Astroparticle physics

Using fundamental physics to learn about astrophysics or the universe as a whole…

…using astro/cosmo phenomena unaccounted for within current theories to learn about what lies beyond standard model(s)

Pasquale Dario Serpico (Annecy, France)
TAE 2023 Benasque, 09/2023

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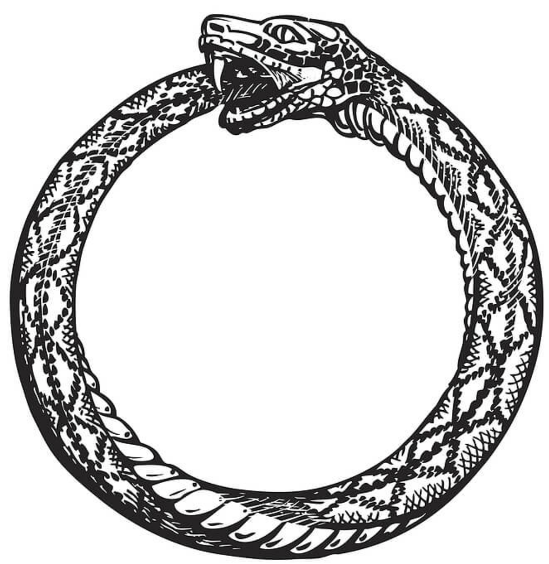

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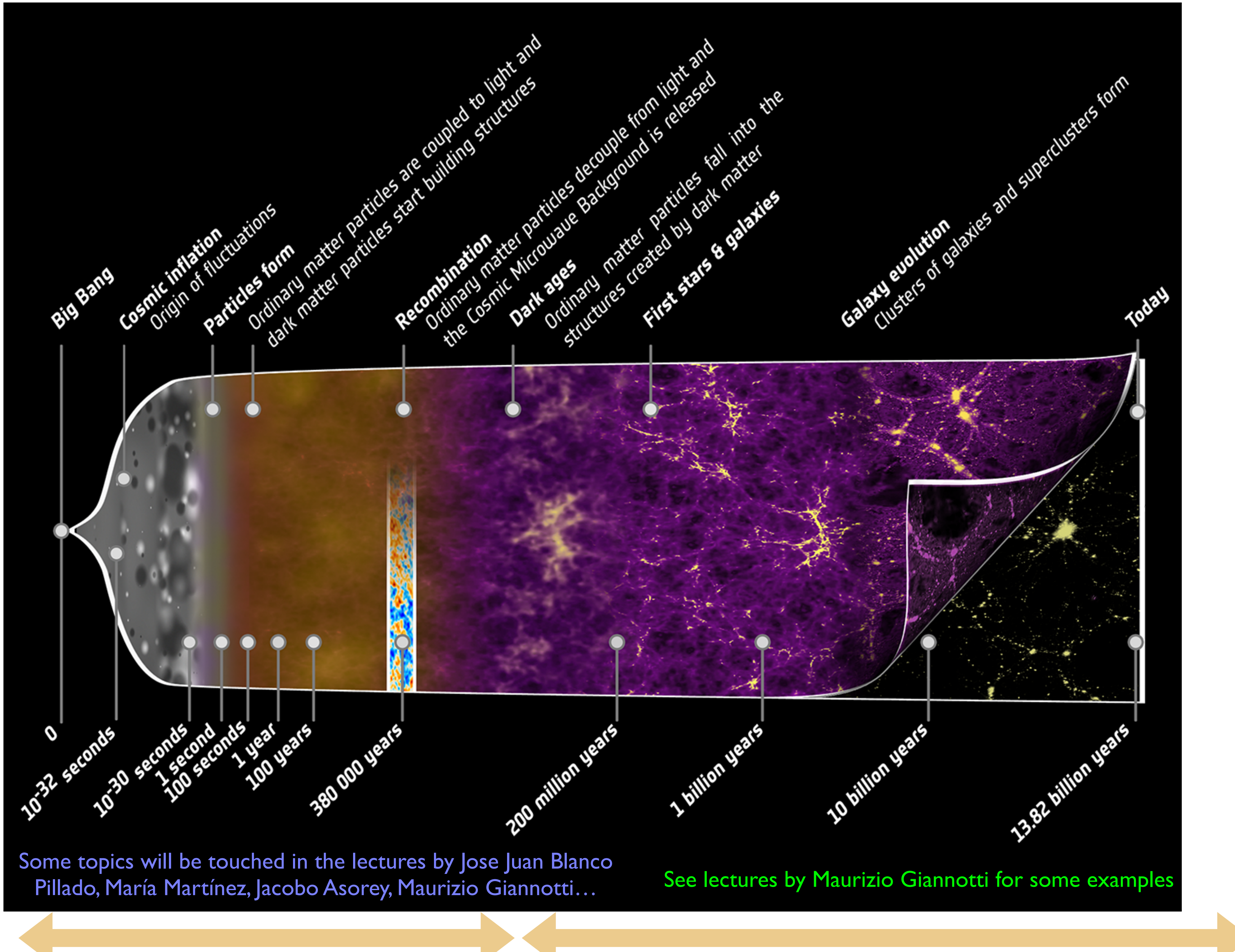
Some taxonomy



Particle cosmology

Thermal/Stellar APP

Non-thermal high-energy APP

Must learn about the dynamics of high-energy particles in astro context (in itself & as a tool)

Plan of the lectures

- I. Intro: Why should we also look for fundamental physics in (high-energy) astrophysics?
- II. Basic facts about cosmic rays & their environments
- III. Phase space approach to CR dynamics
- IV. Basics on CR acceleration & the SNR ‘paradigm’
- V. 'Multimessenger’ approach: photons, neutrinos, secondaries (some notions on collisional aspects; relevant phenomenology)

Feel free to ask questions, better if in real time (it helps the others, too!)
Otherwise write to: serpico@lapth.cnrs.fr

Some references

Gentle introduction to several (not all!) topics, accessible at an undergrad level

- **M. Longair, "high energy astrophysics", Cambridge Univ. Press.**

For the CR propagation part (if you can find it!) it remains useful to look at a classical text like

- **V. S Berezinskii et al. "Astrophysics of cosmic rays" (edited by V.L Ginzburg) Amsterdam: North-Holland, 1990.**

More specialised references (not strictly needed for these lectures)

- **R. Schlickeiser, "Cosmic ray astrophysics," Berlin, Germany: Springer (2002) 519 p**
- **M. Vietri, "Foundations of High-Energy Astrophysics", The Univ. of Chicago press (2008).**
- **G. Sigl, "Astroparticle Physics: Theory and Phenomenology", Atlantis Studies in Astrop. Physics and Cosm. (2017)**

If you feel you need to close a gap in advanced *classical* physics notions, such as statistical physics, plasma physics, fluidodynamics, MHD… the single best recent ref. in my opinion is

- **Kip S. Thorne and Roger D. Blandford, "Modern Classical Physics" Princeton University Press, 2017**

Very good, up-to-date lecture notes on many of the subjects touched can be found at

- **"Foundations of cosmic-ray astrophysics", Varenna (2022) (a few lecture notes also available on arxiv…)**

I. Motivation

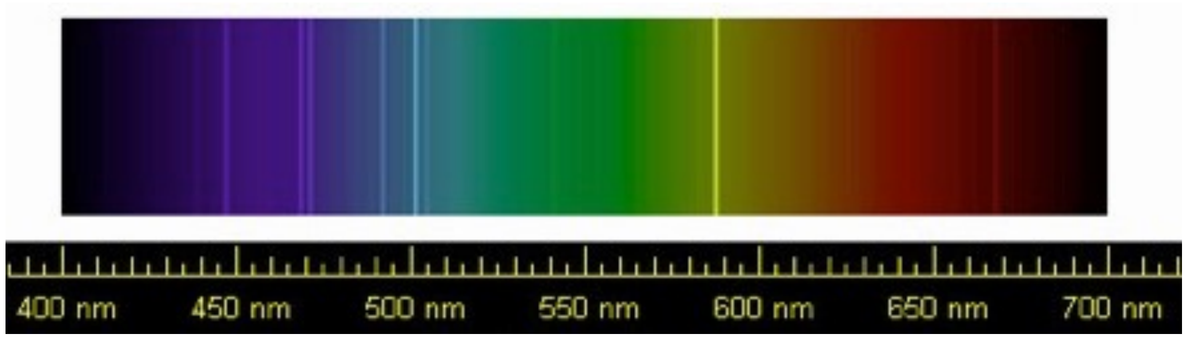
- **Why should we also look for fundamental physics in (high-energy) astrophysics? Surprises can come from**
- **what** ***should be there but ain't*** (often forgotten example of NP found thanks to CR, not yet understood)
- ***Finding what should not be there ('excesses' related to DM processes)***
- ***Something that ain't working as it should ('change the laws', e.g. LIV)***

Introduction: Why should you give it a shot?

Finding New Physics from ‘astrophysics’ (& CR)?

Simply because it happened in the past!

587.49 nm



1868: soon after new tool (spectroscopy) introduced in astro, *new "particle"* (atom) identified *first via astrophysics*:
He in solar spectrum (***Janssen & Lockyer****)
only discovered on Earth ~2 decades later

*founder and first chief editor of "Nature"

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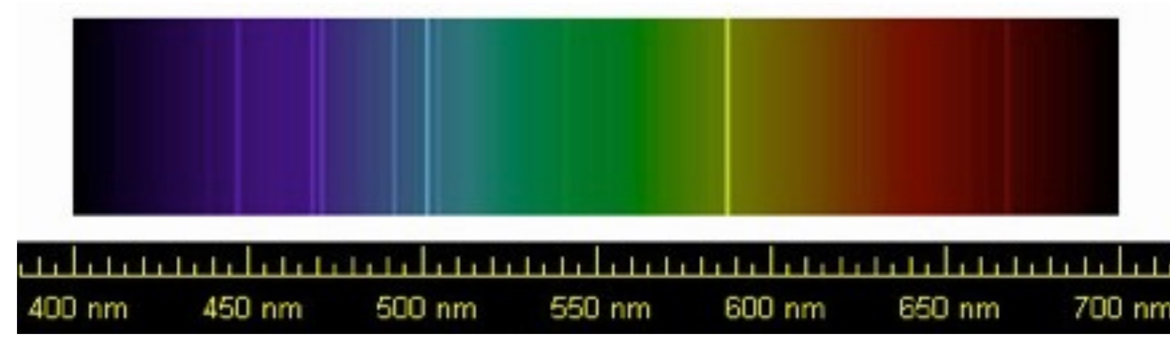

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~1932-53: Particle zoo in cosmic rays such as *positron* e^+ (***Anderson*** ’32), predicted by ***Dirac*** in 1930, but also μ, π, strange particles (K, Λ, Ξ, Σ)...

The Nobel Prize in Physics 1936
Victor F. Hess, Carl D. Anderson

The Nobel Prize in Physics 1936


Victor Franz Hess


Carl David Anderson

The Nobel Prize in Physics 1936 was divided equally between Victor Franz Hess *"for his discovery of cosmic radiation"* and Carl David Anderson *"for his discovery of the positron"*.

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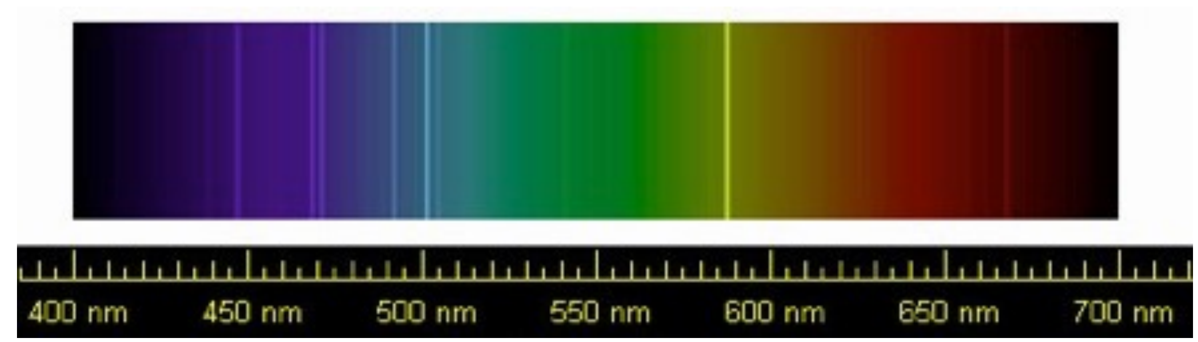

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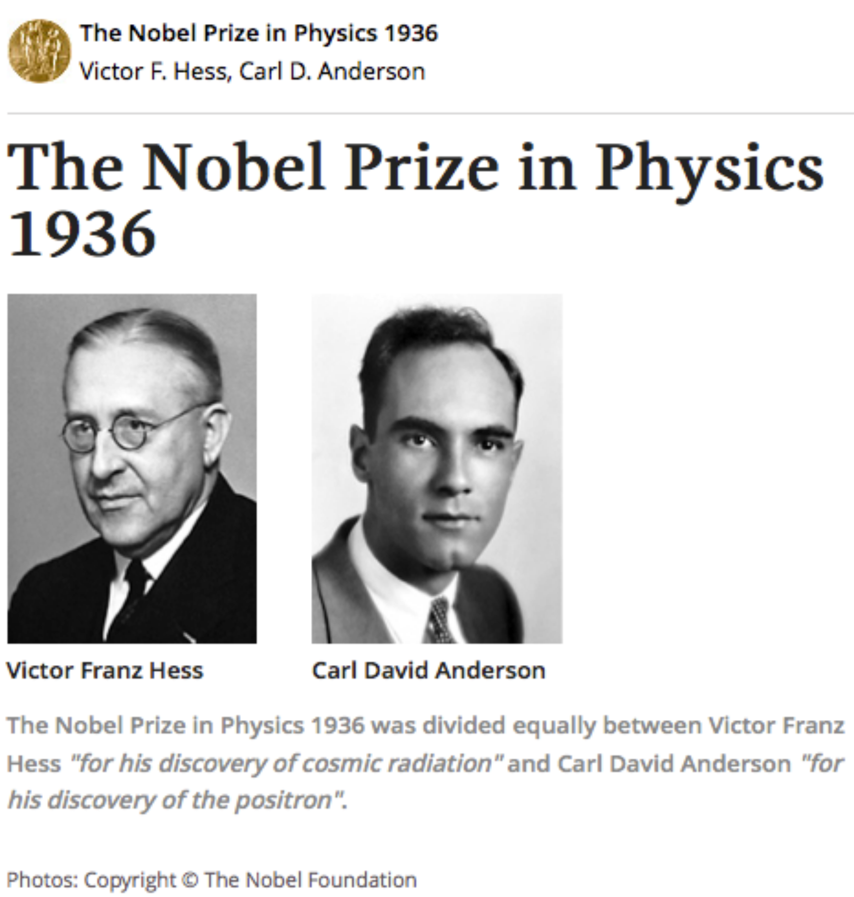
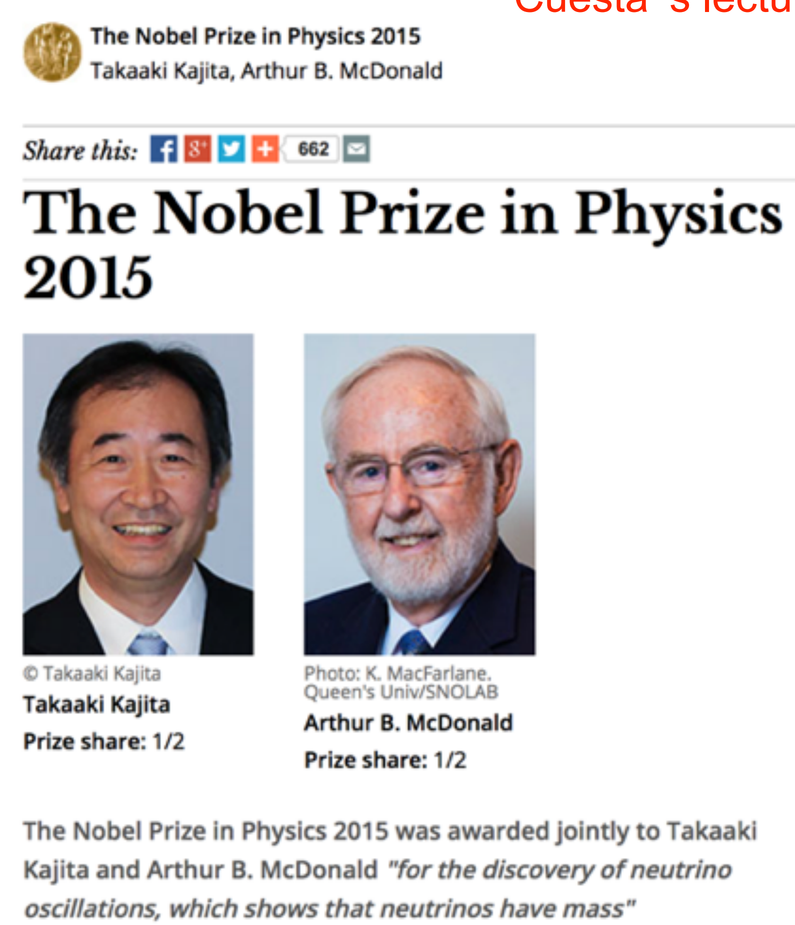


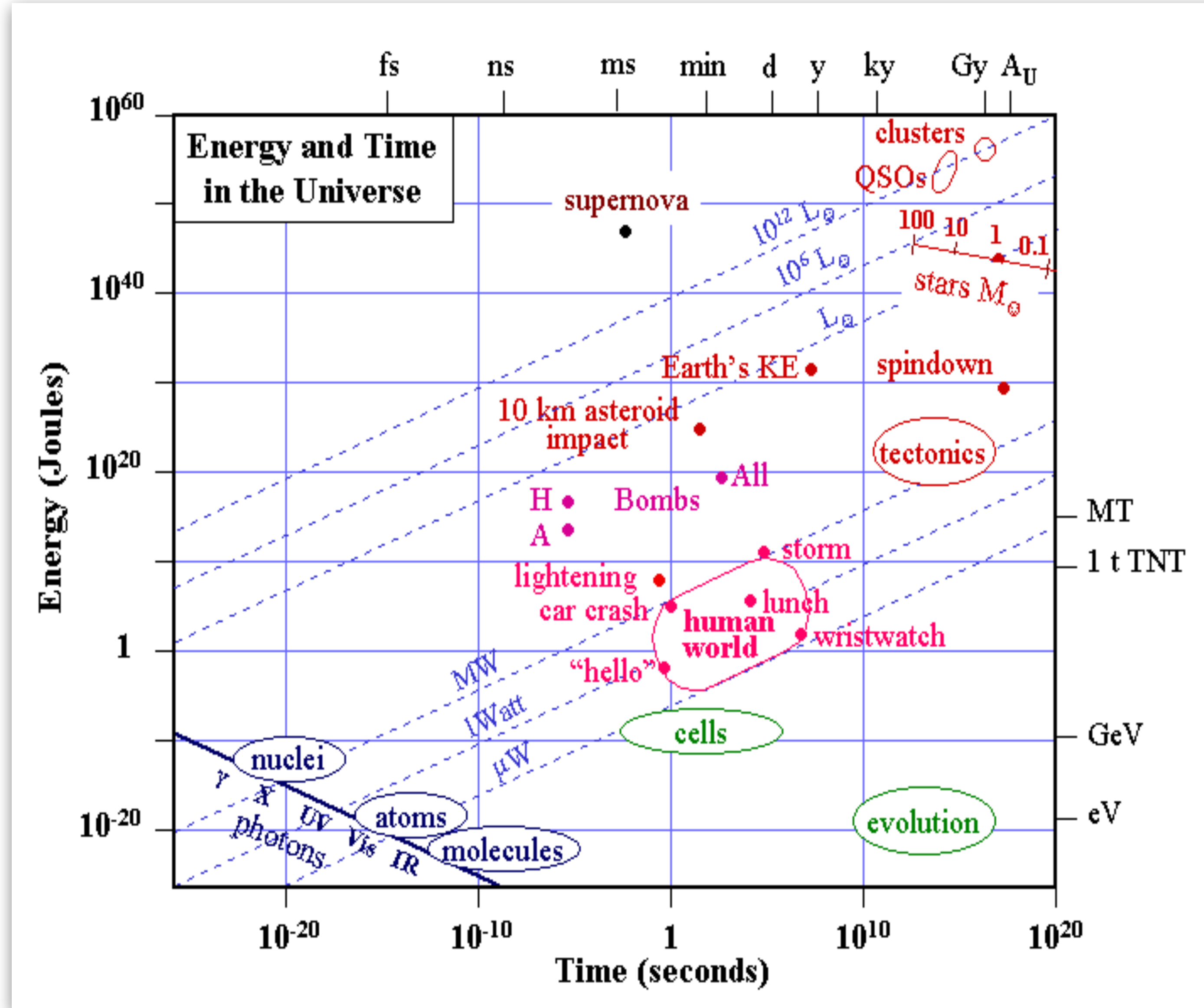
Last decades: systematically detected less ν’s than predicted from the Sun, angular/energy dependence of atmospheric neutrino fluxes:
ν oscillations (hence $m \neq 0$)!

Mariam Tórtola & Clara Cuesta ’s lectures



Just luck or deeper reasons?

- Not surprising, if we think of the unusual scales of density, temperature, size, time, energy… if compared with what achievable in Earth laboratories!
- Orders of magnitude away from familiar ranges: conceivable that some physics extrapolations may fail, highlighting new phenomena/regimes



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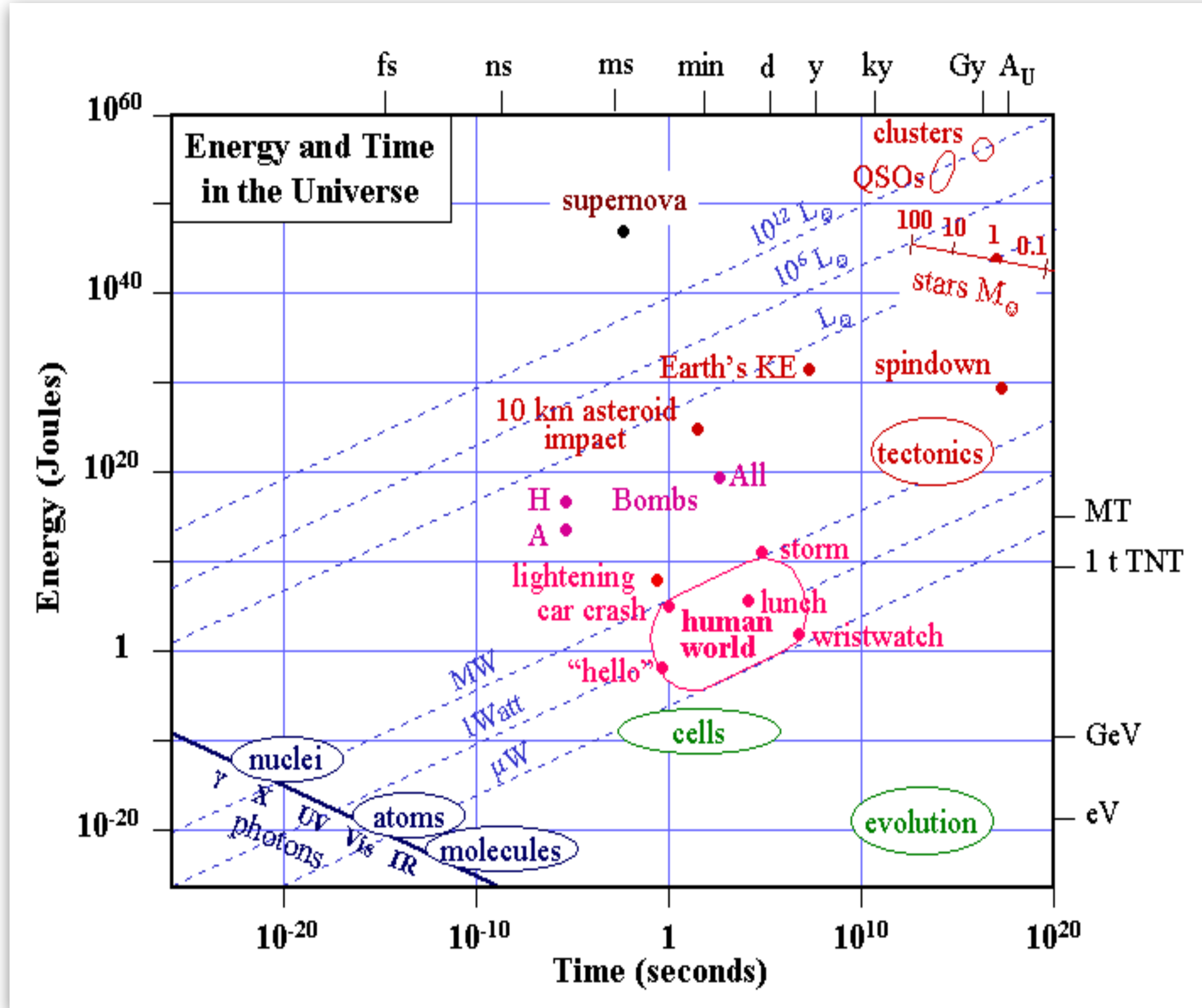


Challenge

We do not control the environment; requires effort in parallel to understand astrophysics, to devise 'robust' signatures, to suggest and cross-check Lab validation.

Example: Surprises from what *should be there but ain't*

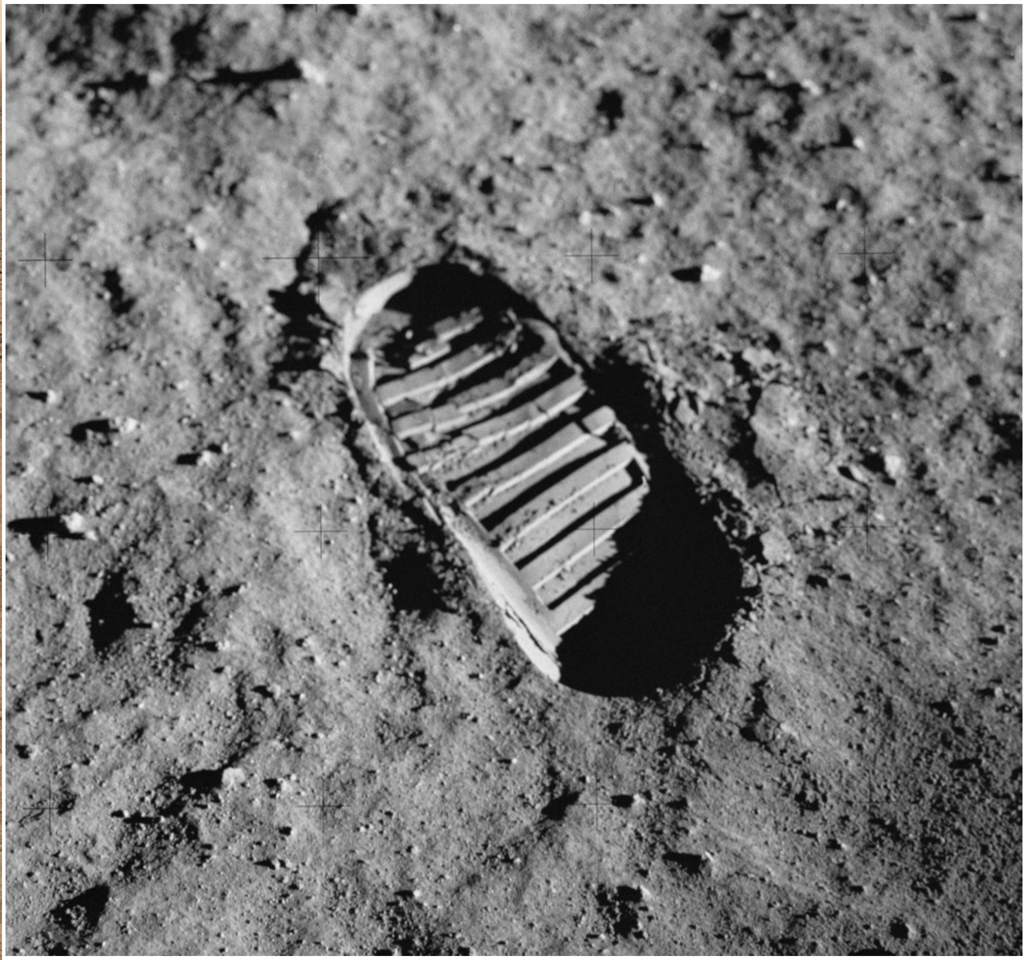
(often forgotten, but new physics we have already found thanks to CR*)

** Here and in the following, I will use 'Cosmic Rays' (CR) in their loose/broad sense of high-energy, non-thermal messengers from the universe.*

A fact we give for granted…

Cassini, Titan

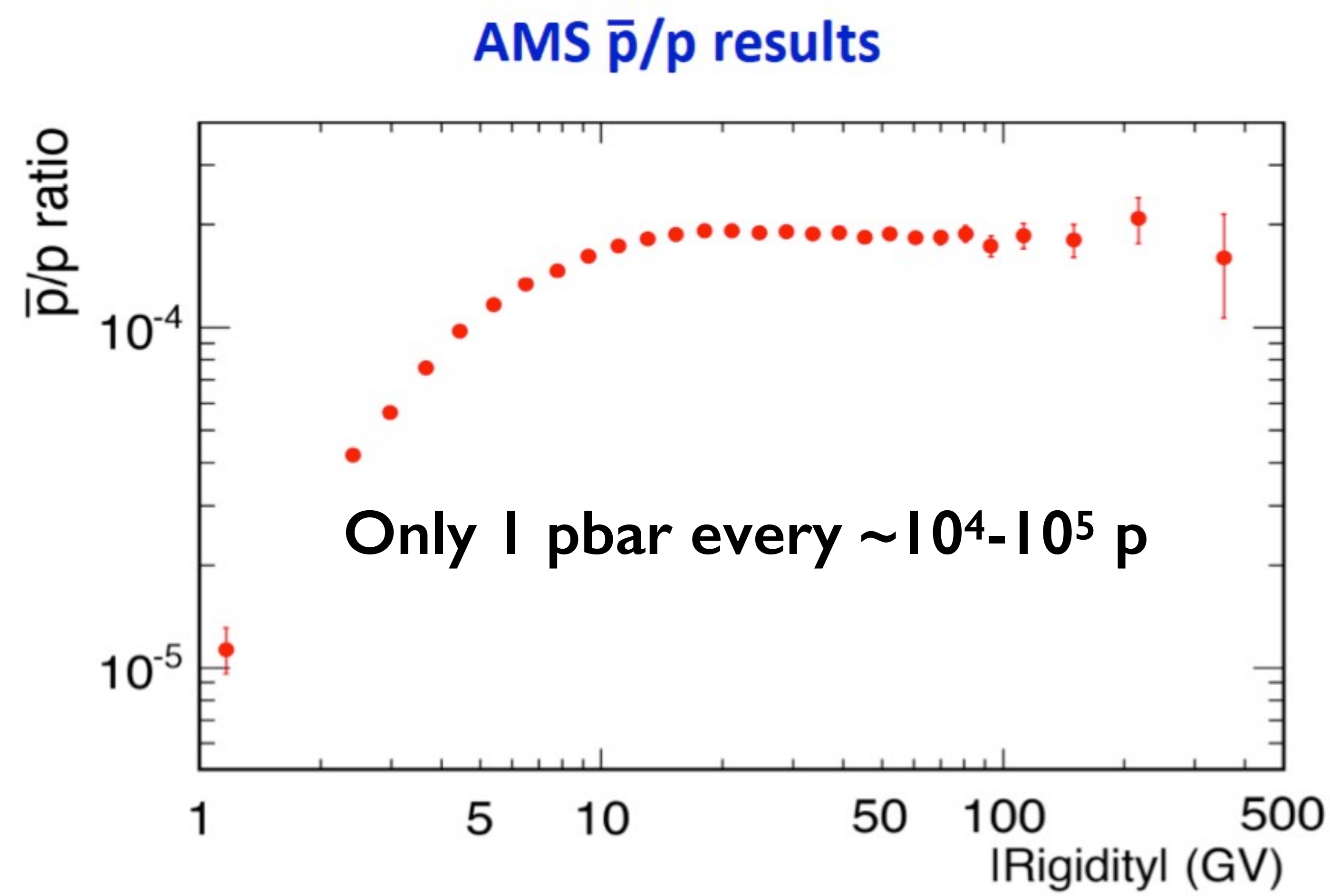
Curiosity self-portrait, Mars



Apollo 11, Moon

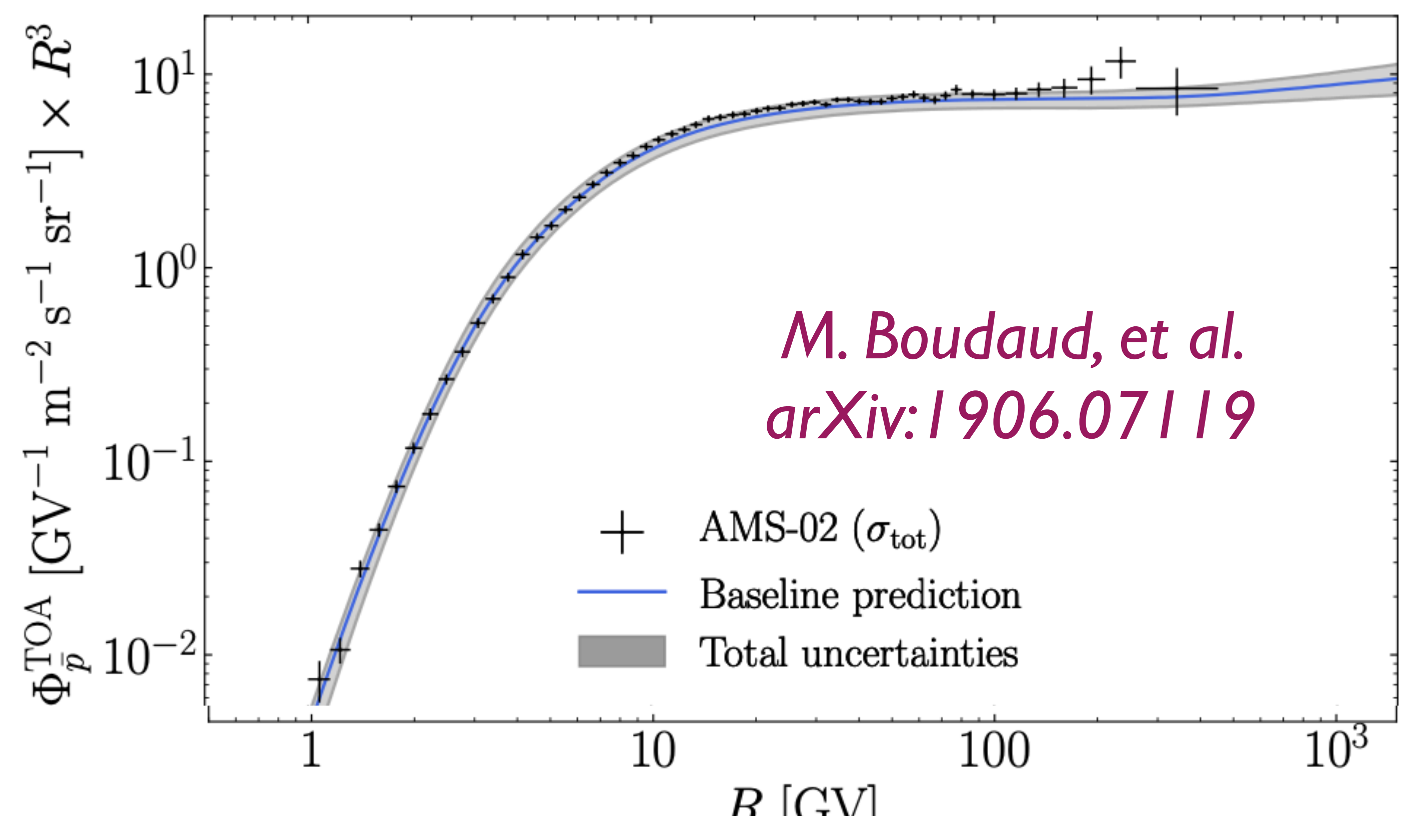
Solar systems seems to be made exclusively of matter! What about the rest of the universe?

CRs: Little to no antimatter in the galaxy



Only 1 pbar every ~10^4-10^5 p

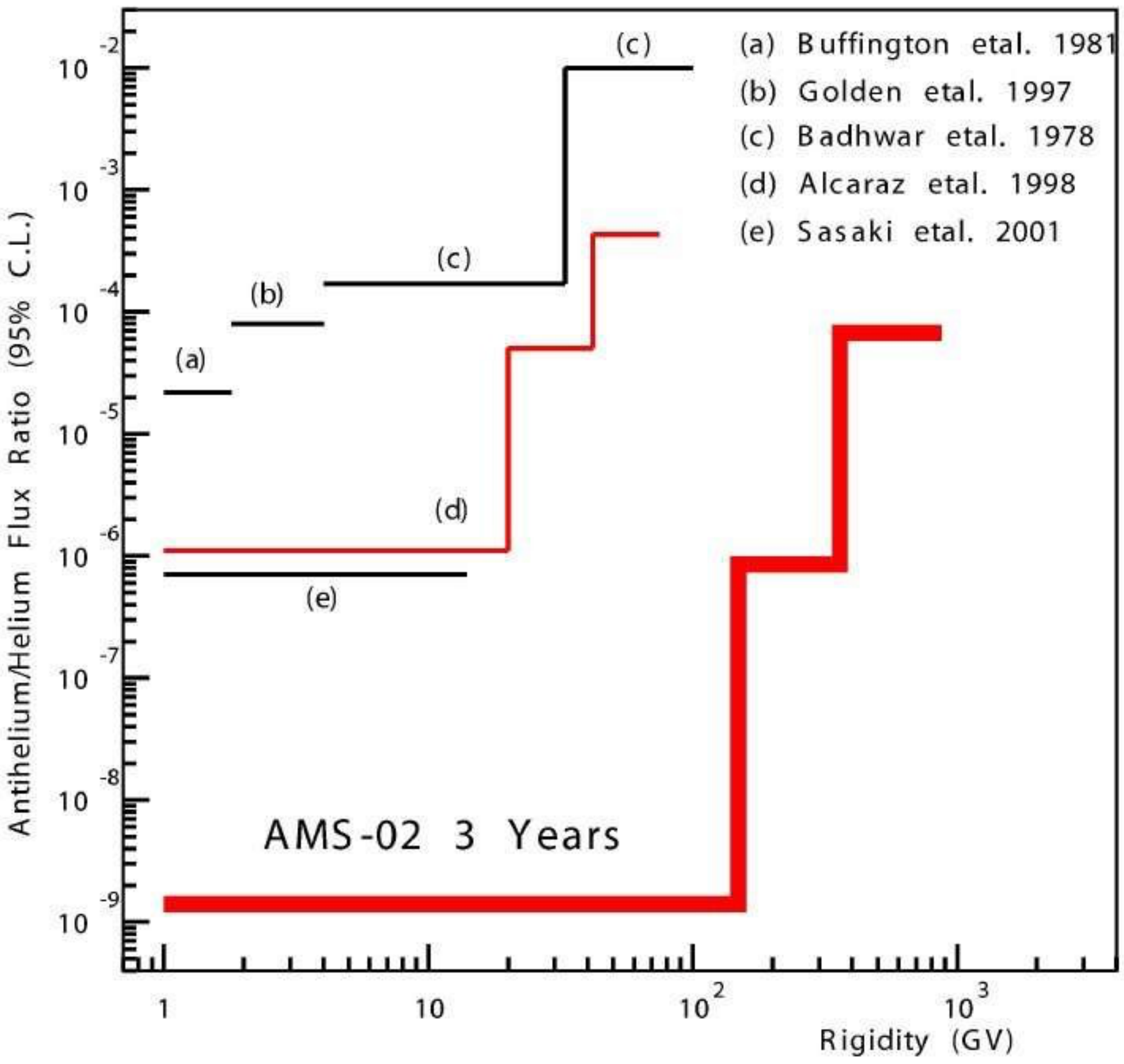
Traces in CRs ; ~ 1 in 10000 (e^+, anti-p) are fully accounted for via rare collisions of cosmic rays (protons, nuclei) in the rarefied interstellar medium



M. Boudaud, et al. arXiv:1906.07119

Even tighter bounds from antinuclei

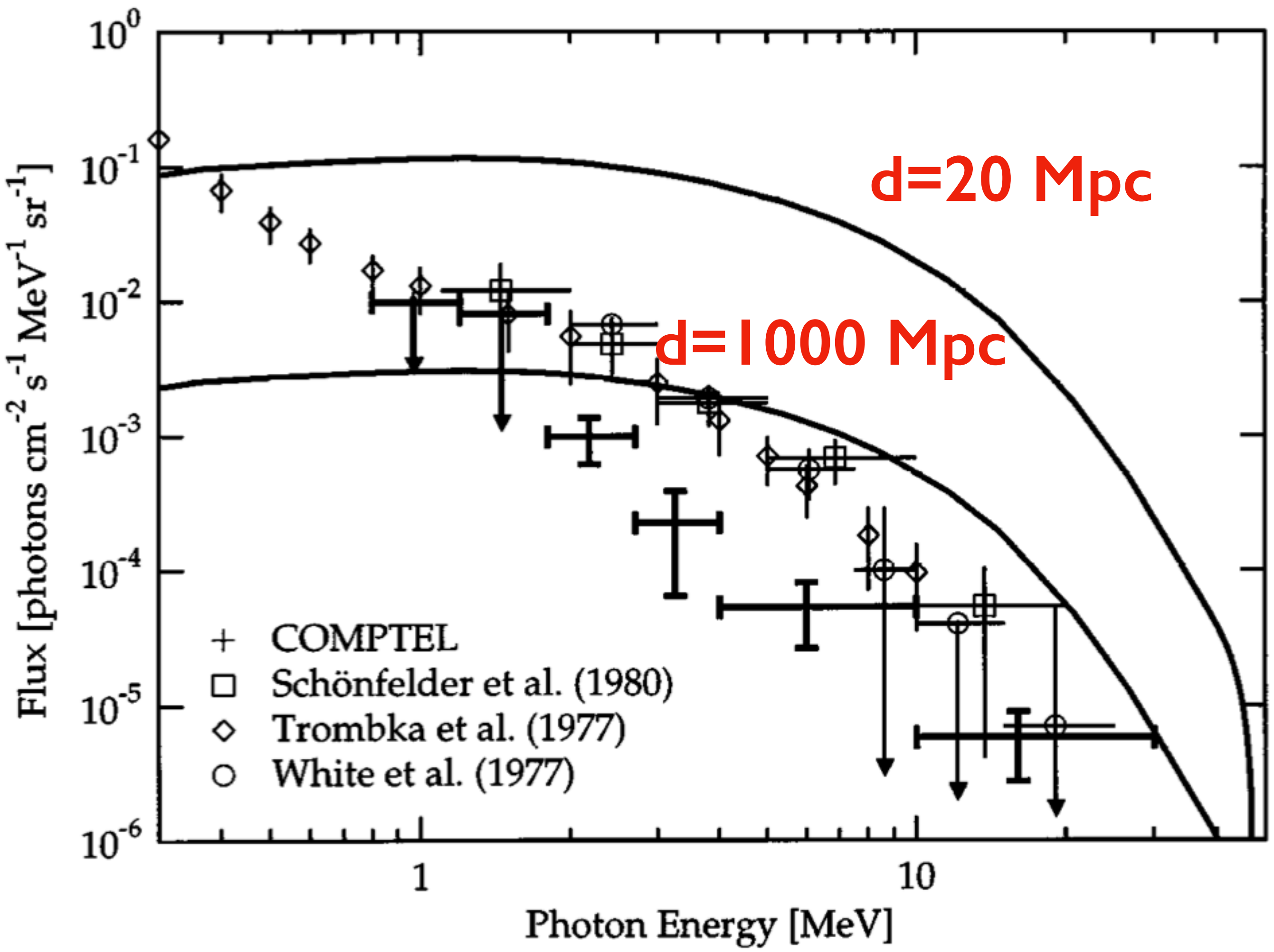
With a comparable number of stars and antistars, one should collect a similar flux of protons and antiprotons, helium and anti-helium, etc.



by Sonia Natale & Martin Pohl

At cosmological scales…

No signs of sizeable traces of antimatter e.g. via gamma annihilation spectra at the borders of putative matter/antimatter domains



A. G. Cohen, A. De Rujula and S. L. Glashow, "A Matter - antimatter universe?" Astrophys. J. 495 (1998), 539-549 [astro-ph/9707087]

Empirical Fact (here on Earth's labs!):
In any reaction creating matter, antimatter particles are also created in equal amounts.
How is it that we live in a Universe dominated by matter?

One of the biggest mysteries in fundamental physics
Matter-Antimatter Asymmetry

Possible explanations

- **Initial condition: Universe is born with this difference.**

Apart from the scarce epistemological value, seems inconsistent with an inflationary era, which would have diluted enormously the initial asymmetry.

- **Dynamical origin**

Creating dynamically the asymmetry starting from a perfectly symmetric condition.

Remarkably

we know *sufficient* conditions capable of doing that:

A.D.Sakharov, (1967) JETP Letters volume 5, issue 1, pages 32-35

Andrei Sakharov

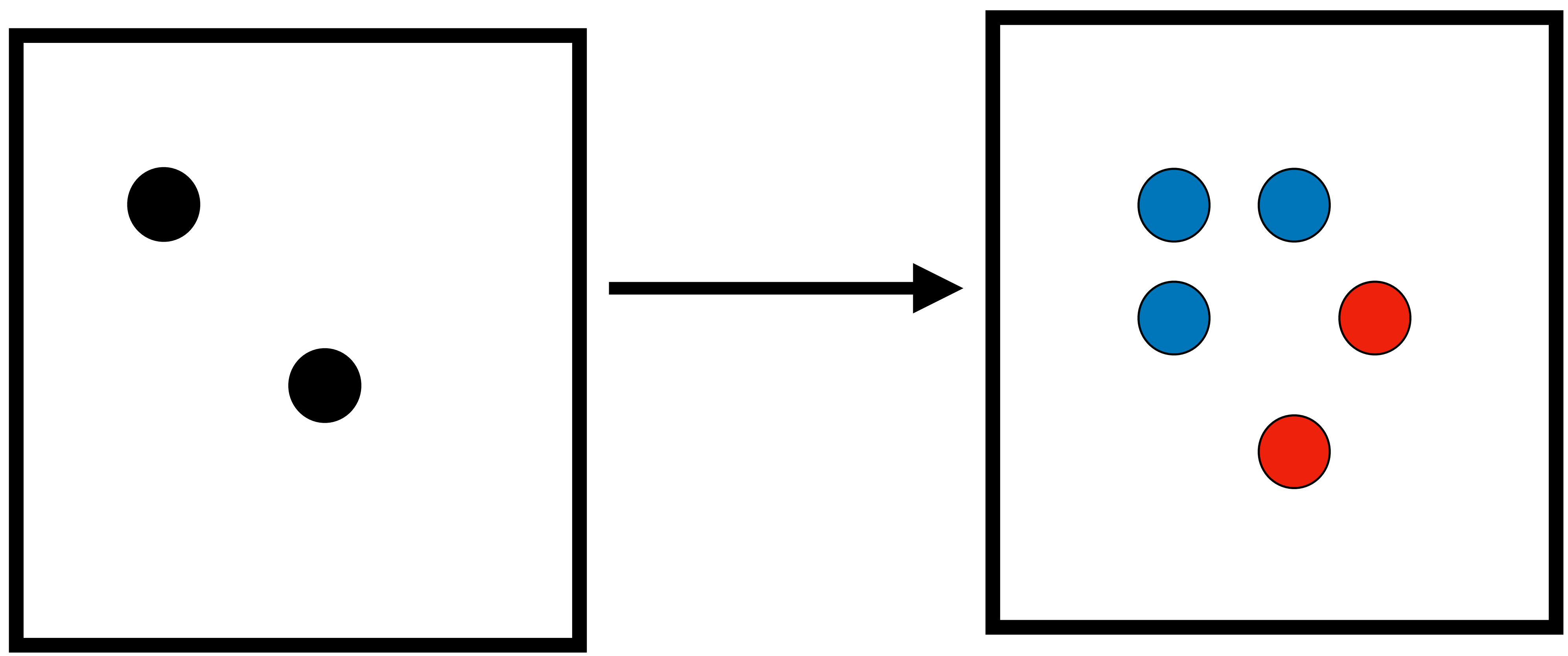
(1921-1989)

Main designer of Soviet thermonuclear bomb RDS-37. Human rights militant, against nuclear proliferation, promoting reforms in the URSS, Nobel Peace Prize 1975

Sakharov condition 1

Must exist reactions breaking the symmetry between matter and antimatter

(B violation)

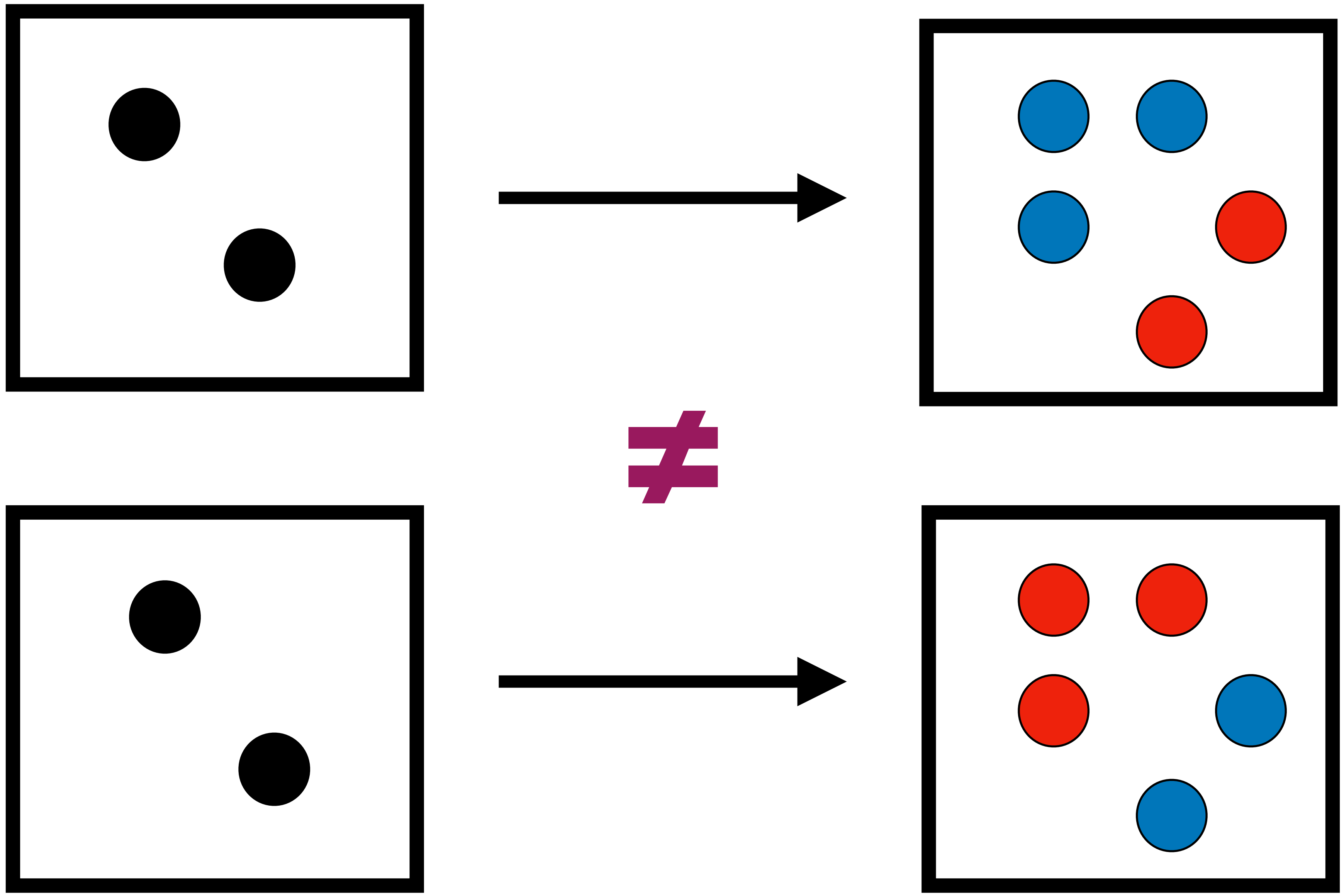


obvious, since if no process exists yielding a change of B between initial state and final state, a dynamical generation is impossible

Sakharov condition II

B-violating reactions not be compensated by their matter-antimatter conjugates (i.e. different reaction rates!)

(C and CP violation)

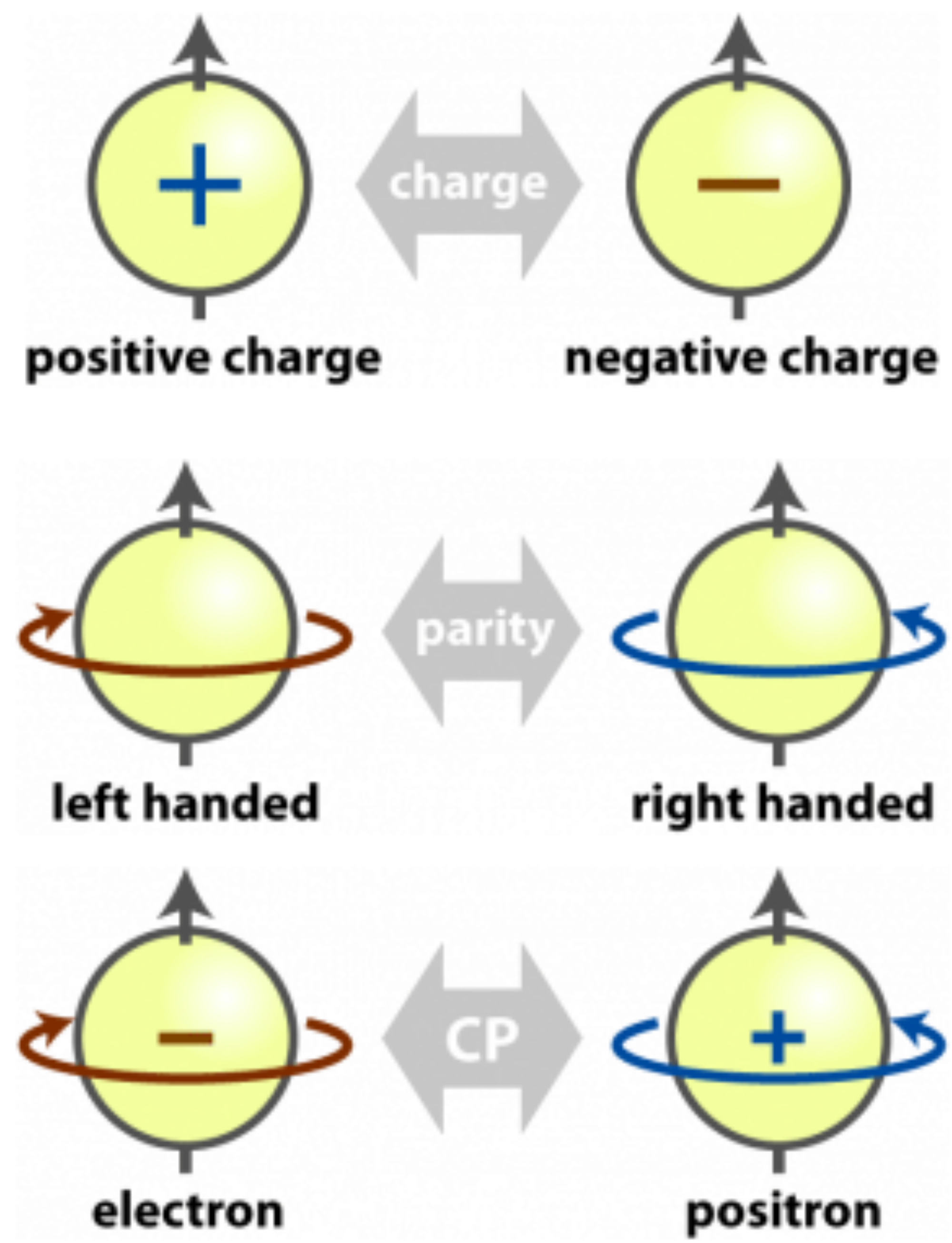


i.e., for a given B-violating process, one needs to make sure that the "anti" processes for the corresponding antiparticles do not have the same yield, otherwise there is no net creation of B.

Sakharov condition II - clarification

Why both C and CP violation?

C converts a particle in the corresponding antiparticle *with the same chirality*.



If CP were preserved, the asymmetry created, once summed over final states of all chiralities, would vanish.

Sakharov condition II - in the SM or beyond

CP violation implies T violation due to CPT theorem (*CPT is an exact discrete symmetry of any local Lorentz-invariant field theory*)

T is anti-unitary: $T i T^{-1} = -i$.

→ *CP violation requires complex parameters in the lagrangian.*

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→ *CP violation requires complex parameters in the lagrangian.*

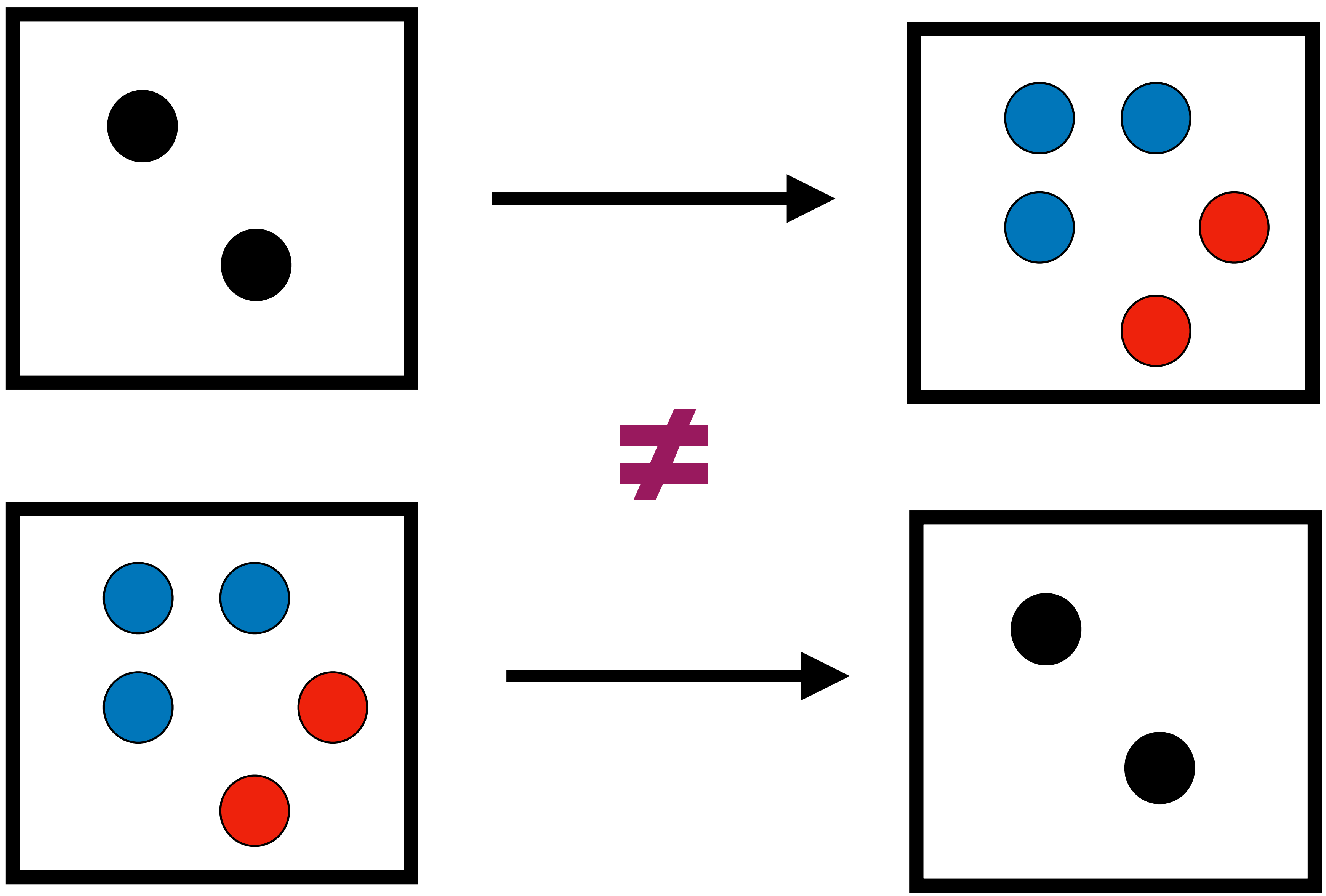
Complex parameters can be achieved by having:

phases in the vacuum expectation values (*spontaneous CP breaking*).
Requires at least two scalars to be possible, so that it ***cannot happen in the SM with a single Higgs doublet***.

phases in the coupling parameters (*explicit CP breaking*)
That's the only origin possible (and known) of CP-violation in the SM, which has *one* physical phase in the Yukawa matrix of the quarks

Sakharov condition III

Departure from thermodynamical equilibrium
(otherwise each reaction balanced by its reverse)



This can take place, for instance, via a (first order) phase transition, decays of decoupled particles…

Rise and fall of the SM baryogengesis

All conditions could be in principle met in the SM (non-perturbative B-violation, CKM phase, EW transition 1st order) but parameters quantitatively far from successful!

One of strongest motivations for physics beyond the SM

Two main classes of alternatives:

New physics at the EW scale (e.g. supersymmetry).
Can change the nature/strength of EW phase transition (enhance cubic term in V_{eff}), plus additional phases and possibly complex vev allowed by multiple Higgses.
+ : 'in principle testable at colliders'
- : rather constrained by negative searches

Baryogenesis via Leptogenesis
generate a B-L asymmetry at $T > T_{EW}$, which is then converted into a B asymmetry (by SM sphaleron processes). Departure from equilibrium from heavy particle decays.
Extra phases among which those entering the neutrino mixing matrix.
+ : Compatible with (hinted to by?) tiny mass of neutrinos, EFT reasoning
- : Typically happens at high scales, not directly testable

Lesson learned

There might be cases where 'cosmic rays' are instrumental in pointing to new physics, but as far as we know in this case there is no useful way they can be used to unveil which physics is behind the puzzle…

Converse could also be true:

Cases where cosmic rays are not involved in the discovery of new physics, but could be used to identify its nature (e.g. indirect dark matter detection, possibly will hear more by María Martínez…)

II. Basic facts and pheno of cosmic rays

Units: hybrid system

natural units ($c = k_B = \hbar = 1$) for microscopic scales: powers of eV and multiples

Astrophysical units common e.g. for astrophysical scales: **parsecs** & multiples (distance) and cgs unit erg (energy)

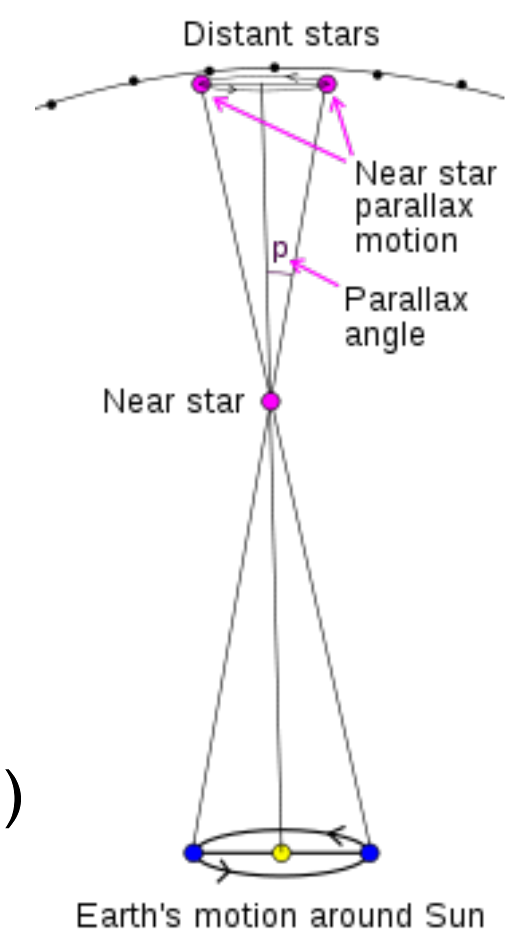
1 pc: distance at which 1 AU seen as arcsec

(Parallax for near stellar distances)

$$d \simeq 1\,\mathrm{A.U.}/p[\mathrm{rad}] = p_{''}^{-1}\ \mathrm{parsec}$$

Pioneered by Bessel, 1838

In turn, AU calibrated via radar measurements within the solar system (once upon a time, timing Venus transits…)



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Differently from quantum gravity community, retain $G_N \equiv M_P^{-2} = (1.22 \times 10^{19}\ \text{GeV})^{-2}$.

Most literature uses Gaussian electromagnetic convention (i.e. 4π's in Maxwell eq.s, not in Coulomb / Biot-Savart laws).

The charge of the positron is $e \simeq \alpha^{1/2} \sim (1/137)^{1/2} \sim 0.085$

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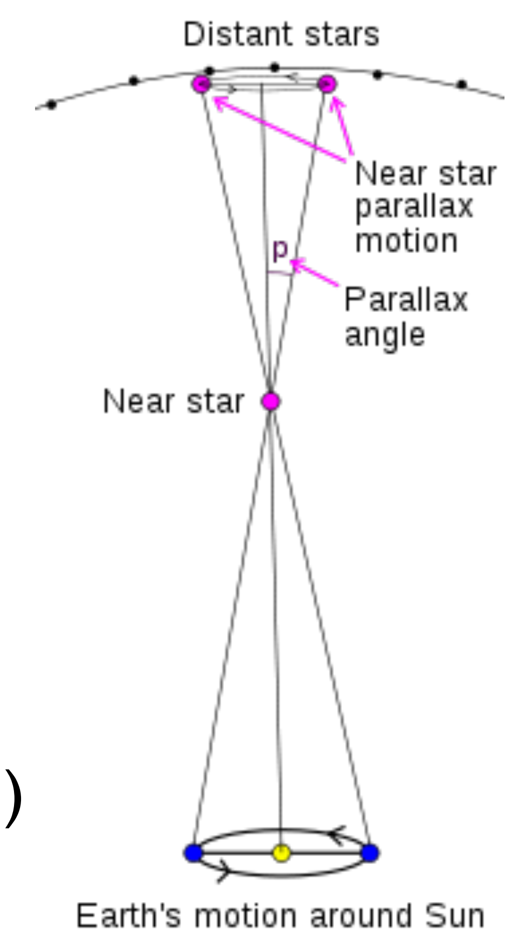

Some conversions

- $1\ \text{s} = 3\times10^{10}\ \text{cm} = 1.5\times10^{15}\ \text{eV}^{-1}$
- $1\ \text{J} = 10^{7}\ \text{erg} = 6.25\times10^{18}\ \text{eV}$
- $1\ \text{pc} = 3.1\times10^{16}\ \text{m}$
- $1\ \text{barn} = 10^{-24}\ \text{cm}^2$
- $1\ \text{G} = 10^{-4}\ \text{T} \simeq 0.069\ \text{eV}^2$

Basics on relevant environments

Galactic		extra-Galactic
$n \simeq \mathcal{O}(1)\,\mathrm{cm}^{-3}$	rarefied densities of matter	$n \lesssim \mathcal{O}(10^{-6})\,\mathrm{cm}^{-3}$
$d_{\mathrm{GC}}^{\odot} \simeq 8\ \mathrm{kpc}$	Very large spatial scales	Gpc! d≃40(z/0.01) Mpc @ $z \ll 1$
Solar orbit ~230 Myr	Very long timescales	Up to ~14 Gyr (age universe)
few μG	Magnetised environment	nG?

Basics on relevant environments

Galactic

$n \simeq \mathcal{O}(1)\,\mathrm{cm}^{-3}$

$d_{\rm GC}^{\odot} \simeq 8$ kpc

Solar orbit ~230 Myr

few μG

rarefied densities of matter

Very large spatial scales

Very long timescales

Magnetised environment

extra-Galactic

$n \lesssim \mathcal{O}(10^{-6})\,\mathrm{cm}^{-3}$

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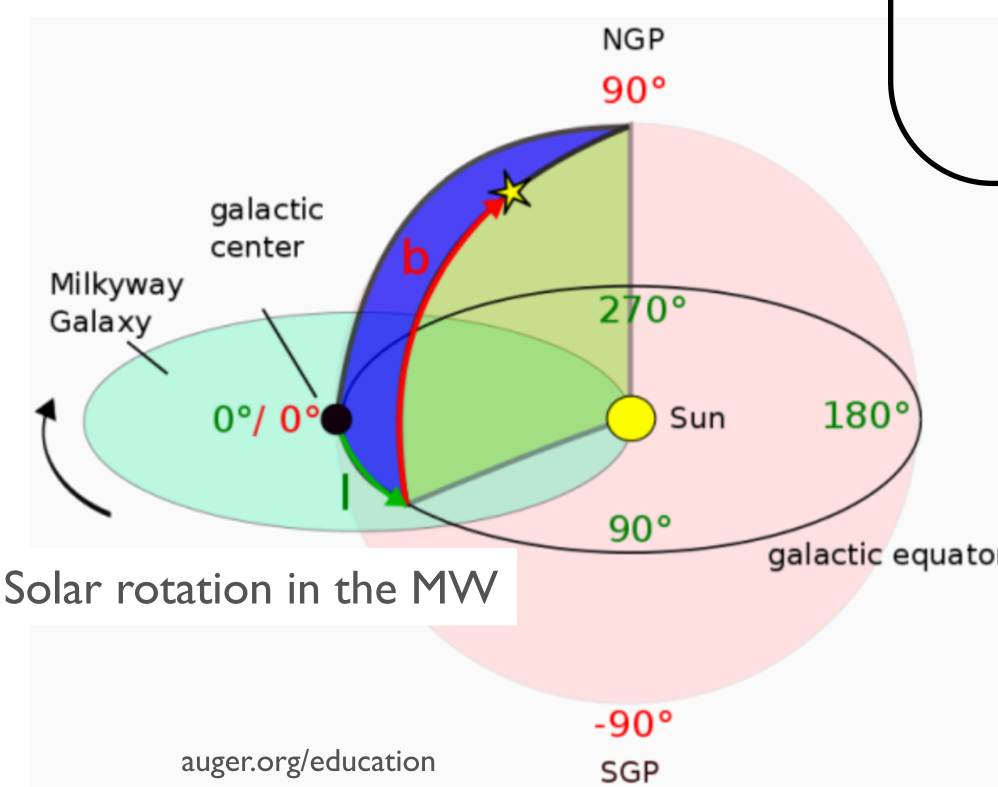
Up to ~14 Gyr (age universe)

nG?

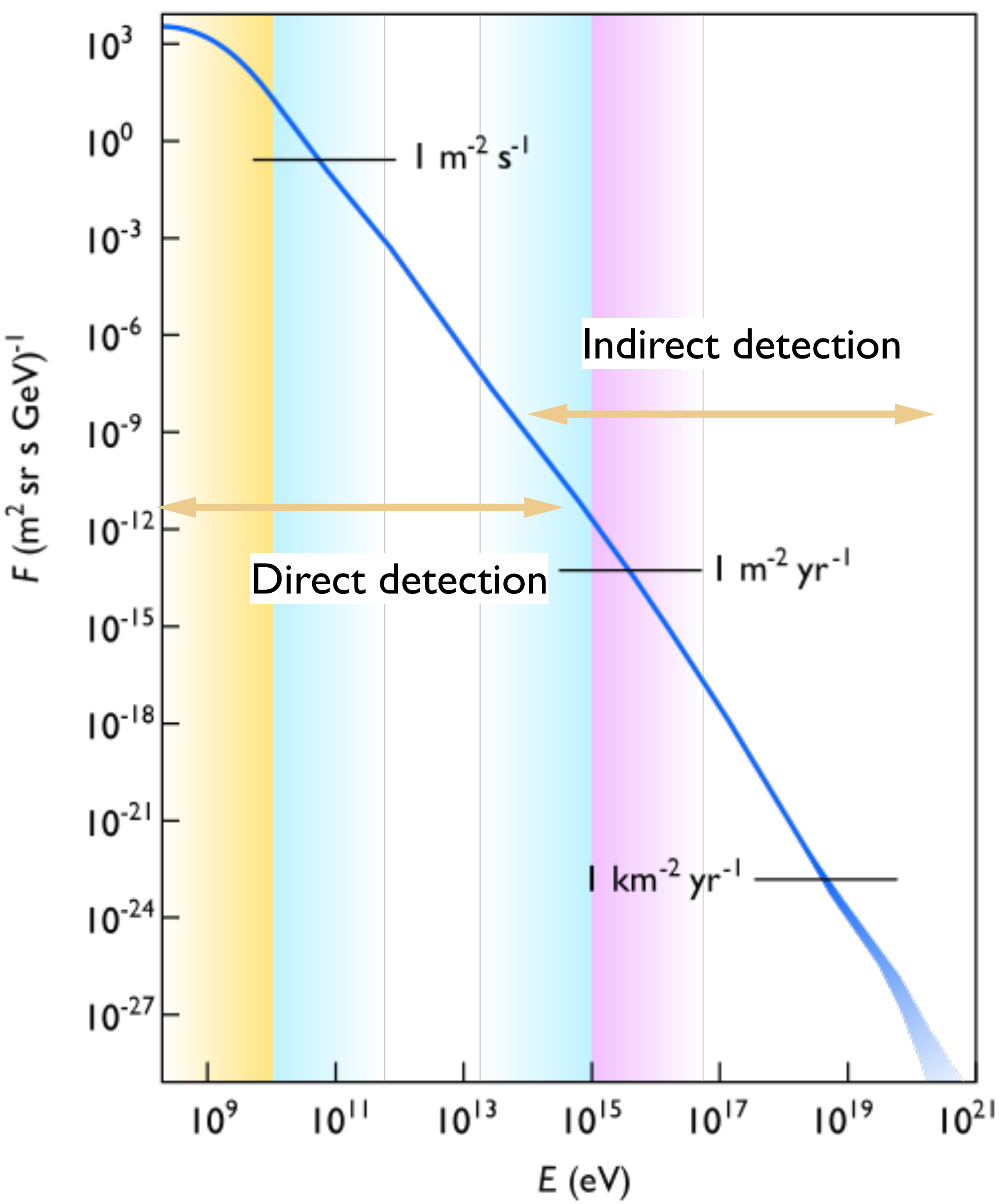
Plots you may find, often use *Galactic coordinates*



Solar rotation in the MW

[Coordinate algorithms available e.g. via Astropy]

All-particle flux spectrum



~13 decades in energy, ~30 decades in flux

Almost featureless spectrum, ~broken power-law with index ~ -2.7 from O(10^{10}) to O(10^{15}) eV

Softening at 3 x10^{15}eV (*knee*),

Hardening at 5x10^{18} eV (*ankle*)

changes in sources, propagation?

Softening at 4x10^{19} eV (*cutoff?*)

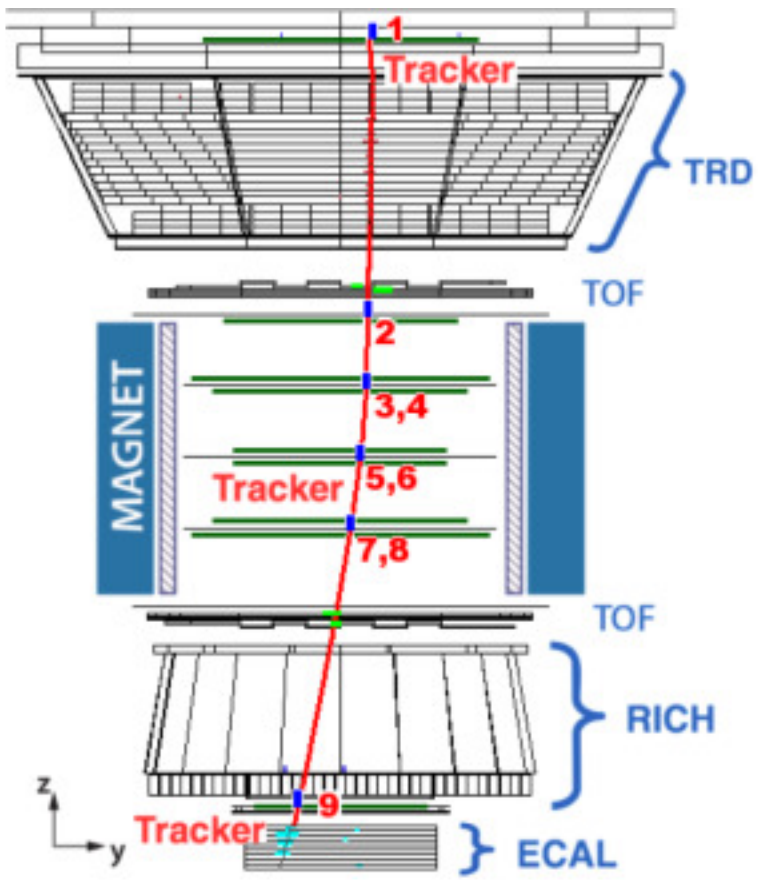
Rather isotropic distribution in arrival directions (<~ 0.1% below the knee)

Direct detection

flying particle physics detectors on balloons/in space to measure direction, charge, momentum, energy, velocity...

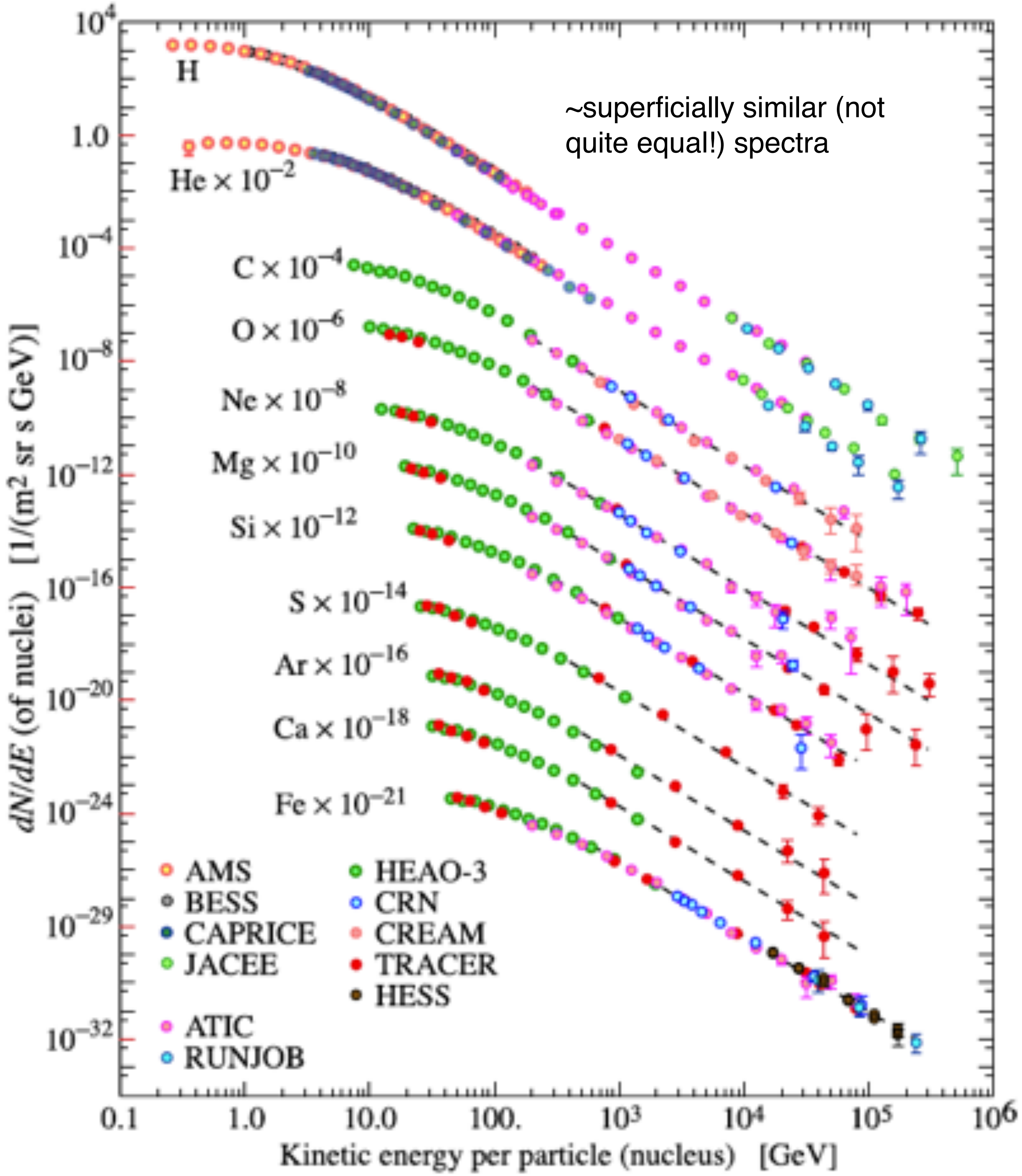
- **spectrometers, magnets & trackers**: determine q and p of the particles
- **Calorimeters**: measure E of particles & do particle discrimination.
- **Cherenkov detectors**: measure the particle v from width of cone
- **Transition radiation detector**: measure γ (hence mass) via radiating probability at interface
- **Time of flight**: measure the time difference and the velocity v

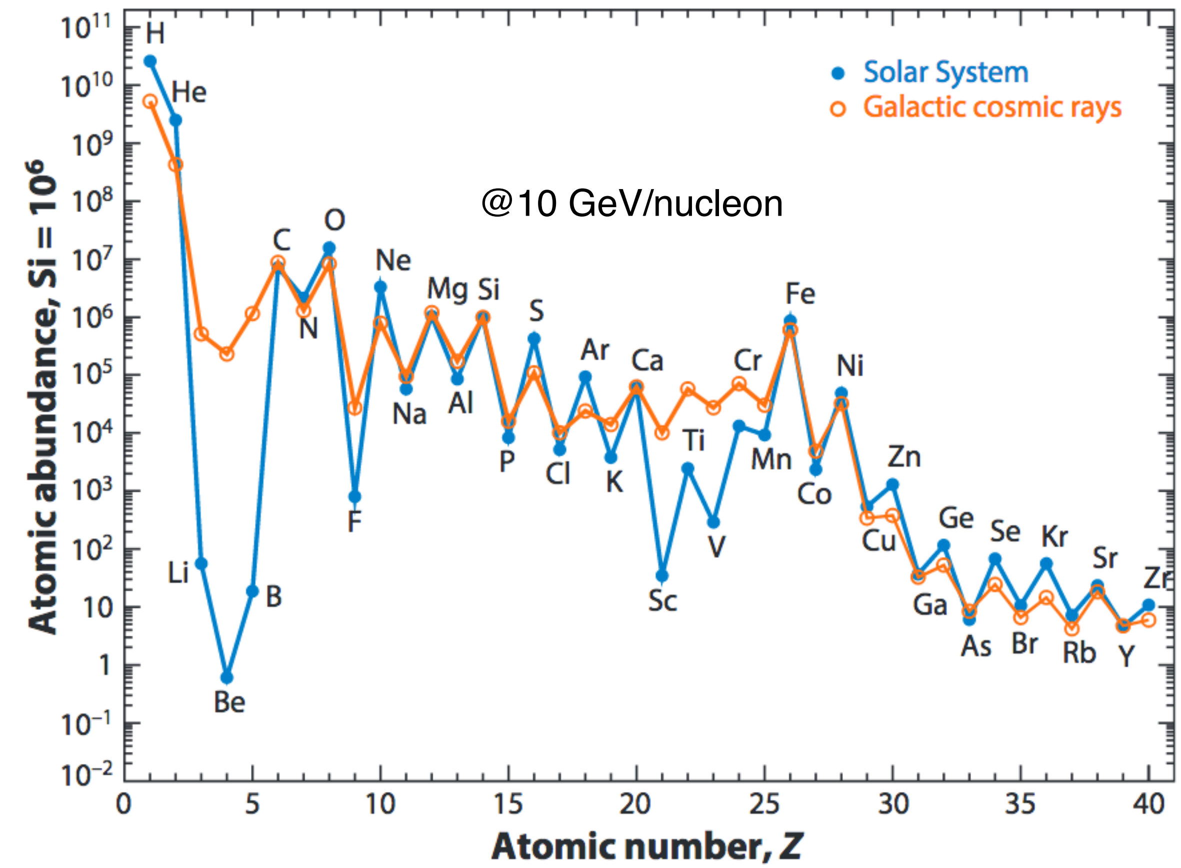
AMS-02

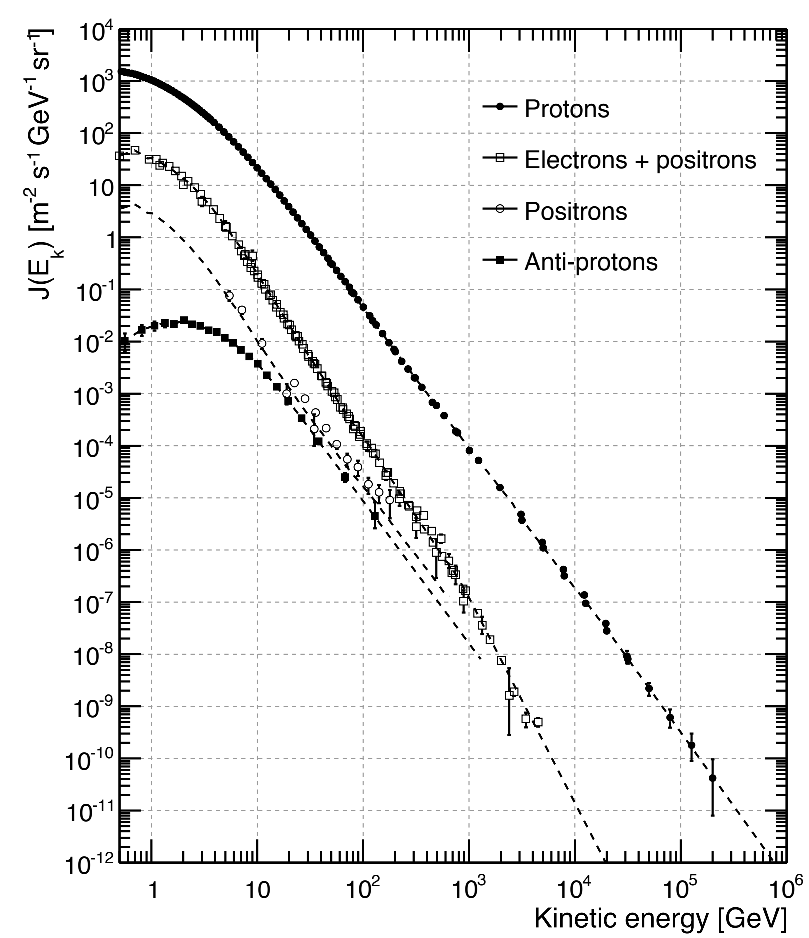


With some difficulties & differences wrt colliders: weight and size matter!
"Unusual" backgrounds (for example # e.m. particles << # hadrons!),
Alignment in space (can't go out there to measure...), etc.

Composition

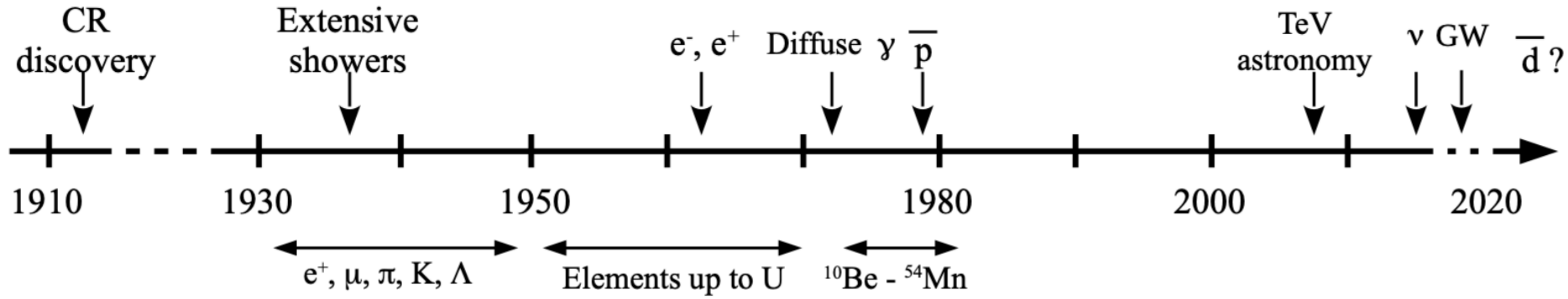






Most (meta)stable nuclei known have been detected

Timeline and use of atmospheric secondaries



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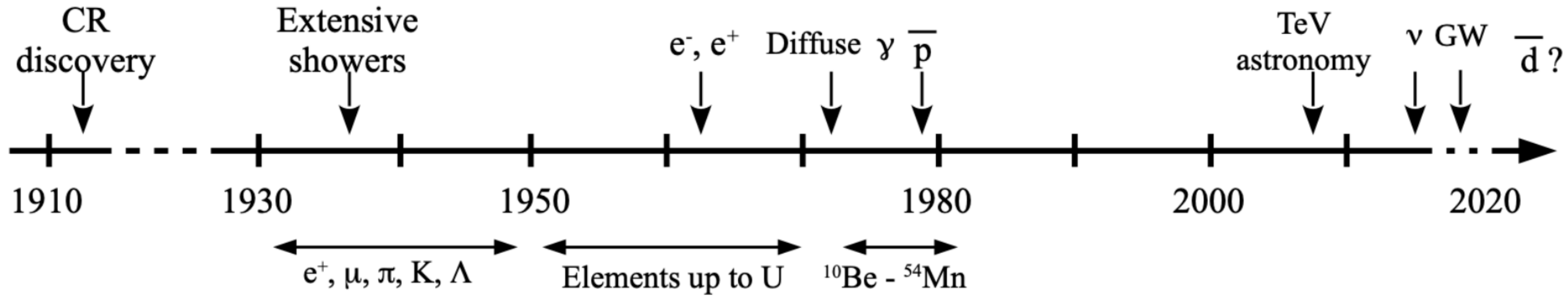
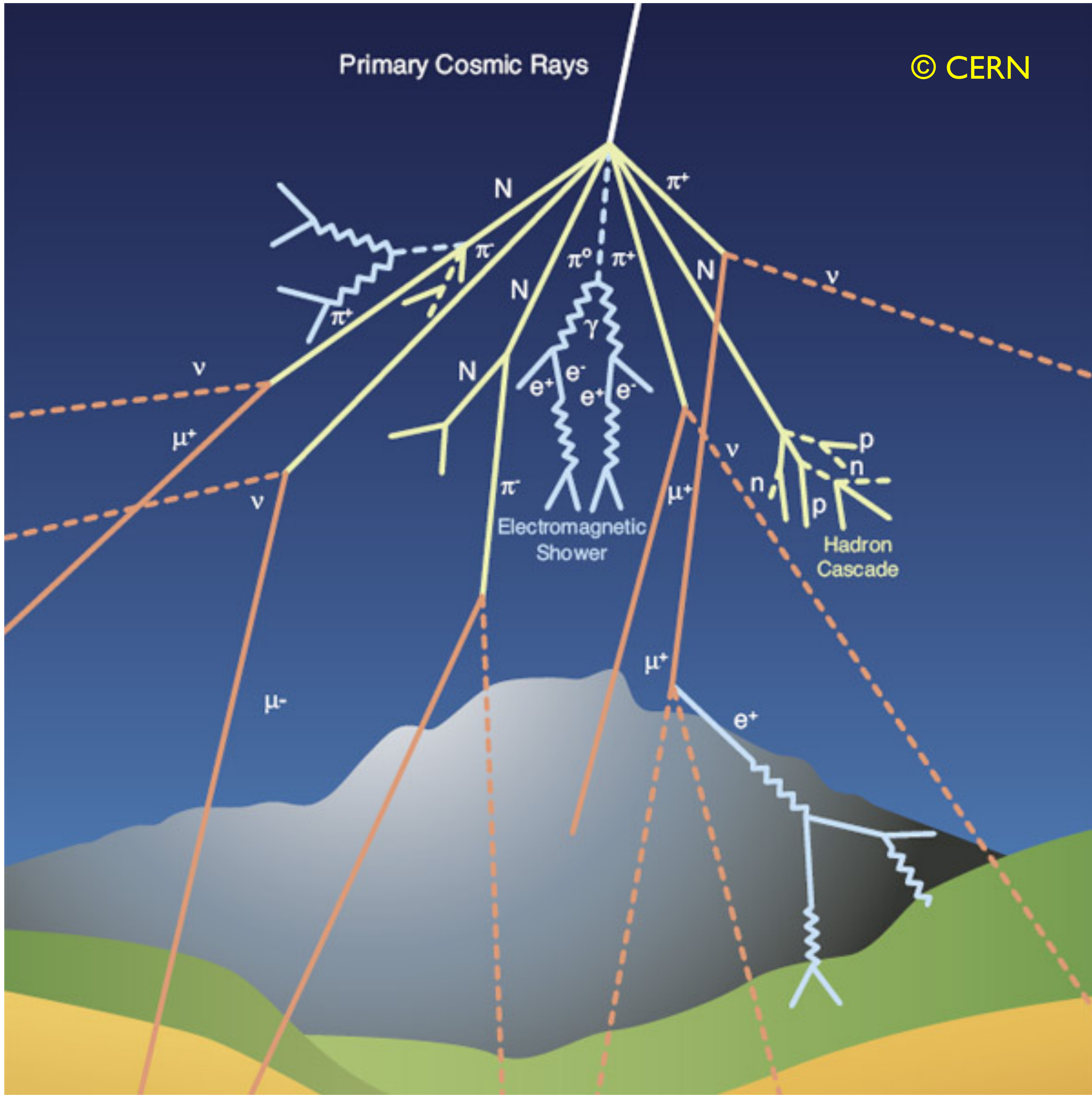


~1932-53

"Particle zoo" among <u>secondary</u> particles

e^+, μ, π, strange particles (K, Λ, Ξ, Σ)…



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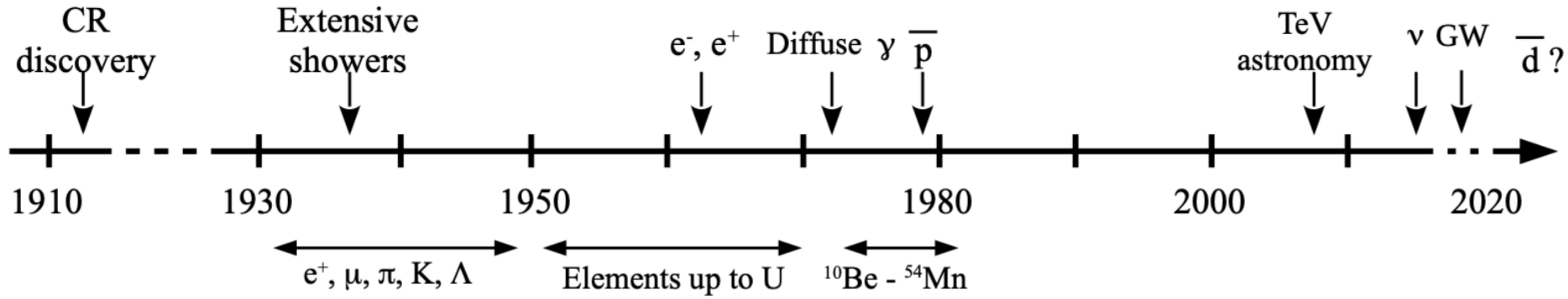
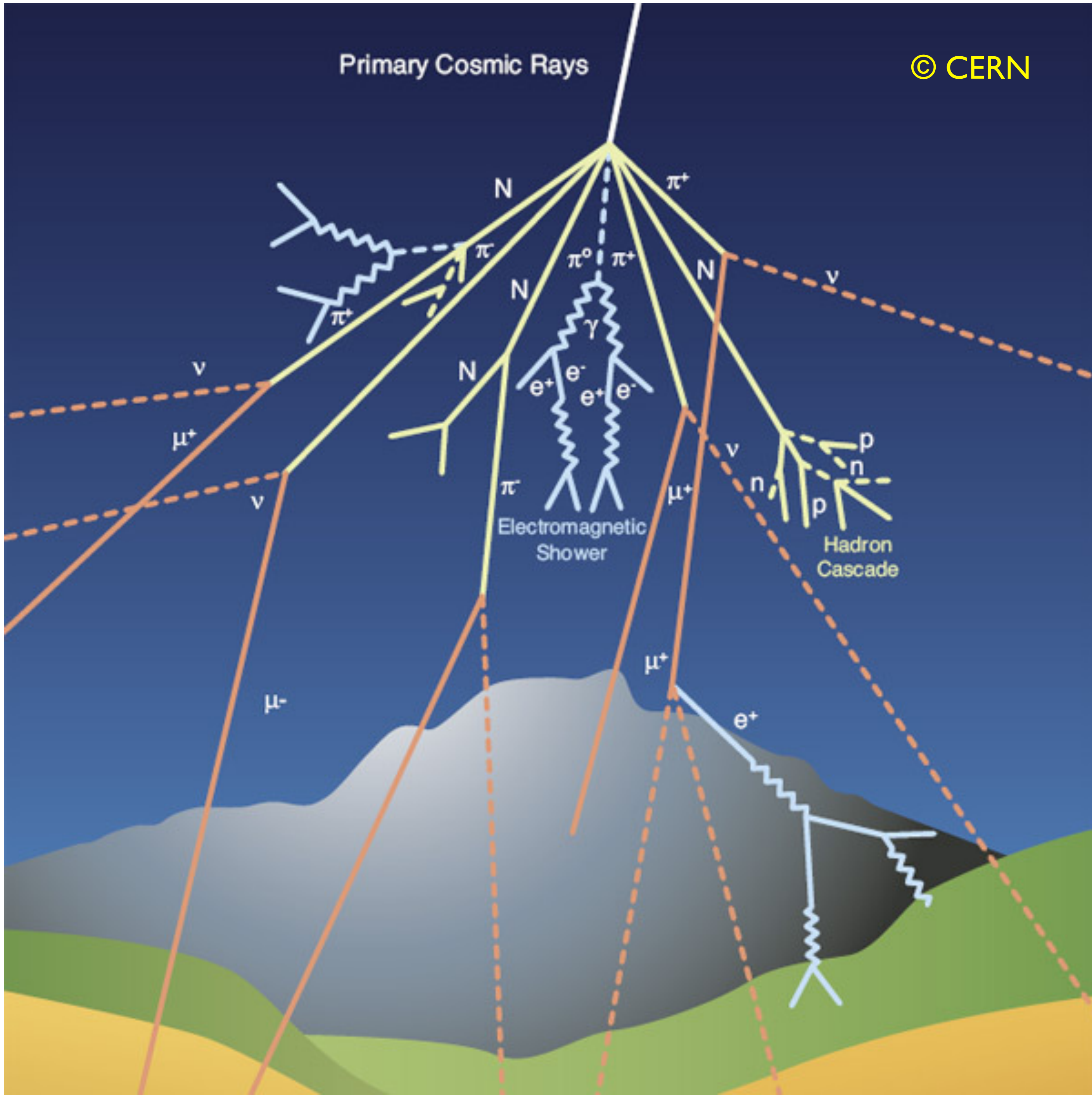


~1932-53

"Particle zoo" among <u>secondary</u> particles

e^+, μ, π, strange particles (K, Λ, Ξ, Σ)…

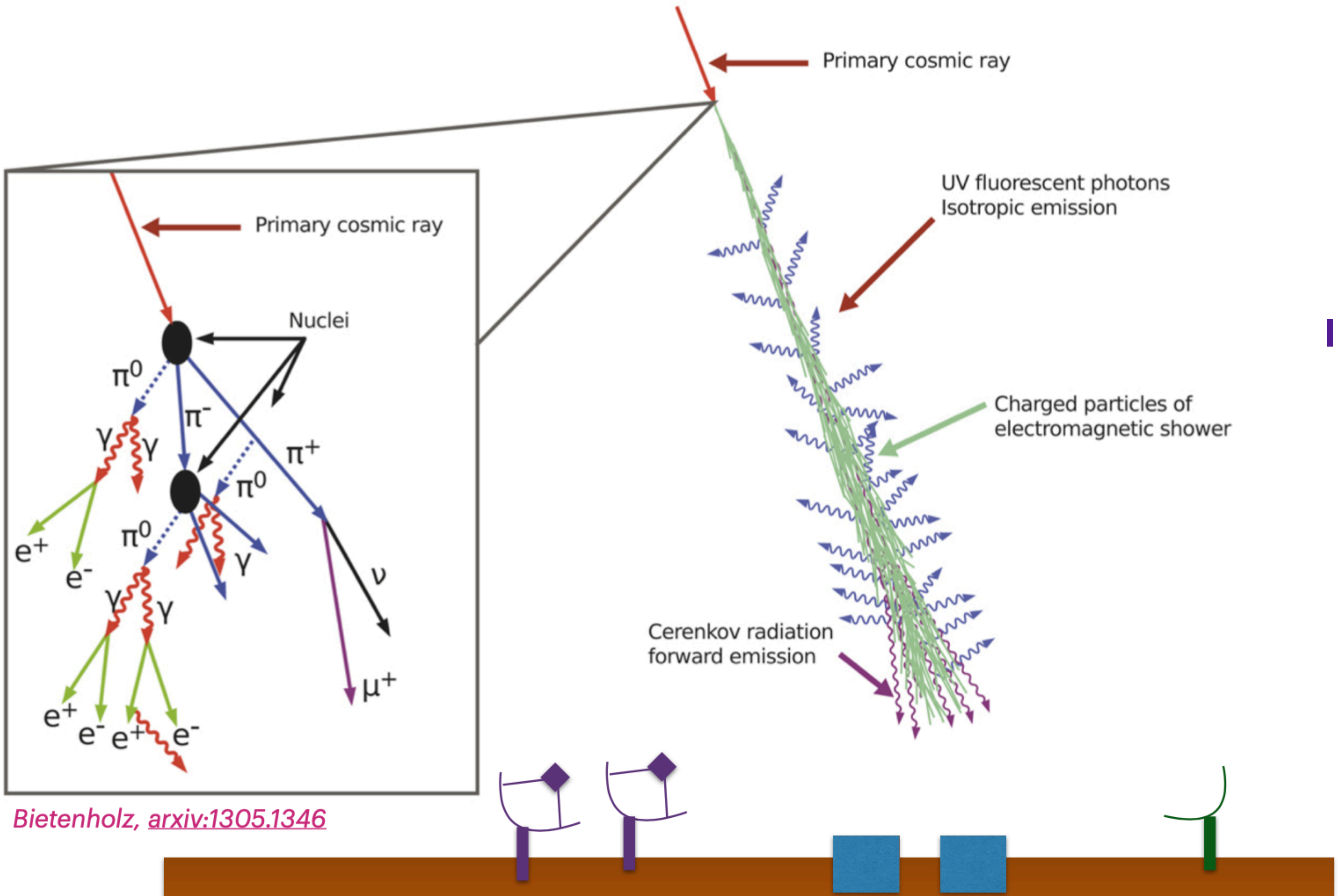
At high-E (hence low fluxes) γ, e±, $\mu^\pm$, ν, + hadrons (nucleons, $\pi^\pm$…) produced in the cascade must used to infer properties of the primary



Indirect detection

Must resort to know particle interactions in the atmosphere to reconstruct properties

Will illustrate how it works with the simple example of the (modified) **Heitler model**



Bietenholz, arxiv:1305.1346

Fluorescence
(e.g. P. Auger observatory telescopes)

Imaging Air Cherenkov Telescopes
(e.g. H.E.S.S., MAGIC, Veritas… CTA)

“Ground arrays”
(HAWC, LHAASO, IceTop, Auger…)

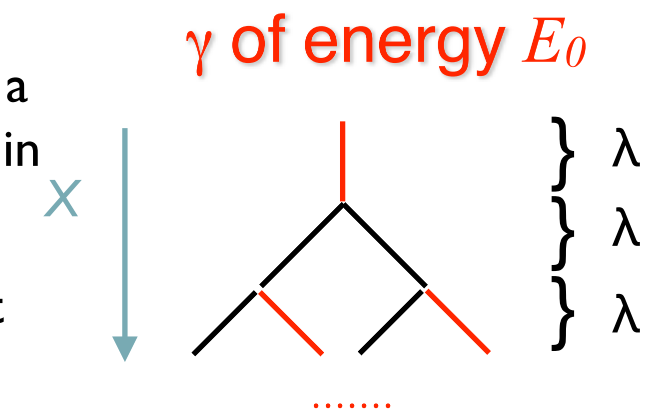
Heitler model for e.m. cascades

Ind. variable: **grammage** $$X = \int \rho(\ell)\mathrm{d}\ell$$

Note the role of particle interactions in shaping the dynamics…

Assume a primary γ, impinging on the atmosphere, generating a pair after a **characteristic grammage λ (g/cm²);** each lepton in turn generates a γ via bremssthralung after about the same λ.

Critical energy E_c below which particles lose energy without radiating new particles (e.g. ionization, etc.)

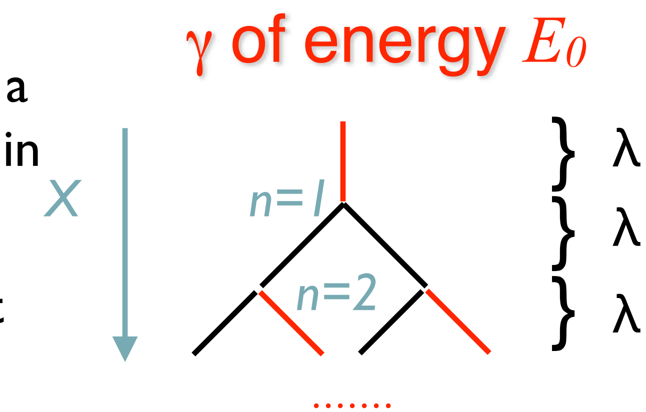


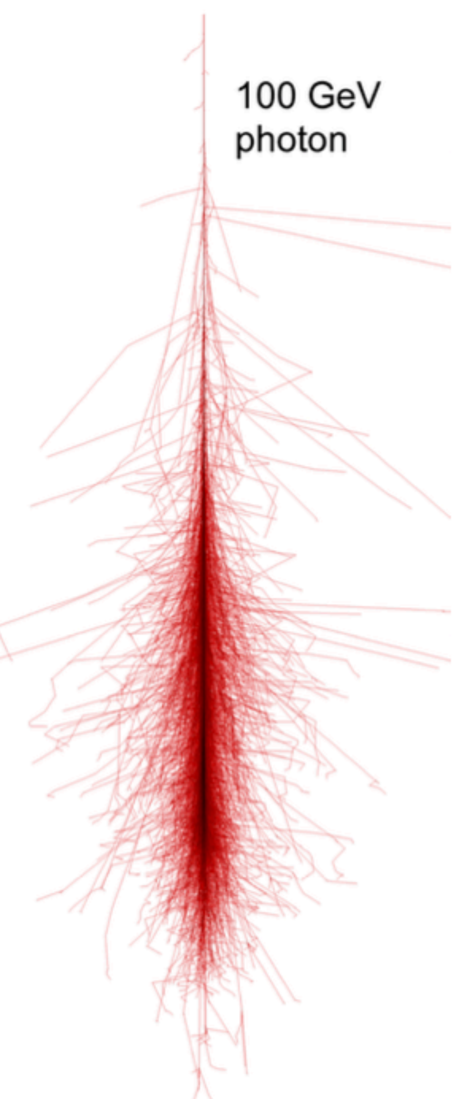
Heitler model for e.m. cascades

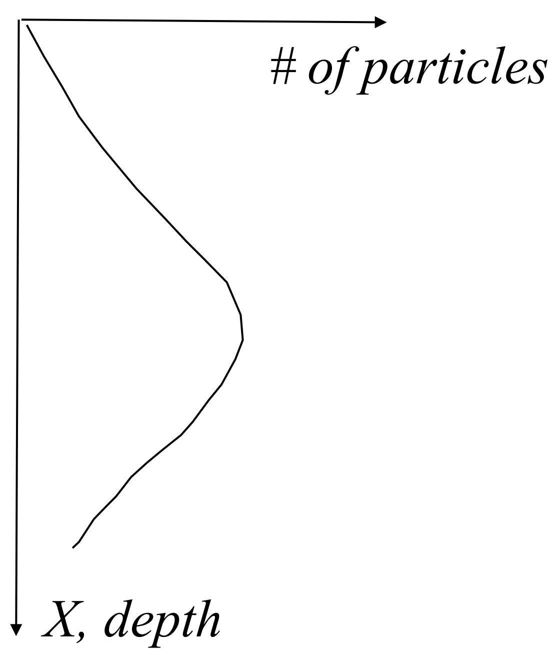
Ind. variable: **grammage** $$X = \int \rho(\ell)\mathrm{d}\ell$$

Assume a primary γ, impinging on the atmosphere, generating a pair after a **characteristic grammage λ (g/cm²);** each lepton in turn generates a γ via bremssthralung after about the same λ.

Critical energy E_c below which particles lose energy without radiating new particles (e.g. ionization, etc.)







2^n particles will be present in the shower after n interactions

$$n = X/\lambda$$
$$N(X) = 2^n = 2^{X/\lambda}$$
$$\langle E \rangle = E_0/2^{X/\lambda}$$

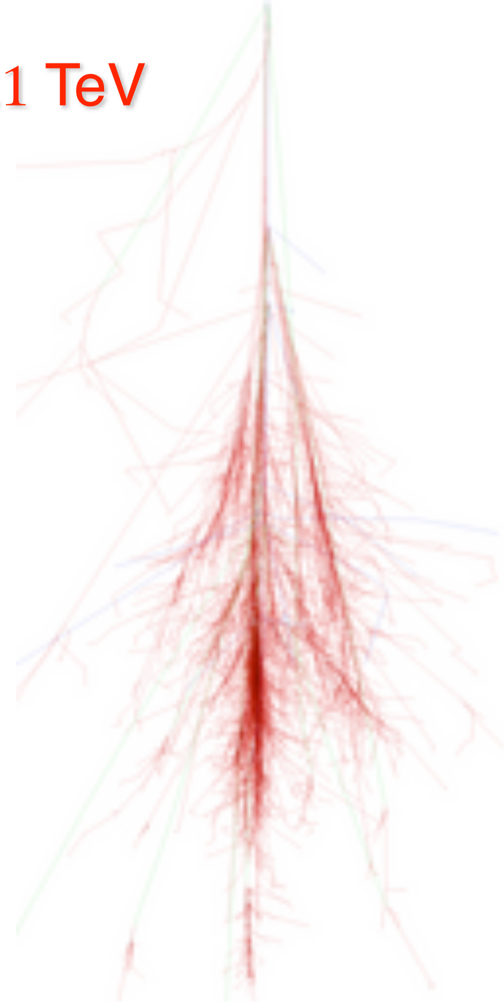
The shower maximum is reached at: $$N_{\max} = E_0/E_c \qquad X_{\max} = \lambda \log_2(E_0/E_c)$$

Since λ≈35 g/cm2 and E_c≈80 MeV are "atmospheric constants" (see PDG, E-losses in matter), once calibrated the method can provide an estimate of primary energy

Hadronic cascades

There are several differences. Even assuming that the only secondary particles produced are pions, one has that

- π^0 decay immediately, starting secondary e.m. cascades.
- $\pi^{\pm}$ initiate new hadronic cascades, until their energy falls below E_d (below which they rather decay than interact), and end-up generating $\mu^{\pm}$ → important diagnostics



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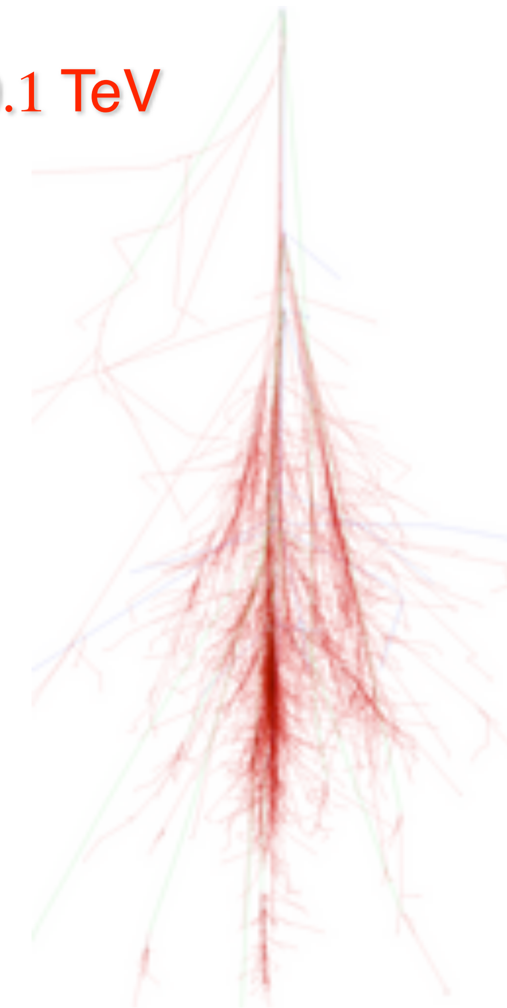
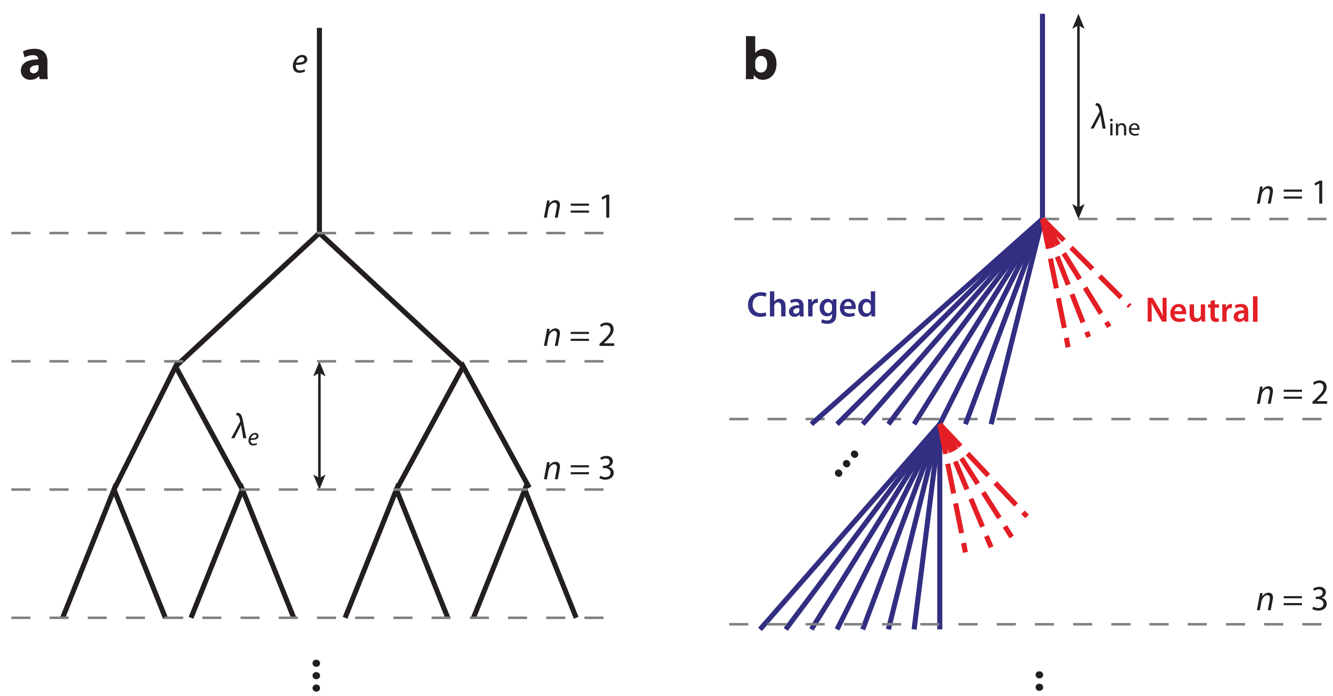
p of 0.1 TeV



assuming "democratic" splitting of E



$$X = n\,\lambda \qquad E_{\rm had} = \left(\frac{2}{3}\right)^n E_0 \qquad E_{\rm em} = \left[1 - \left(\frac{2}{3}\right)^n\right] E_0$$

After a few steps most of energy is in e.m. form (e.g. ~70% at n=3, >90% at n=6)

see e.g. J. Matthews, Astroparticle Physics 22 (2005) 387–397

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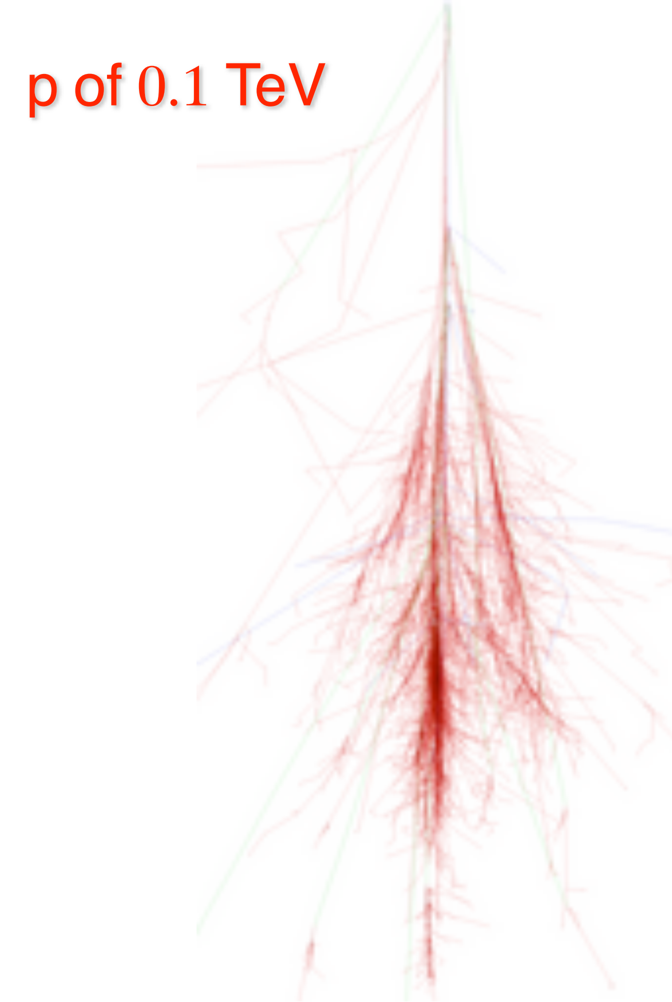


Average energy of charged pions at step n in terms of their multiplicity $\nu_\pm$:

$$\langle E_\pm \rangle (X) = \frac{E_0}{\left(\frac{3}{2}\nu_\pm\right)^n}$$

maximum # reached when average E attains characteristic decay energy E_d:

$$n^\pm_{\max} = \frac{\ln(E_0/E_d)}{\ln(3\,\nu_\pm/2)} \approx 0.85\,\ln(E_0/E_d)$$

$$N_\mu = N_\pm = \nu_\pm^{n^\pm_{\max}}$$

$$\ln N_\mu = n^\pm_{\max} \ln \nu_\pm = \beta \ln(E_0/E_d) \qquad \beta = \frac{\ln \nu_\pm}{\ln(3\nu^\pm/2)} \approx 0.85$$

Can use # muons as proxy for energy!

$$N_\mu = \left(\frac{E_0}{E_D}\right)^{0.85}$$

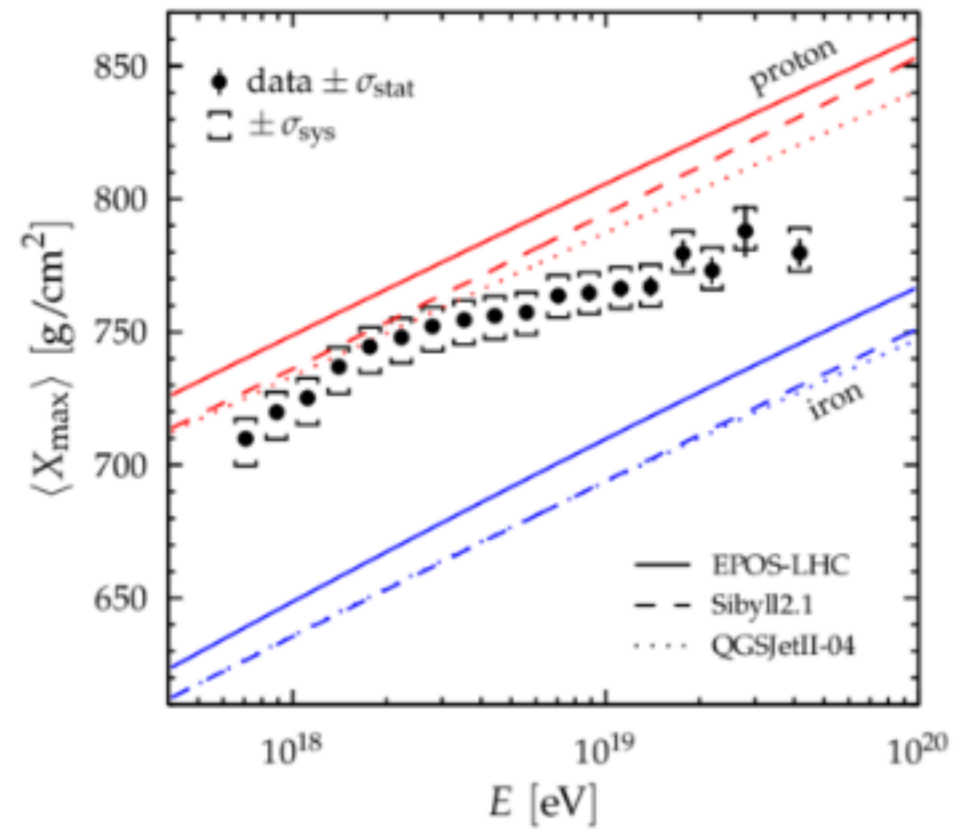
Chemical composition in superposition model

Assumption: a nucleus of mass ***A*** and ***E₀*** acts like ***A*** independent nucleons of energy $E_N = E_0 / A$

$$N_\mu^A = A \left(\frac{E_0/A}{E_d} \right)^\alpha \approx N_\mu^p \, A^{0.15}$$

$$X_{\max}^A = X_{\max}^p - \lambda \ln A$$

$$N_{\max} = A \, E_N / E_c = E_0 / E_c$$



H. Glas, Pierre Auger Observatory

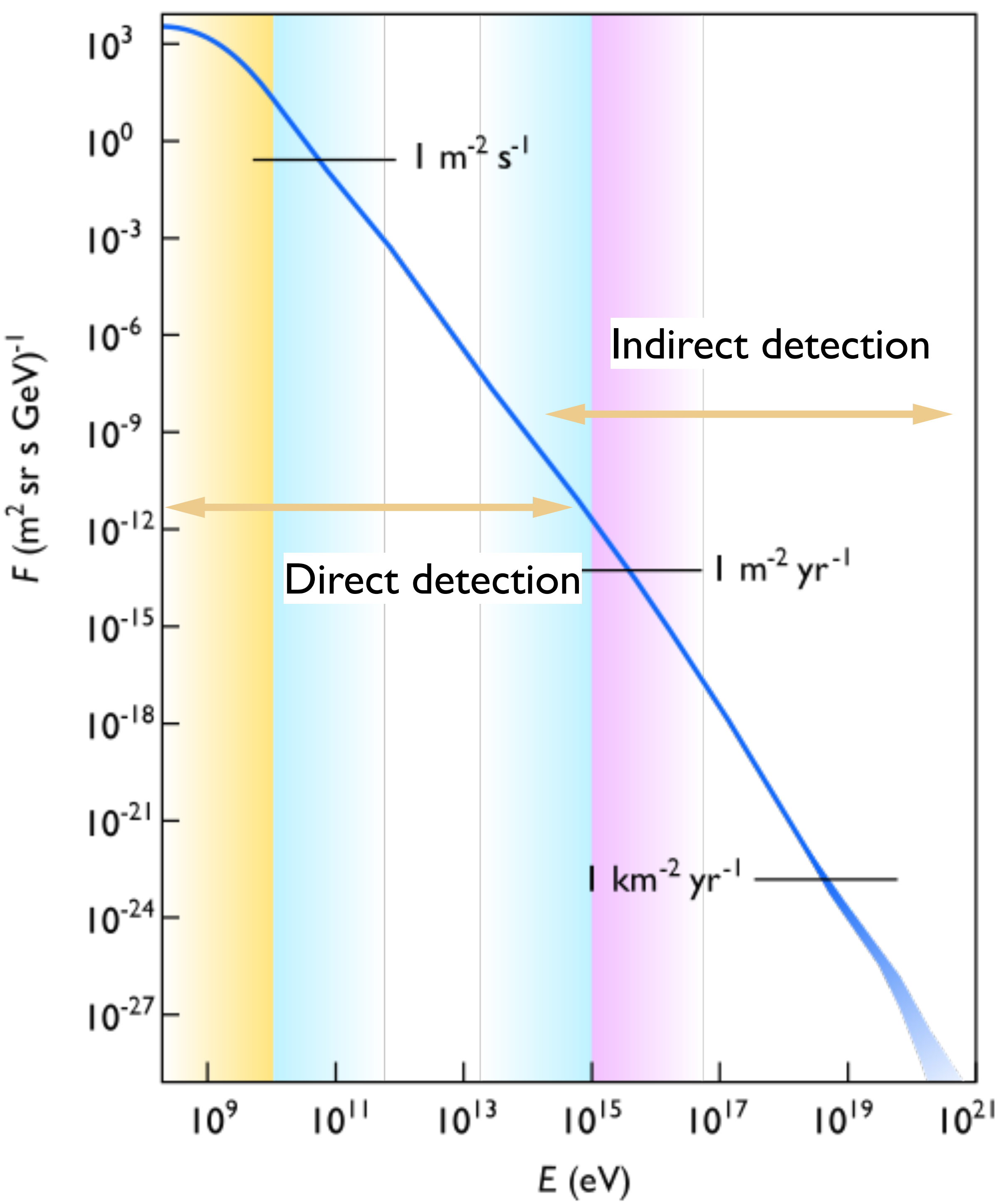
\# particles in the shower proxy of energy
Depth of the maximum (or # muons) as proxy of nuclear mass
(Both average and variance sensitive and used e.g. in PAO)

Quantitative predictions heavily based on simulations, relying on extrapolations of "shaky" models (non-perturbative QCD regime!), not based on first principles

Tackling *directly* the CR problem

How to tackle the century-old CR problems*?

**Where do they come from? How are they produced/accelerated?*



- main problem: charged particles are deflected while propagating in the magnetized ISM: they do not track back to their sources! How to identify them?

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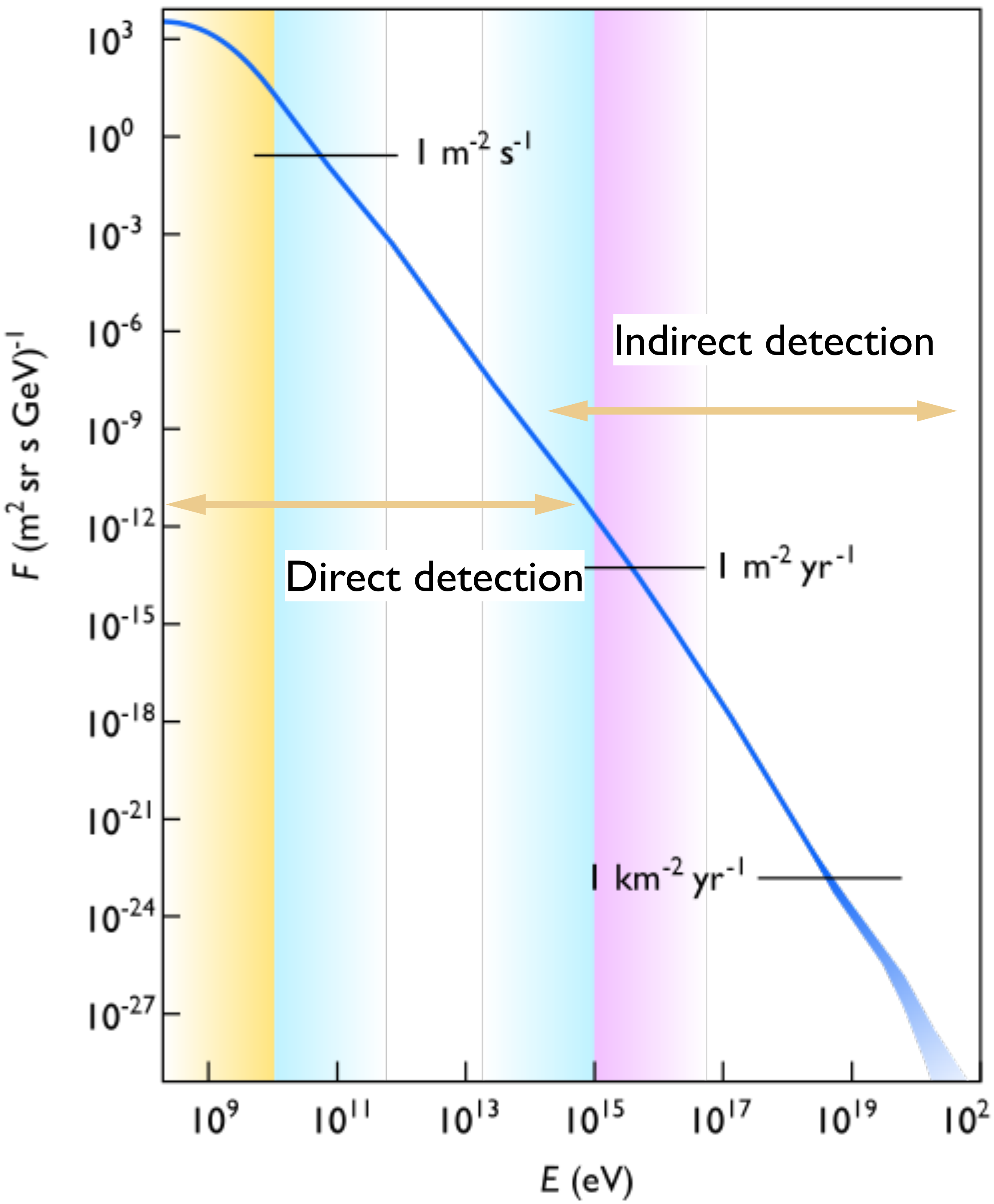

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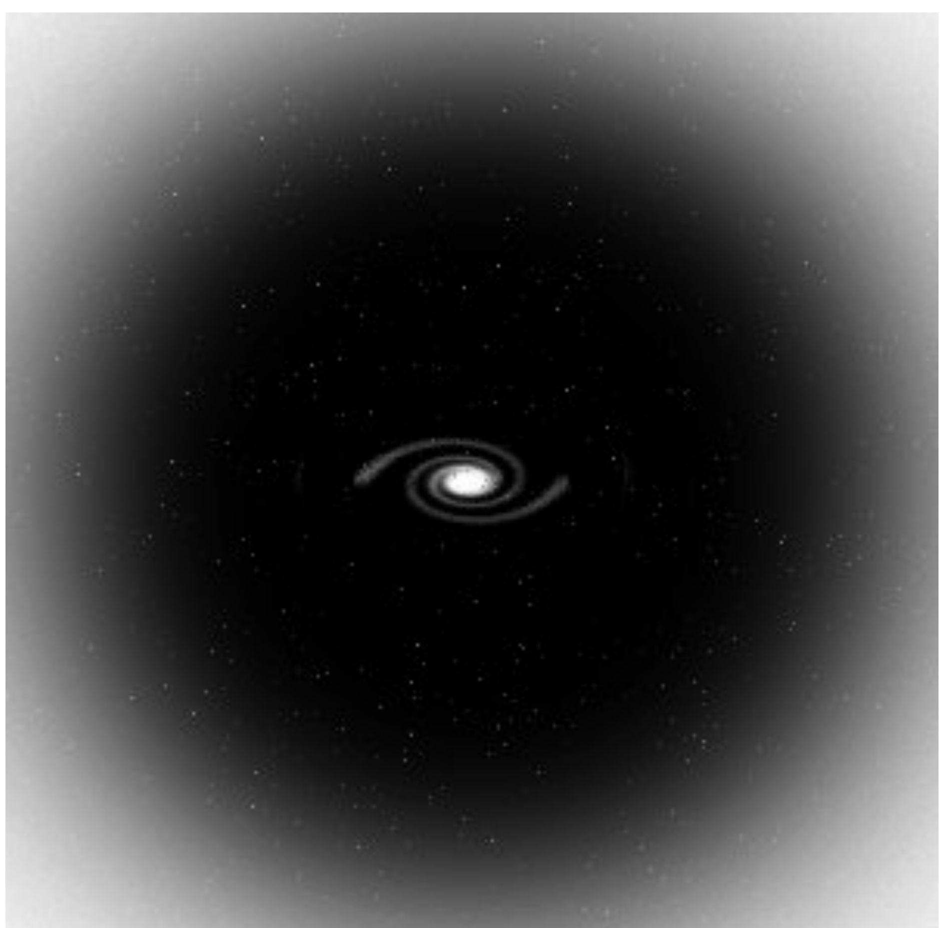
Possible strategies:

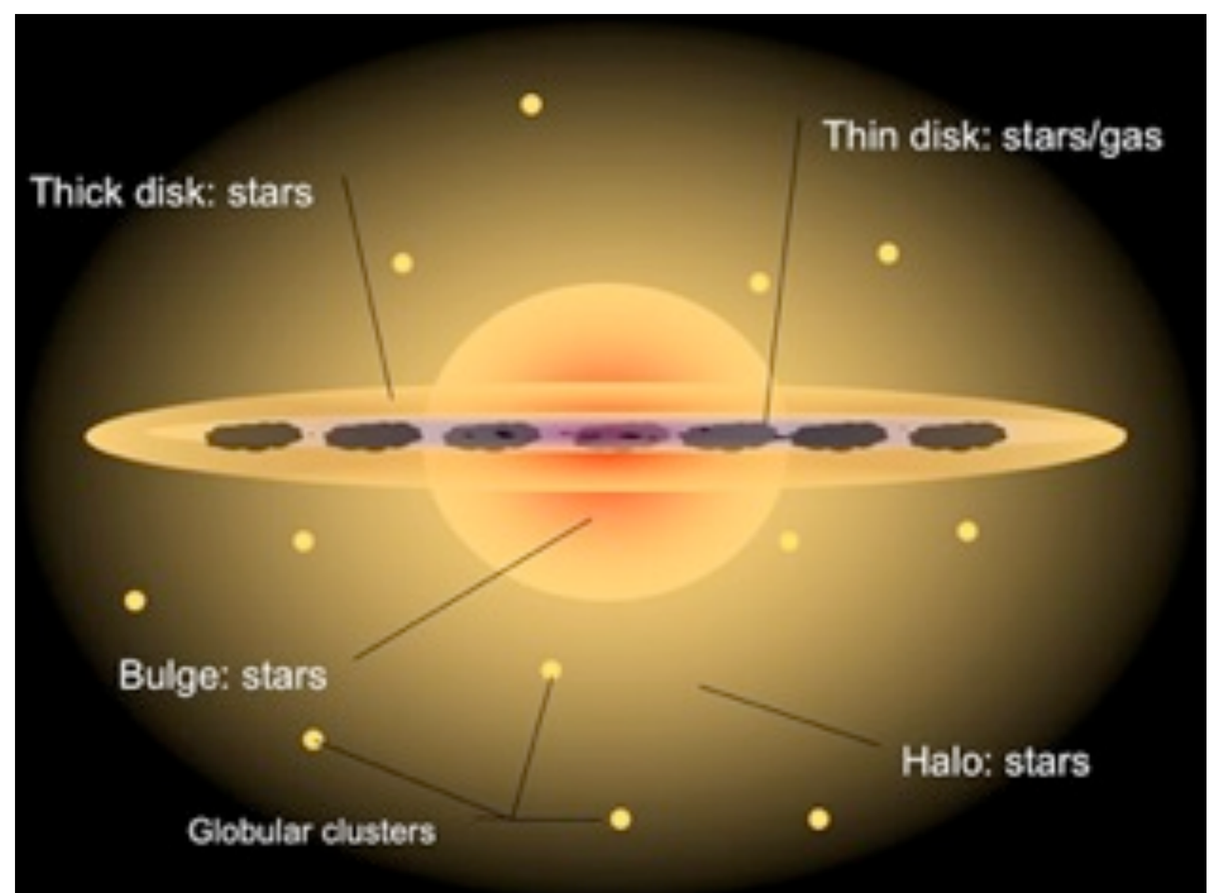
- Compare CR observed at Earth with model predictions accounting for production and propagation of CRs
- Try to identify the source processes via the photons (& ν's) emitted by the CR E-losses in/near the sources
- Go to energies high enough... that their deflections are small enough (UHECR astronomy?)

Familiarising with the Galactic environment

3 constituents, ISM / Stars / Dark Matter with mass ratios ~ 1/10/100
Gas (ISM): collisional (processes exist exchanging E, ang. Momentum…)
Stars: 10^7-10^{14}, collisionless but feedback on ISM (winds, SN expl., etc.)
Dark Matter: collisionless "gas"(of WIMPs?) supported by v-dispersion

~75% H,
~25% He
~1-2% Z>2





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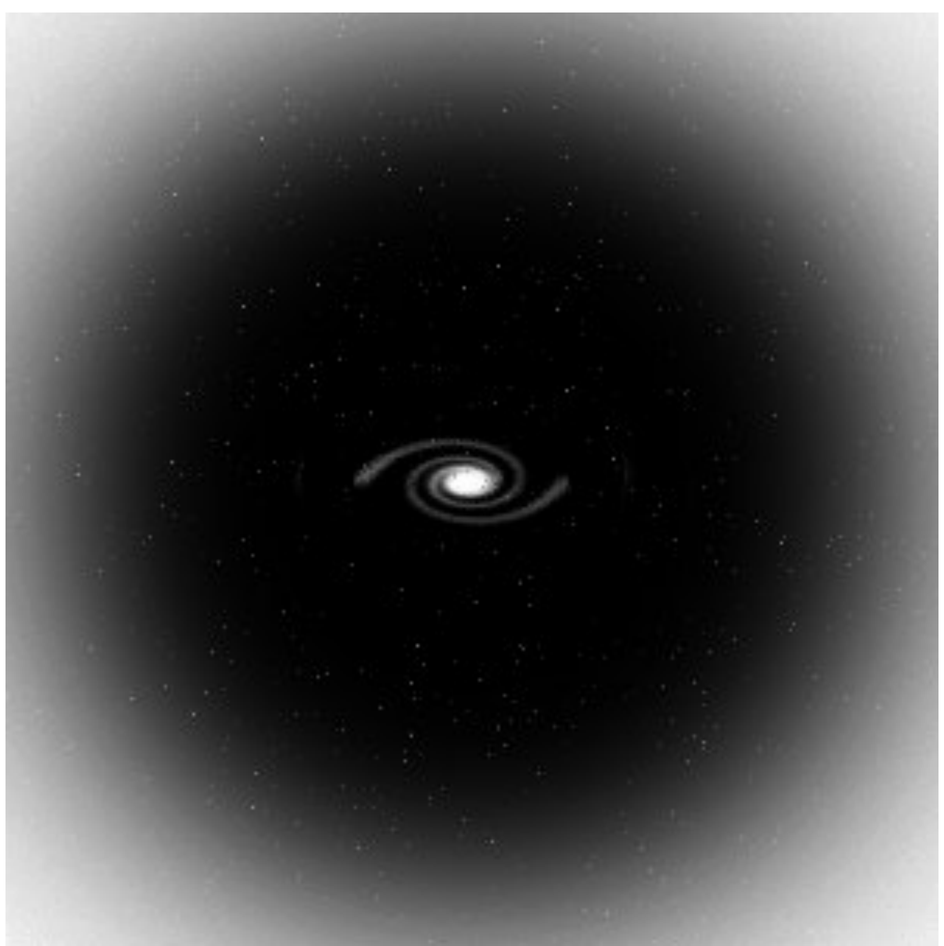
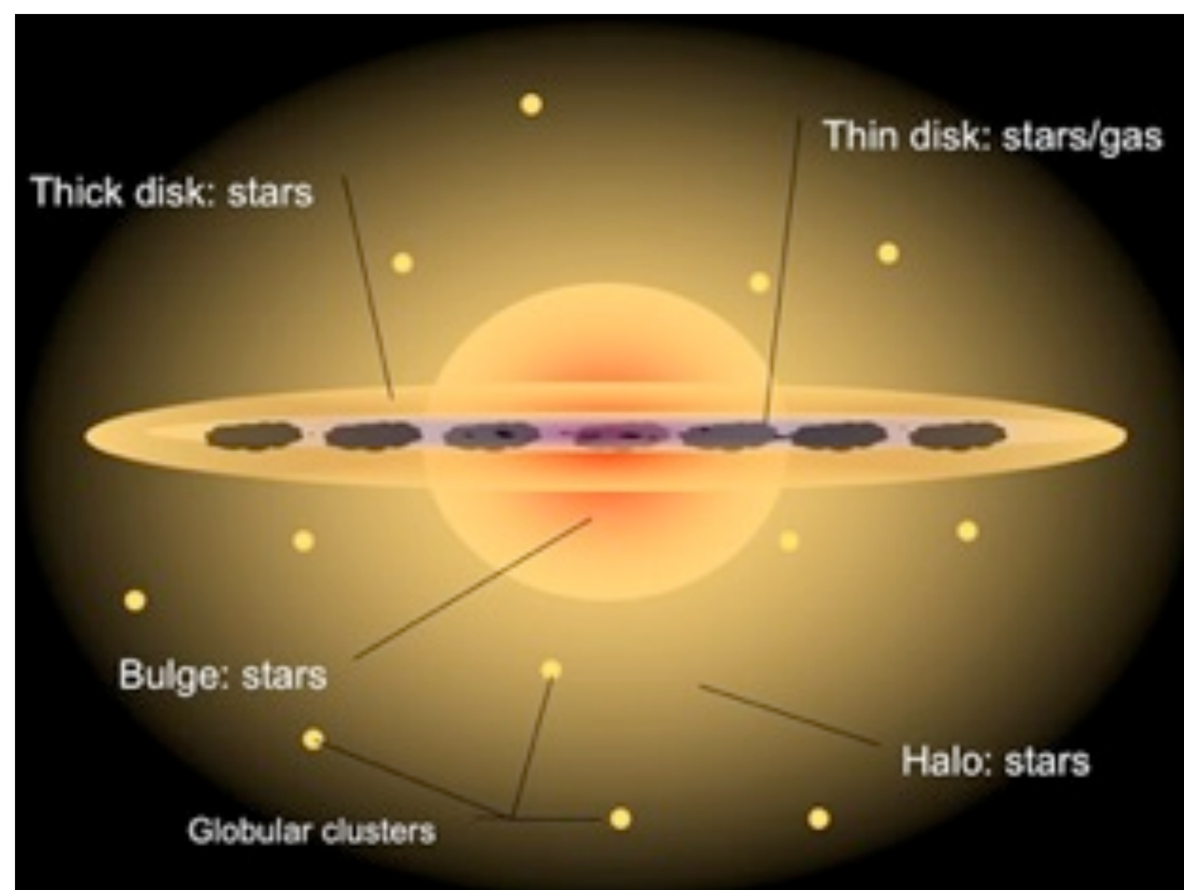
Several components, with varying prominence depending on galaxy type
Nucleus: dense; star formation; supermassive black hole; non-th. activity
Bulge: spheroidal; relatively old; large v-dispersion & little rotation
Disk: gas & stars; younger; spiral arms & star formation; low σ_v , but rotates
Halo: low density; Globular clusters present; old; DM dominates (far from center…)





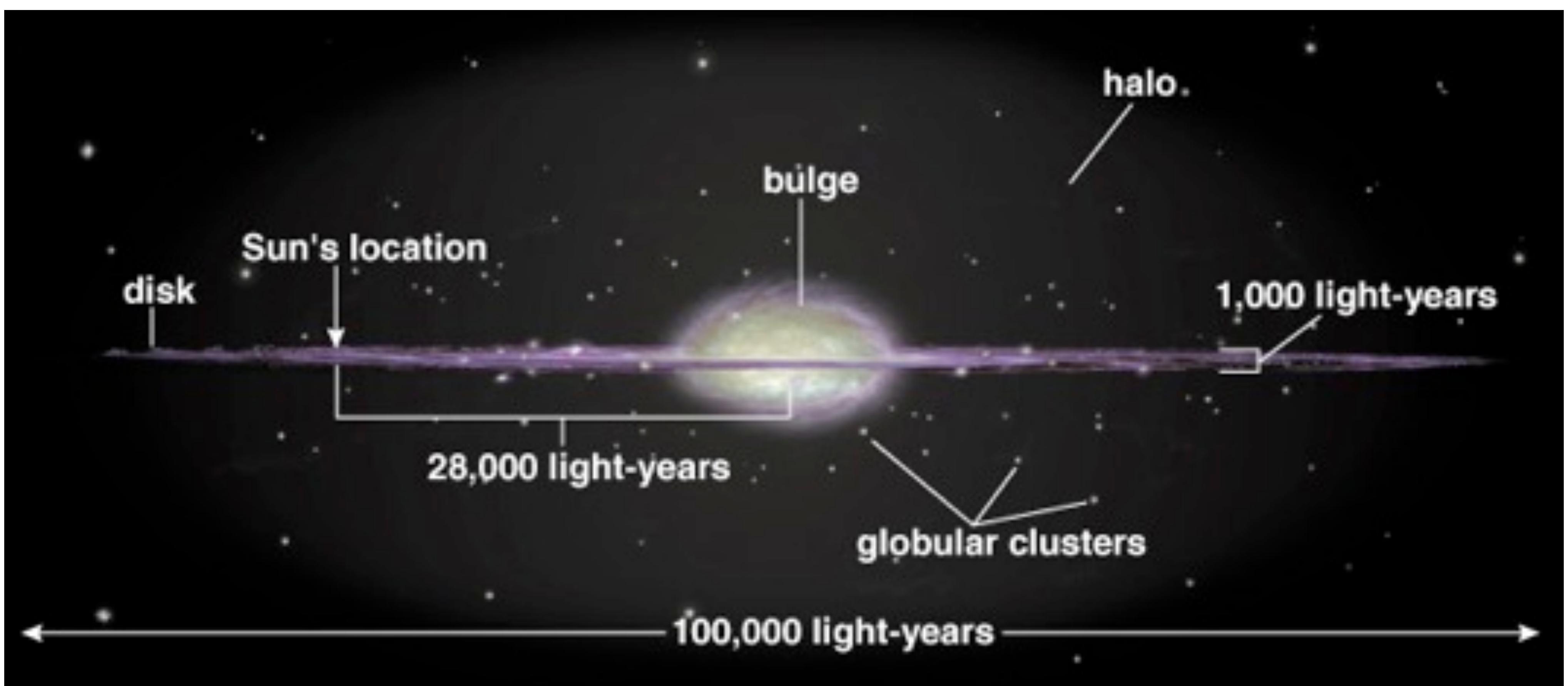
Typical parameters for Milky Way

radius of disk = 50000 l.y. (~15 kpc)

thickness of disk = 1000 l.y. (~300 pc)

number of stars > 200 billion

The Sun is in disk, 30000 l.y. from center (~8 kpc)



Interstellar medium

- It is the low-density "stuff" between the stars (~ 1 atom cm^{-3}).

- It is composed of 90% gas and 10% dust.
  - gas: individual atoms and molecules
  - dust: large grains made of heavier elements

- The ISM effectively absorbs or scatters visible light!
  - it masks most of the Milky Way Galaxy from us

- Radio & infrared light does pass through the ISM.
  - we can study and map the Milk Way Galaxy by making observations at these wavelengths (e.g. 21 cm line)

- There is also an ISR field, made of light (UV, visible, Infrared) with typical overall energy density of ~O(1) eV/cm^3

- Furthermore, the medium is magnetized, with a field of strength of a few μ-Gauss. Magnetization in (molecular) clouds can be much higher

K. M. Ferriere, "The Interstellar Environment of our Galaxy," Rev. Mod. Phys.73, 1031 (2001) [arXiv:astro-ph/0106359].