ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany

37th International
Cosmic Ray Conference
12–23 July 2021

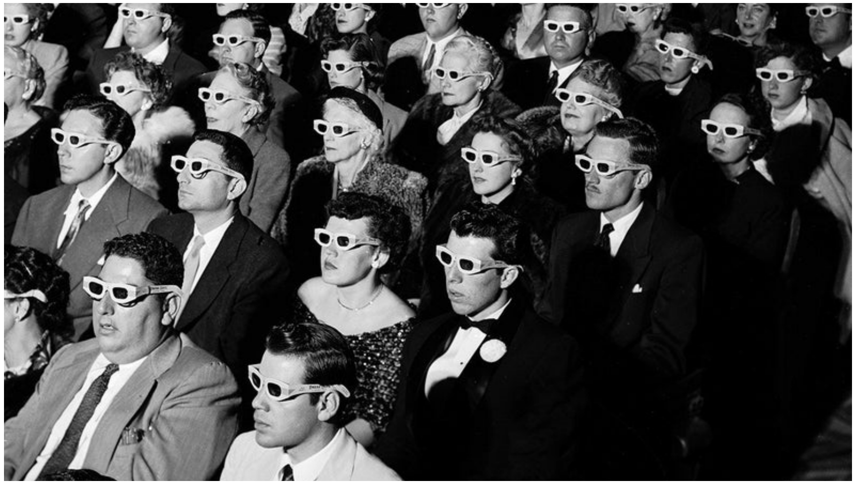
Rapporteur talk Cosmic Ray Direct

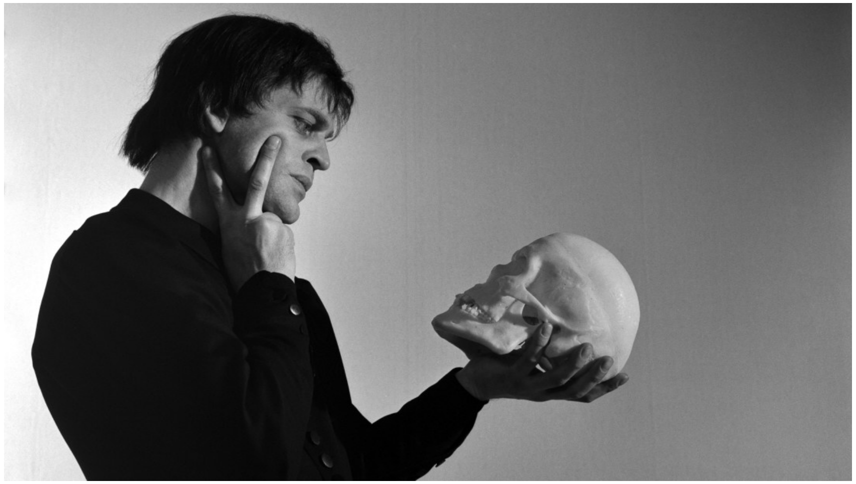
Philipp Mertsch

37th International Cosmic Ray Conference
22 July 2021

TTK Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

Why bother?





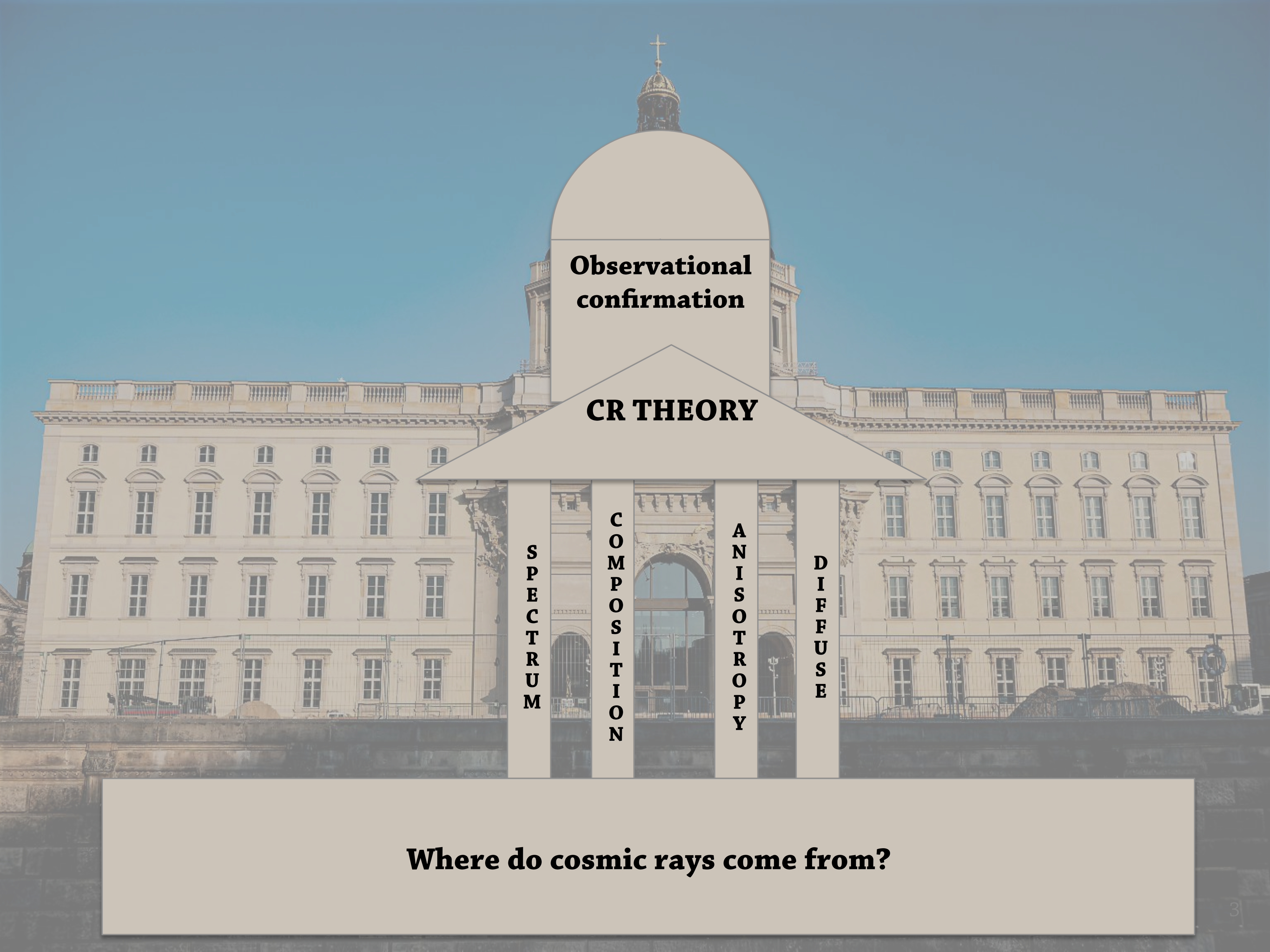
<u>CRs as spectators</u>

- What are their sources?
- Can we find DM in CRs?
- Is there primordial anti-matter in CRs?

<u>CRs as actors</u>

- CRs produce diffuse emission
- CRs contribute to ionisation, heating
- CRs provide gravitational support
- CRs drive winds
- CRs generate turbulence

Very different demands on models!



Observational confirmation

CR THEORY

SPECTRUM

COMPOSITION

ANISOTROPY

DIFFUSE

Where do cosmic rays come from?

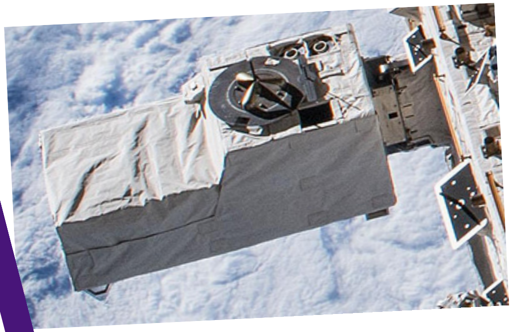
A theorist’s hand

Further contributions at ICRC 2021:

^{3}He, ^{4}He
anisotropies (nuclei)
e$^-$
e$^+$
pbar
anisotropies (e$^+$, e$^-$)
and various posters…

F. Giovacchini
M. A. Velasco
D. Krasnopevtsev
Z. Weng
H.-Y. Chou
M. M. Gonzalez

#96
#108
#111
#122
#116
#120



CALorimetric Electron Telescope

ears in orbit	~ 6
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er consumption	600 W
act	No e$^-$ line!

butions at ICRC 2021:

P. S. Marrocchesi	#19
K. Kobayashi	#98
P. Brogi	#101
P. Maestro	#93
Y. Akaike	#112
S. Tori	#105
F. Stolzi	#109

sters…

DArk Matter Particle Explorer

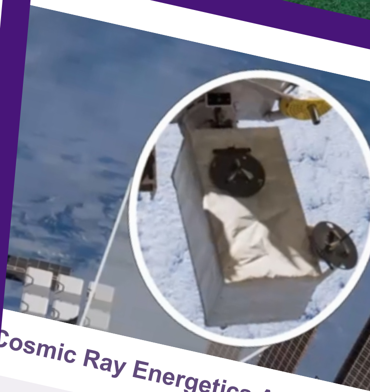
Years in orbit	~ 5.5
Main subsystems	4
eight	1400 kg
wer	400 W
fact	e$^-$ line?

tributions at ICRC 2021:

ew

X. Li	#13
F. Alemanno	#117
M. Di Santo	#114
L. Wu	#128
C. Yue	#126
Z. Zu	#115

us posters…



Cosmic Ray Energetics And Mass

n orbit	~ 1.5
ubsystems	4
	1300 kg
	400 W
	I scream, you scream

ons at ICRC 2021:

E.-S. Seo	#95
G. Choi	#94

ers…

AMS – nuclei

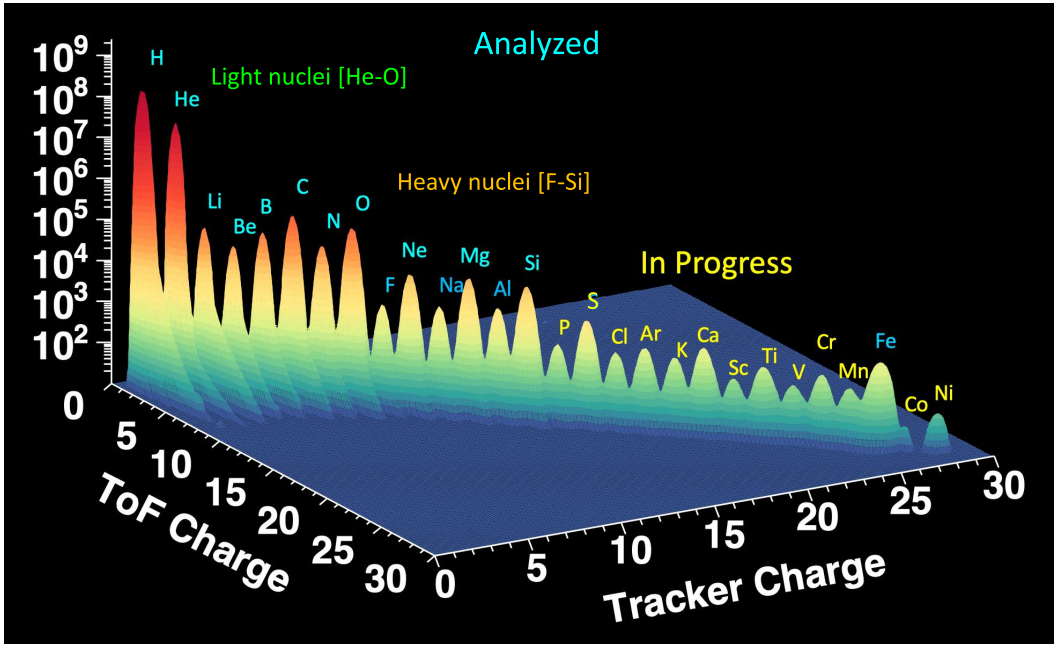
Alpha Magnetic Spectrometer

Years in orbit	~ 10
Main subsystems	5
Weight	7000 kg
Power consumption	2000 W
Fun fact	Anti-helium?

Contributions at ICRC 2021:

He, C, O vs Li, Be, B	H. Gast	#1008
Ne, Mg, Si	A. Oliva	#763
F	Q. Yan	#707
Na	C. Zhang	#743
Fe	Y. Chen	#1145
Li, Be isotopes	L. Derome	#992
deuterons	E. F. Bueno	#113

Please turn…



Importance

- Precision: more statistics → better constraints
- Origin: composition contains clue on sources
- Serendipity: expect the unexpected!

Composition and CR origin

V. Tatischeff #153

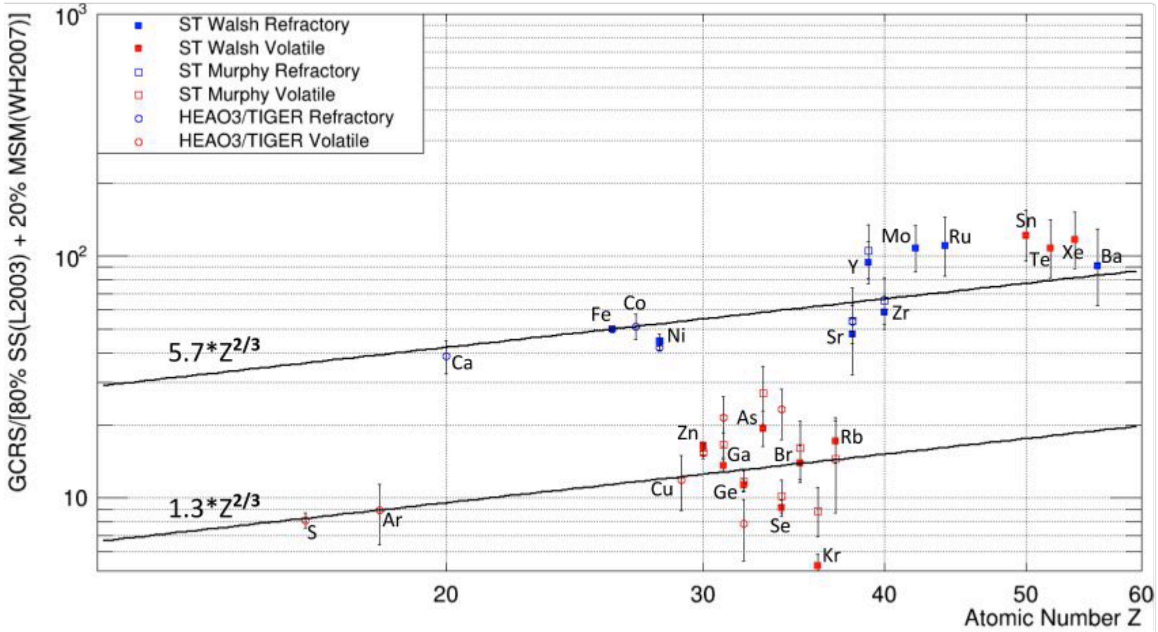
Source abundances depend on
1. composition of source reservoir
2. ISM phase (ionisation state)
3. dust content

Use *measured* chemical composition
to infer the environments
for CR acceleration

1. Volatiles mainly from superbubbles, SNRs in warm ISM contribute <30%
2. ^{22}Ne overabundance due to wind termination shocks of massive stars
3. Refractories can also be from superbubbles, requires continuous replenishing of dust

Composition and CR origin

- N. Walsh (Super-TIGER) #118



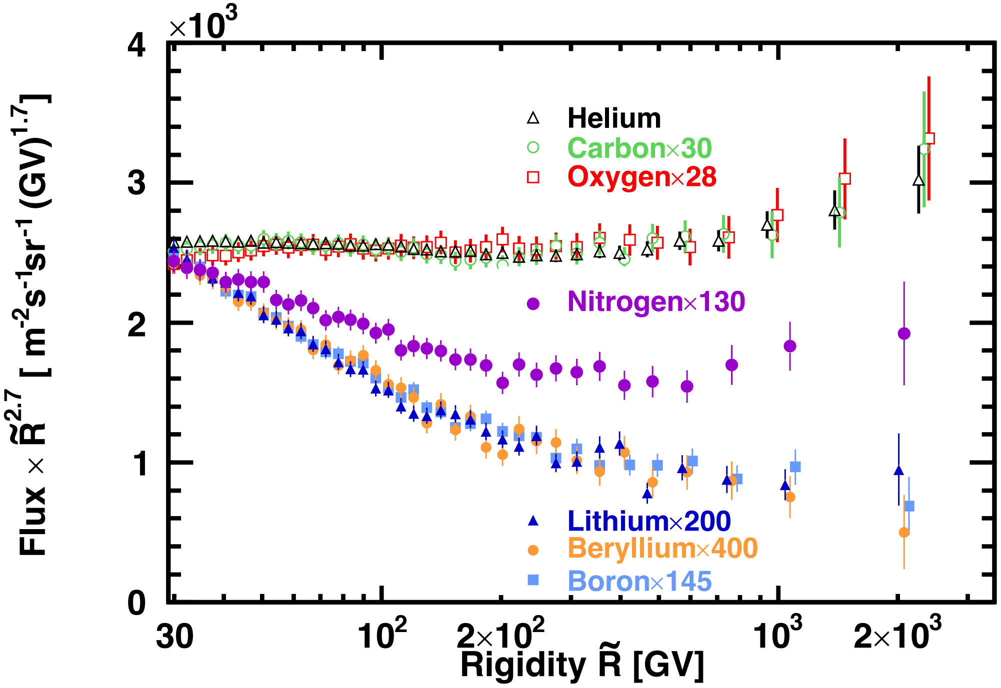
- Up to Z=40: Charge-dependence and preference of refractory over volatiles
- Only if choosing the right mix: 80% solar system, 20% massive (OB) stars

- Beyond Z=40: volatiles not disfavoured anymore

→ r-process elements, NS binary mergers?

AMS – status ca. 2019

H. Gast #1008



He, C, O

- dominantly primary
- agree in shape > 50 GV
- break at ~ 300 GV

Li, Be, B

- dominantly secondary
- agree very well in shape
- also break at ~ 300 GV

The break in secondaries
is ~ twice as big
→ propagation effect

N

sec. and prim. contributions

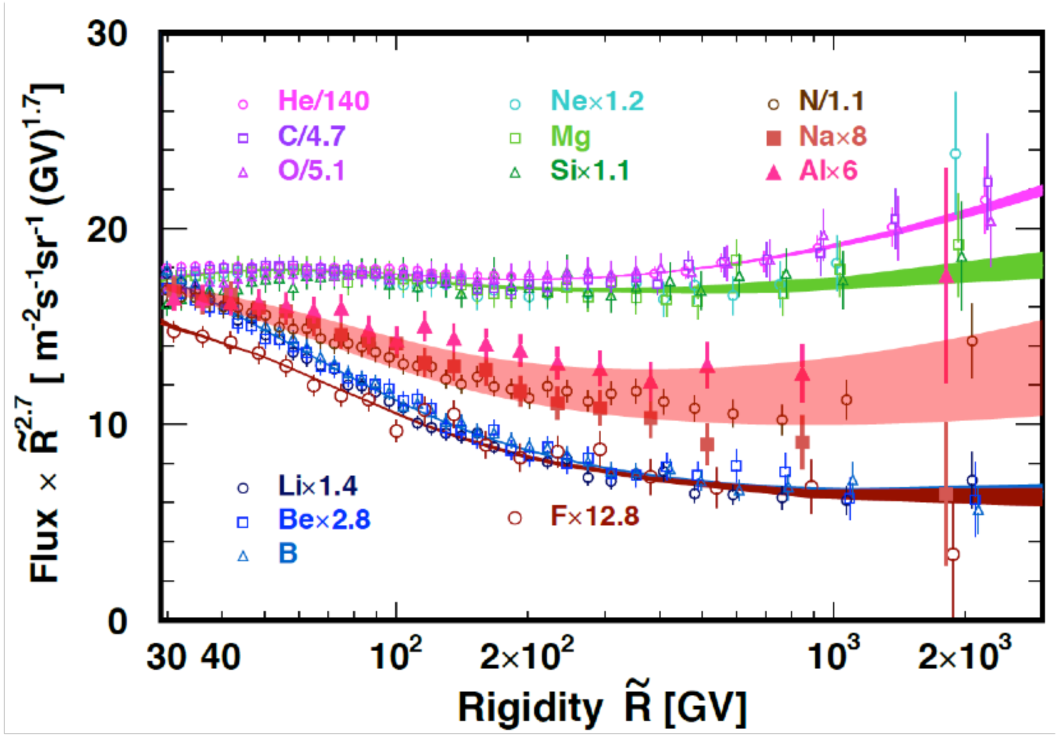
Ne, Mg, Si

Ne, Mg, Si
- dominantly primary
- agree in shape > 100 GV
- differ from He, C, O

→ "two different classes"
- but what does this mean?

F
- purely secondary

Na, Al
- sec. and prim. (see N)

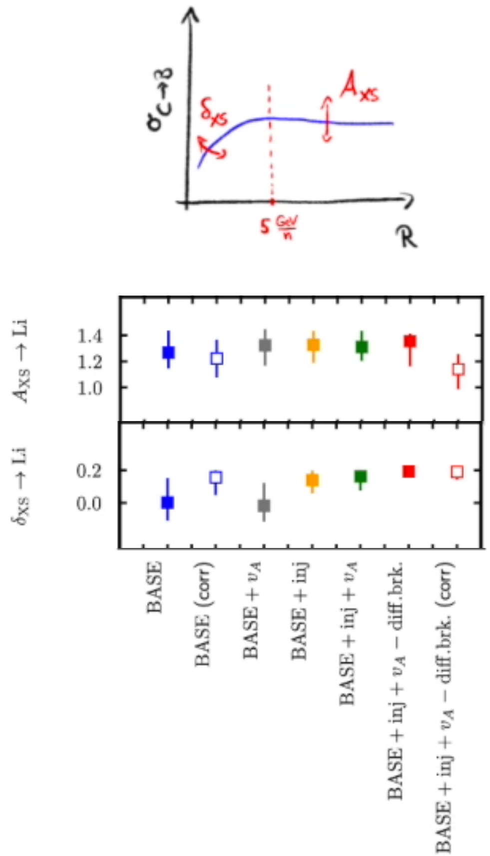


A. Olvia #763

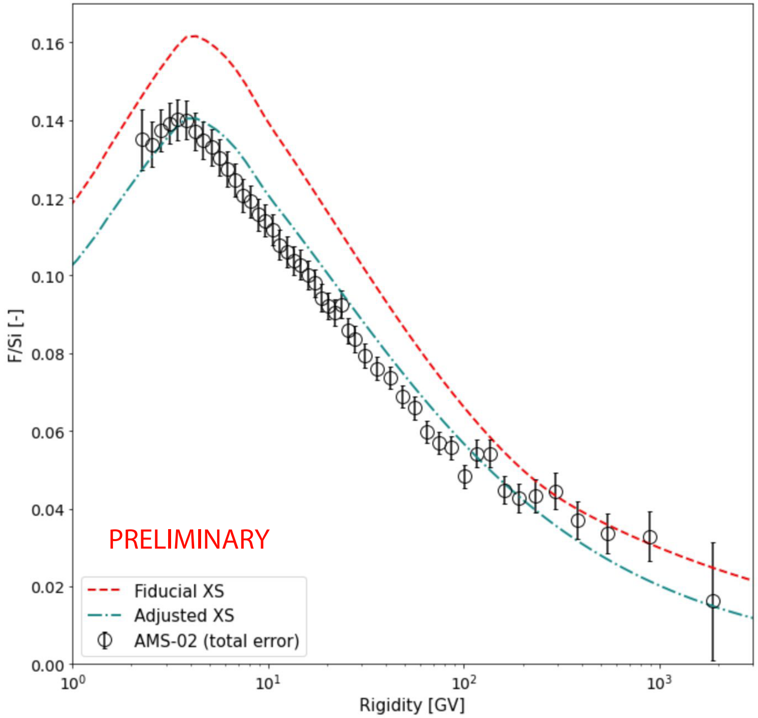
Cross-section uncertainties

M. Korsmeier #176

M. Vecchi #174

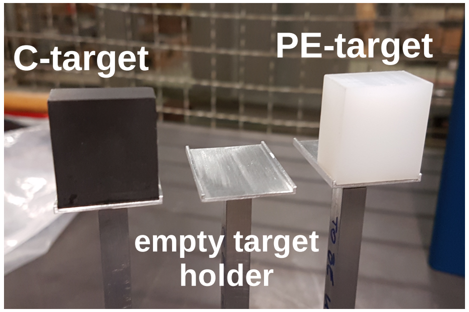


- Parametrise deviations by nuisance parameters and fit to CR data



- parameters as fitted to Li, Be, B, He, C, O
- F/Si overproduced by 20%
- Fixed by modifying Si → F cross-section

NA61/SHINE

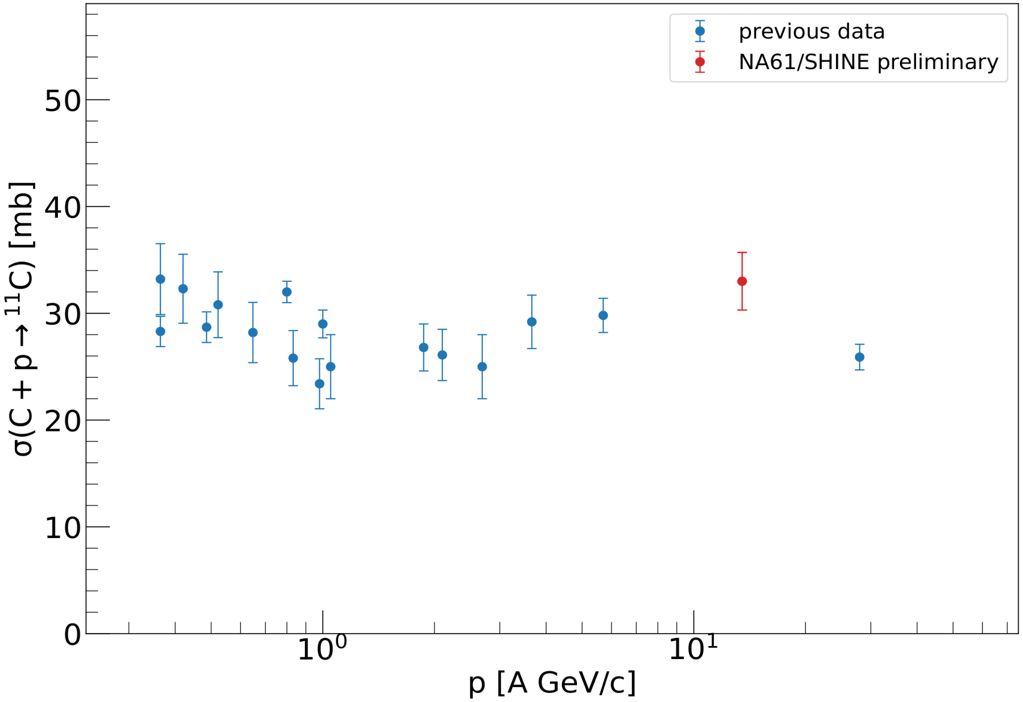


Pilot run in 2018

- Beam energy ~14 A GeV
- C + p reaction on polyethylene and graphite targets

Data taking for light secondary (B, Li, Be) production on light primaries (C, N, O) planned for 2022.

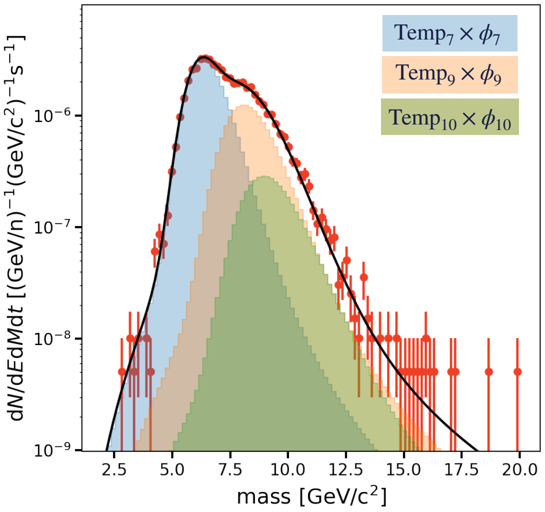
$\sigma\,(^{12}C \longrightarrow {}^{11}C) = (33 \pm 3)$ mb



N. Amin #102

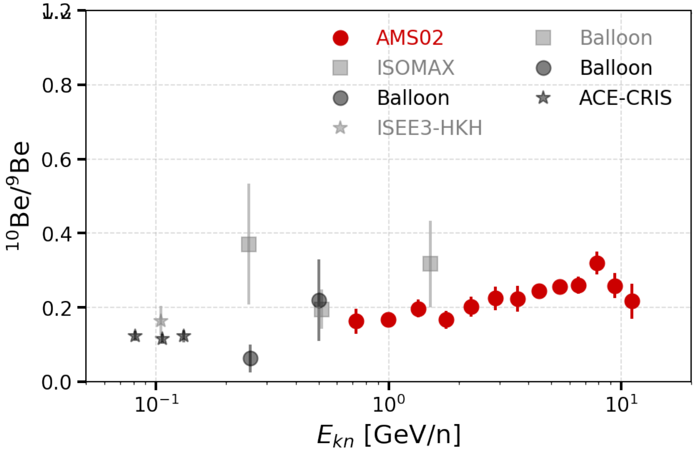
Isotopes

L. Derome #992

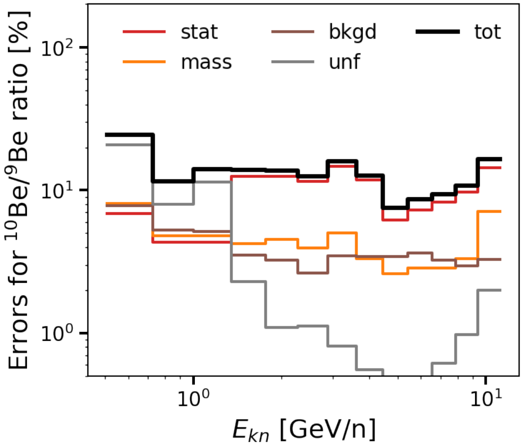


- Δ M ~= 1 a.u. => no event-by-event analysis, but use shape of mass distribution

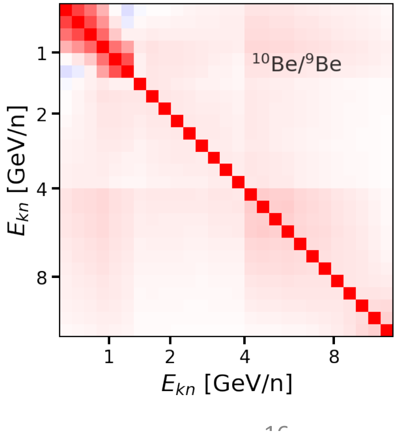
Flux ratios



Errors

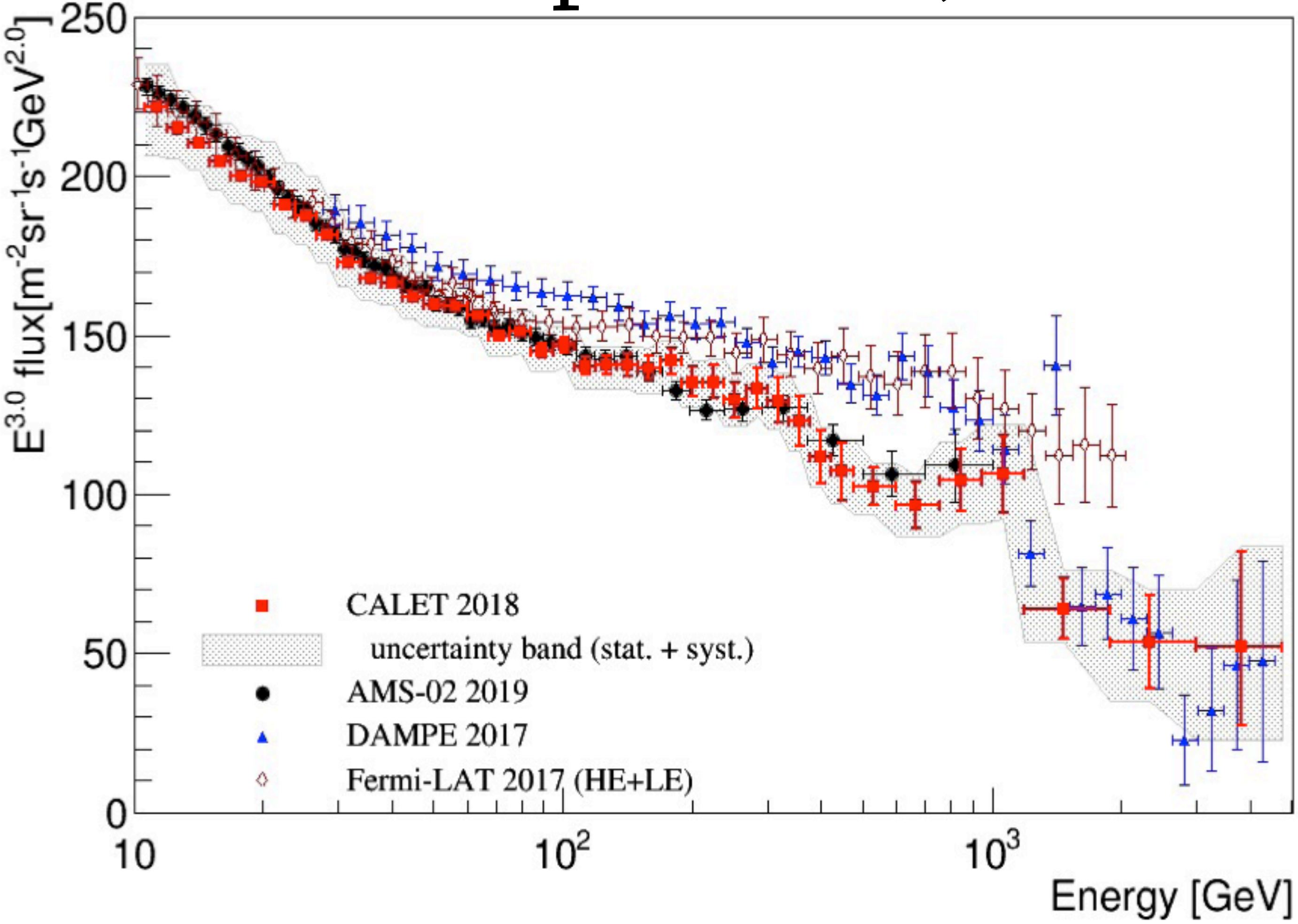


Total correlation matrices



Also ^{2}H/^{1}H (E. F. Bueno #113) and ^{3}He/^{4}He (F. Giovacchini #96)

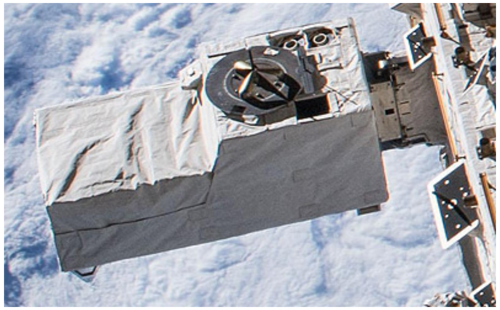
Electron + positron, ca. 2019



Between ~ 50 GeV and 1 TeV, two groups:

- Fermi-LAT and DAMPE
- AMS-02 and CALET

CALET



CALorimetric Electron Telescope

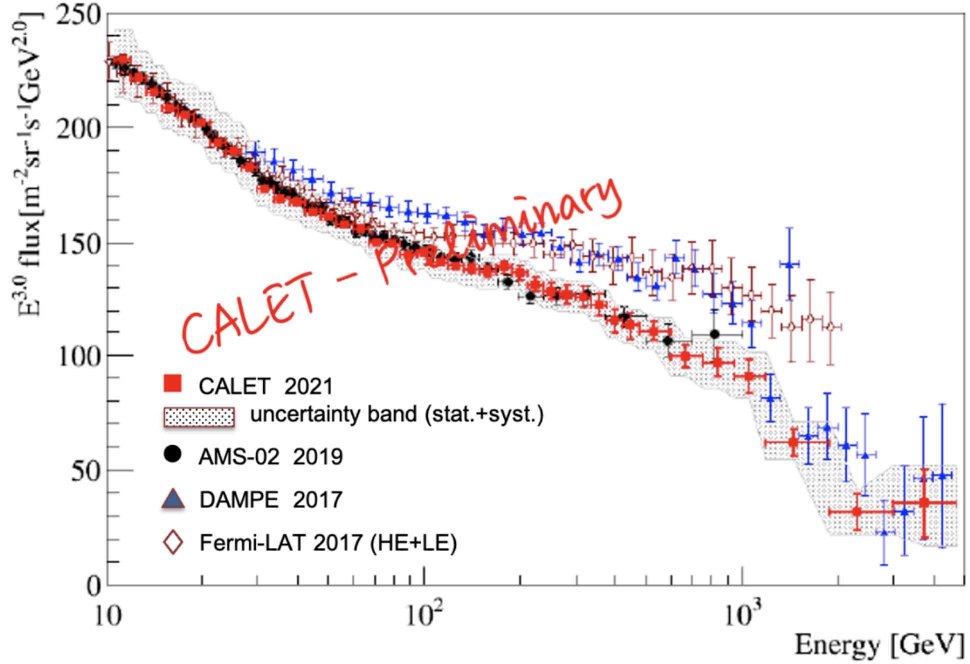
Years in orbit	~ 6
Main subsystems	3
Weight	650 kg
Power consumption	600 W
Fun fact	No e^- line!

Contributions at ICRC 2021:

Overview	P. S. Marrocchesi	#19
p	K. Kobayashi	#98
He	P. Brogi	#101
C, O	P. Maestro	#93
B, B/C	Y. Akaike	#112
e^++e^-	S. Tori	#105
Fe	F. Stolzi	#109

and various posters…

S. Torii #105



- Statistics improved by factor 2.3
- 6.5 sigma suppression above ~ 1TeV
- No preference broken PL or PL with exp. cut-off

Interpretation: electrons & positrons

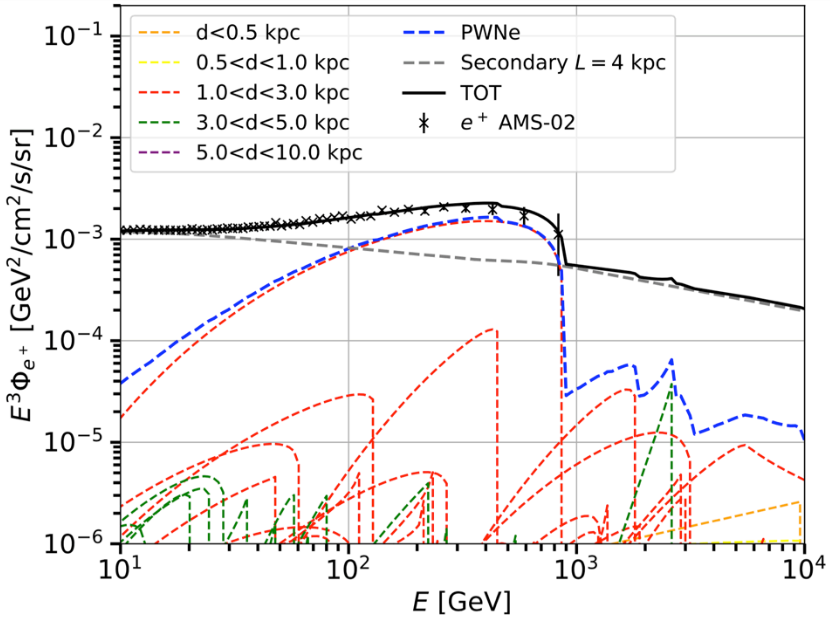
- Most interpretation in framework of conventional model[1]:
- Positrons produced by spallation in ISM fall short of measurements

→ Additional source of positrons required

- PWNe (T. Linden #931, L. Orusa #149, F. Donato #154)
- Vela SNR (H. Motz #100)
- intrabinary shocks of compact binary millisecond pulsars (M. Linares #177)
- Unknown nearby source (S. Recchia #168, D. Gaggero #173)
- Old supernova remnants (PM #144)

Single source vs population

L. Orusa #149



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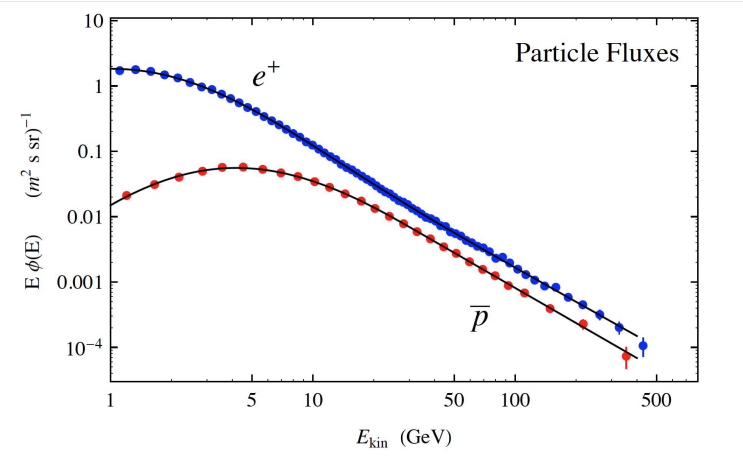
[1] Conventional diffusion model:
- one-zone diffusion model
- typical residence time O(10) Myr at GeV
- radiative losses in muG B-fields and radiation fields with eV/cm^3

Alternative scenarios

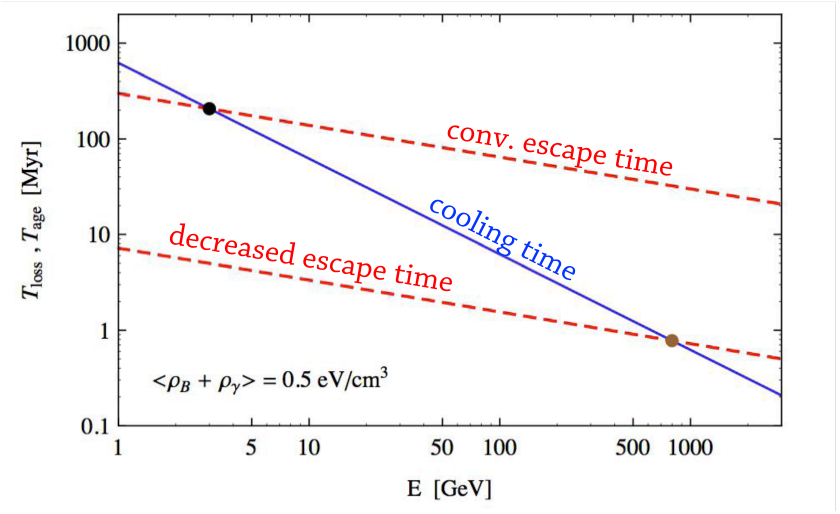
Problems with conventional models:

1. Need additional e+ source
2. Anti-protons harder than expected
3. Energy loss signature in ($e^+ + e^-$)?
4. Individual srcs. in > 1 TeV ($e^+ + e^-$)
5. Issue with ^{9}Be/^{10}Be



Similarity shapes and ratios as prod. cross-sec. Coincidence?

P. Lipari #169



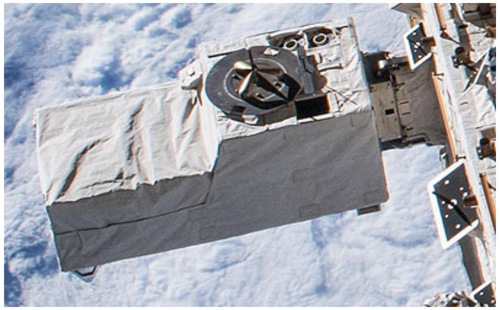
Would need to reduce escape time

Problems of alternative scenarios:

1. Different src. spectra for e^- and p
2. Same softening for e^+ and e^- @ 1TeV
3. Sec. nuclei?

R. Diesing #29

CALET – proton



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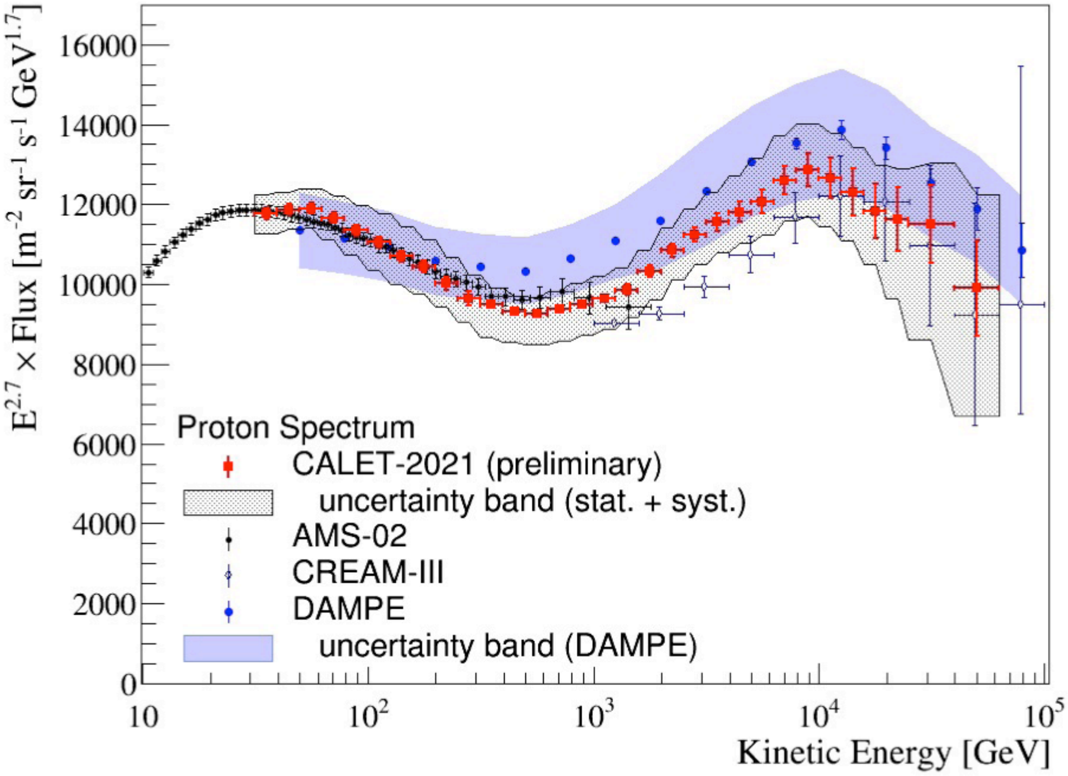
e^+e^-	S. Tori	#105
Fe	F. Stolzi	#109

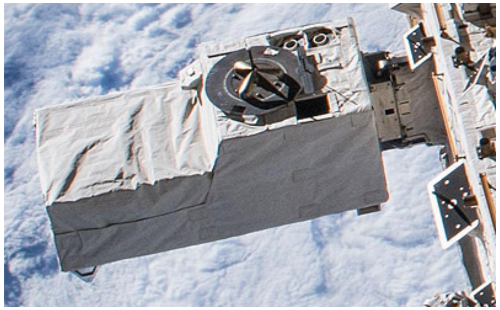
and various posters…

K. Kobayahsi #98



- energy reach extended from ~10 to 60 TeV
- hardening at 550 GV, softening at 11 TeV
- in agreement with DAMPE and CREAM balloon

CALET – helium



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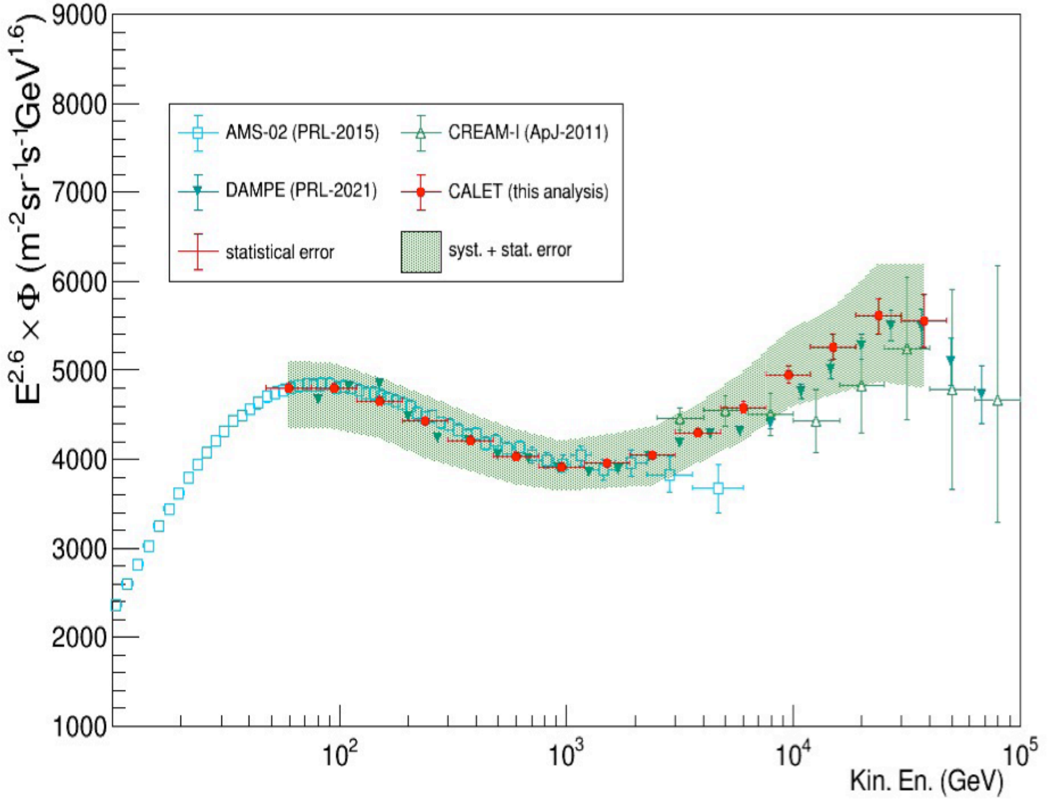
Fe	F. Stolzi	#109

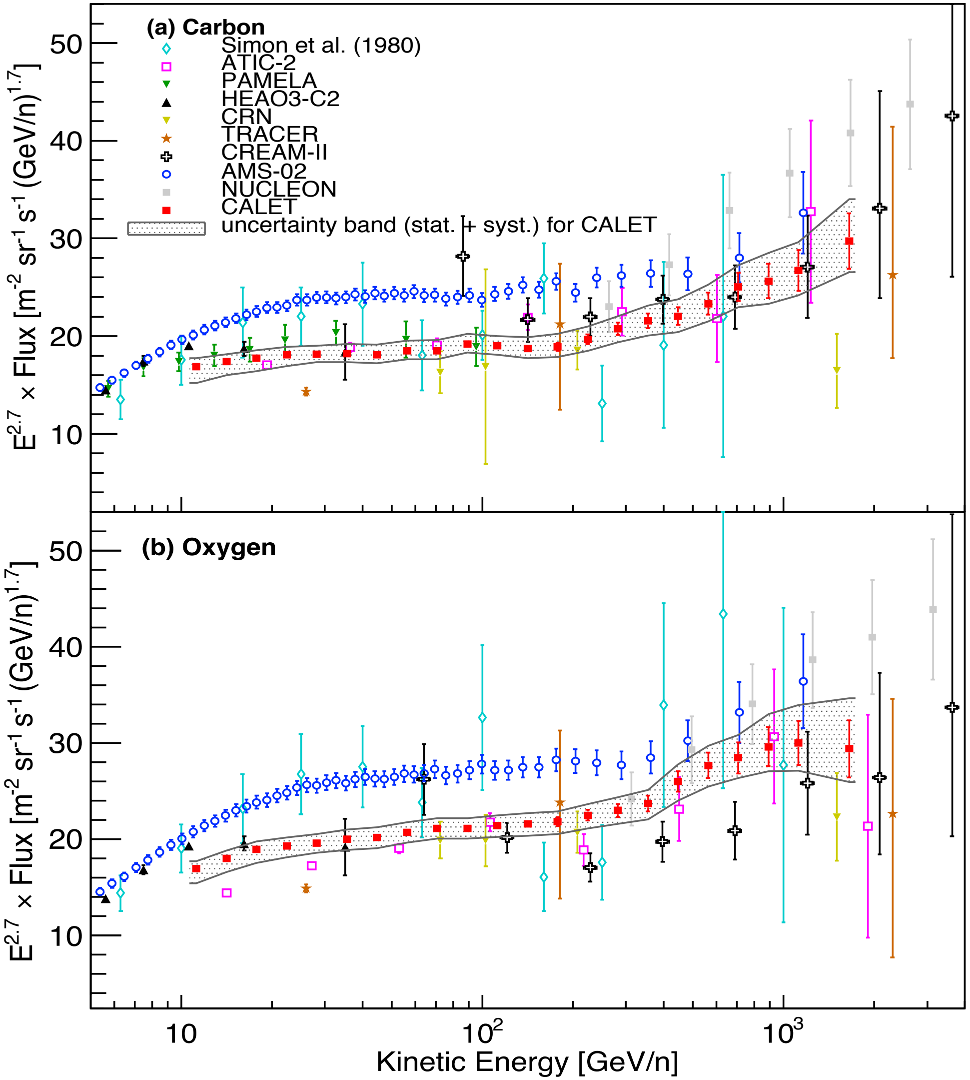
and various posters…

P. Brogi #101



- hardening at 1.3 TeV
- in agreement with DAMPE and CREAM

CALET – carbon, oxygen



P. Maestro #93

- CALET carbon and oxygen lower than AMS-02 by 27%
- Shapes agree though

- Agreement with PAMELA

- C/O flat above 25 GeV/n and agrees with AMS-02 and PAMELA

- N.B.: CALET boron similarly lower than AMS, but B/C agree

DAMPE – proton

DArk Matter Particle Explorer

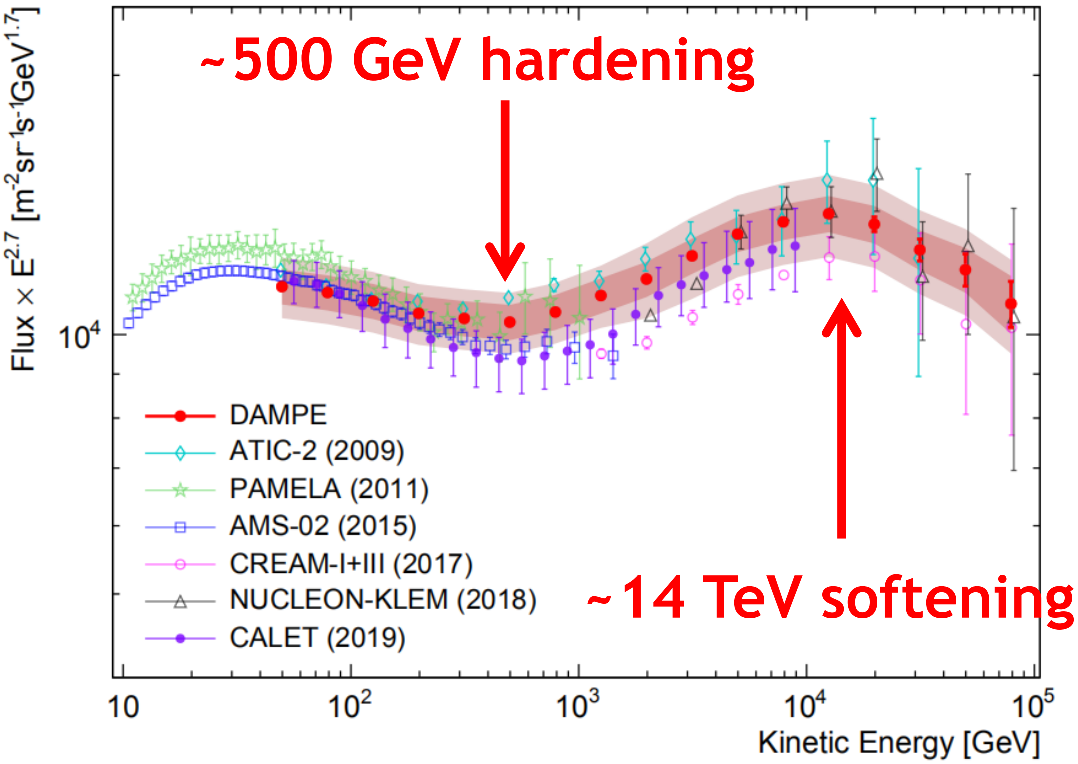
Years in orbit	~ 5.5
Main subsystems	4
Weight	1400 kg
Power	400 W
Fun fact	e^- line?

Contributions at ICRC 2021:

Overview	X. Li	#13
p + He	F. Alemanno	#117
He	M. Di Santo	#114
C, O	L. Wu	#128
B/C	C. Yue	#126
Fe	Z. Zu	#115

and various posters…

X. Li #13



- hardening at ~500 GV, softening at ~14 TeV
- in agreement with CALET and CREAM balloon

DAMPE – helium

DArk Matter Particle Explorer

Years in orbit	~ 5.5
Main subsystems	4
Weight	1400 kg
Power	400 W
Fun fact	e^- line?

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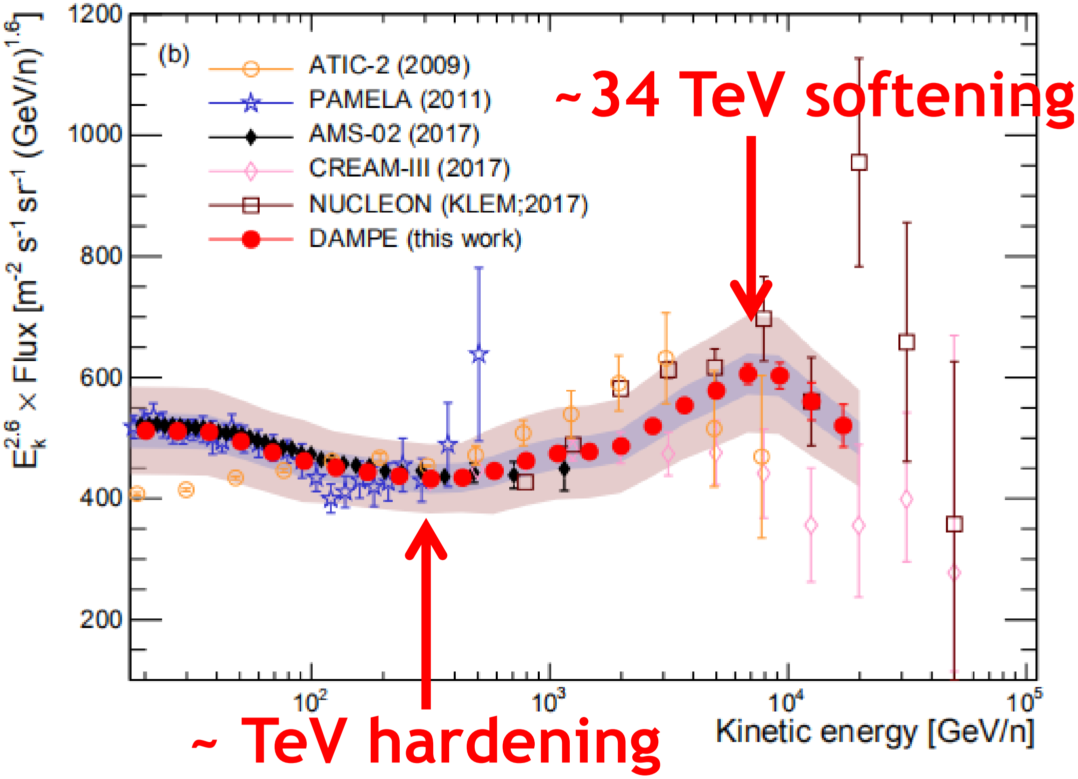
and various posters…

M. Di Santo #114



~34 TeV softening

~ TeV hardening

- hardening at ~1 TV
- softening at ~34 TeV (sig.: 4.3 sigma)
- in agreement with CALET

DAMPE – proton + helium

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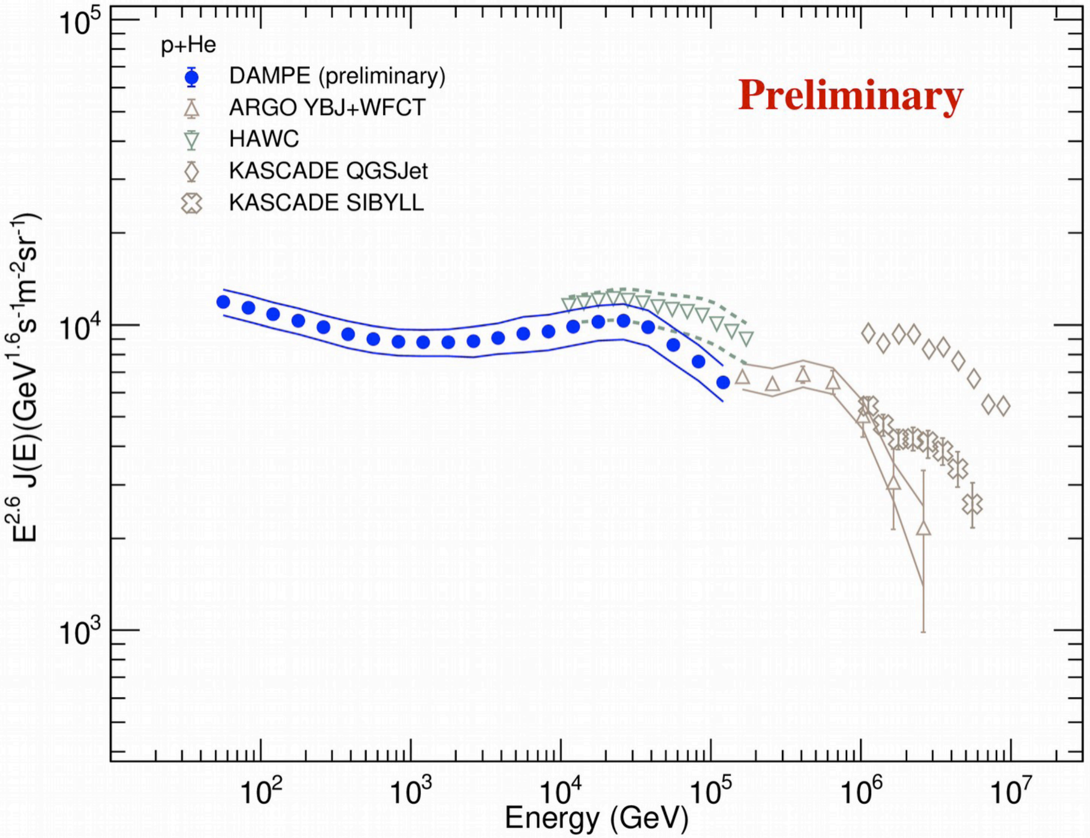
and various posters…

F. Alemanno #117



- allows pushing past 100 TeV
- not the end of the line yet!
- indirect measurements imply another hardening

ISS-CREAM

ISS - Cosmic Ray Energetics And Mass

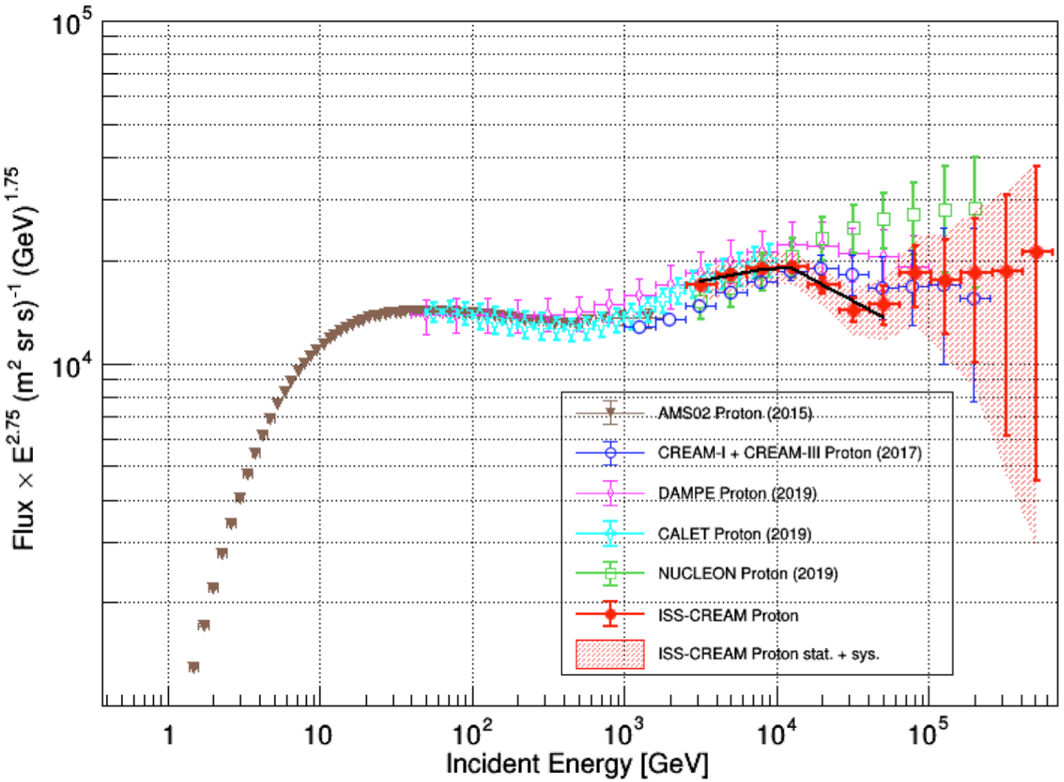
Years in orbit	~ 1.5
Main subsystems	4
Weight	1300 kg
Power	400 W
Fun fact	I scream, you scream

Contributions at ICRC 2021:

Overview	E.-S. Seo	#95
p	G. Choi	#94
heavy nuclei	S. Kang	#97

and various posters…

G. Choi #94



- spectrum from 2.5 to 655 TeV
- softening at ~12TeV (sig.: 4.62 sigma)
- agreement with DAMPE above break?
- above 65 TeV, large errors

Bump hunting?

Bump can be parametrised: broken power law, log-parabola, but what does it mean?

Individual source

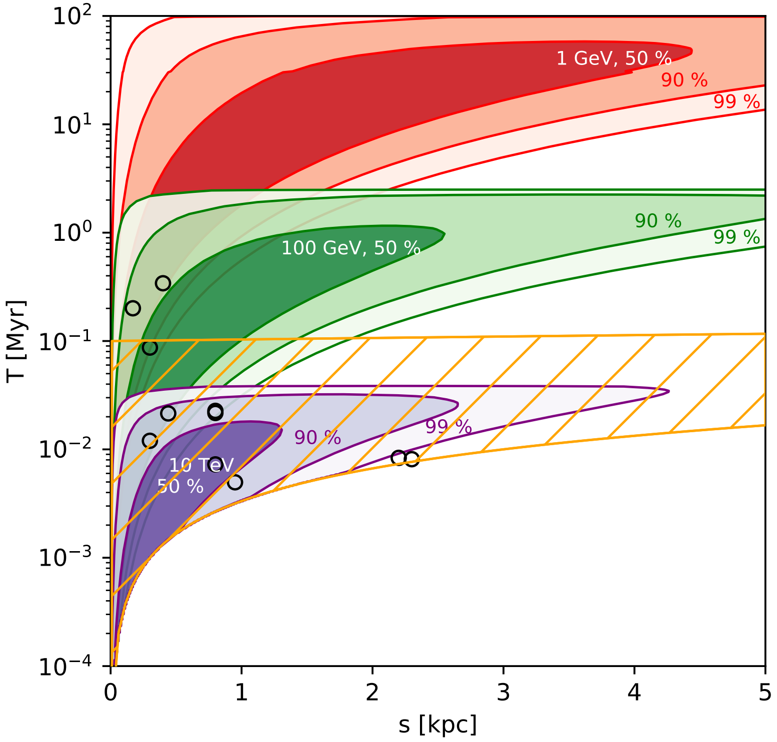
- Shape determined by
  - source spectrum
  - age
  - distance of source
- Power law source spectra and diffusion coefficient, impulsive injection → broad bumps
- Statistical interpretation?!

New population

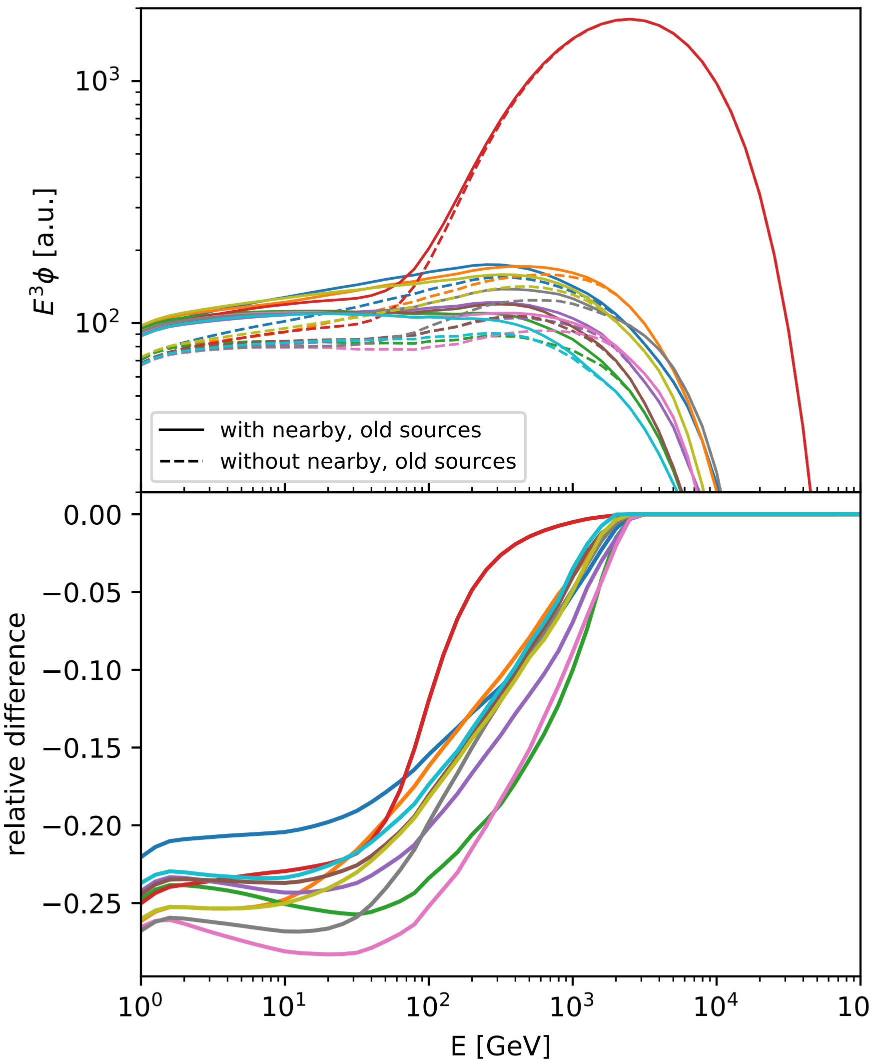
- Position in energy of spectral feature related to environmental parameters
- How much variance expected?

A cautionary tale

Mertsch (2018)



Nearby, but old sources matter!



Softening

- CR spectrum depends on shock compression ratio r:

$$r = \frac{\text{upstream speed}}{\text{downstream speed}} = \frac{u_-}{u_+} \quad \Rightarrow \quad \frac{\mathrm{d}N}{\mathrm{d}E} \propto E^{-\gamma} \quad \text{with} \quad \gamma = \frac{3r}{r-1}$$

- In test particle DSA, the hydrodynamical shock has $r = 4 \quad \Rightarrow \quad \frac{\mathrm{d}N}{\mathrm{d}E} \propto E^{-2}$
- Can infer source dN/dE from locally observed spectra ($\phi(E) \propto E^{-2.8}$) and diffusion coefficient ($\kappa(E) \propto E^{-0.5\ldots-0.3}$):

DSA must explain softer spectra: $\frac{\mathrm{d}N}{\mathrm{d}E} \propto E^{-2.5\ldots-2.3}$

- Aggravated in CR modified shocks with efficient acceleration needed for B-field amplification

R. Diesing #29

Softening

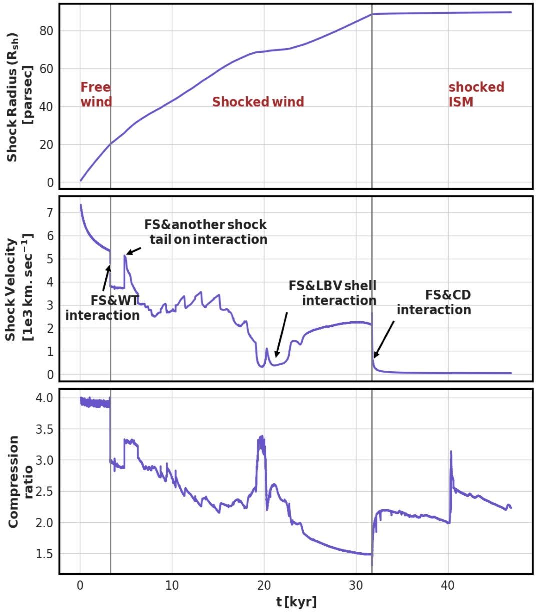
M. Pohl #987

- Turbulence generation is energy loss for ions
- steepening?
- No, precursor too small:

$$\Delta\gamma \lesssim 0.1$$

S. Das #988

- For massive stars, SN shocks expand into wind
- complex velocity evolution
- compression ratio deviates from 4

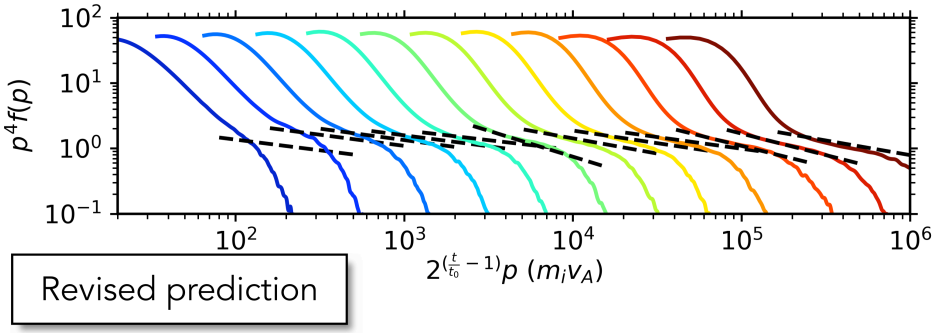


- CRs scatter on waves
- Can measure phase speed in PIC

$$r_{\rm CR} \simeq \frac{u_-}{u_+(1+\alpha)} = \frac{r_{\rm gas}}{1+\alpha} < r_{\rm gas}$$

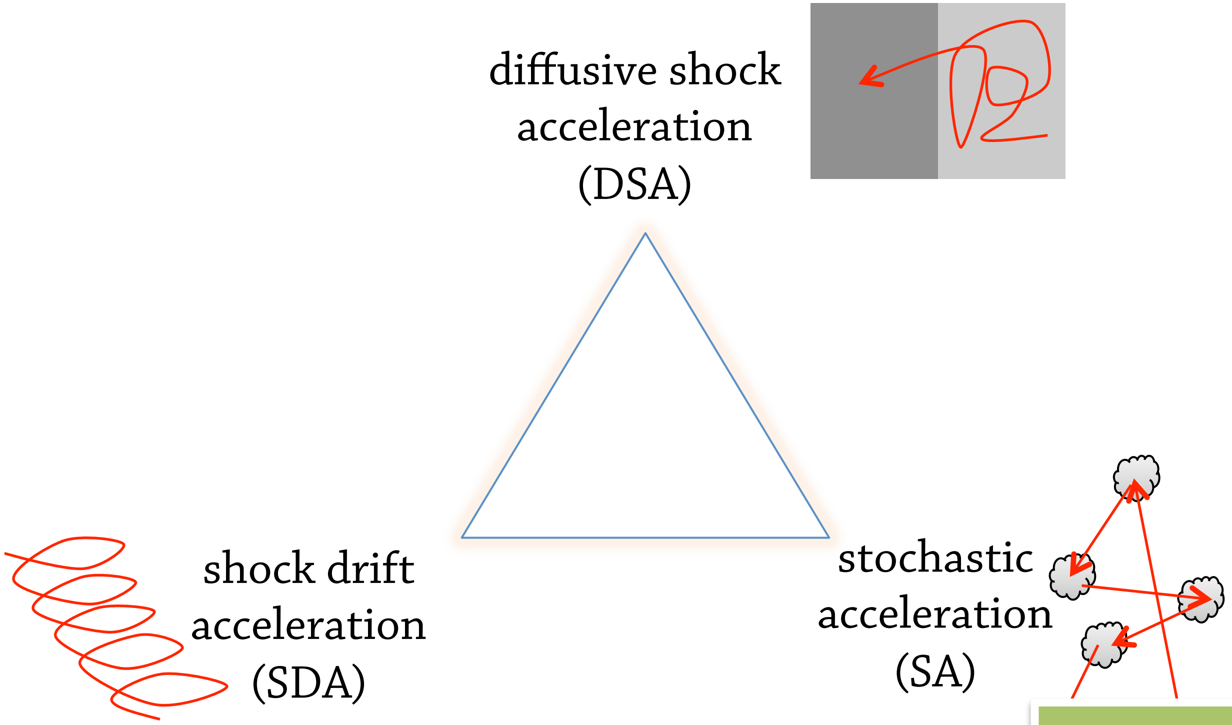
→softer spectra

D. Caprioli #482



Revised prediction

Pre-acceleration



diffusive shock acceleration (DSA)

shock drift acceleration (SDA)

stochastic acceleration (SA)

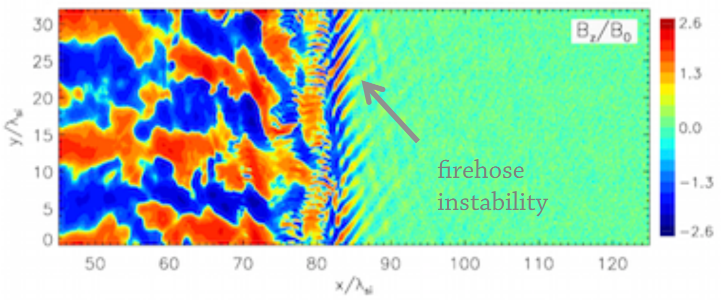
- Example: cluster merger shocks
- quasi-perpendicular, low Mach number
- yet: synchrotron and X-ray point to efficient e- acceleration

- DSA requires $r_g(E_{inj}) >> d_{shock}$
- Not satisfied by thermal particles, certainly not e^-
- Need pre-acceleration

Stochastic shock drift acceleration

J. Niemiec #129

- SDA only gives boost
- But: particles reflected away from shock generate turbulence

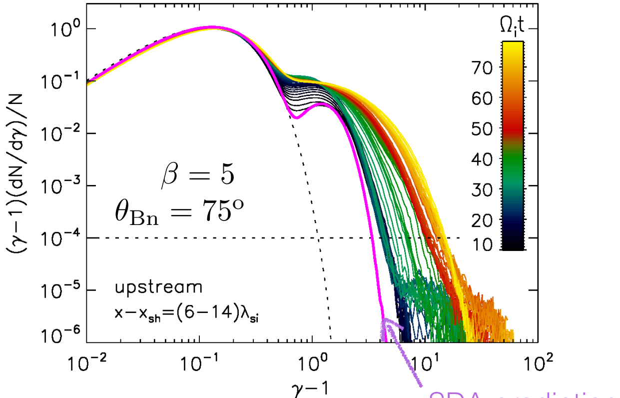


firehose instability

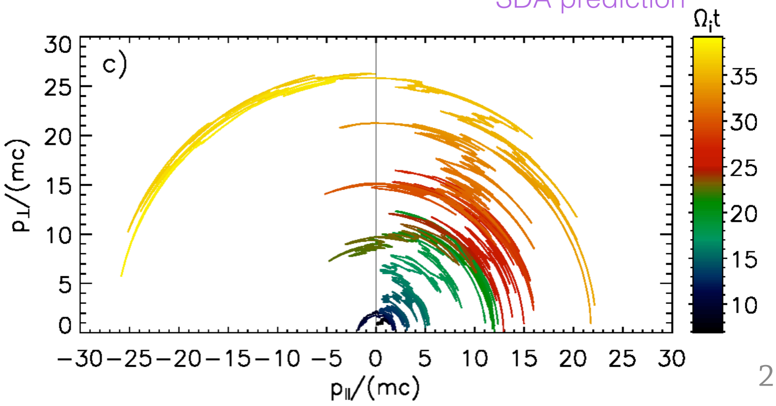
- Scatters particle back to shock

→ more SDA

- Importance of shock front ripples



SDA prediction



SDA

and

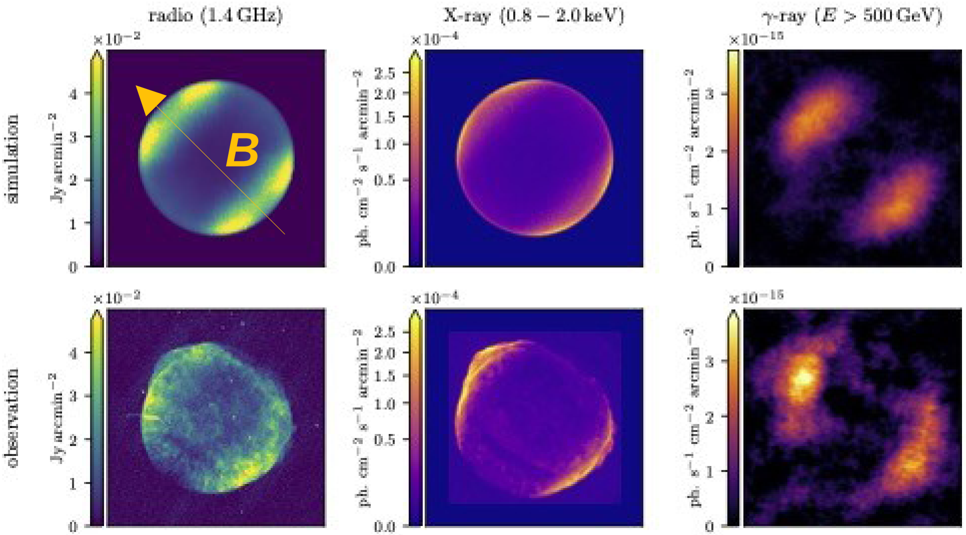
resonant pitch-angle scattering

Bridging the gap

- PIC codes typically run for O(1000) gyro times
- Power law spectra are observed, but textbook DSA not observed yet
- Would need to run for much longer times

<u>PIC-informed MHD simulations</u> C. Pfrommer #425

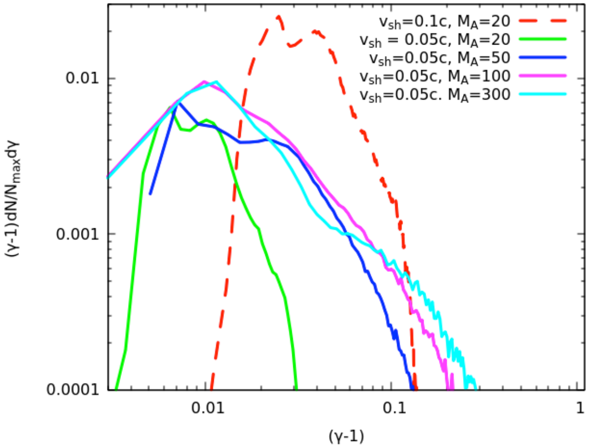
- Measure Mach number $\mathcal{M}$ and obliquity θ_{B} in MHD simulation
- Apply lessons from PIC: acceleration efficiency
- Potentially strong conclusions for outer scale, e- accn. efficiency at quasi-perp. shocks

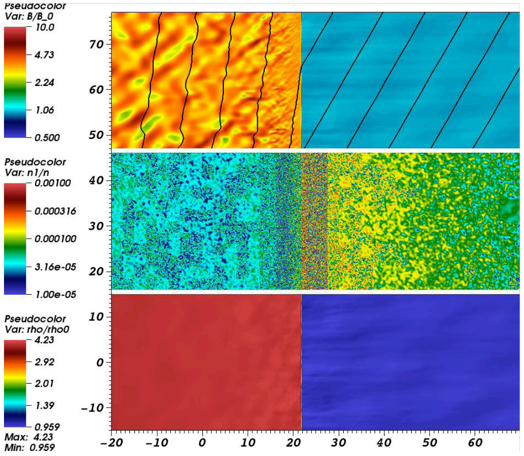


PIC-MHD

A. J. van Marle #447

- Thermal plasma (MHD) and non-thermal particles (PIC)
- MHD-PIC can resolve long-wavelength instabilities, but needs to model injection
- Need large Alfvénic Mach number, e.g. $\mathcal{M}_\mathrm{A} \gtrsim 50$ for $\theta_\mathrm{B} = 60^\circ$

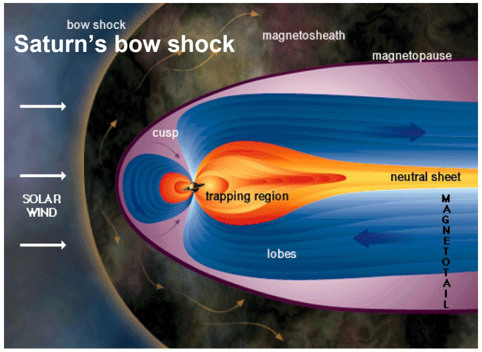


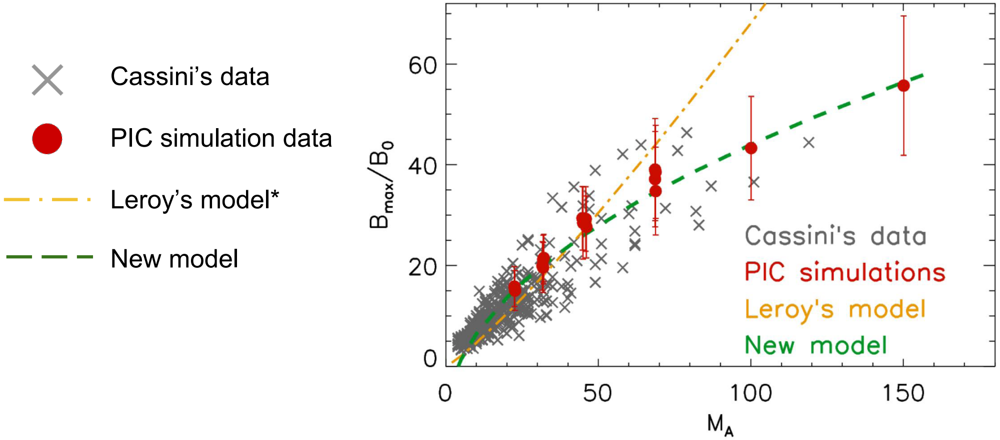


Heliospheric laboratory

A. Bohdan #443

- Saturn's high Mach number bow shock explored *in-situ* by Cassini space craft
- PIC simulations show B-field amplification due to Weibel instability
- Little dependence on shock speed, mass ratio or upstream plasma β





Iron

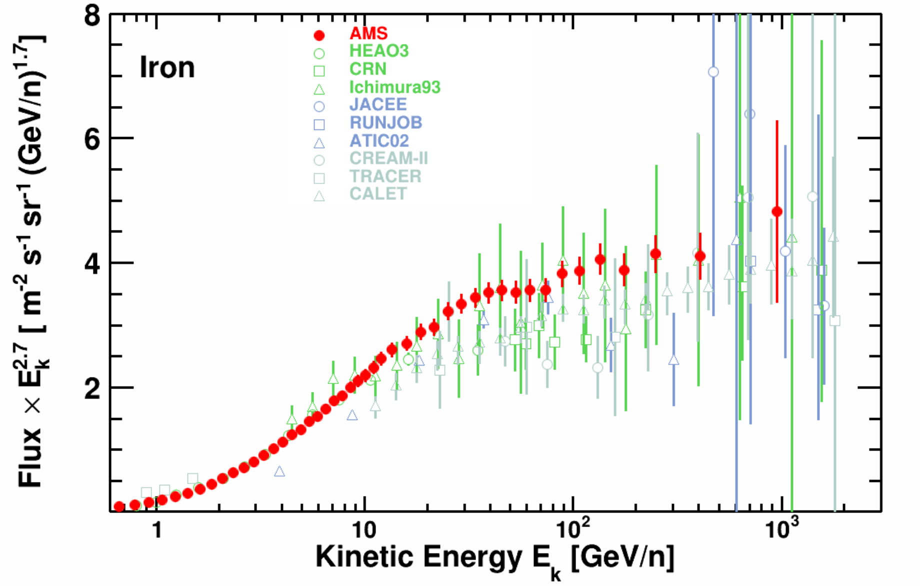
Alpha Magnetic Spectrometer

Years in orbit	~ 10
Main subsystems	5
Weight	7000 kg
Power consumption	2000 W
Fun fact	Anti-helium?

Contributions at ICRC 2021:

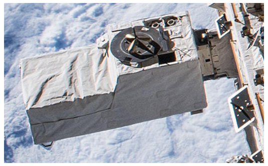
He, C, O vs Li, Be, B	H. Gast	#1008
Ne, Mg, Si	A. Oliva	#763
F	Q. Yan	#707
Na	C. Zhang	#743
Fe	Y. Chen	#1145
Li, Be isotopes	L. Derome	#992
deuterons	E. F. Bueno	#113

Please turn…



Y. Chen #129

Normalisations different, but shapes compatible



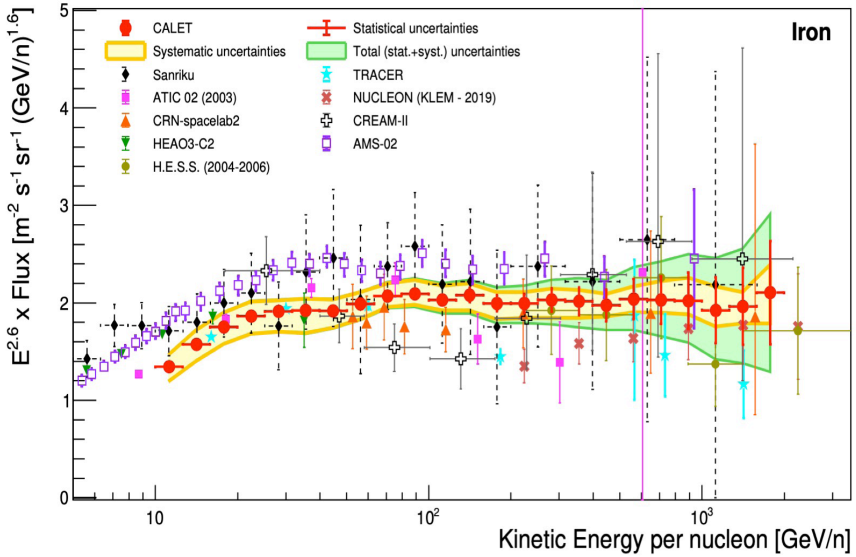
CALorimetric Electron Telescope

Years in orbit	~ 6
Main subsystems	3
Weight	650 kg
Power consumption	600 W
Fun fact	No e^- line!

Contributions at ICRC 2021:

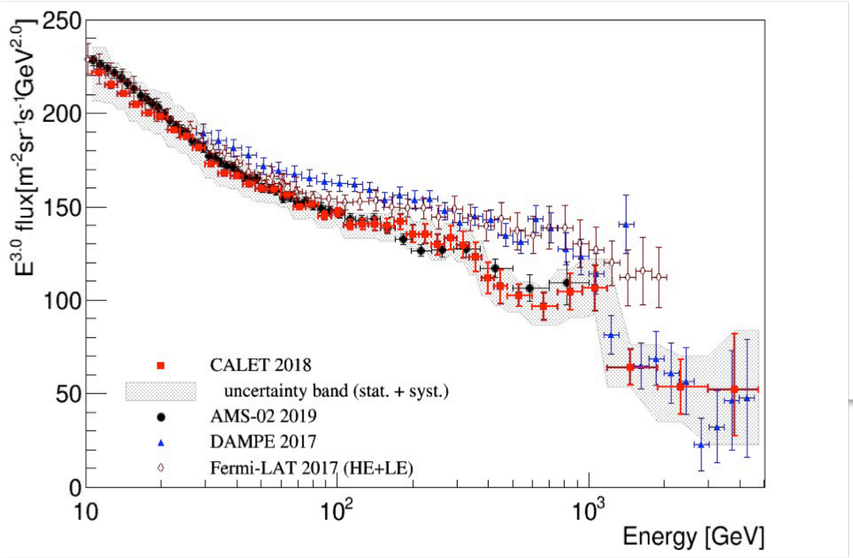
Overview	P. S. Marrocchesi	#19
p	K. Kobayashi	#98
He	P. Brogi	#101
C, O	P. Maestro	#93
B, B/C	Y. Akaike	#112
e^++e^-	S. Tori	#105
Fe	F. Stolzi	#109

and various posters…



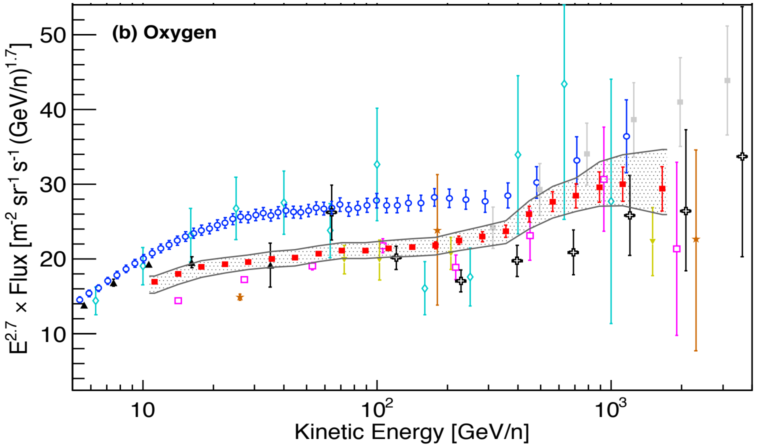
F. Stolzi #109

CALET – AMS agreement



$e^+ + e^-$

agreement in shape **and** normalisation



nuclei

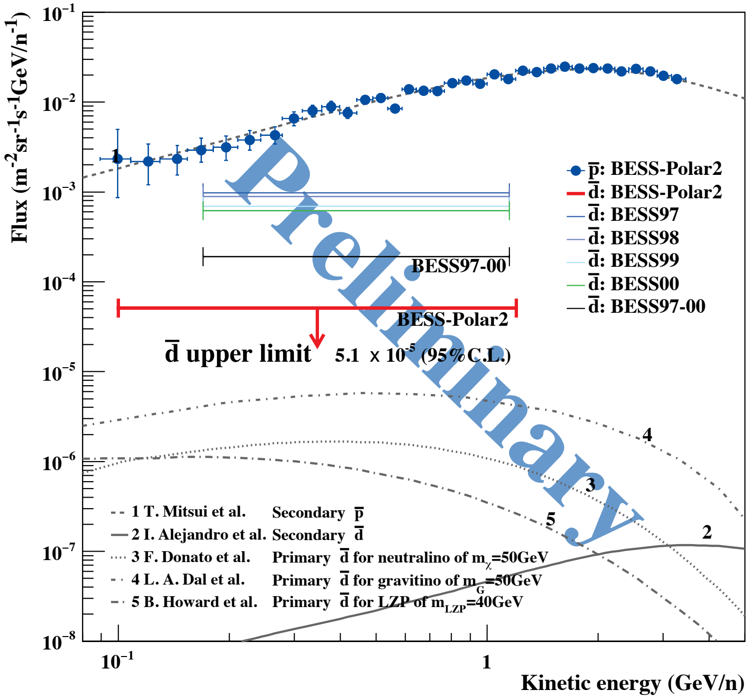
agreement in shape **but not** normalisation

Anti-nuclei

BESS

K. Sakai #123

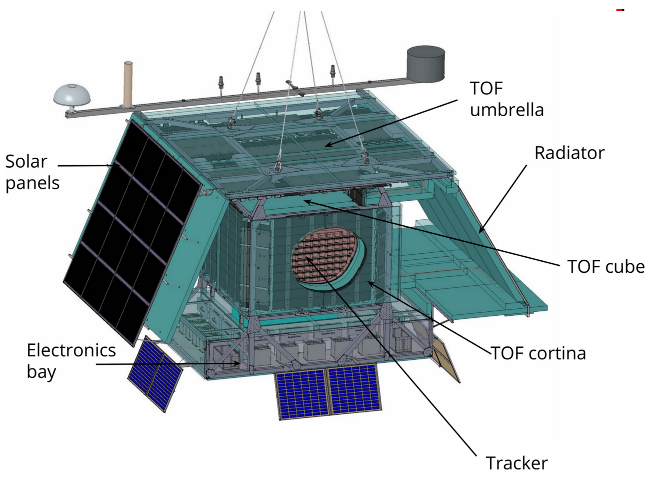
- new $\bar{p}, \bar{d}$
- Getting close to models



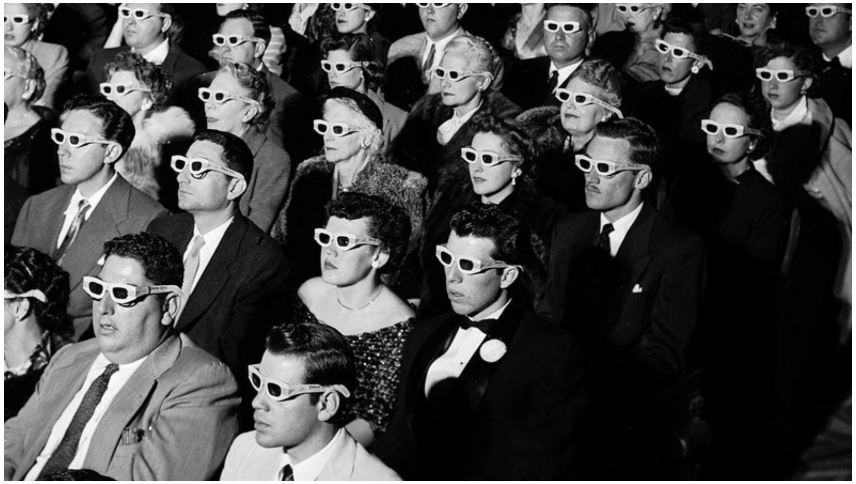
GAPS

P. v. Doentichem

- targets $\bar{p}, \bar{d}, \overline{He}$
- Formation and decay of exotic atoms
- Antarctic balloon flight in late 2022

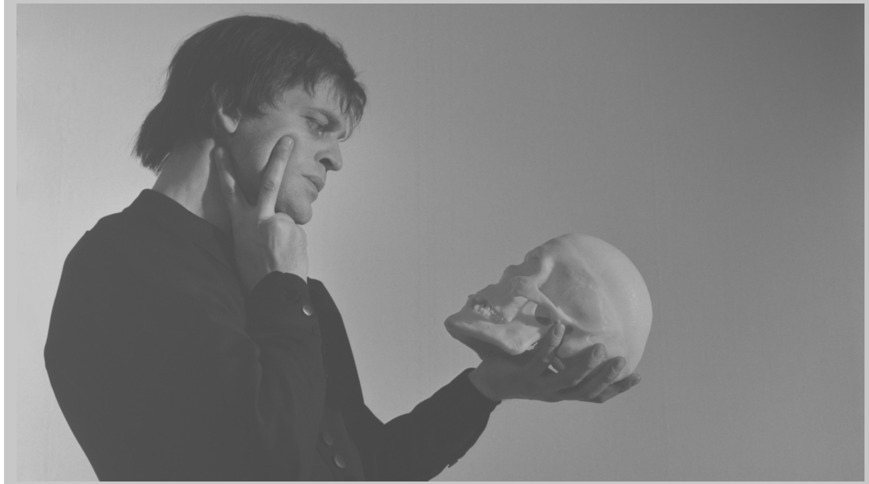


Why bother?



CRs as spectators

- What are their sources?
- Can we find DM in CRs?
- Is there primordial anti-matter in CRs?



CRs as actors

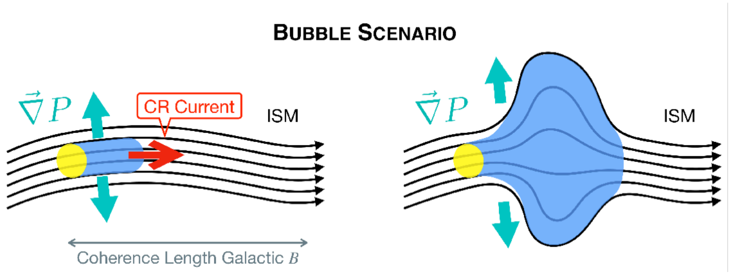
- CRs produce diffuse emission
- CRs contribute to ionisation, heating
- CRs provide gravitational support
- CRs drive winds
- CRs generate turbulence

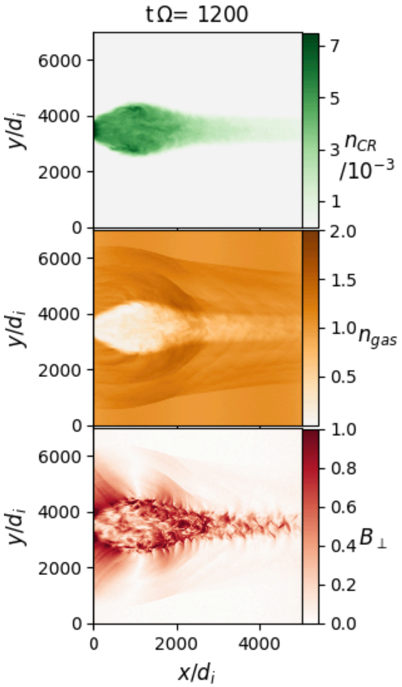
Very different demands on models!

CRs blow bubbles

B. Schroer #163

- Non-resonant streaming instability for TeV CRs escaping from source
- subsequent cascading to larger scales
- CR pressure excavates bubble

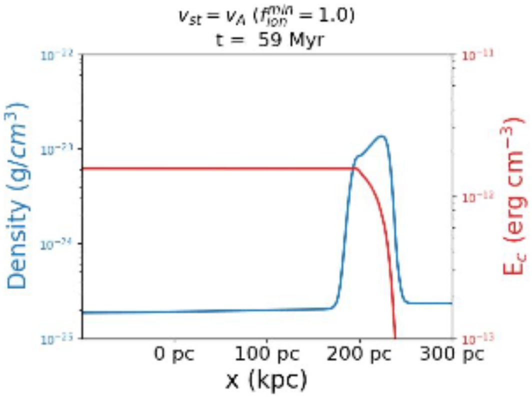


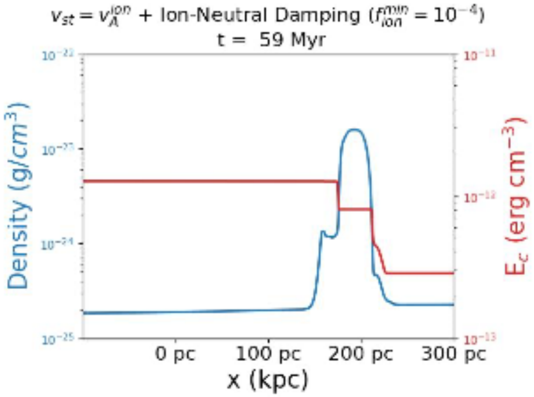


CRs push clouds

C. Bustard #170

- MHD code with streaming CRs
- bottle neck effect: CR pressure gradient drives clouds
- with ion-neutral damping: volume effect → surface effect

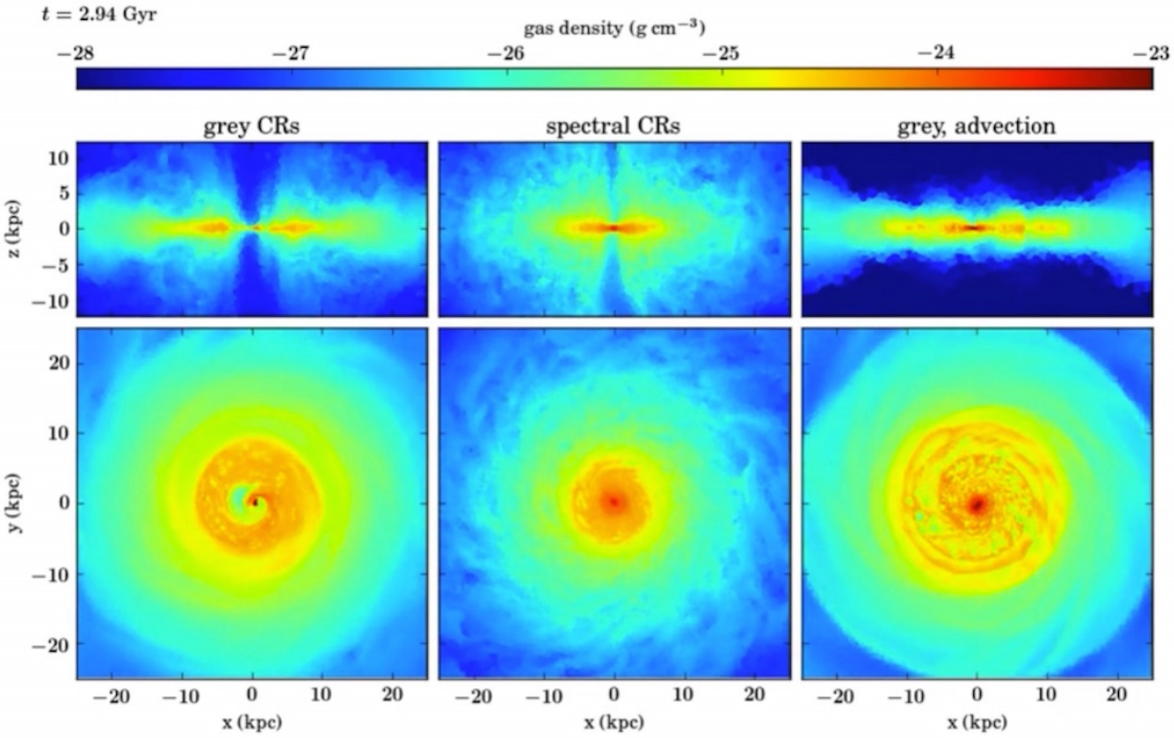


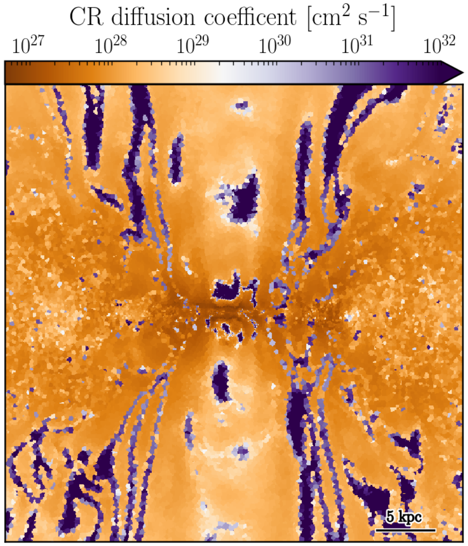


P. Girichidis #180

CRs drive outflows

- traditionally, CRs treated as fluid in MHD simulation
- importance of diffusion
- NEW: spectral treatment, piece-wise power law spectrum
- SF efficiency significantly suppressed!





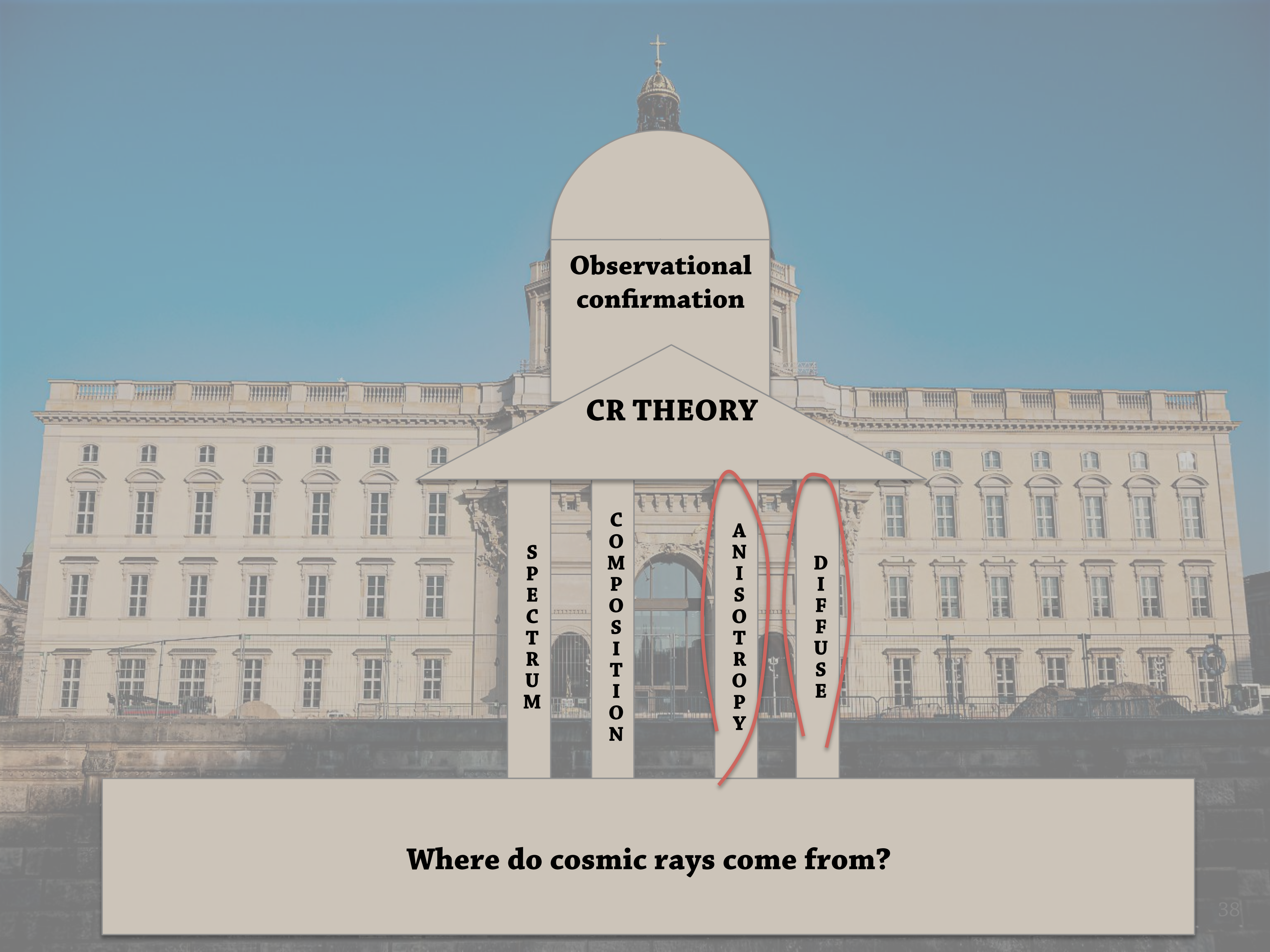
T. Thomas #145

CRs determine their own transport

- two-moment treatment: CR energy density and flux
- can estimate diffusion coefficient κ from energy density ε_{A} available for gyro-resonant scattering:

$$\kappa \propto \Omega \left(\frac{\varepsilon_{\mathrm{A}}}{\varepsilon_{\mathrm{A}}} \right)^{-1}$$

- very large diffusivities!



Observational confirmation

CR THEORY

SPECTRUM

COMPOSITION

ANISOTROPY

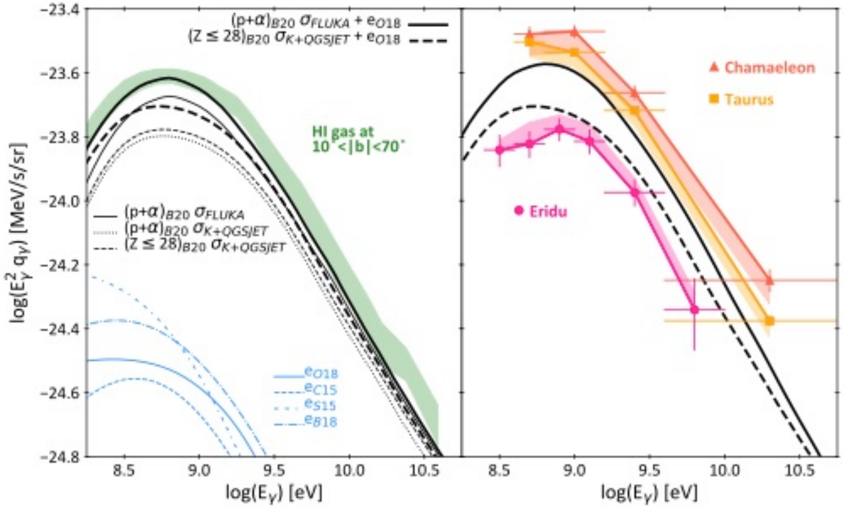
DIFFUSE

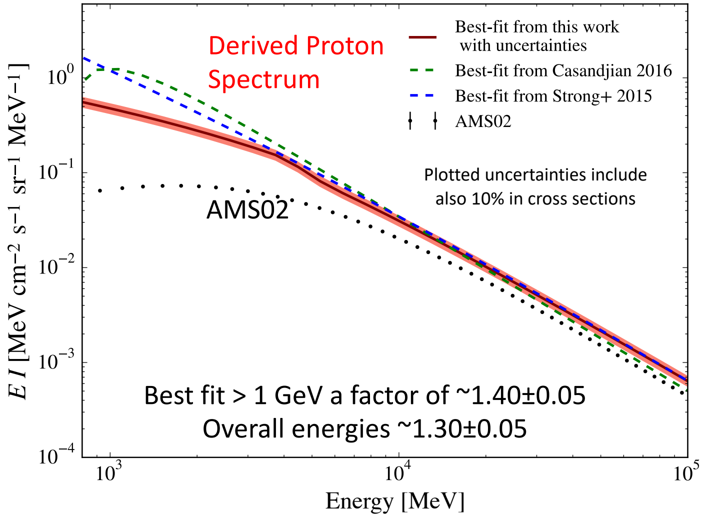
Where do cosmic rays come from?

The very local ISM

Are local fluxes representative of the Galaxy?

I. Grenier #616, E. Orlando #141





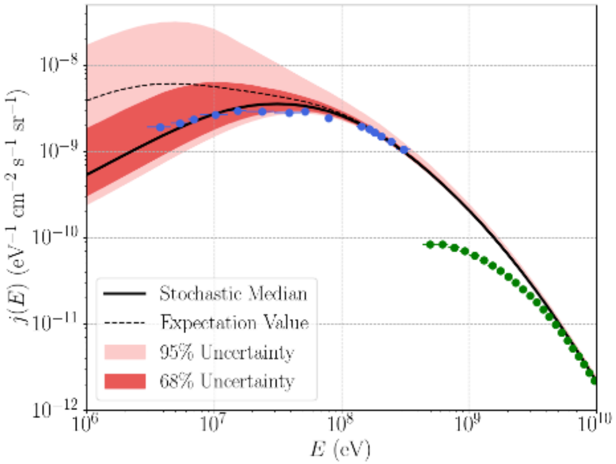
Derived Proton Spectrum

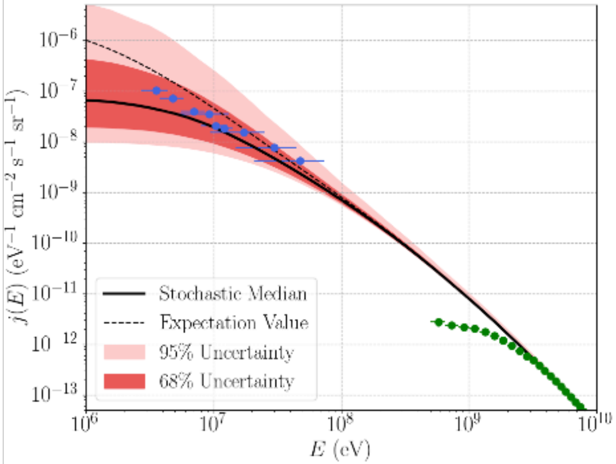
Plotted uncertainties include also 10% in cross sections

Best fit > 1 GeV a factor of ~1.40±0.05
Overall energies ~1.30±0.05

Stochasticity can explain spectral turnover without breaks

M. Phan #165





Anisotropies

Alpha Magnetic Spectrometer

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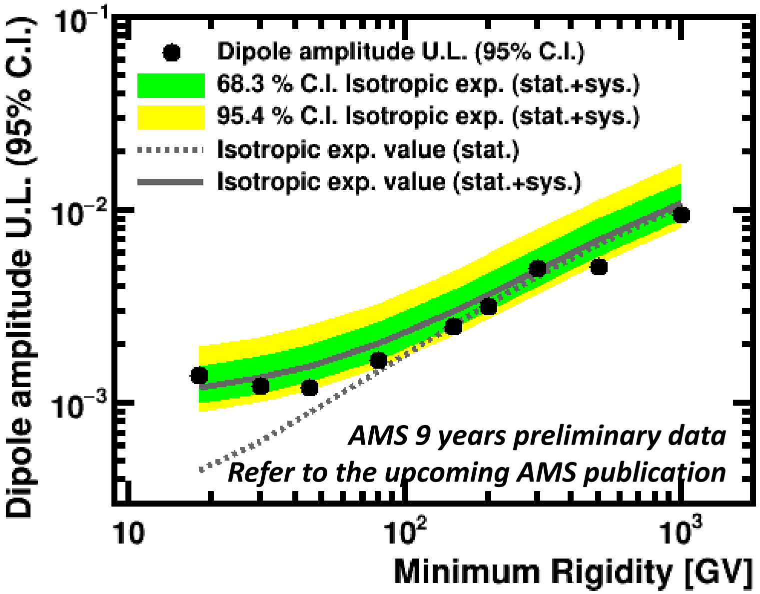
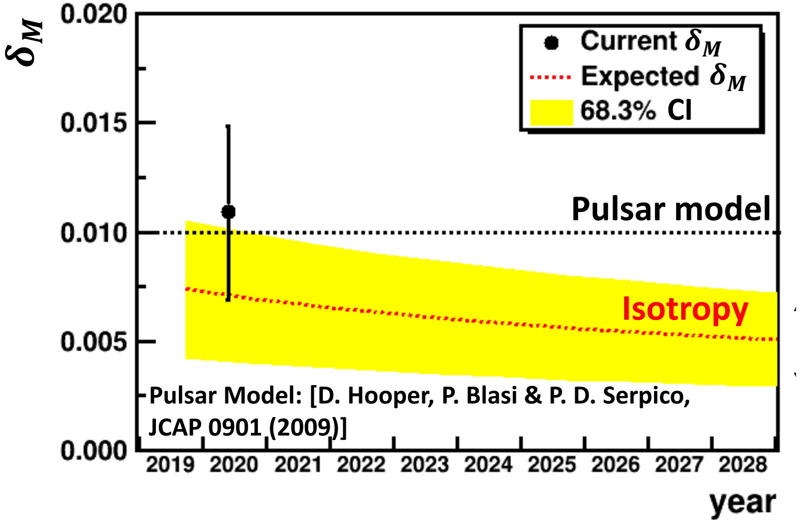
Please turn…



AMS 9 years preliminary data
Refer to the upcoming AMS publication

protons
M. A. Velasco #108



Pulsar Model: [D. Hooper, P. Blasi & P. D. Serpico, JCAP 0901 (2009)]

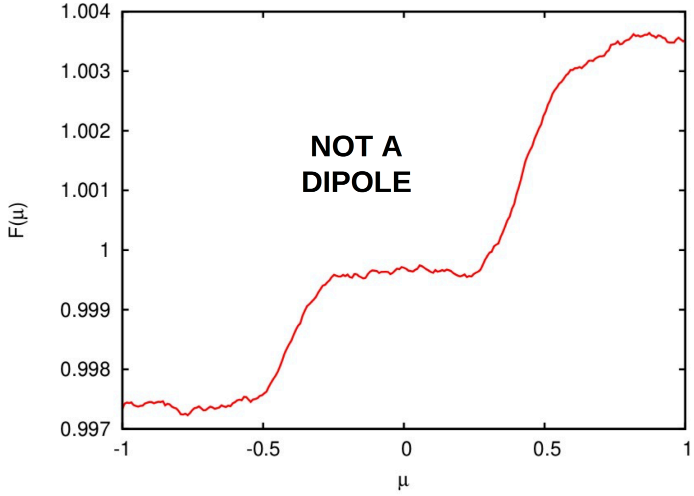
electrons + positrons
M. Molero #120

Anisotropies

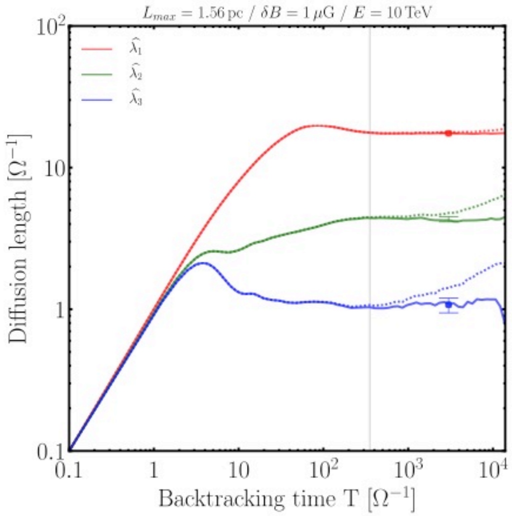
Combination of simulations and analytical work

But: more realistic turbulence needed
H. Yan #38, S. Xu #41

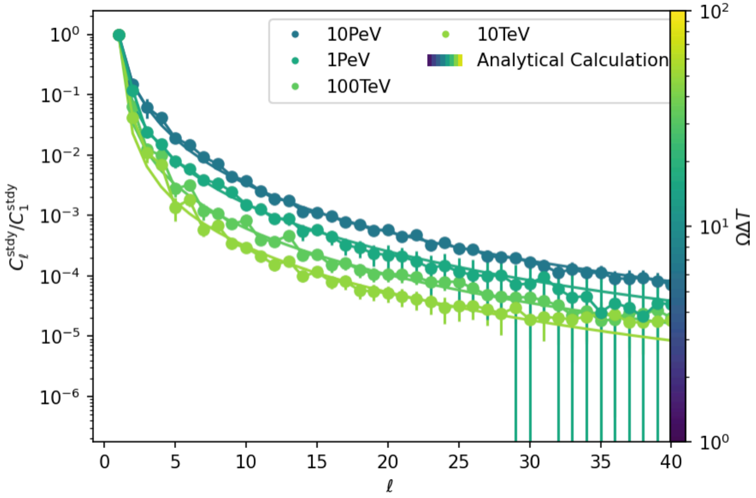
Large-scale anisotropy G. Giacinti #455
→ non-dipolar



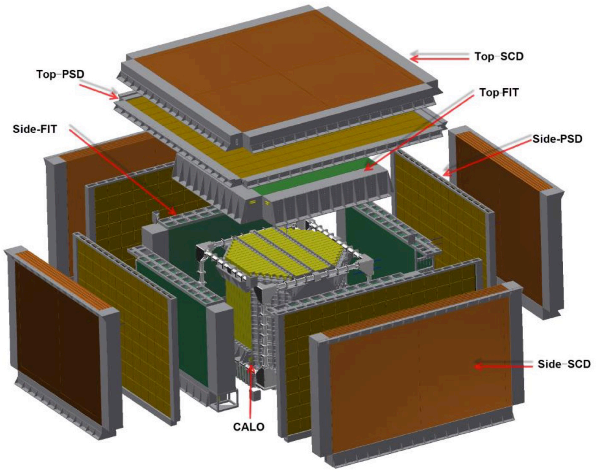
Local vs global diffusion Y. Genolini #164
locally, diffusion very anisotropic



Small-scale anisotropies M. Kuhlen #164
→ new handle on turbulence

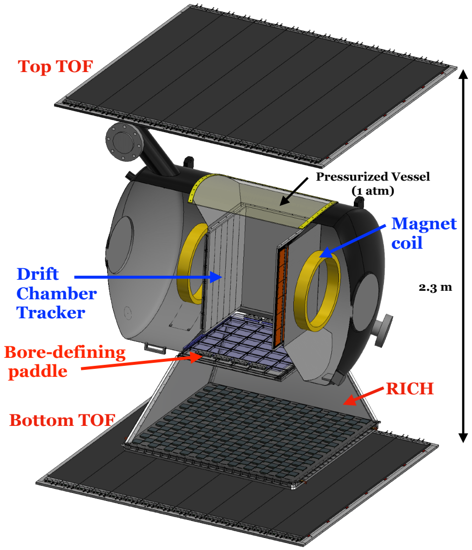


Near-term future



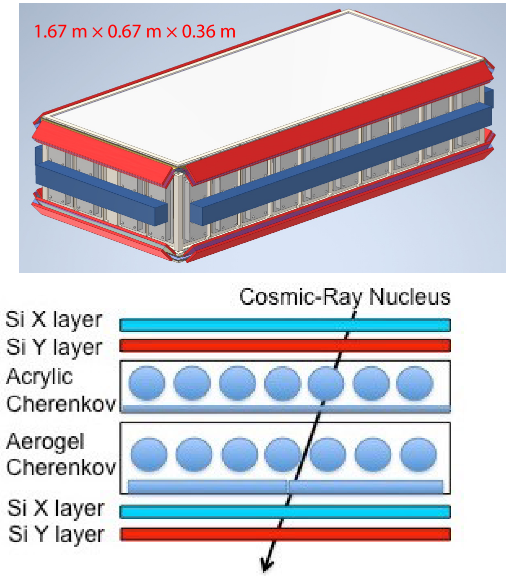
HERD S.-N. Zhang

- expected ~2027
- nuclei (30 GeV … 3 PeV)
- e^- (10 GeV … 100 TeV)



HELIX N. Park # 91

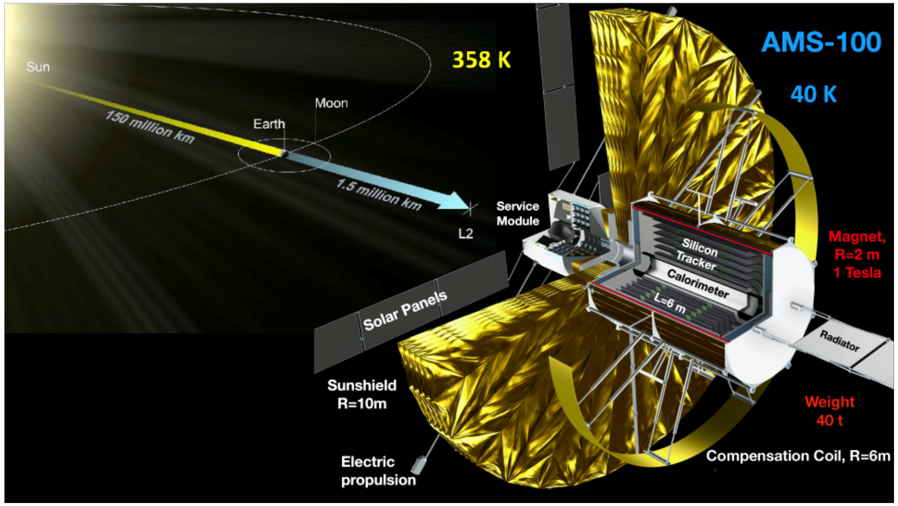
- balloon spectrometer
- drift chamber tracker, TOF, RICH
- flight in 2022



TIGERISS J. Mitchell #86

- ultra-heavies Z=5 to 86
- would deploy to JEM on ISS

Longer term projects

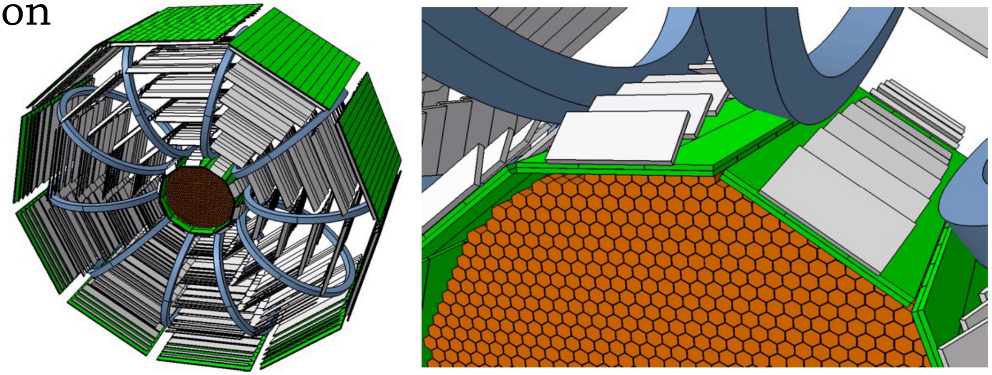


AMS-100 S. Schael

- Lagrange point 2
- 1 Tesla magnetic, (6 × 2) m
- Tracker, MDR = 100 TV
- Central calorimeter
- Targets e$^+$, e$^-$, nuclei (beyond the knee), antinuclei

ALADInO R. Battiston

- Also Lagrange point 2
- Spectrometer: MDR = 20 TV
- Calorimeter
- Targets e$^+$, e$^-$, nuclei, antinuclei
- pathfinder in 2030?



Summary

Observations
- Great new results, more to come
- Yet, systematic differences
- Ambitious projects in future

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Main subsystems	5
Weight	7000 kg
Power consumption	2000 W
Fun fact	Anti-helium?

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Please turn…

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K. Kobayashi	#98
P. Brogi	#101
P. Maestro	#93
Y. Akaike	#112
S. Tori	#105
F. Stolzi	#109

sters…

DArk Matter Particle Explorer

Years in orbit	~ 5.5
Main subsystems	4
eight	1400 kg
wer	400 W
fact	e^- line?

tributions at ICRC 2021:

ew

X. Li	#13
F. Alemanno	#117
M. Di Santo	#114
L. Wu	#128
C. Yue	#126
Z. Zu	#115

us posters…

Cosmic Ray Energetics And Mass

n orbit	~ 1.5
ubsystems	4
	1300 kg
	400 W
	I scream, you scream

ons at ICRC 2021:

E.-S. Seo	#95
G. Choi	#94

ers…

Phenomenology
- Bumps, breaks everywhere!
- Source hunting, but beware of statistics!
- Keep an open mind!

Modelling
- Microscopic picture is complex
- Bridging the gap
- Cosmic rays as actors