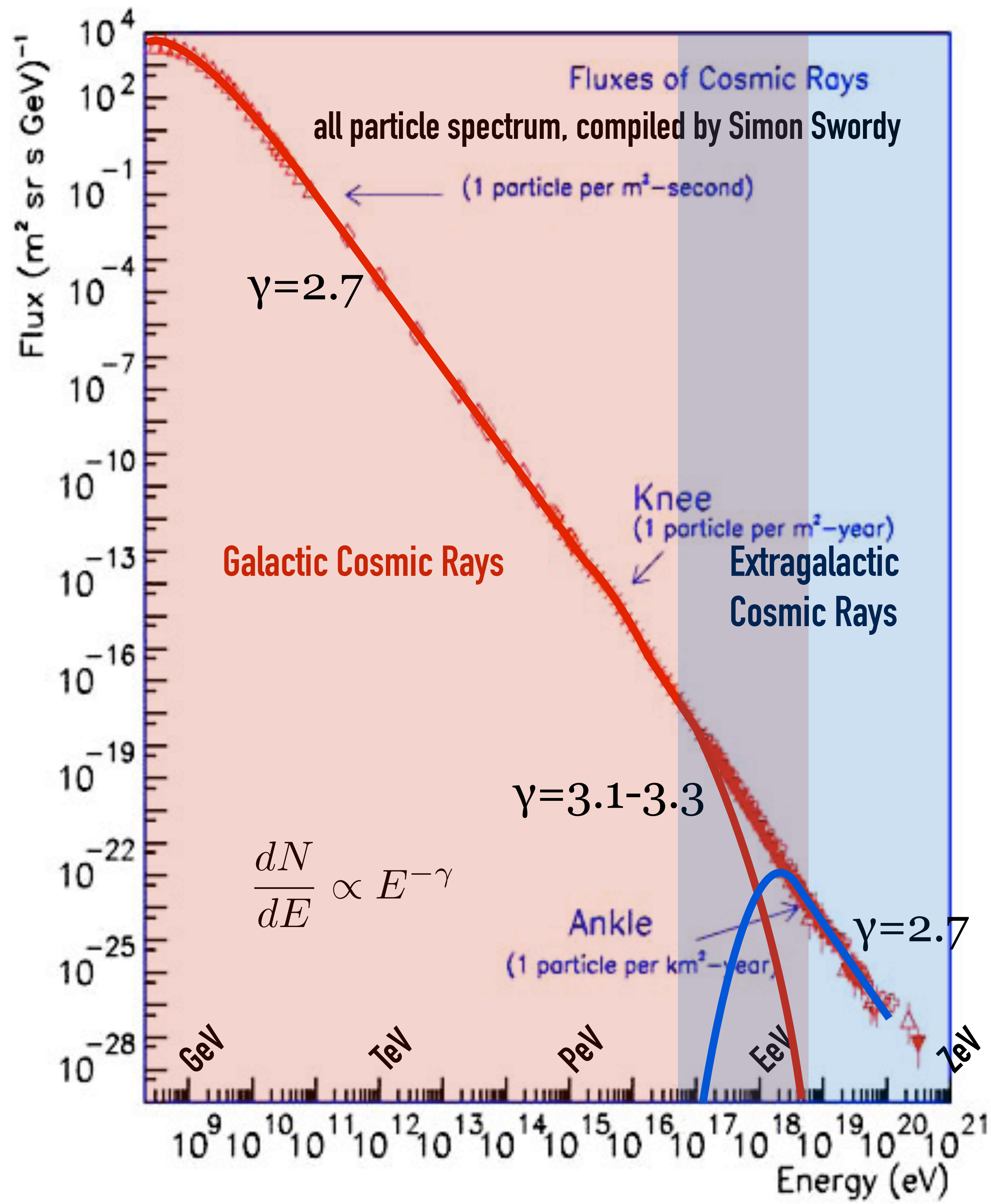
Direct Cosmic-ray Measurement below knee

Presented by Nahee Park
(University of Chicago)

What are Cosmic Rays?

High energy charged particles, originating in outer space

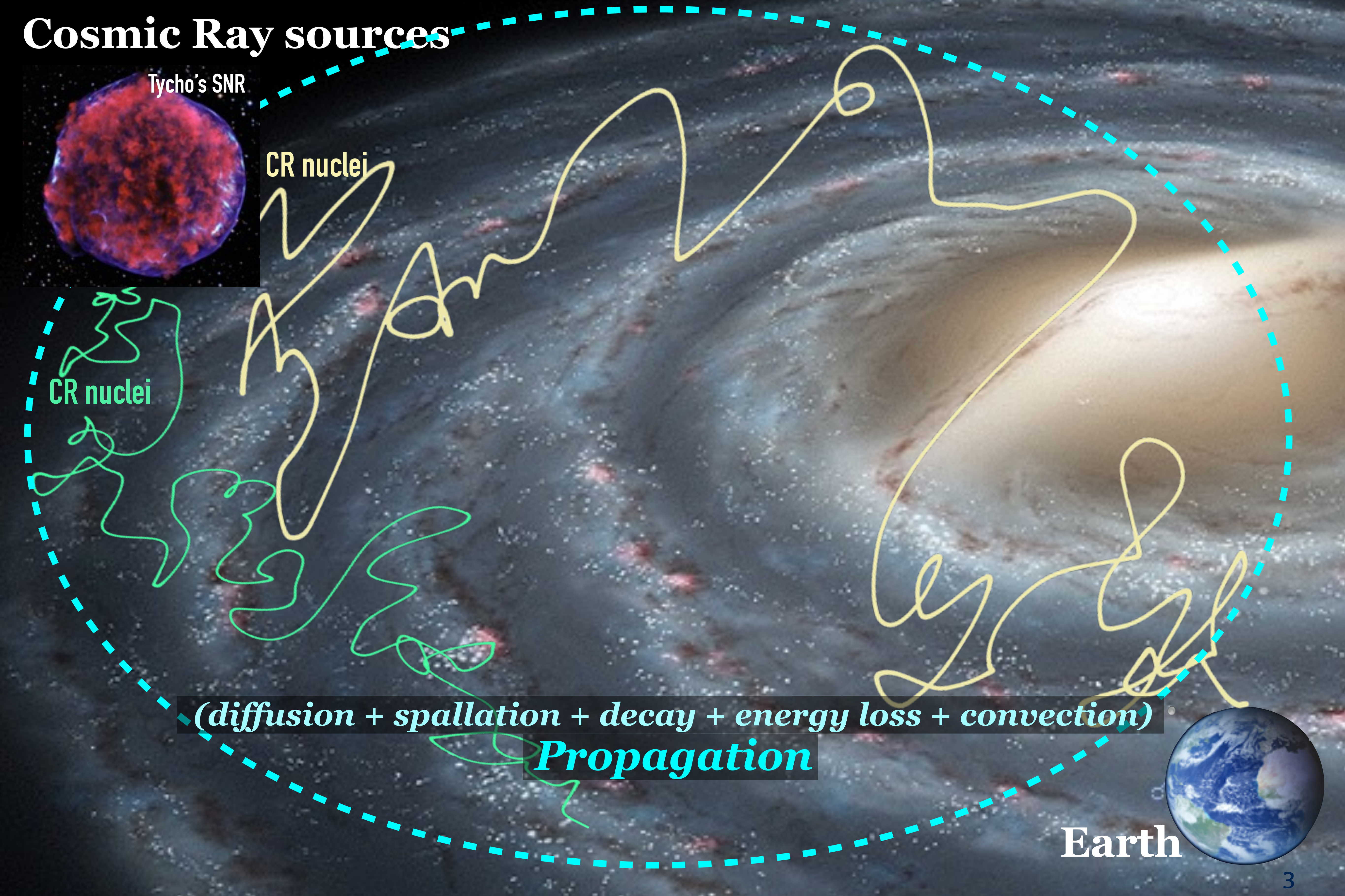
- Mostly nuclei of atoms (85% proton, 12% helium, 2% heavy nuclei & 1% leptons at 10^9eV)
- Spectrum follows a smooth power-law distribution over wide energy range
  - Notable spectral features
    - Knee (~4×10^{15}eV)
    - Ankle (~10^{18}eV)

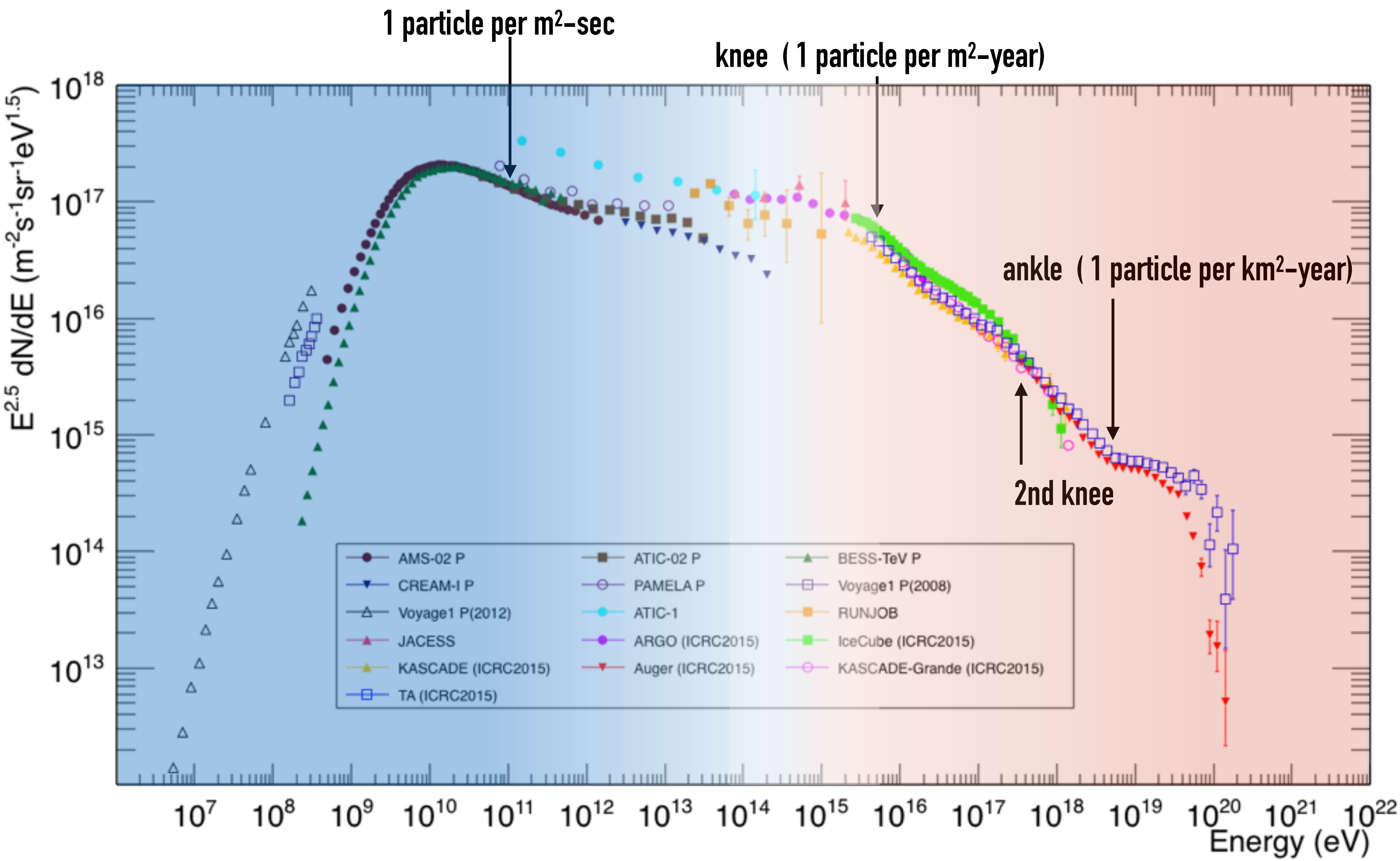


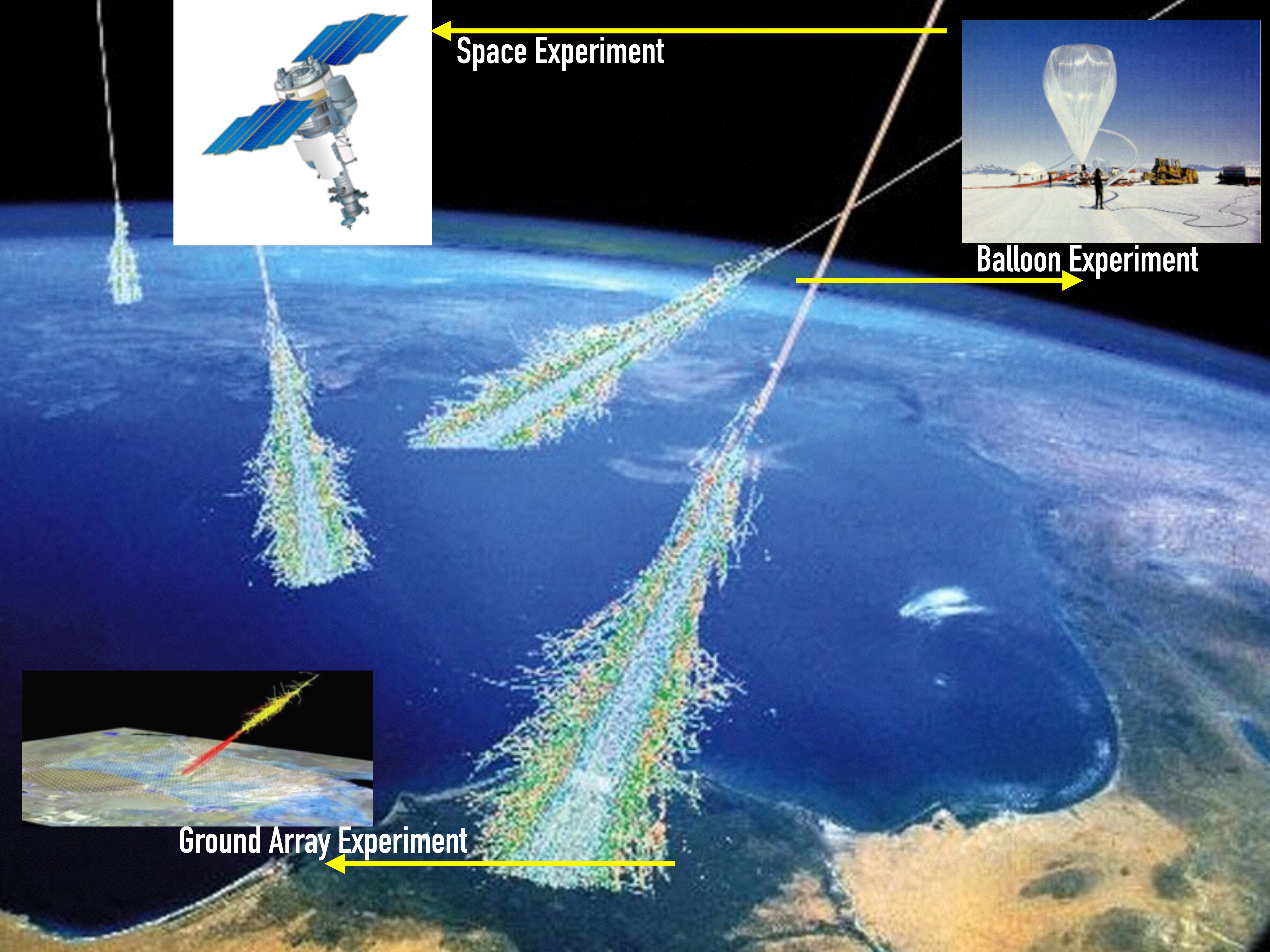
Scientific Goals:

- What is the origin of CRs?
- How do they get their energies?
- How do they propagate to us?

Galactic Cosmic Rays

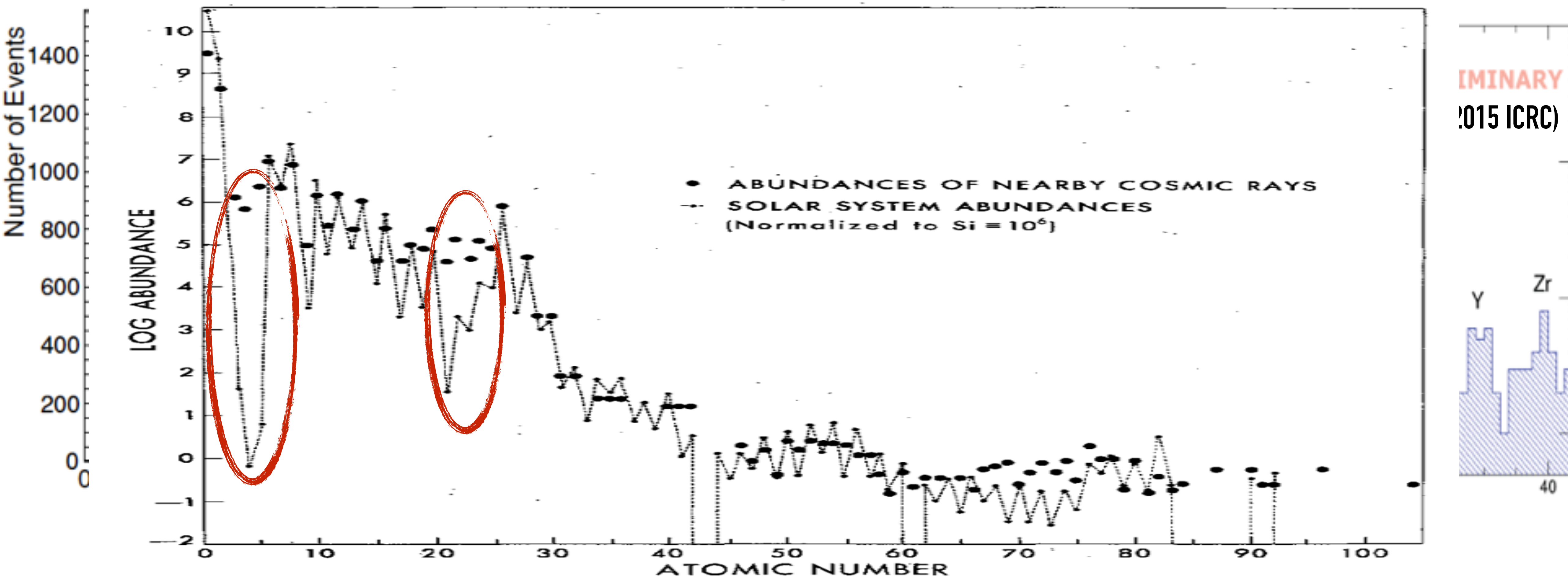



1 particle per m2-sec
knee (1 particle per m2-year)
ankle (1 particle per km2-year)
2nd knee
E2.5 dN/dE (m-2s-1sr-1eV1.5)
Energy (eV)
AMS-02 P
CREAM-I P
Voyage1 P(2012)
JACESS
KASCADE (ICRC2015)
TA (ICRC2015)
ATIC-02 P
PAMELA P
ATIC-1
ARGO (ICRC2015)
Auger (ICRC2015)
BESS-TeV P
Voyage1 P(2008)
RUNJOB
IceCube (ICRC2015)
KASCADE-Grande (ICRC2015)


Space Experiment
Balloon Experiment
Ground Array Experiment

What direct measurement can provide

Direct composition measurements

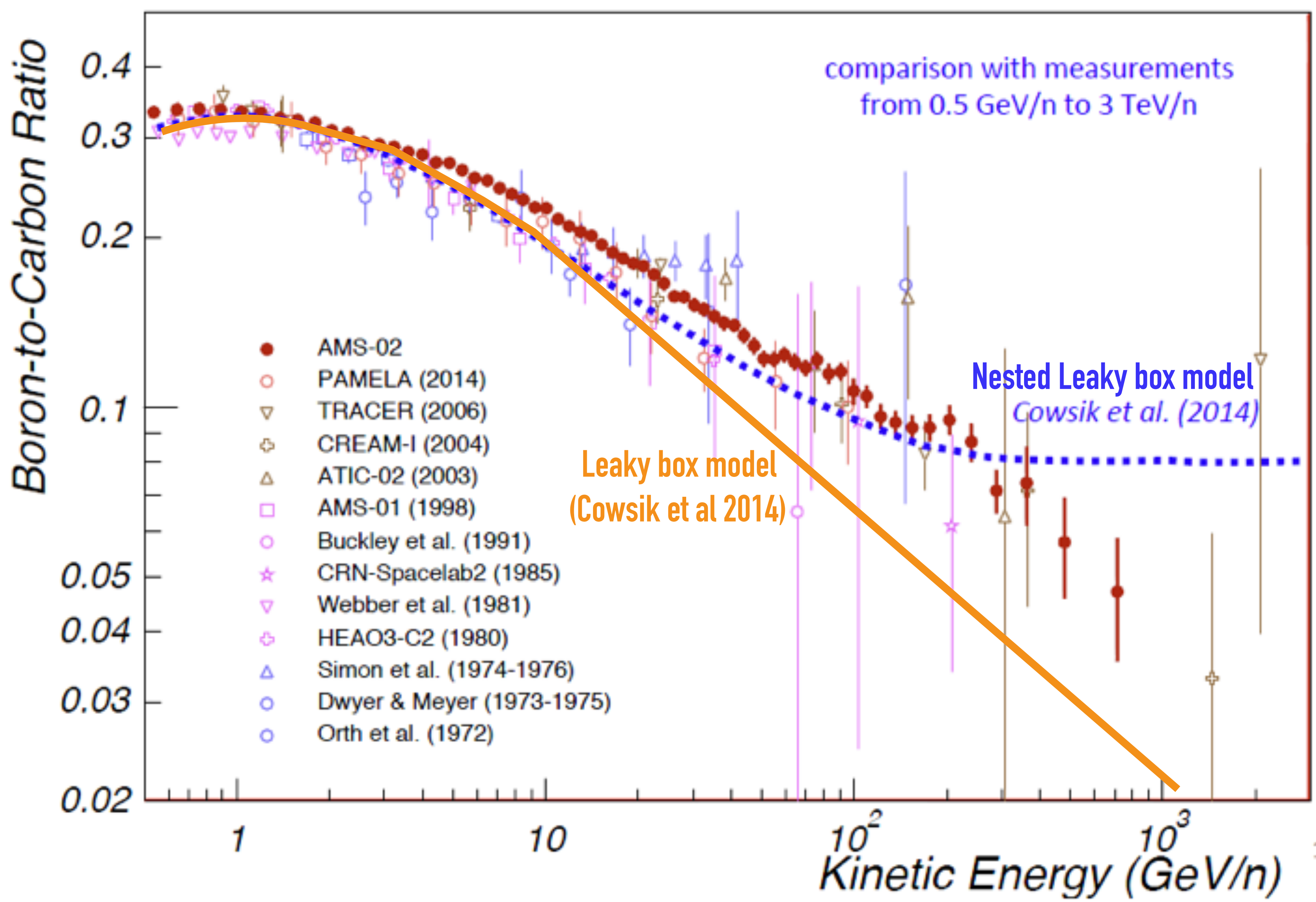


- Can study the composition of the source site of CRs
  - e.g. Super-bubble origin of CRs

What direct measurement can provide

Primary & secondary elemental spectrum

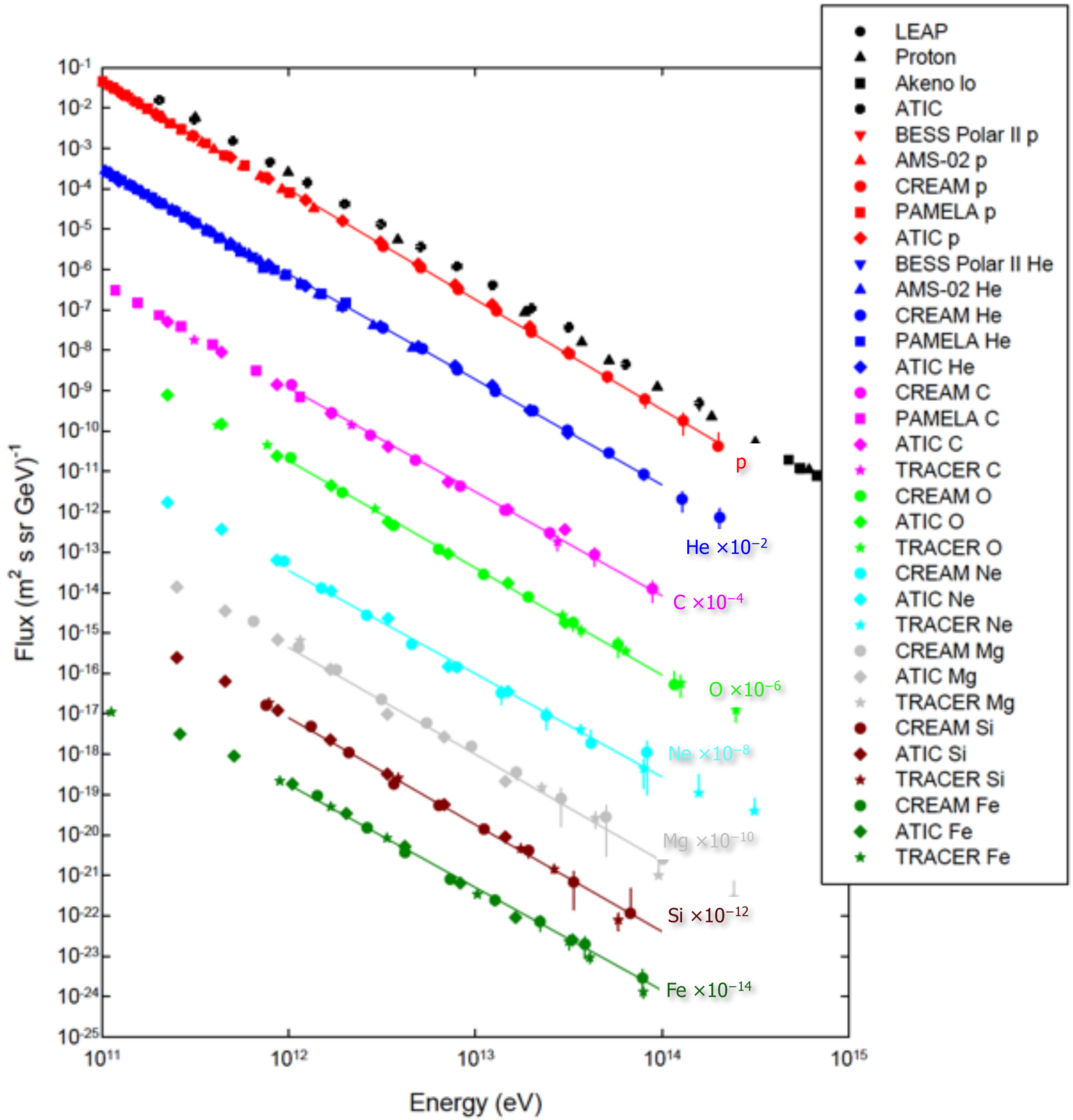
- Important data set to understand the propagation of CRs



What direct measurement can provide

Elemental spectrum

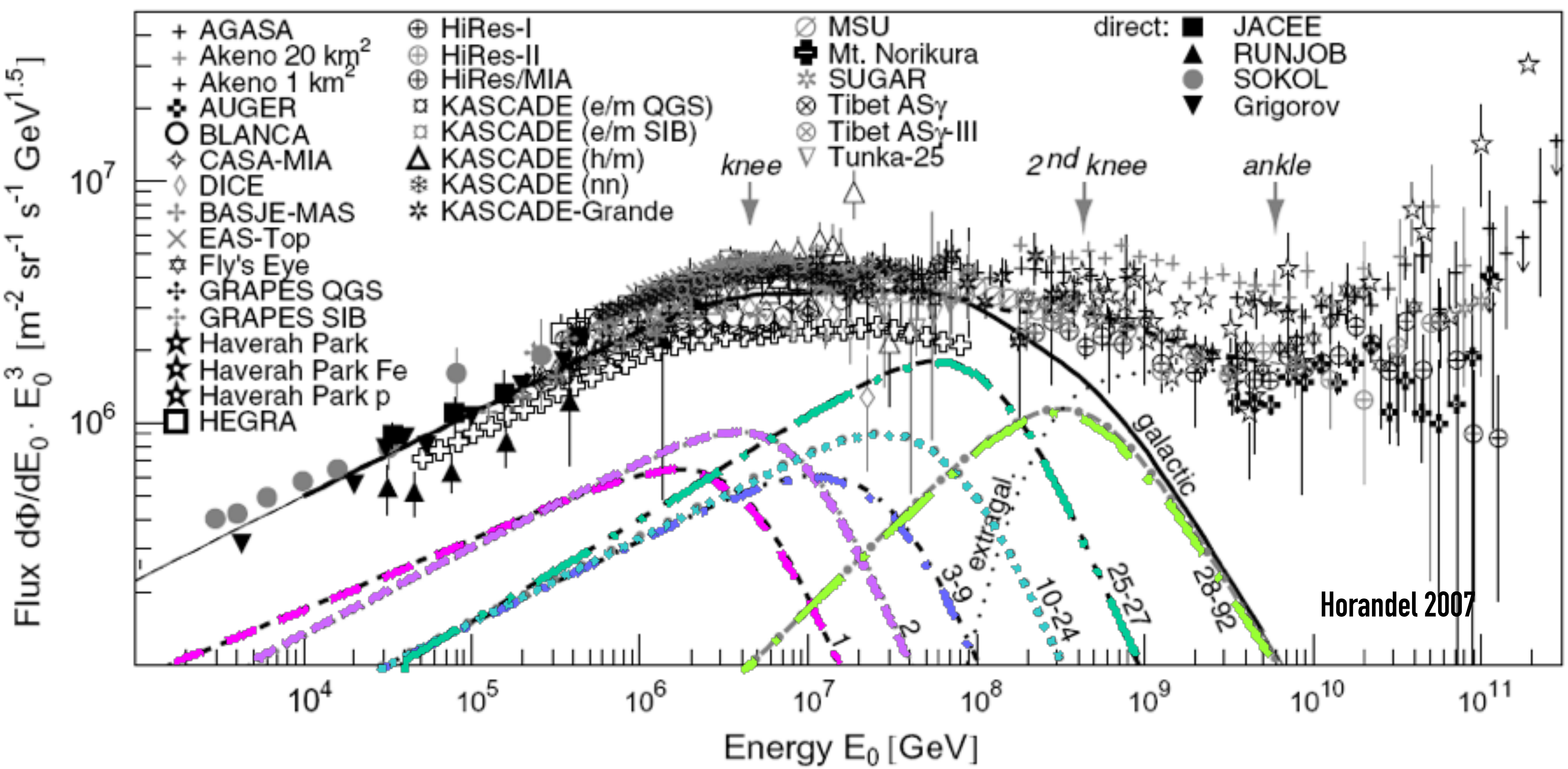
- Can study the elemental dependency
  in acceleration and propagation of CRs



What direct measurement can provide

Elemental spectrum

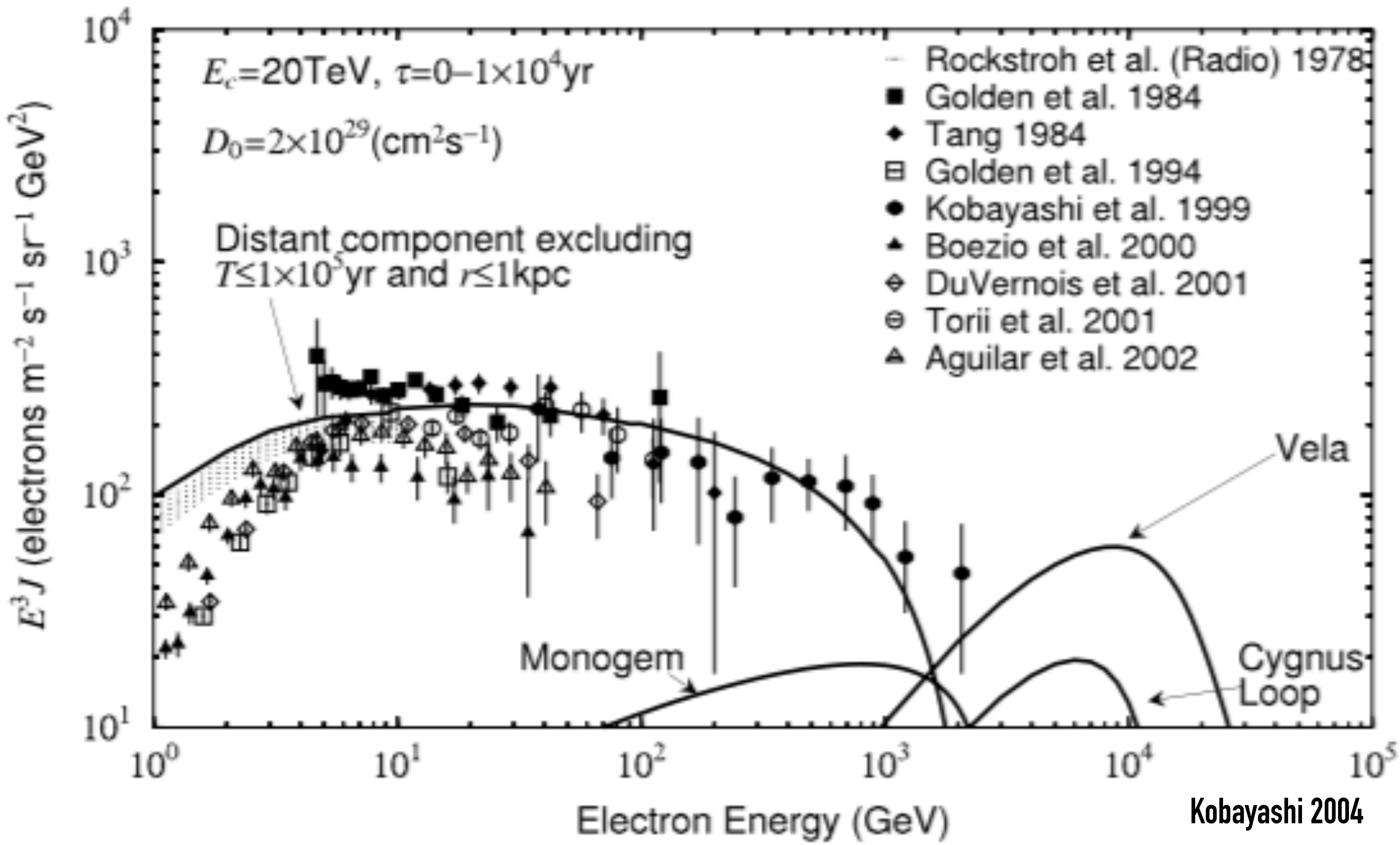
- Can study the elemental dependency in acceleration and propagation of CRs
  - e.g. Cut-off energy differences around knee region per each element



What direct measurement can provide

Elemental spectrum

- Can study the local accelerators with leptonic spectrum studies
    - Multi-TeV electron flux will reflect the local accelerators (<1kpc)



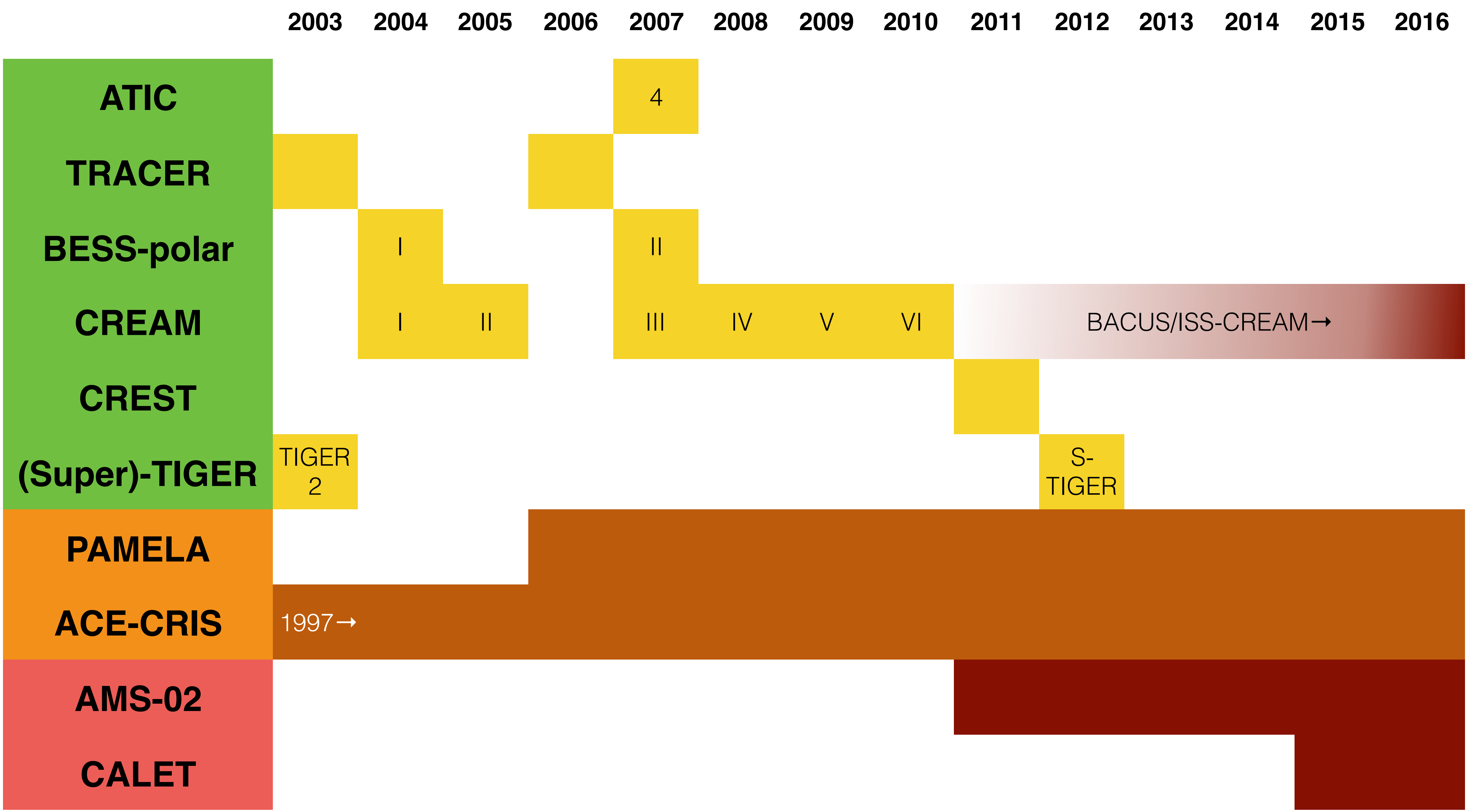
Kobayashi 2004

What direct measurement can provide

Isotopic flux measurement

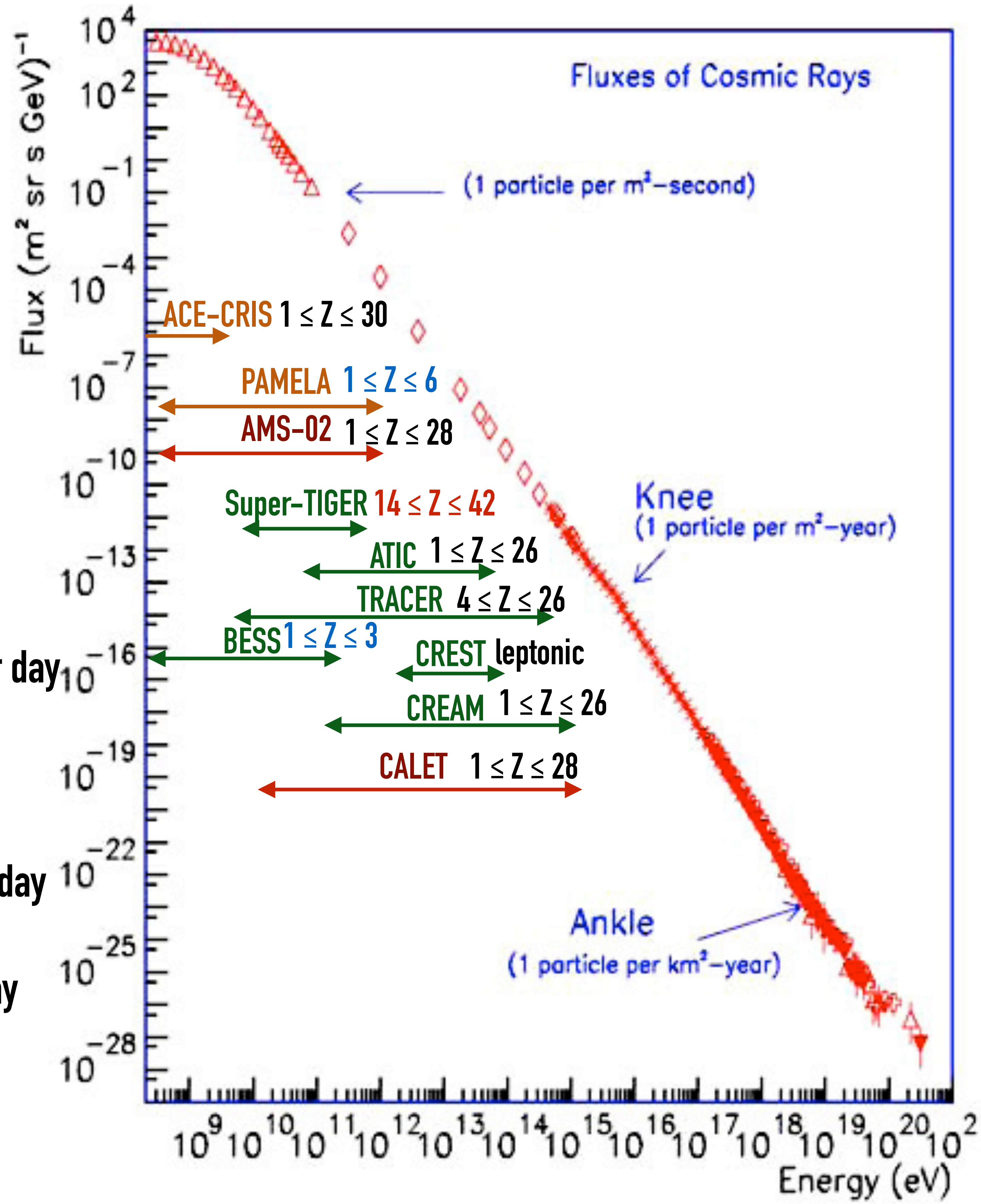
- Measurement of isotopes w/ known half life can provide “time scale” for propagation and acceleration
  - Propagation clock : life time of CRs in our Galaxy
    - Secondary isotopes which decay by $\beta^{\pm}$ decay
      - e.g. ^{10}Be : half life of 1.5 Myr
  - Acceleration clock : time delay between nucleosynthesis to acceleration
    - Primary isotopes which decay by electron capture
      - e.g. ^{59}Ni : half life of 7.6×10^4 yr
  - Re-acceleration clock : probe potential re-accelerating during the propagation
    - Secondary isotopes which decay solely by electron capture
      - e.g. ^{51}Cr : half life of 28 days

Recent Experiments



Recent Experiments

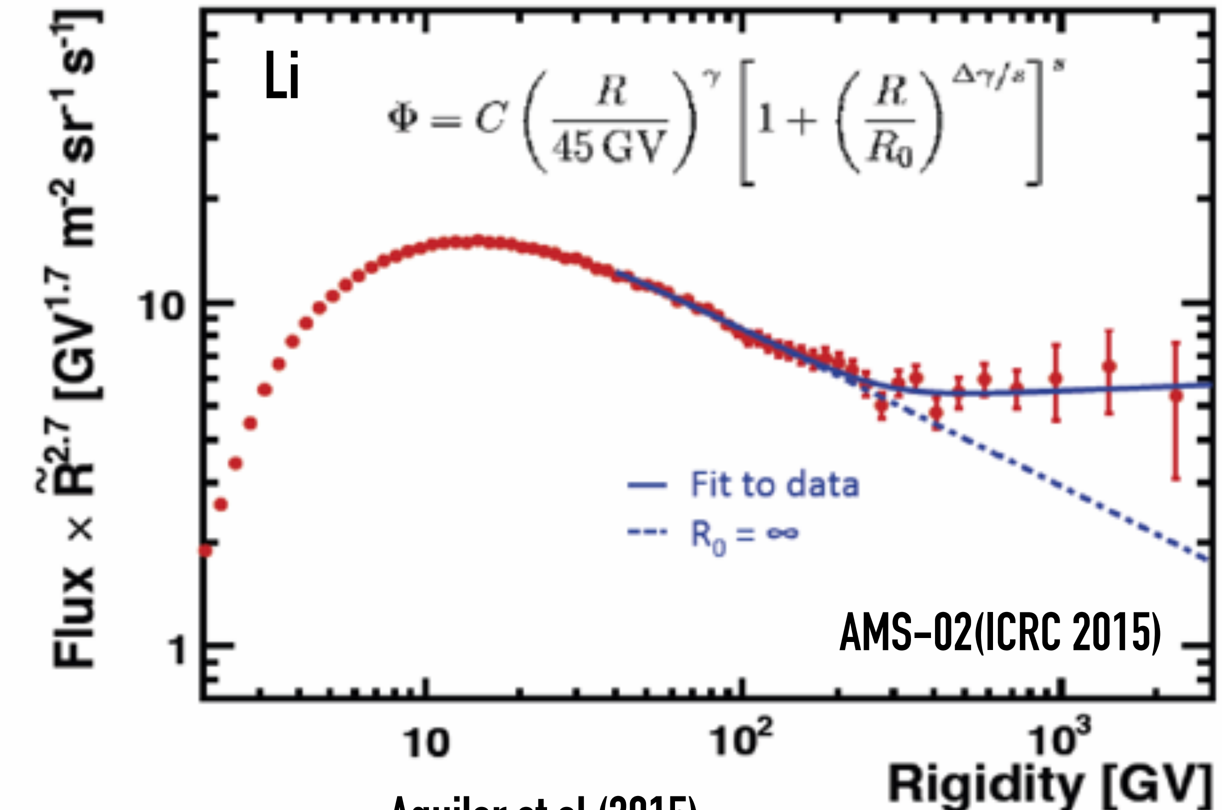
ATIC	43 days (3 flights) $\times$ 0.25 m^2sr =11 m^2sr day
TRACER	19 days (2 flights) $\times$ 5 m^2sr =95 m^2sr day
BESS-polar	33 days (2 flights)
CREAM	161 days (6 flights) $\times$ 0.4 m^2sr = 64 m^2sr day
CREST	10 days (1 flight)
(Super)-TIGER	105 days (3 flights)
PAMELA	10 years $\times$ 0.002 m^2sr =7.2 m^2sr day
ACE-CRIS	17 years
AMS-02	5 years $\times$ 0.05 m^2sr? =91 m^2sr day
CALET	1 years $\times$ 0.1 m^2sr =37 m^2sr day

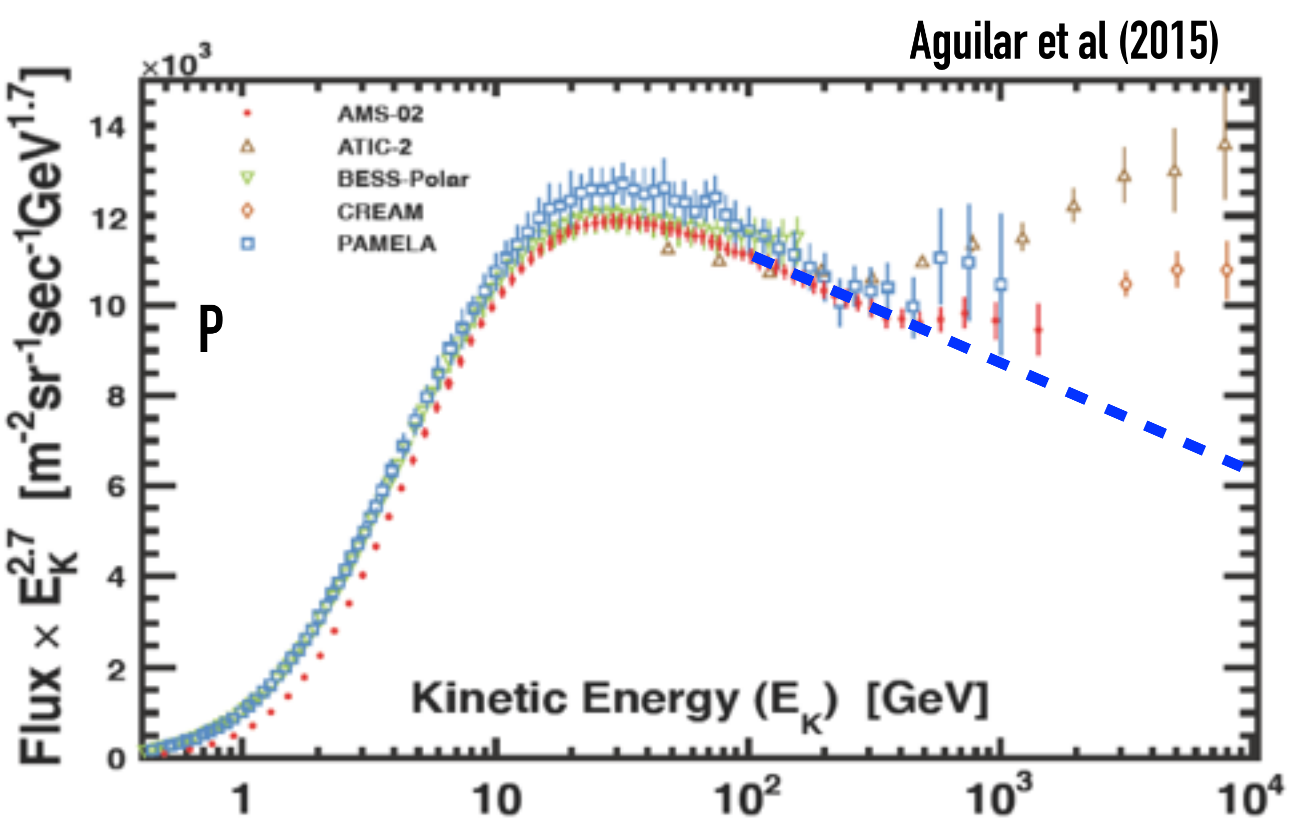


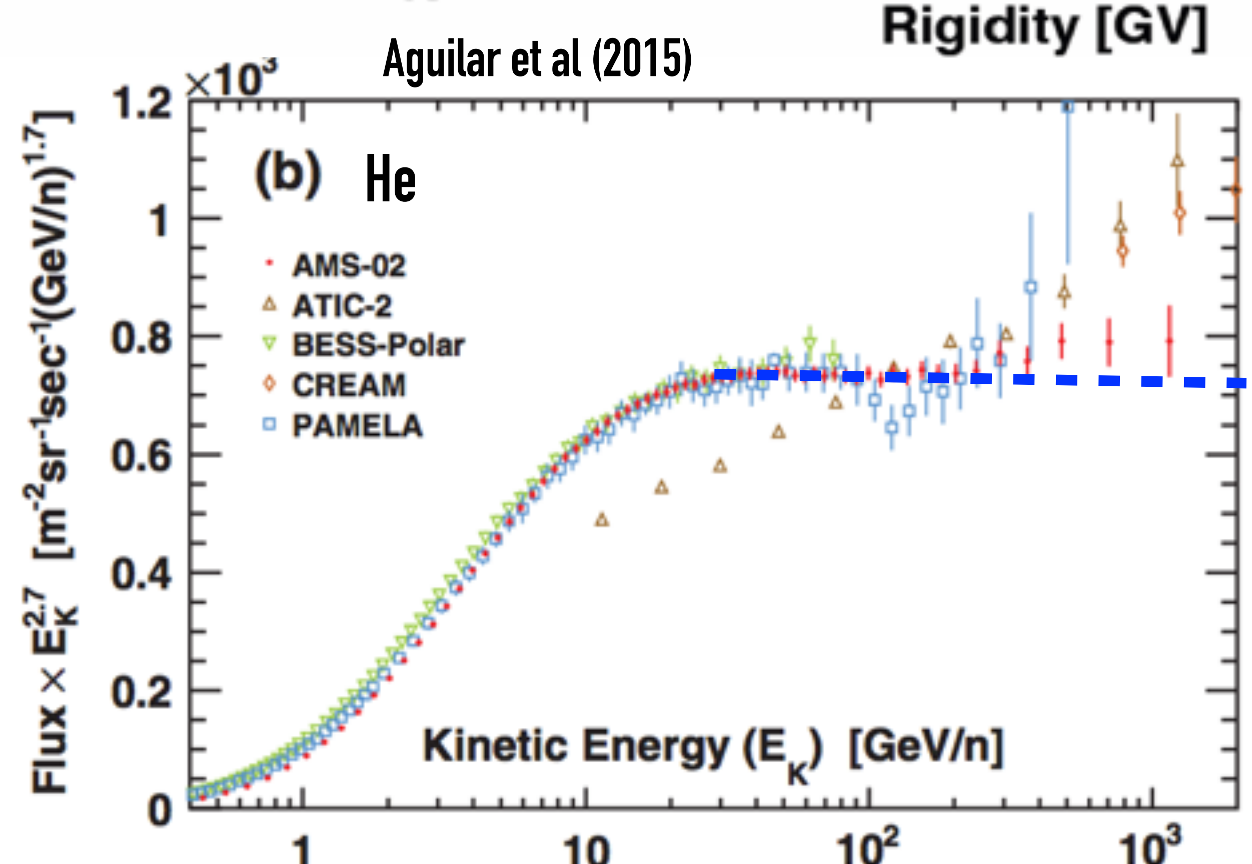
Hardening of spectra

Light nuclei spectra measured by PAMELA & AMS-02

- Proton, helium & lithium show spectral break
  - Propagation effect?
    Source population?
    Acceleration mechanism?





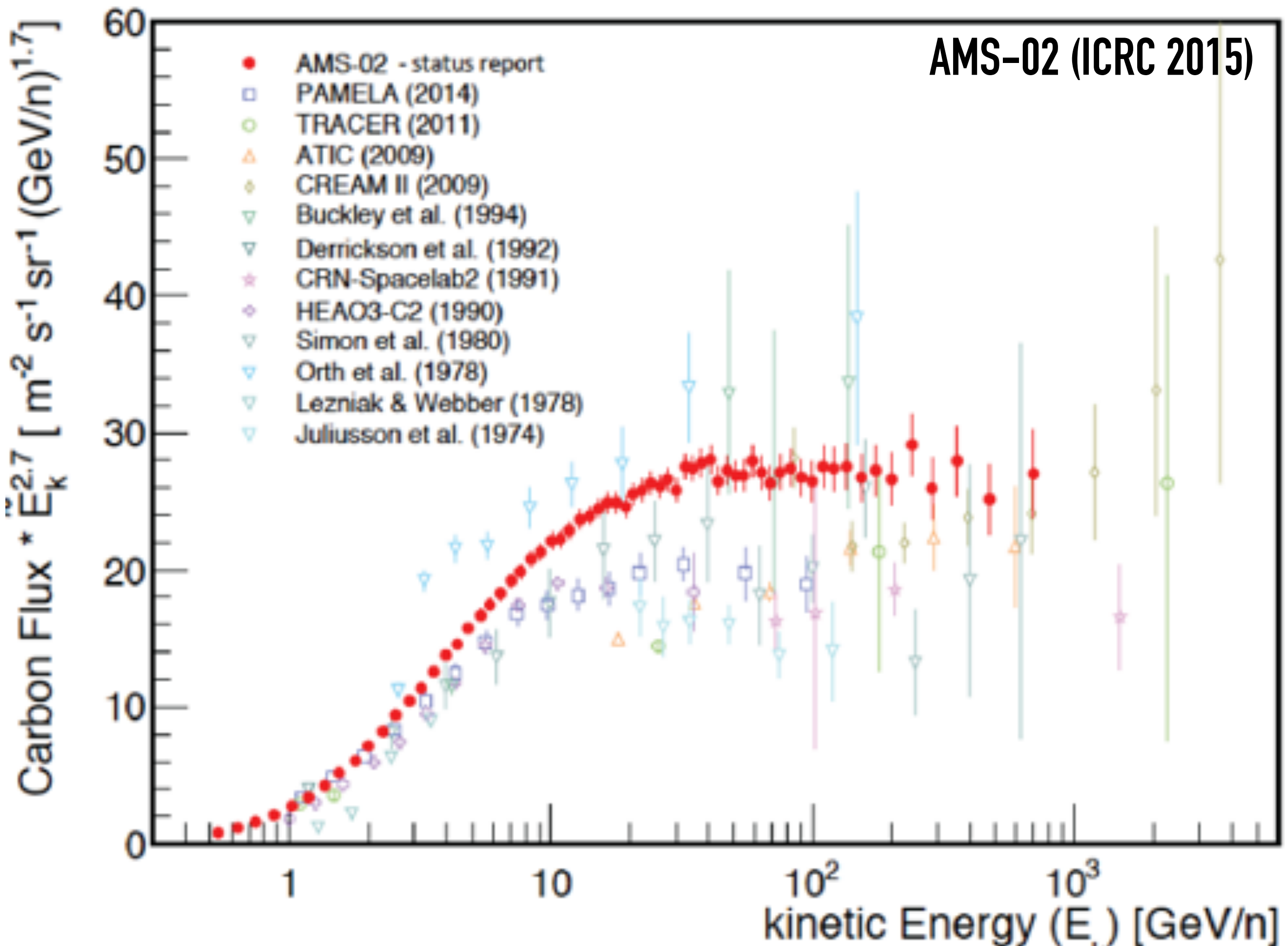


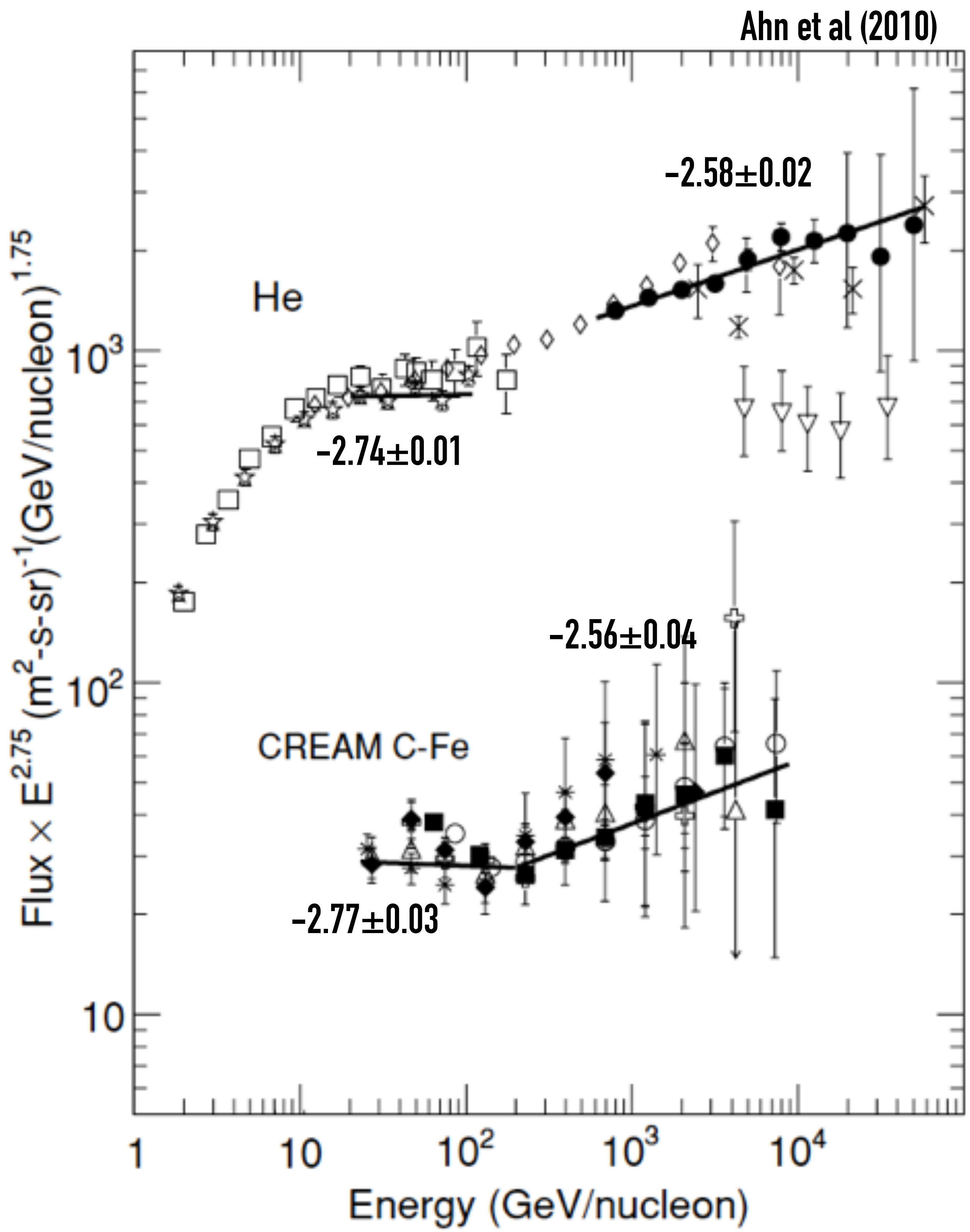
Hardening of spectra at heavy nuclei?

Hint of elemental spectra hardening at 200 GeV/n by CREAM?

- w/ ~ 70 days of exposure time (2 flights)

No break observed for preliminary AMS-02 Carbon spectrum?



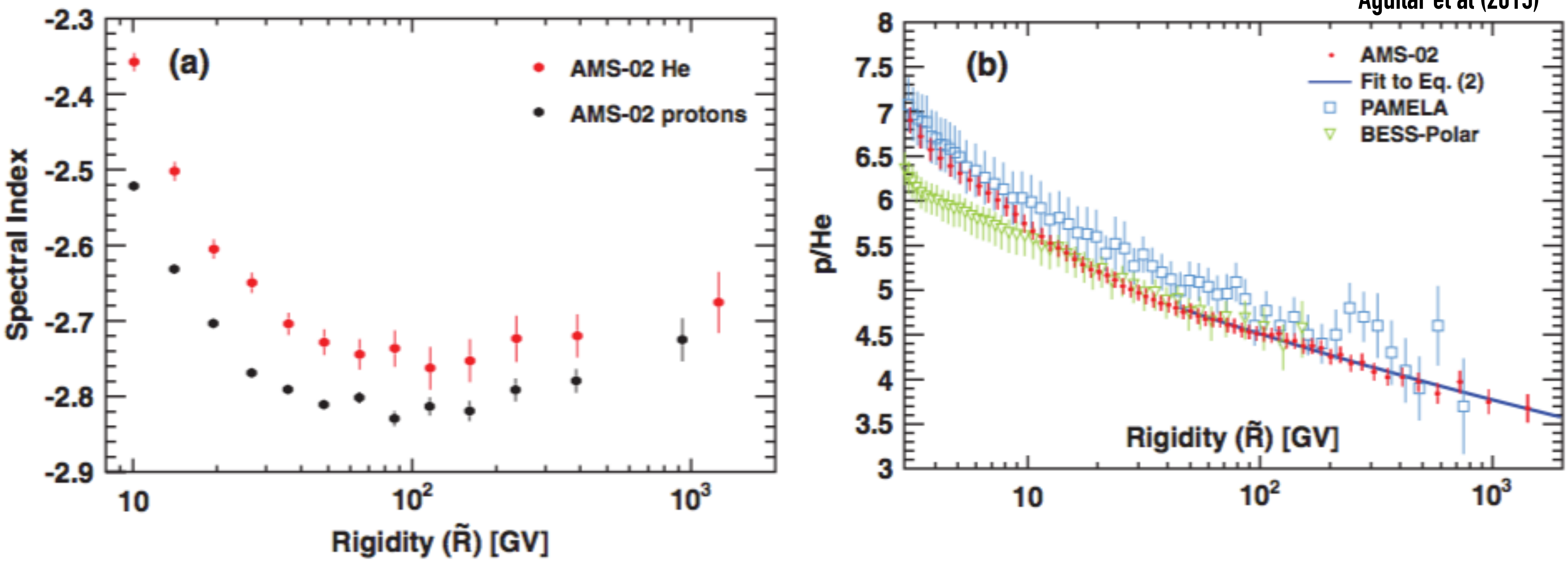


Difference between Proton & Helium

Measured by PAMELA & AMS-02

- Different acceleration? Source population? Propagation effect?

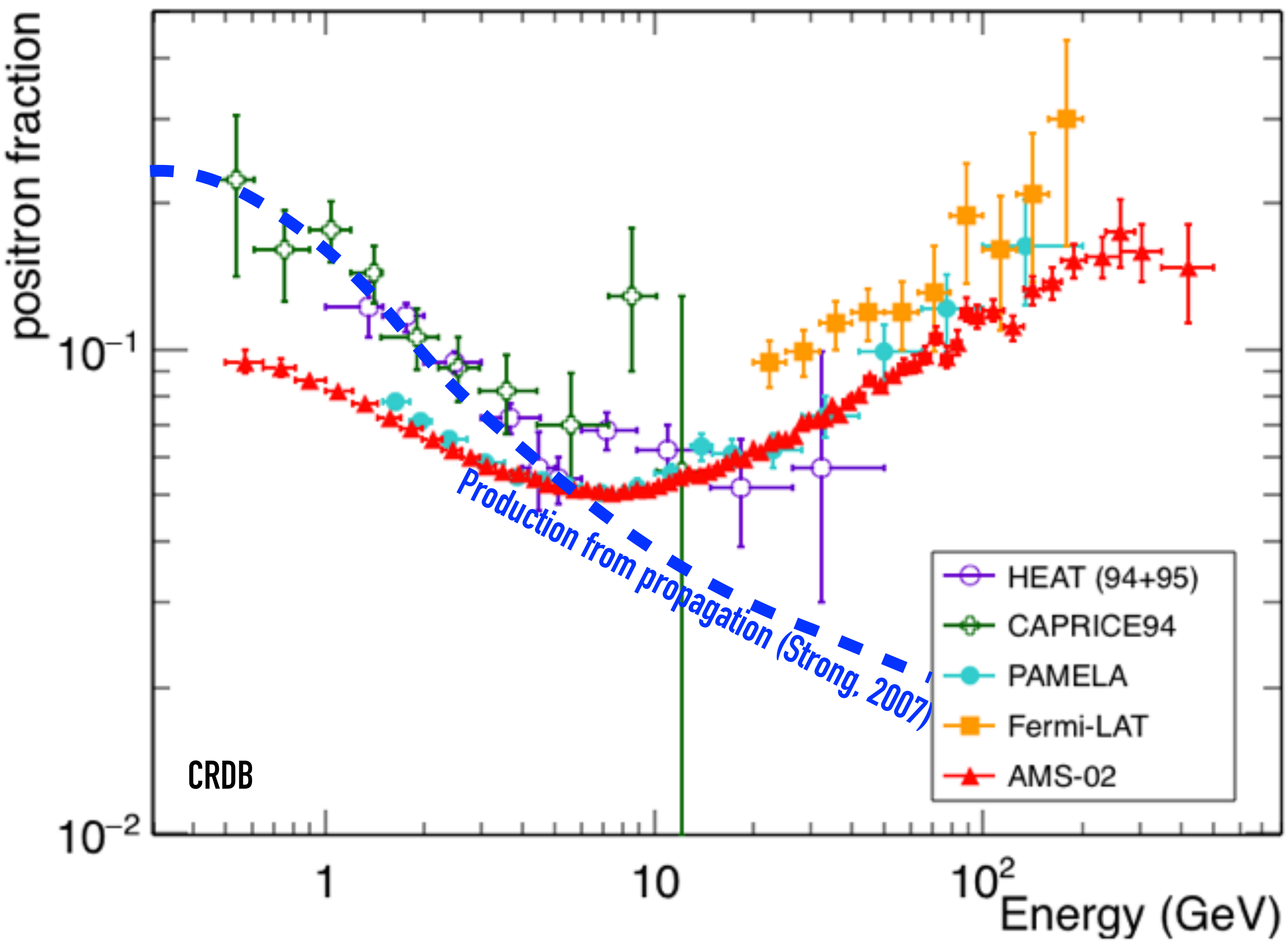
Aguilar et al (2015)



Rise of positron fraction

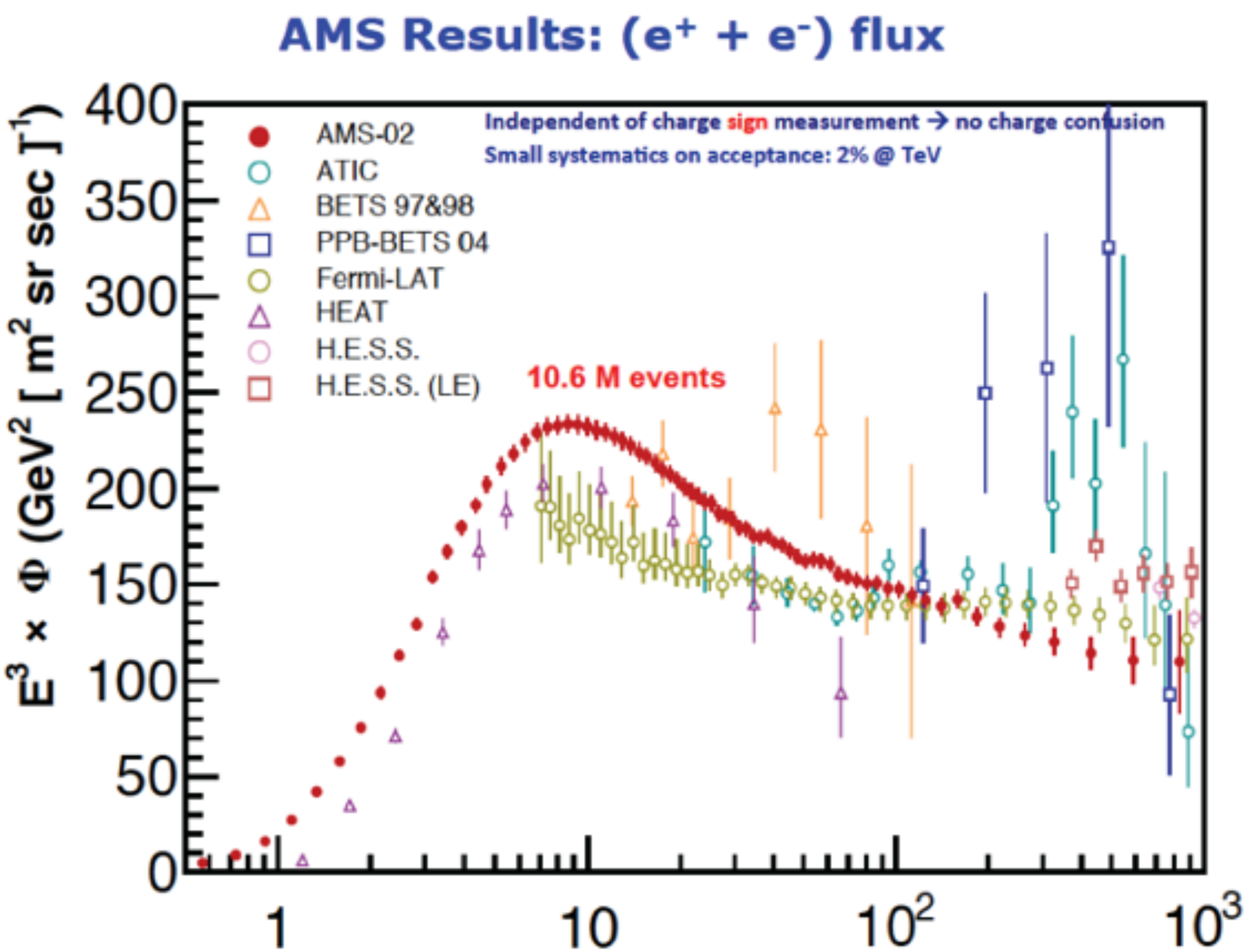
Measured by PAMELA, AMS-02 & Fermi-LAT

- More positrons than classical propagation estimated
  - Additional sources? (pulsar? SNR? PWN? exotic particle?) Propagation?

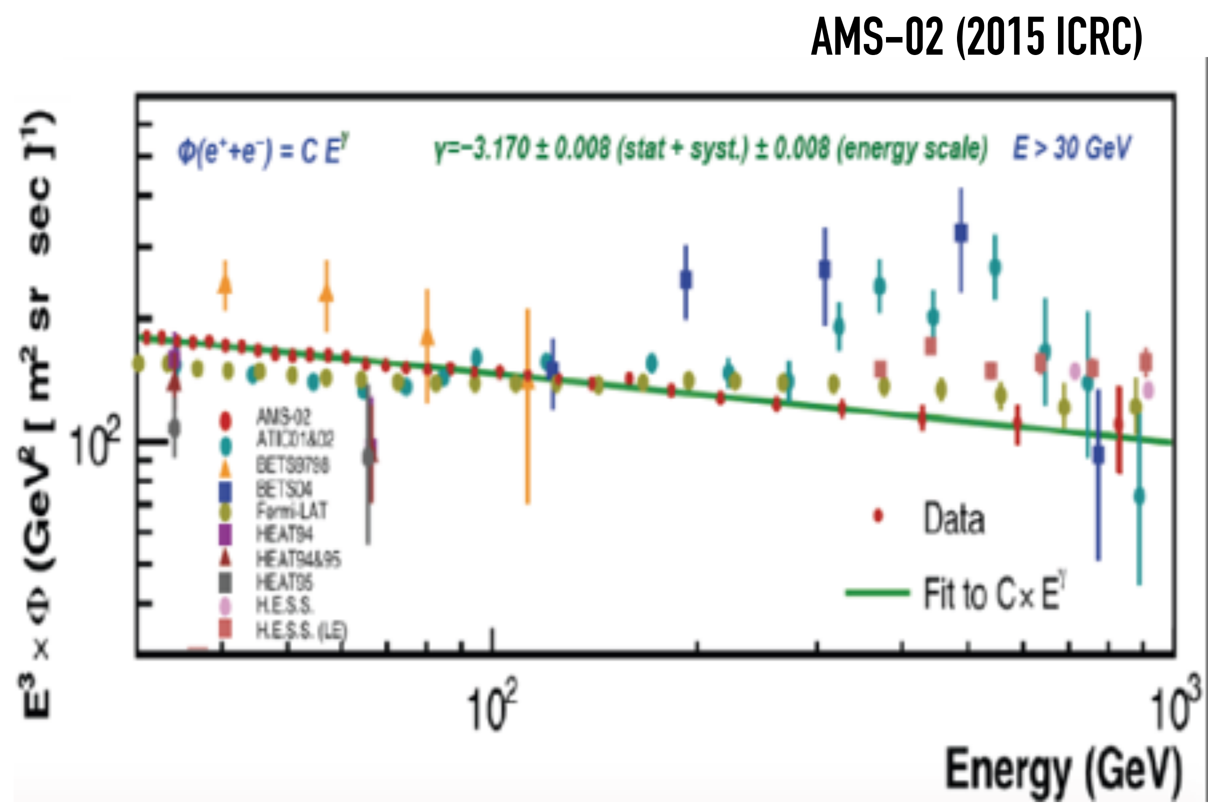


No bump in HE leptonic spectrum

AMS-02's leptonic flux is consistent with a single power-law above 30 GeV

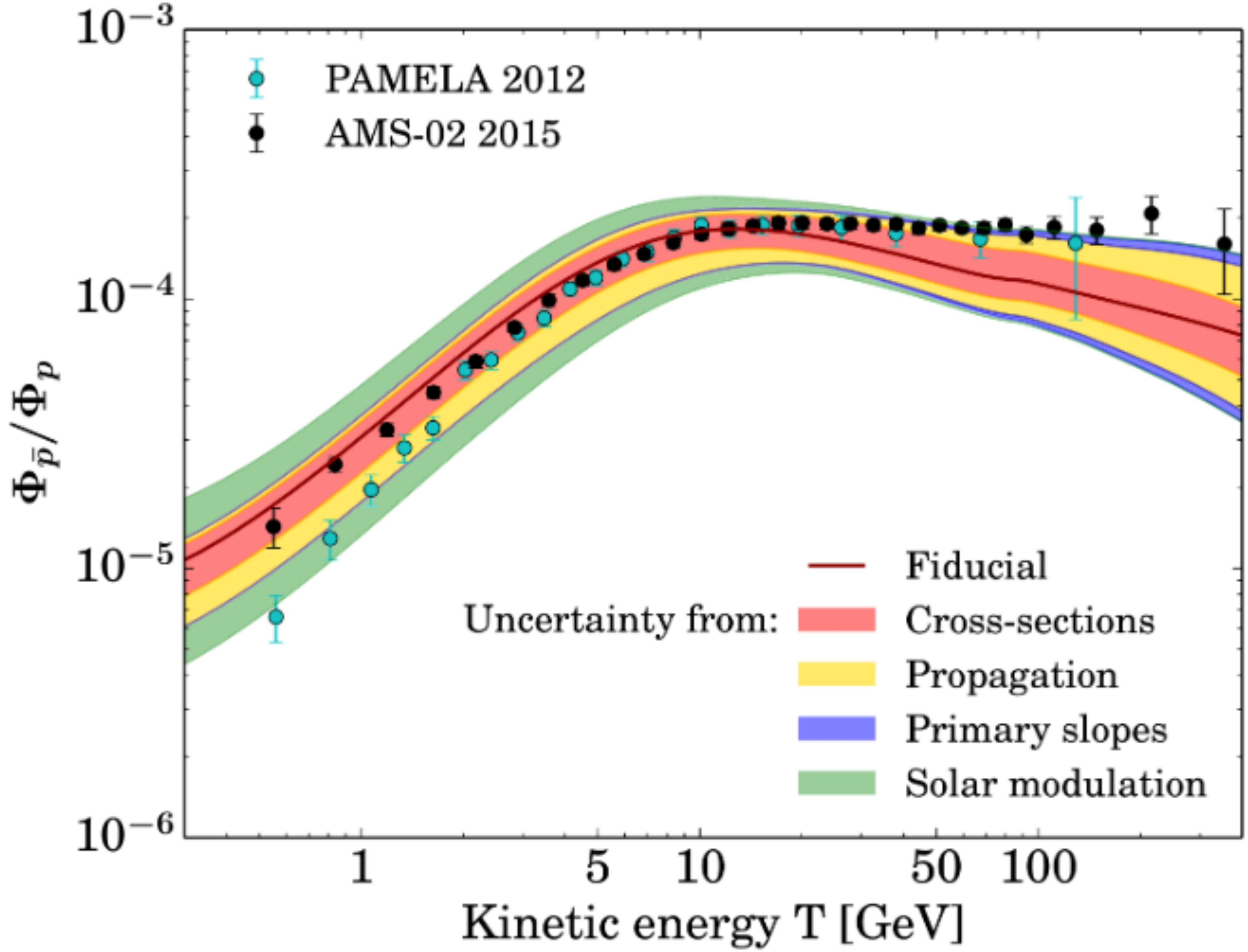


PRL 113, 221102 (2014)



Flattening anti-proton-proton ratio

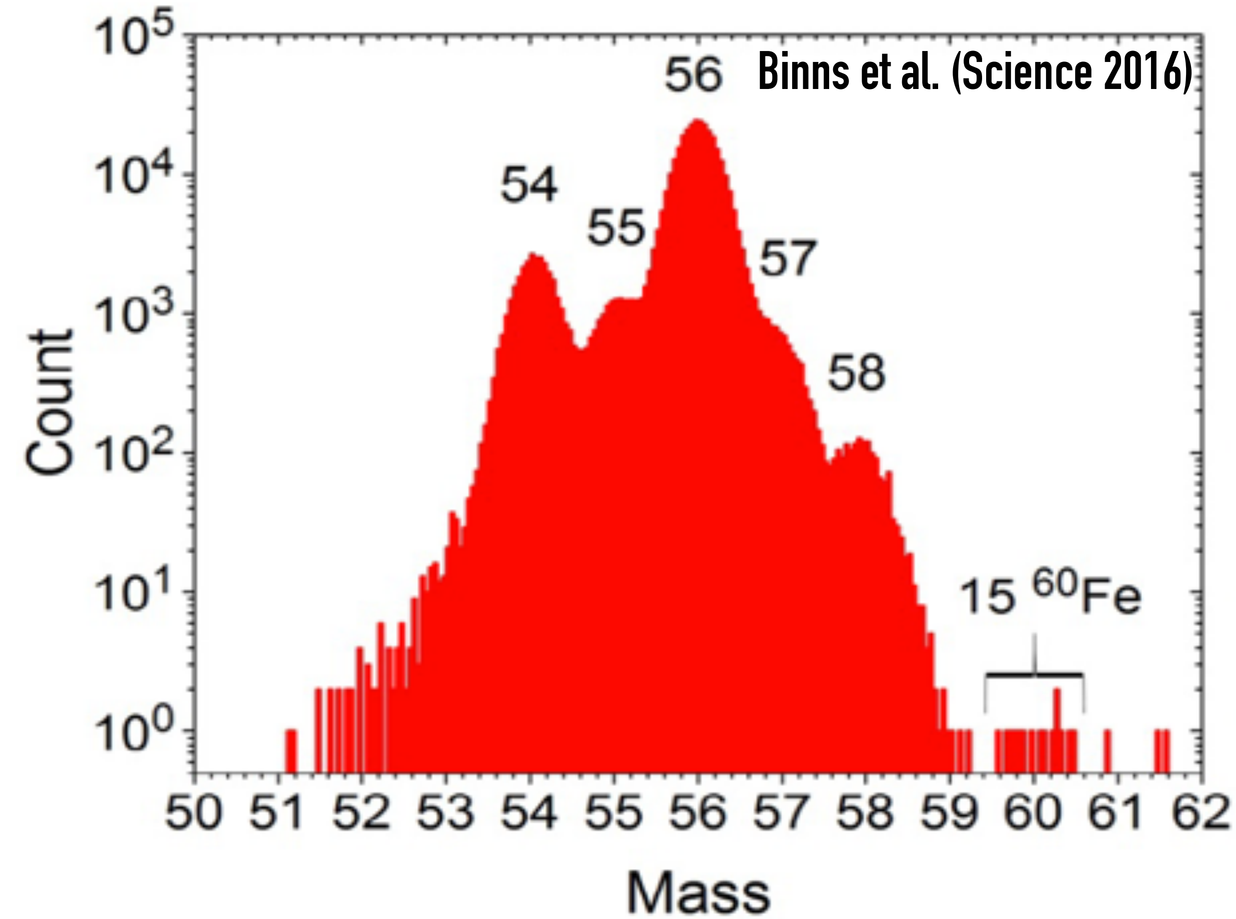
Including the hardening of CRs, current measurement of anti-proton-proton ratio is consistent with secondary origin of anti-proton

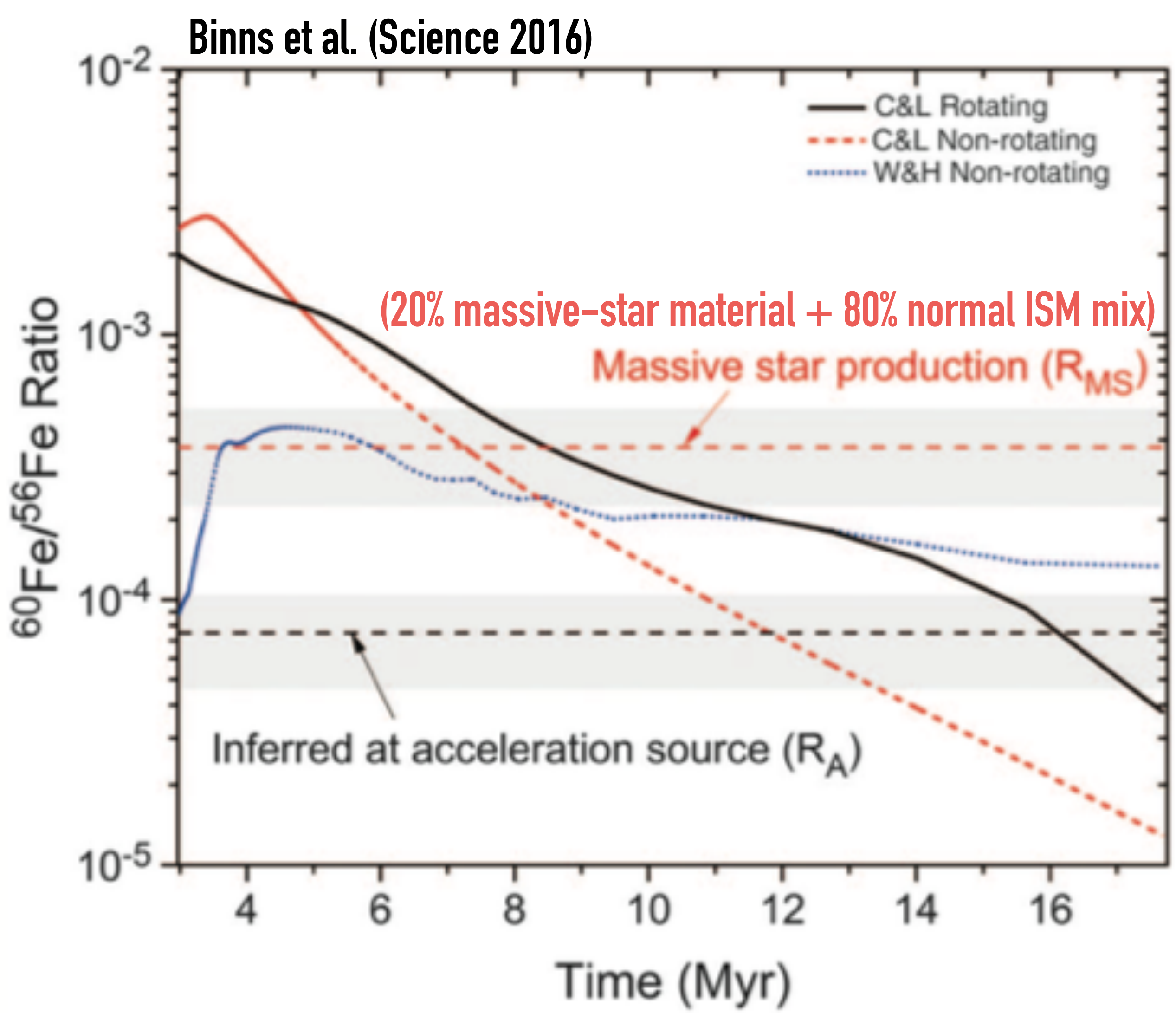


First measurement of primary CR clock - ^{60}Fe

15 ^{60}Fe detected over 16.8 yr of data

- $^{60}Fe/^{56}Fe = (4.6 \pm 1.7) \times 10^{-5}$
- Half life of ^{60}Fe : 2.62×10^{6} yr
- Mostly primary particles from core collapse SN

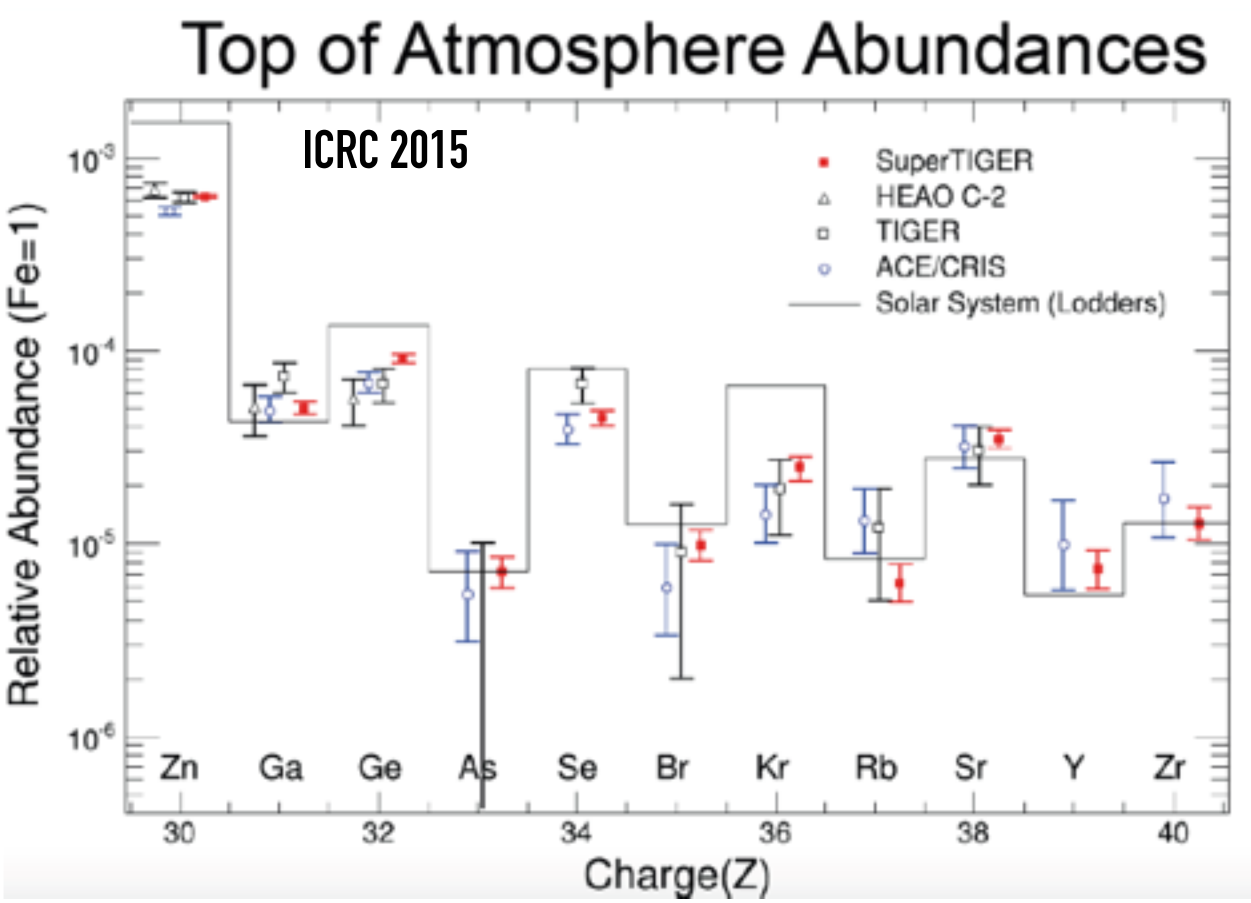


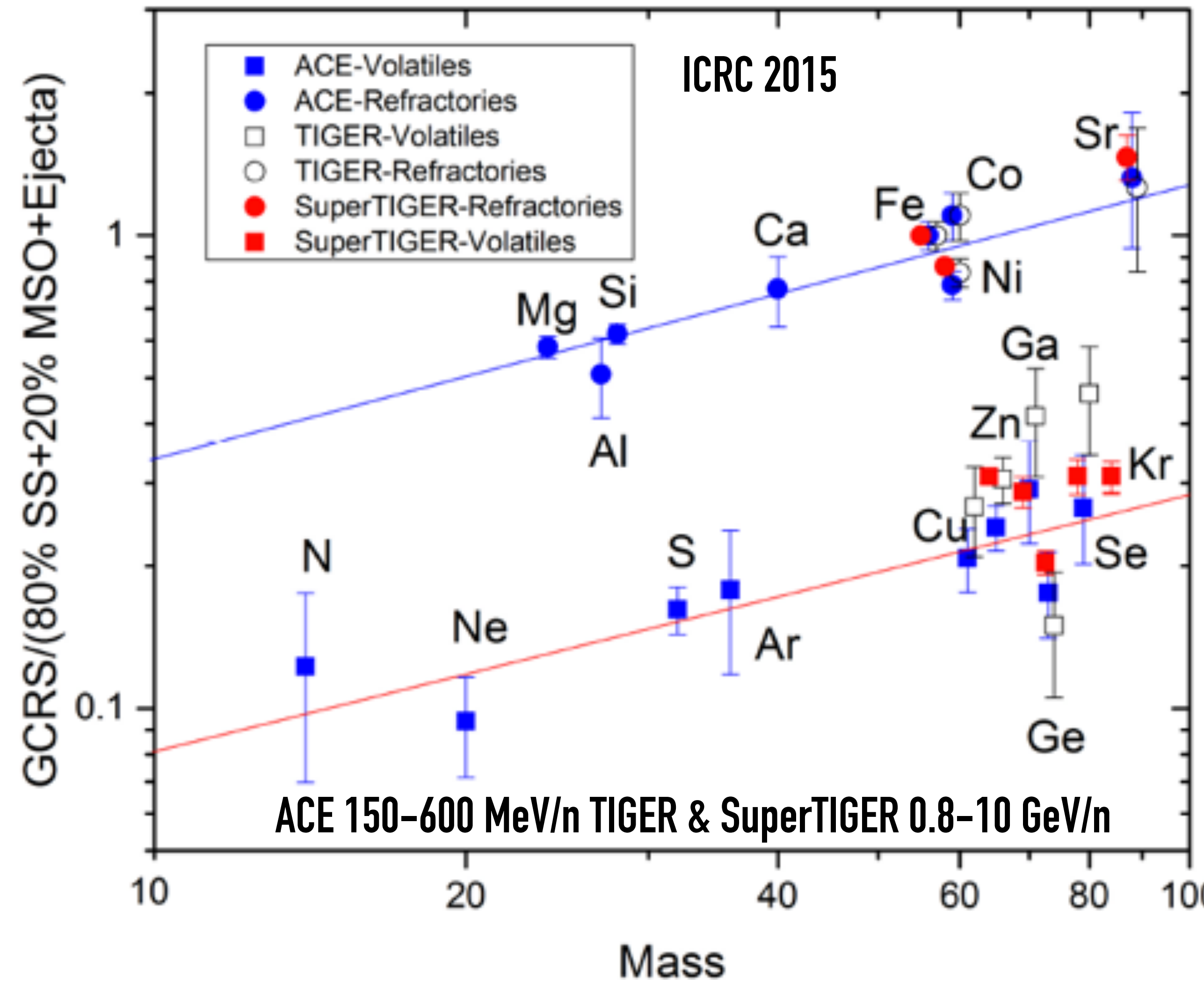


Time between nucleosynthesis to acceleration:
10^5 yr < T < several Myr

- Lower bound comes from lack of ^{59}Ni (half-life 7.6×10^4 yr)
- ^{60}Fe has to be accelerated relatively in short time after nucleosynthesis →accelerated by other SNRs nearby
- Source site distance order of kpc

Heavy Nuclei Abundance





Better ordering of refractory & volatiles by mass assuming 20% ejecta from massive stars + 80% Solar system

- Origin of GCR in OB associations
- Refractory elements (dust, grain) are more effectively accelerated than volatile ones (gas)

Summary

Hardening of light nuclei (P, He, Li) spectra at ~ 250 GV

- Will this continue to heavier elements?
  - CREAM data show weak evidence for this
  - No clear hardening of preliminary Carbon spectrum by AMS-02

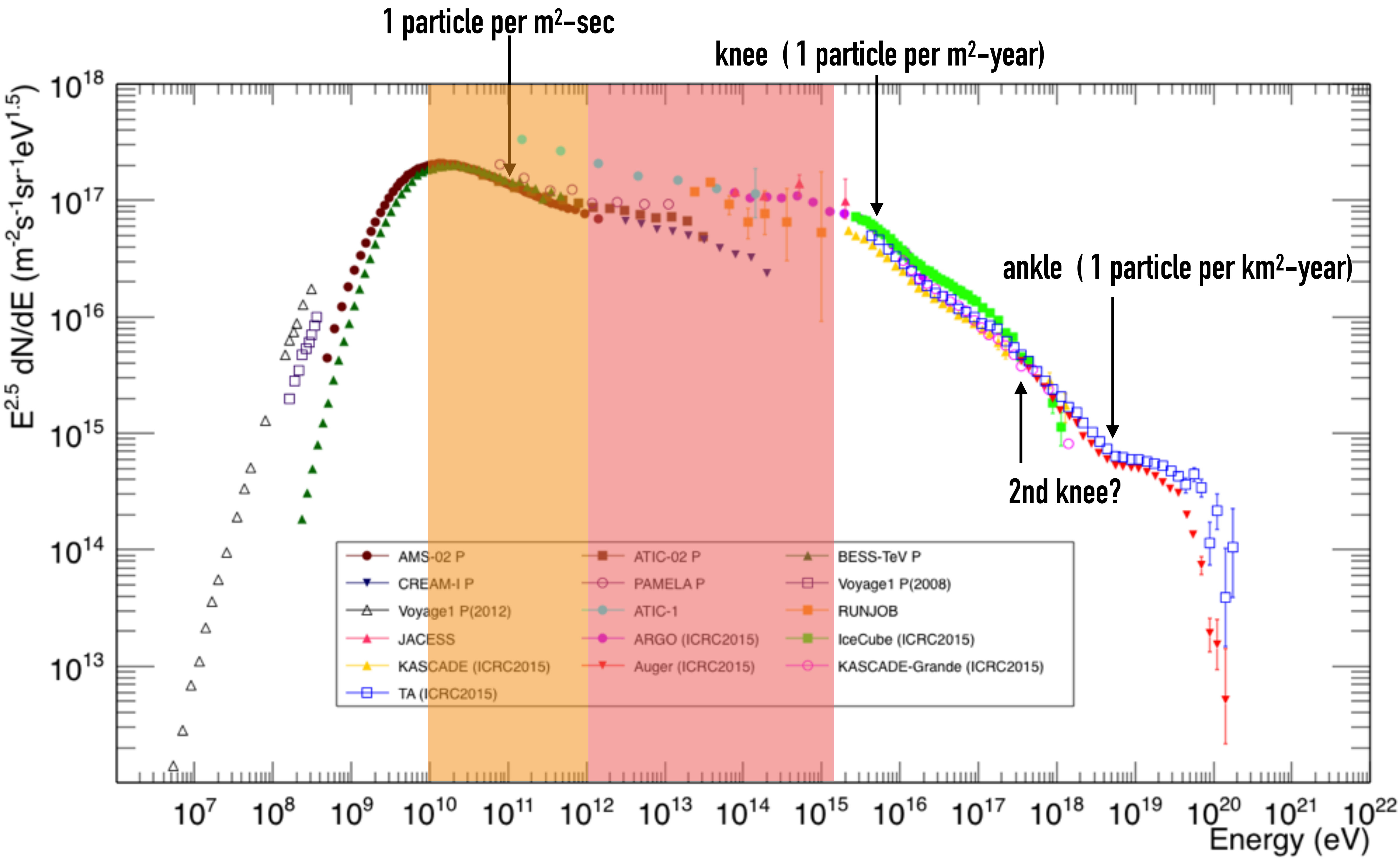
Different spectral index between Proton & Helium

No clear feature in preliminary B/C ratio

Issues on CR propagation and local sources	Kfir Blum

Rise of positron fraction

Pulsars as local electron-positron sources	Matt Kistler
Astrophysical electron-positron factories	Norita Kawanaka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2nd knee?
E2.5 dN/dE (m-2s-1sr-1eV1.5)
Energy (eV)
AMS-02 P
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PAMELA P
ATIC-1
ARGO (ICRC2015)
Auger (ICRC2015)
BESS-TeV P
Voyage1 P(2008)
RUNJOB
IceCube (ICRC2015)
KASCADE-Grande (ICRC2015)

What to Expect in the future?

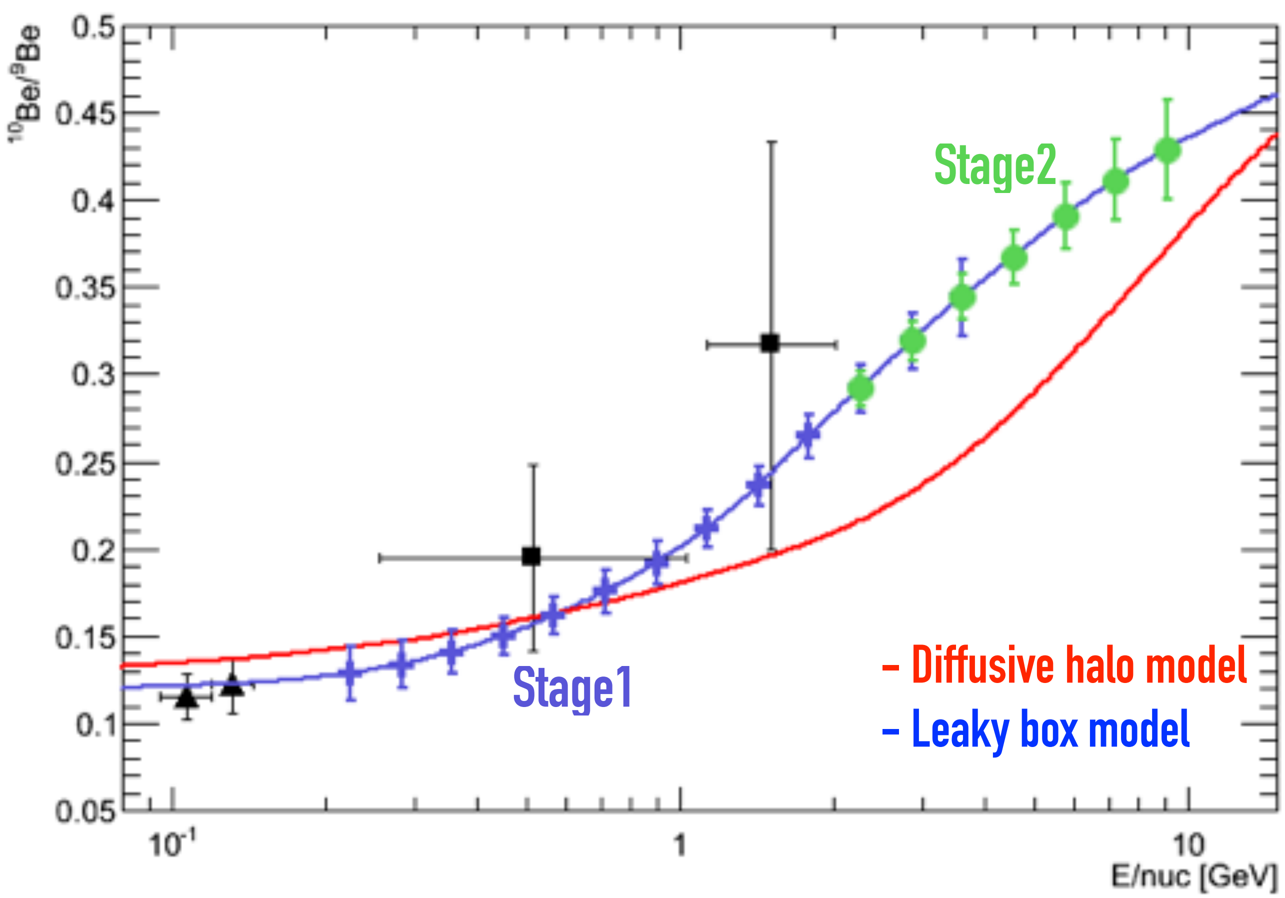
Experiment	$e^{+}+e^{-}$	CR	UHGCR	gamma	Type	Launch
NUCLEON	100 GeV-3 TeV	Z= 1-30 100 GeV-1 PeV			SAT	Dec. 26th 2014
CALET	1 GeV-10 TeV	p-Fe 10 GeV-1 PeV	26<Z≤40 ~GeV/n	10 GeV-10 TeV X-ray 7-20 MeV	ISS	Aug. 16th 2015
ISS-CREAM	100 GeV-10 TeV	p-Fe 1 TeV-1 PeV			ISS	2016
DAMPE	5 GeV-10 TeV	Z=1-20 100 GeV-100 TeV		5 GeV-10 TeV	SAT	Dec. 2015
CSES	3-200 MeV	p 30-300 MeV			SAT	End 2016
GAMMA-400	1 GeV-20 TeV	1 TeV-3 PeV p-Fe		20 MeV-1 TeV	SAT	2023-2025
HELIX		Light isotopes <10 GeV/n			LDB	proposal
HNX			6 ≤ Z ≤ 96 ~GeV/n		SAT	proposal
GAPS		Anti-p,D <1GeV/n			LDB	proposal

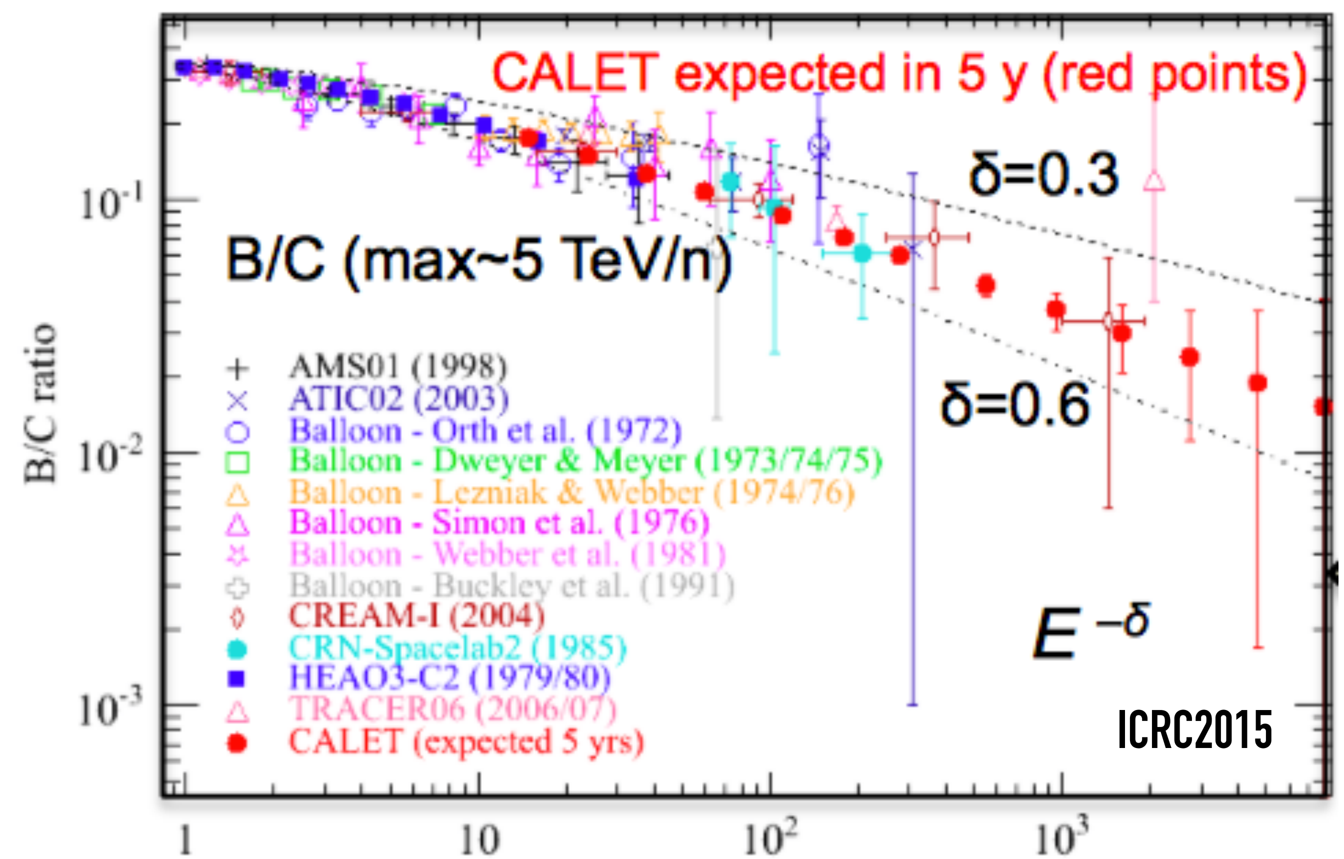
ICRC 2015

Better data set for the propagation studies

Updates on ^{10}Be measurement (by HELIX)

Updates on B/C measurements (by ISS-CREAM, CALET)

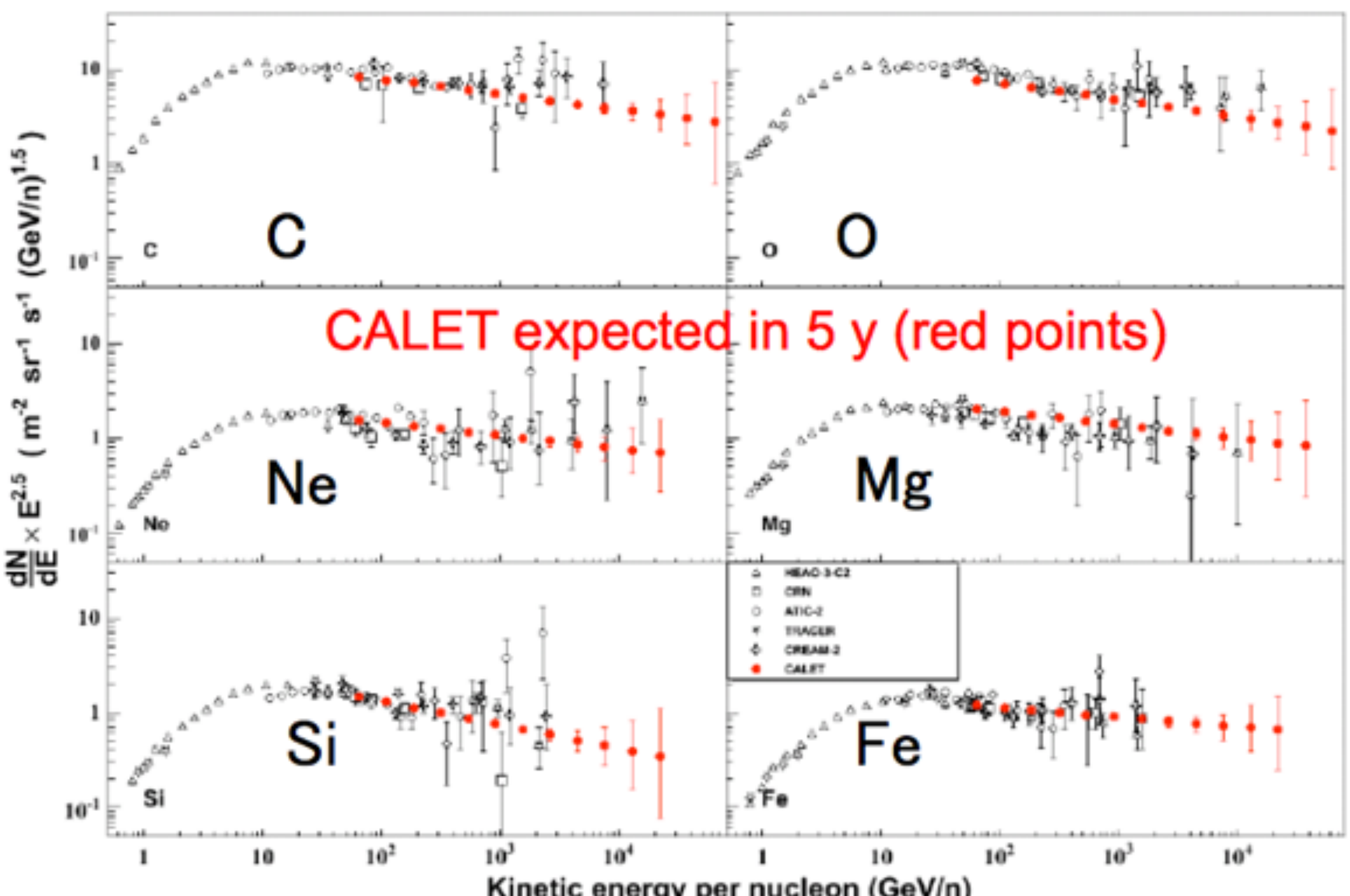




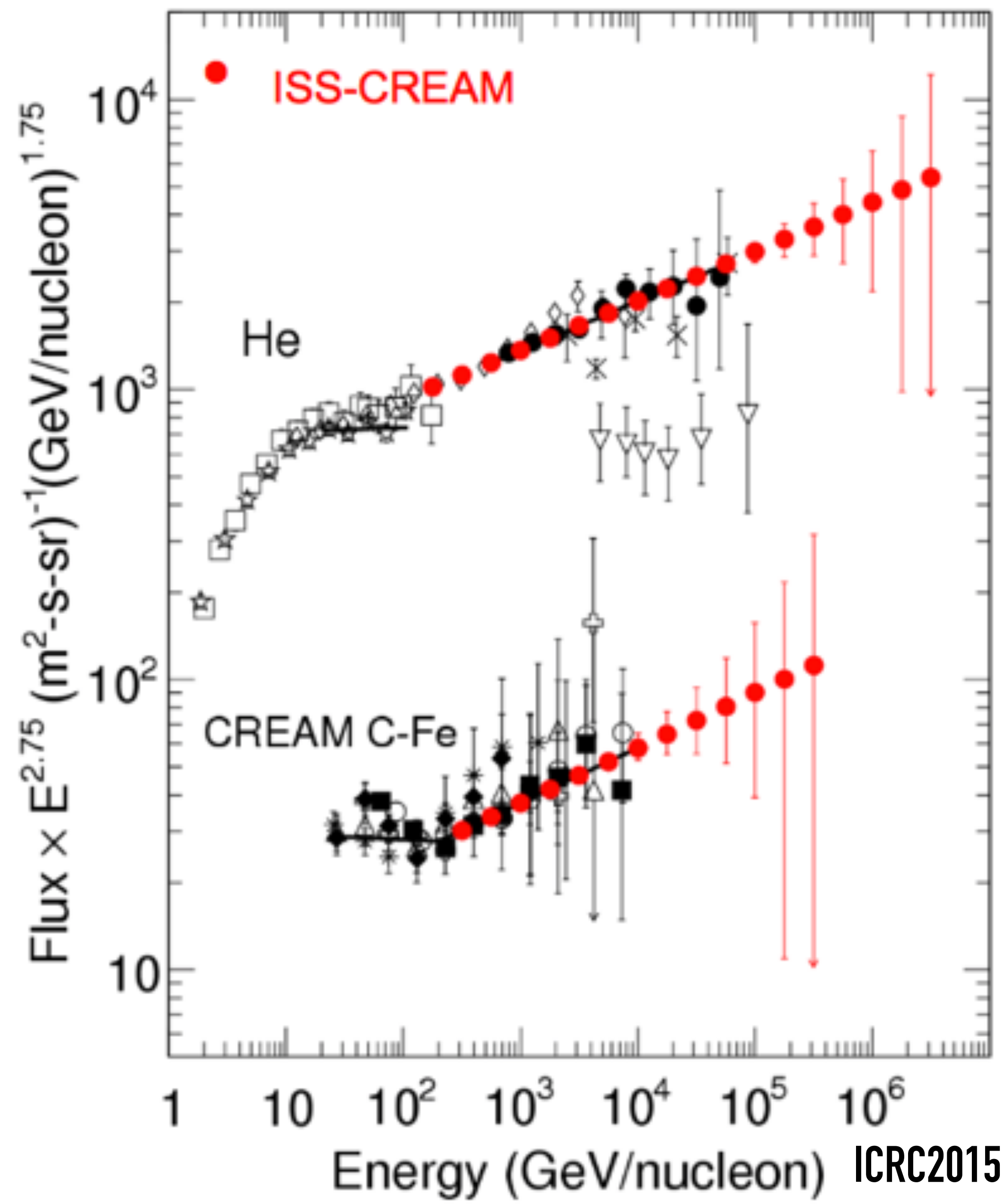
Good elemental measurements

Good elemental spectrum measurement of ~ 100 GeV/n - few tens of TeV/n (CALET - 5 yr, ISS-CREAM - 3 yr)

- Not good enough to reach knee region?



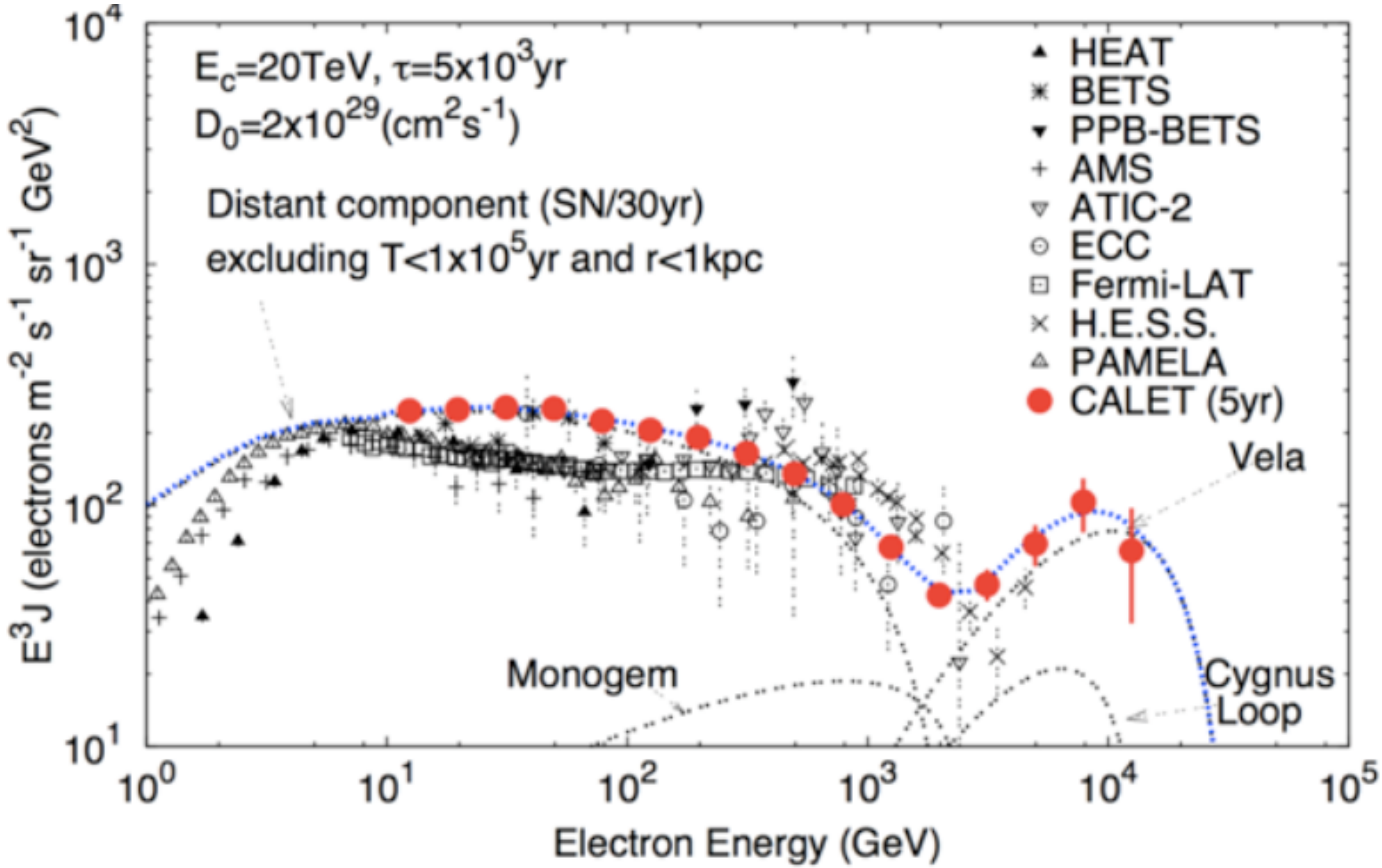
ICRC2015



ICRC2015

Study of nearby sources w/ electron

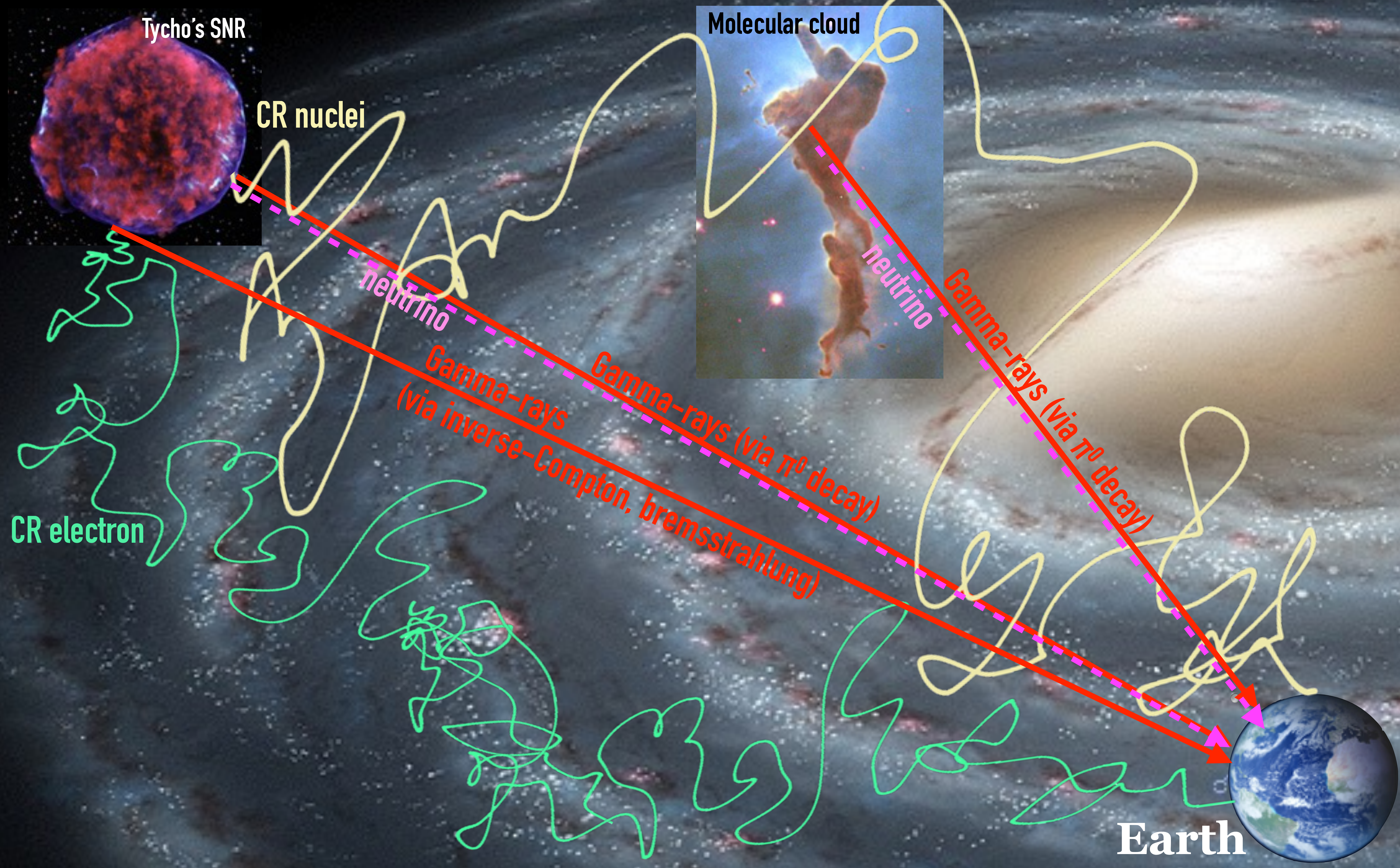
HE electron measurement by CALET



Multiwavelength Approach

Cosmic Ray sources

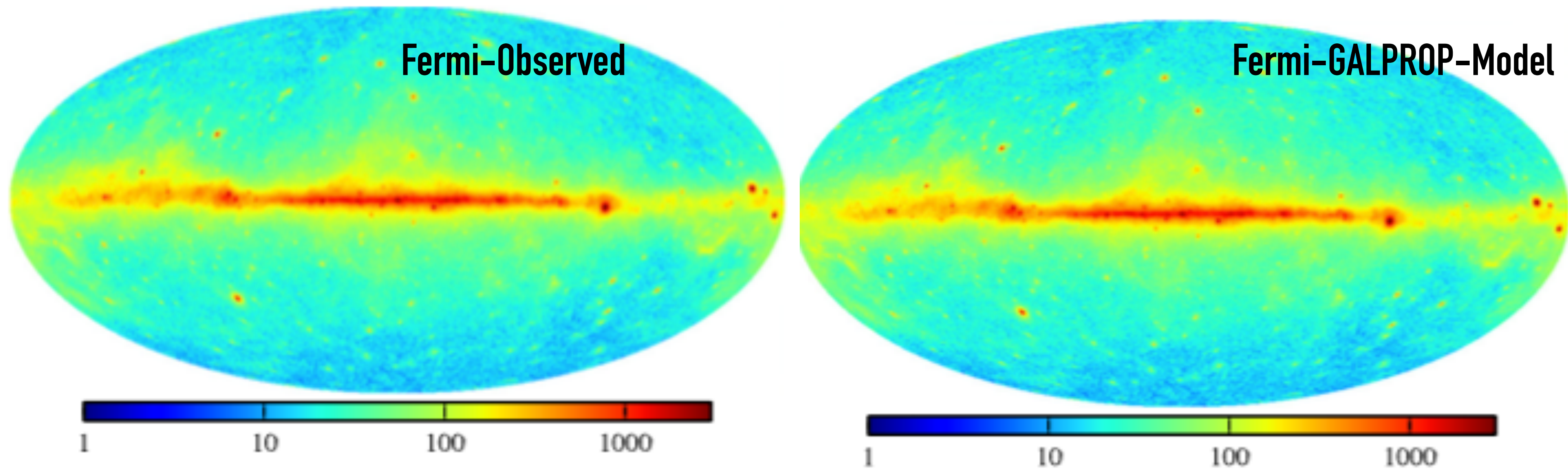
Gamma-ray & neutrino can point to the source!



Multiwavelength Approach (2)

Galactic diffusive emission

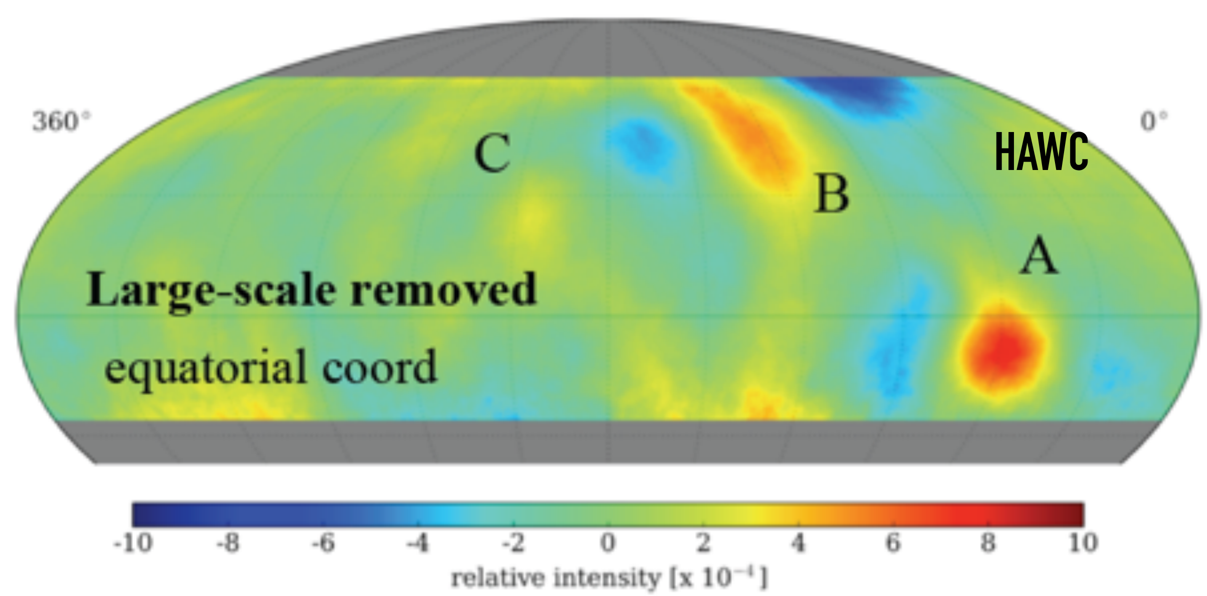
- Gamma-ray
  - Fermi, HESS, …
- Neutrino?



Galactic diffuse gamma (HESS)	Aion Viana

Anisotropy

- Large scale
- Smaller scale
- HAWC, Ice-top, Tibet,…

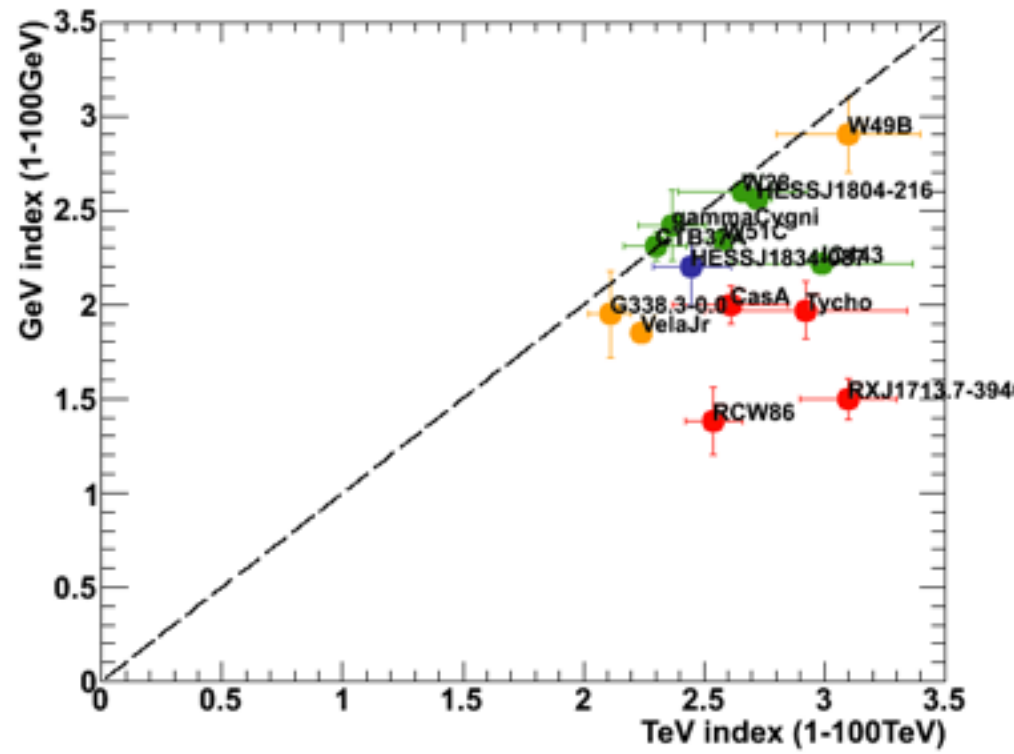


anisotropy (observation)	Dan Fiorino
anisotropy (theory)	Markus Ahlers

Multiwavelength Approach (3)

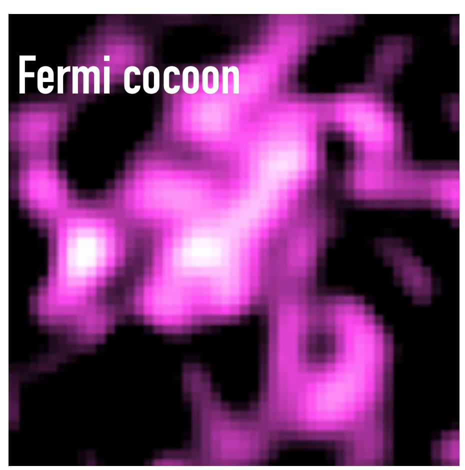
Source observation in gamma-ray & neutrino

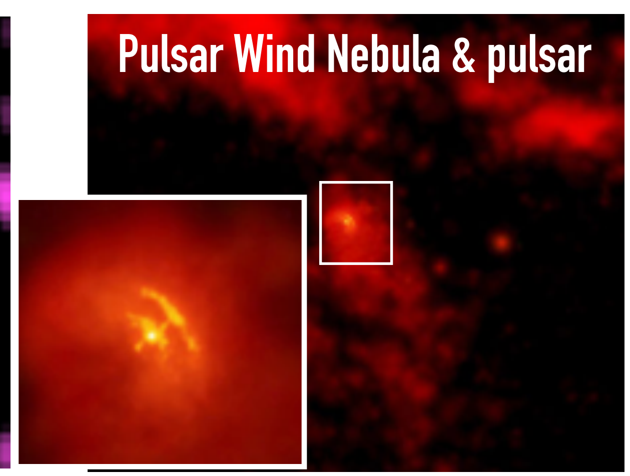
- SNR
  - Understanding the acceleration, local diffusion, source population, …

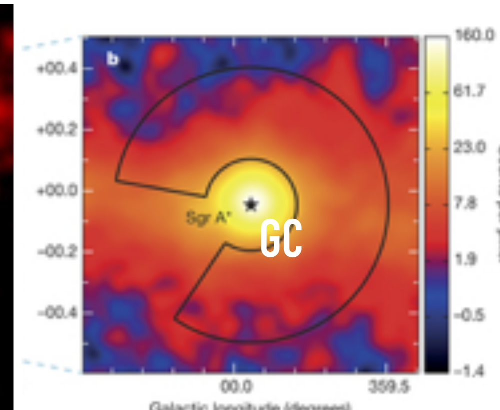


Average age : 0~3 kyr
3~10 kyr
10~50 kyr
> 50 kyr

- Other sources?







- Neutrino sources?

Galactic neutrinos (from ANTARES to KM3Net) Veronique Van Elewyck