PERUGIA
7 | 8 LUGLIO
2025

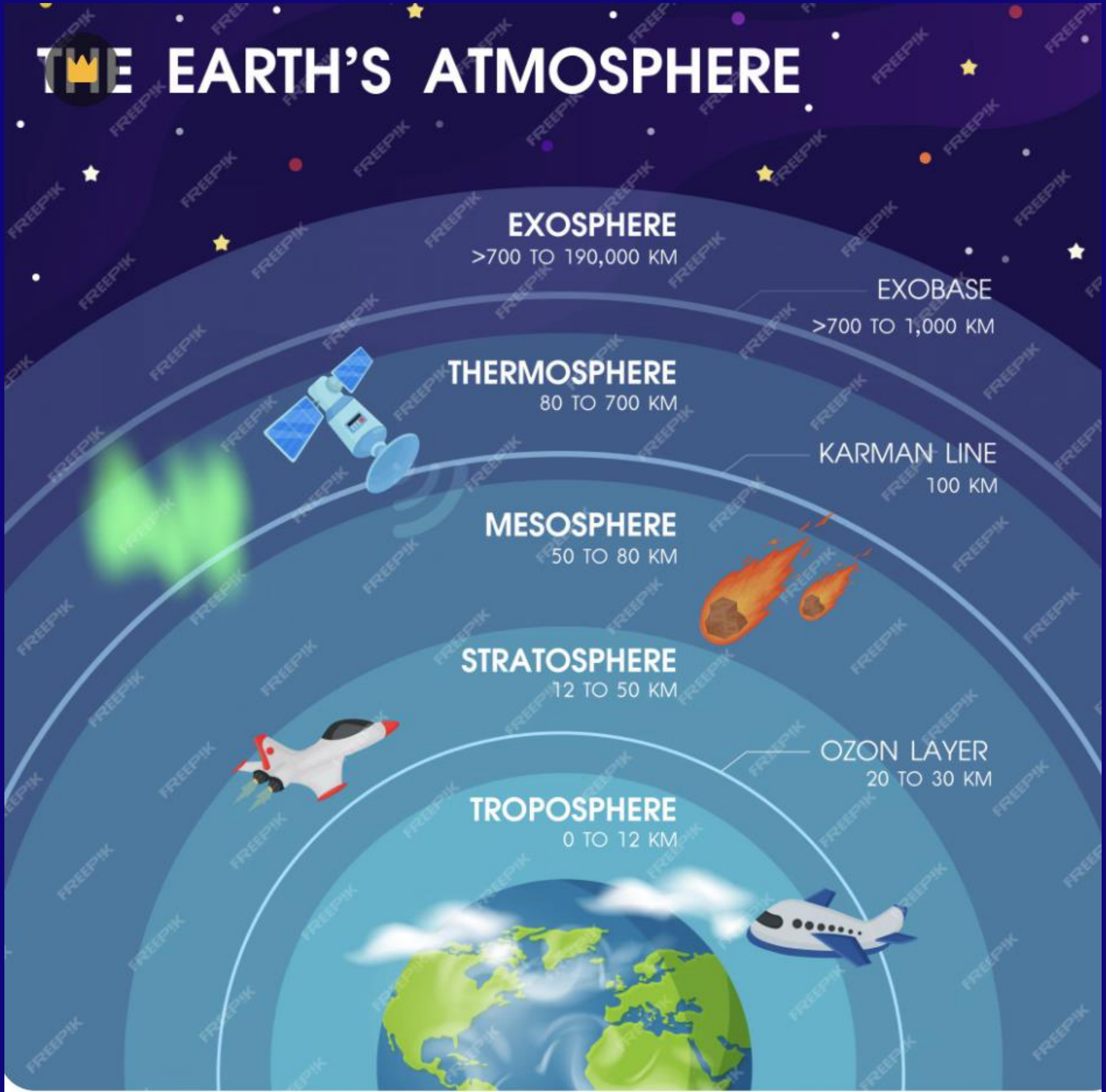
Oltre i confini della terra: la Fisica nello spazio

Oscar Adriani

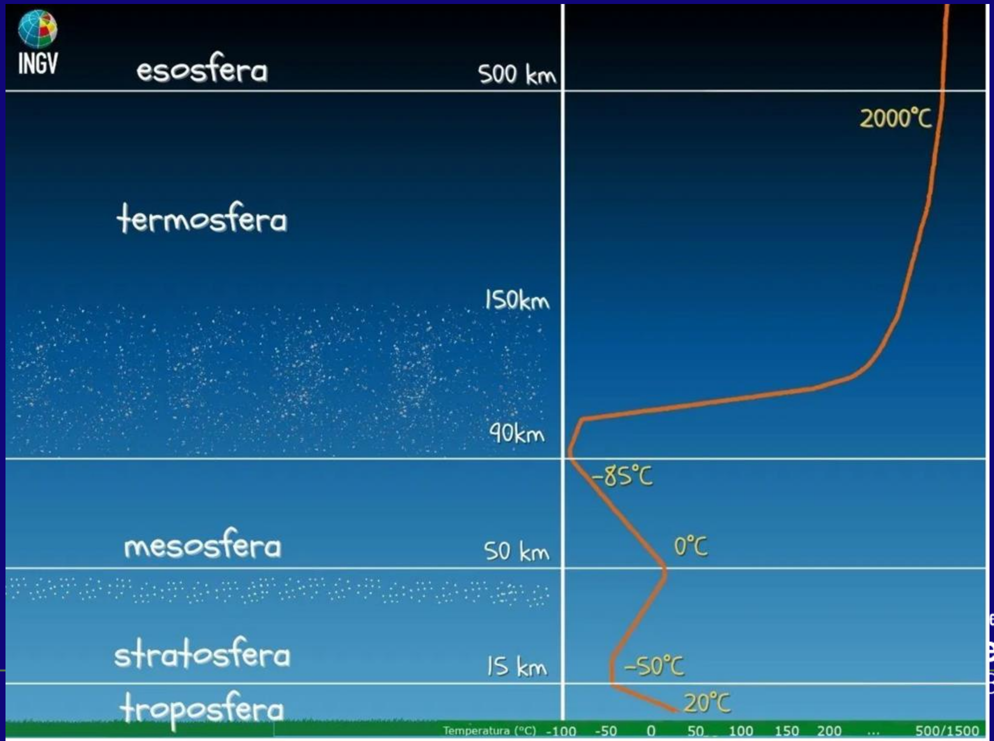
INFN

OLTRE
le frontiere

Istituto Nazionale di Fisica Nucleare
Piano Triennale
2026 | 2028

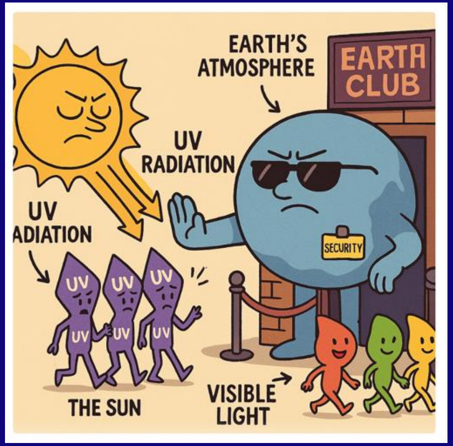

THE EARTH'S ATMOSPHERE
EXOSPHERE
>700 TO 190,000 KM
EXOBASE
>700 TO 1,000 KM
THERMOSPHERE
80 TO 700 KM
KARMAN LINE
100 KM
MESOSPHERE
50 TO 80 KM
STRATOSPHERE
12 TO 50 KM
OZON LAYER
20 TO 30 KM
TROPOSPHERE
0 TO 12 KM
FREEPIK

- Atmosfera: strato di gas che avvolge la terra
- Fondamentale per la vita!
  - Blocca la radiazione UV
  - Limita le escursioni termiche tra il giorno e la notte
  - Non si disperde nello spazio a causa della forza di gravità
  - Primi 32 km: 99% dei gas



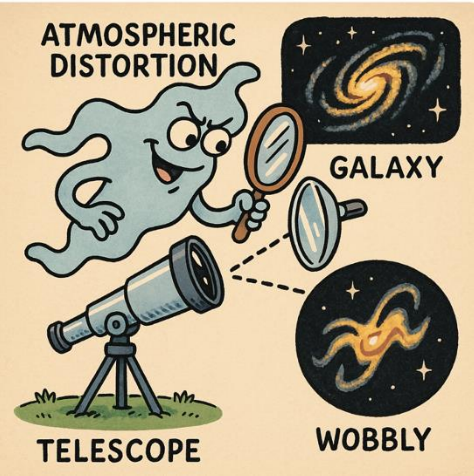
Ma per la fisica (e anche per l’astronomia e l’astrofisica) ....

- L’atmosfera funge da filtro per:
  - la gran parte dei Raggi Cosmici
  - i Raggi X e γ emessi dalle sorgenti astrofisiche
  - la radiazione cosmica di fondo


EARTH'S ATMOSPHERE
EARTH CLUB
UV RADIATION
UV ADIATION
UV
SECURITY
THE SUN
VISIBLE LIGHT

- E distorce in modo importante le immagini dei telescopi ottici

- E’ necessario andare ‘Oltre i confini della terra’ per fare con precisione questo tipo di misure

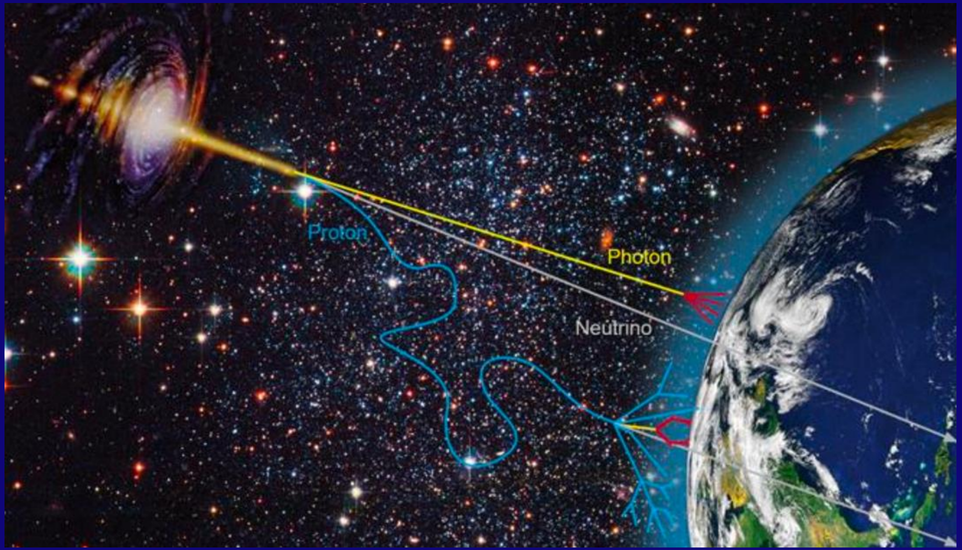

ATMOSPHERIC DISTORTION
GALAXY
TELESCOPE
WOBBLY

DISCLAIMER

- Questa non sarà una review scientifica completa di tutte le attività INFN nello spazio
- Focus storico per far vedere come l'INFN ha 'cambiato il modo di approcciarsi' alla fisica nello spazio

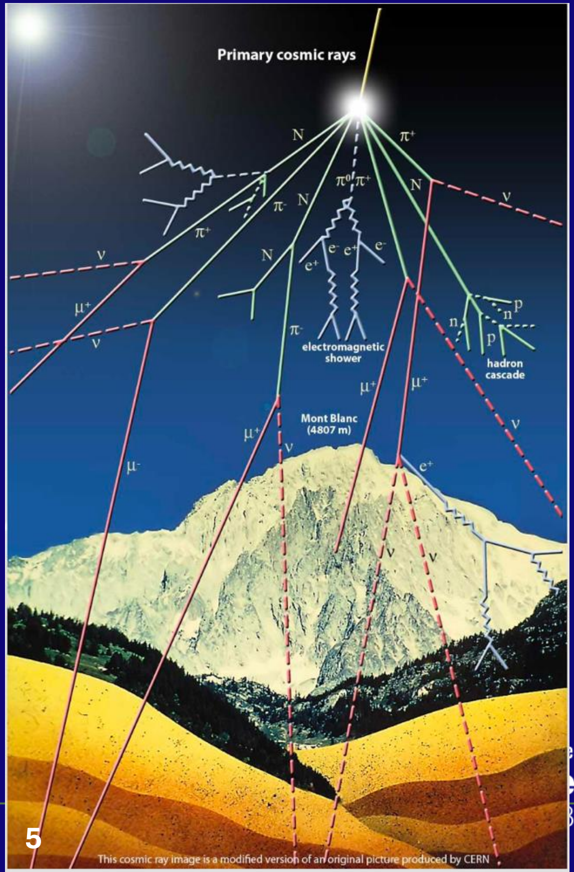
Cominciamo dai Raggi Cosmici carichi

- I raggi cosmici sono un flusso di particelle cariche ad alta energia che colpisce la terra
- Origine:
    - Il Sole
    - Le stelle della nostra galassia (Galattici)
    - Sorgenti al di fuori della Via Lattea (Extragalattici)
- La Terra è bombardata costantemente da un flusso di particelle con uno spettro estremamente ampio di energia
    - da 10^6 eV a 10^{20} eV
- La maggior parte dei RC di bassa energia non supera il campo magnetico terrestre e/o l'atmosfera


Proton
Photon
Neutrino

Raggi Cosmici Primari

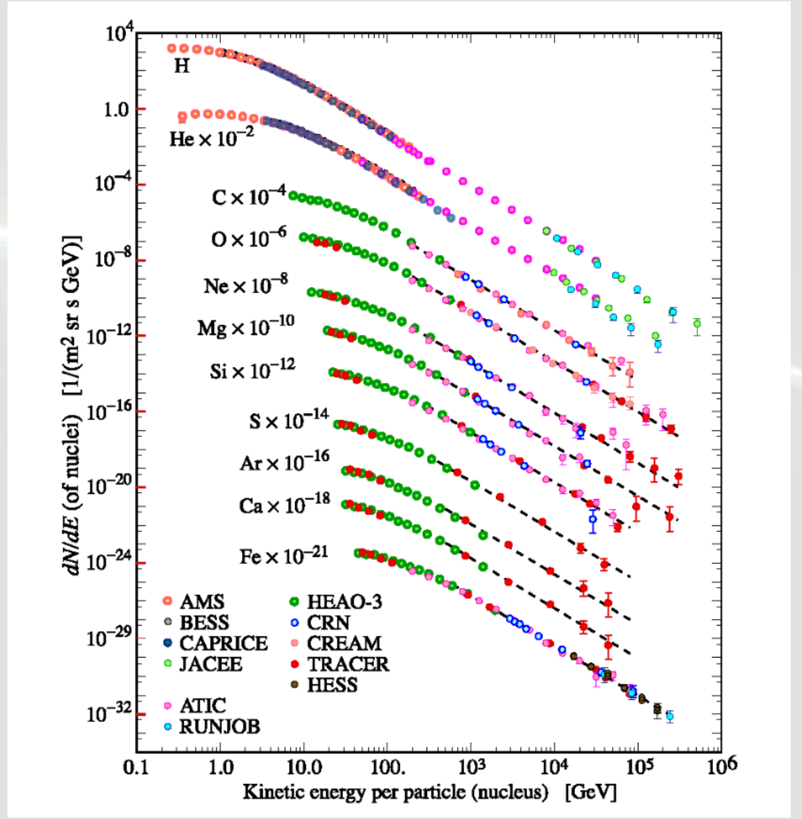
Raggi Cosmici Secondari

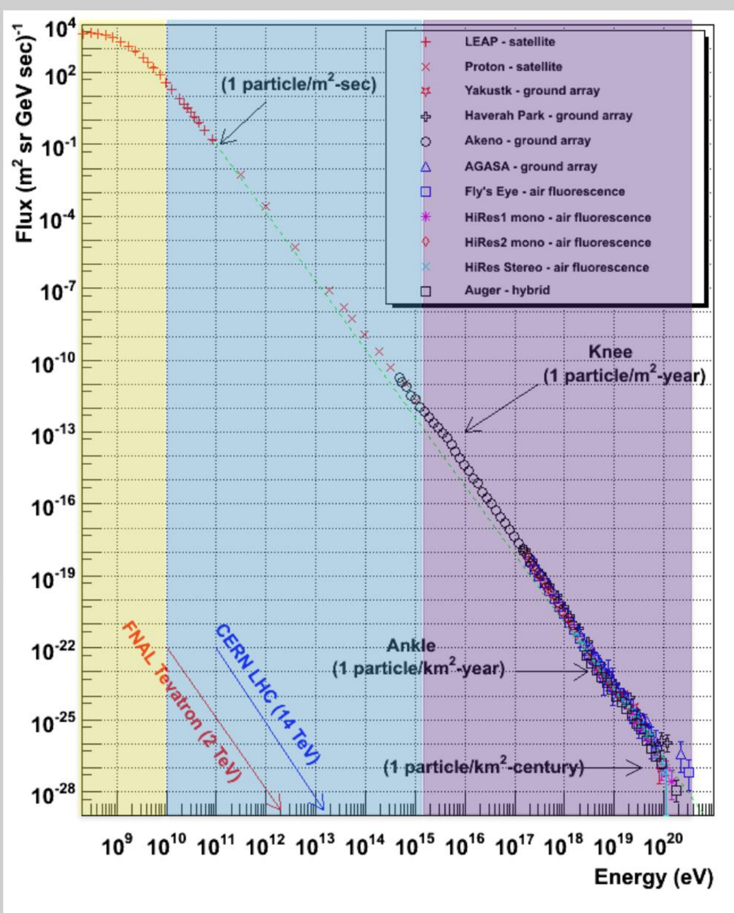

Primary cosmic rays
N
π⁺
π⁰π⁺
π⁻
e⁻
e⁺
ν
μ⁺
μ⁻
n
p
electromagnetic shower
hadron cascade
Mont Blanc (4807 m)

This cosmic ray image is a modified version of an original picture produced by CERN

Composizione dei Raggi Cosmici

- Protoni (nuclei di idrogeno) ~ 87%
- Nuclei di He ~12%
- 1% nuclei pesanti (principalmente carbonio)
- < 1% elettroni
- Anti-protoni e positroni





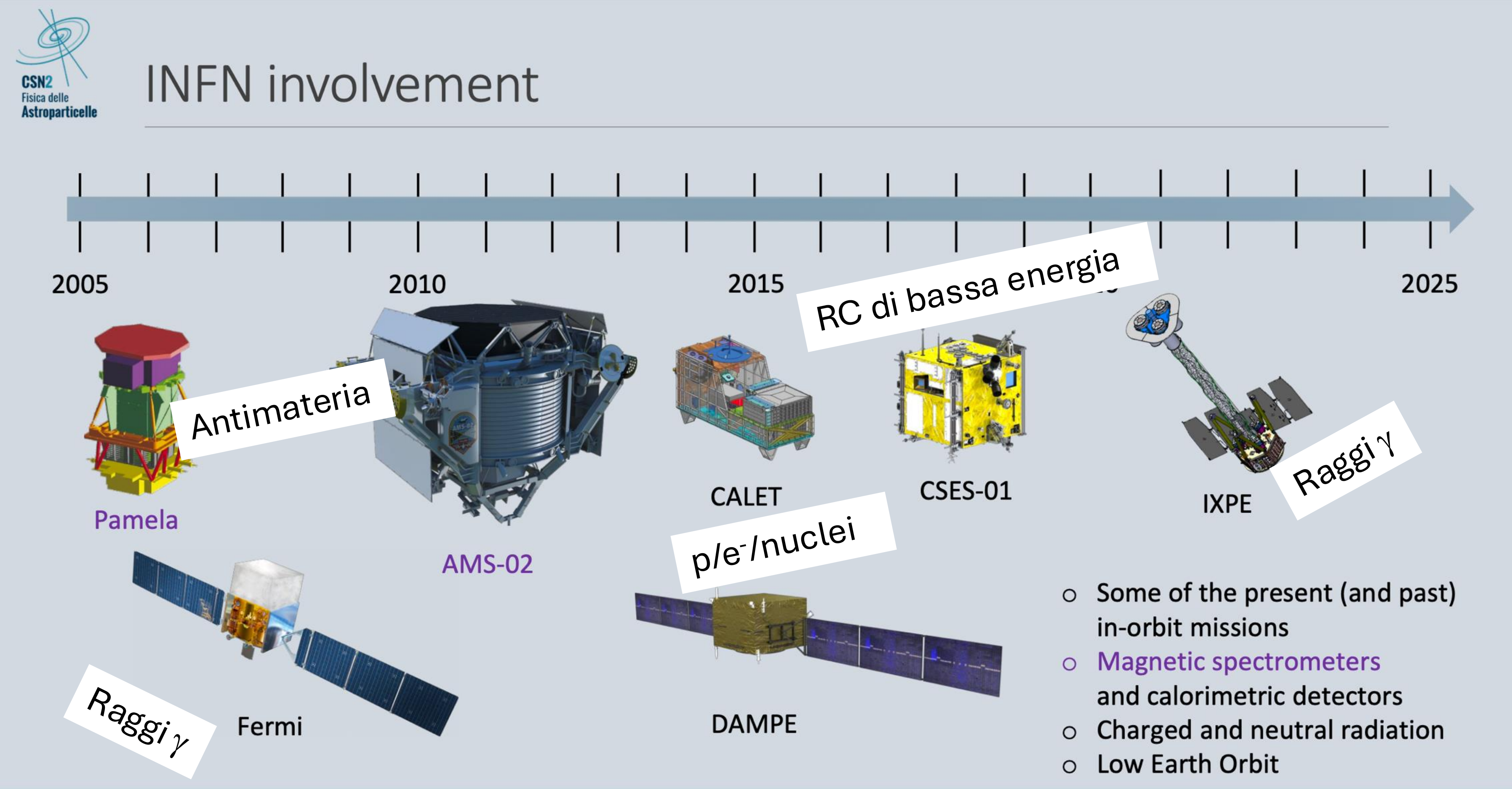
Cosa è necessario misurare?

- L'energia del RC
- Il segno della carica del RC
- La carica Z del RC
- La tipologia di RC (adrone vs leptone)
- La direzione di arrivo (non molto importante…..)

- Tutte cose che l'INFN ha sempre saputo fare benissimo fin dall'inizio delle sue attività, nel campo della fisica delle particelle e della fisica nucleare!

- In questa maniera si identifica completamente il RC

E qui comincia l’avventura INFN!



CSN2
Fisica delle
Astroparticelle

INFN involvement

2005
2010
2015
2025
Pamela
AMS-02
CALET
CSES-01
IXPE
Fermi
DAMPE

- Some of the present (and past) in-orbit missions
- Magnetic spectrometers and calorimetric detectors
- Charged and neutral radiation
- Low Earth Orbit

Antimateria

RC di bassa energia

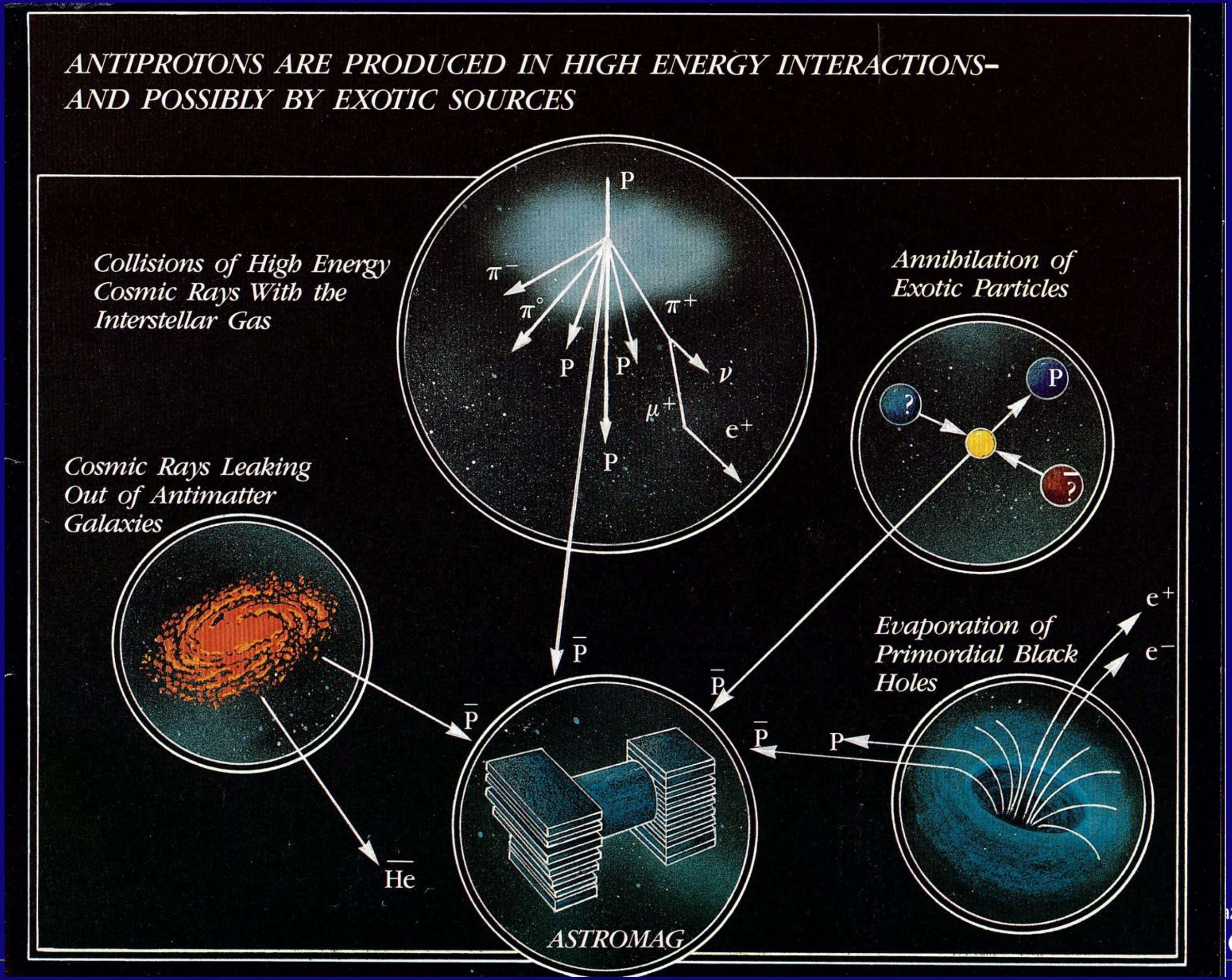
p/e^-/nuclei

Raggi γ

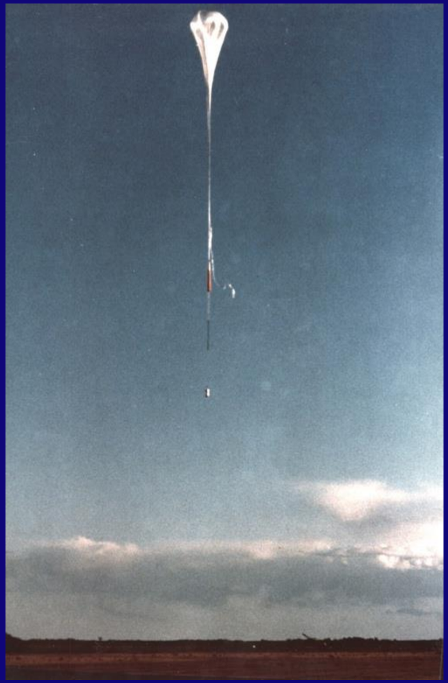
Raggi γ

PAMELA: la prima avventura scientifica nello spazio per l’INFN

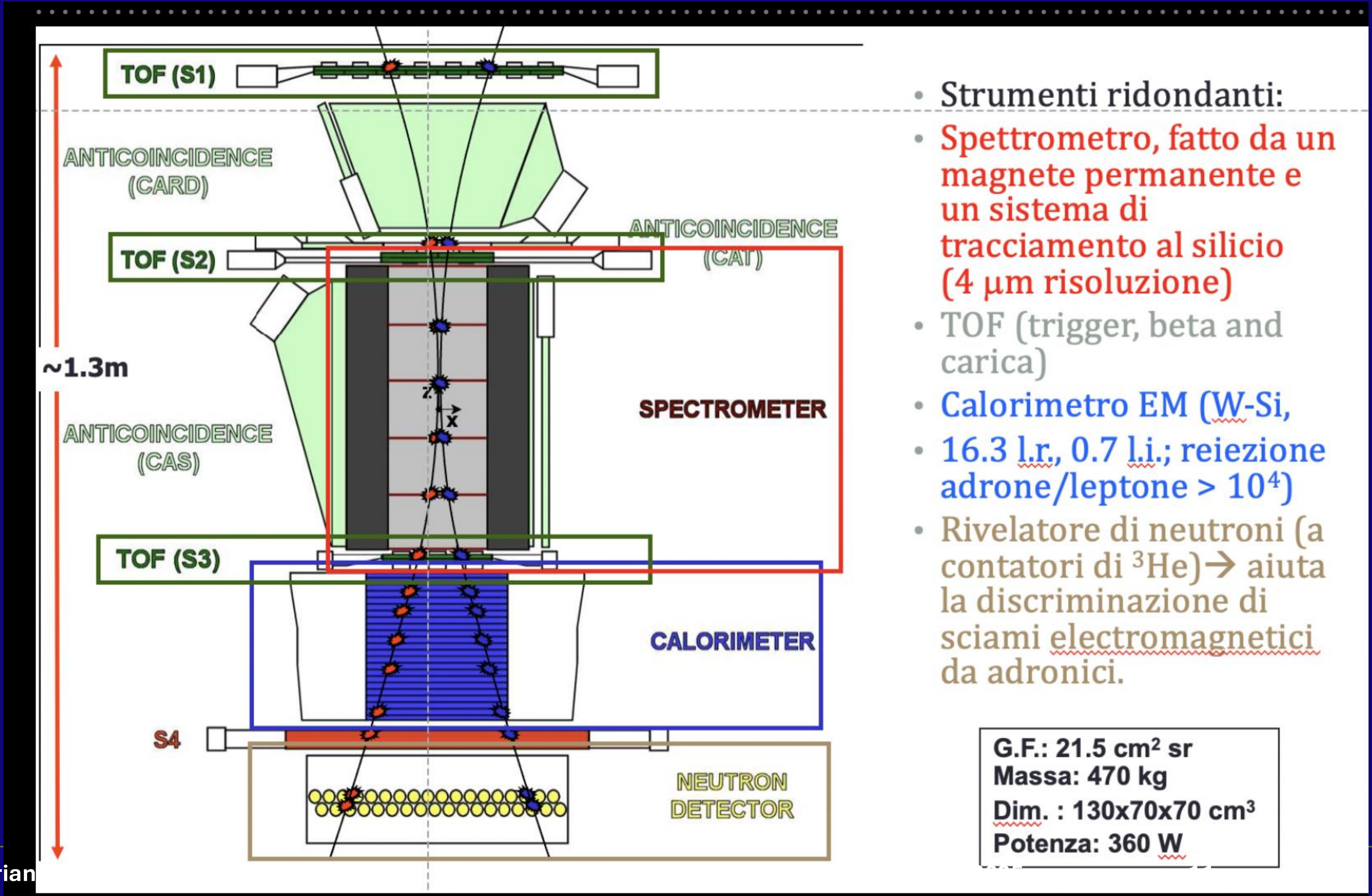
La domanda degli anni 80:
Esistono anti-galassie, con anti-stelle, che emettono anti-Raggi Cosmici?
Antiprotoni e antielettroni


ANTIPROTONS ARE PRODUCED IN HIGH ENERGY INTERACTIONS– AND POSSIBLY BY EXOTIC SOURCES
Collisions of High Energy Cosmic Rays With the Interstellar Gas
P
π^-
π°
π^+
P
P
ν
μ^+
e^+
P
Annihilation of Exotic Particles
?
$\bar{P}$
$\bar{?}$
Cosmic Rays Leaking Out of Antimatter Galaxies
Evaporation of Primordial Black Holes
e^+
e^-
$\bar{P}$
$\bar{P}$
$\bar{P}$
$\bar{P}$
P
$\overline{He}$
ASTROMAG

Cominciando dai palloni stratosferici (MASS e Caprice)



Lo strumento PAMELA


TOF (S1)
ANTICOINCIDENCE (CARD)
TOF (S2)
ANTICOINCIDENCE (CAT)
~1.3m
Z
X
SPECTROMETER
ANTICOINCIDENCE (CAS)
TOF (S3)
CALORIMETER
S4
NEUTRON DETECTOR

- Strumenti ridondanti:
- Spettrometro, fatto da un magnete permanente e un sistema di tracciamento al silicio (4 μm risoluzione)
- TOF (trigger, beta and carica)
- Calorimetro EM (W-Si,
- 16.3 l.r., 0.7 l.i.; reiezione adrone/leptone > 10^4)
- Rivelatore di neutroni (a contatori di ^{3}He)→ aiuta la discriminazione di sciami electromagnetici da adronici.

G.F.: 21.5 cm^2 sr
Massa: 470 kg
Dim. : 130x70x70 cm^3
Potenza: 360 W

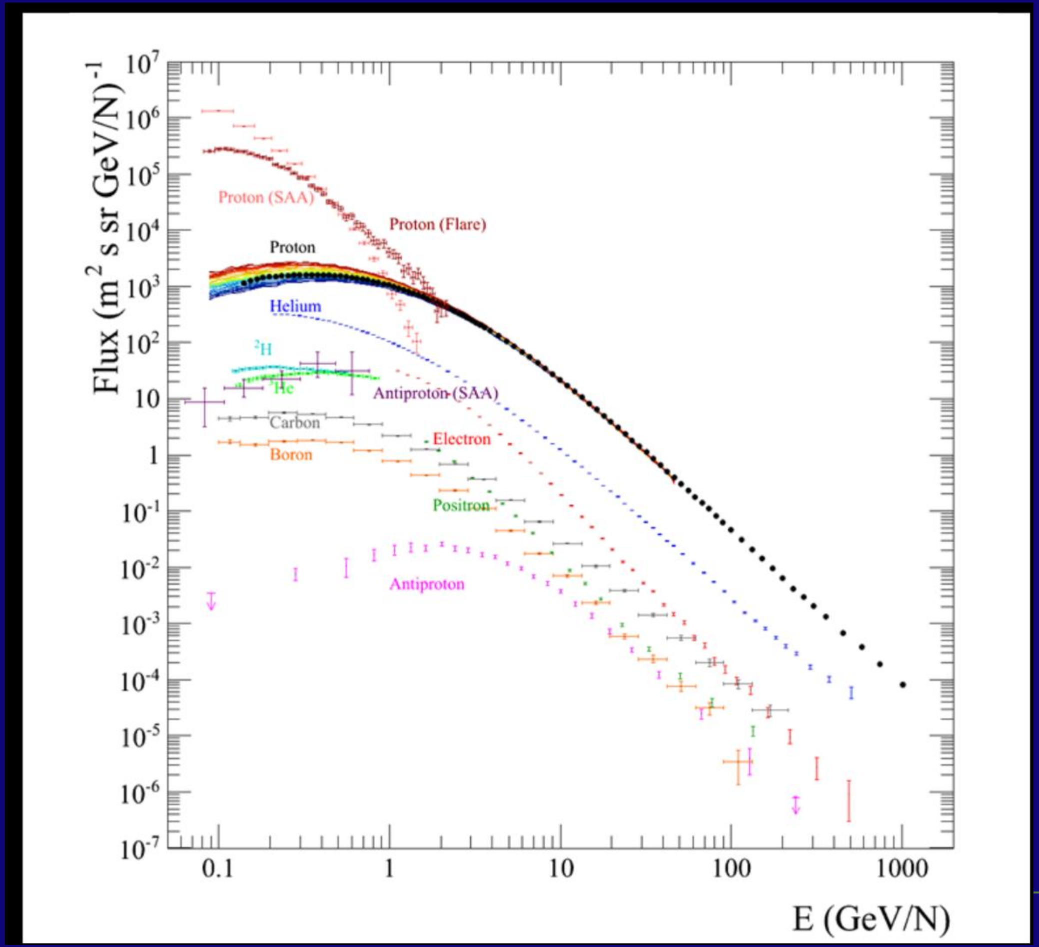
Un nuovo modo di produrre un esperimento per lo spazio: lo ‘spirito INFN’

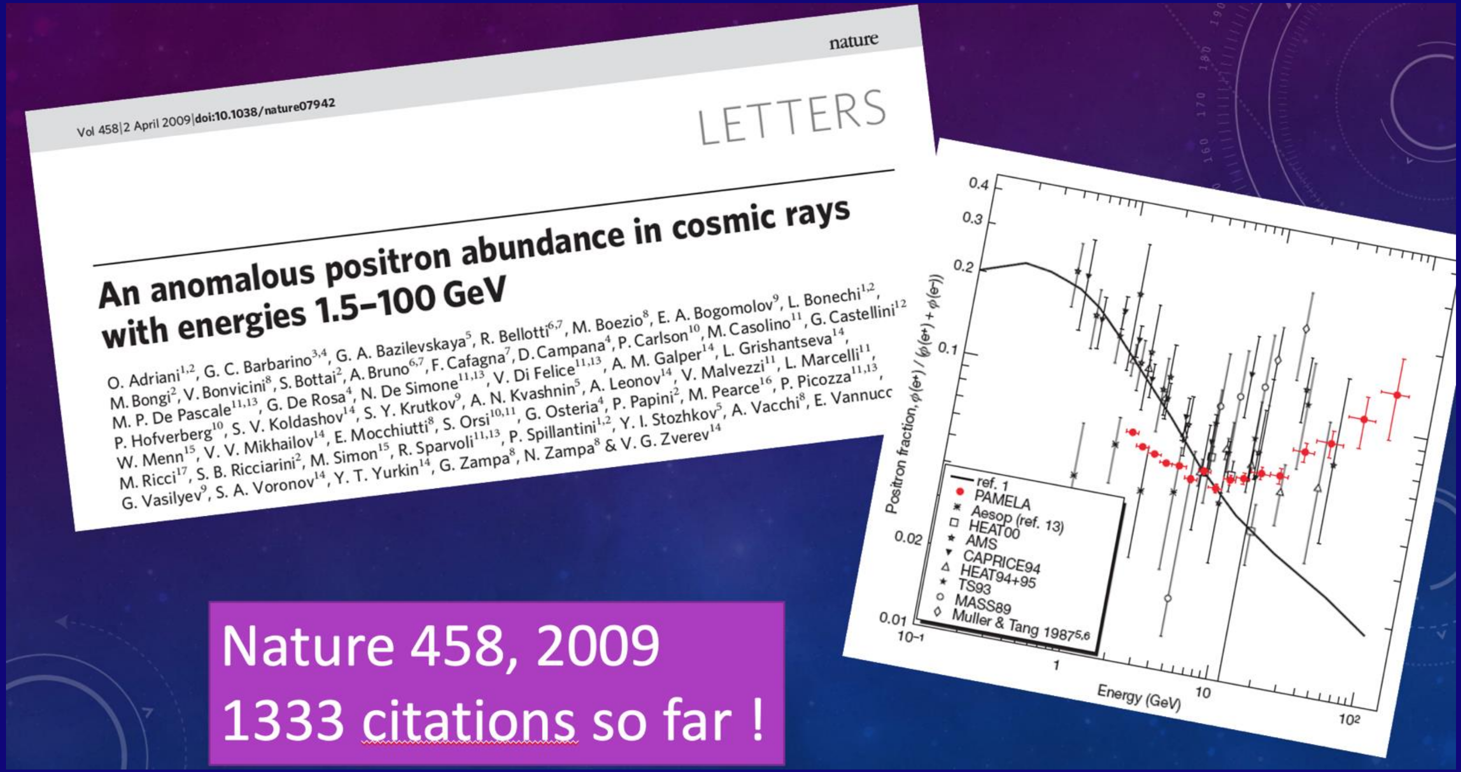
REUSABLE CONTAINER
DO NOT DESTROY
DO NOT DROP
TIEDOWN
MAX LOAD 1000 DAN
13

Il lancio da Bajkonur (15/06/2006)

ФЕДЕРАЛЬНОЕ КОСМИЧЕСКОЕ АГЕНТСТВО
ФГУП "КБОМ им. В.П. БАРМИНА"
ФИЛИАЛ
ЦЕНТР ИСПЫТАНИЙ №1
СТАРТОВЫЙ КОМПЛЕКС
"СОЮЗ"
пл.1
КБОМ

I risultati scientifici di Pamela




nature
Vol 458|2 April 2009|doi:10.1038/nature07942

LETTERS

An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV

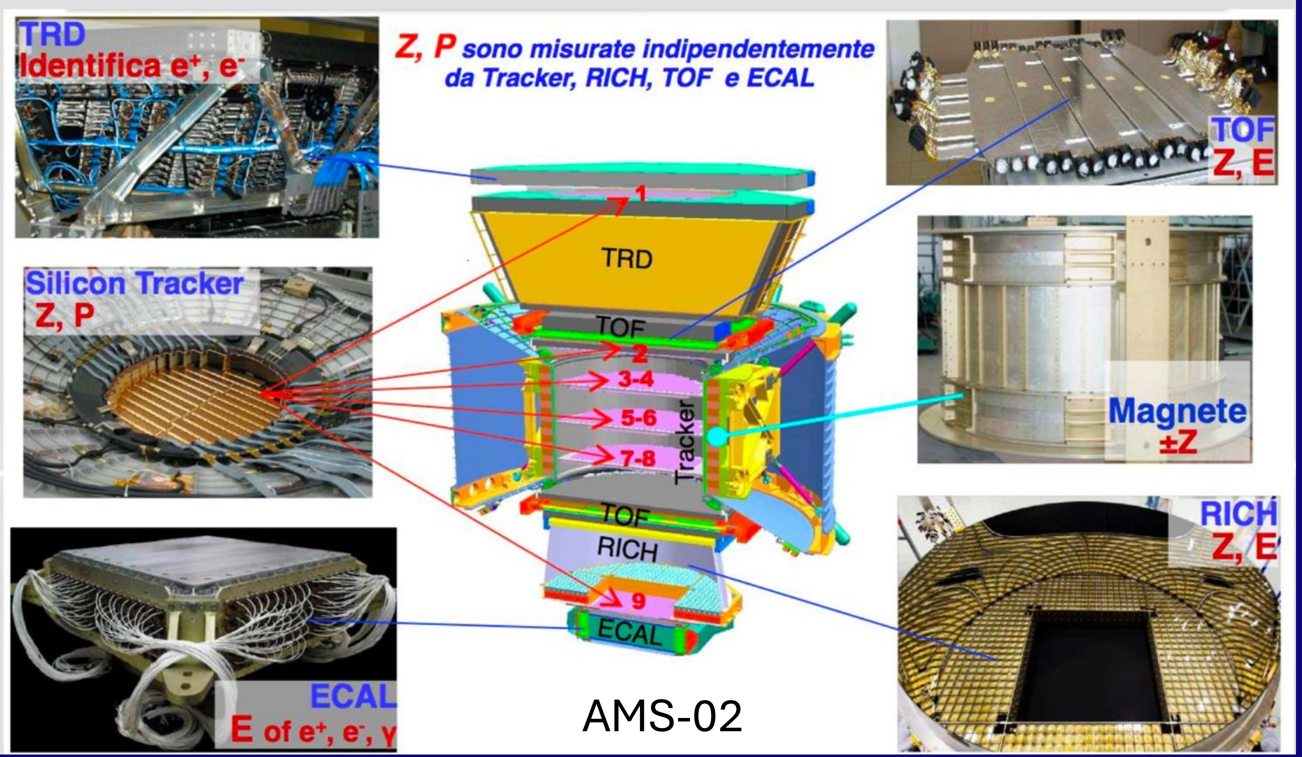
O. Adriani[1,2], G. C. Barbarino[3,4], G. A. Bazilevskaya[5], R. Bellotti[6,7], M. Boezio[8], E. A. Bogomolov[9], L. Bonechi[1,2], M. Bongi[2], V. Bonvicini[8], S. Bottai[2], A. Bruno[6,7], F. Cafagna[7], D. Campana[4], P. Carlson[10], M. Casolino[11], G. Castellini[12], M. P. De Pascale[11,13], G. De Rosa[4], N. De Simone[11,13], V. Di Felice[11,13], A. M. Galper[14], L. Grishantseva[14], P. Hofverberg[10], S. V. Koldashov[14], S. Y. Krutkov[9], A. N. Kvashnin[5], A. Leonov[14], V. Malvezzi[11], L. Marcelli[11], W. Menn[15], V. V. Mikhailov[14], E. Mocchiutti[8], S. Orsi[10,11], G. Osteria[4], P. Papini[2], M. Pearce[16], P. Picozza[11,13], M. Ricci[17], S. B. Ricciarini[2], M. Simon[15], R. Sparvoli[11,13], P. Spillantini[1,2], Y. I. Stozhkov[5], A. Vacchi[8], E. Vannucc G. Vasilyev[9], S. A. Voronov[14], Y. T. Yurkin[14], G. Zampa[8], N. Zampa[8] & V. G. Zverev[14]

Positron fraction, φ(e+) / (φ(e+) + φ(e−))
0.4
0.3
0.2
0.1
0.02
0.01
10⁻¹
1
10
10²
Energy (GeV)
ref. 1
PAMELA
Aesop (ref. 13)
HEAT00
AMS
CAPRICE94
HEAT94+95
TS93
MASS89
Muller & Tang 1987[5,6]

Nature 458, 2009
1333 citations so far !

E poi?

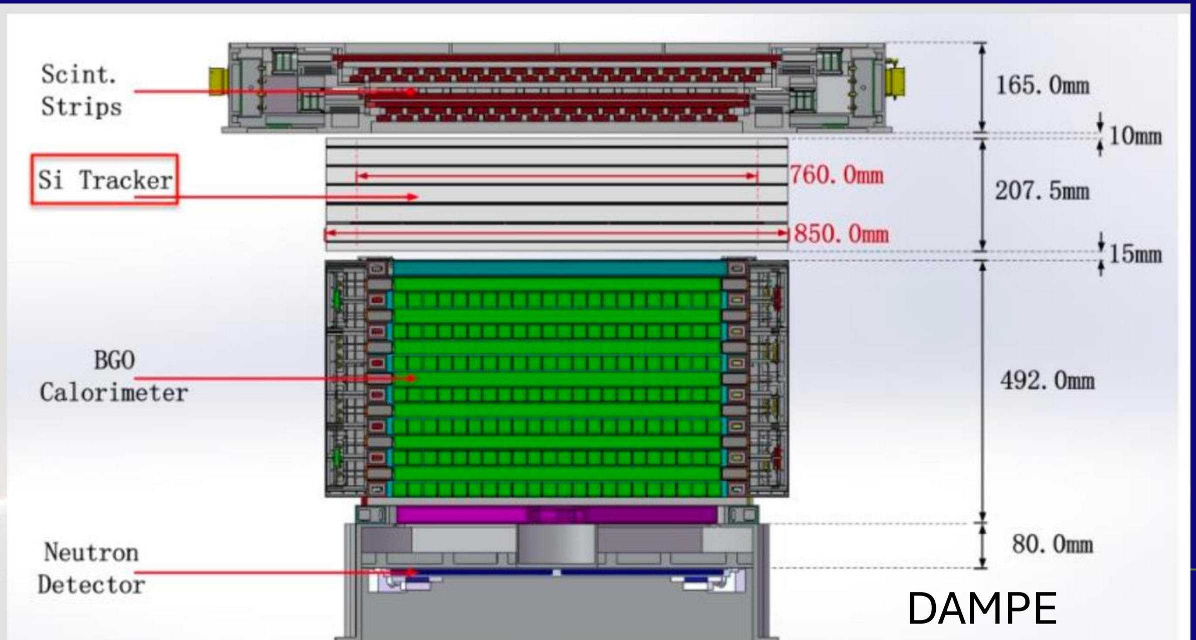
- PAMELA è stato solo il primo di una lunga serie di esperimenti di grande successo!
  - FERMI (dal 2008)
  - AMS-02 (dal 2011)
  - DAMPE (dal 2015)
  - CALET (dal 2015)
  - CSES-01 – CSES-02 (2018 e 2025)
  - IXPE (dal 2021)
  - ….


Z, P sono misurate indipendentemente da Tracker, RICH, TOF e ECAL

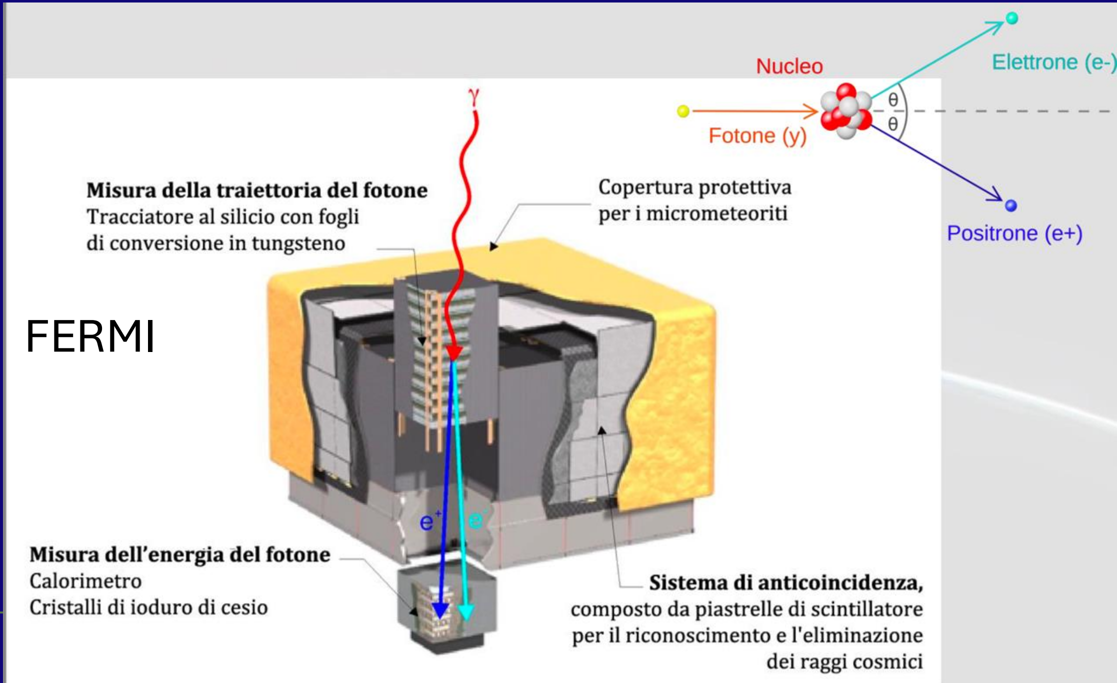
TRD
Identifica e+, e-
Silicon Tracker
Z, P
ECAL
E of e+, e-, γ
TOF
Z, E
Magnete
±Z
RICH
Z, E
TRD
TOF
Tracker
TOF
RICH
ECAL
1
2
3-4
5-6
7-8
9

AMS-02

FERMI


Scint.
Strips
Si Tracker
BGO
Calorimeter
Neutron
Detector
165. 0mm
10mm
760. 0mm
207. 5mm
850. 0mm
15mm
492. 0mm
80. 0mm

DAMPE


FERMI

Misura della traiettoria del fotone
Tracciatore al silicio con fogli
di conversione in tungsteno

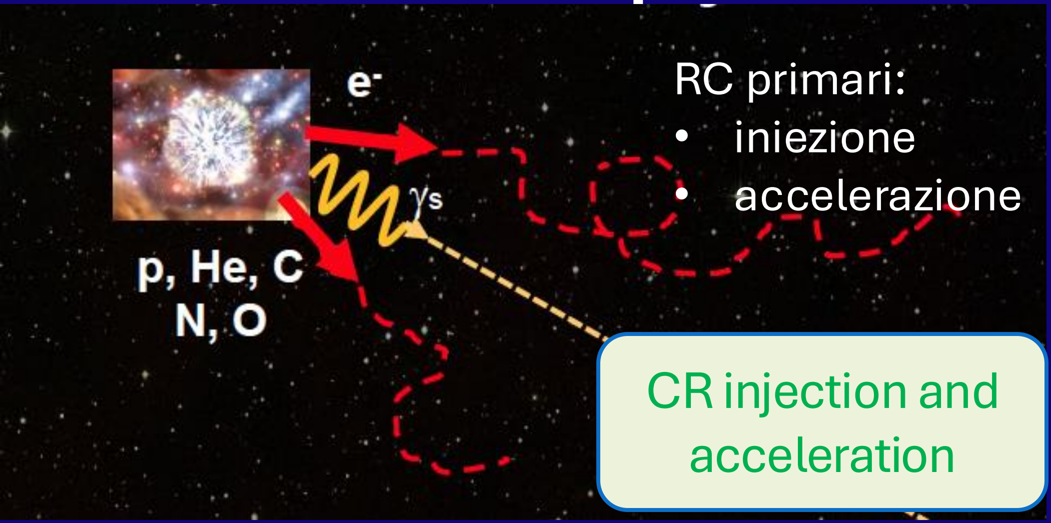
Copertura protettiva
per i micrometeoriti

Misura dell'energia del fotone
Calorimetro
Cristalli di ioduro di cesio

Sistema di anticoincidenza,
composto da piastrelle di scintillatore
per il riconoscimento e l'eliminazione
dei raggi cosmici

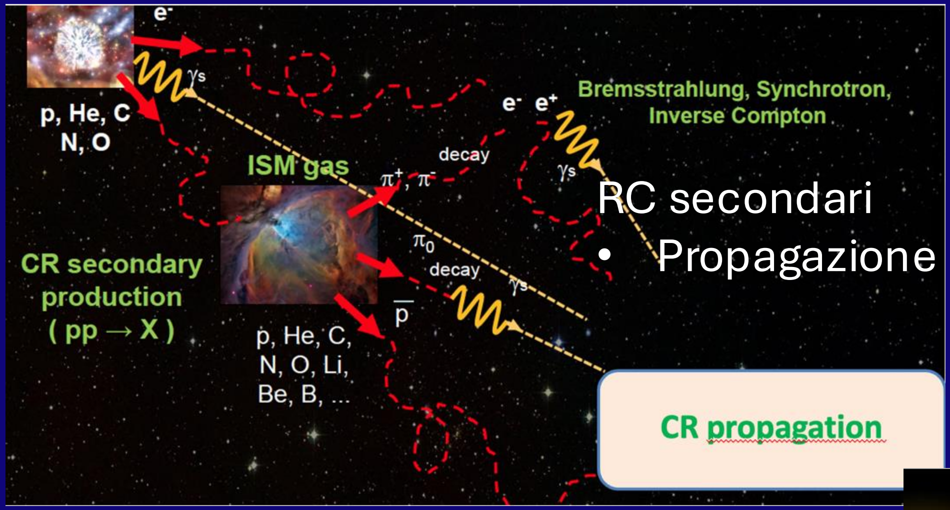
γ
e+
e-
Nucleo
Fotone (γ)
Elettrone (e-)
Positrone (e+)
θ
θ

Cosa possiamo imparare dai RC carichi



RC primari:
- iniezione
- accelerazione

CR injection and acceleration

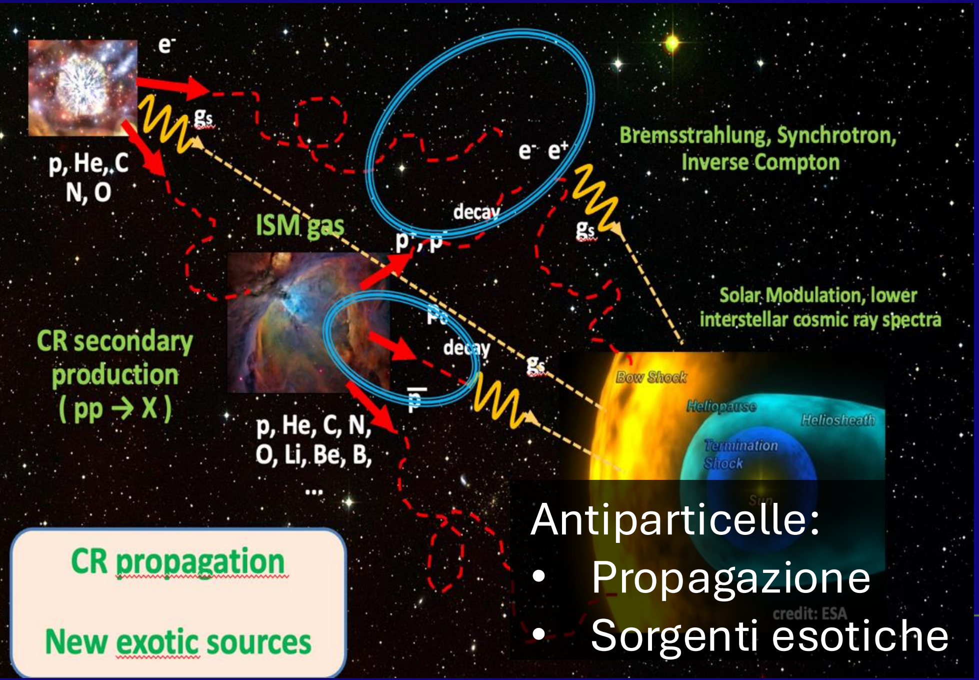

e-
γs
p, He, C
N, O
ISM gas
decay
e- e+
Bremsstrahlung, Synchrotron, Inverse Compton
γs
π+, π-
π0
decay
γs
p̄
CR secondary production (pp → X)
p, He, C, N, O, Li, Be, B, ...

RC secondari
- Propagazione

CR propagation

RC di bassa energia
- Fisica solare
- Space weather
- Geofisica

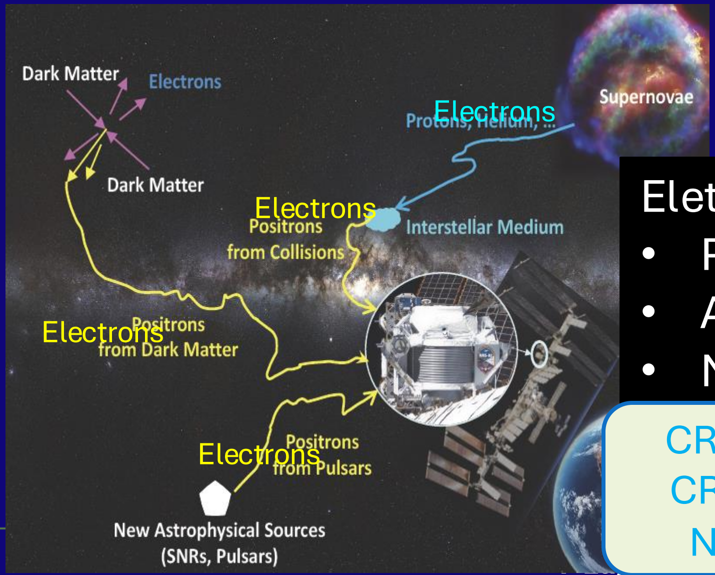
Solar physics
Space weather


e-
gs
p, He, C
N, O
e- e+
Bremsstrahlung, Synchrotron, Inverse Compton
ISM gas
decay
p+, p-
gs
Solar Modulation, lower interstellar cosmic ray spectra
P0
decay
gs
p̄
CR secondary production (pp → X)
p, He, C, N, O, Li, Be, B, ...
Bow Shock
Heliopause
Heliosheath
Termination Shock
credit: ESA

Antiparticelle:
- Propagazione
- Sorgenti esotiche

CR propagation

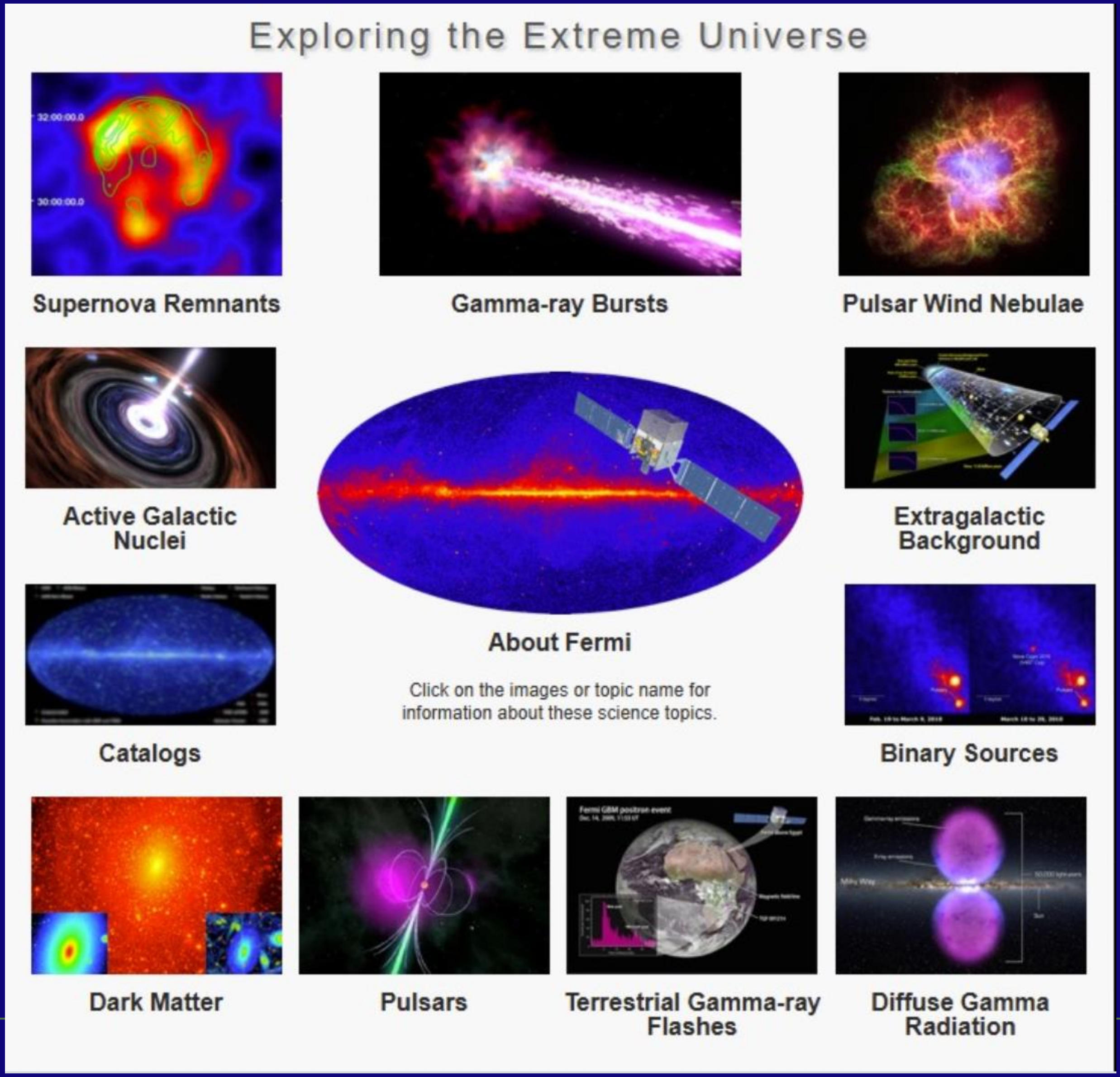
New exotic sources


Dark Matter
Electrons
Dark Matter
Electrons
Protons, Helium, ...
Supernovae
Electrons
Positrons
from Collisions
Interstellar Medium
Electrons
Positrons
from Dark Matter
Electrons
Positrons
from Pulsars
New Astrophysical Sources
(SNRs, Pulsars)

Elettroni+positroni:
- Propagazione
- Accelerazione
- Nuove sorgenti

CR acceleration
CR propagation
New sources

E cosa possiamo imparare dai Raggi γ

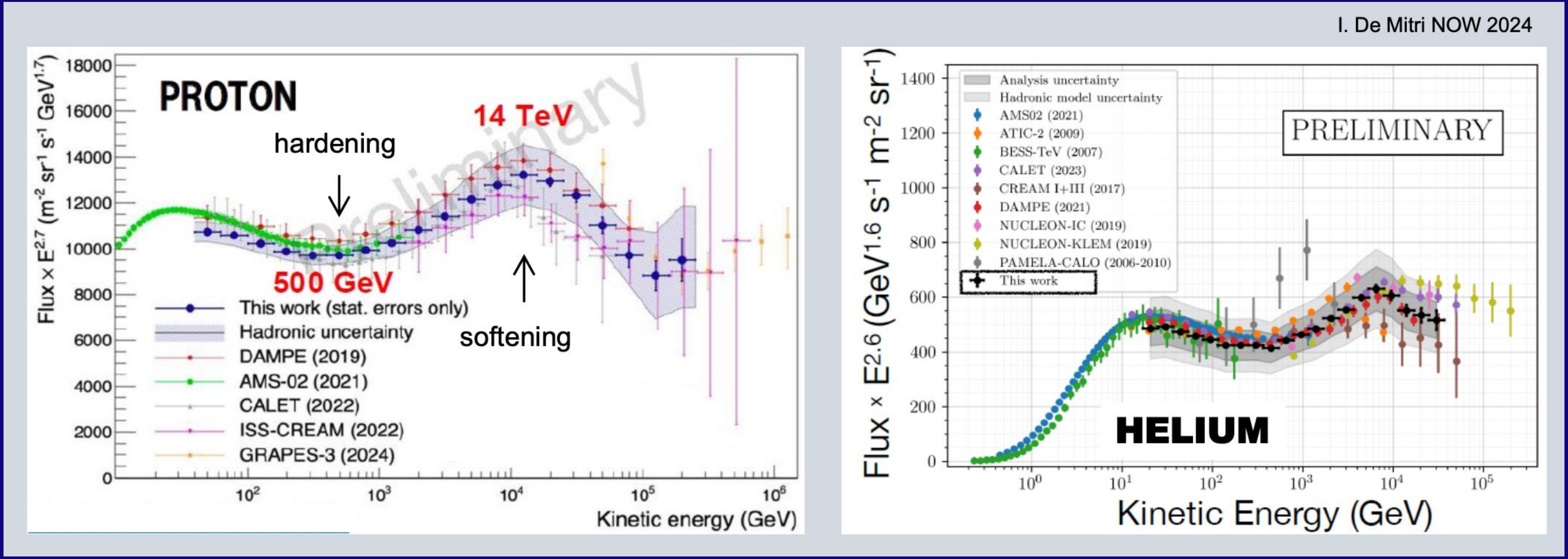

Exploring the Extreme Universe

Supernova Remnants
Gamma-ray Bursts
Pulsar Wind Nebulae
Active Galactic Nuclei
Extragalactic Background
About Fermi
Catalogs
Binary Sources
Dark Matter
Pulsars
Terrestrial Gamma-ray Flashes
Diffuse Gamma Radiation

Click on the images or topic name for information about these science topics.

Ed ora alcuni highlight

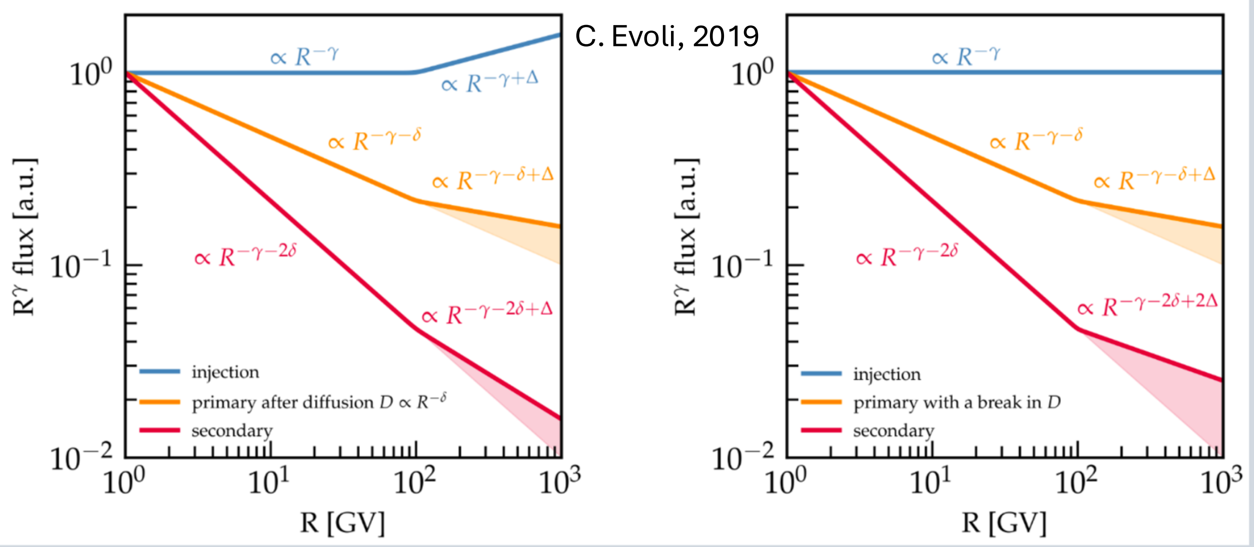
RC primari: flussi di Protoni ed Elio



I. De Mitri NOW 2024

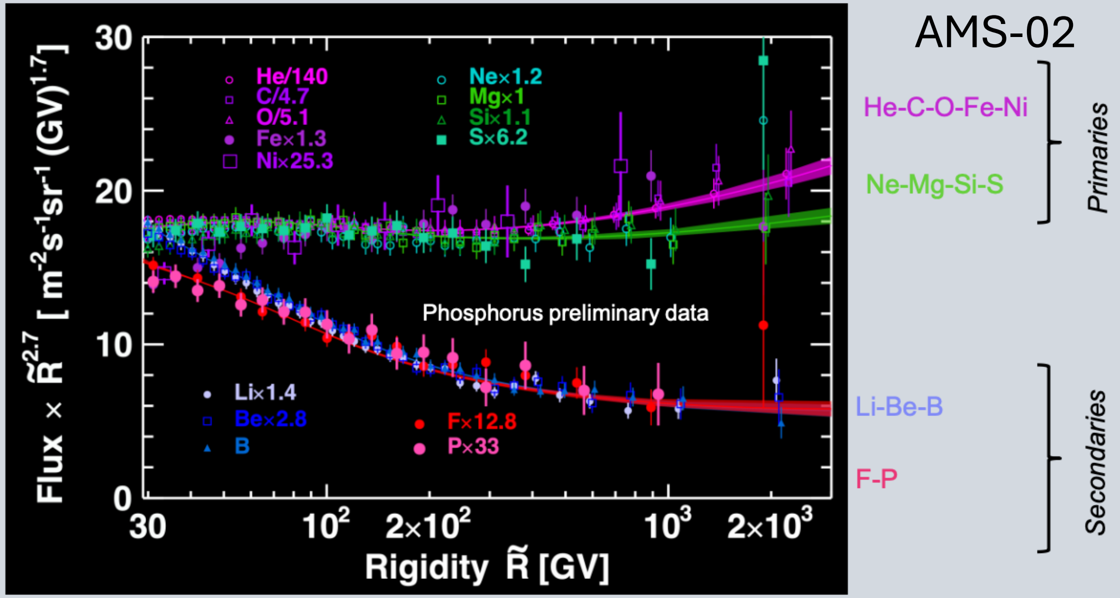
Lo scenario ‘tradizionale’ (‘tutto va come una legge di potenza’!) è stato «distrutto» dalle misure degli ultimi 15 anni!!!

RC secondari: da dove viene il break nello spettro? Iniezione o diffusione?

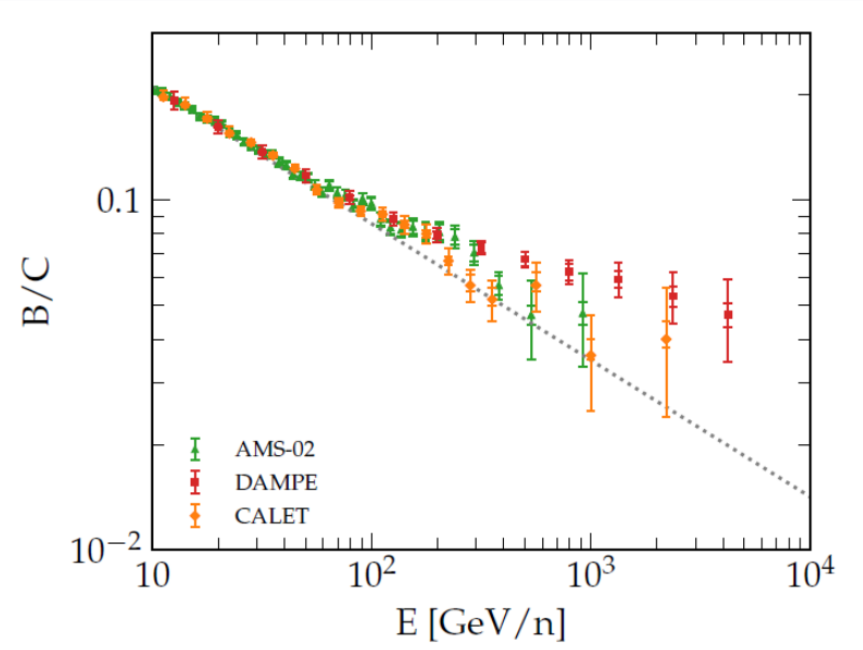


C. Evoli, 2019

M. Aguilar *et al.*, Phys. Rep. 894 (2021) 1-116



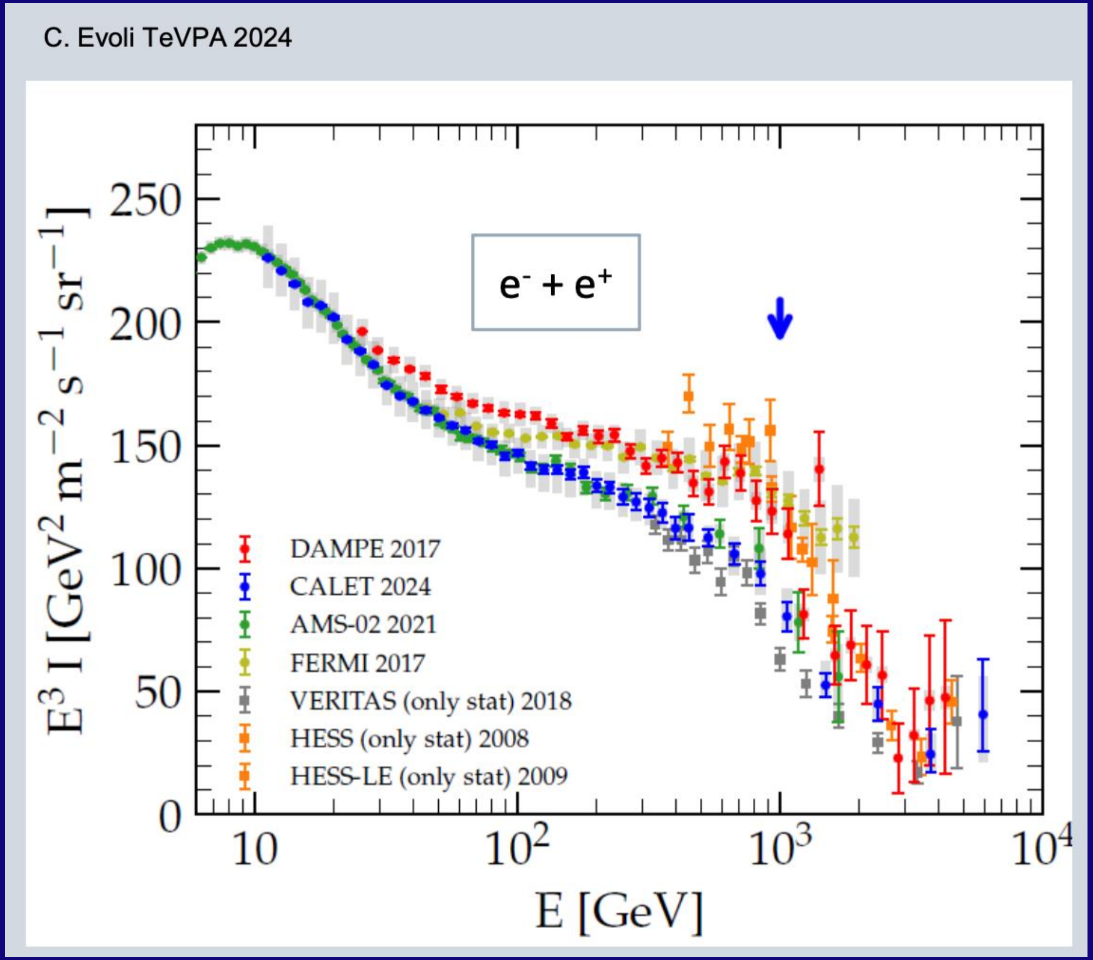
C. Evoli CRISM-MAC 2024

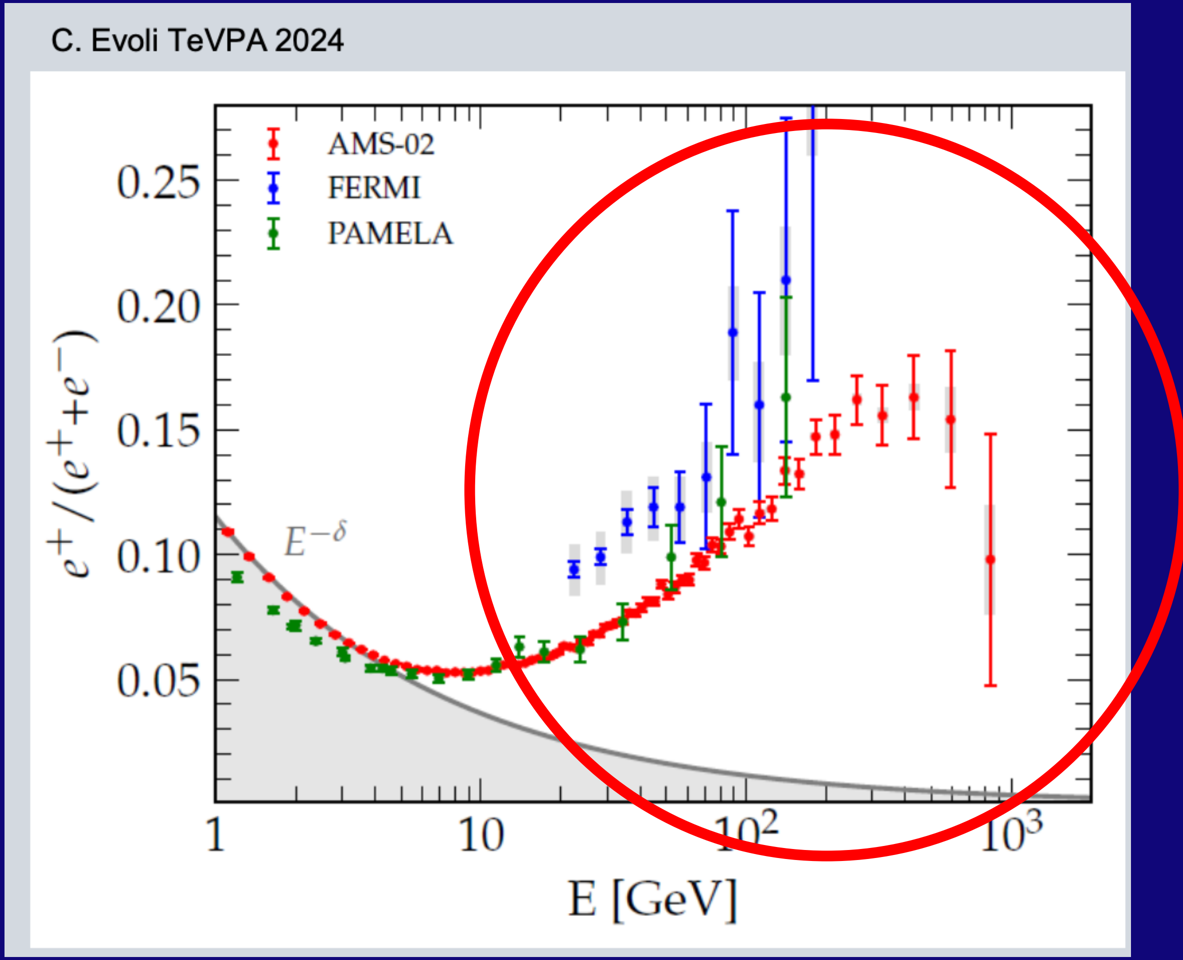


Ci si aspetta che i RC secondari abbiano spettri diversi nelle due ipotesi ‘break nella iniezione / break nella diffusione

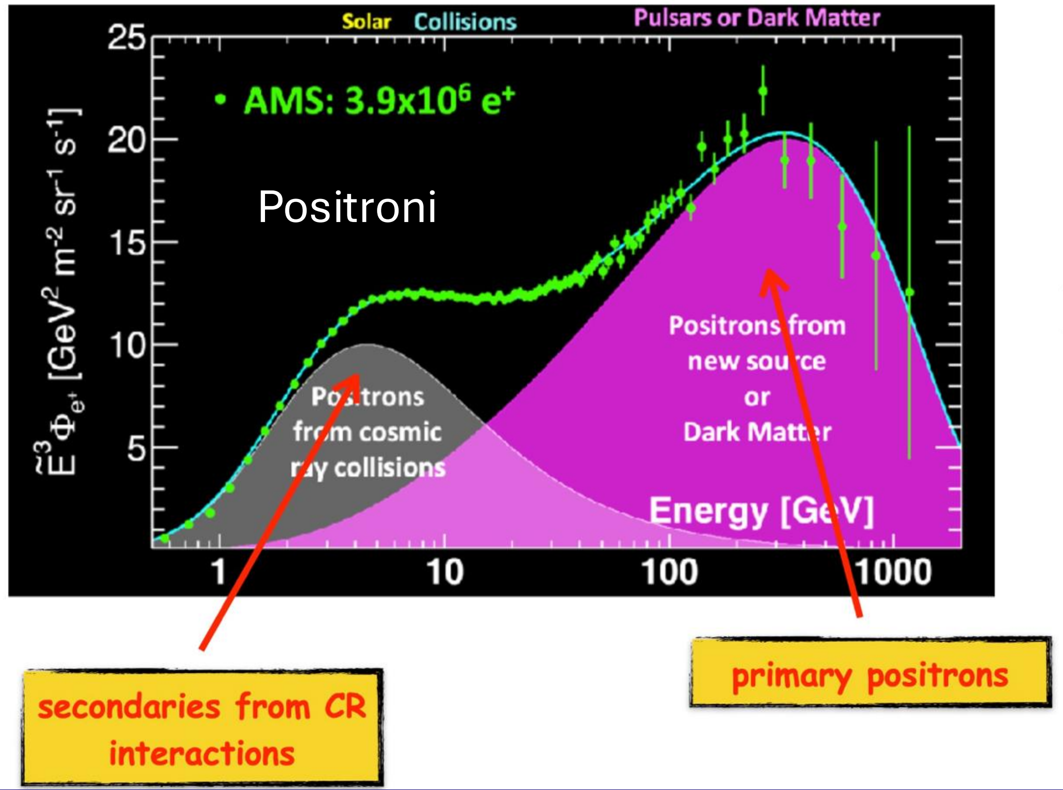
Elettroni+positroni

Positroni



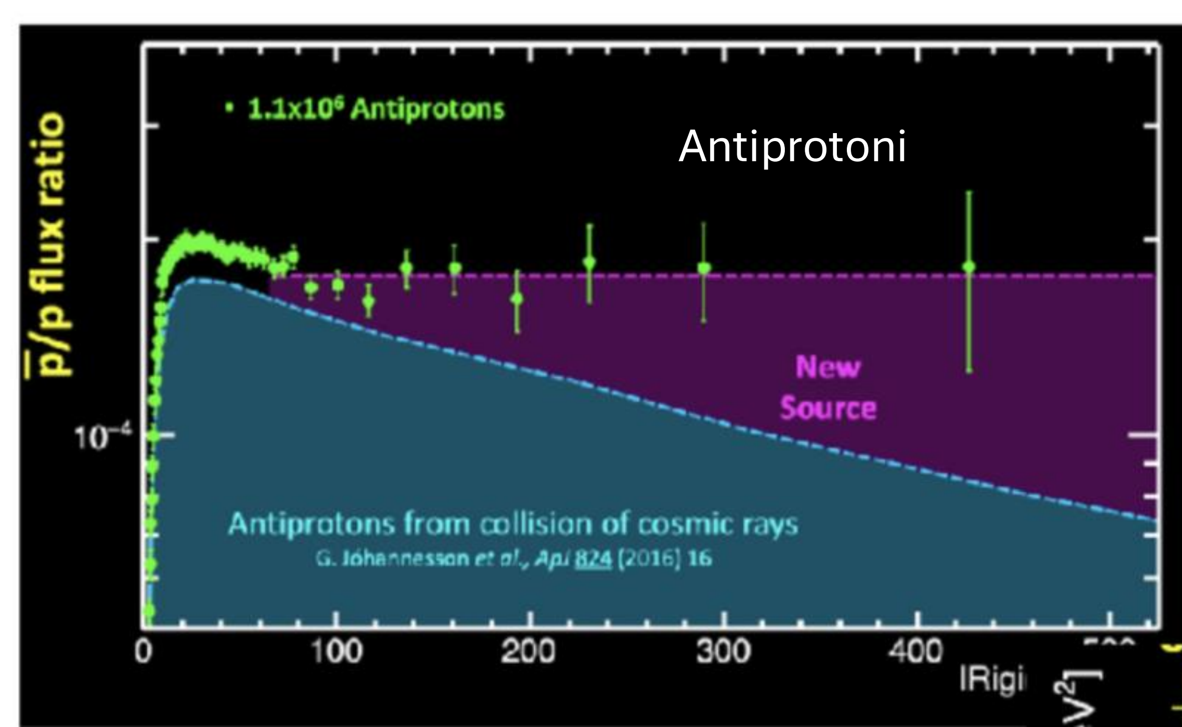


Le antiparticelle nei RC



Positroni

Pulsar or Dark Matter?

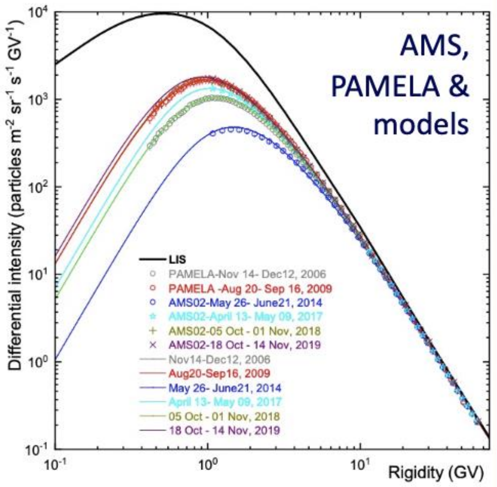


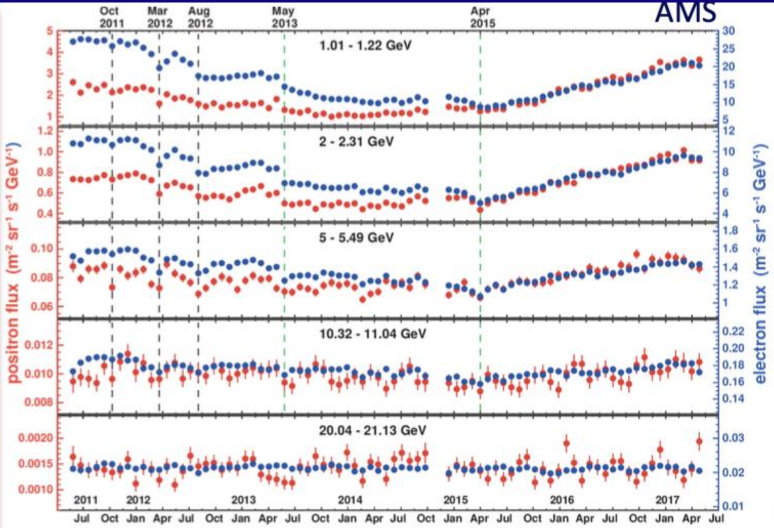
Antiprotoni

RC di bassa energia

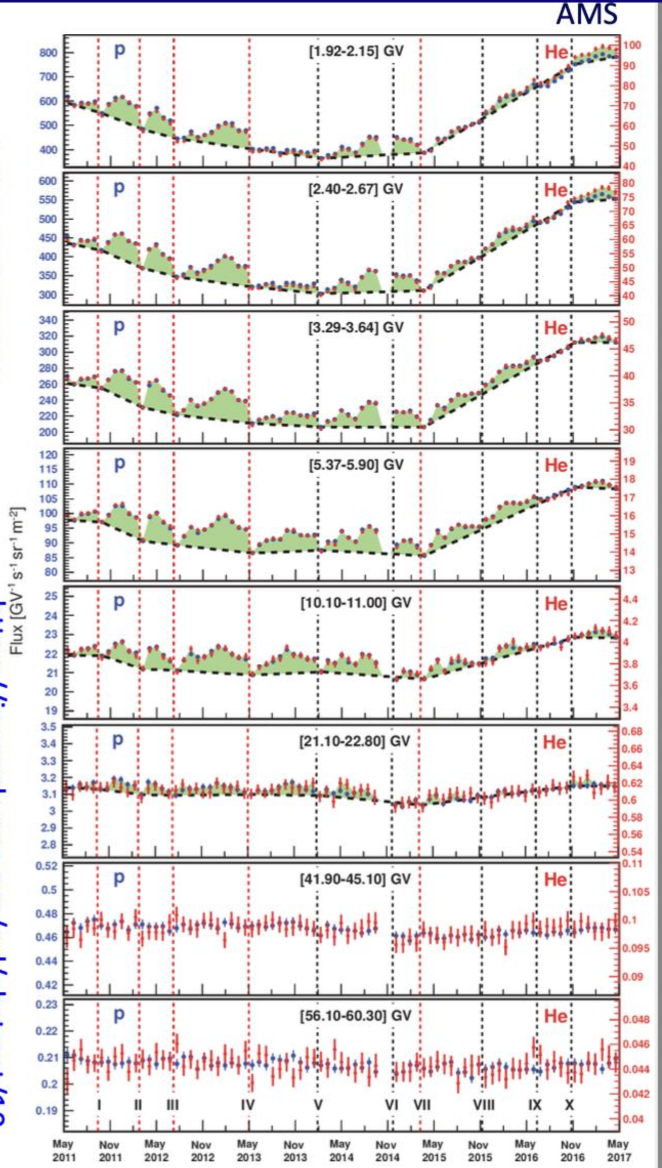
- Modulazione solare
    - Cicli solari
- Fenomeni solari transitori
    - Space weather, pericoloso per i satelliti!
- Studio del campo geomagnetico
    - Fasce di Van Allen
    - Particelle intrappolate

https://pos.sissa.it/444/1318/pdf





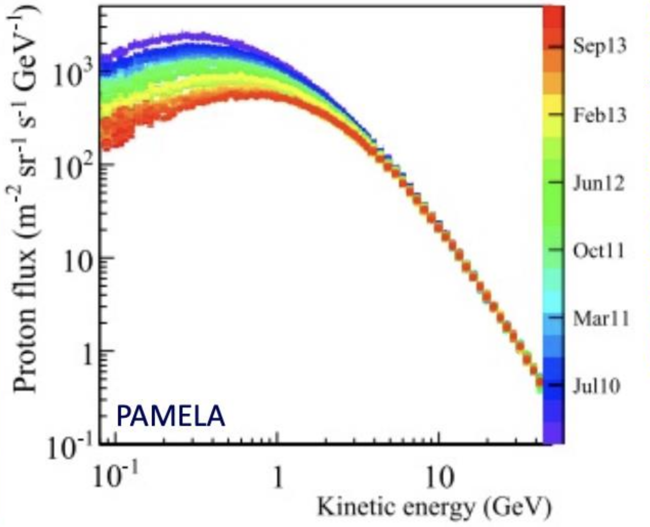
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.121.051102



Take-home message

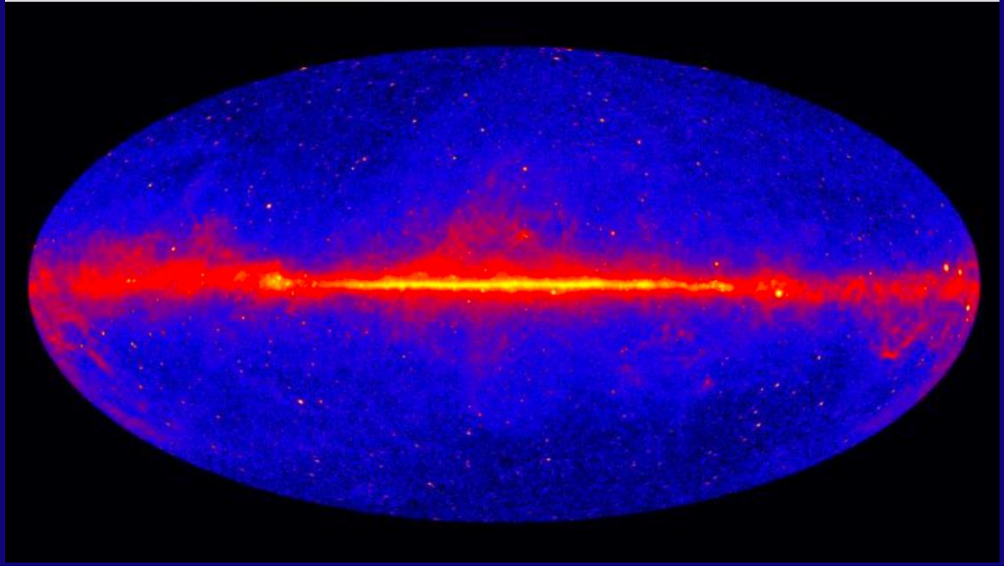
→ experiments operated in the last ~ 15 years (mainly AMS and PAMELA) provided a lot of data of extreme interest for the HelioPhysics and SpaceWeather communities

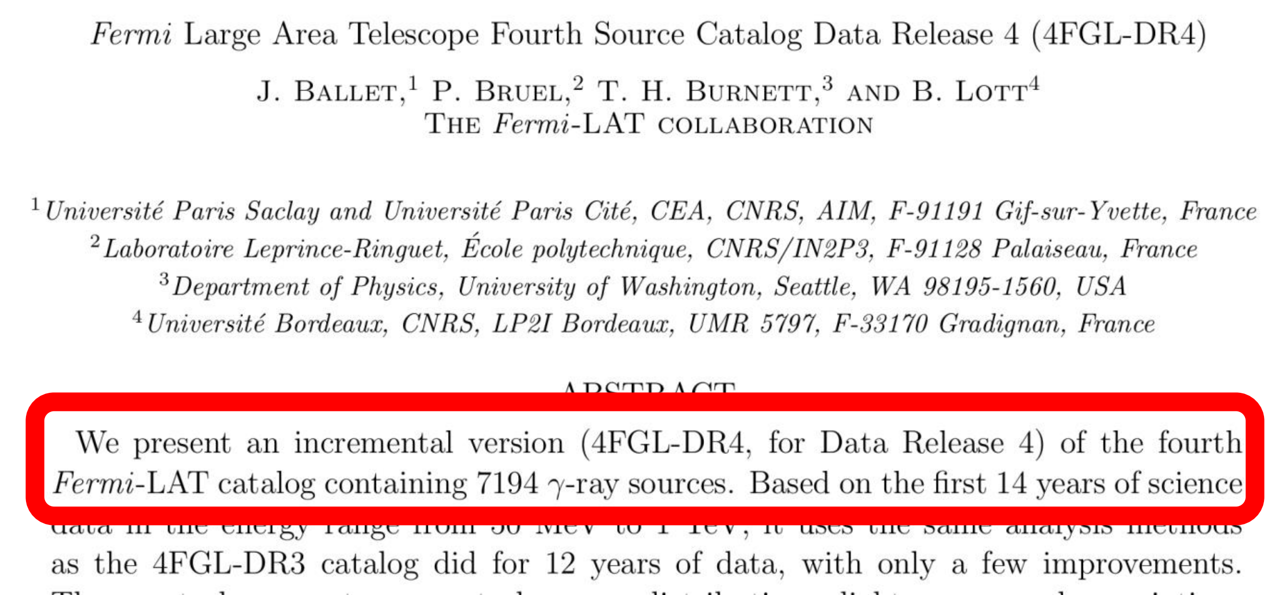
https://iopscience.iop.org/article/10.3847/2041-8213/aaa9b2



https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.121.051101

Il catalogo delle sorgenti γ di FERMI





Fermi Large Area Telescope Fourth Source Catalog Data Release 4 (4FGL-DR4)

J. Ballet,[1] P. Bruel,[2] T. H. Burnett,[3] and B. Lott[4]
The *Fermi*-LAT collaboration

[1] *Université Paris Saclay and Université Paris Cité, CEA, CNRS, AIM, F-91191 Gif-sur-Yvette, France*
[2] *Laboratoire Leprince-Ringuet, École polytechnique, CNRS/IN2P3, F-91128 Palaiseau, France*
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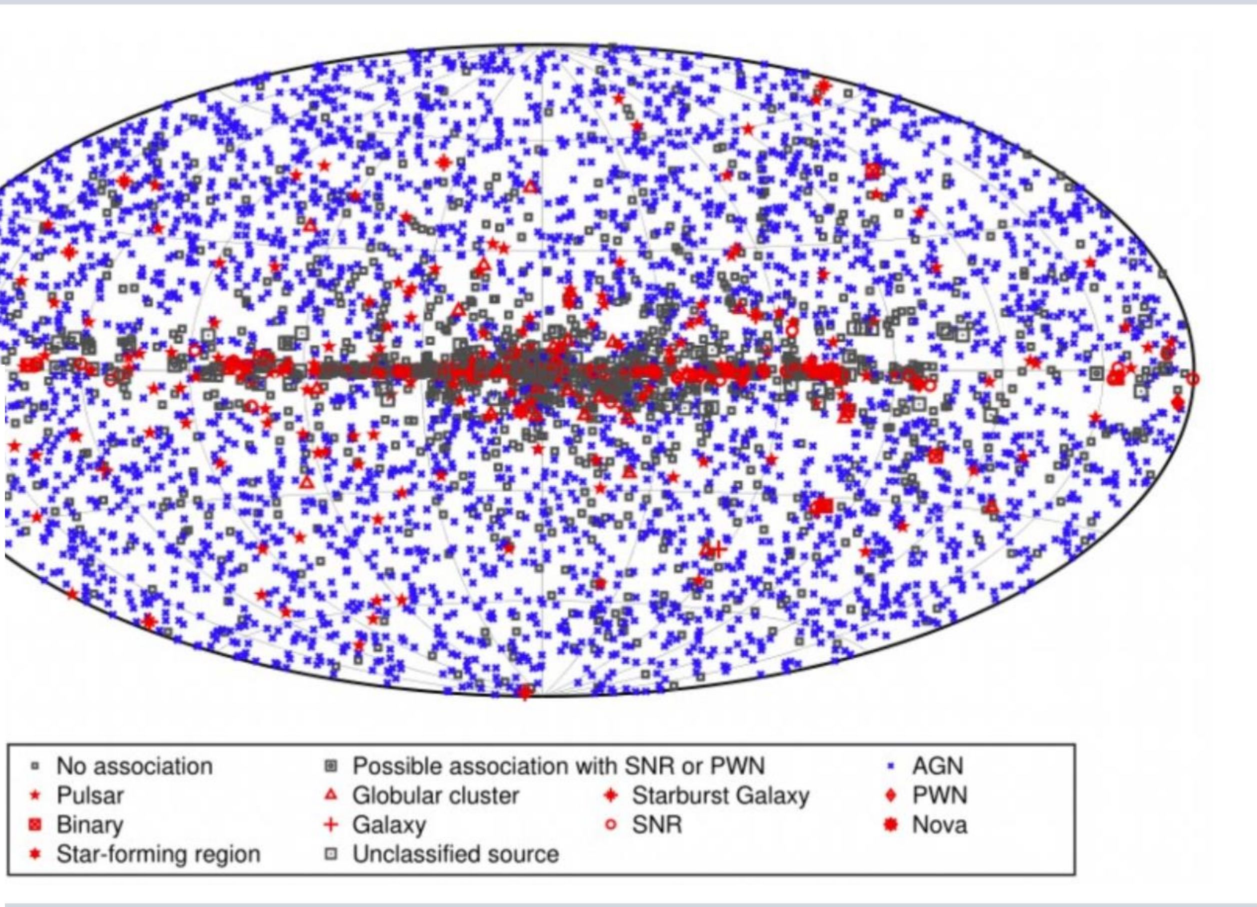
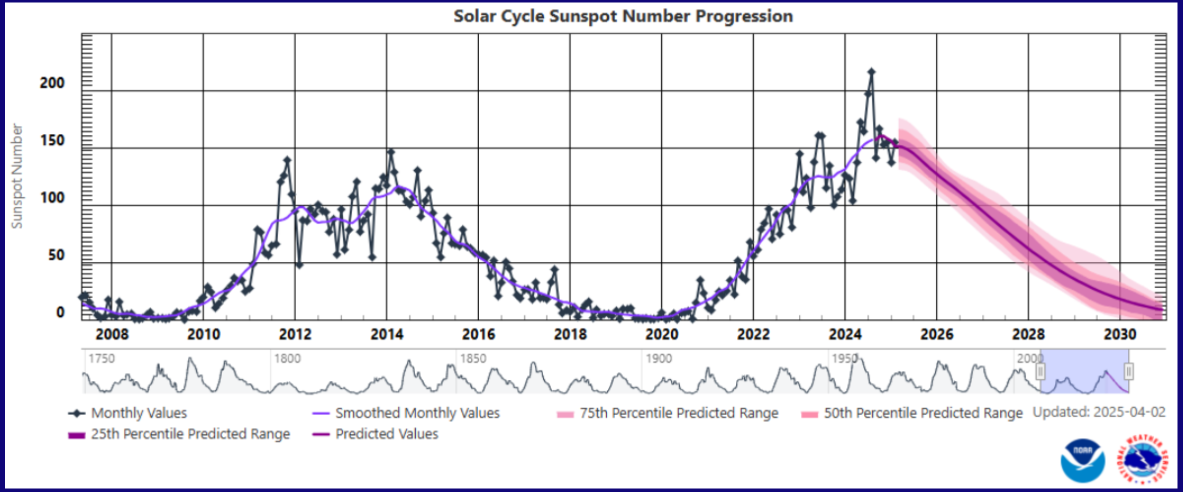
ABSTRACT

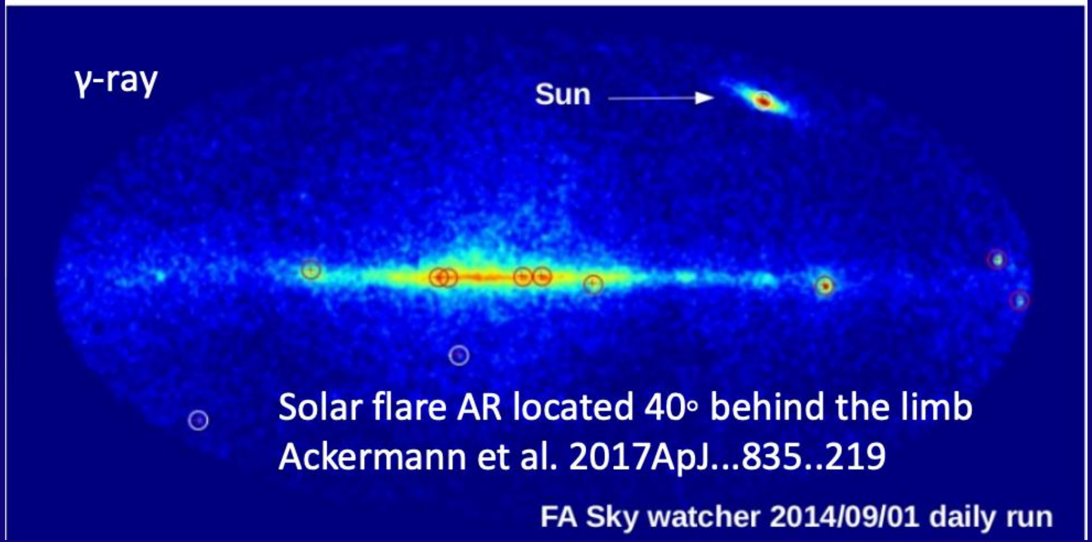
We present an incremental version (4FGL-DR4, for Data Release 4) of the fourth *Fermi*-LAT catalog containing 7194 γ-ray sources. Based on the first 14 years of science data in the energy range from 50 MeV to 1 TeV, it uses the same analysis methods as the 4FGL-DR3 catalog did for 12 years of data, with only a few improvements.


▪ No association
★ Pulsar
▨ Binary
✸ Star-forming region
▣ Possible association with SNR or PWN
△ Globular cluster
+ Galaxy
□ Unclassified source
✦ Starburst Galaxy
○ SNR
· AGN
♦ PWN
✸ Nova

4 - 4° Fermi Catalogue, Data Release 4

La fisica solare e lo ‘space weather’ anche con i γ

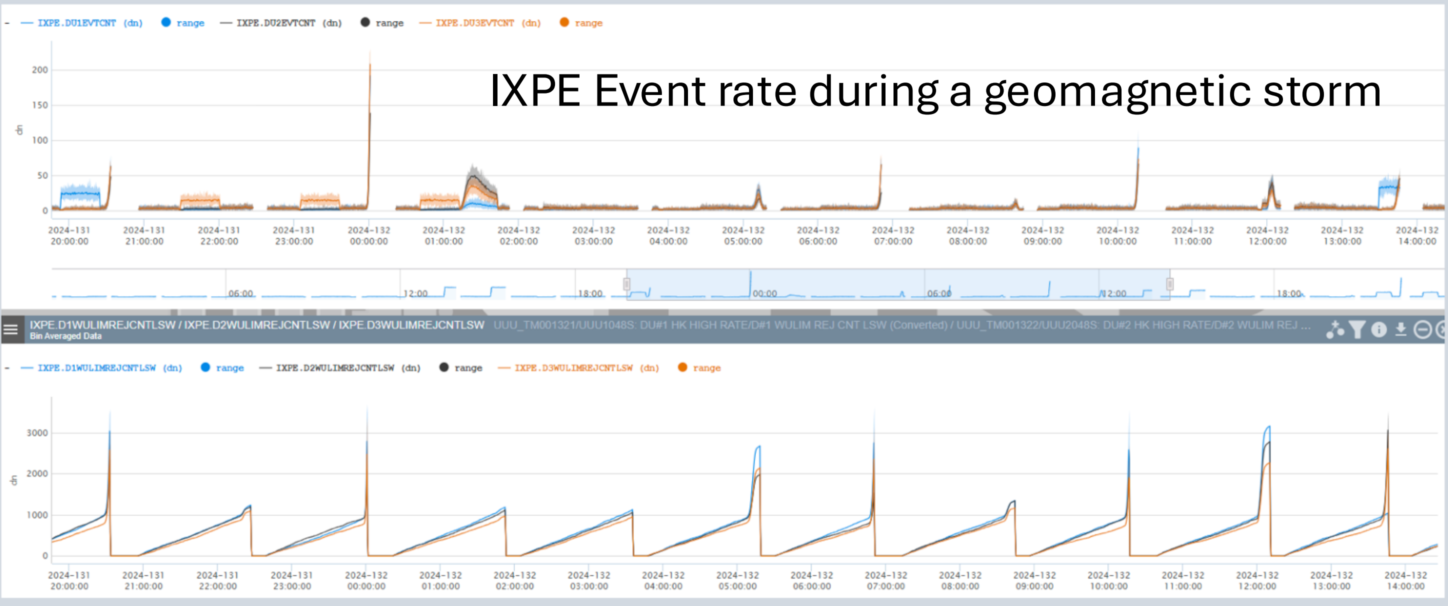




Solar flare AR located 40° behind the limb

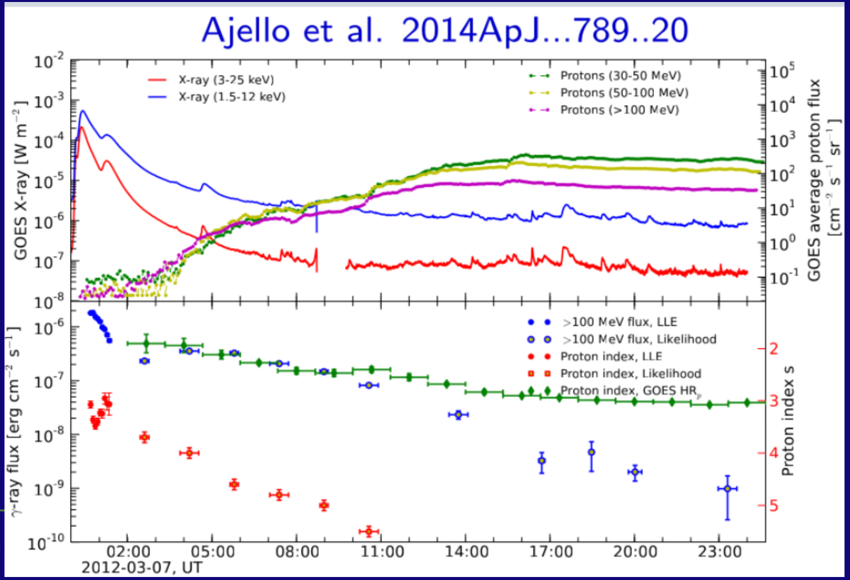
Ackermann et al. 2017ApJ...835..219

FA Sky watcher 2014/09/01 daily run



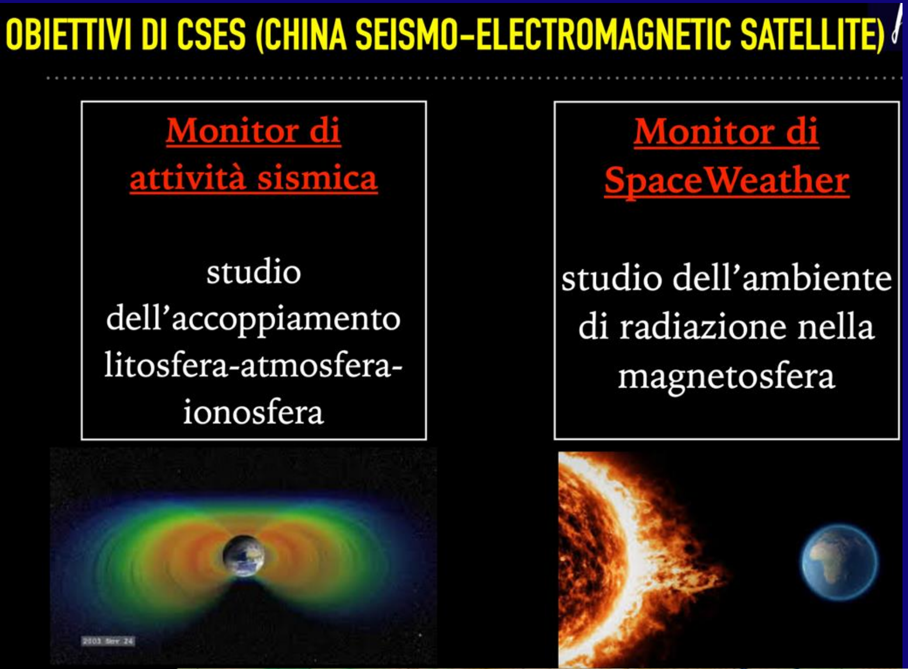
IXPE Event rate during a geomagnetic storm

IXPE.DU1EVTCNT (dn)
range
IXPE.DU2EVTCNT (dn)
range
IXPE.DU3EVTCNT (dn)
range
200
150
100
50
0
2024-131 20:00:00
2024-131 21:00:00
2024-131 22:00:00
2024-131 23:00:00
2024-132 00:00:00
2024-132 14:00:00
IXPE.D1WULIMREJCNTLSW / IXPE.D2WULIMREJCNTLSW / IXPE.D3WULIMREJCNTLSW
Bin Averaged Data
IXPE.D1WULIMREJCNTLSW (dn)
range
IXPE.D2WULIMREJCNTLSW (dn)
range
IXPE.D3WULIMREJCNTLSW (dn)
range
3000
2000
1000
0



Ajello et al. 2014ApJ...789..20

CSES-01 e CSES-02



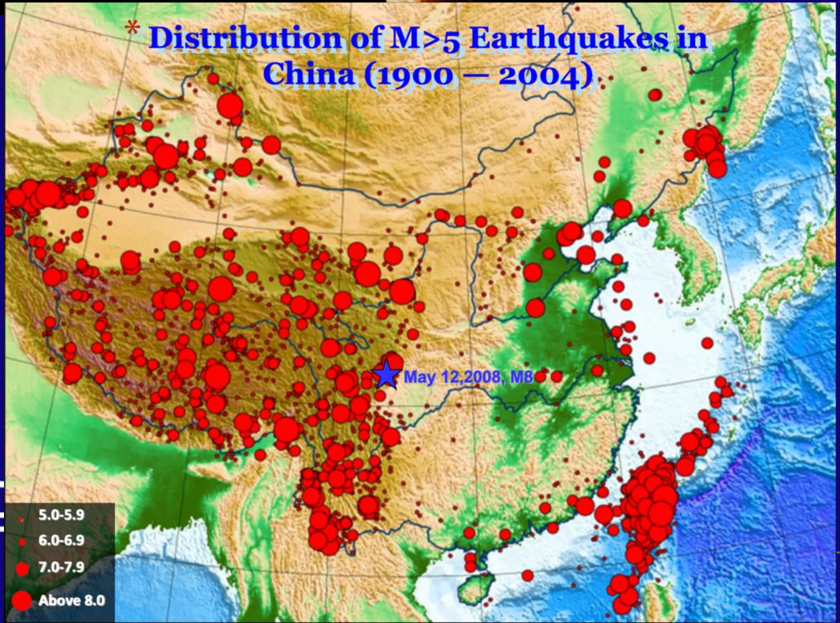
OBIETTIVI DI CSES (CHINA SEISMO-ELECTROMAGNETIC SATELLITE)

Monitor di attività sismica

studio dell'accoppiamento litosfera-atmosfera-ionosfera

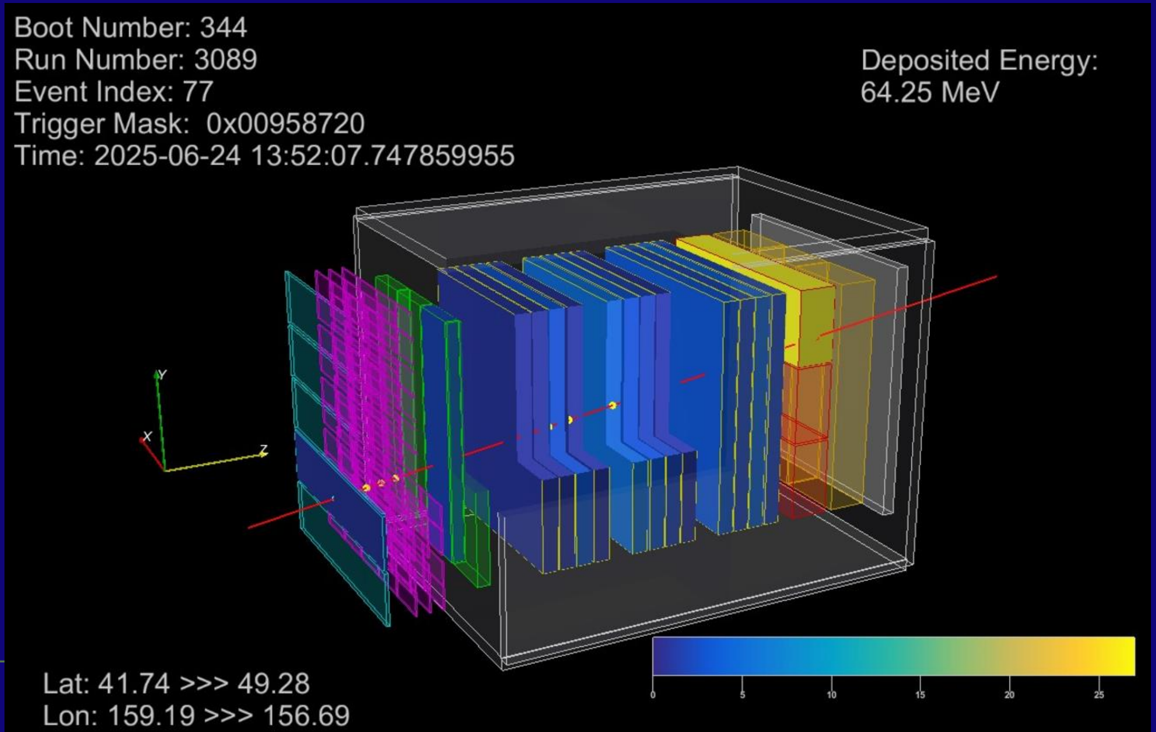
Monitor di SpaceWeather

studio dell'ambiente di radiazione nella magnetosfera



Distribution of M>5 Earthquakes in China (1900 — 2004)

Il lancio di CSES-02 a Giugno 25, fresco fresco!



Boot Number: 344
Run Number: 3089
Event Index: 77
Trigger Mask: 0x00958720
Time: 2025-06-24 13:52:07.747859955

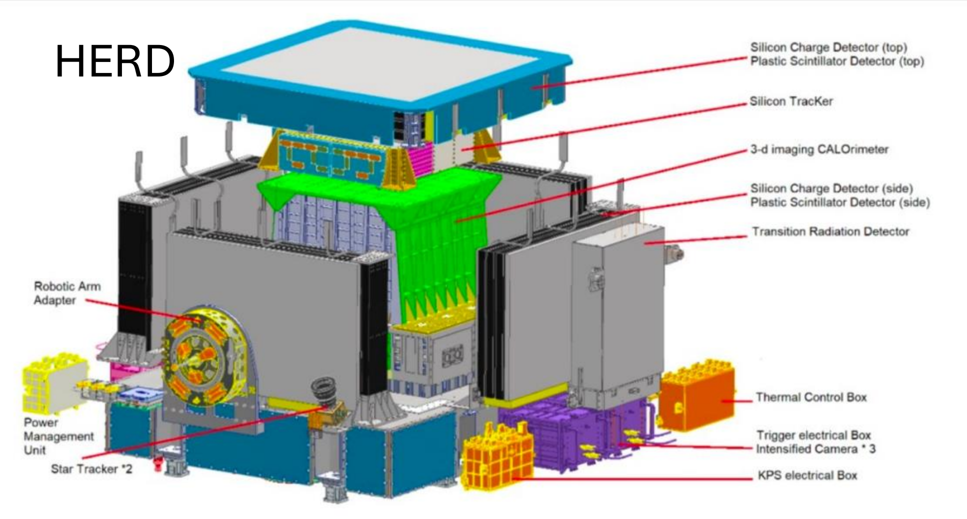
Deposited Energy:
64.25 MeV

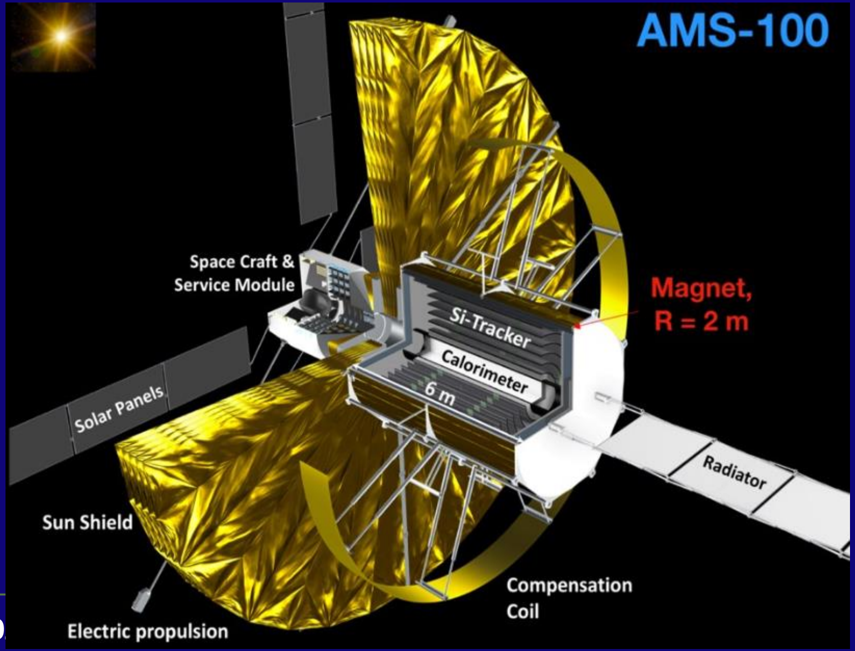
Lat: 41.74 >>> 49.28
Lon: 159.19 >>> 156.69

E poi?

Futuri esperimenti per RC

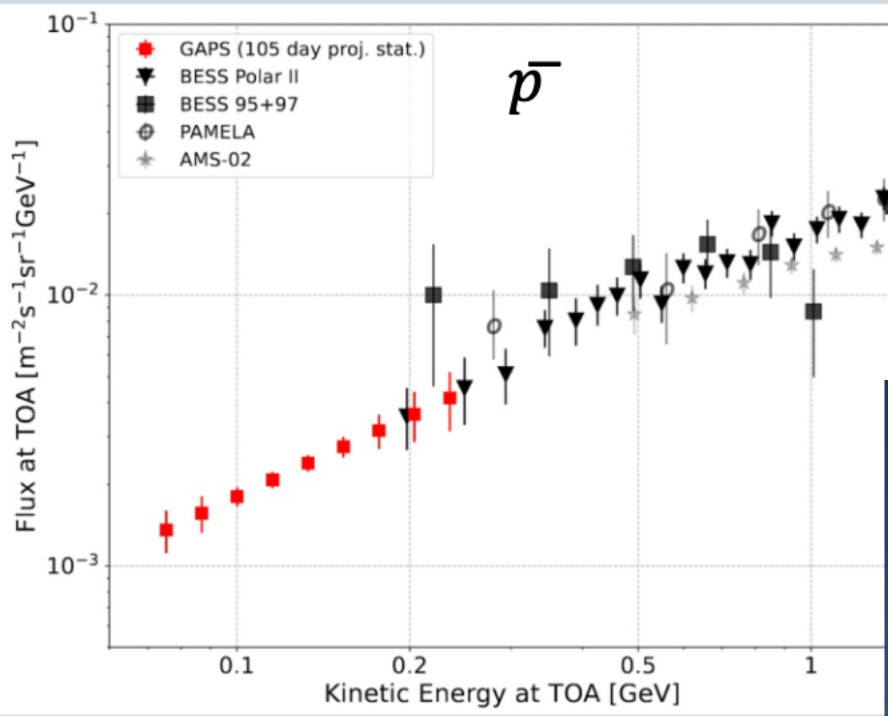
- GAPS, su pallone stratosferico dall’Antartide (2025)
- HERD, sulla Stazione Spaziale Cinese
- Intensa attività di R&D per vedere gli sciami atmosferici di altissima energia dallo spazio
  - SPB1-2 (nel 2023 su pallone)
  - POEMMA
- NUSES su minisatellite italiano
- Un grande esperimento ‘Post FERMI’ per i raggi γ, anche di bassa energia
- Un grande spettrometro magnetico ‘Post AMS’
  - AMS100?
  - Aladino?

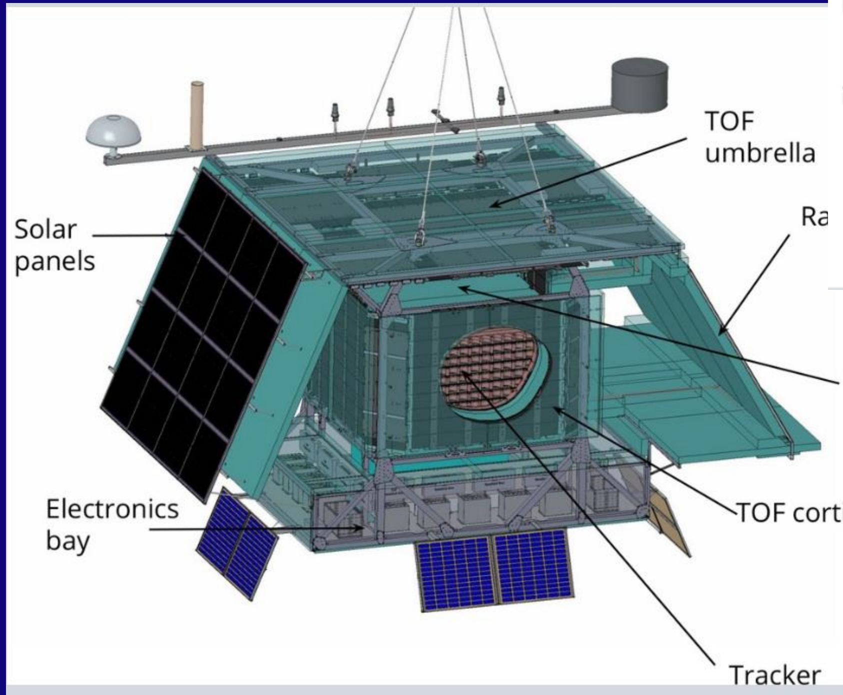

HERD
Silicon Charge Detector (top)
Plastic Scintillator Detector (top)
Silicon TracKer
3-d imaging CALOrimeter
Silicon Charge Detector (side)
Plastic Scintillator Detector (side)
Transition Radiation Detector
Robotic Arm Adapter
Thermal Control Box
Power Management Unit
Trigger electrical Box
Intensified Camera * 3
Star Tracker *2
KPS electrical Box


AMS-100
Space Craft & Service Module
Si-Tracker
Calorimeter
6 m
Magnet, R = 2 m
Solar Panels
Radiator
Sun Shield
Compensation Coil
Electric propulsion

GAPS

- Misura di antiprotoni e antideuterio da pallone stratosferico


GAPS (105 day proj. stat.)
BESS Polar II
BESS 95+97
PAMELA
AMS-02
$\bar{p}$
Flux at TOA [m^{-2}s^{-1}sr^{-1}GeV^{-1}]
10^{-1}
10^{-2}
10^{-3}
0.1
0.2
0.5
1
Kinetic Energy at TOA [GeV]


TOF umbrella
Solar panels
Ra
TOF cube
Electronics bay
TOF cortina
Tracker

Tentativo di lancio – 1 gennaio 2025

Il pallone in attesa di essere rilasciato.

Altri tipi di Fisica per i quali lo spazio è essenziale

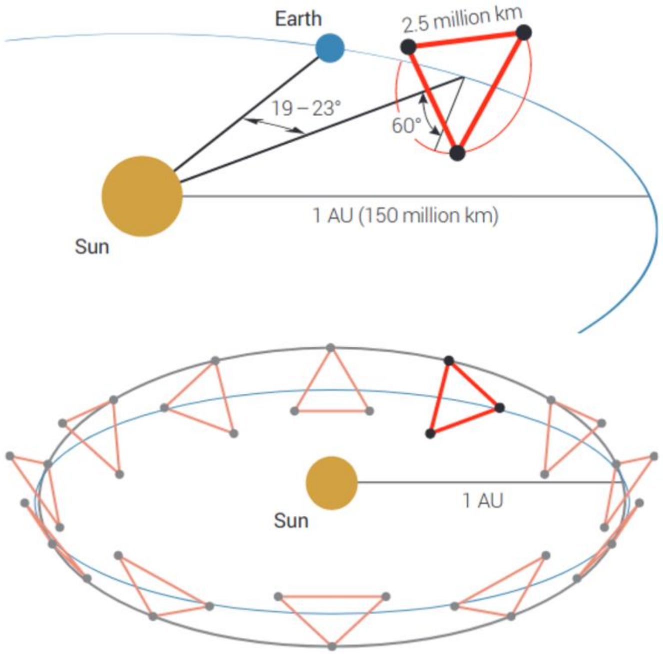
- Misure cosmologiche
  - Misura della radiazione cosmica di fondo (CMB)
  - Materia oscura ed energia oscura
- Astronomia multimessaggera
- Onde gravitazionali

} Non coperte per mancanza di tempo

LISA: Osservazione di Onde Gravitazionali dallo spazio

Lancio previsto nel 2034

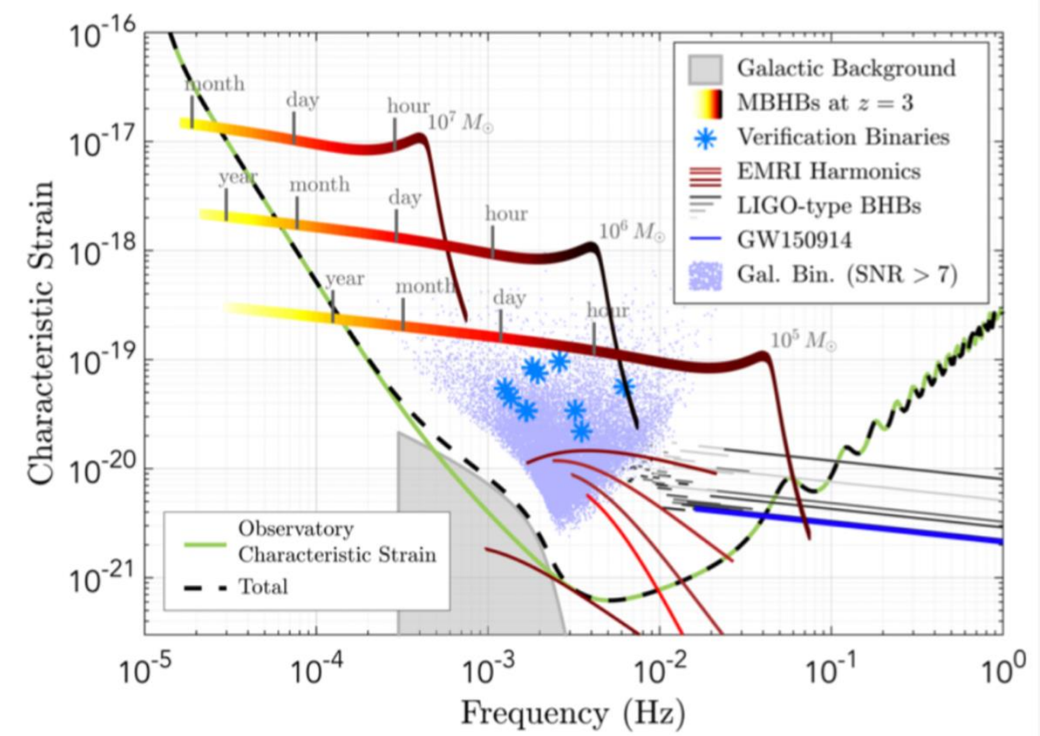
- Long baseline: 2.5 Mkm
- Sensitivity bucket ~ mHz
- Mission duration: 4 to 10 years
- Dominating laser phase noise: synthetic interferometry (TDI)
- LISA Red Book: arXiv:2402.07571



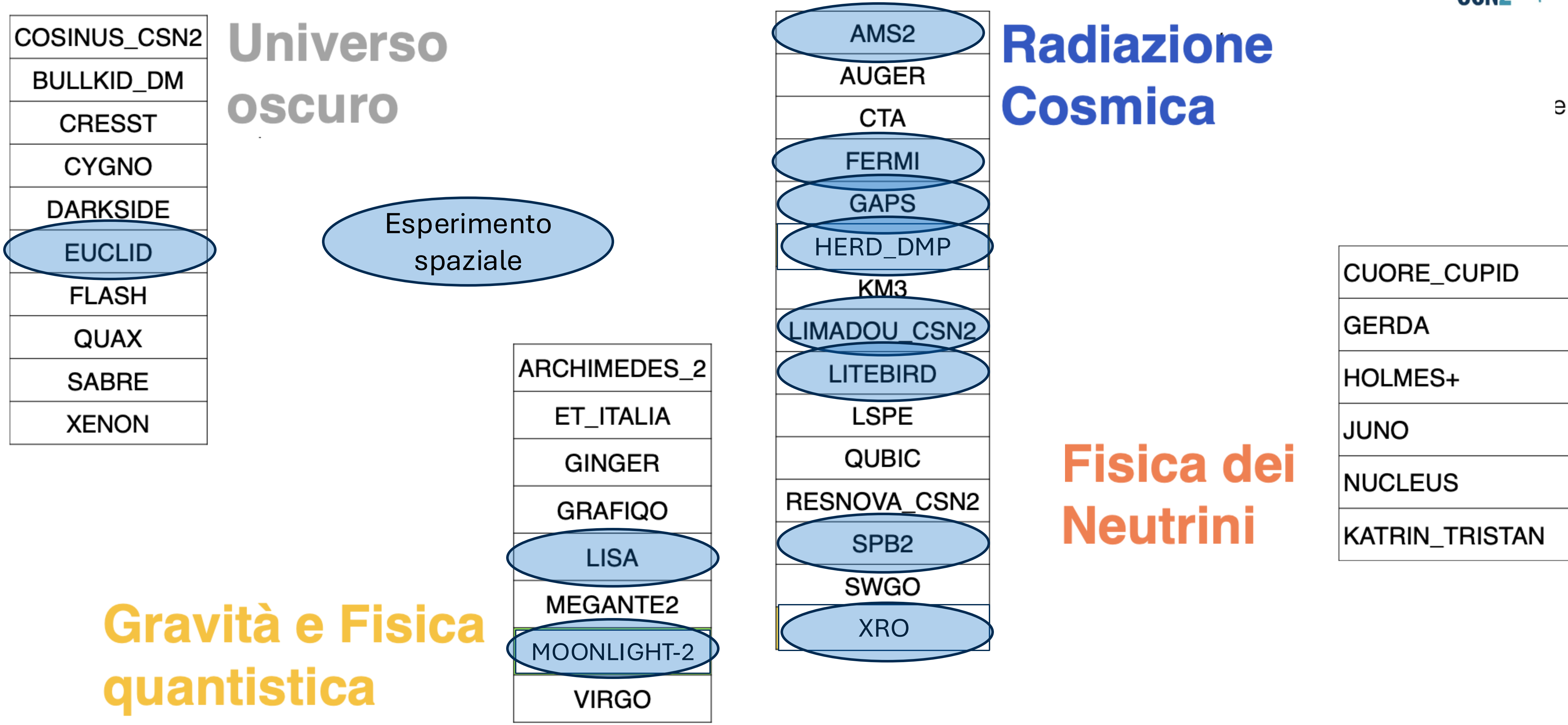
- Con LISA è possibile esplorare le basse frequenze
- Complementare a ET

- Several classes of compact binaries expected
  - Supermassive black hole binaries (SMBH)
  - Stellar mass black hole binaries (sBH)
  - Double white dwarfs
  - Extreme mass ratio inspirals

Challenge principale: Osservazione contemporanea di diverse GW, dato che la sensibilità a basse frequenze permette una ‘early observation’ del segnale



La Commissione Scientifica 2 dell’INFN



Universo oscuro

- COSINUS_CSN2
- BULLKID_DM
- CRESST
- CYGNO
- DARKSIDE
- EUCLID
- FLASH
- QUAX
- SABRE
- XENON

Esperimento spaziale

Gravità e Fisica quantistica

- ARCHIMEDES_2
- ET_ITALIA
- GINGER
- GRAFIQO
- LISA
- MEGANTE2
- MOONLIGHT-2
- VIRGO

Radiazione Cosmica

- AMS2
- AUGER
- CTA
- FERMI
- GAPS
- HERD_DMP
- KM3
- LIMADOU_CSN2
- LITEBIRD
- LSPE
- QUBIC
- RESNOVA_CSN2
- SPB2
- SWGO
- XRO

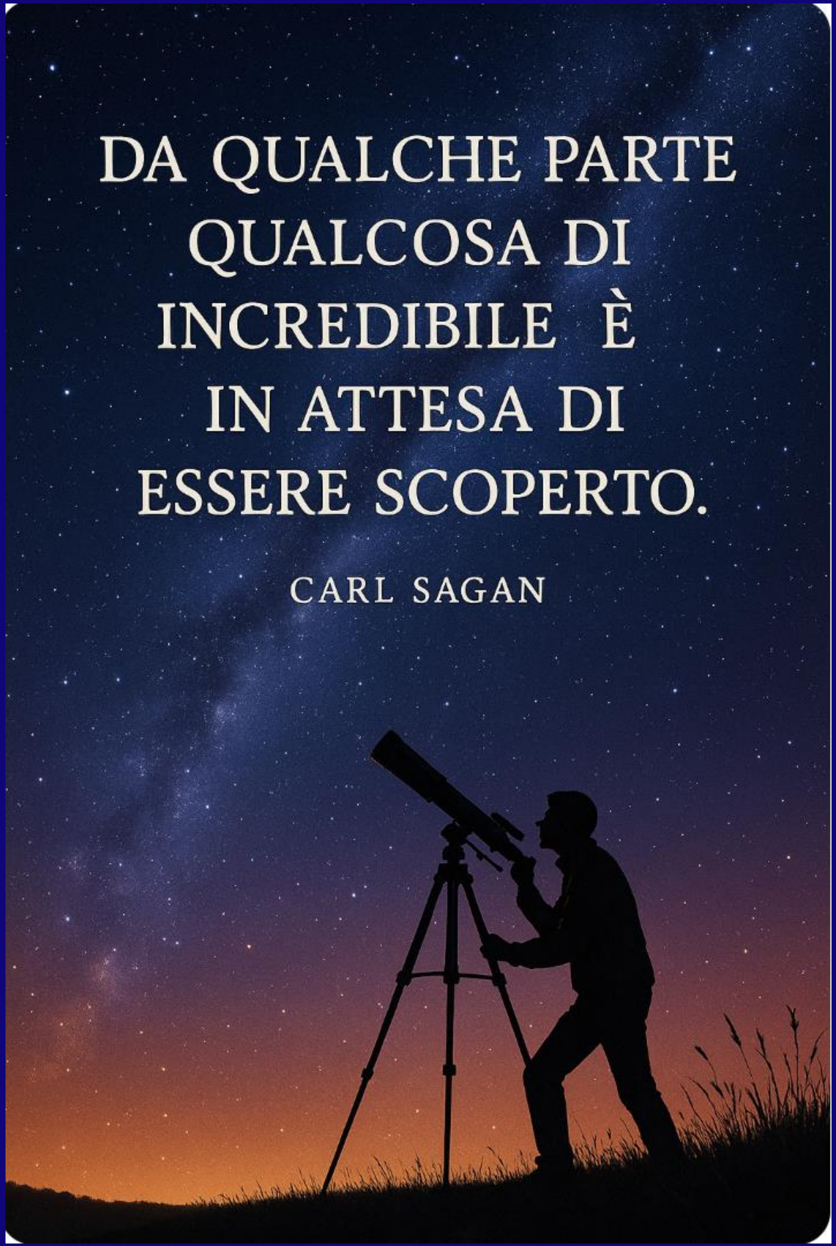
Fisica dei Neutrini

- CUORE_CUPID
- GERDA
- HOLMES+
- JUNO
- NUCLEUS
- KATRIN_TRISTAN

Conclusioni

- Gi esperimenti spaziali sono stati ‘rivoluzionati’ dal ‘metodo INFN’
- Negli ultimi 20 anni sono stati fatti progressi incredibili e del tutto inaspettati andando a fare misure ‘Oltre le frontiere’
- La Fisica nello spazio si e’ rivelata incredibilmente interessante, inaspettata, vitale

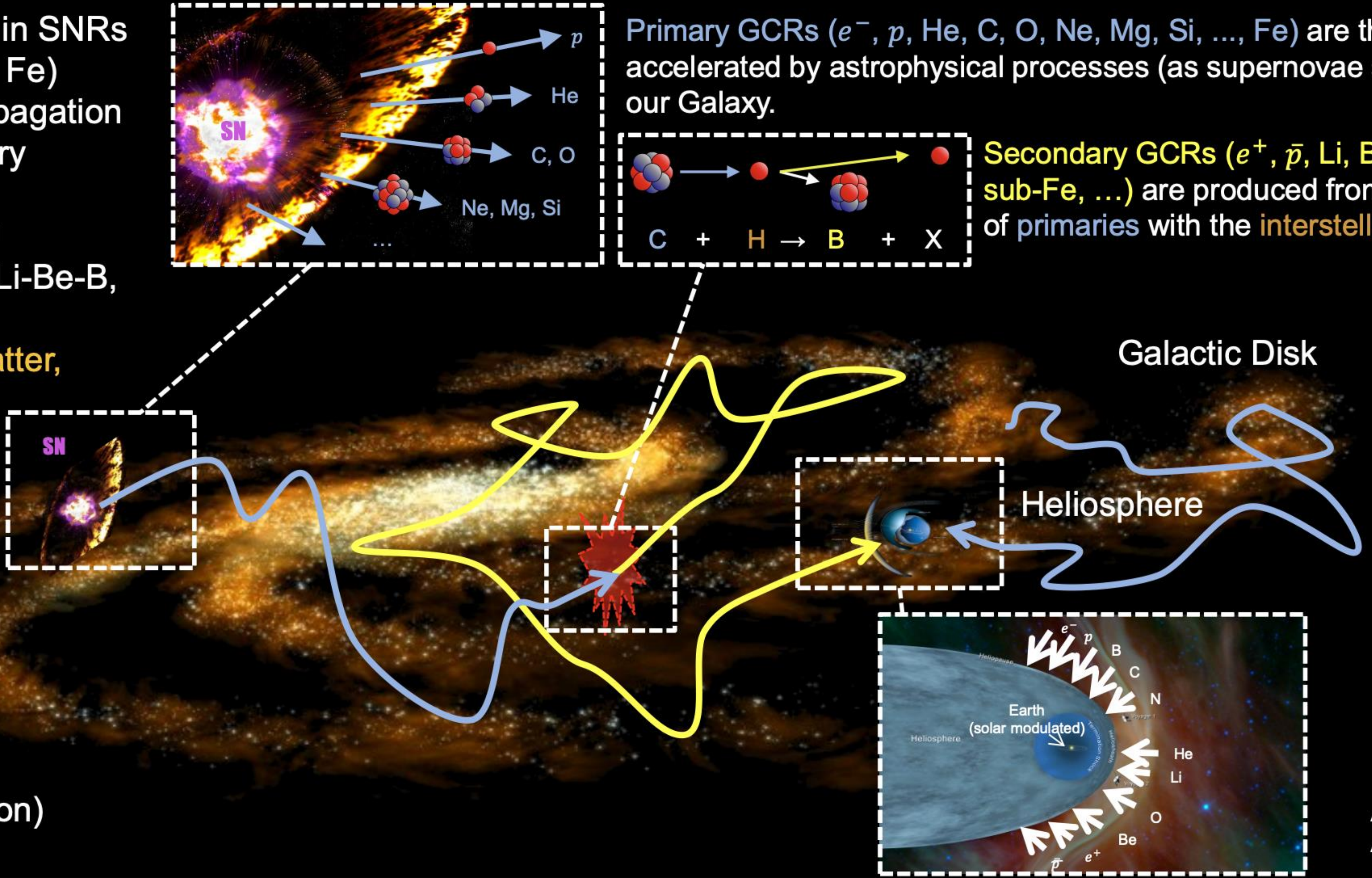
- Cosa ci riserva il futuro?


DA QUALCHE PARTE
QUALCOSA DI
INCREDIBILE È
IN ATTESA DI
ESSERE SCOPERTO.
CARL SAGAN

Backups

Cosa possiamo imparare dai RC carichi

- **Origin**: Shock acceleration in SNRs for primary CRS (p, C-N-O, Fe)
- **Propagation**: Diffusive propagation in interstellar & interplanetary turbulence.
- Collisions with ISM gas and production of secondaries: Li-Be-B, antimatter, γ-rays, etc.
- Exotic contribution: dark matter, primordial antimatter.


SN
p
He
C, O
Ne, Mg, Si
...
C + H → B + X
Galactic Disk
SN
Heliosphere
e^-
p
B
C
N
Heliopause
Earth
(solar modulated)
Heliosphere
He
Li
O
Be
e^+
$\bar{p}$

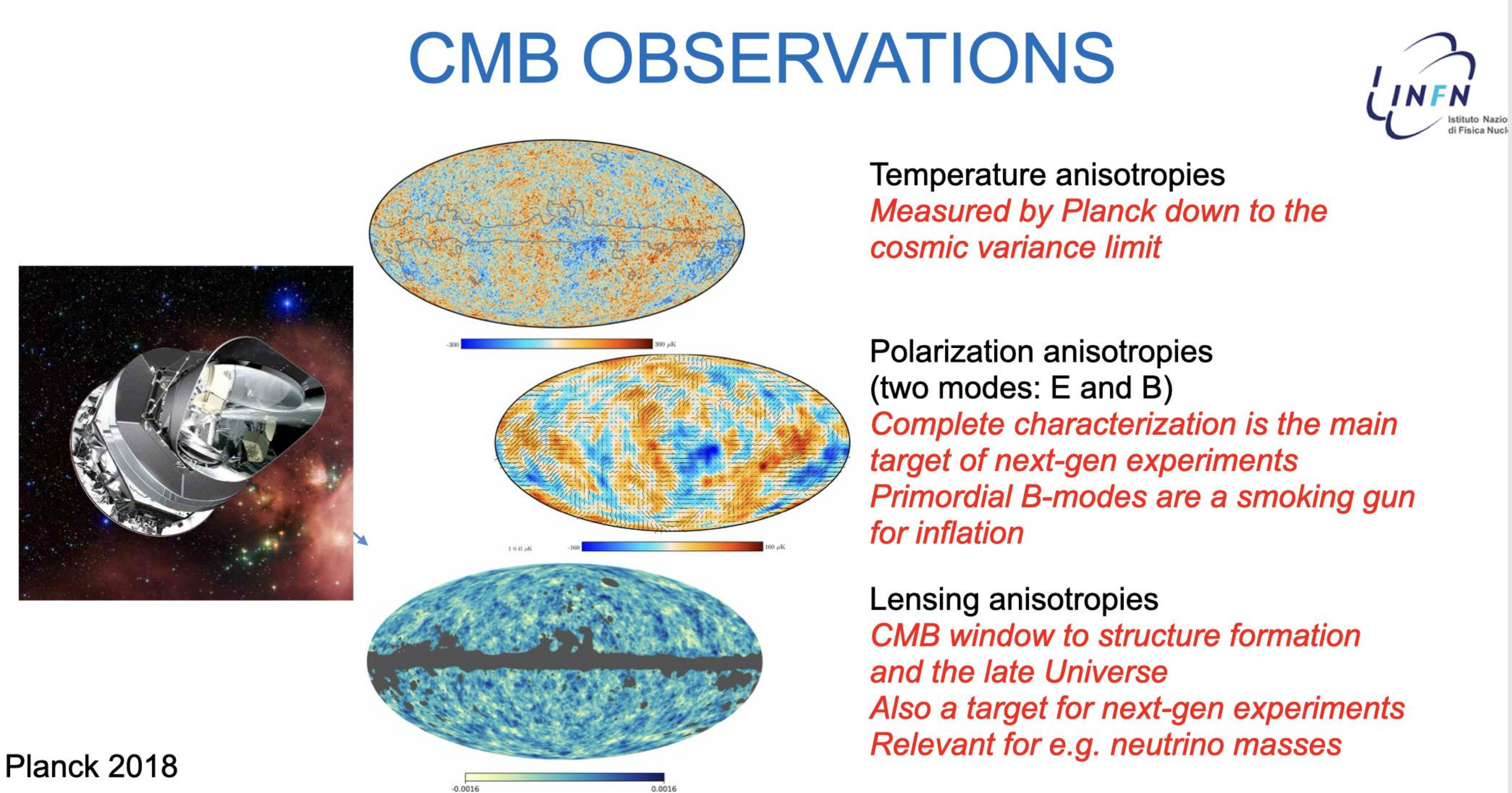
Primary GCRs (e^-, p, He, C, O, Ne, Mg, Si, ..., Fe) are thought to be accelerated by astrophysical processes (as supernovae shocks) in our Galaxy.

Secondary GCRs (e^+, $\bar{p}$, Li, Be, B, F, sub-Fe, ...) are produced from collision of primaries with the interstellar medium.

Cosmic rays close to Earth

- Solar activity (e.g. modulation)
- Earth magnetic field

Adapted from
A. Oliva


-300
300 μK
1 0.41 μK
-160
160 μK
-0.0016
0.0016

CMB OBSERVATIONS

Temperature anisotropies
Measured by Planck down to the cosmic variance limit

Polarization anisotropies
(two modes: E and B)
Complete characterization is the main target of next-gen experiments
Primordial B-modes are a smoking gun for inflation

Lensing anisotropies
CMB window to structure formation and the late Universe
Also a target for next-gen experiments
Relevant for e.g. neutrino masses

Planck 2018

THE EUCLID MISSION

Euclid is an ESA M-class space mission devoted to studying :

- the origin of the **accelerated expansion** of the Universe
- **Dark energy**, **dark matter** and the behaviour of **gravity at large scales**
- + **neutrino masses, the initial conditions of cosmological evolution, …**

Euclid will measure **weak lensing** and **galaxy clustering** observing 15.000 deg^2 (>1/3 of the sky) down to z=2 (lookback time 10 Gyrs) + 3 deep fields (40 deg^2)

This will allow to reconstruct the **expansion history** and the **growth of cosmological structuree**

Euclid lift-off on July 1st, 2023!