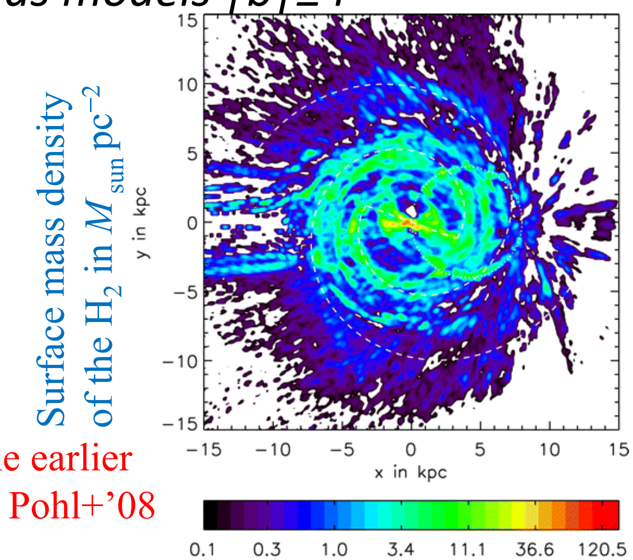
3D gas: H I & H_2

- ✧ Forward folding model fitting technique
- ✧ Max-likelihood fit to H I LAB and the DHT CO surveys
- ✧ Re-binned to HEALPix order 7 (H I) and 8 (CO), degraded to 2 km/s v-bins
- ✧ Built iteratively, starting with 2D disk, adding warping, central bulge/bar, flaring (outer Galaxy), and spiral arms



Longitude profiles of gas models |b|≤4°

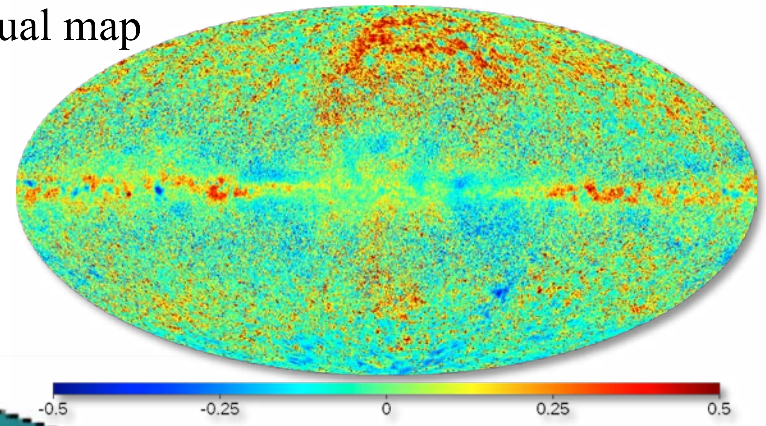
- ✧ The location and shape of the spiral arms are identical between the H I and CO models, but the radial and vertical profiles differ
- ✧ Each spiral arm also has a free normalization

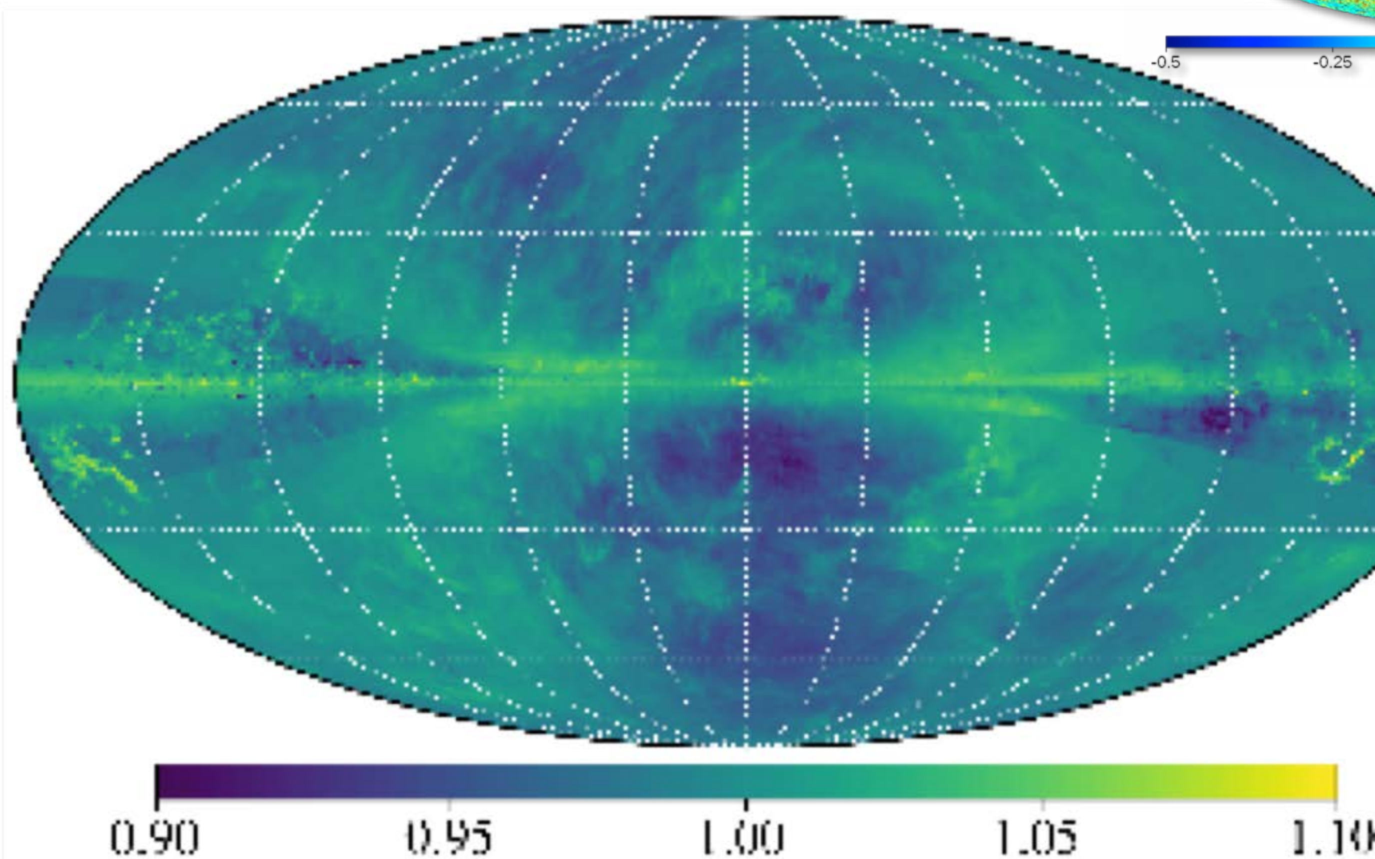


One of the earlier attempts: Pohl+'08

Effect of 3D gas on gamma-ray skymaps

Fermi-LAT residual map

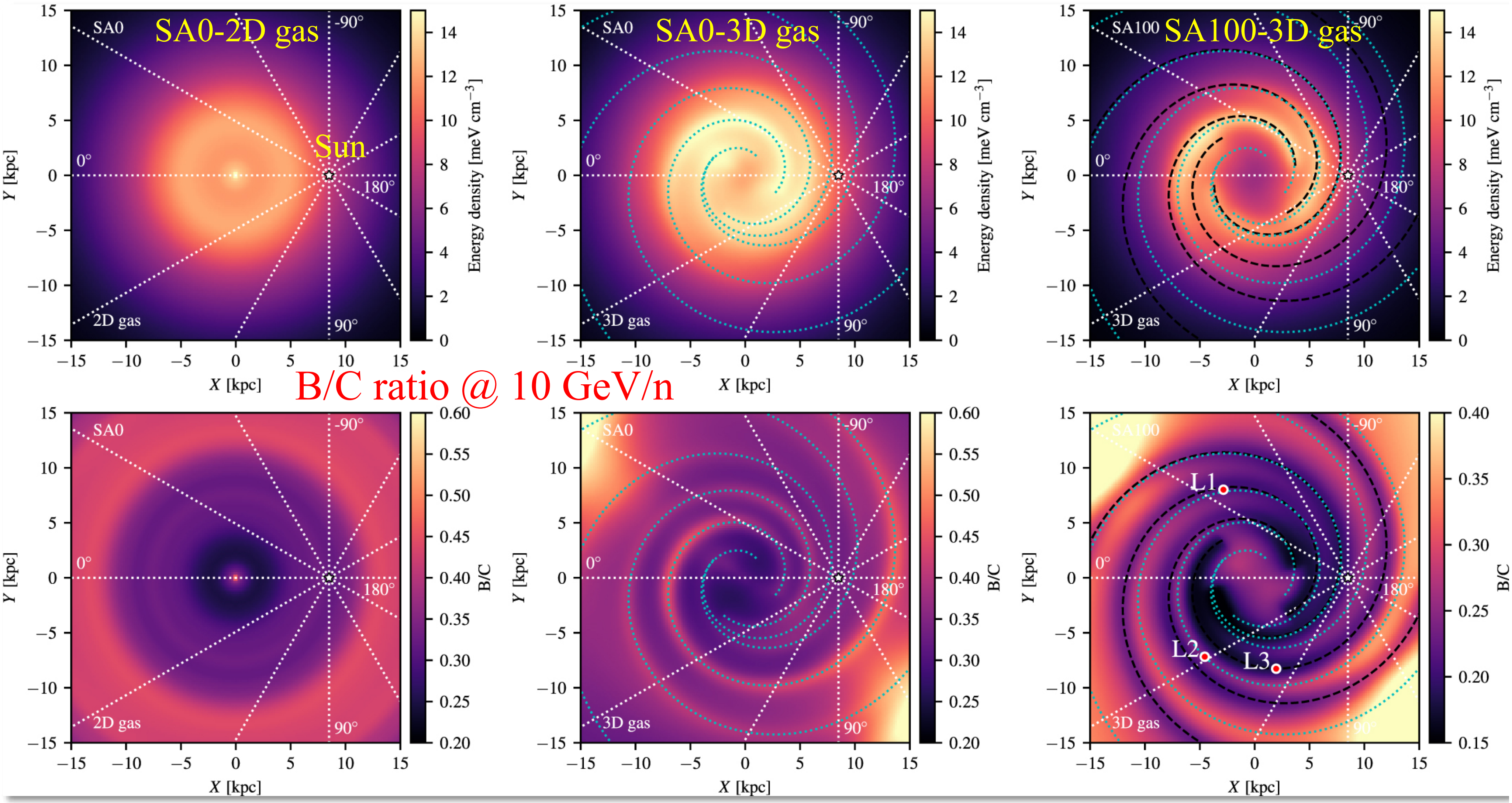




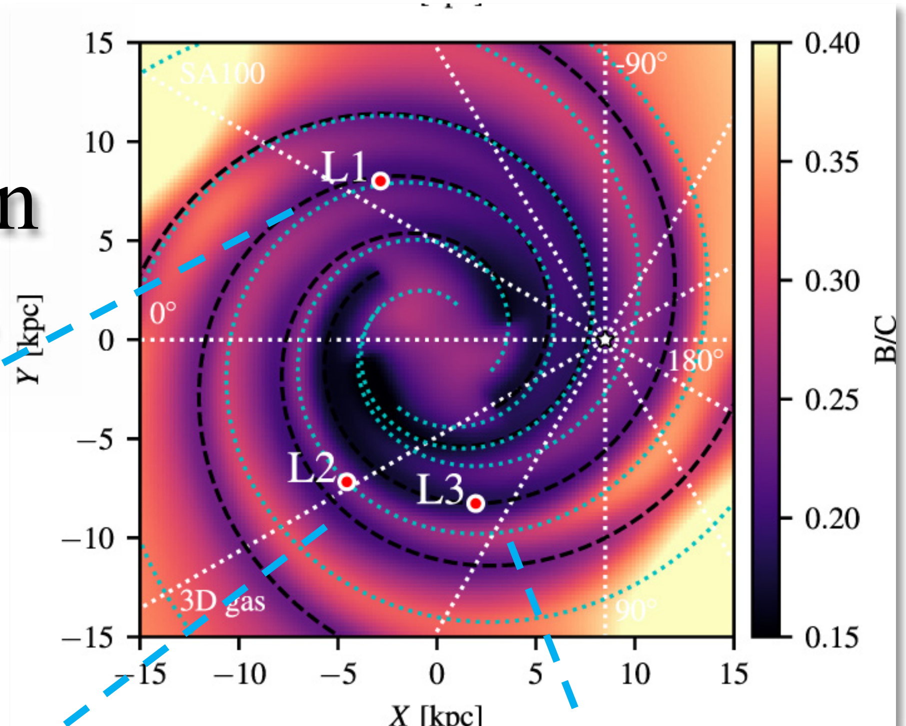
- ✧ Ratio of the total gamma-ray skymaps at 1 GeV for 3D/2D models
- ✧ The 3D/2D ratio demonstrates features similar to the Fermi-LAT residual map

Secondary e^+ and B/C ratio in models with CR sources in spiral arms

Energy density of secondary positrons in the mid-plane of the MW

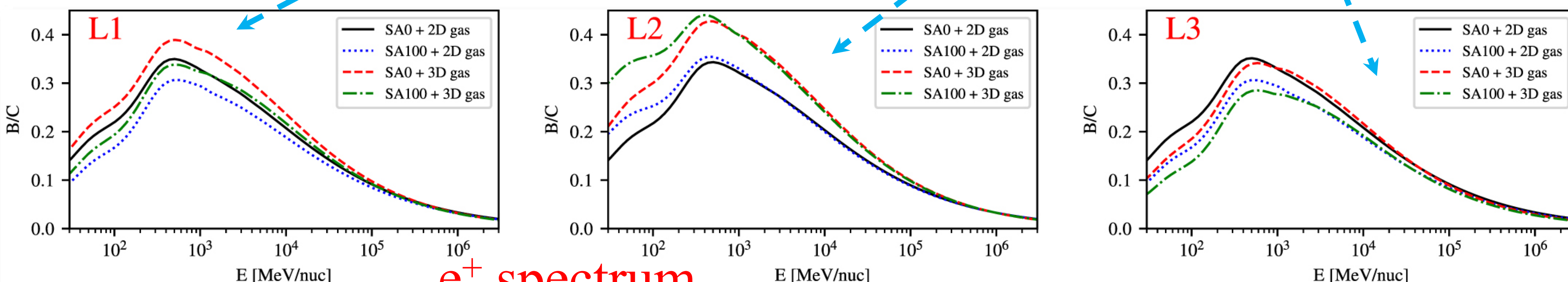


Spatial variations of the B/C ratio and positron spectrum in the Galaxy in 2D/3D models

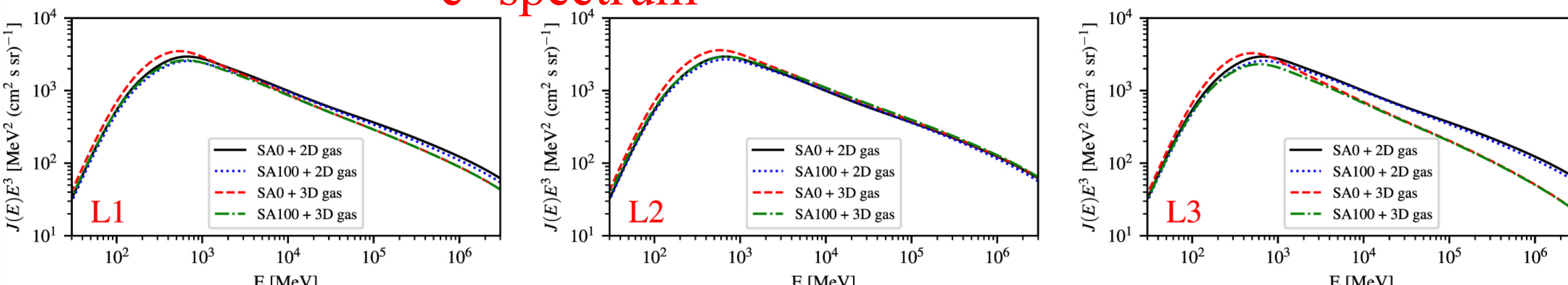


The B/C ratio and positron spectrum at $R_\odot$ but in different environments

B/C ratio

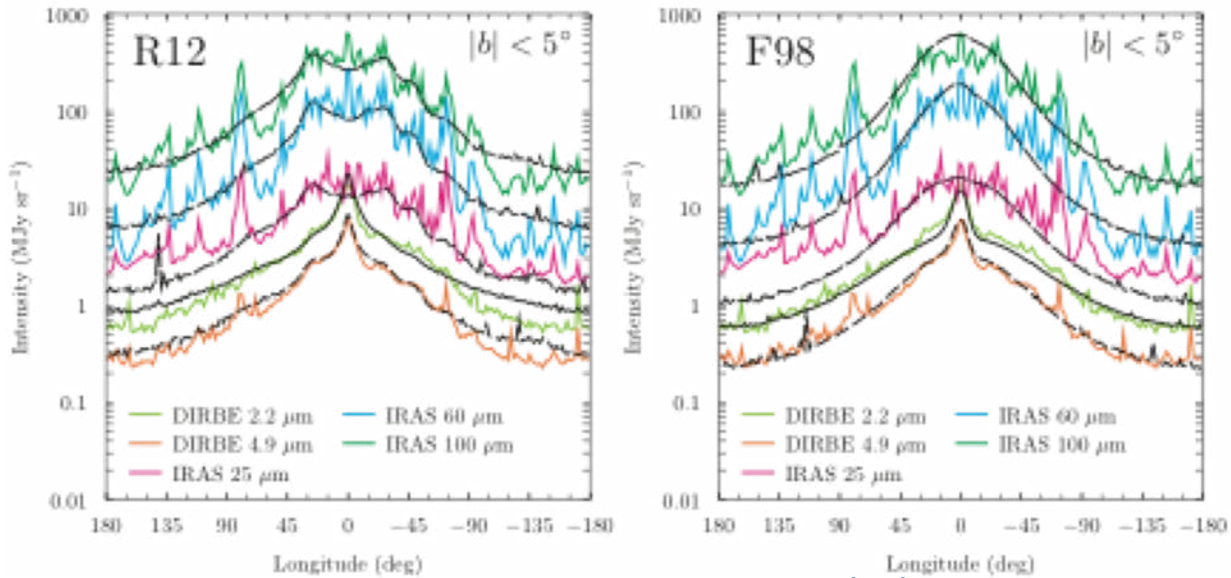


e^+ spectrum

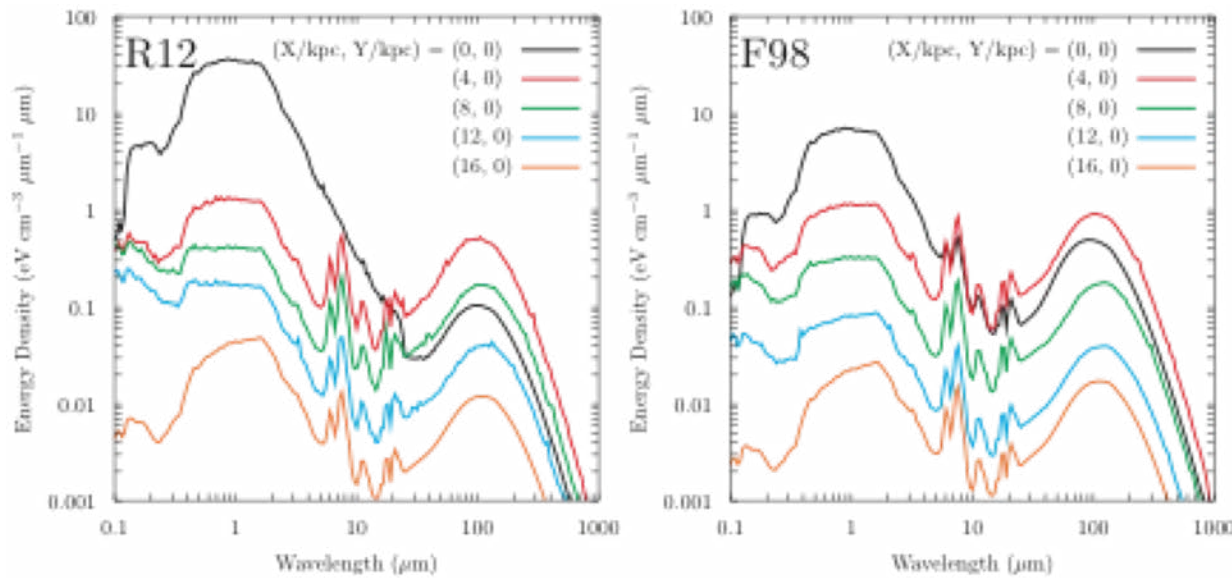


3D interstellar radiation field

- ✧ Monte Carlo radiation transfer code FRaNKIE
- ✧ Two models for the stellar and dust distributions are chosen from the literature:
  - ✦ R12 = Robitaille+'2012
  - ✦ F98 = Freudenreich'1998
- ✧ The simulation volume for the radiation transfer: a box X,Y=±15 kpc, Z=±3 kpc
- ✧ λ-grid = 0.0912–10000 µm



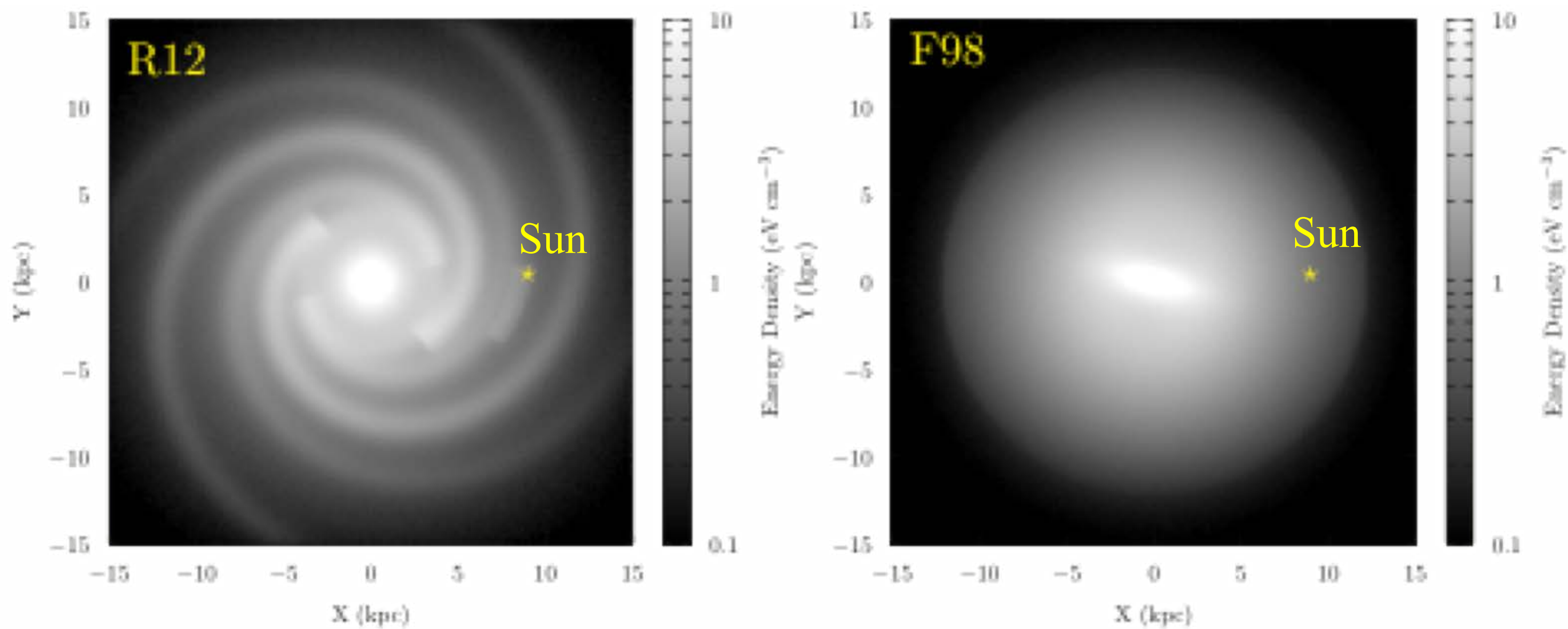
Longitude profile averaged over |b|<5°



Energy density for distances X=0,4,8,12,16 kpc

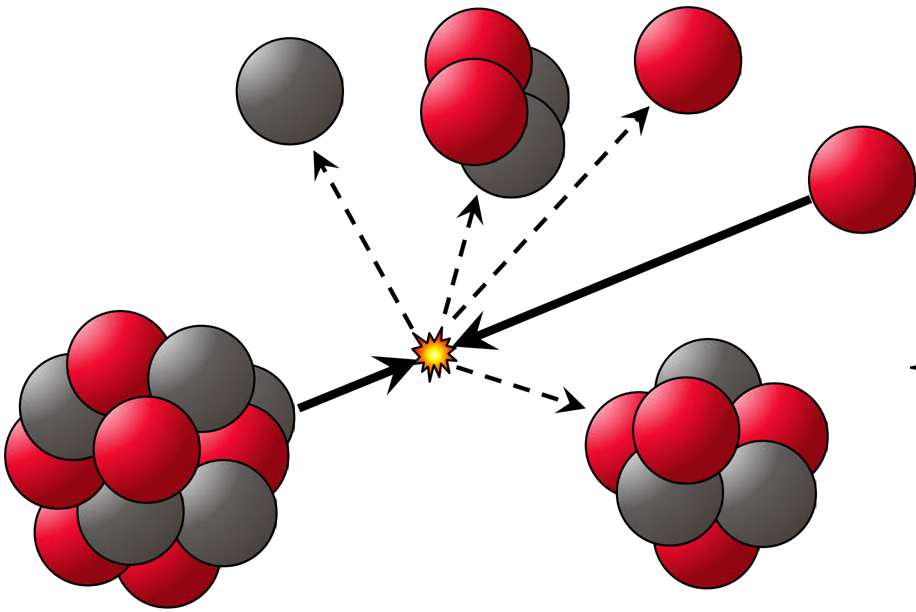
Porter+'2017

Energy density of interstellar radiation field



- ✧ Integrated ISRF energy densities in the Galactic plane
- ✧ The ISRF structure will translate into the structure in the inverse Compton
- ✧ A comparison with the Fermi-LAT data is not made yet
- ✧ Affects spectra of electrons/positrons at HE and diffuse emission

Nuclear & particle production cross sections



- Bottle neck for further advances in Astrophysics of CRs
- To improve:
  - Use advanced Monte Carlo event generators tuned to accelerator data (e.g., QGSJET-II-04 & EPOS-LHC)
  - New measurements of astrophysically important cross sections
- Examples:
  - Kachelriess, IM, Ostapchenko, 2014 "Nuclear enhancement of the photon yield in cosmic ray interactions"
  - Kachelriess, IM, Ostapchenko, 2015 "New calculation of antiproton production by cosmic ray protons and nuclei"
- New international collaboration to measure/improve on the astrophysically important cross sections was formed at XSCRC2017: Cross sections for cosmic rays @ CERN (March 29-31, 2017)

GALPROP package for calculation of the Xsections

- nuc_package.cc
- Includes an extensive nuclear reaction network built using the Nuclear Data Sheets
- Takes into account all intermediate unstable nuclei and follows the decay chains down to 5 generations of the decay products
- Based on a careful inspection of the quality and systematics of various datasets and semi-empirical formulae
- Uses the best of parametric formulae (normalized to the data when exists) and results of nuclear codes: SEM, HMS-ALICE, LAQGSM
- Sometimes – a direct fit to the data for particular reactions
- Can handle H-like ions, electron pick-up from the interstellar gas, and electron stripping – important for isotopes decaying through electron capture (EC)

Current status and desired accuracy of the isotopic production cross sections relevant to astrophysics of cosmic rays I. Li, Be, B, C, N

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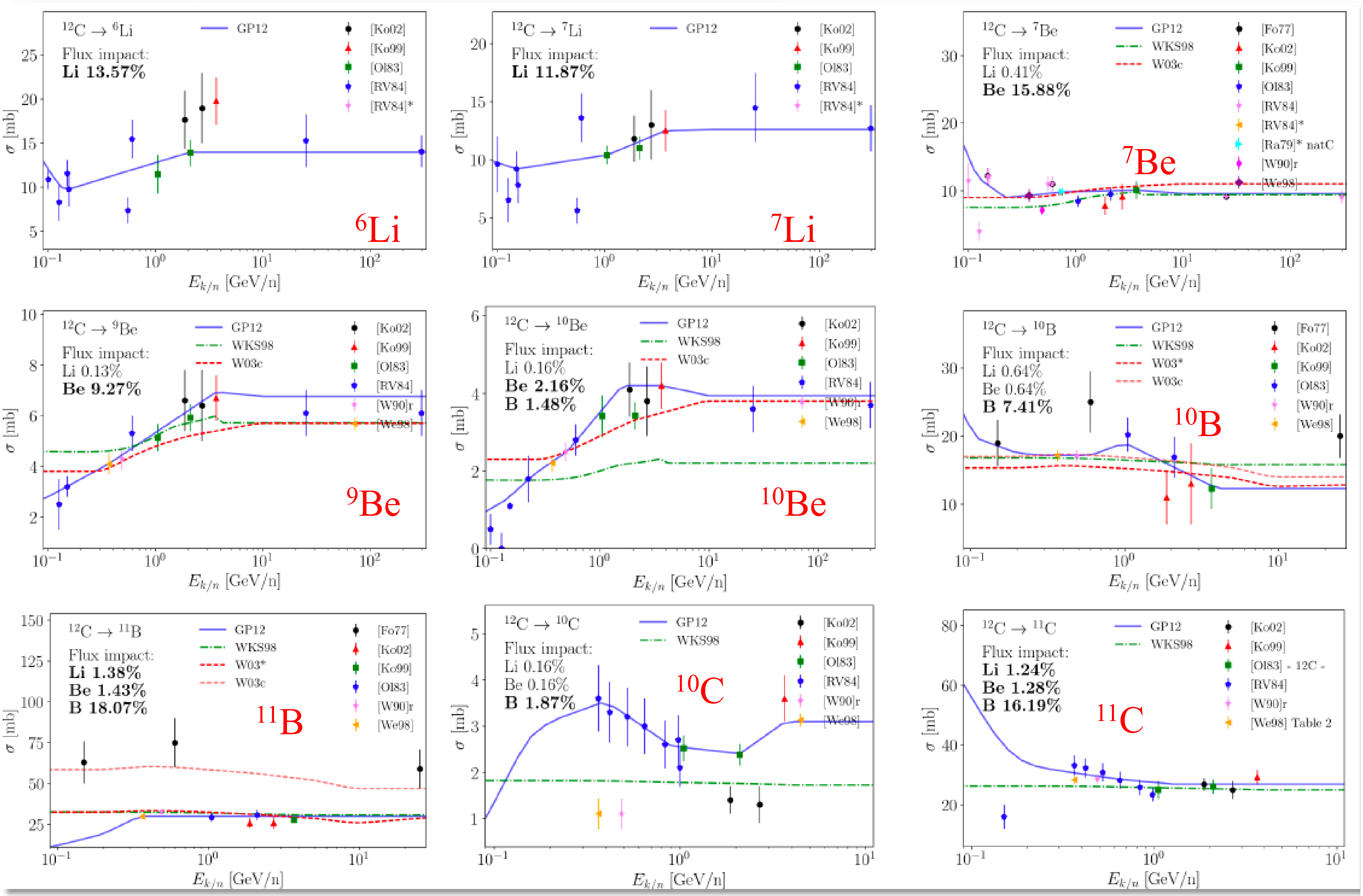
(Dated: March 14, 2018)

PRC submitted (arXiv:1803.04686)

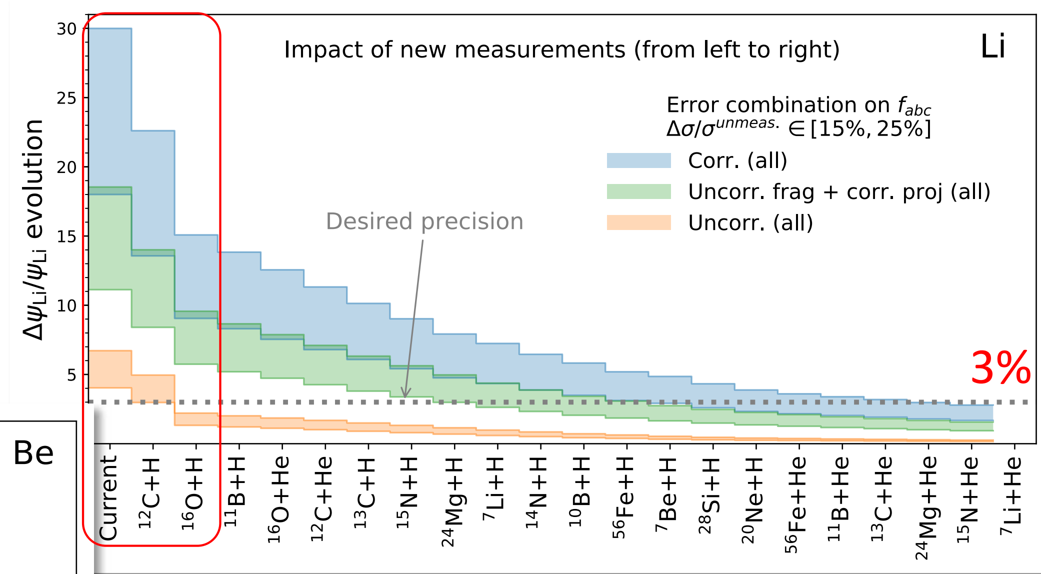
- Provides a motivation for a proposal to make new measurements of isotopic production cross sections using secondary ion beams, isotopes of Li, Be, B, C, N, O. Nuclear fragments from CERN SPS, Pb beam on primary target with momentum 13A GeV/c at different A/Z settings.
- Got time at the NA61/SHINE facility at the end of 2018!

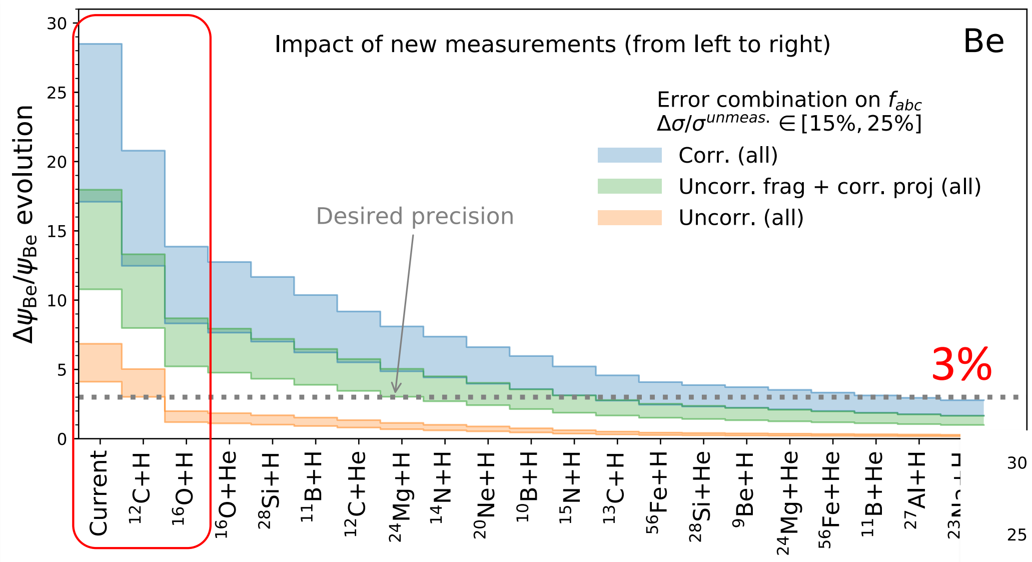
Examples of Xsections ^{12}C+H

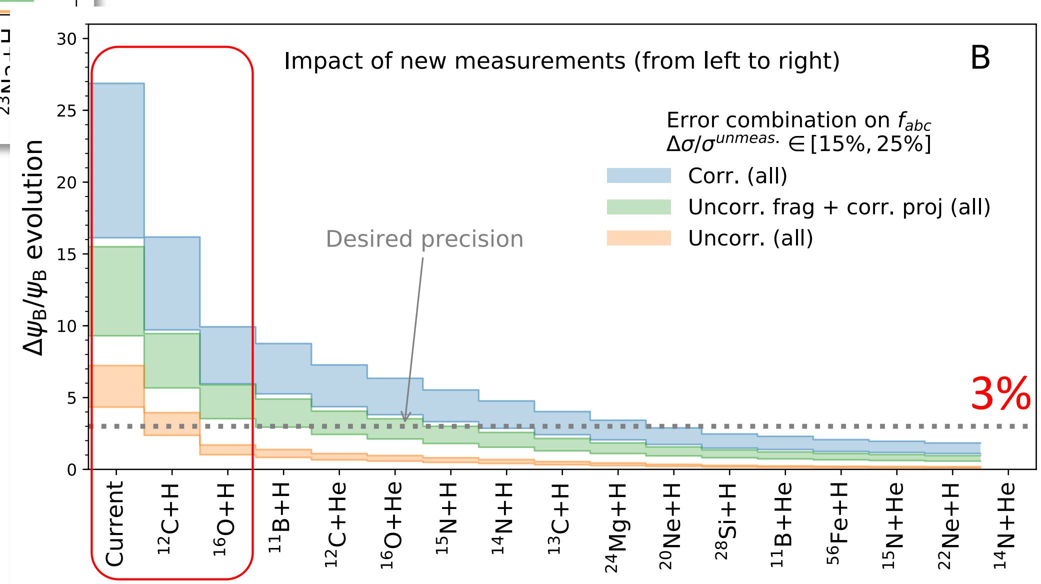
GP12 = GALPROP, option 12
WKS98, W03 = Webber et al.



Error impact on calculations of CR Li, Be, B fluxes



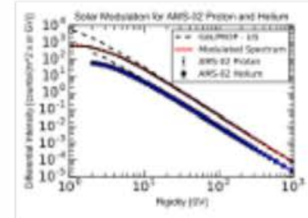




Fully correlated errors
Intermediate case (realistic)
Uncorrelated errors

- The bands are shown for 15%-25% errors on all cross sections
- "Current" – indicates current uncertainty
- Most impact is due to reactions with ^{12}C, ^{16}O on ^{1}H target (shown assuming 0% error)

HelMod:
The Heliospheric Modulation Model
Online Calculator
(version 3.5.0)



HelMod Forecasting of the Intensities of Ion Cosmic Rays

M. J. Boschini, S. Della Torre, M. Gervasi, D. Grandi, G. La Vacca, S. Pensotti, P.G. Rancoita, D. Rozza and M. Tacconi

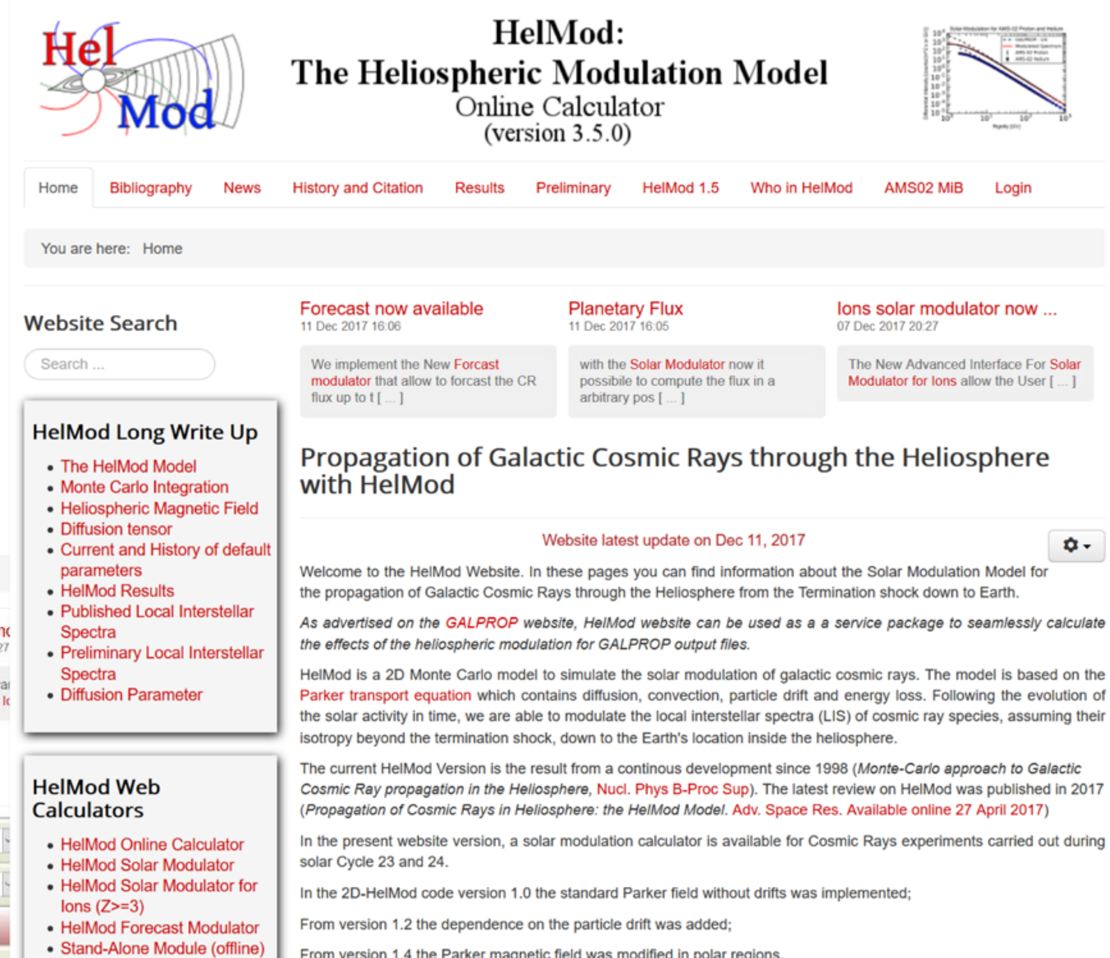
INFN Sezione Milano-Bicocca

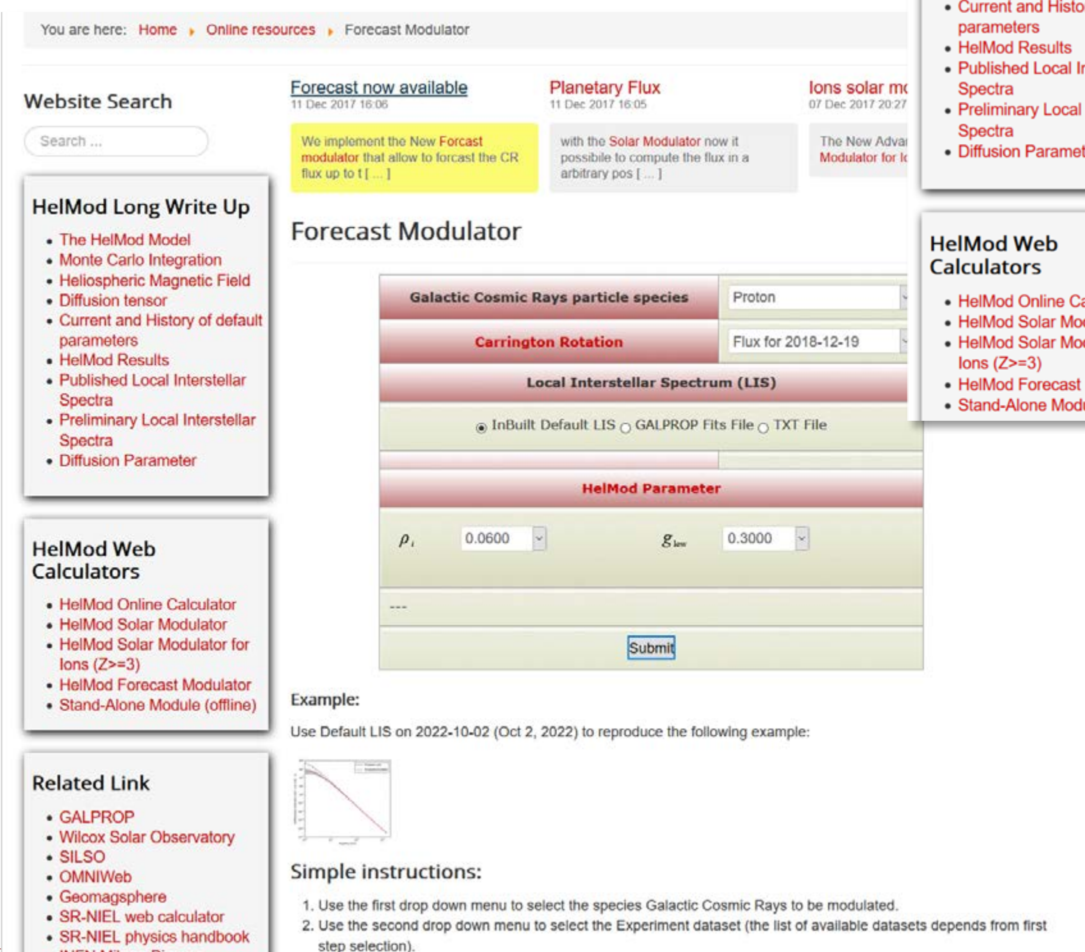
N. Masi, L. Quadrani

INFN Sezione Bologna

GALPROP/HelMod

- ✧ Goal #1: reliable local interstellar spectra of all CR species (>100 MeV/n)
- ✧ Goal #2: reliable heliospheric modulation for an arbitrary epoch in the past
- ✧ GALPROP/HelMod
  - ✦ Boschini, et al., ApJ 840 (2017) 115 (p, He, $\bar{p}$)
  - ✦ – – – ApJ 854 (2018) 94 (e^-)
  - ✦ – – – ApJ 2018, in press (He, C, O)
  - ✦ – – – ApJ 2018, in preparation

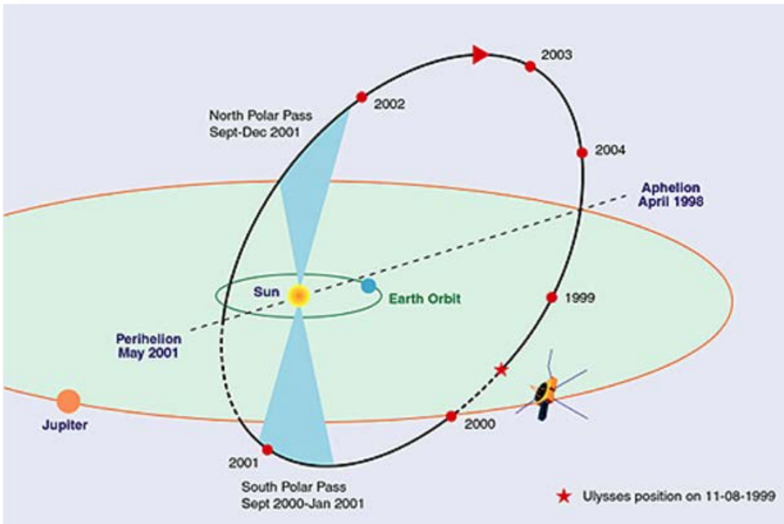


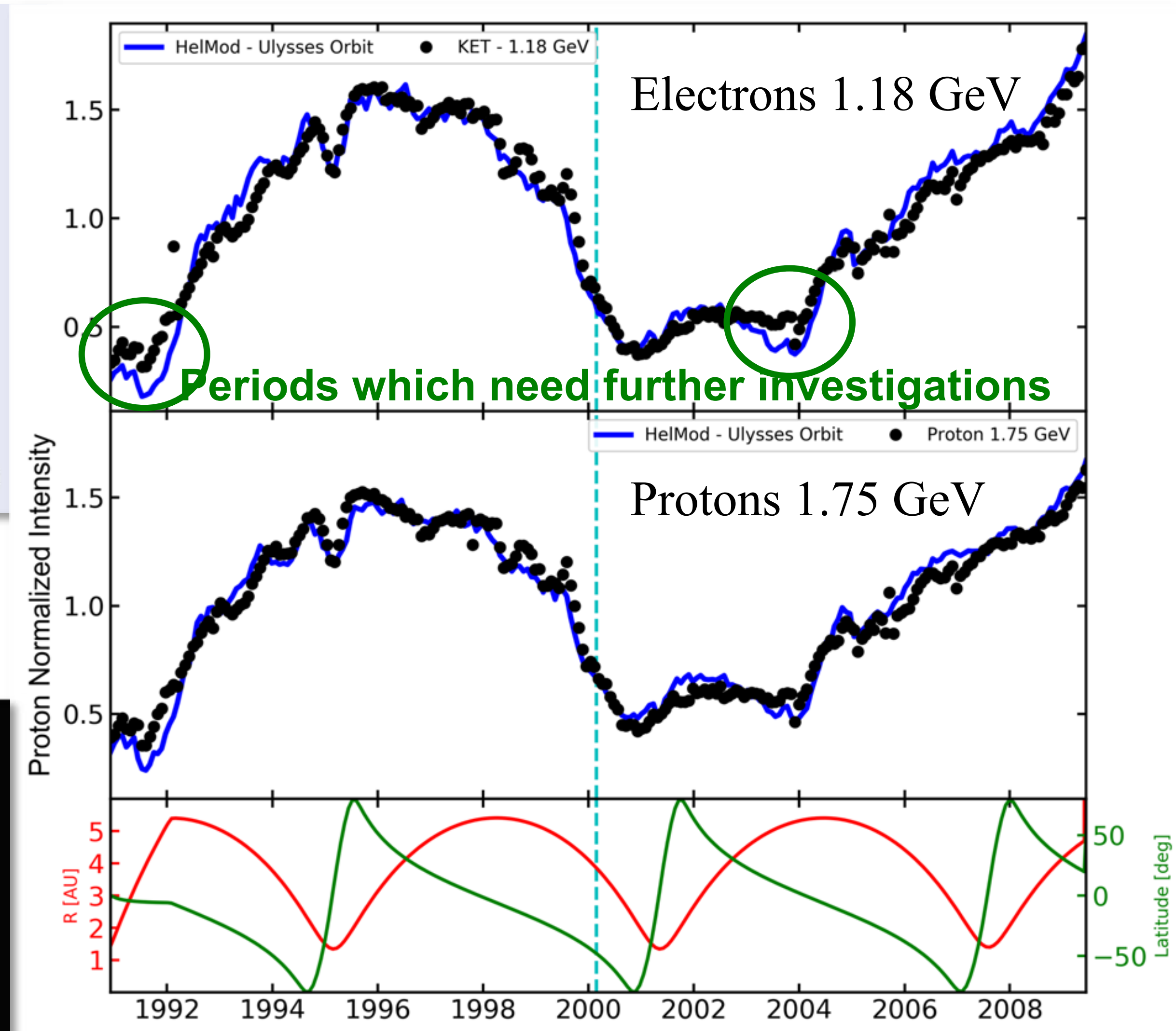


- ✧ Time dependent Parker (1965) equation
- ✧ 2D Monte Carlo, backward in time
- ✧ Convection, energy loss, full description of the diffusion tensor (charge sign effect)
- ✧ http://www.helmod.org

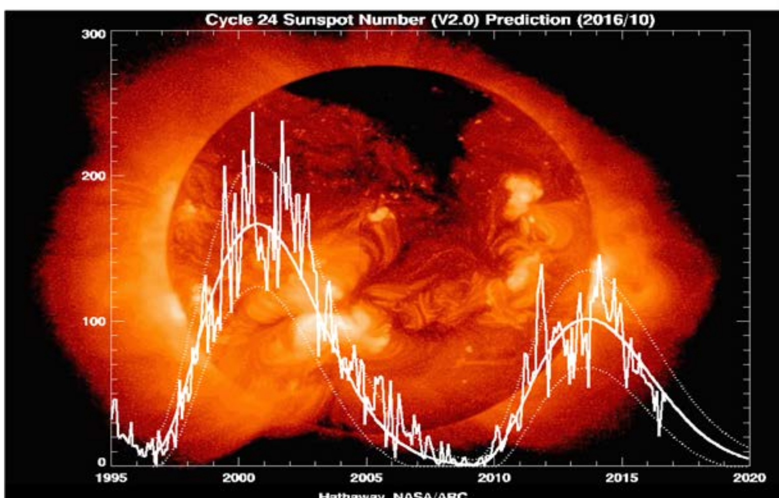
Time and Spatial Variation of Cosmic Rays

The Ulysses Probes explore the tridimensional view of the inner heliosphere.

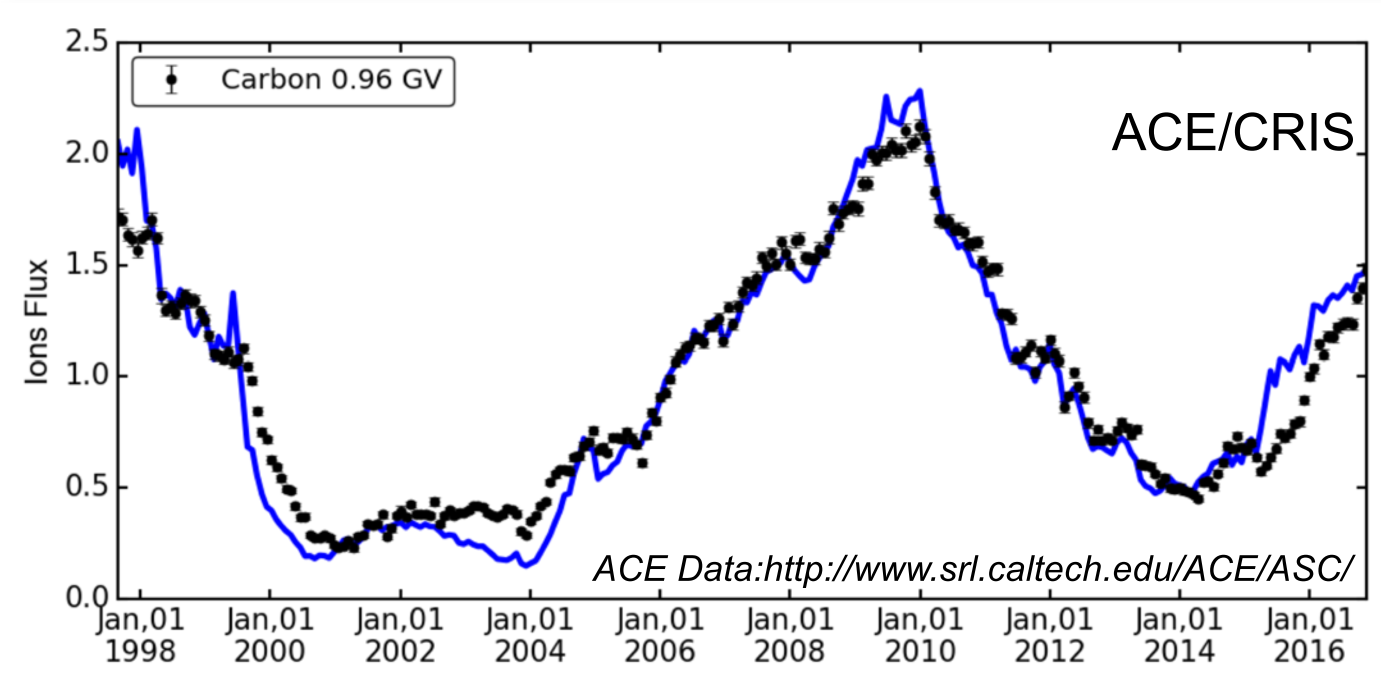




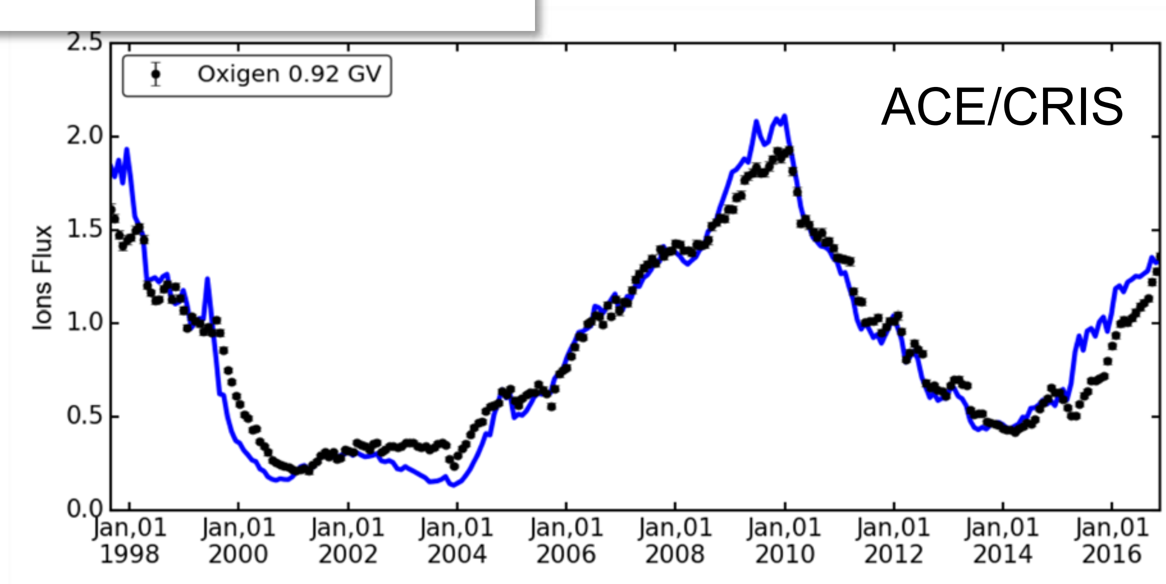
Ulysses allow to probe the interplanetary space up to 5 AU and +/- 80 degree of Solar Latitude: Outside ecliptic Plane



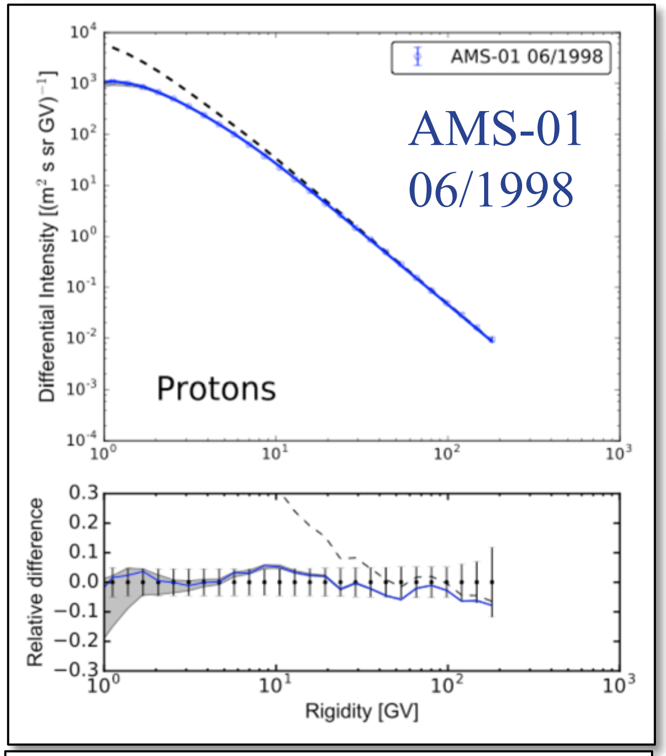
Time and Spatial variation of Cosmic Rays

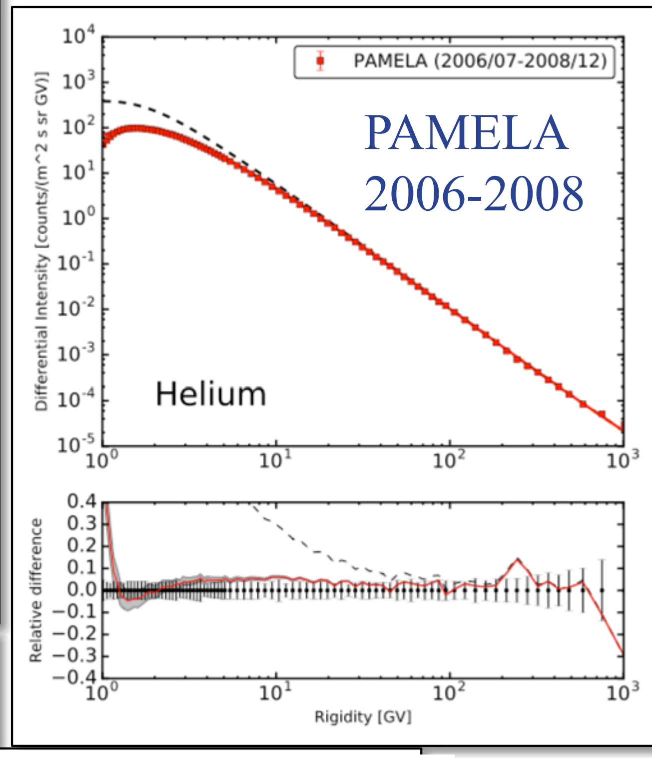


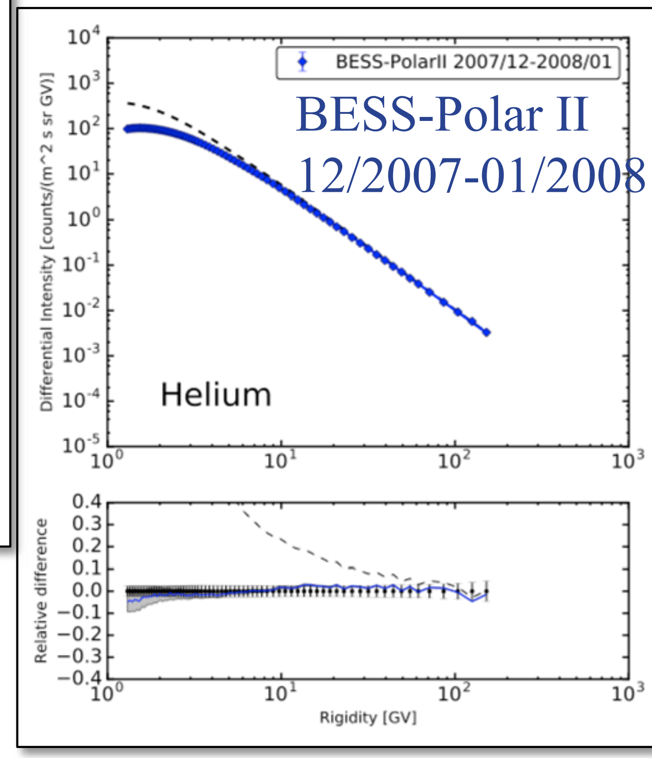
Using derived LIS HelMod is also able to simulate solar modulation for Ions.

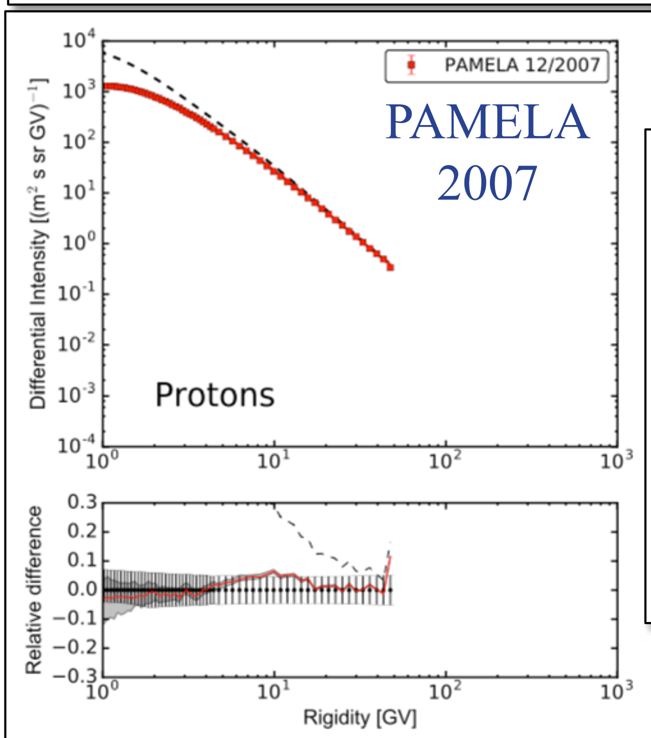


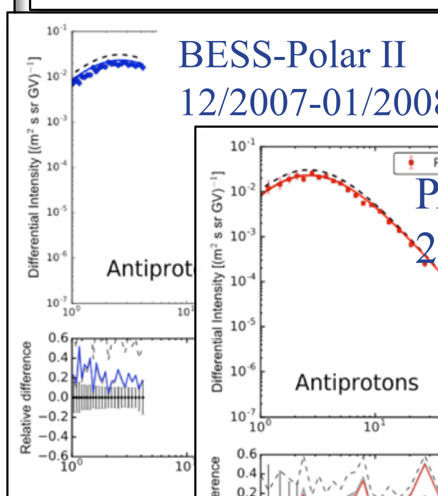
Low level of solar activity (A≷0)

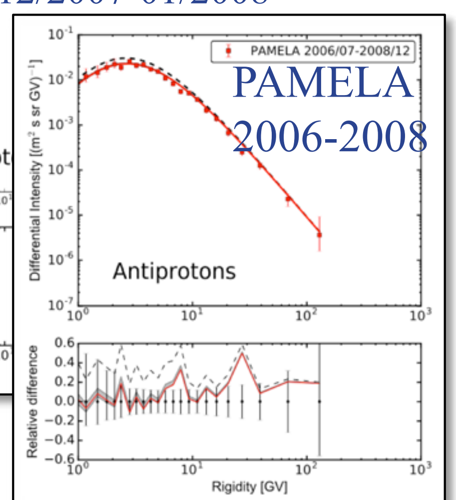






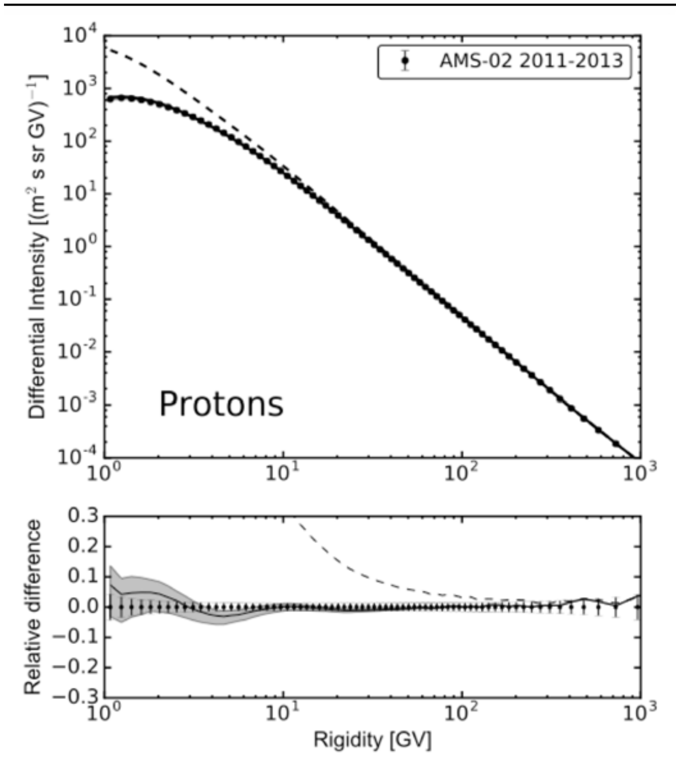




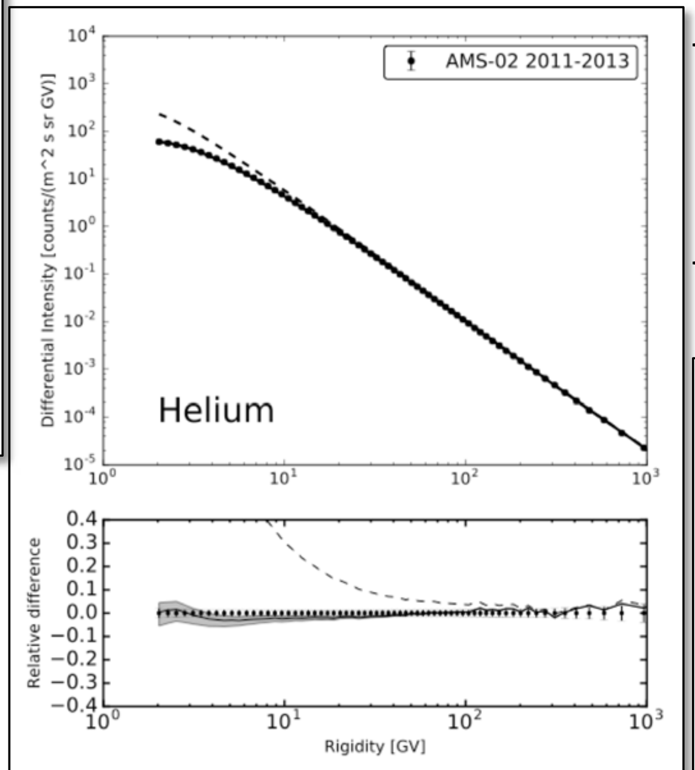


- ✧ GALPROP/HelMod calcs for the low level of solar activity and both polarities of the solar magnetic field

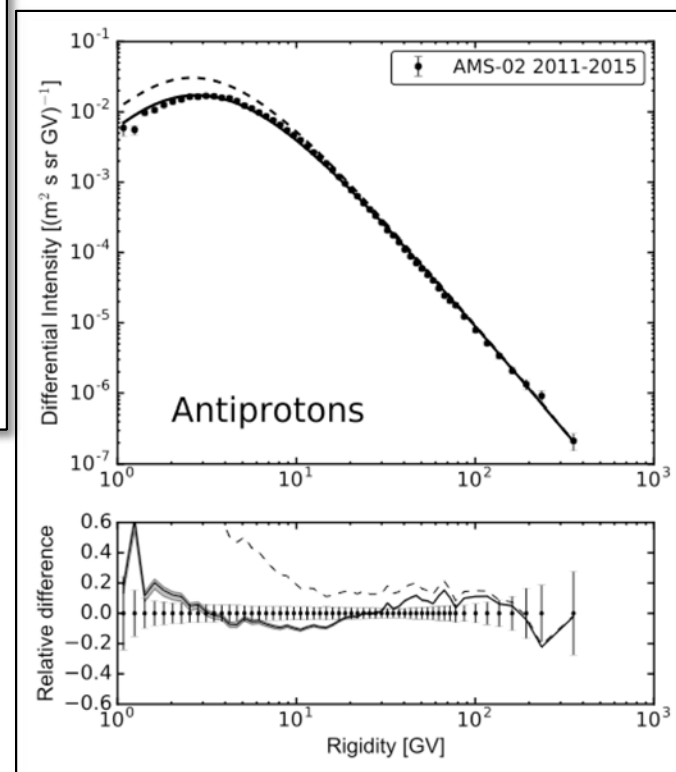
Active Sun: 2011-15



AMS-02: 2011-2013

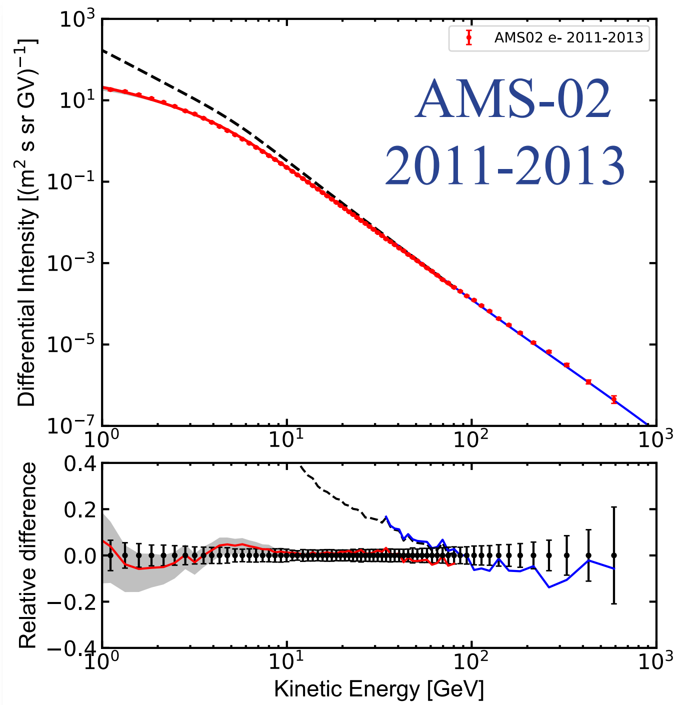


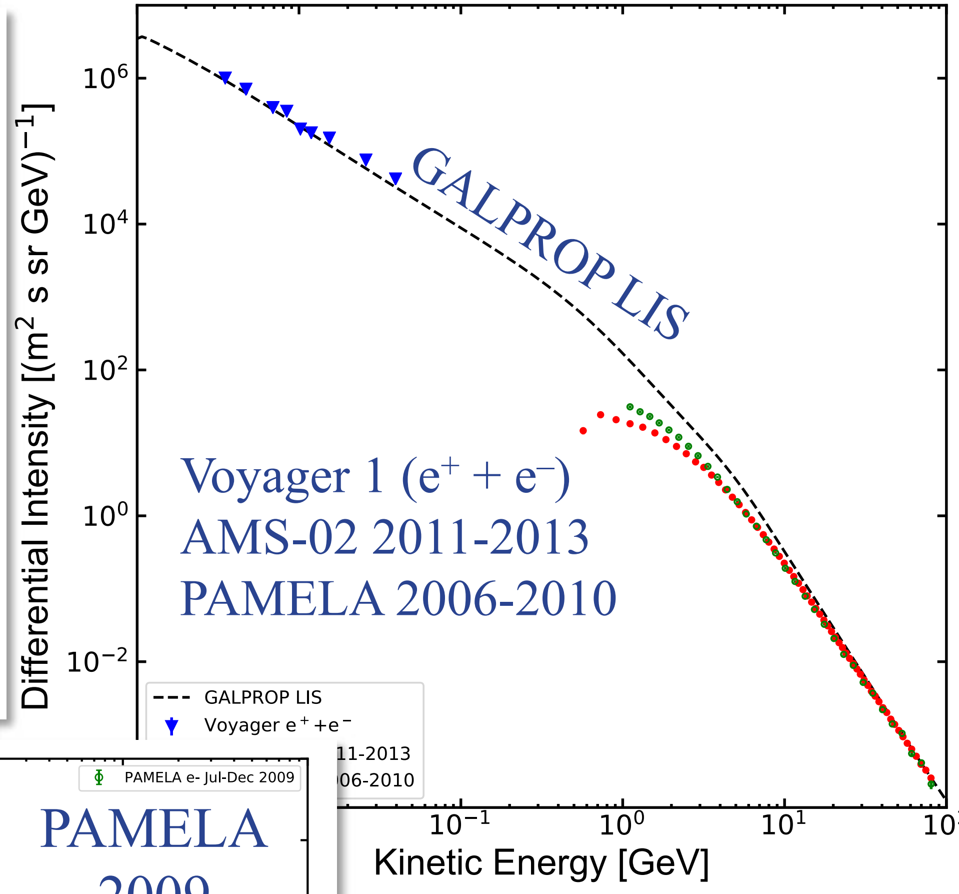
- ✧ Accuracy of AMS-02 data is a few per cent
- ✧ Fitting such data with a physical model is a challenge
- ✧ But we managed!

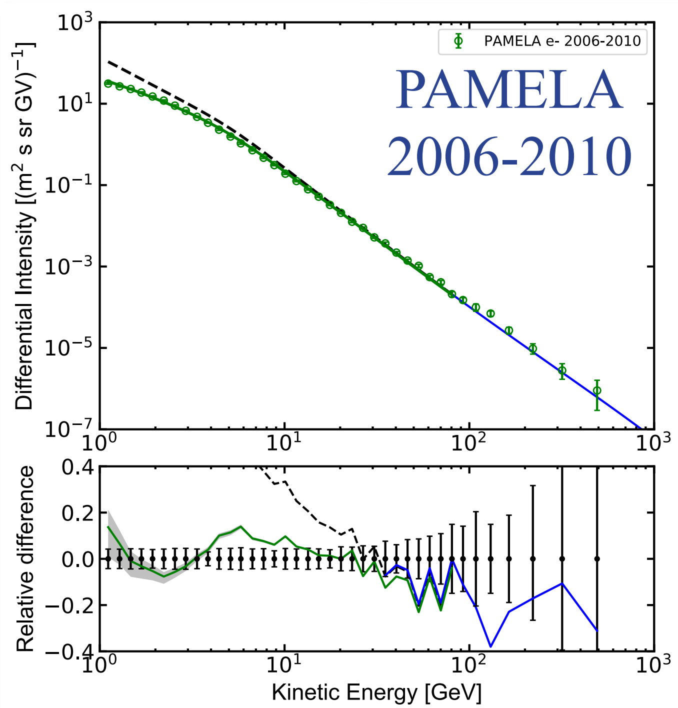


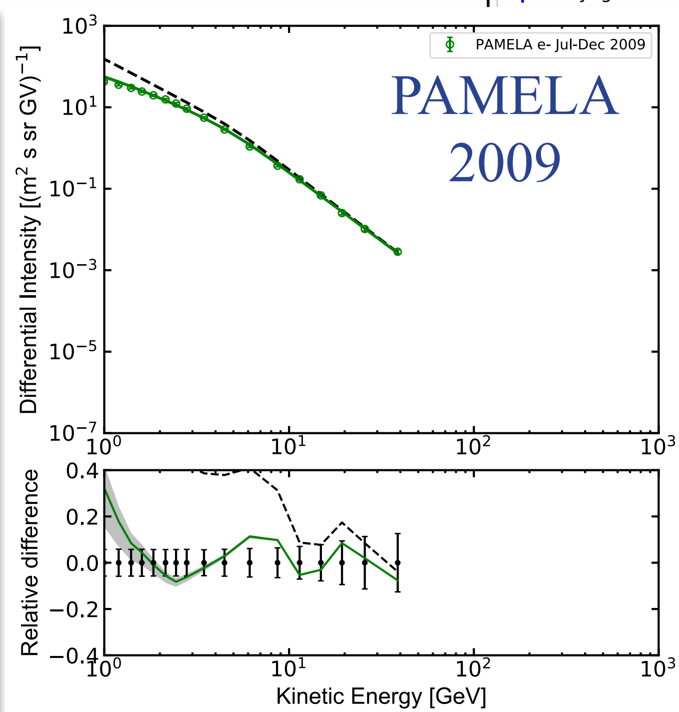
- ✧ Antiprotons were not fitted !
- ✧ GALPROP/HelMod calcs for high activity periods vs. AMS-02 data

CR e^{-}





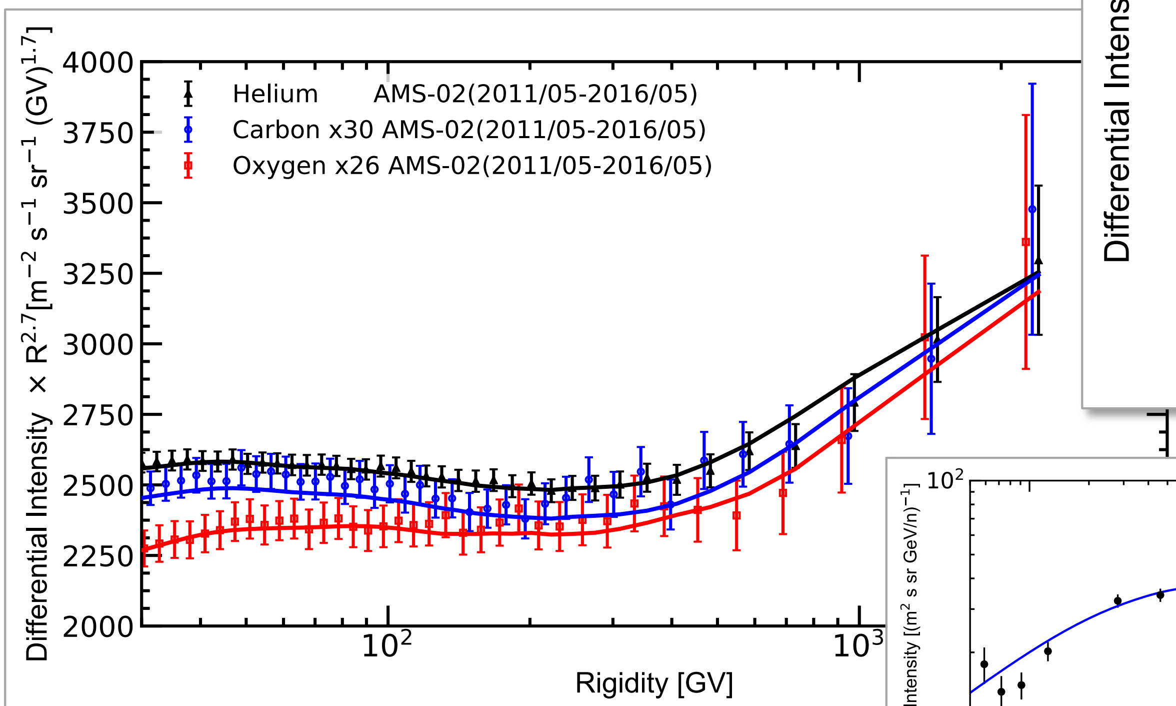


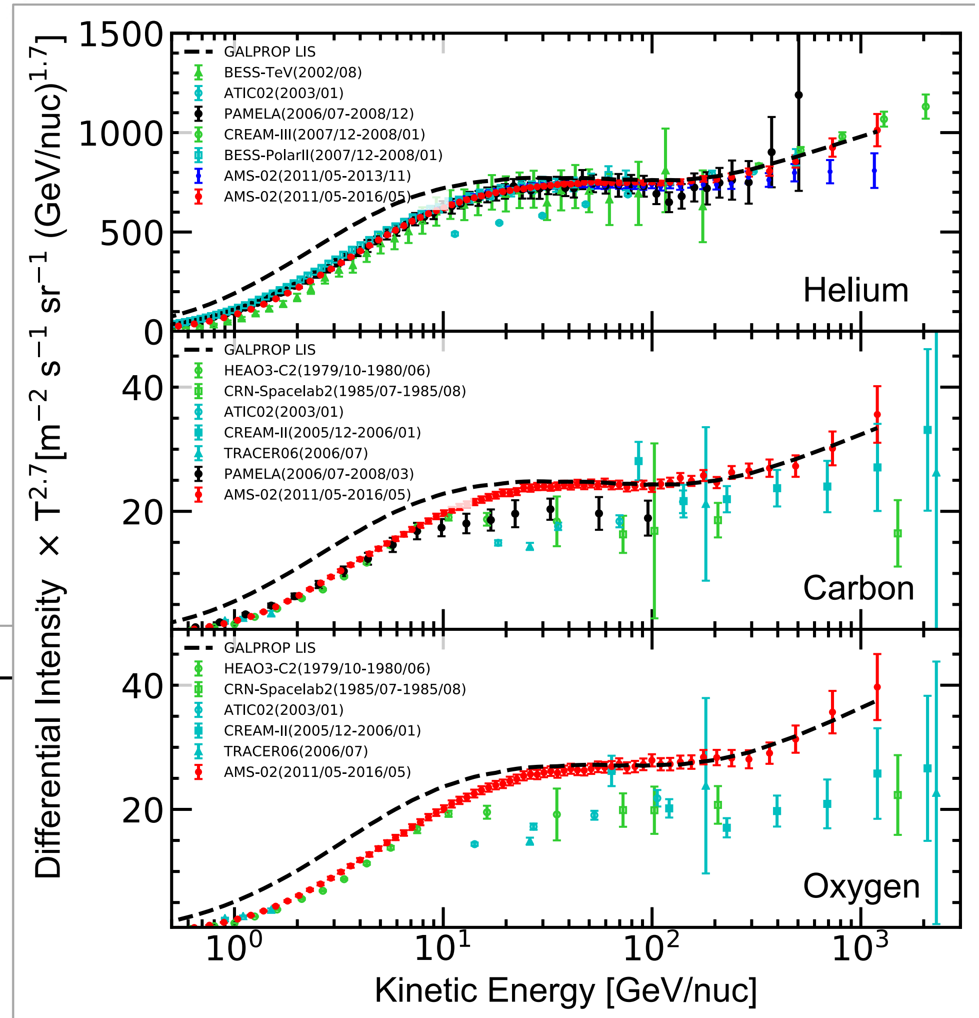


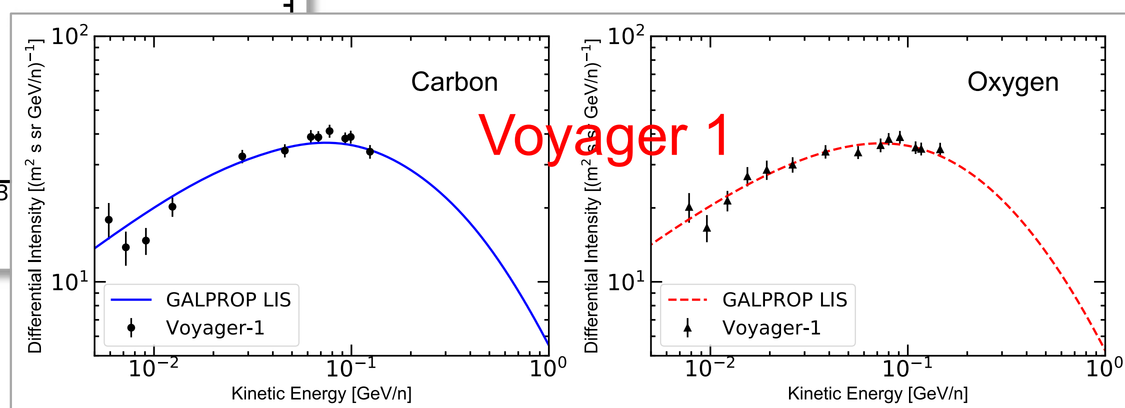
Heliospheric propagation of electrons uses parameters derived from propagation of protons

He, C, O fluxes

- Excellent agreement of calculated spectra with precise measurements by AMS-02
- Same models/parameters were used for Galactic and heliospheric propagation







Why the Local Interstellar spectra are important

The derived local interstellar spectra of CR species can be used to facilitate significantly studies of CR propagation in the Galaxy and in the heliosphere by disentangling these two massive tasks and will lead to further progress in understanding of both processes

The follow up paper on secondary nuclei (Li, Be, B) is in progress

Long life to the ISS and CR detectors docked to it!

There are so many astrophysical puzzles that just await for more precise data to be solved