Highlights from AMS
7 years on the International Space Station

November 1st, 2018
Institutsseminar Nuclear and Particle Physics, TU Dresden

Iris Gebauer

INSTITUTE FOR EXPERIMENTAL PARTICLE PHYSICS

“The subject [of cosmic rays] is unique in modern physics for

the minuteness of the phenomena,

the delicacy of the observations,

the adventurous excursions of the observers,

the subtlety of the analysis,

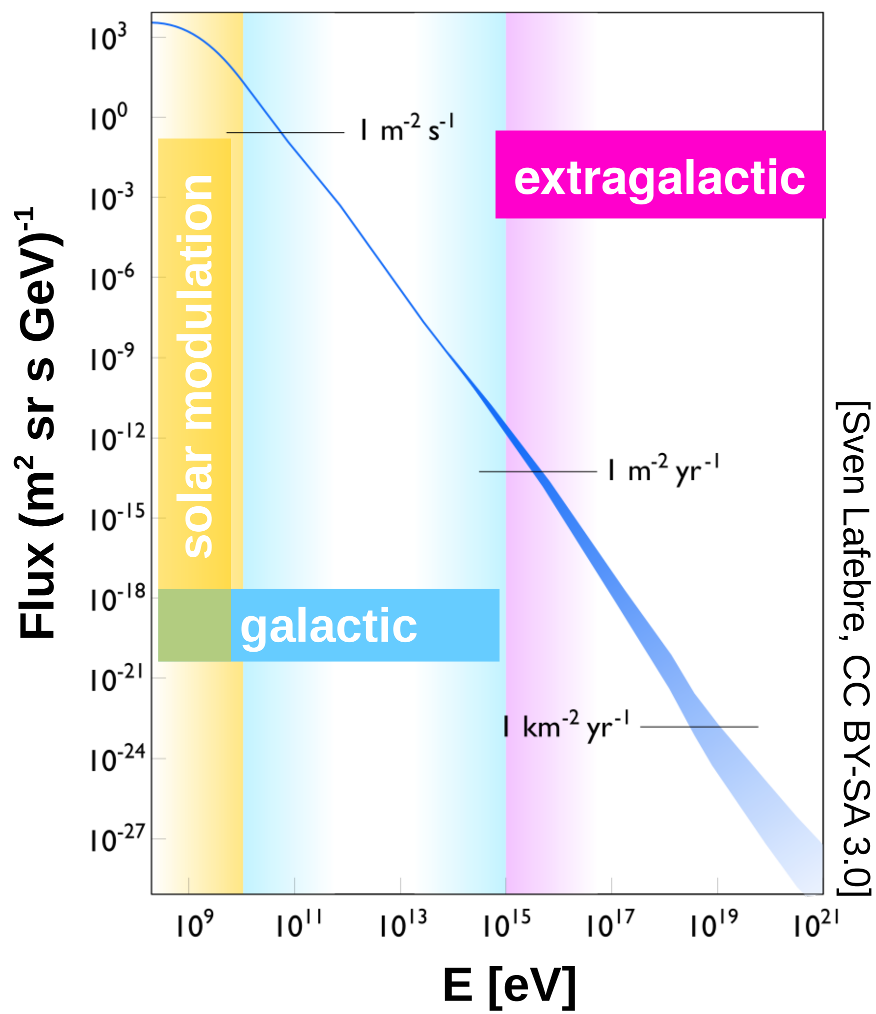
and the grandeur of the inferences.”

[Courtesy of AIP]

Karl K. Darrow

as quoted by Bruno Rossi in “Cosmic Rays”.
New York: McGraw-Hill (1964).

THE COSMIC RAY SPECTRUM



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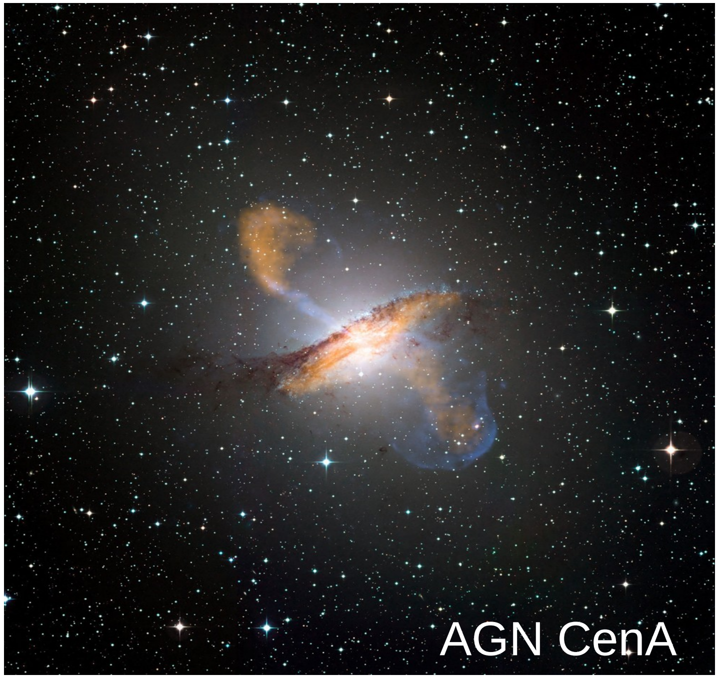
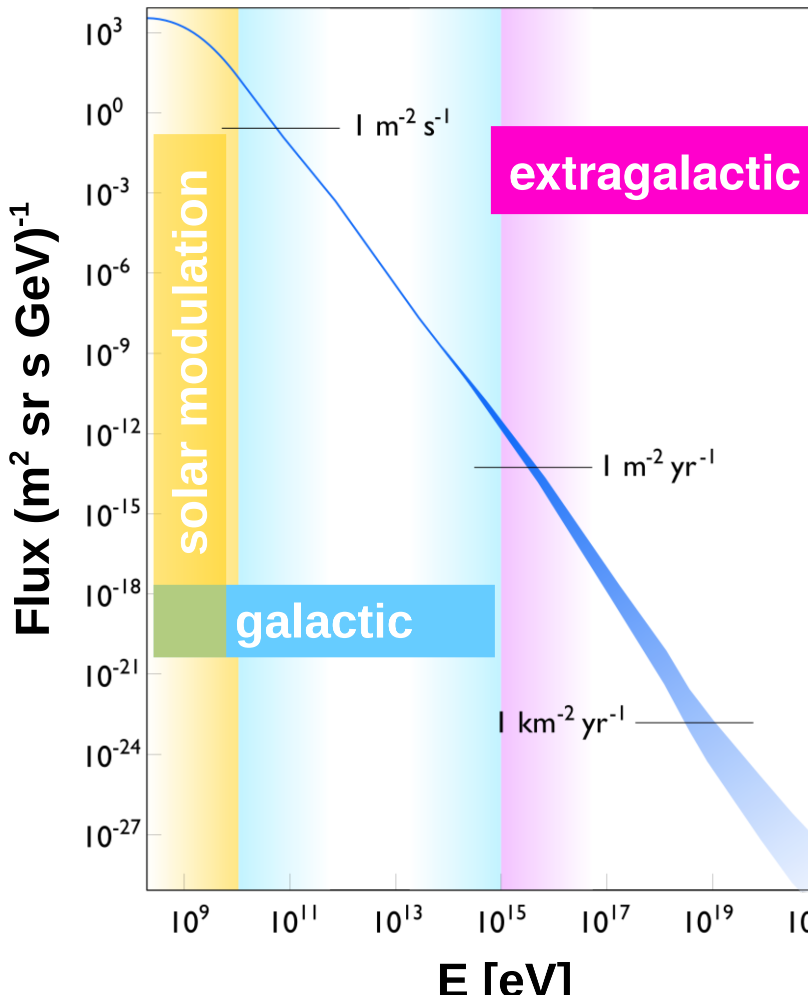
SOURCES OF COSMIC RAYS

Karlsruhe Institute of Technology



Extragalactic cosmic rays: 1 PeV -1 ZeV

Possible sources: active galactic nuclei?



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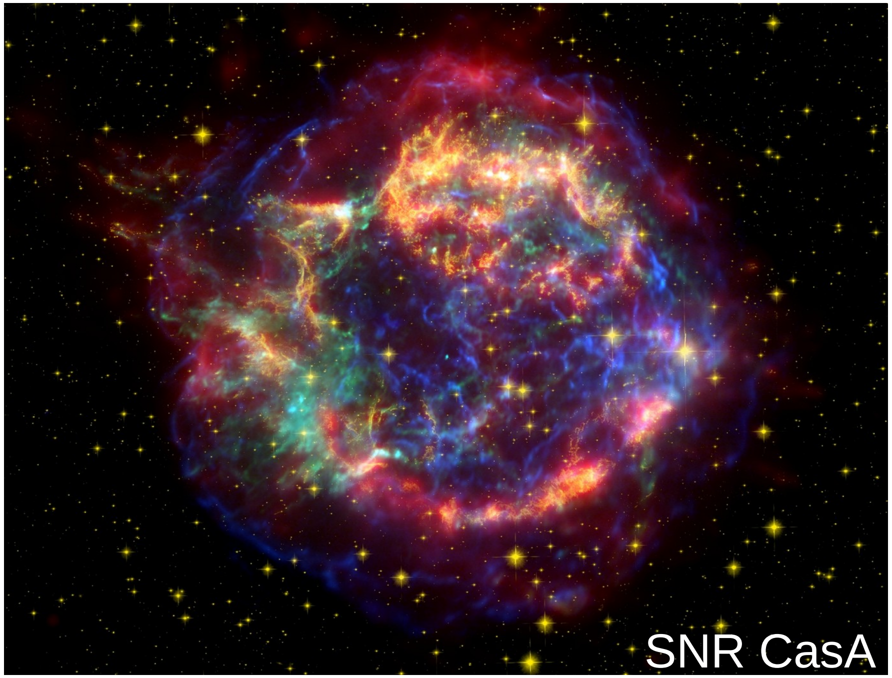
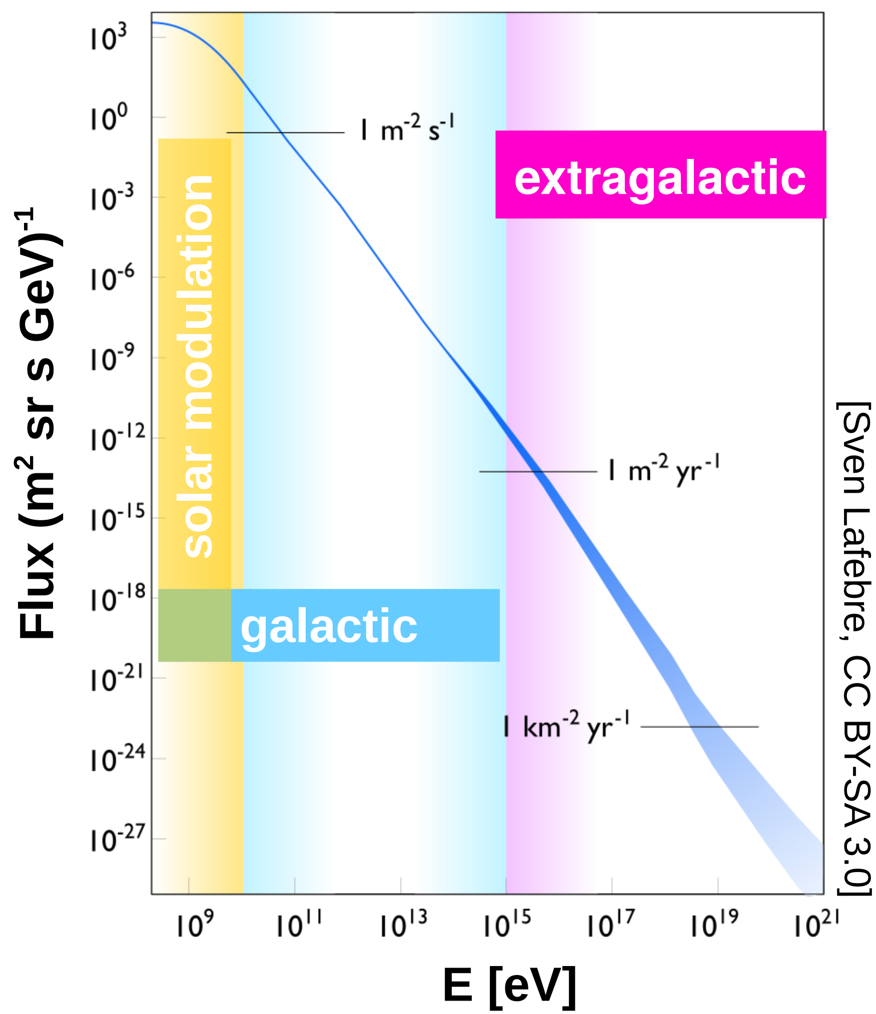
SOURCES OF COSMIC RAYS

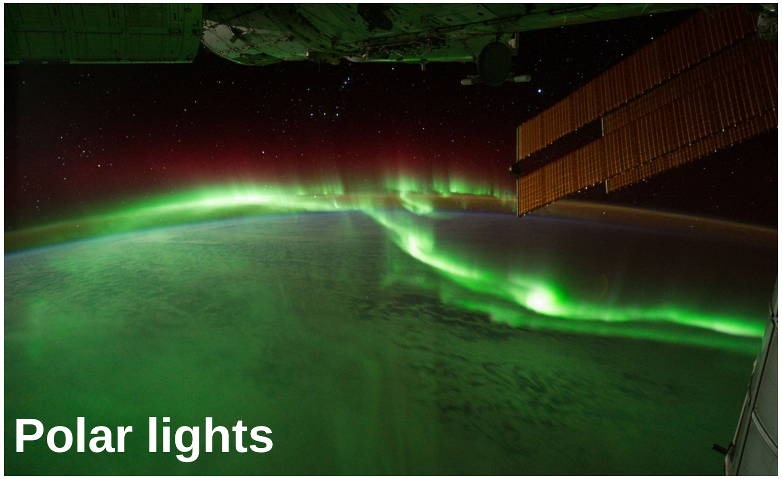


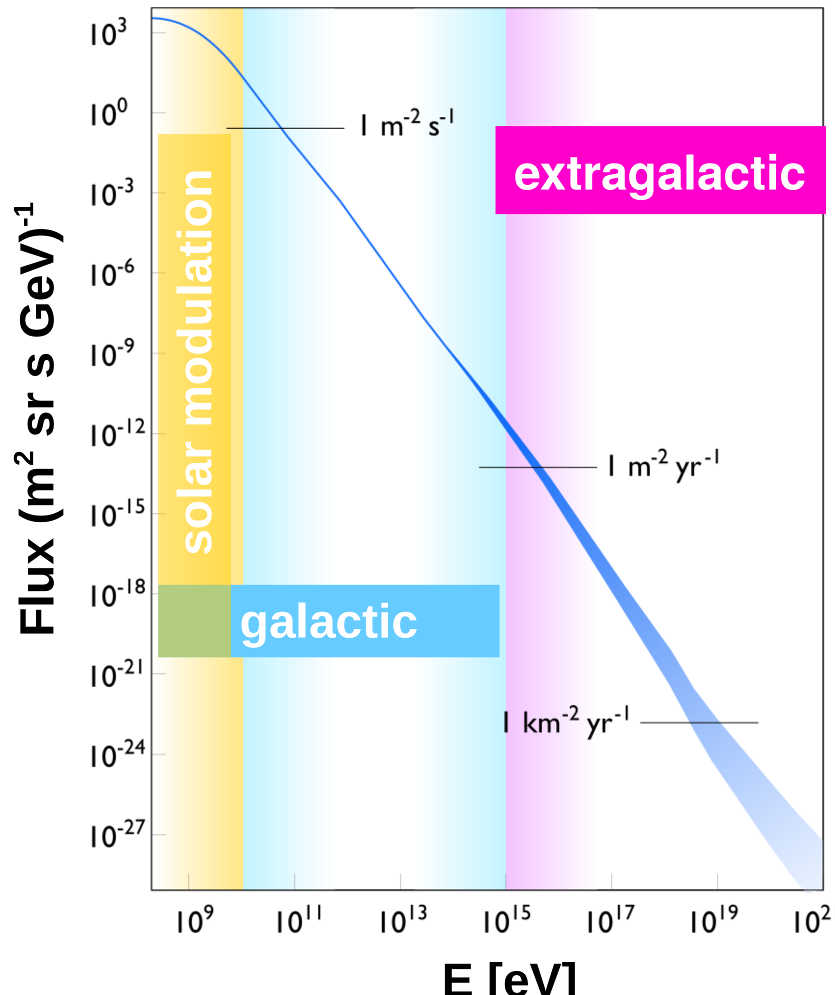


Galactic cosmic rays:
100 MeV-1 PeV

Sources: old supernova remnants, heavy stars, pulsars

SOURCES OF COSMIC RAYS





[Sven Lafebre, CC BY-SA 3.0]

Solar cosmic rays:
1.5 -10 keV

Sources: Solar wind, solar energetic events

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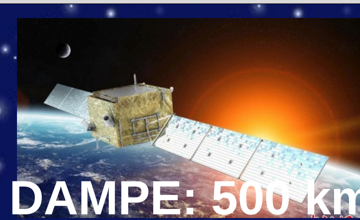
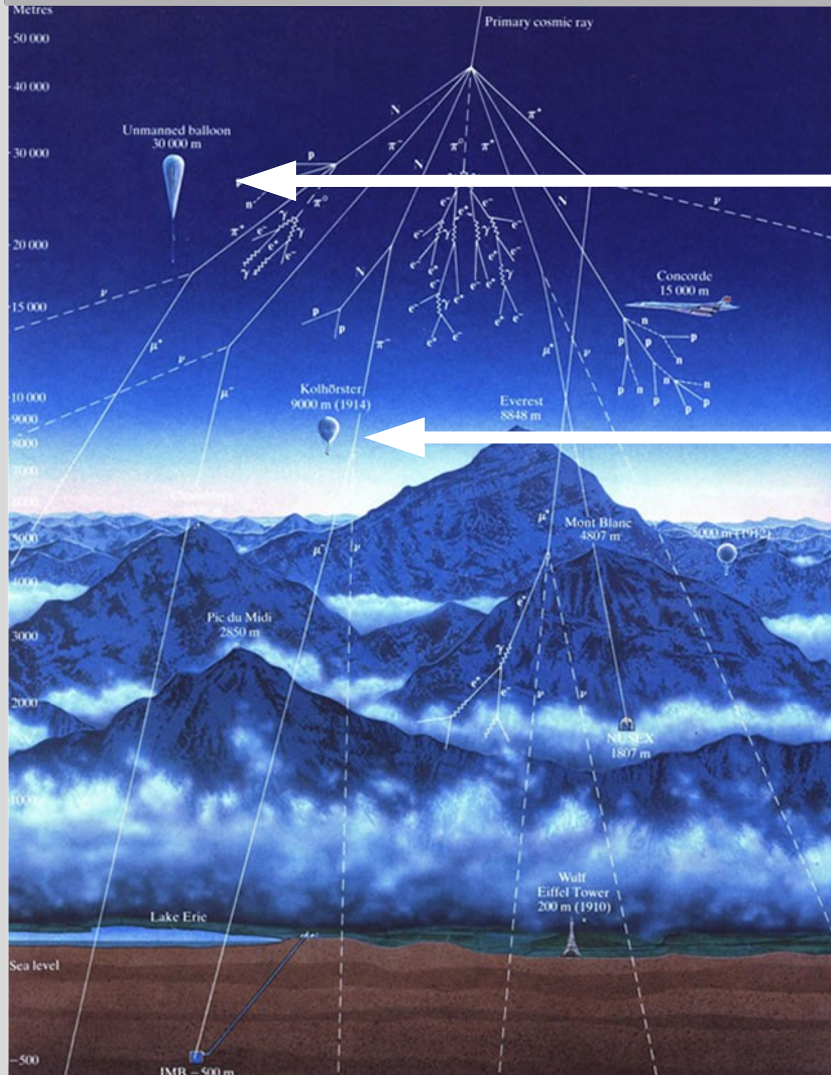
ISS: 400 km
AMS-02
CALET
ISS-CREAM

PAMELA: 350-600 km



DAMPE: 500 km

Fermi: 550 km

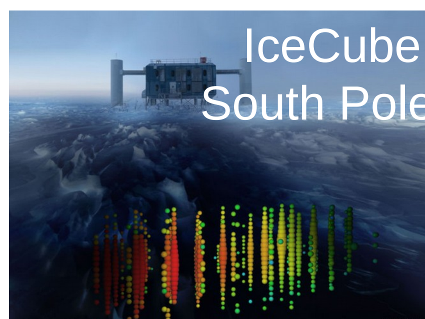


Modern balloons
~30 km

Kolhörster
9 km

CREAM launch,
McMurdo

“...the adventurous excursions of the observers...”



IceCube,
South Pole

Auger Observatory,
Argentina

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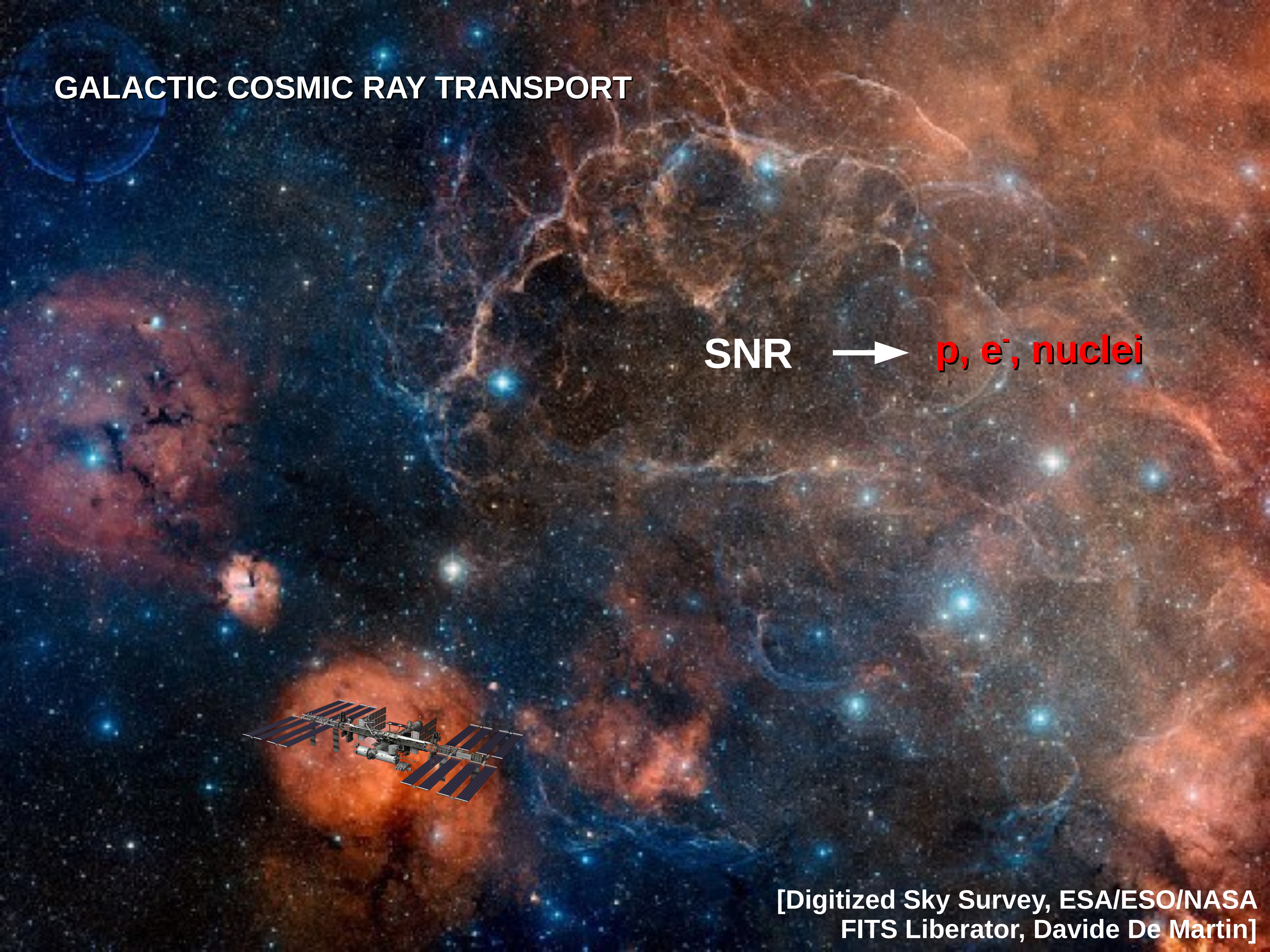
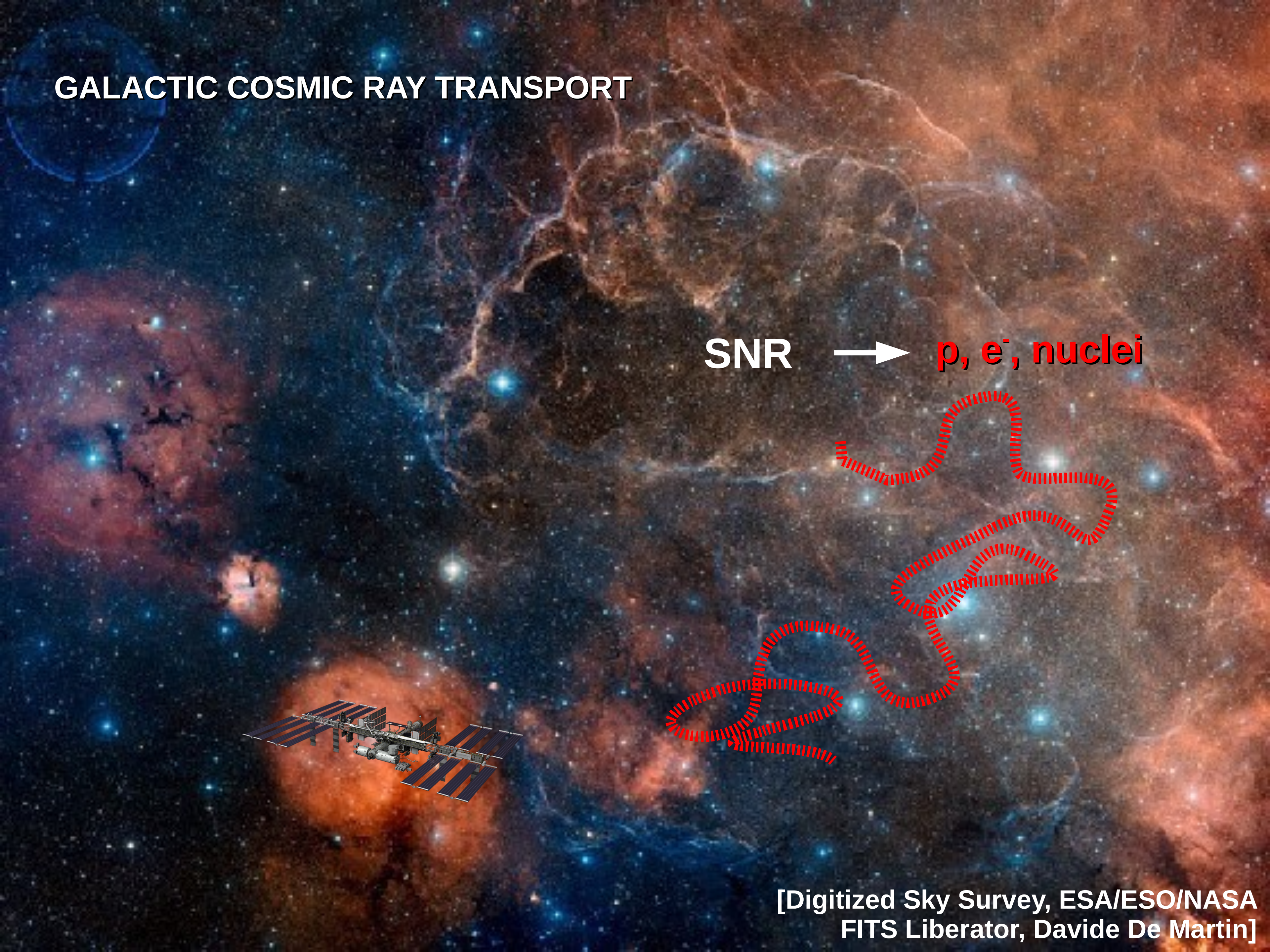
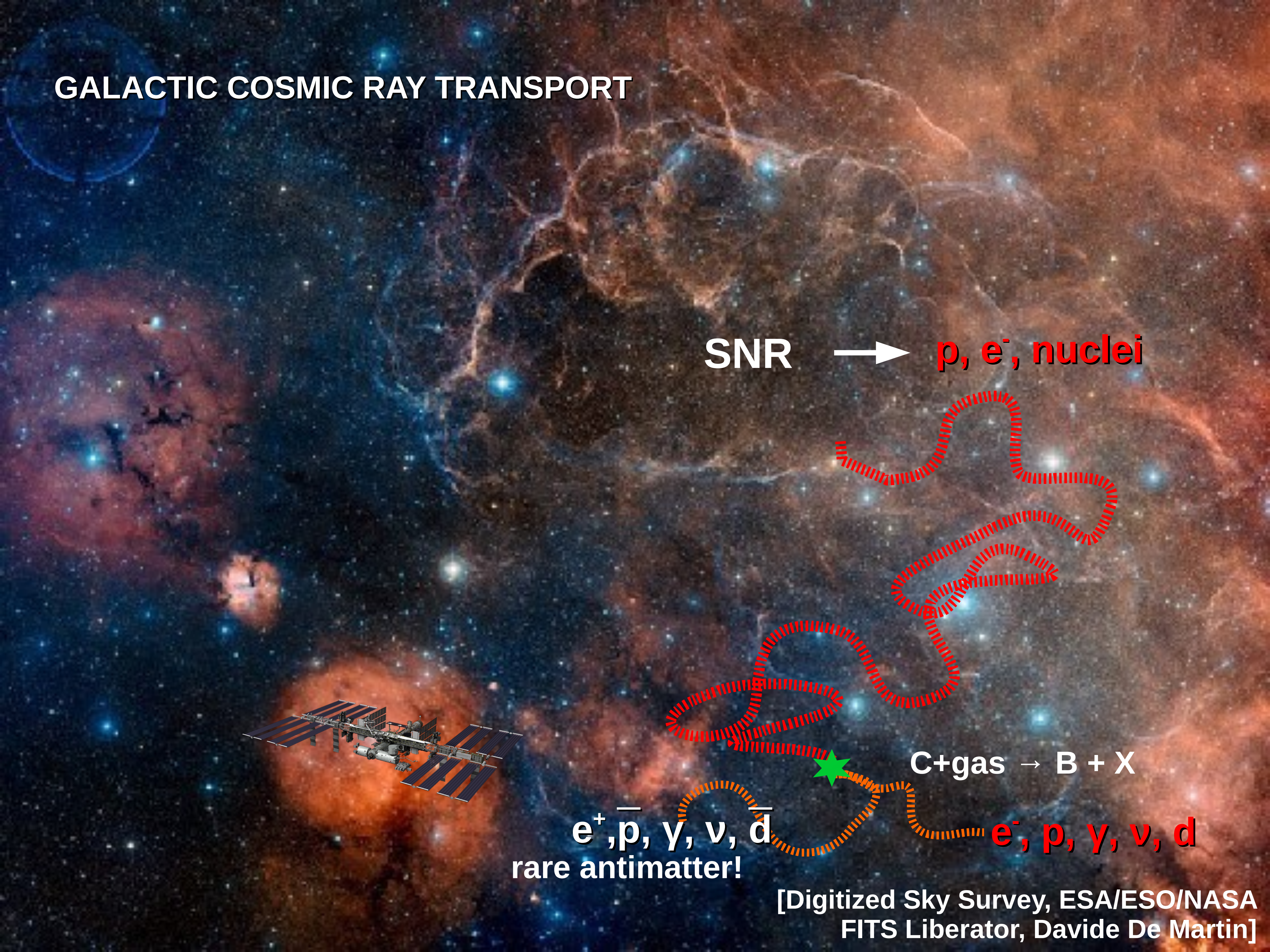
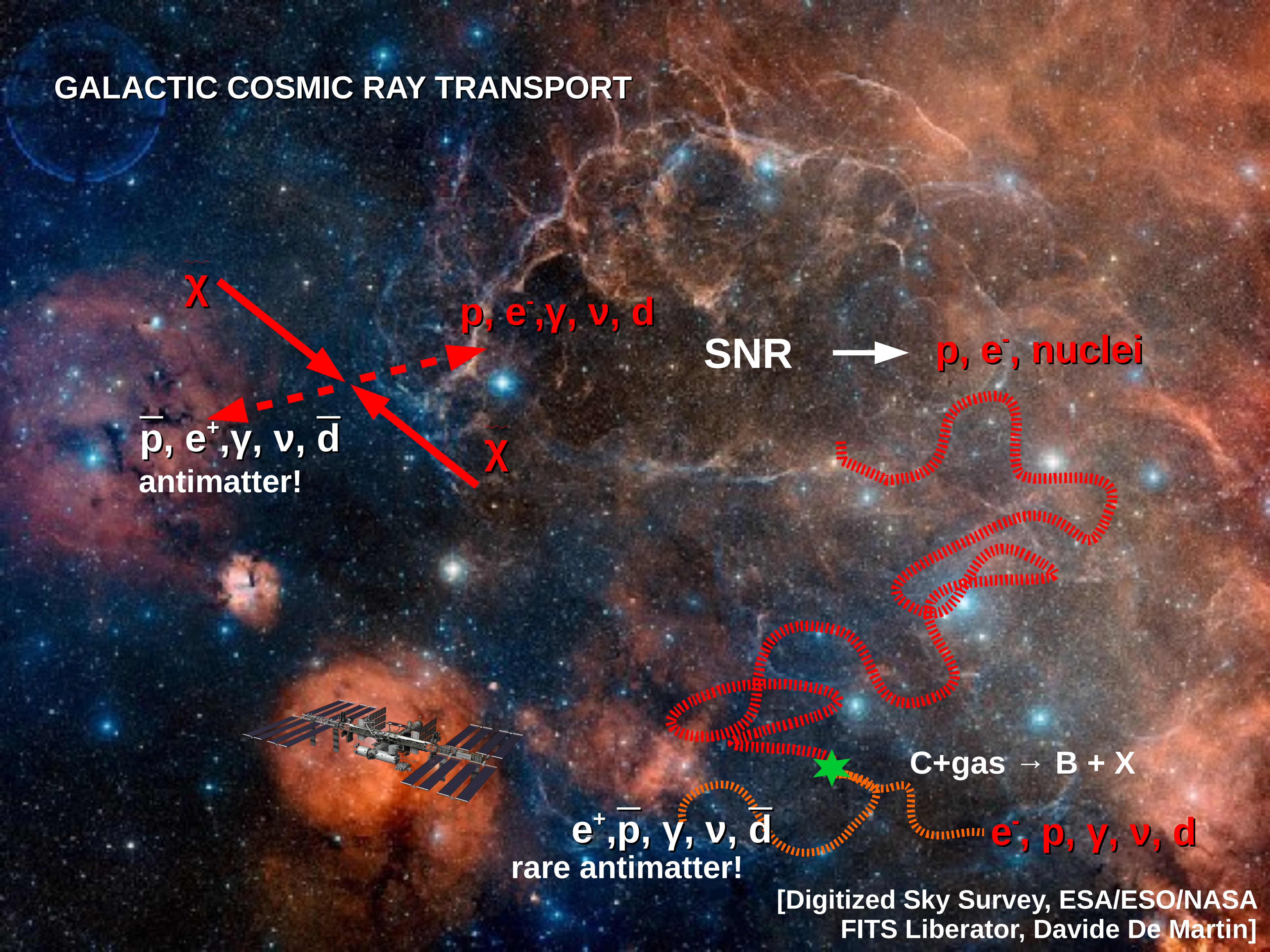

GALACTIC COSMIC RAY TRANSPORT
SNR → p, e^-, nuclei
[Digitized Sky Survey, ESA/ESO/NASA
FITS Liberator, Davide De Martin]

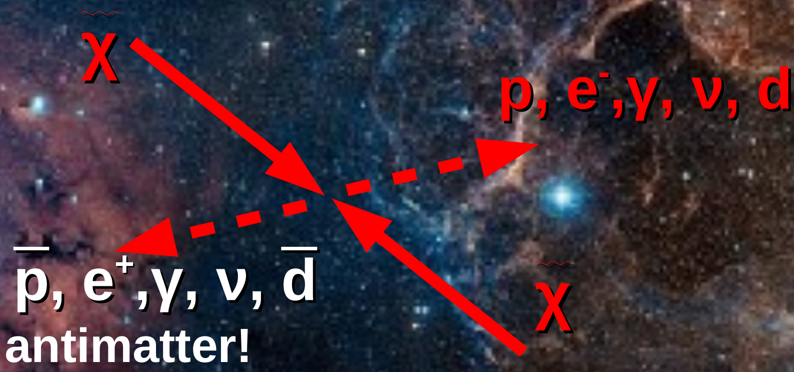

GALACTIC COSMIC RAY TRANSPORT
SNR → p, e⁻, nuclei
[Digitized Sky Survey, ESA/ESO/NASA
FITS Liberator, Davide De Martin]

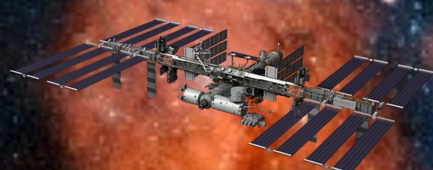

GALACTIC COSMIC RAY TRANSPORT
SNR → p, e-, nuclei
C+gas → B + X
e+, p̄, γ, ν, d̄
rare antimatter!
e-, p, γ, ν, d
[Digitized Sky Survey, ESA/ESO/NASA
FITS Liberator, Davide De Martin]

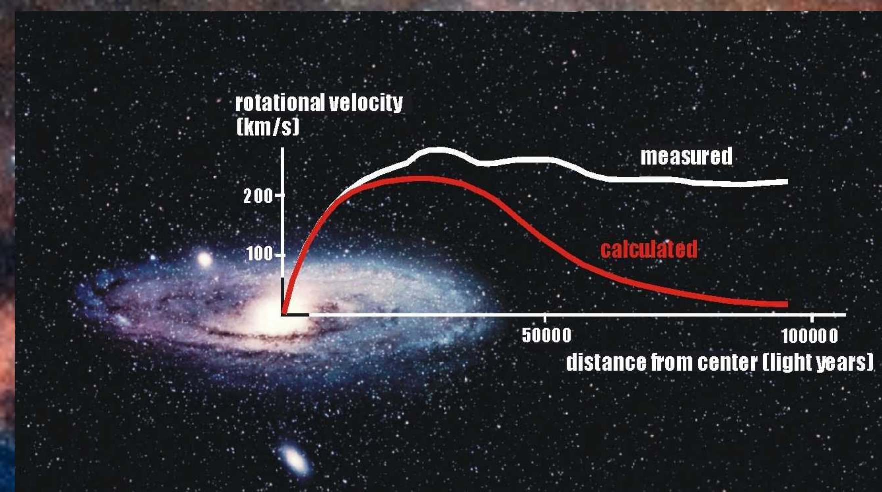

GALACTIC COSMIC RAY TRANSPORT
$\tilde{\chi}$
p, e^-, γ, ν, d
SNR → p, e^-, nuclei
$\bar{p}, e^+, \gamma, \nu, \bar{d}$
antimatter!
$\tilde{\chi}$
C+gas → B + X
$e^+, \bar{p}, \gamma, \nu, \bar{d}$
rare antimatter!
e^-, p, γ, ν, d
[Digitized Sky Survey, ESA/ESO/NASA
FITS Liberator, Davide De Martin]

INDIRECT DARK MATTER SEARCHES

“... the grandeur of the inferences...”



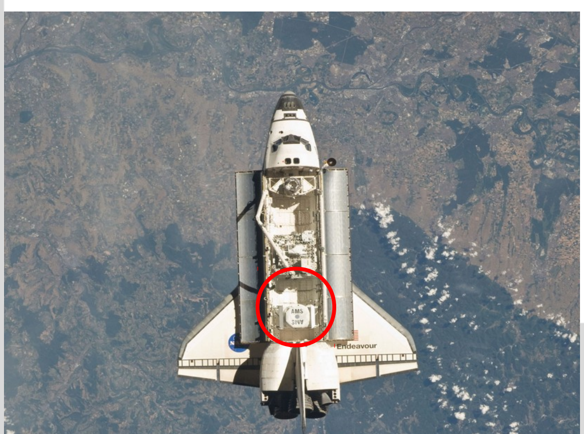


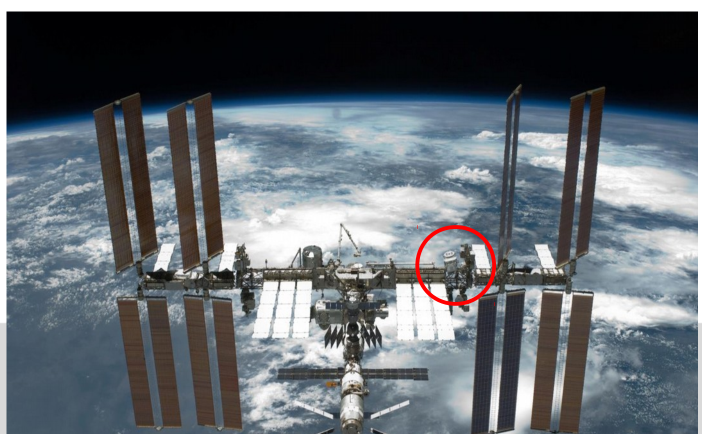


[Digitized Sky Survey, ESA/ESO/NASA FITS Liberator, Davide De Martin]

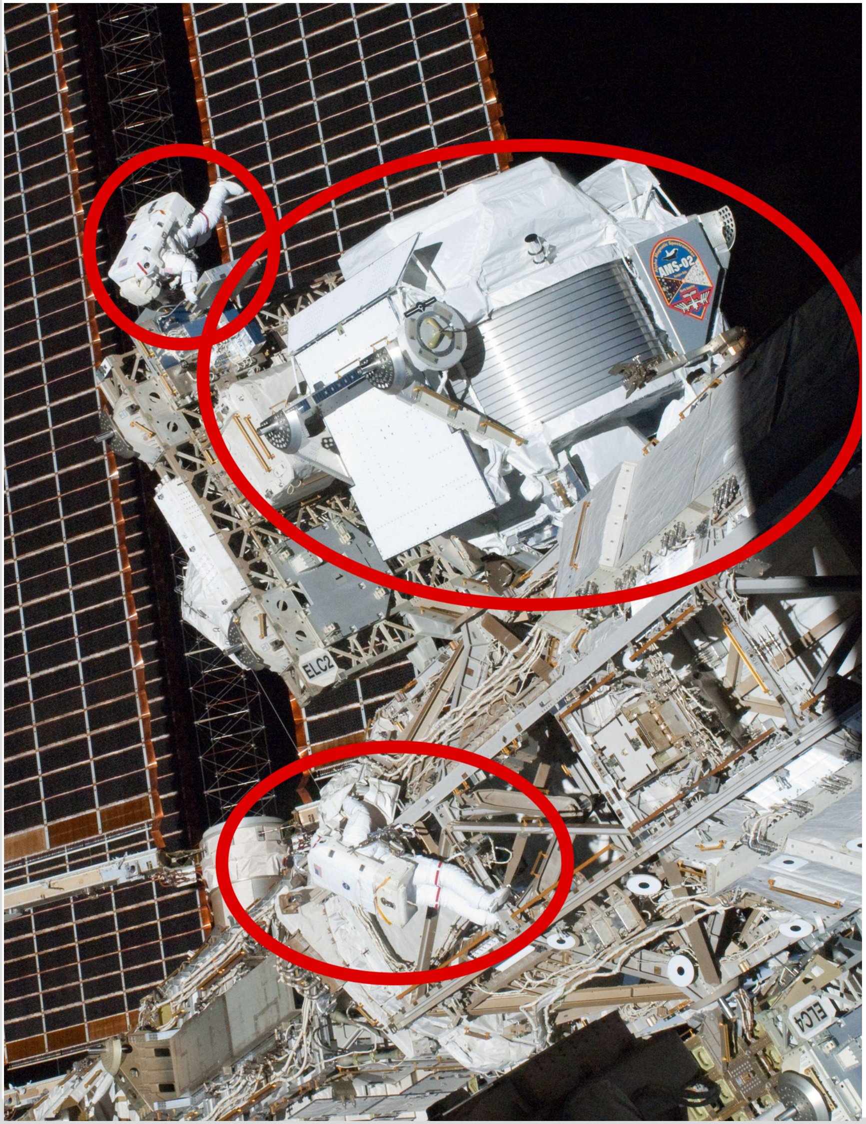

May 16th 2011


May 19th 2011





AMS-02: THE ALPHA MAGNETIC SPECTROMETER



- **Volume** 64 m^3, height 4 m
- **Weight** 8500 kg
- **Power consumption** 2500 W
- **Data downlink** 9 Mbps (minimum)
- **Magnetic field** 0.15 T (400 x Earth)
- **Mission duration:** Until the end of ISS operation (currently 2024)

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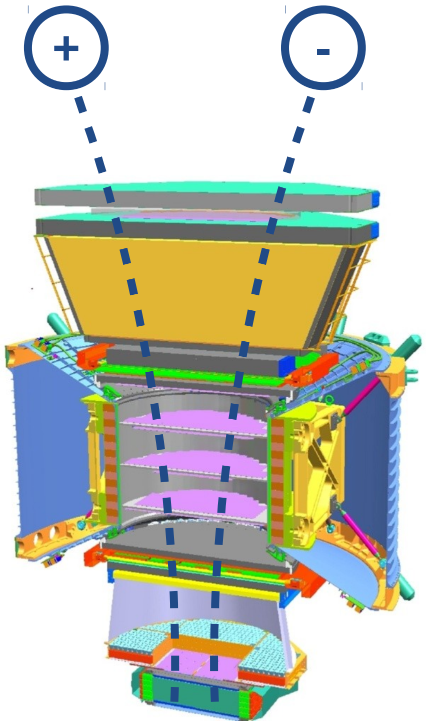
AMS-02: A TeV PRECISION SPECTROMETER



Particles and nuclei are defined by their charge (**Z**) and mass (**m**).

Flux measurement: energy (**E**) or rigidity (**R=p/Z**).

Charge, mass, energy are measured *redundantly and independently* by 5 subdetectors.

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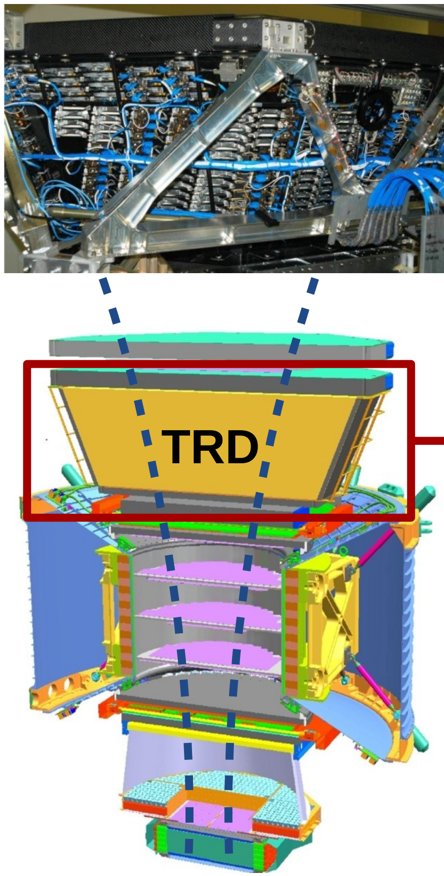
TRANSITION RADIATION DETECTOR



	e^-	p	Fe	e^+	$\bar{p}$
TRD	x-rays +ion.	ion.	ion.	x-rays +ion.	ion.

e/p?
Q

→ **Identify e^+, e^-**
→ **Charge Q**

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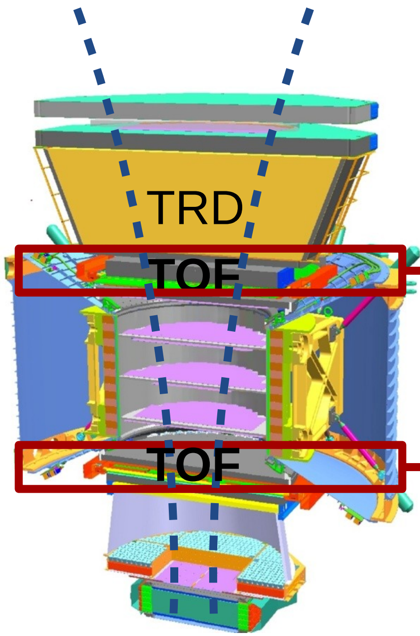
TIME-OF-FLIGHT COUNTER



	e^-	p	Fe	e^+	$\bar{p}$	
TRD	x-rays +ion.	ion.	ion.	x-rays +ion.	ion.	**e/p? Q**
TOF	**dE/dx**	**dE/dx**	**dE/dx**	**dE/dx**	**dE/dx**	**Q, β**

→ **charge Q**
→ **velocity β**

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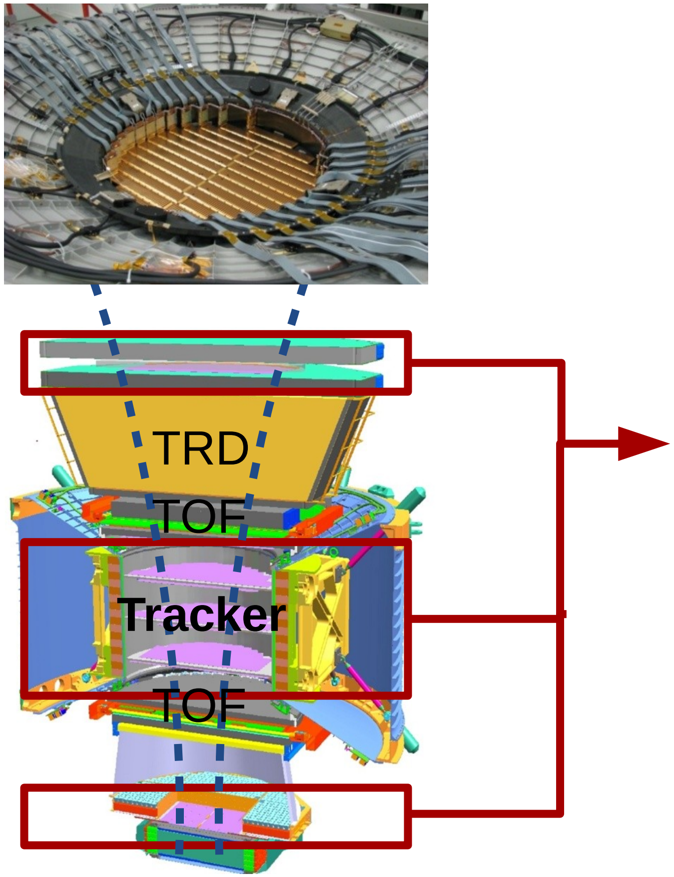
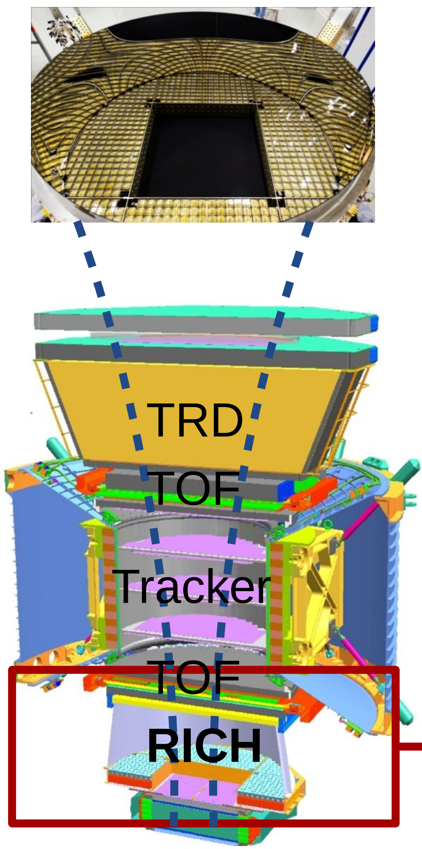
SILICON TRACKER AND MAGNET



	e^-	p	Fe	e^+	$\bar{p}$	
TRD	x-rays +ion.	ion.	ion.	x-rays +ion.	ion.	**e/p? Q**
TOF	**dE/dx**	**dE/dx**	**dE/dx**	**dE/dx**	**dE/dx**	**Q, E**
Tracker Magnet	**dE/dx**	**dE/dx**	**dE/dx**	**dE/dx**	**dE/dx**	**Q, R**

→ **charge Q, sgn (Q)**
→ **rigidity R=p/Z**

RING IMAGING CHEREKOV DETECTOR



	e^-	p	Fe	e^+	$\bar{p}$	
TRD	x-rays +ion.	ion.	ion.	x-rays +ion.	ion.	**e/p? Q**
TOF	**dE/dx**	**dE/dx**	**dE/dx**	**dE/dx**	**dE/dx**	**Q, β**
Tracker Magnet	**dE/dx**	**dE/dx**	**dE/dx**	**dE/dx**	**dE/dx**	**Q, R**
RICH						**Q, β**

→ **charge Q**
→ **velocity β**

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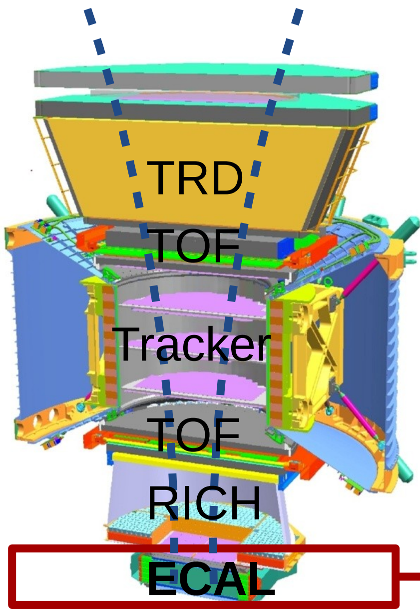
ELECTROMAGNETIC CALORIMETER

Karlsruhe Institute of Technology



Identify e^+, e^-
Energy of e^+, e^-

	e^-	p	Fe	e^+	$\bar{p}$	
TRD	x-rays +ion.	ion.	ion.	x-rays +ion.	ion.	**e/p? Q**
TOF	**dE/dx**	**dE/dx**	**dE/dx**	**dE/dx**	**dE/dx**	**Q, β**
Tracker Magnet	**dE/dx**	**dE/dx**	**dE/dx**	**dE/dx**	**dE/dx**	**Q, R**
RICH						**Q, β**
ECAL		MIP	MIP		MIP	**E, e/p?**
Physics	**Transport + production of CRs**			**Dark Matter**		

Particle properties are measured redundantly

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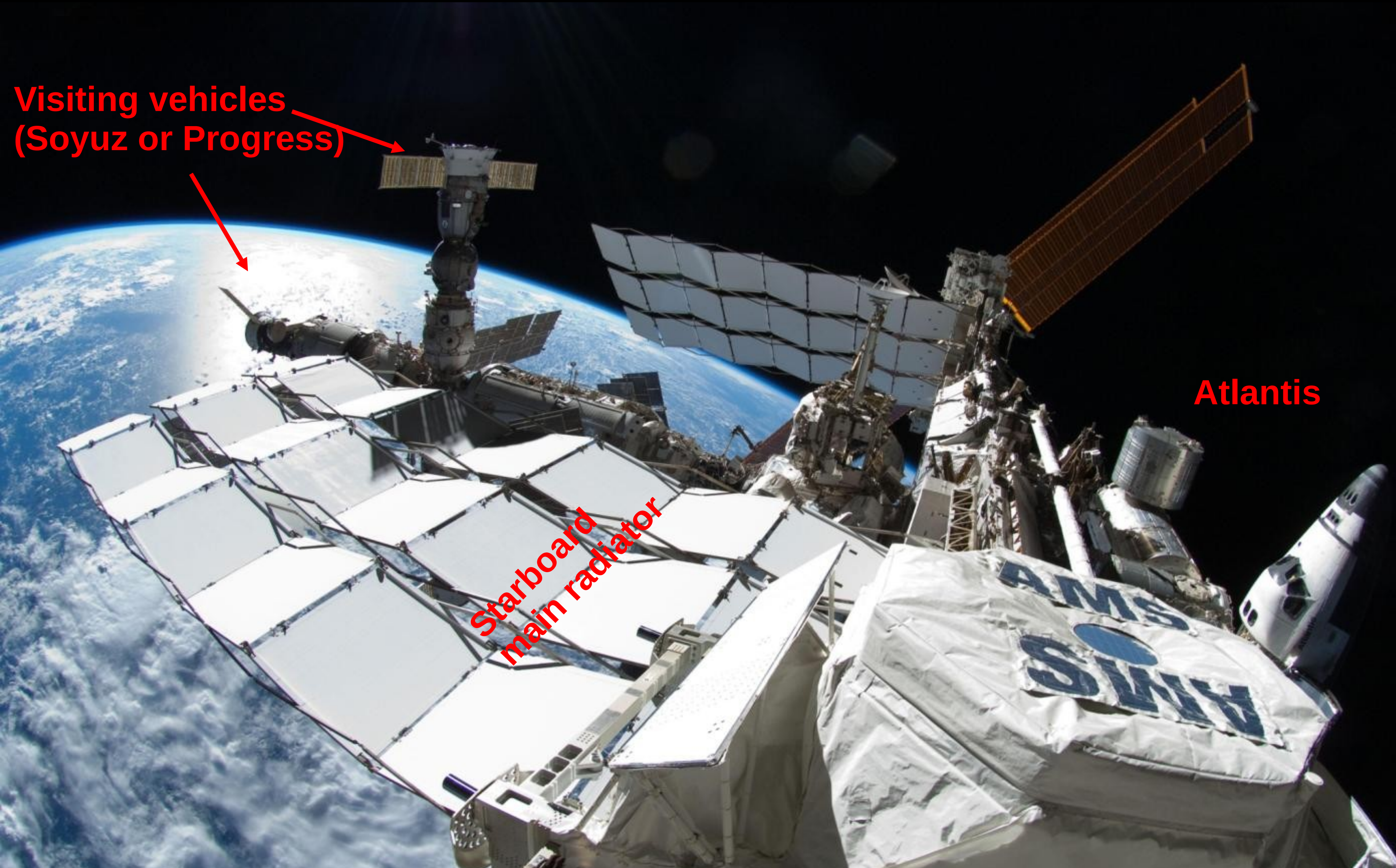
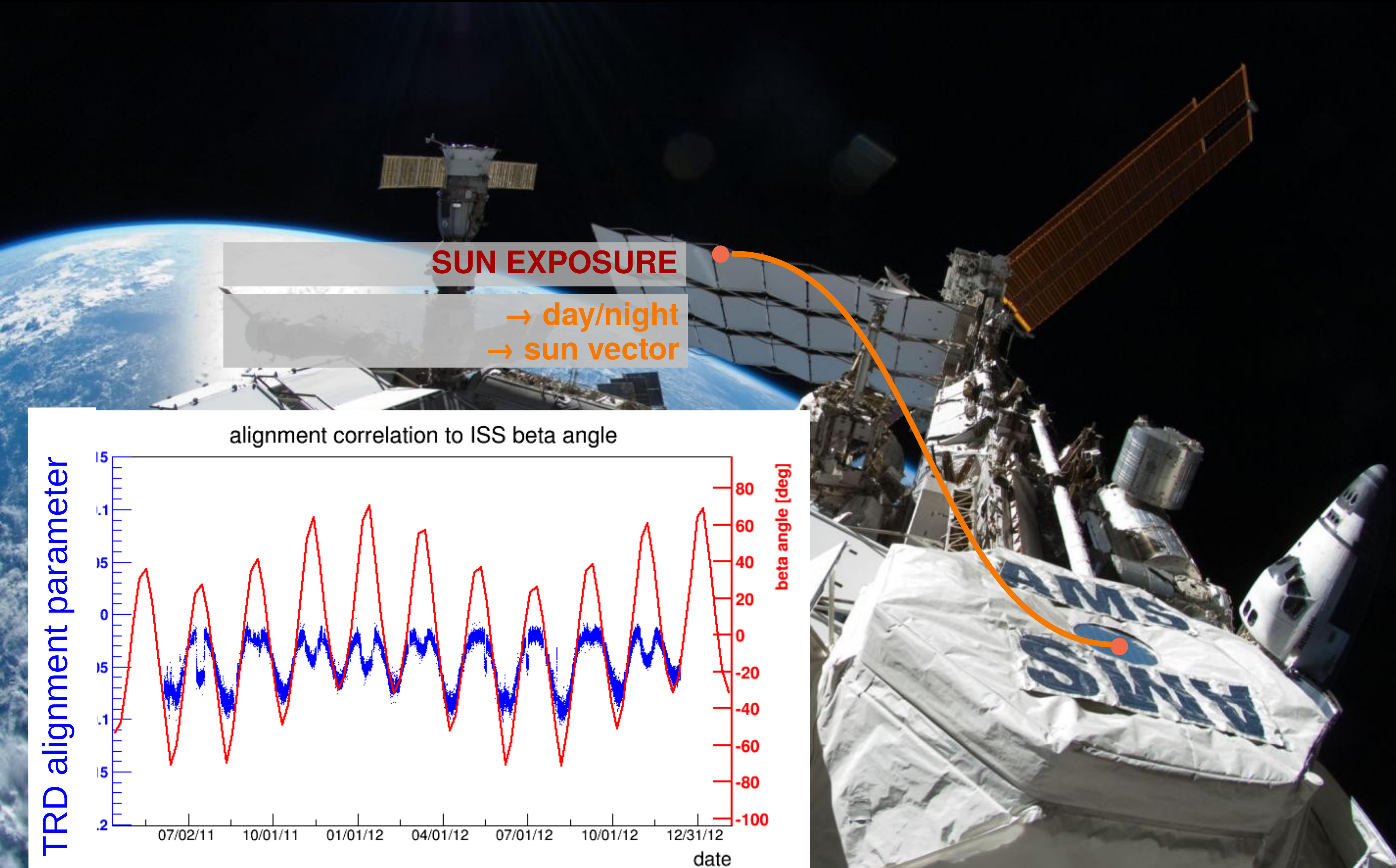
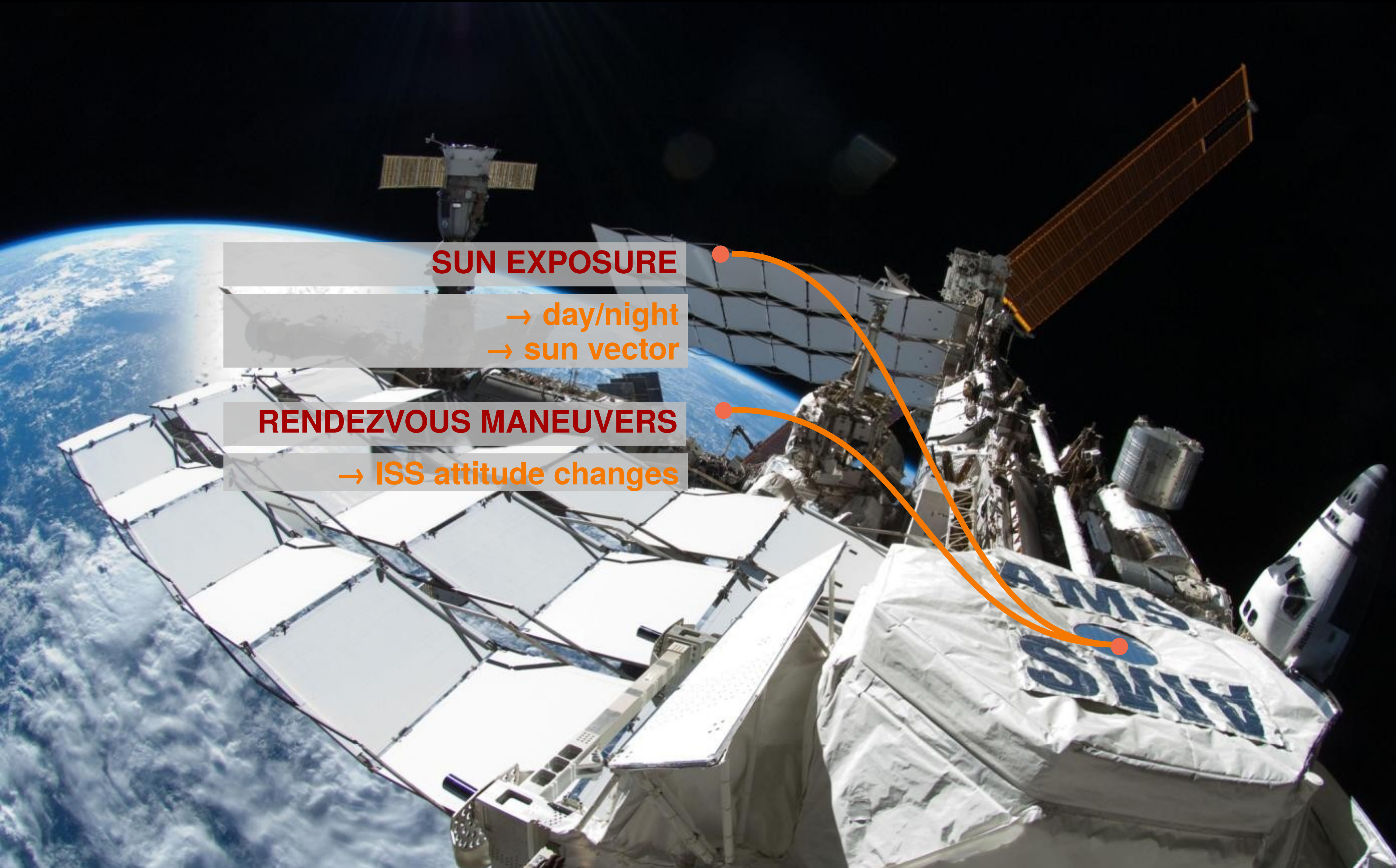
OPERATING AMS-02 ON THE ISS



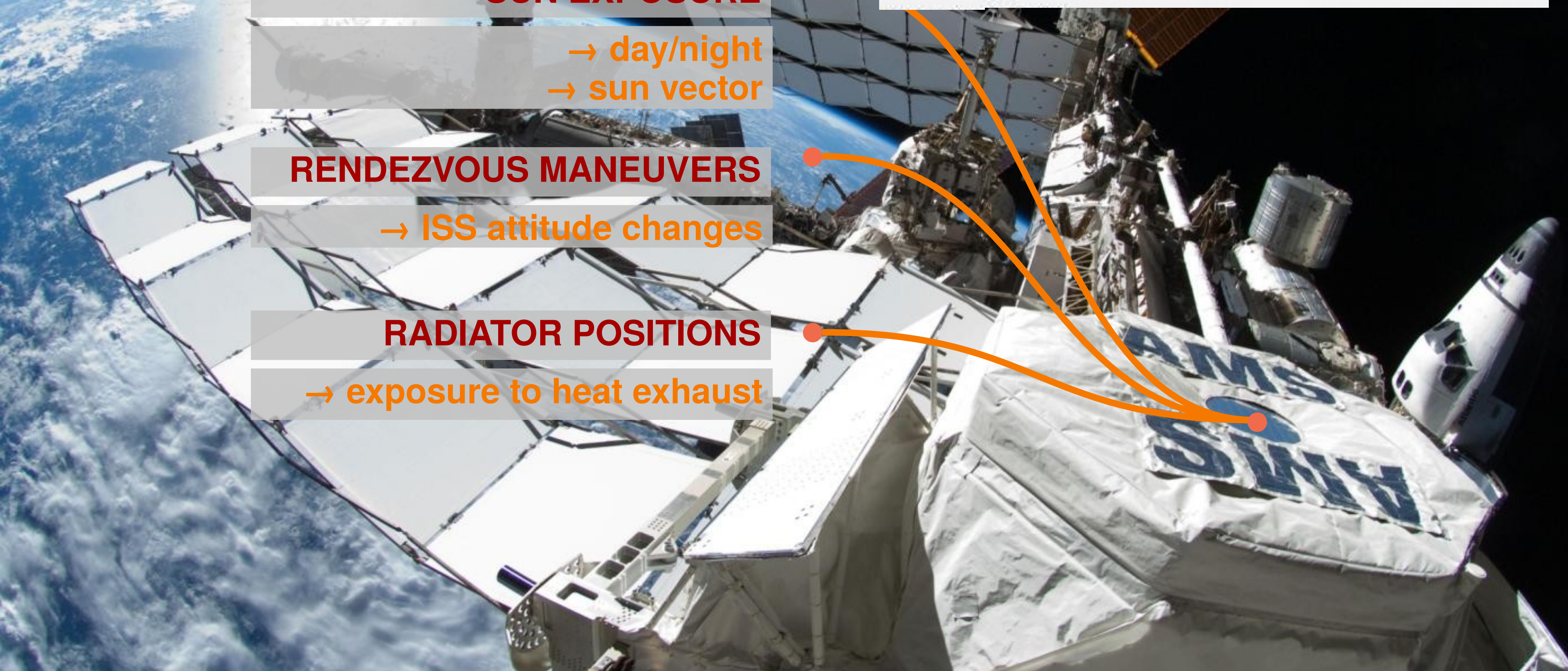
OPERATING AMS-02 ON THE ISS

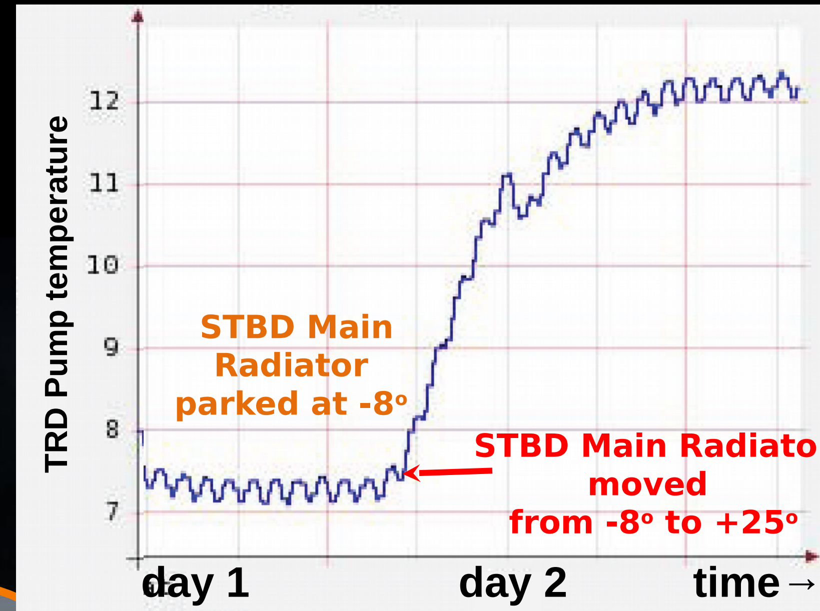


OPERATING AMS-02 ON THE ISS

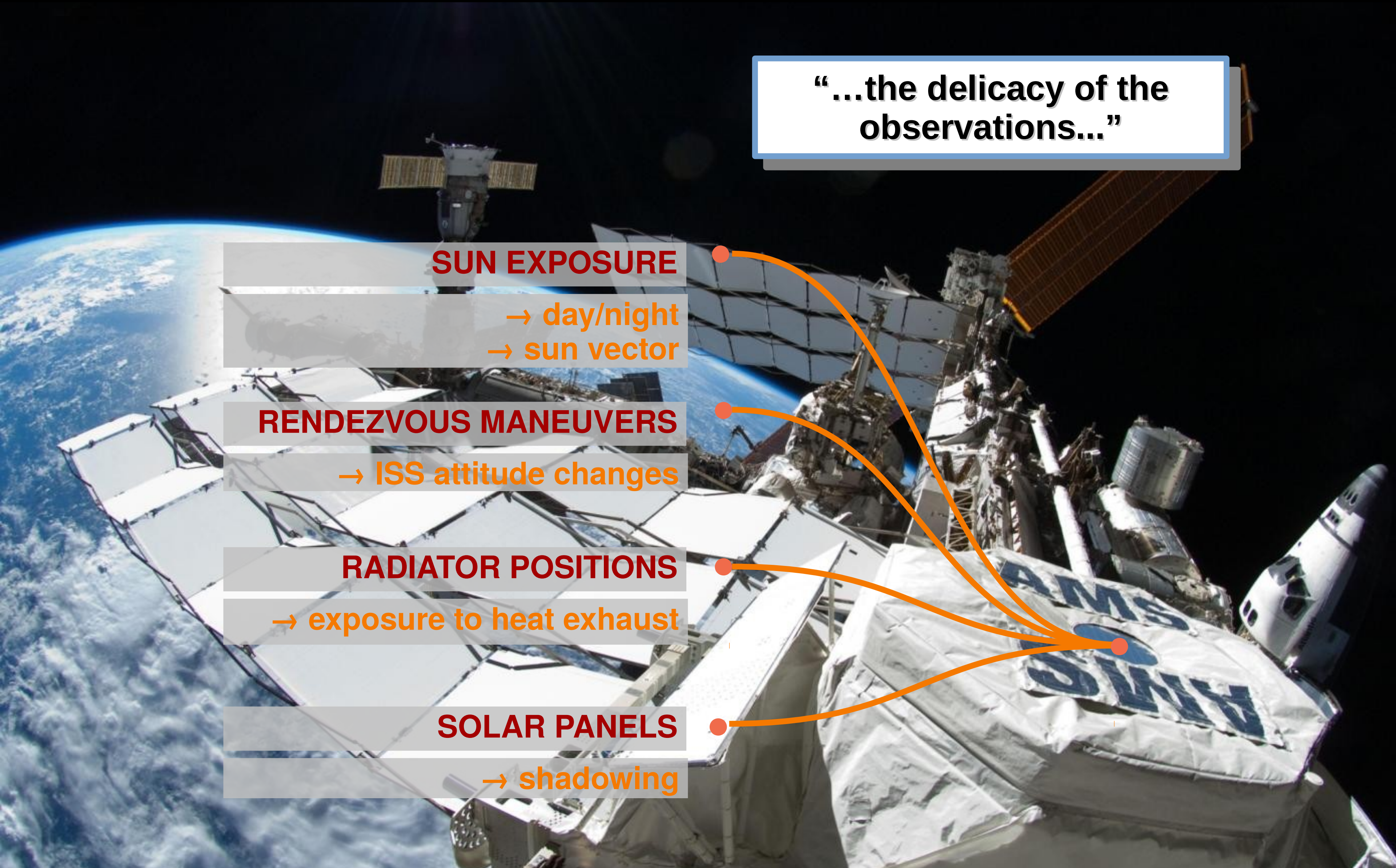


OPERATING AMS-02 ON THE ISS





OPERATING AMS-02 ON THE ISS



"…the delicacy of the observations…"

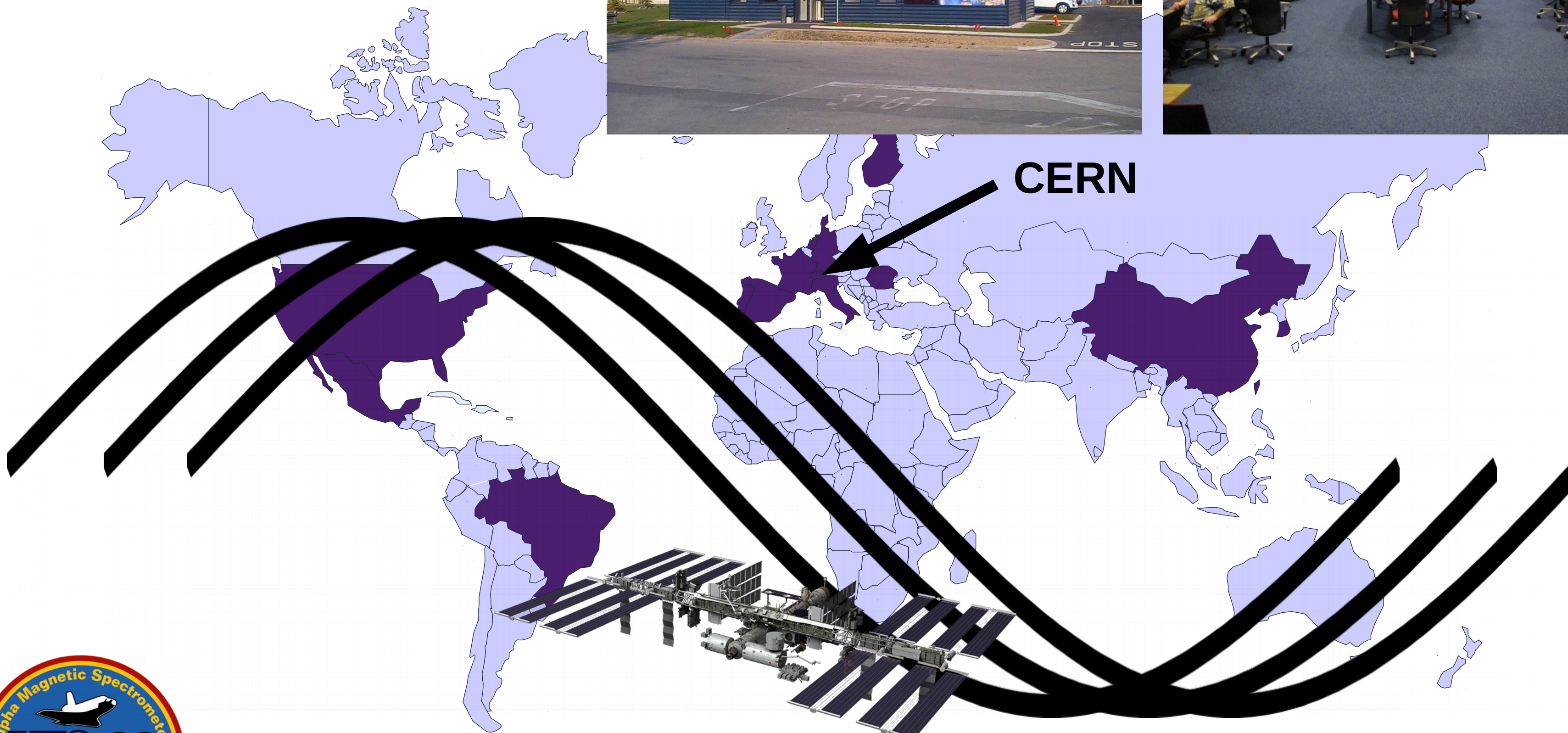
SUN EXPOSURE
→ day/night
→ sun vector

RENDEZVOUS MANEUVERS
→ ISS attitude changes

RADIATOR POSITIONS
→ exposure to heat exhaust

SOLAR PANELS
→ shadowing

PAYLOAD OPERATIONS



16 countries, 56 institutes, ~500 physicists

Germany: RWTH Aachen, KIT → future: + CAU Kiel

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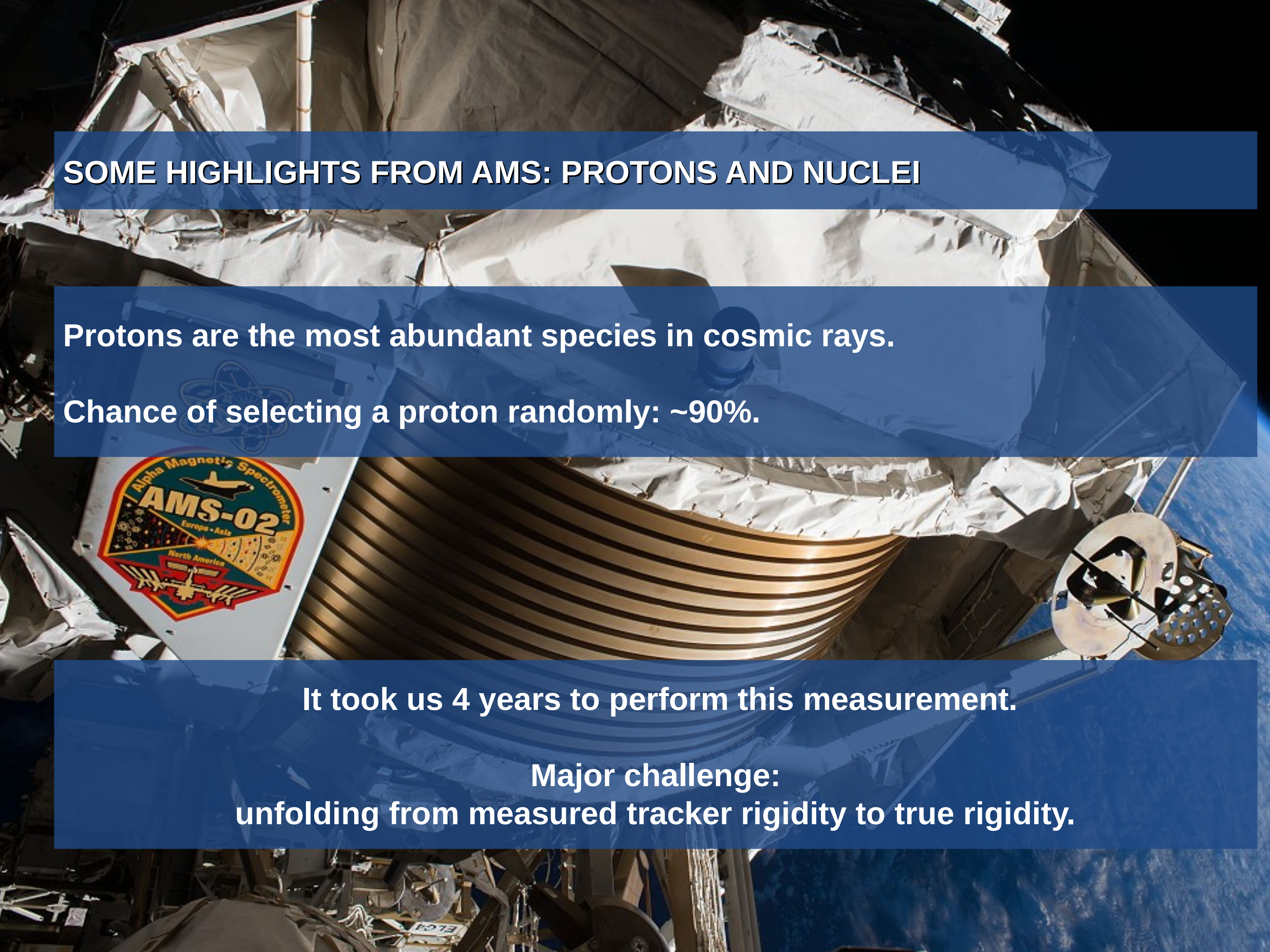


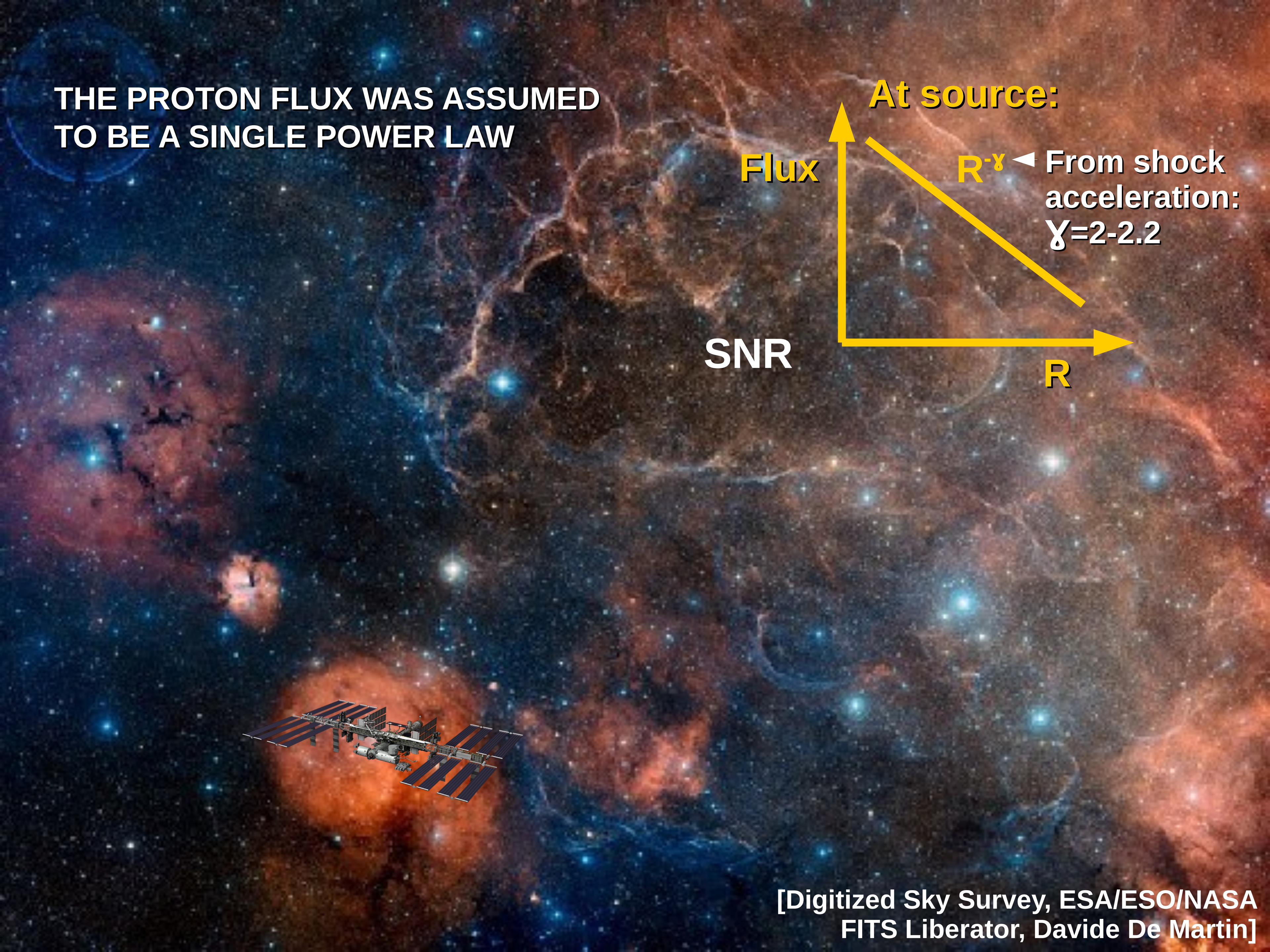
SOME HIGHLIGHTS FROM AMS: PROTONS AND NUCLEI

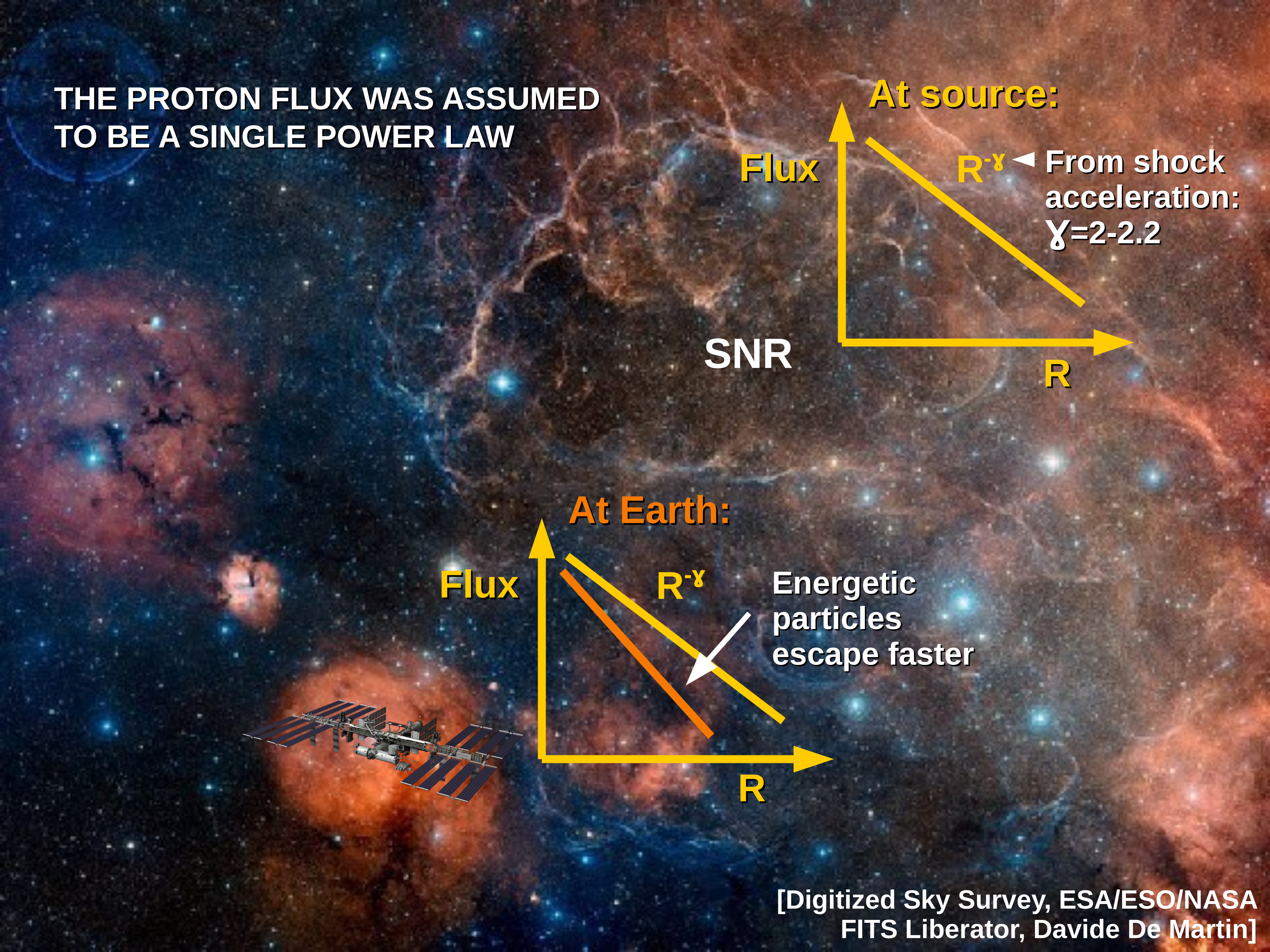
Protons are the most abundant species in cosmic rays.

Chance of selecting a proton randomly: ~90%.

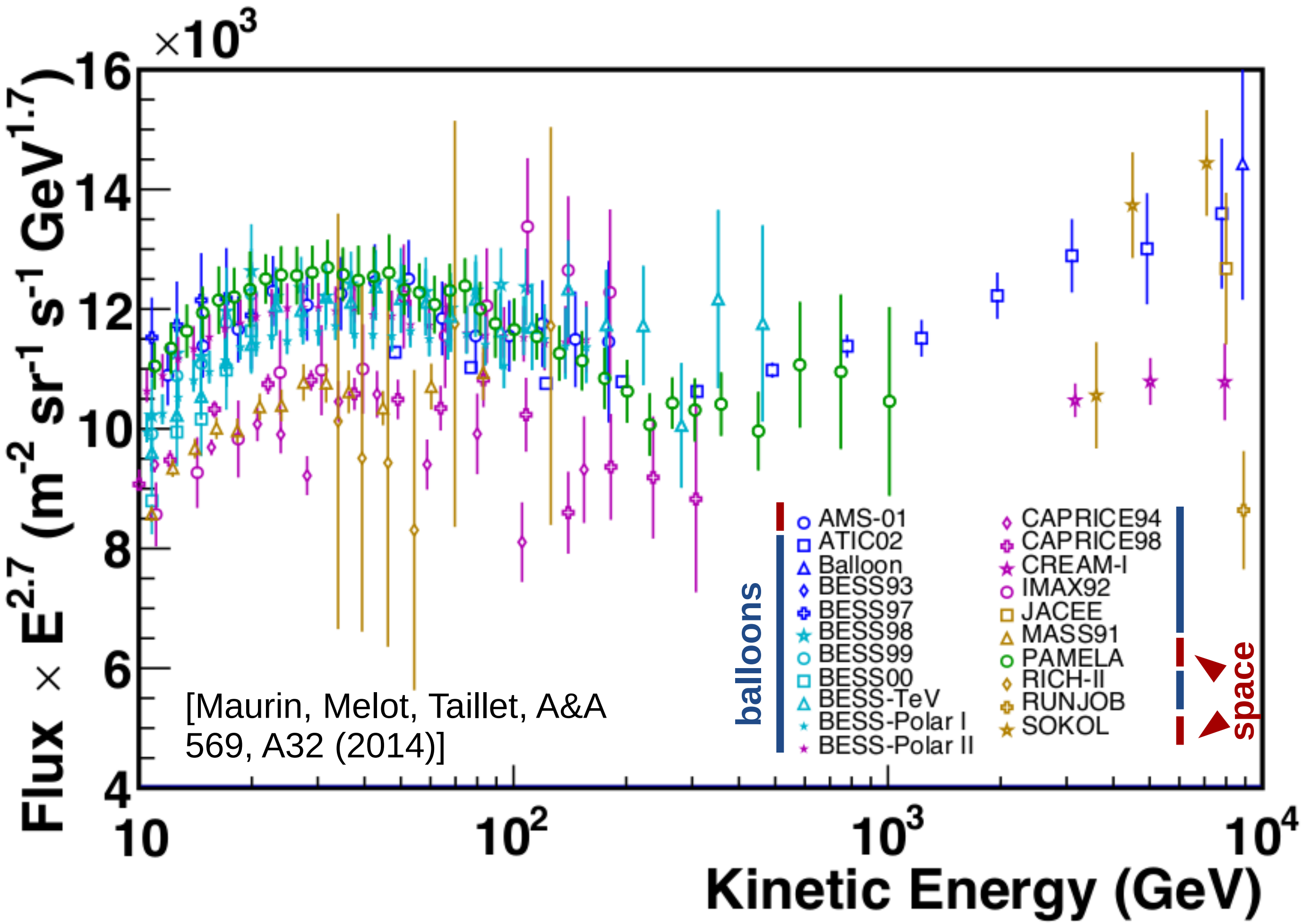
It took us 4 years to perform this measurement.

Major challenge:
unfolding from measured tracker rigidity to true rigidity.


THE PROTON FLUX WAS ASSUMED
TO BE A SINGLE POWER LAW
At source:
Flux
R
$R^{-\gamma}$
From shock acceleration:
γ=2-2.2
SNR
[Digitized Sky Survey, ESA/ESO/NASA
FITS Liberator, Davide De Martin]

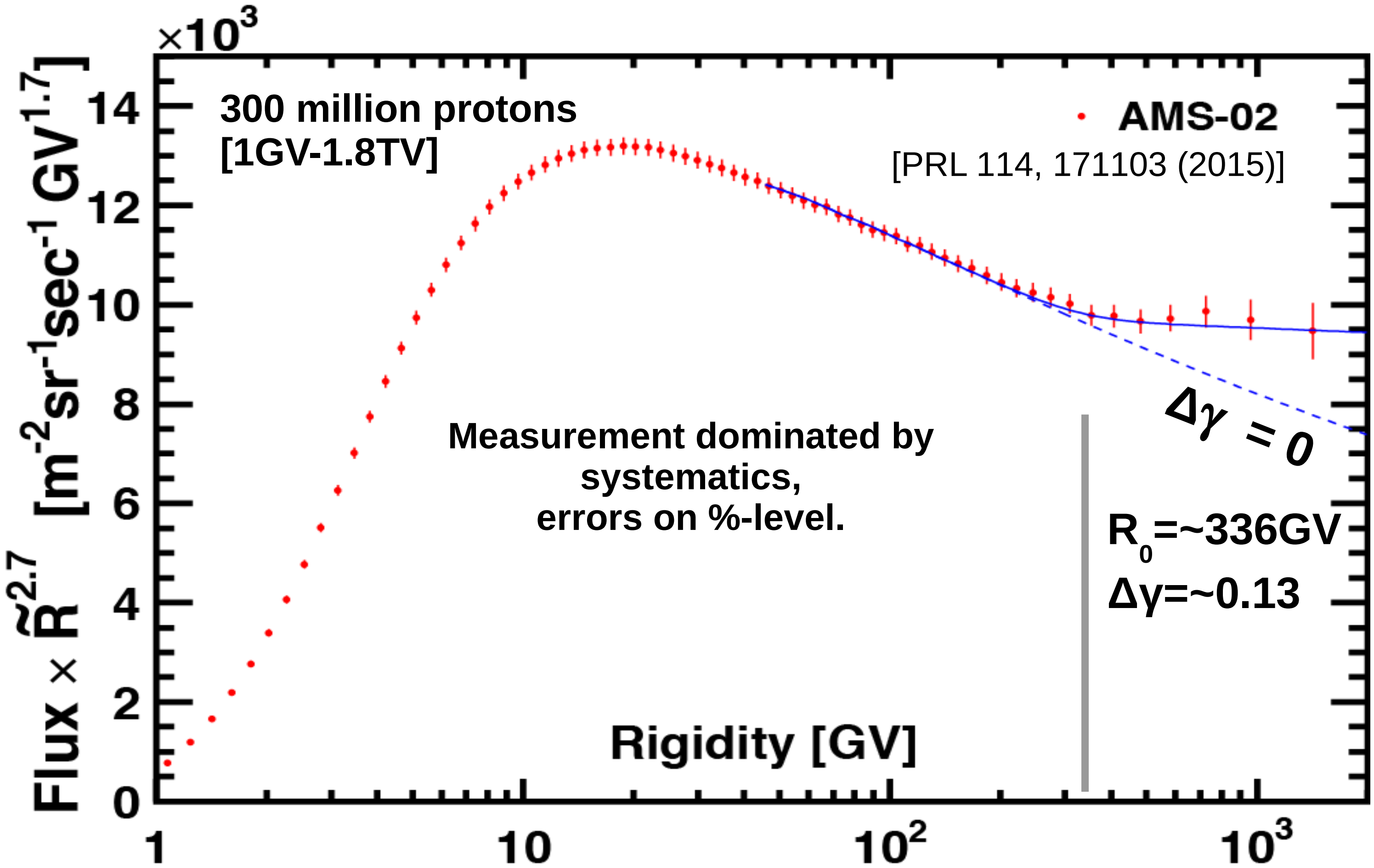

THE PROTON FLUX WAS ASSUMED
TO BE A SINGLE POWER LAW
At source:
Flux
R^-ɣ
From shock
acceleration:
ɣ=2-2.2
SNR
R
At Earth:
Flux
R^-ɣ
Energetic
particles
escape faster
R
[Digitized Sky Survey, ESA/ESO/NASA
FITS Liberator, Davide De Martin]

PROTON FLUX … BEFORE AMS



Traditionally, the proton flux was assumed to be a single power law $\Phi = CE^{-\gamma}$, $\gamma = 2.7$.

PROTON FLUX ... WITH AMS



The proton flux cannot be described by a single power law.

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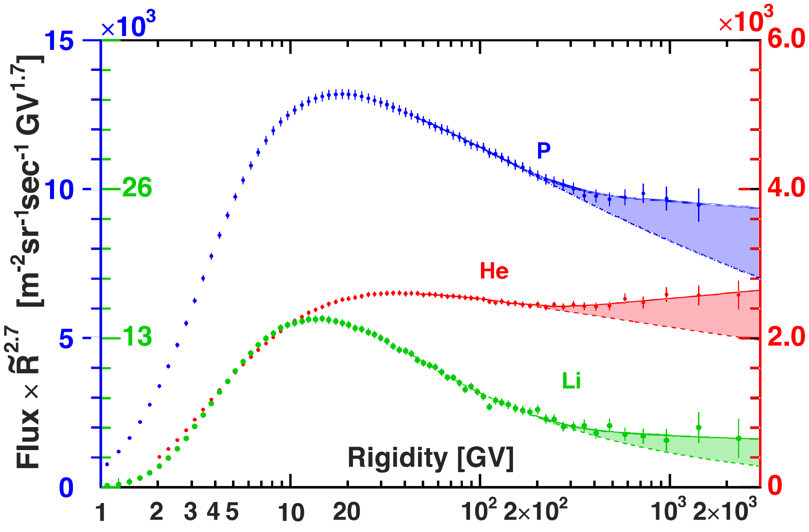
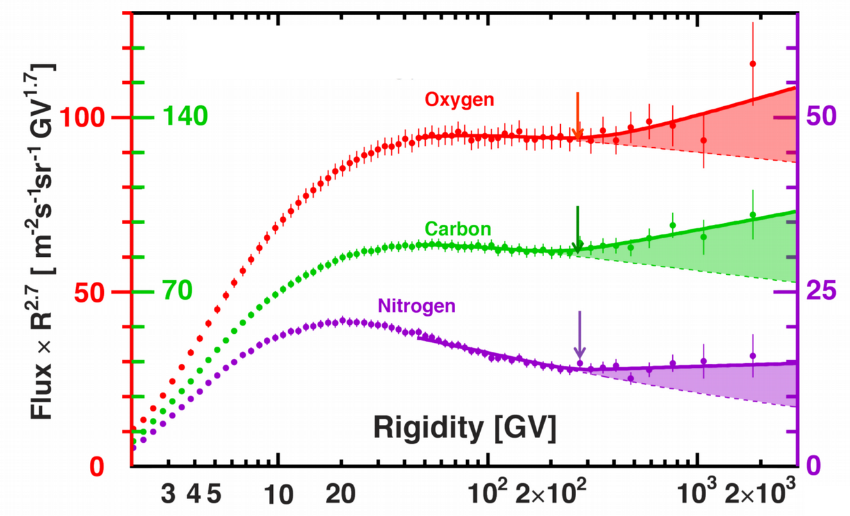
NUCLEI

The spectra of p, He, Li, Be, B, C, N, O do not follow the traditional power law.



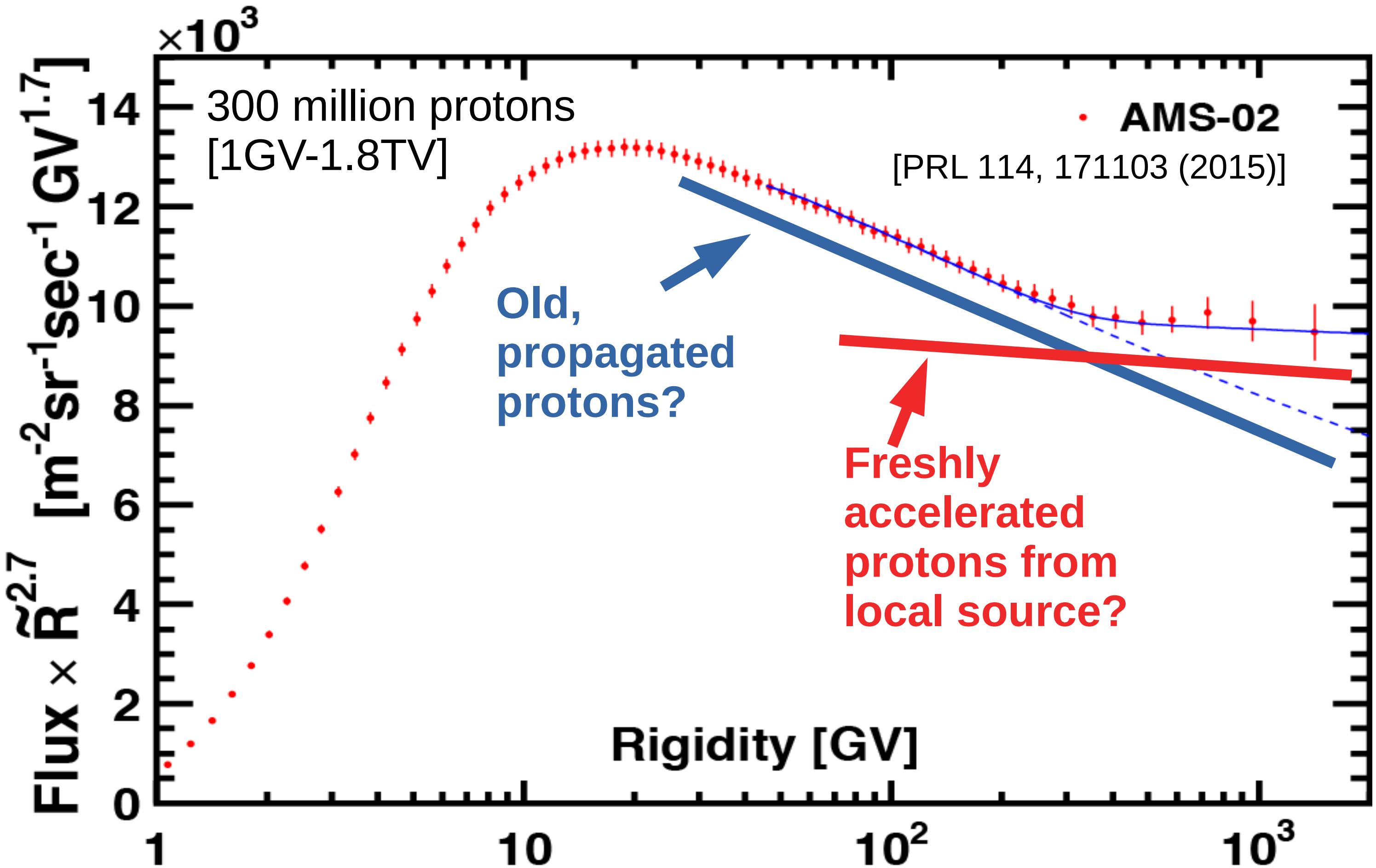


A spectral hardening is observed for all nuclei.

- **at around 300 GV for primary cosmic ray species**
- **at around 200 GV for secondary cosmic ray species**

[PRL 114, 171103 (2015)]
[PRL 115, 211101 (2015)]
[PRL 119, 251101 (2017)]
[PRL 120, 021101 (2018)]

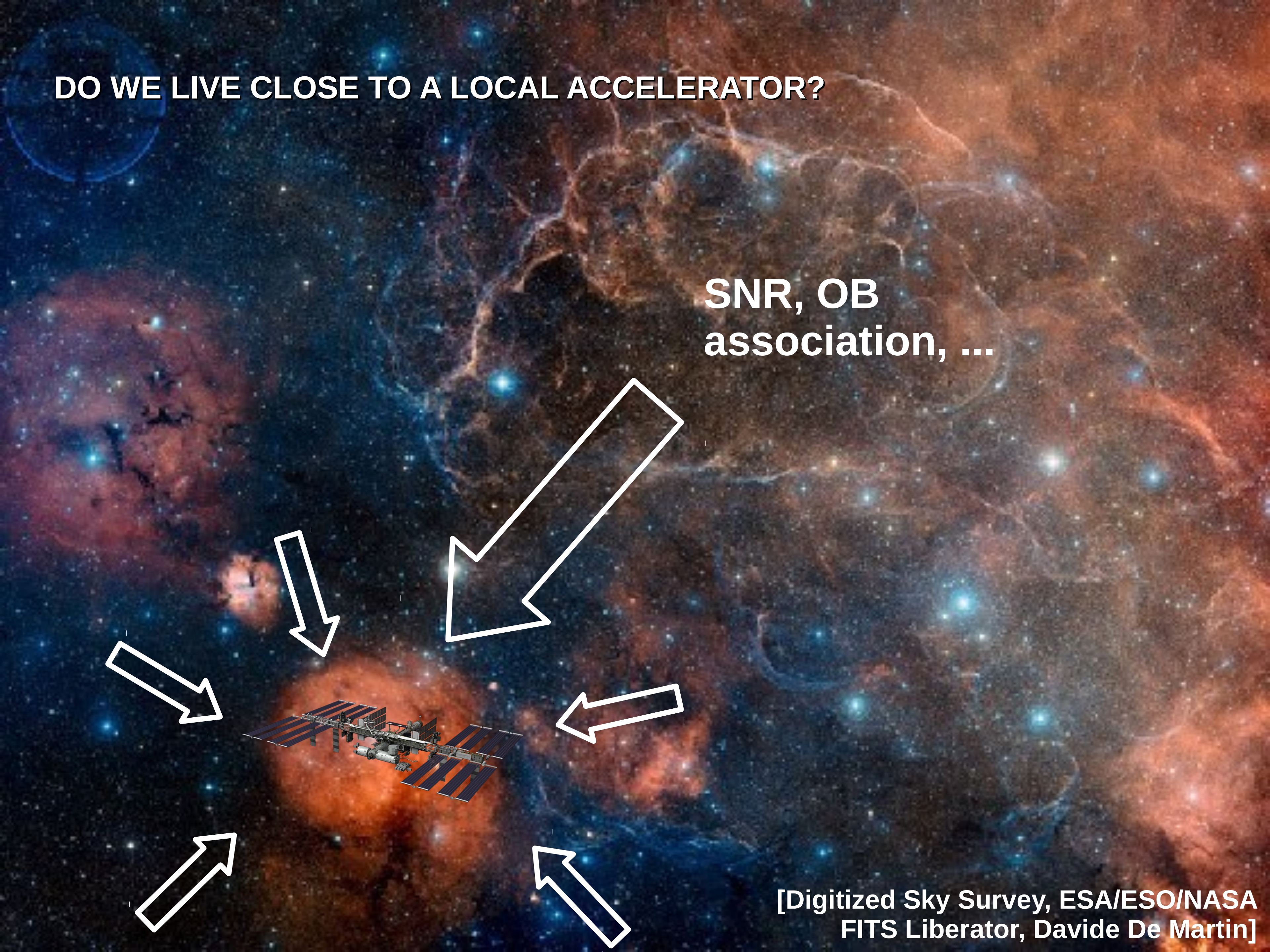
DO WE LIVE CLOSE TO A LOCAL ACCELERATOR?



Bernard et al., A&A 555, A48 (2013)

Ptuskin et al., APJ 763, 47 (2013)

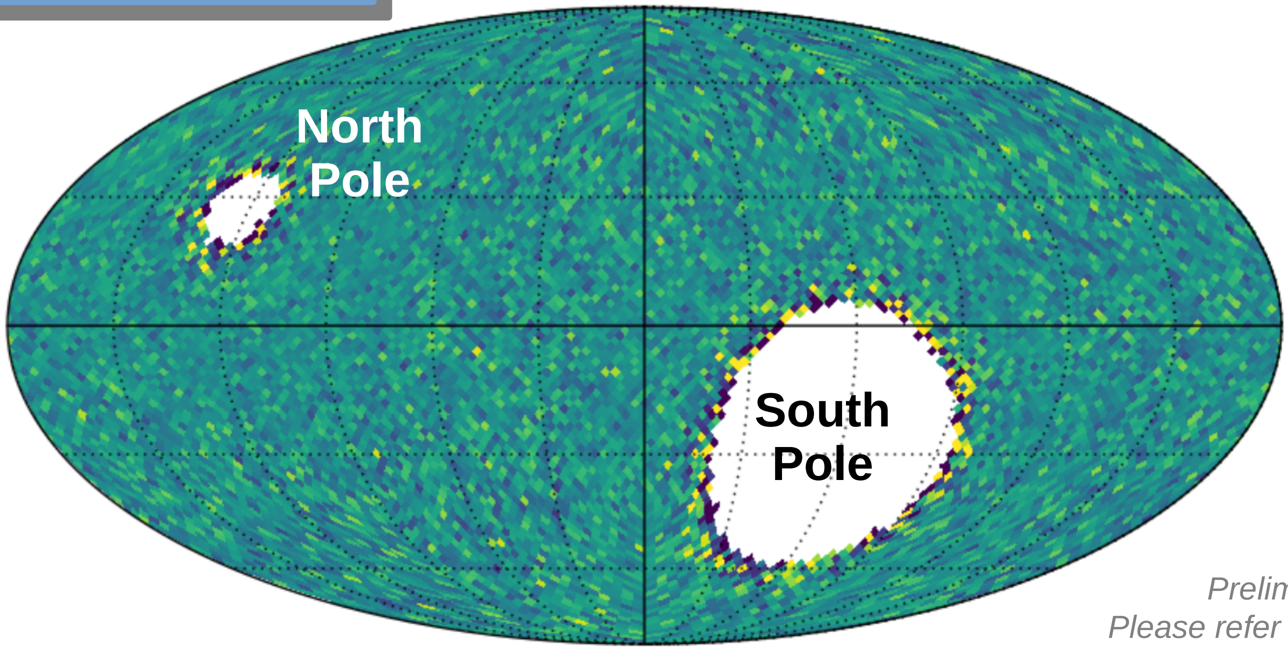
+ many more excellent papers


DO WE LIVE CLOSE TO A LOCAL ACCELERATOR?
SNR, OB
association, ...
[Digitized Sky Survey, ESA/ESO/NASA
FITS Liberator, Davide De Martin]

SEARCHING FOR DIPOLE ANISOTROPIES IN PROTONS

"… the subtlety of the analysis…"

Proton sky map:



Preliminary data. Please refer to the forthcoming publication in PRL.

The proton sky is perfectly isotropic within the AMS statistics.

δ_p(>16 GV) < 0.1% at 95% C.L.

(Local accelerator is not excluded by this limit)

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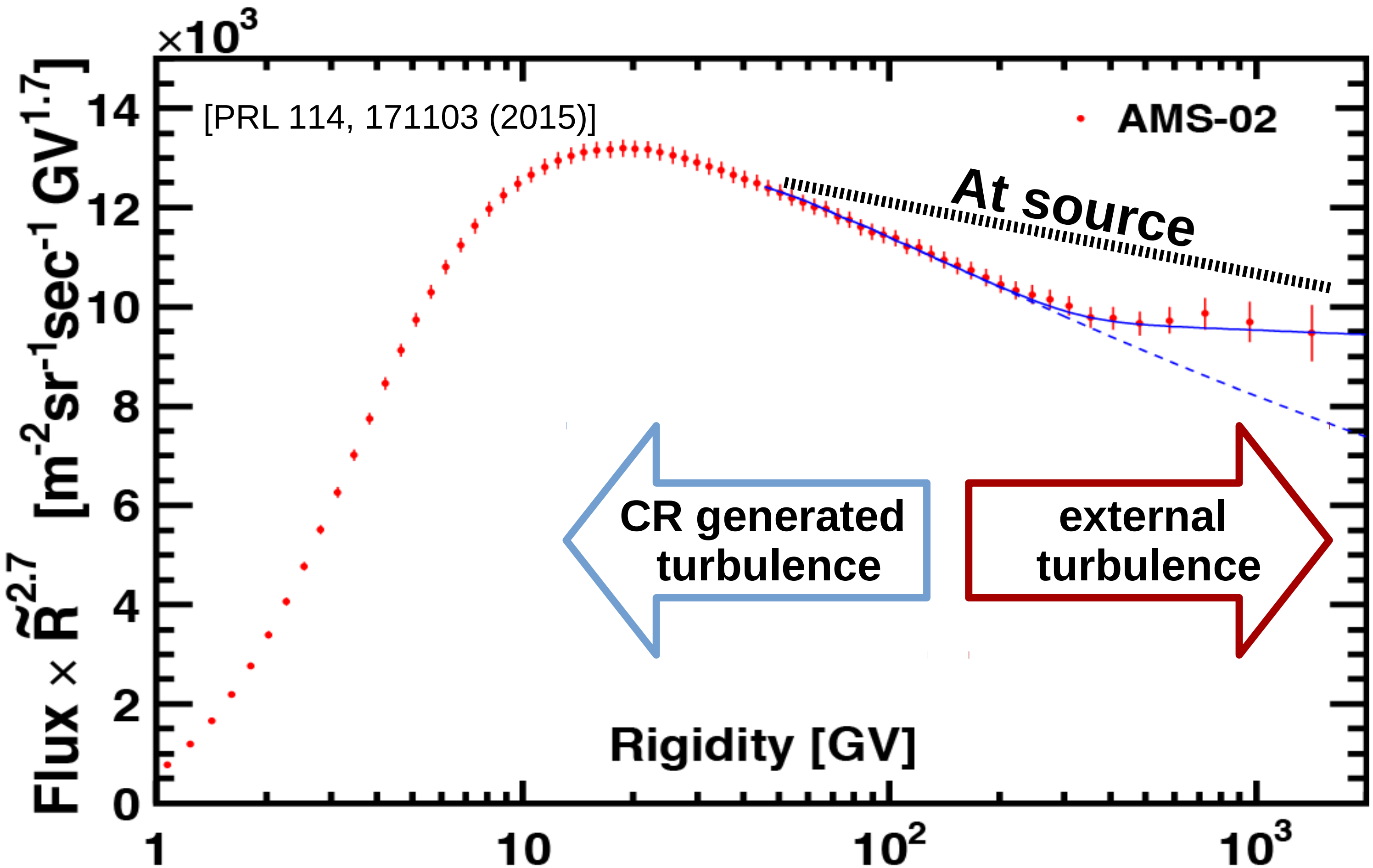
DOES COSMIC RAY TRANSPORT CHANGE?



Cesarsky, ARA&A 18, 289C (**1980**) → **100 GV**

Blasi et al. PRL109, 061101 (**2012**) → **200 GV**

+ many more excellent papers

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WHAT WE ARE LEARNING FROM COSMIC RAY NUCLEI

The spectra of cosmic ray nuclei are not single power laws
→ we do not understand cosmic ray sources or we do not understand cosmic ray transport.

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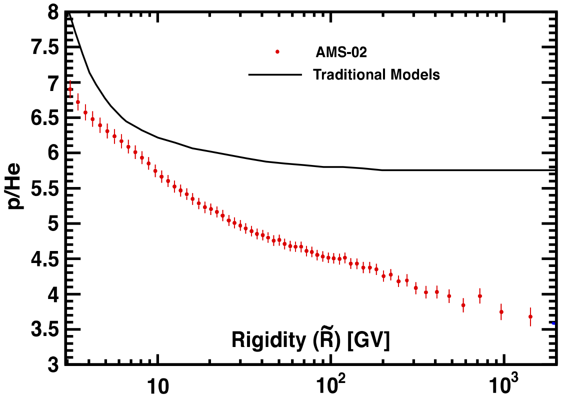
WHAT WE ARE LEARNING FROM COSMIC RAY NUCLEI

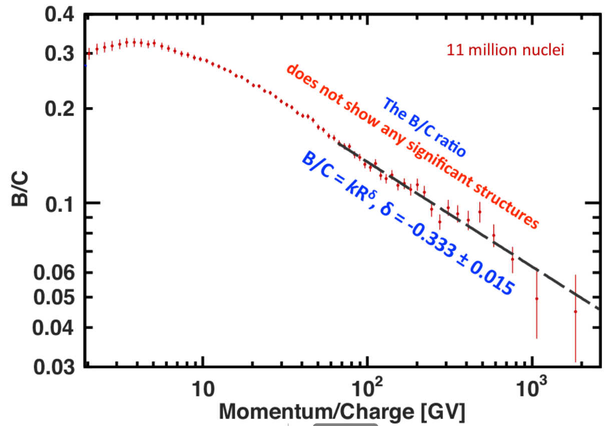
The spectra of cosmic ray nuclei are not single power laws
→ we do not understand cosmic ray sources or we do not understand cosmic ray transport.

The proton/helium ratio is not flat!



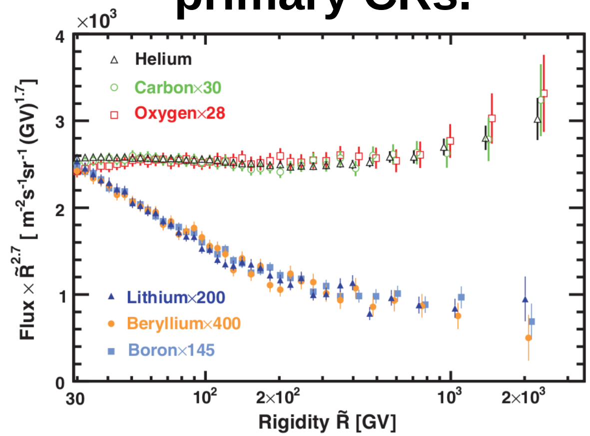
Cosmic ray sources are more complicated than we assumed.

The boron/carbon ratio falls with 0.33!



Interstellar turbulence follows Kolmogorov cascade.

Secondary CRs harden more than primary CRs.



Probably meaningful.

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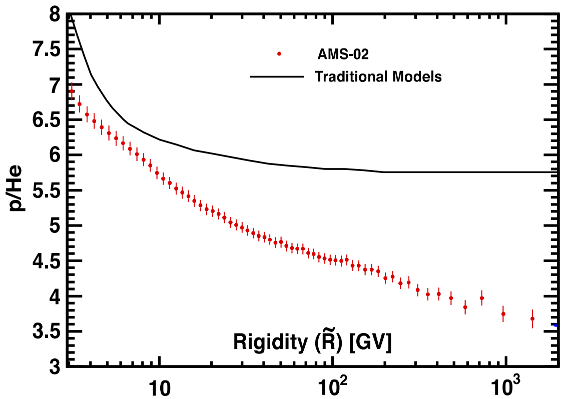
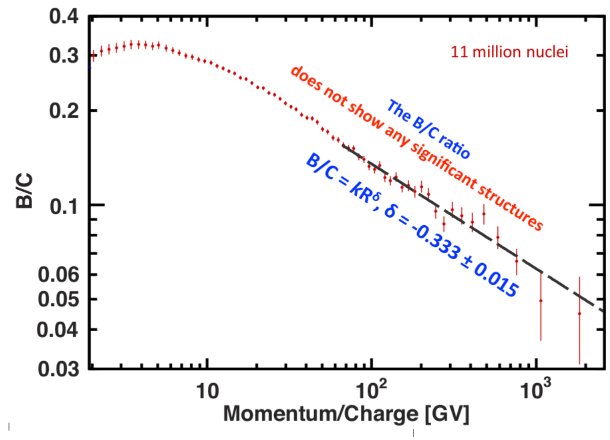
The spectra of cosmic ray nuclei are not single power laws
→ we do not understand cosmic ray sources or we do not understand cosmic ray transport.

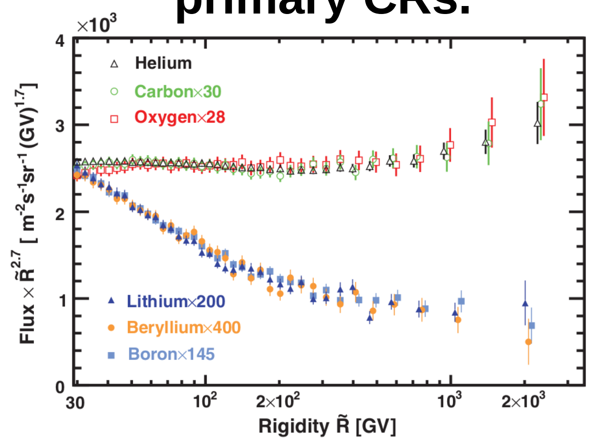
The proton/helium ratio is not flat!

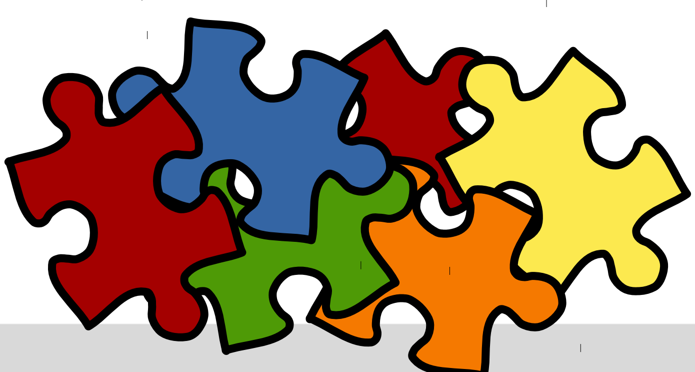


The boron/carbon ratio falls with 0.33!



Secondary CRs harden more than primary CRs.





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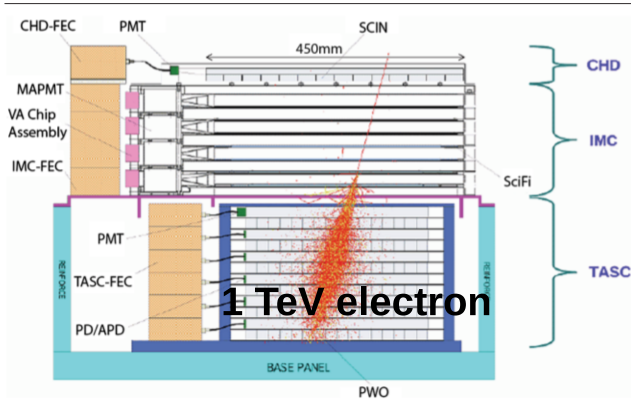
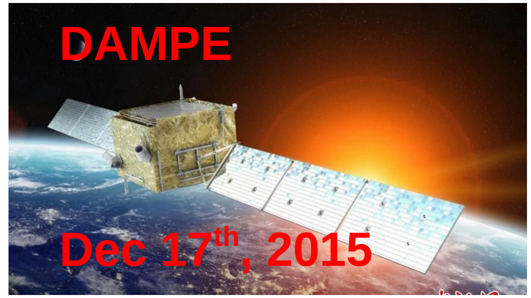
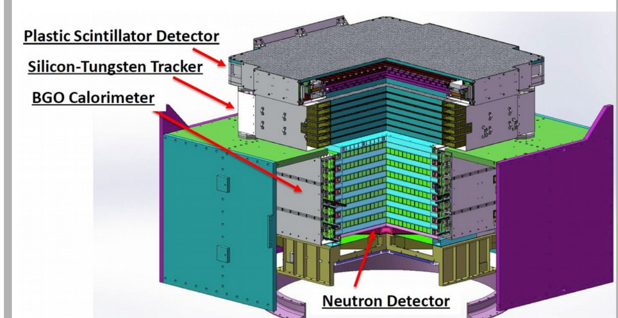
NEW CALORIMETRIC COSMIC RAY EXPERIMENTS



Total absorbtion calorimeter 30 X_0

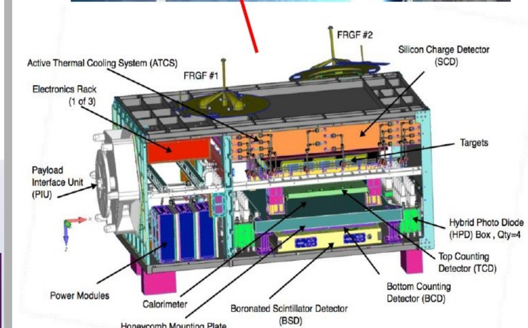
Nuclei: 10 GeV- 1 TeV
Electrons: 1 GeV -20 TeV





BGO imaging calorimeter 32 X_0

Nuclei: 50 GeV- 500 TeV
Electrons: 10 GeV -10 TeV

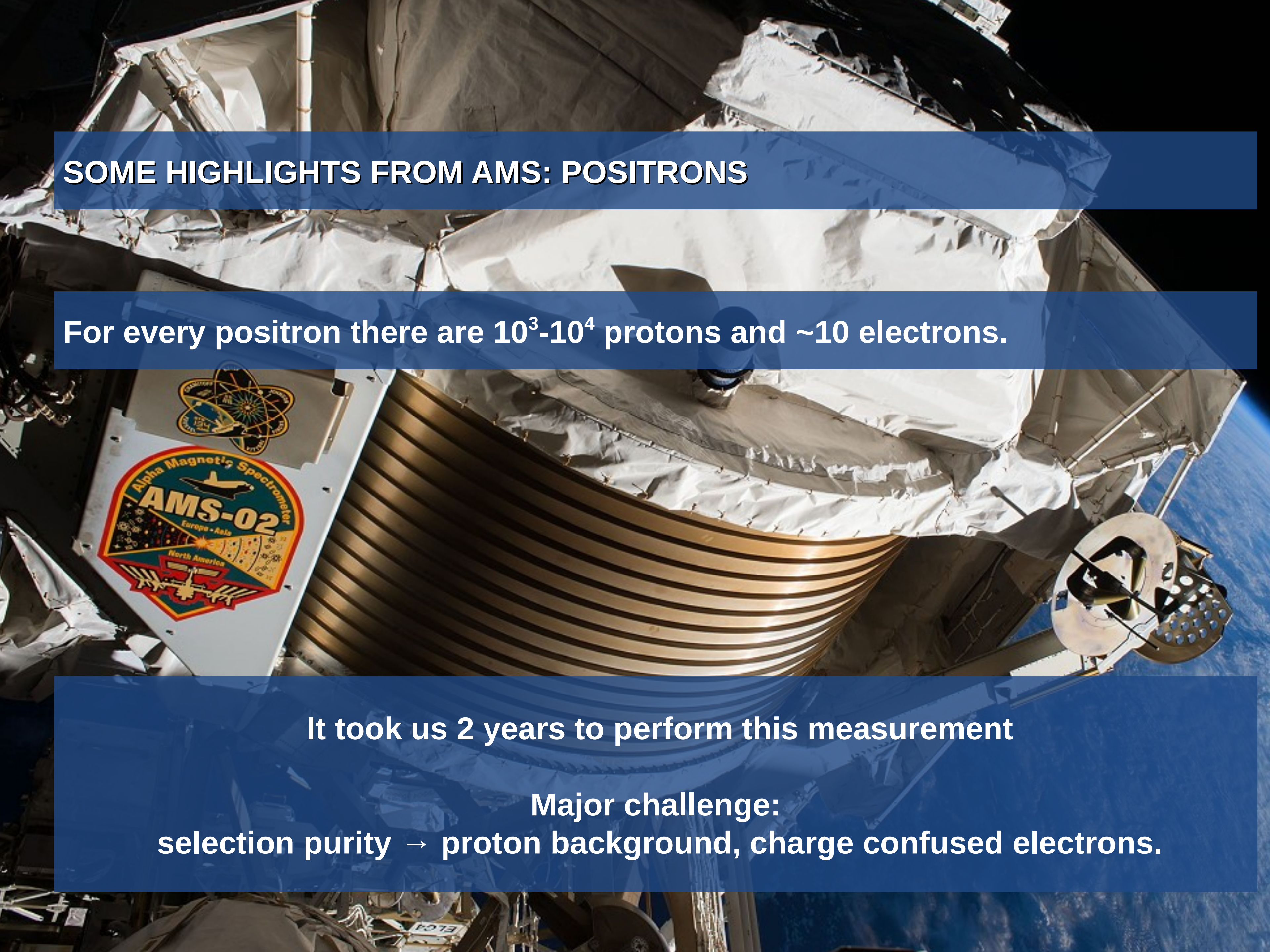


Tungsten calorimeter 20 X_0 + carbon target

Nuclei: 1TeV-1PeV
Electrons: 100 GeV -10 TeV

SOME HIGHLIGHTS FROM AMS: POSITRONS

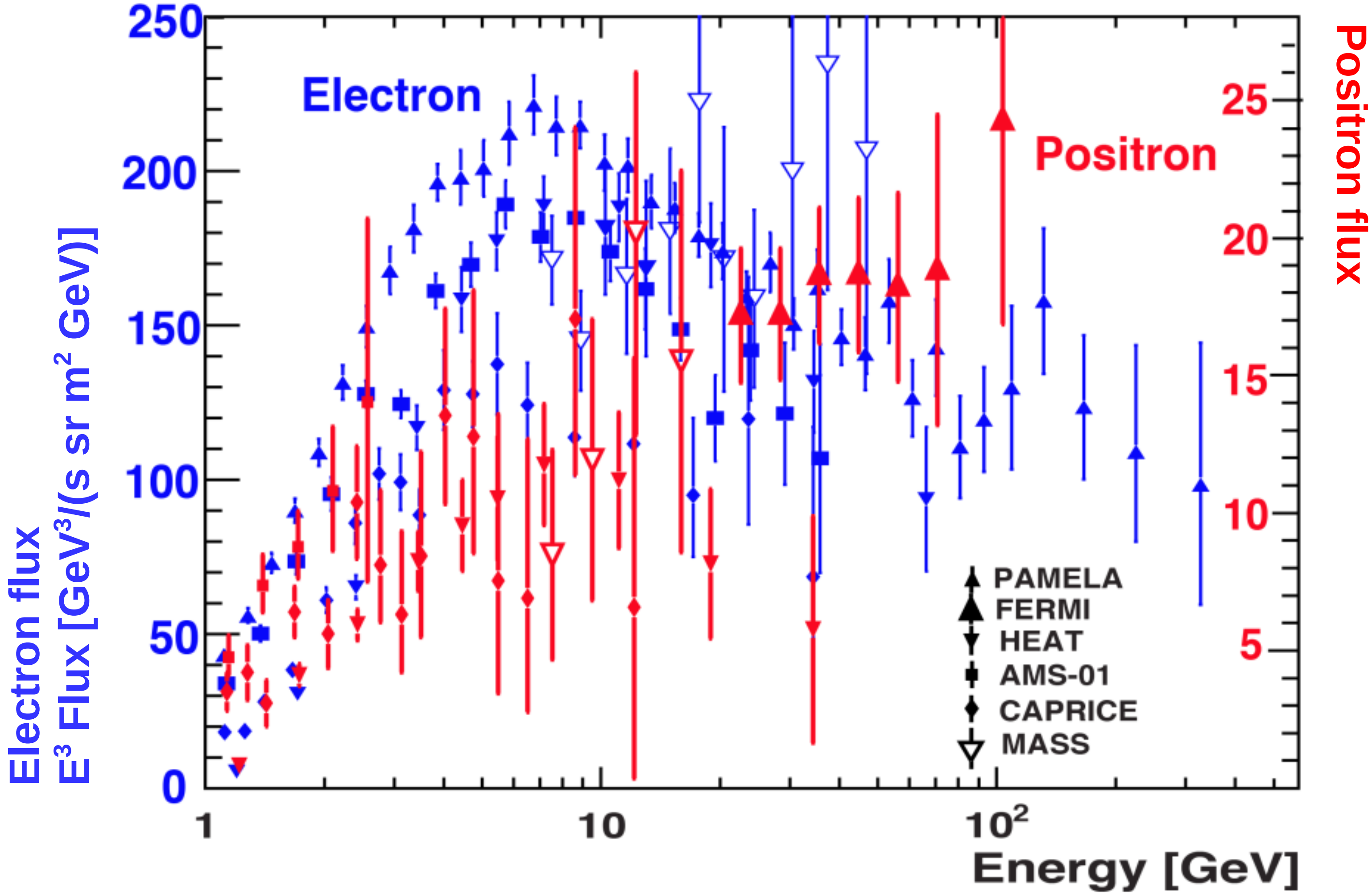
For every positron there are 10^3-10^4 protons and ~10 electrons.



It took us 2 years to perform this measurement

Major challenge:
selection purity → proton background, charge confused electrons.

ELECTRONS AND POSITRONS….BEFORE AMS



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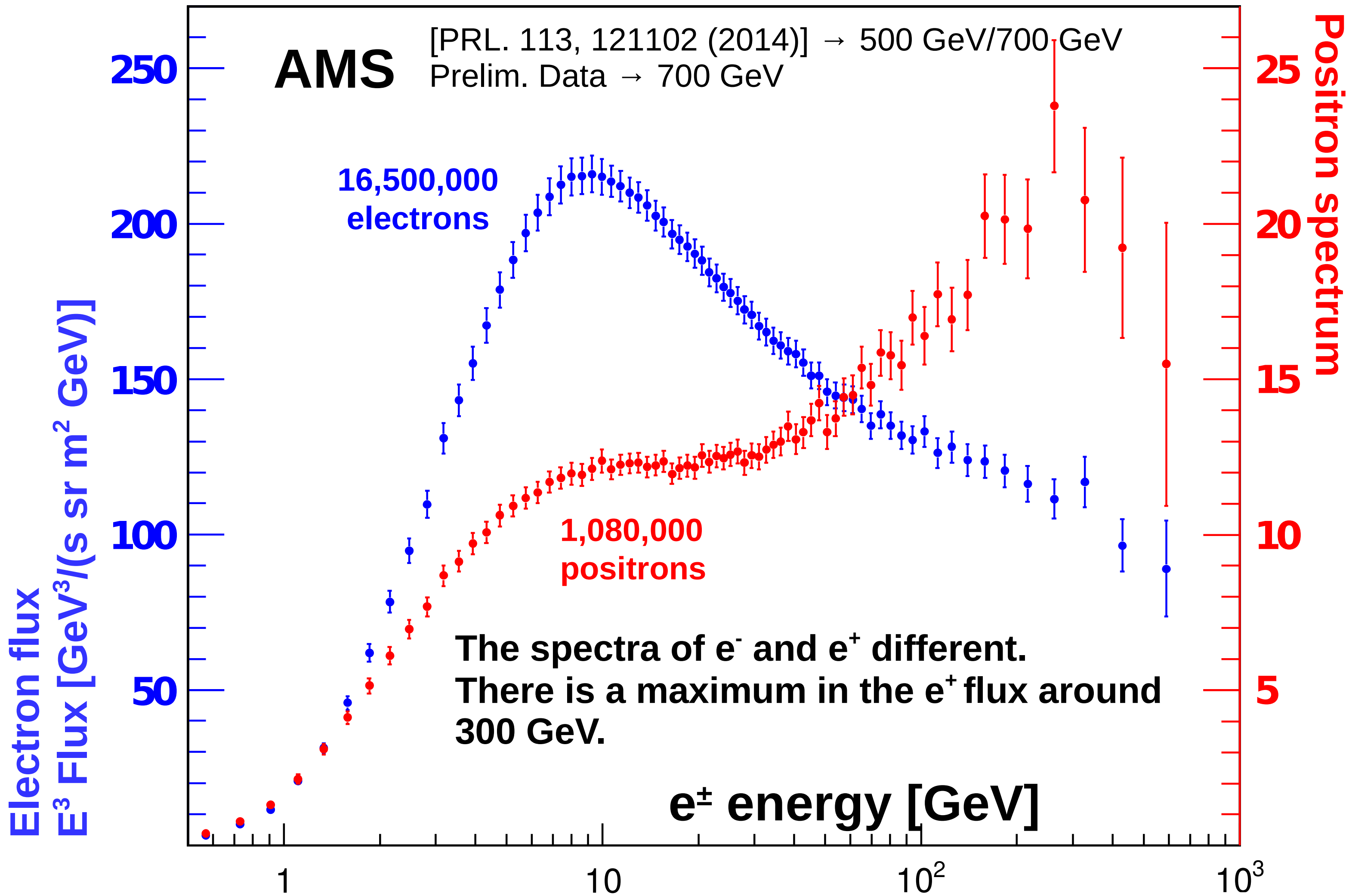
ELECTRONS AND POSITRONS WITH AMS



The spectra of e^- and e^+ different.
There is a maximum in the e^+ flux around 300 GeV.

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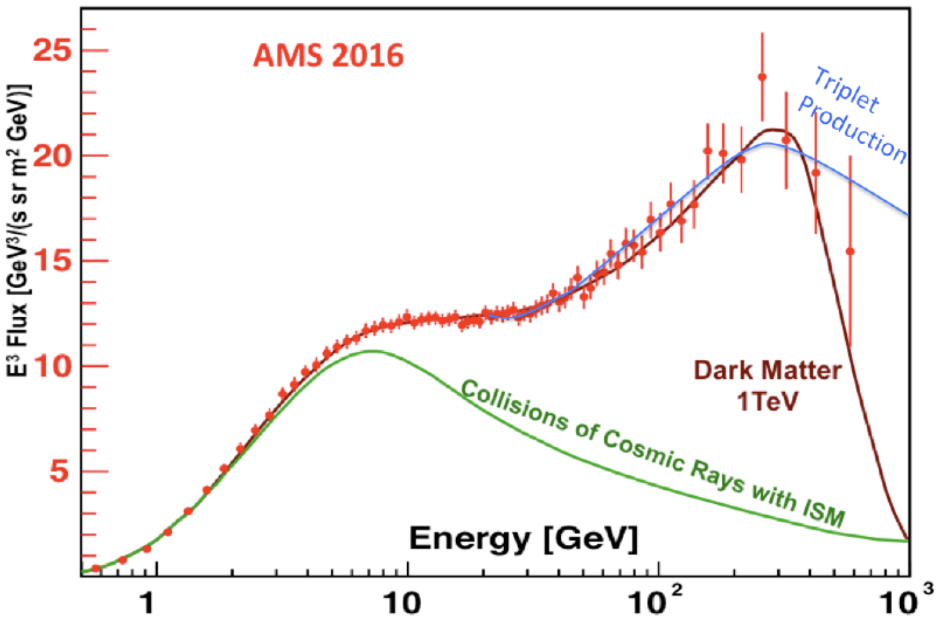
INTERPRETATION OF THE POSITRON EXCESS

The data are consistent with a symmetric contribution in e^+ and e^-.



[PRL. 113, 121102 (2014)] → 500 GeV
Prelim. Data → 700 GeV

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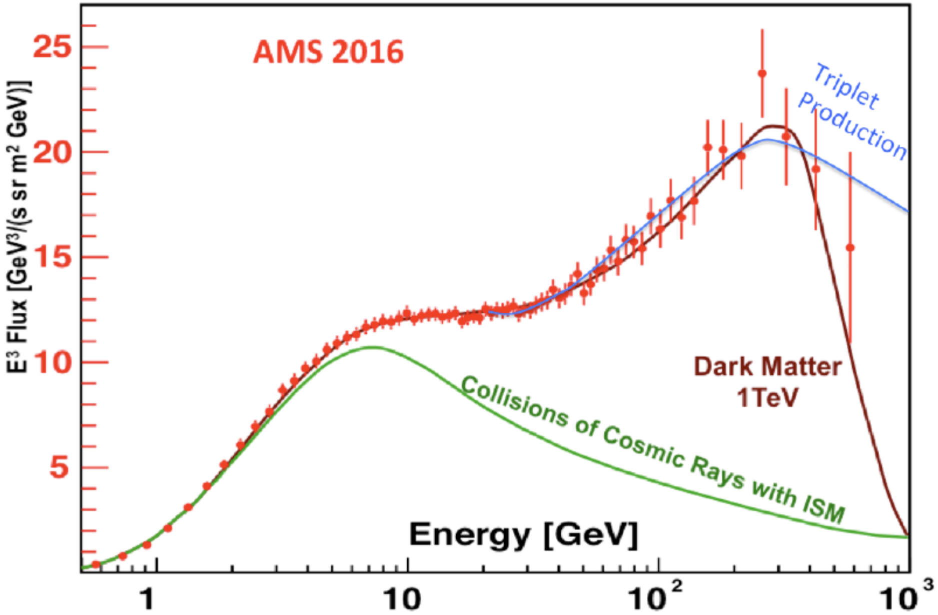

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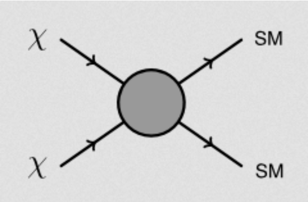

Could be explained by:

- **Dark Matter annihilation** → $O(100)$ papers

INTERPRETATION OF THE POSITRON EXCESS

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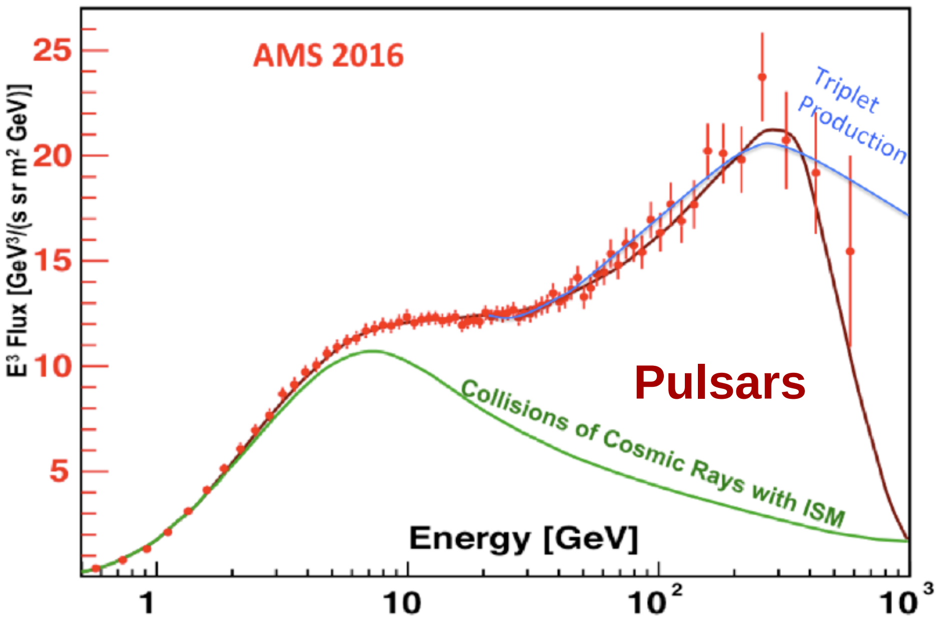

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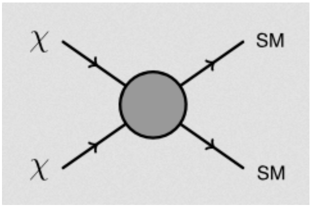
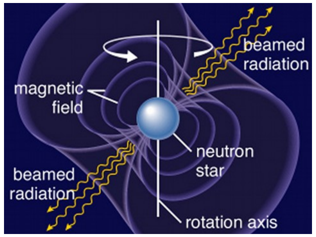


- **Dark Matter annihilation**
  → *O*(100) papers

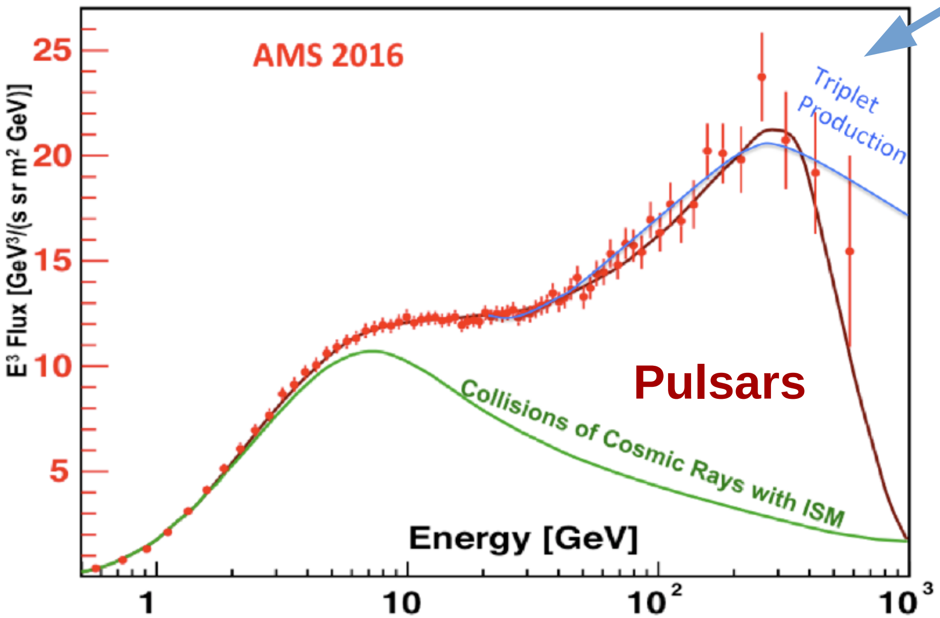


- **Astrophysical point sources like pulsars**
  → *O*(100) papers

First proposed:
Harding&Ramaty, ICRC (**1987**)

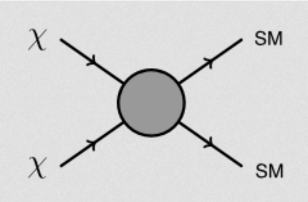
INTERPRETATION OF THE POSITRON EXCESS

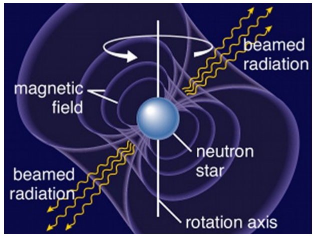
The data are consistent with a symmetric contribution in e^+ and e^-.



P.L. Biermann et al. (2018)

[PRL. 113, 121102 (2014)] → 500 GeV
Prelim. Data → 700 GeV

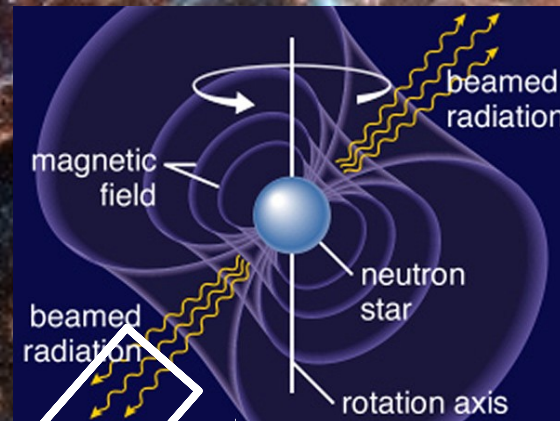




Could be explained by:

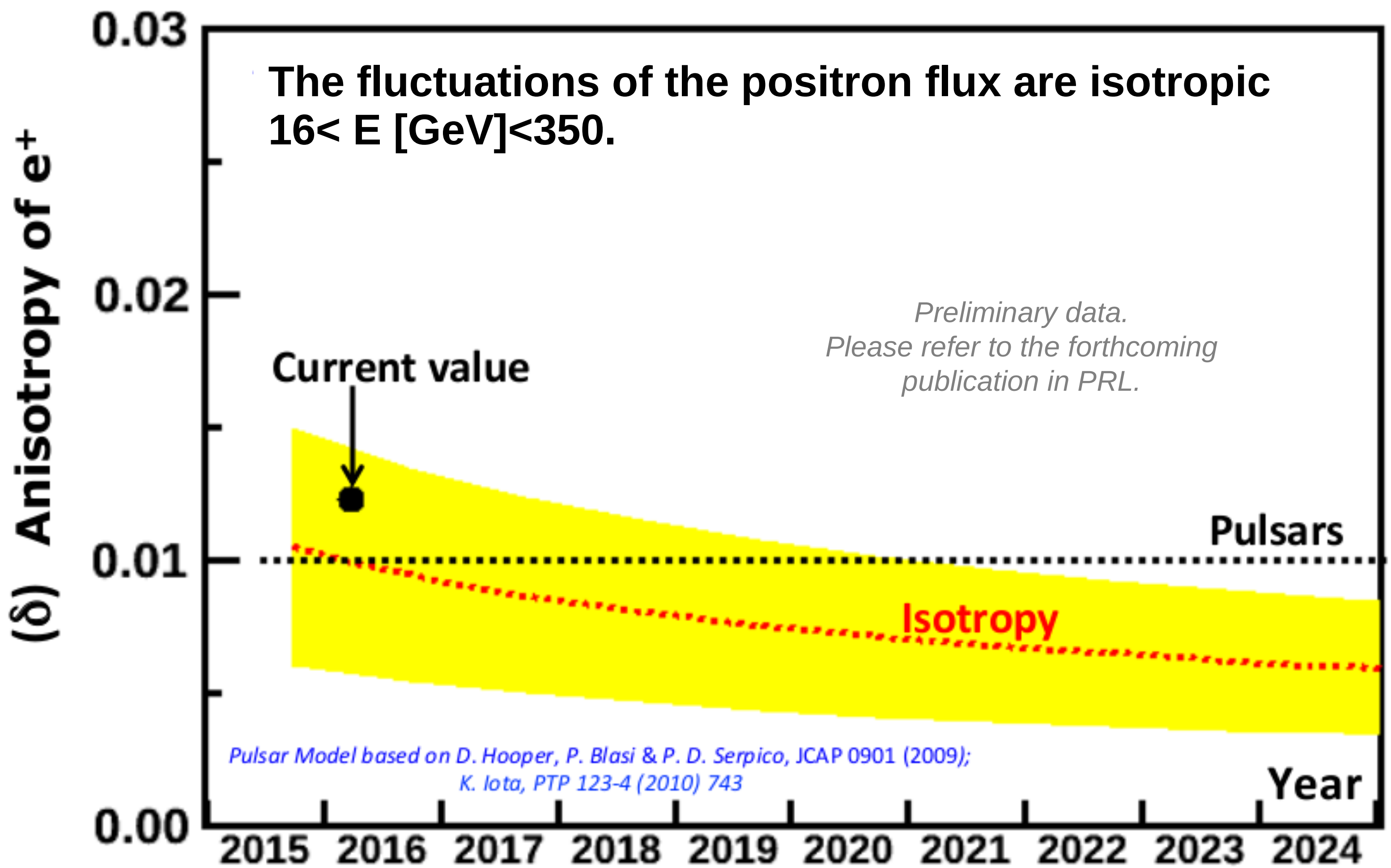
- **Dark Matter annihilation**
  → *O*(100) papers
- **Astrophysical point sources like pulsars**
  → *O*(100) papers
- **Secondary e^+ production**
  → a few papers

DO WE LIVE CLOSE TO A LOCAL POSITRON SOURCE?



[Digitized Sky Survey, ESA/ESO/NASA
FITS Liberator, Davide De Martin]

SEARCHING FOR DIPOLE ANISOTROPIES IN POSITRONS



SOME HIGHLIGHTS FROM AMS: ANTIPROTONS

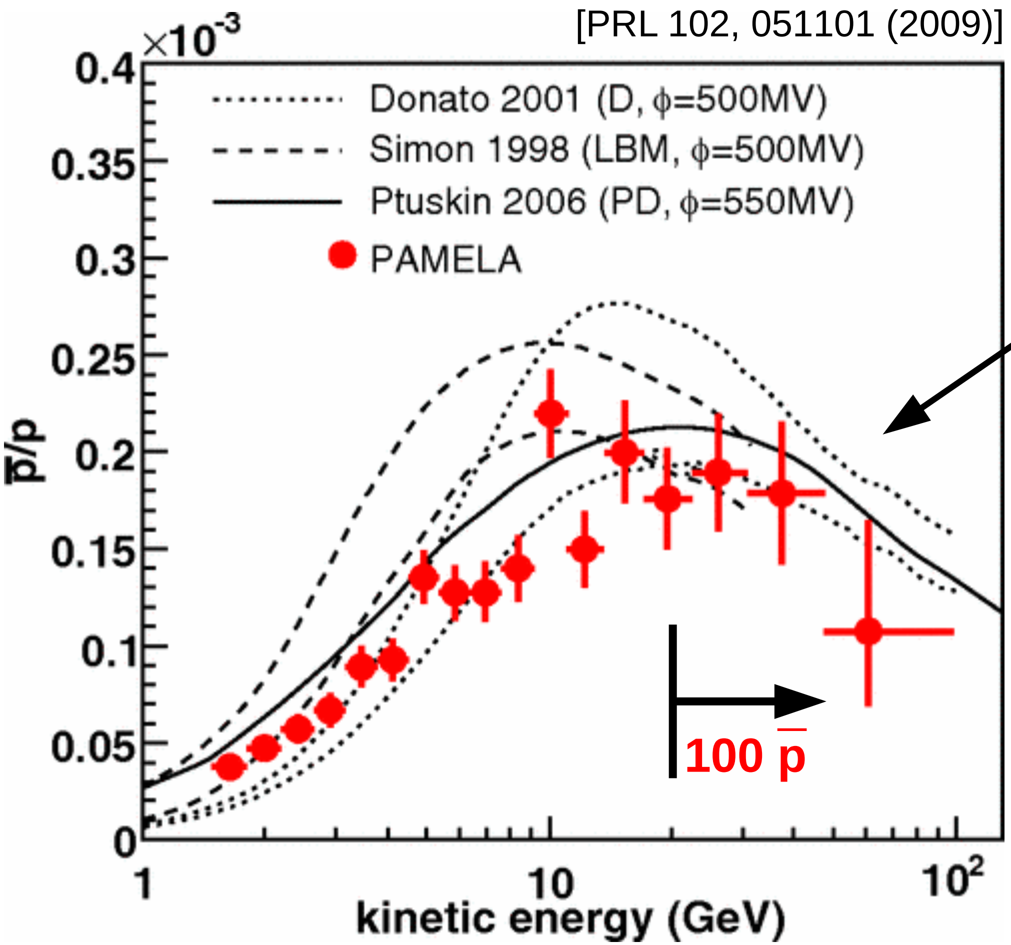
There is only 1 antiproton for 10,000 protons.

→ A percent precision experiment requires a background rejection close to 1 in a million.

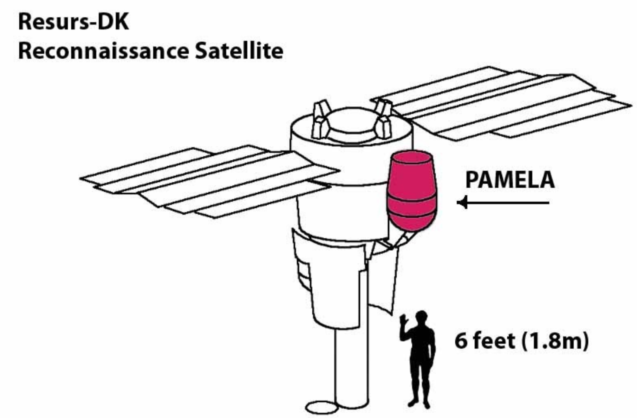
It took us 5 years to perform this measurement.

Major challenge:
purity of selection and tracker unfolding.

ANTIPROTON/PROTON RATIO … BEFORE AMS



Model expectation for secondary $\bar{p}$ production.



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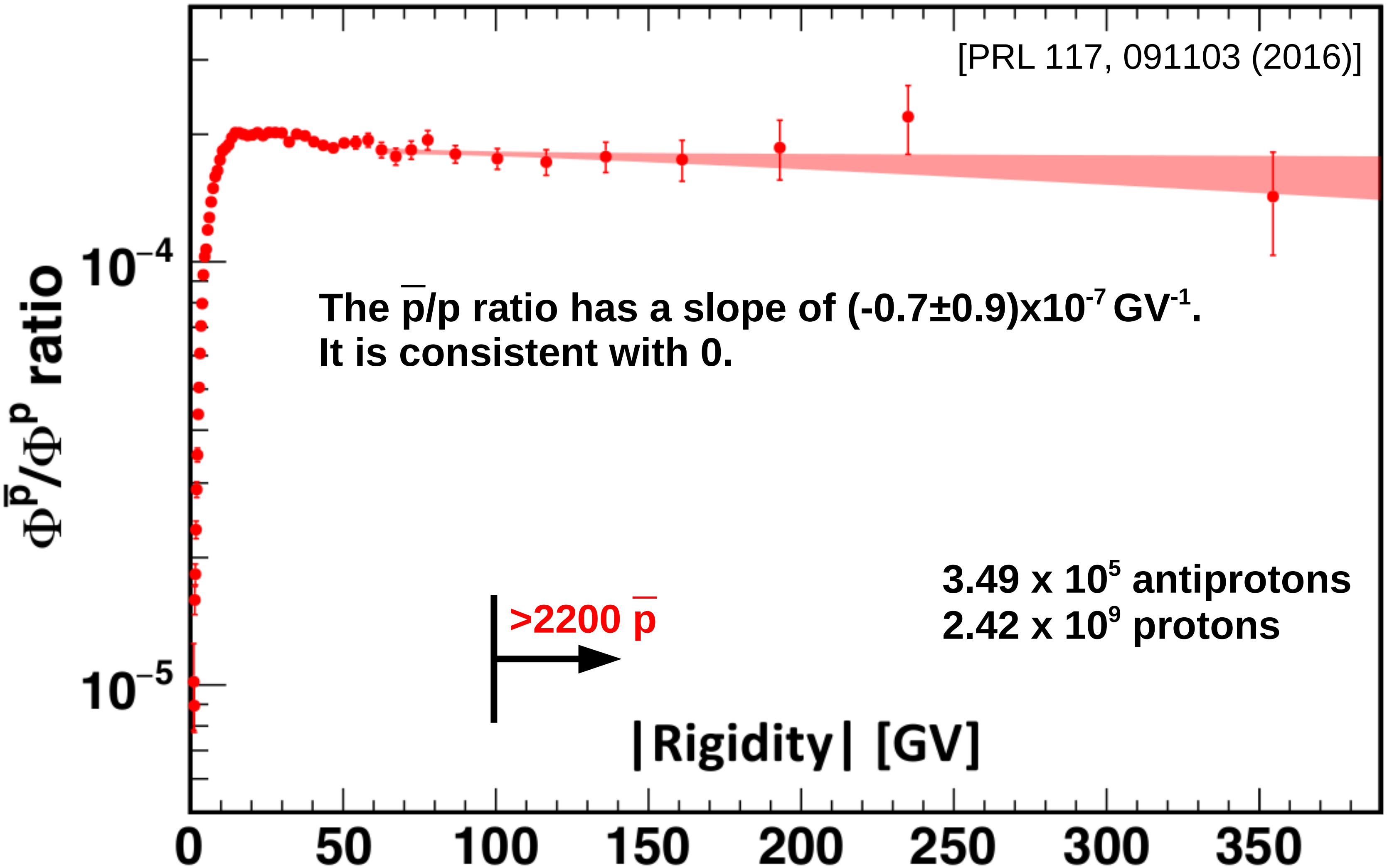
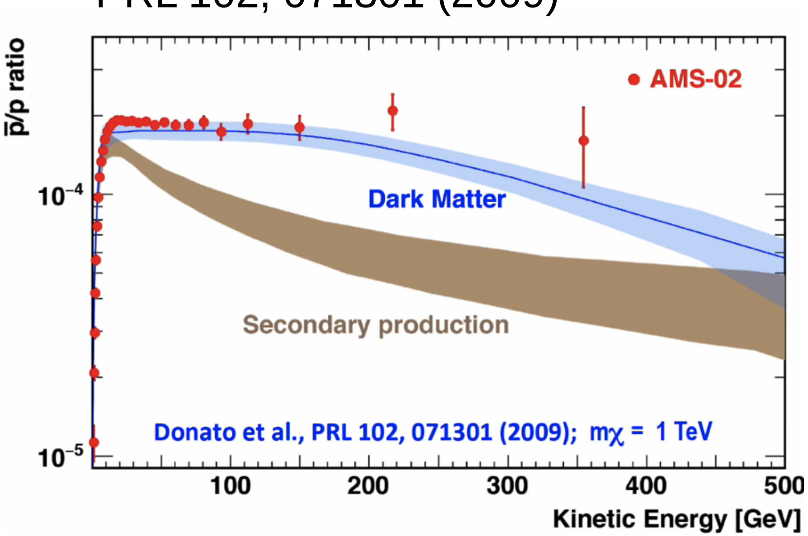
THE ANTIPROTON/PROTON RATIO IS FLAT



IS THERE AN EXCESS OF ANTIPROTONS?

F. Donato et al.
PRL 102, 071301 (2009)



Expectation in 2009:

- tuned on pre-AMS data

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F. Donato et al.
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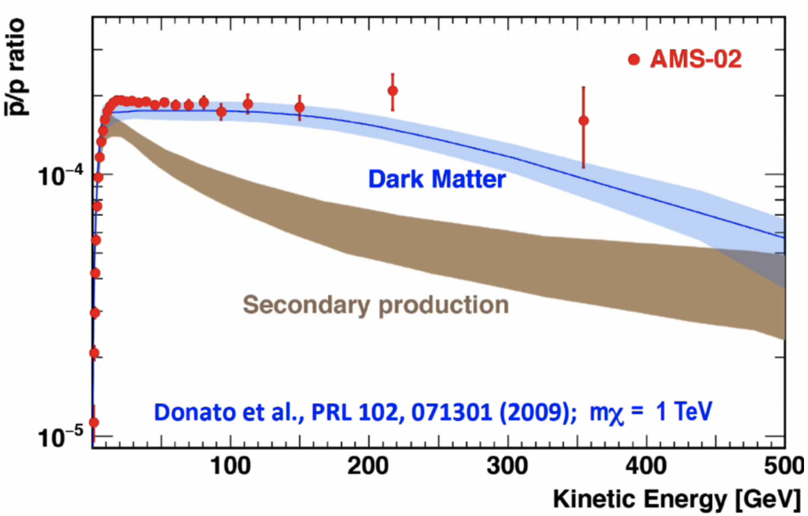
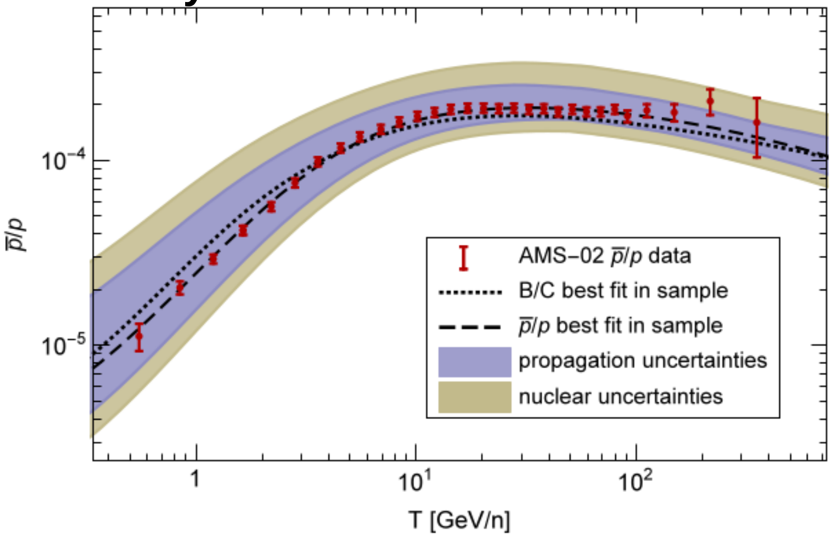


M. Winkler et al.
JCAP 09 (2014), JCAP 10 (2015),
JCAP 02 (2017) **+ many other excellent analyses**



Expectation in 2009:

- tuned on pre-AMS data

Major changes:

- tuned on AMS B/C
- new cross sections

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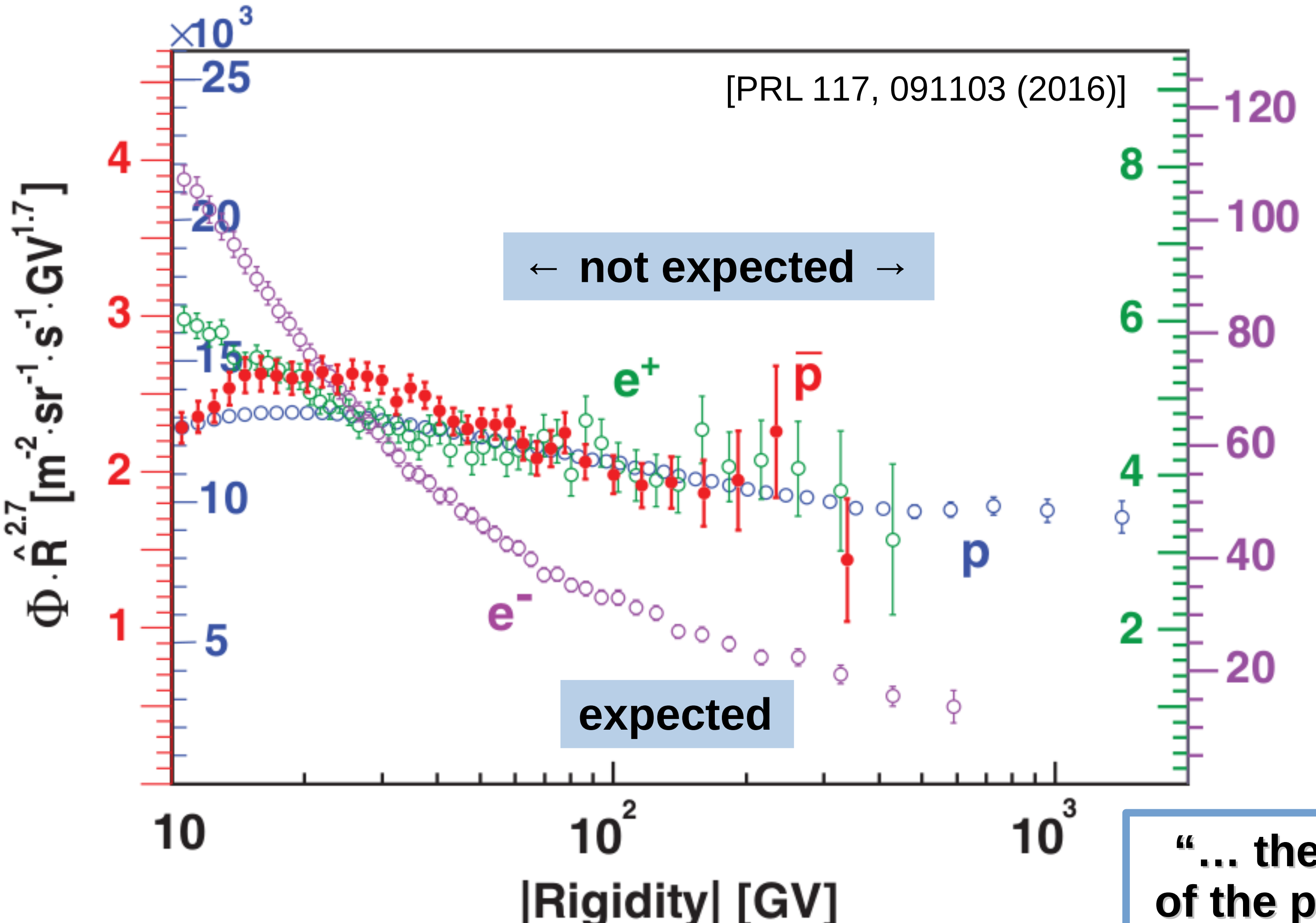
RIGIDITY DEPENDENCE OF ELEMENTARY PARTICLES



"… the minuteness of the phenomena…"

The rigidity dependence of e^+, $\bar{p}$, p is identical from 60-500 GV.

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WHAT WE ARE LEARNING FROM ANTIMATTER

There is an excess of positrons

→ we do need a new source of energetic positrons. The source may be symmetric in positrons and electrons.
We have many ideas how to explain this: Pulsars, Dark Matter, triplet production, ...

The antiproton/proton ratio is flat

→ unexpected, but not anomalous.

The spectra of protons, positrons and antiprotons are identical between 60 and 500 GV

→ *currently* very few ideas.

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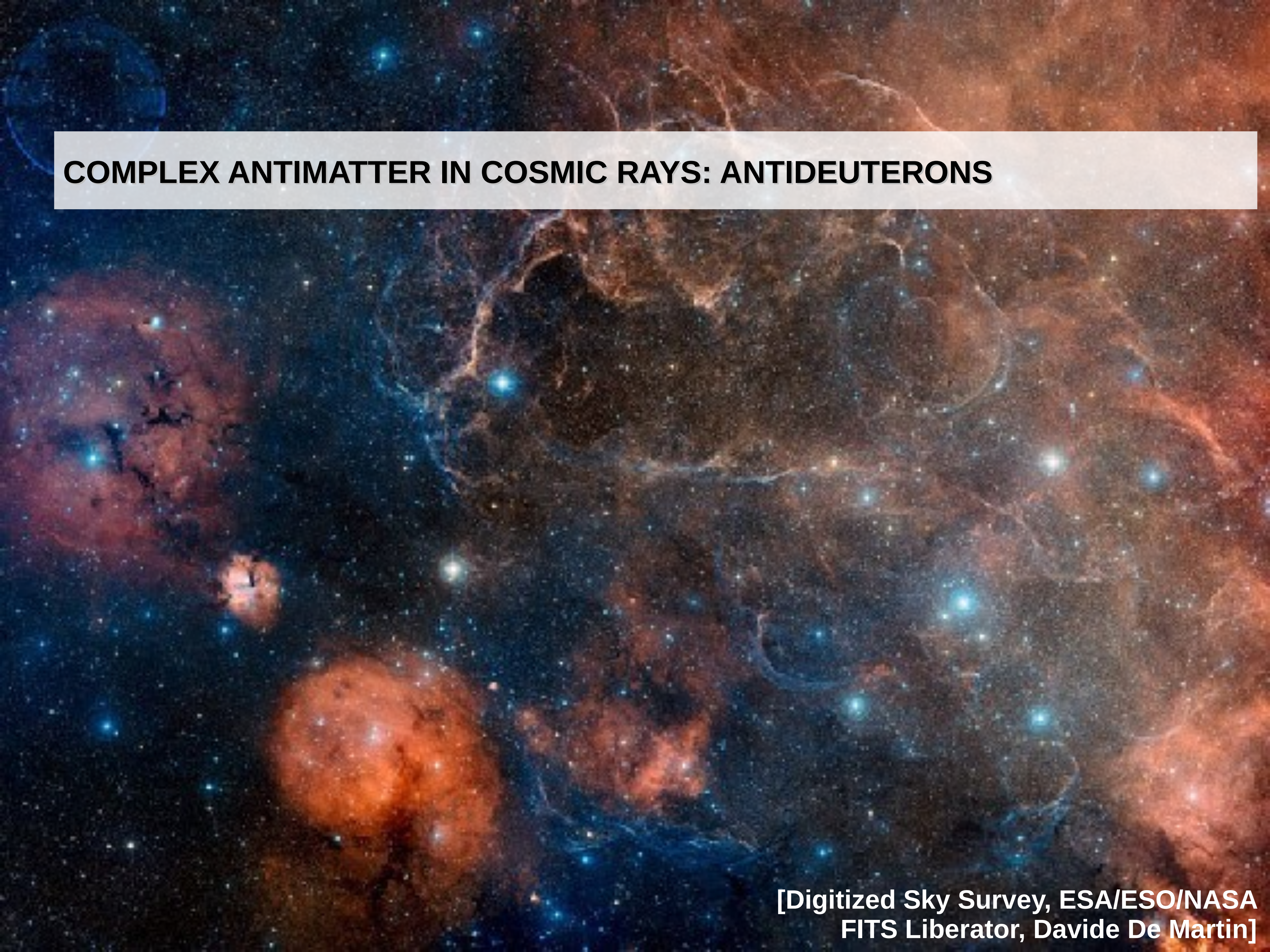
COMPLEX ANTIMATTER IN COSMIC RAYS: ANTIDEUTERONS



[Digitized Sky Survey, ESA/ESO/NASA
FITS Liberator, Davide De Martin]

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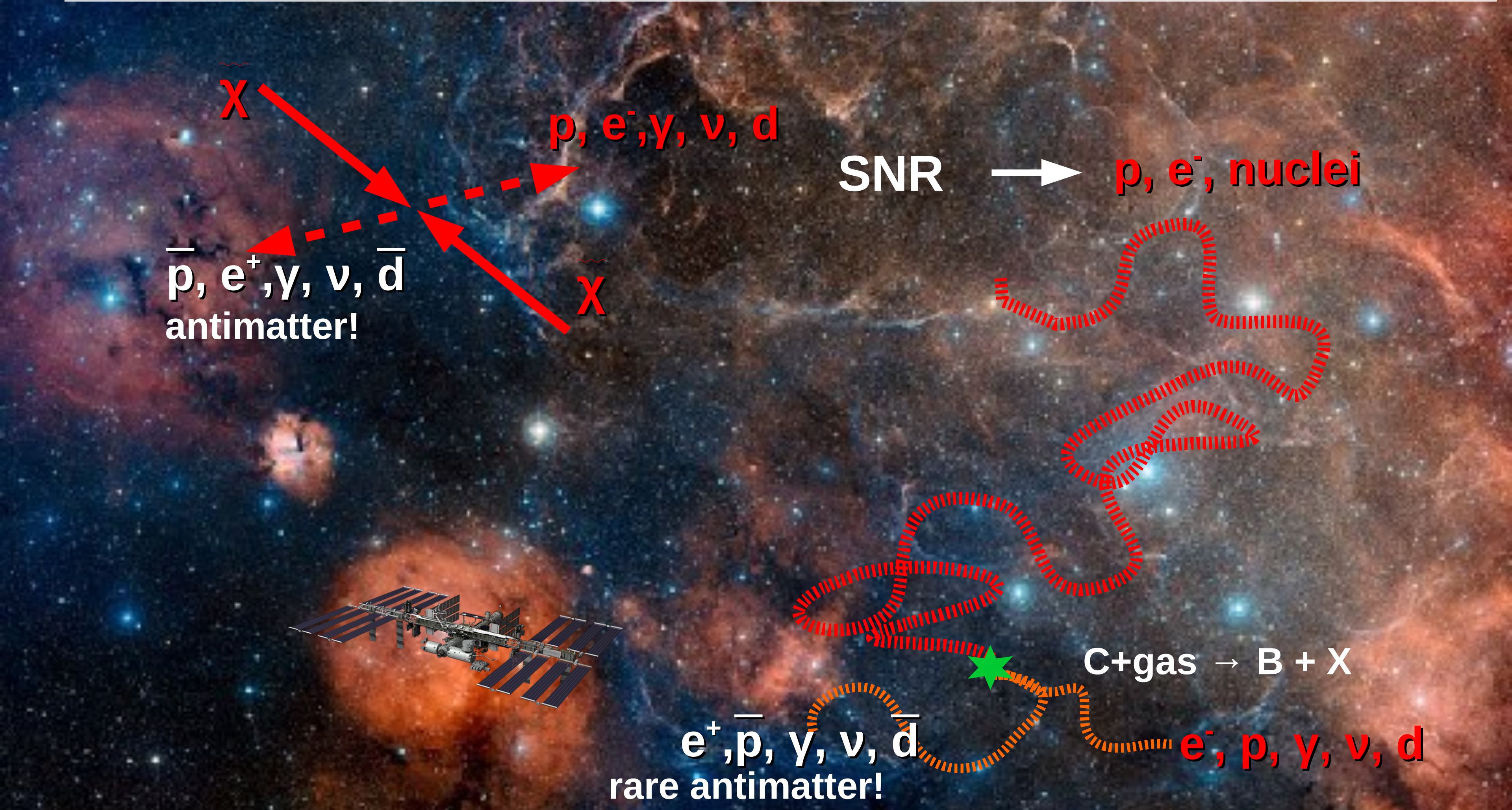

[Digitized Sky Survey, ESA/ESO/NASA FITS Liberator, Davide De Martin]

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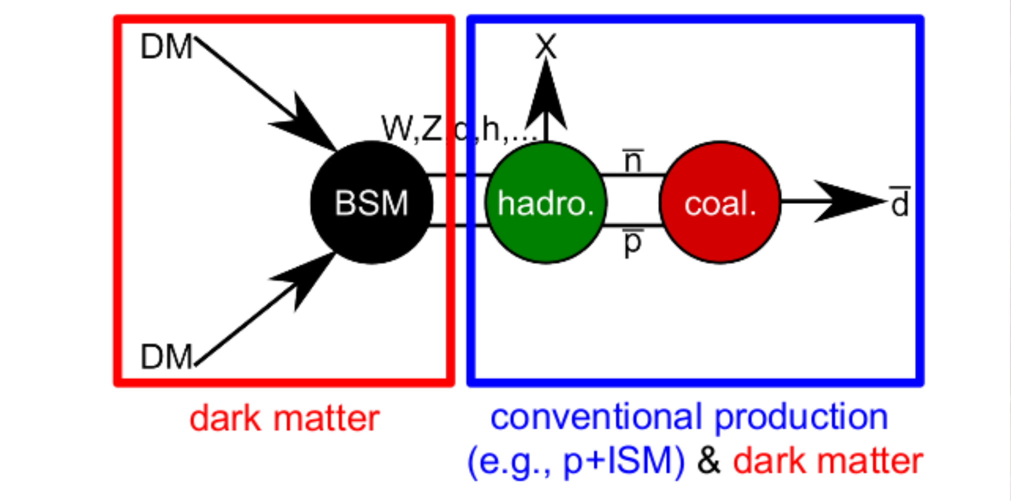


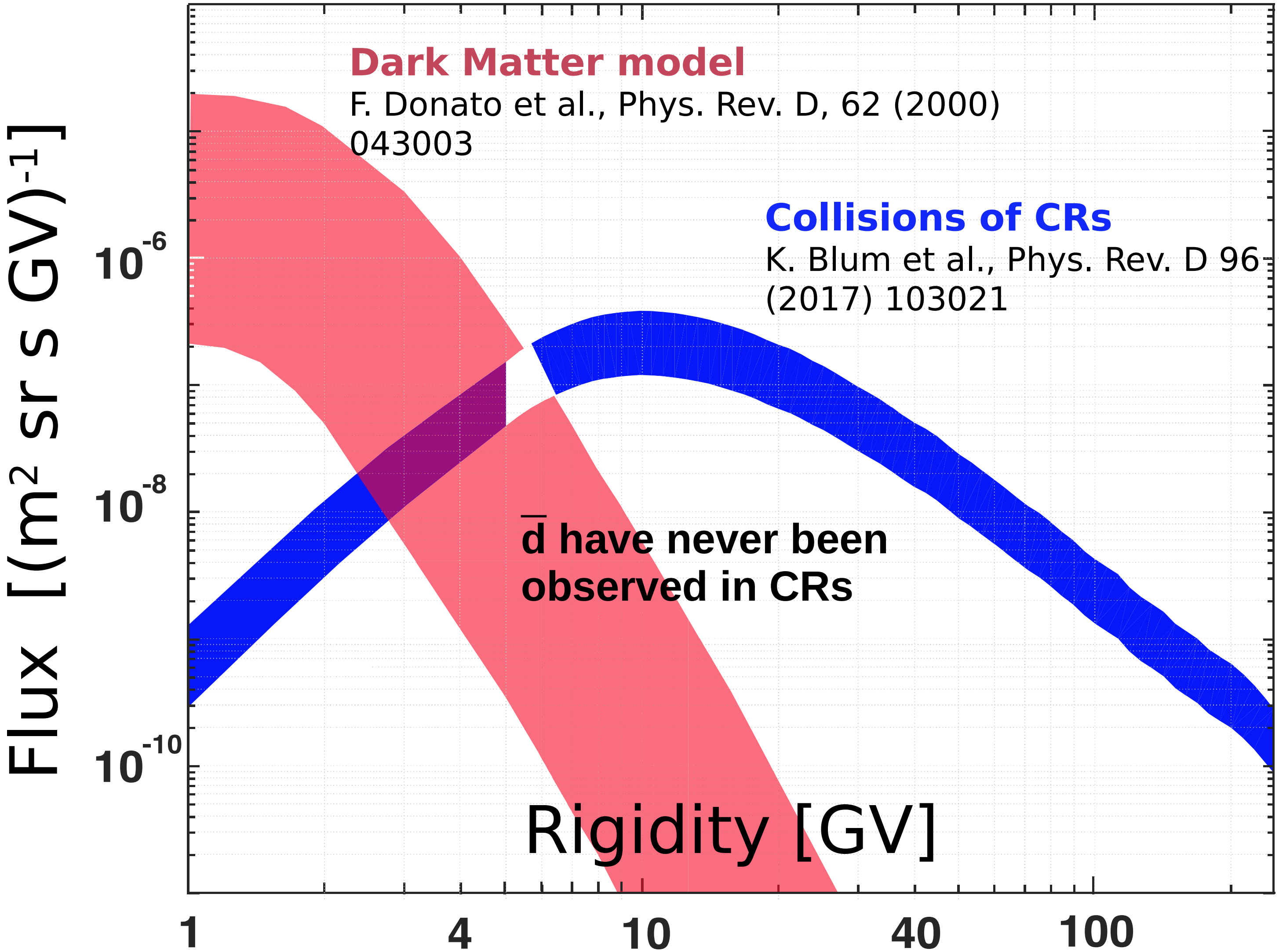
d ($\bar{d}$) can be formed by a p-n ($\bar{p}$-$\bar{n}$) pair, if coalescence momentum is small.

$$\gamma_d \frac{\mathrm{d}^3 N_d}{\mathrm{d}p_d^3} = \frac{4\pi}{3} p_0^3 \left(\gamma_p \frac{\mathrm{d}^3 N_p}{\mathrm{d}p_p^3} \right) \left(\gamma_n \frac{\mathrm{d}^3 N_n}{\mathrm{d}p_n^3} \right)$$

Coalescence uncertainties are about a factor of 10 on the flux.

[Digitized Sky Survey, ESA/ESO/NASA
FITS Liberator, Davide De Martin]

EXPECTED ANTI-DEUTERON FLUX IN CRs



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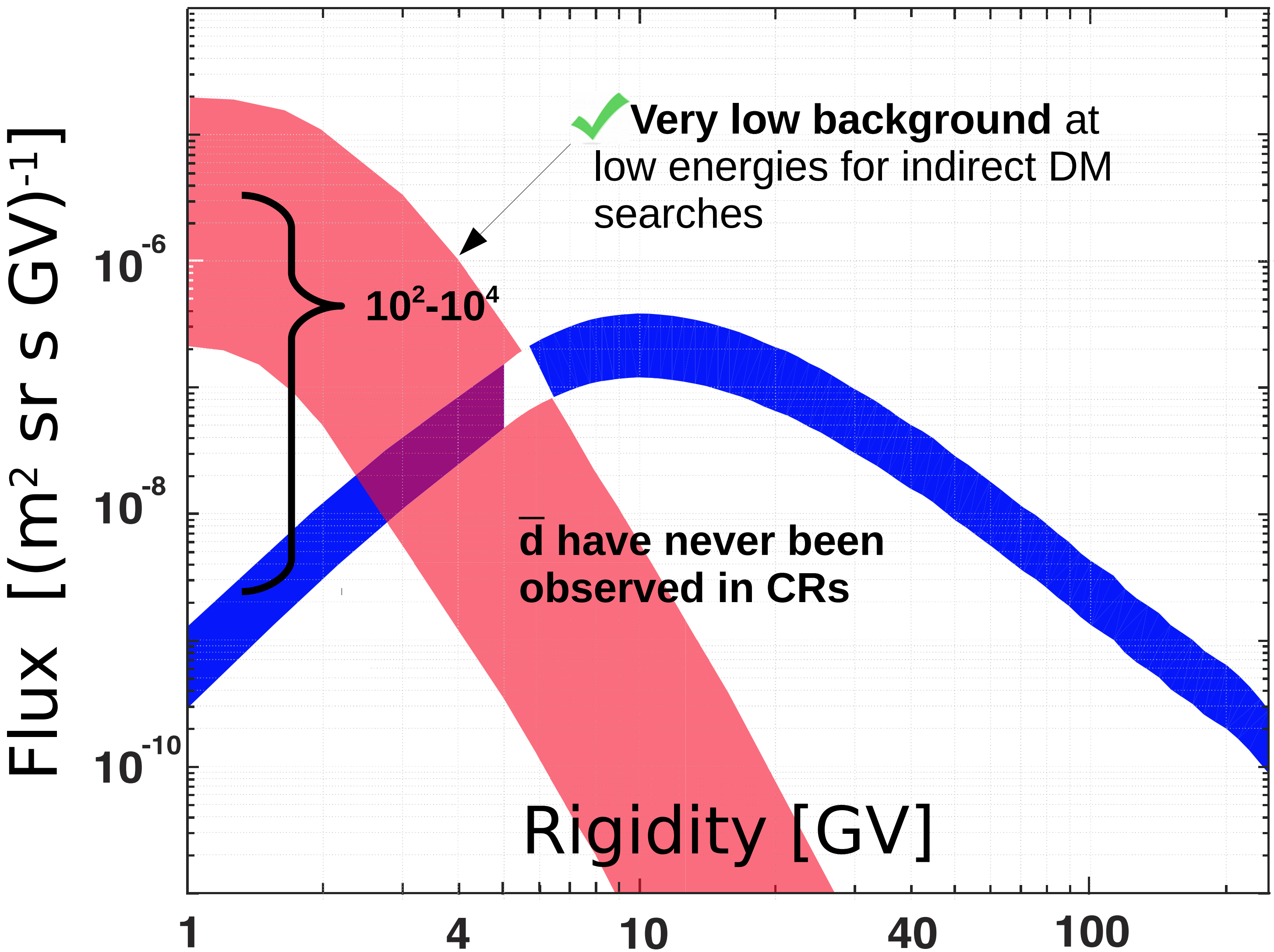

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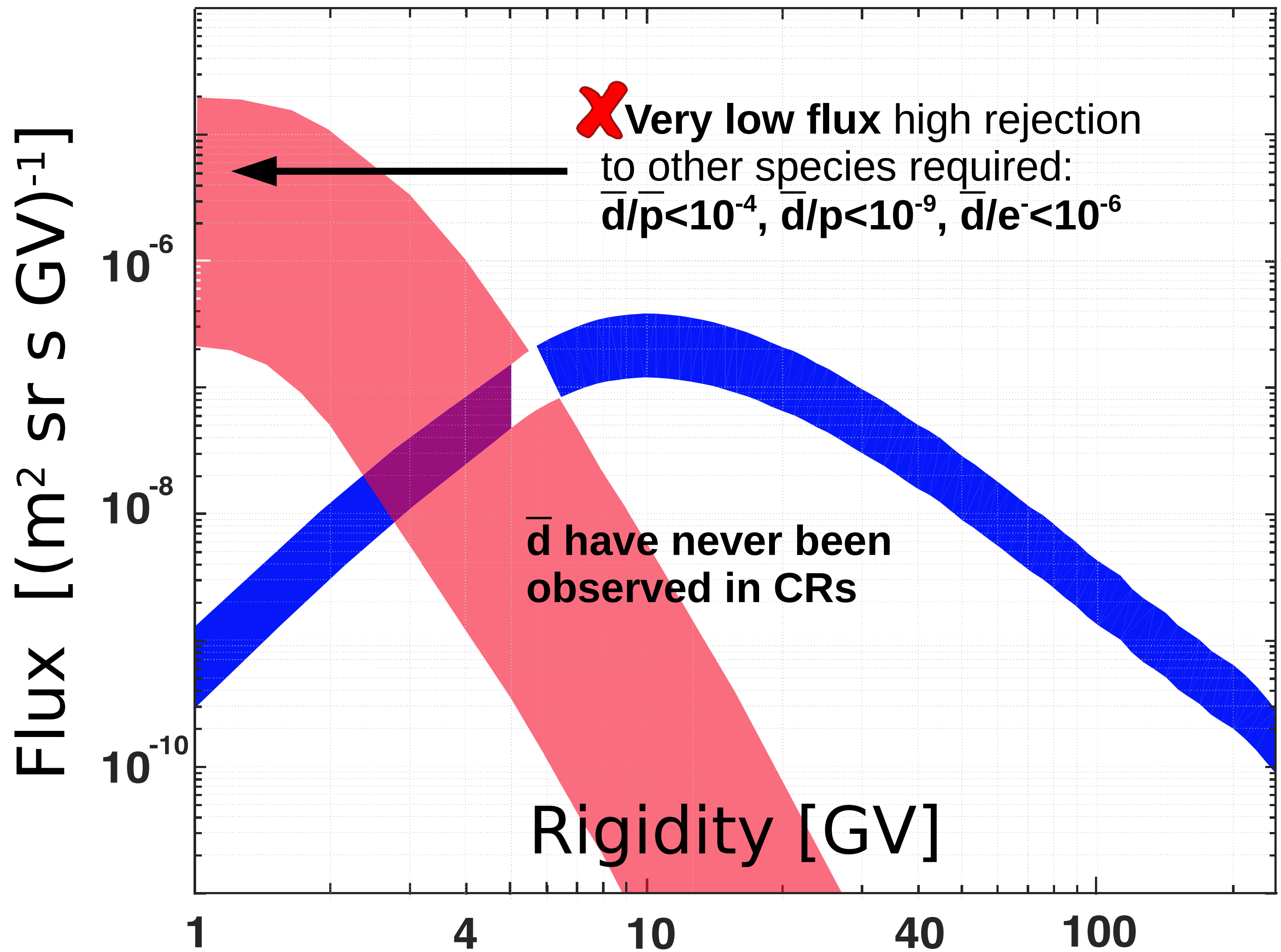
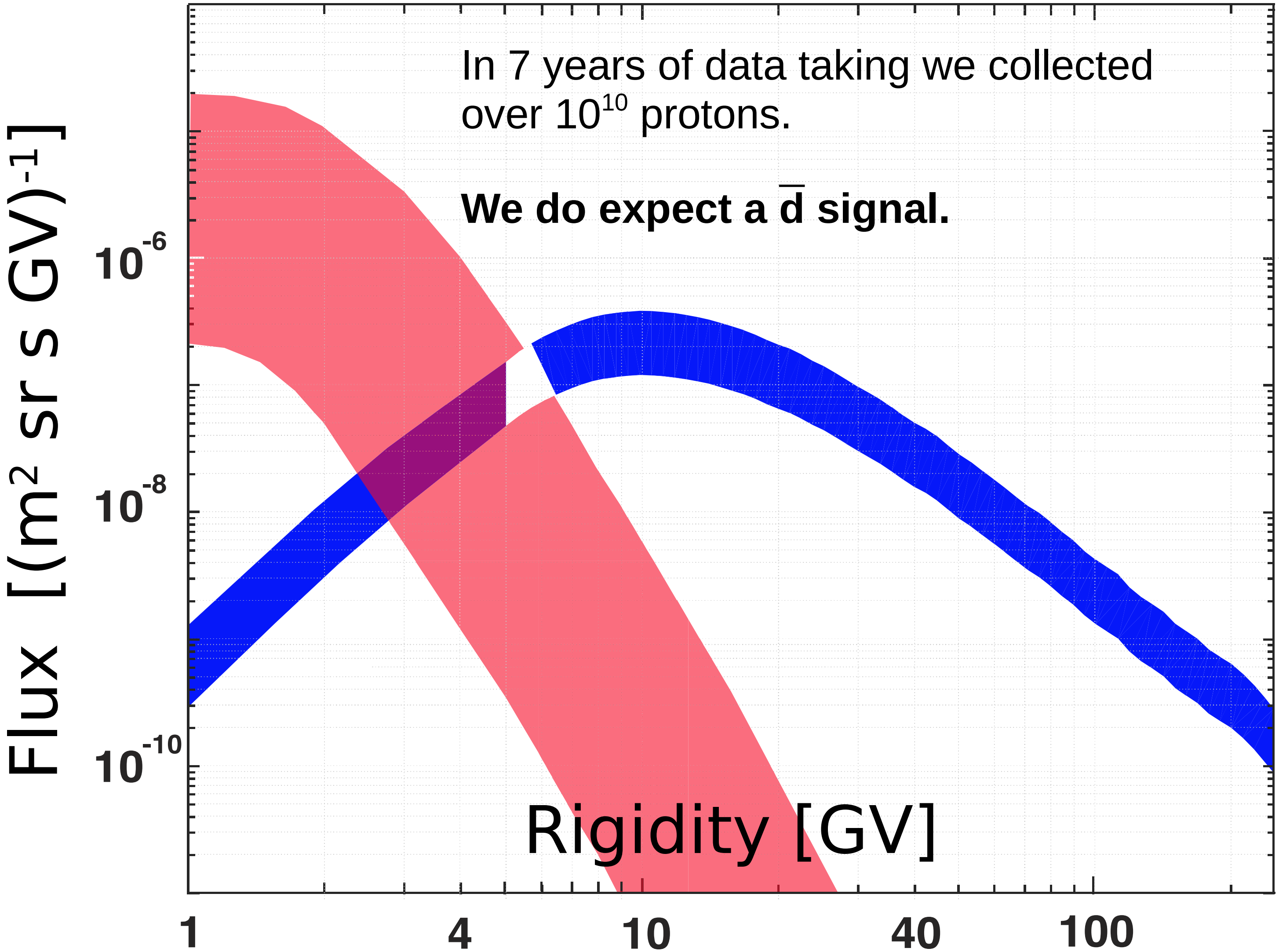


EXPECTED ANTI-DEUTERON FLUX IN CRs



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COMPLEX ANTIMATTER IN COSMIC RAYS: ANTIDEUTERONS

There is only 1 antideuteron for 10^9 protons expected.

→ At a signal to background ratio of one in one billion, a detailed understanding of the instrument is required.

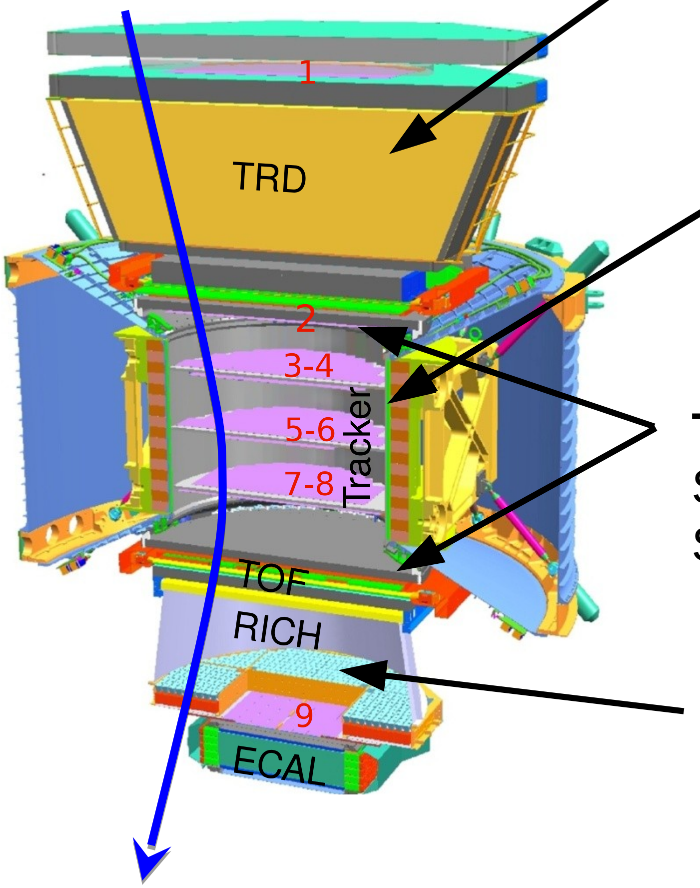
In 7 years more than 10 billion proton and 100 million deuteron cosmic rays were collected. An equivalent of 100 billion of proton, deuteron and antiproton events needs to be simulated.

Major challenge:
Controlling charge confusion and mass reconstruction.

ANTI-DEUTERON IDENTIFICATION WITH AMS

To identify an anti-deuteron, we need to measure its charge and its mass.

Charge measurement:



TRD
Elimination of electron background.
Select **|Z|=1** particles (ΔZ/Z≈0.1 c.u.).

Tracker
Select **|Z|=1** particles (ΔZ/Z≈0.05 c.u.).
Particle charge sign (+/-).

TOF
Select **|Z|=1** particles (ΔZ/Z≈0.06 c.u.).
Separate **upgoing/downgoing** particles

RICH
Select **|Z|=1** particles (ΔZ/Z≈0.3 c.u.)

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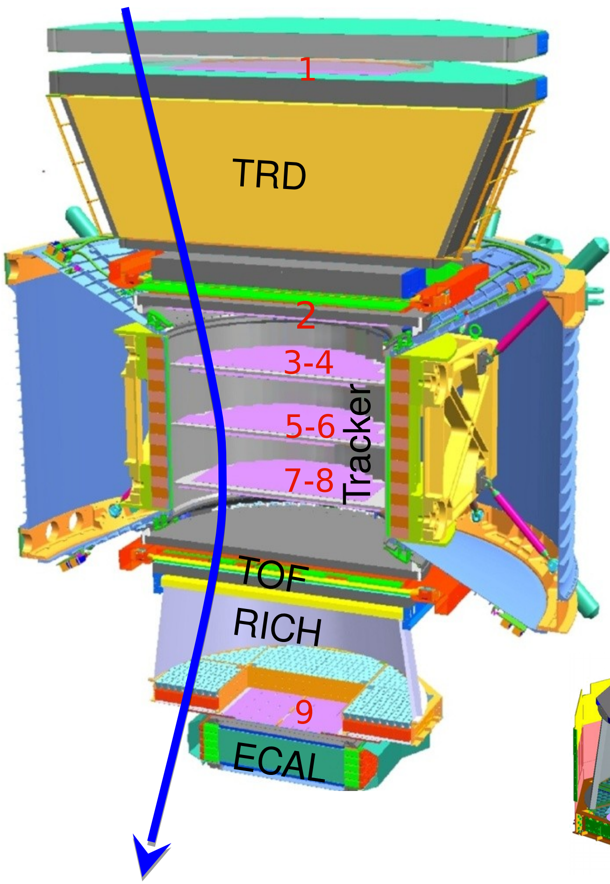
ANTI-DEUTERON IDENTIFICATION WITH AMS

To identify an anti-deuteron, we need to measure its charge and its mass.

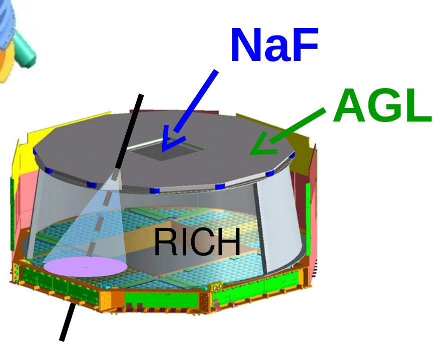
Mass measurement:



Tracker
Momentum p, Δp/p≈10% up to 20 GV.

TOF
Velocity β, Δ β/β²≈4%.

RICH
Velocity β in two radiators
NaF radiator: Δ β/β≈0.4%, β>0.75.
Aerogel radiator: Δ β/β≈0.1%, β>0.96.



$$M = p\frac{\sqrt{1-\beta^2}}{\beta}$$

→ Mass resolution ~10%

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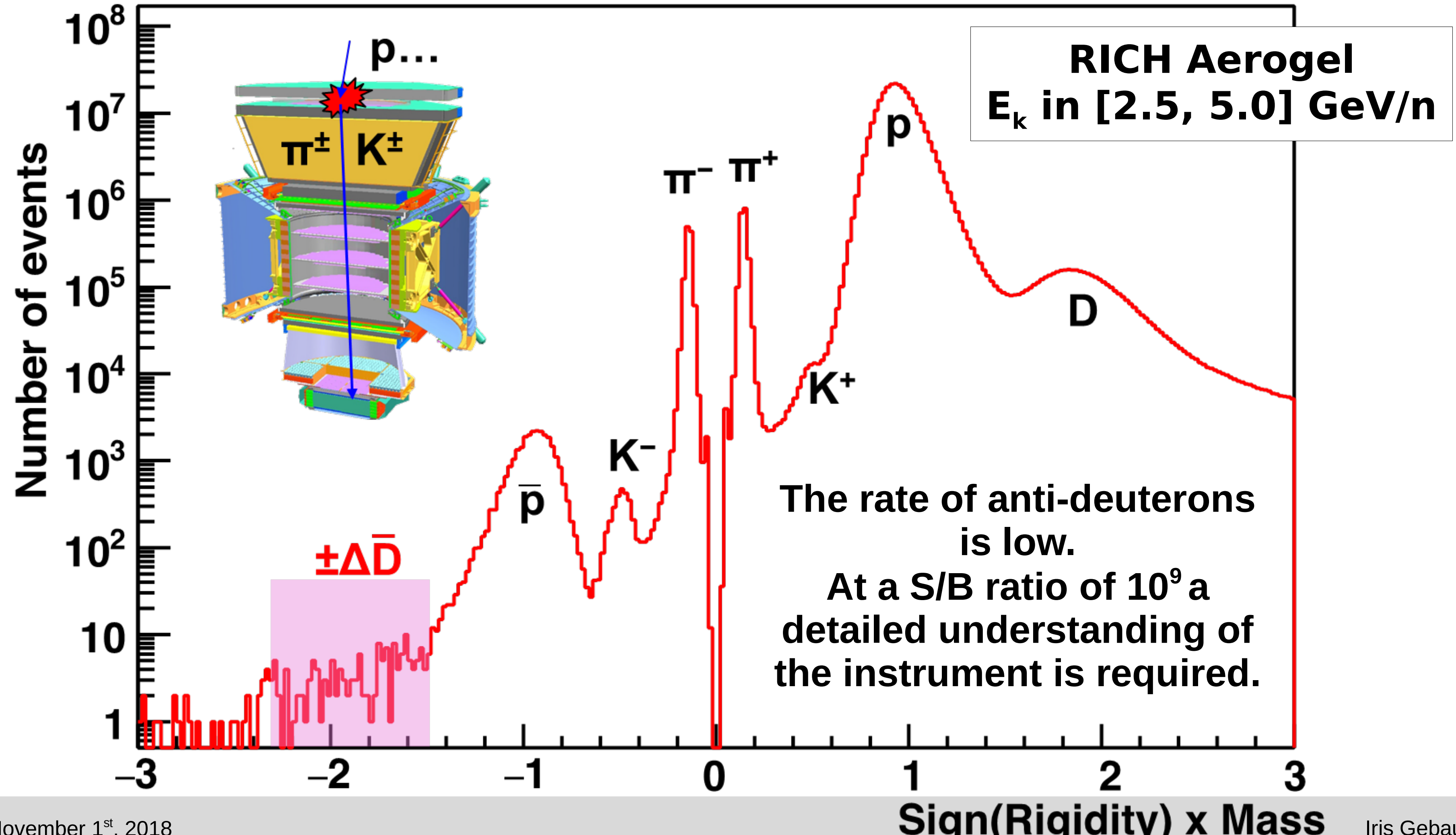
Data Sample (May 2011 – May 2017): TRD – Inner Tracker Acceptance
41 x 10^9 events selected with TOF ($\beta > 0.5$) and Tracker $|R| > 0.8$



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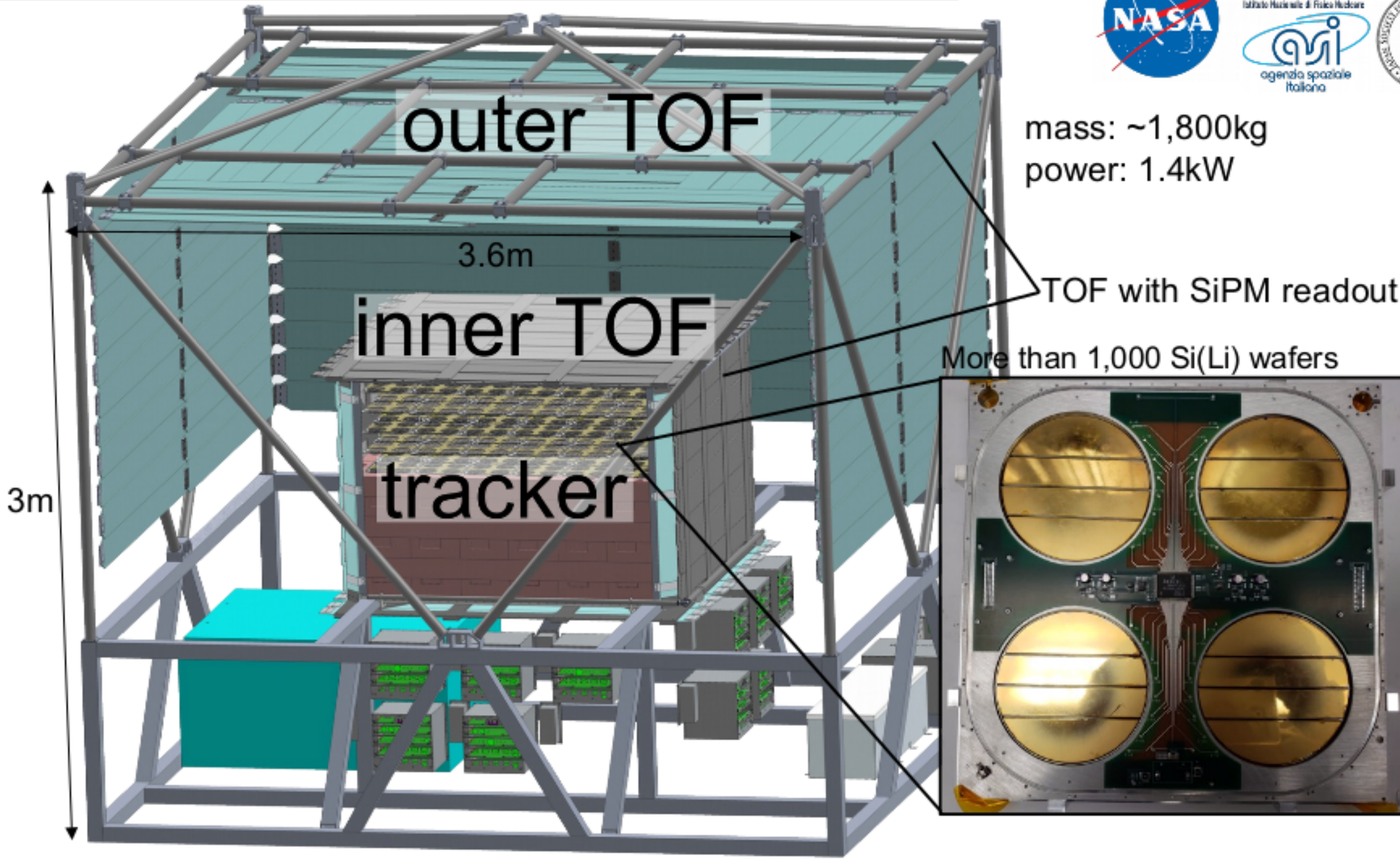
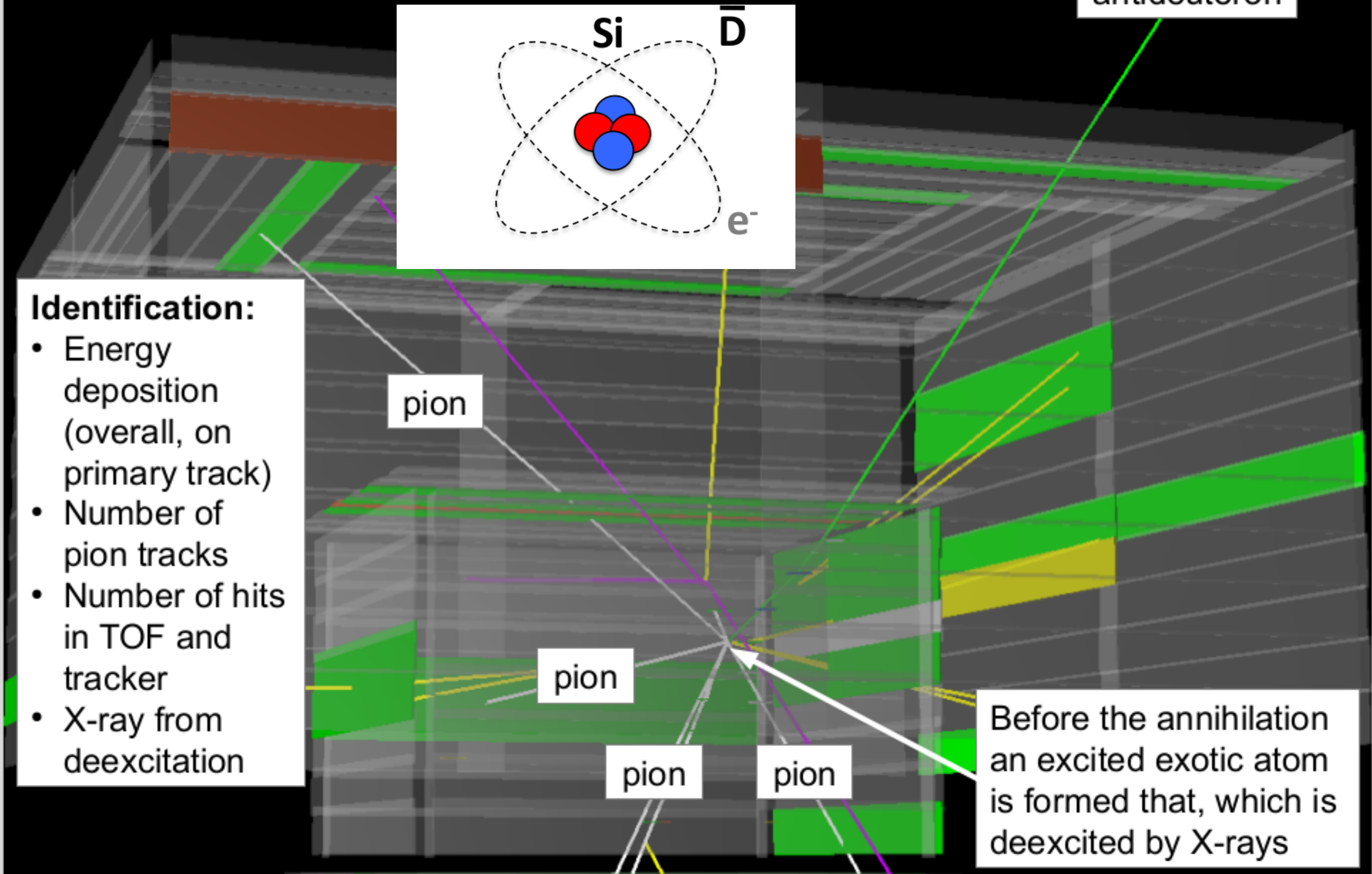
The GAPS experiment

Columbia U, UCSD
UCLA, UCB,
U Hawaii, MIT



- the **G**eneral **A**nti**P**article **S**pectrometer is specifically designed for low-energy antideuterons, antiprotons and antihelium nuclei
- **GAPS is under construction → first Long Duration Balloon flights from Antarctica flight 2020**

Simulated antideuteron in GAPS

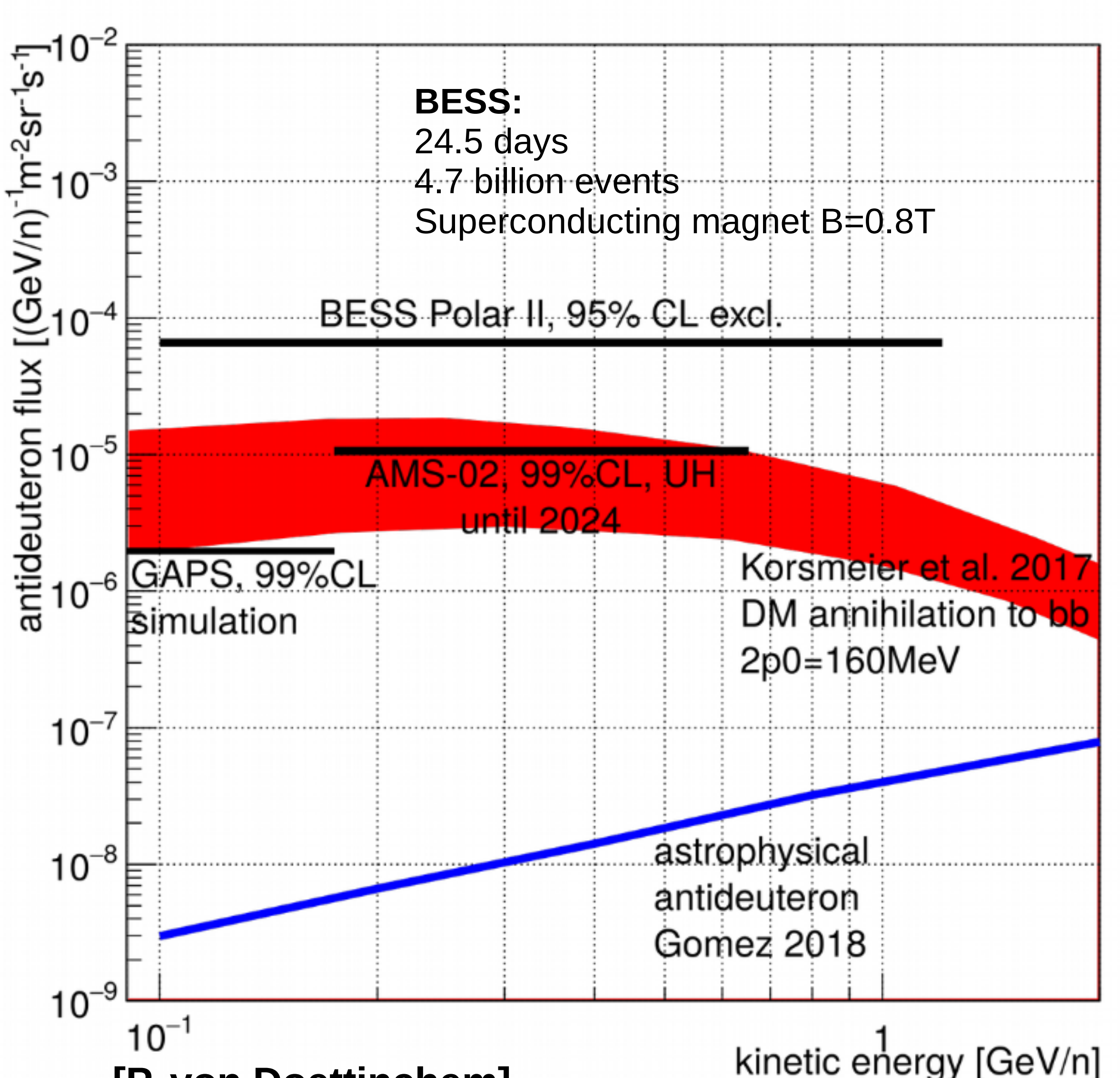


Identification:

- Energy deposition (overall, on primary track)
- Number of pion tracks
- Number of hits in TOF and tracker
- X-ray from deexcitation

Before the annihilation an excited exotic atom is formed that, which is deexcited by X-rays

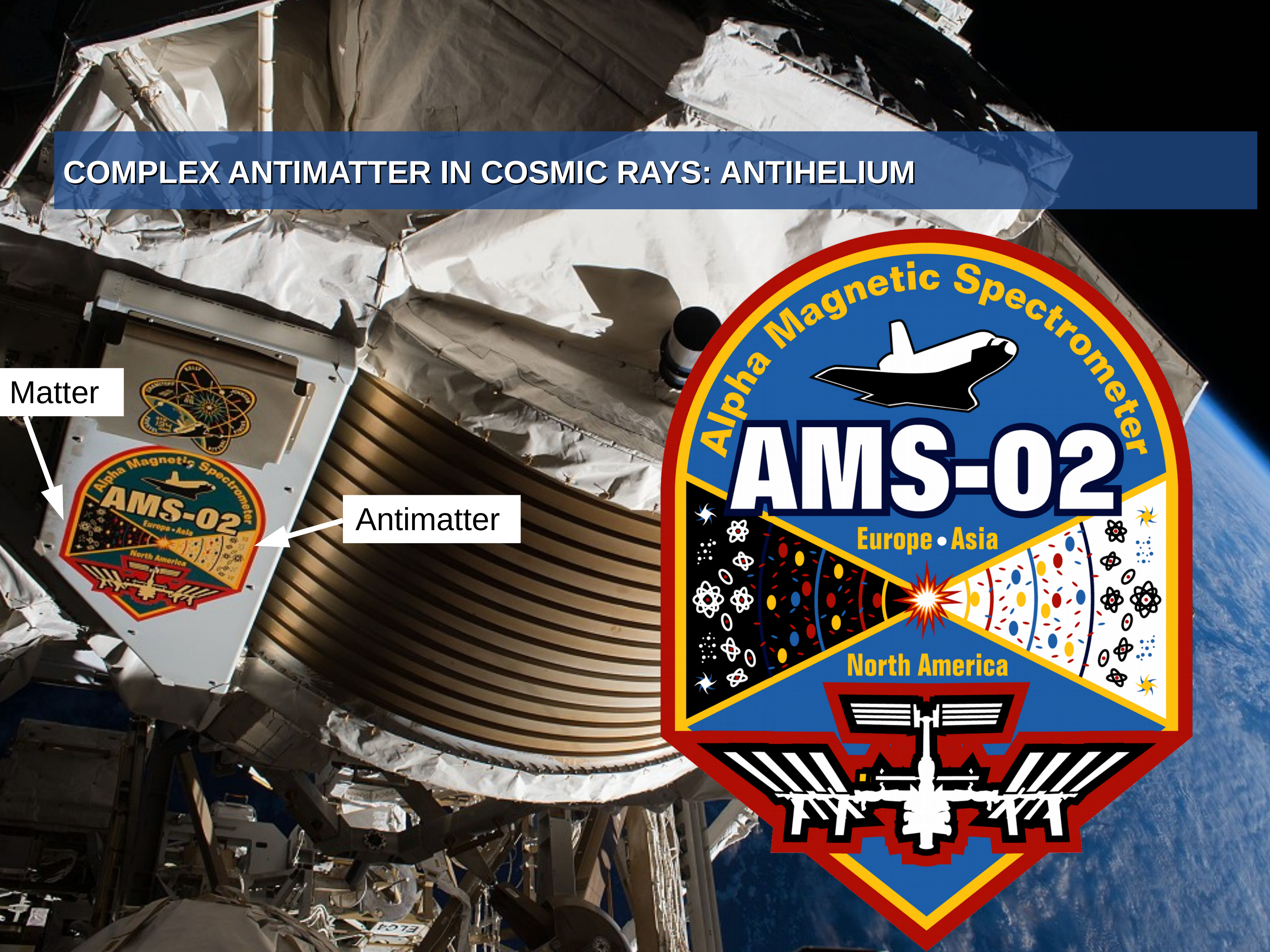
SUMMARY ON ANTIDEUTERONS



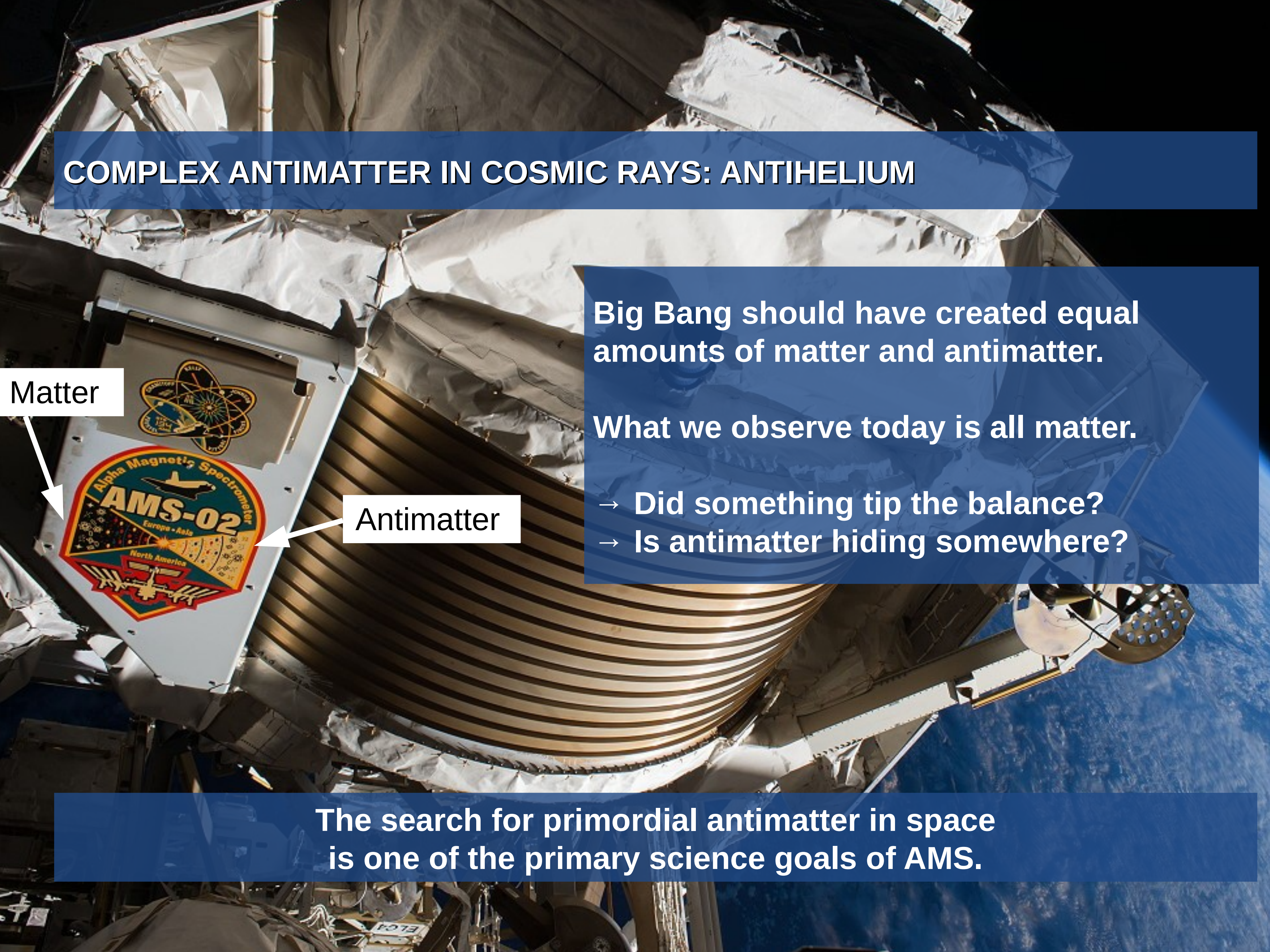
[P. von Doettinchem]

- Antideuterons are a promising way to search for Dark Matter and other new physics.
- Current best limit from BESS-polar II.
- AMS will improve this limit by about a factor 7.
- Balloon experiment GAPS for very low energies is under construction → first flight Dec. 2020.

COMPLEX ANTIMATTER IN COSMIC RAYS: ANTIHELIUM



COMPLEX ANTIMATTER IN COSMIC RAYS: ANTIHELIUM



Big Bang should have created equal amounts of matter and antimatter.

What we observe today is all matter.

→ Did something tip the balance?
→ Is antimatter hiding somewhere?

The search for primordial antimatter in space is one of the primary science goals of AMS.

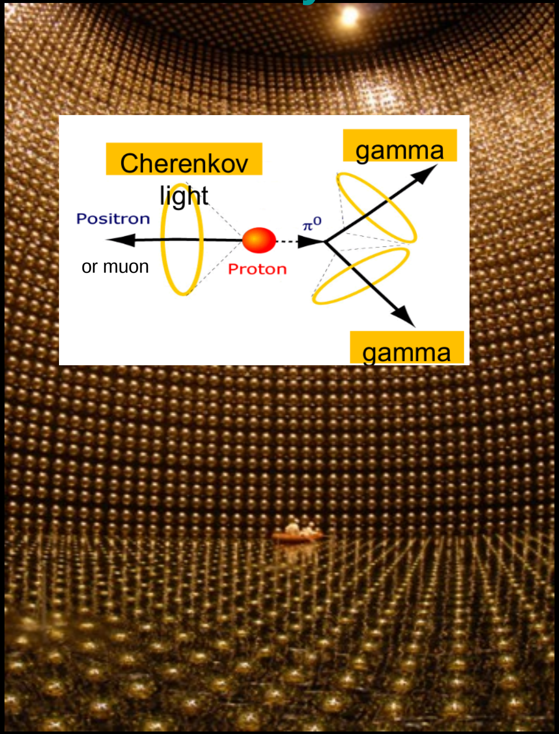
WHERE IS ALL THE ANTIMATTER?
EXPERIMENTAL SEARCHES

Did something tip the balance?

Search for new CP symmetry breaking

LHC-b, ATLAS,CMS

Search for proton decays

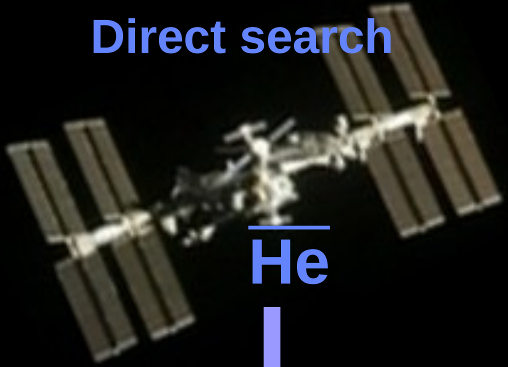


Super Kamiokande:

$\tau_p > 10^{34}$ years

Is antimatter hiding?

Direct search



$\overline{\text{He}}$

AMS

[LHCb: Nature Physics, 13, 391–396 (2017)]

ANTIHELIUM ANALYSIS STATUS

To date we have observed 8 events with Z=-2.
All events are in the ^{3}He (6 events) and ^{4}He (2 events) mass region.

All 8 events are clean single track events without additional hits.

All 8 events are in the momentum range <100 GeV, where the momentum resolution is better than 10%.

The event rate is 1 antihelium nucleus in 100 million helium nuclei.

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Currently we generated 7 times more simulated events than measured events and have found no background events from the simulation, our best evaluation of the probability of the background origin for the eight $\overline{\text{He}}$ events is less than 3×10^{-8}.

By 2022 AMS will have 100 million Carbon and Oxygen events to study anti-carbon and anti-oxygen → antistars!

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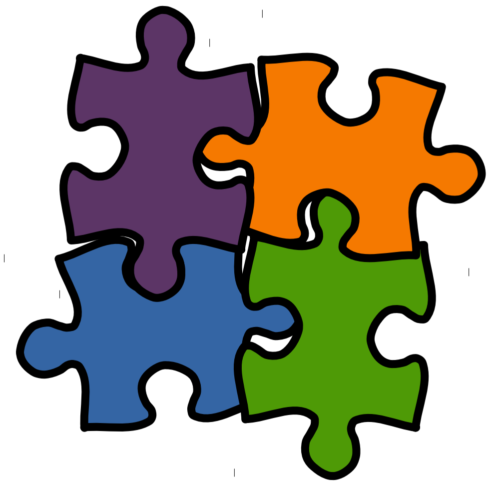
7 YEARS OF AMS

Before AMS:



A "standard paradigm" for cosmic ray transport (with some problems).

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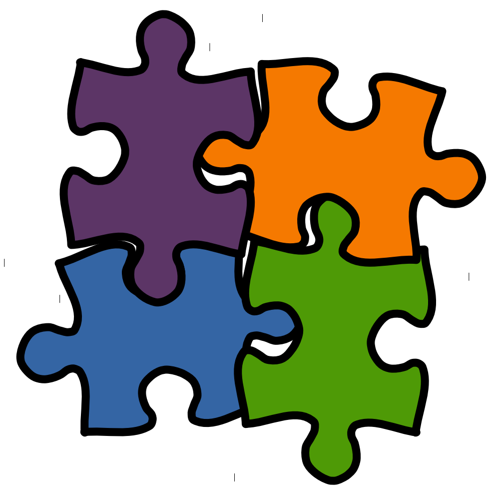
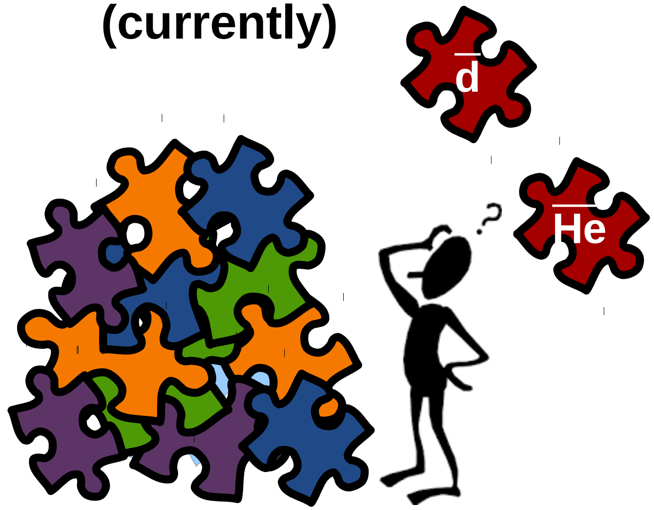
7 YEARS OF AMS

Before AMS:



A "standard paradigm" for cosmic ray transport (with some problems).

Improvement with AMS: (currently)



The accuracy of the data challenges the "standard paradigm".

7 YEARS OF AMS

Karlsruhe Institute of Technology

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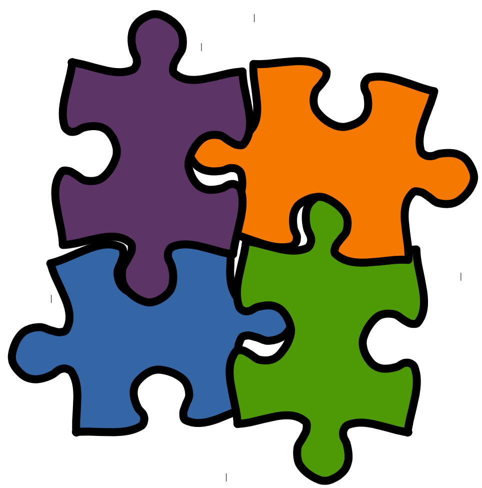

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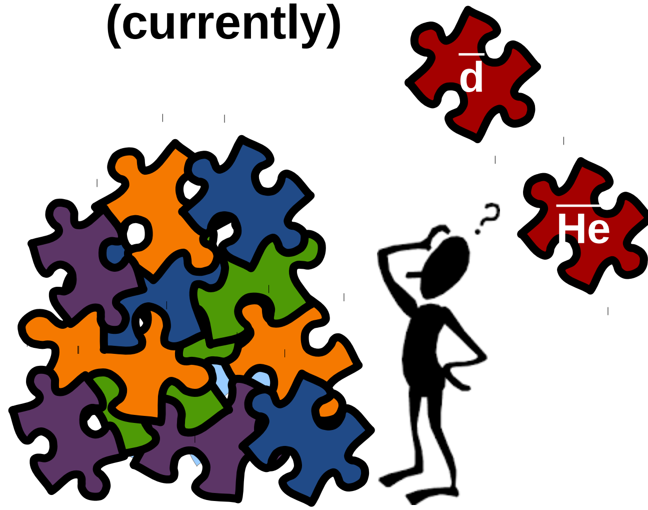

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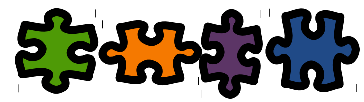
Future:

CALET, DAMPE, ISS-CREAM,...



- Statistics!
- High energies!
- Only matter.

GAPS:

- Unique signal
- Low energies

Iris Gebauer
Institute for Experimental Particle Physics

SUMMARY

Since 2011 AMS has collected a total of 127 billion events.

The accuracy of the data is challenging our understanding of cosmic ray transport.

AMS will continue to take data until 2024 or longer.

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WHAT TO EXPECT

- **High statistics antimatter fluxes (e^+, $\bar{p}$) → understanding of secondary production + Dark Matter searches**
- **Heavier nuclei** → understanding of cosmic ray sources (+ CALET, DAMPE, ISS-CREAM).
- **Time dependencies of low energy fluxes** → understanding of solar modulation (very important for Dark Matter searches) → **published.**
- **Complex antimatter ($\overline{He}$)** → search for primordial antimatter.