USINE
A code for the propagation of Galactic cosmic rays

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Grenoble, France

TOOLS 2017 - Tools for SM and the New Physics
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Maurin et al., ApJ 555 (2001), Putze et al., A&A 516, 66 (2010), Boudaud et al., A&A 605, 17 (2017)

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Enigmass

1- Introduction

2- Cosmic ray physics

3- USINE: introduction

4- Several ways to run USINE: examples

5- Electrons and positrons soon in USINE

6- Conclusions and prospects

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Introduction

Precision era for cosmic rays

The AMS-02 detector measures the flux of cosmic rays with rigidities from ~0.5 GV to ~500 GV with an unprecedented high accuracy.

Rigidity: $$R \equiv \frac{p}{q}$$

- Electrons and positrons (2013, 2014)
  PRL113,121102 (2014), PRL113,121101 (2014)
- Protons (2015) *PRL114,171103 (2015)*
- Helium (2015) *PRL115,211101 (2015)*
- Antiprotons (2016) *PRL117,091103 (2016)*
- Boron/Carbon (2016) *PRL117,231102 (2016)*
- Preliminary results for Li, Be, B, O, C, N, etc.

Launched in 2011. Installed on the ISS.

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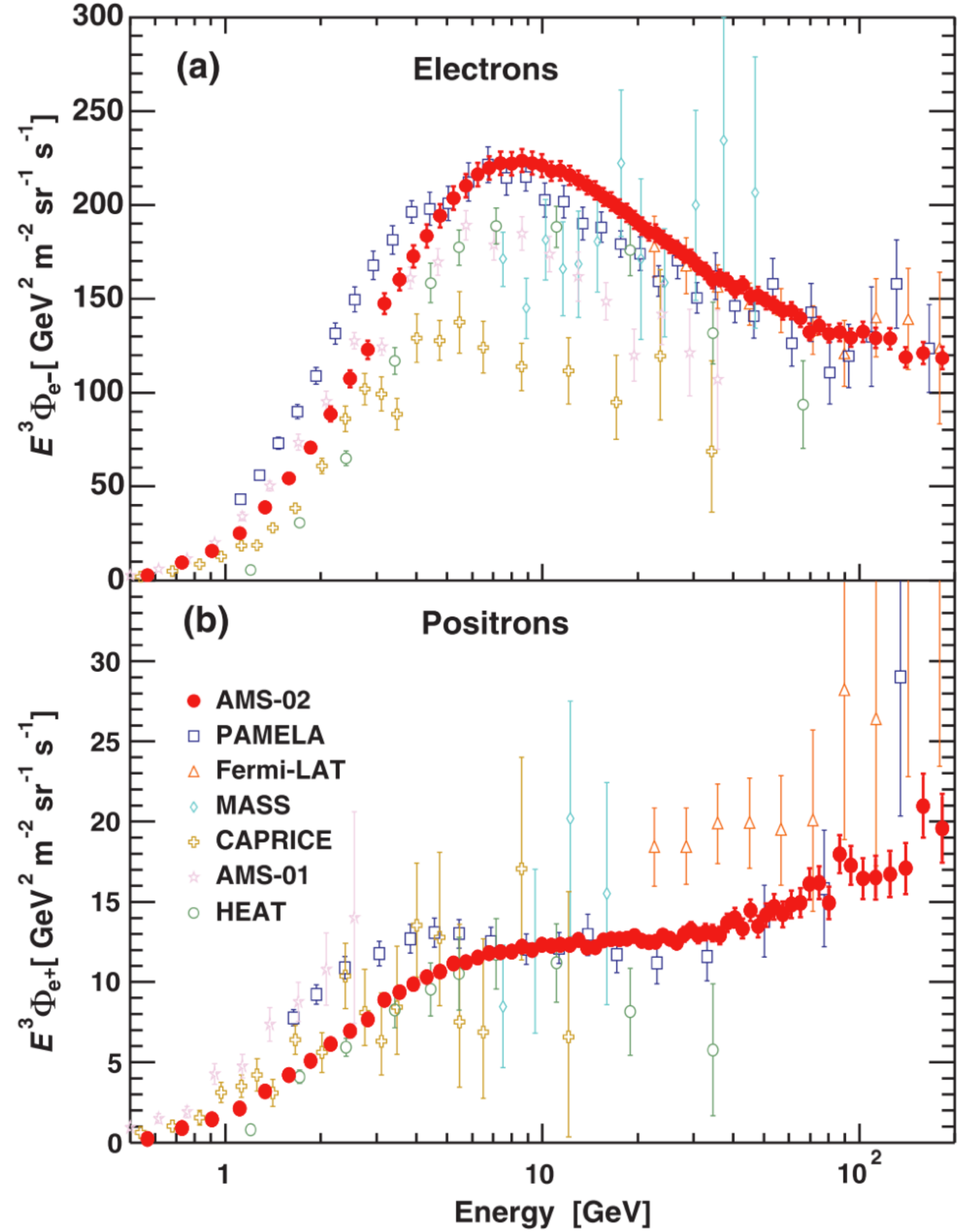

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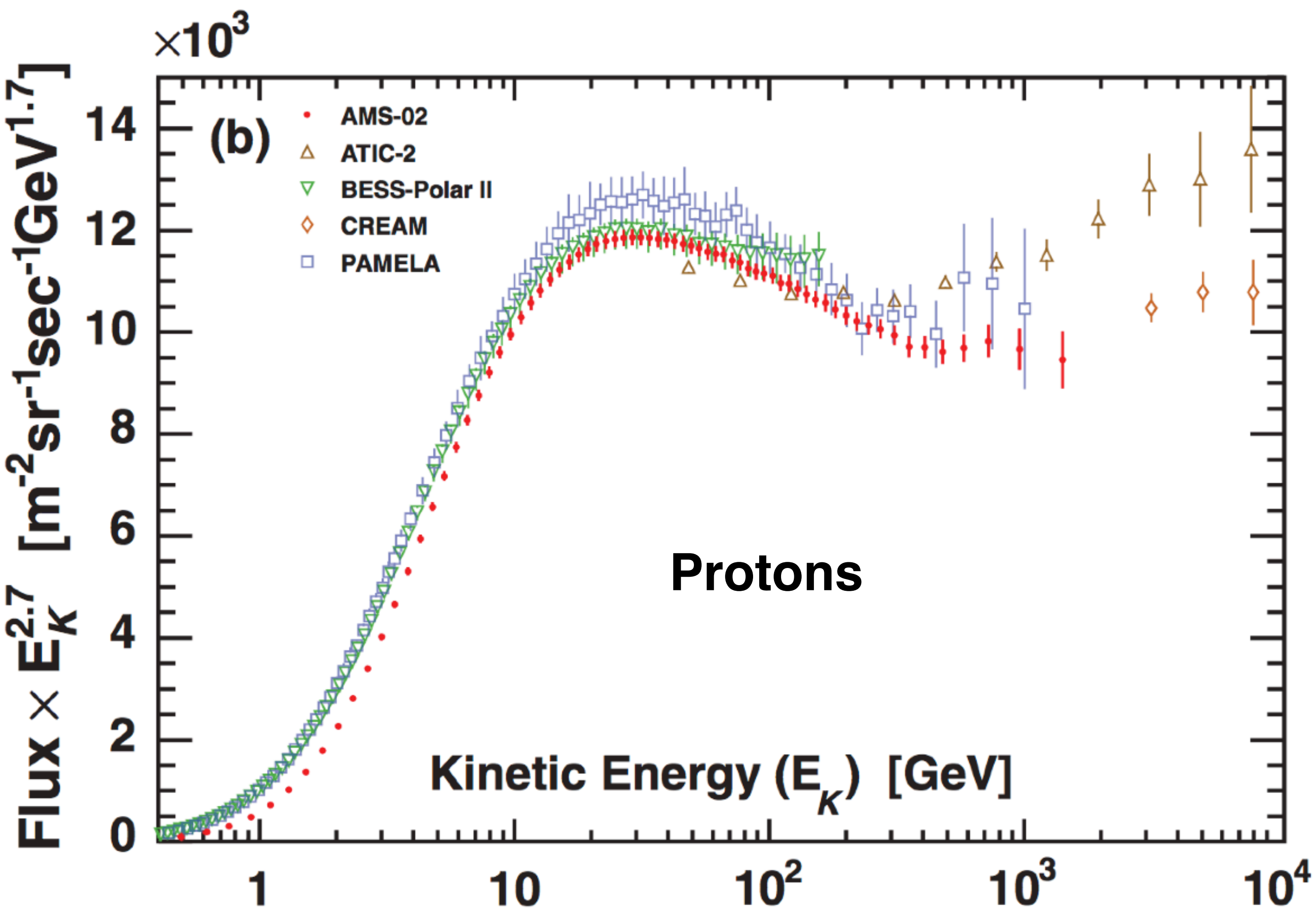

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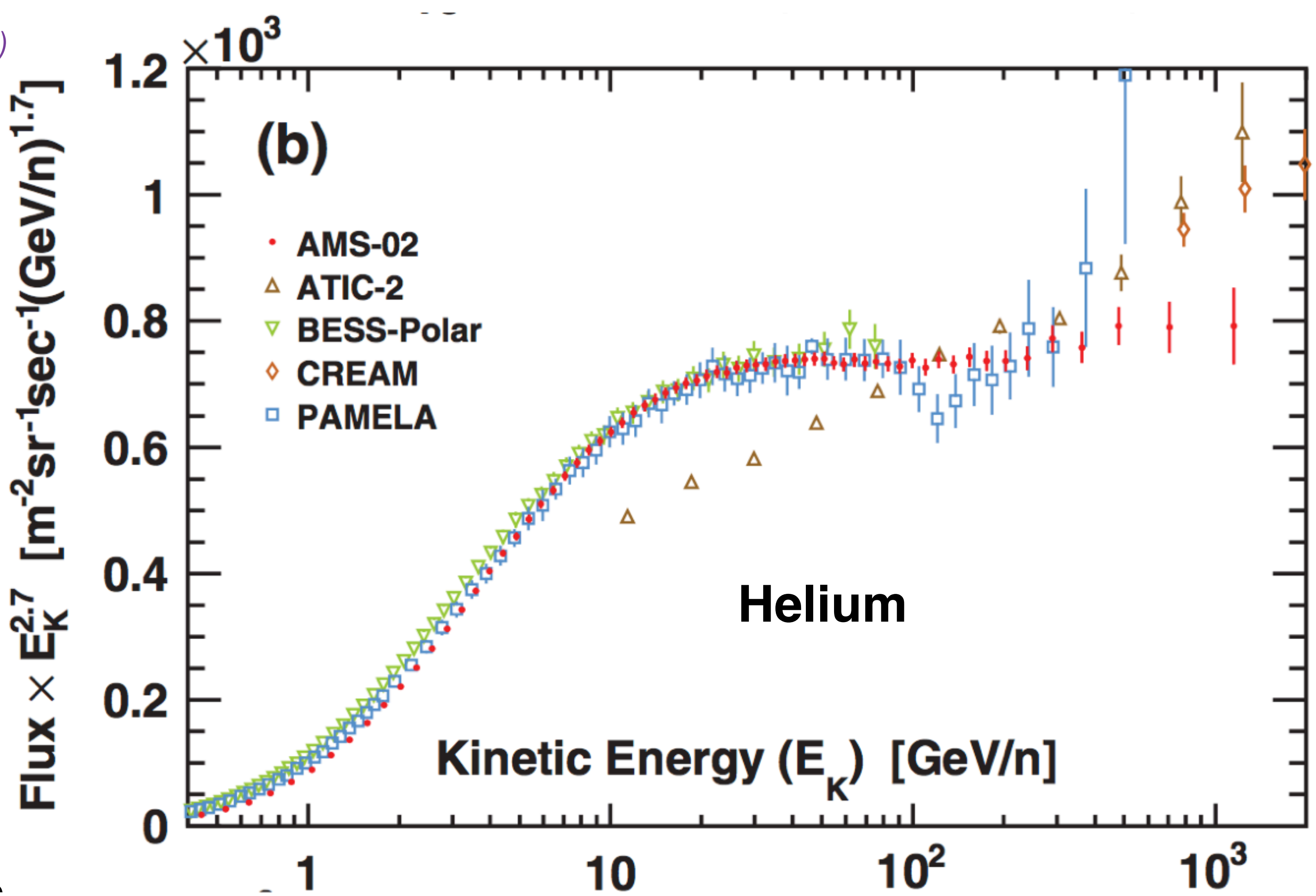

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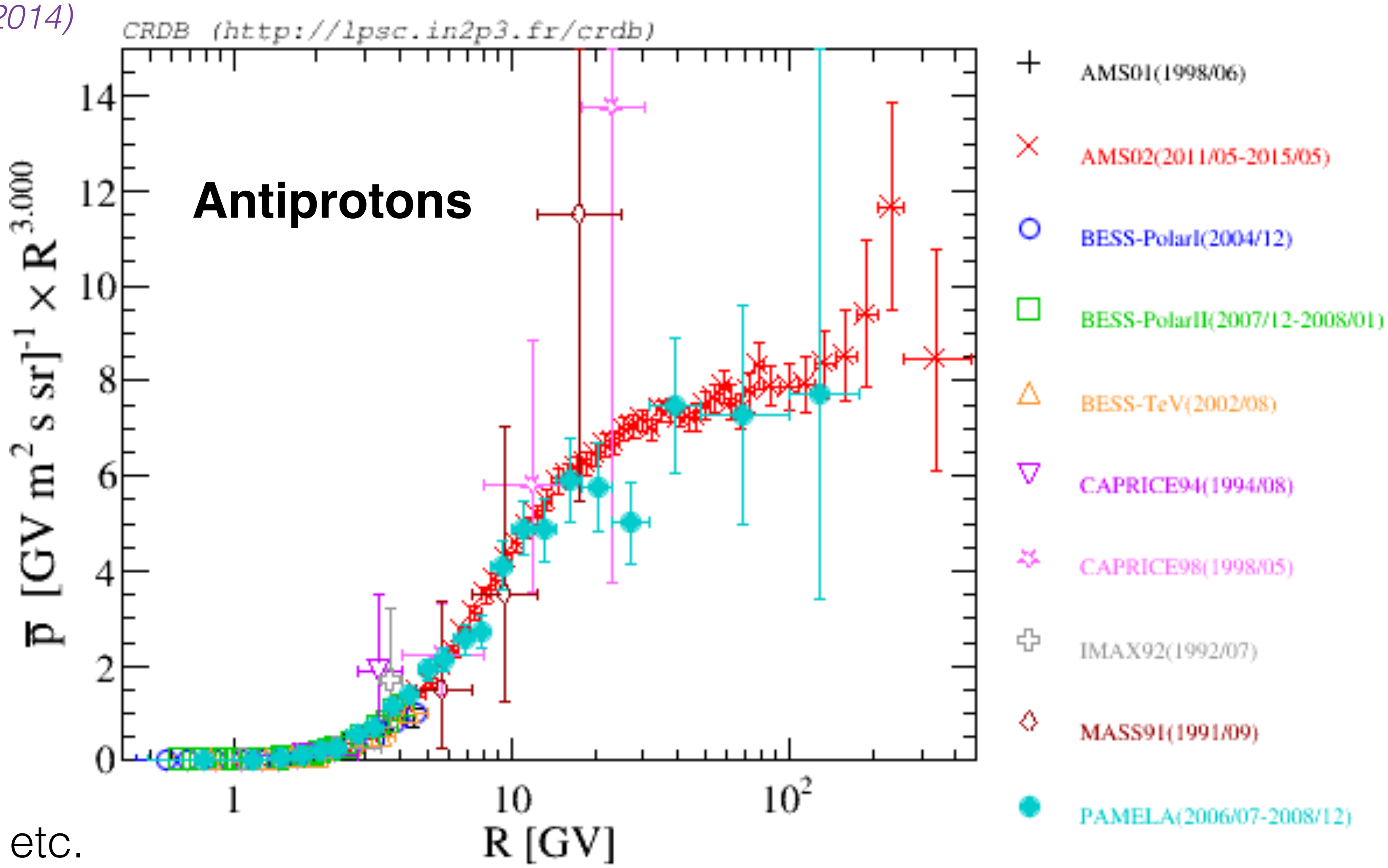

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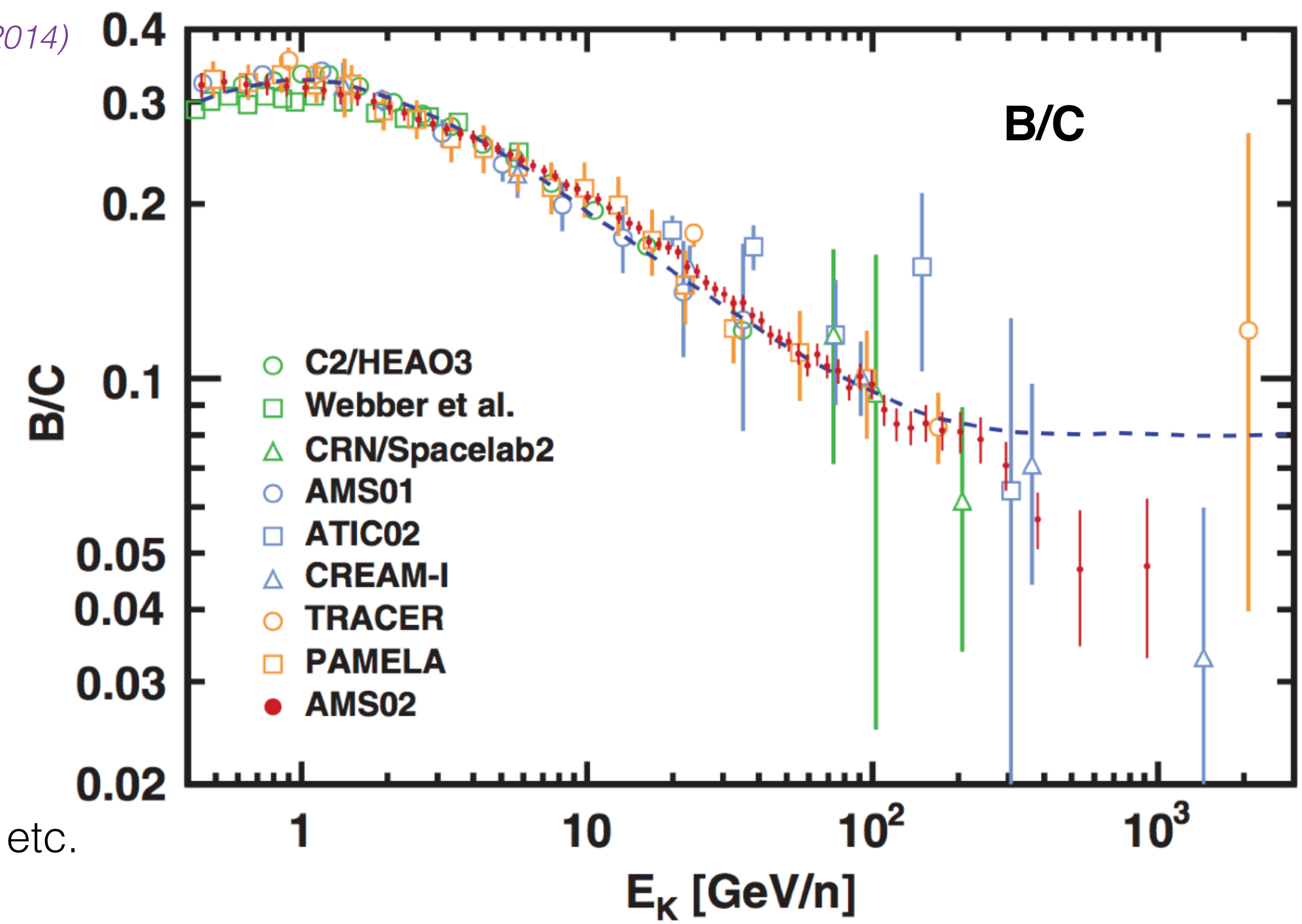

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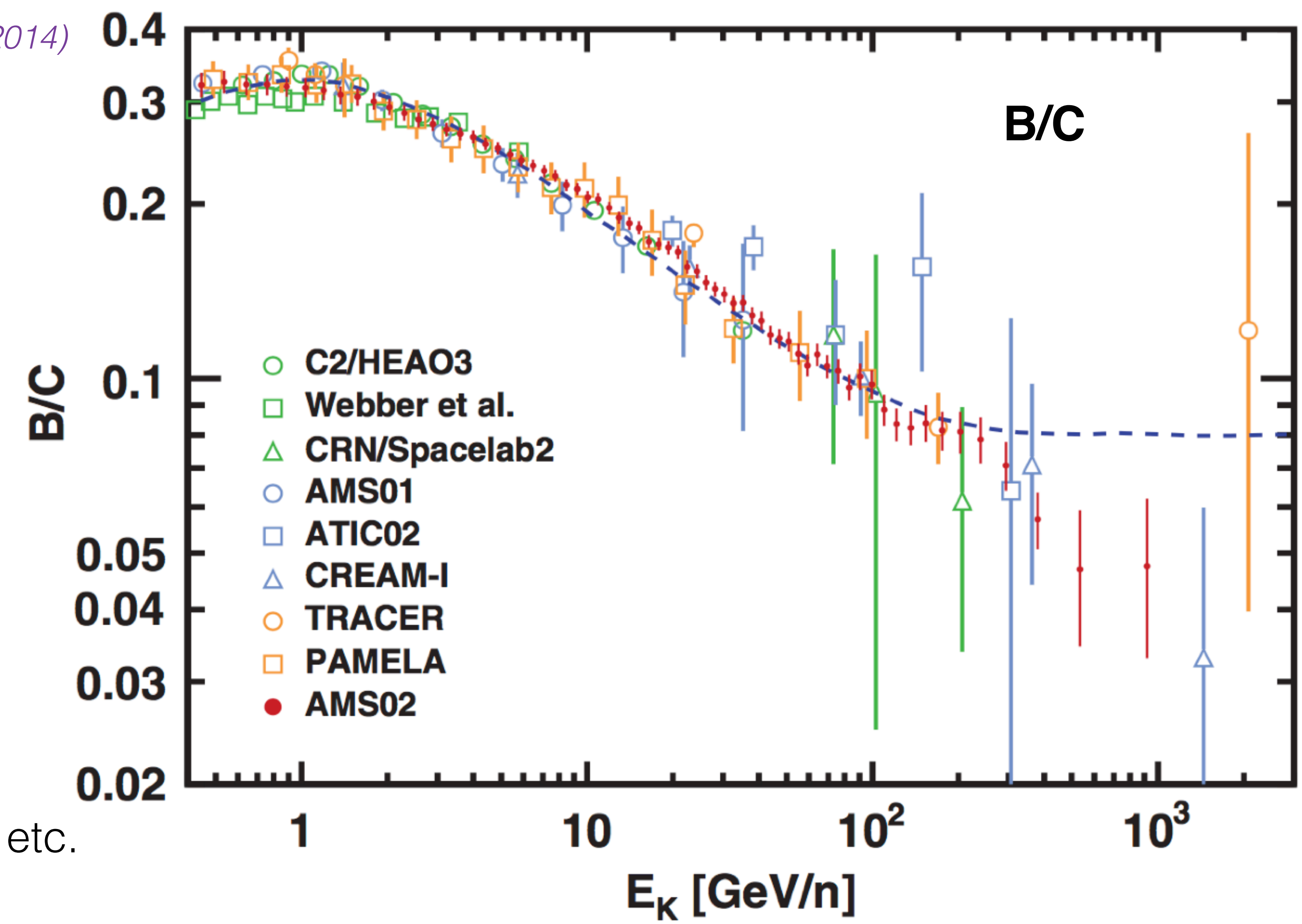
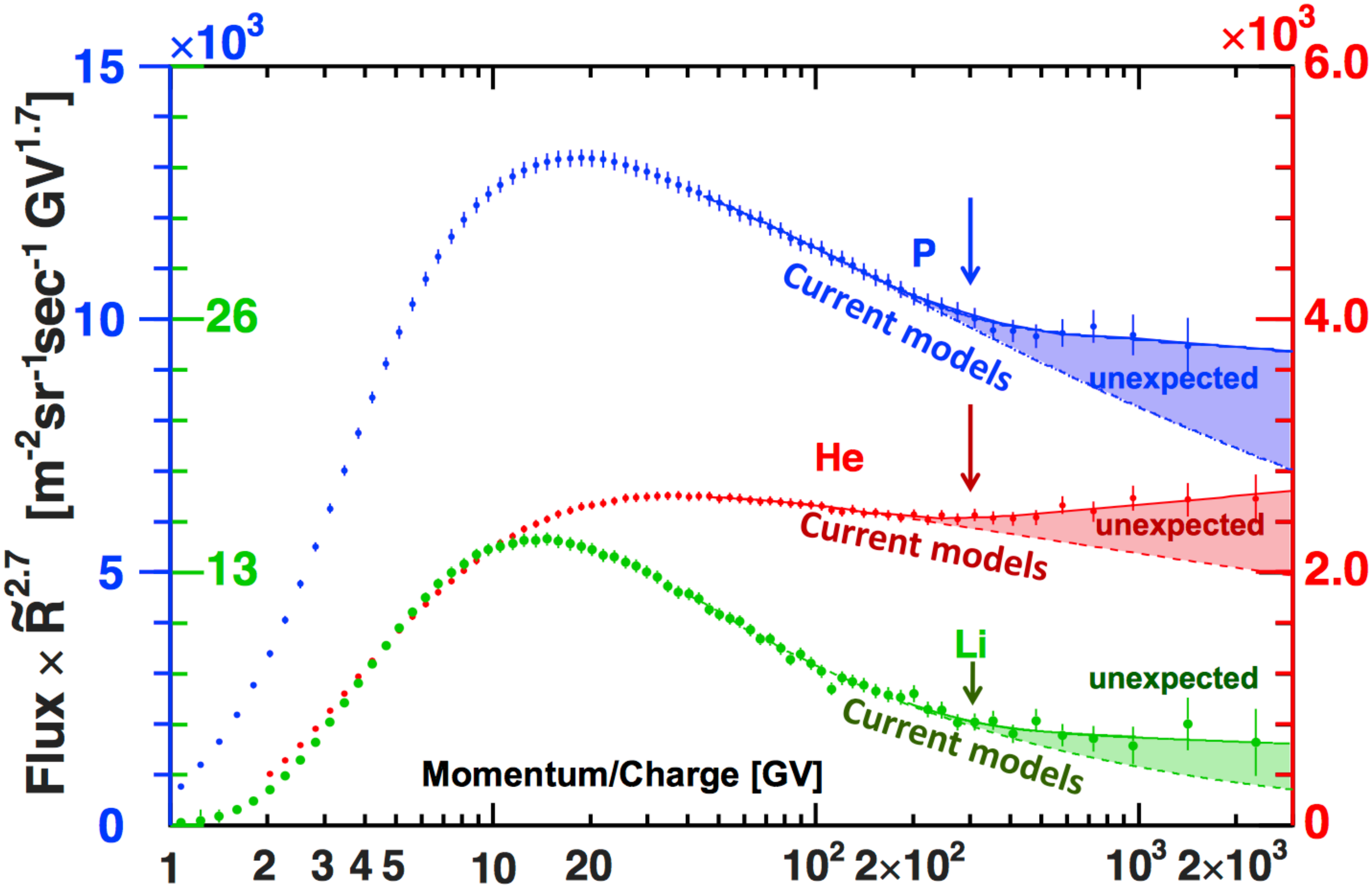


AMS-02 is reaching the accuracy to detect unexpected features in cosmic ray data.

A universal break in the spectra of cosmic ray nuclei?

Pointed by PAMELA and confirmed by AMS-02: an universal kink at R~200 GV?

$\Delta_{kinck} \sim 0.12 - 0.13$



This feature was not predicted by the conventional propagation models!

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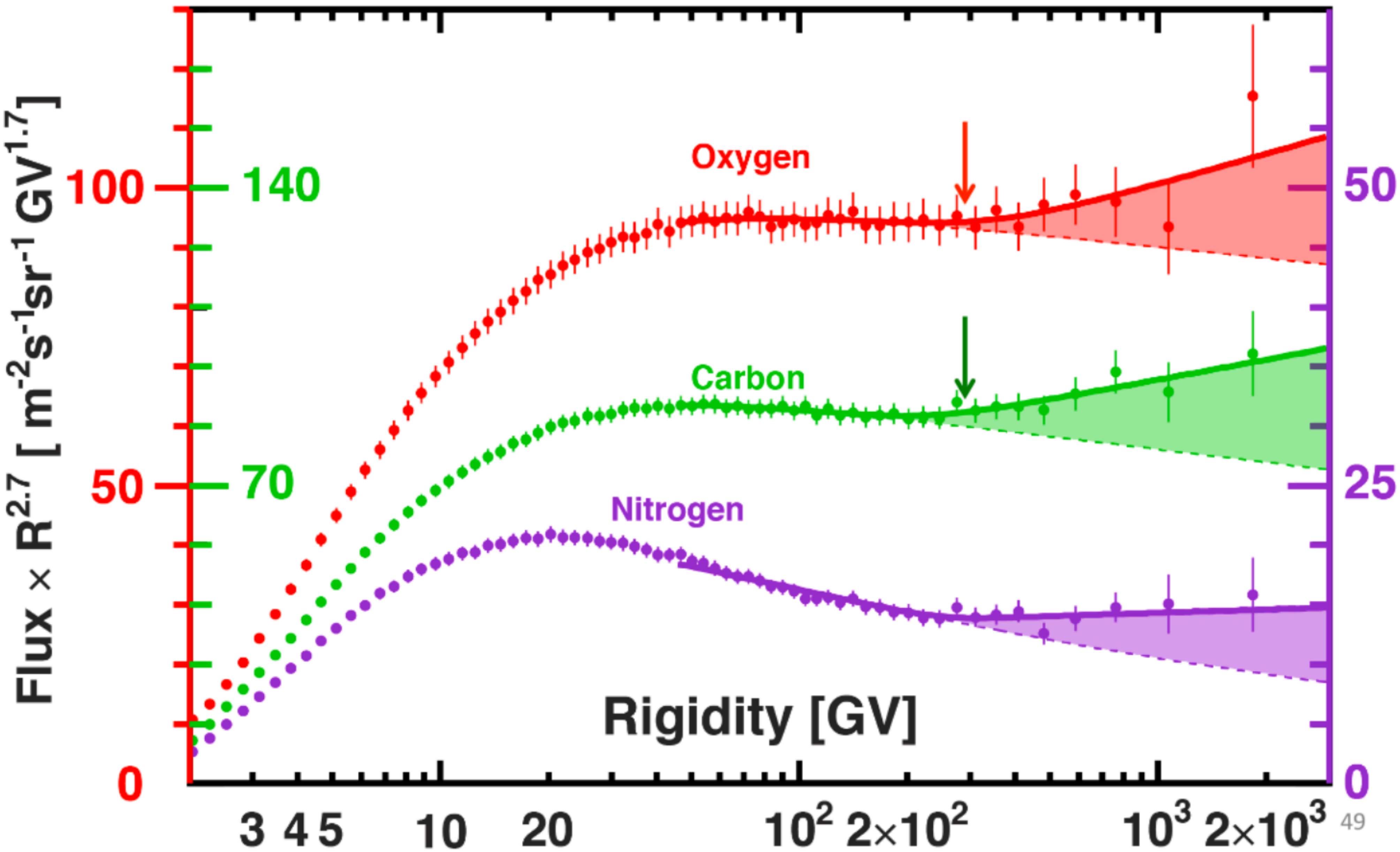


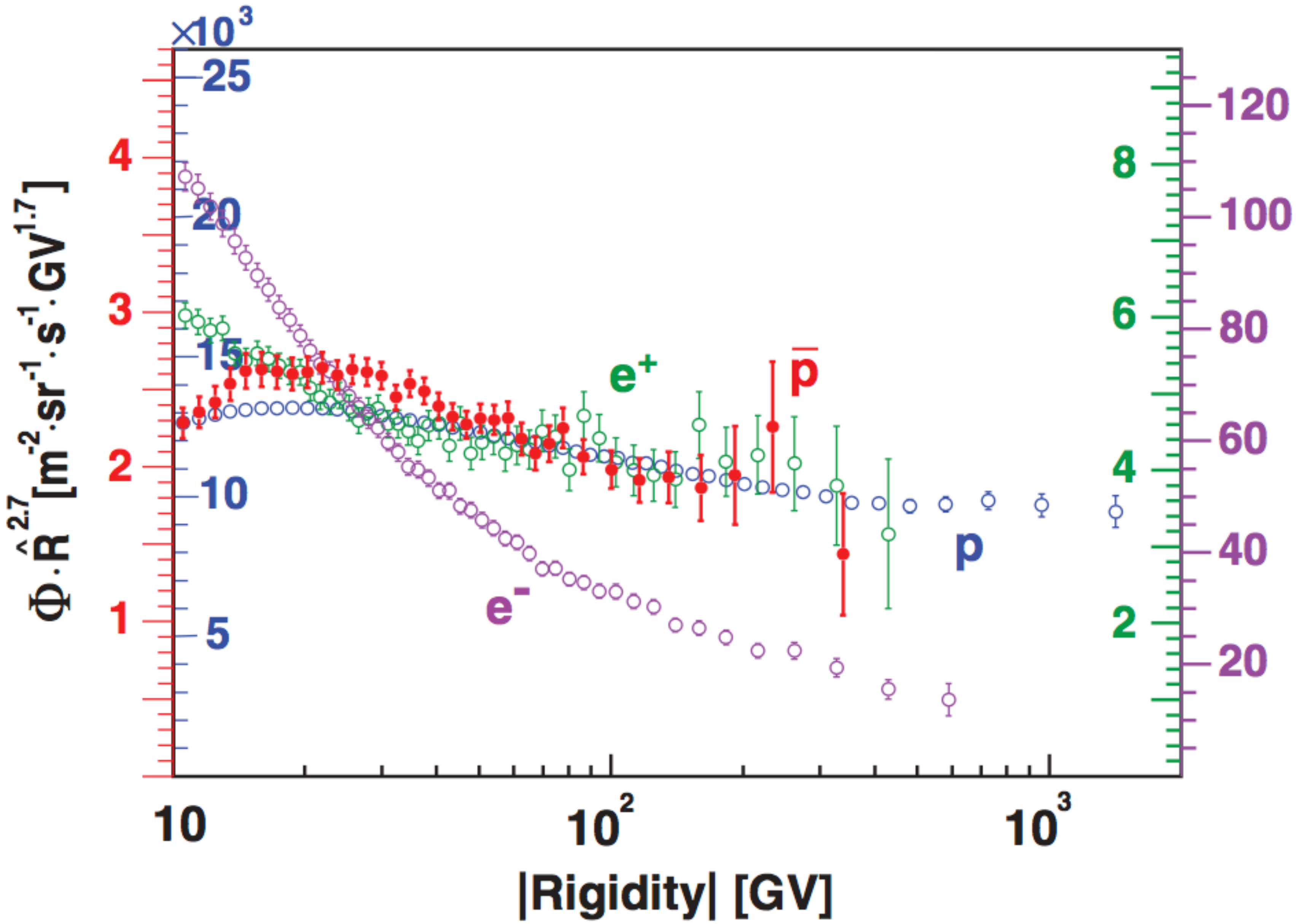
This feature was not predicted by the conventional propagation models!

Same spectral index for p, He, $\bar{p}$, and positrons

Cosmic ray nuclei and leptons (e^- and e^+) do not undergo the same propagation processes.

Electrons and positrons lose energy through:

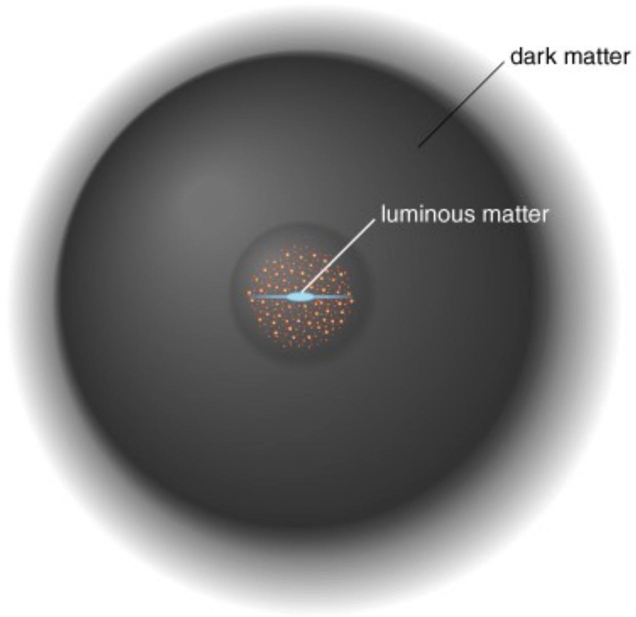
- Synchrotron emission (Galactic magnetic field)
- IC scattering on the interstellar radiation field

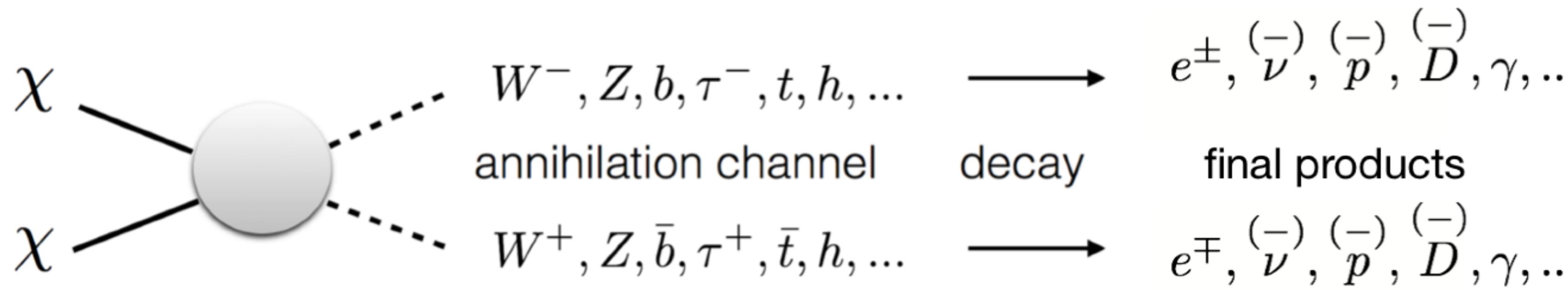


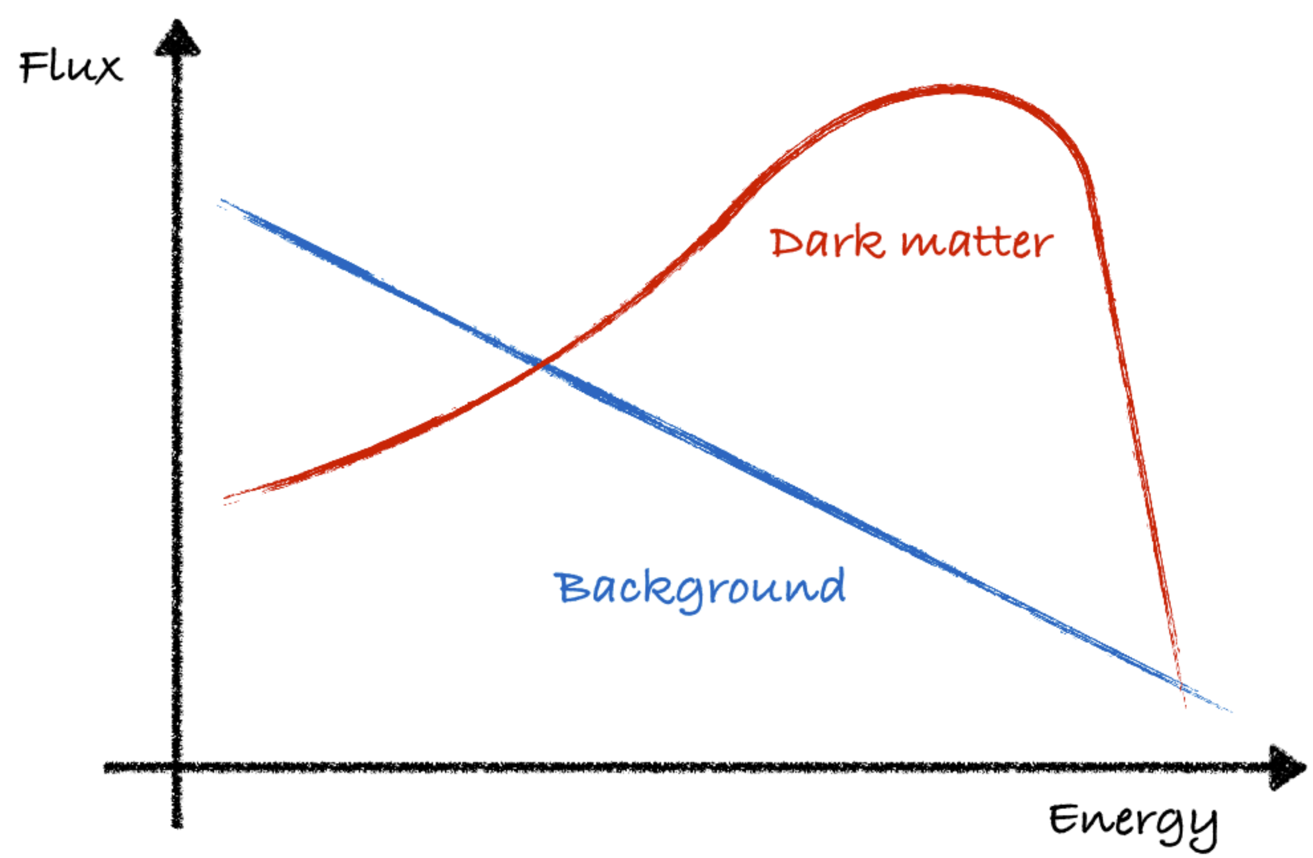
Why the spectral index of positrons is so close to the proton and antiproton ones?

Dark Matter indirect searches

See Marco's talk on Mon. at 11.45







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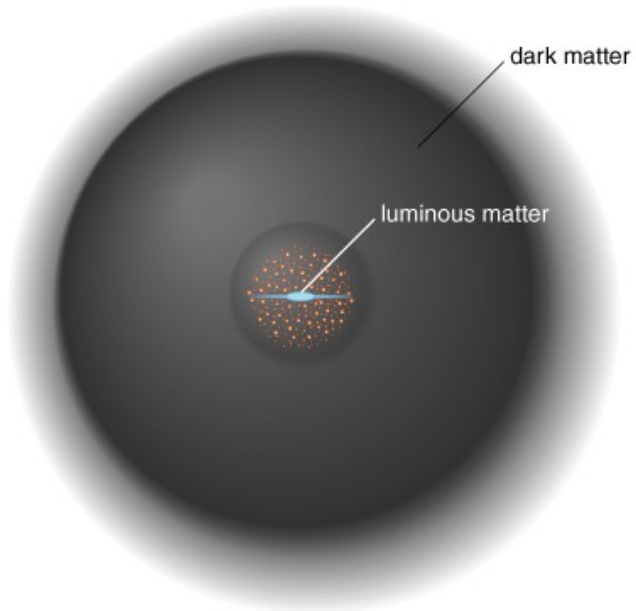

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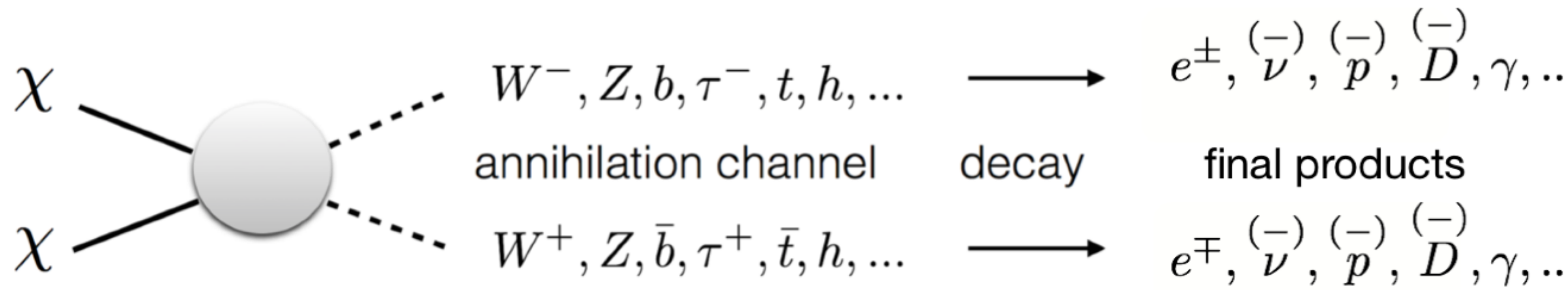
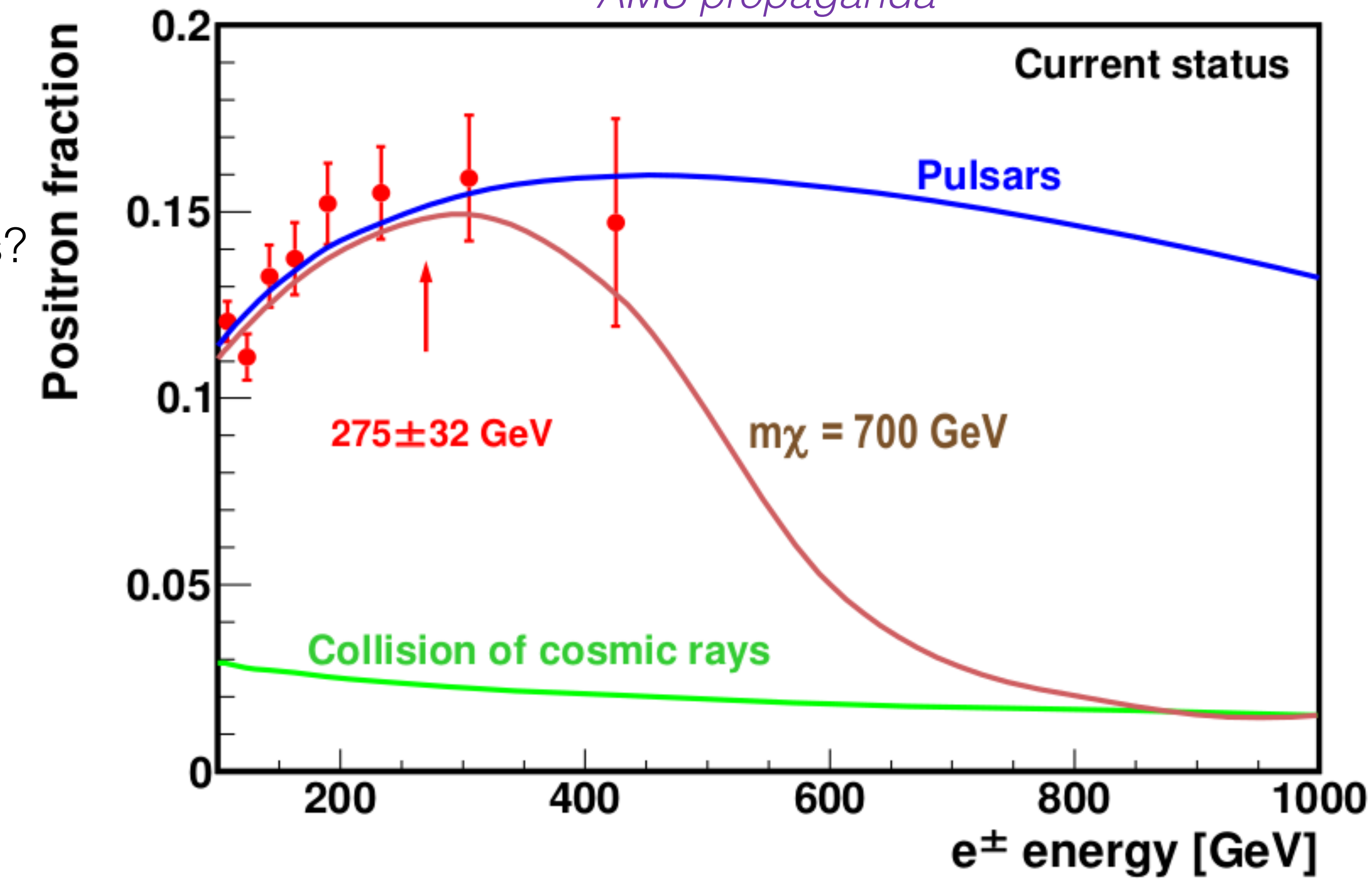


- Where do come from the positron excess?

AMS propaganda



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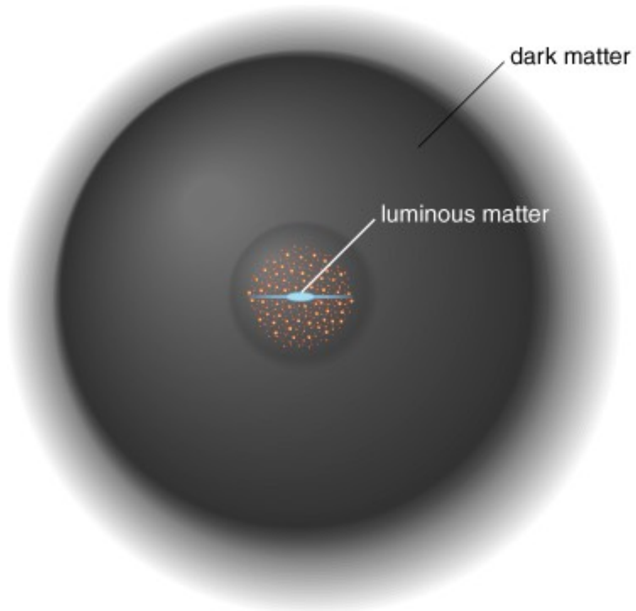

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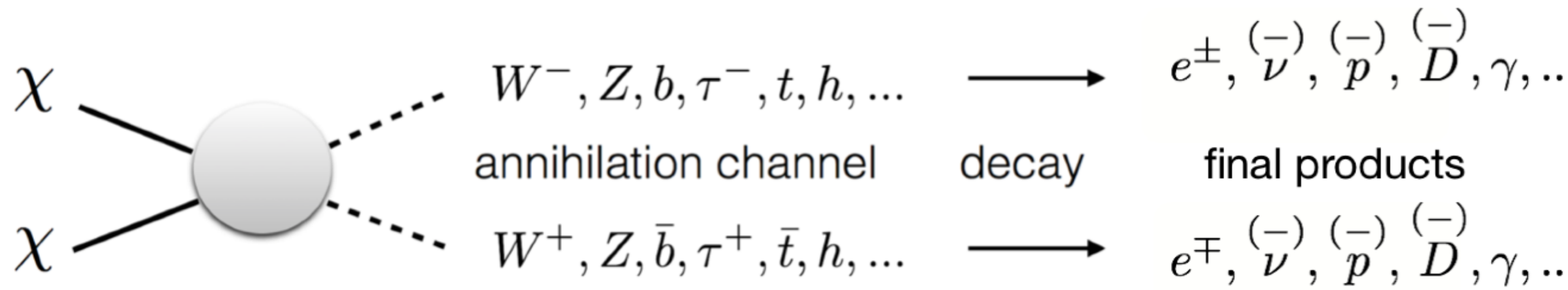

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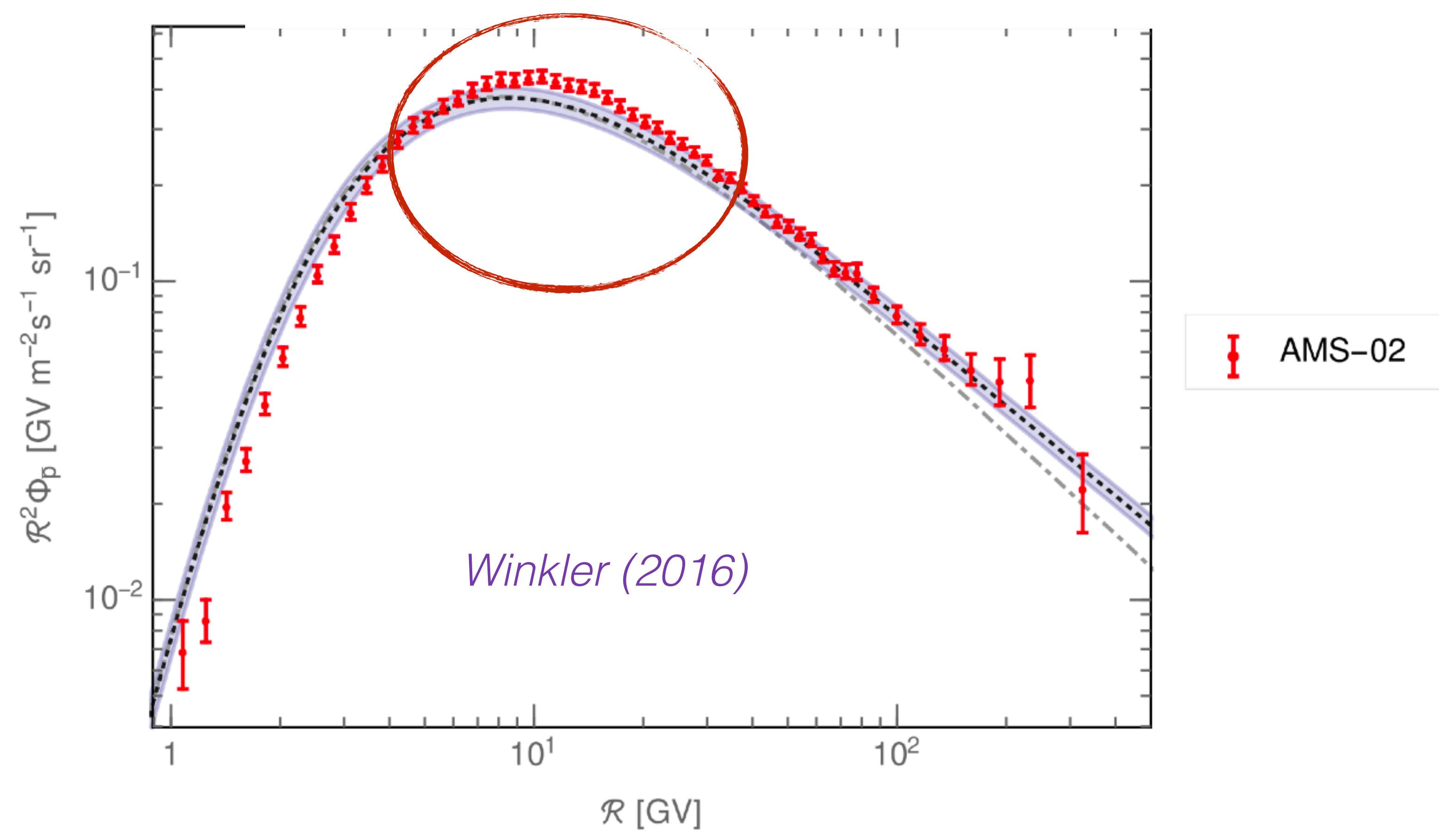
- Is there an excess in the antiproton flux?



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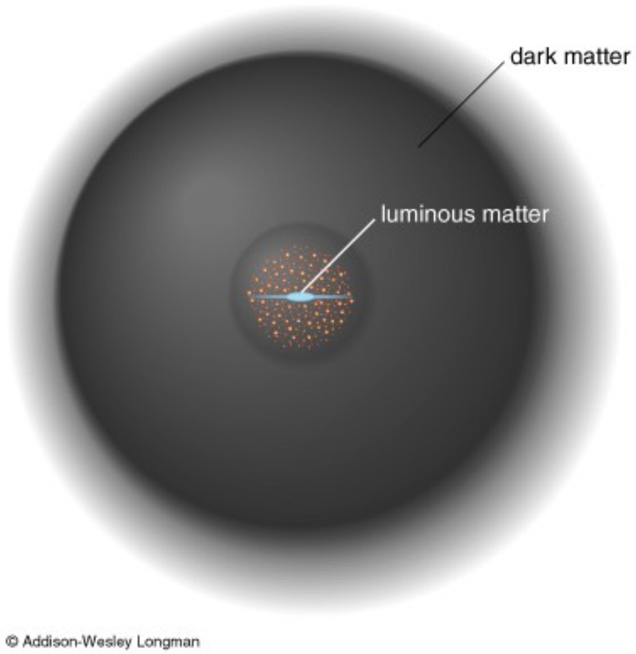

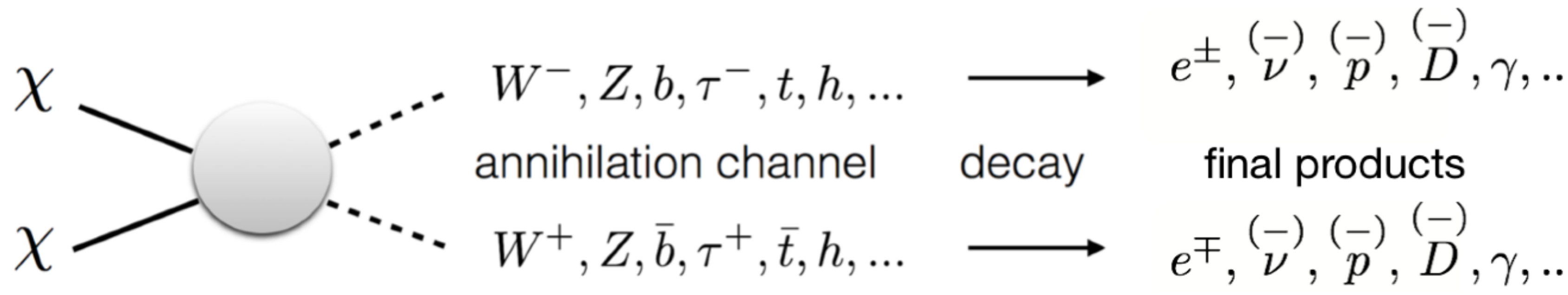

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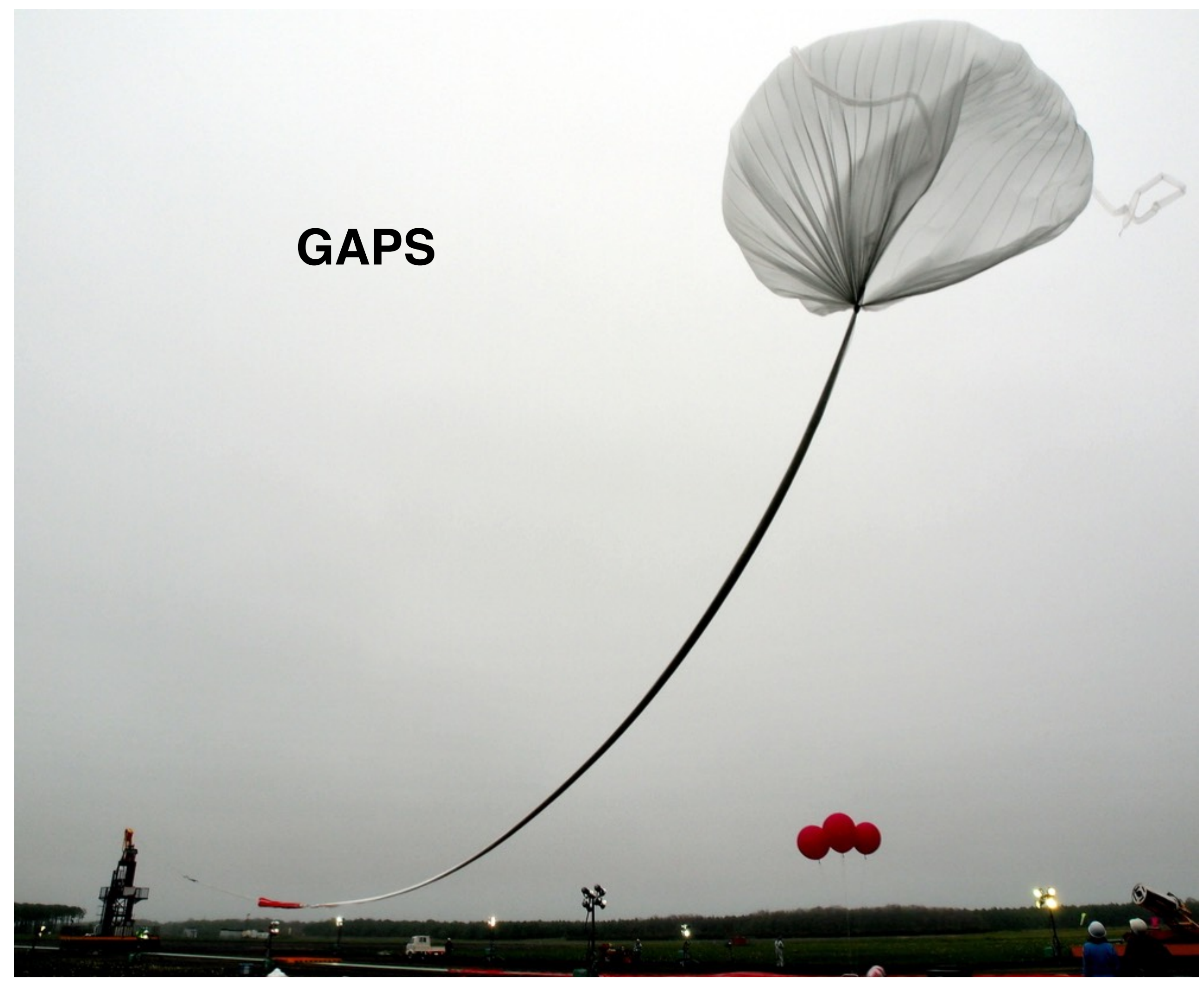

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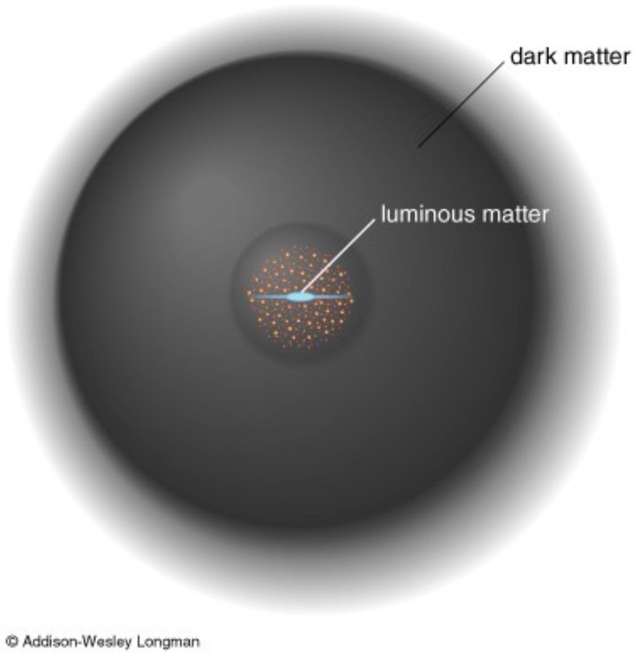

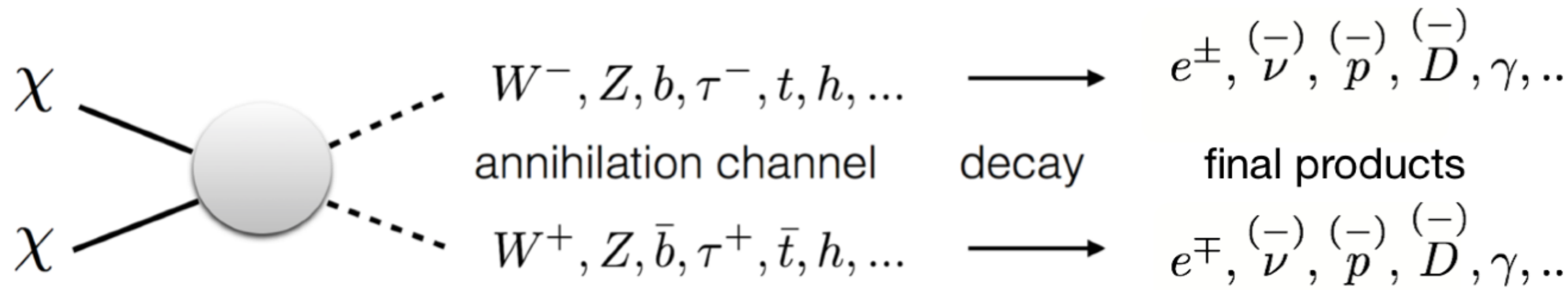

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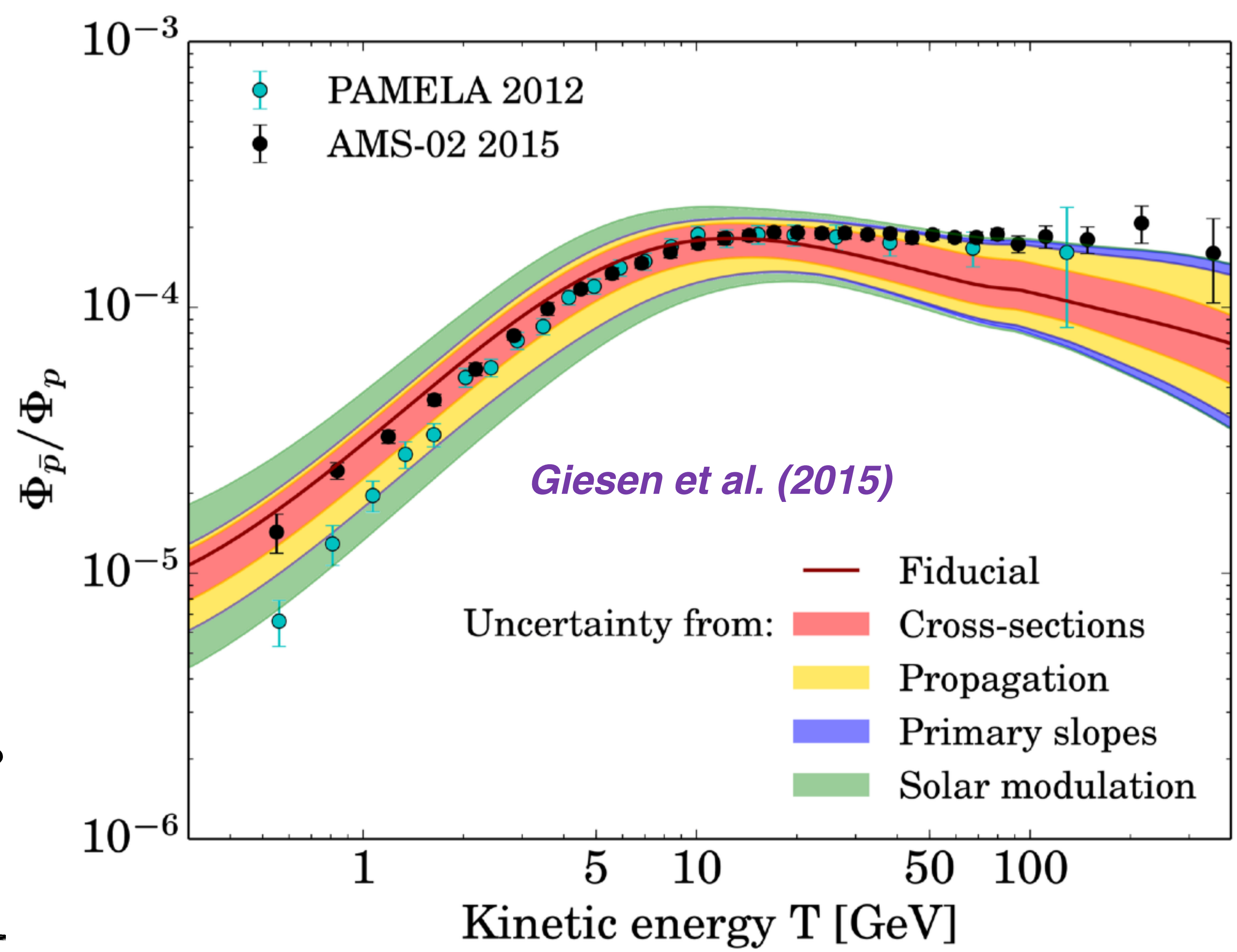
- What about the astrophysical uncertainties?



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Cosmic ray physics

Victor Hess - 1912

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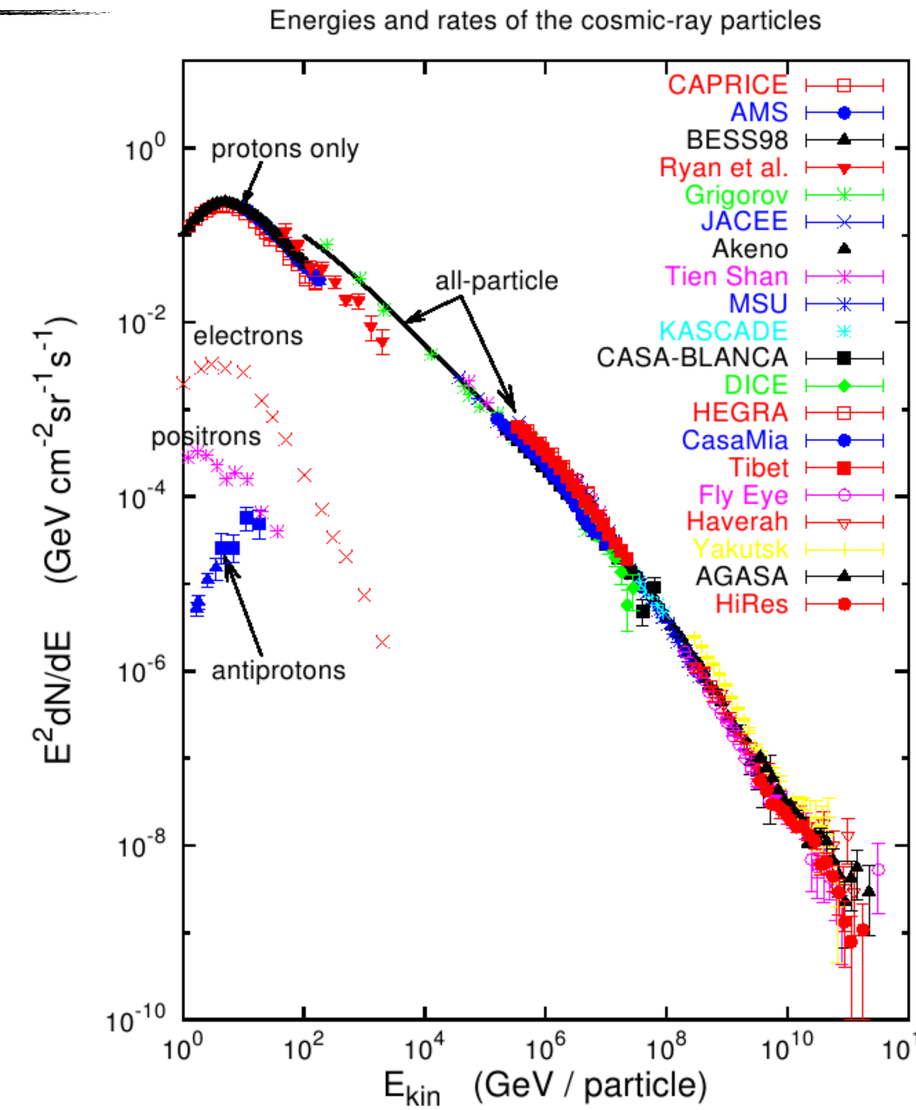

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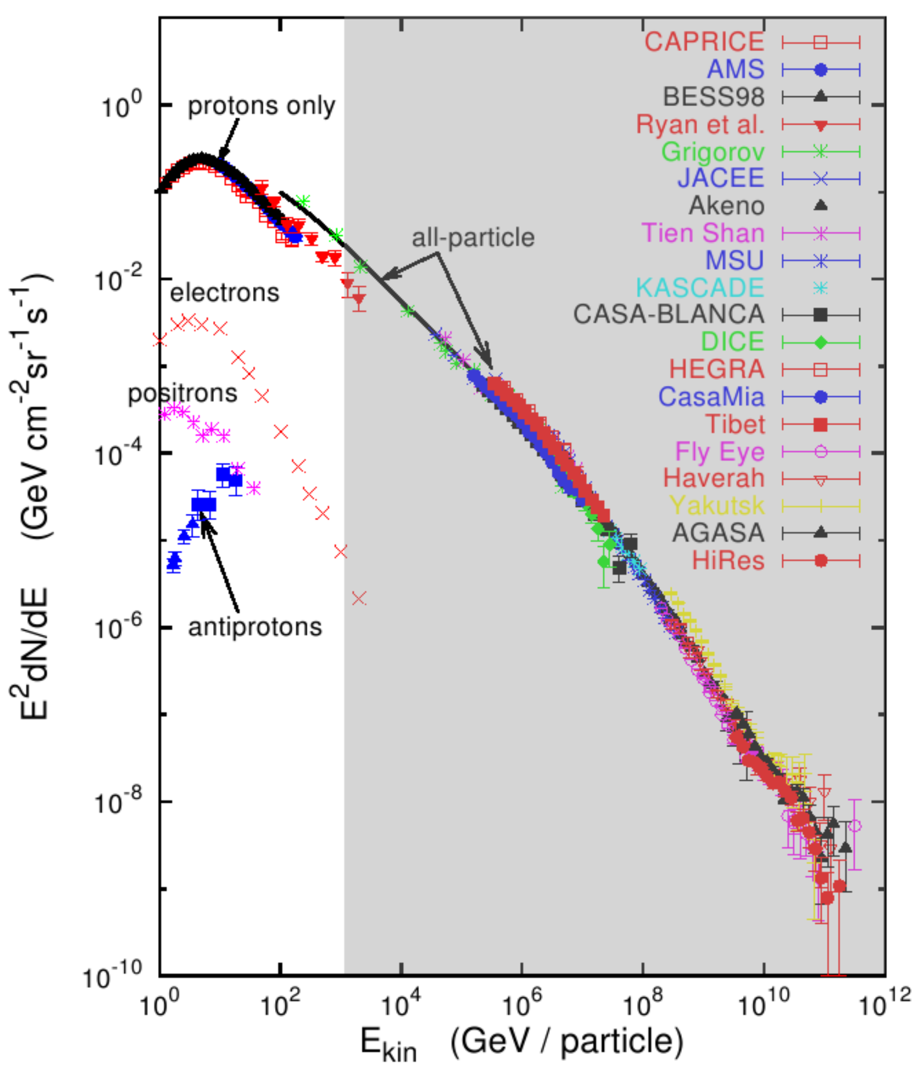

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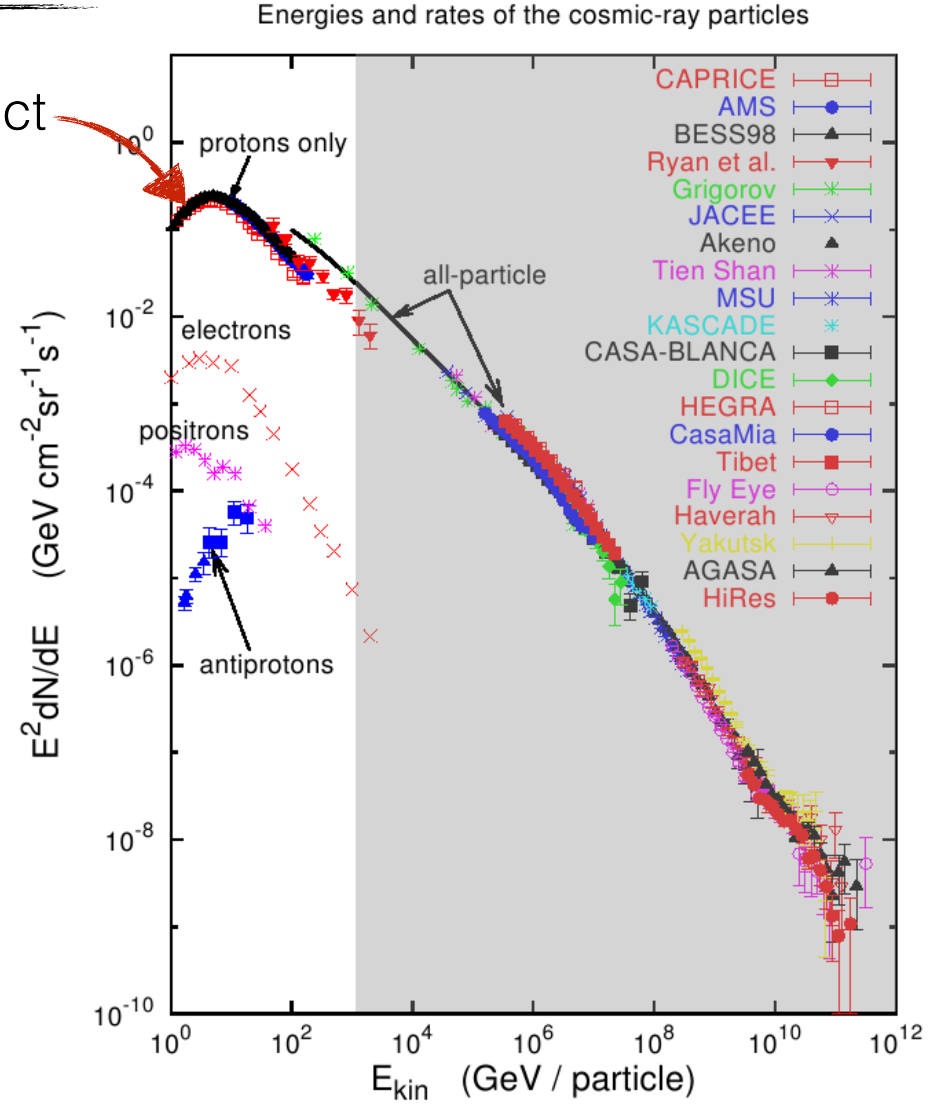

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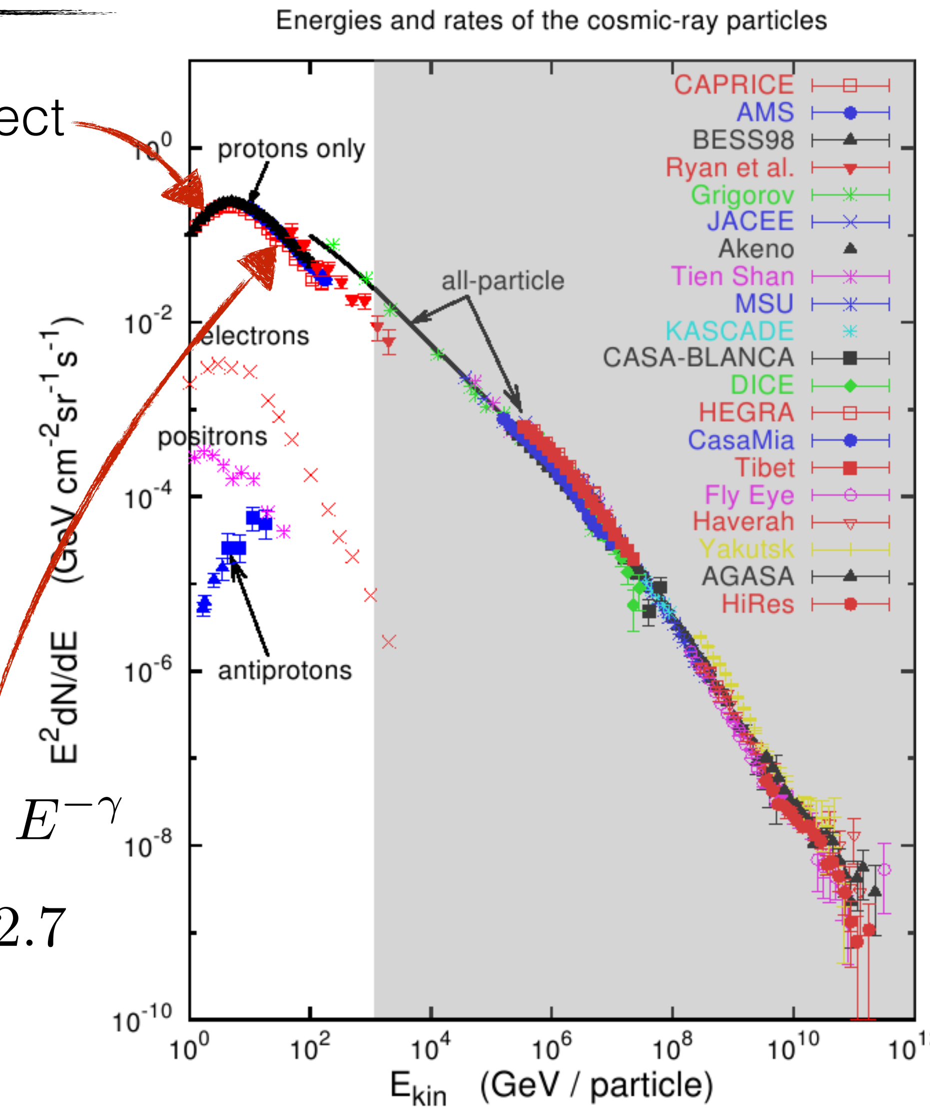
$$\Phi_{\odot}(E) \propto E^{-\gamma}$$

$$\gamma \simeq 2.7$$



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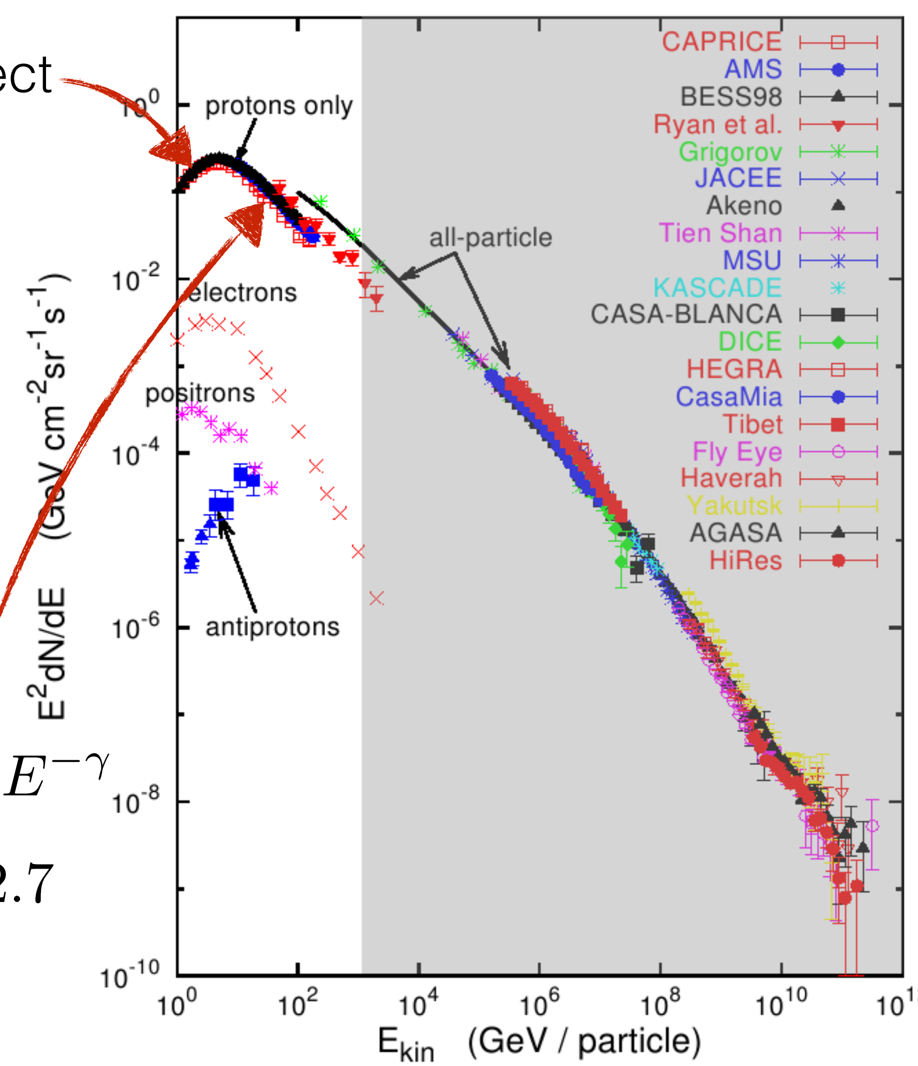
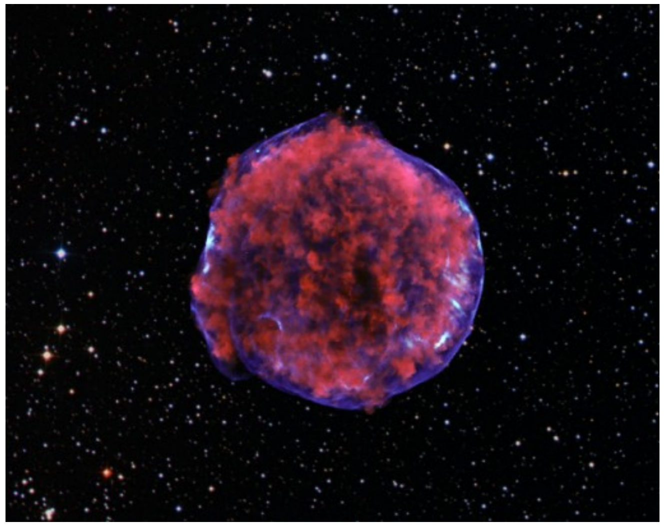


Supernovae remnants (SNR) as accelerators of cosmic rays (CR)



Tycho SNR - Chandra

$$\Phi_{\rm SNR}(E) \propto E^{-\alpha}, \quad \alpha \simeq 2$$

Acceleration by shock wave,
first order Fermi mechanism

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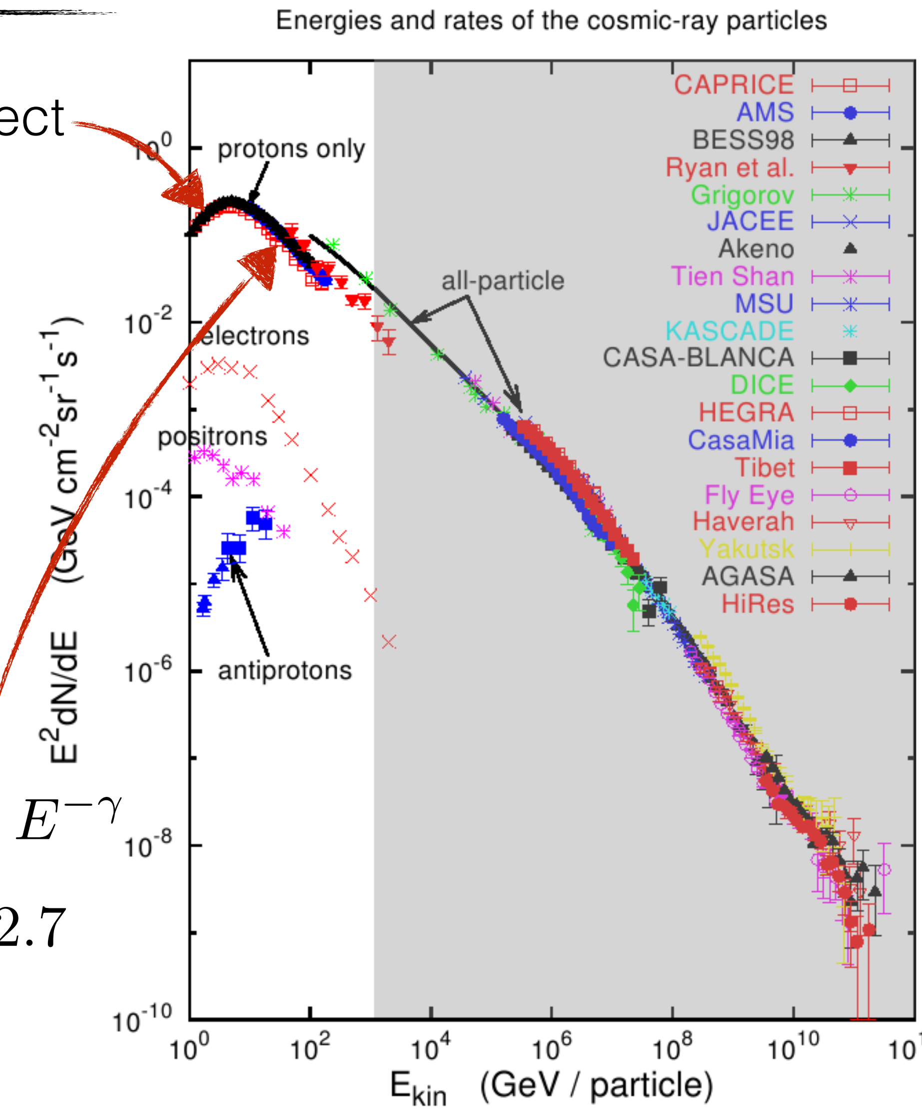

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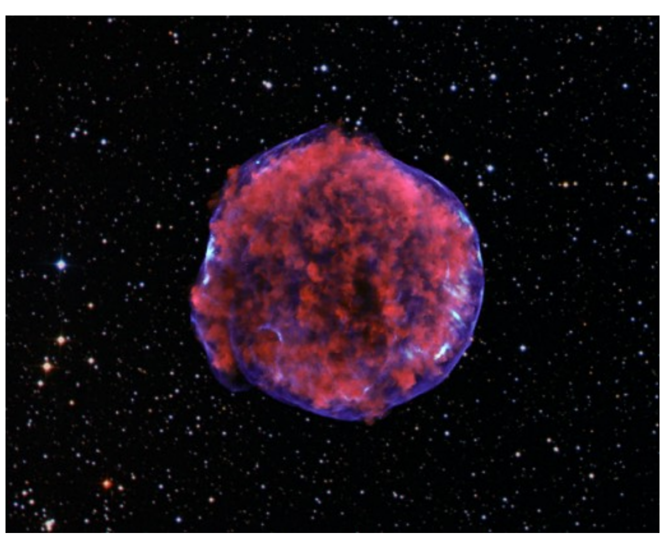

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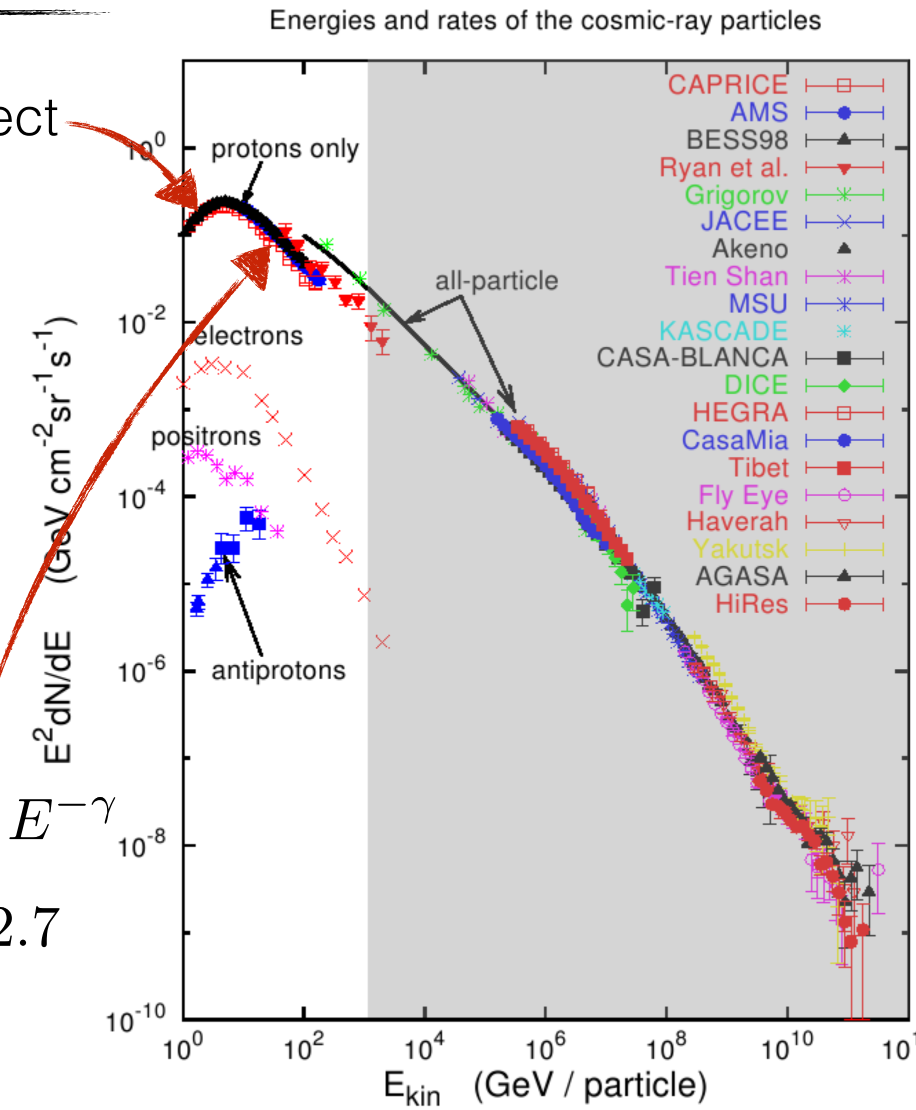

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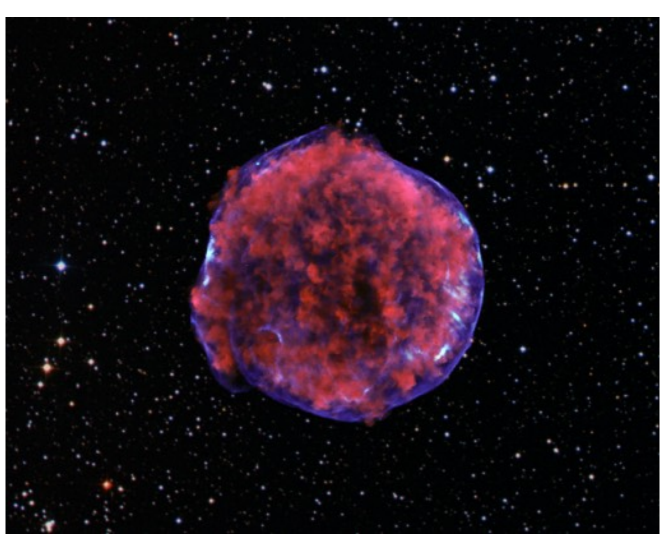

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Propagation in the Galaxy

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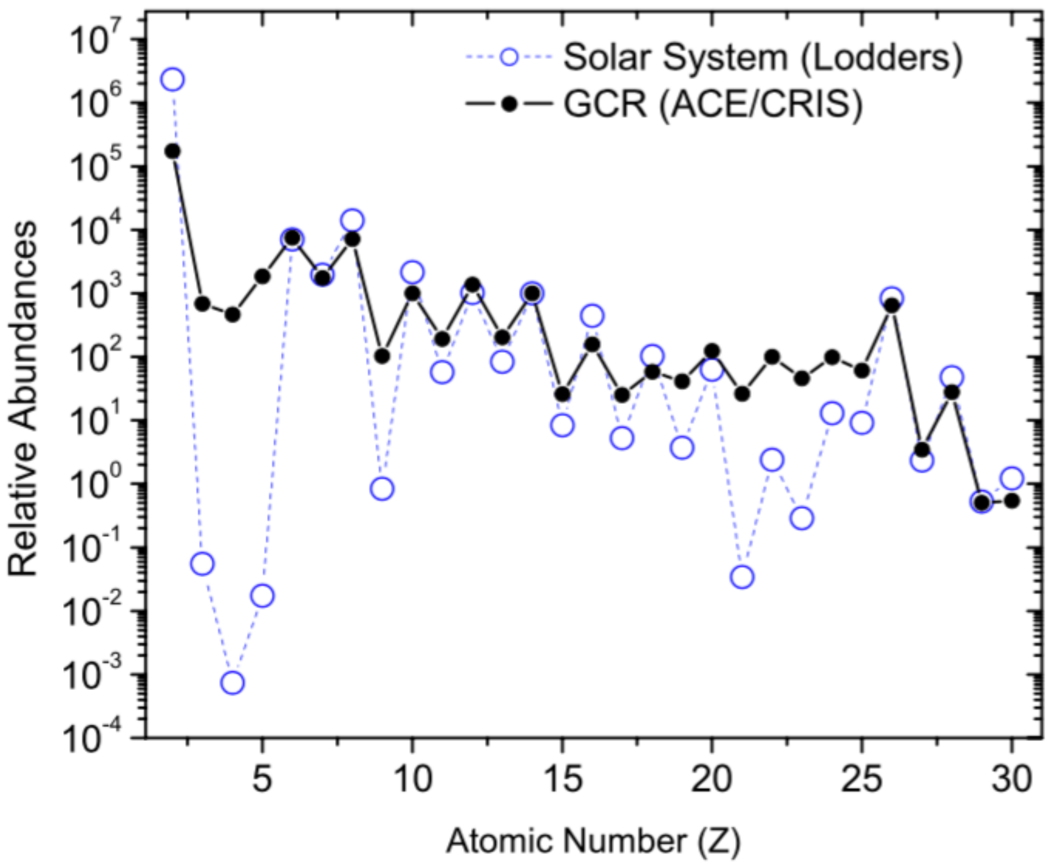
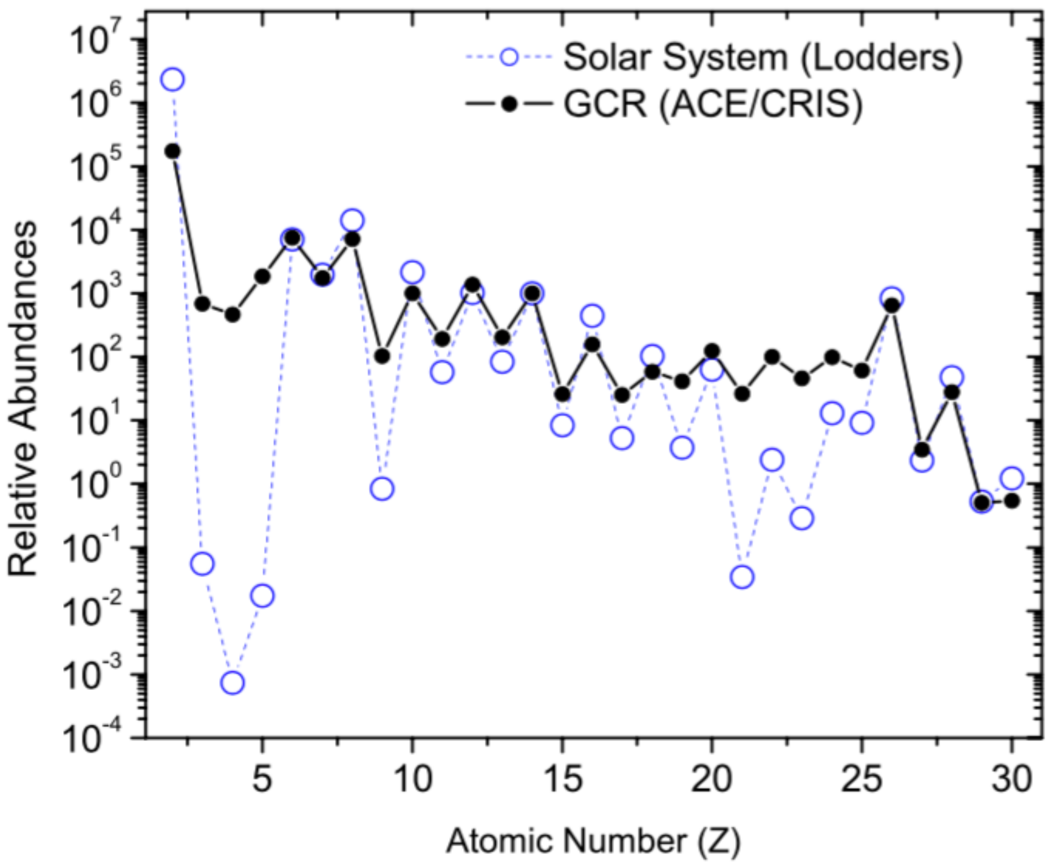


Li-Be-B (3-5) and Sc-Ti-V-Cr-Mn (21-25) are secondary CRs.

$$\mathrm{C}\,(\mathrm{CR}) \;+\; \mathrm{H}\,(\mathrm{ISM}) \;\longrightarrow\; \mathrm{B} \;+\; X$$



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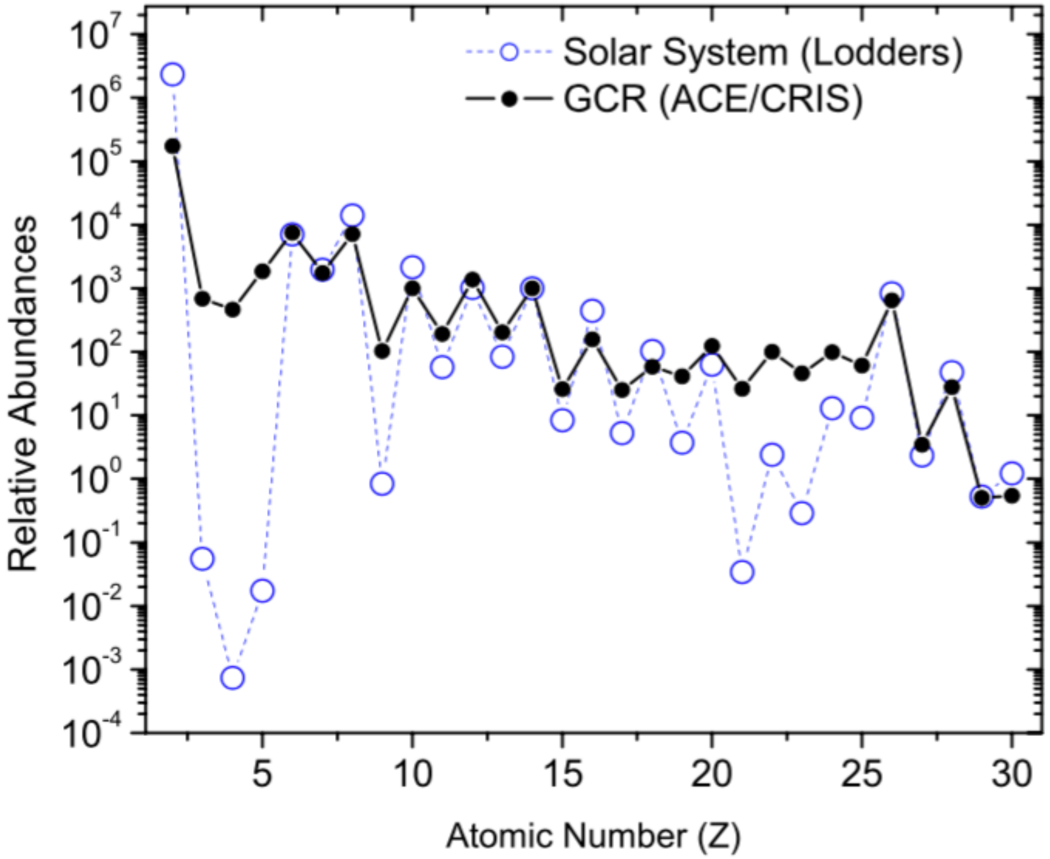
(grammage)



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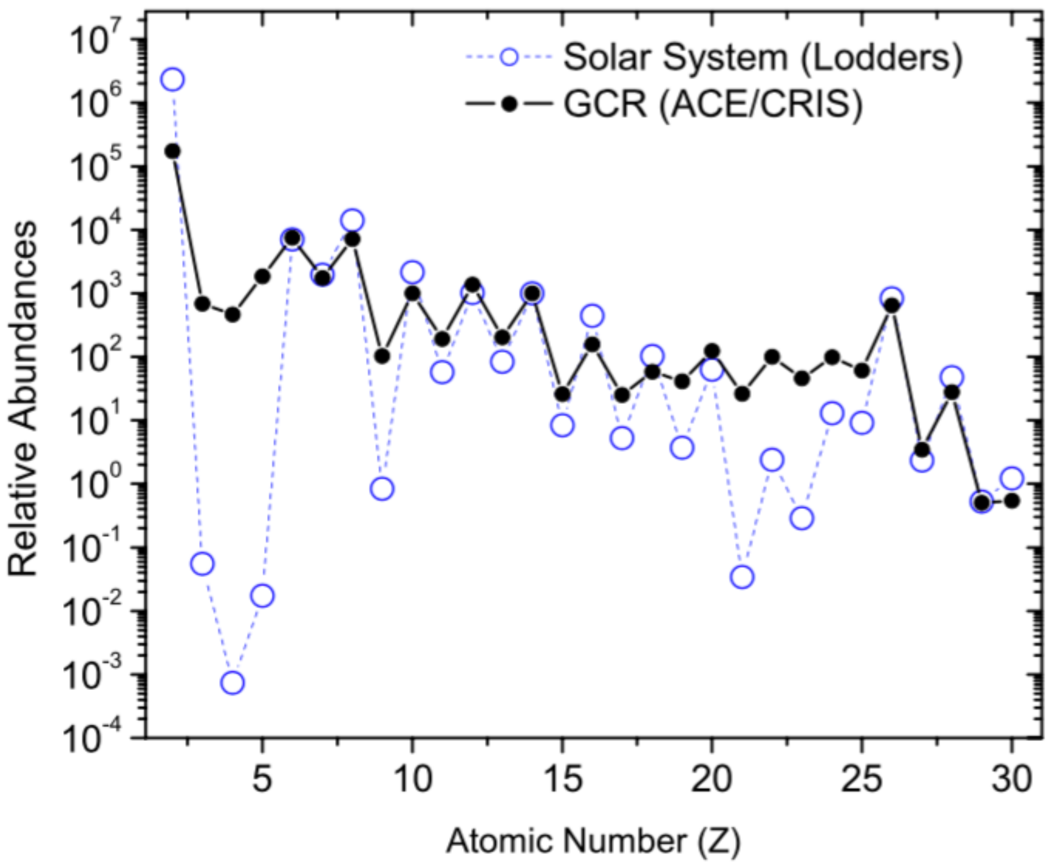
$$\lambda(100\ \mathrm{GeV}) \sim 10\ \mathrm{g\,cm^{-2}}, \quad \tau^{esc} \sim 10\ \mathrm{Myrs} \;\; \neq \tau = \frac{h}{c} \sim 600\ \mathrm{yrs}$$

Cosmic rays do not propagate straight ahead.



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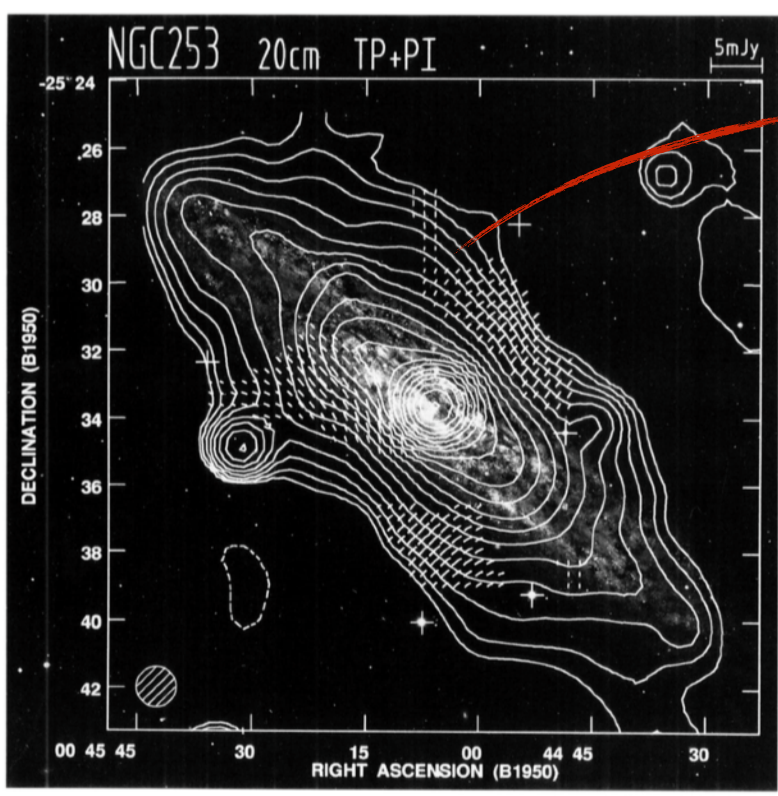


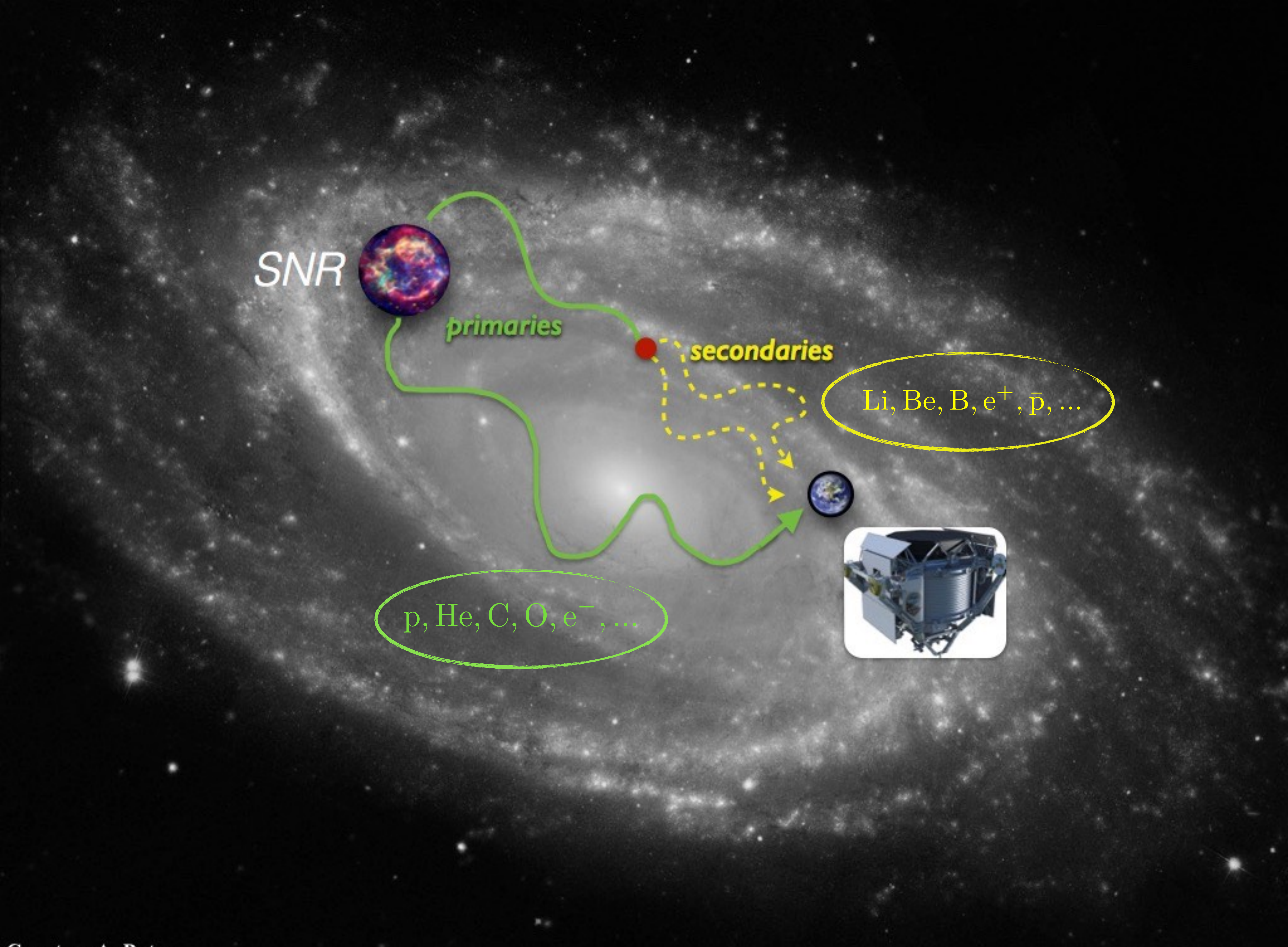
Galaxy NGC-253

Synchrotron radio emission.

Cosmic ray electrons propagate in a spread out region around of the galactic disc.

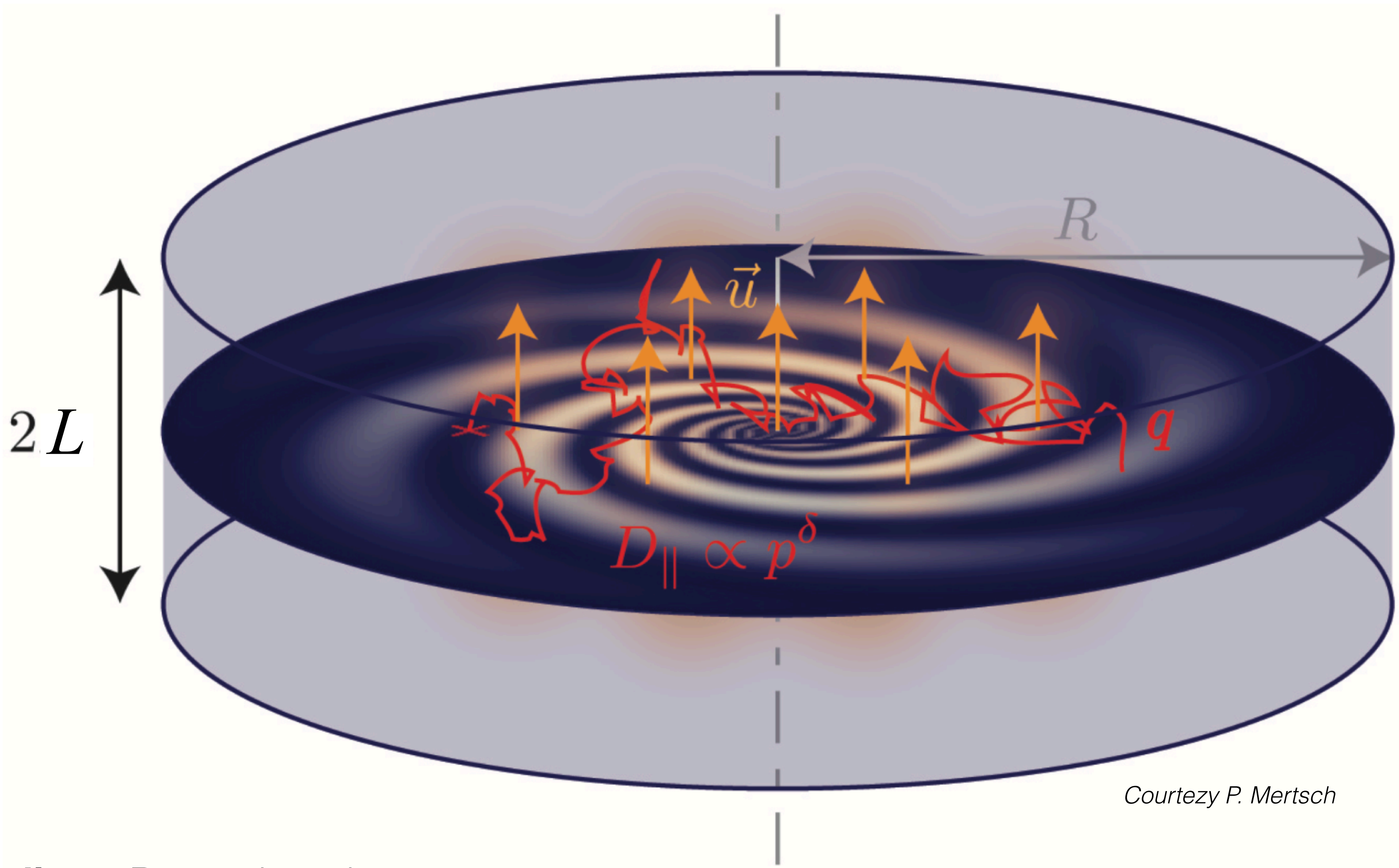
The galactic disc is embedded in a magnetic halo with the height *L* ~ kpc.

The magnetic field explains why CRs are confined in the Galaxy during Myrs.



Courtesy A. Putze

The two-zone diffusion model



The galactic disc - *R ~ 20 kpc, h ~ 100 pc*

Contains the gaz, the stars and the dust of the Galaxy. Distributed in the spiral arms.
Cosmic rays are accelerated in the galactic disc.

The magnetic halo - *R ~ 20 kpc, 1 ≲ L ≲ 20 kpc*

The diffusion zone of the model. Cosmic rays that escape the magnetic halo cannot go back.

Interaction of cosmic rays

- **Space diffusion**

  Diffusion on the turbulent component of the magnetic field. $K(E, \vec{x})$

- **Convection**

  Galactic wind due to supernovae explosions in the galactic disc. $\vec{V}_C(\vec{x})$

- **Destruction** $Q^{sink}(E, \vec{x})$
  - Interaction with the interstellar medium (ISM)
  - Decay

- **Energy losses**
  - Interaction with the ISM (Coulomb, ionisation, bremsstrahlung, adiabatic expansion) $b(E, \vec{x})$
  - Synchrotron emission, inverse Compton scattering (electrons)

- **Diffusive reacceleration**

  Second order Fermi mechanism. Diffusion in momentum space.
  Depends on the velocity of the Alfven waves V_A.

$$D(E, \vec{x}) = \frac{2}{9} V_A^2 \frac{E^2 \beta^4}{K(E, \vec{x})}$$

The transport equation

$$\psi(E,t,\vec{x}) = \frac{\mathrm{d}^4 N}{\mathrm{d}^3 x \, \mathrm{d}E}$$

$$\partial_t \psi - K(E,\vec{x})\, \Delta\psi + \vec{\nabla}\cdot[\vec{V}_C(\vec{x})\, \psi] + \partial_E\, [b(E,\vec{x})\, \psi - D(E,\vec{x})\, \partial_E \psi] = Q(E,t,\vec{x})$$

$$Q(E,t,\vec{x}) = Q^{source}(E,t,\vec{x}) - Q^{sink}(E,\vec{x})$$

Production

- Supernova remnants
- Pulsar wind nebula
- Decay of primary CRs
- Spallation of primary CRs
- *Dark matter?*

Destruction

- Spallation
- Decay
- Annihilation

Cosmic rays propagation

$$\partial_t\psi - K(E,\vec{x})\Delta\psi + \vec{\nabla}\cdot\left[\vec{V}_C(\vec{x})\psi\right] + \partial_E\left[b(E,\vec{x})\psi - D(E,\vec{x})\partial_E\psi\right] = Q^{source}(E,t,\vec{x}) - Q^{sink}(E,\vec{x})$$

	(Semi-)analytical	*Numerical*	*Monte Carlo*
Approach	Simplify the problem: • keep dominant effects only • simplify the geometry	Finite difference scheme: • discretise the equation • scheme (e.g., Crank-Nicholson)	Follow each particle: • N particles at t=0 • evolve each of them to t+1 $1\text{D} : \Delta z = \pm\sqrt{2D\Delta t}$
Tools	• Differential equations (Green functions, Fourier+Bessel expansions...)	• Numerical recipes/solvers (NAG, GSL libraries)	• Stochastic differential equations (Markov process) + MPI
Pros	• Useful to understand the physics • Fast (MCMC analyses "simple")	• Very simple algebra • Any new input easily included	• Statistical properties (along path) • No grid but t step (for/back)-ward
cons	• Only solve approximate model • New solution for new problem	• Slower, memory for high res. • "Less" insight in the physics	• Even slower (+ statistical errors) • Massively parallel problem
Codes and/or references	Webber (1970+) Ptuskin (1980+) Schlickeiser (1990+) **USINE (2000+)** PPPC4DMID (2010+)	GALPROP (Strong et al. 1998) DRAGON (Evoli et al. 2008) PICARD (Kissmann et al., 2013)	Webber & Rockstroh (1997) Farahat et al. (2008) Kopp, Büshing et al. (2012)

Cosmic rays propagation

$$\partial_t \psi - K(E,\vec{x})\Delta\psi + \vec{\nabla}\cdot\left[\vec{V}_C(\vec{x})\psi\right] + \partial_E\left[b(E,\vec{x})\psi - D(E,\vec{x})\partial_E\psi\right] = Q^{source}(E,t,\vec{x}) - Q^{sink}(E,\vec{x})$$

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Approach	Simplify the problem: • keep dominant effects only • simplify the geometry	Finite difference scheme: • discretise the equation • scheme (	Follow each particle: • N particles at t=0 ... to t+1 ... DΔt
Tools		• Numerica... (NAG, GS...	...al equations ...MPI
Pros	• Fast (MCMC analyses "simple")	• Very simp... • Any new...	...(along path) ...or/back)-ward
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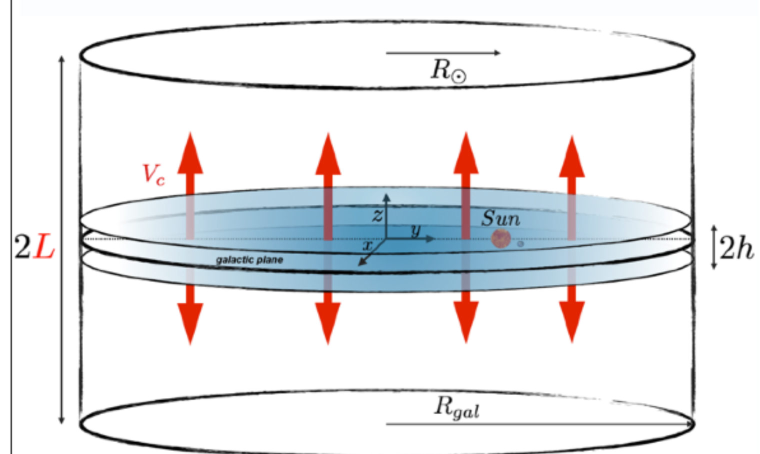

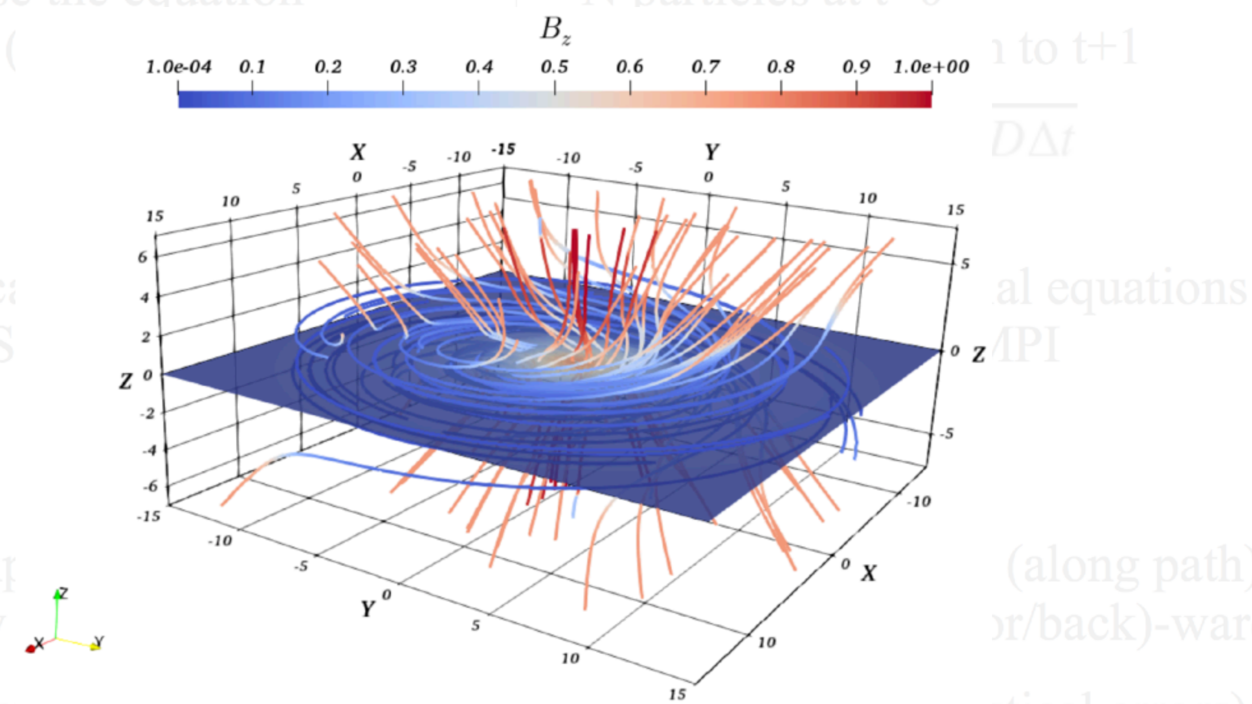

Cosmic rays propagation

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1- Introduction

2- Cosmic ray physics

3- USINE: introduction

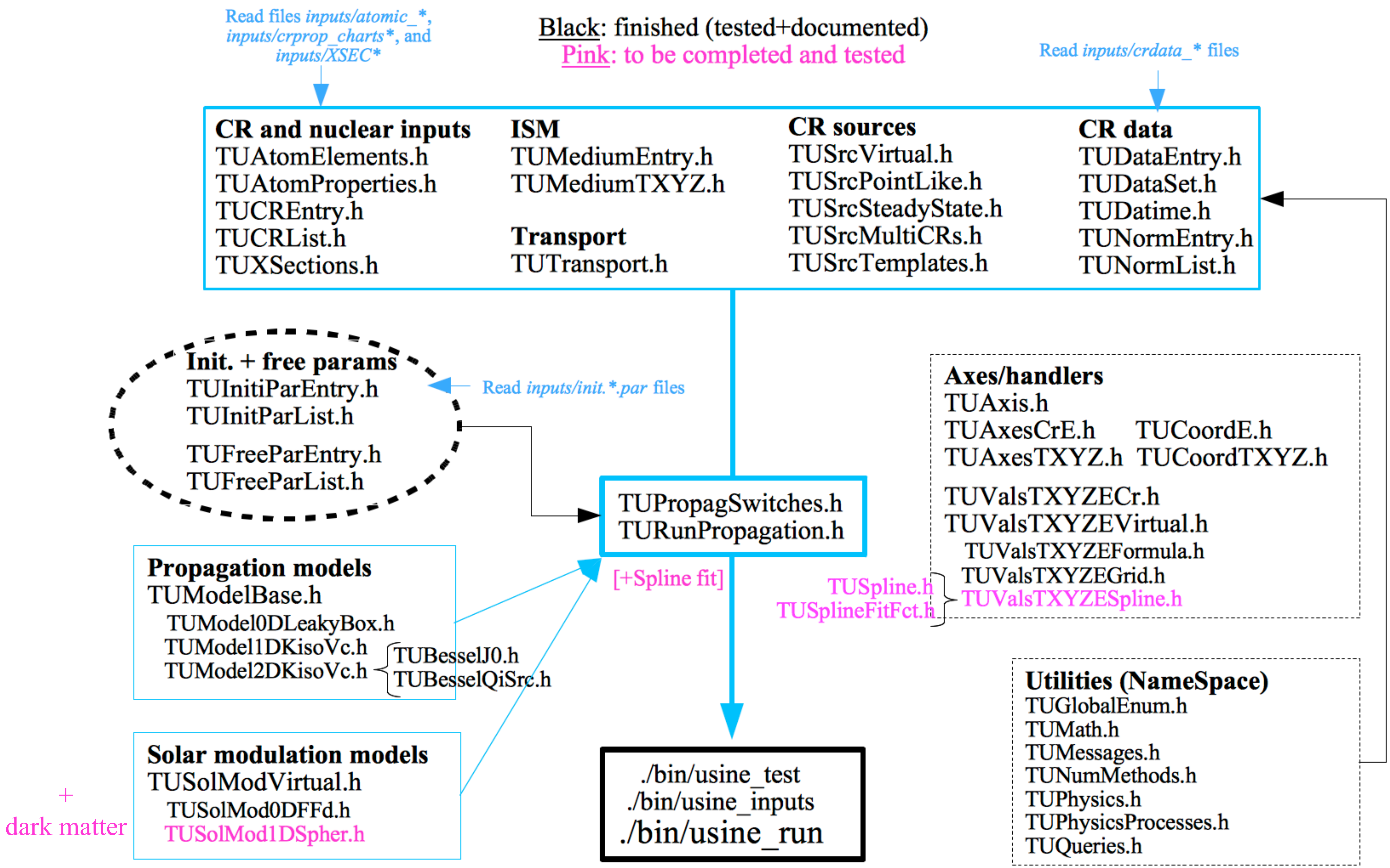
4- Several ways to run USINE: examples

5- Electrons and positrons soon in USINE

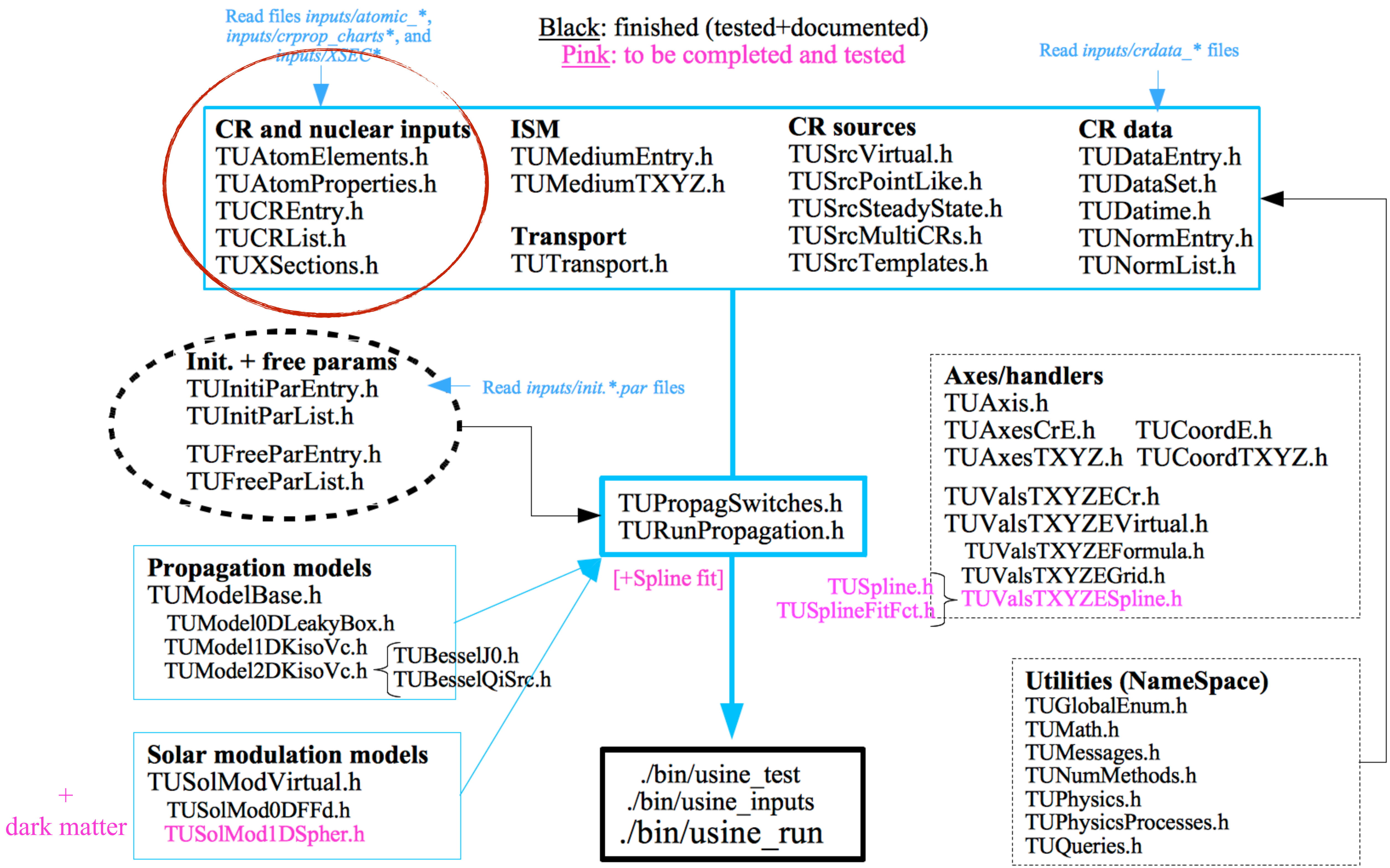
6- Conclusions and prospects

USINE: introduction

Structure of the code



Structure of the code



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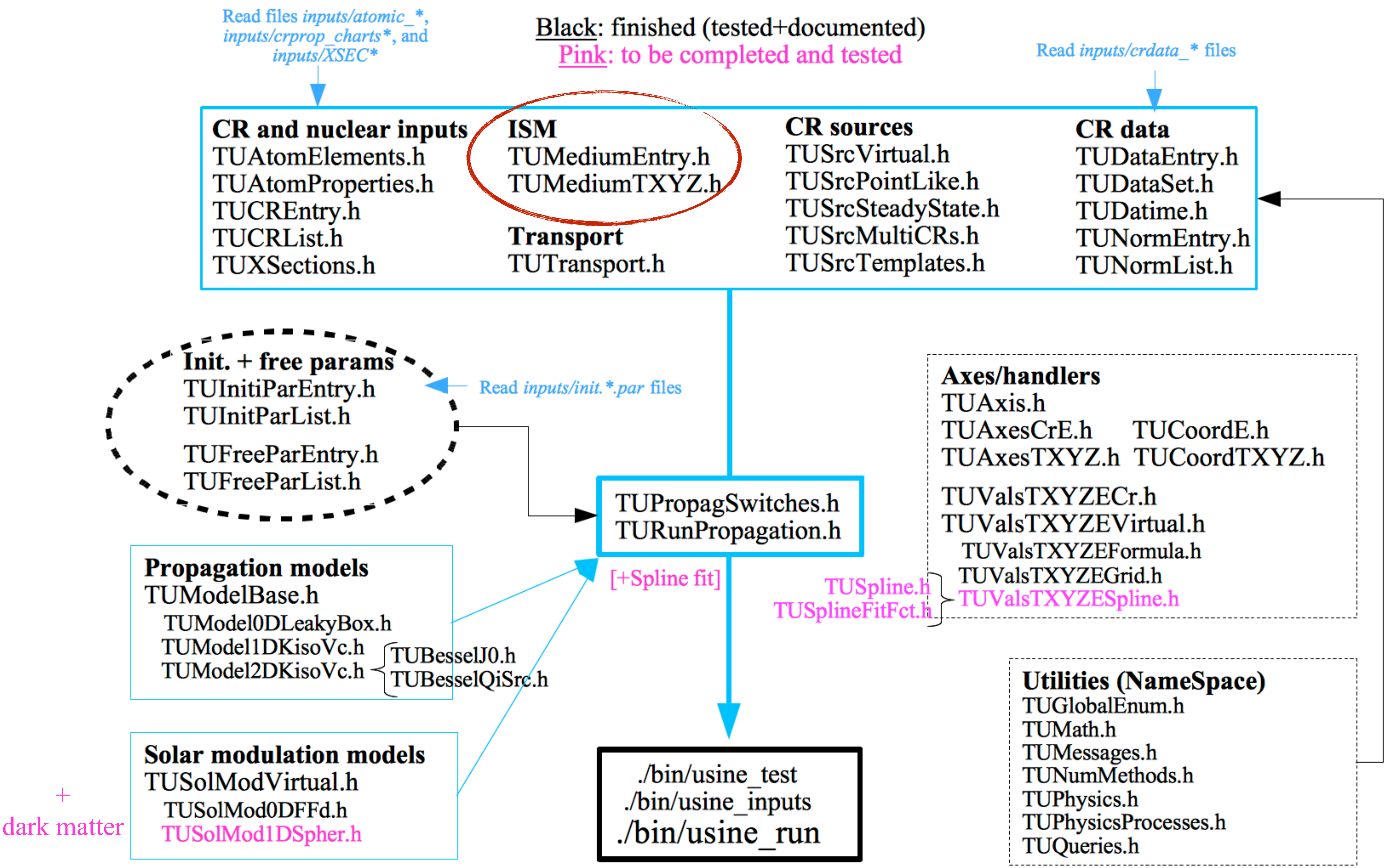
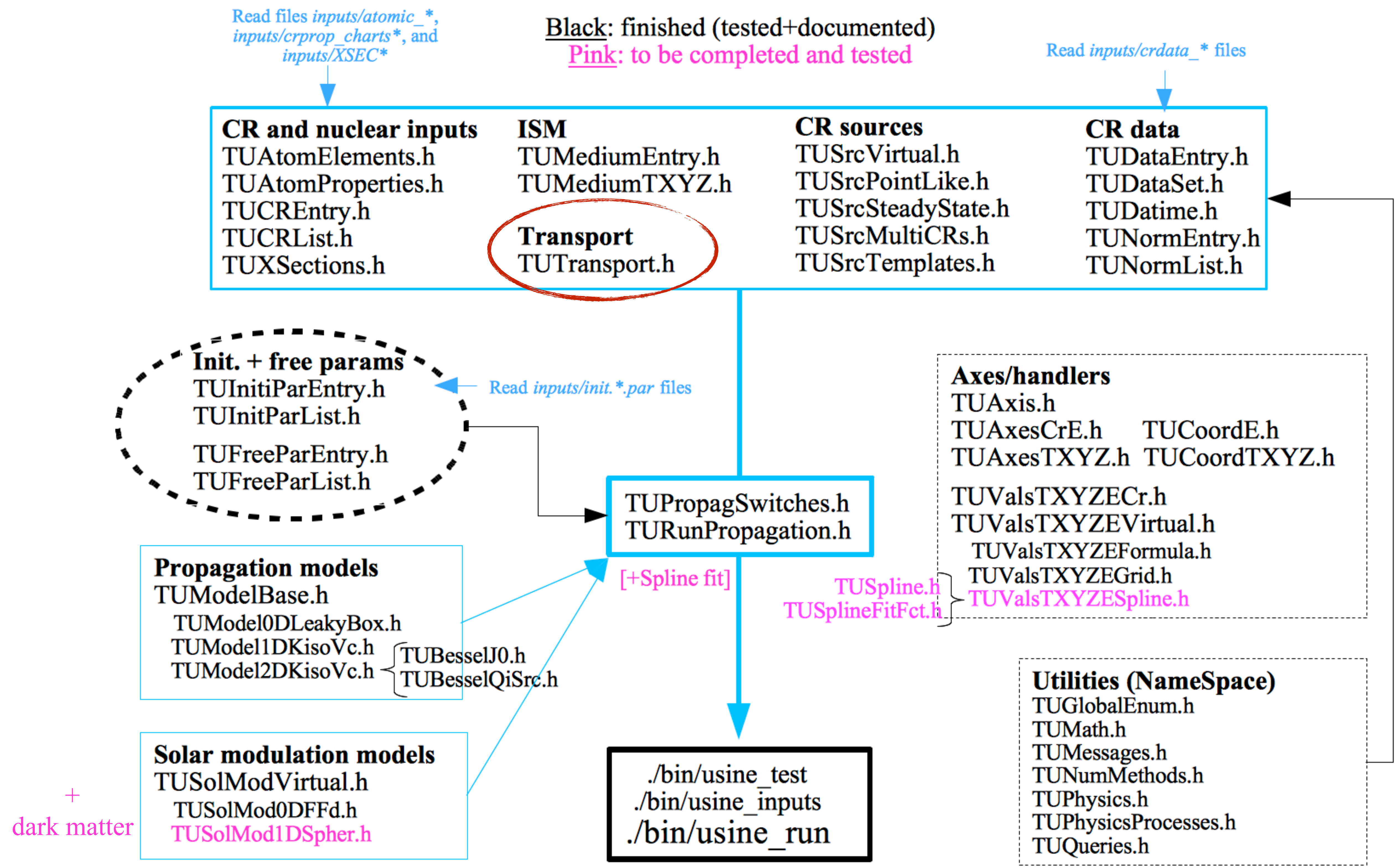


Structure of the code



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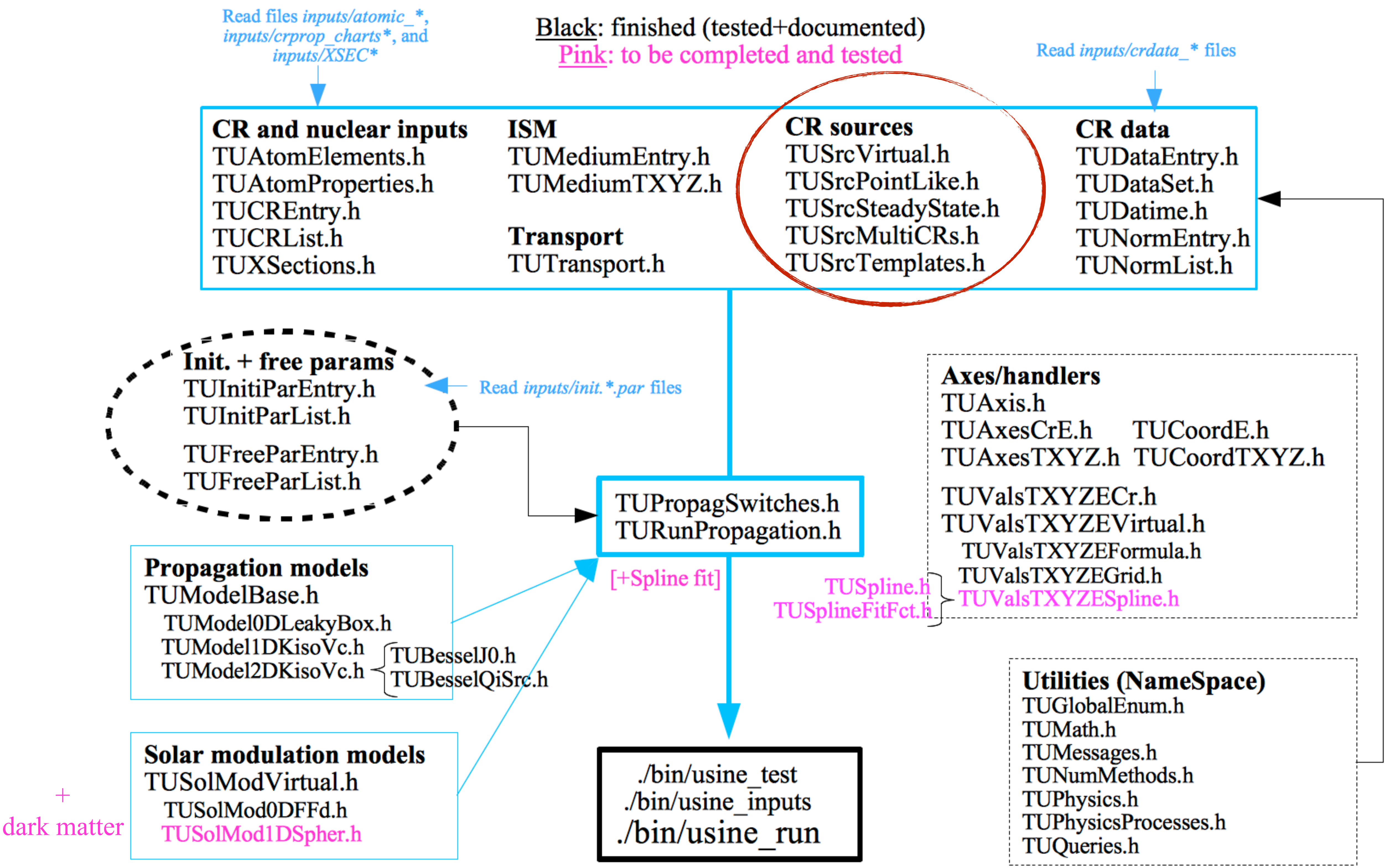
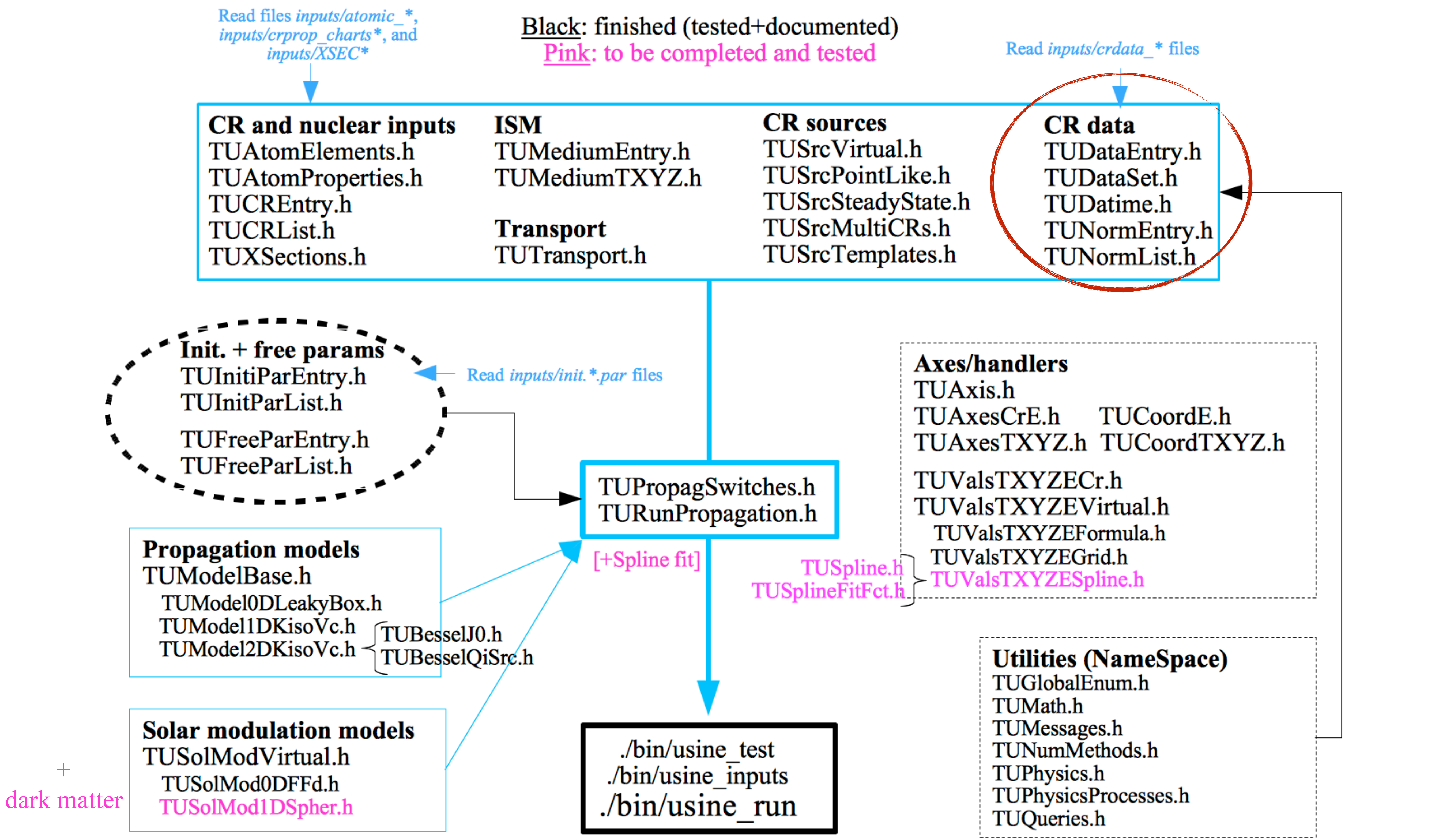
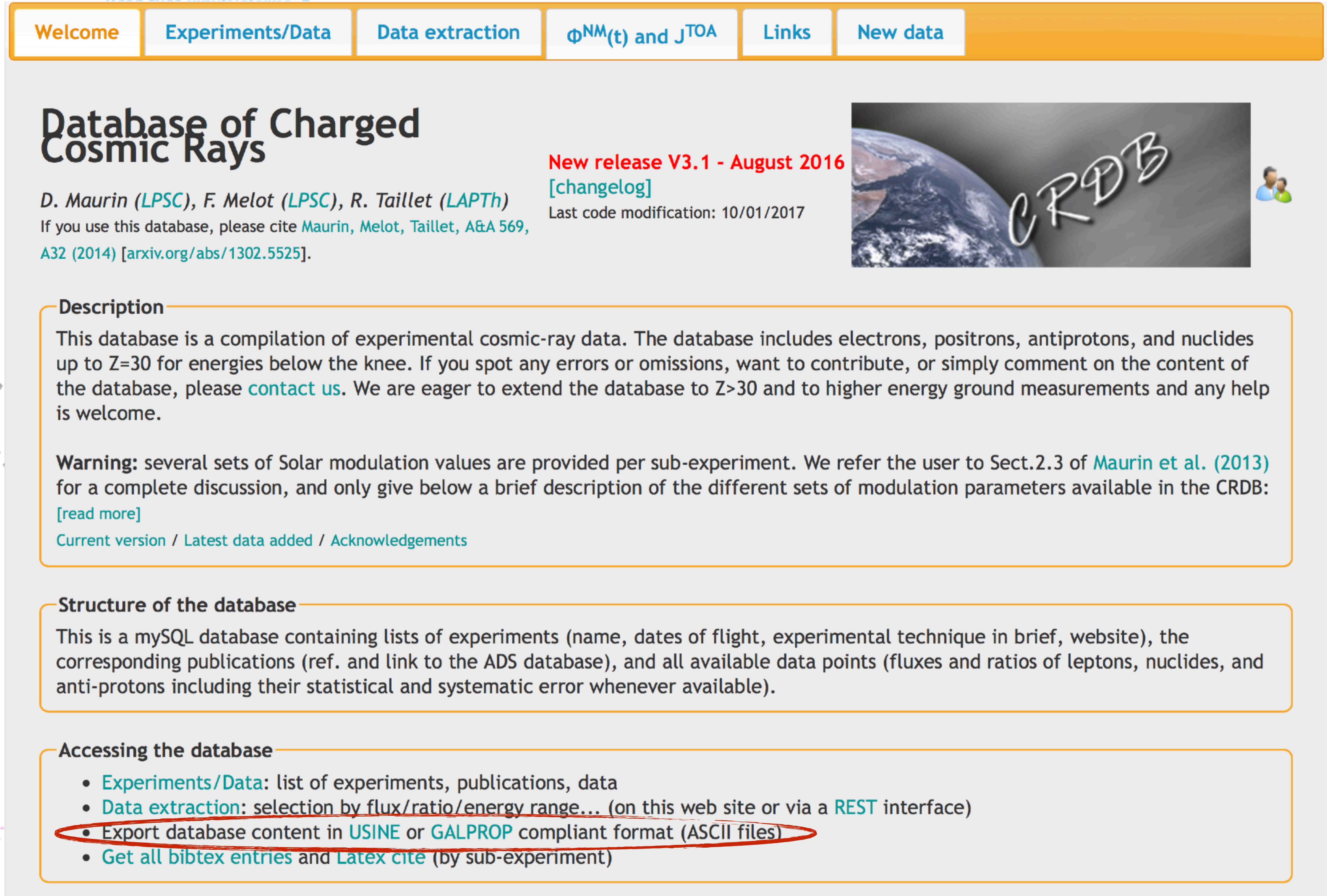


Structure of the code



Structure of the code

https://lpsc.in2p3.fr/cosmic-rays-db/



Welcome | Experiments/Data | Data extraction | $\Phi^{NM}(t)$ and J^{TOA} | Links | New data

Database of Charged Cosmic Rays

D. Maurin (LPSC), F. Melot (LPSC), R. Taillet (LAPTh)

If you use this database, please cite Maurin, Melot, Taillet, A&A 569, A32 (2014) [arxiv.org/abs/1302.5525].

New release V3.1 - August 2016

[changelog]

Last code modification: 10/01/2017

Description

This database is a compilation of experimental cosmic-ray data. The database includes electrons, positrons, antiprotons, and nuclides up to Z=30 for energies below the knee. If you spot any errors or omissions, want to contribute, or simply comment on the content of the database, please contact us. We are eager to extend the database to Z>30 and to higher energy ground measurements and any help is welcome.

Warning: several sets of Solar modulation values are provided per sub-experiment. We refer the user to Sect.2.3 of Maurin et al. (2013) for a complete discussion, and only give below a brief description of the different sets of modulation parameters available in the CRDB: [read more]

Current version / Latest data added / Acknowledgements

Structure of the database

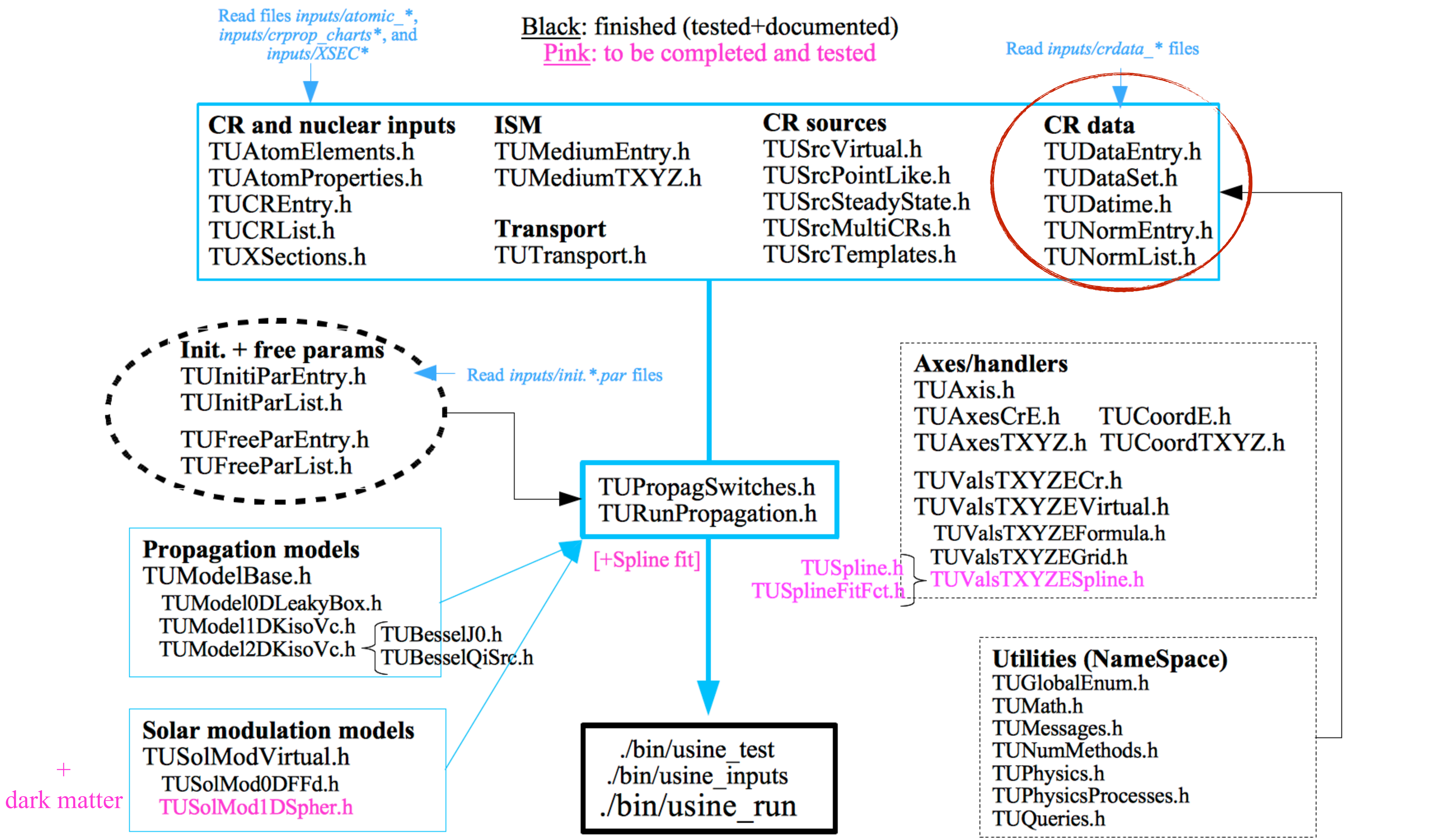
This is a mySQL database containing lists of experiments (name, dates of flight, experimental technique in brief, website), the corresponding publications (ref. and link to the ADS database), and all available data points (fluxes and ratios of leptons, nuclides, and anti-protons including their statistical and systematic error whenever available).

Accessing the database

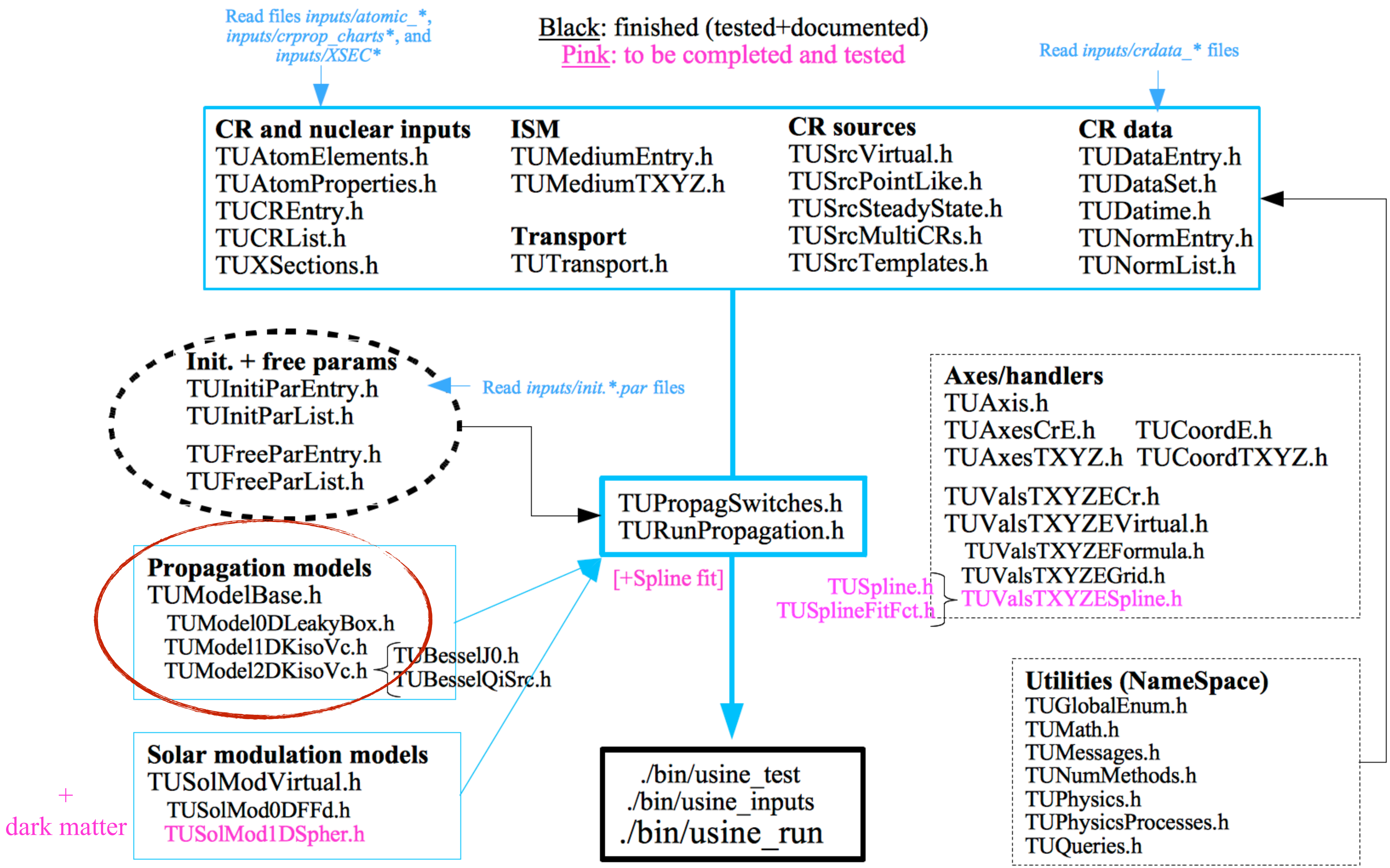
- Experiments/Data: list of experiments, publications, data
- Data extraction: selection by flux/ratio/energy range... (on this web site or via a REST interface)
- Export database content in USINE or GALPROP compliant format (ASCII files)
- Get all bibtex entries and Latex cite (by sub-experiment)

\+ dark matter

Structure of the code



Structure of the code



Structure of the code

Black: finished (tested+documented)
Pink: to be completed and tested

Read files *inputs/atomic_**, *inputs/crprop_charts**, and *inputs/XSEC**

CR and nuclear inputs
TUAtomElements.h
TUAtomProperties.h
TUCREntry.h
TUCRList.h
TUXSections.h

ISM
TUMediumEntry.h
TUMediumTXYZ.h

Transport
TUTransport.h

CR sources
TUSrcVirtual.h

CR data
TUDataEntry.h

Read *inputs/crdata_** files

Init. + free params
TUInitiParEntry.h
TUInitParList.h
TUFreeParEntry.h
TUFreeParList.h

Read *inputs/init.*.par* files

TUPropagSwi
TURunPropag
[+Spline fit]

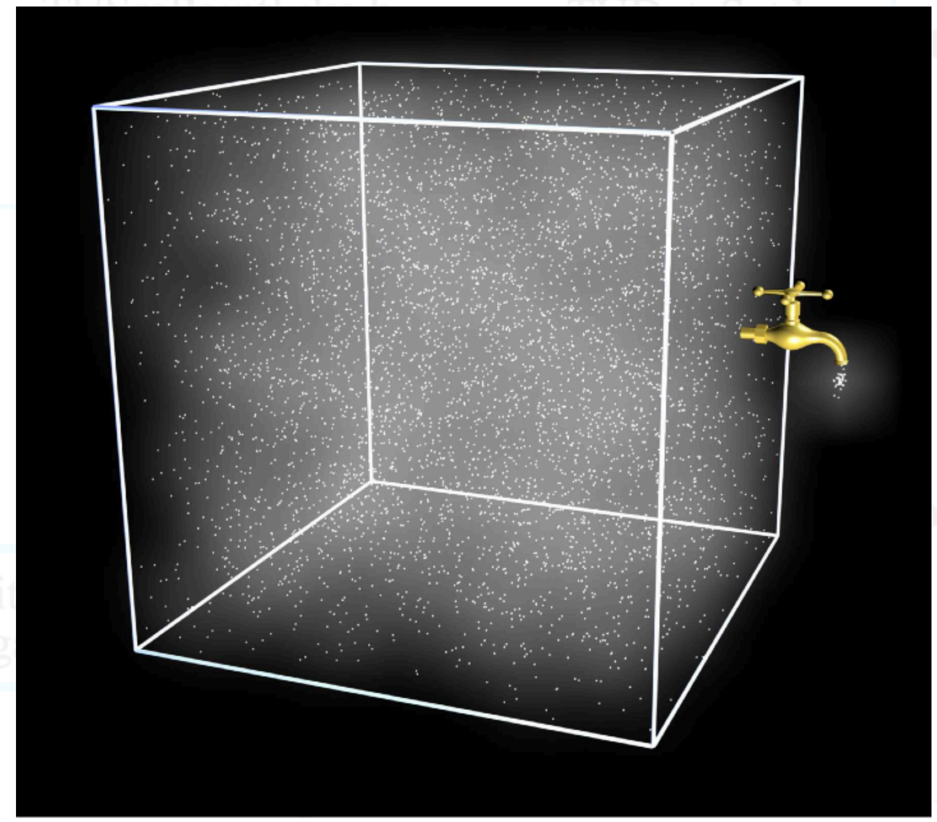
Propagation models
TUModelBase.h
TUModel0DLeakyBox.h
TUModel1DKisoVc.h
TUModel2DKisoVc.h
TUBessel J0.h
TUBessel QiSrc.h

Solar modulation models
TUSolModVirtual.h
TUSolMod0DFFd.h
TUSolMod1DSpher.h

+ dark matter

./bin/usine_test
./bin/usine_inputs
./bin/usine_run

Utilities (NameSpace)
TUGlobalEnum.h
TUMath.h
TUMessages.h
TUNumMethods.h
TUPhysics.h
TUPhysicsProcesses.h
TUQueries.h



0D model: Leaky box

Structure of the code

Read files *inputs/atomic_**, *inputs/crprop_charts**, and *inputs/XSEC**

CR and nuclear inputs
TUAtomElements.h
TUAtomProperties.h
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TUCRList.h
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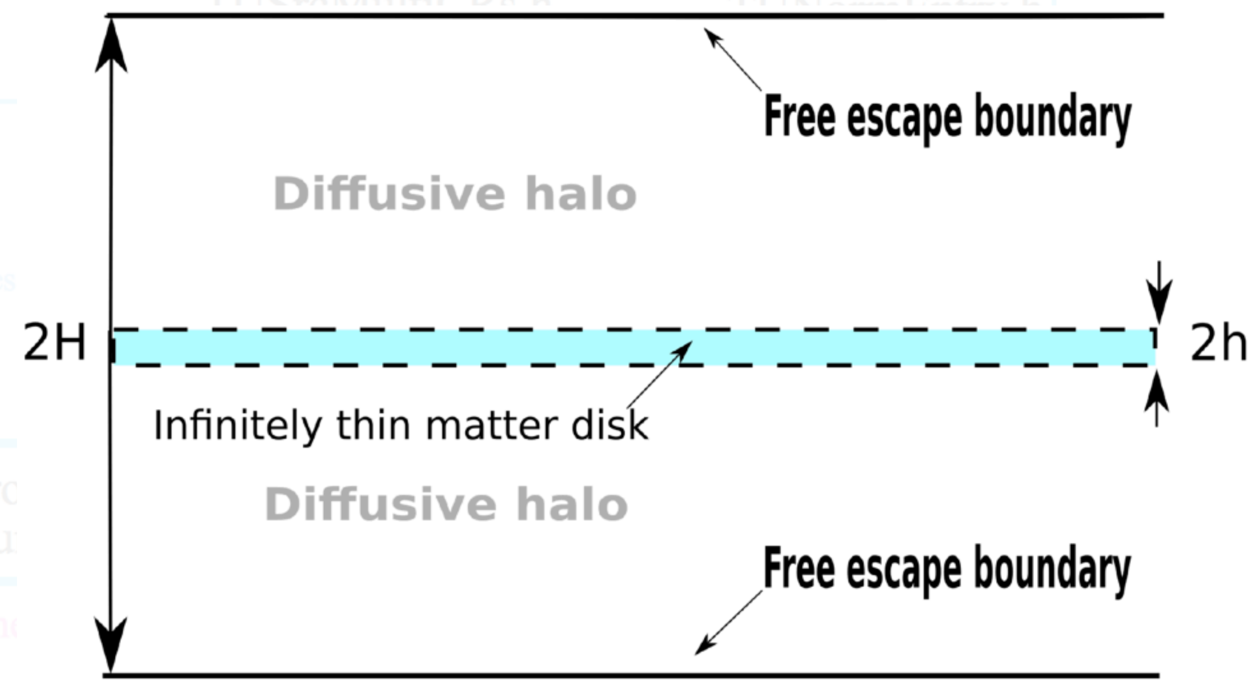
Init. + free params
TUInitiParEntry.h
TUInitParList.h
TUFreeParEntry.h
TUFreeParList.h

Propagation models
TUModelBase.h
TUModel0DLeakyBox.h
TUModel1DKisoVc.h
TUModel2DKisoVc.h
TUBessel
TUBessel

Solar modulation models
TUSolModVirtual.h
TUSolMod0DFFd.h
TUSolMod1DSpher.h

\+ dark matter



1D model

Structure of the code

Black: finished (tested+documented)
Pink: to be completed and tested

Read files *inputs/atomic_**, *inputs/crprop_charts**, and *inputs/XSEC**

CR and nuclear inputs
TUAtomElements.h
TUAtomProperties.h
TUCREntry.h
TUCRList.h
TUXSections.h

ISM
TUMediumEntry.h
TUMediumTXYZ.h

CR sources
TUSrcVirtual.h
TUSrcPointLike.h

CR data
TUDataEntry.h
TUDataSet.h

Read *inputs/crdata_** files

Transport
TUTransport.h

Init. + free params
TUInitParEntry.h
TUInitParList.h
TUFreeParEntry.h
TUFreeParList.h

Read *inputs/init.*.par* files

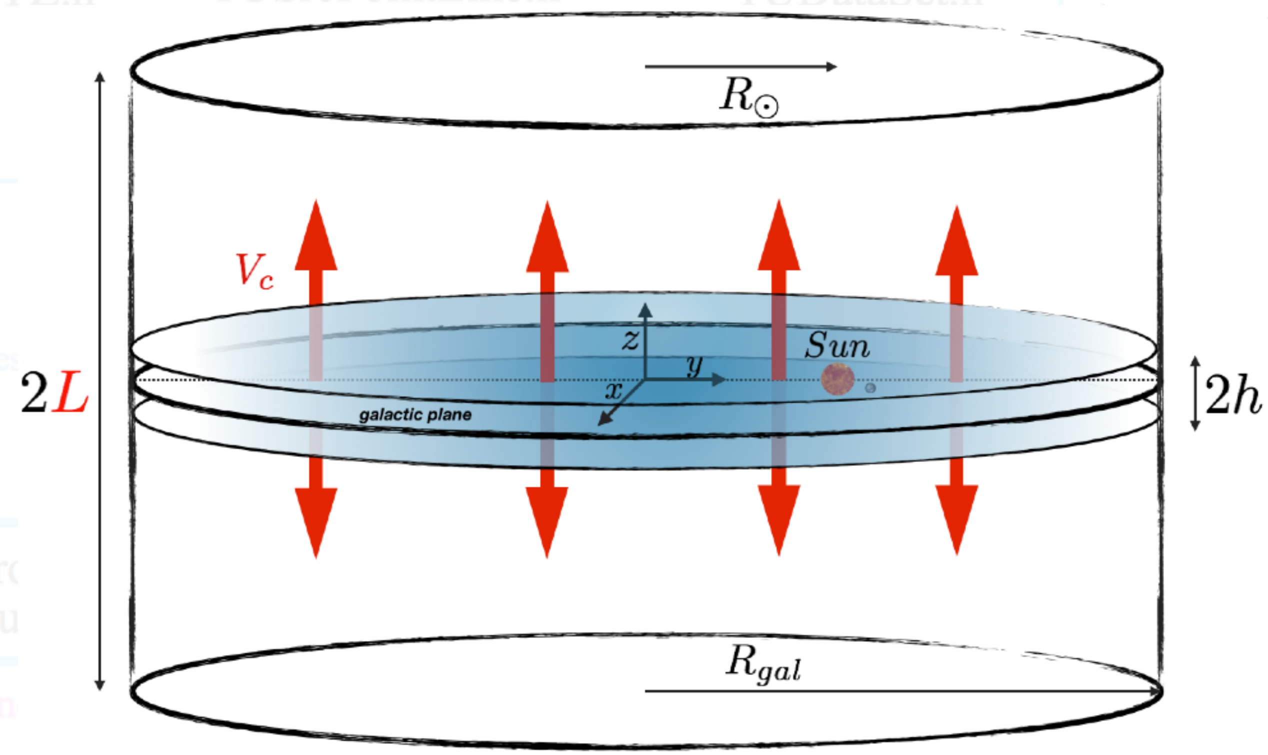
Propagation models
TUModelBase.h
TUModel0DLeakyBox.h
TUModel1DKisoVc.h
TUModel2DKisoVc.h
TUBesselJ0.h
TUBesselQiSrc.h

Solar modulation models
TUSolModVirtual.h
TUSolMod0DFFd.h
TUSolMod1DSpher.h

\+ dark matter

./bin/usine_test
./bin/usine_inputs
./bin/usine_run

Utilities (NameSpace)
TUGlobalEnum.h
TUMath.h
TUMessages.h
TUNumMethods.h
TUPhysics.h
TUPhysicsProcesses.h
TUQueries.h



2D model

Structure of the code

Read files *inputs/atomic_**, *inputs/crprop_charts**, and *inputs/XSEC**

CR and nuclear inputs
TUAtomElements.h
TUAtomProperties.h
TUCREntry.h
TUCRList.h
TUXSections.h

Init. + free params
TUInitiParEntry.h
TUInitParList.h
TUFreeParEntry.h
TUFreeParList.h

Propagation models
TUModelBase.h
TUModel0DLeakyBox.h
TUModel1DKisoVc.h
TUModel2DKisoVc.h
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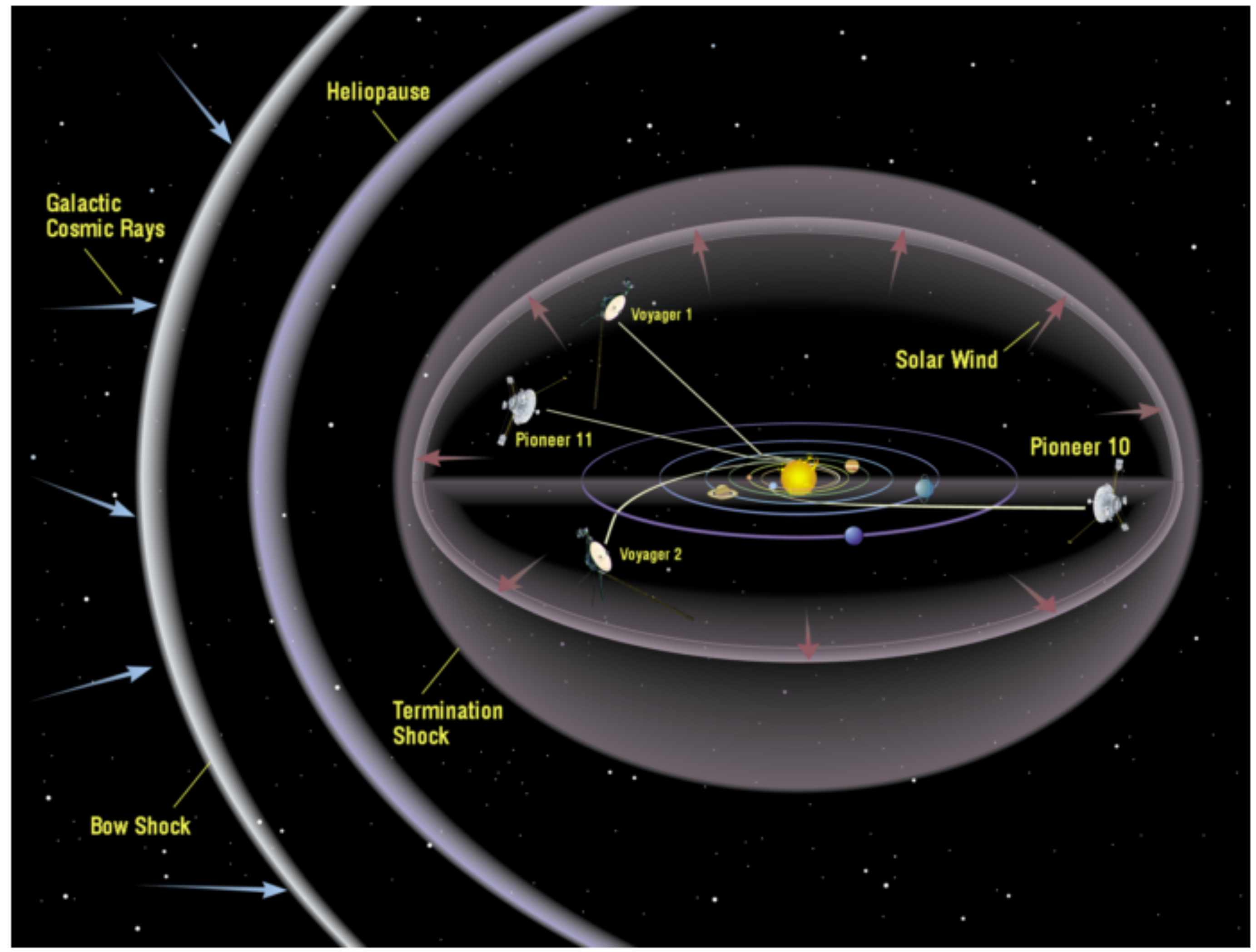
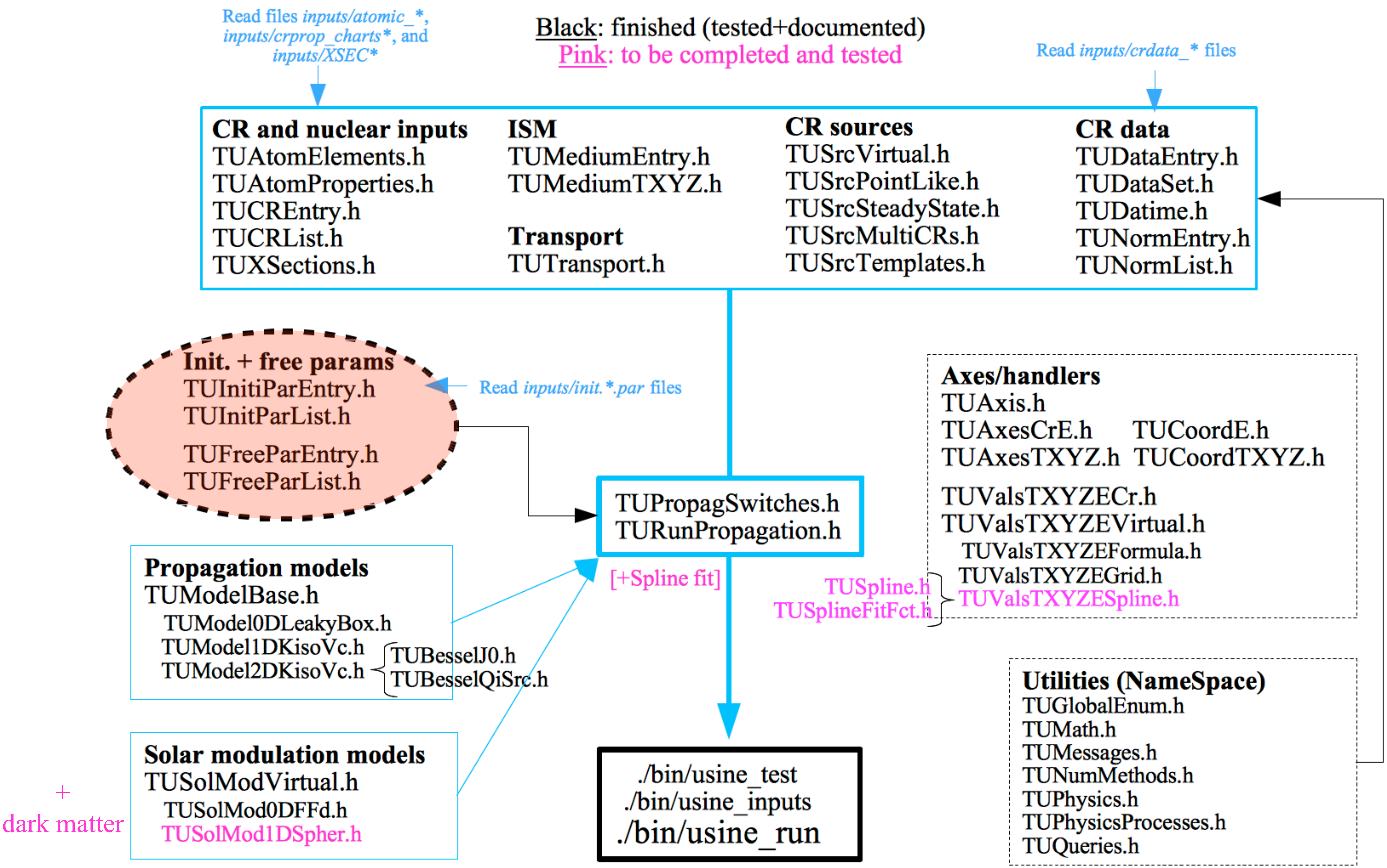
TUBesselQiSrc.h

Solar modulation models
TUSolModVirtual.h
TUSolMod0DFFd.h
TUSolMod1DSpher.h

\+ dark matter



Structure of the code



***Message**: only one ASCII file has to be handled by the user! (inputs/init.par)*

inputs/init.par

All input ingredients are controlled by *only one* ASCII parameter file.

```
###############################################################################
#####                  LIST of PARAMETERS (and VALUES)                    #####
#####  group @subgroup @parameter @type @M= @unit @val @H= @B= @[opt]Info  #####
###############################################################################

Base            @ CRData          @ fCRData            @ string         @ M=1    @ -                  @ $USINE/inputs/crdata_crdb20170523.dat
Base            @ CRData          @ fCRData            @ string         @ M=1    @ -                  @ $USINE/inputs/crdata_dummy.dat
Base            @ CRData          @ NormList           @ string         @ M=0    @ -                  @ H,He:AMS02|100.|kR;C,N,O,F,Ne,Na,Mg,Al,Si,P,S,Cl,A
Base            @ EnergyGrid      @ NBins              @ int            @ M=0    @ -                  @ 300
Base            @ EnergyGrid      @ NUC_EknRange       @ string         @ M=0    @ GeV/n              @ [1.e-3,1.e6]
Base            @ EnergyGrid      @ ANTINUC_EknRange   @ string         @ M=0    @ GeV/n              @ [5e-2,1.e4]
Base            @ EnergyGrid      @ LEPTONS_EkRange    @ string         @ M=0    @ GeV                @ [5e-2,1.e4]
Base            @ EnergyGrid      @ GAMMA_ERange       @ string         @ M=0    @ GeV                @ [5e-3,1.e2]
Base            @ EnergyGrid      @ NEUTRINO_ERange    @ string         @ M=0    @ GeV                @ [1e-3,1.e2]
Base            @ ListOfCRs       @ fAtomicProperties  @ string         @ M=0    @ -                  @ $USINE/inputs/atomic_properties.dat
Base            @ ListOfCRs       @ fChartsForCRs      @ string         @ M=0    @ -                  @ $USINE/inputs/crprop_chartsZmax30_ghost97.dat
Base            @ ListOfCRs       @ IsGhosts           @ bool           @ M=0    @ -                  @ 0
Base            @ ListOfCRs       @ ListOfCRs          @ string         @ M=0    @ -                  @ [1H,30Si]

Base            @ ListOfCRs       @ ListOfParents      @ string         @ M=0    @ -                  @ 1H-bar:1H,4He
Base            @ ListOfCRs       @ ErrorBETADecay     @ double         @ M=0    @ -                  @ 0.
Base            @ ListOfCRs       @ ErrorECDecay       @ double         @ M=0    @ -                  @ 0.
Base            @ ListOfCRs       @ PureSecondaries    @ string         @ M=0    @ -                  @ Li,Be,B,1H-bar
Base            @ ListOfCRs       @ SSRelativeAbund    @ string         @ M=0    @ -                  @ $USINE/inputs/crprop_abundances2003.dat
Base            @ MediumCompo     @ Targets            @ string         @ M=0    @ -                  @ H,He
Base            @ PropagOnOff     @ IsDecayBETA        @ bool           @ M=0    @ -                  @ 1
Base            @ PropagOnOff     @ IsDecayFedBETA     @ bool           @ M=0    @ -                  @ 1
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Base            @ PropagOnOff     @ IsELossSynchrotron @ bool           @ M=0    @ -                  @ 0
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Base            @ PropagOnOff     @ IsPrimStandard     @ bool           @ M=0    @ -                  @ 1
Base            @ PropagOnOff     @ IsSecondaries      @ bool           @ M=0    @ -                  @ 1
Base            @ PropagOnOff     @ IsTertiaries       @ bool           @ M=0    @ -                  @ 1
```

inputs/init.par

All input ingredients are controlled by ***only one*** ASCII parameter file.

The User can customise this file to his own tastes:

- Propagation model (leaky box, 1D, 2D)
- Description of the interstellar medium
- Functional form of many functions ($K(R)$, $V_C(z)$, D(E), etc.)
- Propagation effects to take into account
- Value of the propagation parameters
- Nuclear X-sections
- CR data
- …

This makes USINE very flexible and customisable!

inputs/init.par

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Base            @ ListOfCRs       @ ListOfCRs          @ string        @ M=0   @ -              @ [1H,30Si]

Base            @ ListOfCRs       @ ListOfParents      @ string        @ M=0   @ -              @ 1H-bar:1H,4He
Base            @ ListOfCRs       @ ErrorBETADecay     @ double        @ M=0   @ -              @ 0.
Base            @ ListOfCRs       @ ErrorECDecay       @ double        @ M=0   @ -              @ 0.
Base            @ ListOfCRs       @ PureSecondaries    @ string        @ M=0   @ -              @ Li,Be,B,1H-bar
Base            @ ListOfCRs       @ SSRelativeAbund    @ string        @ M=0   @ -              @ $USINE/inputs/crprop_abundances2003.dat
Base            @ MediumCompo     @ Targets            @ string        @ M=0   @ -              @ H,He
Base            @ Pr[illegible]                                                                  @ 1
Base            @ PropagOnOff     @ IsDecayFedBETA     @ bool          @ M=0   @ -              @ 1
Base            @ PropagOnOff     @ IsDecayEC          @ bool          @ M=0   @ -              @ 1
Base            @ PropagOnOff     @ IsDecayFedEC       @ bool          @ M=0   @ -              @ 1
Base            @ PropagOnOff     @ IsDestruction      @ bool          @ M=0   @ -              @ 1
Base            @ PropagOnOff     @ IsELossAdiabatic   @ bool          @ M=0   @ -              @ 1
Base            @ PropagOnOff     @ IsELossBremss      @ bool          @ M=0   @ -              @ 0
Base            @ PropagOnOff     @ IsELossCoulombIon  @ bool          @ M=0   @ -              @ 1
Base            @ PropagOnOff     @ IsELossIC          @ bool          @ M=0   @ -              @ 0
Base            @ PropagOnOff     @ IsELossSynchrotron @ bool          @ M=0   @ -              @ 0
Base            @ PropagOnOff     @ IsEReacc           @ bool          @ M=0   @ -              @ 1
Base            @ PropagOnOff     @ IsPrimExotic       @ bool          @ M=0   @ -              @ 0
Base            @ PropagOnOff     @ IsPrimStandard     @ bool          @ M=0   @ -              @ 1
Base            @ PropagOnOff     @ IsSecondaries      @ bool          @ M=0   @ -              @ 1
Base            @ PropagOnOff     @ IsTertiaries       @ bool          @ M=0   @ -              @ 1
```

Calculation of the flux at the Earth of all CRs from ^{1}H to ^{30}Si.

inputs/init.par

All input ingredients are controlled by ***only one*** ASCII parameter file.

```
################################################################################
#####                 LIST of PARAMETERS (and VALUES)                      #####
#####  group @subgroup @parameter @type @M= @unit @val @H= @B= @[opt]Info  #####
################################################################################

Base            @ CRData        @ fCRData            @ string      @ M=1   @ -          @ $USINE/inputs/crdata_crdb20170523.dat
Base            @ CRData        @ fCRData            @ string      @ M=1   @ -          @ $USINE/inputs/crdata_dummy.dat
Base            @ CRData        @ NormList           @ string      @ M=0   @ -          @ H,He:AMS02|100.|kR;C,N,O,F,Ne,Na,Mg,Al,Si,P,S,Cl,A
Base            @ EnergyGrid    @ NBins              @ int         @ M=0   @ -          @ 300
Base            @ EnergyGrid    @ NUC_EknRange       @ string      @ M=0   @ GeV/n      @ [1.e-3,1.e6]
Base            @ EnergyGrid    @ ANTINUC_EknRange   @ string      @ M=0   @ GeV/n      @ [5e-2,1.e4]
Base            @ EnergyGrid    @ LEPTONS_EkRange    @ string      @ M=0   @ GeV        @ [5e-2,1.e4]
Base            @ EnergyGrid    @ GAMMA_ERange       @ string      @ M=0   @ GeV        @ [5e-3,1.e2]
Base            @ EnergyGrid    @ NEUTRINO_ERange    @ string      @ M=0   @ GeV        @ [1e-3,1.e2]
Base            @ ListOfCRs     @ fAtomicProperties  @ string      @ M=0   @ -          @ $USINE/inputs/atomic_properties.dat
Base            @ ListOfCRs     @ fChartsForCRs      @ string      @ M=0   @ -          @ $USINE/inputs/crprop_chartsZmax30_ghost97.dat
Base            @ ListOfCRs     @ IsGhosts           @ bool        @ M=0   @ -          @ 0
Base            @ ListOfCRs     @ ListOfCRs          @ string      @ M=0   @ -          @ [1H,30Si]
```

Switch **on/off** propagation effects (destruction, Coulomb interaction, Bremsstrahlung, etc.)

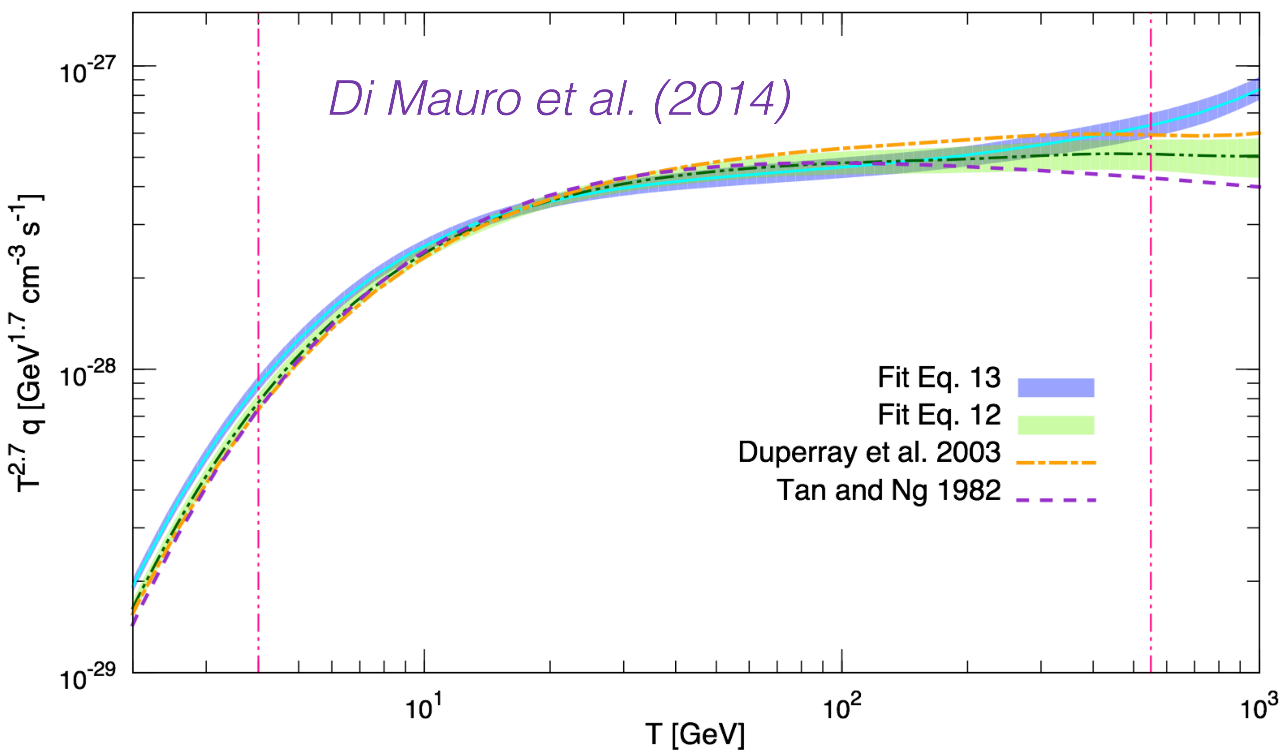
```
Base            @ ListOfCRs     @ ListOfParents      @ string      @ M=0   @ -          @ 1H-bar:1H,4He
Base            @ ListOfCRs     @ ErrorBETADecay     @ double      @ M=0   @ -          @ 0.
Base            @ ListOfCRs     @ ErrorECDecay       @ double      @ M=0   @ -          @ 0.
Base            @ ListOfCRs     @ PureSecondaries    @ string      @ M=0   @ -          @ Li,Be,B,1H-bar
Base            @ ListOfCRs     @ SSRelativeAbund    @ string      @ M=0   @ -          @ $USINE/inputs/crprop_abundances2003.dat
Base            @ MediumCompo   @ Targets            @ string      @ M=0   @ -          @ H,He
Base            @ PropagOnOff   @ IsDecayBETA        @ bool        @ M=0   @ -          @ 1
Base            @ PropagOnOff   @ IsDecayFedBETA     @ bool        @ M=0   @ -          @ 1
Base            @ PropagOnOff   @ IsDecayEC          @ bool        @ M=0   @ -          @ 1
Base            @ PropagOnOff   @ IsDecayFedEC       @ bool        @ M=0   @ -          @ 1
Base            @ PropagOnOff   @ IsDestruction      @ bool        @ M=0   @ -          @ 1
Base            @ PropagOnOff   @ IsELossAdiabatic   @ bool        @ M=0   @ -          @ 1
Base            @ PropagOnOff   @ IsELossBremss      @ bool        @ M=0   @ -          @ 0
Base            @ PropagOnOff   @ IsELossCoulombIon  @ bool        @ M=0   @ -          @ 1
Base            @ PropagOnOff   @ IsELossIC          @ bool        @ M=0   @ -          @ 0
Base            @ PropagOnOff   @ IsELossSynchrotron @ bool        @ M=0   @ -          @ 0
Base            @ PropagOnOff   @ IsEReacc           @ bool        @ M=0   @ -          @ 1
Base            @ PropagOnOff   @ IsPrimExotic       @ bool        @ M=0   @ -          @ 0
Base            @ PropagOnOff   @ IsPrimStandard     @ bool        @ M=0   @ -          @ 1
Base            @ PropagOnOff   @ IsSecondaries      @ bool        @ M=0   @ -          @ 1
Base            @ PropagOnOff   @ IsTertiaries       @ bool        @ M=0   @ -          @ 1
```

inputs/init.par

All input ingredients are controlled by ***only one*** ASCII parameter file.

```
###############################################################################
#####                  LIST of PARAMETERS (and VALUES)                    #####
#####  group @subgroup @parameter @type @M= @unit @val @H= @B= @[opt]Info  #####
###############################################################################

Base      @ XSections    @ fProd            @ string    @ M=1    @ -        @ $USINE/inputs/XS_ANTINUC/dSdEpbar_p+HTanNg_p+HeDTUNUC.dat
Base      @ XSections    @ fProd            @ string    @ M=1    @ -        @ $USINE/inputs/XS_ANTINUC/dSdEpbar_He+HHe_DTUNUC2001.dat
Base      @ XSections    @ fProd            @ string    @ M=1    @ -        @ $USINE/inputs/XS_ANTINUC/dSdEpbar_p+HHe_BringmannSalati07.dat
Base      @ XSections    @ fProd            @ string    @ M=1    @ -        @ $USINE/inputs/XS_ANTINUC/dSdEpbar_He+HHe_BringmannSalati07.dat
Base      @ XSections    @ fProd            @ string    @ M=1    @ -        @ $USINE/inputs/XS_ANTINUC/dSdEpbar_H_on_HHe_MDGSF12.dat
Base      @ XSections    @ fProd            @ string    @ M=1    @ -        @ $USINE/inputs/XS_ANTINUC/dSdEpbar_He_on_HHe_MDGSF12.dat
Base      @ XSections    @ fProd            @ string    @ M=1    @ -        @ $USINE/inputs/XS_ANTINUC/dSdEdbar_p+HHe_Coal79MeV.dat
Base      @ XSections    @ fProd            @ string    @ M=1    @ -        @ $USINE/inputs/XS_ANTINUC/dSdEdbar_He+HHe_Coal79MeV.dat
Base      @ XSections    @ fProd            @ string    @ M=1    @ -        @ $USINE/inputs/XS_ANTINUC/dSdEdbar_pbar+HHe_Coal79MeV.dat
Base      @ XSections    @ fProd            @ string    @ M=1    @ -        @ $USINE/inputs/XS_LEPTONS/dSdEElect_p+HHe_kamae06.dat
Base      @ XSections    @ fProd            @ string    @ M=1    @ -        @ $USINE/inputs/XS_LEPTONS/dSdEElect_He+HHe_kamae06.dat
Base      @ XSections    @ fProd            @ string    @ M=1    @ -        @ $USINE/inputs/XS_LEPTONS/dSdEPosit_p+HHe_kamae06.dat
Base      @ XSections    @ fProd            @ string    @ M=1    @ -        @ $USINE/inputs/XS_LEPTONS/dSdEPosit_He+HHe_kamae06.dat
Base      @ XSections    @ fTotInelNonAnn   @ string    @ M=1    @ -        @ $USINE/inputs/XS_ANTINUC/sigInelNONANN_pbar_TanNg83.dat
Base      @ XSections    @ fTotInelNonAnn   @ string    @ M=1    @ -        @ $USINE/inputs/XS_ANTINUC/sigInelNONANN_dbar_Duperray05.dat
Base      @ XSections    @ fdSigdEknINA     @ string    @ M=1    @ -        @ $USINE/inputs/XS_ANTINUC/dSdEpbar_tertiaryHHe_AndersonHE.dat
Base      @ XSections    @ fdSigdEknINA     @ string    @ M=1    @ -        @ $USINE/inputs/XS_ANTINUC/dSdEdbar_tertiaryHHe_AndersonHE.dat
```



inputs/XS_ANTIdSdEpbar_He_on_HHe_MDGSF12.dat

```
# Type  Unit     Targets
dsigma  mb/GeV   H,He

# EknMIN[GeV/n]  EknMAX[GeV/n]  nEk  (PROJECTILE GRID)
1.0              1.000000e+06   501

# EknMIN[GeV/n]  EknMAX[GeV/n]  nEkn  (FRAGMENT GRID)
1.000000e-01     1.000000e+05   301

# Repeated loop
2

4He -> 1H-bar
6.56018e-02     1.04125e-01
6.15260e-02     9.76551e-02
5.76449e-02     9.14944e-02
5.39516e-02     8.56319e-02
5.04394e-02     8.00567e-02
4.71017e-02     7.47586e-02
4.39321e-02     6.97273e-02
4.09244e-02     6.49532e-02
3.80728e-02     6.04268e-02
3.53714e-02     5.61388e-02
3.28147e-02     5.20805e-02
3.03972e-02     4.82431e-02
```

inputs/init.par

All input ingredients are controlled by ***only one*** ASCII parameter file.

```
##############################################################################
#####                   LIST of PARAMETERS (and VALUES)                   #####
#####  group @subgroup @parameter @type @M= @unit @val @H= @B= @[opt]Info  #####
##############################################################################

  Model1DKisoVc    @ ISM            @ ParNames          @ string      @ M=0   @ -           @ -
  Model1DKisoVc    @ ISM            @ ParUnits          @ string      @ M=0   @ -           @ -
  Model1DKisoVc    @ ISM            @ ParVals           @ string      @ M=0   @ -           @ -
  Model1DKisoVc    @ ISM            @ Density           @ string      @ M=1   @ cm-3        @ HI:FORMULA|0.867
  Model1DKisoVc    @ ISM            @ Density           @ string      @ M=1   @ cm-3        @ HII:FORMULA|0.033
  Model1DKisoVc    @ ISM            @ Density           @ string      @ M=1   @ cm-3        @ H2:FORMULA|0.
  Model1DKisoVc    @ ISM            @ Density           @ string      @ M=1   @ cm-3        @ He:FORMULA|0.1
  Model1DKisoVc    @ ISM            @ Te                @ string      @ M=0   @ K           @ FORMULA|1.e4
  Model1DKisoVc    @ SrcPointLike   @ Species           @ string      @ M=1   @ -           @ -
  Model1DKisoVc    @ SrcPointLike   @ SpectraAbundInit  @ string      @ M=1   @ -           @ -
  Model1DKisoVc    @ SrcPointLike   @ SpectraNormInTempl @ string     @ M=1   @ -           @ -
  Model1DKisoVc    @ SrcPointLike   @ SpectraPerCR      @ string      @ M=1   @ -           @ -
  Model1DKisoVc    @ SrcPointLike   @ SrcXPosition      @ string      @ M=1   @ -           @ -
  Model1DKisoVc    @ SrcPointLike   @ SrcYPosition      @ string      @ M=1   @ -           @ -
  Model1DKisoVc    @ SrcPointLike   @ SrcZPosition      @ string      @ M=1   @ -           @ -
  Model1DKisoVc    @ SrcPointLike   @ TStart            @ int         @ M=1   @ -           @ -
  Model1DKisoVc    @ SrcPointLike   @ TStop             @ int         @ M=1   @ -           @ -
  Model1DKisoVc    @ SrcSteadyState @ Species           @ string      @ M=1   @ -           @ ASTRO_STD|ALL
  Model1DKisoVc    @ SrcSteadyState @ SpectraAbundInit  @ string      @ M=1   @ -           @ ASTRO_STD|kSSISOTFRAC,kSSISOTABUND,kFIPBIAS
  Model1DKisoVc    @ SrcSteadyState @ SpectraNormInTempl @ string     @ M=1   @ -           @ ASTRO_STD|q
  Model1DKisoVc    @ SrcSteadyState @ SpectraPerCR      @ string      @ M=1   @ -           @ ASTRO_STD|STEADYSTATE_GEN|q[PERCR:DEFAULT=1.e-5,1H=6.37e-5,4He=3.75e-3];alph
  Model1DKisoVc    @ Transport      @ ParNames          @ string      @ M=0   @ -           @ Va,Vc,K0,delta,eta_t
  Model1DKisoVc    @ Transport      @ ParUnits          @ string      @ M=0   @ -           @ km/s,km/s,kpc^2/Myr,-,-
  Model1DKisoVc    @ Transport      @ ParVals           @ string      @ M=0   @ -           @ 2.0,0.0,0.059,0.66,1.
  Model1DKisoVc    @ Transport      @ Wind              @ string      @ M=1   @ km/s        @ W0:FORMULA|Vc
  Model1DKisoVc    @ Transport      @ VA                @ string      @ M=0   @ km/s        @ FORMULA|Va
  Model1DKisoVc    @ Transport      @ K                 @ string      @ M=1   @ kpc^2/Myr   @ K00:FORMULA|beta^eta_t*K0*Rig^delta
  Model1DKisoVc    @ Transport      @ Kpp               @ string      @ M=0   @ GeV^2/Myr   @ FORMULA|(4./3.)*(Va*1.022712e-3*beta*Etot)^2/(delta*(4-delta^2)*(4-delta)*K0
```

inputs/init.par

All input ingredients are controlled by ***only one*** ASCII parameter file.

```
##############################################################################
#####                   LIST of PARAMETERS (and VALUES)                 #####
#####  group @subgroup @parameter @type @M= @unit @val @H= @B= @[opt]Info  #####
##############################################################################

  Model1DKisoVc   @ ISM            @ ParNames          @ string     @ M=0  @ -          @ -
  Model1DKisoVc   @ ISM            @ ParUnits          @ string     @ M=0  @ -          @ -
  Model1DKisoVc   @ ISM            @ ParVals           @ string     @ M=0  @ -          @ -
  Model1DKisoVc   @ ISM            @ Density           @ string     @ M=1  @ cm-3       @ HI:FORMULA|0.867
  Model1DKisoVc   @ ISM            @ Density           @ string     @ M=1  @ cm-3       @ HII:FORMULA|0.033
  Model1DKisoVc   @ ISM            @ Density           @ string     @ M=1  @ cm-3       @ H2:FORMULA|0.
  Model1DKisoVc   @ ISM            @ Density           @ string     @ M=1  @ cm-3       @ He:FORMULA|0.1
  Model1DKisoVc   @ ISM            @ Te                @ string     @ M=0  @ K          @ FORMULA|1.e4
  Model1DKisoVc   @ SrcPointLike   @ Species           @ string     @ M=1  @ -          @ -
  Model1DKisoVc   @ SrcPointLike   @ SpectraAbundInit  @ string     @ M=1  @ -          @ -
  Model1DKisoVc   @ SrcPointLike   @ SpectraNormInTempl @ string    @ M=1  @ -          @ -
  Model1DKisoVc   @ SrcPointLike   @ SpectraPerCR      @ string     @ M=1  @ -          @ -
  Model1DKisoVc   @ SrcPointLike   @ SrcXPosition      @ string     @ M=1  @ -          @ -
  Model1DKisoVc   @ SrcPointLike   @ SrcYPosition      @ string     @ M=1  @ -          @ -
  Model1DKisoVc   @ SrcPointLike   @ SrcZPosition      @ string     @ M=1  @ -          @ -
  Model1DKisoVc   @ SrcPointLike   @ TStart            @ int        @ M=1  @ -          @ -
  Model1DKisoVc   @ SrcPointLike   @ TStop             @ int        @ M=1  @ -          @ -
  Model1DKisoVc   @ SrcSteadyState @ Species           @ string     @ M=1  @ -          @ ASTRO_STD|ALL
  Model1DKisoVc   @ SrcSteadyState @ SpectraAbundInit  @ string     @ M=1  @ -          @ ASTRO_STD|kSSISOTFRAC,kSSISOTABUND,kFIPBIAS
  Model1DKisoVc   @ SrcSteadyState @ SpectraNormInTempl @ string    @ M=1  @ -          @ ASTRO_STD|q
  Model1DKisoVc   @ SrcSteadyState @ SpectraPerCR      @ string     @ M=1  @ -          @ ASTRO_STD|STEADYSTATE_GEN|q[PERCR:DEFAULT=1.e-5,1H=6.37e-5,4He=3.75e-3];alph
  Model1DKisoVc   @ Transport      @ ParNames          @ string     @ M=0  @ -          @ Va,Vc,K0,delta,eta_t
  Model1DKisoVc   @ Transport      @ ParUnits          @ string     @ M=0  @ -          @ km/s,km/s,kpc^2/Myr,-,-
  Model1DKisoVc   @ Transport      @ ParVals           @ string     @ M=0  @ -          @ 2.0,0.0,0.059,0.66,1.
  Model1DKisoVc   @ Transport      @ Wind              @ string     @ M=1  @ km/s       @ W0:FORMULA|Vc
  Model1DKisoVc   @ Transport      @ VA                @ string     @ M=0  @ km/s       @ FORMULA|Va
  Model1DKisoVc   @ Transport      @ K                 @ string     @ M=1  @ kpc^2/Myr  @ K00:FORMULA|beta^eta_t*K0*Rig^delta
  Model1DKisoVc   @ Transport      @ Kpp               @ string     @ M=0  @ GeV^2/Myr  @ FORMULA|(4./3.)*(Va*1.022712e-3*beta*Etot)^2/(delta*(4-delta^2)*(4-delta)*K0
```

e.g.: change the functional form of the diffusion coefficient:

power law

$$K(E) = {\color{red}K_0}\, \beta^{\eta} \left(\frac{R}{1\,\mathrm{GV}}\right)^{\color{red}\delta}$$

inputs/init.par

All input ingredients are controlled by ***only one*** ASCII parameter file.

```
################################################################################
#####                    LIST of PARAMETERS (and VALUES)                   #####
#####  group @subgroup @parameter @type @M= @unit @val @H= @B= @[opt]Info  #####
################################################################################

 Model1DKisoVc     @ ISM            @ ParNames          @ string       @ M=0    @ -             @ -
 Model1DKisoVc     @ ISM            @ ParUnits          @ string       @ M=0    @ -             @ -
 Model1DKisoVc     @ ISM            @ ParVals           @ string       @ M=0    @ -             @ -
 Model1DKisoVc     @ ISM            @ Density           @ string       @ M=1    @ cm-3          @ HI:FORMULA|0.867
 Model1DKisoVc     @ ISM            @ Density           @ string       @ M=1    @ cm-3          @ HII:FORMULA|0.033
 Model1DKisoVc     @ ISM            @ Density           @ string       @ M=1    @ cm-3          @ H2:FORMULA|0.
 Model1DKisoVc     @ ISM            @ Density           @ string       @ M=1    @ cm-3          @ He:FORMULA|0.1
 Model1DKisoVc     @ ISM            @ Te                @ string       @ M=0    @ K             @ FORMULA|1.e4
 Model1DKisoVc     @ SrcPointLike   @ Species           @ string       @ M=1    @ -             @ -
 Model1DKisoVc     @ SrcPointLike   @ SpectraAbundInit  @ string       @ M=1    @ -             @ -
 Model1DKisoVc     @ SrcPointLike   @ SpectraNormInTempl @ string      @ M=1    @ -             @ -
 Model1DKisoVc     @ SrcPointLike   @ SpectraPerCR      @ string       @ M=1    @ -             @ -
 Model1DKisoVc     @ SrcPointLike   @ SrcXPosition      @ string       @ M=1    @ -             @ -
 Model1DKisoVc     @ SrcPointLike   @ SrcYPosition      @ string       @ M=1    @ -             @ -
 Model1DKisoVc     @ SrcPointLike   @ SrcZPosition      @ string       @ M=1    @ -             @ -
 Model1DKisoVc     @ SrcPointLike   @ TStart            @ int          @ M=1    @ -             @ -
 Model1DKisoVc     @ SrcPointLike   @ TStop             @ int          @ M=1    @ -             @ -
 Model1DKisoVc     @ SrcSteadyState @ Species           @ string       @ M=1    @ -             @ ASTRO_STD|ALL
 Model1DKisoVc     @ SrcSteadyState @ SpectraAbundInit  @ string       @ M=1    @ -             @ ASTRO_STD|kSSISOTFRAC,kSSISOTABUND,kFIPBIAS
 Model1DKisoVc     @ SrcSteadyState @ SpectraNormInTempl @ string      @ M=1    @ -             @ ASTRO_STD|q
 Model1DKisoVc     @ SrcSteadyState @ SpectraPerCR      @ string       @ M=1    @ -             @ ASTRO_STD|STEADYSTATE_GEN|q[PERCR:DEFAULT=1.e-5,1H=6.37e-5,4He=3.75e-3];alpha[P
 Model1DKisoVc     @ Transport      @ ParNames          @ string       @ M=0    @ -             @ Va,Vc,K0,delta,eta_t,Rbreak,Deltabreak,sbreak
 Model1DKisoVc     @ Transport      @ ParUnits          @ string       @ M=0    @ -             @ km/s,km/s,kpc^2/Myr,-,-,GV,-,-
 Model1DKisoVc     @ Transport      @ ParVals           @ string       @ M=0    @ -             @ 2.,0.,0.071,0.53,1.,312.,0.14,0.040
 Model1DKisoVc     @ Transport      @ Wind              @ string       @ M=1    @ km/s          @ W0:FORMULA|Vc
 Model1DKisoVc     @ Transport      @ VA                @ string       @ M=0    @ km/s          @ FORMULA|Va
 Model1DKisoVc     @ Transport      @ K                 @ string       @ M=1    @ kpc^2/Myr     @ K00:FORMULA|beta^eta_t*K0*Rig^delta*(1+(Rig/Rbreak)^(Deltabreak/sbreak))^(-sbre
 Model1DKisoVc     @ Transport      @ Kpp               @ string       @ M=0    @ GeV^2/Myr     @ FORMULA|(4./3.)*(Va*1.022712e-3*beta*Etot)^2/(delta*(4-delta^2)*(4-delta)*K00)
```

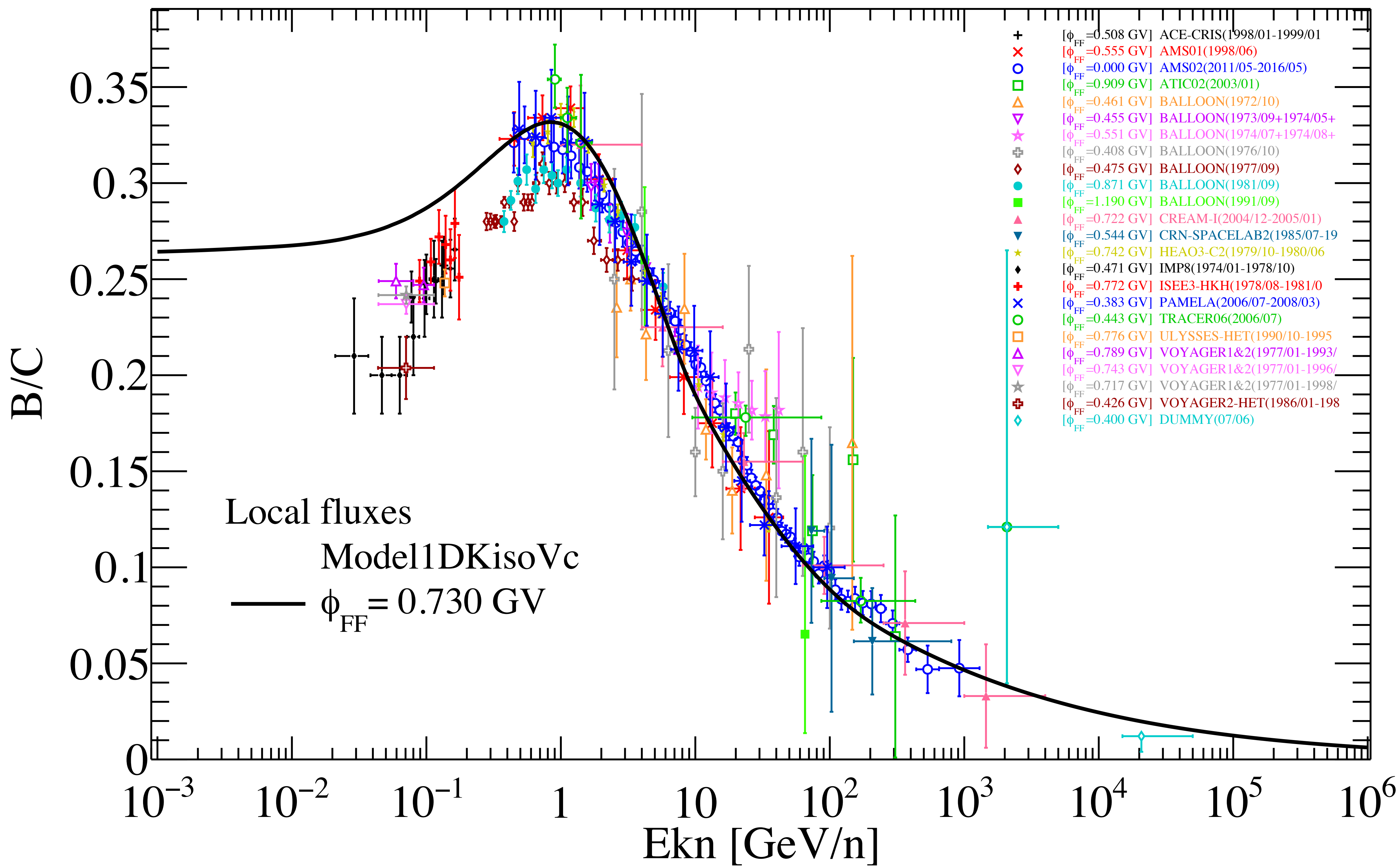
e.g.: change the functional form of the diffusion coefficient:

power law $\Rightarrow$ **broken power law**

$$K(E) = K_0\,\beta^\eta \left(\frac{R}{1\,\mathrm{GV}}\right)^\delta \quad\Longrightarrow\quad K(E) = K_0\,\beta^\eta \frac{(R/1\,\mathrm{GV})^\delta}{\left\{1+(R/R_b)^{\Delta\delta/s}\right\}^s}$$

USINE is interfaced with ROOT6

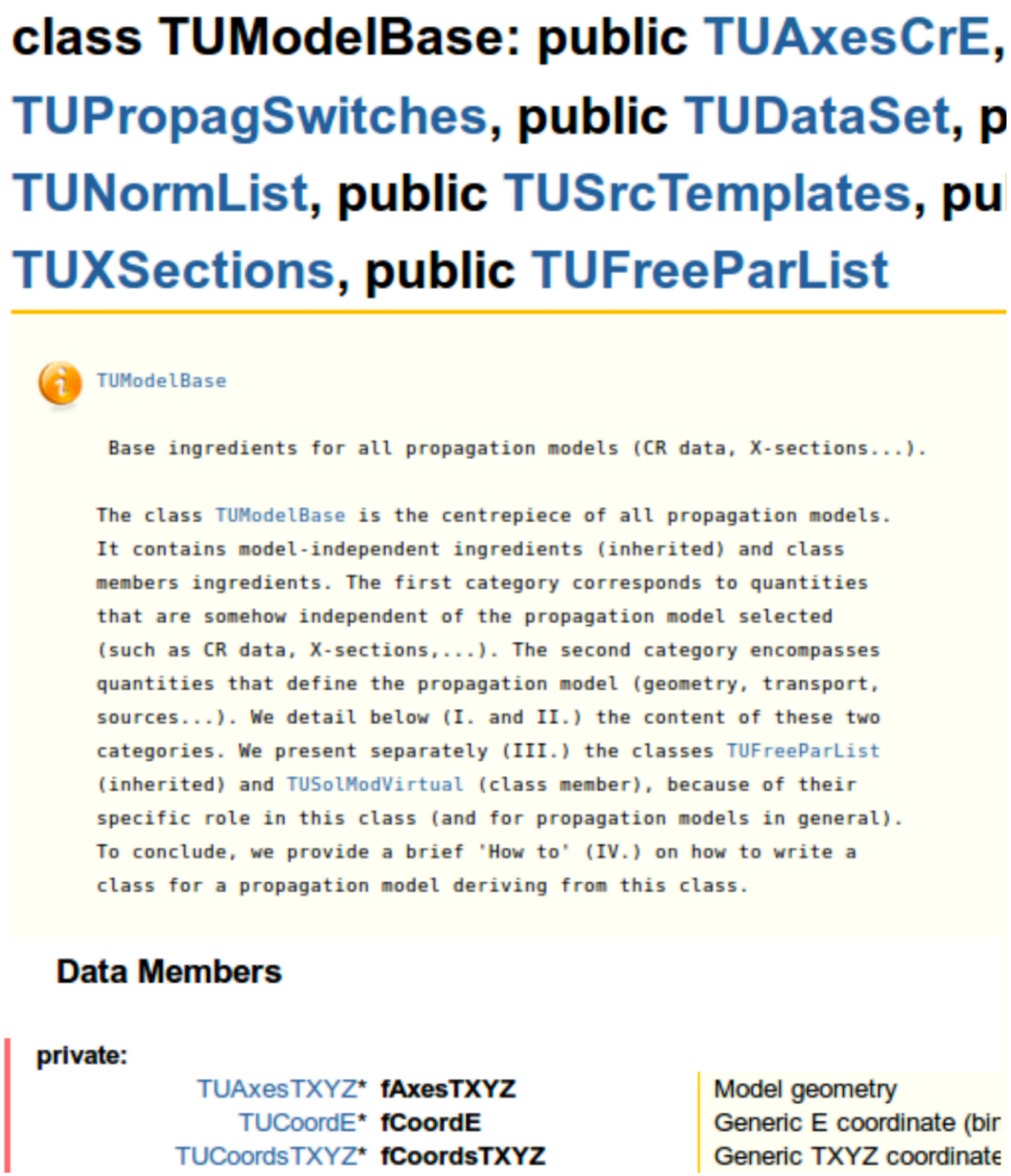
Output figures are generated with ROOT6.



Documentation

A full documentation of classes and methods.

ROOT style (THTML)



class TUModelBase: public TUAxesCrE, TUPropagSwitches, public TUDataSet, p TUNormList, public TUSrcTemplates, pu TUXSections, public TUFreeParList

TUModelBase

Base ingredients for all propagation models (CR data, X-sections...).

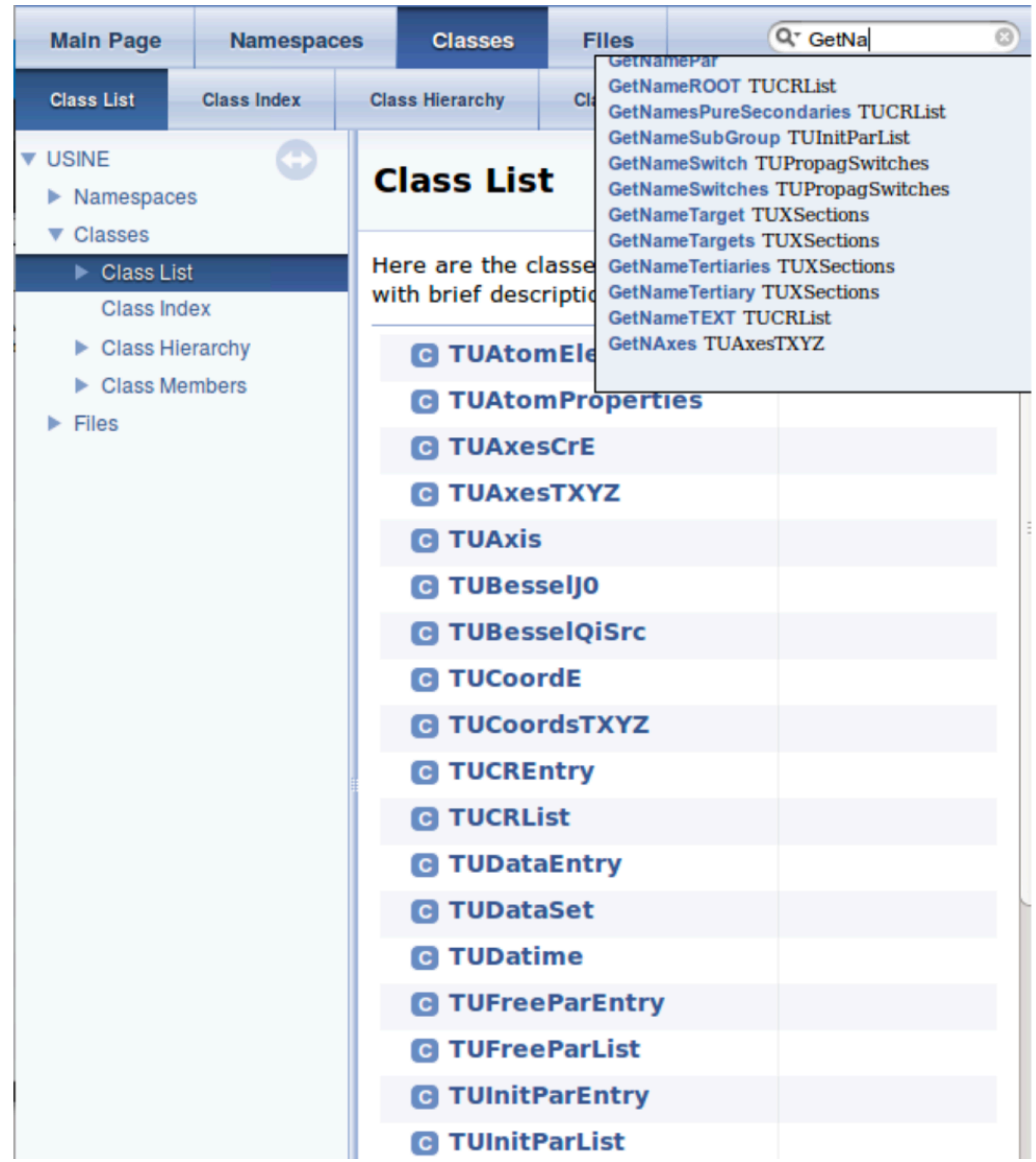
The class TUModelBase is the centrepiece of all propagation models. It contains model-independent ingredients (inherited) and class members ingredients. The first category corresponds to quantities that are somehow independent of the propagation model selected (such as CR data, X-sections,...). The second category encompasses quantities that define the propagation model (geometry, transport, sources...). We detail below (I. and II.) the content of these two categories. We present separately (III.) the classes TUFreeParList (inherited) and TUSolModVirtual (class member), because of their specific role in this class (and for propagation models in general). To conclude, we provide a brief 'How to' (IV.) on how to write a class for a propagation model deriving from this class.

Data Members

private:

TUAxesTXYZ*	**fAxesTXYZ**	Model geometry
TUCoordE*	**fCoordE**	Generic E coordinate (bir
TUCoordsTXYZ*	**fCoordsTXYZ**	Generic TXYZ coordinate

Doxygen style



1- Introduction

2- Cosmic ray physics

3- USINE: introduction

4- Several ways to run USINE: examples

5- Electrons and positrons soon in USINE

6- Conclusions and prospects

Several ways to run USINE: examples

1- Text-user interface, e.g.: relative contributions

> ./bin/usine_run -t inputs/init.par 1 0

```
       ***********************
         Text-User Interface
       ***********************

   A) PROPAGATION MODEL RESULTS (PRINTS & PLOTS)
      A1. Local IS and TOA CR fluxes [A1+ for extra plots]
      A2. [TODO] Spatial distribution (1D or 2D depending on models selected)

   B) MODIFY MODEL PARAMETERS AND RERUN (B to modify all)
      B1. Propagation switches
      B2. Transport parameters
      B3. CR source parameters

   C) INFO ON MODEL/PARAMETERS (C to print all)
      C1. Models (propagation and modulation)
      C2. Geometry
      C3. Transport parameters
      C4. Propagation switches
      C5. CR sources
      C6. ISM
      C7. CR list and parents (and E grids)
      C8. CR and normalisation data
      C9. X-section files and targets
```

1- Text-user interface, e.g.: relative contributions

> ./bin/usine_run -t inputs/init.par 1 0

```
   D) EXTRA PLOTS
      ... Nuclear production related ...
          D0. Relative contributions (primary, secondary, radioactive) in isotopes and elements
          D1. Ranking (propag.-weighted) of multi-step reactions
          D2a. Ranking (propag.-weighted) of individual XS
          D2b. Ranking (propag.-weighted) of ghost-separated XS
              [D1+, D2a+, D2b+ to use hard-coded propag.params]
              (see TURunPropagation::ExtraPlots_XProdFraction)
      ... Decay related ...
          D3. BETA-decay species [D3+ to check decayed=appeared]
          D4. [TODO] EC-decay species [D4+ to check decayed=appeared]
      ... Differential production ...
          D5. Source terms per reaction (before propagation)
          D6. Contributions per reaction (with propagation)
          D7. Contributions per energy range (with propagation)
          D8. Tertiary contributions for antinuclei [D7- to set sigINAtot to 0.]

   E) COMPARISON PLOTS VARYING SOME INGREDIENTS ('+' to normalise to data for each config., e.g. E3+)
      E1. Switch on/off propagation effects (losses, decay, etc.)
      E2. Boundary conditions
      ... X-sections ...
          E3. [NUC] Inelastic (files $USINE/inputs/XS_NUCLEI/sigTot*)
          E4. [NUC] Production (files $USINE/inputs/XS_NUCLEI/sigSpal*)
          E5. [ANTINUC] Inelastic (files $USINE/inputs/XS_ANTINUC/sigInel*)
          E6. [ANTINUC] Production (files $USINE/inputs/XS_ANTINUC/dSdE*)
          E7. [ANTINUC] Tertiary: NONAN (files $USINE/inputs/XS_ANTINUC/sigInelNONANN*)
          E8. [ANTINUC] Tertiary: redistribution (files $USINE/inputs/XS_ANTINUC/*tertiary*)

   [Q to quit]

>> selection [e.g., A1]: D0
```

1- Text-user interface, e.g.: relative contributions

> ./bin/usine_run -t inputs/init.par 1 0

```
   D) EXTRA PLOTS
      ... Nuclear production related ...
          D0. Relative contributions (primary, secondary, radioactive) in isotopes and elements
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          D2a. Ranking (propag.-weighted) of individual XS
          D2b. Ranking (propag.-weighted) of ghost-separated XS
              [D1+, D2a+, D2b+ to use hard-coded propag.params]
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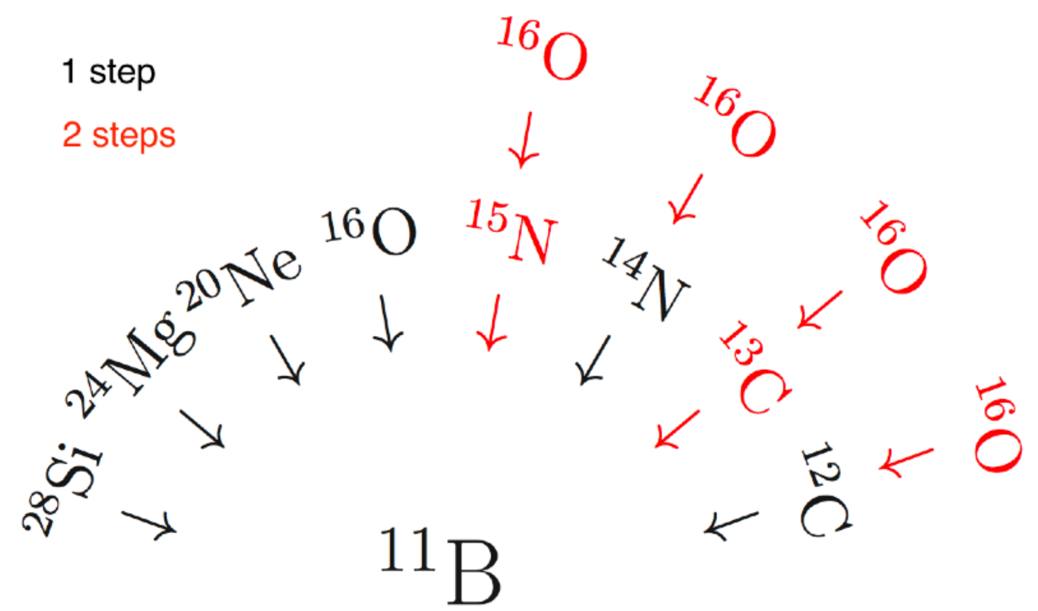
   [Q to quit]

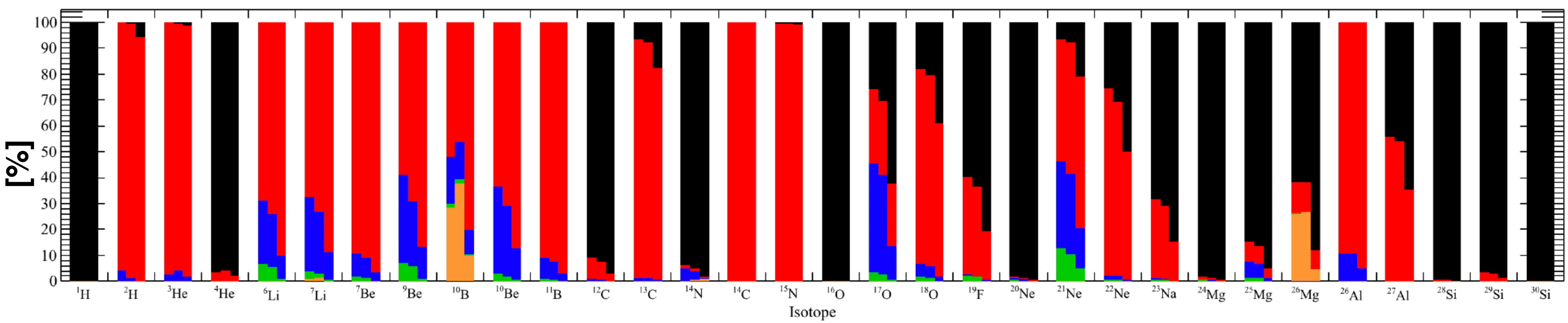
>> selection [e.g., A1]: D0
```

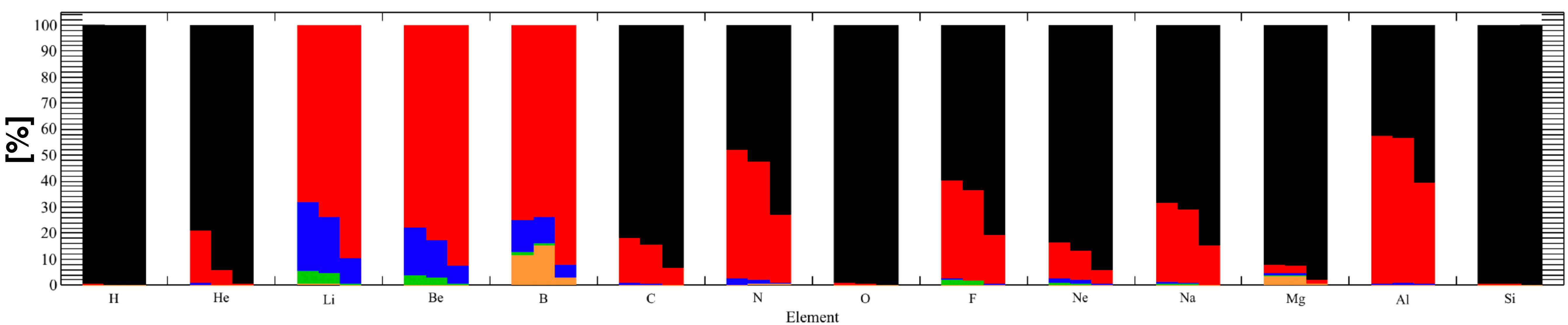
1- Text-user interface, e.g.: relative contributions

- **primaries (SNRs)**
- **1-step (fragmentation of primaries)**
- **2-steps**
- **> 2-steps**
- **decay-fed**



1, 10, 100 GV





2- Command line, e.g.: antiprotons flux

$$p\,(\mathrm{CR})\ +\mathrm{H}\,(\mathrm{ISM})\ \longrightarrow\ \bar{p}\ +\ X\ \ (\simeq 70\%)$$
$$\alpha\,(\mathrm{CR})\ +\mathrm{H}\,(\mathrm{ISM})\ \longrightarrow\ \bar{p}\ +\ X\ \ (\simeq 25\%)$$
$$p\,(\mathrm{CR})\ +\mathrm{He}\,(\mathrm{ISM})\ \longrightarrow\ \bar{p}\ +\ X\ \ (\simeq 4\%)$$
$$\alpha\,(\mathrm{CR})\ +\mathrm{He}\,(\mathrm{ISM})\ \longrightarrow\ \bar{p}\ +\ X\ \ (\simeq 1\%)$$

```
> ./bin/usine_run -l  inputs/init.par $USINE/output   1    1   1   H,He,H-BAR     0.564    3.0     R
```

```
[init_file]        USINE initialisation file init.XXX.par (used for calculation)
[output_dir]       Directory for outputs (plots, files, etc.)
[is_logfile]       If true, all run informations printed in output_dir/last_run.log, otherwise print on screen
[is_verbose]       To have more informations on the run (printed in logfile)
[is_batch]         Batch run (1) or show plots (0): macro and plots saved in both cases
[qties_to_show]    Comma-separated list of CRs (e.g., "10B+11B,B/C,O" or "<LNA>" or "ALLSPECTRUM"
[phiff_values]     Comma-separated list of Force-field modulation level in GV (e.g., 0.,0.5,1.)
[e_index]          Fluxes are multiplied by E^(e_index), with E selected from e_type
[e_type]           Fluxes displayed in "kEKN" [GeV/n], "kEK" or "kETOT" [GeV], or "kR" [GV]
```

2- Command line, e.g.: antiprotons flux

$$p\,(\mathrm{CR}) \;+ \mathrm{H}\,(\mathrm{ISM}) \;\longrightarrow\; \bar{p} \;+\; X \;\; (\simeq 70\%)$$

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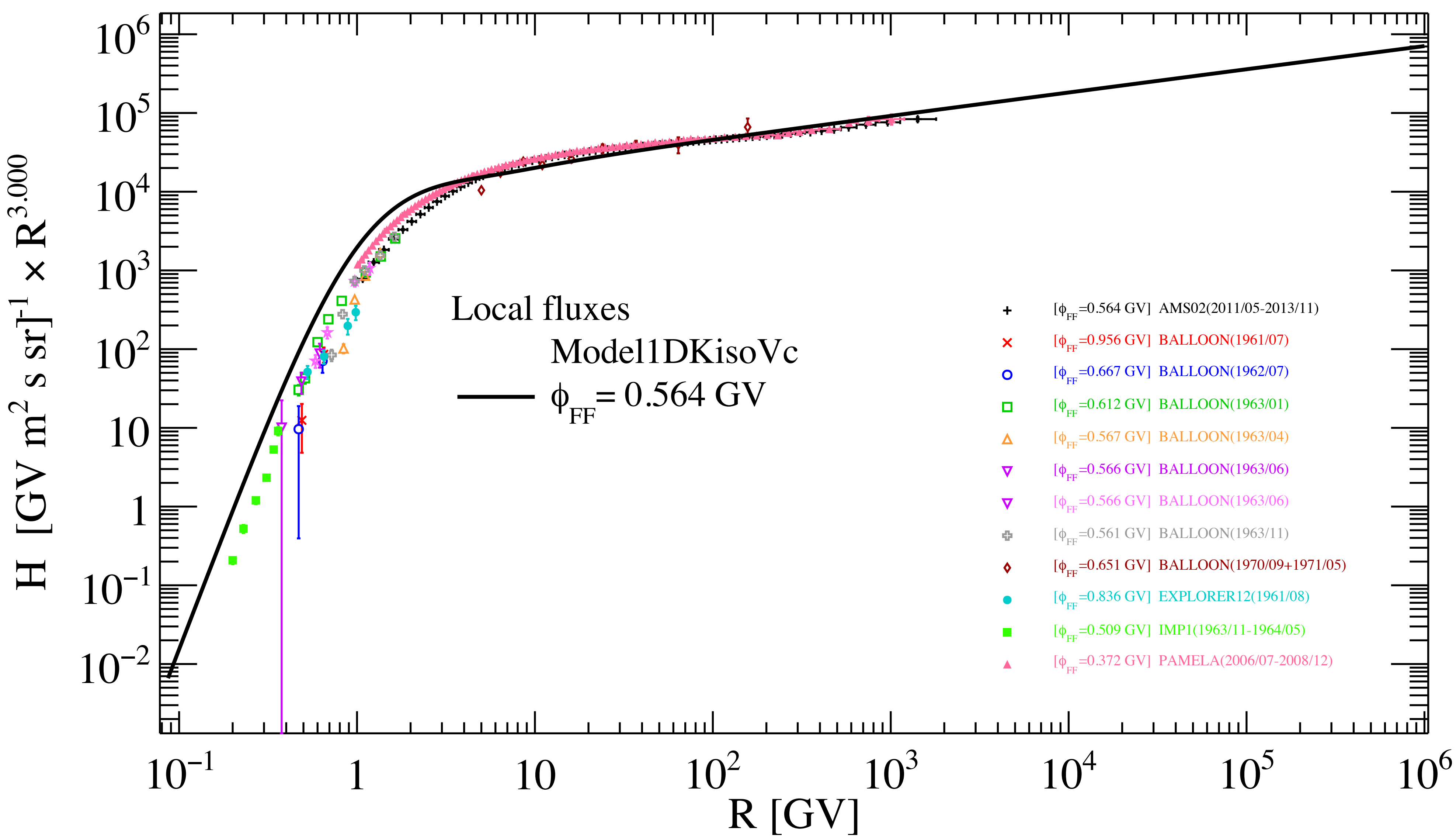
```
> ./bin/usine_run -l  inputs/init.par $USINE/output   1    1    1   H,He,H-BAR     0.564    3.0     EkN
```



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```
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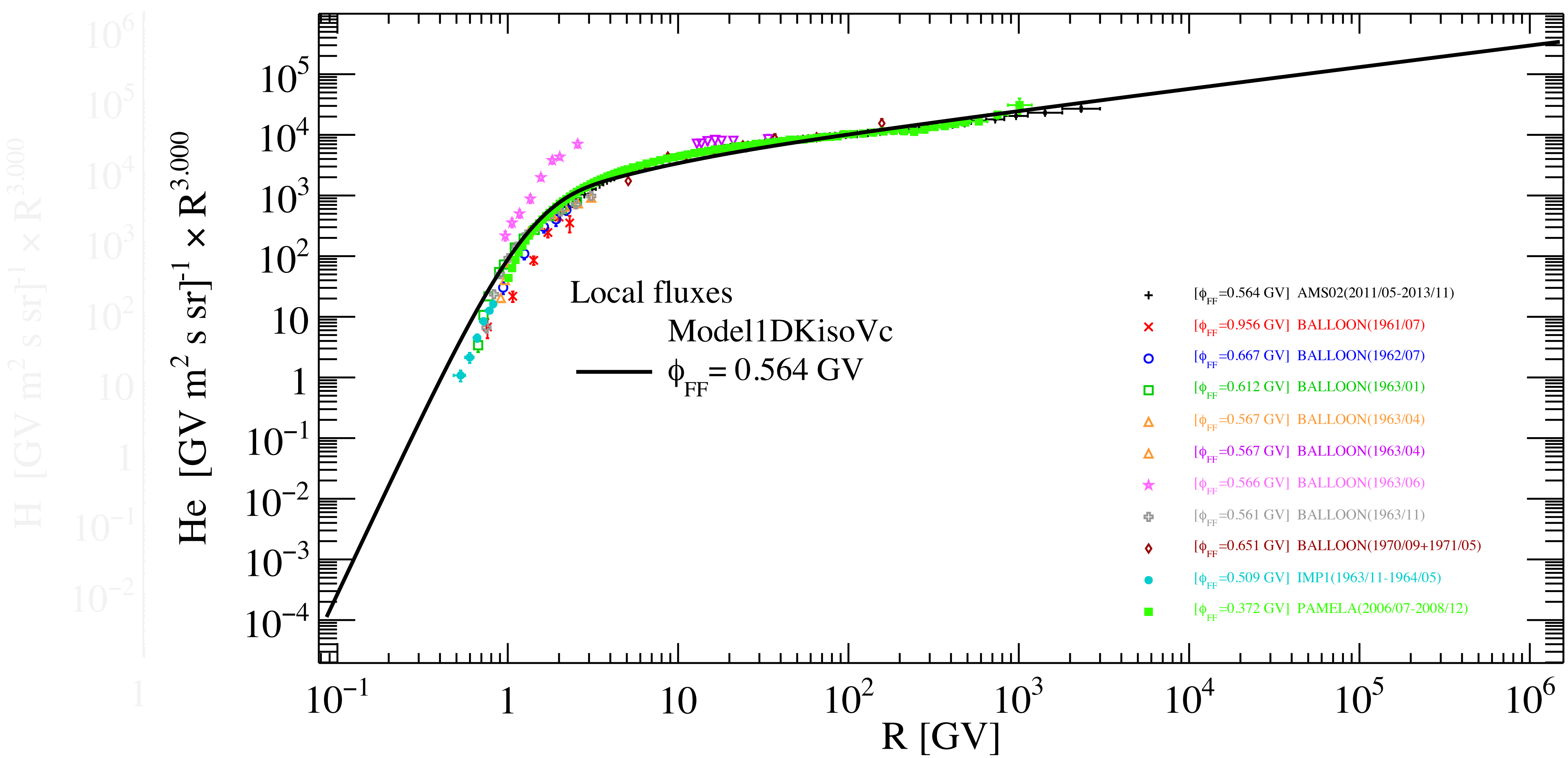
```



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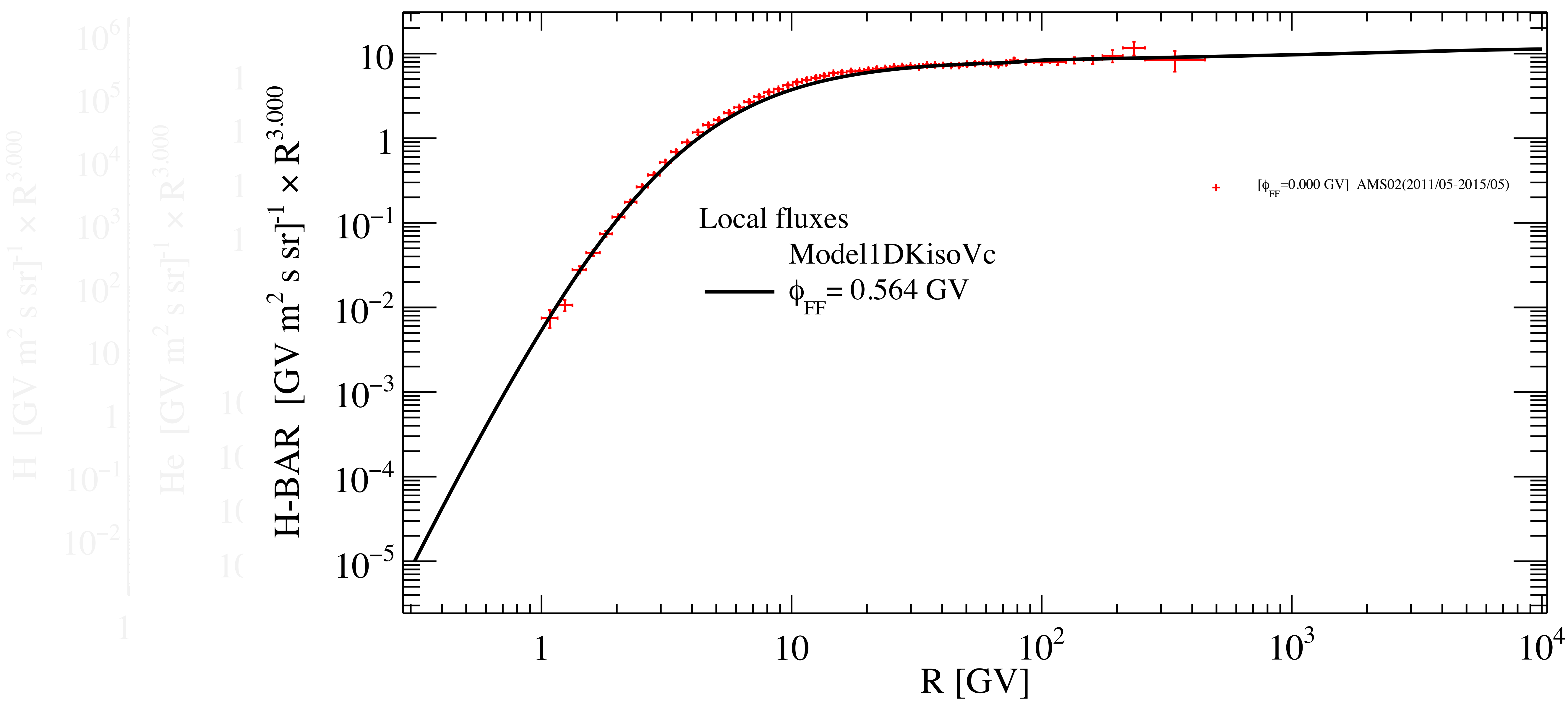
```



3- Minimisation, e.g.: determination of the propagation parameters using B/C

USINE is interfaced with ROOT6 and takes avantage of the MINUIT package for minimisation.

> ./bin/usine_run -m2 inputs/init.fit_bc.par $USINE/output 1 1 1

```
UsineRun         @ Fit            @ Minimiser        @ string        @ M=0    @ -              @ Minuit
UsineRun         @ Fit            @ Algorithm        @ string        @ M=0    @ -              @ combined
UsineRun         @ Fit            @ NMaxCall         @ int           @ M=0    @ -              @ 500000
###### N.B.: EDMmax=0.001*tolerance*up (from minuit doc)
UsineRun         @ Fit            @ Tol              @ double        @ M=0    @ -              @ 1.e-1
UsineRun         @ Fit            @ Precision        @ double        @ M=0    @ -              @ 1.e-8
UsineRun         @ Fit            @ PrintLevel       @ int           @ M=0    @ -              @ 2
UsineRun         @ Fit            @ IsMINOS          @ bool          @ M=0    @ -              @ 0
UsineRun         @ Fit            @ IsUseBinRange    @ bool          @ M=0    @ -              @ 0
UsineRun         @ Fit            @ NExtraInBinRange @ int           @ M=0    @ -              @ 5

UsineRun         @ FitFreePars    @ Transport        @ string        @ M=1    @ -              @ delta:FIT,LIN,[0.1,0.9],0.701,0.02
UsineRun         @ FitFreePars    @ Transport        @ string        @ M=1    @ -              @ Va:FIT,LIN,[2,100],81.,1
UsineRun         @ FitFreePars    @ Transport        @ string        @ M=1    @ -              @ Vc:FIT,LIN,[0.,30],4,1
UsineRun         @ FitFreePars    @ Transport        @ string        @ M=1    @ -              @ K0:FIT,LOG,[-4,0],-1.68,0.5

UsineRun         @ FitTOAData     @ QtiesExpsEType   @ string        @ M=0    @ -              @ B/C:AMS:kR
UsineRun         @ FitTOAData     @ ErrType          @ string        @ M=0    @ -              @ kERRTOT
UsineRun         @ FitTOAData     @ EminData         @ string        @ M=0    @ -              @ 45
UsineRun         @ FitTOAData     @ EmaxData         @ string        @ M=0    @ -              @ 5e9
UsineRun         @ FitTOAData     @ TStartData       @ string        @ M=0    @ -              @ 1950-01-01_00:00:00
UsineRun         @ FitTOAData     @ TStopData        @ string        @ M=0    @ -              @ 2100-01-01_00:00:00
```

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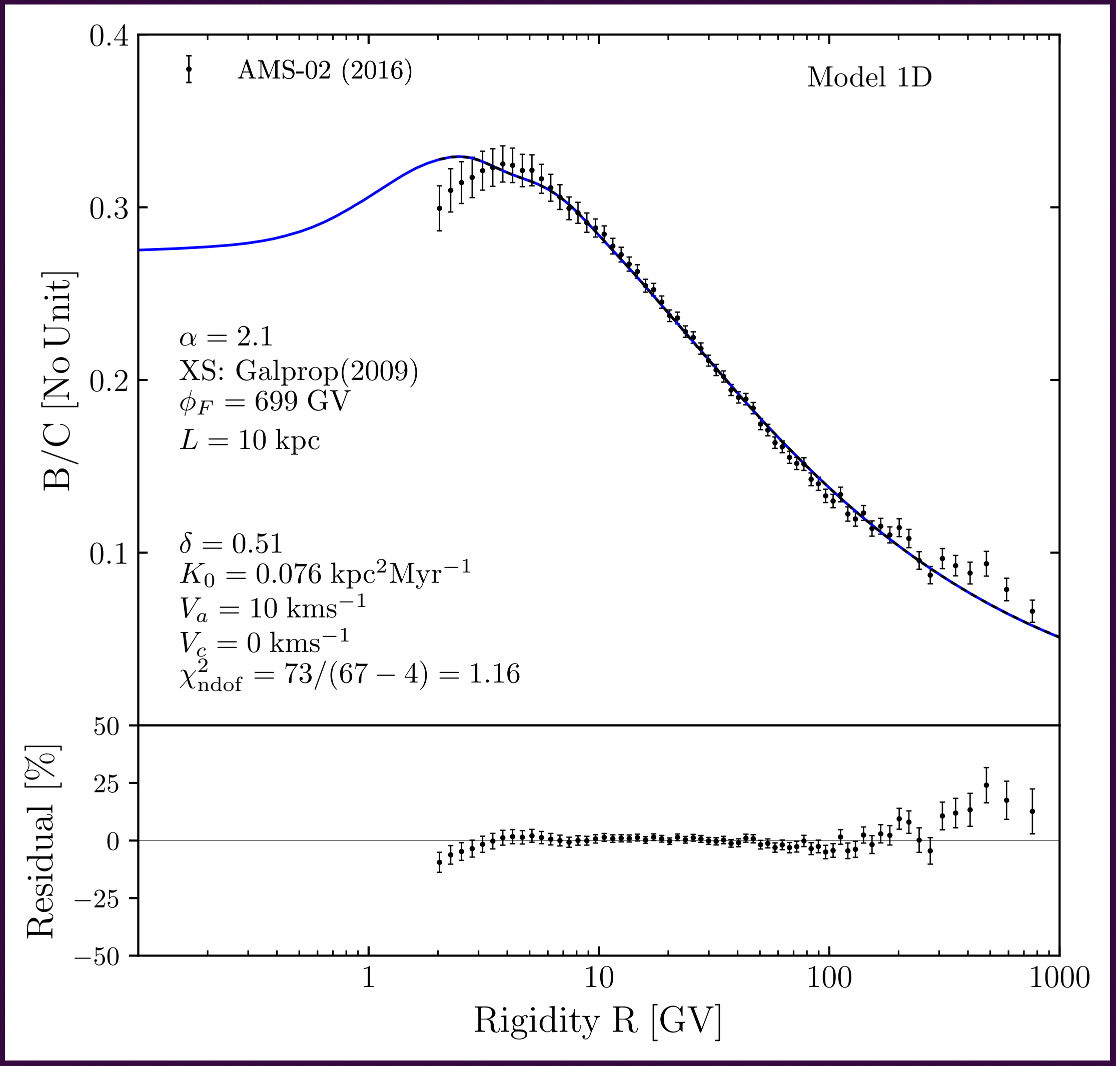
```
                      EDM=0.091268    STRATEGY= 2      ERR MATRIX NOT POS-DEF
  EXT PARAMETER                 APPROXIMATE        STEP         FIRST
  NO.   NAME       VALUE          ERROR          SIZE       DERIVATIVE
   1  delta         4.34181e-01   6.27294e-04  -0.00000e+00   1.44019e+01
   2  Va            9.99436e+01   5.50057e+00   0.00000e+00  -1.59966e-01
   3  Vc            4.31510e-03   5.02120e-01   0.00000e+00  -4.25280e-01
   4  log10_K0     -1.00096e+00   1.02342e-03   0.00000e+00   3.41672e+01
 EXTERNAL ERROR MATRIX.    NDIM=  25    NPAR=  4    ERR DEF=1
  3.935e-07 -1.991e-05  3.960e-06 -3.215e-07
 -1.991e-05  1.266e+00  6.603e-02  1.137e-04
  3.960e-06  6.603e-02  8.717e-03  2.120e-05
 -3.215e-07  1.137e-04  2.120e-05  1.047e-06
ERR MATRIX NOT POS-DEF
 PARAMETER  CORRELATION COEFFICIENTS
       NO.  GLOBAL      1      2      3      4
        1  0.54653   1.000 -0.028  0.068 -0.501
        2  0.63932  -0.028  1.000  0.628  0.099
        3  0.67633   0.068  0.628  1.000  0.222
        4  0.57139  -0.501  0.099  0.222  1.000
 ERR MATRIX NOT POS-DEF
 >>> Minimized in 1.133038e+03 s
          /---------------- ANALYSIS RESULT ----------------\
          | chi2_min=3.987551e+01 for 42 data and 4 pars
          | => chi2/dof=1.049356e+00
          \-------------------------------------------------/

              - Best-fit parameters after minimisation
                                       delta = +4.342e-01(+/-6.27e-04) [-] from delta_init=[+1.0e-01,+9.0e-01],+7.0e-01,+2.0e-02
                                          Va = +9.994e+01(+/-5.50e+00) [km/s] from Va_init=[+2.0e+00,+1.0e+02],+8.1e+01,+1.0e+00
                                          Vc = +4.315e-03(+/-5.02e-01) [km/s] from Vc_init=[+0.0e+00,+3.0e+01],+4.0e+00,+1.0e+00
                                    log10_K0 = -1.001e+00(+/-1.02e-03) [kpc^2/Myr] from log10_K0_init=[-4.0e+00,+0.0e+00],-1.7e+00,+5.0e-01
```



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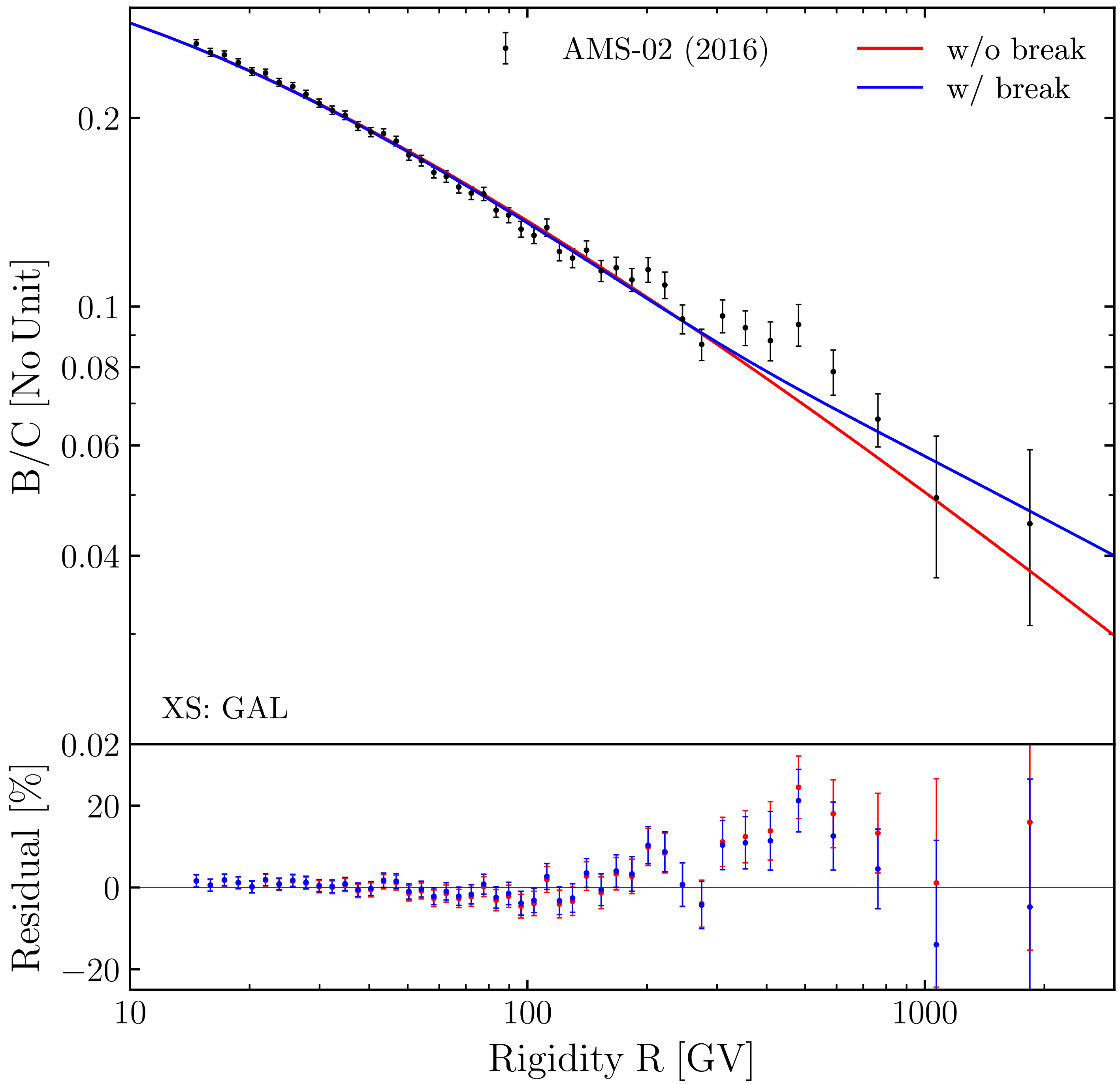
```



$$K(E) = K_0\,\beta^\eta \left(\frac{R}{1\,\mathrm{GV}}\right)^\delta$$

$$\Delta\chi^2 = 11$$

Decisive evidence! (Bayesian terms)

$$K(E) = K_0\,\beta^\eta \frac{(R/1\,\mathrm{GV})^\delta}{\left\{1 + (R/R_b)^{\Delta\delta/s}\right\}^s}$$

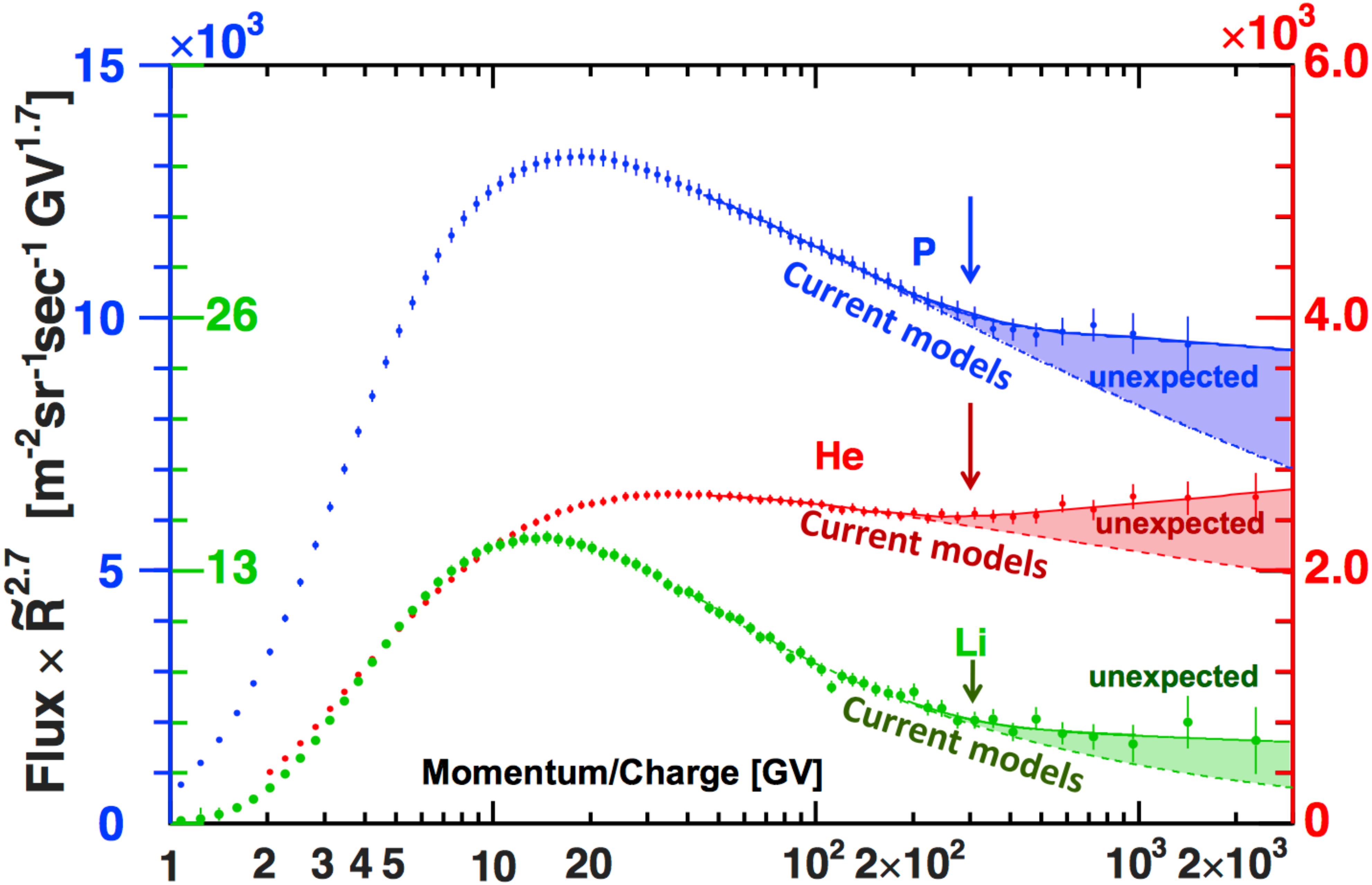
The break at ~200 GV is most likely due to propagation effects!

Y. Genolini, P. Serpico, MB, S. Caroff, V. Poulin, L. Derome, J. Lavalle, D. Maurin, V. Poireau, S. Rosier-Lee, P. Salati, and M. Vecchi (2017)

A universal break in the spectra of cosmic ray nuclei?

Pointed by PAMELA and confirmed by AMS-02: an universal kink at R~200 GV?

Δ_{kinck} ~ 0.12 - 0.13



This feature is not predicted by the conventional propagation models!

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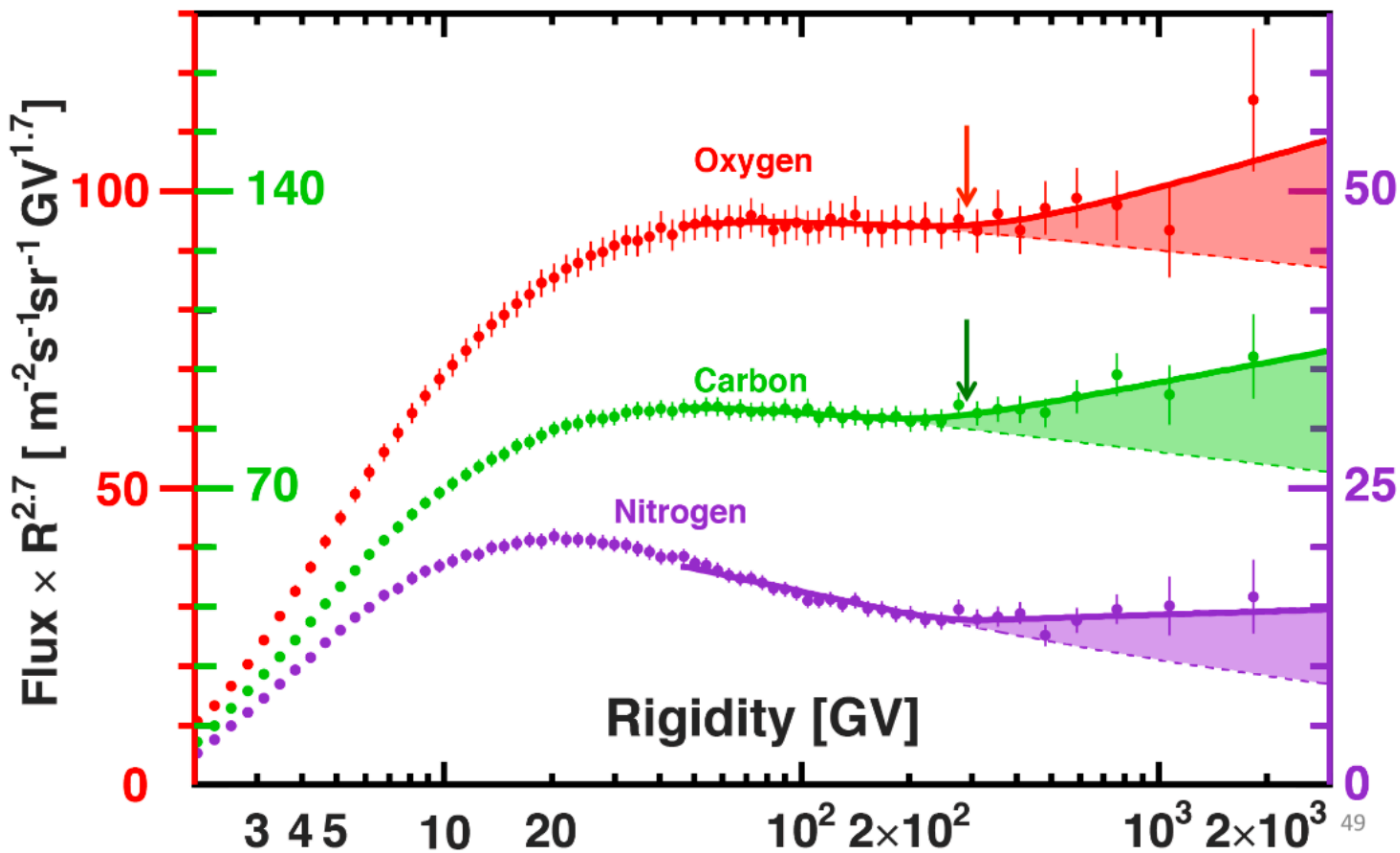

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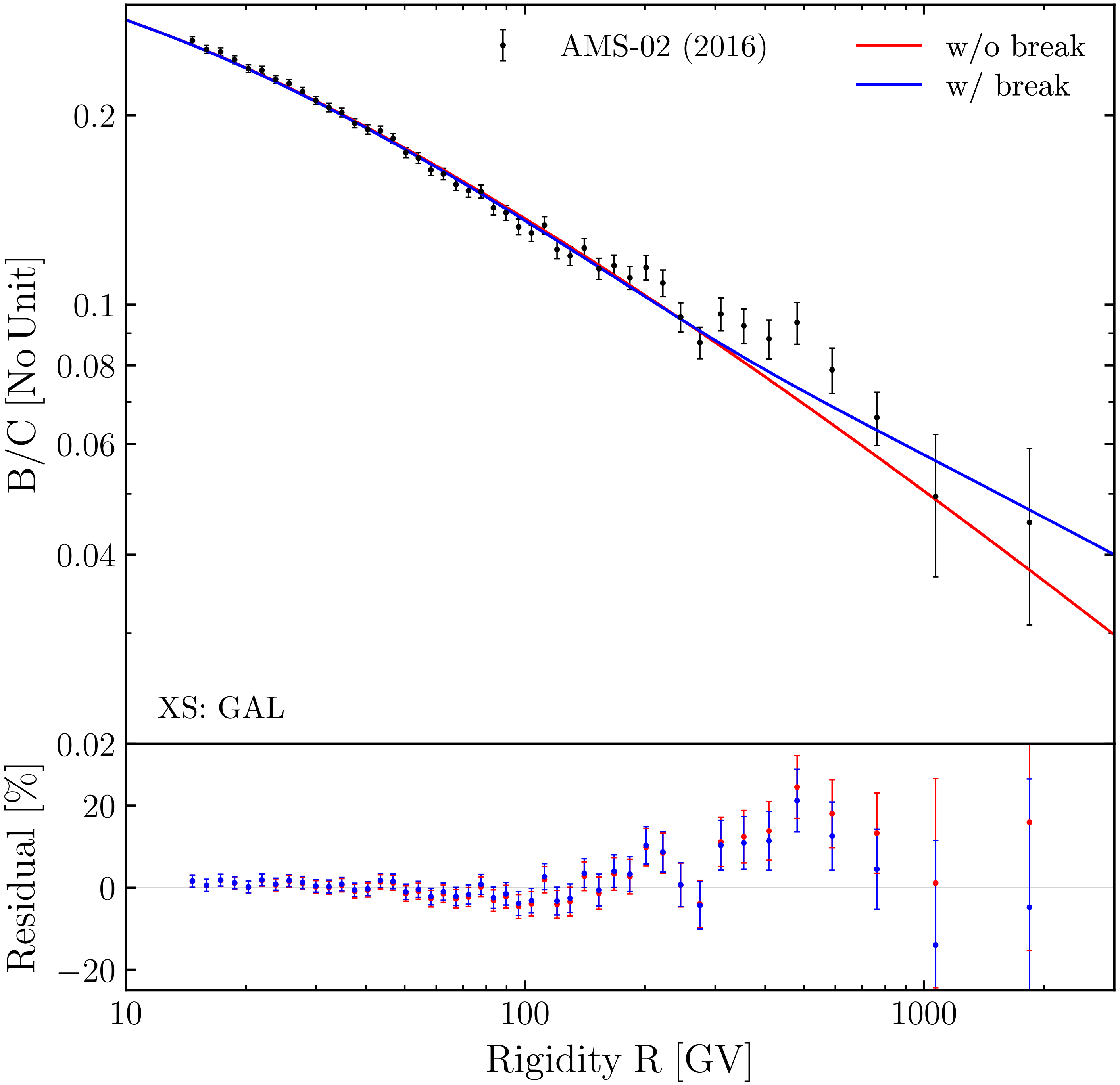

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$$\Delta\chi^2 = 11$$

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1- Introduction

2- Cosmic ray physics

3- USINE: introduction

4- Several ways to run USINE: examples

5- Electrons and positrons soon in USINE

6- Conclusions and prospects

Electrons and positrons soon in USINE

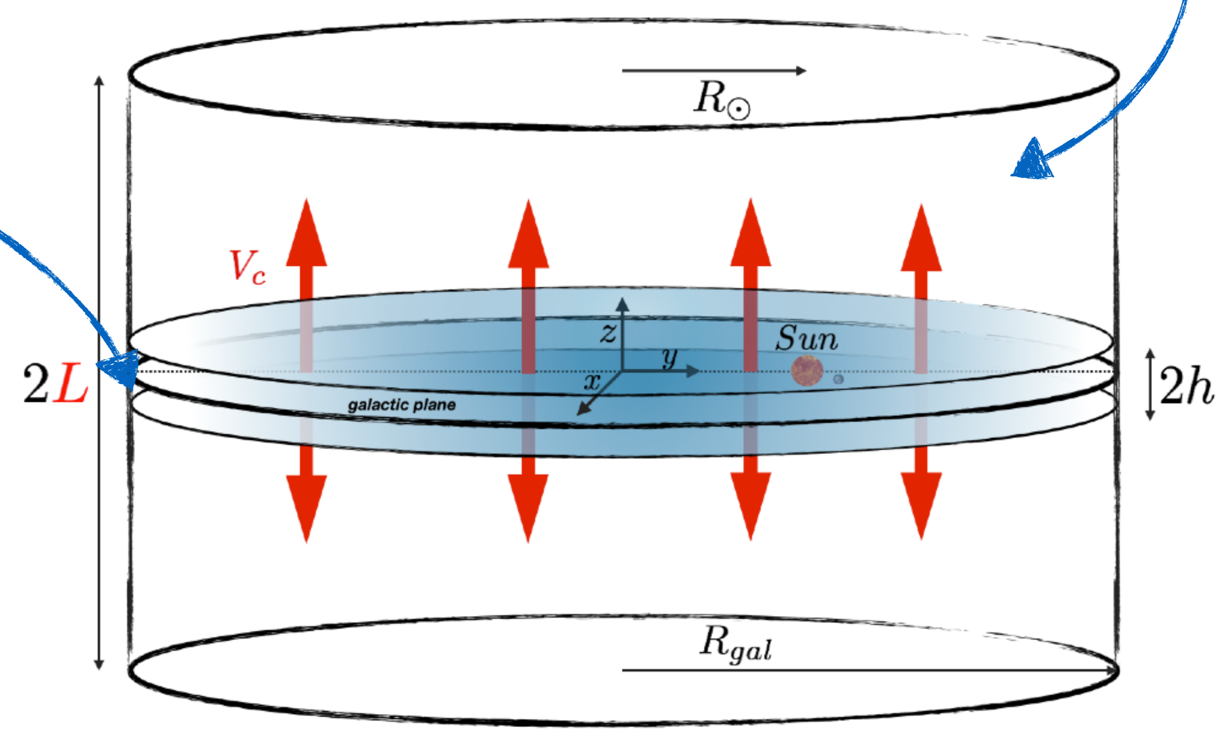
Electrons and positrons: the high-energy approximation

Cosmic rays transport equation (steady state)

$$\partial_z[V_C\,\mathrm{sign(z)}\,\psi] - K(E)\,\Delta\,\psi + 2h\,\delta(z)\,\partial_E\,[b_{\mathrm{disc}}(E)\,\psi] - D(E)\,\partial_E\,\psi] + \partial_E[b_{\mathrm{halo}}(E)\,\psi] = Q(E,\vec{x})$$

$$b_{\mathrm{disc}} = b_{\mathrm{adia}} + b_{\mathrm{ioni}} + b_{\mathrm{brem}} + b_{\mathrm{coul}}$$

$$b_{\mathrm{halo}} = b_{\mathrm{IC}} + b_{\mathrm{sync}}$$



We cannot solve analytically the transport equation when energy losses processes take place in different places in the Galaxy.

We need a **numerical** algorithm to solve the transport equation (GALPROP, DRAGON, PICARD, etc.)

Electrons and positrons: the high-energy approximation

Cosmic rays transport equation (steady state)

$$\partial_z [V_C \,\text{sign(z)}\, \psi] - K(E)\,\Delta\psi + 2h\,\delta(z)\,\partial_E\,[b_{\text{disc}}(E)\,\psi] - D(E)\,\partial_E\,\psi] + \partial_E[b_{\text{halo}}(E)\,\psi] = Q(E,\vec{x})$$

$$b_{\text{disc}} = b_{\text{adia}} + b_{\text{ioni}} + b_{\text{brem}} + b_{\text{coul}}$$

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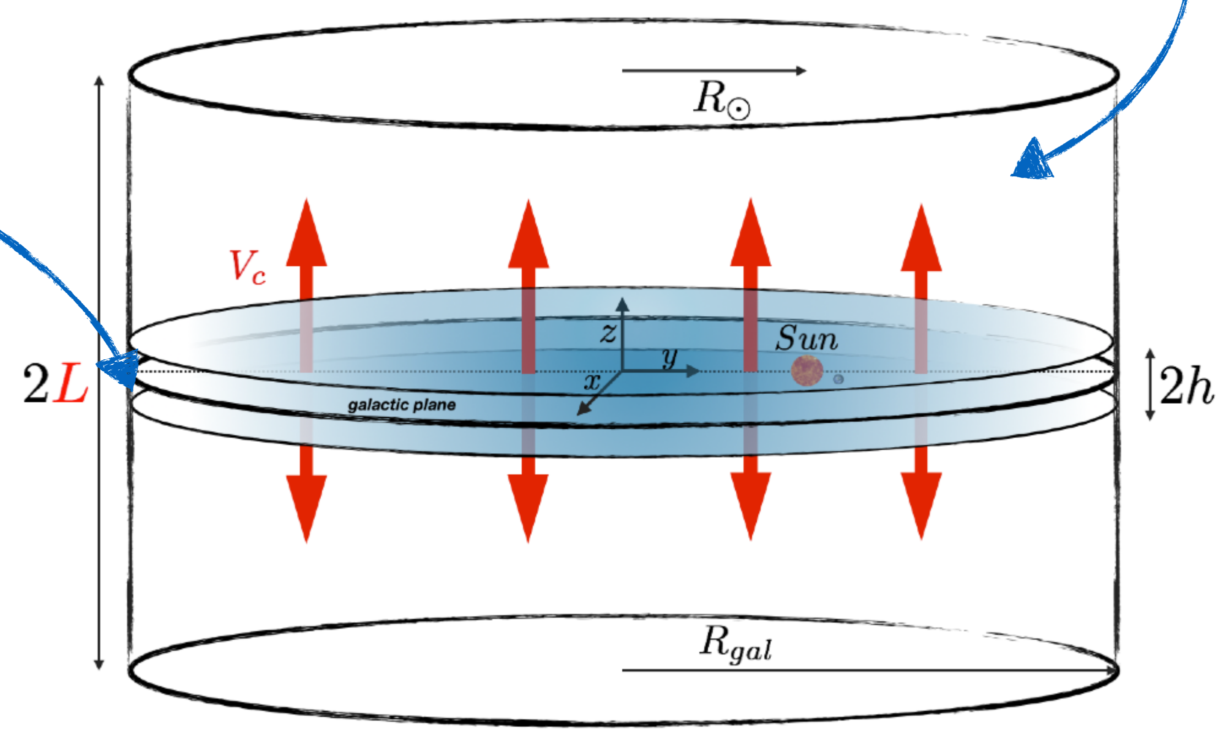

***E* > 10 GeV**

High energy approximation

$$-K(E) + \partial_E\,[b_{\text{halo}}(E)\psi] = Q(E,\vec{x})$$

Baltz & Edsjö (1998)
Delahaye+(2008)
MB+(2014)
etc.

Is E = 10 GeV a correct threshold to get rid of low energy effects?
(Especially with the high accuracy of the AMS-02 data at E ~ 10 GeV)

The pinching method

Cosmic rays transport equation (steady state)

$$\partial_z[V_C\,\mathrm{sign(z)}\,\psi] - K(E)\,\Delta\psi + 2h\,\delta(z)\,\partial_E\,[b_{\rm disc}(E)\,\psi] - D(E)\,\partial_E\,\psi] + \partial_E[b_{\rm halo}(E)\,\psi] = Q(E,\vec{x})$$

$$b_{\rm disc} = b_{\rm adia} + b_{\rm ioni} + b_{\rm brem} + b_{\rm coul}$$

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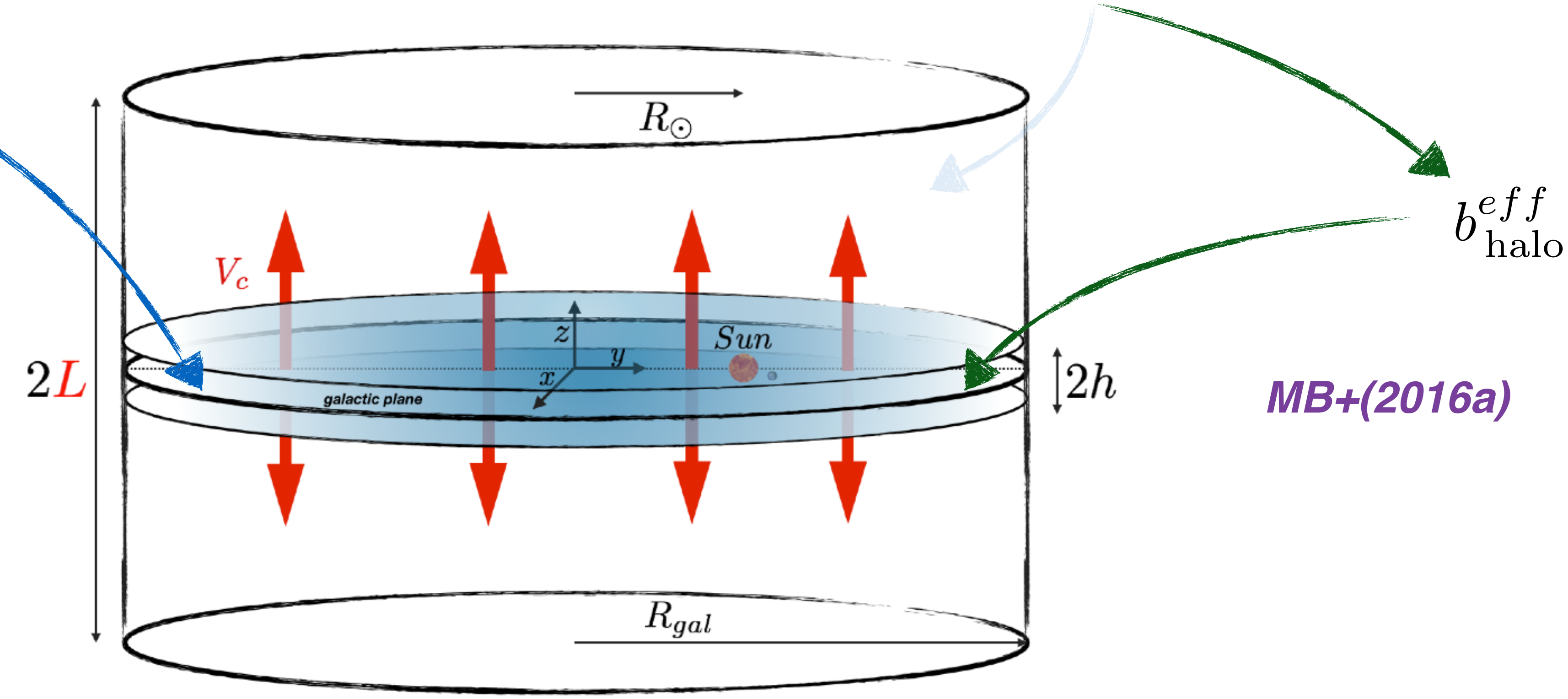


MB+(2016a)

The pinching method

$$\partial_z[V_C\,\mathrm{sign(z)}\,\psi] - K(E)\,\Delta\psi + 2h\,\delta(z)\,\partial_E\left\{\left[b_{\rm disc}(E) + b^{eff}_{\rm halo}(E)\right]\,\psi - D(E)\,\partial_E\,\psi\right\} = Q(E,\vec{x})$$

The pinching method

MB+(2016a)

$$\partial_z[V_C\,\mathrm{sign(z)}\,\psi] - K(E)\,\Delta\,\psi + 2h\,\delta(z)\,\partial_E\left\{\left[b_{\rm disc}(E) + b^{eff}_{\rm halo}(E)\right]\,\psi - D(E)\,\partial_E\,\psi\right\} = Q(E,\vec{x})$$

$$b_{\rm halo} = b_{\rm IC} + b_{\rm sync} \longrightarrow b^{eff}_{\rm halo}(E,r) = \bar{\xi}(E,r)\,b_{\rm halo}(E)$$

pinching factor

$$\bar{\xi}(E,r) = \frac{1}{\psi(E,r,0)}\sum_{i=1}^{+\infty} J_0(\alpha_i\frac{r}{R})\,\bar{\xi}_i(E)\,P_i(E,0)$$

$$\bar{\xi}_i(E) = \frac{\int_E^{+\infty} dE_S\left[J_i(E_S) + 4k_i^2\int_E^{E_S} dE'\,\frac{K(E')}{b(E')}\,B_i(E',E_S)\right]}{\int_E^{+\infty} dE_S\,B_i(E,E_S)}$$

$$J_i(E_S) = \frac{1}{h}\int_0^L dz_S\;\mathcal{F}_i(z_S)\,Q_i(E_S,z_S) \qquad Q_i(E,z) = \frac{2}{R^2 J_1^2(\alpha_i)}\int_0^R dr\,r\,J_0(\xi_i)\;Q(E,r,z)$$

$$B_i(E,E_S) = \sum_{n=2m+1}^{+\infty} Q_{i,n}(E_S)\,\exp\left[-C_{i,n}\lambda_D^2\right] \qquad C_{i,n} = \frac{1}{4}\left[\left(\frac{\alpha_i}{R}\right)^2 + (nk_0)^2\right]$$

$$Q_{i,n}(E) = \frac{1}{L}\int_{-L}^{L} dz\;\varphi_n(z)\;\frac{2}{R^2 J_1^2(\alpha_i)}\int_0^R dr\,r\,J_0\left(\alpha_i\frac{r}{R}\right)\;Q(E,r,z)$$

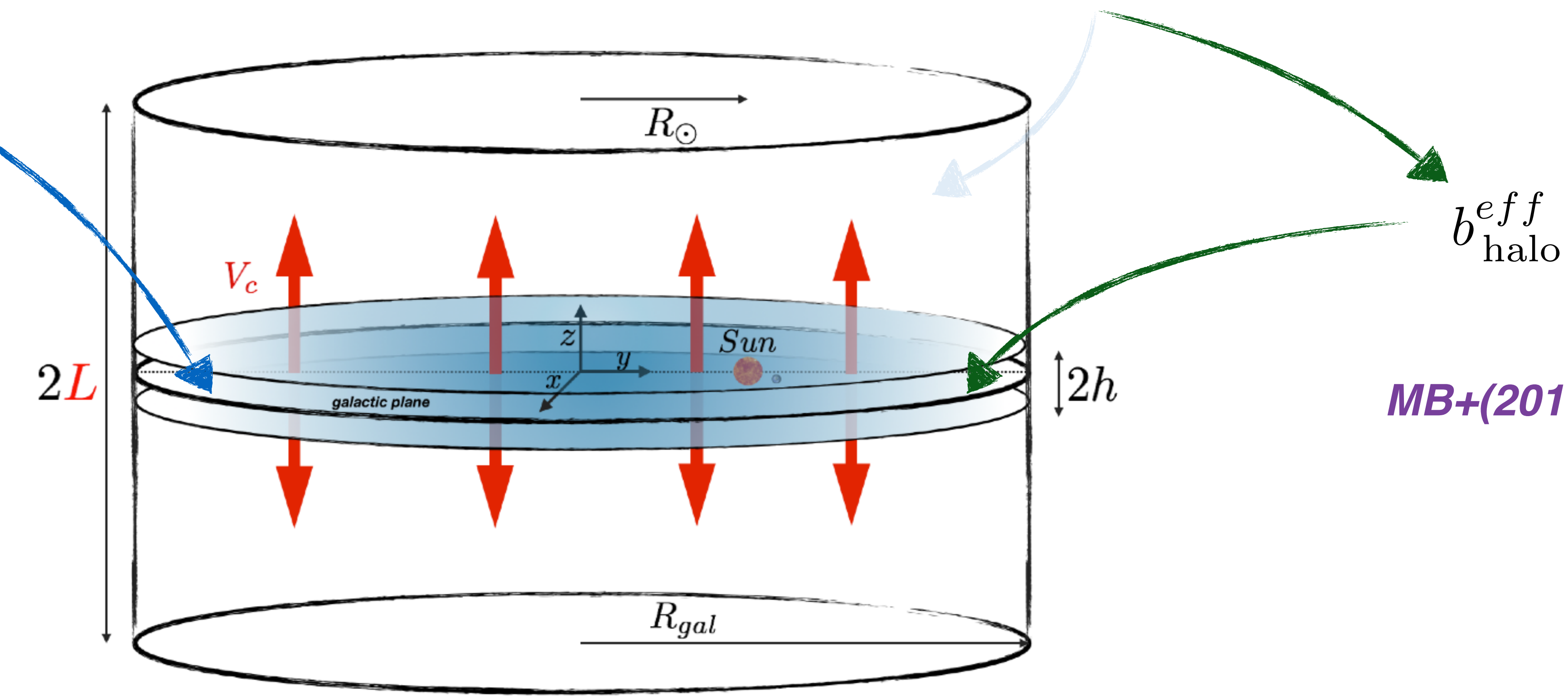
The pinching method

Cosmic rays transport equation (steady state)

$$\partial_z [V_C \, \mathrm{sign(z)} \, \psi] - K(E) \, \Delta \psi + 2h \, \delta(z) \, \partial_E \left[b_{\rm disc}(E) \, \psi \right] - D(E) \, \partial_E \, \psi] + \partial_E [b_{\rm halo}(E) \, \psi] = Q(E, \vec{x})$$

$$b_{\rm disc} = b_{\rm adia} + b_{\rm ioni} + b_{\rm brem} + b_{\rm coul}$$

$$b_{\rm halo} = b_{\rm IC} + b_{\rm sync}$$



MB+(2016a)

The pinching method

$$\partial_z [V_C \, \mathrm{sign(z)} \, \psi] - K(E) \, \Delta \psi + 2h \, \delta(z) \, \partial_E \left\{ \left[b_{\rm disc}(E) + b^{eff}_{\rm halo}(E) \right] \, \psi - D(E) \, \partial_E \, \psi \right\} = Q(E, \vec{x})$$

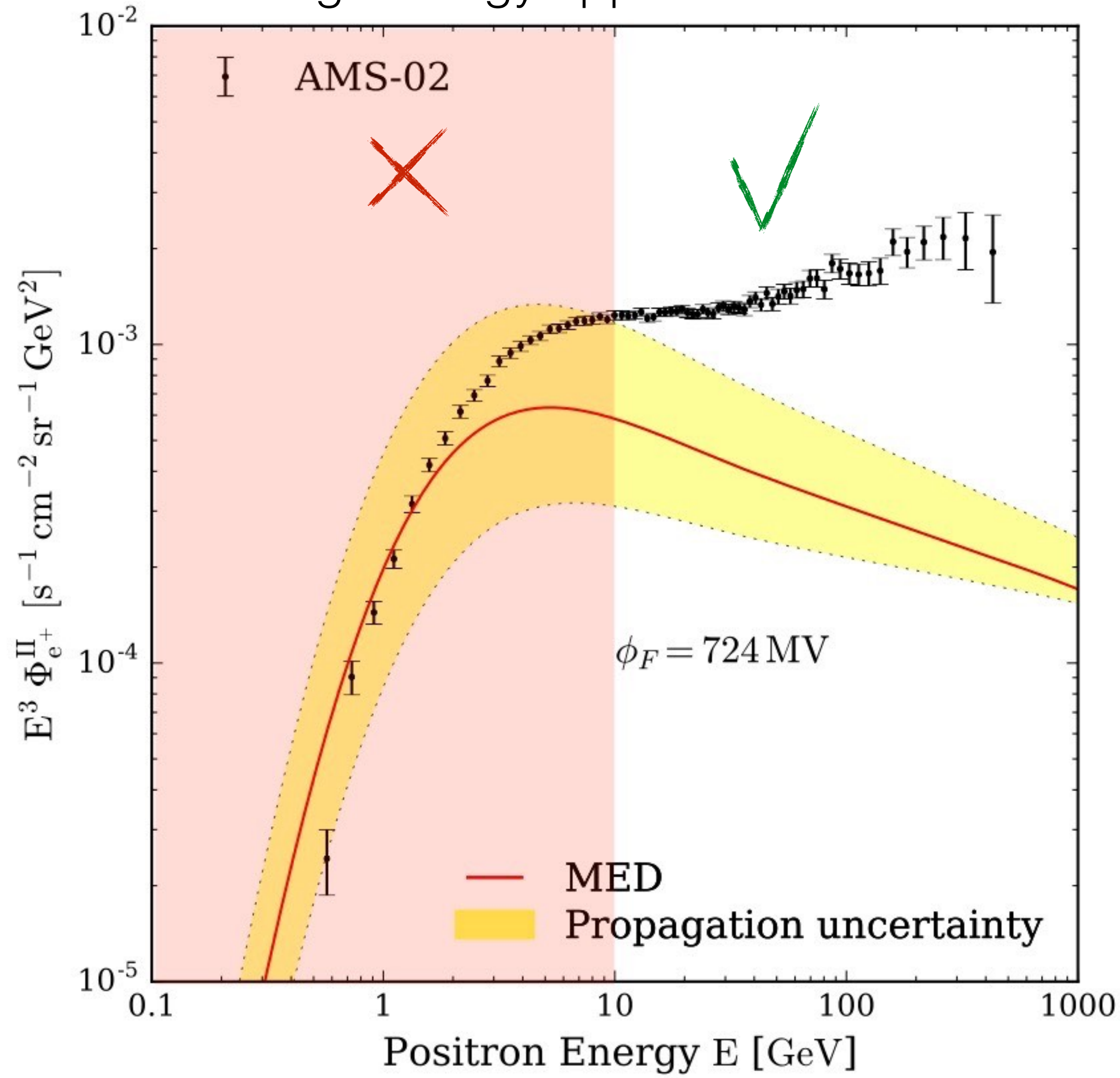
From now we are able to compute the positron flux analytically, **including all propagation effects**!

Astrophysical secondary positrons

$$Q^{\mathrm{II}}(E,\vec{x}) = 4\pi \sum_{i=p,\alpha} \sum_{j=H,He} n_j \int_{E_0}^{+\infty} dE_i\, \phi_i(E_i,\vec{x})\, \frac{d\sigma}{dE_i}(E_j \to E) \qquad \begin{cases} i = projectile \\ j = target \end{cases}$$

$$p + p \longrightarrow \begin{cases} p + \Delta^+ \\ \quad \Delta^+ \longrightarrow n + \pi^+ \\ \qquad \pi^+ \longrightarrow \nu_\mu + \mu^+ \\ \qquad\quad \mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+ \\ X + \pi^+ \\ \quad \pi^+ \longrightarrow \nu_\mu + \mu^+ \\ \qquad \mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+ \\ X + K^+ \\ \quad K^+ \longrightarrow \begin{cases} \nu_\mu + \mu^+ \\ \quad \mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+ \\ \pi^0 + \pi^+ \\ \quad \pi^+ \longrightarrow \nu_\mu + \mu^+ \\ \qquad \mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+ \end{cases} \end{cases}$$

High energy approximation

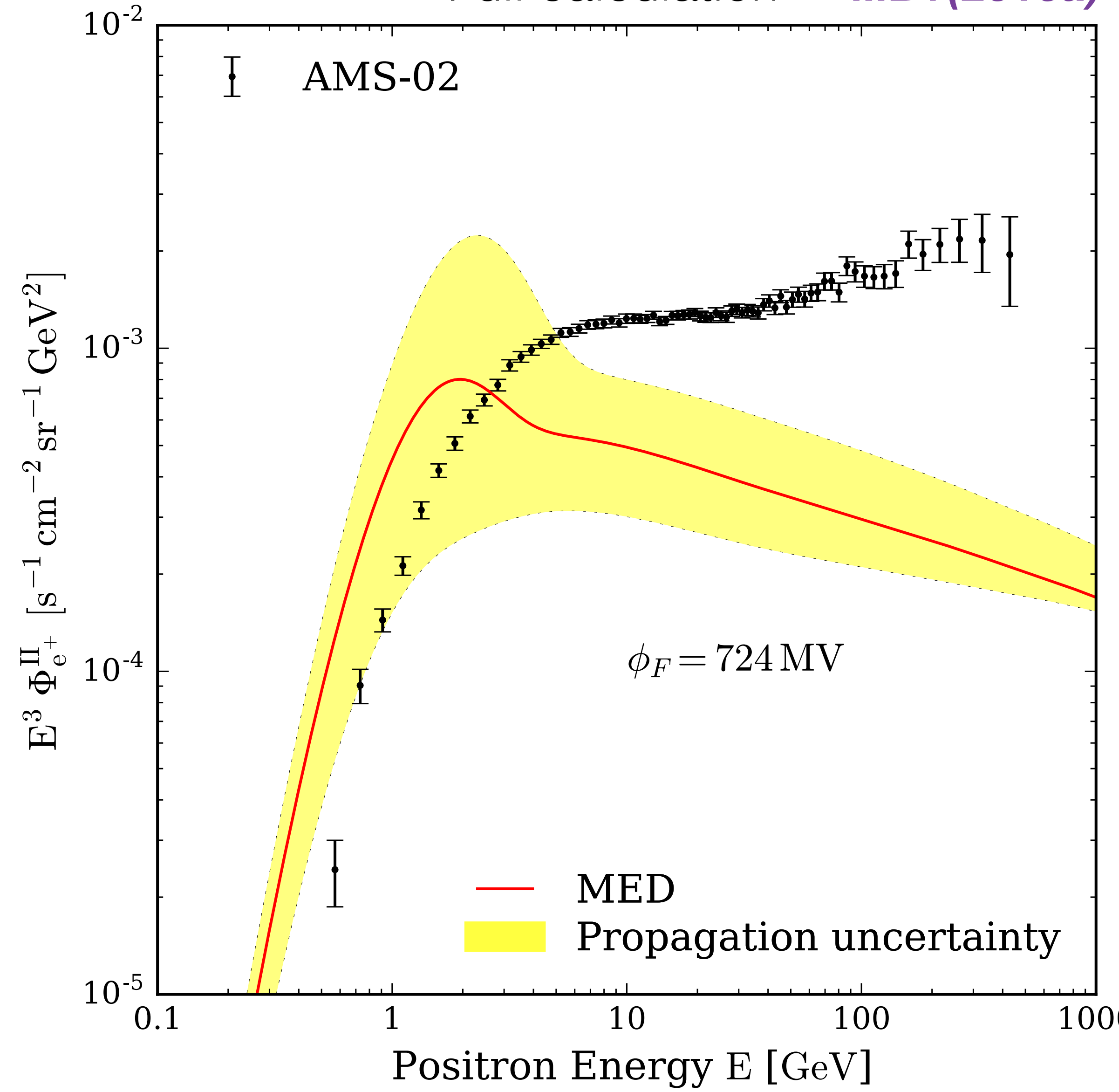


Astrophysical secondary positrons

$$Q^{\mathrm{II}}(E,\vec{x}) = 4\pi \sum_{i=p,\alpha} \sum_{j=H,He} n_j \int_{E_0}^{+\infty} dE_i\, \phi_i(E_i,\vec{x})\, \frac{d\sigma}{dE_i}(E_j \to E) \qquad \begin{cases} i = projectile \\ j = target \end{cases}$$

$$p + p \longrightarrow \begin{cases} p + \Delta^+ \\ \quad \Delta^+ \longrightarrow n + \pi^+ \\ \qquad \pi^+ \longrightarrow \nu_\mu + \mu^+ \\ \qquad\quad \mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+ \\ X + \pi^+ \\ \quad \pi^+ \longrightarrow \nu_\mu + \mu^+ \\ \qquad \mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+ \\ X + K^+ \\ \quad K^+ \longrightarrow \begin{cases} \nu_\mu + \mu^+ \\ \quad \mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+ \\ \pi^0 + \pi^+ \\ \quad \pi^+ \longrightarrow \nu_\mu + \mu^+ \\ \qquad \mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+ \end{cases} \end{cases}$$

Full calculation ***MB+(2016a)***



The HE approximation ⇒ error up to 50% at 10 GeV!

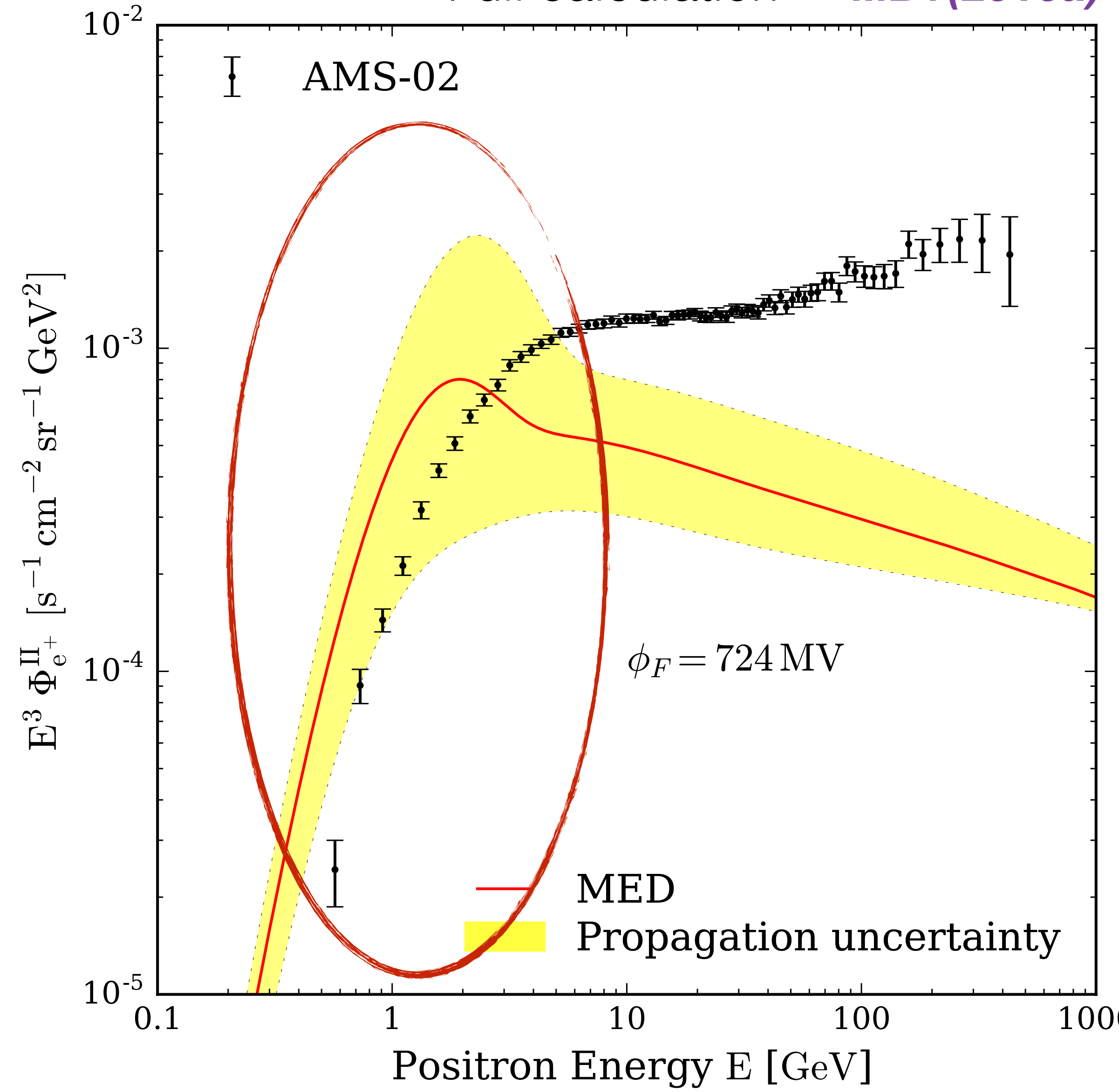
Astrophysical secondary positrons

$$Q^{\mathrm{II}}(E,\vec{x}) = 4\pi \sum_{i=p,\alpha} \sum_{j=H,He} n_j \int_{E_0}^{+\infty} dE_i\, \phi_i(E_i,\vec{x})\, \frac{d\sigma}{dE_i}(E_j \to E) \qquad \begin{cases} i = projectile \\ j = target \end{cases}$$

$p + p \longrightarrow$

- $p + \Delta^+$
  - $\Delta^+ \longrightarrow n + \pi^+$
    - $\pi^+ \longrightarrow \nu_\mu + \mu^+$
      - $\mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+$
- $X + \pi^+$
  - $\pi^+ \longrightarrow \nu_\mu + \mu^+$
    - $\mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+$
- $X + K^+$
  - $K^+ \longrightarrow$
    - $\nu_\mu + \mu^+$
      - $\mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+$
    - $\pi^0 + \pi^+$
      - $\pi^+ \longrightarrow \nu_\mu + \mu^+$
        - $\mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+$

Full calculation ***MB+(2016a)***



Astrophysical secondary positrons

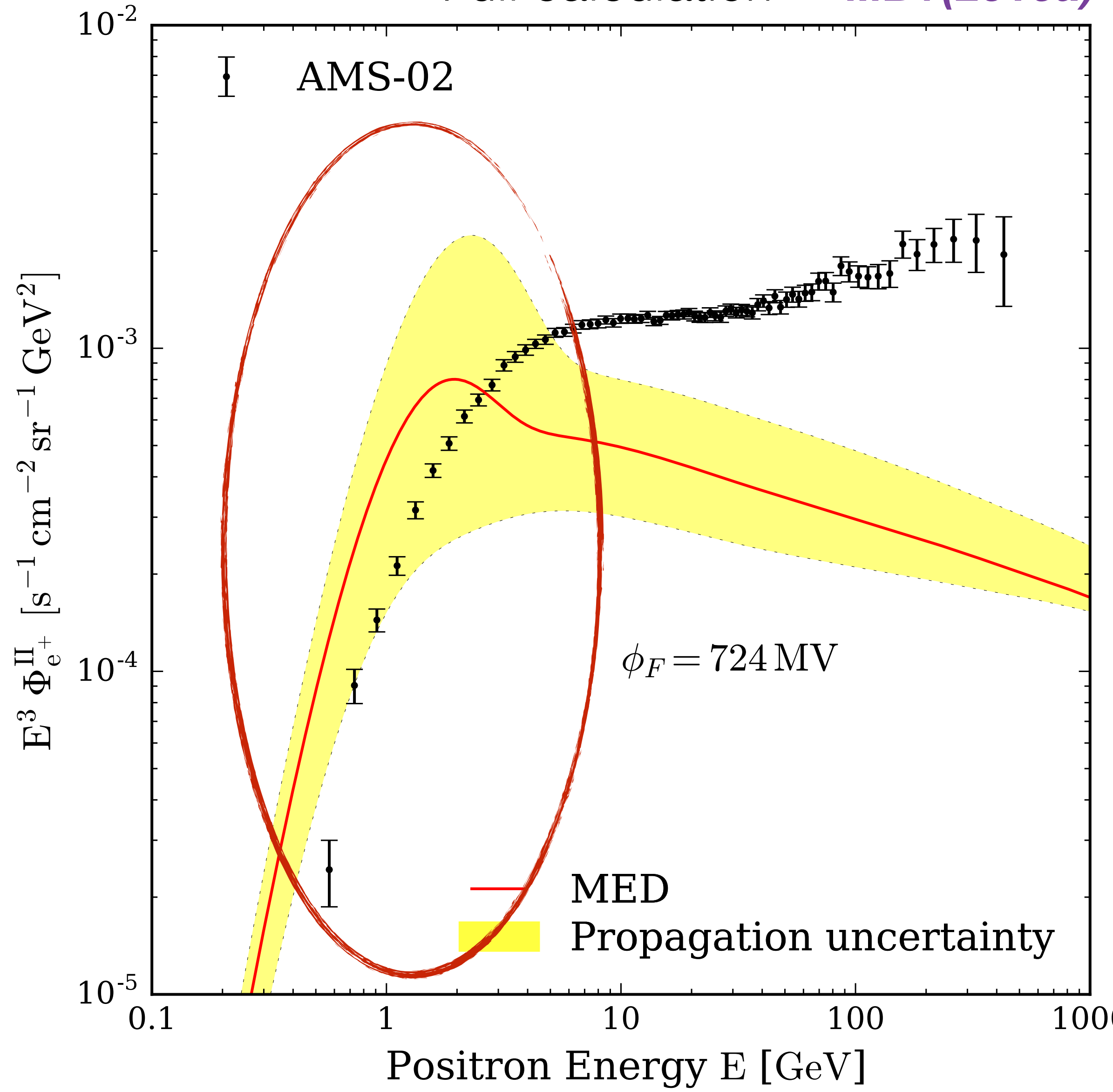
$$Q^{\mathrm{II}}(E,\vec{x}) = 4\pi \sum_{i=p,\alpha} \sum_{j=H,He} n_j \int_{E_0}^{+\infty} dE_i \, \phi_i(E_i,\vec{x}) \, \frac{d\sigma}{dE_i}(E_j \to E) \qquad \begin{cases} i = projectile \\ j = target \end{cases}$$

Positrons can be used as an independent probe for the propagation parameters.

The degeneracy between K_0 and L can be lifted!

Lavalle+(2014)

Full calculation *MB+(2016a)*



Astrophysical secondary positrons

$$Q^{\mathrm{II}}(E,\vec{x}) = 4\pi \sum_{i=p,\alpha} \sum_{j=H,He} n_j \int_{E_0}^{+\infty} dE_i\, \phi_i(E_i,\vec{x}) \frac{d\sigma}{dE_i}(E_j \to E) \qquad \begin{cases} i = projectile \\ j = target \end{cases}$$

Positrons can be used as an independent probe for the propagation parameters.

The degeneracy between K_0 and L can be lifted!

Lavalle+(2014)

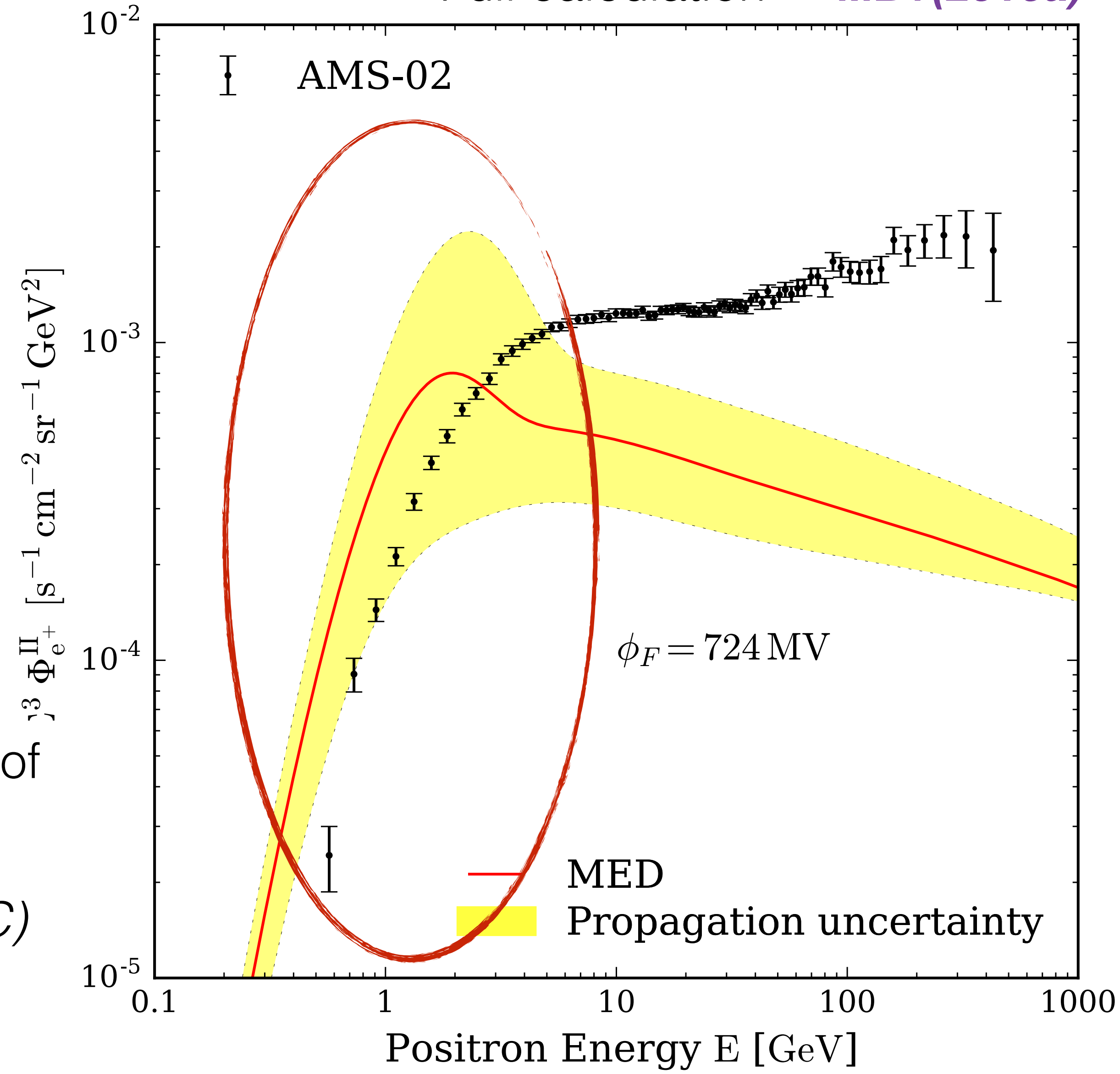
Case	δ	K_0 [kpc^2/Myr]	L [kpc]	V_C [km/s]	V_a [km/s]
MIN	0.85	0.0016	1	13.5	22.4
MED	0.70	0.0112	4	12	52.9
MAX	0.46	0.0765	15	5	117.6

Ruled out!

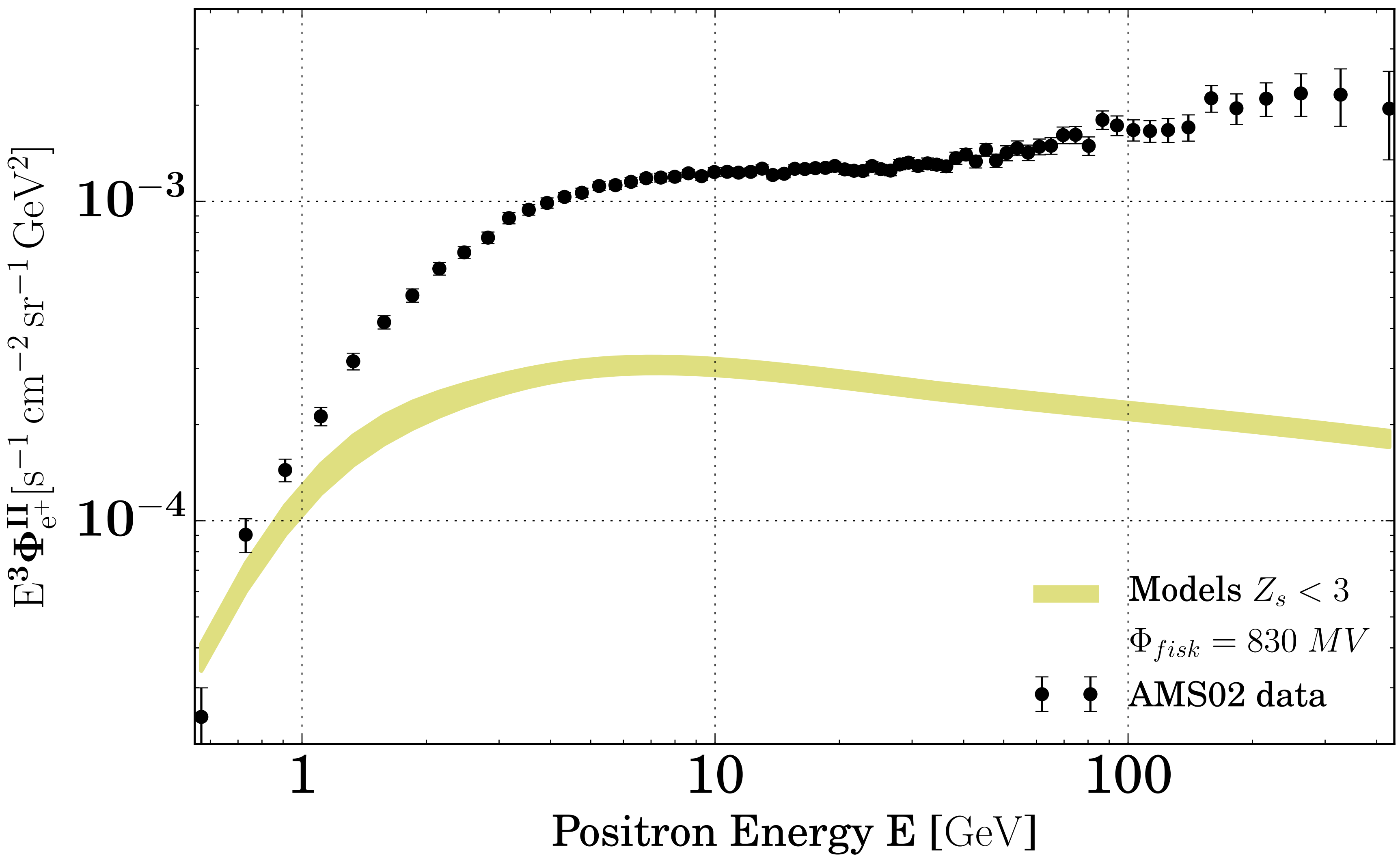
The AMS-02 positrons data favour the **MAX-type** sets of propagation parameters.

(result confirmed by AMS-02 antiprotons and recent B/C)

Full calculation ***MB+(2016a)***



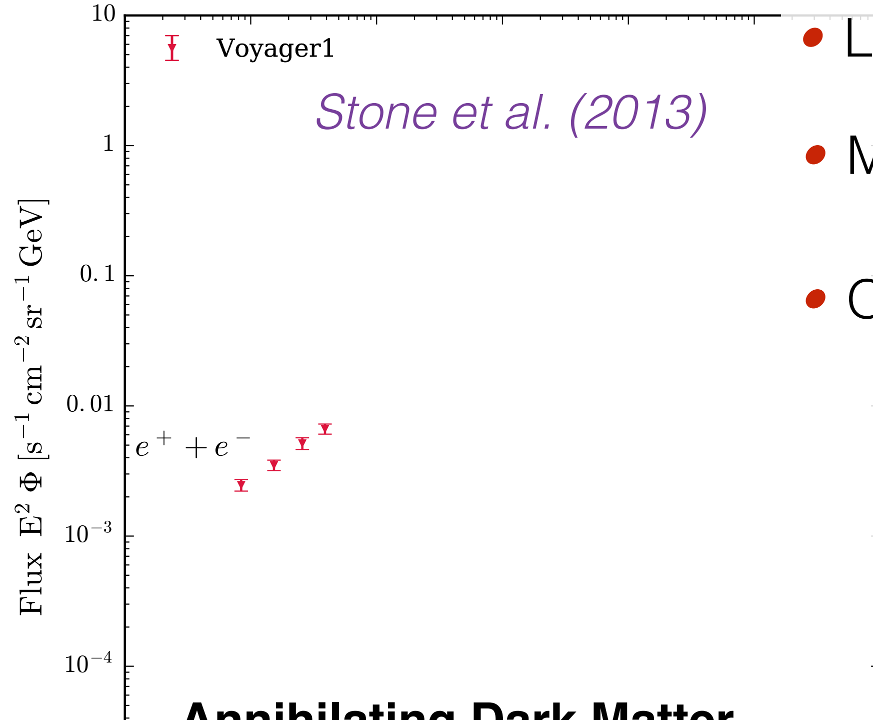
Astrophysical secondary positrons



MB+(2016a)

- The uncertainty band for the e⁺ is now very narrow.
- The positron excess appears now from ~1 GeV.
- Where do come from the remained positrons?
- We need another component(s) to explain the positron data **from ~1 GeV to ~500 GeV**.

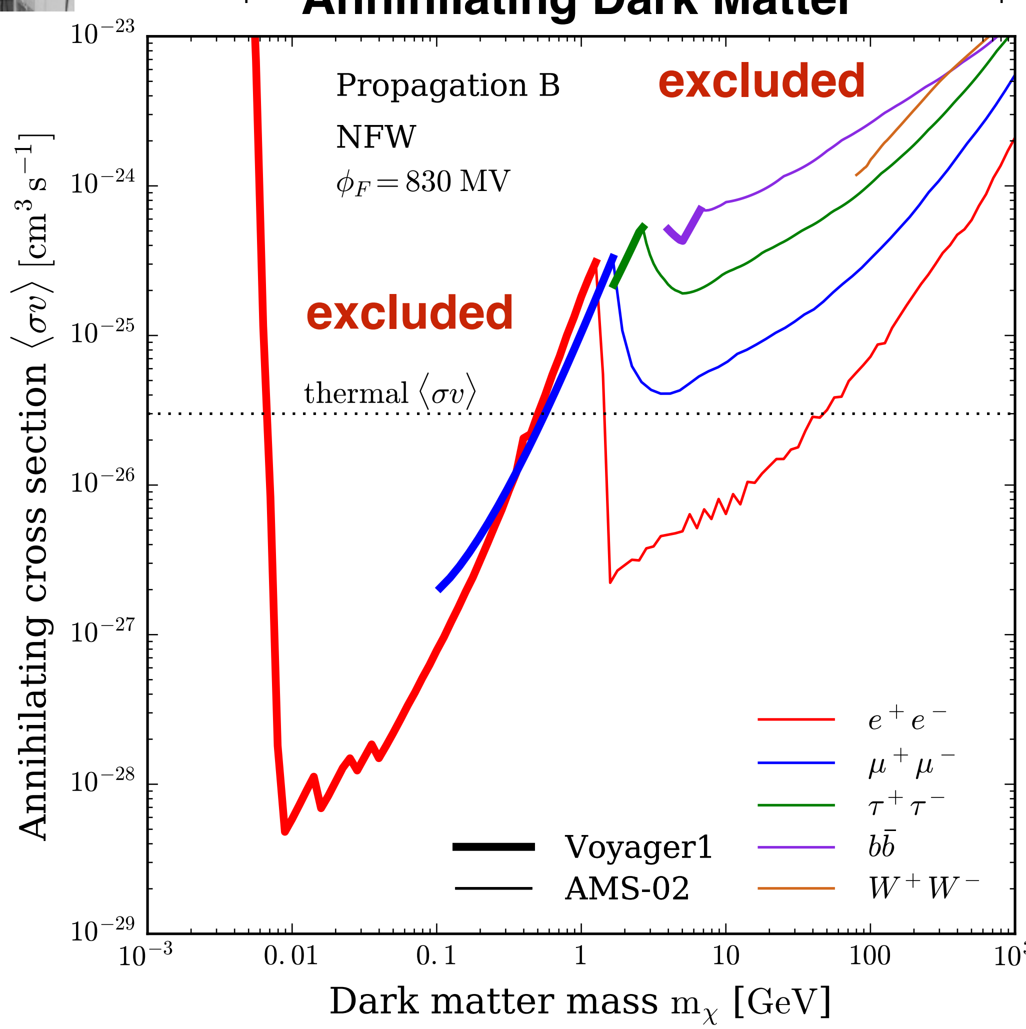
Constraints on MeV DM with Voyager I



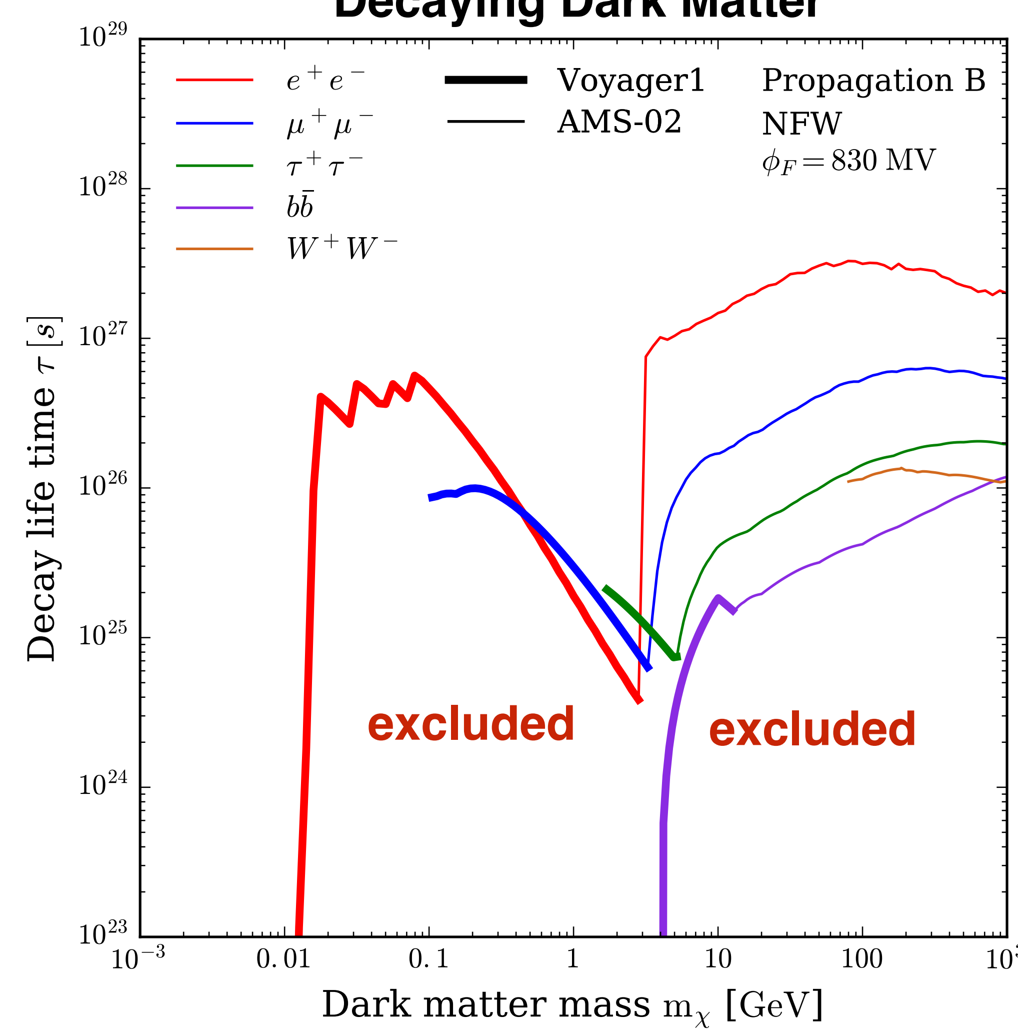
- Launched in 1977
- Measures the flux of **electrons + positrons**
- Outside the heliosphere since august 2012

→ independent of solar effects

Annihilating Dark Matter



Decaying Dark Matter



MB, J. Lavalle, P. Salati (2016)

1- Introduction

2- Cosmic ray physics

3- USINE: introduction

4- Several ways to run USINE: examples

5- Electrons and positrons soon in USINE

6- Conclusions and prospects

Conclusions and prospects

What does USINE do?

- Computes the flux of Galactic nuclei and anti-nuclei

Why/when should you use USINE?

- Training in GCRs physics
- To test/study propagation models
- To test/study CR acceleration models
- To test/study impact of nuclear X-sections
- When speed matters! (e.g. for MCMC analysis)
- …

Available now (beta version)

- CR nuclei and antinuclei for Z<30
- Leaky box, 1D model, 2D model

git clone https://gitlab.in2p3.fr/david-maurin/USINE.git

By the end of 2017 (if possible)

- Electrons and positrons
- Interface with MCMC engine

2018 (if possible)

- CRs from Dark Matter
- Solar modulation: 1D spherical symmetry
- Z>30
- …

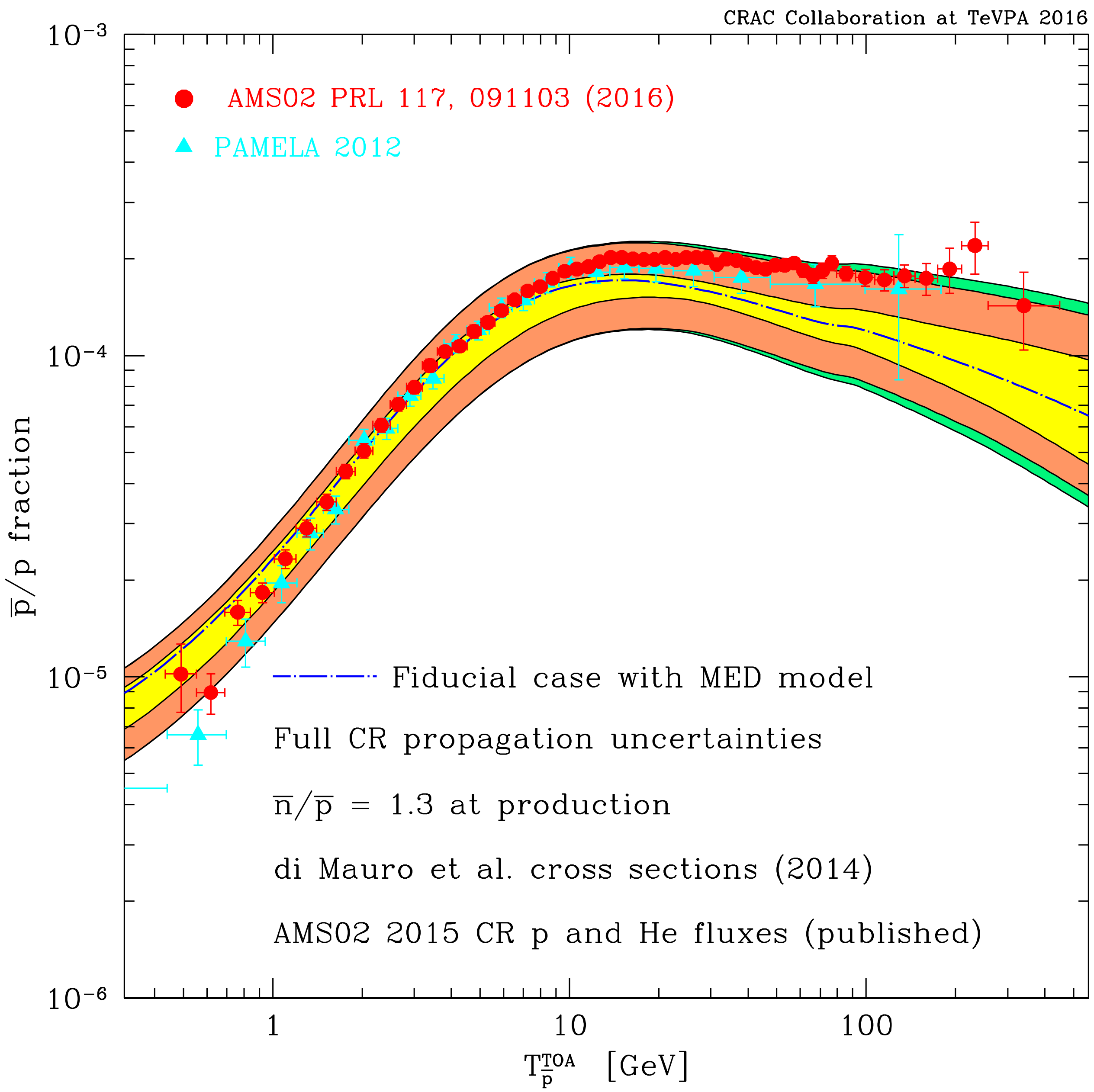
Thank you for your attention!

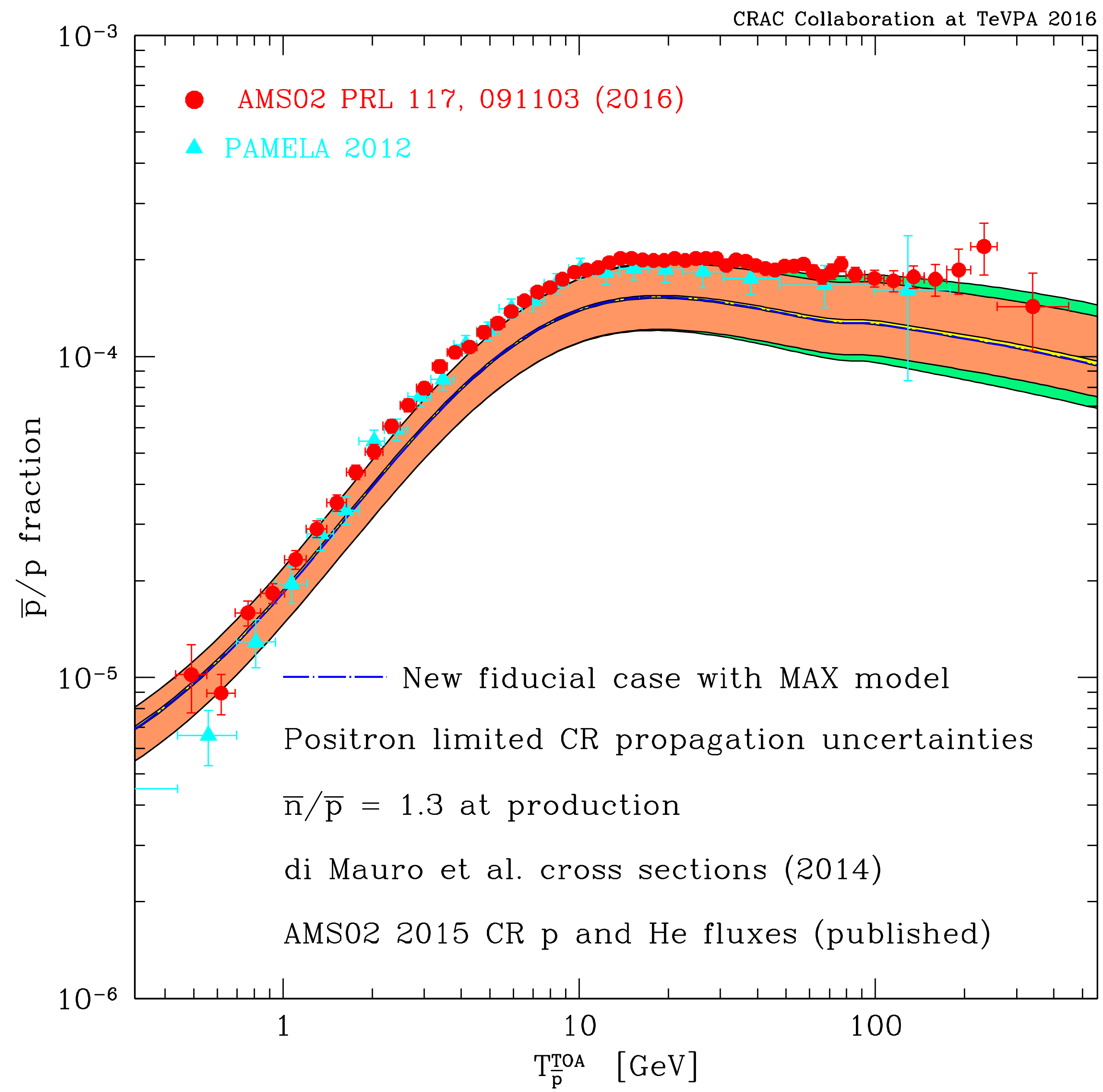
Questions?

Back up

Astrophysical background of secondary antiprotons

$$q^{\mathrm{II}}(E,r) = 4\pi \sum_{i=p,\alpha} \sum_{j=\mathrm{H,He}} \int_{E^0}^{+\infty} dE_i \, \frac{d\sigma_{ij\to\bar{p}X}}{dE}(E_i \to E)\, \phi_i(E_i,r)\, n_j$$





Giesen et al. (2015)