Chapter 6

Astroparticle detectors

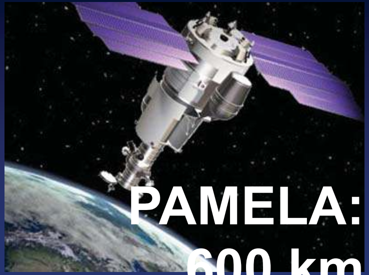
Similar detectors

Different system configurations

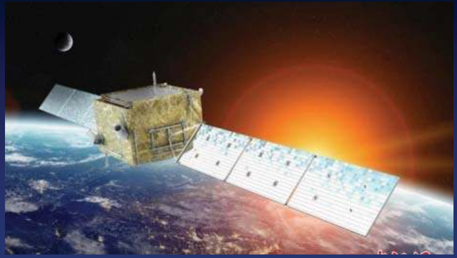
and different difficulties, ie. locations, size

ISS: 400 km

- AMS-02
- CALET
- ISS-CREAM

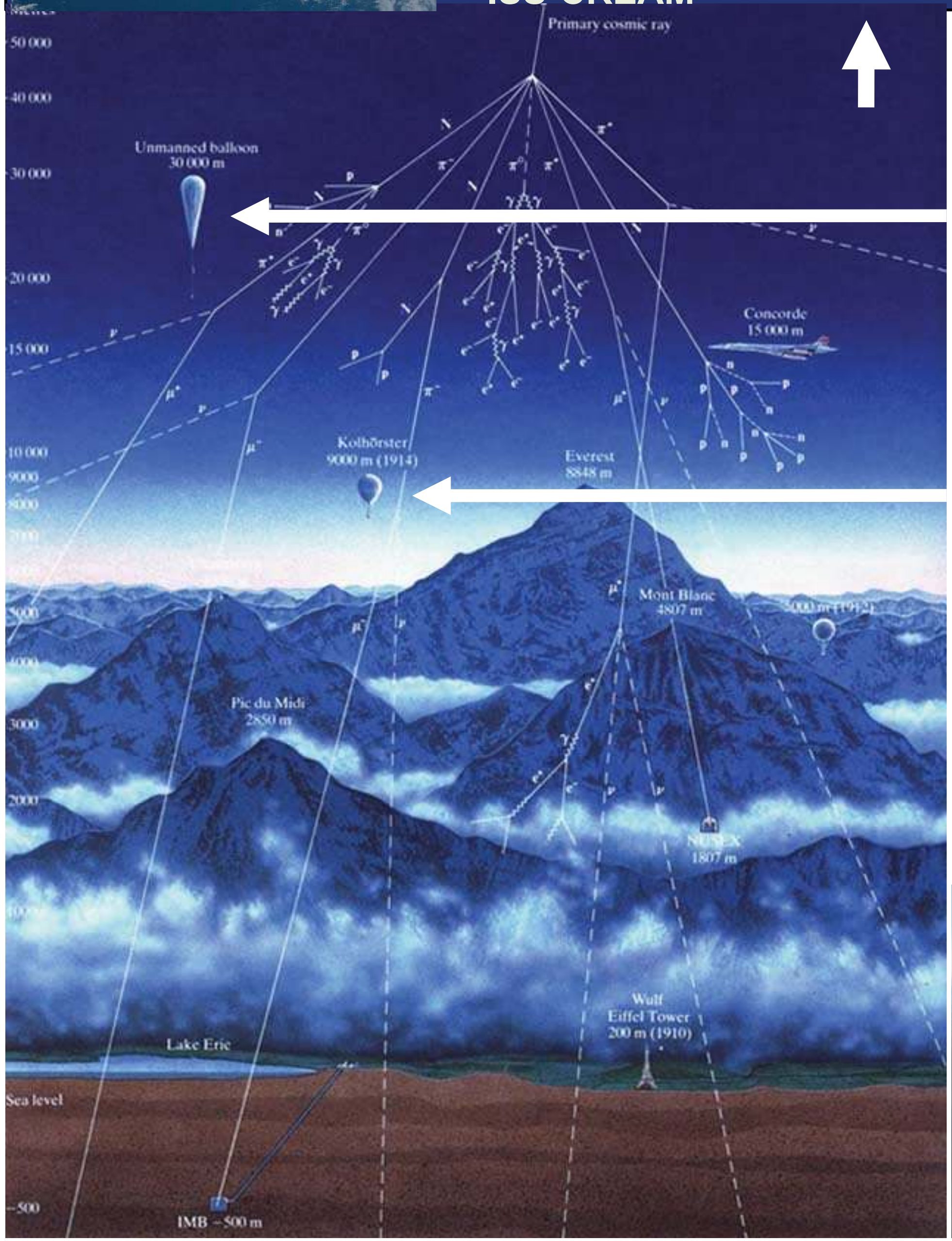


PAMELA: 600 km



DAMPE: 500

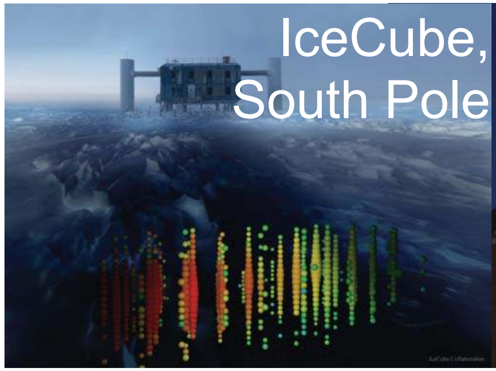
Fermi: 550 km


Primary cosmic ray
50 000
40 000
30 000
20 000
15 000
10 000
9000
8000
7000
5000
4000
3000
2000
1000
-500
Unmanned balloon
30 000 m
Concorde
15 000 m
Kolhörster
9000 m (1914)
Everest
8848 m
Mont Blanc
4807 m
5000 m (1912)
Pic du Midi
2850 m
NUSEX
1807 m
Wulf
Eiffel Tower
200 m (1910)
Lake Erie
Sea level
IMB – 500 m

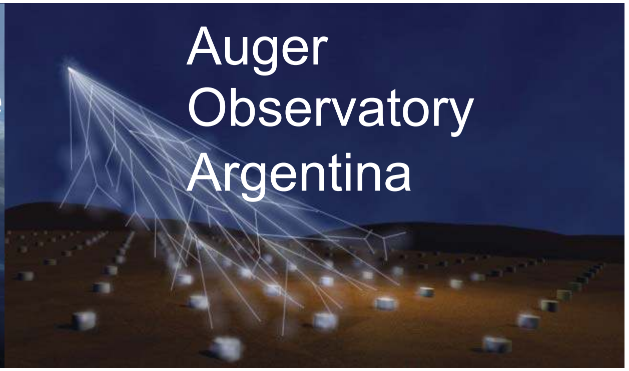
Modern Balloons
~30 km

BESS-Polar II launch, McMurdo

Kolhörster
9 km



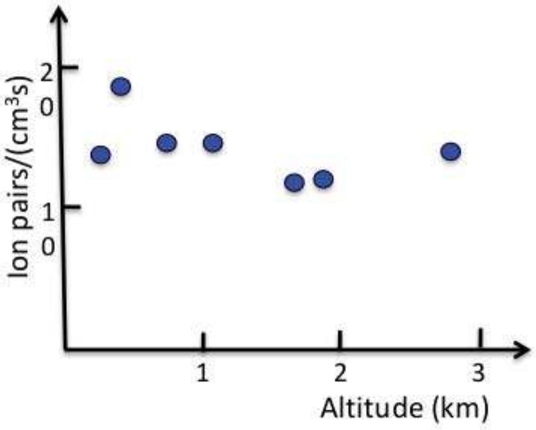
IceCube, South Pole



Auger Observatory Argentina

Finding Cosmic Rays

- 1900: Theory: all radiation comes from soil/ground → **$\sim e^{-h/\lambda}$**
- 1908: Wulf (electrometer) measure on ground and Eifeltower – inconclusive
- 1909: Gockel: Ballon upto 3km – **no decrease** - does it come from the sun?
- 1912: Hess: Balloon up to 5.2km – **radiation increases** - does it come from the sun? Measure also during night and partial eclipse!
- 1914 Kohlhörster up to 9.2km – **radiation increases**
- 1928: Using Geiger counters
- 1931-1933 Compton starts world tour – yes, it is everywhere



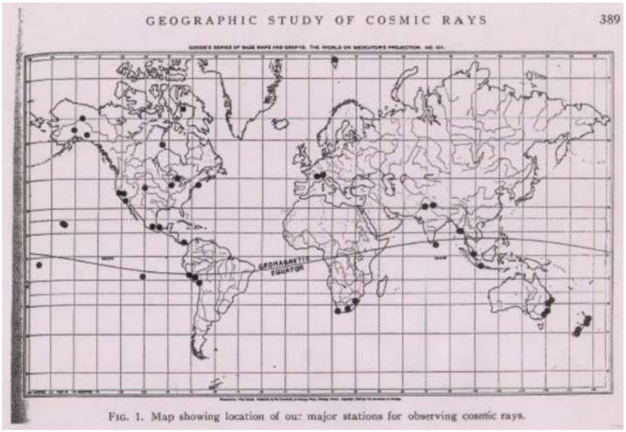
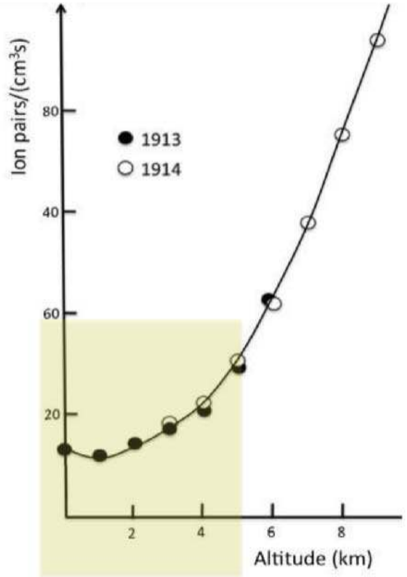
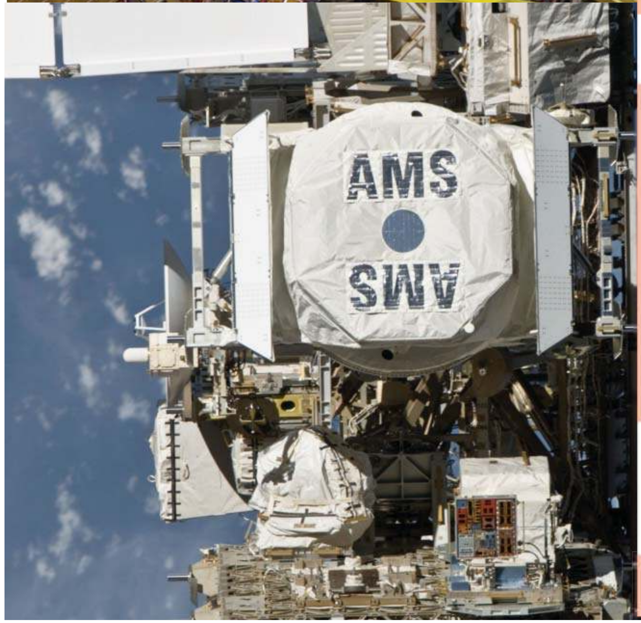
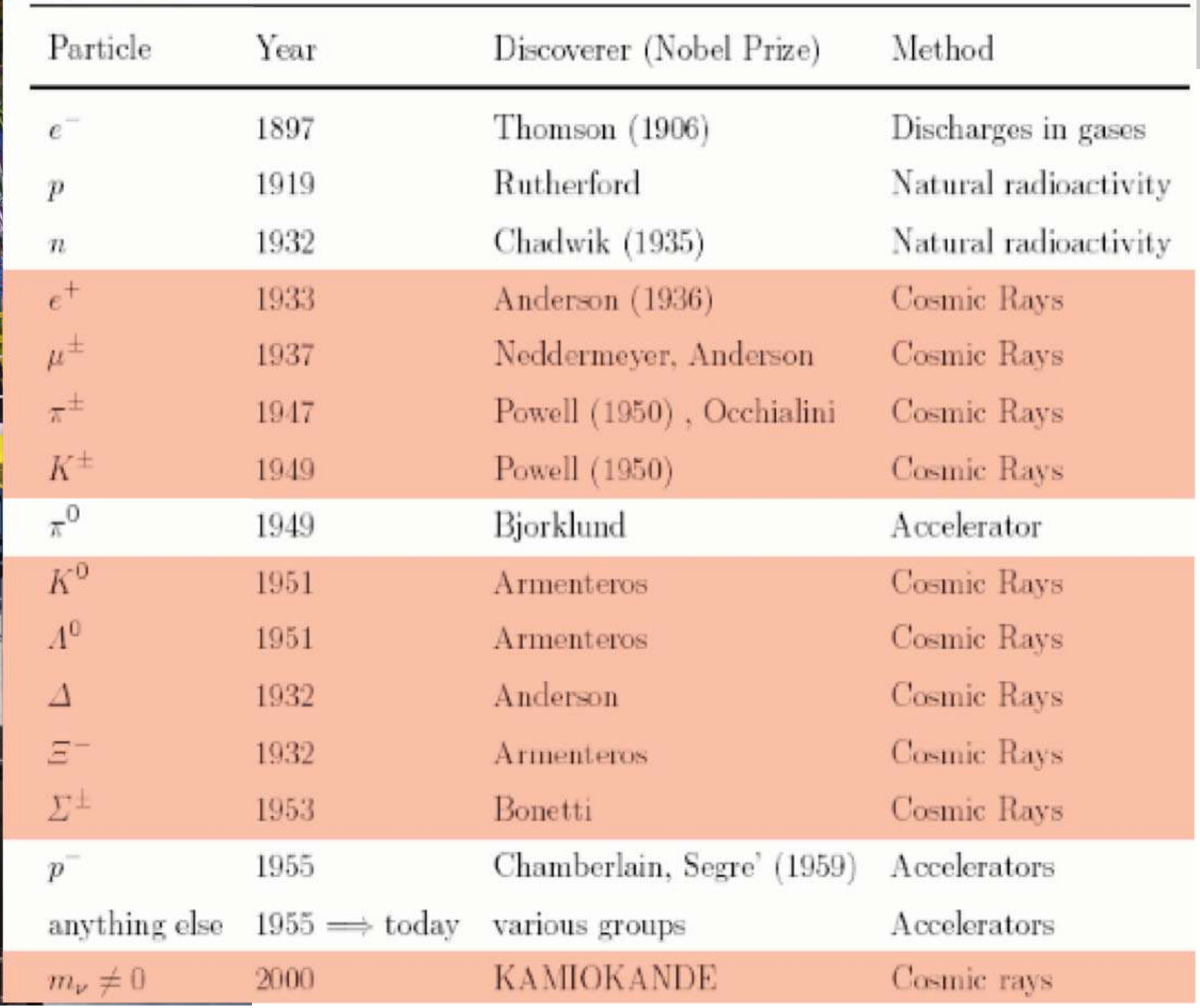

GEOGRAPHIC STUDY OF COSMIC RAYS 389

FIG. 1. Map showing location of our major stations for observing cosmic rays.



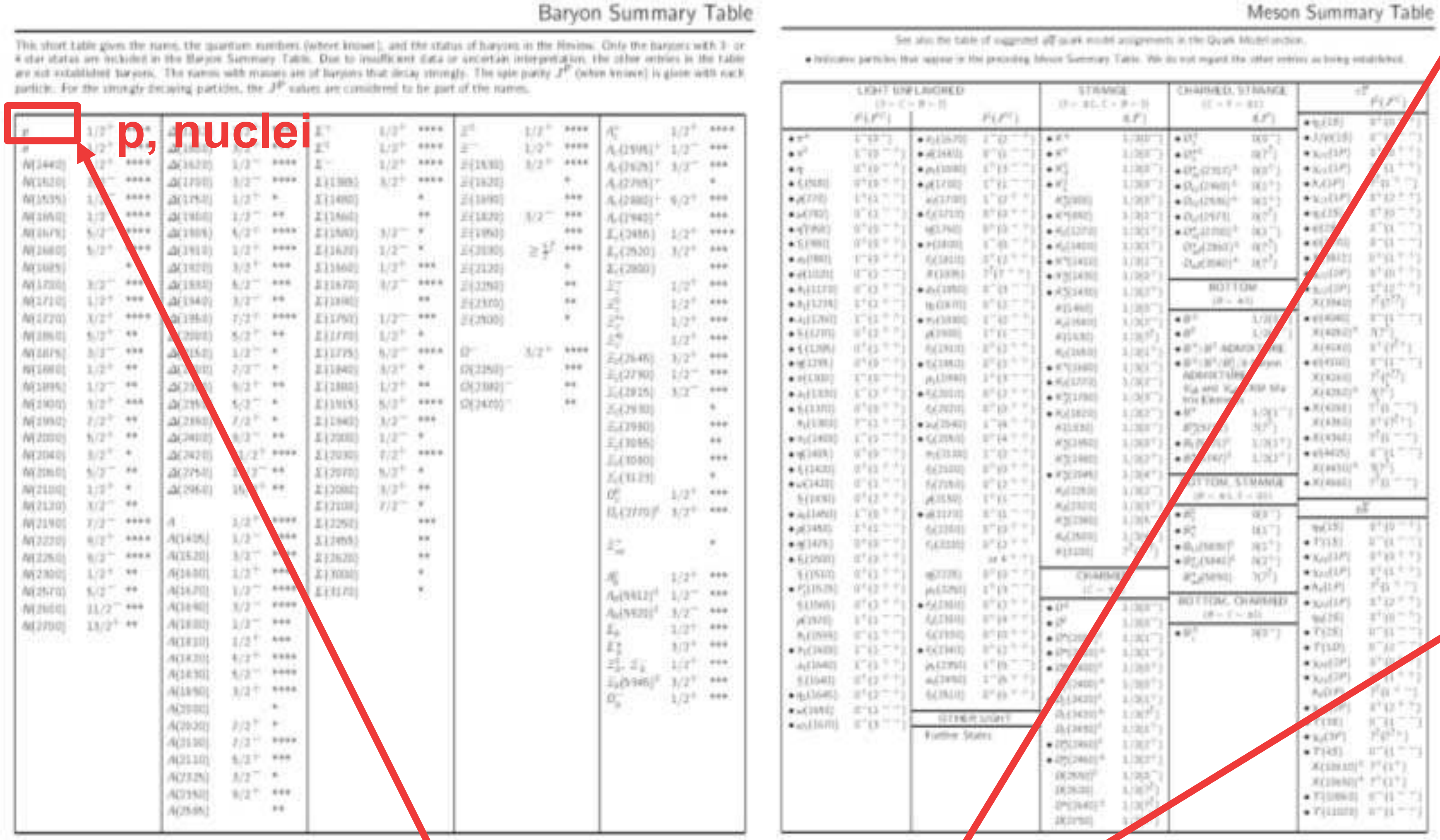
Many Discoveries from Cosmic Ray Observations





Particle	Year	Discoverer (Nobel Prize)	Method
e^-	1897	Thomson (1906)	Discharges in gases
p	1919	Rutherford	Natural radioactivity
n	1932	Chadwik (1935)	Natural radioactivity
e^+	1933	Anderson (1936)	Cosmic Rays
$\mu^\pm$	1937	Neddermeyer, Anderson	Cosmic Rays
$\pi^\pm$	1947	Powell (1950) , Occhialini	Cosmic Rays
$K^\pm$	1949	Powell (1950)	Cosmic Rays
π^0	1949	Bjorklund	Accelerator
K^0	1951	Armenteros	Cosmic Rays
Λ^0	1951	Armenteros	Cosmic Rays
Δ	1932	Anderson	Cosmic Rays
Ξ^-	1932	Armenteros	Cosmic Rays
$\Sigma^\pm$	1953	Bonetti	Cosmic Rays
p^-	1955	Chamberlain, Segre' (1959)	Accelerators
anything else	1955 $\Longrightarrow$ today	various groups	Accelerators
$m_\nu \neq 0$	2000	KAMIOKANDE	Cosmic rays

Many (hundreds) particles known, see PDG (Particle Data Group):



Baryon Summary Table

Meson Summary Table

Leptons

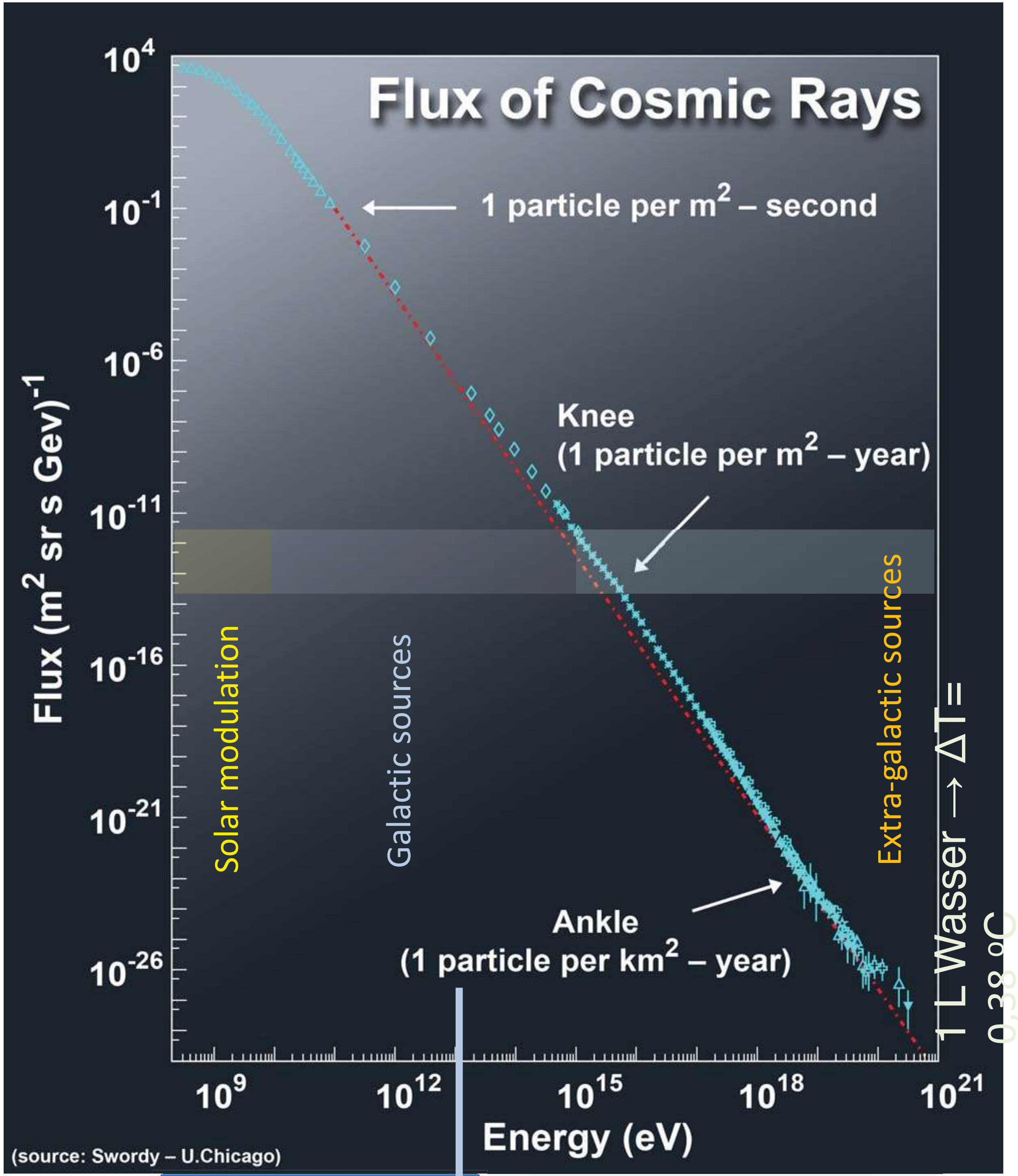
- e
- μ
- τ
- ν_e
- ν_μ
- ν_τ

Gauge bosons

- γ
- $W^{+/-}$
- Z
- g
- H

What we look for in cosmic rays

Cosmic Ray Spectrum



(source: Swordy – U.Chicago)

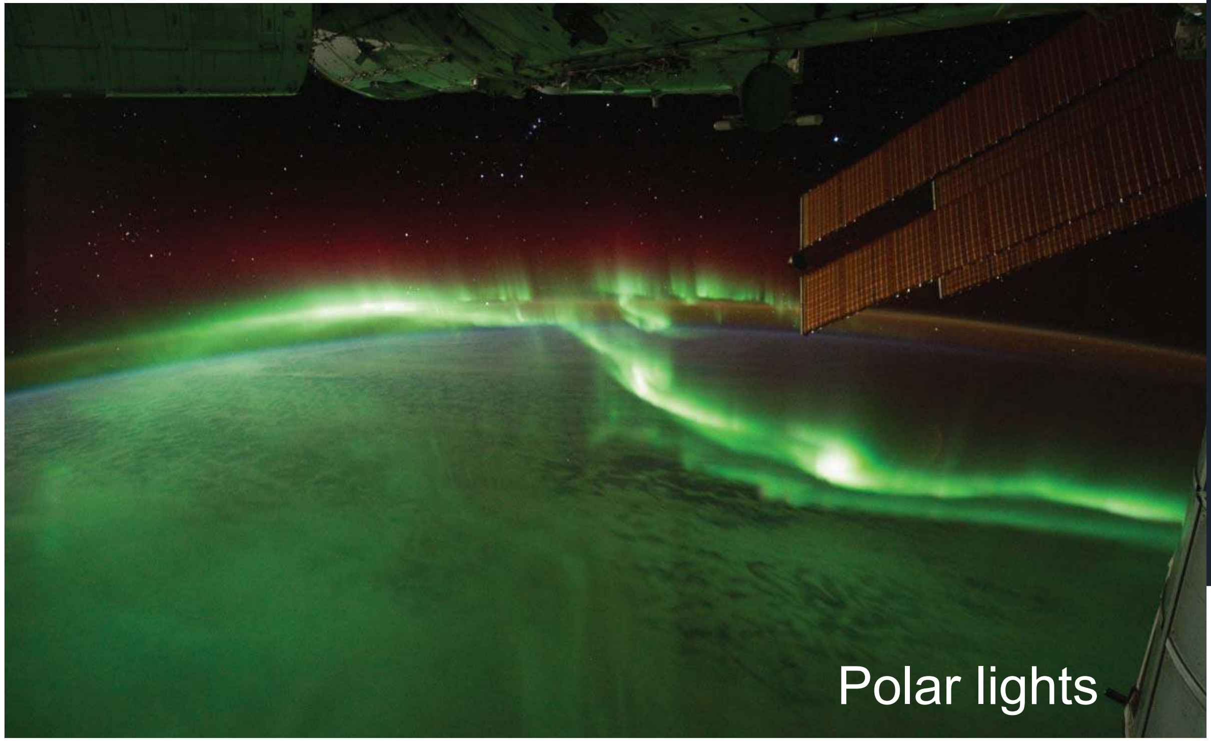
Direct measurement:
Balloon, Satellite

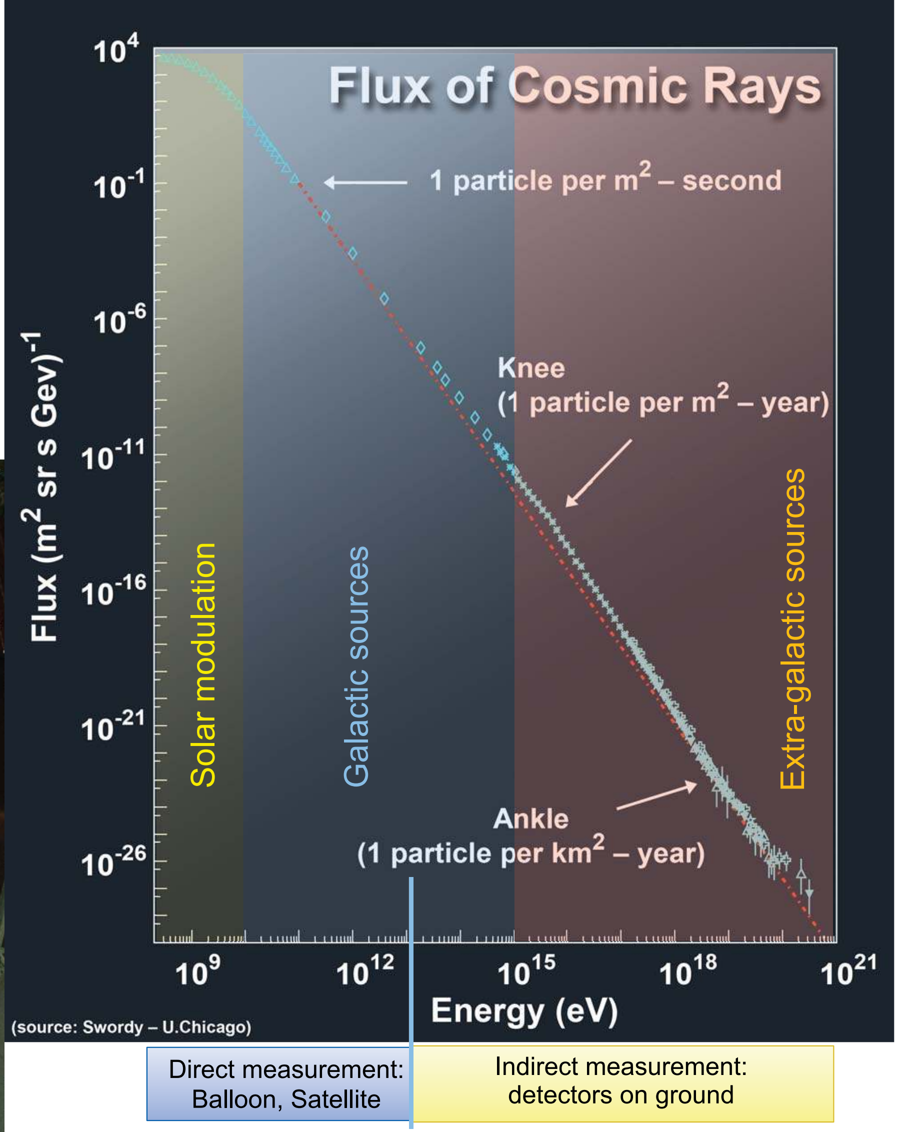
Indirect measurement:
detectors on ground

WHAT do we measure?

Particles that reach
Earth from space!

Source 1: Solar Wind


Polar lights


Flux of Cosmic Rays

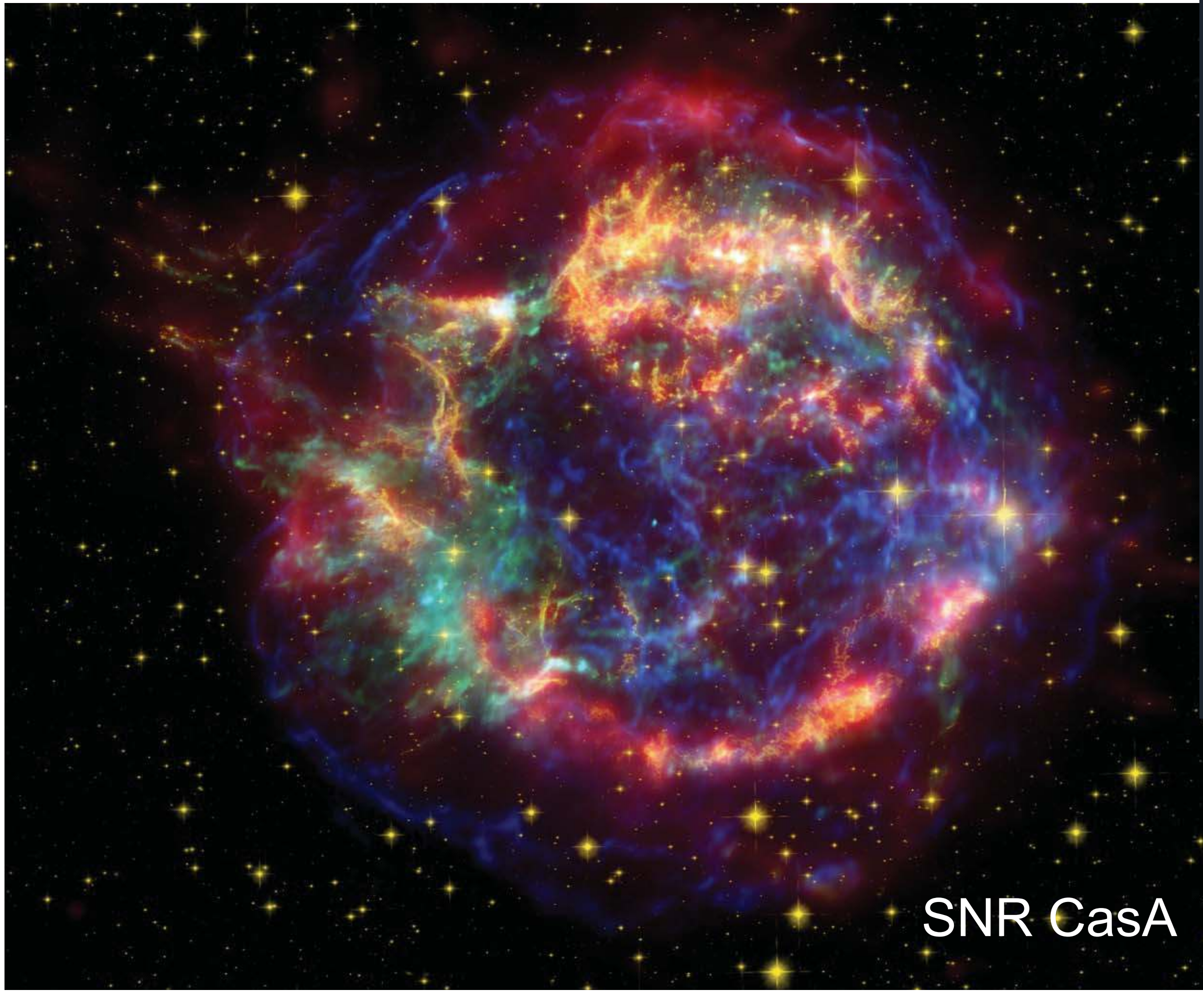
(source: Swordy – U.Chicago)

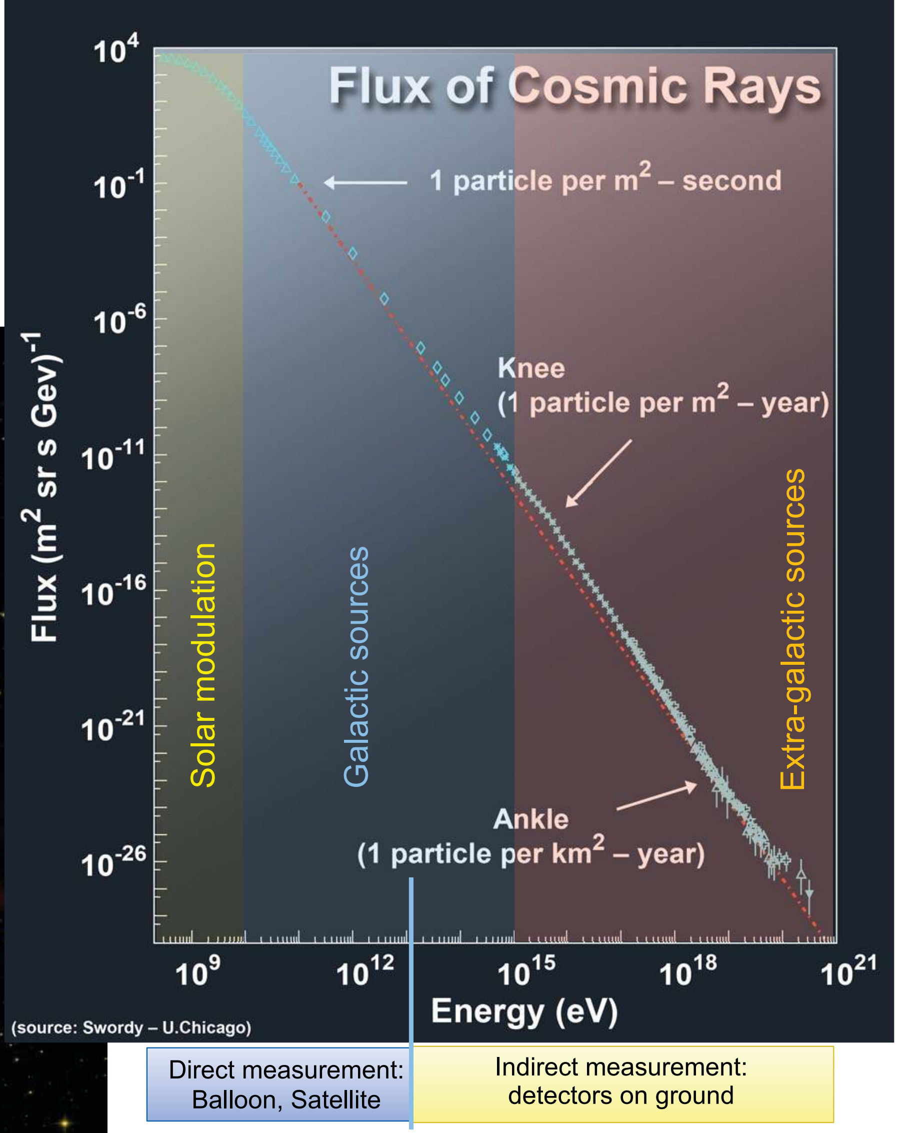
Direct measurement:
Balloon, Satellite

Indirect measurement:
detectors on ground

Energy: 1,5-10 keV
Mainly protons

Source 2: Supernova Remnants, Massive Stars, Pulsars





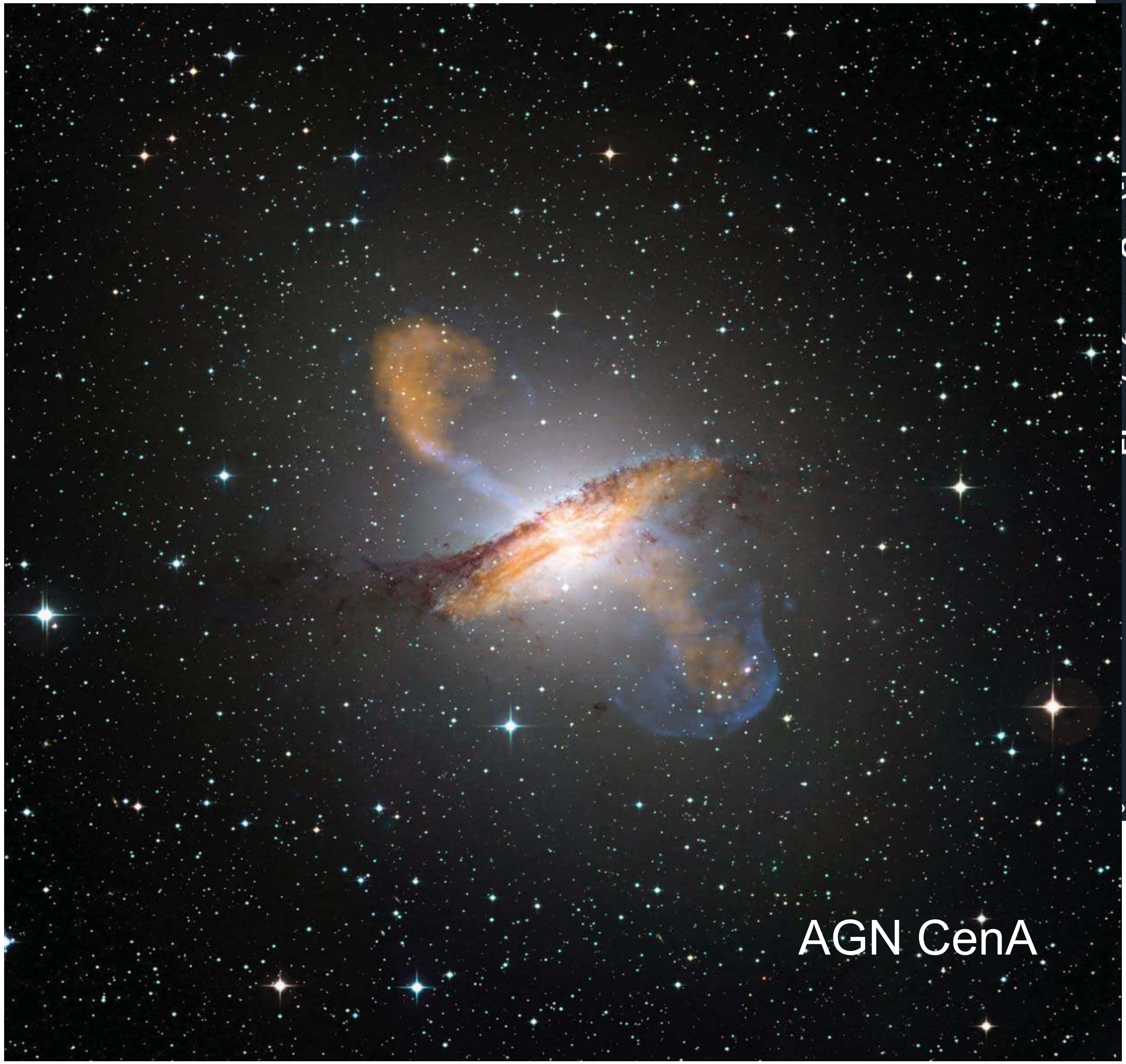
(source: Swordy – U.Chicago)

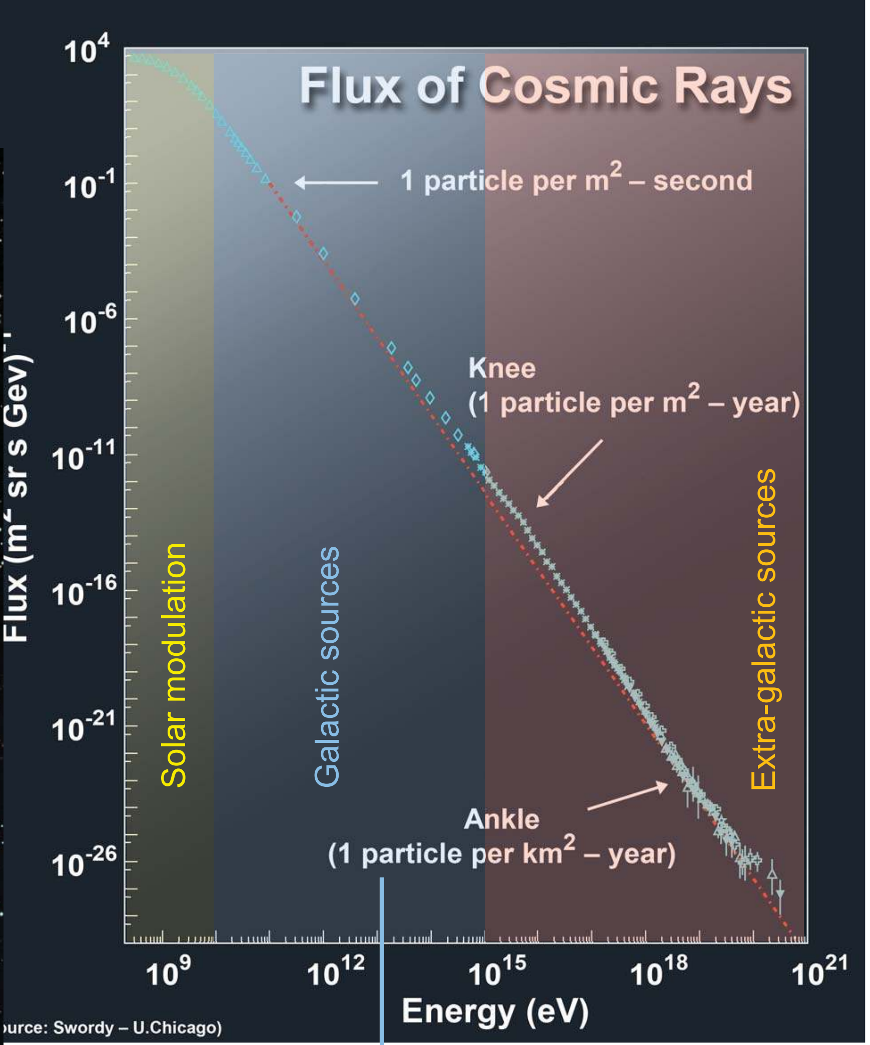
Direct measurement:
Balloon, Satellite

Indirect measurement:
detectors on ground

Energy: 100 MeV (10^8 eV) –1 PeV (10^{15} eV)
Mainly protons

Source 3: Active galactic nuclei



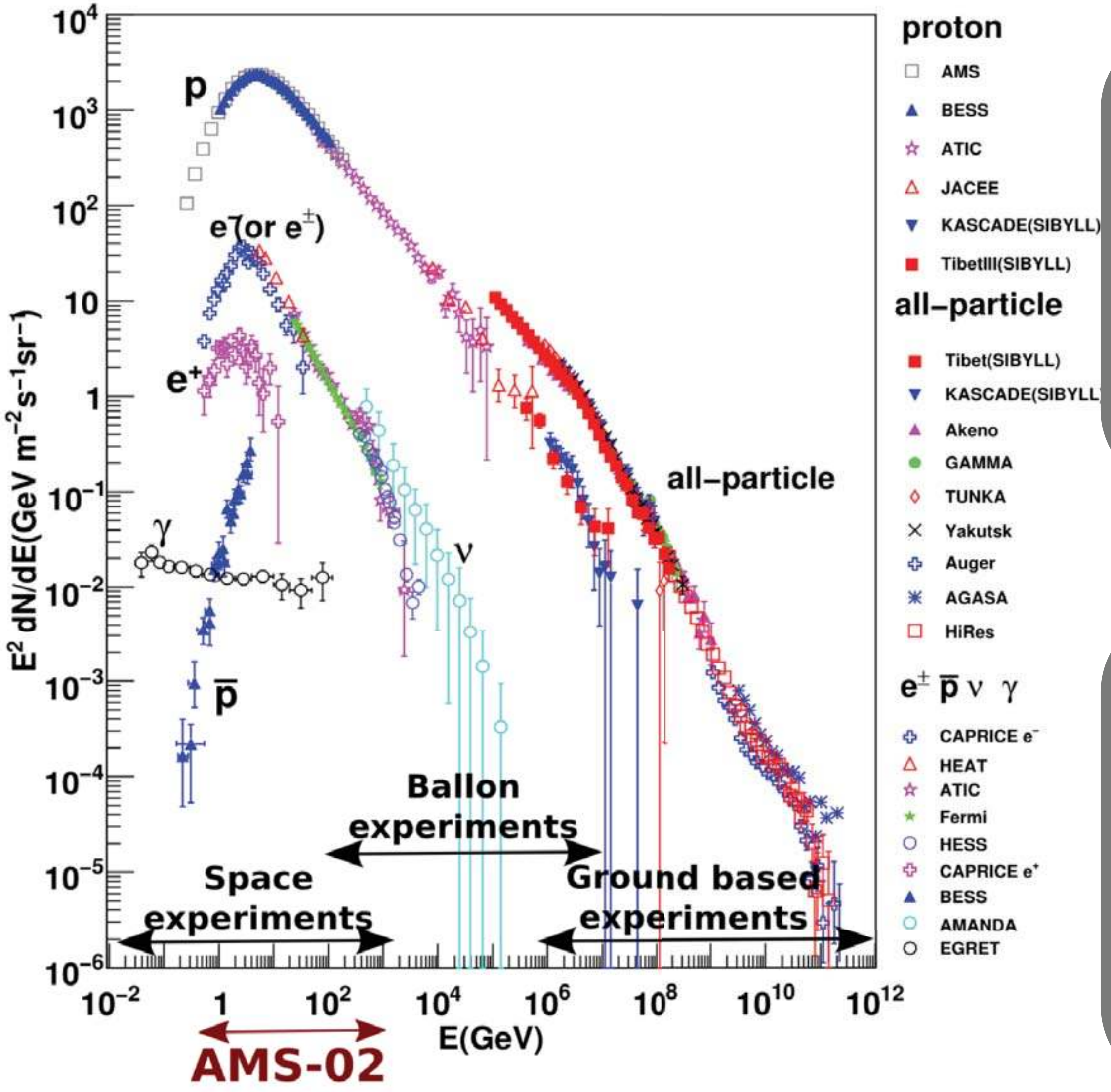


urce: Swordy – U.Chicago)

Direct measurement: Balloon, Satellite	Indirect measurement: detectors on ground

Energy: 1 PeV (10^{15} eV) – 1 ZeV (10^{21} eV)
Mainly protons and nuclei

Single Particle Fluxes



Primary cosmic rays:

- Protons ~89%
- He ~10%
- Heavy nuclei (C) ~1%
- e^- ~1%

Secondary nuclei (from cosmic ray interactions):

- Traces of e^+
- Traces of p
- Traces of nuclei

NB.: with special telescopes like x-ray and radio, we see that we have gases in addition to stars

→ **Universe = Stars 1.5% + Gas 13.5% + 85% unknown**

6.1 Earth based systems

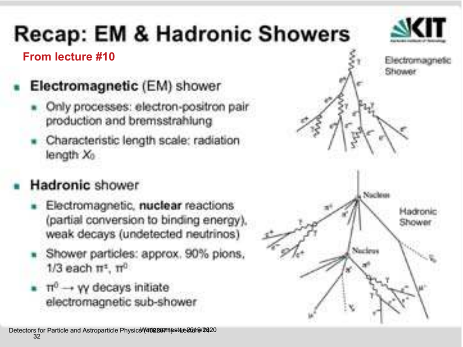
Auger
Magic

Gound Based: Extensive Shower Arrays

Detection principle: **use Earth's atmosphere as calorimeter**,
detect shower particles at observation level (defines energy threshold!).
→ **No/limited particle ID of primary particle!**

The highest energies: 10^{16} eV - 10^{21} eV

Acceptances: can be very high.
Limited by hemisphere and angular dependence of effective are



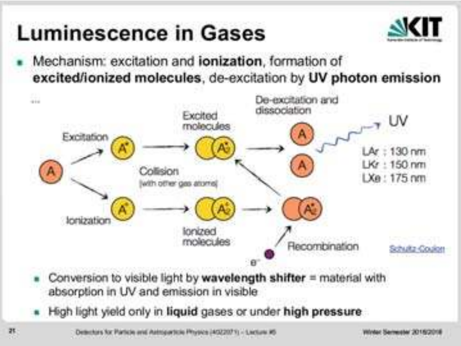
Recap: EM & Hadronic Showers

From lecture #10

- **Electromagnetic** (EM) shower
  - Only processes: electron-positron pair production and bremsstrahlung
  - Characteristic length scale: radiation length X_0
- **Hadronic** shower
  - Electromagnetic, **nuclear** reactions (partial conversion to binding energy), weak decays (undetected neutrinos)
  - Shower particles: approx. 90% pions, 1/3 each $\pi^{\pm}$, π^0
  - $\pi^0 \rightarrow \gamma\gamma$ decays initiate electromagnetic sub-shower

Electromagnetic Shower
Nucleus
Hadronic Shower
Nucleus

Detectors for Particle and Astroparticle Physics
32



Luminescence in Gases

- Mechanism: excitation and **ionization**, formation of **excited/ionized molecules**, de-excitation by **UV photon emission**

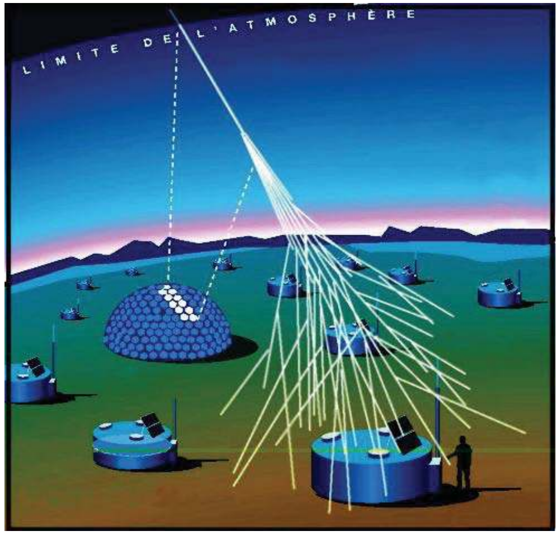
Excitation
Excited molecules
De-excitation and dissociation
UV
LAr : 130 nm
LKr : 150 nm
LXe : 175 nm
Collision
(with other gas atoms)
Ionization
Ionized molecules
Recombination
e⁻
Schultz-Coulon

- Conversion to visible light by **wavelength shifter** = material with absorption in UV and emission in visible
- High light yield only in **liquid** gases or under **high pressure**

Techniques:

water **Cherenkov** telescopes, air Cherenkov telescopes, **fluorescence light**, **scintillation** counters, **PMs, SiPMs**, **tracking** detectors (drift chambers, Geiger tubes).

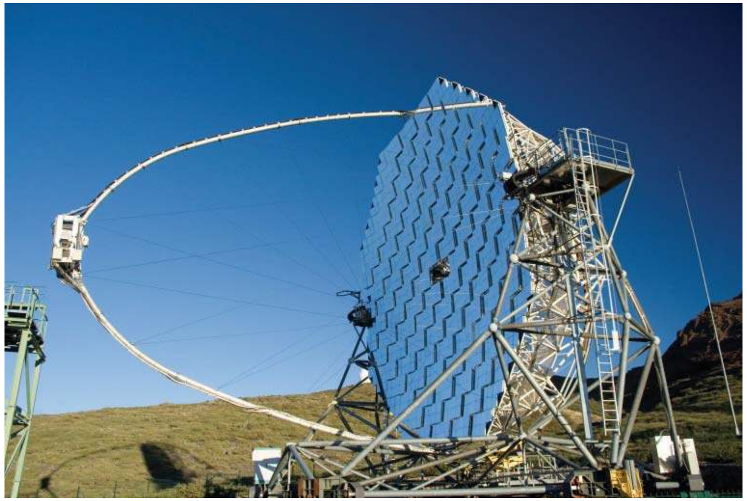
Auger



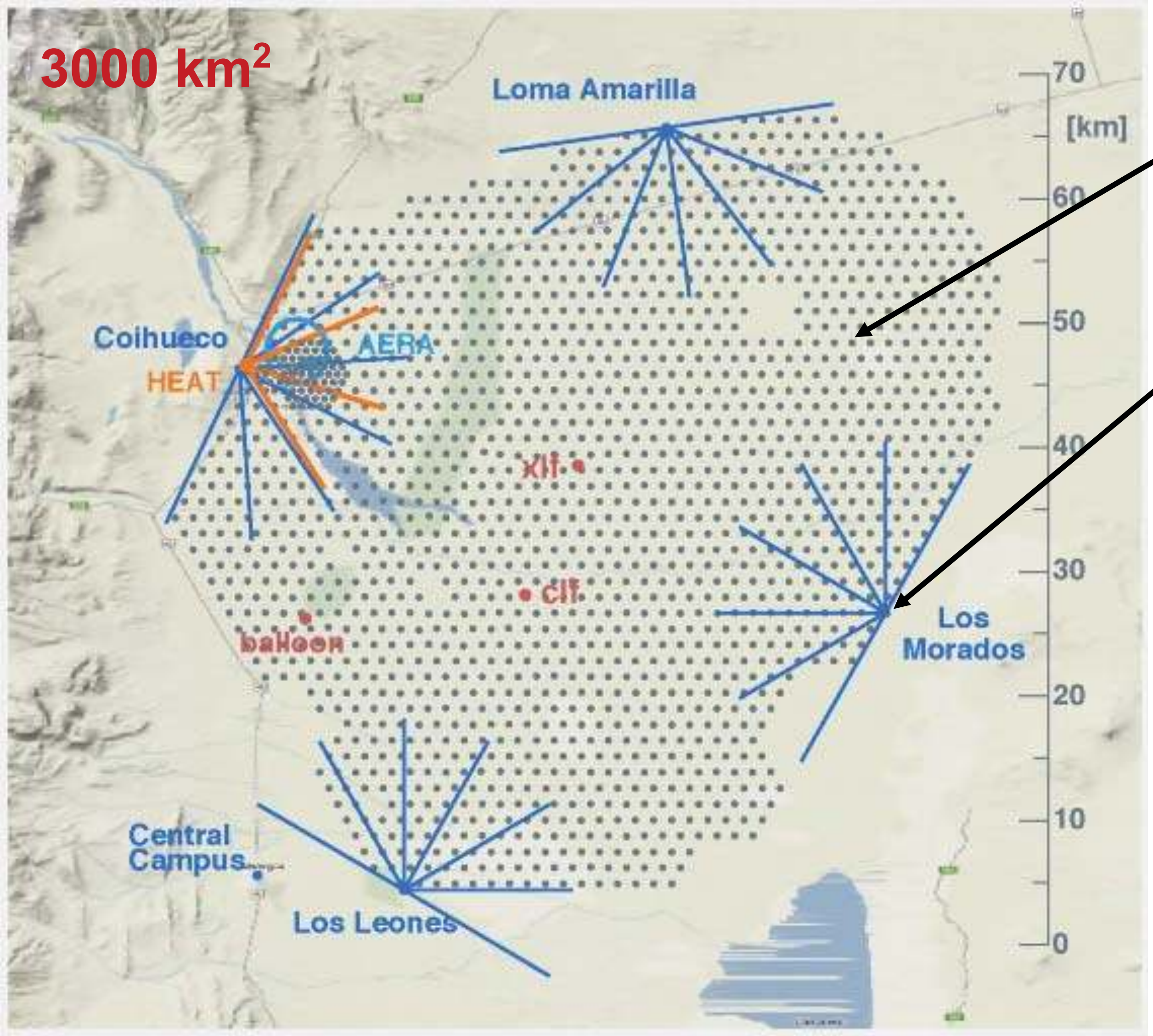
LIMITE DE L'ATMOSPHERE

Milagro/Hawc

MAGIC



1. Pierre Auger Observatory, La Pampa


3000 km^2
Loma Amarilla
Coihueco
HEAT
AERA
xlf
clf
balloon
Los Morados
Central Campus
Los Leones
70
[km]
60
50
40
30
20
10
0

Surface detector:
1600 water cherenkov tanks on a 1.5 km hexagonal grid

Fluorescence detector:
4x6 fluorescence telescopes

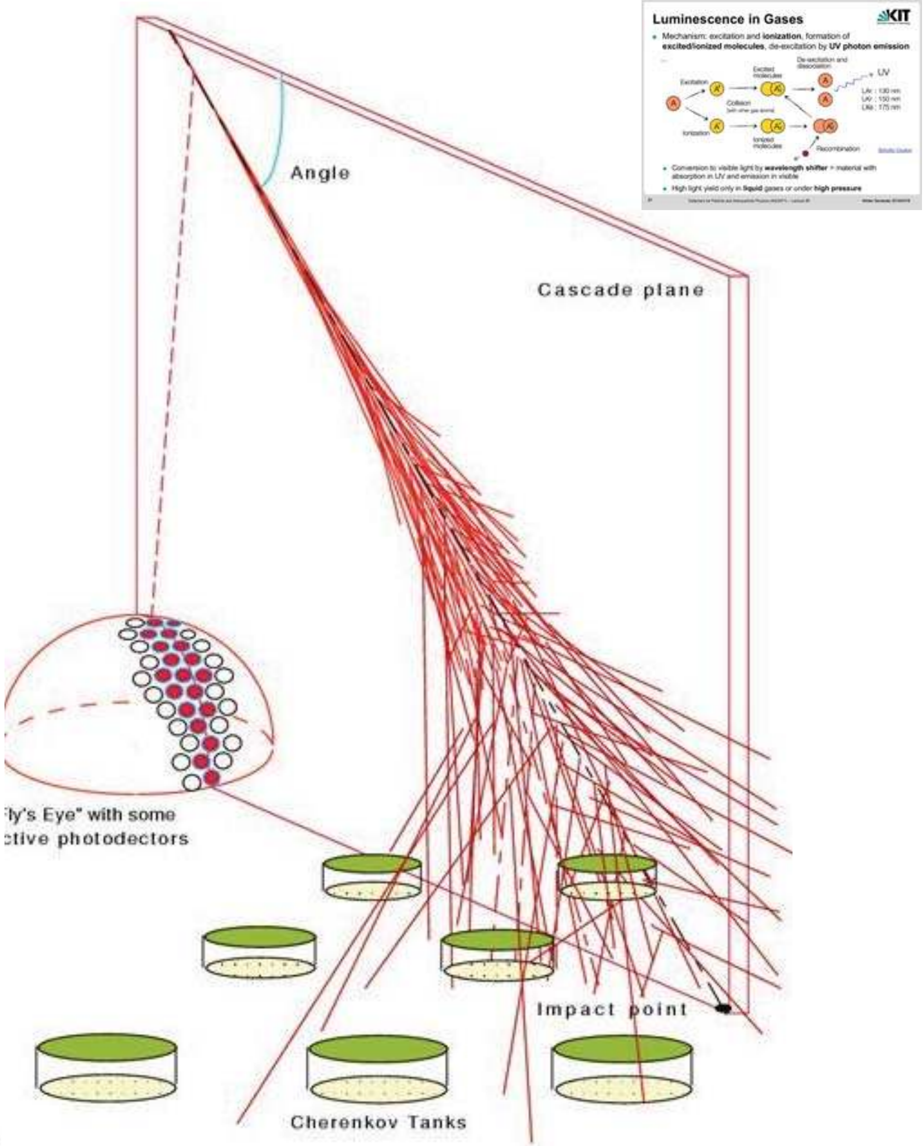
https://www.auger.org

Auger– A “Hybrid Detector”

Fluorescence from air N2 molecules
isotropic emission along shower axis

Limited to dark, moonless nights →
10% duty cycle

Range > 30km (for 1020 eV air shower)



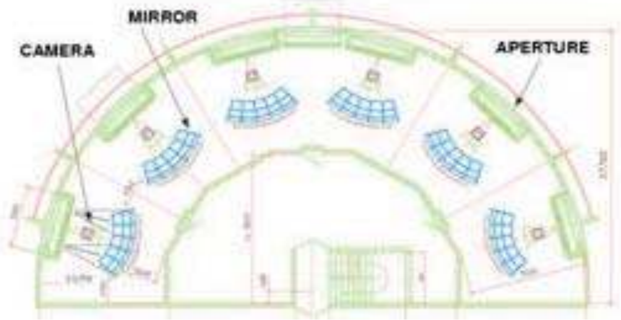
Luminescence in Gases

- Mechanism: excitation and **ionization**, formation of **excited/ionized molecules**, de-excitation by **UV photon emission**
- Conversion to visible light by **wavelength shifter** = material with absorption in UV and emission in visible
- High light yield only in **liquid** gases or under **high pressure**

KIT
Excitation
Ionization
Excited molecules
Collision
Ionized molecules
De-excitation and dissociation
UV
Recombination

Angle
Cascade plane
Fly's Eye" with some active photodectors
Impact point
Cherenkov Tanks

FD 4 x 6 fluorescence telescopes



MIRROR
CAMERA
APERTURE

440 Photomultipliers

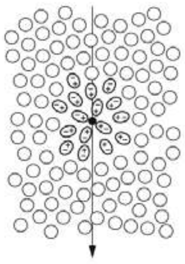
Auger Water Cherenkov Detectors

Surface detector station

- Plastic tank
- Reflective tyvek liner
- 12 m^3 purified water
- 3 PMTs (9 inches)
- 100% duty cycle

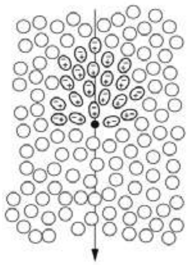
Reminder

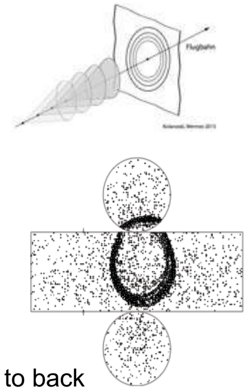
Cherenkov Radiation



$v < \frac{c}{n}$

- Symmetric polarization
- No directed dipole moment





$v > \frac{c}{n}$

Polarization only to back

→ changing dipole moment

→ radiation

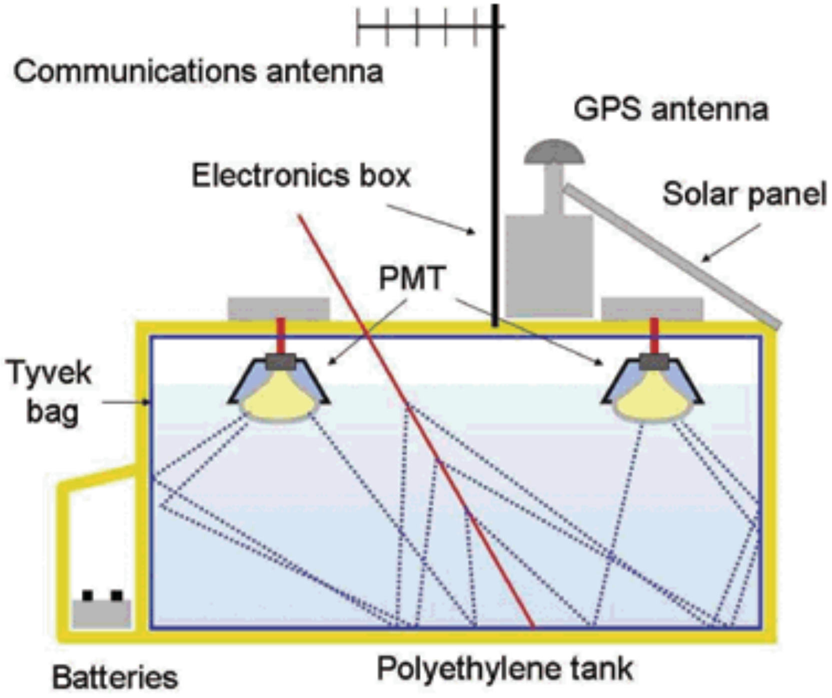
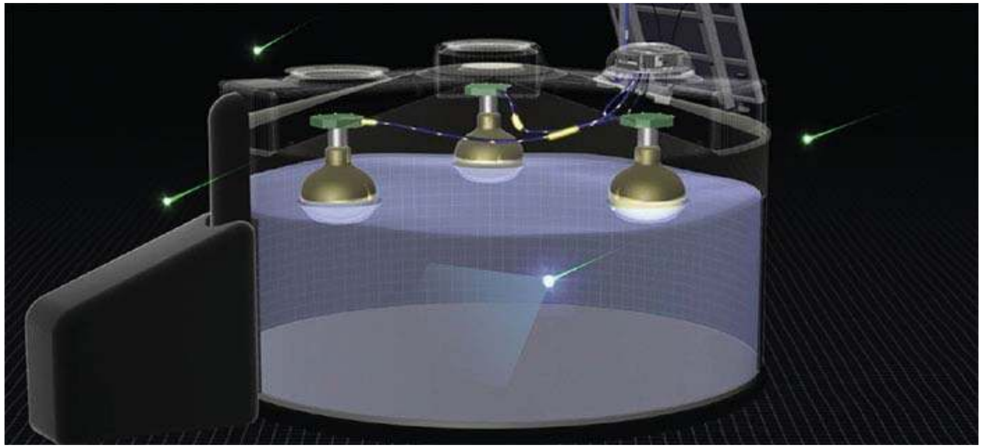
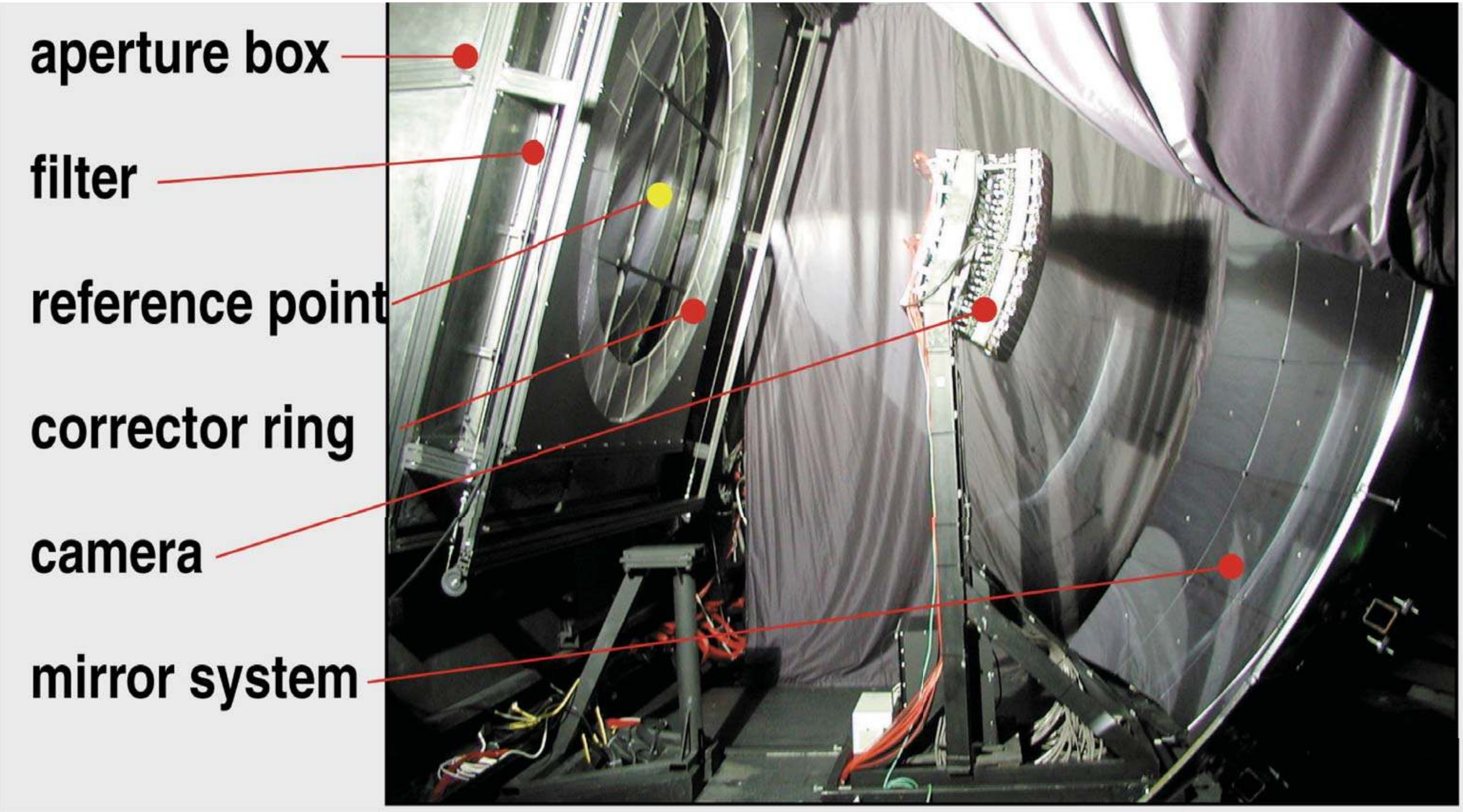

Communications antenna
GPS antenna
Electronics box
Solar panel
PMT
Tyvek bag
Batteries
Polyethylene tank

FIG. 2: A schematic view of the Cherenkov water tanks, with the components indicated in the figure.



Fluorescence Camera



aperture box

filter

reference point

corrector ring

camera

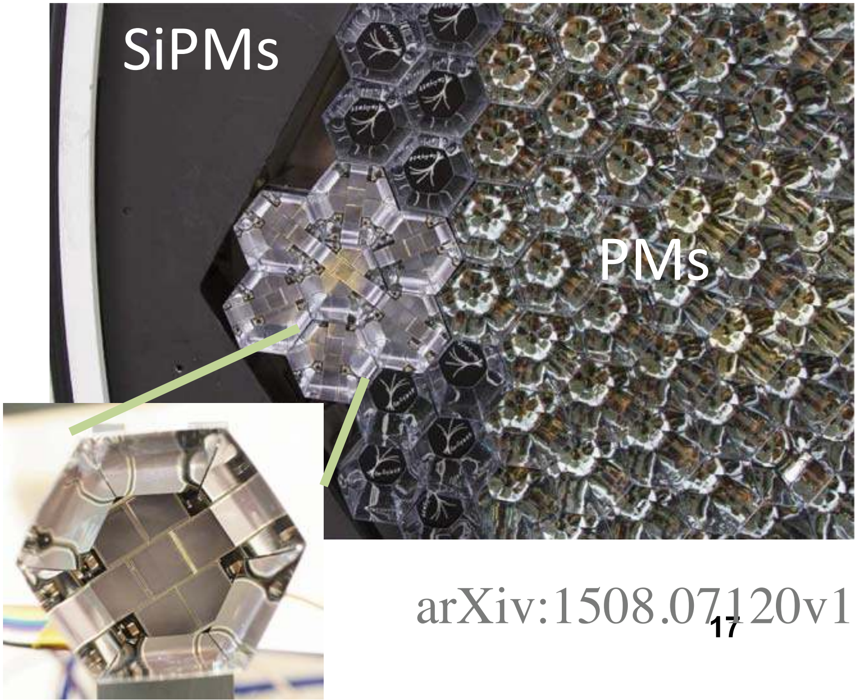
mirror system

2. Magic, La Palma

© Daniel Lopez, IAC

- The telescopes measure Cherenkov light images of extended air showers from a target source direction.
  - Mirror + PM and starting to use SiPMS

- **Previous: VERITAS & HESS**
- **Next:** The Cherenkov Telescope Array (**CTA**) is the next generation ground-based observatory for gamma-ray astronomy at very-high energies. With more than 100 telescopes located in the northern (La Palma) and souther hemispheres (Chile).



arXiv:1508.07120v1

Limits on ground based detection

Ground based detectors use the Earth’s atmosphere as a giant calorimeter.

Achievements: large acceptance (can cover 3000 km^2 on ground rather cheap),
highest energies accessible (observation level, statistics)

Challenges: Primary Particle ID difficult or impossible
Low energy threshold → need to move to high altitude to access galactic cosmics

→ Ballons!

Gockel again!

What is the composition of cosmic rays? (particle ID)

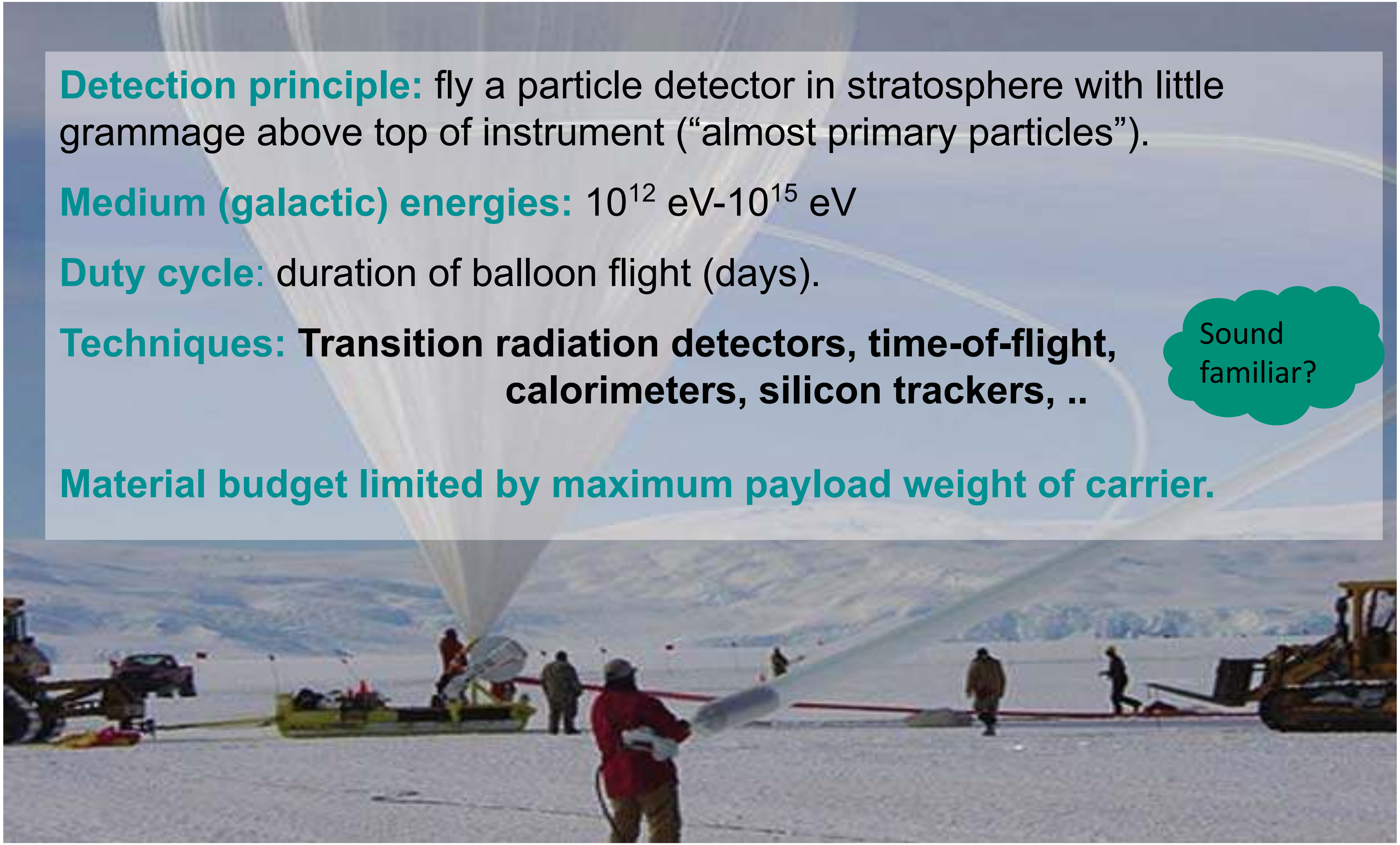
What about galactic cosmic ray sources? (lower energies)

..and dark matter? (lower energies)

6.2 Balloon, Satellite and ISS based systems

CREAM
ISS CREAM
DAMPE
CALET
AMS
PAMELA

Balloon Experiments in Stratosphere



Detection principle: fly a particle detector in stratosphere with little grammage above top of instrument (“almost primary particles”).

Medium (galactic) energies: 10^{12} eV-10^{15} eV

Duty cycle: duration of balloon flight (days).

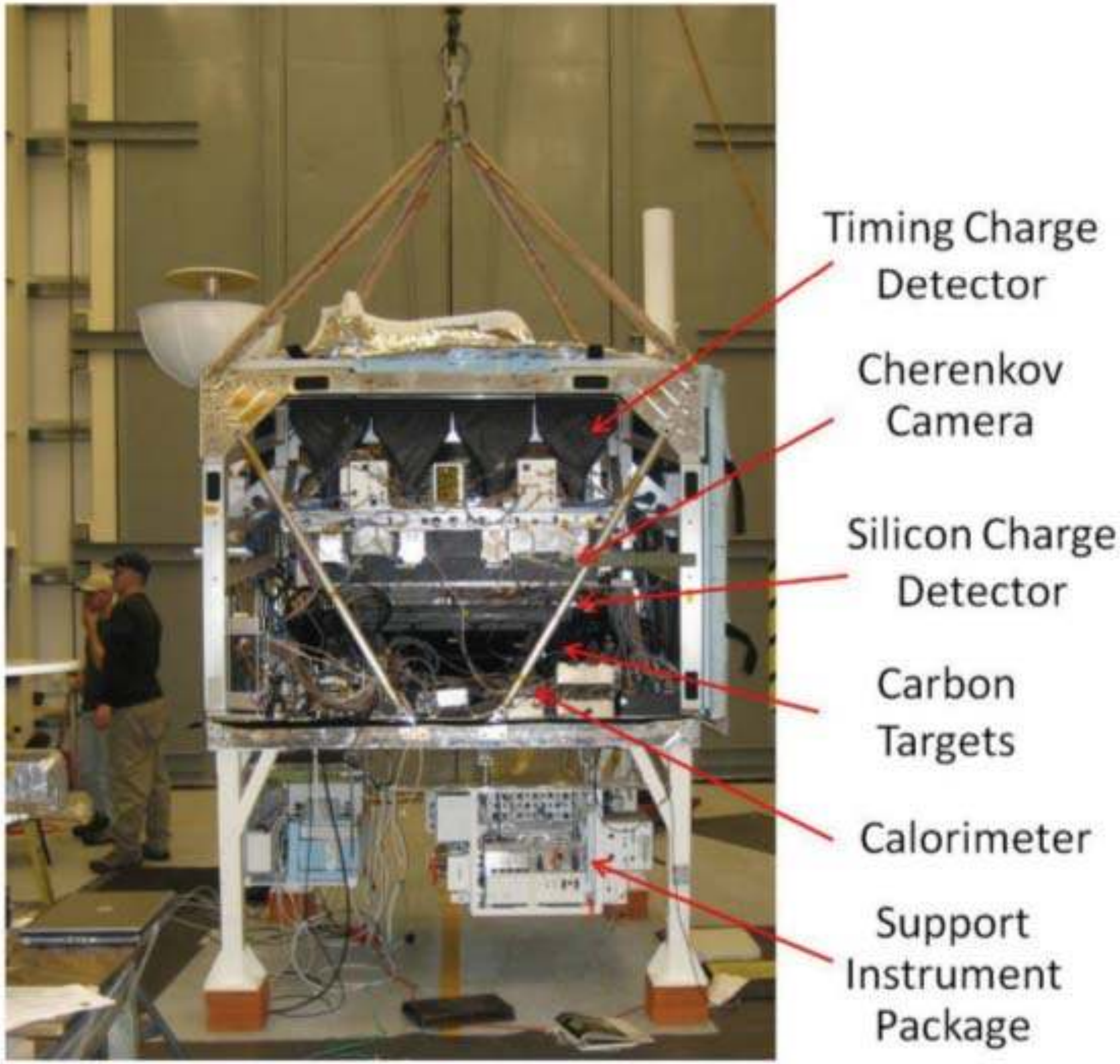
Techniques: **Transition radiation detectors, time-of-flight, calorimeters, silicon trackers, ..**

Sound familiar?

Material budget limited by maximum payload weight of carrier.

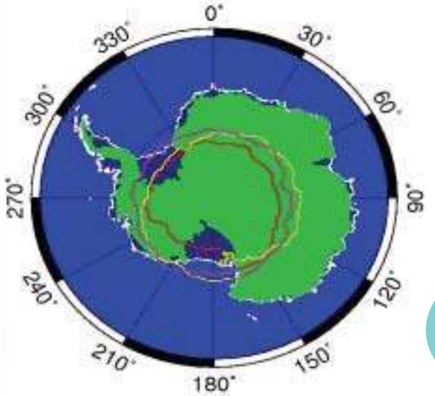
1. CREAM Detector

Cosmic Ray Energetics and Mass (CREAM)


Timing Charge Detector
Cherenkov Camera
Silicon Charge Detector
Carbon Targets
Calorimeter
Support Instrument Package

CREAM-V integration at Williams field near McMurdo, Antarctica.

CREAM Flights



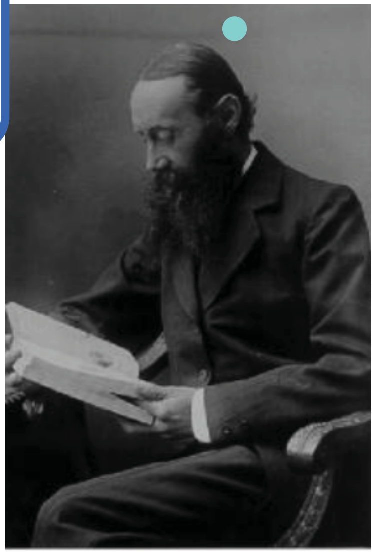
How can I improve these measurements?

Table 1
Summary of the six CREAM balloon flights in Antarctica.

	Launch	Termination	Duration
CREAM-I	2004.12.16	2005.1.27	42 days
CREAM-II	2005.12.15	2006.1.13	28 days
CREAM-III	2007.12.19	2008.1.17	29 days
CREAM-IV	2008.12.18	2009.1.7	19 days
CREAM-V	2009.12.1	2010.1.8	37 days
CREAM-VI	2010.12.21	2010.12.26	6 days

[Advances in Space Research 53 (2014) 1451–1455]

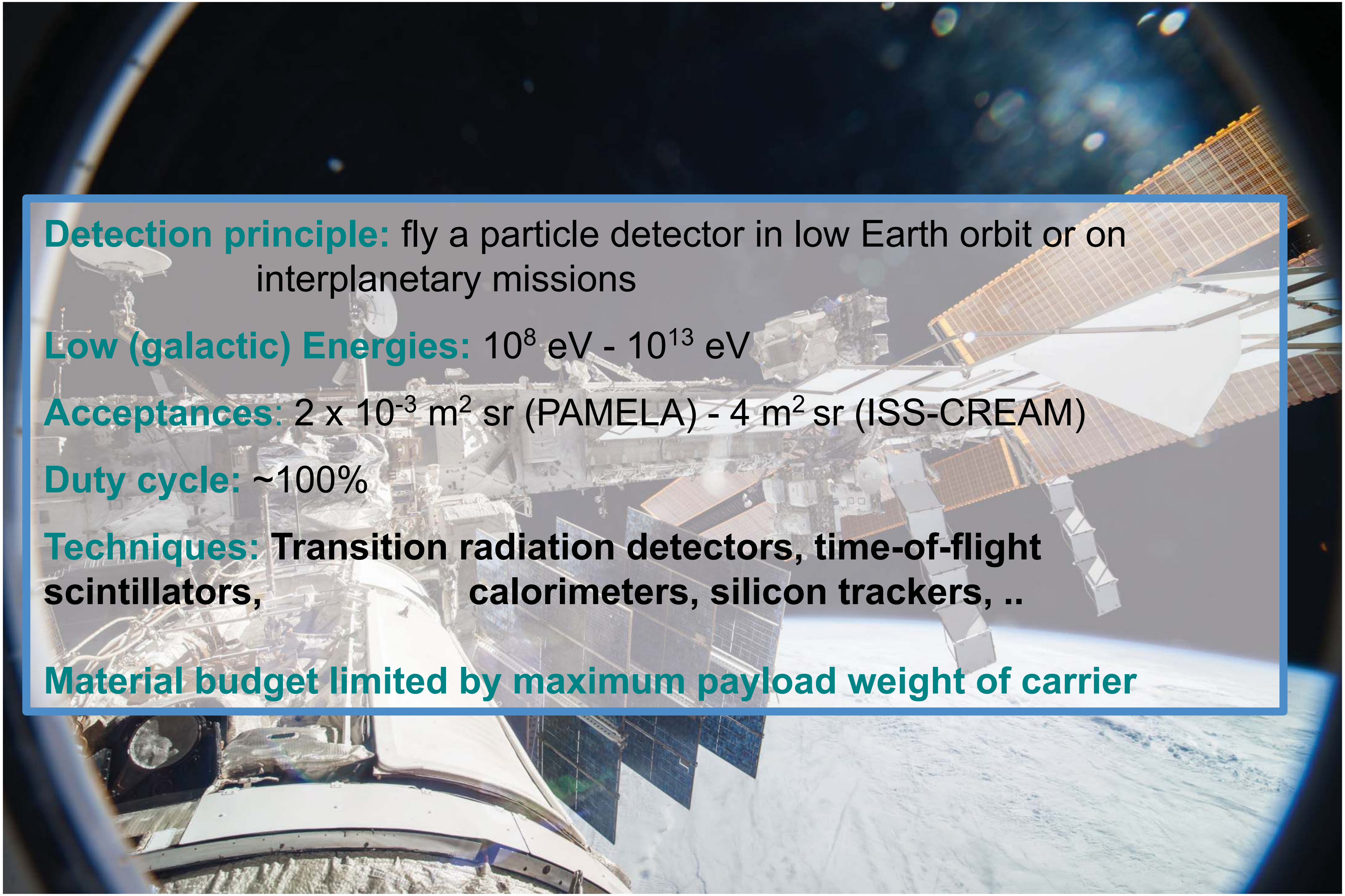
Limited statistics



Balloon then ISS

➔ **ISS-CREAM** Pronounced "ice-cream"

SPACE: SATELLITE EXPERIMENTS



Detection principle: fly a particle detector in low Earth orbit or on interplanetary missions

Low (galactic) Energies: 10^{8} eV - 10^{13} eV

Acceptances: 2×10^{-3} m^2 sr (PAMELA) - 4 m^2 sr (ISS-CREAM)

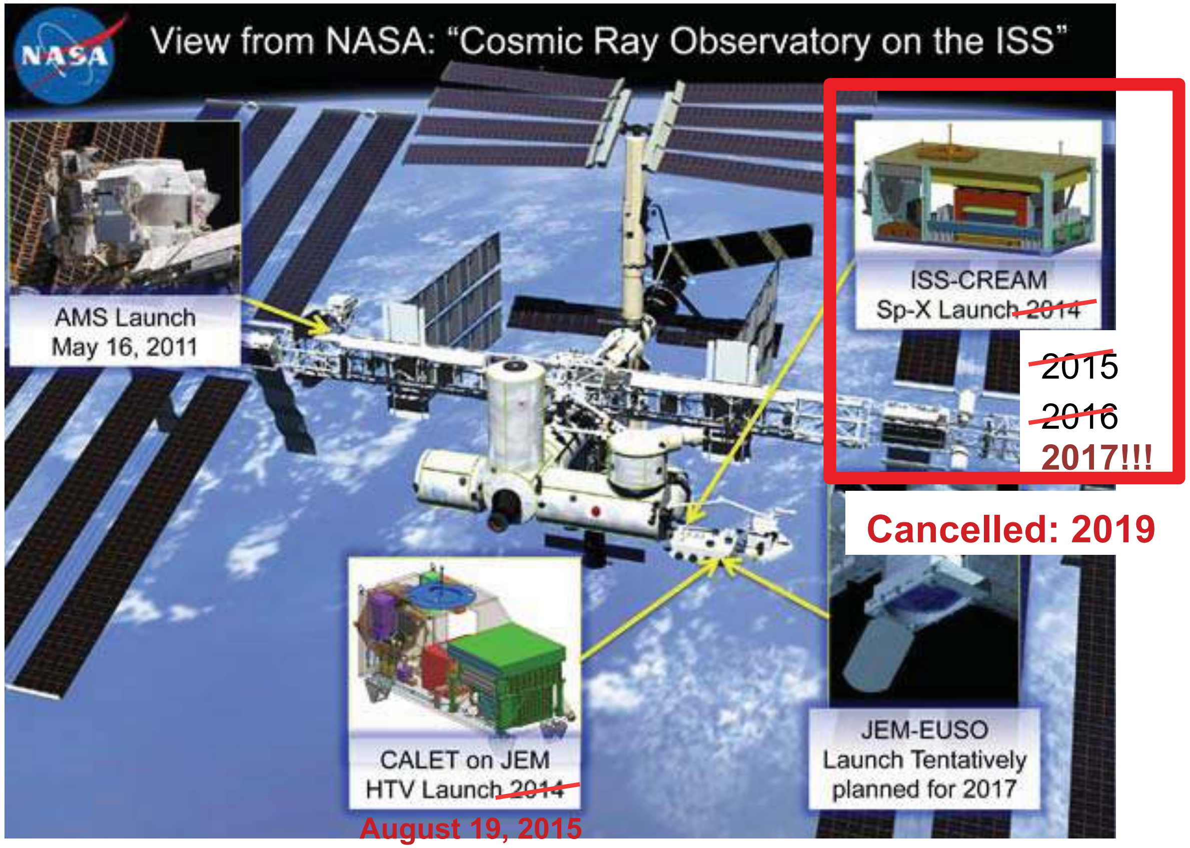
Duty cycle: ~100%

Techniques: **Transition radiation detectors, time-of-flight scintillators, calorimeters, silicon trackers, ..**

Material budget limited by maximum payload weight of carrier

A Lift from Stratosphere into Space

2. ISS-CREAM (pronounced “ice cream”)


NASA
View from NASA: “Cosmic Ray Observatory on the ISS”
AMS Launch
May 16, 2011
ISS-CREAM
Sp-X Launch ~~2014~~
CALET on JEM
HTV Launch ~~2014~~
JEM-EUSO
Launch Tentatively
planned for 2017

~~2015~~

~~2016~~

2017!!!

Cancelled: 2019

August 19, 2015

Space based data taking increases measurement time, but simultaneously:

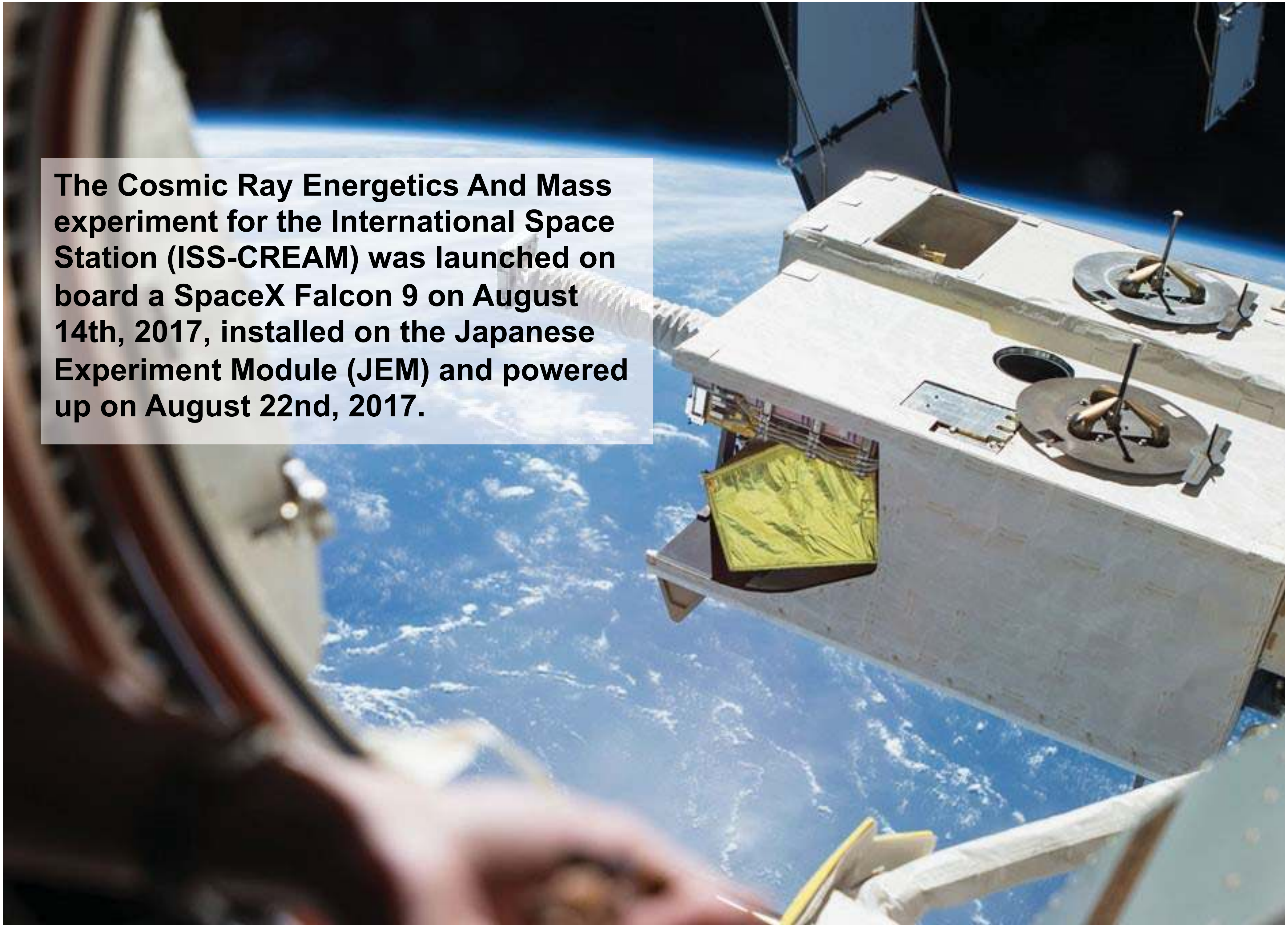
- challenging hardware requirements

→ electronics needs to be ‘radiation’ hard and **redundant**

→ payload **weight** and dimensions need to fit carrier

→ detector operation (EM-radiation) must not interfere with ISS ops

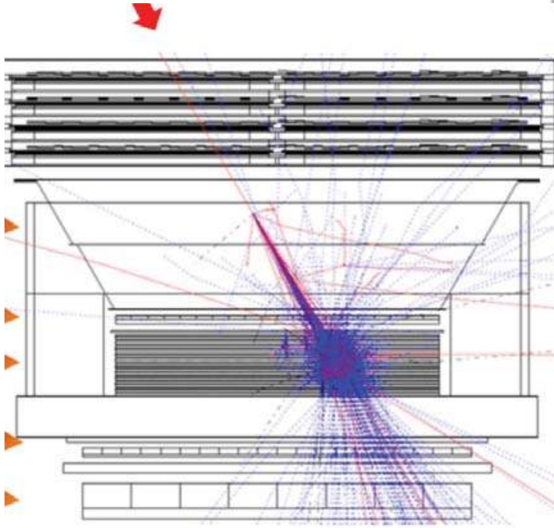
- high costs
- huge imponderables and risks

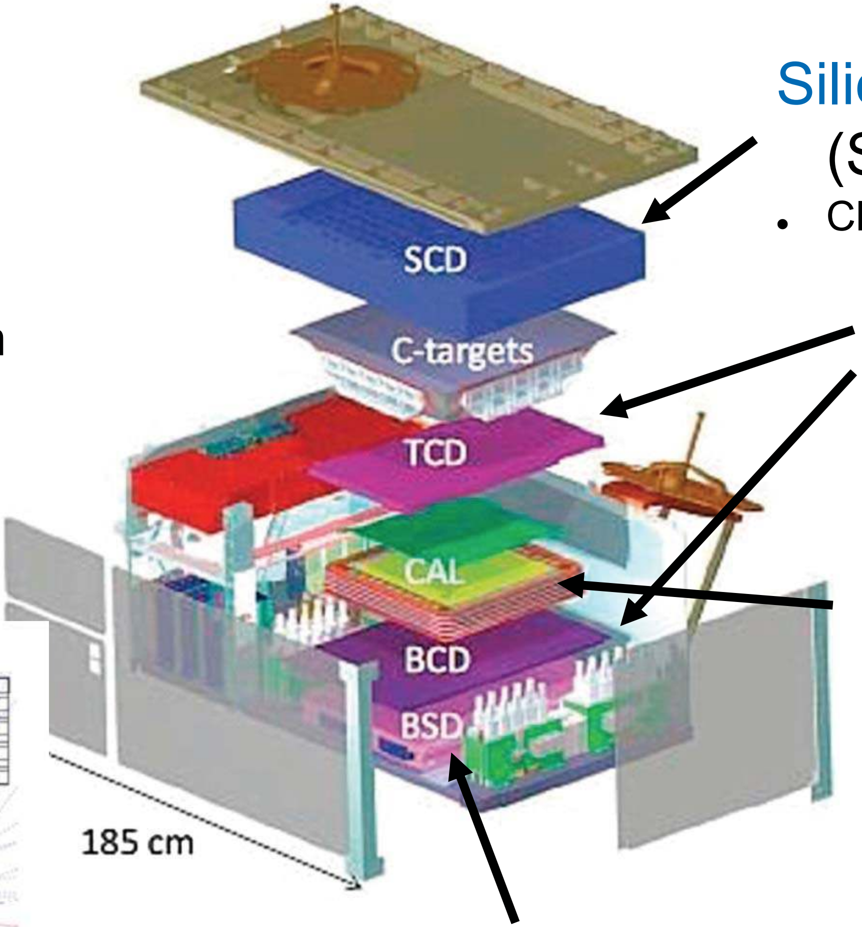


The Cosmic Ray Energetics And Mass experiment for the International Space Station (ISS-CREAM) was launched on board a SpaceX Falcon 9 on August 14th, 2017, installed on the Japanese Experiment Module (JEM) and powered up on August 22nd, 2017.

ISS-CREAM will measure cosmic ray energy spectra from **TeV to PeV**

- **Nuclei spectra** → sources and propagation
- **Secondary/primary ratios** → propagation and interactions
- **Individual isotopes** close to the knee





Silicon charge detector (SCD):

- Charge measurement

Top/bottom counting detector (T/BCD):

- **Plastic scintillator** for e/p sep.
- Independent trigger

Calorimeter (CAL):

- **20 layers tungsten + scintillating fibers**
- Energy measurement up to 1 PeV
- Tracking and trigger

No magnet

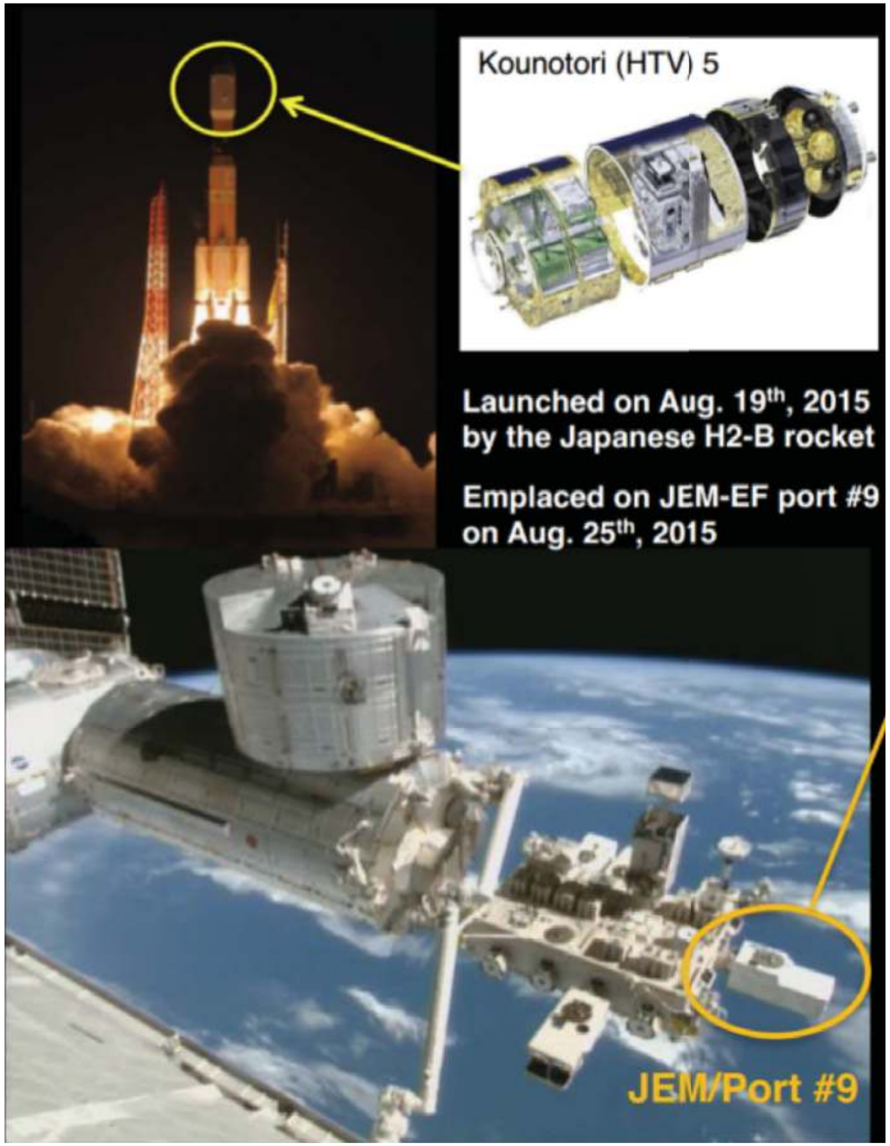
Boronated scintillator detector (BSD):

- Measures thermal neutrons → e/p separation

Advances in Space Research, Volume 53, Issue 10, 15 May 2014, Pages 1451–1455

PoS(ICRC2019)1177 PoS(ICRC2017)199

3. CALET – **CAL**orimetric **E**lectron **T**elescope

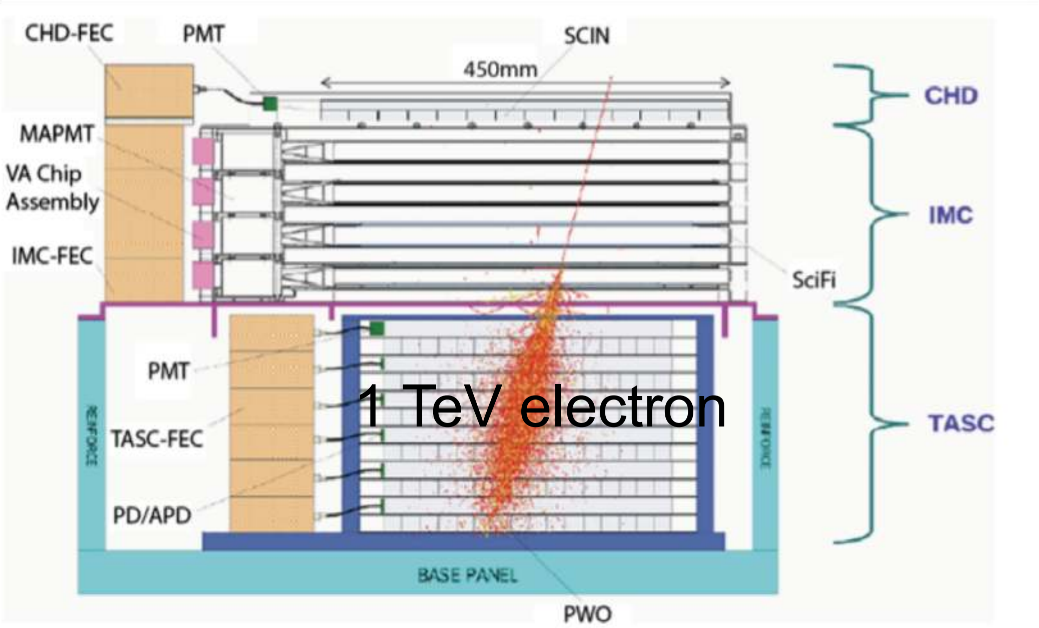

Kounotori (HTV) 5
JEM/Port #9

Launched on Aug. 19th, 2015 by the Japanese H2-B rocket

Emplaced on JEM-EF port #9 on Aug. 25th, 2015

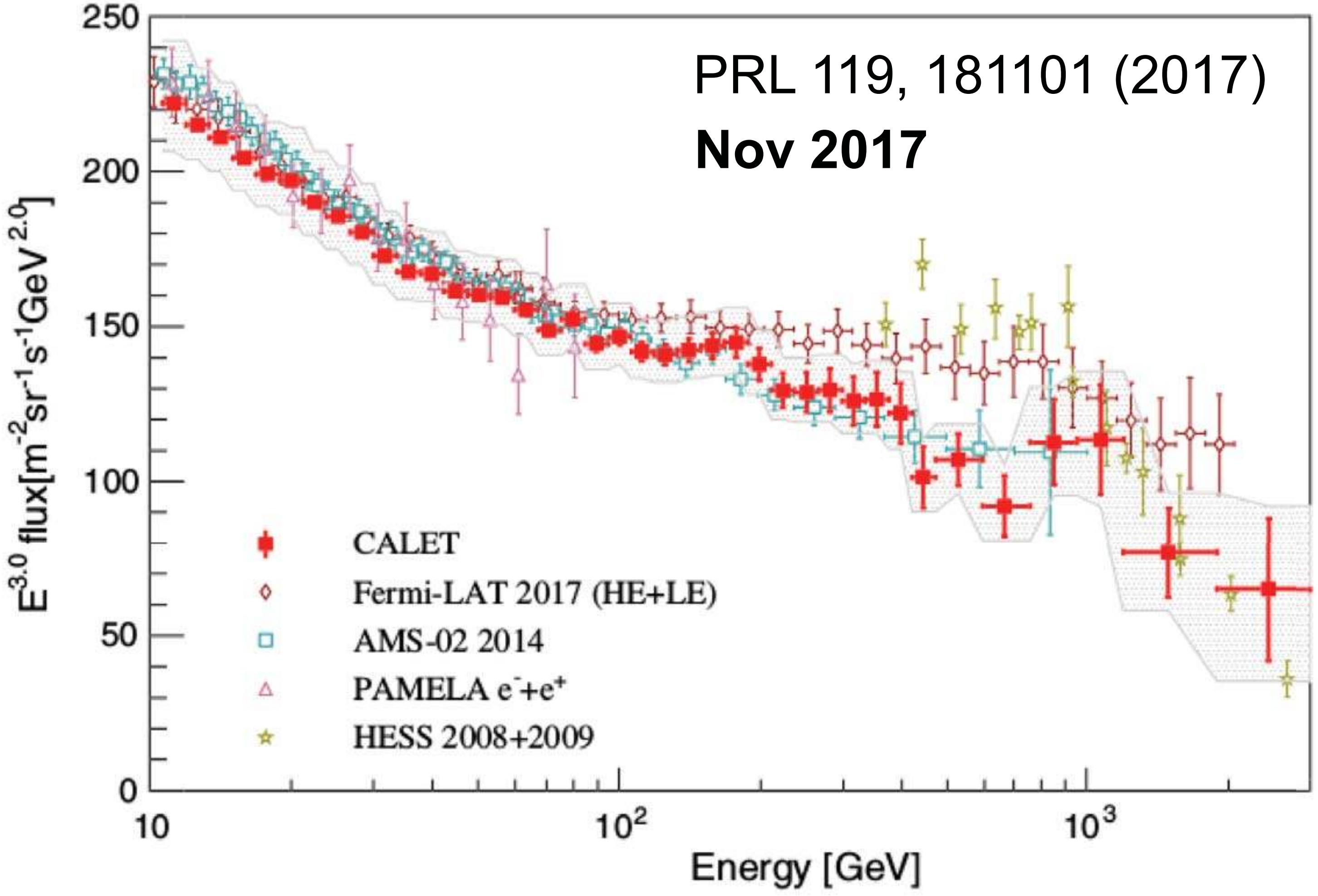
All-calorimetric experiment:

- Charge detector (CHD)
- Pre-shower imaging calorimeter (IMG)
- Total absorption calorimeter (TASC) 30 X_0
- CGBM (CALET Gamma-Ray Burst Monitor)


CHD-FEC
PMT
SCIN
450mm
CHD
MAPMT
VA Chip Assembly
IMC-FEC
IMC
SciFi
PMT
1 TeV electron
TASC-FEC
PD/APD
REINFORCE
REINFORCE
TASC
BASE PANEL
PWO

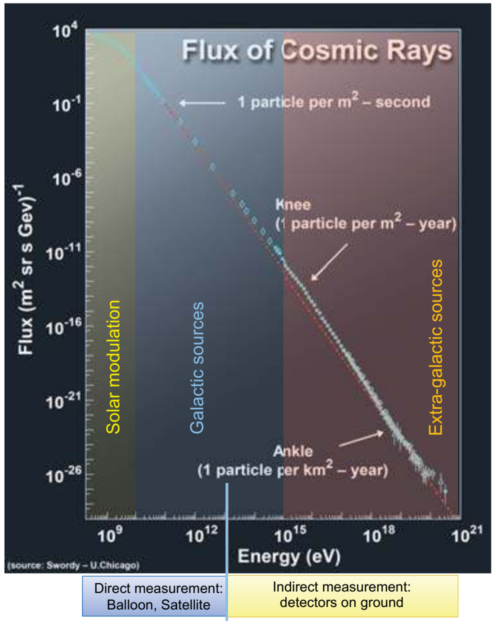
Japan, Italy, USA

$e^+ + e^-$ Flux: CALET



PRL 119, 181101 (2017)

Nov 2017

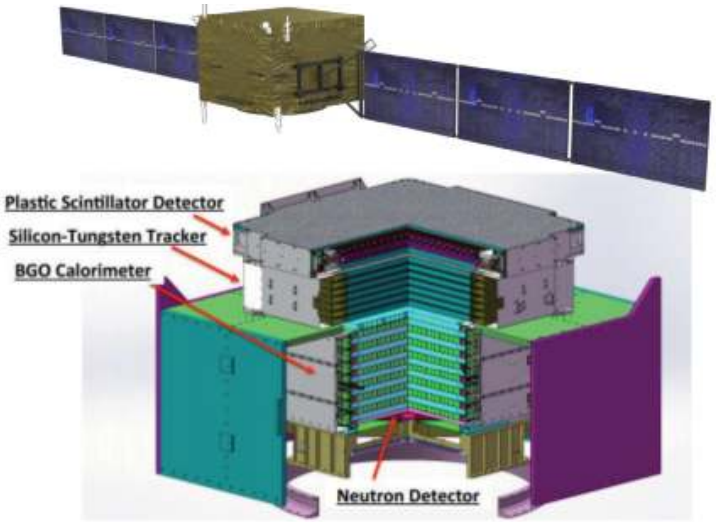


CALET CAL: 30 X_0 → fully contains TeV shower, **E-scale uncert: TBD, but small**
AMS ECAL: 18X_0 → contains 70% of TeV shower, **E-scale: 4% uncert. at 1TeV**
Fermi ECAL: 10 X_0 → contains 35% of TeV shower, **E-scale: 5% uncert. at 1 TeV**
HESS: **E-scale: 15% uncert.**

4. DAMPE – **DA**rk **M**atter **P**article **E**xplorer

DAMPE Collaboration:

- 🇨🇳 Purple Mountain Observatory, National Space Science Center, Inst. High Energy Physics, Inst. Modern Physics, University of Science and Technology
- 🇨🇭 Geneva University
- 🇮🇹 Bari, Lecce, Perugia (Universities and INFN)


Plastic Scintillator Detector
Silicon-Tungsten Tracker
BGO Calorimeter
Neutron Detector

DAMPE

Dark Matter Particle Explorer successfully launched on December 17, 2015

Satellite

- DAMPE detector, consists of 4 subsystems:
  - the plastic scintillator strips detector (PSD), ← Charge
  - the silicon-tungsten tracker-converter (STK), ← Track & charge
  - the BGO imaging calorimeter (BGO), and ← Energy, 32 X_0
  - the neutron detector (NUD). ← e/p discrimination

The DAMPE BGO Calorimeter

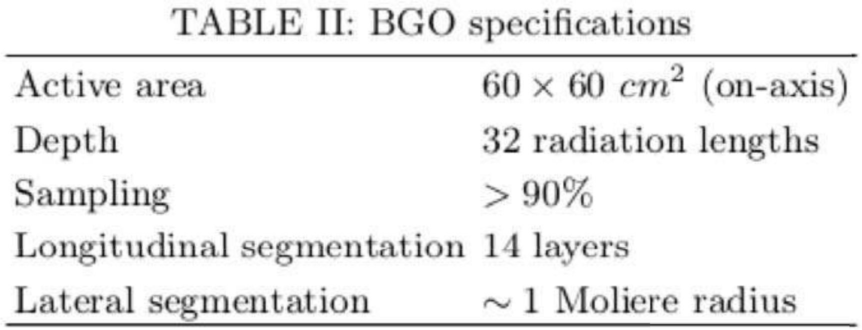
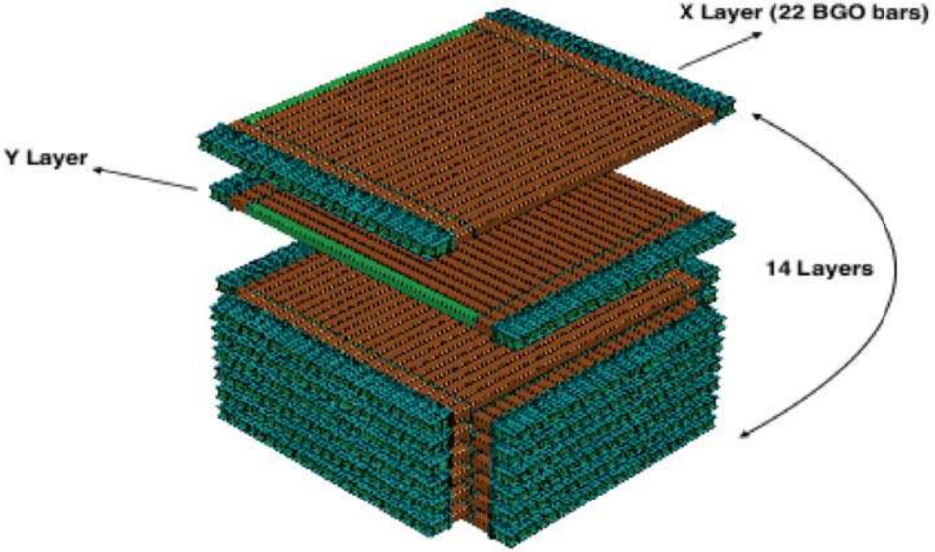
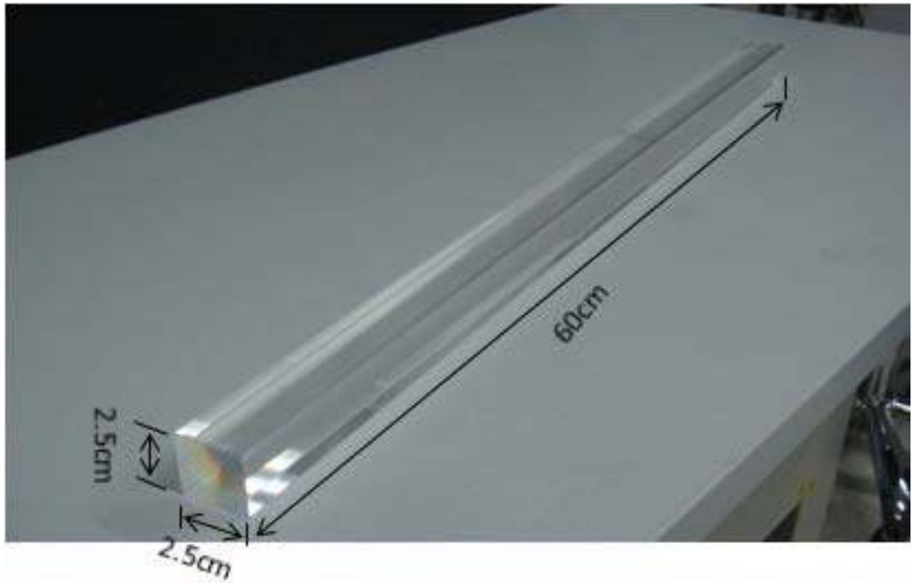
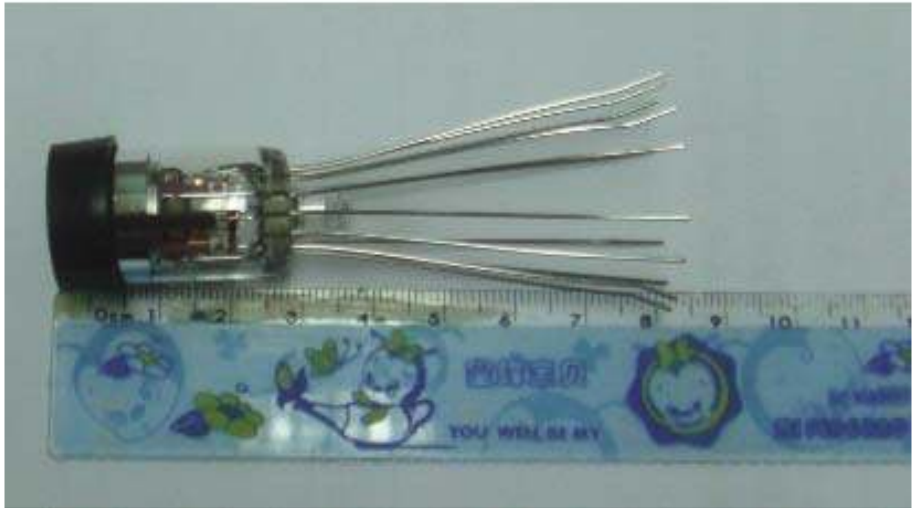


TABLE II: BGO specifications

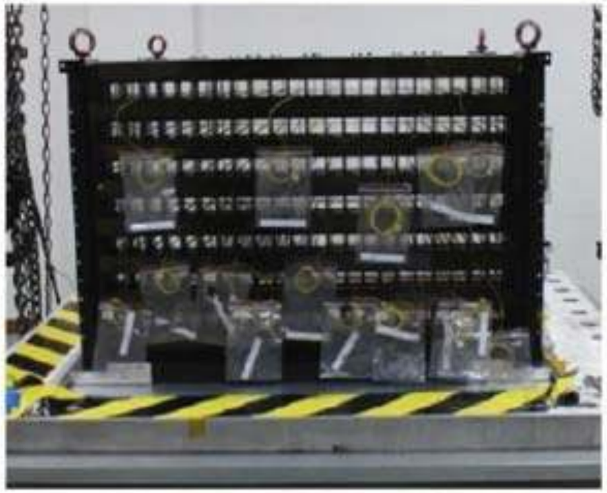
Active area	$60 \times 60\ cm^2$ (on-axis)
Depth	32 radiation lengths
Sampling	$> 90\%$
Longitudinal segmentation	14 layers
Lateral segmentation	~ 1 Moliere radius


X Layer (22 BGO bars)
Y Layer
14 Layers


60cm
2.5cm
2.5cm



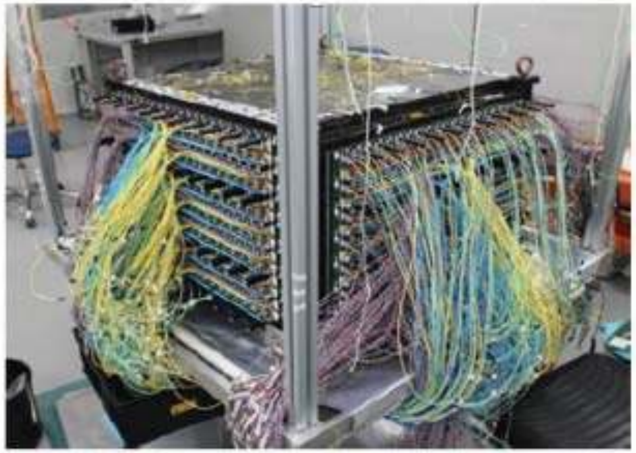
BGO (Bi4Ge3O12)
is a high Z, high density scintillation material



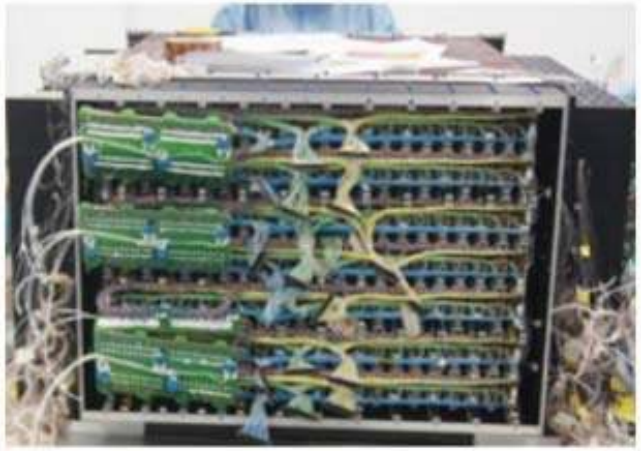
Carbon Fiber Structure

BGO crystal installation

PMT installation



Cableing



Cable connector

BGO Calorimeter

MISSIONS AND SELECTED RESULTS (no magnet after AMS!)

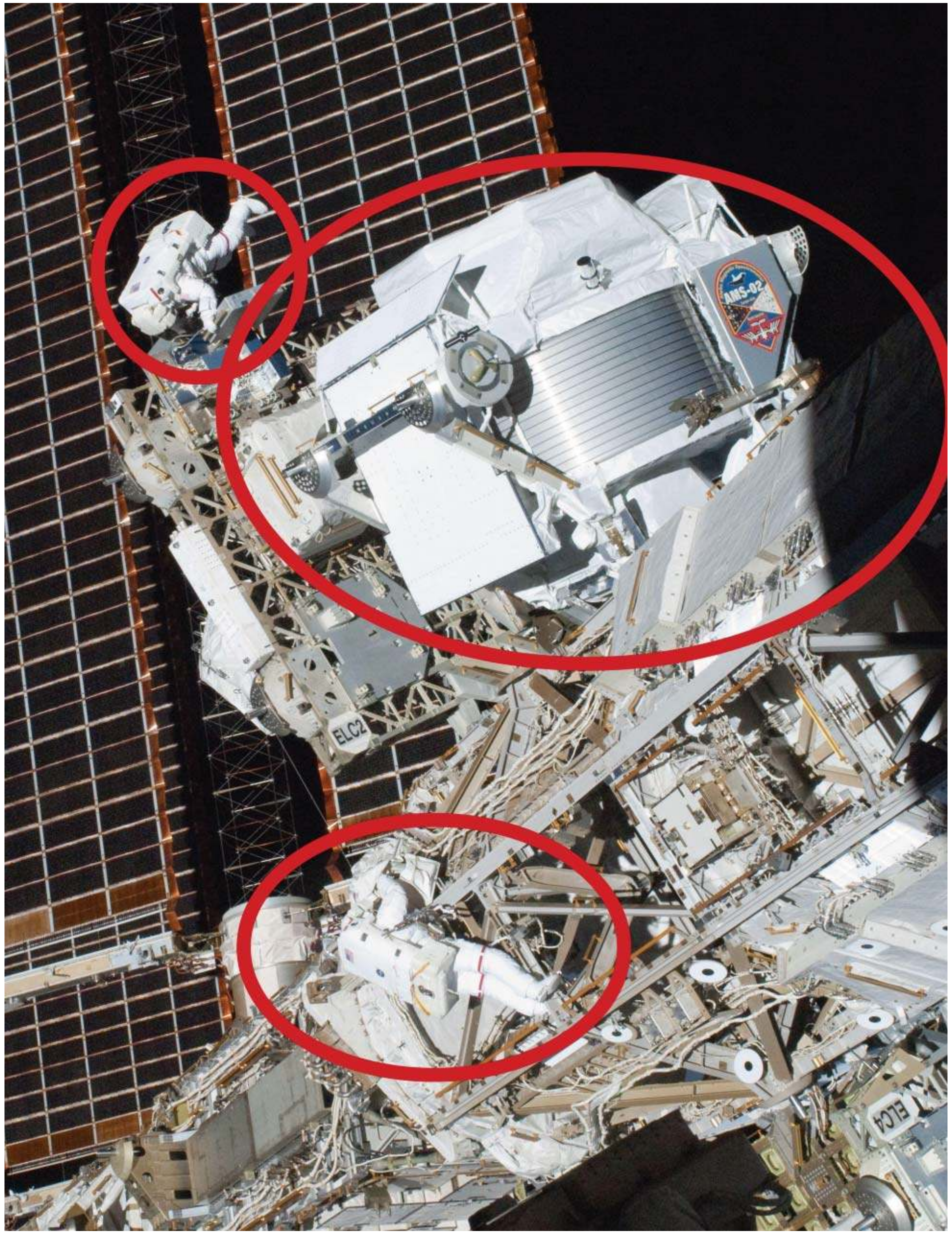
Experiment	e^+|e^- (present data)	e^++e^- (energy range)	CR nuclei (energy range)	Charge	Gamma-ray	Type	Launch
PAMELA	e^+<300 GeV e^-<625 GeV	1-700 GeV (3 TeV with cal)	1 GeV-1.2 TeV (ext. -> 2TeV)	1-8	-	SAT	2006 Jun 15
FERMI	-	7 GeV -2 TeV	50 GeV-1TeV	1	200 MeV-300GeV GRB 8 keV-35 MeV	SAT	2008 Nov 11
AMS-02	e^+<500 GeV e^-<700GeV	0.5 GeV-1 TeV (extendable)	0.5 GV-1.9 TV (extendable)	1-26++	1 GeV-1TeV (calorimeter)	ISS	2011 May 16
NUCLEON	-	100 GeV–3 TeV	100 GeV-1TeV	1-30	-	SAT	2014 Dec 26
CALET	-	1 GeV -20 TeV	10 GeV-1TeV	1-40	10 GeV-10 TeV GRB 7-20 MeV	ISS	2015 Aug 19
DAMPE	-	10 GeV -10 TeV	50 GeV-500TeV	1-20	5 GeV-10 TeV	SAT	2015 Dec 17
ISS-CREAM	-	100 GeV-10 TeV	1TeV-1PeV	1-28++	-	ISS	2017 Aug 14
CSES	-	3-200 MeV	30-300 MeV	1	-	SAT	2018
GAMMA-400	-	1 GeV-20 GeV	1 TeV-3 PeV	1-26	20 MeV – 1 TeV	SAT	2023-25
HERD	-	10(s)-10^4 GeV	Up to PeV	TBD	10(s)-10^4 GeV	CSS	2022-25
HELIX	-	-	<10 GeV/n	light isotopes	-	LDB	proposal
HNS	-	-	~GeV/n	6-96	-	SAT	proposal
GAPS	-	-	<1GeV/n	p, D	-	LDB	

Future

Atempause

Then AMS

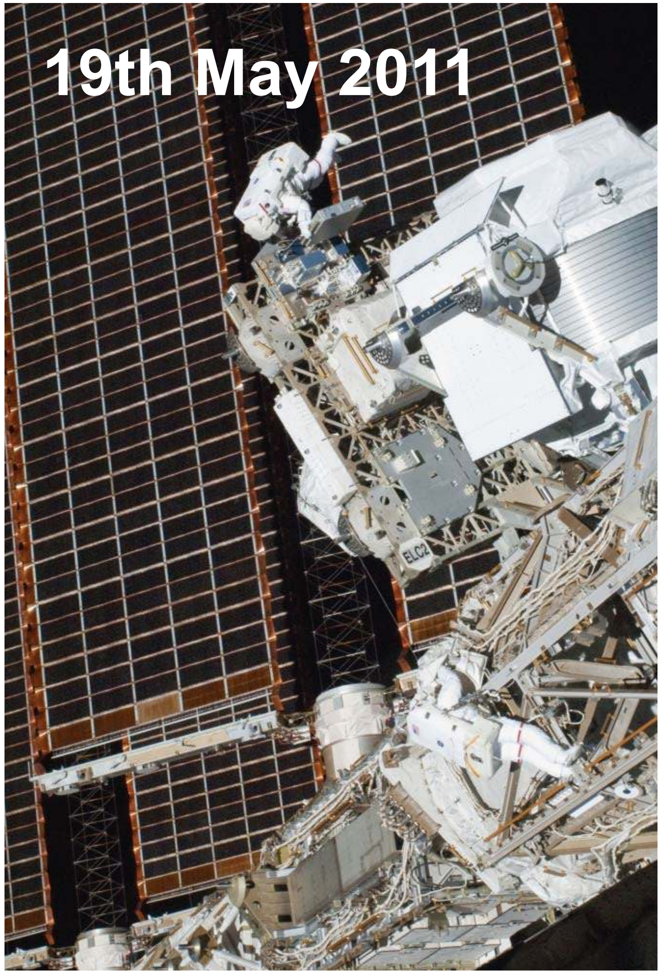
5. AMS-02: The Alpha Magnetic Spectrometer 02

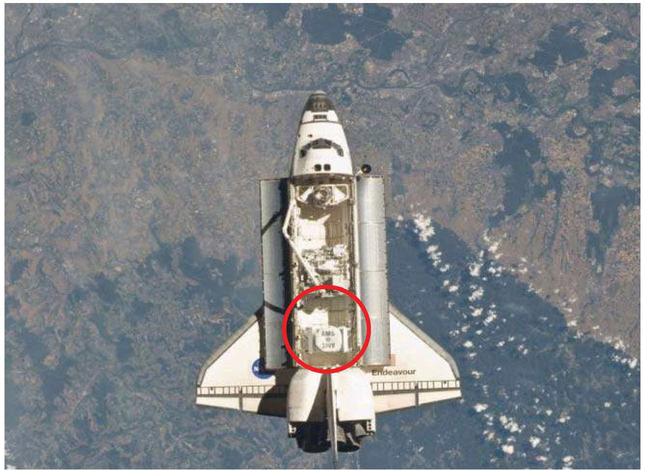


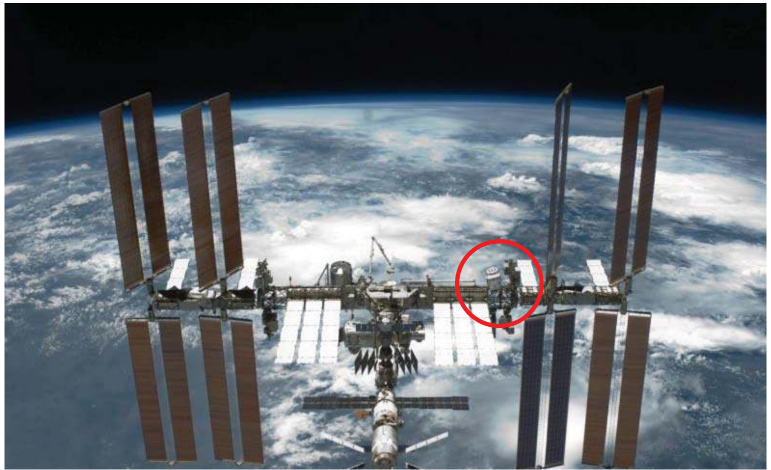
- **Volume** 64 m^3, height 4 m
- **Weight** 8500 kg
- **Power** 2500 W
- **Data downlink** 9 Mbps (minimum)
- **Magnetic field** 0.15 T (400 x Earth, PAMELA: 0.4 T, but H=44.5 cm)
- **Launch** May 16th, 2011 (Endeavour)
- **Data taking** as of May 19th, 2011
- **Construction** 1999-2010 (>3 PhD generations)
- **Mission duration:** until the end of ISS operation

D

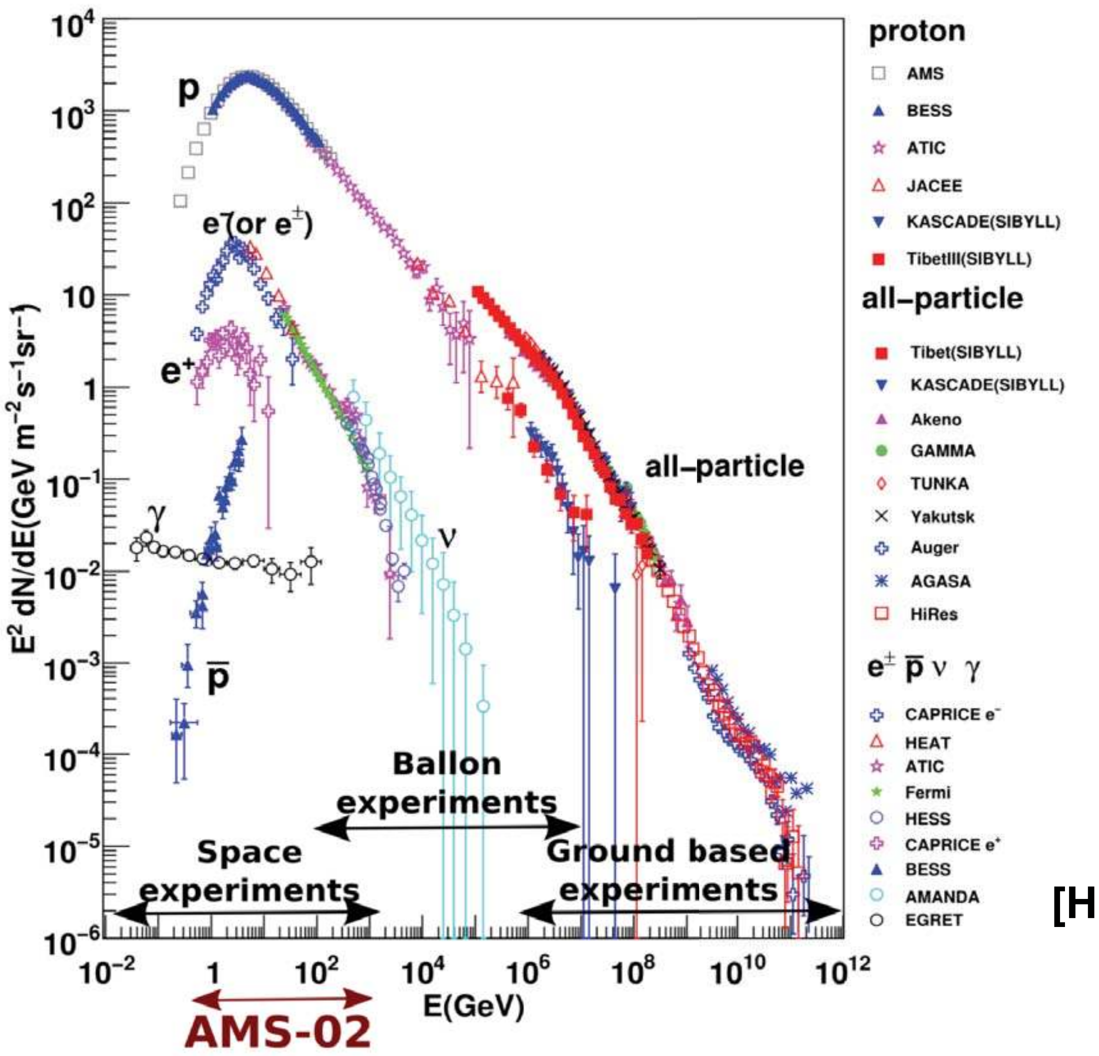
16th May 2011


19th May 2011





To measure:



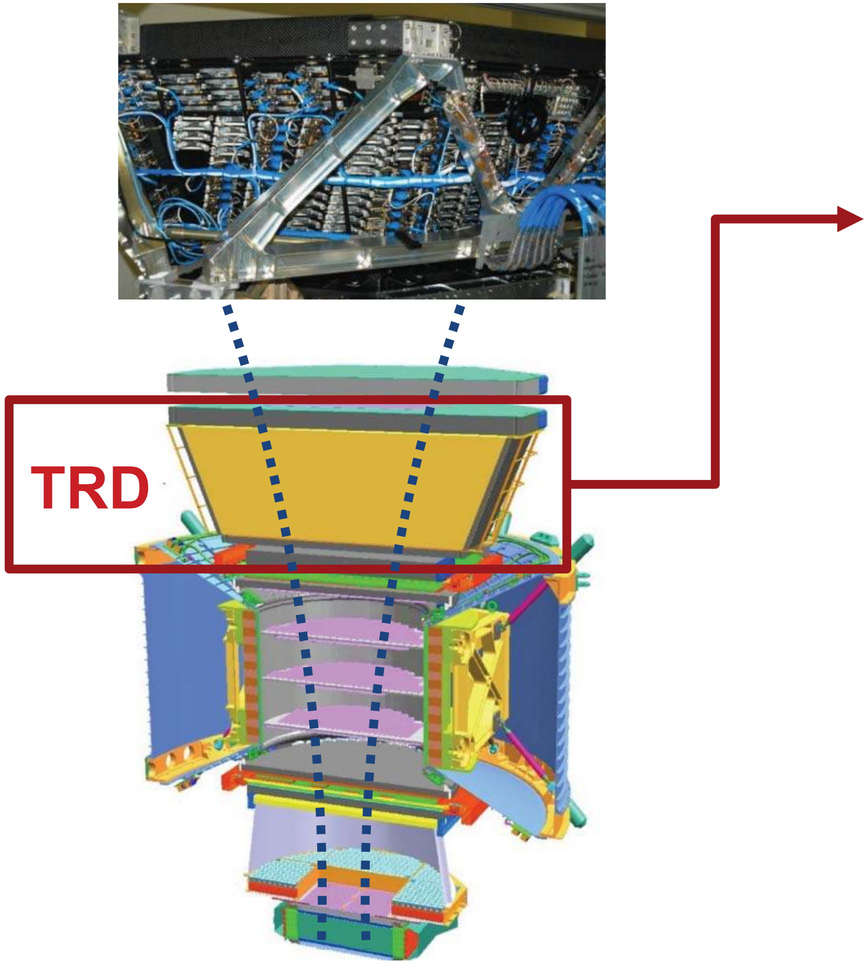
[Hillas 2006,arXiv:astro-ph/0607109 v2]

- $\Phi(p)$ / $\Phi(e^+)$ ~ 10^3-10^4

- $\Phi(e^-)$ / $\Phi(e^+)$ ~ O(10)

How to find a positron:
Among all collected events we need to find the 0.1%-0.01% signal positrons.

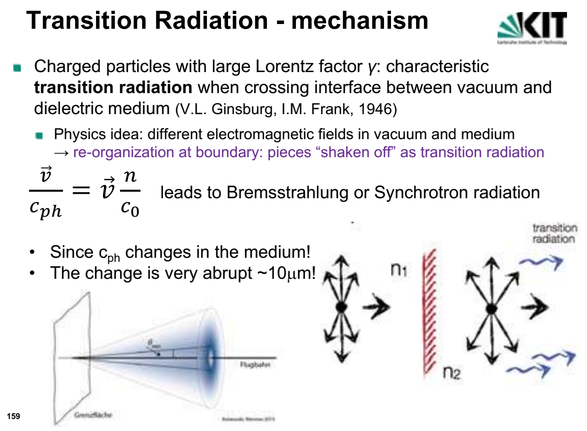
Transition Radiation Detector: TRD



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

Identifies e^+, e^-

LEPTON/HADRON SEPARATION WITH THE TRD



Transition Radiation - mechanism

- Charged particles with large Lorentz factor γ: characteristic **transition radiation** when crossing interface between vacuum and dielectric medium (V.L. Ginsburg, I.M. Frank, 1946)
  - Physics idea: different electromagnetic fields in vacuum and medium → re-organization at boundary: pieces "shaken off" as transition radiation

$\frac{\vec{v}}{c_{ph}} = \vec{v}\frac{n}{c_0}$ leads to Bremsstrahlung or Synchrotron radiation

- Since c_{ph} changes in the medium!
- The change is very abrupt ~10μm!

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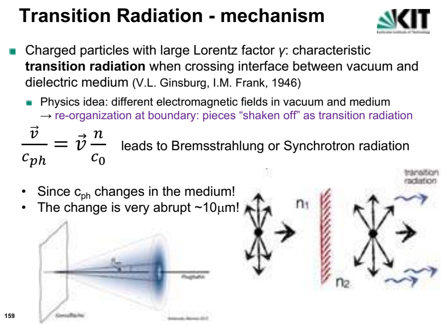

Transition Radiation - mechanism

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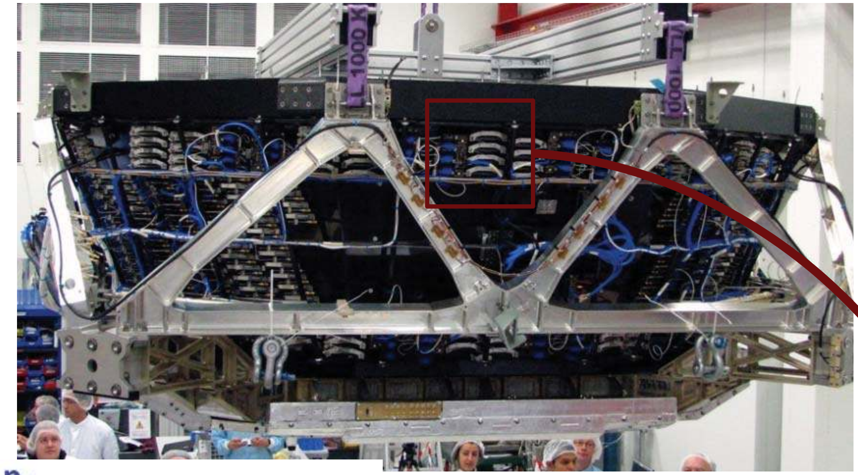
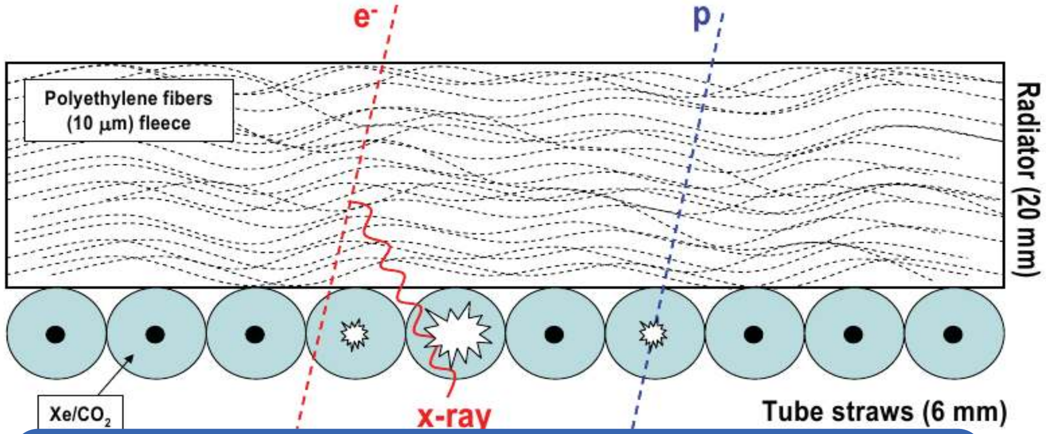
$\frac{\vec{v}}{c_{ph}} = \vec{v}\frac{n}{c_0}$ leads to Bremsstrahlung or Synchrotron radiation

- Since c_{ph} changes in the medium!
- The change is very abrupt ~10µm!

transition radiation
n_1
n_2

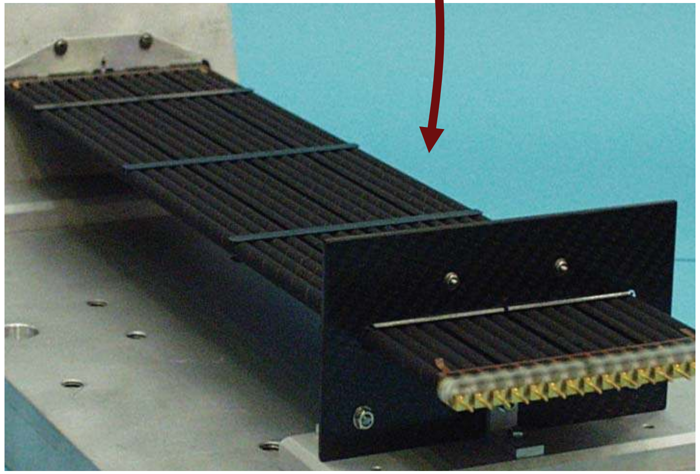


1000 X
1000 X

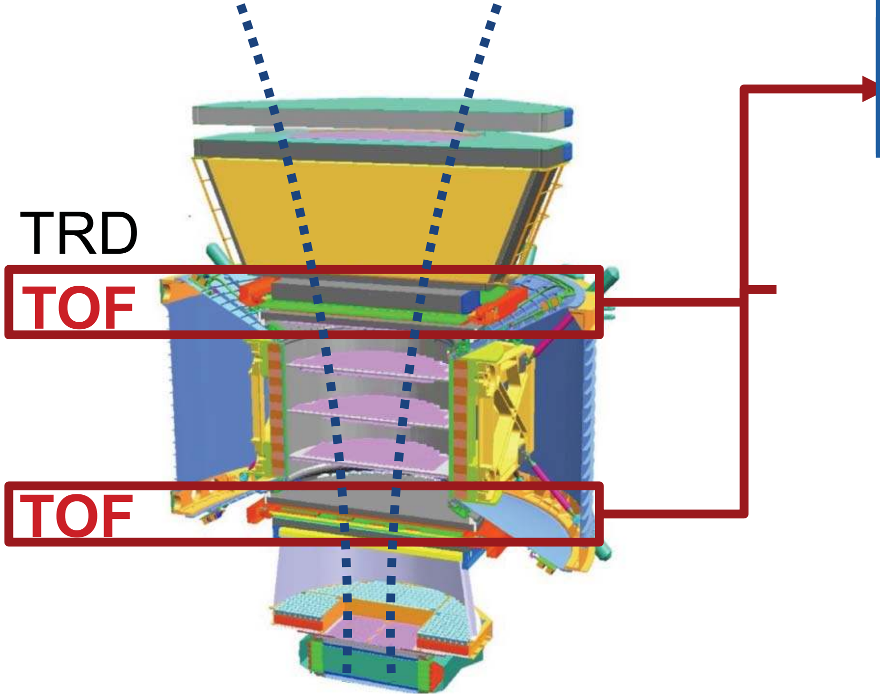


e-
p
Polyethylene fibers (10 µm) fleece
Radiator (20 mm)
Xe/CO2
x-ray
Tube straws (6 mm)

20 layer of radiator (fleece) and straw tubes for Xrays (~KeV) detection

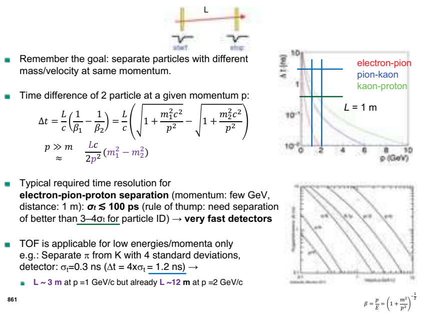


Time – of Flight: TOF



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

→ **Charge Q**
→ **Velocity β**



- Remember the goal: separate particles with different mass/velocity at same momentum.
- Time difference of 2 particle at a given momentum p:

$$\Delta t = \frac{L}{c}\left(\frac{1}{\beta_1}-\frac{1}{\beta_2}\right) = \frac{L}{c}\left(\sqrt{1+\frac{m_1^2c^2}{p^2}}-\sqrt{1+\frac{m_2^2c^2}{p^2}}\right)$$

$$\overset{p \gg m}{\approx} \frac{Lc}{2p^2}(m_1^2-m_2^2)$$

- Typical required time resolution for **electron-pion-proton separation** (momentum: few GeV, distance: 1 m): $\sigma_t \lesssim$ **100 ps** (rule of thump: need separation of better than 3–4σt for particle ID) → **very fast detectors**
- TOF is applicable for low energies/momenta only e.g.: Separate π from K with 4 standard deviations, detector: σ_t=0.3 ns ($\Delta t = 4x\sigma_t$ = 1.2 ns) →
  - **L ~ 3 m** at p =1 GeV/c but already **L ~12 m** at p =2 GeV/c

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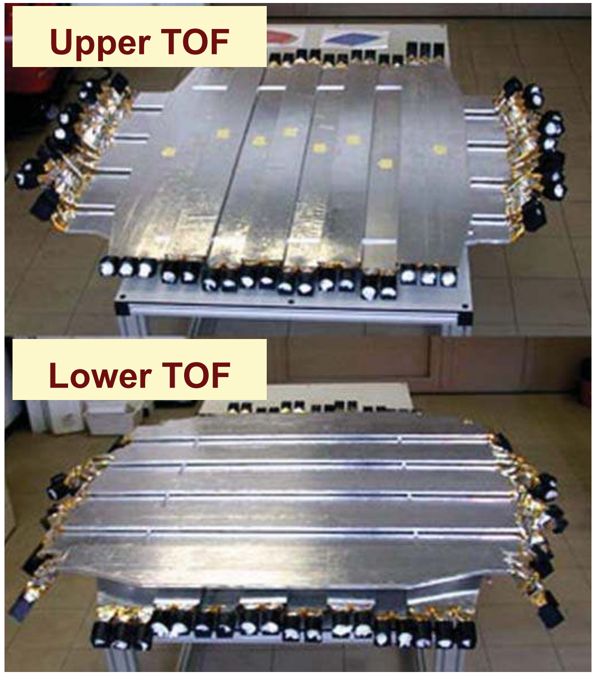
$\beta = \frac{p}{E} = \left(1+\frac{m^2}{p^2}\right)^{-\frac{1}{2}}$



4 scintillator planes (2 above, 2 below magnet)

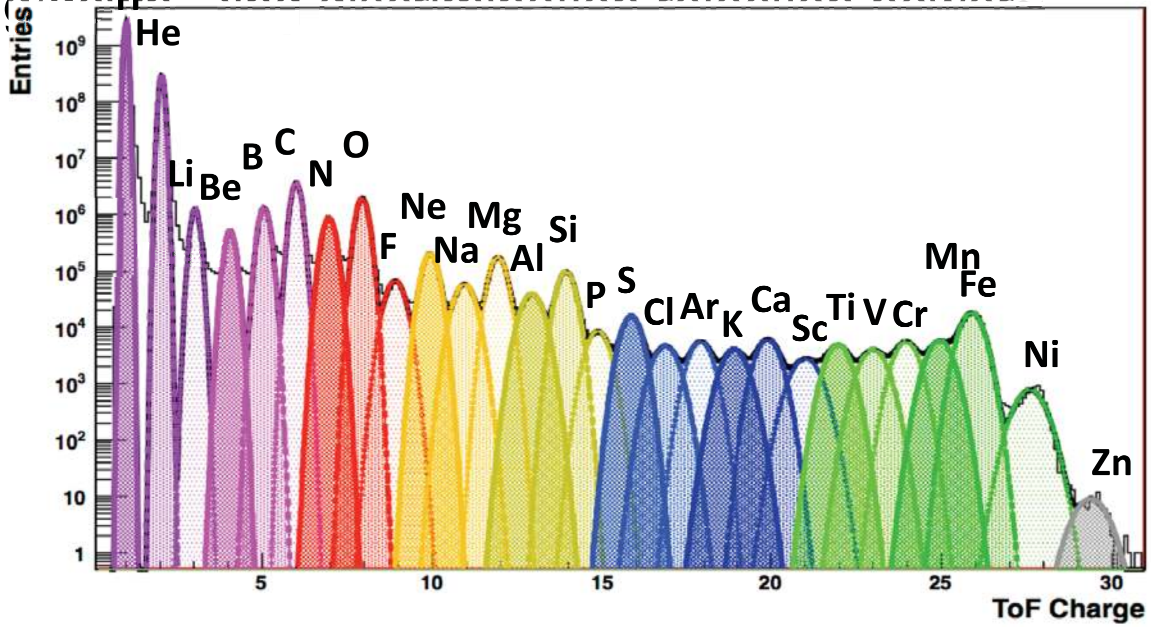
The TOF provides to AMS-02

– Fast trigger to charged particles through different thresholds

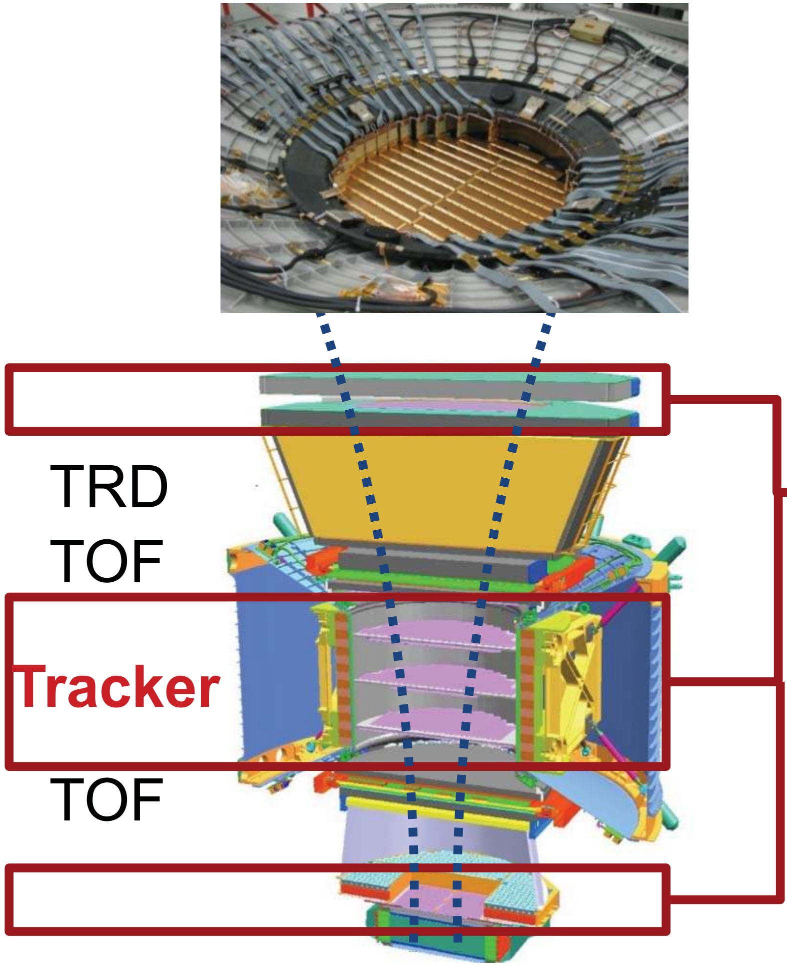
– Time-Of-Flight dT (res ~160ps) to determine velocity with few % resolution

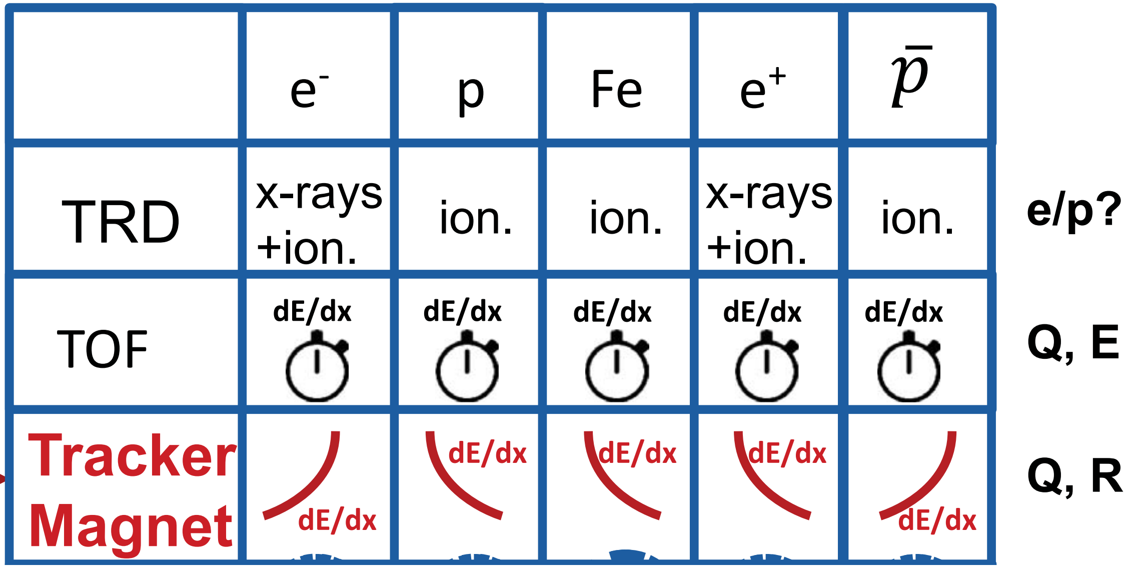
– Particle charge Z up to Z=15

– Upgoing/downgoing discrimination rejection power ~ 10^{-9}



Silicon Strip Tracker and Magnet





	e$^-$	p	Fe	e$^+$	$\bar{p}$	
TRD	x-rays +ion.	ion.	ion.	x-rays +ion.	ion.	**e/p?**
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
→ Rigidity R=p/Z

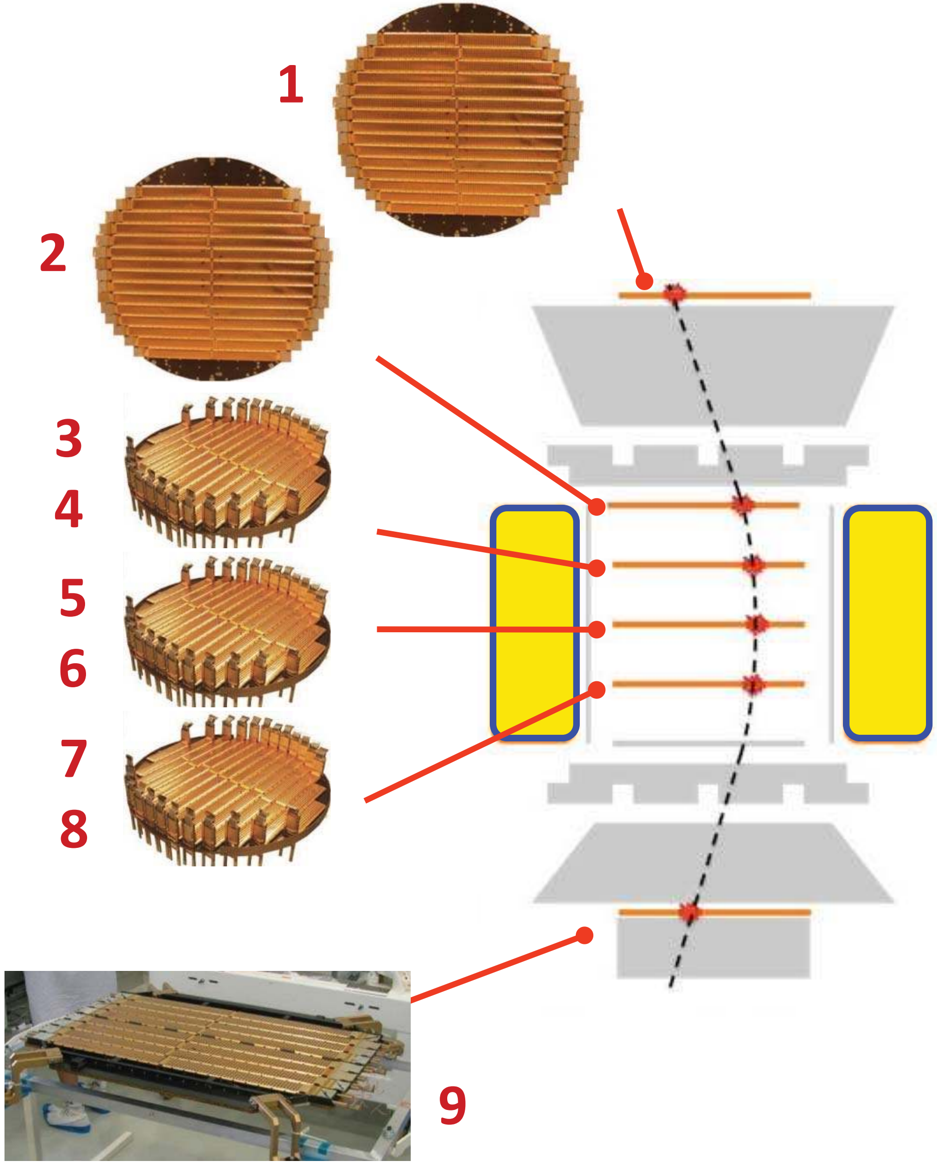
9 Silicon planes

Single coordinates resolution
10μm (bend plane) 30μm (not-bend plane)

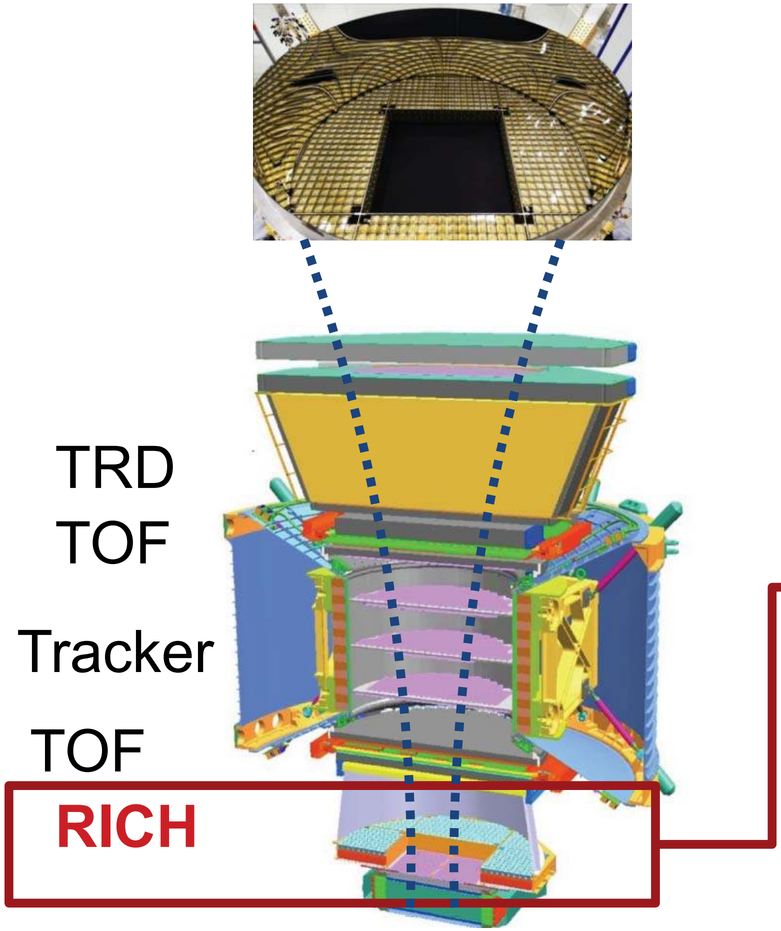
2264 double-sided Si micro-strip sensors
For a total of 6.4m^2 active area
200K readout channels

Channels aligned to 3μm using
- 20 UV laser (inner tracker)
- cosmic rays (outer planes)

Maximum detectable rigidity ~ 2TeV

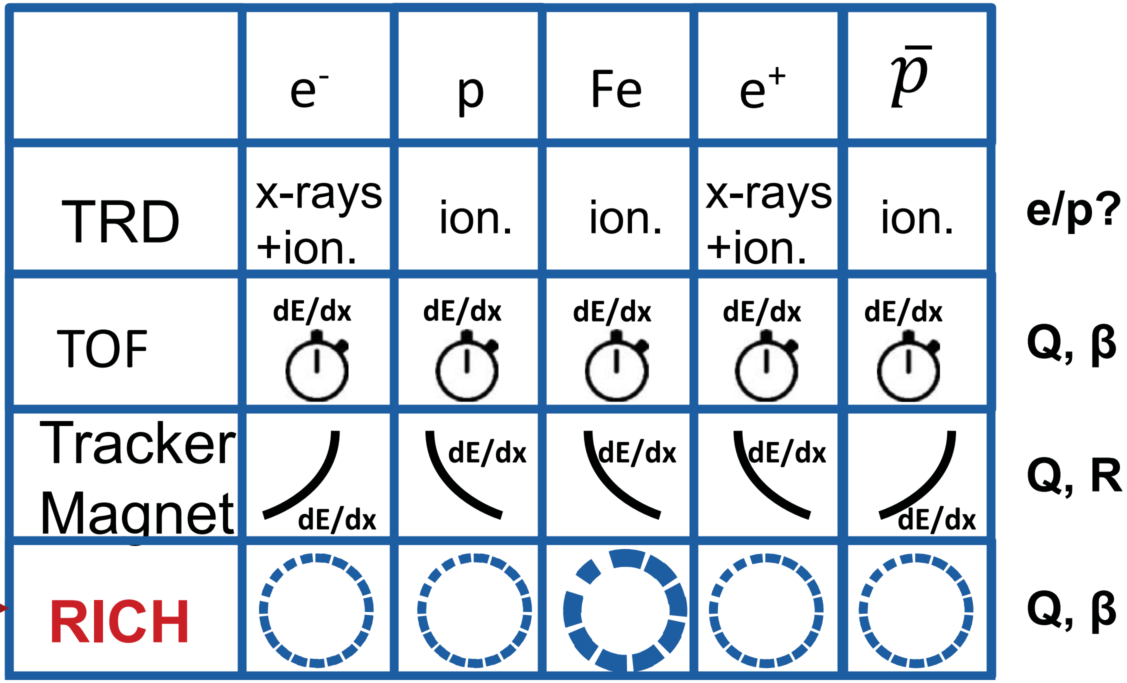


Ring Imaging Detector RICH

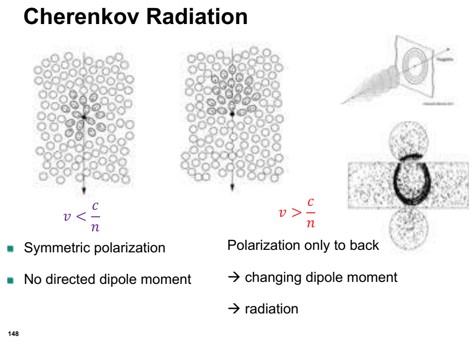


→ **Charge Q**

→ **Velocity β**



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



Cherenkov Radiation

$v < \frac{c}{n}$

- Symmetric polarization
- No directed dipole moment

$v > \frac{c}{n}$

Polarization only to back

→ changing dipole moment

→ radiation

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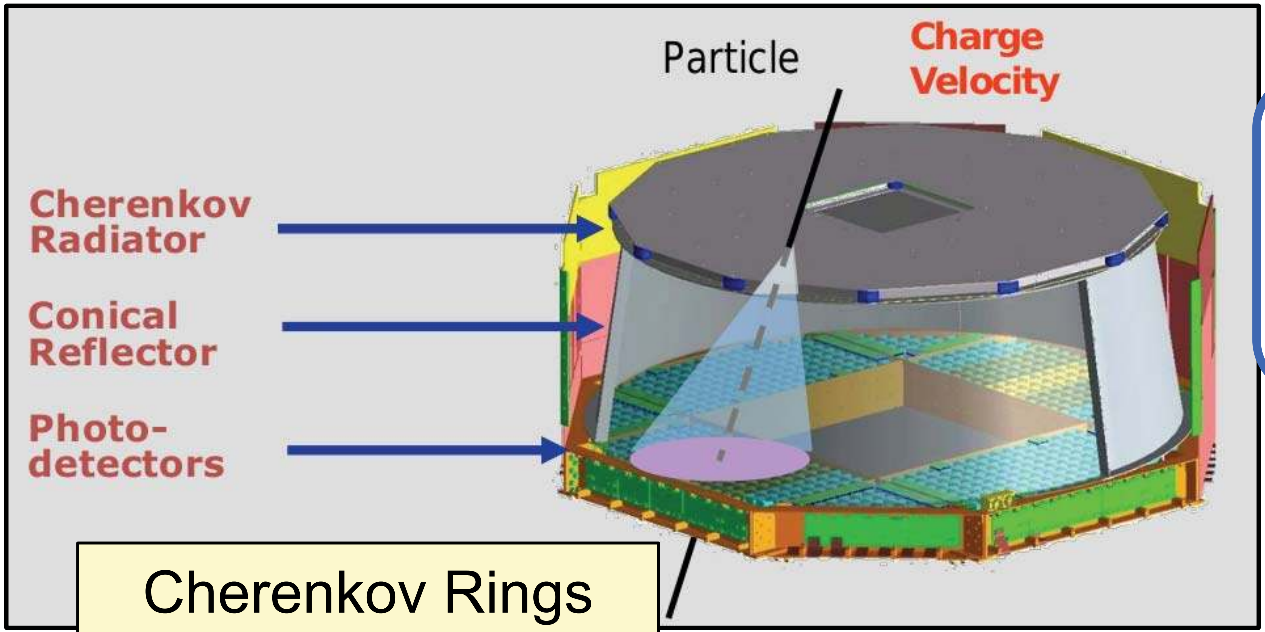
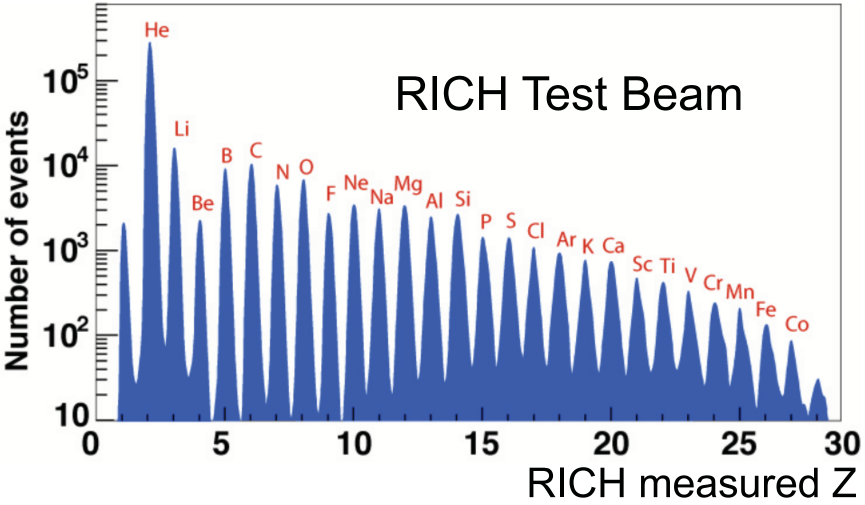

Particle
Charge
Velocity
Cherenkov Radiator
Conical Reflector
Photo-detectors

Cherenkov Rings
Intensity ~ Z^2
Opening Angle ~ β

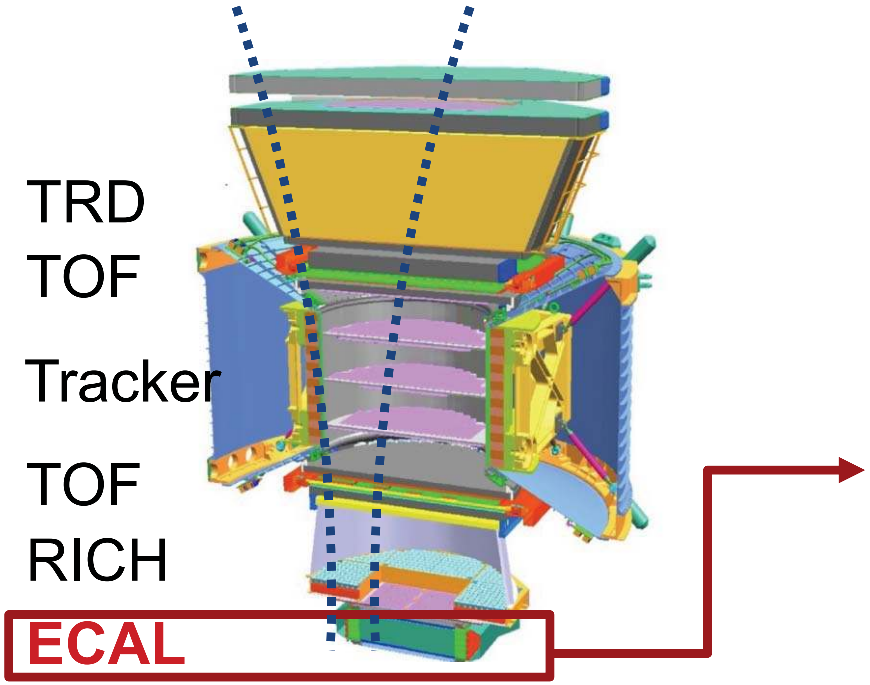
– 134 cm diameter collection surface
– 640 4X4 PMTs
– Conical reflector to increase RICH acceptance

- β measurement with a resolution ~ 0.1% for Z=1 particles, and ~ 0.01% for ions (Z>1).

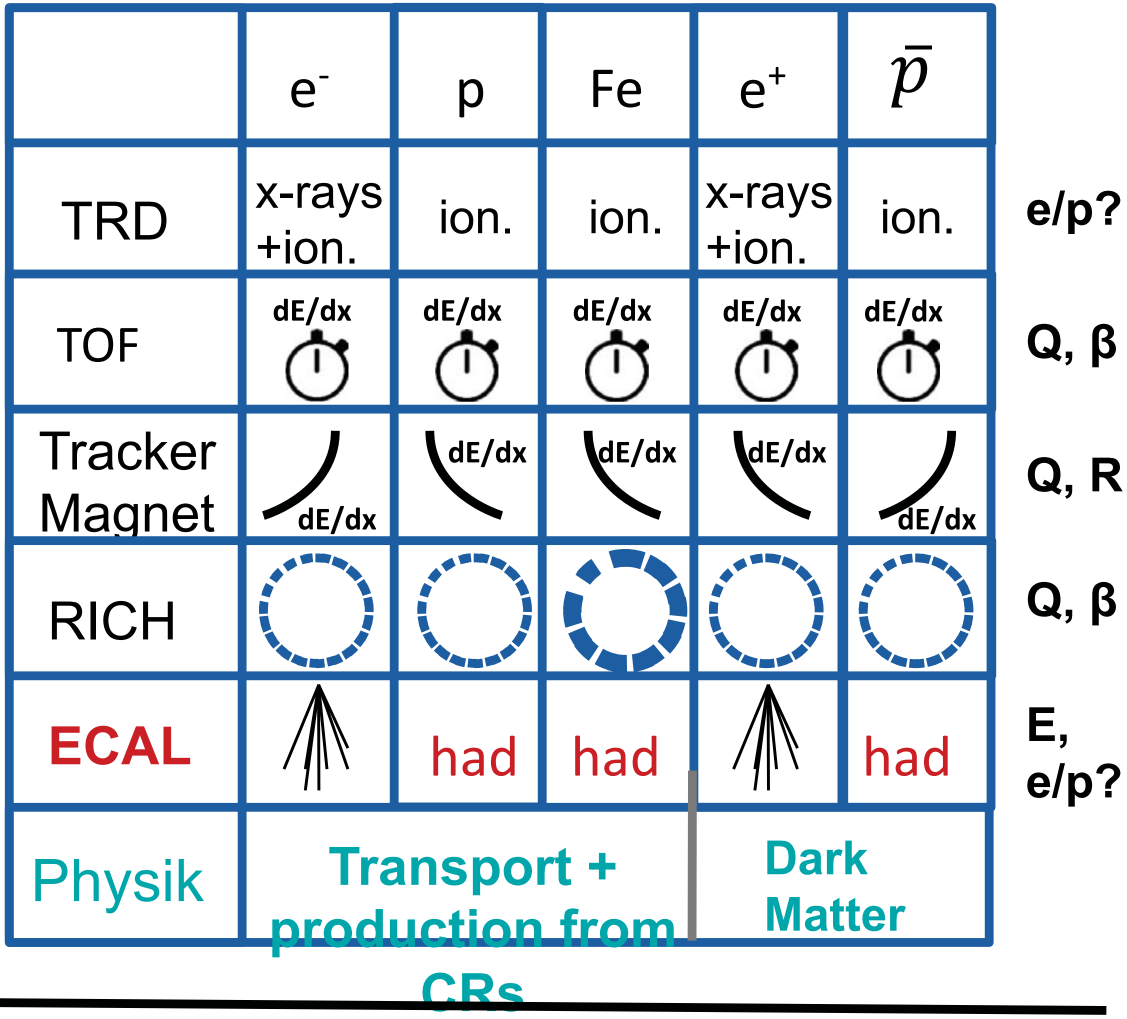
- Particle charge measurement with a charge confusion of the order of 10 % up to Z=30



Electromagnetic Calorimeter: ECAL

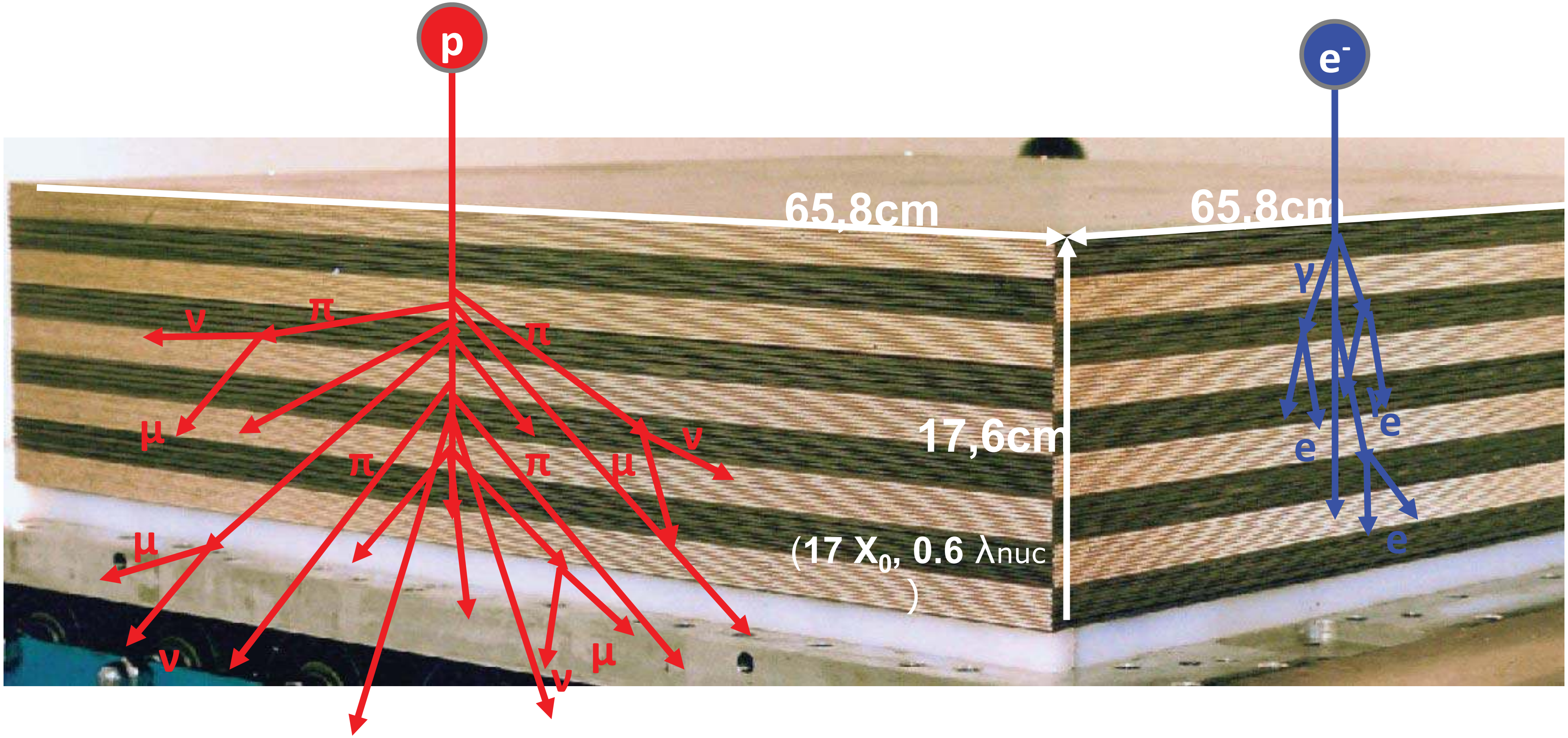


Identify e^+, e^-
Energy for e^+, e^-



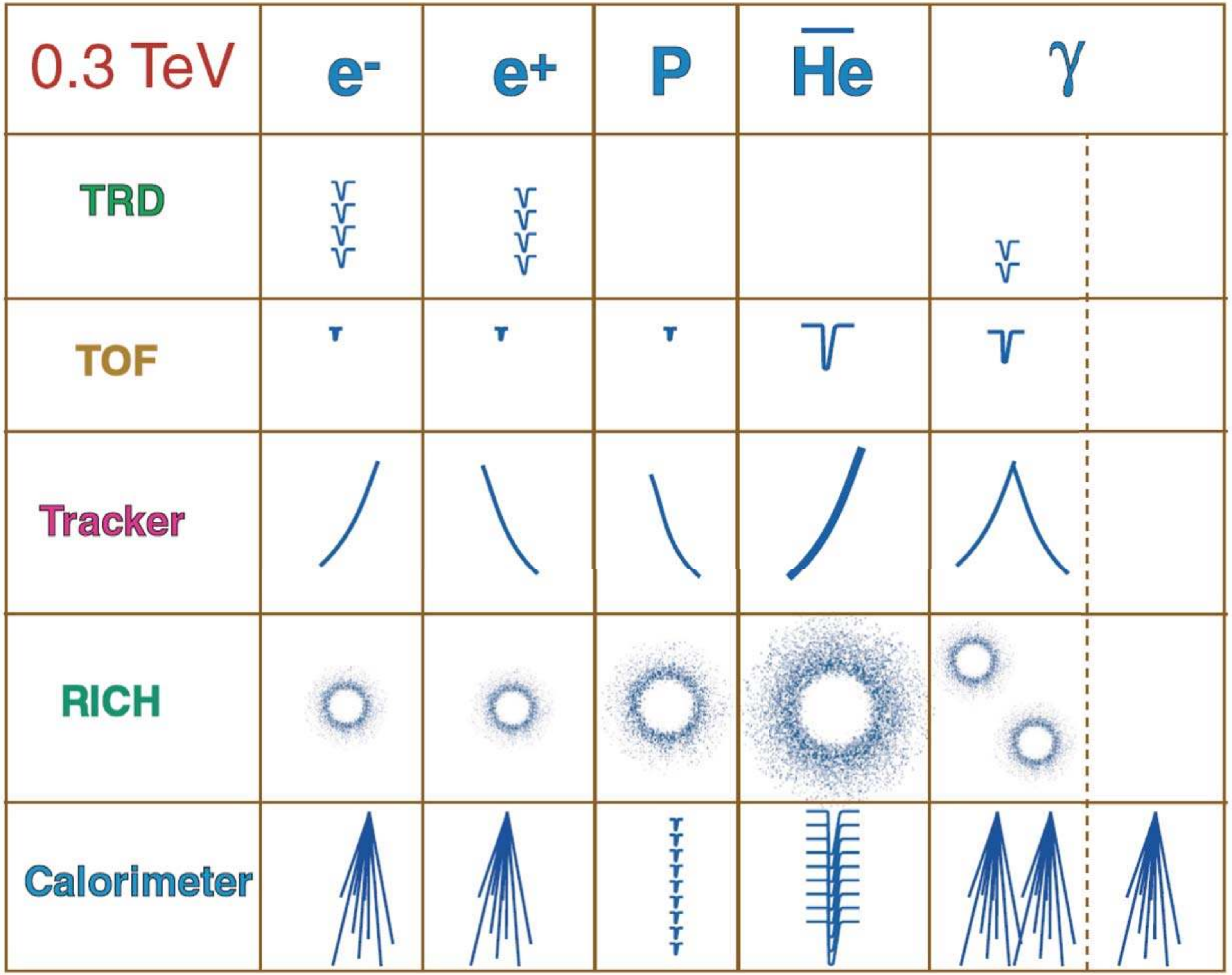
	e^-	p	Fe	e^+	$\bar{p}$	
TRD	x-rays +ion.	ion.	ion.	x-rays +ion.	ion.	**e/p?**
TOF	dE/dx ⏱	dE/dx ⏱	dE/dx ⏱	dE/dx ⏱	dE/dx ⏱	**Q, β**
Tracker Magnet	dE/dx	dE/dx	dE/dx	dE/dx	dE/dx	**Q, R**
RICH	◌	◌	◌	◌	◌	**Q, β**
ECAL		had	had		had	**E, e/p?**
Physik	**Transport + production from CRs**			**Dark Matter**		

Particle properties - redundant measurements


p
e-
65,8cm
65,8cm
17,6cm
(17 X0, 0.6 λnuc)
π
ν
μ
π
π
π
μ
ν
μ
ν
ν
μ
ν
γ
e
e
e

- **Lead (58%); Scintillating fibre (33%); Optic glue (9%)**
- **1296 readout cells**
- **18 Layers (17 X_0, 0.6 λ_{nuc})**
- Volume: 65.8 x 65.8 x 16.7 cm^3,

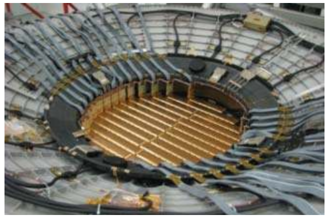
Particle Signatures in AMS


0.3 TeV
e^-
e^+
P
$\overline{He}$
γ
TRD
TOF
Tracker
RICH
Calorimeter

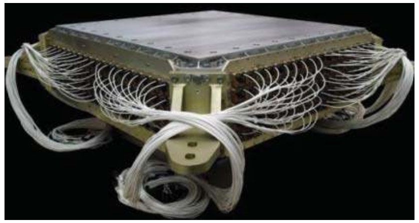
Operating AMS-02 on the ISS

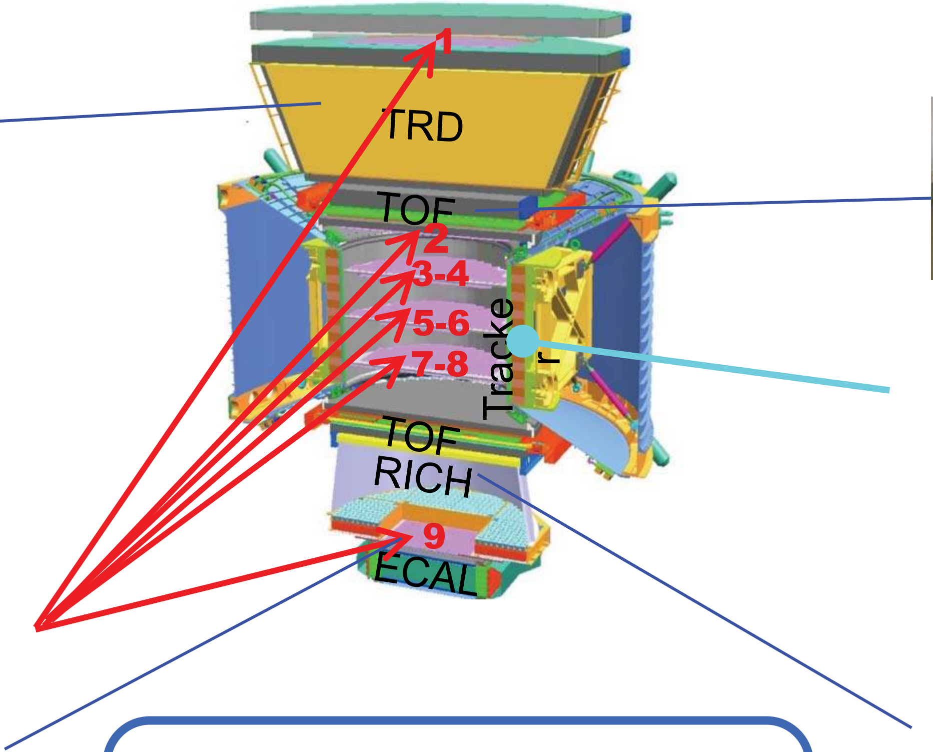
TRD
24 Heaters
8 Pressure Sensors
482 T Sensors

Silicon Tracker
4 Pressure Sensors
32 Heaters
142 T Sensors



ECAL
80 T Sensors

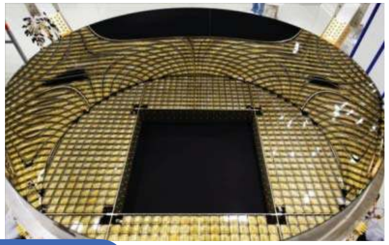




TOF & ACC
64 T Sensors

Magnet
68 T Sensors

RICH
96 T Sensors



1118 temperature sensors
5 radiators
298 thermostatically controlled heaters

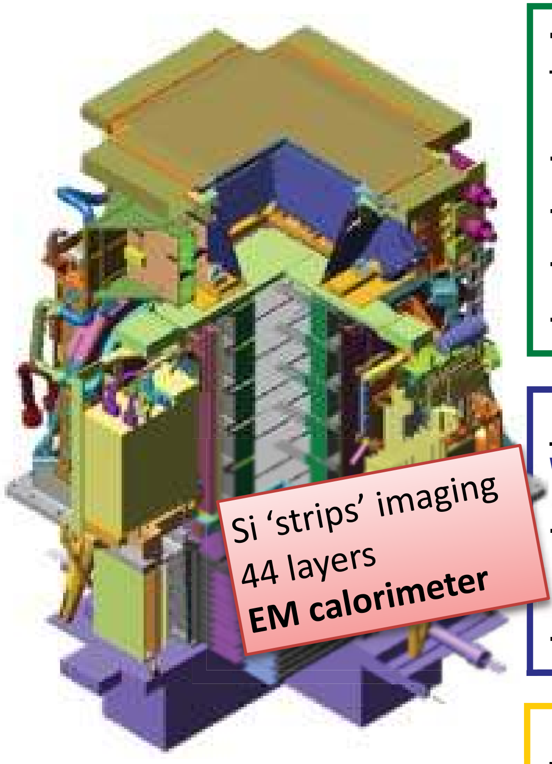
Tracker front-end electronics are kept stable to 1ºC (optimal performance) radiating ~ 150W to Space

Satellite

PaMeLa a Payload for Antimatter Matter Exploration and Light–nuclei Astrophysics

6. PAMELA was launched on 15 June 2006 and was the first satellite-based experiment for the **detection** of cosmic rays, with a particular focus on **positrons and antiprotons**.

Main requirements → high-sensitivity antiparticle identification

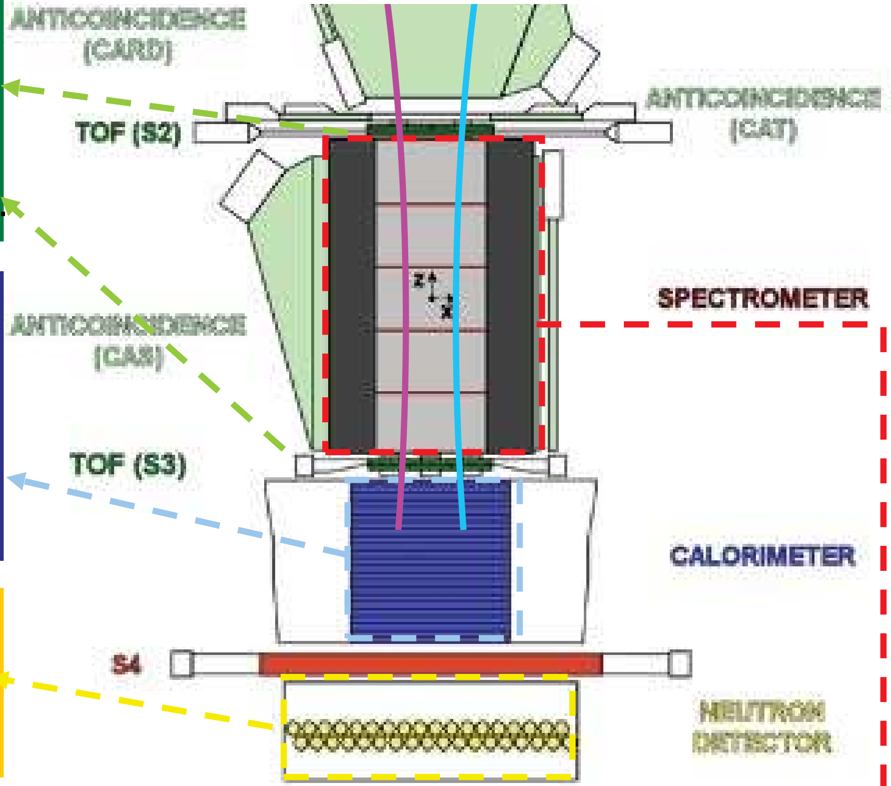


Si ‘strips’ imaging
44 layers
EM calorimeter

Time-Of-Flight
plastic scintillators + PMT:
- Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX.

Electromagnetic calorimeter
W/Si sampling (16.3 X_0, 0.6 λ_I)
- Discrimination e^+ / p, anti-p / e^- (shower topology)
- Direct E measurement for e^-

Neutron detector
^{3}He Tubes:
- High-energy e/h discrimination


ANTICOINCIDENCE (CARD)
TOF (S2)
ANTICOINCIDENCE (CAT)
SPECTROMETER
ANTICOINCIDENCE (CAS)
TOF (S3)
CALORIMETER
S4
NEUTRON DETECTOR

GF: 21.5 cm^2 sr
Mass: 470 kg
Size: 130x70x70 cm^3
Power Budget: 360W

Spectrometer
microstrip silicon tracking system + permanent magnet
It provides:
- ***Magnetic rigidity*** → R = pc/Ze
- ***Charge sign***
- ***Charge value from dE/dx***

0.43 T permanent magnet
Double sides Si sensors

Oscar Adriani
ICHEP 2010

Chapter 7

Neutrino Detectors

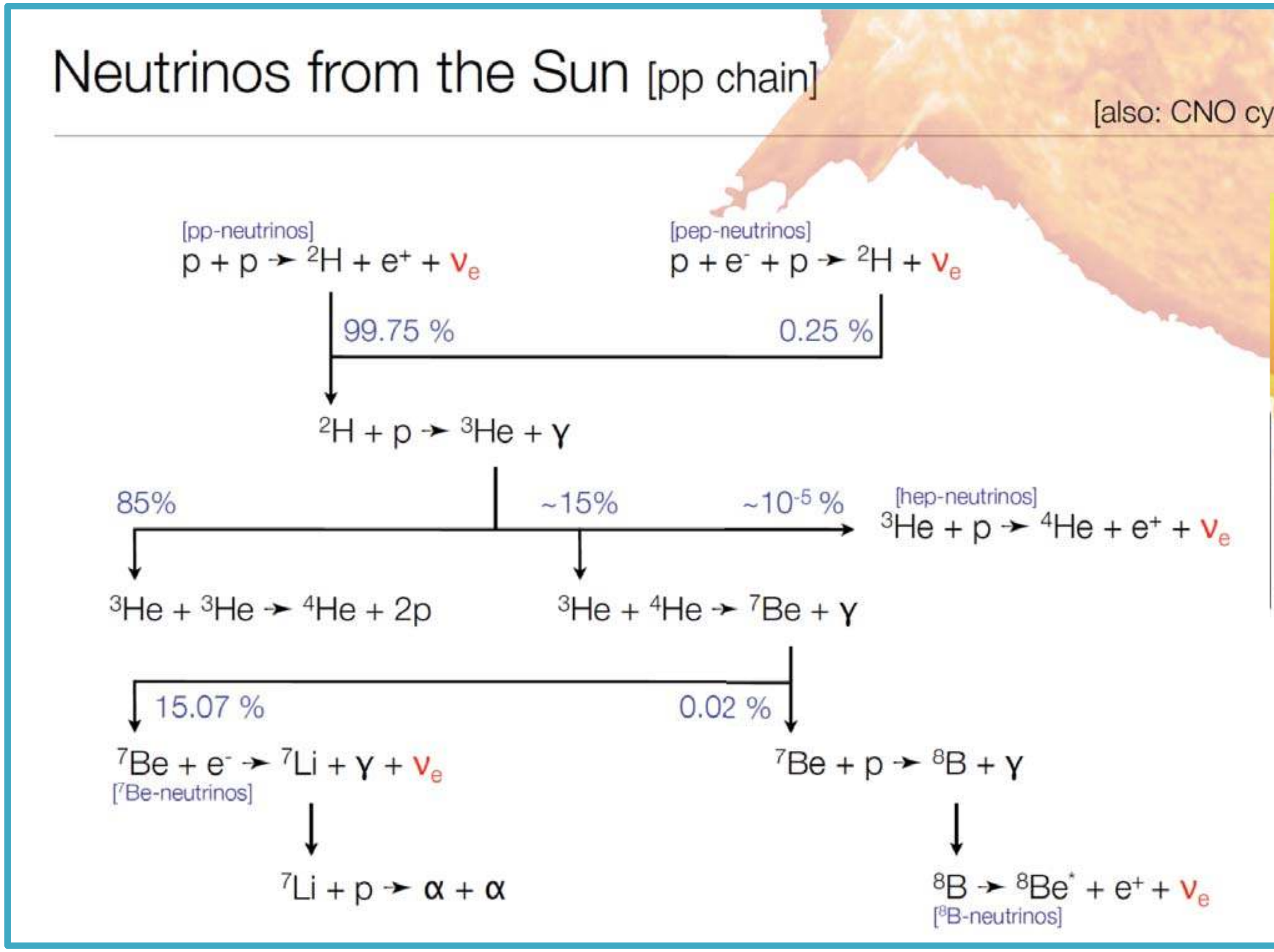
Homestake
SNO
Kamiokande
ICECUBE

Neutrinos - Properties

- Where from?
  - Atmosphere
  - Cosmic Rays, Supernova

  - Sun
  - Collider
  - Reactor
  - Decay
    - Neutrinoless double beta decay

- Cross section
  - Interactions/forces?
  - **What material to interact with?**
    - **Which resulting particles to measure?**
- What do we measure?
  - Just count and compare to theory, e.g. sun CNO cycle
  - Mass
  - Oscillations
  - Disappereance / Appearance



Neutrinos from the Sun [pp chain]

[also: CNO cycle]

[pp-neutrinos]
$p + p \rightarrow {}^{2}H + e^{+} + \nu_e$

[pep-neutrinos]
$p + e^{-} + p \rightarrow {}^{2}H + \nu_e$

99.75 %

0.25 %

${}^{2}H + p \rightarrow {}^{3}He + \gamma$

85%

~15%

~10^{-5} %

[hep-neutrinos]
${}^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu_e$

${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$

${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$

15.07 %

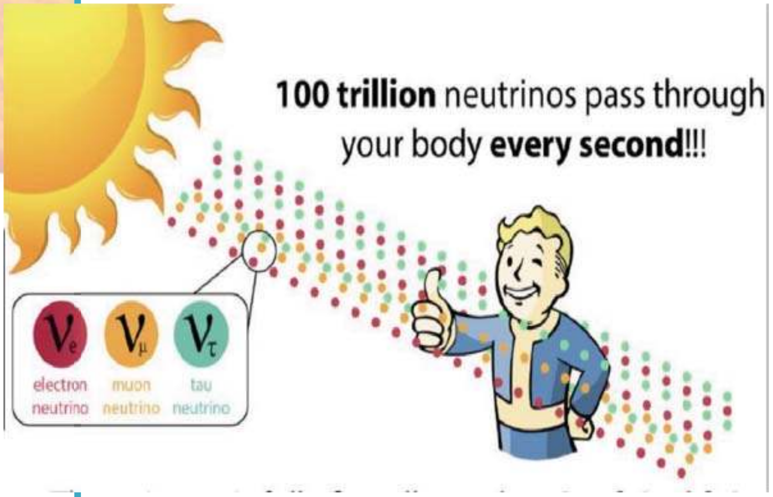
0.02 %

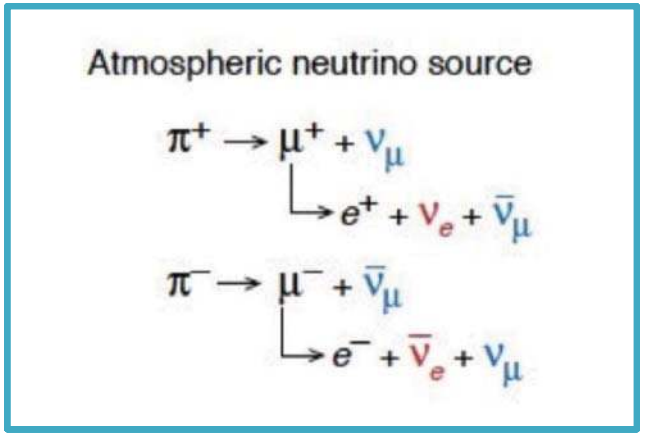
${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \gamma + \nu_e$
[^{7}Be-neutrinos]

${}^{7}Be + p \rightarrow {}^{8}B + \gamma$

${}^{7}Li + p \rightarrow \alpha + \alpha$

${}^{8}B \rightarrow {}^{8}Be^{*} + e^{+} + \nu_e$
[^{8}B-neutrinos]


100 trillion neutrinos pass through your body **every second**!!!
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino



Atmospheric neutrino source

$$\pi^{+} \rightarrow \mu^{+} + \nu_\mu$$
$$\hookrightarrow e^{+} + \nu_e + \bar{\nu}_\mu$$
$$\pi^{-} \rightarrow \mu^{-} + \bar{\nu}_\mu$$
$$\hookrightarrow e^{-} + \bar{\nu}_e + \nu_\mu$$

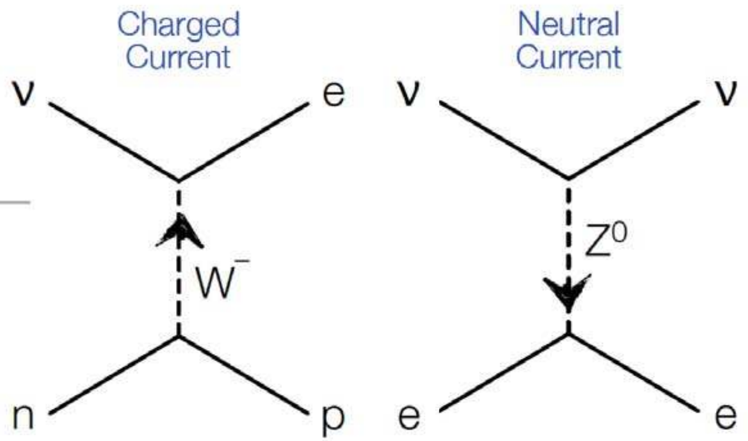
I have done a terrible thing, I have postulated a particle that cannot be detected.

W. Pauli

Pauli on β-decay

$n \rightarrow p + e^{-} + \bar{\nu}_e$

Detection of Neutrinos



Neutron detection only via weak interaction ...

Possible reactions:

Charged Current Reactions:

$$\nu_e + n \rightarrow e^- + p$$
$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$\nu_\mu + n \rightarrow \mu^- + p$$
$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$
$$\nu_\tau + n \rightarrow \tau^- + p$$
$$\bar{\nu}_\tau + p \rightarrow \tau^+ + n$$

...

$$\bar{\nu}_e + e^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\bar{\nu}_e + e^- \rightarrow \tau^- + \bar{\nu}_\tau$$

Neutral Current Reactions:

$$\nu_e + e^- \rightarrow \nu_e + e^-$$
$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$
$$\nu_\tau + e^- \rightarrow \nu_\tau + e^-$$

Remark:
Neutral Current νN-interactions not usable due to small energy transfer

---

Neutrino nucleon x-Section:
[examples]

10 GeV neutrinos: $\sigma = 7 \cdot 10^{-38}$ cm^2/nucleon

Interaction probability for 10 m Fe-target: $R = \sigma \cdot N_A\,[\mathrm{mol}^{-1}/\mathrm{g}] \cdot d \cdot \rho = 3.2 \cdot 10^{-10}$
with $N_A = 6.023 \cdot 10^{23}\ \mathrm{g}^{-1}$; $d = 10$ m; $\rho = 7.6$ g/cm^3

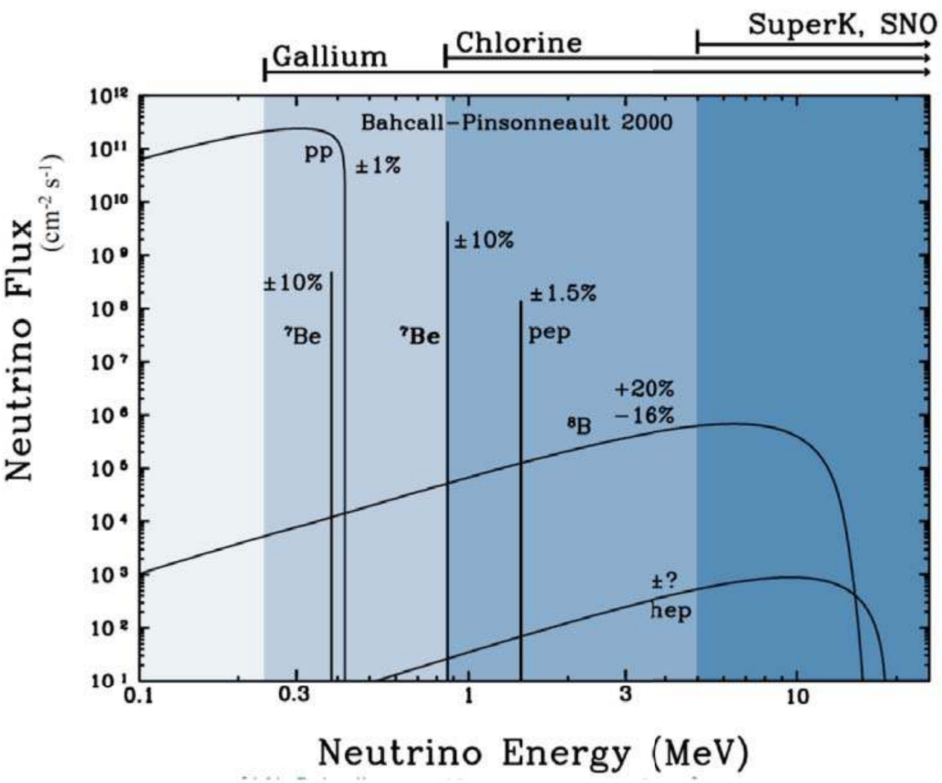
Solar neutrinos [100 keV]: $\sigma = 7 \cdot 10^{-45}$ cm^2/nucleon

Interaction probability for earth: $R = \sigma \cdot N_A\,[\mathrm{mol}^{-1}/\mathrm{g}] \cdot d \cdot \rho \approx 4 \cdot 10^{-14}$
with $N_A = 6.023 \cdot 10^{23}\ \mathrm{g}^{-1}$; $d = 12000$ km; $\rho = 5.5$ g/cm^3

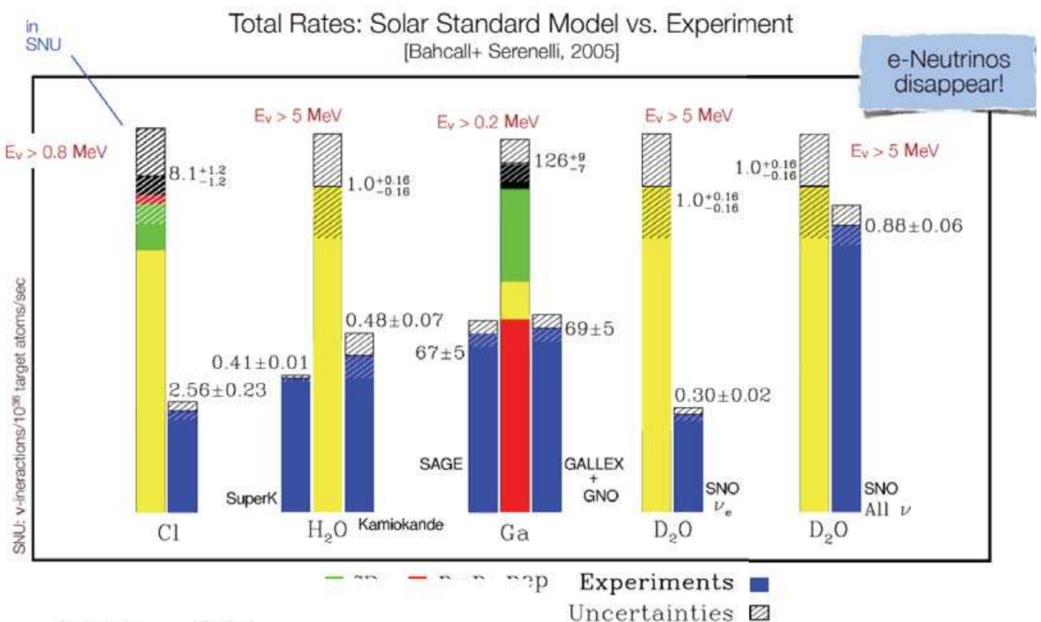
In HEP detectors ν= MET

Neutrinos need a light year of lead(~10^{13}km) to be stopped with 50% chance

Detection of Solar Neutrinos



Solar Electron Neutrino Problem



$^{37}\text{Cl} \rightarrow {}^{37}\text{Ar}$
[Homestake]

Exp: ~ 2.6 SNU
BS05: ~ 8.1 SNU

$^{37}\text{Ga} \rightarrow {}^{37}\text{Ge}$
[Gallex, GNO, Sage]

Exp: ~ 70 SNU
BS05: ~ 126 SNU

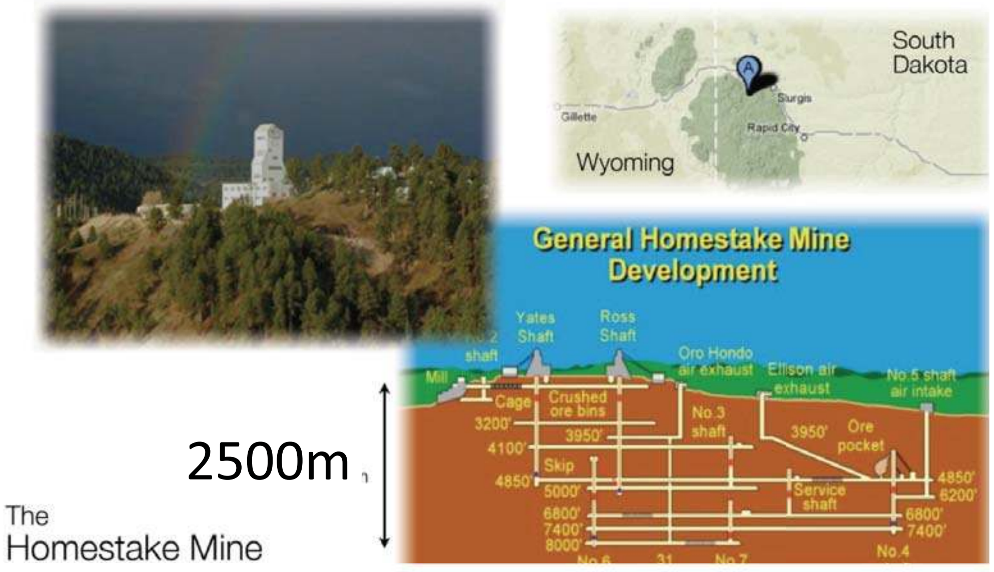
^{8}B ν-flux
[Kamikande, SNO]

νₑ only

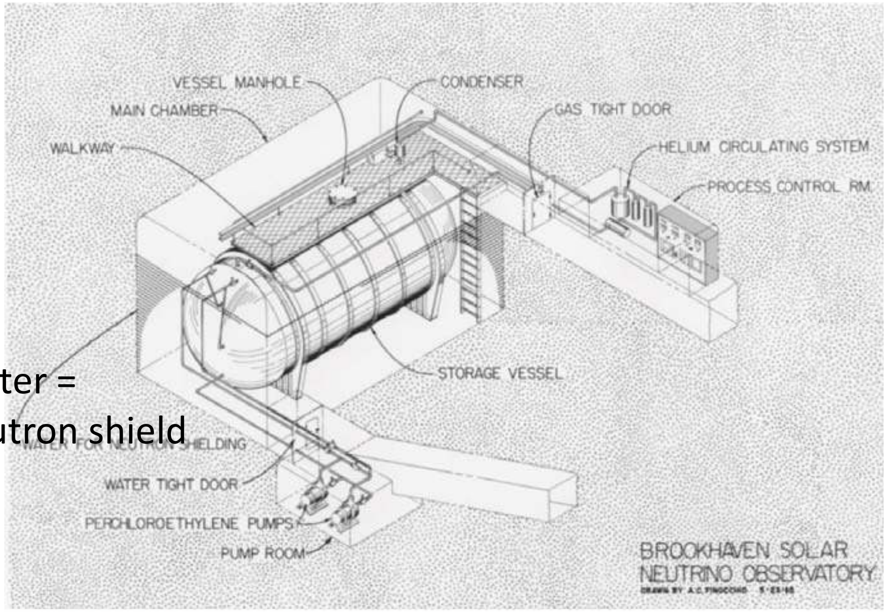
Exp: ~ 2.4 SNU
BS05: ~ 5.7 SNU

The solar **neutrino** unit (**SNU**) is a unit of Solar **neutrino** flux widely used in **neutrino** astronomy

1. Homestake (1970-1994)


South Dakota
Wyoming
Gillette
Sturgis
Rapid City
General Homestake Mine Development
No.2 shaft
Yates Shaft
Ross Shaft
Mill
Oro Hondo air exhaust
Ellison air exhaust
No.5 shaft air intake
Cage
Crushed ore bins
No.3 shaft
3200'
3950'
4100'
3950'
Ore pocket
Skip
4850'
5000'
Service shaft
4850'
6200'
6800'
7400'
8000'
6800'
7400'
No.4
No.6
31
No.7
The Homestake Mine

2500m


VESSEL MANHOLE
CONDENSER
MAIN CHAMBER
GAS TIGHT DOOR
WALKWAY
HELIUM CIRCULATING SYSTEM
PROCESS CONTROL RM.
STORAGE VESSEL
WATER OR NEUTRON SHIELDING
WATER TIGHT DOOR
PERCHLOROETHYLENE PUMPS
PUMP ROOM
BROOKHAVEN SOLAR NEUTRINO OBSERVATORY

Water = neutron shield

Neutrino capture:

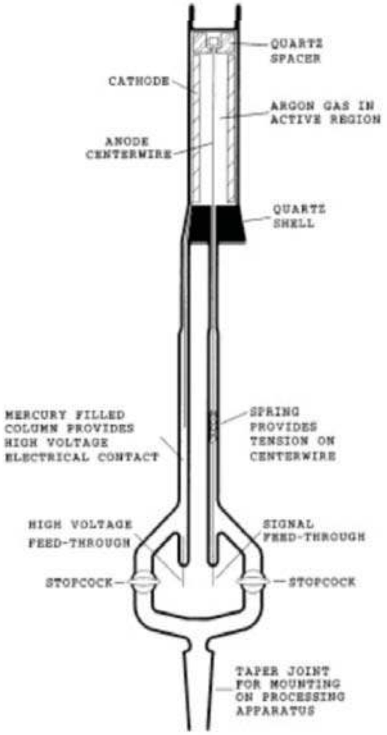
Lifetime: 35 days

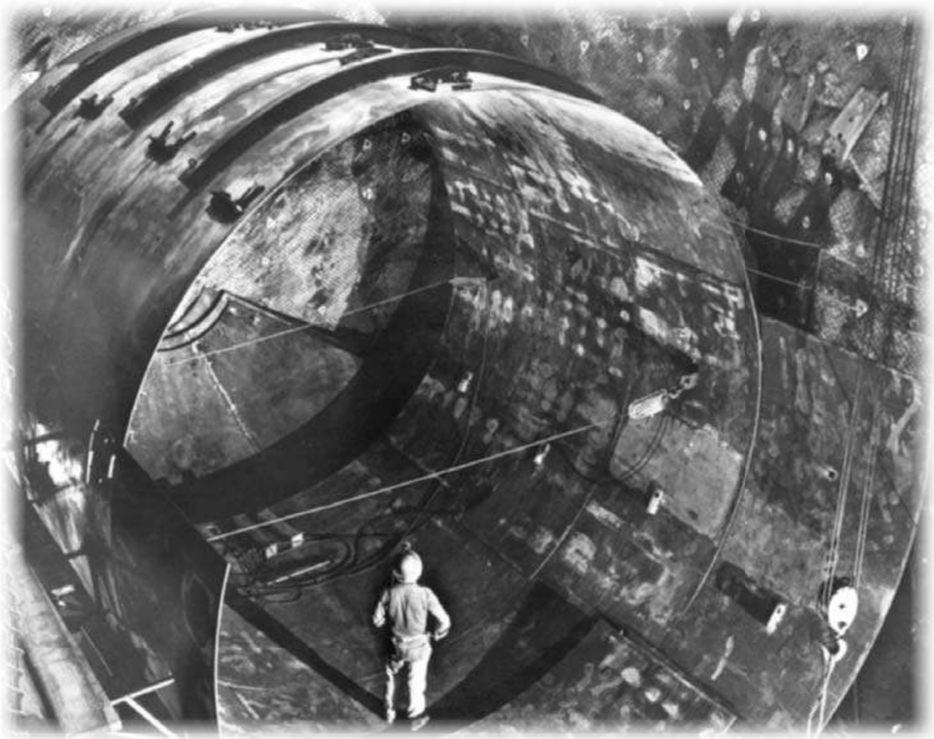
$$^{37}\mathrm{Cl} + \nu_e \rightarrow {}^{37}\mathrm{Ar} + e$$

Detection of ^{37}Ar via e$^-$-capture [$^{37}\mathrm{Ar}(e,\nu_e)^{37}\mathrm{Cl}$]; $\tau \approx 35$ days results in Auger-electron @ 2.82 keV which after extraction is detected in proportional counter

Experimental details:

- 615 tons of C_2Cl_4
- Threshold: 814-keV threshold
- Bubble He gas through to extract Ar [every 2-3 month]
- Ar trapped in cold trap
- Proportional Counter filled with Ar gas (7% methane)
- Important: ^{37}Cl is 24% abundant.


QUARTZ SPACER
CATHODE
ARGON GAS IN ACTIVE REGION
ANODE CENTERWIRE
QUARTZ SHELL
MERCURY FILLED COLUMN PROVIDES HIGH VOLTAGE ELECTRICAL CONTACT
SPRING PROVIDES TENSION ON CENTERWIRE
HIGH VOLTAGE FEED-THROUGH
SIGNAL FEED-THROUGH
STOPCOCK
STOPCOCK
TAPER JOINT FOR MOUNTING ON PROCESSING APPARATUS



➔ Clorine for primary interaction
Trap Ar (tens atoms/month) - Ar via Auger e$^-$ in proportional chamber

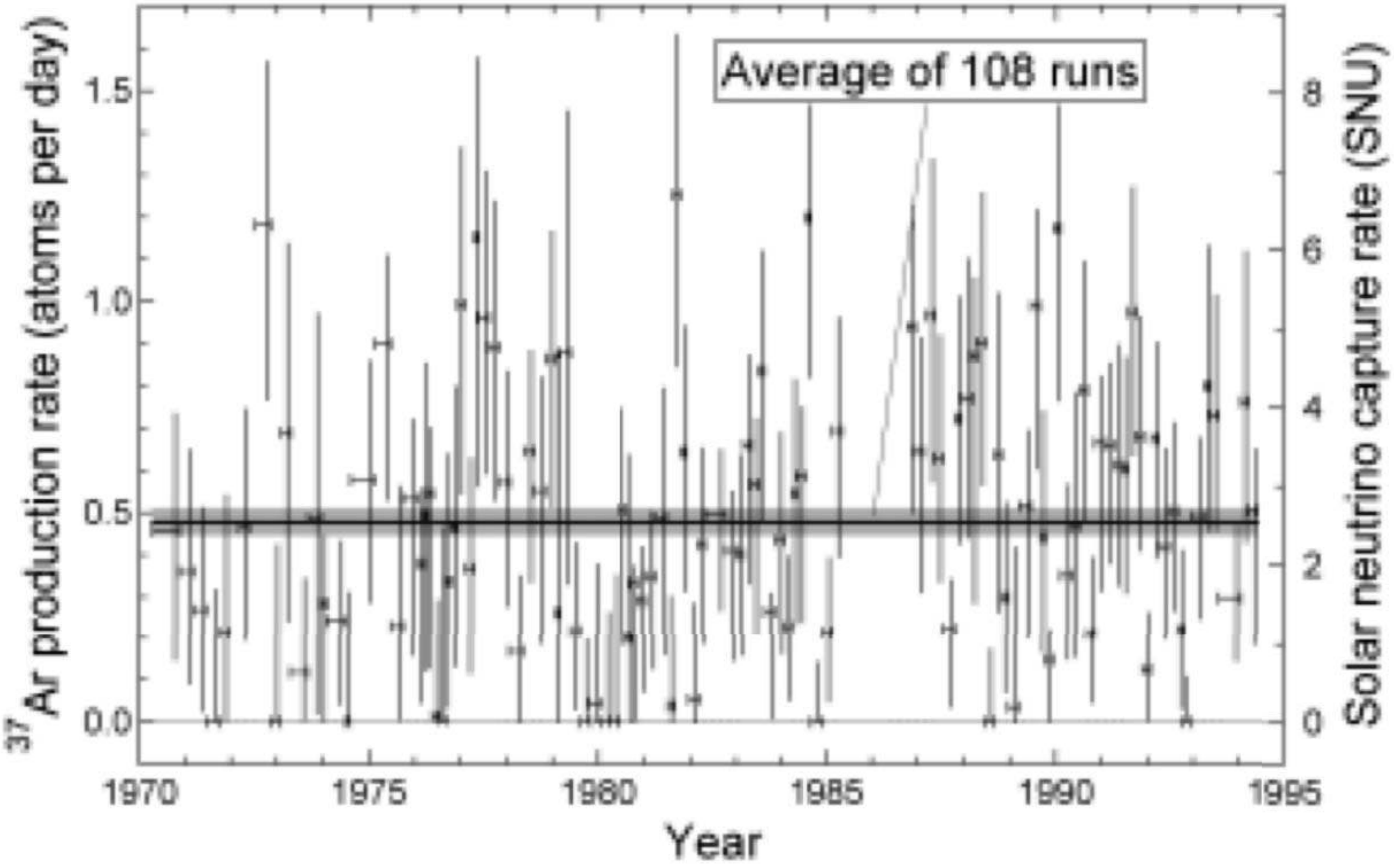
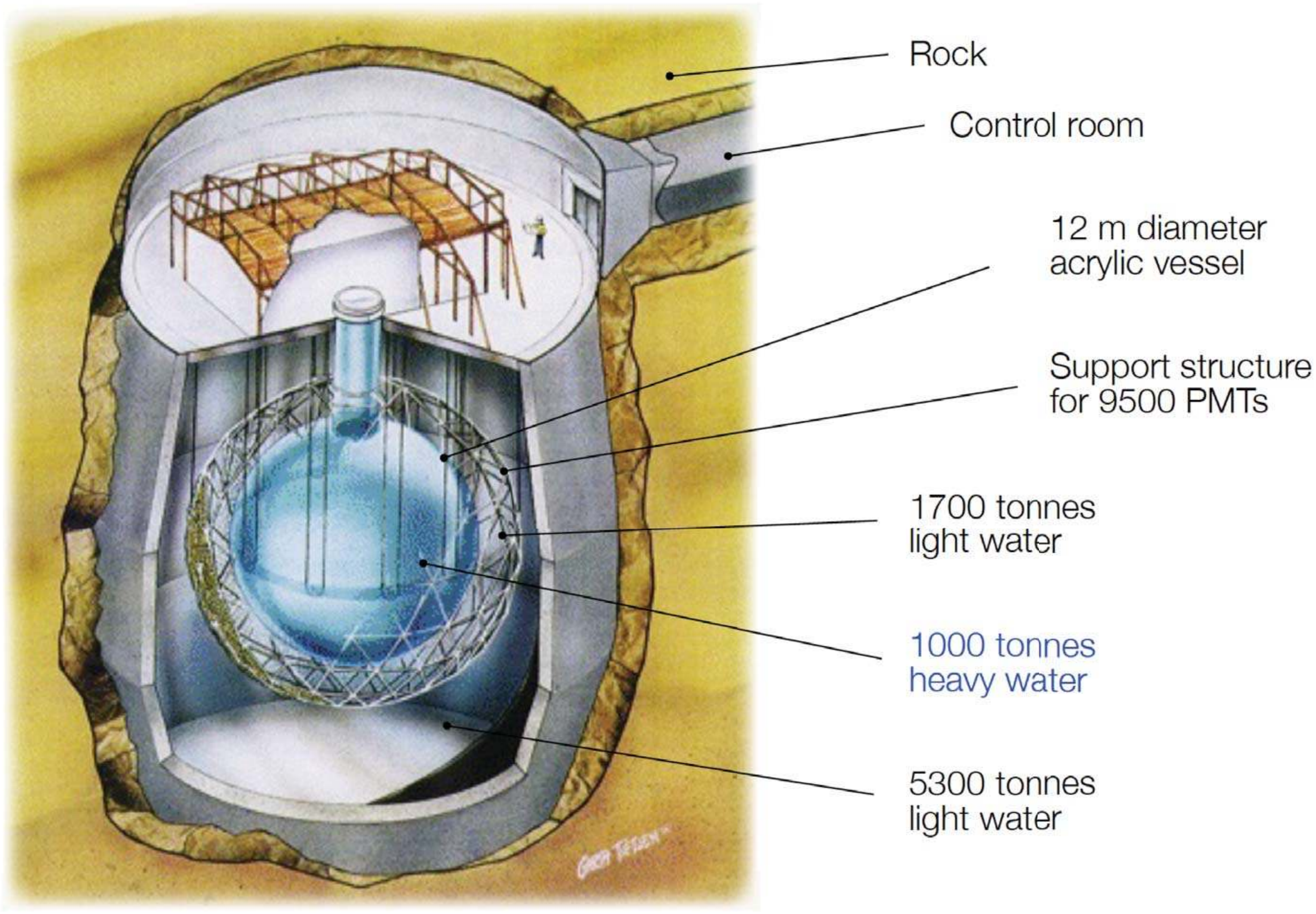


Figure 15. A summary of all of the runs made at Homestake after implementation of rise-time counting. Background has been subtracted. Over a period of 25 years, 2200 atoms of ^{37}Ar were detected, corresponding to an average solar neutrino flux of 2.56 SNU. The gap in 1986 occurred when both perchloroethylene circulation pumps failed. Based on data from Cleveland *et al.* (1998).

2. Sudbury Neutrino Observatory
SNO


Rock
Control room
12 m diameter acrylic vessel
Support structure for 9500 PMTs
1700 tonnes light water
1000 tonnes heavy water
5300 tonnes light water

- SNO uses heavy water as a target
  - Goal to distinguish ν_e and ν_x (Homestake only ν_e)

$$\nu_e + d \rightarrow p + p + e^- - 1.44\,\mathrm{MeV}\,(\mathrm{CC}),$$

$$\nu_x + d \rightarrow p + n + \nu_x - 2.22\,\mathrm{MeV}\,(\mathrm{NC}), \quad \text{and}$$

$$\nu_x + e^- \rightarrow \nu_x + e^-\,(\mathrm{ES}),$$

e^- → **Cherenkov light**

n → capture (n+p→d) + γ → Compton scattering → e^- → **Cherenkov light**

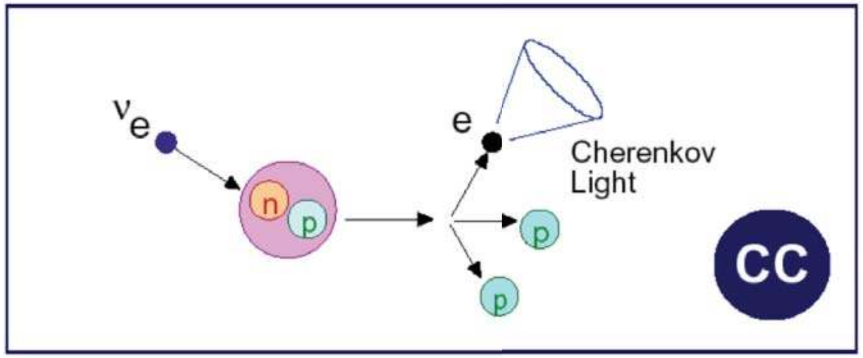
- Cherenkov light – detection PM
- Ratio of CC/NC → ν_e too low → ν oscillation

Annu. Rev. Nucl. Part. Sci. 2009. 59:431–65

The SNO Experiment

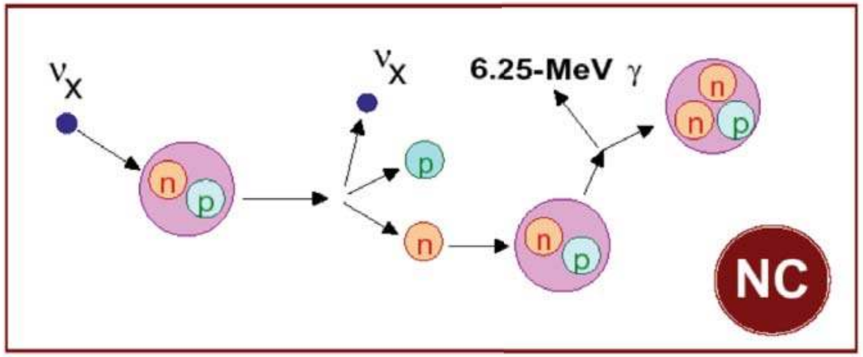
CC $\nu_e + d \rightarrow p + p + e^-$

- Measurement of ν_e energy spectrum
- Weak directionality: $1 - 0.340\cos\theta$


ν_e
n
p
e
Cherenkov Light
p
p
CC

NC $\nu_x + d \rightarrow p + n + \nu_x$

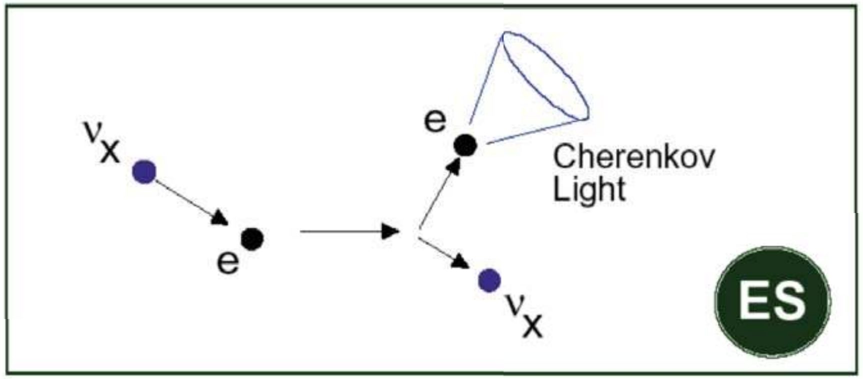
- Measure total ^{8}B ν flux from the sun
- $\sigma(\nu_e) = \sigma(\nu_\mu) = \sigma(\nu_\tau)$


ν_x
n
p
ν_x
6.25-MeV γ
p
n
n
p
n
n
p
NC

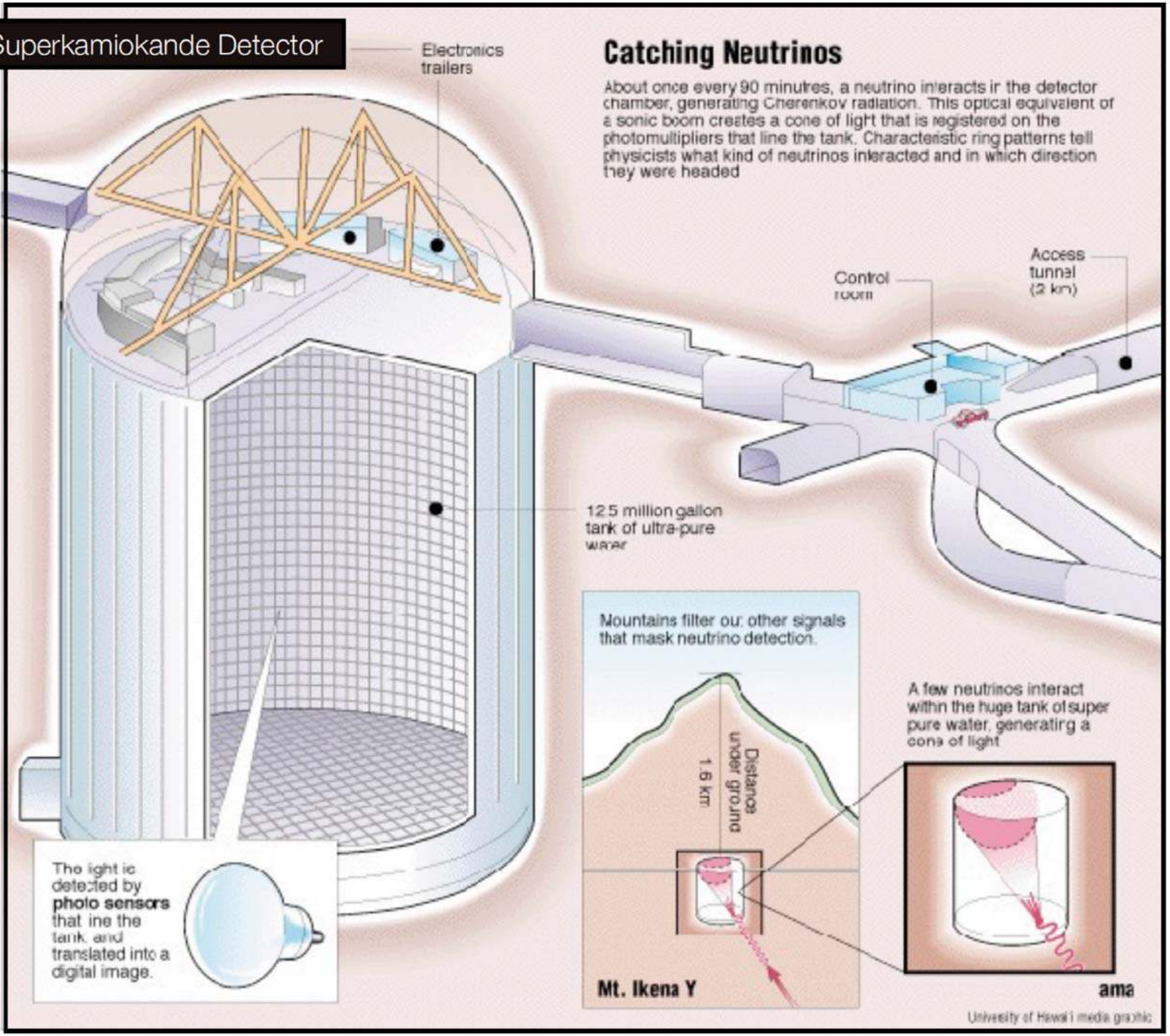
ES $\nu_x + e^- \rightarrow \nu_x + e^-$

- Low Statistics
- $\Sigma\phi = \phi(\nu_e) + 0.154\,\phi(\nu_\mu + \nu_\tau)$
- Strong directionality:

  $\theta_e \le 18^\circ$ (T_e = 10 MeV)


ν_x
e
e
Cherenkov Light
ν_x
ES

3. Super-Kamiokande 1998


Superkamiokande Detector
Electronics trailers
Control room
Access tunnel (2 km)
12.5 million gallon tank of ultra-pure water
Distance under ground
1.6 km
Mt. Ikena Y
ama

Catching Neutrinos

About once every 90 minutes, a neutrino interacts in the detector chamber, generating Cherenkov radiation. This optical equivalent of a sonic boom creates a cone of light that is registered on the photomultipliers that line the tank. Characteristic ring patterns tell physicists what kind of neutrinos interacted and in which direction they were headed.

Mountains filter out other signals that mask neutrino detection.

A few neutrinos interact within the huge tank of super pure water, generating a cone of light

The light is detected by **photo sensors** that line the tank and translated into a digital image.

University of Hawaii media graphic

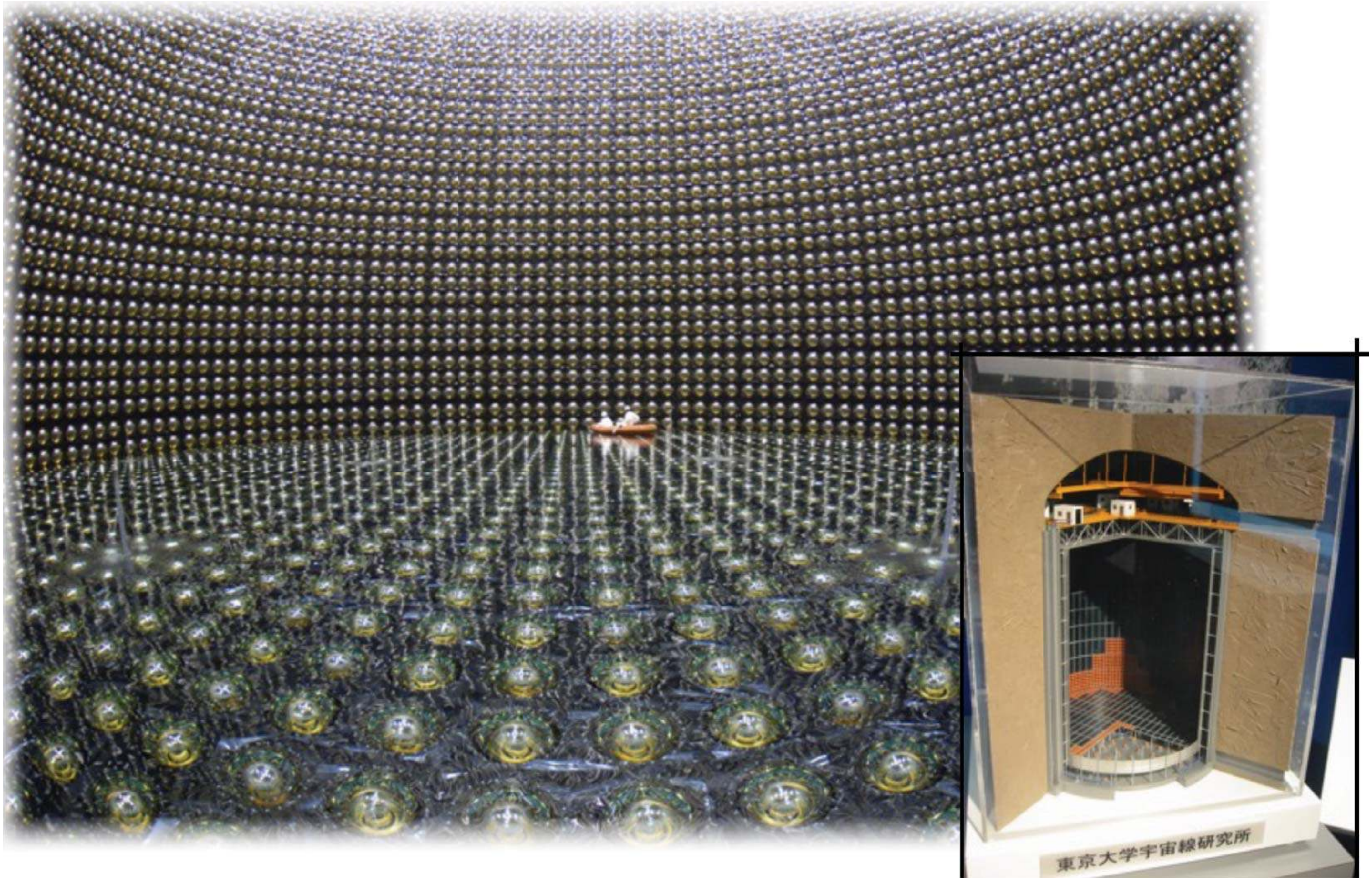
Water tank
1.6 km below ground

50 Million liter
ultra-pure water

1 Neutrino-interaction
every 1.5 hours

Neutrino detection
via Cherenkov light

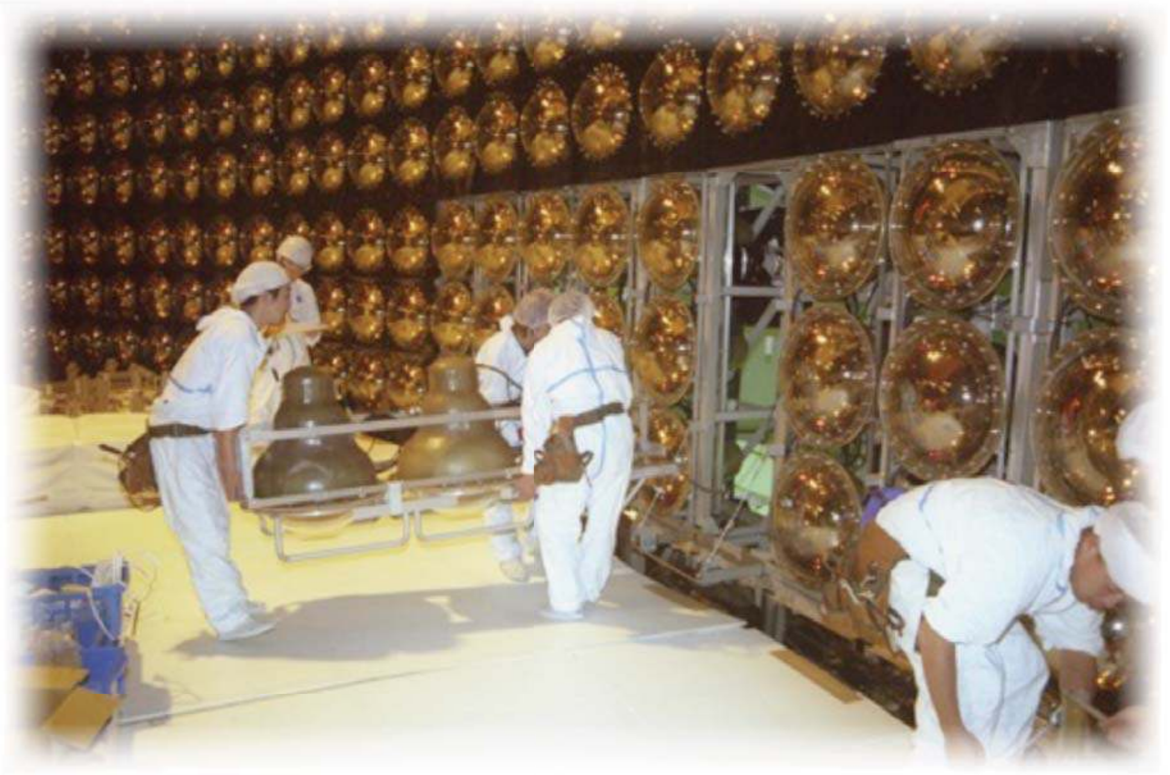
& many PMs

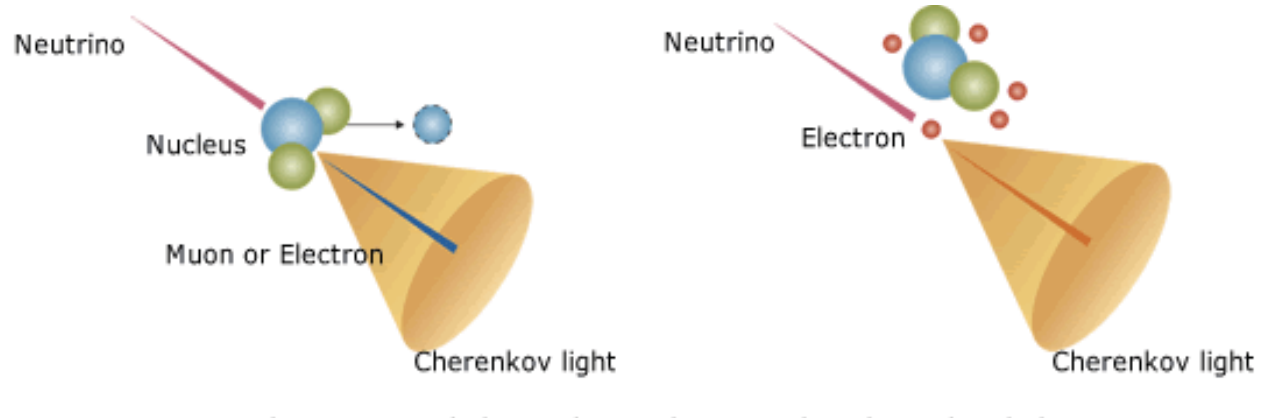


東京大学宇宙線研究所

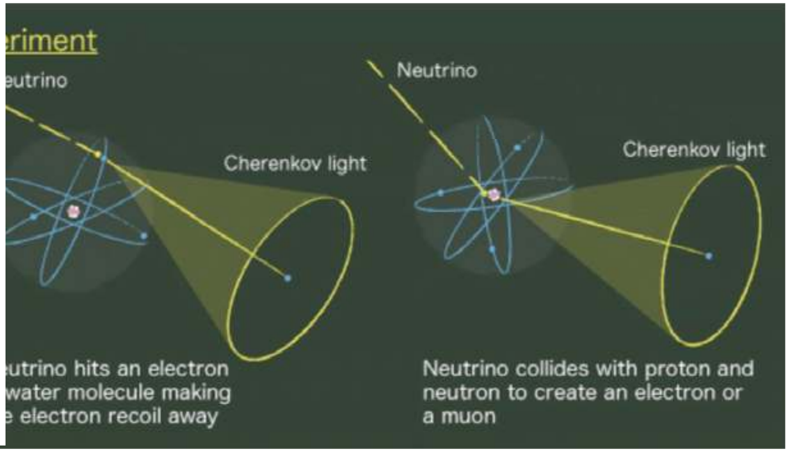
Mounting of Photomultiplier Tubes

Total:	11,146	20″ pmts
	1,885	8″ pmts




Neutrino
Nucleus
Muon or Electron
Cherenkov light
Neutrino
Electron
Cherenkov light

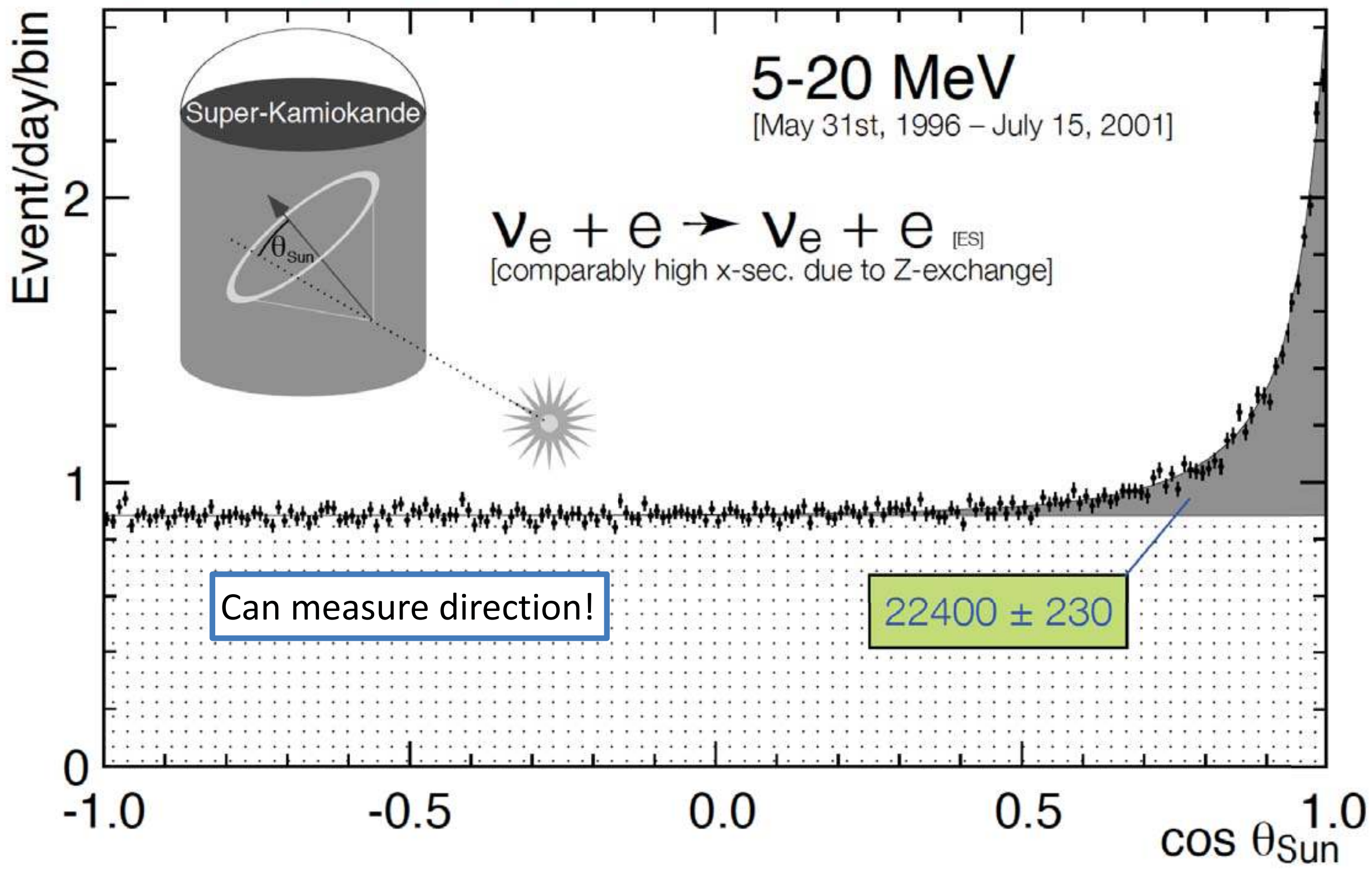
The generated charged particle emits the Cherenkov light.


riment
eutrino
Cherenkov light
Neutrino
Cherenkov light
utrino hits an electron
water molecule making
e electron recoil away
Neutrino collides with proton and
neutron to create an electron or
a muon

Direction from cone (with time measurement)

Well, there is quite an error on the direction ...

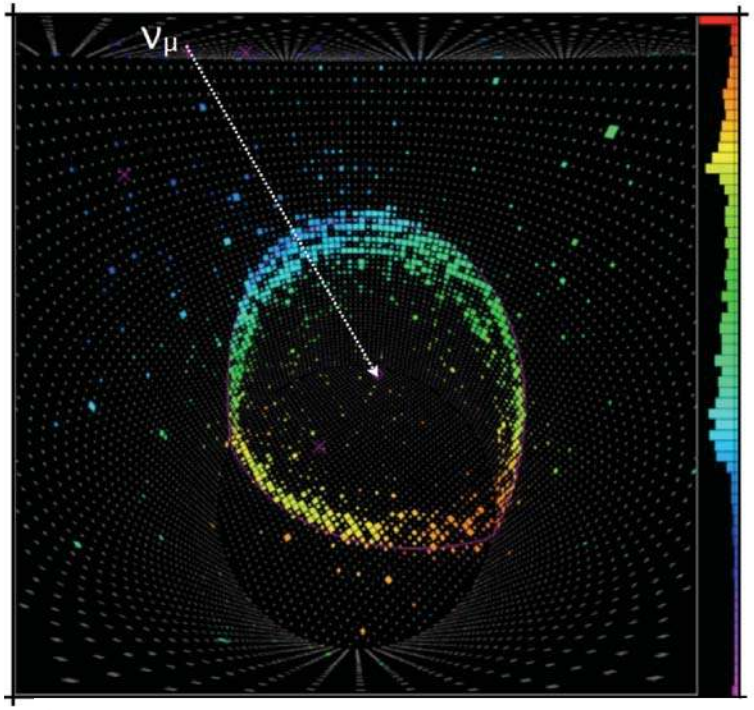
SK-I: ^{8}B Solar Neutrino Flux



Can measure direction!

22400 ± 230

→ sun is source of neutrinos



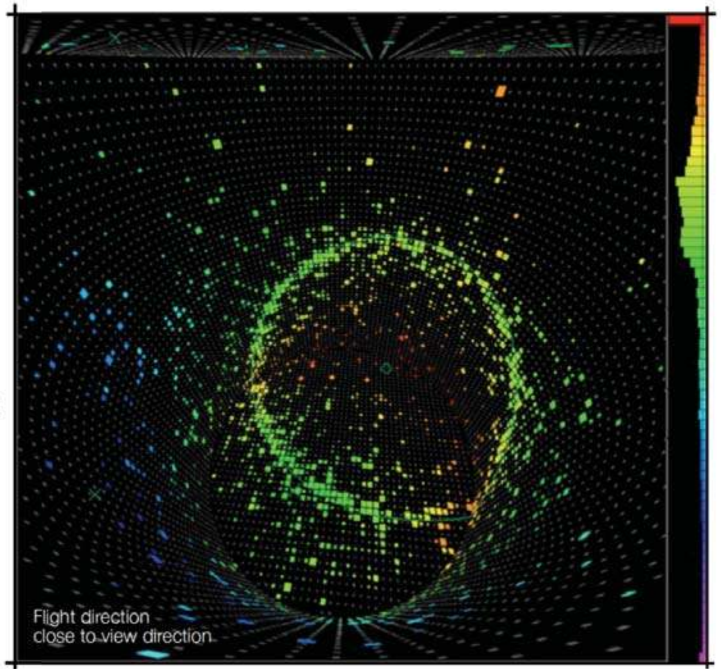
Muon event

[603 MeV]

Observation of
clean Cherenkov ring
with sharp edges

Flight direction from
timing measurements
[blue: early; red: late]

Energy from amount
of light observed in PMT


Flight direction
close to view direction

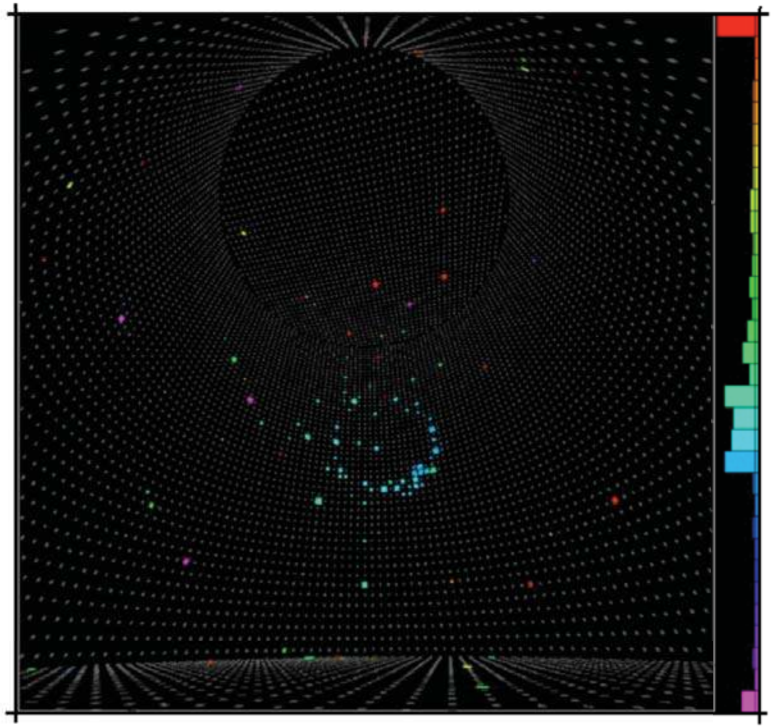
Electron event

[492 MeV]

Observation of
Cherenkov ring
with fuzzy edge
[from e.m. shower]

Flight direction from
timing measurements
[blue: early; red: late]

Energy from amount
of light observed in PMTs



Solar neutrino

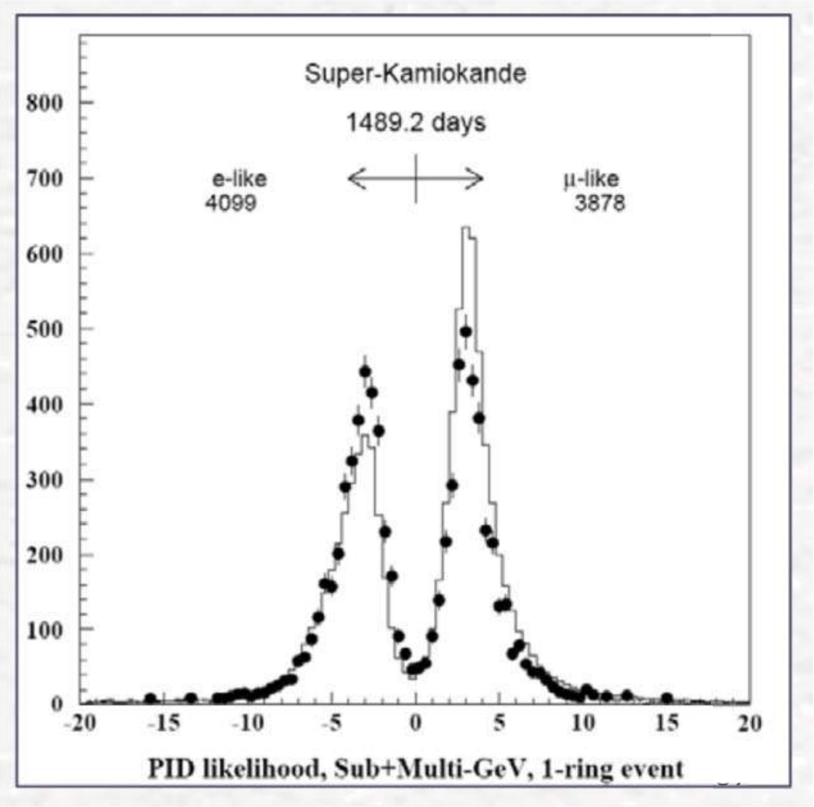
[12.5 MeV]

Unusually nice,
well-defined

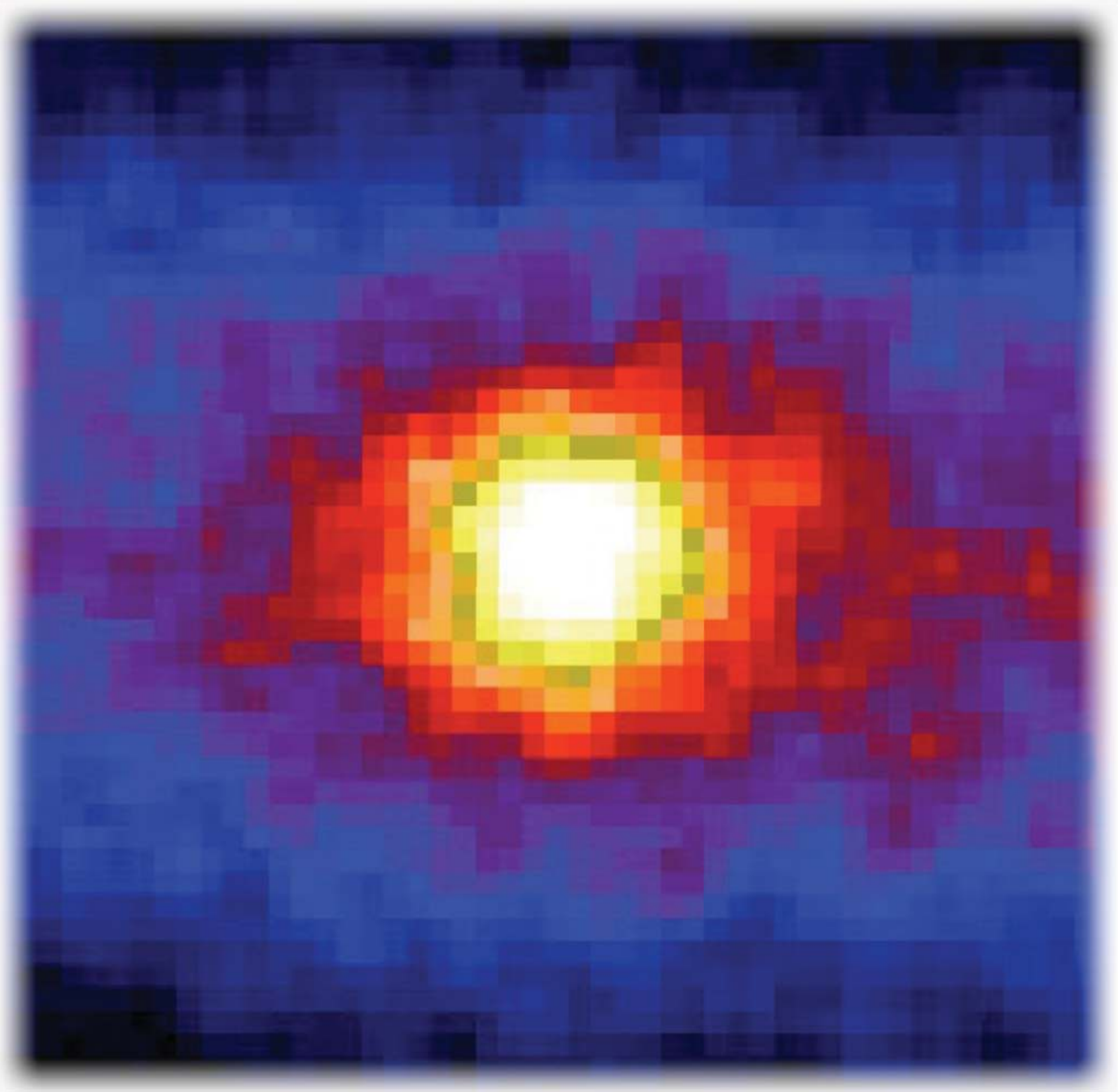
Flight direction from
timing measurements
[blue: early; red: late]

Energy from amount
of light observed in PMTs

Frequency 1/90min



The Sun Shine with Neutrinos!



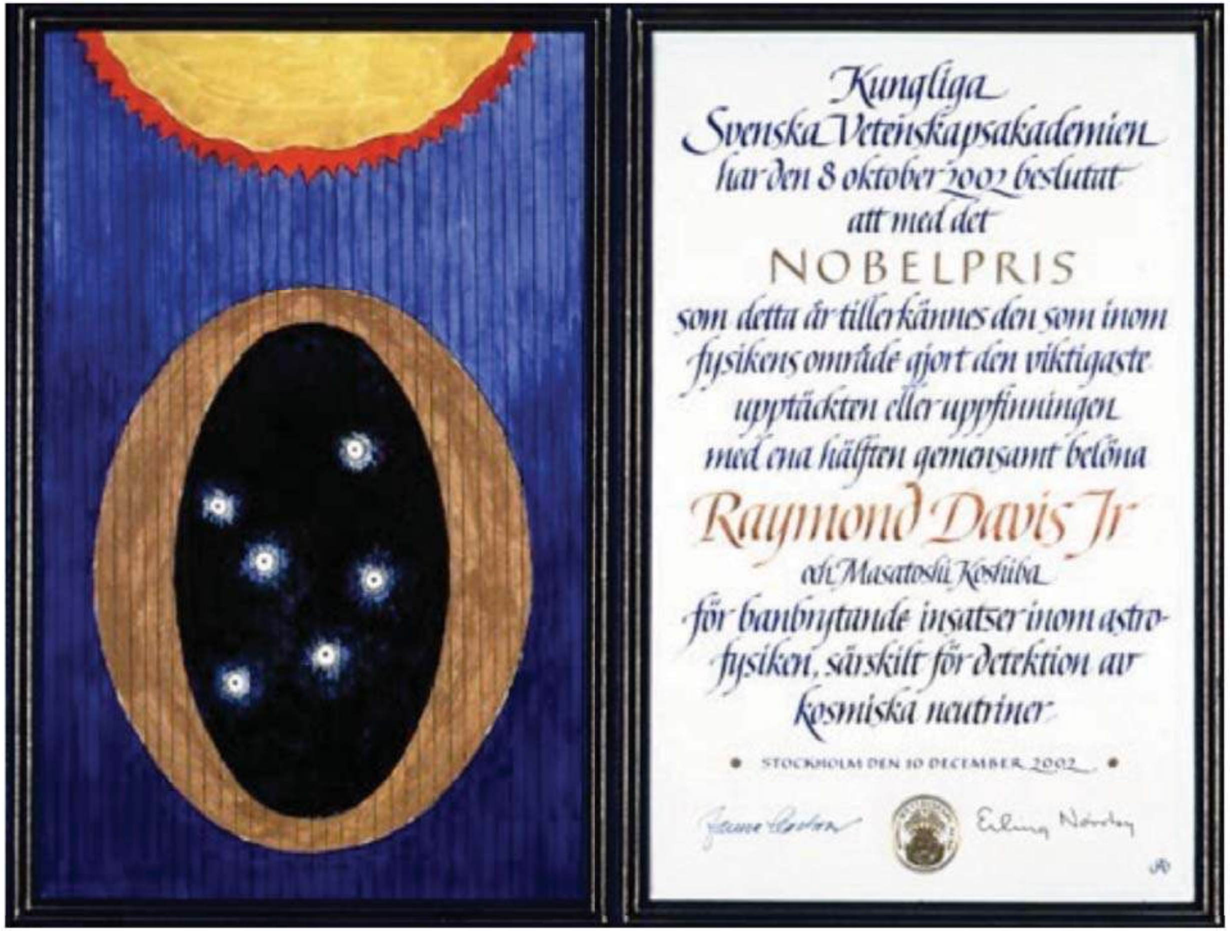
The sun seen through the earth in neutrino light

Also here neutrino oscillations:

Only half ν_μ through earth then directly from above ➔

ν_μ ➔ ν_τ during travel

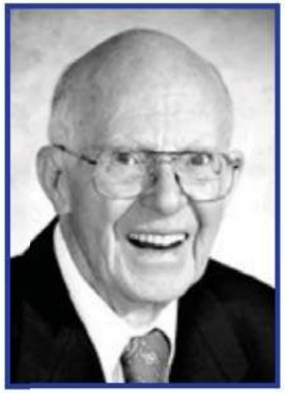
Nobel Prize 2002



Kungliga
Svenska Vetenskapsakademien
har den 8 oktober 2002 beslutat
att med det
NOBELPRIS
som detta år tillerkännes den som inom
fysikens område gjort den viktigaste
upptäckten eller uppfinningen
med ena hälften gemensamt belöna
Raymond Davis Jr
och Masatoshi Koshiba
för banbrytande insatser inom astro-
fysiken, särskilt för detektion av
kosmiska neutriner

• STOCKHOLM DEN 10 DECEMBER 2002 •

Erling Norrby



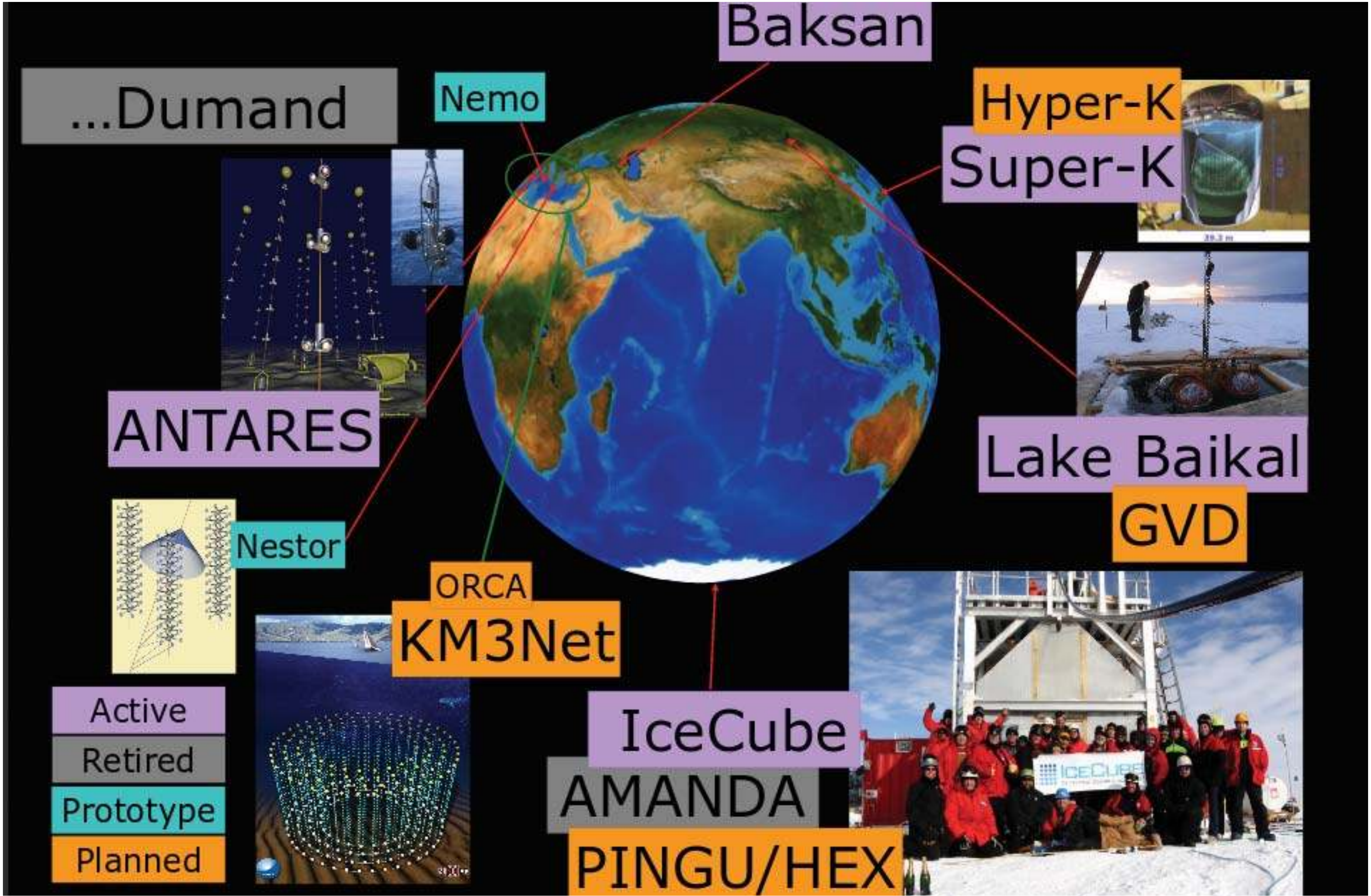
Raymond
Davis Jr.
[Homestake]

Masatoshi
Koshiba
[Kamiokande]

Riccardo
Giacconi
[X-Ray Sources]

Finding Extraterrestial Neutrinos

Water/ice as medium → Cherenkov light → Photomultiplier (PMs)



Baksan

...Dumand

Nemo

Hyper-K

Super-K

ANTARES

Lake Baikal

GVD

Nestor

ORCA

KM3Net

IceCube

AMANDA

PINGU/HEX

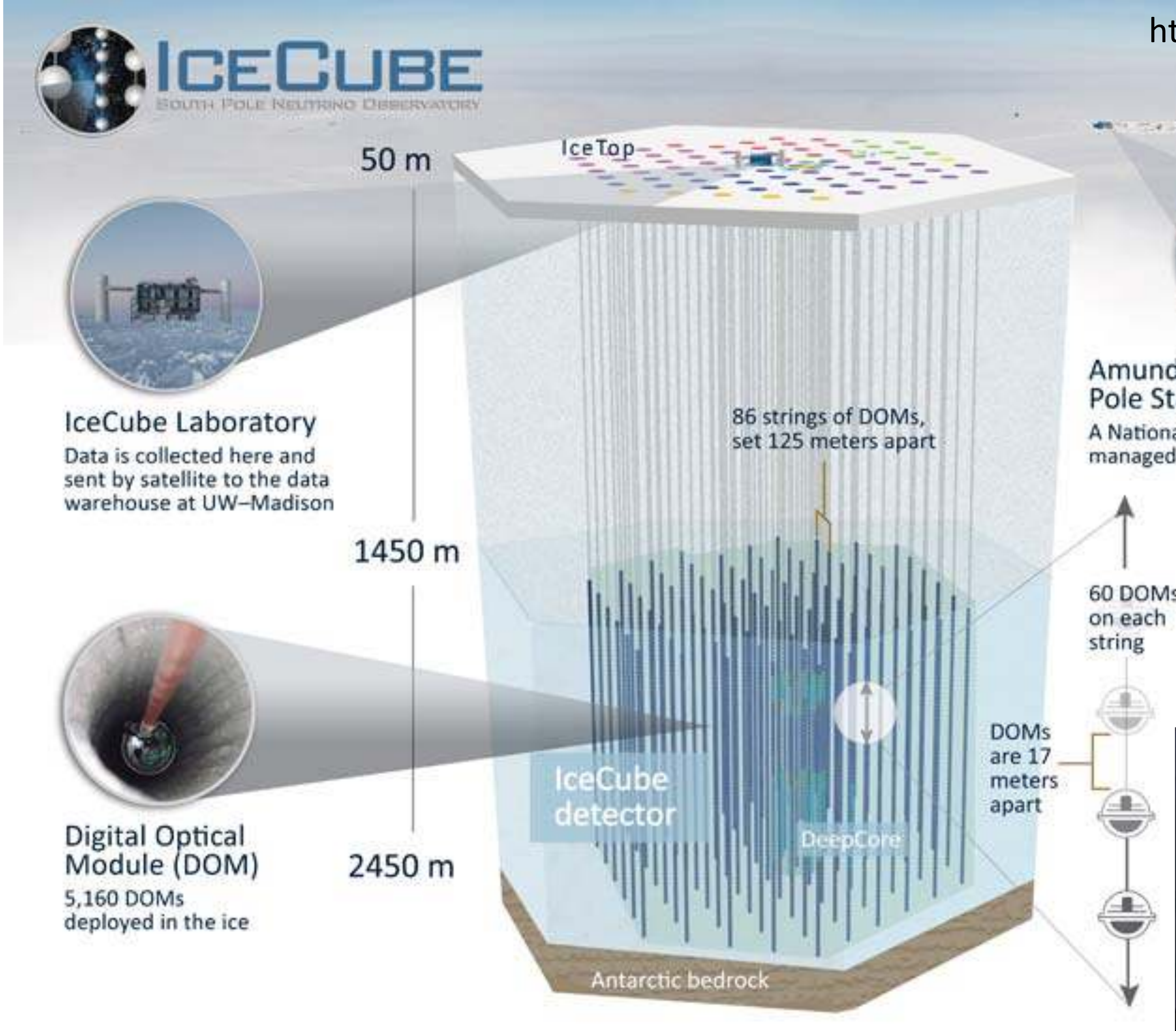
Active

Retired

Prototype

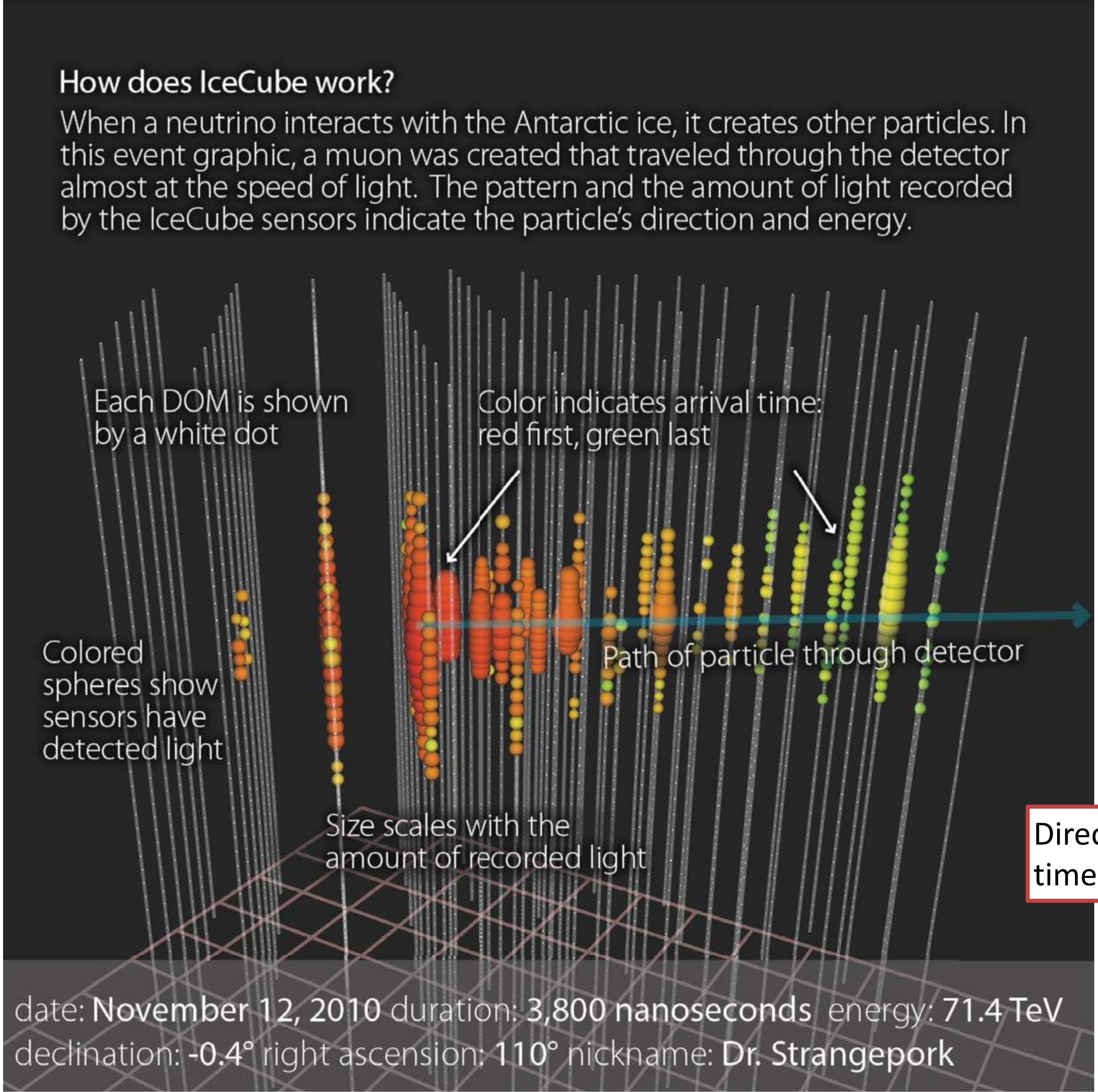
Planned

https://icecube.wisc.e


ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
50 m
IceTop
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
IceCube detector
DeepCore
Antarctic bedrock

IceTop is the veto array for IceCube, and is used for cosmic ray showe

It consists of two Cherenkov tanks above each IceCube string on the s



How does IceCube work?

When a neutrino interacts with the Antarctic ice, it creates other particles. In this event graphic, a muon was created that traveled through the detector almost at the speed of light. The pattern and the amount of light recorded by the IceCube sensors indicate the particle's direction and energy.

Each DOM is shown by a white dot
Color indicates arrival time: red first, green last
Colored spheres show sensors have detected light
Path of particle through detector
Size scales with the amount of recorded light

date: November 12, 2010 duration: 3,800 nanoseconds energy: 71.4 TeV
declination: -0.4° right ascension: 110° nickname: Dr. Strangepork

Neutrinos are not observed directly, but when they happen to interact with the ice they **produce electrically charged secondary particles that in turn emit Cherenkov light**, as a result of traveling through the ice faster than light travels in ice.

Direction/path from time measurement

https://icecube.wisc.edu