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Astroparticle physics

Roberto A. Lineros

Departamento de Física, Universidad Católica del Norte

Winter School HEP-PUC 2019 "Topics on Gravitículas"

The Plan

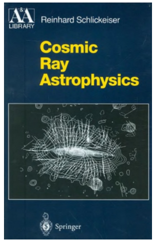
1. Astroparticles
2. Cosmic-rays
3. Neutrinos
4. Gamma-rays
5. Gravitational Waves

Dark Matter

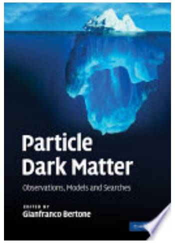
Astrophysical Sources

The Basics

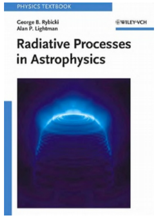
Bibliography



Cosmic ray astrophysics
R. Schlickeiser
http://link.springer.com/book/10.1007/978-3-662-04814-6



Particle Dark Matter: Observations, Models and Searches
G. Bertone
https://www.cambridge.org/cl/academic/subjects/physics/cosmology-relativity-and-gravitation/particle-dark-matter-observations-models-and-searches



Radiative processes in astrophysics
G. B. Rybicki, A. P. Lightman
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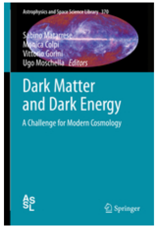

Dark Matter and Dark Energy: A Challenge for Modern Cosmology
Matarrese, S, et al.
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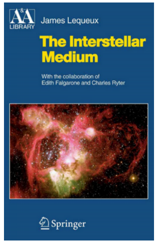

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J. Lequeux
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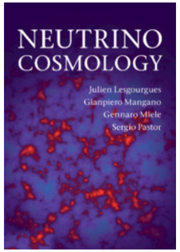
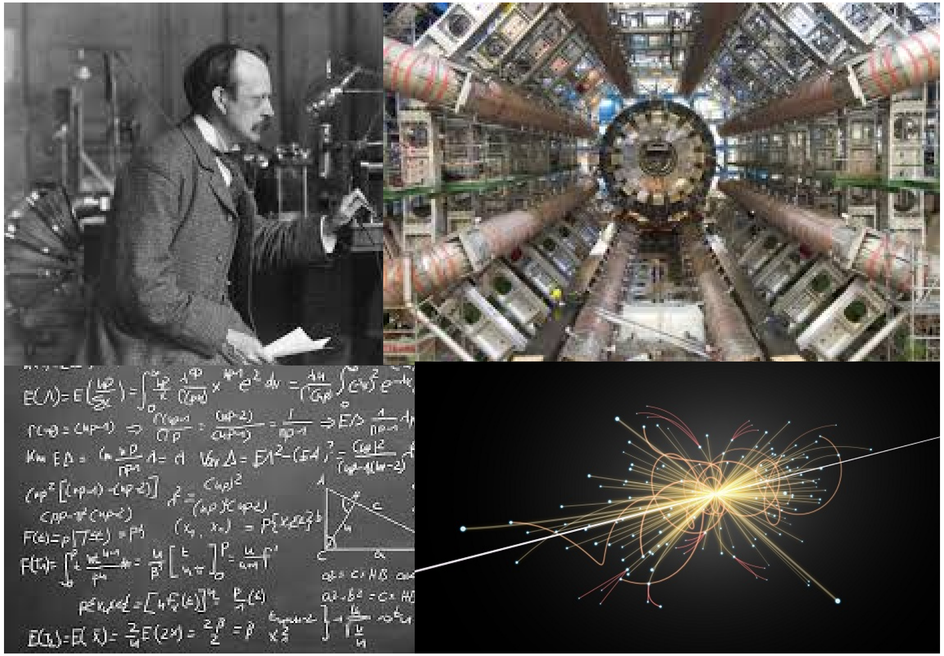


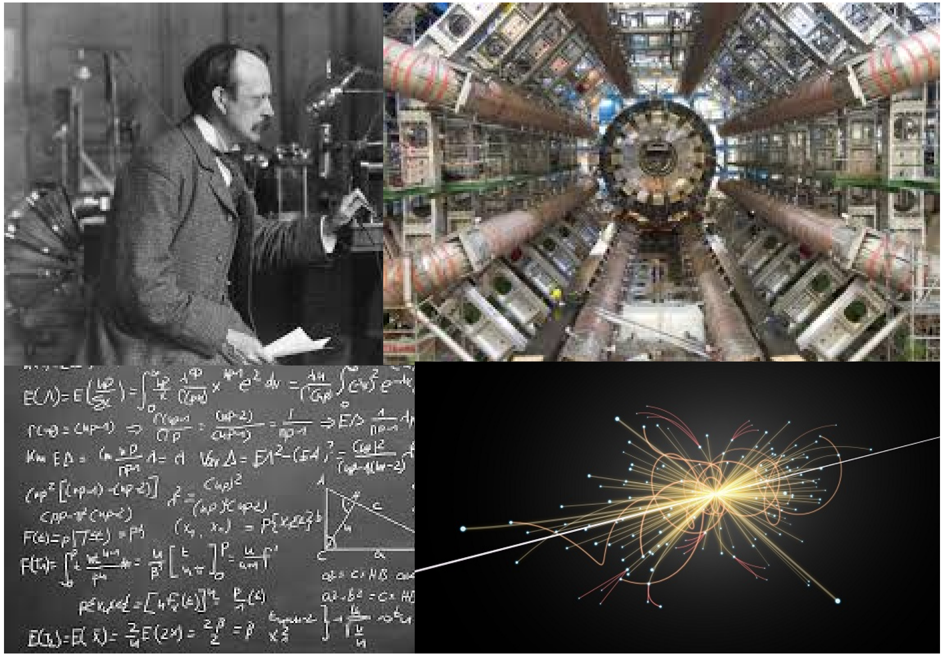
Neutrino Cosmology
Lesgourges et al.
https://www.cambridge.org/core/books/neutrino-cosmology/44AF52C5F02A1943850F3B239B2F9588

Astroparticle as research area



It is an emergent research area at the frontier of many fields

Astroparticle as research area



Astrophysics and Astronomy + Cosmology + Particle and Nuclear physics

Astroparticle as research area

Future scientists with interests in:

- Astronomy and Astrophysics
- Particle physics
- Mathematical physics
- Numerical simulations
- Cosmology and Gravity
- Data Analysis and Statistics
- Data Visualization
- Cosmic ray physics

… are welcome

Astroparticle as research area

Future scientists with interests in:

- Astronomy and Astrophysics
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- Cosmic ray physics

+ soft skills

Astroparticle as research area

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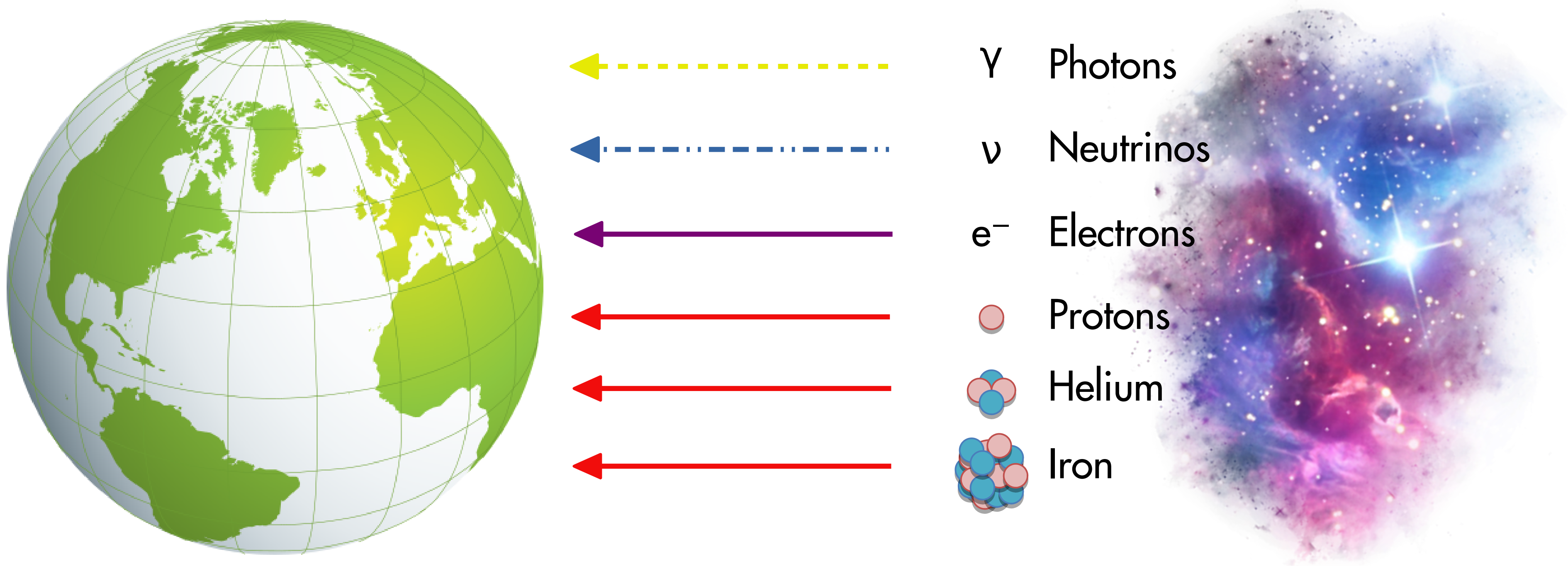
+ soft skills

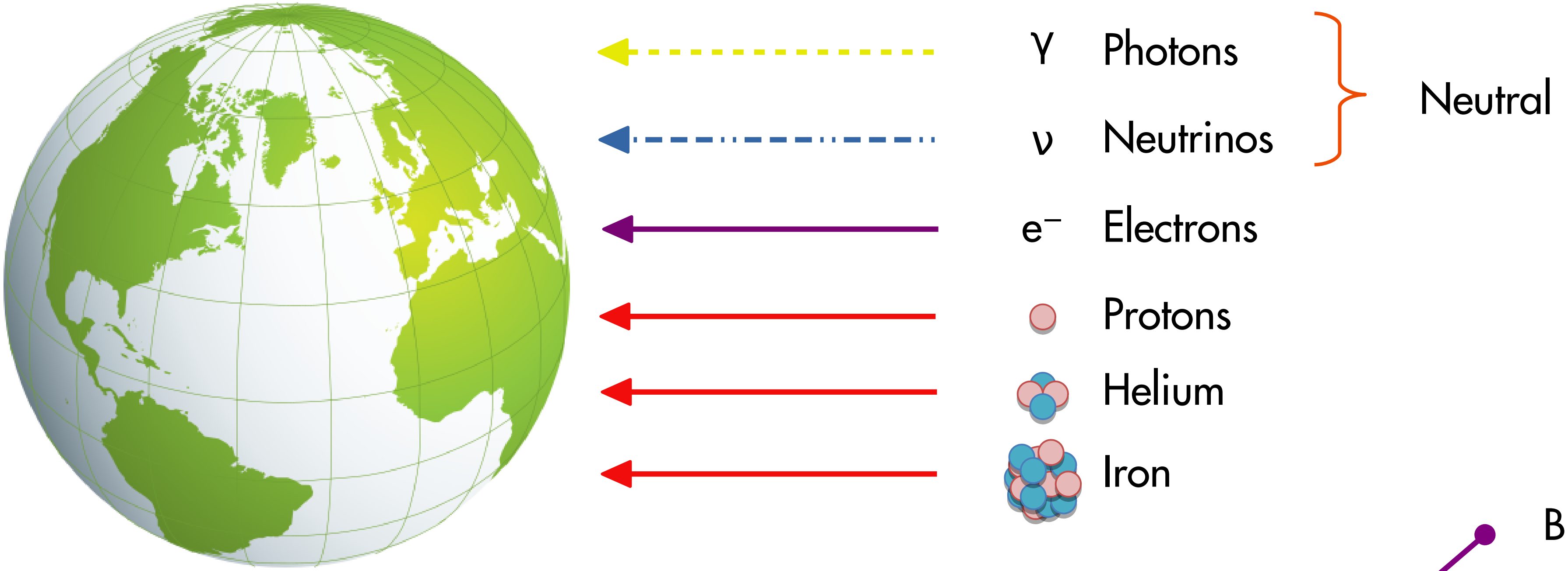
No scientist research alone

Particles from outer space

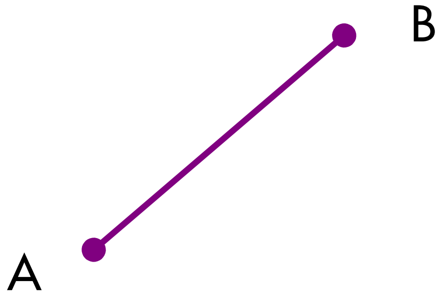


The atmosphere is constantly bombarded with particles originated outside the Solar System

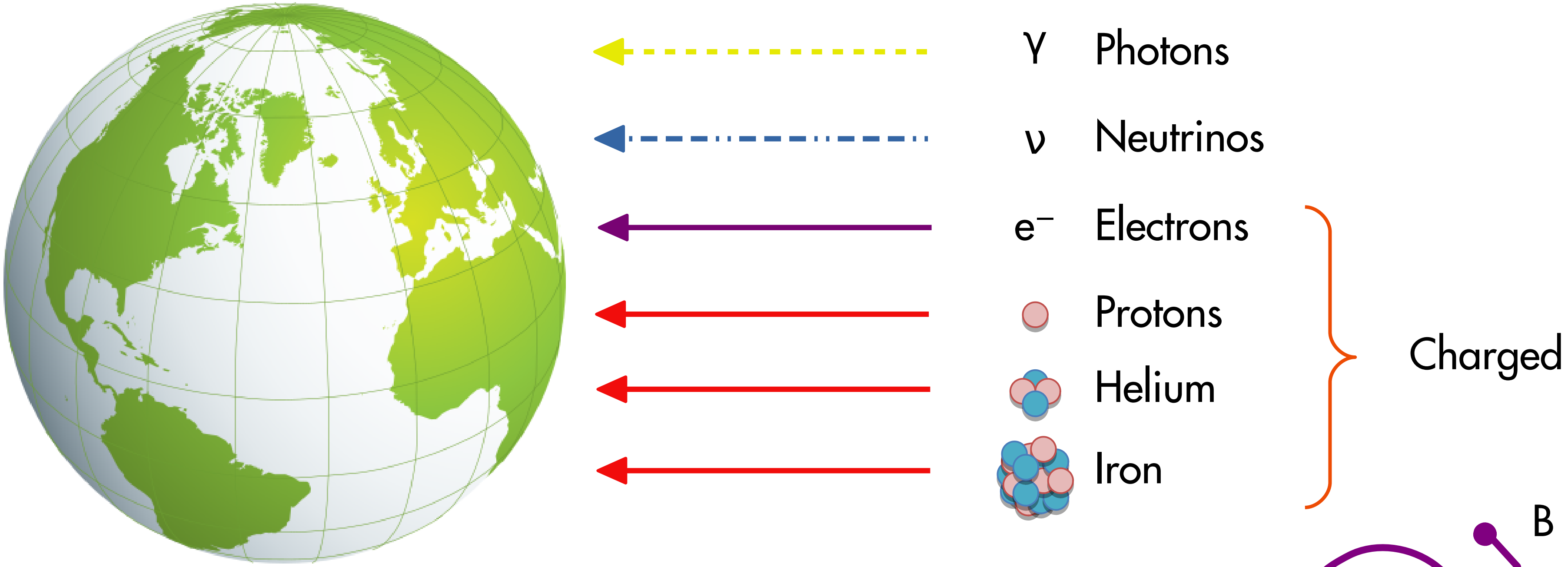
Particles from outer space



Neutral particles propagates in a straight line

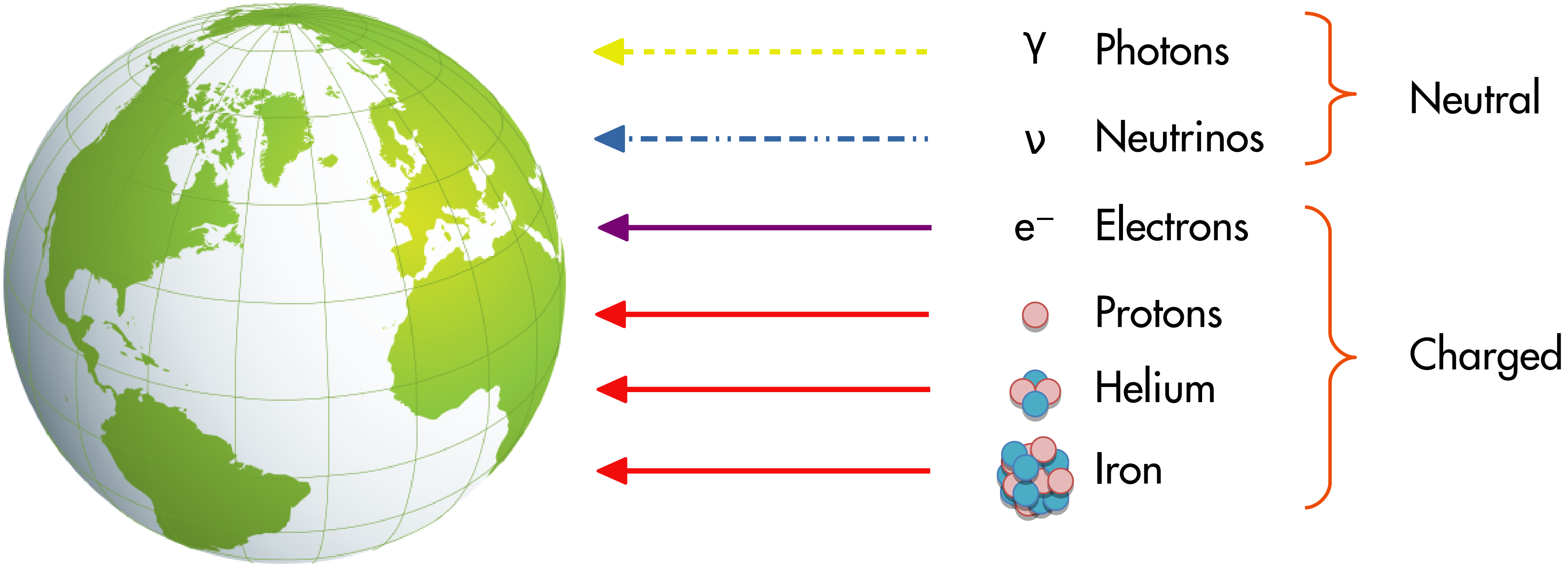


Particles from outer space



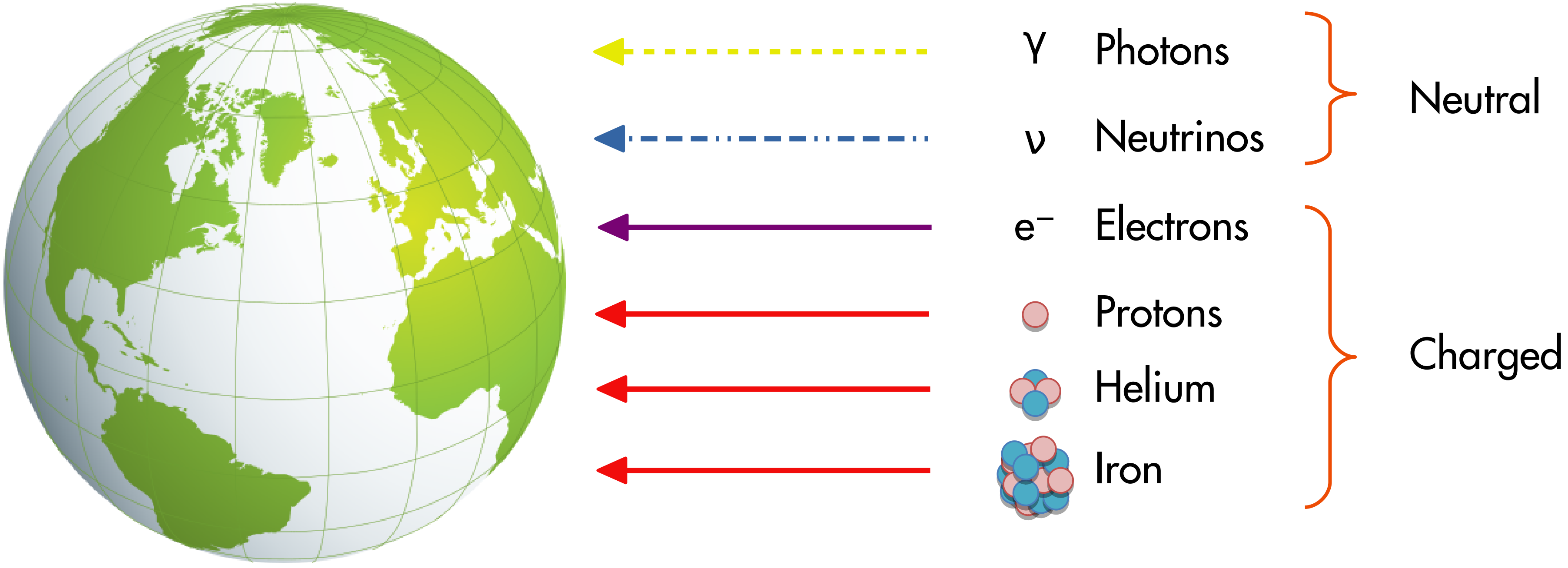
Charged particle are deflected mainly due to electromagnetic interactions

Particles from outer space



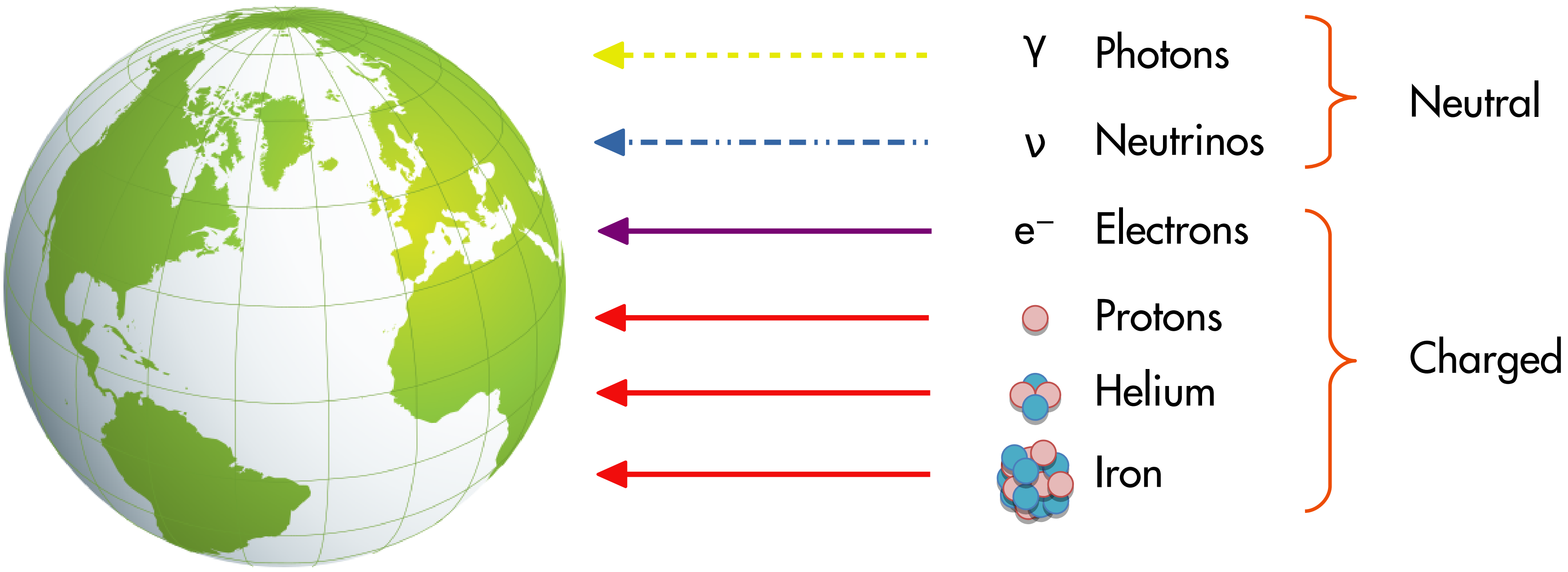
Notice that each type of particles propagate differently

Particles from outer space



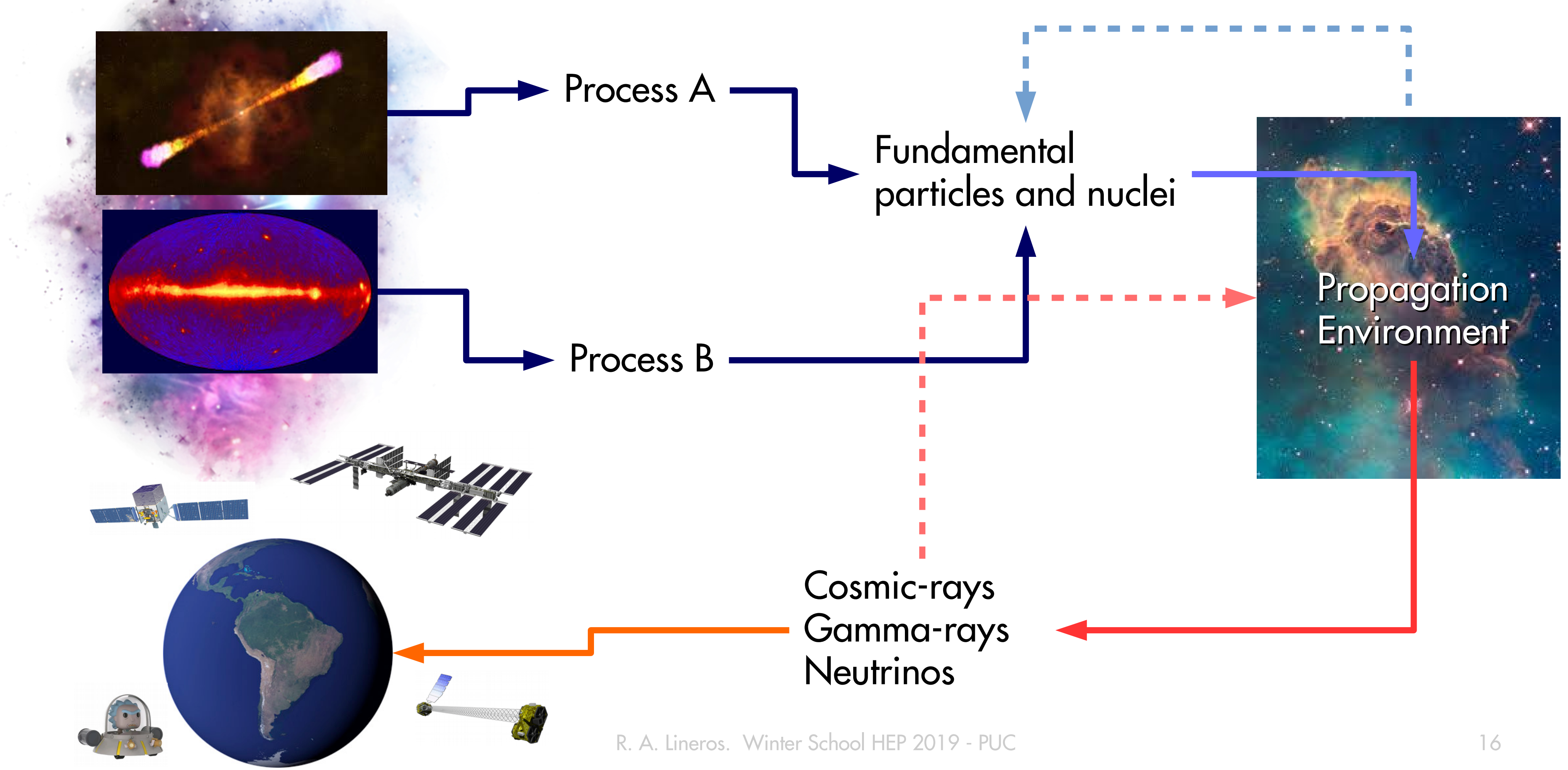
All of these astroparticles help us to study:
sources, interstellar medium, (extra) galactic magnetic fields, etc.

Particles from outer space



Astroparticles = Multimessenger and Multiwavelength

Multimessengers

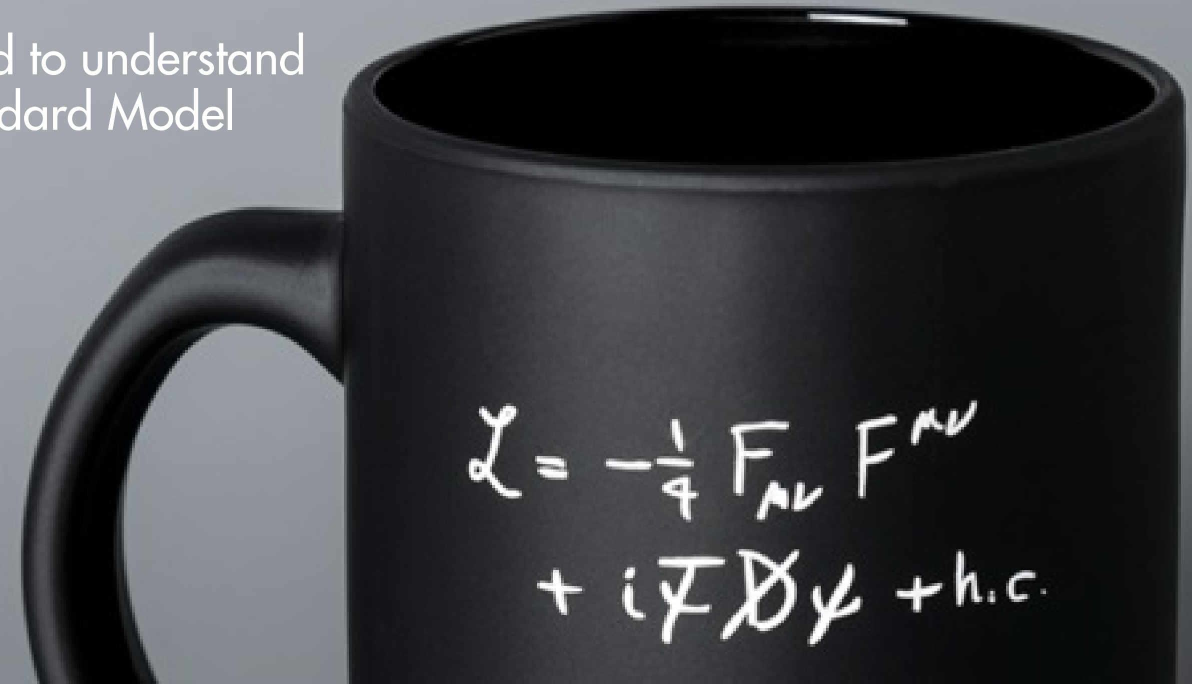


The Physics

The building blocks

The physics of production and propagation of astroparticles requires to understand how particles behave.

We need to understand the Standard Model



The building blocks

The physics of production and propagation of astroparticles requires to understand how particles behave.

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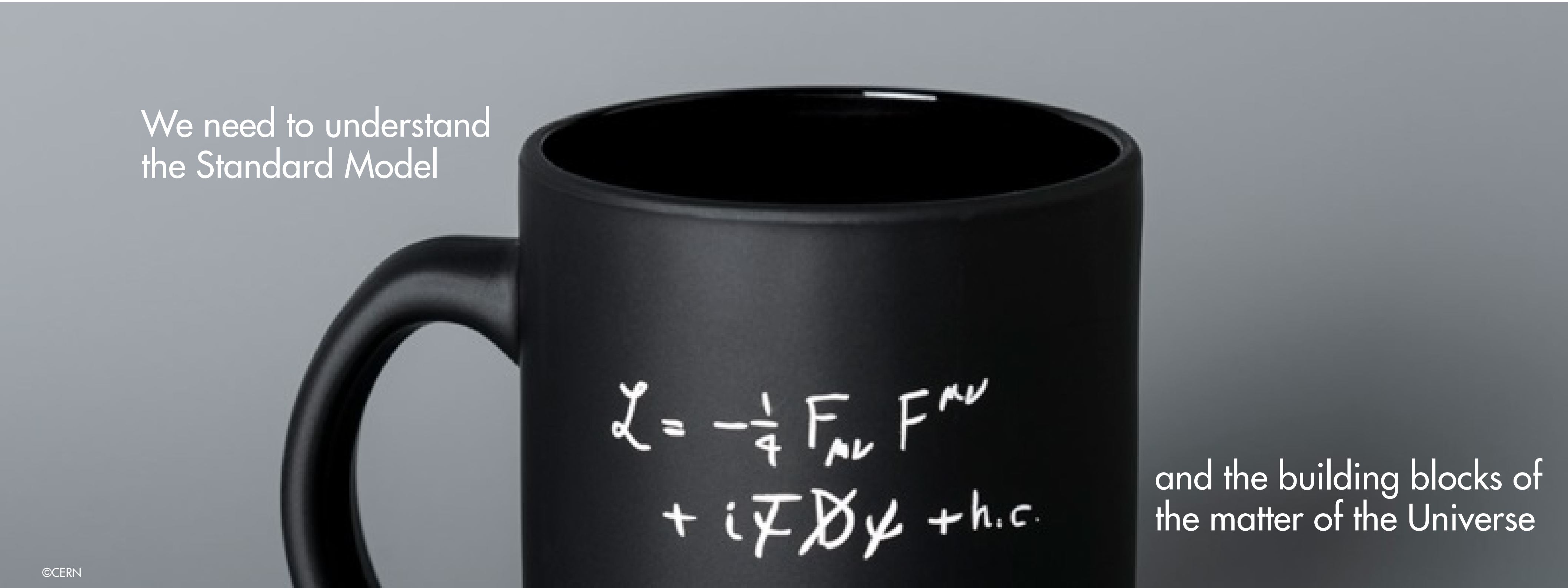


and the building blocks of the matter of the Universe

The Standard Model

SM matter families

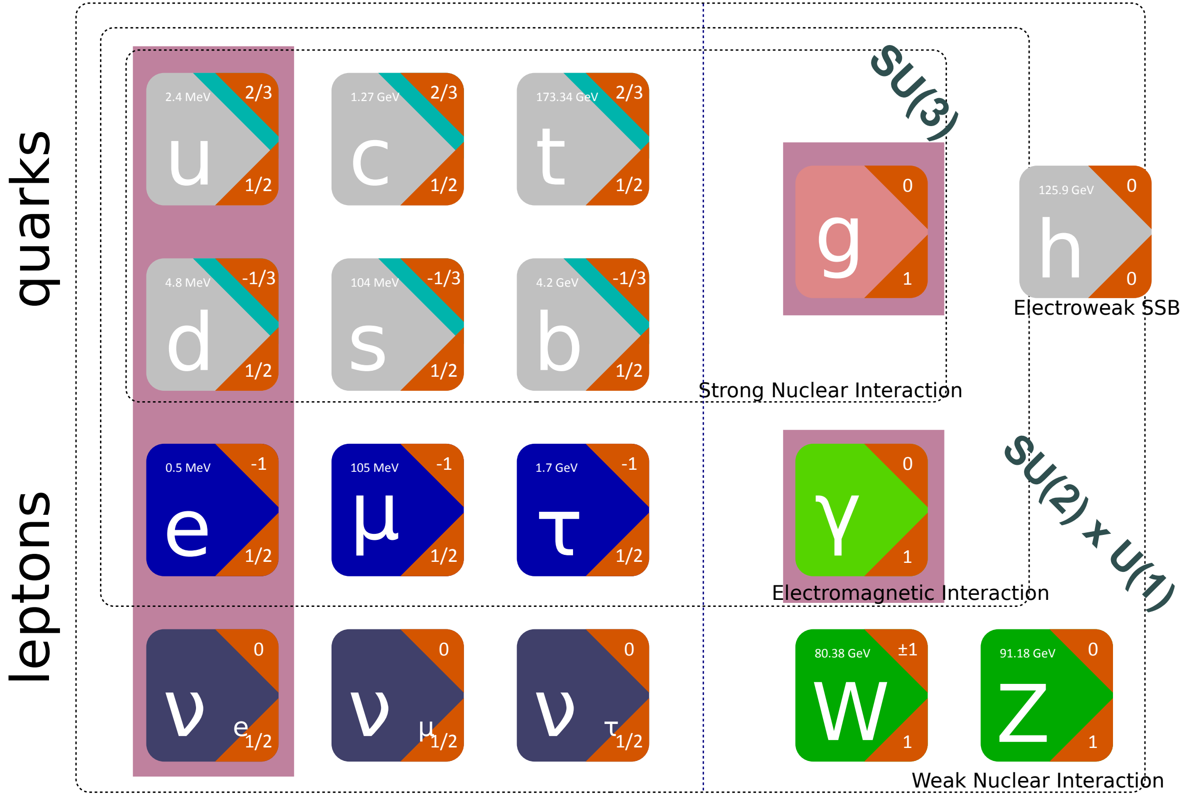
Symmetries
- CPT
- $SU(3)_c$: Color
- $SU(2)_L$: Isospin
- $U(1)_y$: Hypercharge

Matter content
- 3 families quarks
- 3 families leptons

Higgs fields
- $SU(2)_L x U(1)_y \rightarrow U(1)_{EM}$
- Mass to fundamental particles

The Standard Model

SM matter families



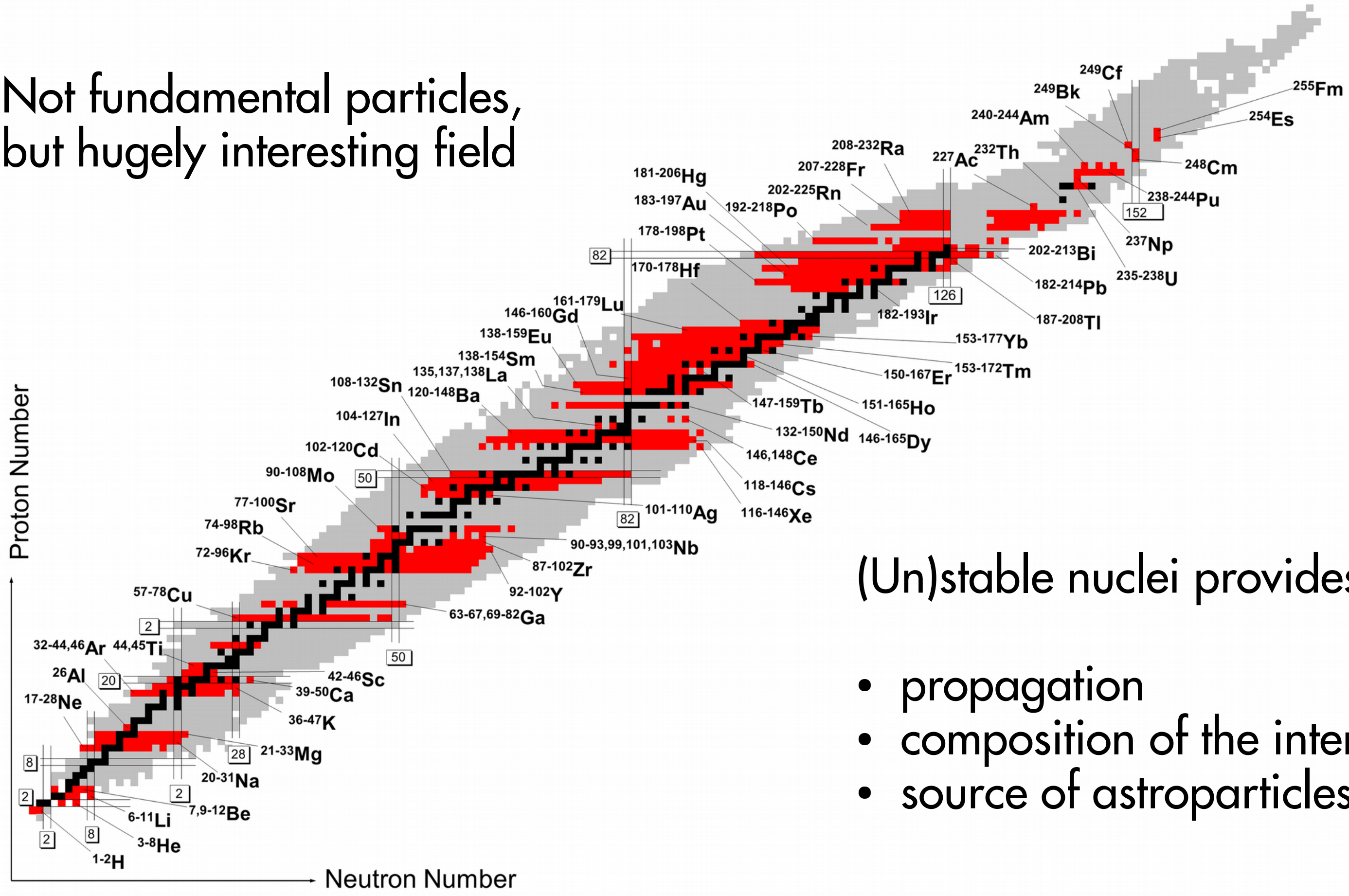
- Massless neutrinos
- Baryon Number
- Lepton Number

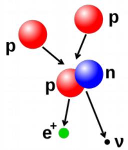
Stable objects:

- Photons
- Electrons, Neutrinos
- Protons (quarks bound states)
- Nuclear matter
- Atoms
- Etc.

Nuclear physics

Not fundamental particles,
but hugely interesting field



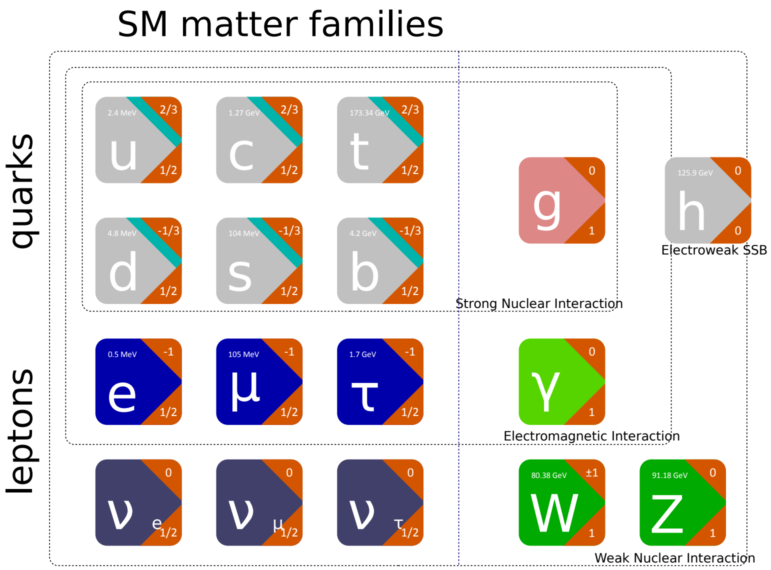


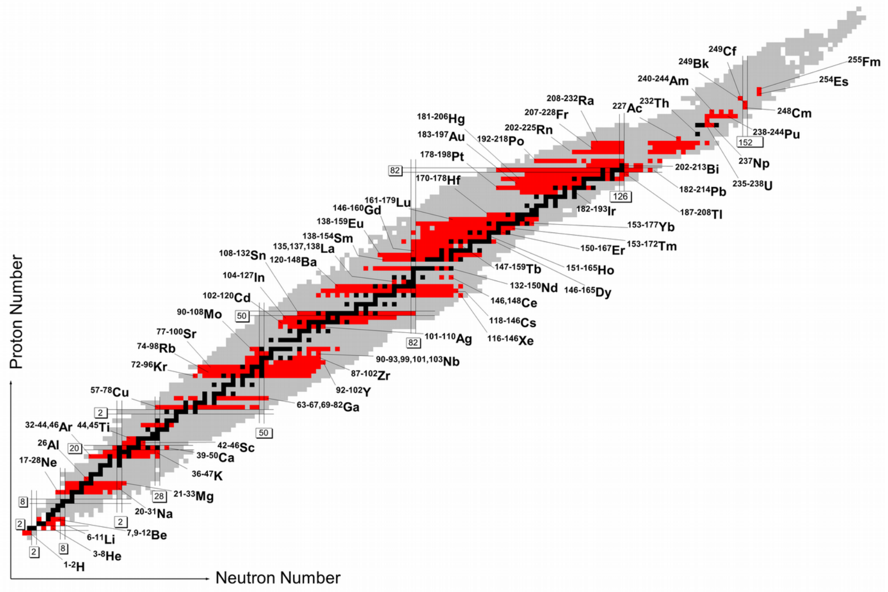
Nucleosynthesis

(Un)stable nuclei provides information about

- propagation
- composition of the interstellar medium
- source of astroparticles

Great success!



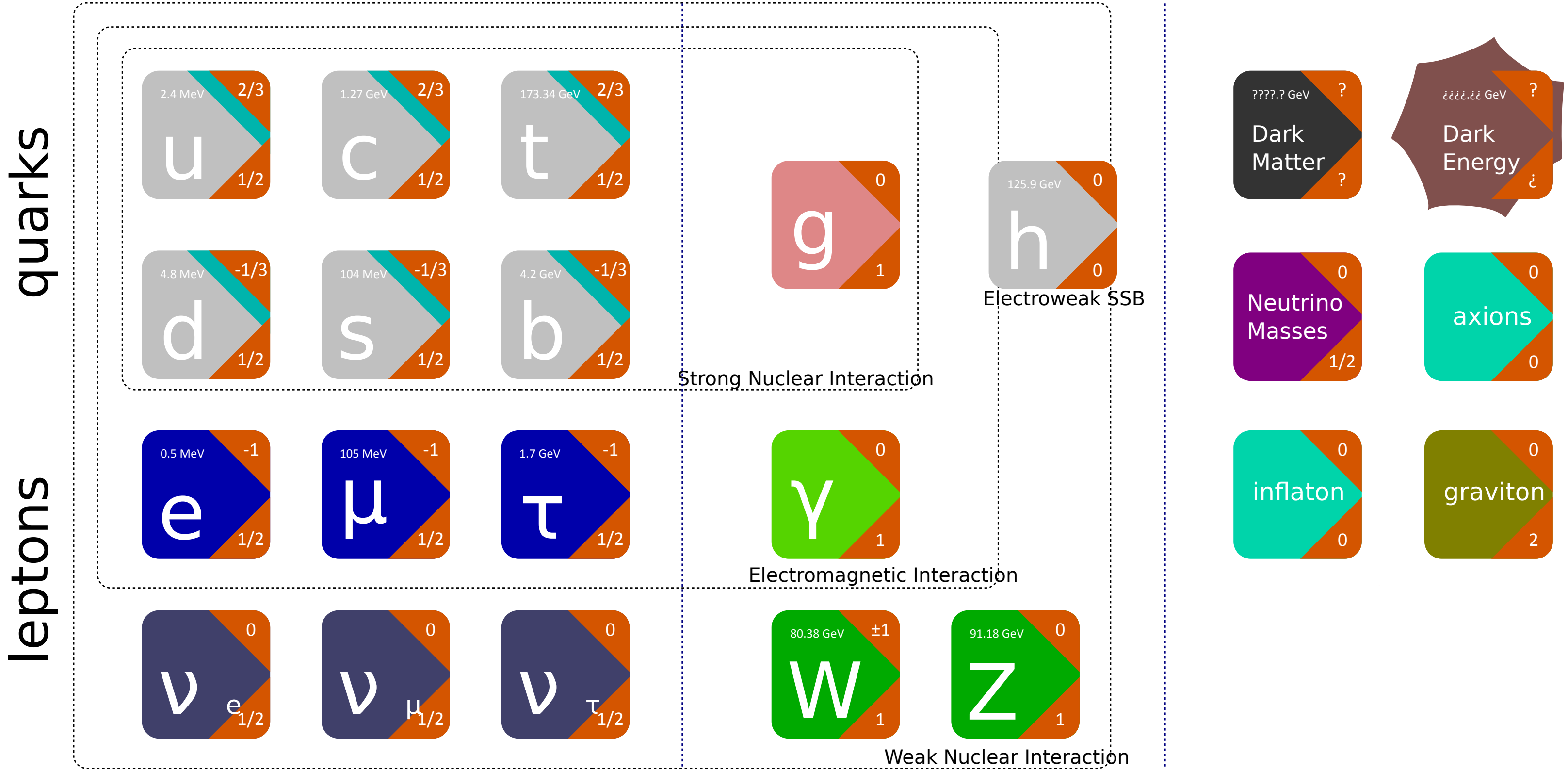


Great description of the smallest components of the Universe and backed up by observations

Not everything is explained

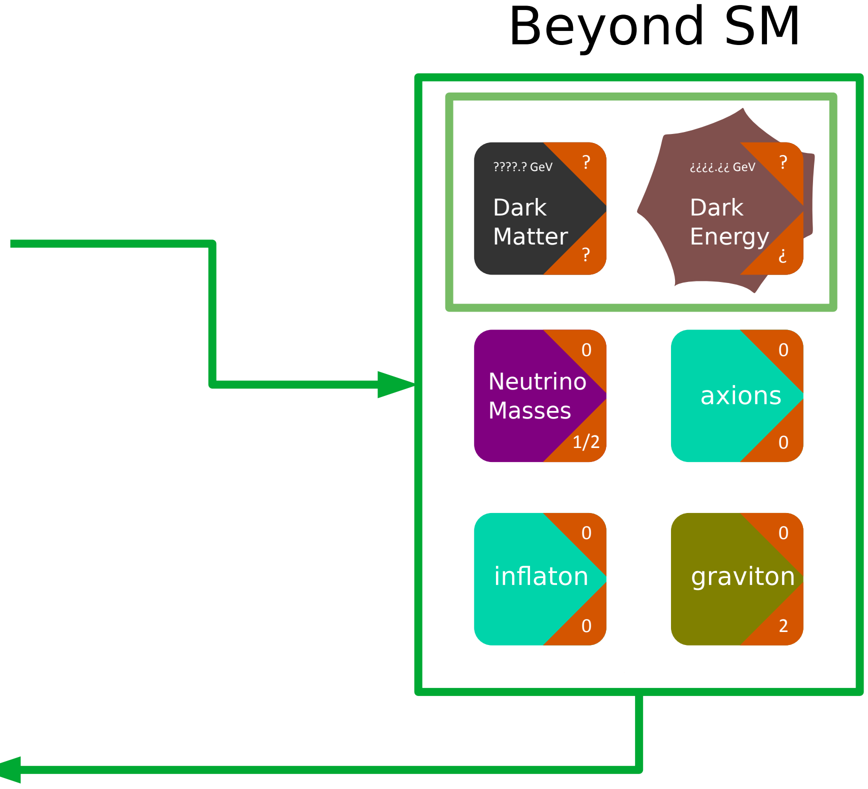
SM matter families

Beyond SM



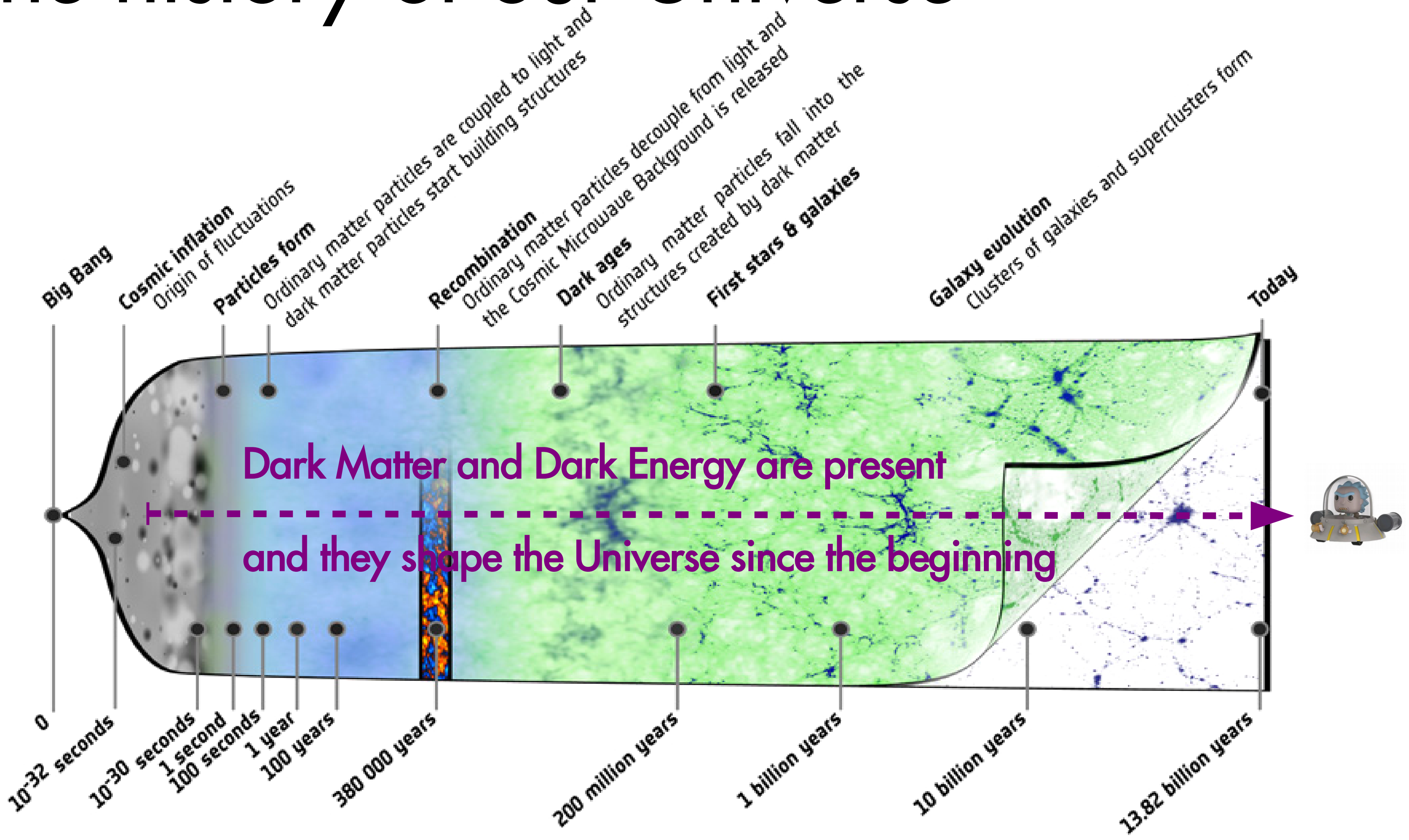
Not everything is explained

Cosmology and Particle Physics

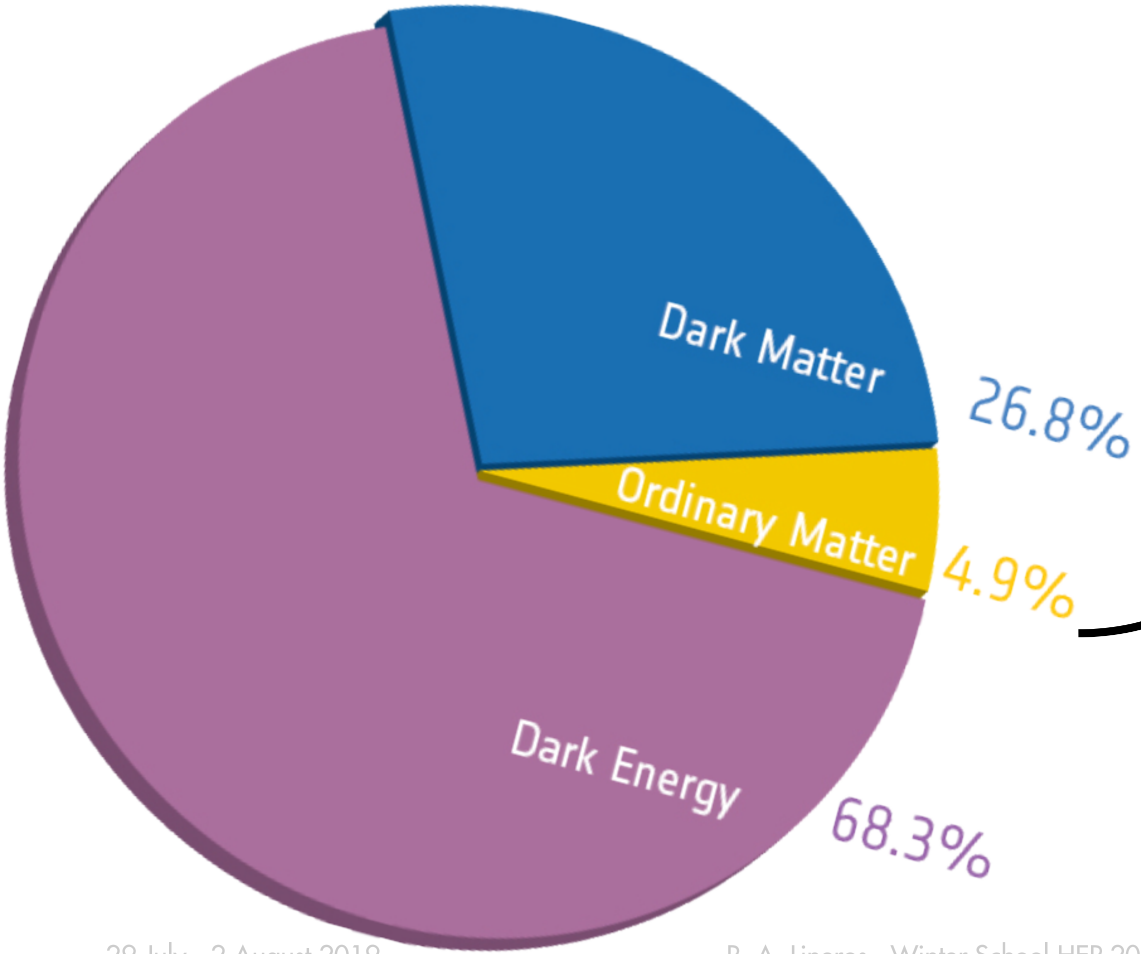


Astroparticles

The history of our Universe

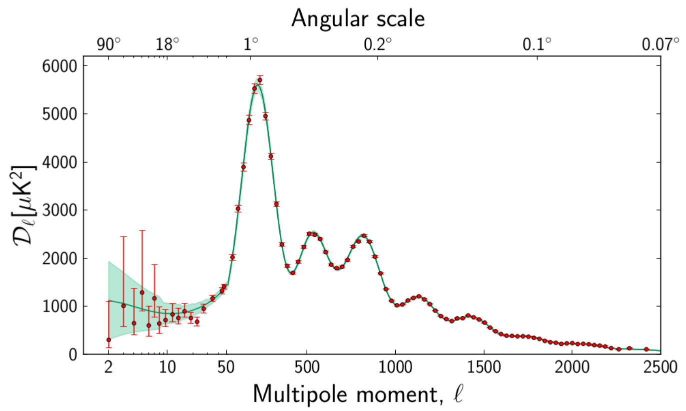


Cosmic Pie



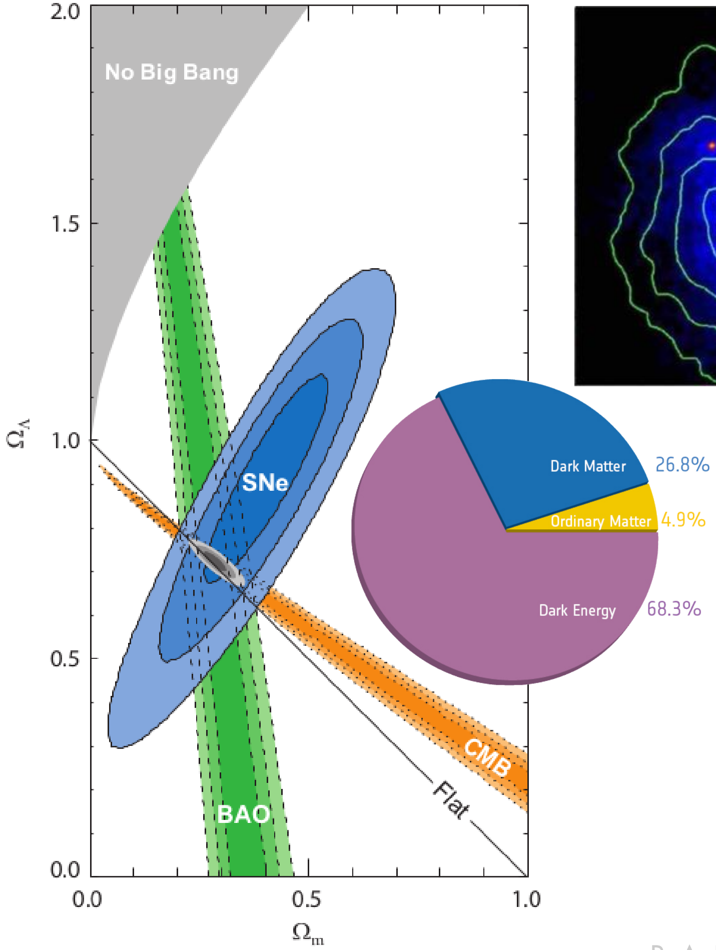
From the matter of the Universe

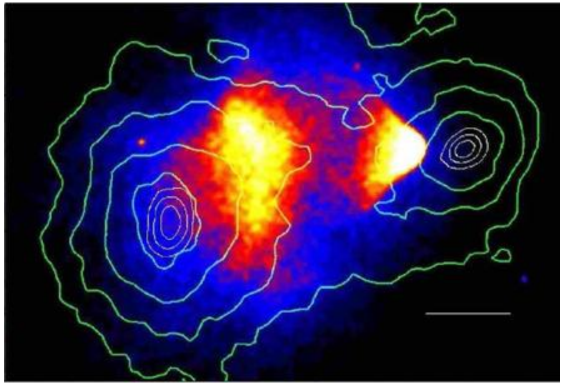
- 15.4% Ordinary Matter
- 84.5% Dark Matter

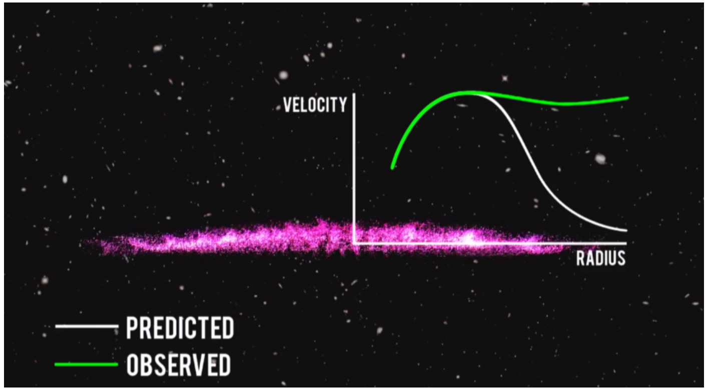


CMB anisotropies helps to unveil them

Dark Matter





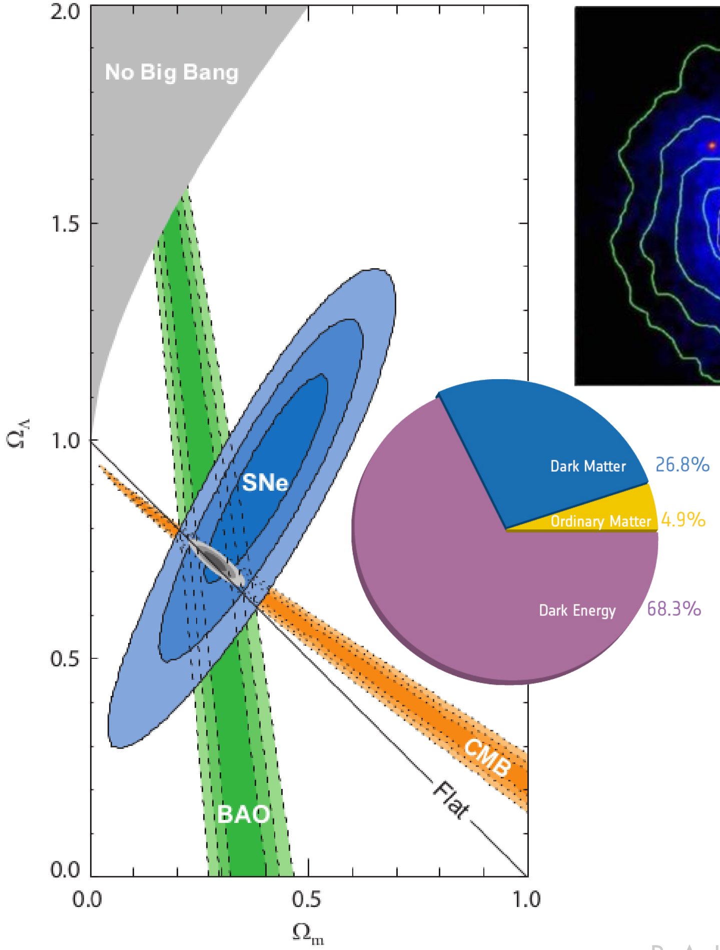


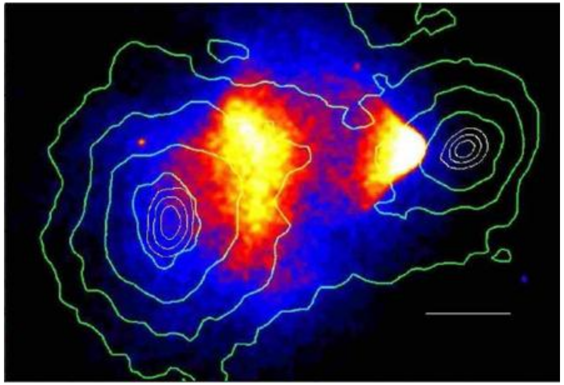
Observations support Dark Matter

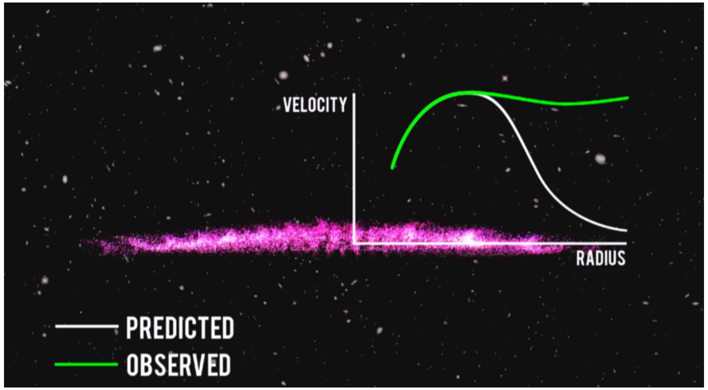
- Dynamics of clusters and galaxies
- Structure formation
- CMB anisotropies
- Baryon Acoustic Oscillation

$$\Omega_{DM}h^2 = 0.1196 \pm 0.0031$$

Dark Matter



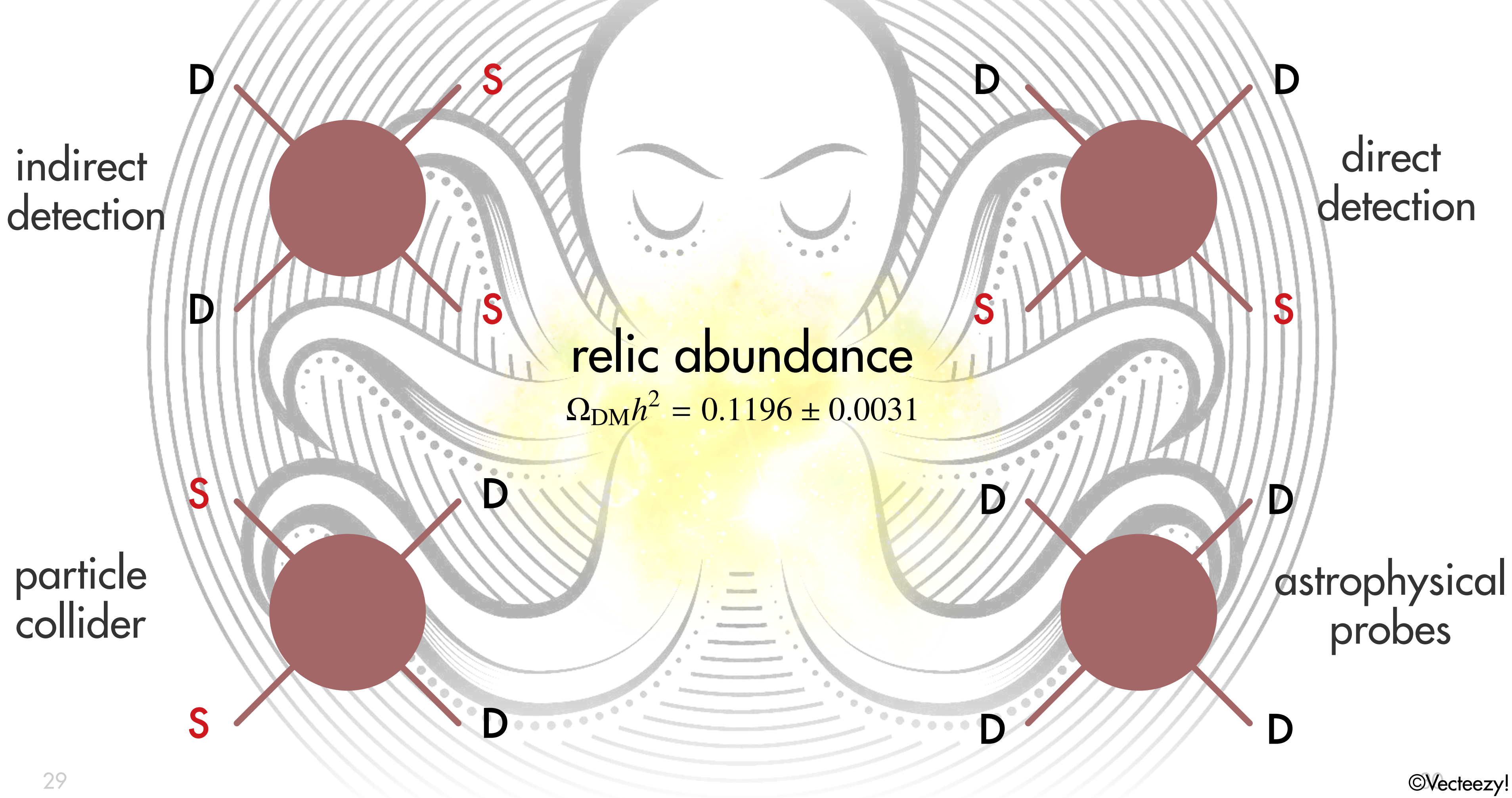




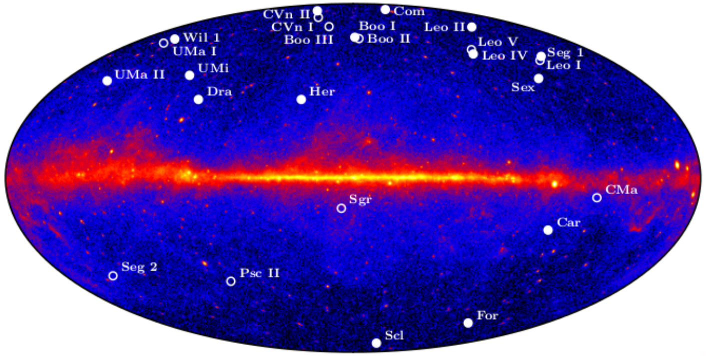
If Dark Matter has a particle origin

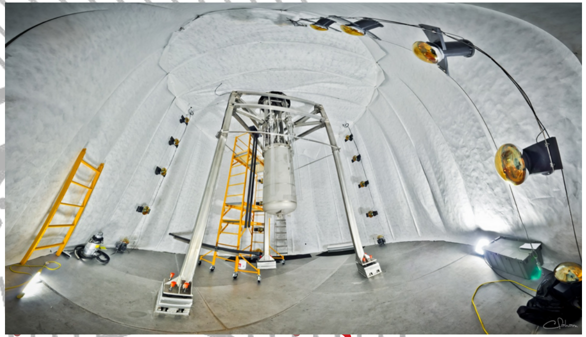
- Electrically Neutral
- Massive
- Non Baryonic
- Stable or very long lived
- Weakly interacting

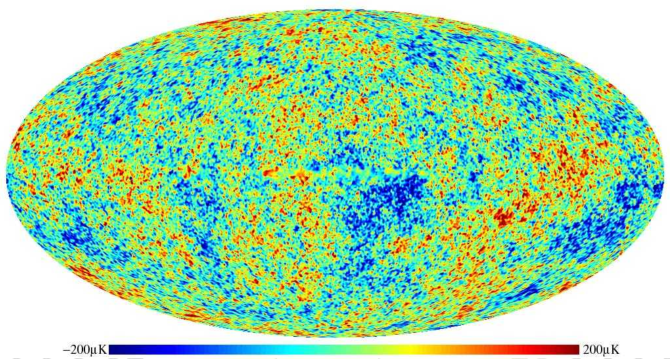
Dark Matter Searches



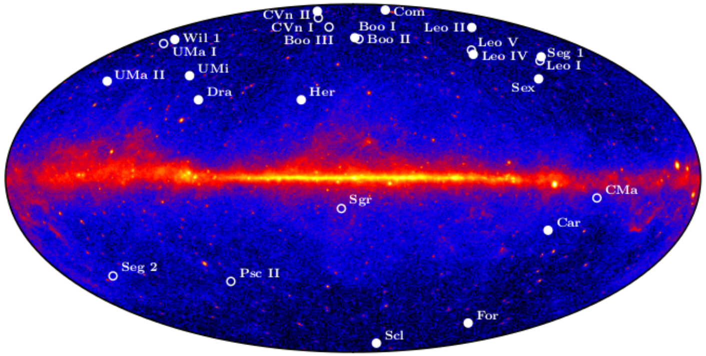
Dark Matter Searches

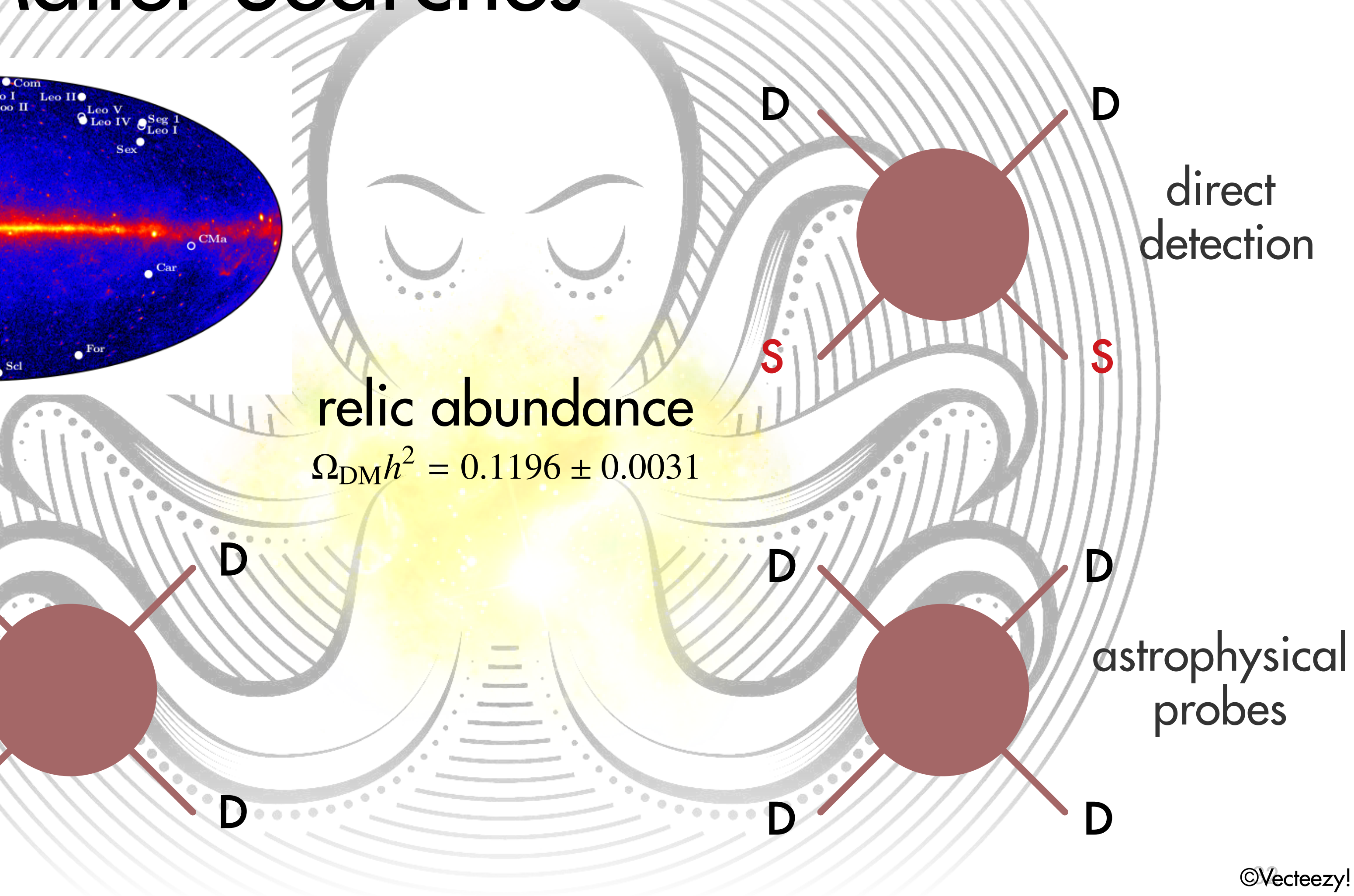




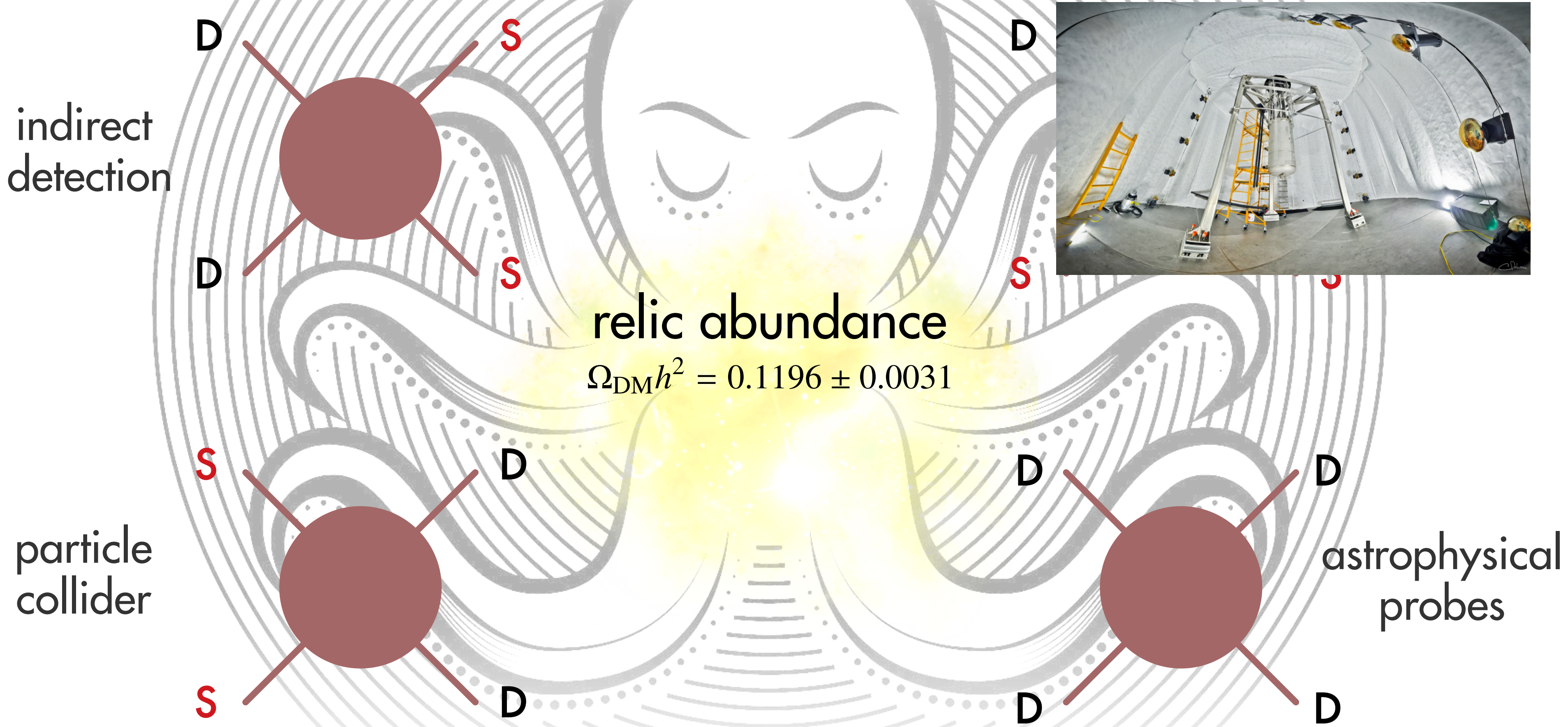


Dark Matter Searches



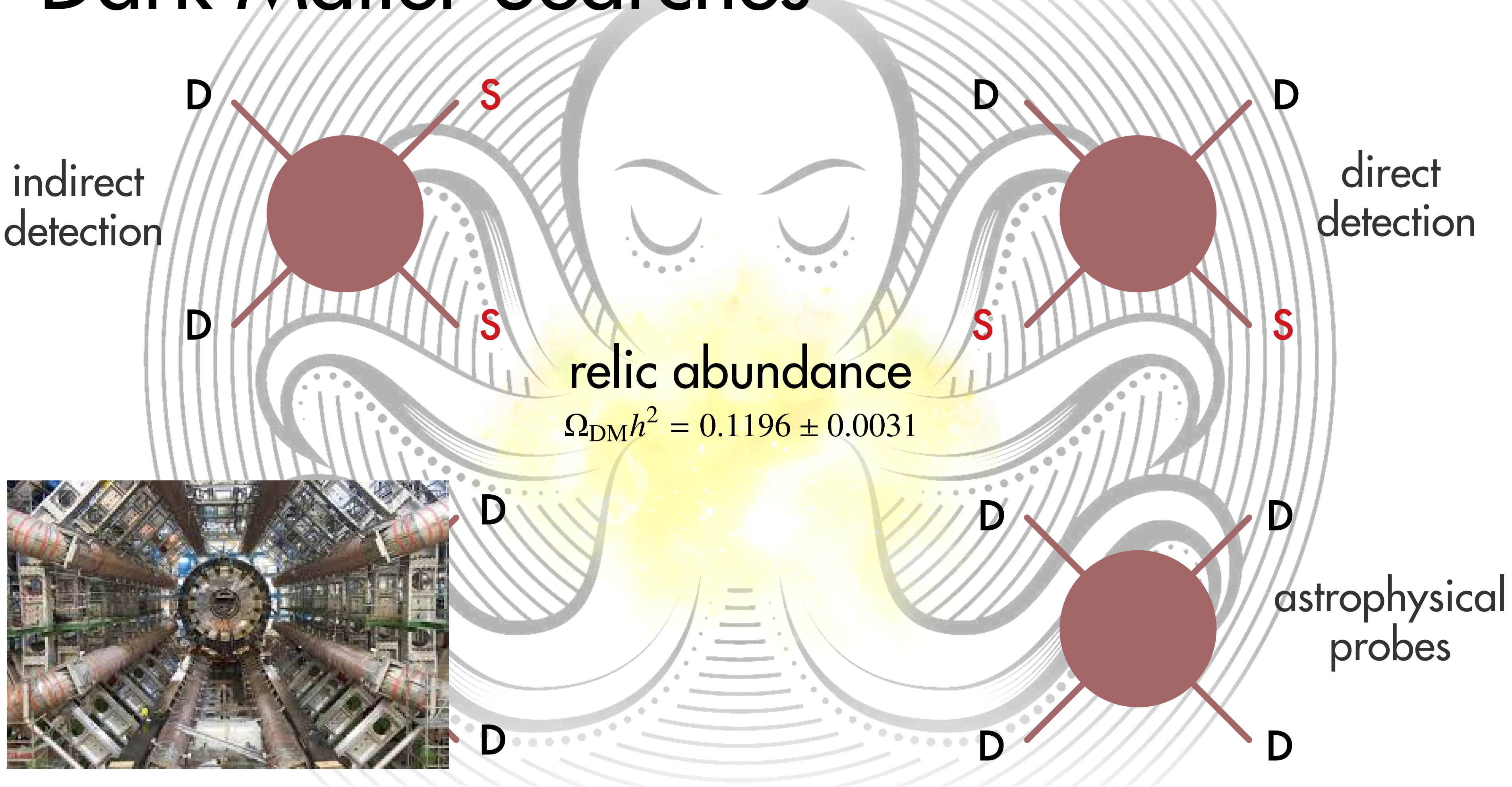


Dark Matter Searches

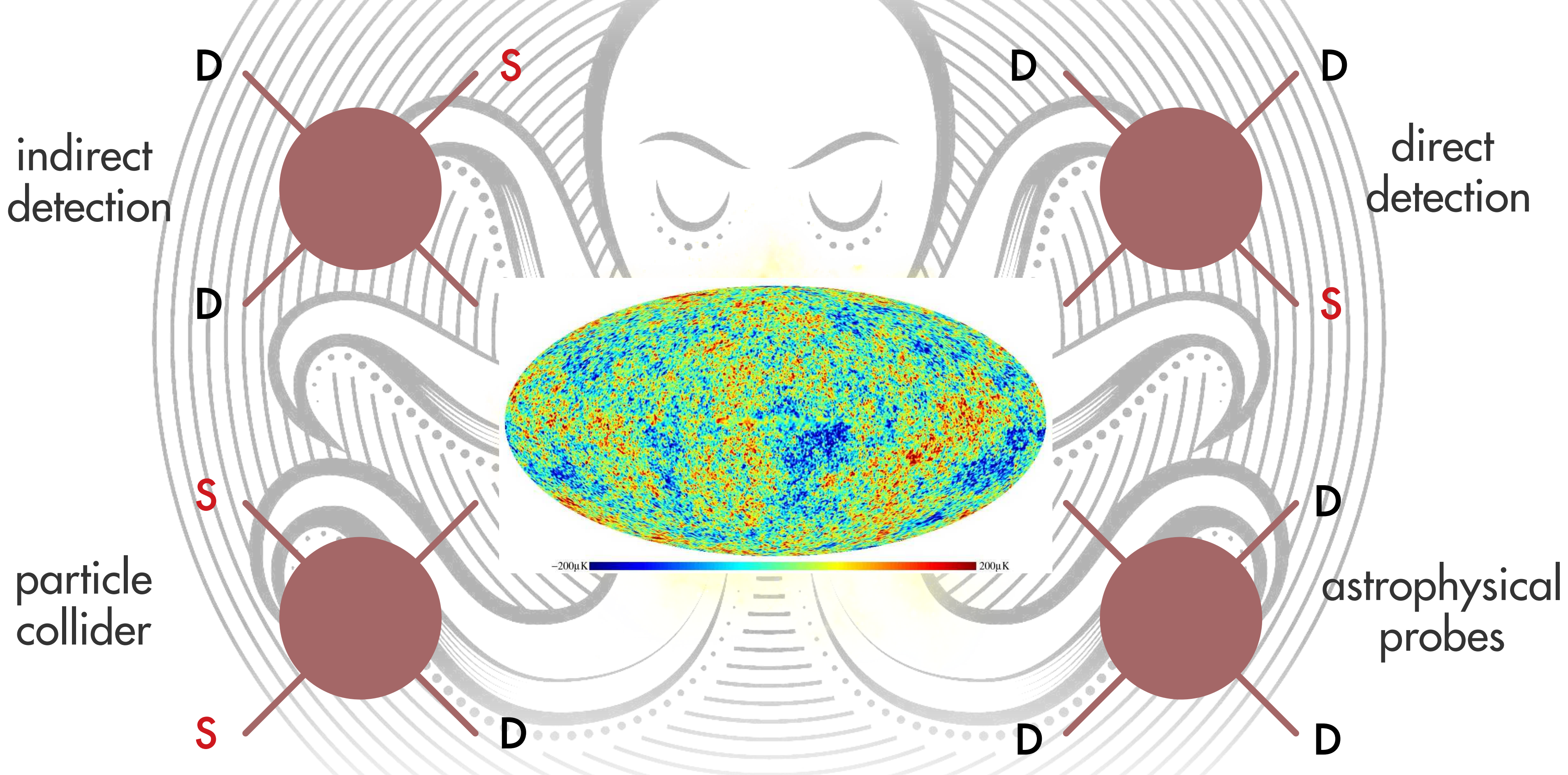


$$\Omega_{DM}h^2 = 0.1196 \pm 0.0031$$

Dark Matter Searches

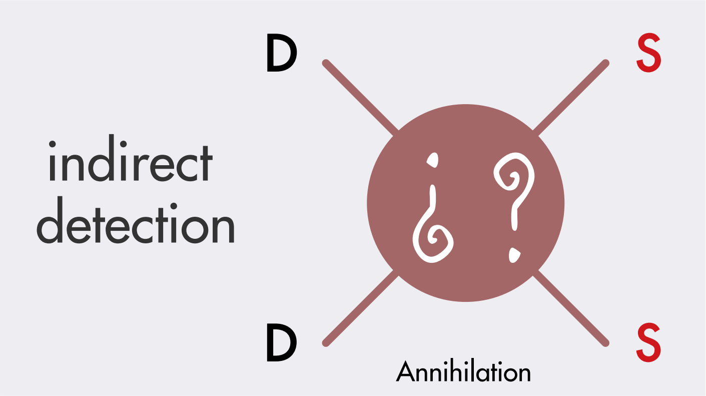


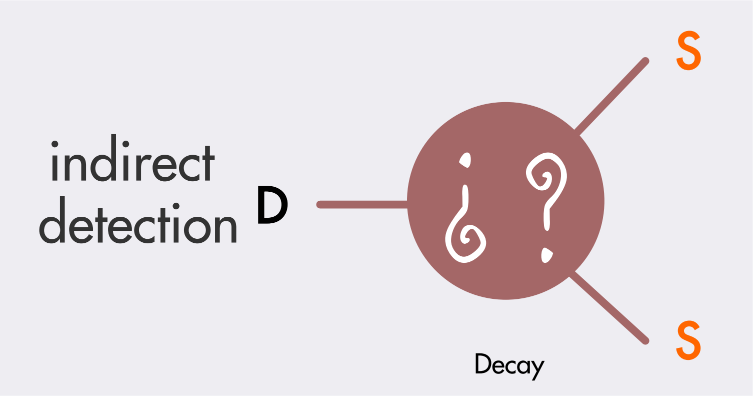
Dark Matter Searches



Astroparticle searches of Dark Matter

Dark Matter as Source

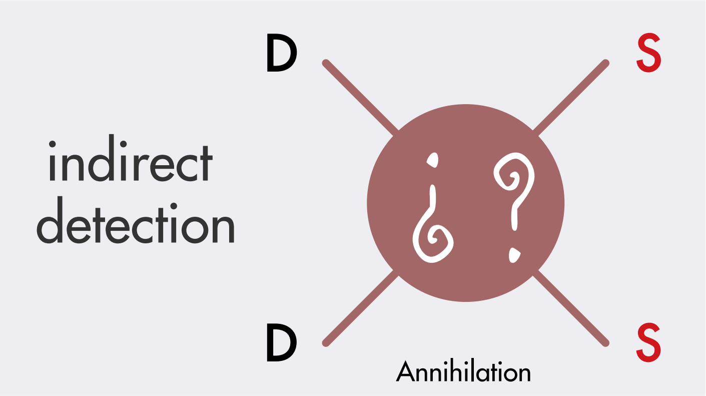


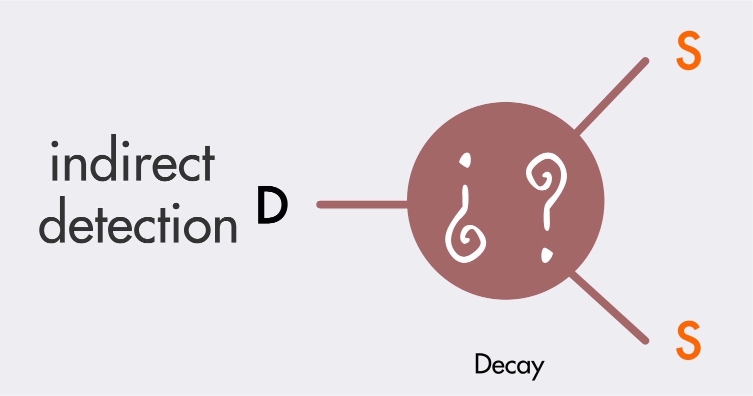


The production of SM particles from DM are excellent examples to learn about astroparticles

Indeed, the search with astroparticles has been one of the main drives of the field!

Dark Matter as Source





Astroparticle's transport equation

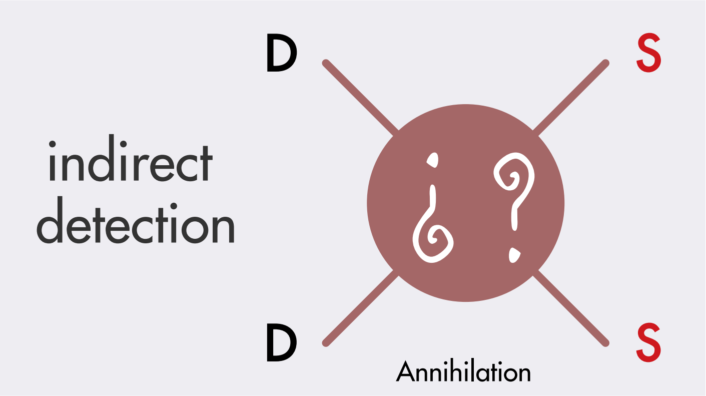
(Tomorrow)

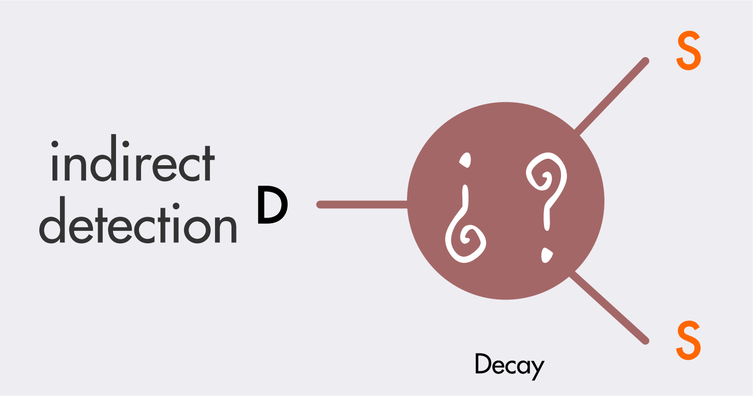
$$\frac{D\Psi}{Dt} = s$$

Source term due to

- Dark Matter
- Astrophysical source
- Astroparticle interactions

Dark Matter as Source





Depending of the way how DM produces SM particles, the source term follows:

$$s_{\rm DM}(\vec{x},\epsilon) = \eta\,\langle\sigma v\rangle\,\frac{\rho^2_{\rm DM}(\vec{x})}{m^2_{\rm DM}}\,\frac{dn_X}{d\epsilon}(\epsilon)$$

Annihilation

$$s_{\rm DM}(\vec{x},\epsilon) = \frac{1}{\tau_{\rm DM}}\,\frac{\rho_{\rm DM}(\vec{x})}{m_{\rm DM}}\,\frac{dn_X}{d\epsilon}(\epsilon)$$

Decay

Dark Matter as Source

Annihilation cross section

Production spectrum

$$s_{\rm DM}(\vec{x},\epsilon) = \eta \left\langle \sigma v \right\rangle \frac{\rho^2_{\rm DM}(\vec{x})}{m^2_{\rm DM}} \frac{dn_X}{d\epsilon}(\epsilon)$$

Number density

Dark Matter as Source

Particle physics/Cosmology

Particle physics

$$s_{\mathrm{DM}}(\vec{x}, \epsilon) = \eta \, \langle \sigma v \rangle \, \frac{\rho^2_{\mathrm{DM}}(\vec{x})}{m^2_{\mathrm{DM}}} \, \frac{dn_X}{d\epsilon}(\epsilon)$$

Particle Physics/Cosmology

A simple particle model for DM

Inert singlet DM model

The simplest DM model.

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu \phi\right)^2 - \frac{m_\phi}{2}\phi^2 - \frac{\lambda_\phi}{4}\phi^4 - \frac{\lambda_{\phi h}}{2}\phi^2 H^\dagger H + \mathcal{L}_{SM}$$

Features:

DM is a real scalar charged with a Z2 symmetry
The interaction with the SM is via Higgs particle

The relevant parameter are mass and coupling to the Higgs

Inert singlet DM model

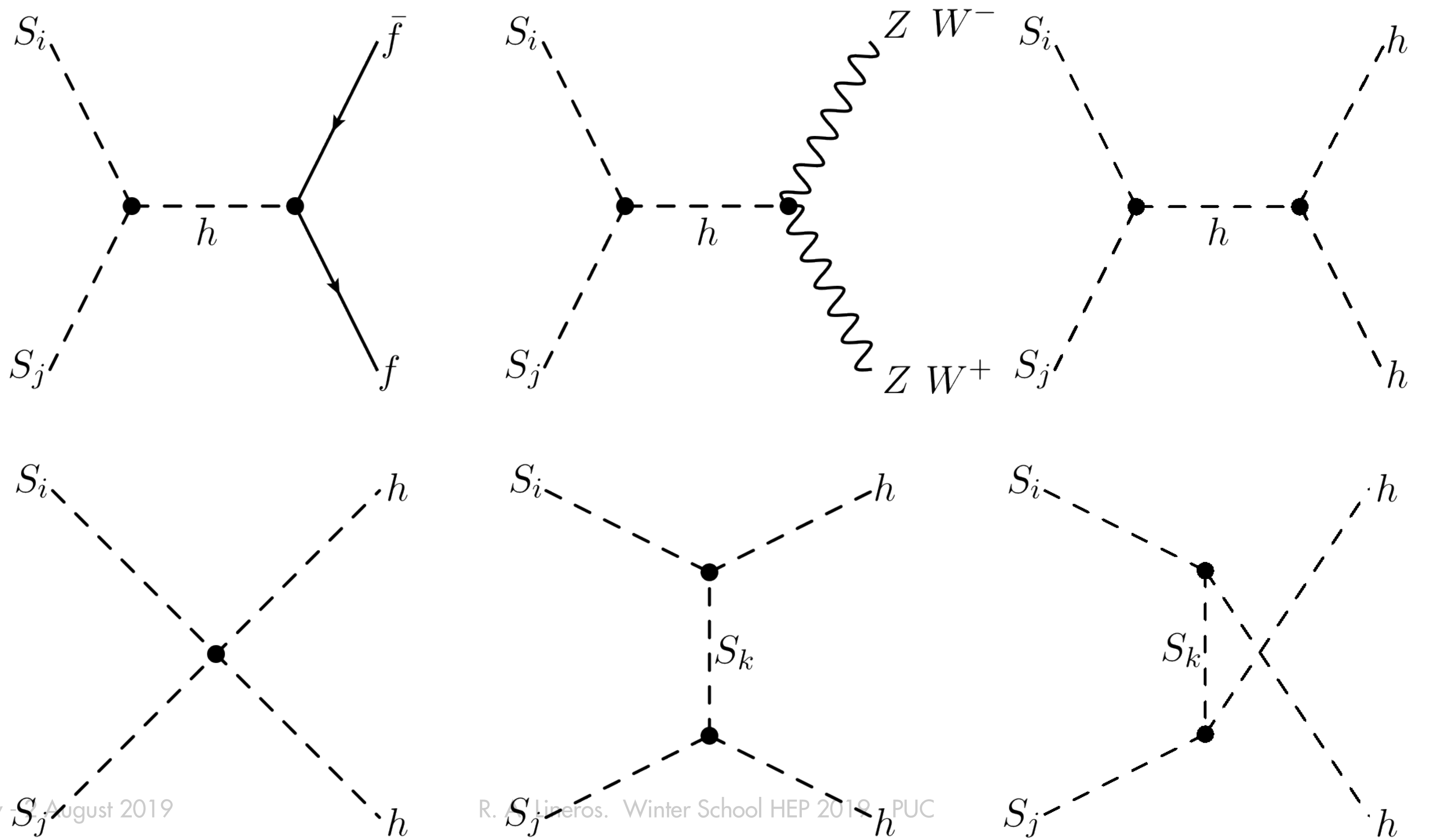
The simplest DM model.

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu \phi\right)^2 - \frac{m_\phi}{2}\phi^2 - \frac{\lambda_\phi}{4}\phi^4 - \frac{\lambda_{\phi h}}{2}\phi^2 H^\dagger H + \mathcal{L}_{SM}$$

Small exercise:

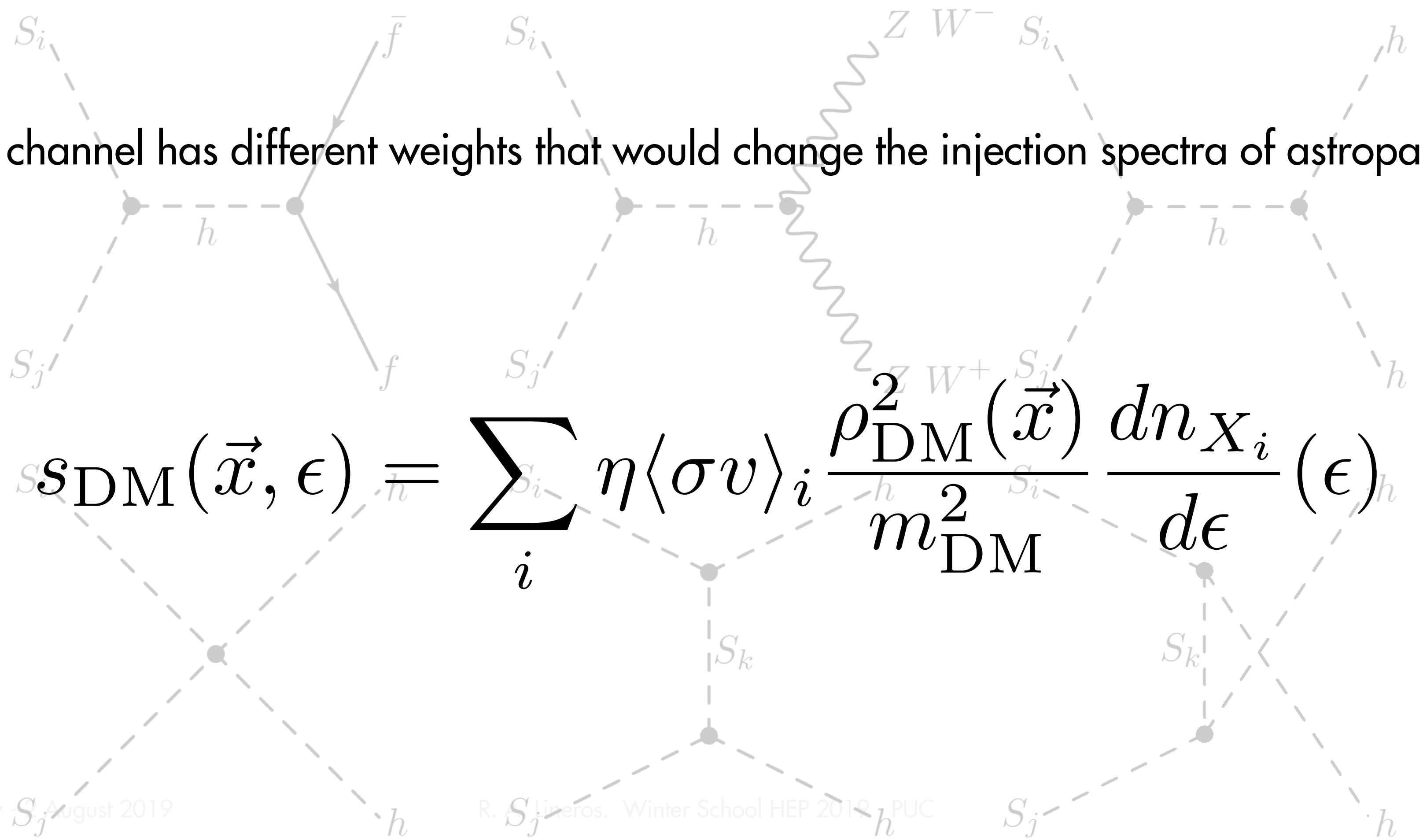
Draw diagrams relevant for the relic abundance

Inert singlet DM model



Inert singlet DM model

Each channel has different weights that would change the injection spectra of astroparticle



$$s_{\rm DM}(\vec{x},\epsilon) = \sum_i \eta\langle\sigma v\rangle_i \frac{\rho^2_{\rm DM}(\vec{x})}{m^2_{\rm DM}} \frac{dn_{X_i}}{d\epsilon}(\epsilon)$$

The Tools

Why tools?

Research on Astroparticles
could be hard without
a good set tools

disclaimer: I don't know who is this guy

Why tools?

We hope for a unique tool that solves all our problems (in physics)

Why tools?

… but most of the tools are made by physicists to solve their own problems

The minimum setup for astroparticles

laptop

internet access

coffee

Data Visualization

images edition

inkscape

GIMP

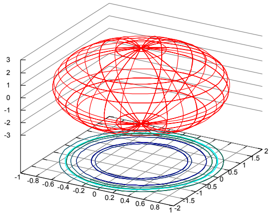
The visual presentation of results in plots and slides is VERY important

Sometimes results passed unnoticed because people cannot visualize them

These are some free/open source tools to help on these issues

Nice plots

matplotlib



gnuplot

Collaborative work

Video conference

Latex

Git repositories

No scientist research alone

File sharing

Data from papers

We must work with experimental results, because physics is an experimental science.

A problem, a collaboration released results but only in the form of a plot.

WebPlotDigitizer

Web based tool to extract data from plots, images, and maps

https://automeris.io/WebPlotDigitizer/

Data from papers

http://dx.doi.org/10.1103/PhysRevLett.110.141102

Selected for a Viewpoint in *Physics*

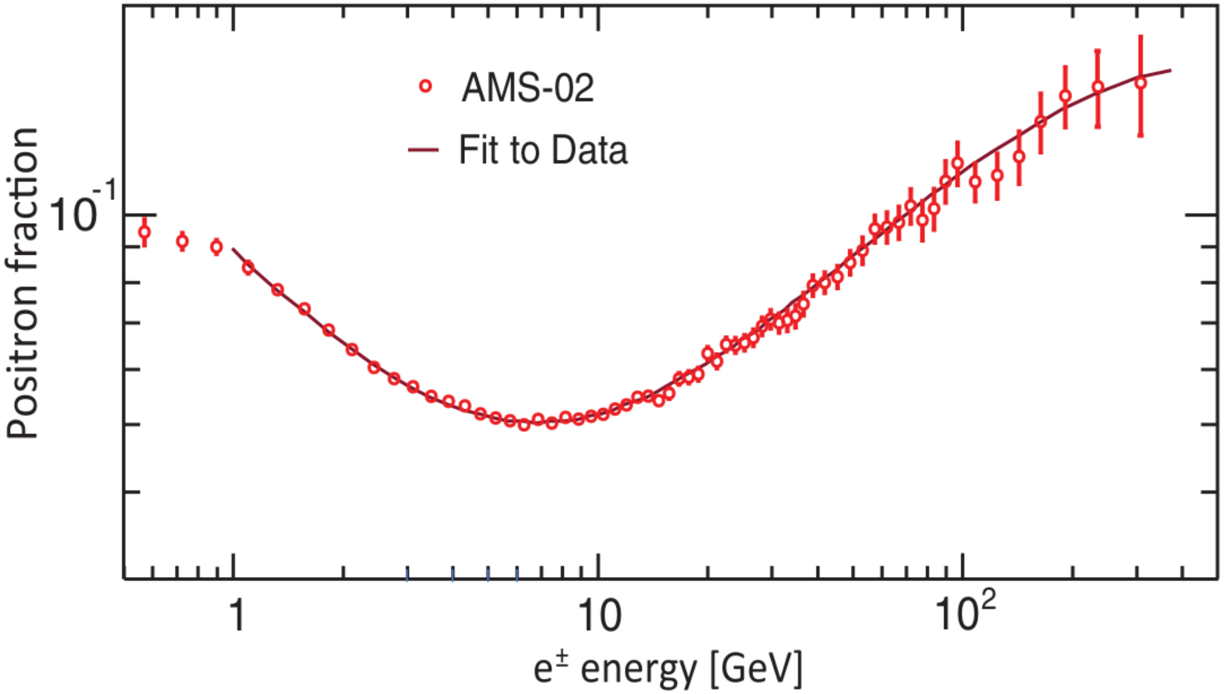
PRL **110,** 141102 (2013) PHYSICAL REVIEW LETTERS week ending 5 APRIL 2013

First Result from the Alpha Magnetic Spectrometer on the International Space Station: Precision Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5–350 GeV

M. Aguilar,[32,20] G. Alberti,[42,43] B. Alpat,[42] A. Alvino,[42,43] G. Ambrosi,[42] K. Andeen,[28] H. Anderhub,[54] L. Arruda,[30] P. Azzarello,[42,21,*] A. Bachlechner,[1] F. Barao,[30] B. Baret,[22] A. Barrau,[22] L. Barrin,[20] A. Bartoloni,[47] L. Basara,[5] A. Basili,[11] L. Batalha,[30] J. Bates,[25] R. Battiston,[42,43,46] J. Bazo,[42] R. Becker,[11] U. Becker,[11] M. Behlmann,[11] B. Beischer,[1] J. Berdugo,[32] P. Berges,[11] B. Bertucci,[42,43] G. Bigongiari,[44,45] A. Biland,[54] V. Bindi,[24] S. Bizzaglia,[42] G. Boella,[36,37] W. de Boer,[28] K. Bollweg,[25] J. Bolmont,[38] B. Borgia,[47,48] S. Borsini,[42,43] M. J. Boschini,[36] G. Boudoul,[22] M. Bourquin,[21] P. Brun,[5] M. Buénerd,[22] J. Burger,[11] W. Burger,[43] F. Cadoux,[5,21] X. D. Cai,[11] M. Capell,[11] D. Casadei,[9,10] J. Casaus,[32] V. Cascioli,[42,43] G. Castellini,[18] I. Cernuda,[32] F. Cervelli,[44] M. J. Chae,[49] Y. H. Chang,[12] A. I. Chen,[11] C. R. Chen,[26] H. Chen,[11] G. M. Cheng,[8] H. S. Chen,[8] L. Cheng,[50] N. Chernoplyiokov,[39] A. Chikanian,[41] E. Choumilov,[11] V. Choutko,[11] C. H. Chung,[1] C. Clark,[25] R. Clavero,[29] G. Coignet,[5] V. Commichau,[54] C. Consolandi,[36,24] A. Contin,[9,10] C. Corti,[24] M. T. Costado Dios,[29] B. Coste,[22] D. Crespo,[32] Z. Cui,[50] M. Dai,[7] C. Delgado,[32] S. Della Torre,[36,37] B. Demirkoz,[4] P. Dennett,[11] L. Derome,[22] S. Di Falco,[44] X. H. Diao,[23] A. Diago,[29] L. Djambazov,[54] C. Díaz,[32] P. von Doetinchem,[1]

Data from papers

We use Fig 6.



Data from papers

In this case, they provide the data. Sometimes not

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TABLE I. Representative bins of the positron fraction as a function of energy. Errors due to *stat.*, statistical error; *acc.*, acceptance asymmetry; *sel.*, event selection; *mig.*, bin-to-bin migration; *ref.*, reference spectra; *c.c.*, charge confusion; and *syst.*, total systematic error. For the complete table, see [13].

Energy[GeV]	N_{e^+}	Fraction	σ_{stat}	σ_{acc}	σ_{sel}	σ_{mig}	σ_{ref}	$\sigma_{c.c.}$	σ_{syst}
1.00–1.21	9335	0.0842	0.0008	0.0005	0.0009	0.0008	0.0001	0.0005	0.0014
1.97–2.28	23 893	0.0642	0.0004	0.0002	0.0005	0.0002	0.0001	0.0002	0.0006
3.30–3.70	20 707	0.0550	0.0004	0.0001	0.0003	0.0000	0.0001	0.0002	0.0004
6.56–7.16	13 153	0.0510	0.0004	0.0001	0.0000	0.0000	0.0001	0.0002	0.0002
09.95–10.73	7161	0.0519	0.0006	0.0001	0.0000	0.0000	0.0001	0.0002	0.0002
19.37–20.54	2322	0.0634	0.0013	0.0001	0.0001	0.0000	0.0001	0.0002	0.0003
30.45–32.10	1094	0.0701	0.0022	0.0001	0.0002	0.0000	0.0001	0.0003	0.0004
40.00–43.39	976	0.0802	0.0026	0.0002	0.0005	0.0000	0.0001	0.0004	0.0007
50.87–54.98	605	0.0891	0.0038	0.0002	0.0006	0.0000	0.0001	0.0004	0.0008
64.03–69.00	392	0.0978	0.0050	0.0002	0.0010	0.0000	0.0002	0.0007	0.0013
74.30–80.00	276	0.0985	0.0062	0.0002	0.0010	0.0000	0.0002	0.0010	0.0014
86.00–92.50	240	0.1120	0.0075	0.0002	0.0010	0.0000	0.0003	0.0011	0.0015
100.0–115.1	304	0.1118	0.0066	0.0002	0.0015	0.0000	0.0003	0.0015	0.0022
115.1–132.1	223	0.1142	0.0080	0.0002	0.0019	0.0000	0.0004	0.0019	0.0027
132.1–151.5	156	0.1215	0.0100	0.0002	0.0021	0.0000	0.0005	0.0024	0.0032
151.5–173.5	144	0.1364	0.0121	0.0002	0.0026	0.0000	0.0006	0.0045	0.0052
173.5–206.0	134	0.1485	0.0133	0.0002	0.0031	0.0000	0.0009	0.0050	0.0060
206.0–260.0	101	0.1530	0.0160	0.0003	0.0031	0.0000	0.0013	0.0095	0.0101
260.0–350.0	72	0.1550	0.0200	0.0003	0.0056	0.0000	0.0018	0.0140	0.0152

Coding

python™

```
rlineros@dm1: ~
File  Edit  View  Search  Terminal  Help
rlineros@dm1:~$ python
Python 3.6.3 |Anaconda custom (64-bit)| (default, Nov  3 2017, 19:19:16)
[GCC 7.2.0] on linux
Type "help", "copyright", "credits" or "license" for more information.
>>> print("Hola mundo")
Hola mundo
>>> a = 1
>>> b = 2
>>> print(a+b)
3
>>> 
```

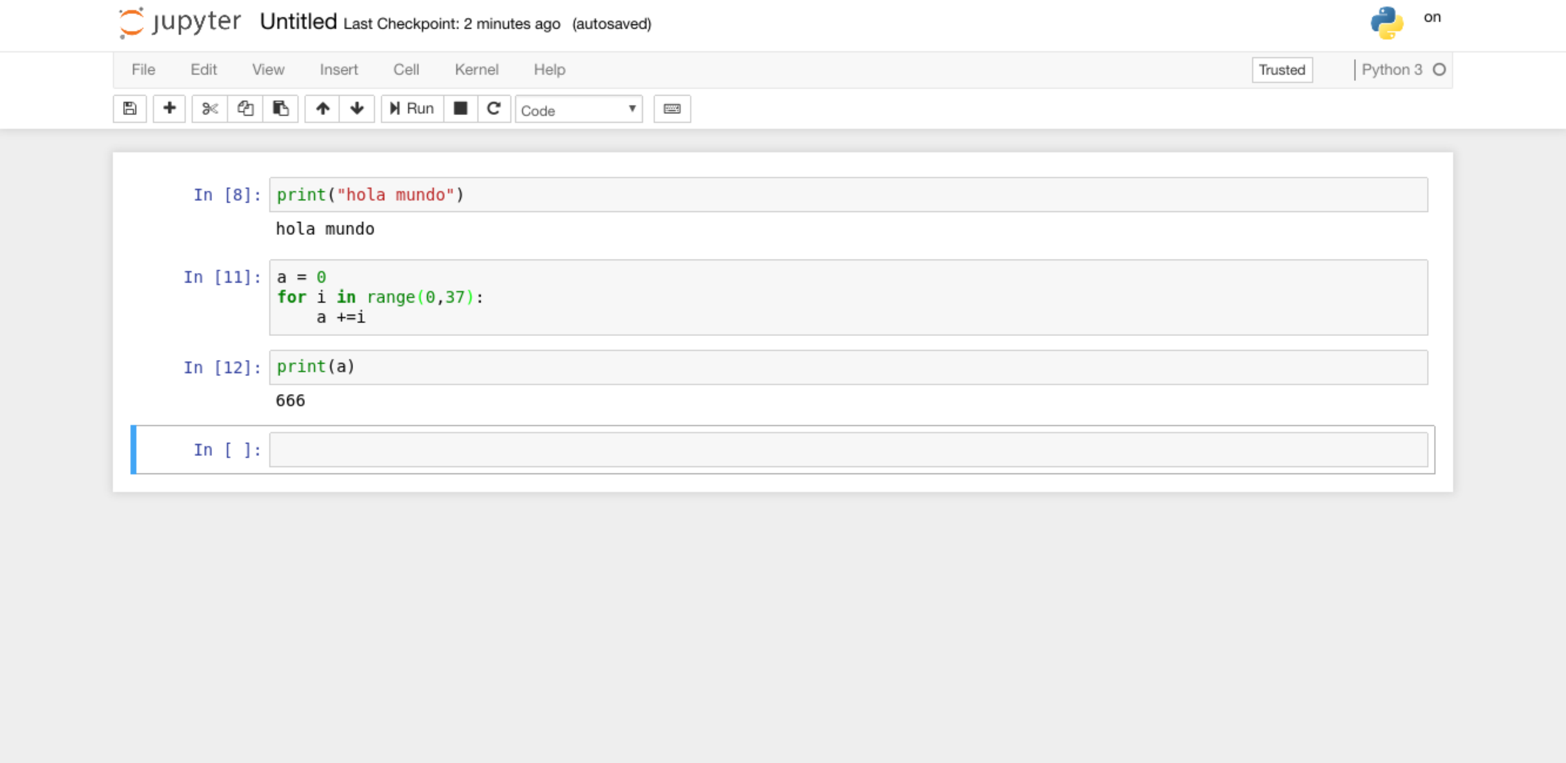
ANACONDA®

https://www.anaconda.com

Python is currently one of the most used languages.
It is oriented to do “almost everything”.

But you can work in any language: Fortran, C/C++, etc.

Jupyter



if you have anacoda in your system.
Run in a terminal: jupyter notebook or enter to https://try.jupyter.org

Science Tools in Anaconda

https://www.scipy.org

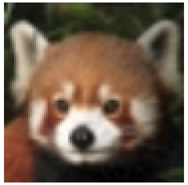
NumPy
Base N-dimensional array package

SciPy library
Fundamental library for scientific computing

Matplotlib
Comprehensive 2D Plotting

IPython
Enhanced Interactive Console

Sympy
Symbolic mathematics



pandas
Data structures & analysis

Mathematica

Very useful to deal with symbolic calculation, etc.

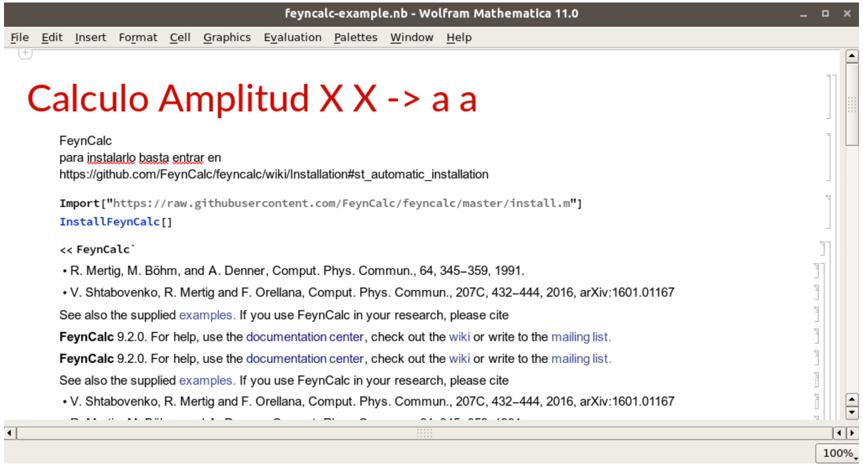
but it is **not** free.

Many tools for High Energy Physics use Mathematica as a basis:

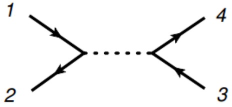
- Feynrules
- Feyncalc
- Sarah
- Etc.

FeynCalc

https://github.com/FeynCalc/feyncalc/wiki/Installation#st_automatic_installation



Symbolic calculation for amplitudes!



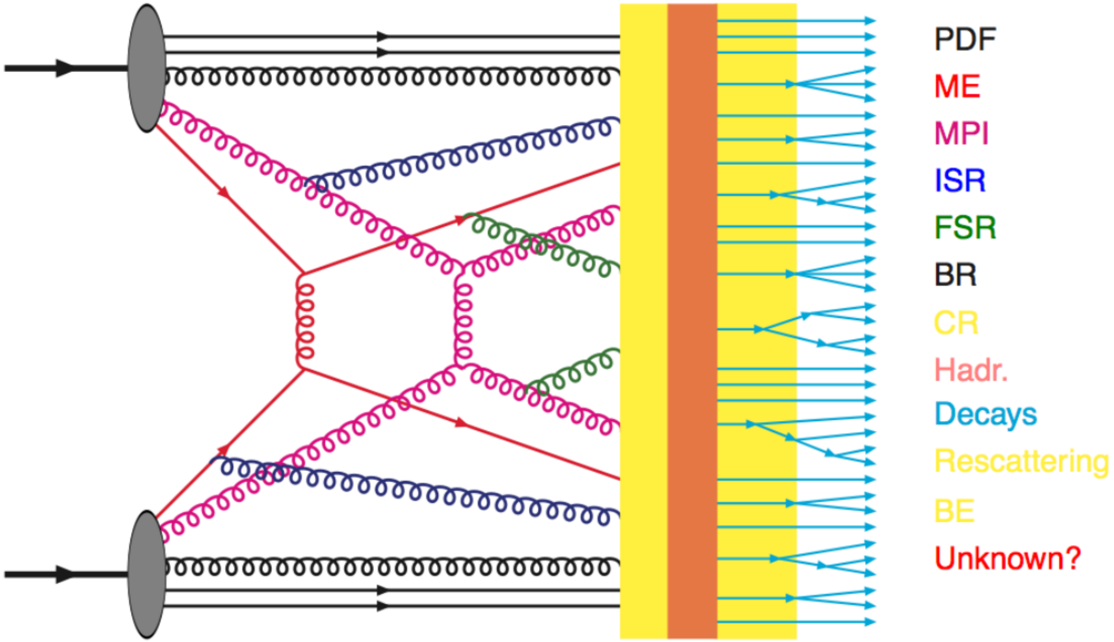
$$= ig\,\bar{u}_4 v_3 \times \frac{-i}{(p_1+p_2)^2} \times ig\,\bar{u}_2 v_1$$

To install run in a Mathematica notebook:

```
Import["https://raw.githubusercontent.com/FeynCalc/feyncalc/master/install.m"]
InstallFeynCalc[]
```

Pythia

Montecarlo event generator for high energy physics.



Astroparticles are the very final state of a scattering/decay process

Calculate this analytically is MADNESS!

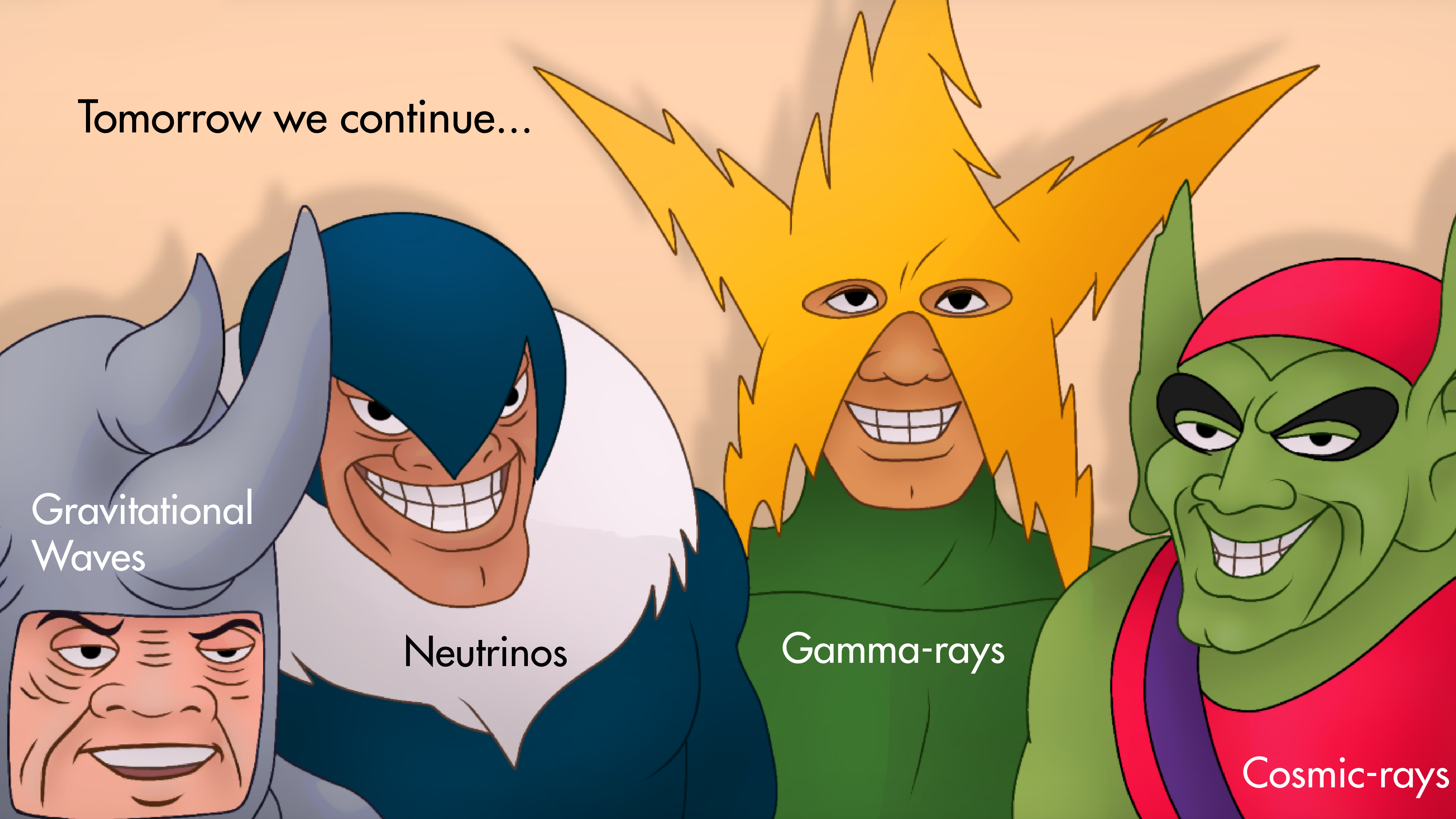
Pythia8 is a C++ program

Tools for Dark Matter

There are so many tools, that is very easy to get confuse when one tools is good or not

The tools to learn are:

- Lanhep: to write the particle model's lagrangian
- Calchep: to calculate cross sections, amplitudes, etc.
- Micromegas: to calculate WIMP DM observables.
- MadGraph, MadEvent: Calculate and simulate events.
- SARAH: a toolbox for implementing BSM models.


Tomorrow we continue...
Gravitational Waves
Neutrinos
Gamma-rays
Cosmic-rays