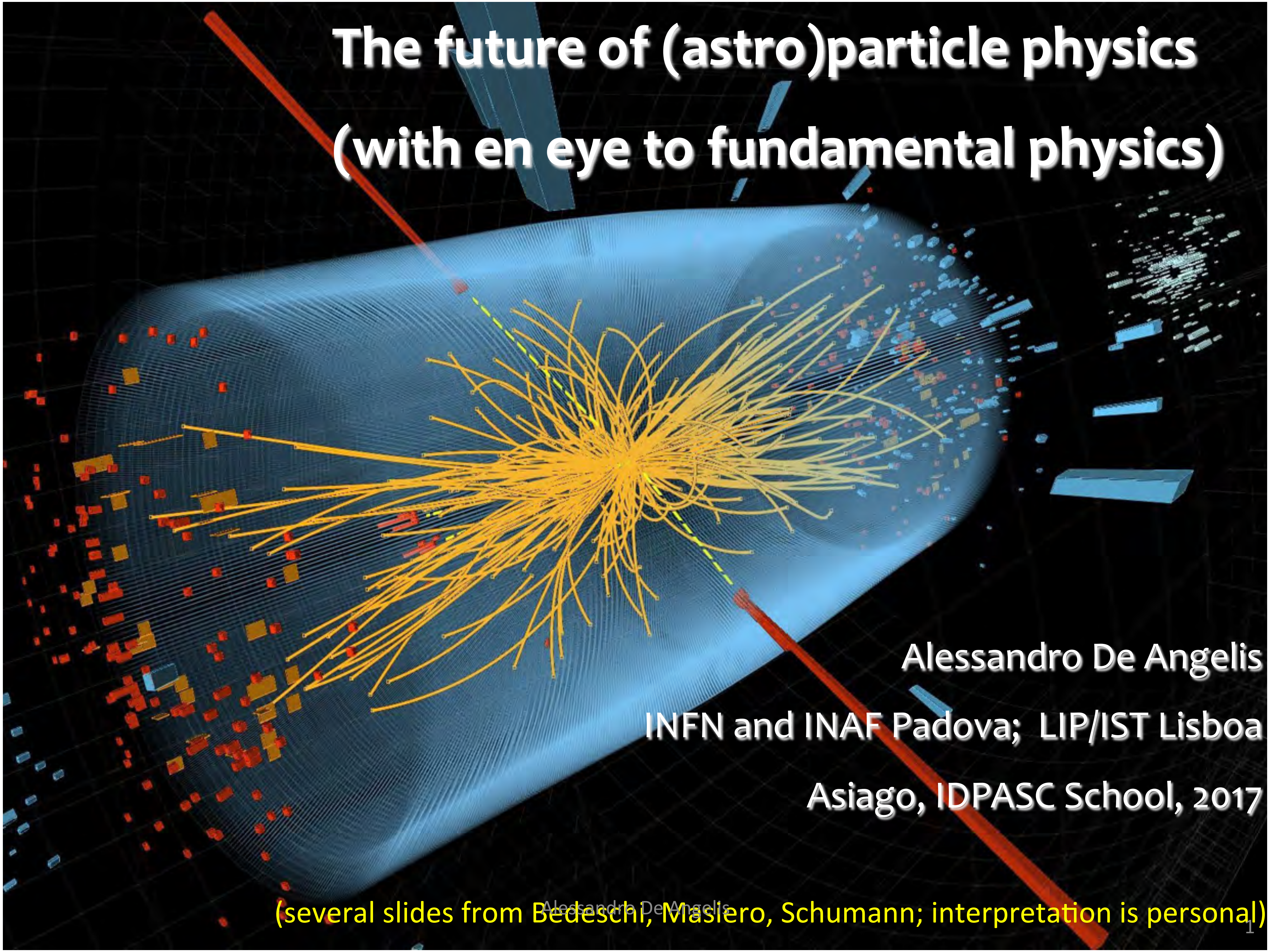
The future of (astro)particle physics
(with en eye to fundamental physics)



Alessandro De Angelis

INFN and INAF Padova; LIP/IST Lisboa

Asiago, IDPASC School, 2017

(several slides from Bedeschi, Masiero, Schumann; interpretation is personal)

The future of (astro)particle physics

Clouds in 1900

- At the end of XIX century, after Maxwell's work, many were convinced that the end of physics had been reached. On April 27, 1900, the British scientist William Thomson, aka Lord Kelvin, gave a speech entitled ”19th Century Clouds over the Dynamical Theory of Heat and Light," which began:

  "The beauty and clearness of the dynamical theory, which asserts heat and light to be modes of motion, is at present obscured by two clouds.”

- The "clouds" to which Kelvin was referring were:
  – The inability to detect the luminous ether, specifically the failure of the Michelson-Morley experiment
  – The blackbody radiation effect known as the ultraviolet catastrophe.
- During the subsequent discussion, a third cloud emerged:
  – The quantized light emission from atoms.

- We know how the story went…

150 years later: the success of the Standard Model

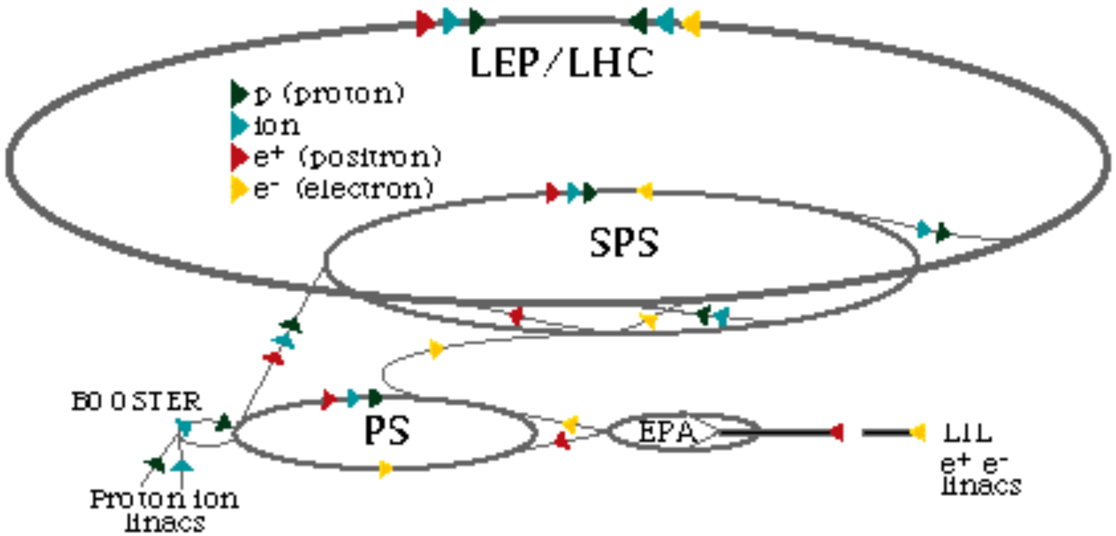
- 2012: The Standard Model of Particle Physics (SM) had a success similar to Maxwell's theory, thanks to the Higgs discovery at LHC
- Now we have a theory, the SM, explaining all interactions relevant at the level of elementary particle physics, and an (independent, and not quantized) theory of gravity
- Although not particularly elegant according to many, the SM is a predictive theory, as theory of gravity.

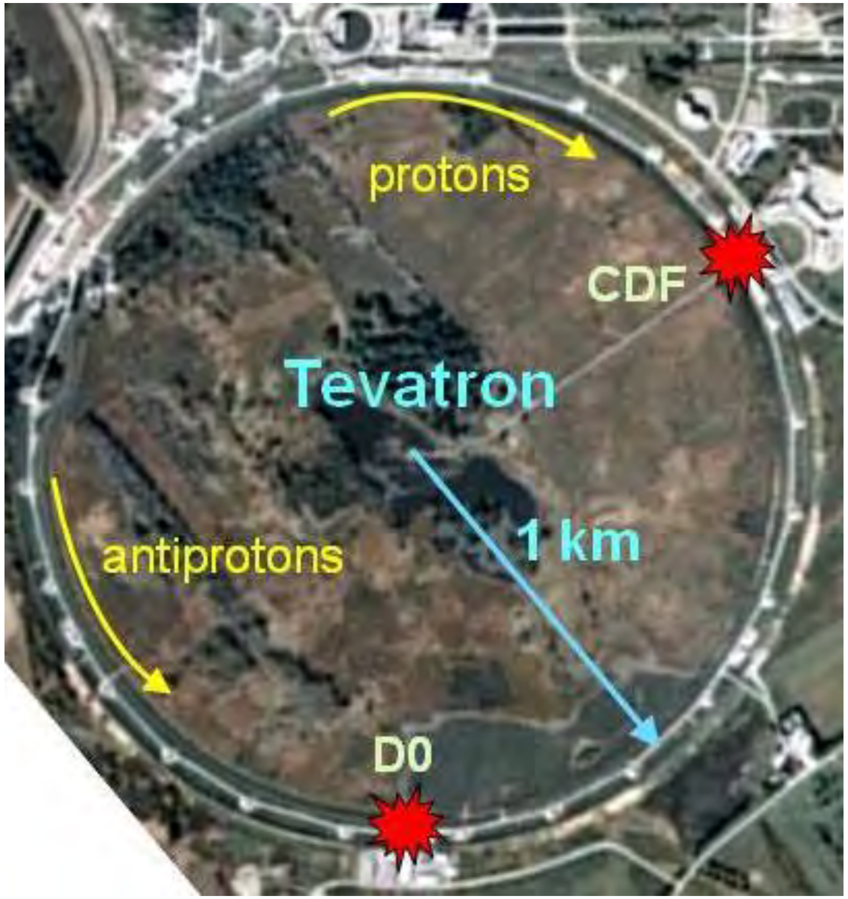
Are there clouds today?

- One big cloud: the dark sector of the Universe
  - Dark Energy, Dark Matter
  - Evidence both from cosmological and from astrophysical observations
  - This is the largest part of the energy budget of the Universe
- A few smaller clouds, which might just be anthropic
  - Elegance, Naturalness
    - So many parameters…
    - Why the masses are what they are?
    - Why this funny replica of families (unification, compositeness, …)
  - Physics as we know it looses significance at $\sim 10^{-40}$ m
  - Could just be the consequence of the fact that we want a "human-image" Universe?
  - Anyway, elegant solutions exist which can be demonstrated by the existence of new particles.
  - *(Plus a bigger cloud, that I'll probably not discuss, related to Kurt Godel)*

What can we do to make these clouds part?

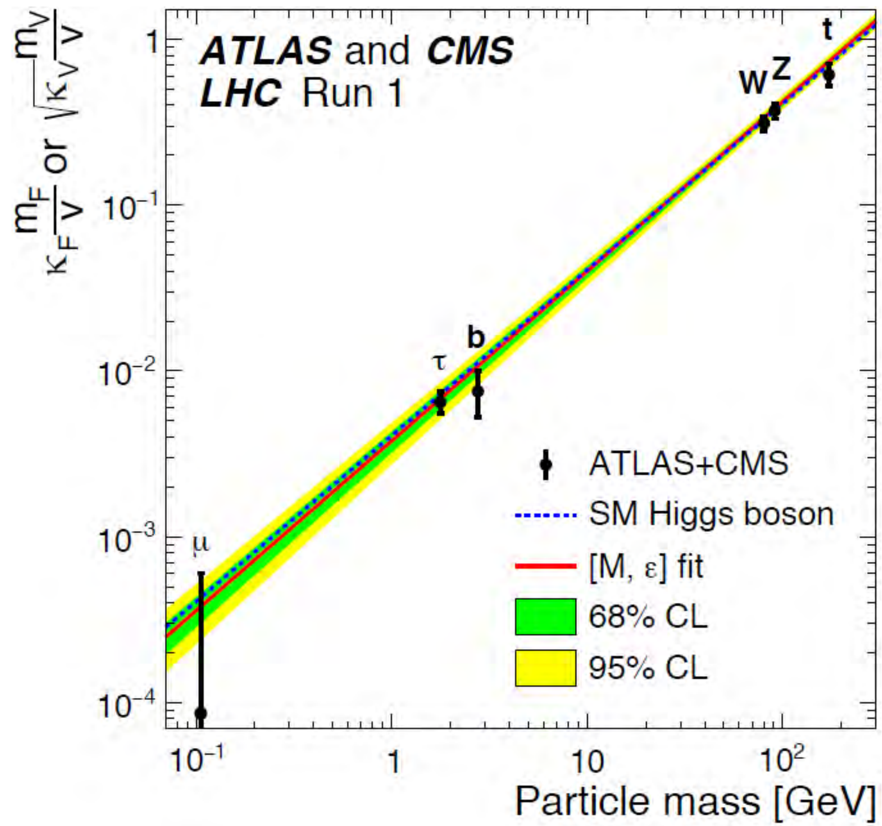
Accelerators: in the recent years, the main source of estabilished discoveries and precision measurements

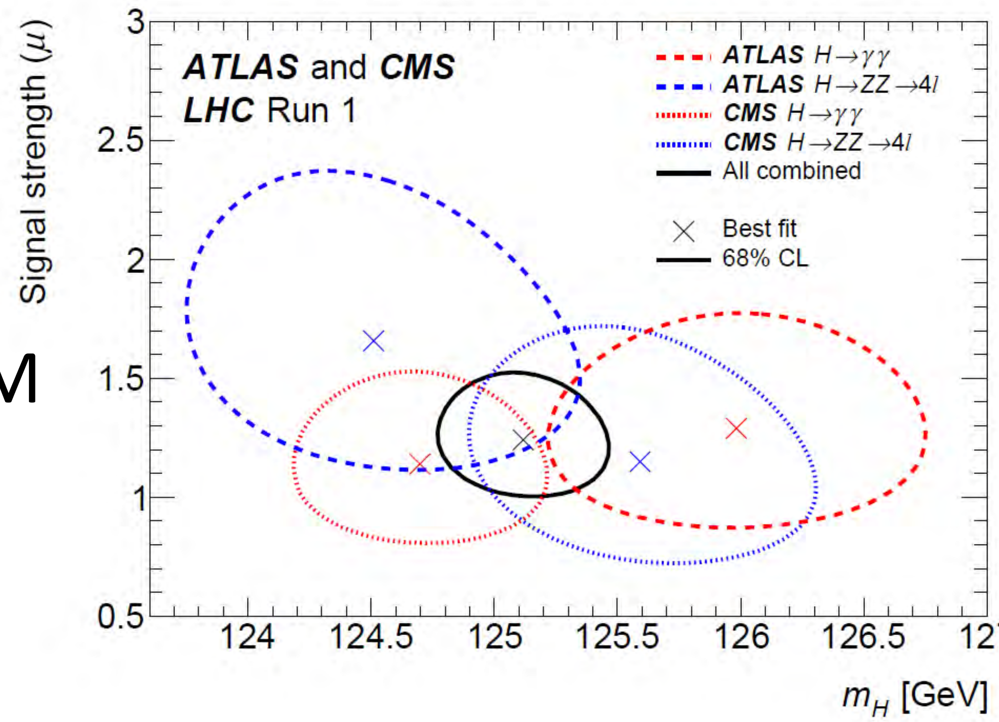




LHC & LEP: Great Success of the SM! (1)

- Higgs discovered!
  - Couplings ~ SM
  - Quantum numbers ~ SM

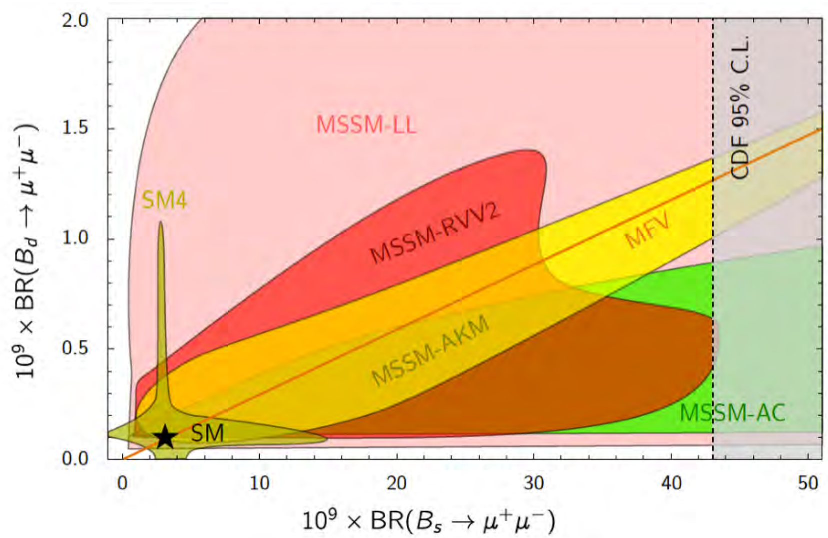


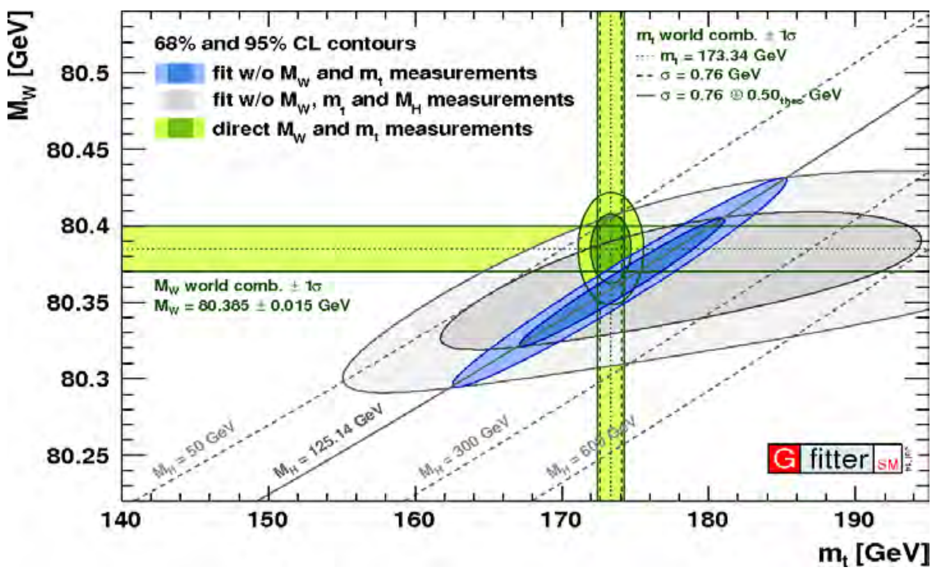


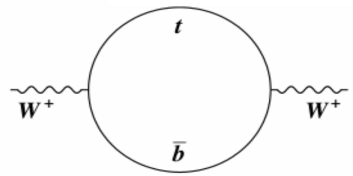
arXiv:1503.07589

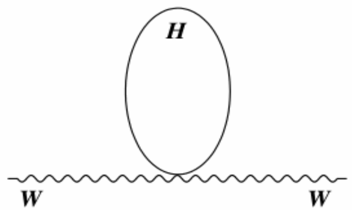
LHC & LEP: Great Success of the SM! (2)

- Also indirect measurements sensitive to radiative corrections
  - M(top), Mw, $M_{H,}$ BR(B)

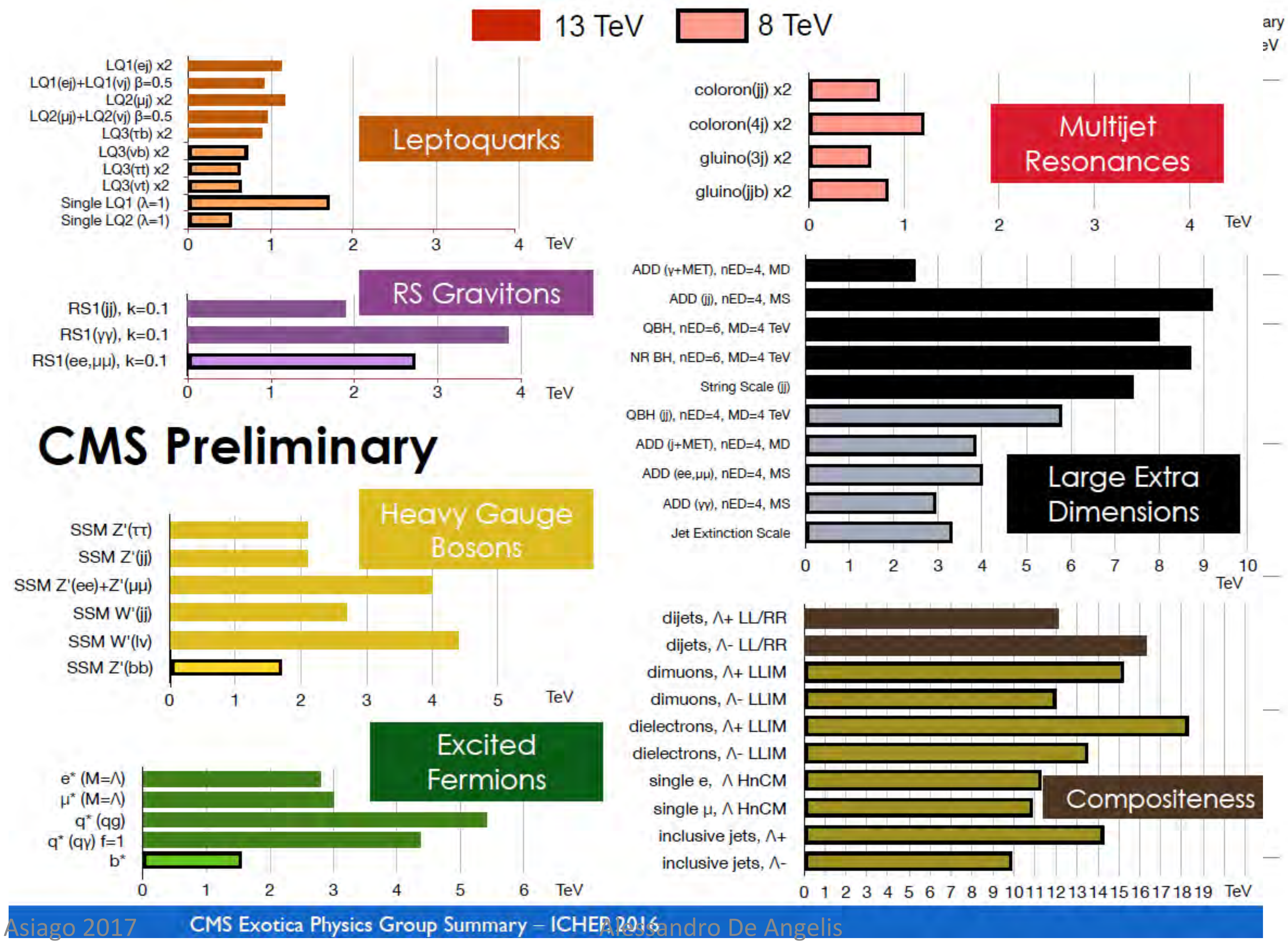








No signs of new physics



Hints of new physics from LHC?

- Despite some attractive theoretical motivations for unification, no signs (a few ~3σ effects, but…)

- No signs of SUSY up to ~1 TeV
- No signs of compositeness up to scales ~ few TeV

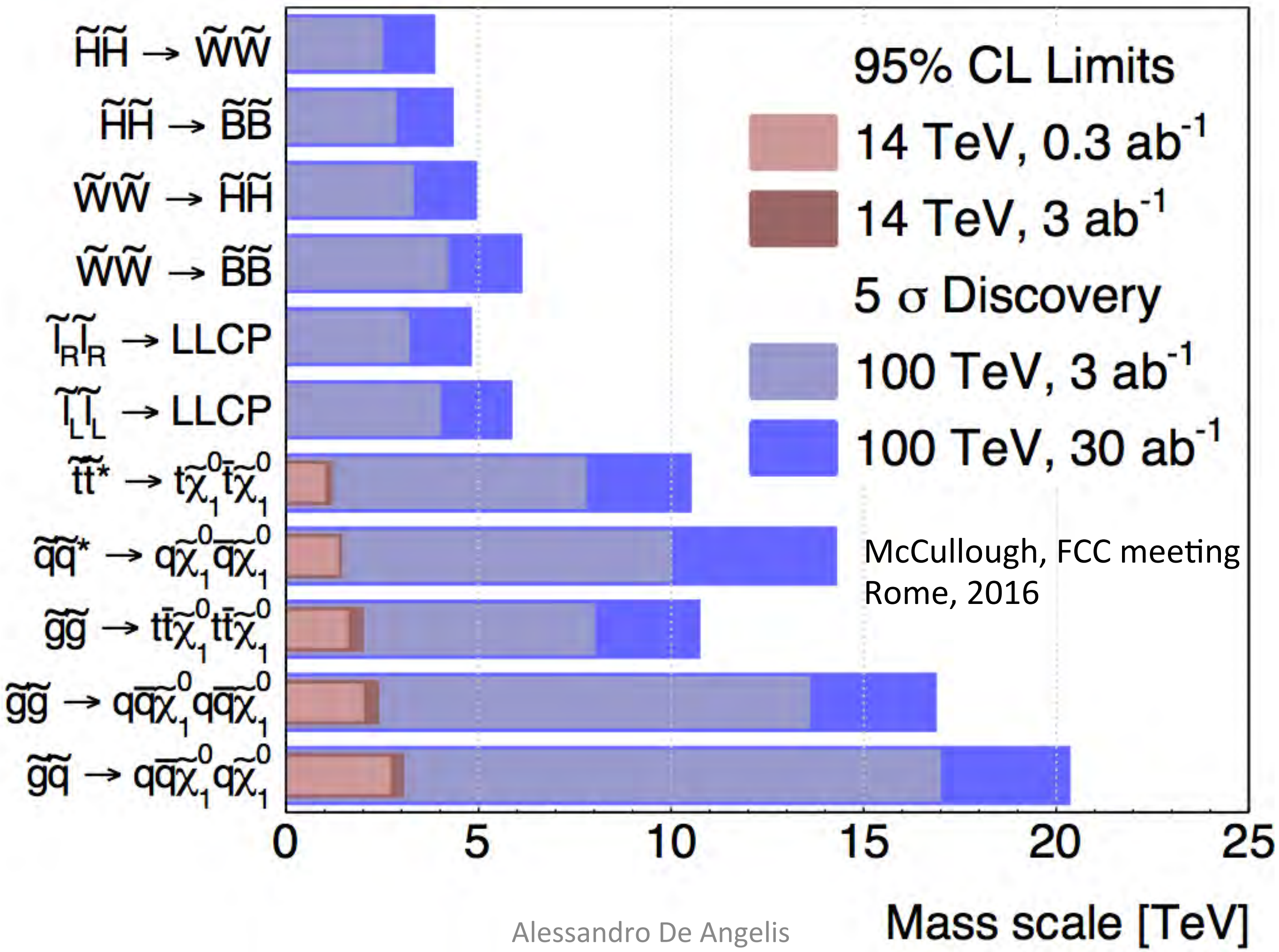
- Absence of evidence is not evidence for absence.

Directions?

- *"The discussion of the future in HEP must start from the understanding that there is no experiment/ facility, proposed or conceivable […] which can guarantee discoveries beyond the SM, and answers to the big questions of the field." (*M. Mangano, 98° ECFA meeting, Nov. 2015)

- What to do, then?

- For the moment the high luminosity way has been chosen (minimum resistance)



The HE way: guaranteed deliverables from a higher energy (100 TeV pp? 500 GeV ee?) accelerator

- Detailed study of Higgs boson (ee preferred)
  - Higgs is very special
  - Beyond HL-LHC precision

- Extreme precision physics (ee preferred)
  - Electroweak sector
  - Heavy Flavor sector

- 100 TeV pp only: Discovery of DM if WIMP up to the sensitivity of direct searches
  - But, with some more model dependence

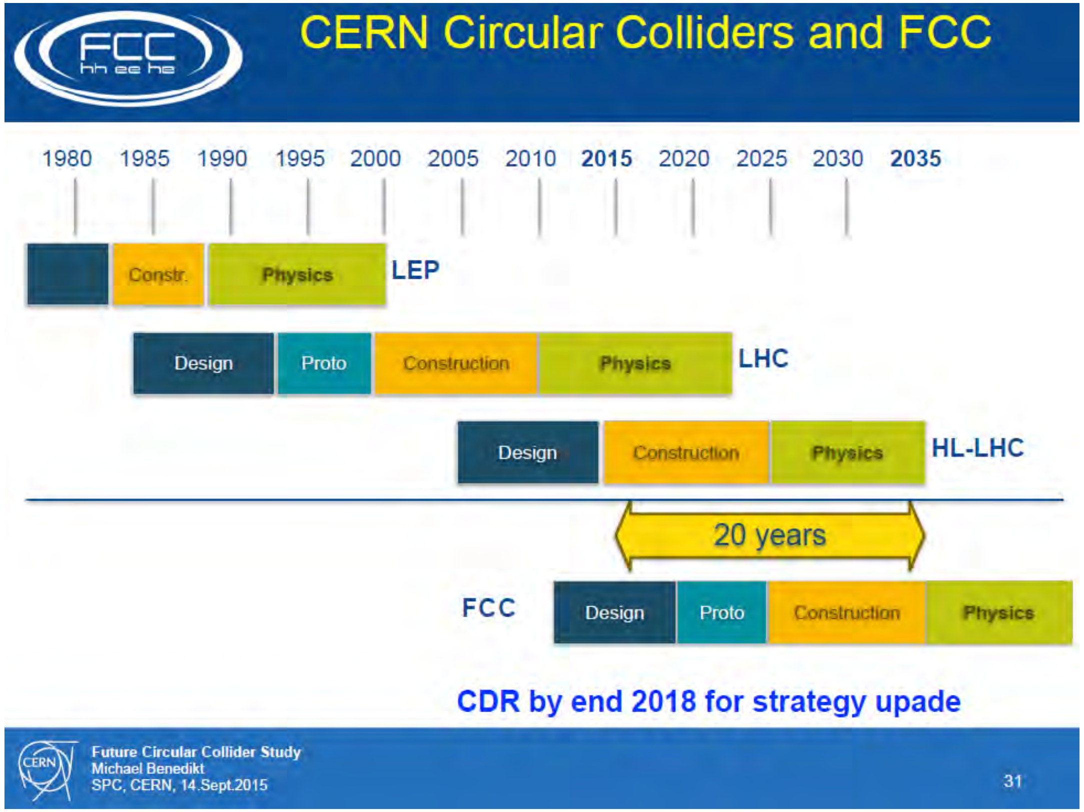
- 100 TeV pp only: Exploration potential for reasonable particles could be pushed to some 10-20 TeV

Electron machines with known technology

- ILC: linear e+e- collider
  - SC Linac 500 GeV (→1 TeV)
- Circular accelerators (CERN, China)
  - ~350 GeV
- 2030-2035?

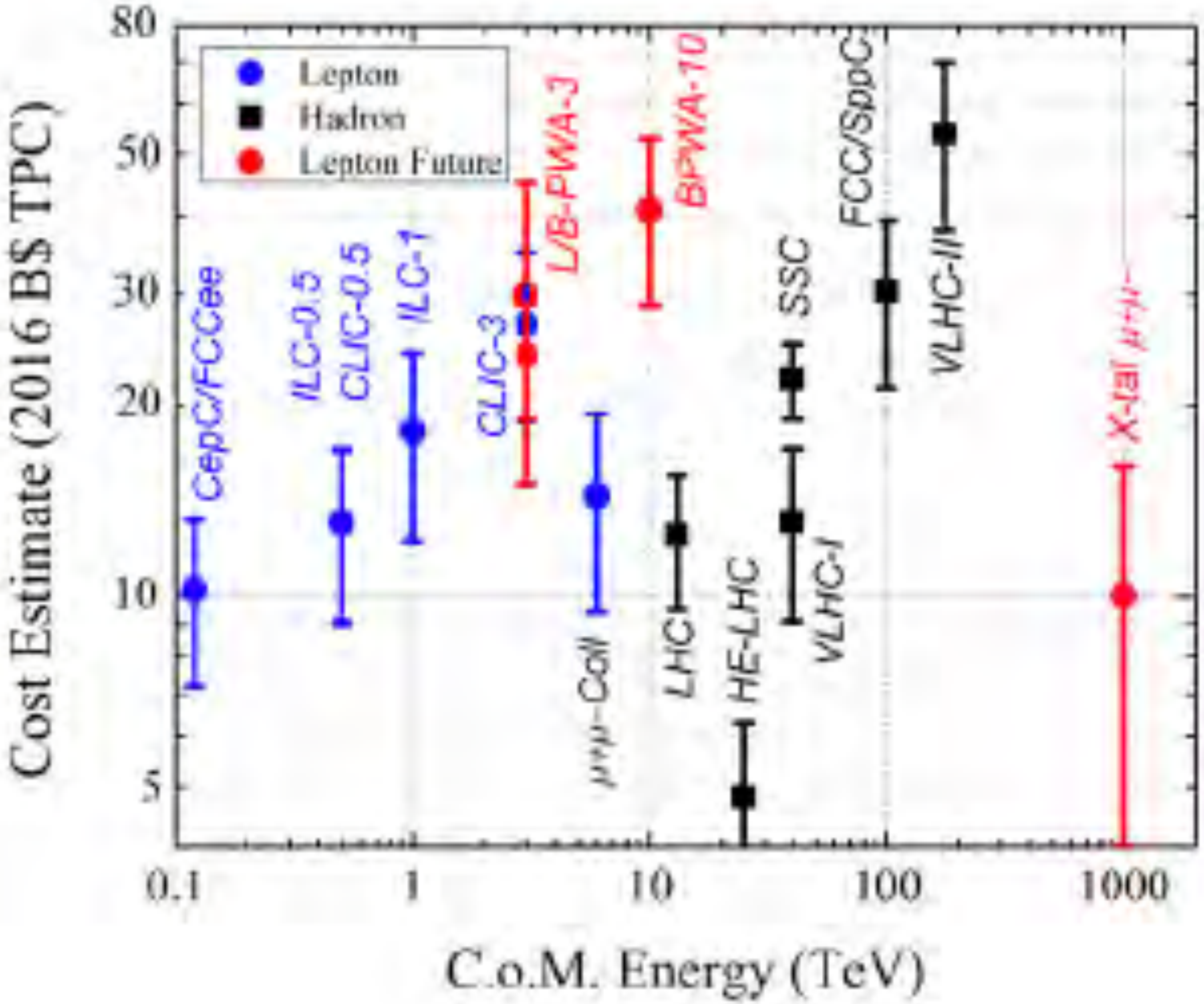
100 TeV LHC: might need some R&D

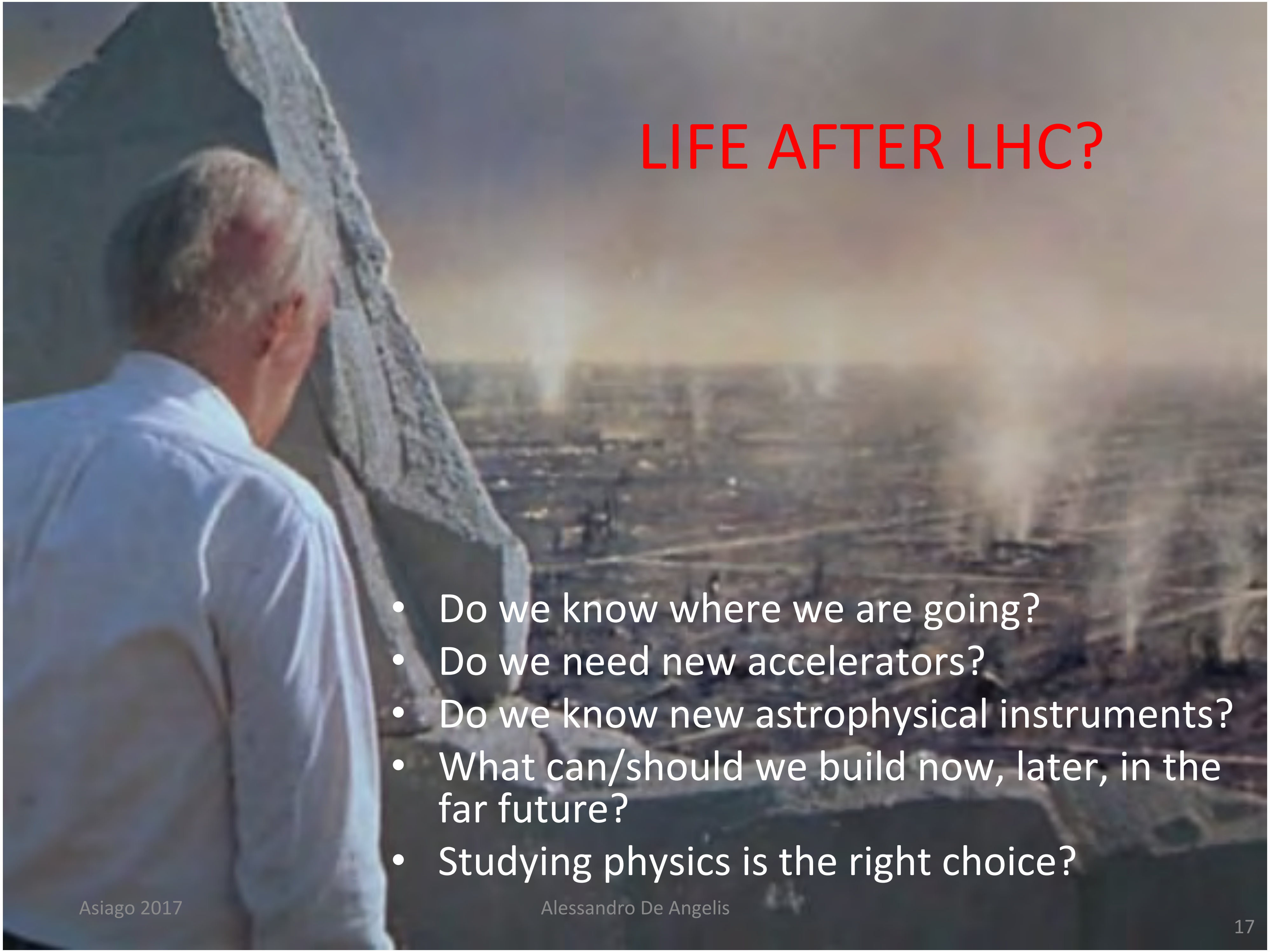
- Share tunnels with LHC
- Need high field Nb_3Sn magnets
  - 8 T (LHC) → 16 T: feasible with ~6 GEUR
  - 20 T? 50T?
    - Complex construction



- ~20 years from t_0

Will this allow to ask for an investment of (5 GEUR, 10 GEUR, 50 GEUR)?




LIFE AFTER LHC?
• Do we know where we are going?
• Do we need new accelerators?
• Do we know new astrophysical instruments?
• What can/should we build now, later, in the far future?
• Studying physics is the right choice?

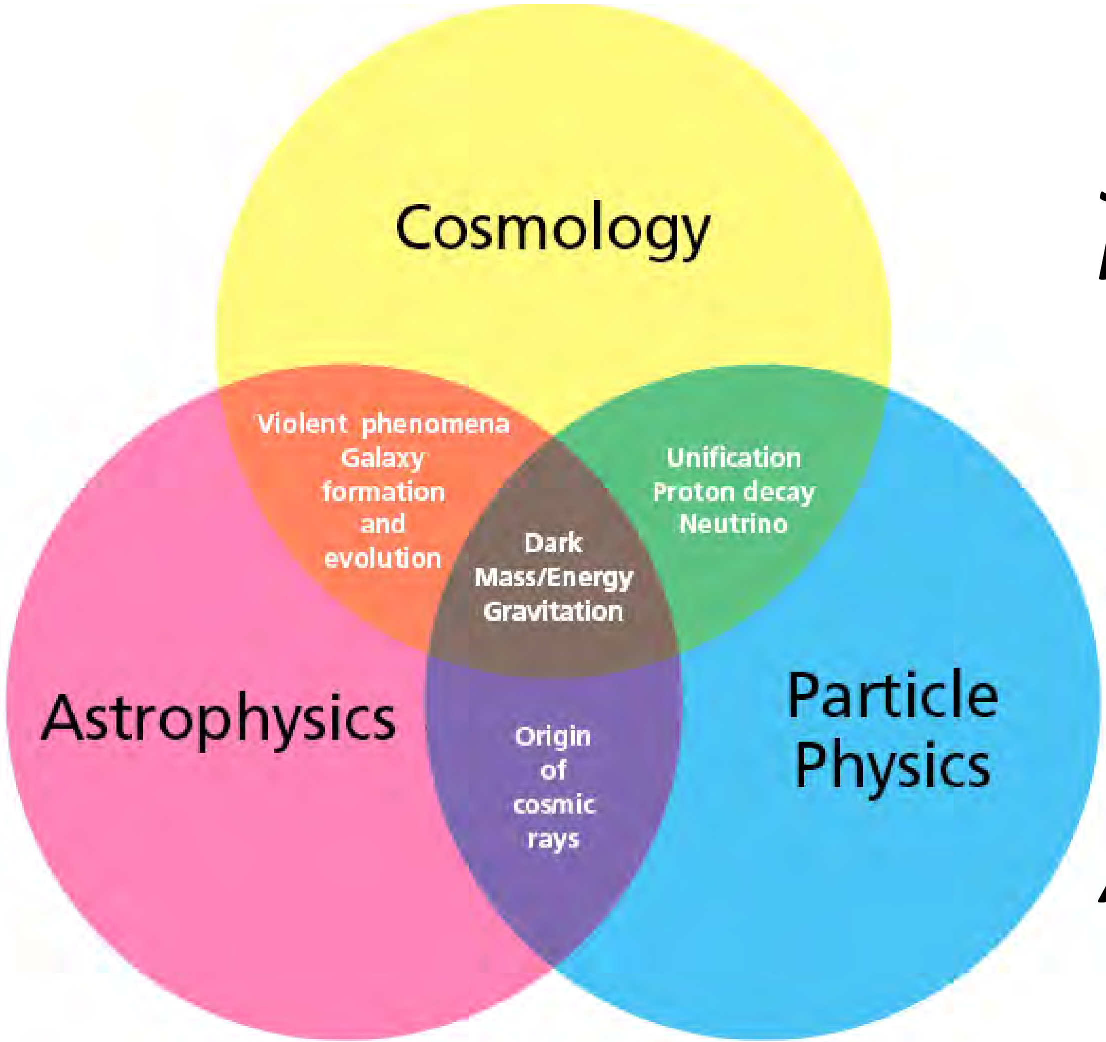
- *No experiment/facility, proposed or conceivable […] can guarantee discoveries beyond the SM, and answers to the big questions of the field.*

Let's start from the questions, now

- Dark Energy, Dark Matter: where? what?
- Elegance, Naturalness
  - So many parameters… why?
  - Why the masses are what they are?
  - Why this funny replica of families (unification, compositeness, …)?
  - Why physics as we know it looses significance at $\sim 10^{-40}$ m?
  - Why there is more matter than antimatter?

Why not?

Astroparticle physics



A multimessenger science

1. ***HE gammas***
2. ***HE neutrinos***
3. ***HE protons/nuclei***
4. ***Gravitational waves***

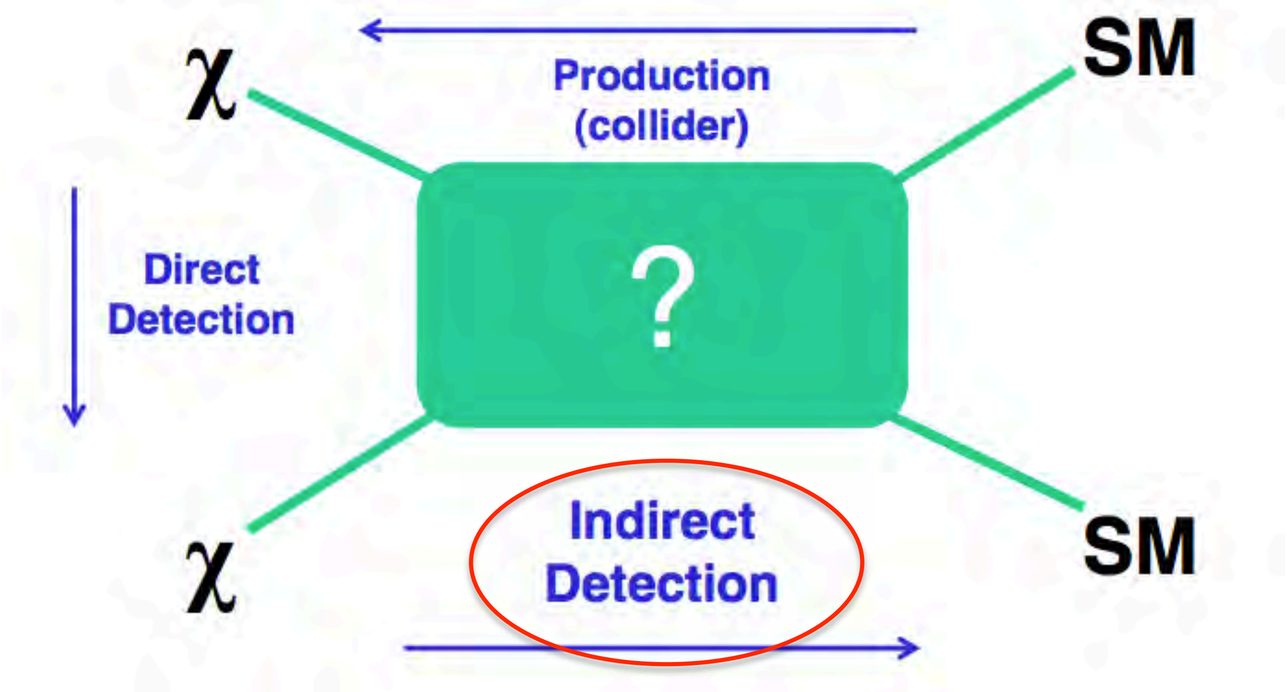
Several possible fundamental physics objectives

1. ***Dark matter/energy***
2. ***Extremely high energy collisions***
3. ***Axions, ALPs***
4. ***Neutrino properties (nature, mass, mixing)***
5. ***CMB***

And of course, astrophysics

1. ***Behavior of physics near (SM)BHs***
2. ***Acceleration mechanisms***

Dark Matter: complementarity between Direct Searches, Indirect Searches, Accelerators

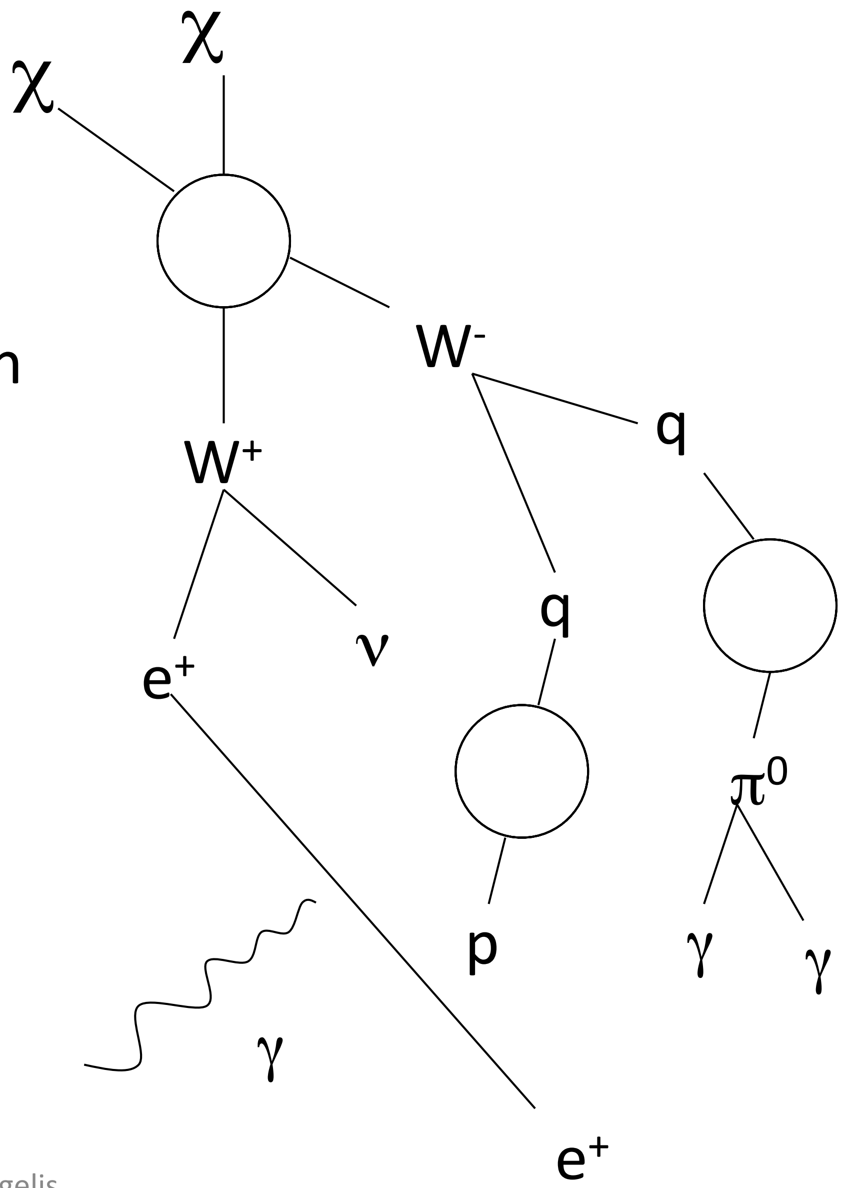


- *Indirect* detection is sensitive to high mass scales (particles already exist, stable final state particle spectrum peaks at ~10% of m_{DM}). And we know where to look. But: unknown DM-DM cross section.
- *Direct detection* is sensitive to scattering off nuclei. But: ultimate limit from neutrinos; depends on DM-nucleon cross section.
- *Production* (accelerators) allows a precise measurement of couplings and mass. Depends on DM-vector boson or nucleus cross section.

The indirect detection of DM

- **WIMP Annihilation** Typical final states include heavy fermions, gauge or Higgs bosons

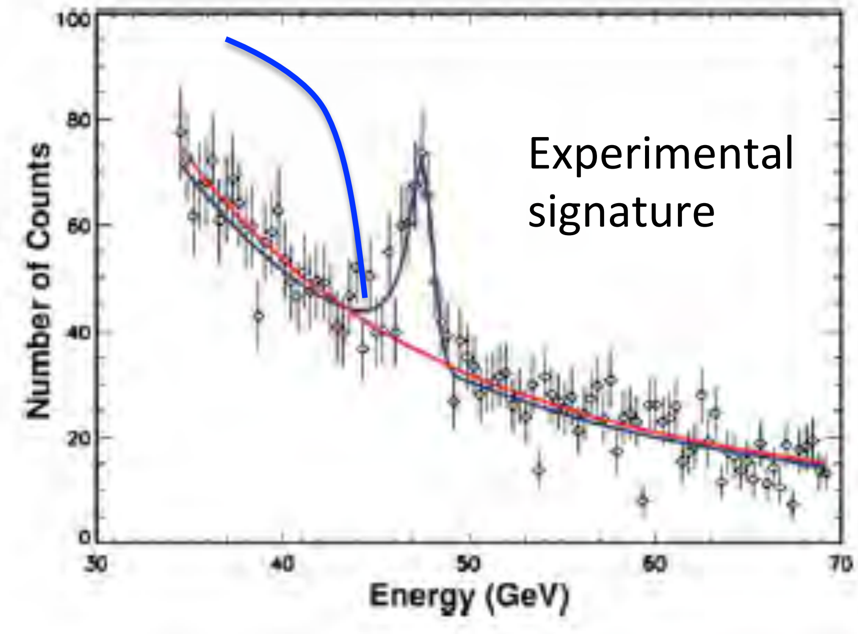
- **Fragmentation/Decay** Annihilation products decay and/or fragment into combinations of electrons, protons, deuterium, (and their antiparticles), gamma-rays and neutrinos

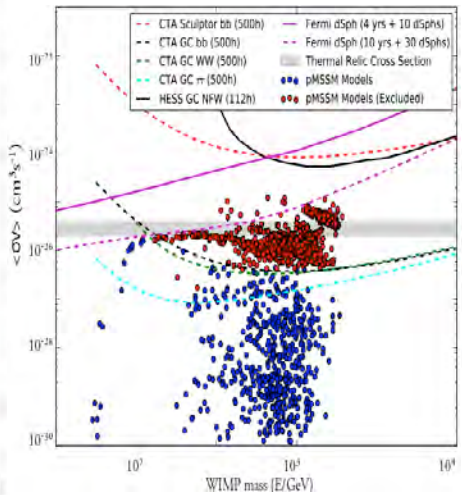


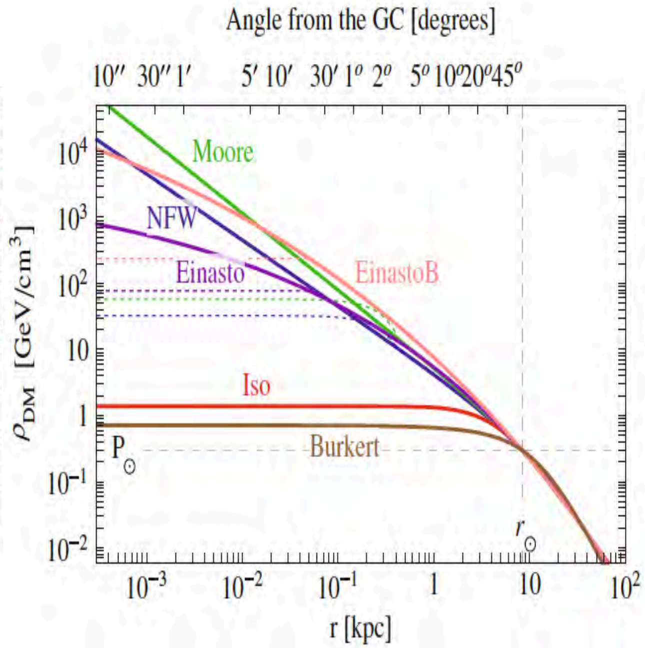
The key formula for WIMP Searches

Particle Physics | **Astrophysics (*J*-Factor)**

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los}\rho^2(r(l,\phi'))dl(r,\phi')$$







- *J*-factor includes distance, i.e., *J*-factor would decrease by four if a point-like source were twice as far away => look as close as possible
- The factor of $1/m_\chi^2$ is due to the fact we express the *J*-factor as a function of mass density (which we can measure), not number density
- We usually call χ the generic WIMP, like the SUSY neutralino, but it's more general

Targets for indirect searches

Satellites

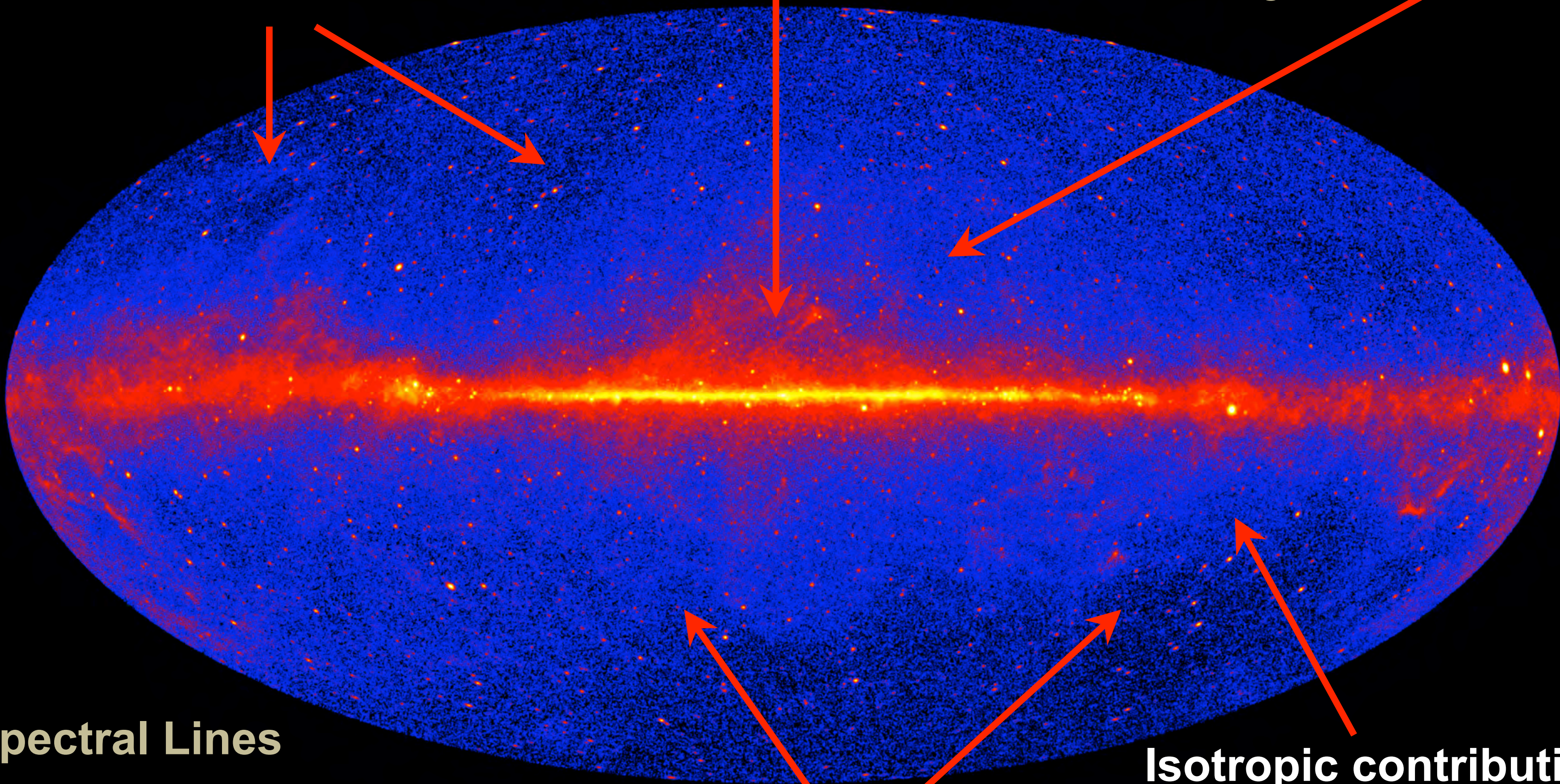
Low background and good source id, but low statistics

Galactic Center

Good statistics, but source confusion/diffuse background

Milky Way Halo

Large statistics, but diffuse background



Spectral Lines

Little or no astrophysical uncertainties, good source id, but low sensitivity because of expected small branching ratio

Galaxy Clusters

Low background, but low statistics

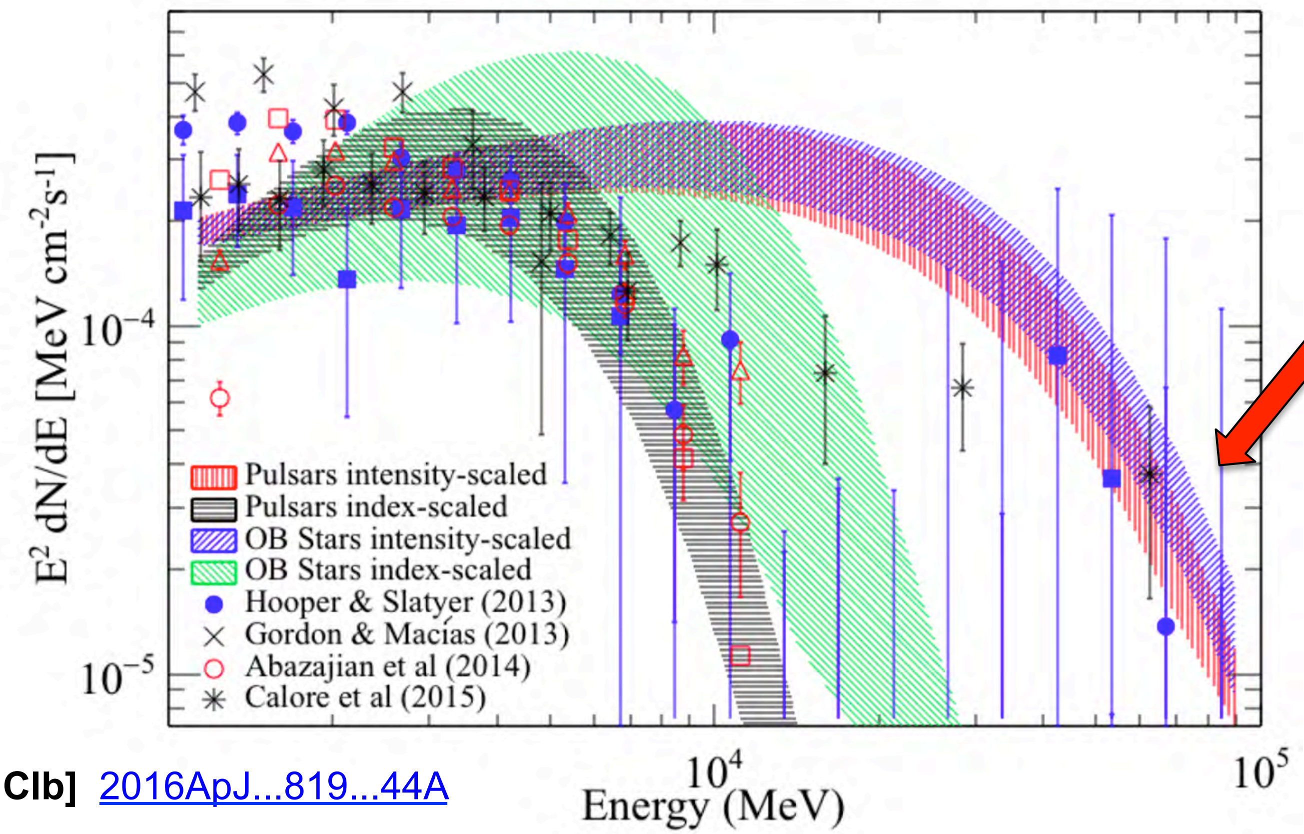
Isotropic contributions

Large statistics, but astrophysics, galactic diffuse background

LAT 7 Year Sky > 1 GeV

Some hints at ~40-80 GeV

Spectral Energy Density for Galactic Center Excess Compared to Several Models

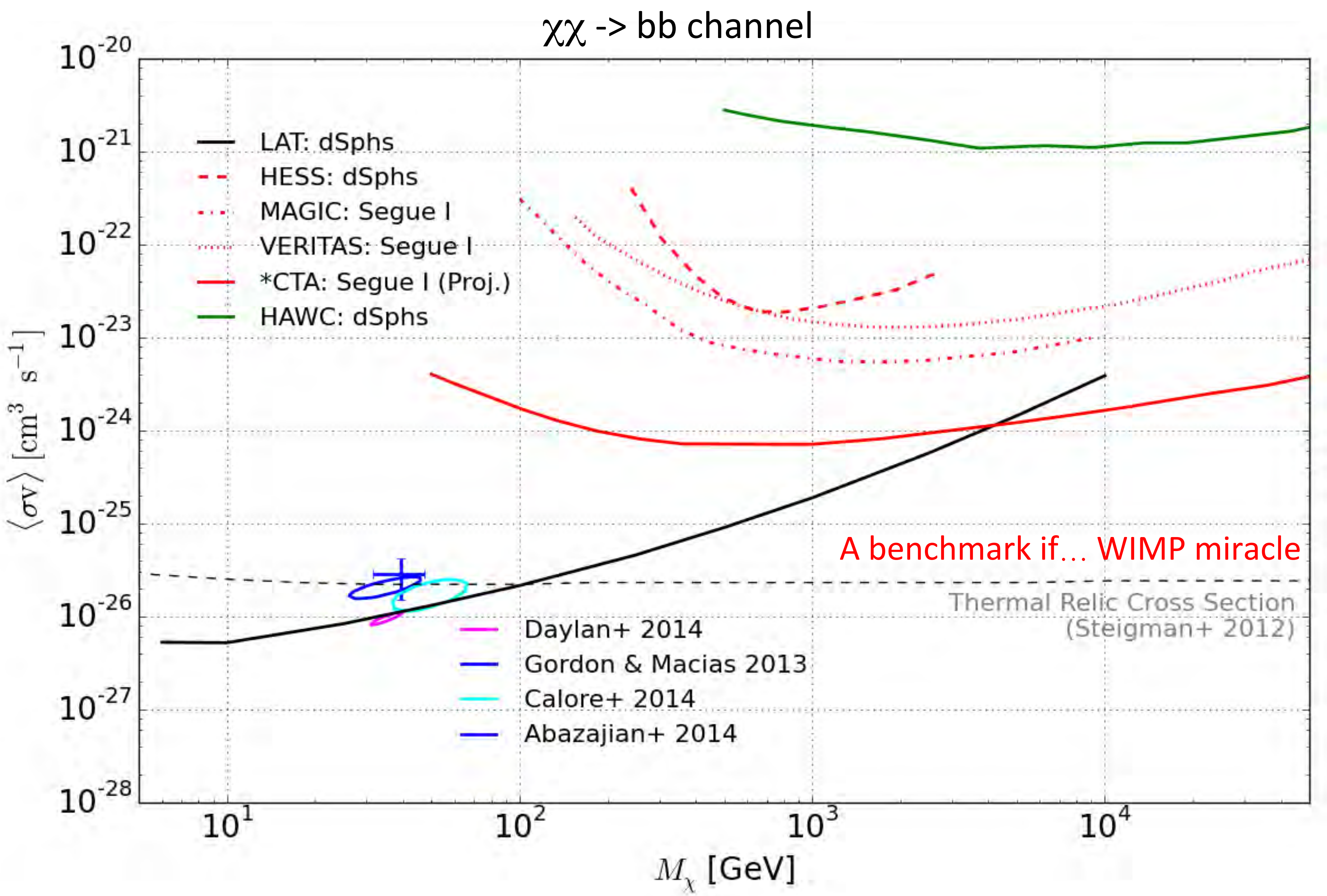


Emission above 50 GeV not from 50 GeV dark matter

Ajello+ [LAT CIb] 2016ApJ...819...44A

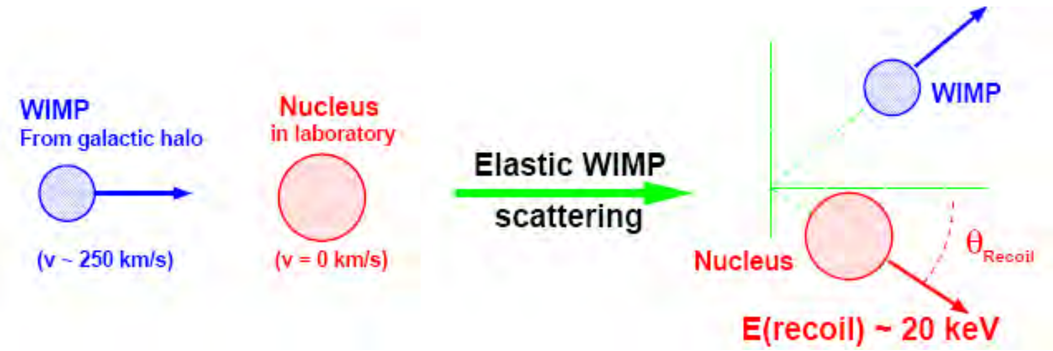
- The presence for an γ-ray excess with respect to the modeled diffuse emission at the Galactic center at a few GeV is well established
- However, the details (and the interpretation) of the excess depend on the modeling of the astrophysical fore/background

Indirect searches for Dark Matter



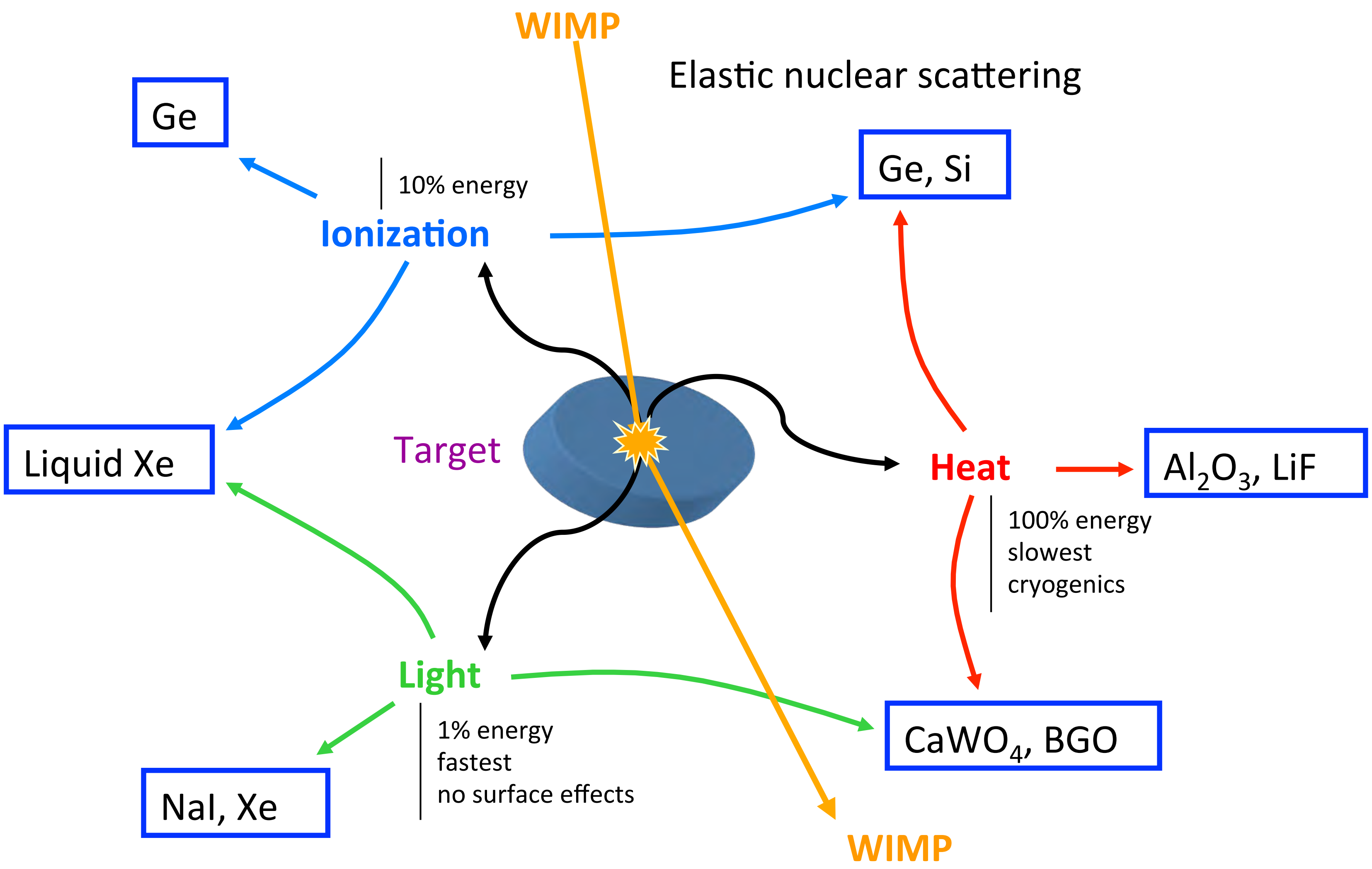
Direct search principle

- Detection of the energy deposit due to elastic scattering on nuclei of detector in laboratory experiment



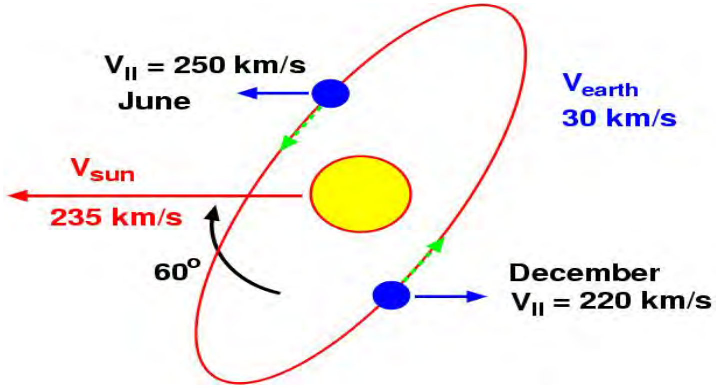
- Optimum sensitivity for $M_{WIMP} \sim M_{RECOIL}$
- Rate < 1 evt/day/kg of detector
  - Need low background
    - Deep underground sites
    - Radio-purity of components
    - Active/passive shielding
  - Need large detector mass (> ton)
- Recoil energy ~ 20 keV
  - Need low recoil energy threshold

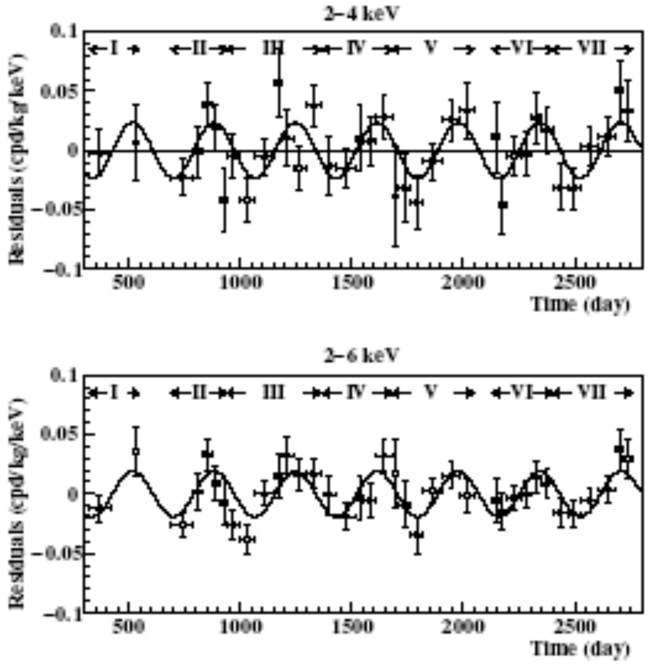
Direct detection techniques



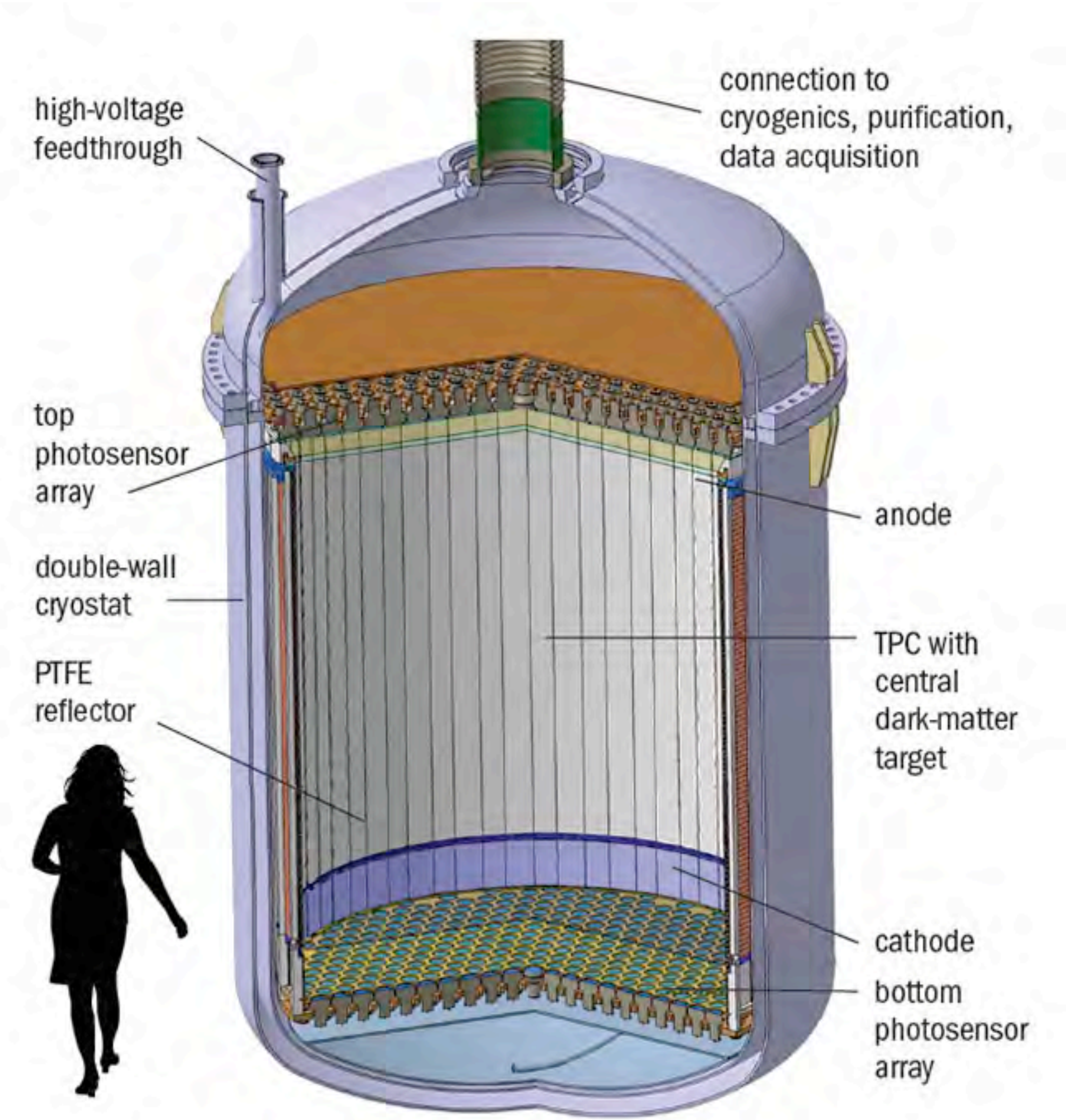
NaI scintillation : DAMA

- Based in Gran Sasso lab (3500 mwe)
- 100 kg of NaI(Tl)
- Exposure : 107731 kg.d
- Coincidence between 2 PMTs
- Pulse shape rejection inefficient at 2 keV_{ee}
- Used annual modulation
- Claim annual modulation at 6.3σ over 7 annual cycles
  - $M\chi \sim 52\ GeV/c^2$
  - $\sigma_n \sim 7.2\ 10^{-6}$ pb
- Not compatible with CDMS, EDELWEISS experiments
- Future = LIBRA (250 kg of NaI)

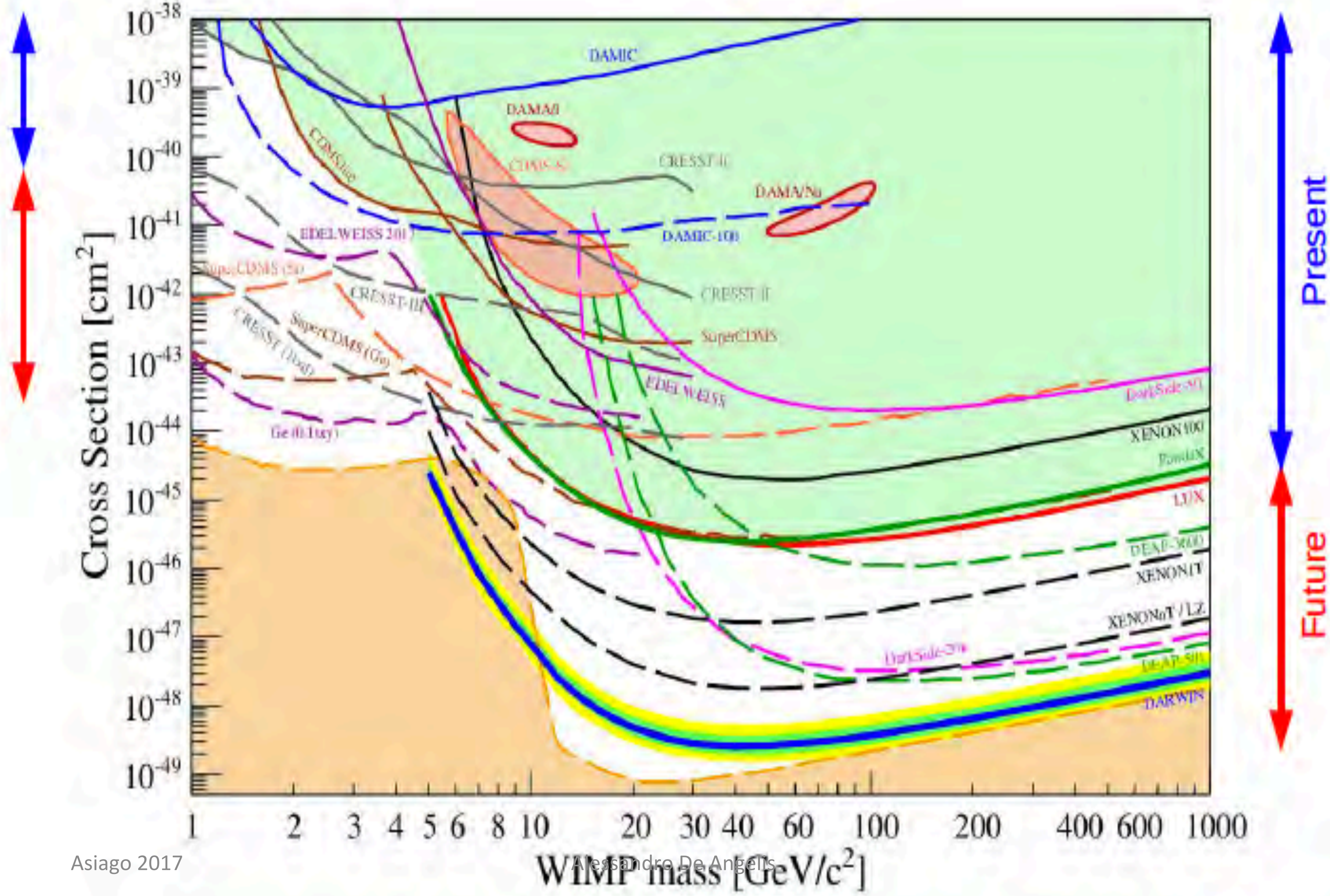




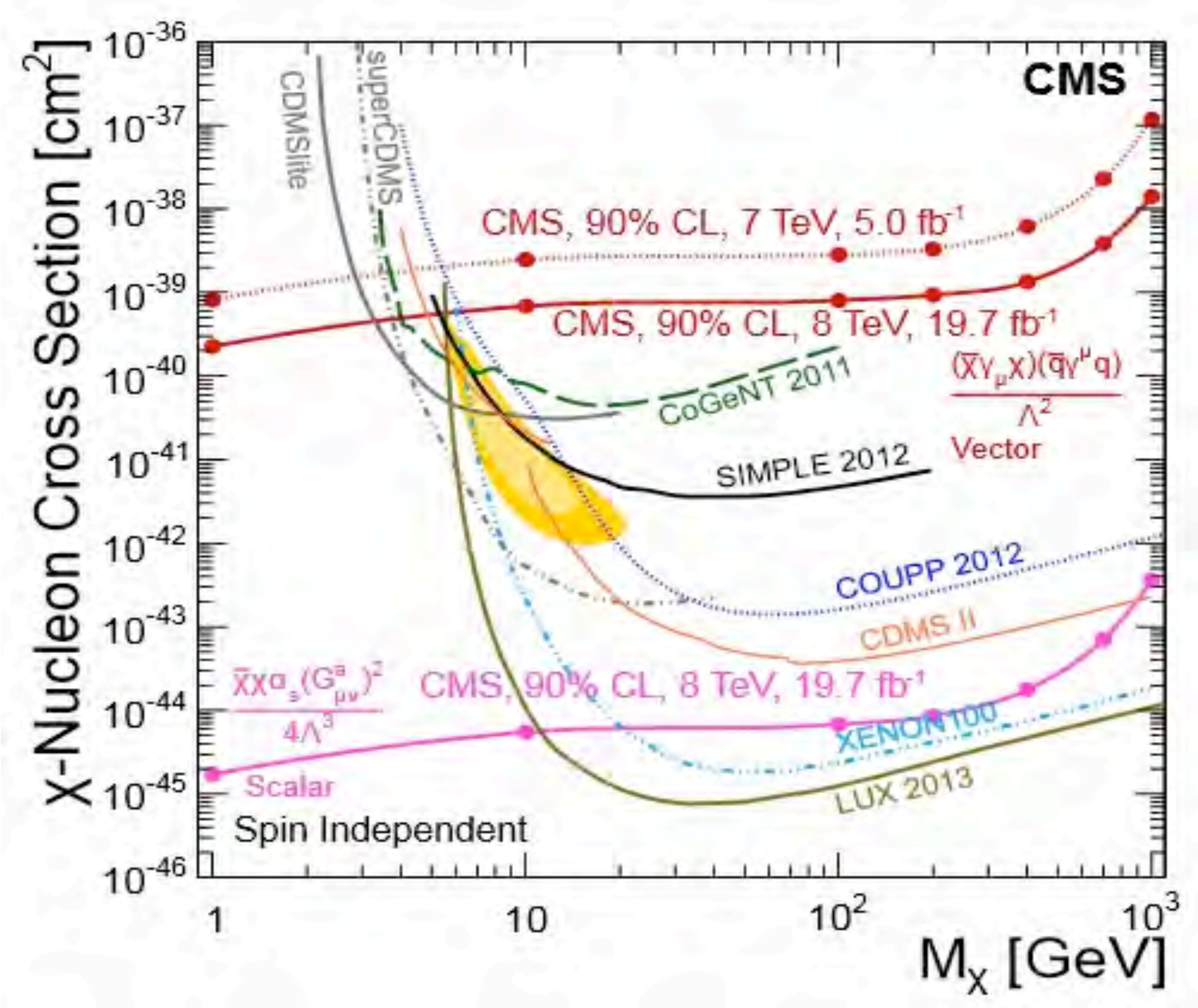
- A multi-ton direct DM project could be realized, for example at the Italian Gran Sasso Laboratory (LNGS) by the mid-2020s



Direct searches: present and future



LHC: limits presently competitive only for small mass (model-dependent)



- In a few years, we'll explore the full explorable range for a WIMP

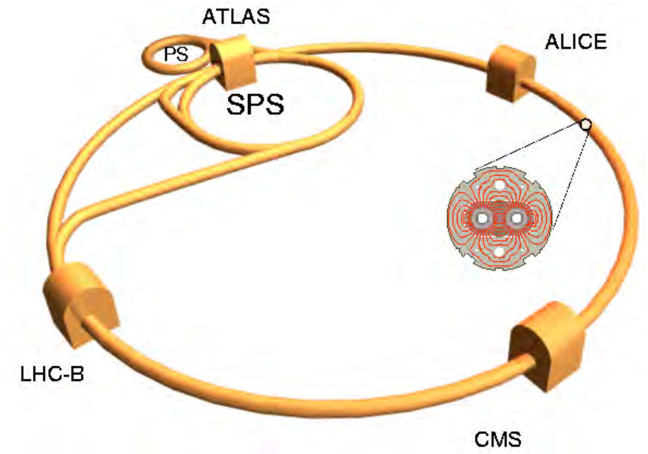
What if we don't find DM?

- Very low coupling, it is not a WIMP
  - Very difficult to find out
- It is not a particle
  - Very difficult to find out
- It does not exist: gravity is different from what we expect
  - We might find out
- The only reasonable thing seems to travel in the unknown

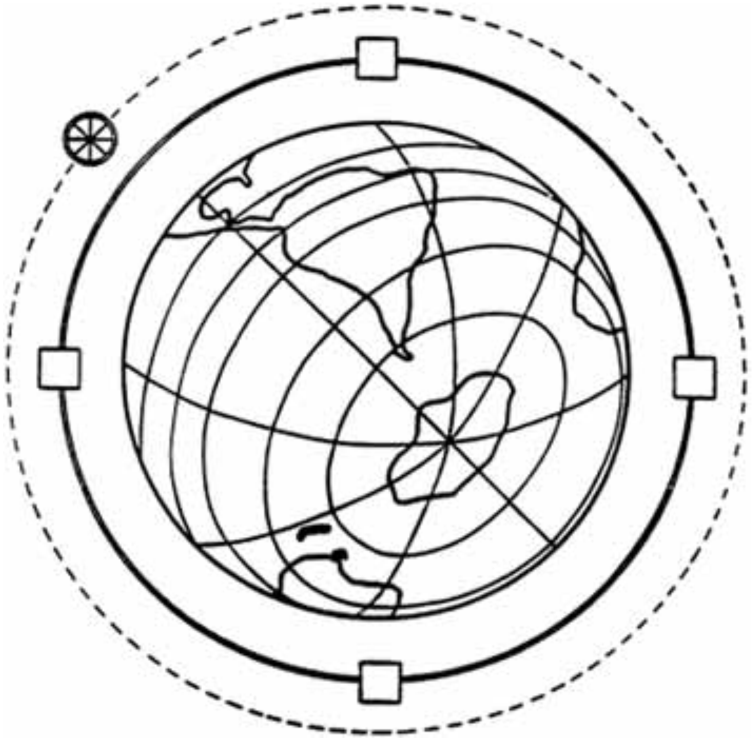
E ∝ BR

The unknown

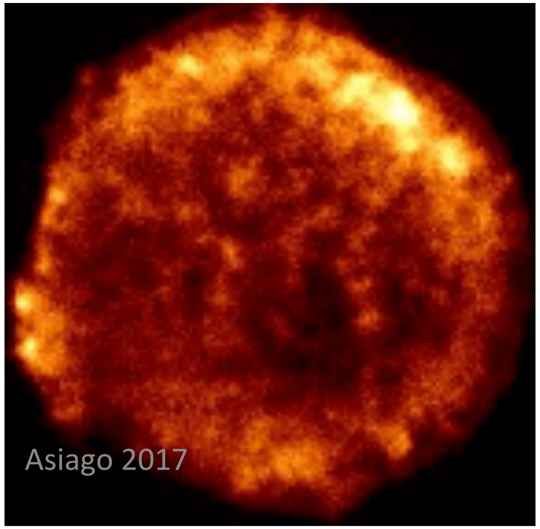
Large Hadron Collider



R ~ 10 km, B ~ 10 T
⇒ E ~ 10 TeV



Tycho SuperNova Remnant



R ~ 10^{15}km, B ~ 10^{-10}T
⇒ E ~ 1000 TeV

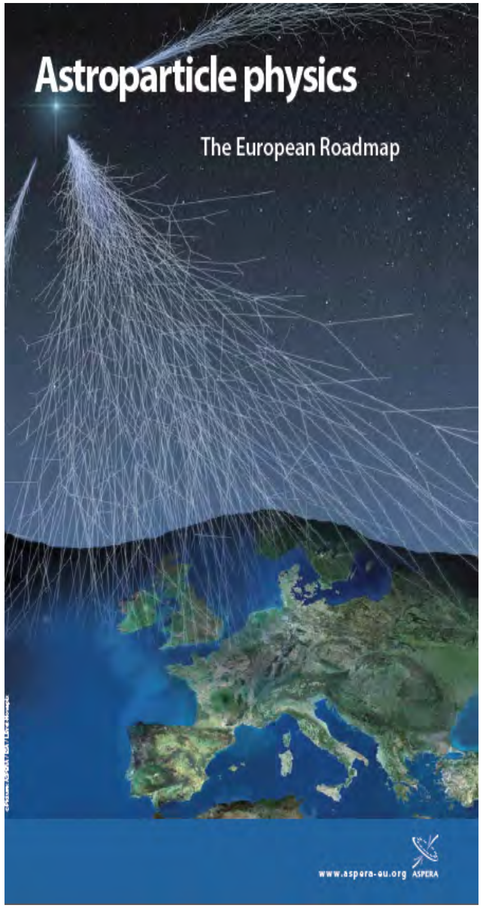
The maximum energy attainable on Earth is ~ 5000 TeV

But low luminosity, uncertain initial conditions.
Anyway, keep on eye on Auger!!!

APPEC: *roadmapping*

2008

2011



From the Nature article

Magnificent 7

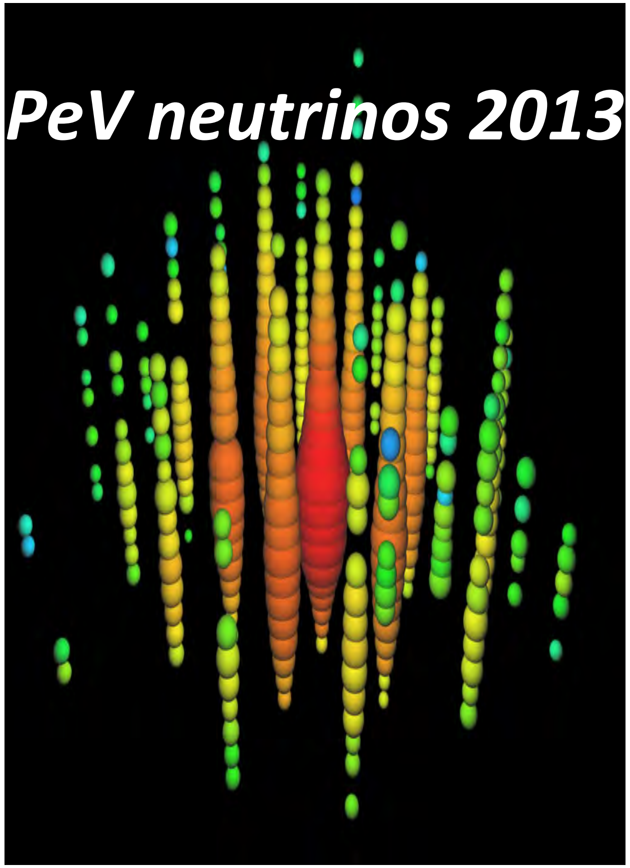
1. ***HE gammas***
2. ***HE neutrinos***
3. ***HE cosmic rays***
4. ***Gravitational waves***
5. ***Dark matter***
6. ***ν-mass***
7. ***ν-mixing & p-decay***

CMB

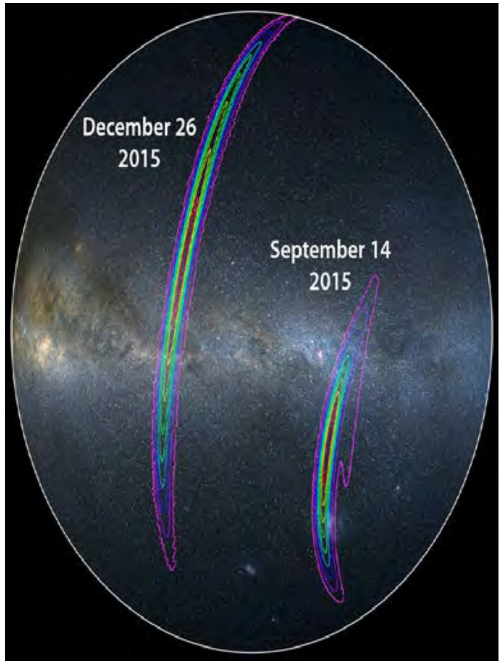
Dark Energy

Food for thoughts: they rank in the 5th place the most fundamental problem we can tackle

Two new multimessenger domains have detected a signal recently

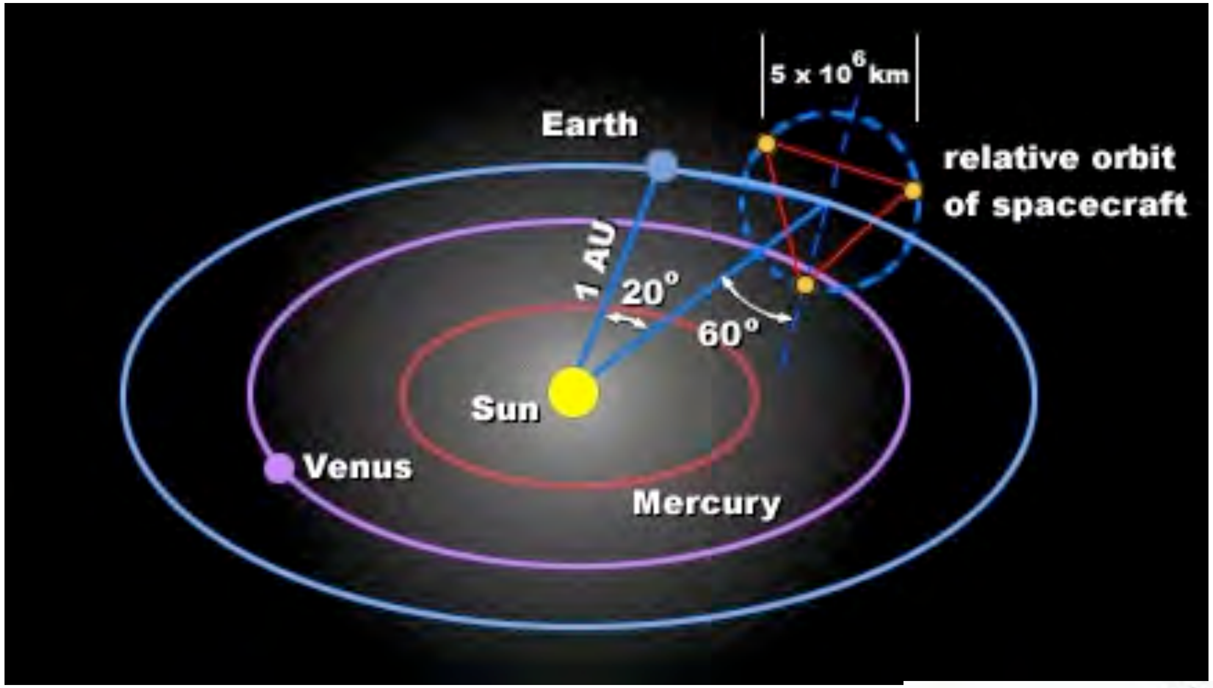


GW1509-2014

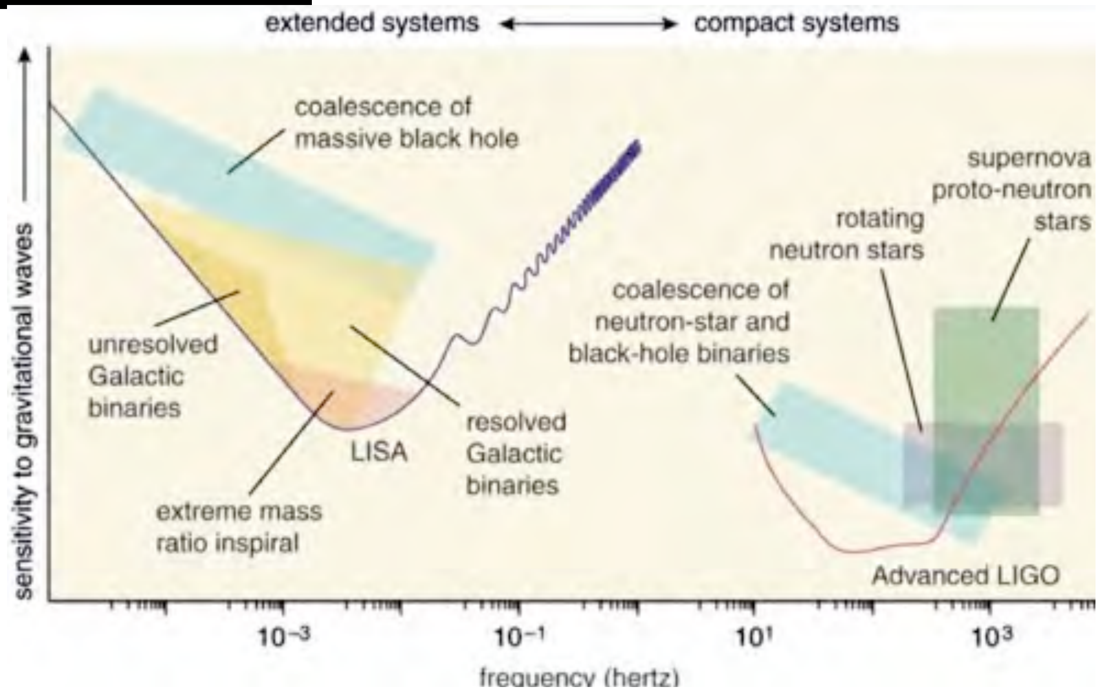


The search of point sources for HE cosmic-rays, neutrinos and GW (better pointing) ongoing

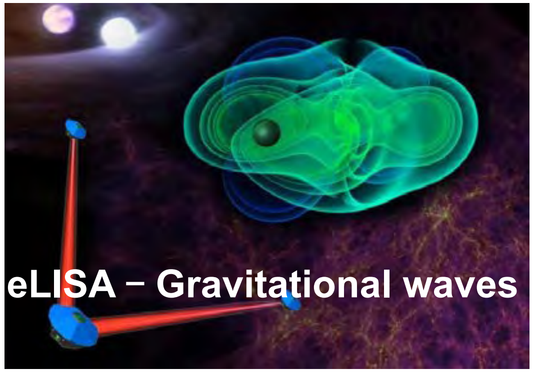
VIRGO will soon improve LIGO localization accuracy…



LISA: the frontier of gravitational waves (approved Jun 2017)

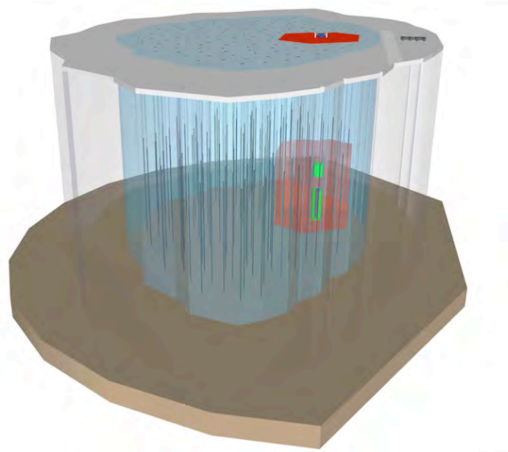


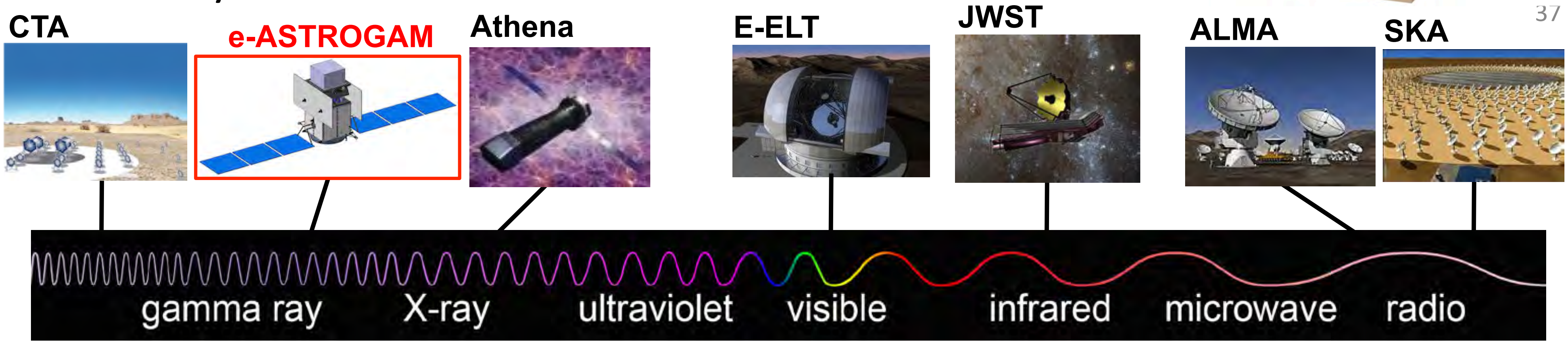
e-ASTROGAM (Europe) & AMEGO (US) – 2028/29



1. Processes at the heart of the extreme Universe (AGNs, GRBs, microquasars): prospects for the Astronomy of the 2030s
    - Multi-wavelength, multi-messenger coverage of the sky (with CTA, SKA, eLISA, ν detectors...), with special focus on transient phenomena
2. The origin of high-energy particles and impact on galaxy evolution, from cosmic rays to antimatter
3. Nucleosynthesis and the chemical enrichment of our Galaxy

Km3Net/IceCube-Gen2 - ν



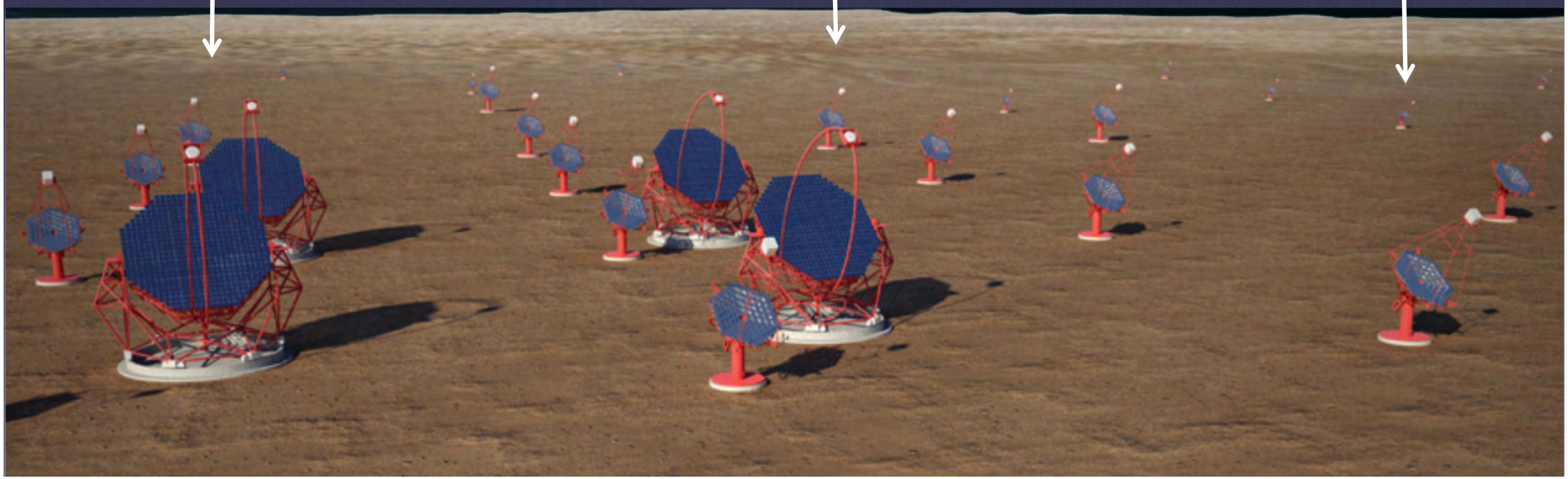


CTA, a multi-telescope Cherenkov array
(1500 scientists from 200 insitutes in 32 countries)

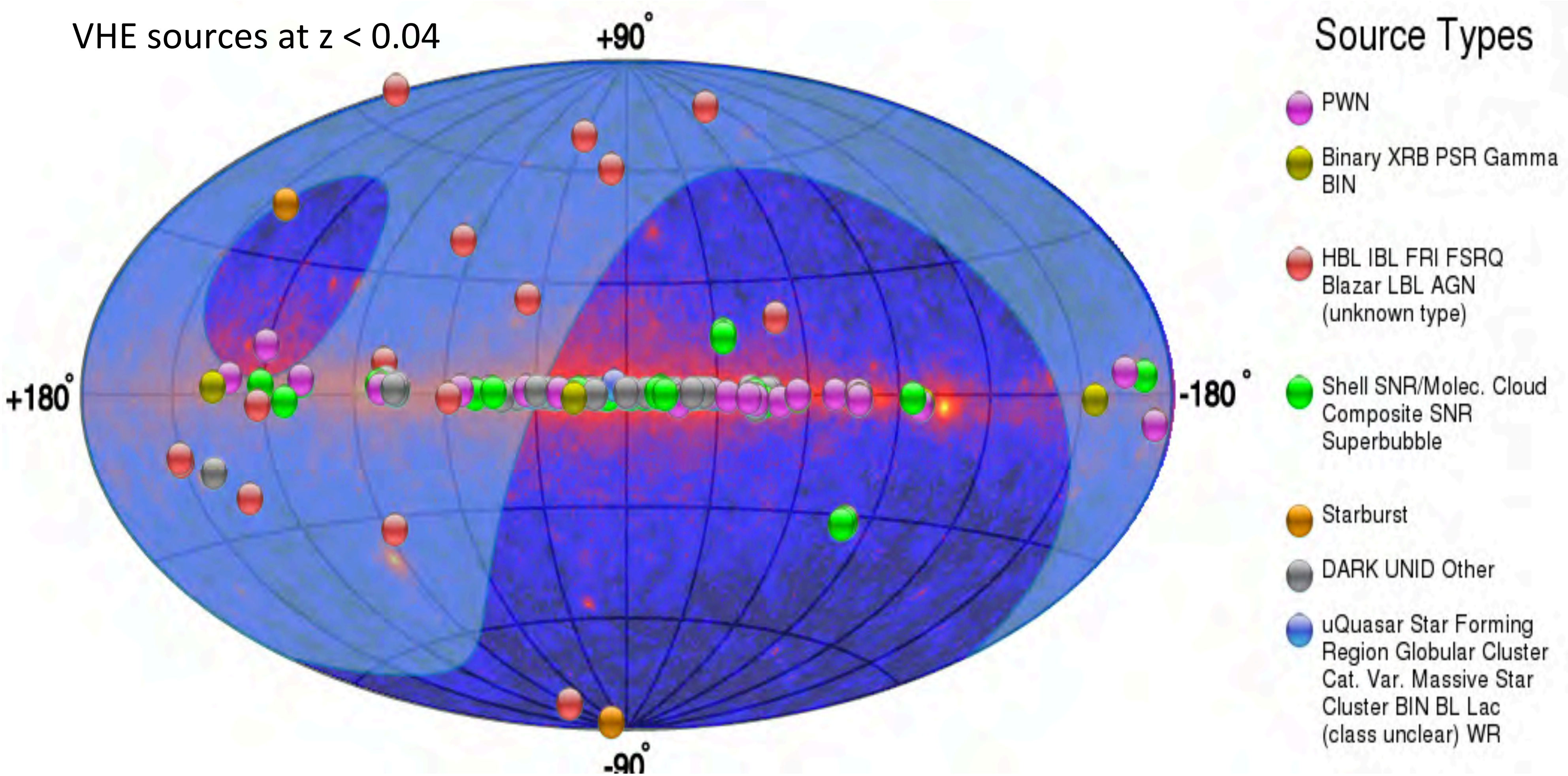
Low energies
Energy threshold 20 GeV
23 m diameter
4 telescopes
(LST)

Medium energies (MST)
100 GeV – 10 TeV
9.5 to 12 m diameter
25 single-mirror telescopes
up to 24 dual-mirror telescopes
mCrab sensitivity in 50h at 0.1-10 TeV

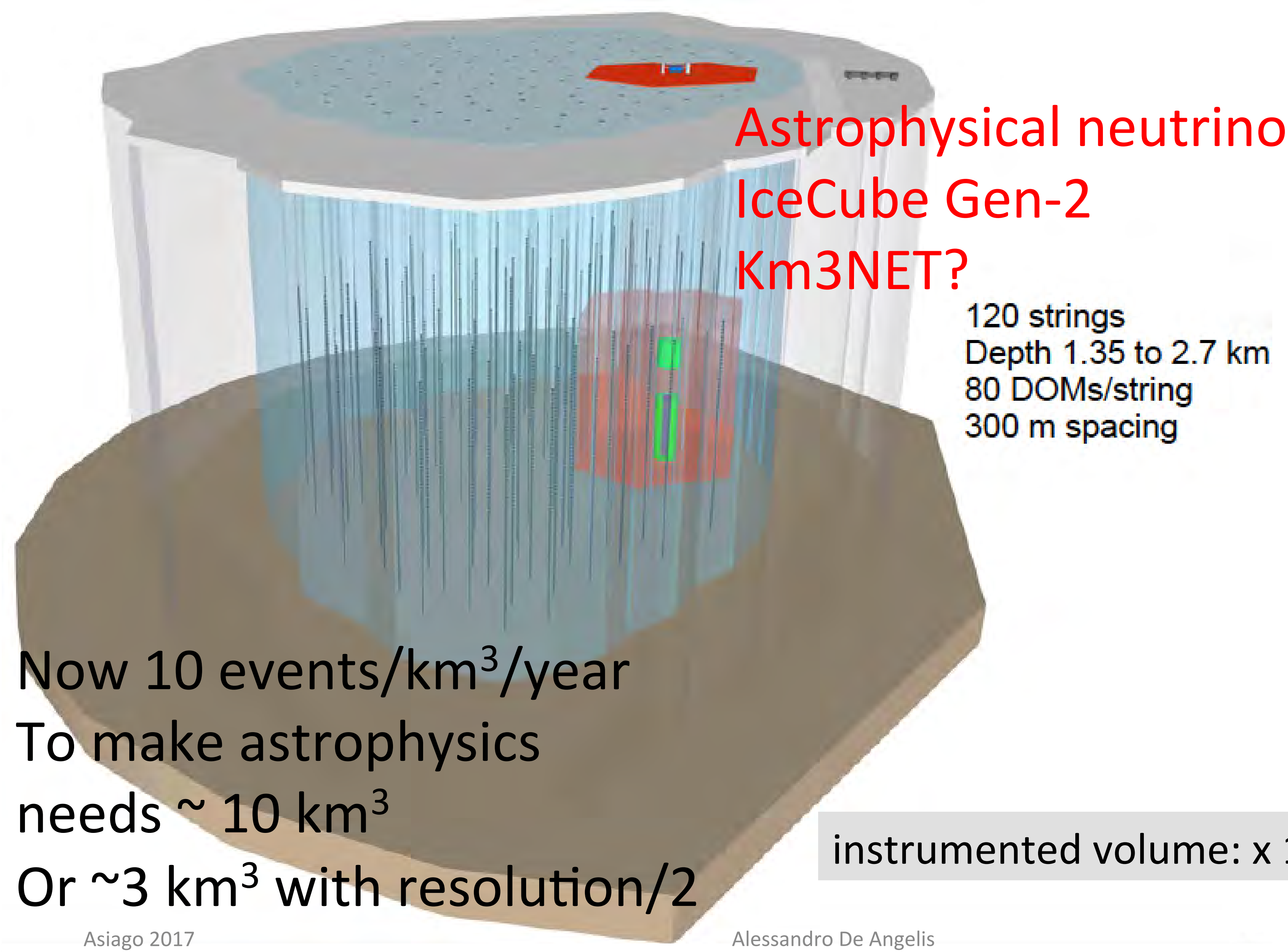
High energies
10 km^2 area at few TeV
4 to 6 m diameter
70 telescopes
(SST)



HAWC+, LHAASO, HiSCORE ~ funded, but strong case for a sub-PeV EAS experiment in the Southern hemisphere LATTES? HAWC-South?



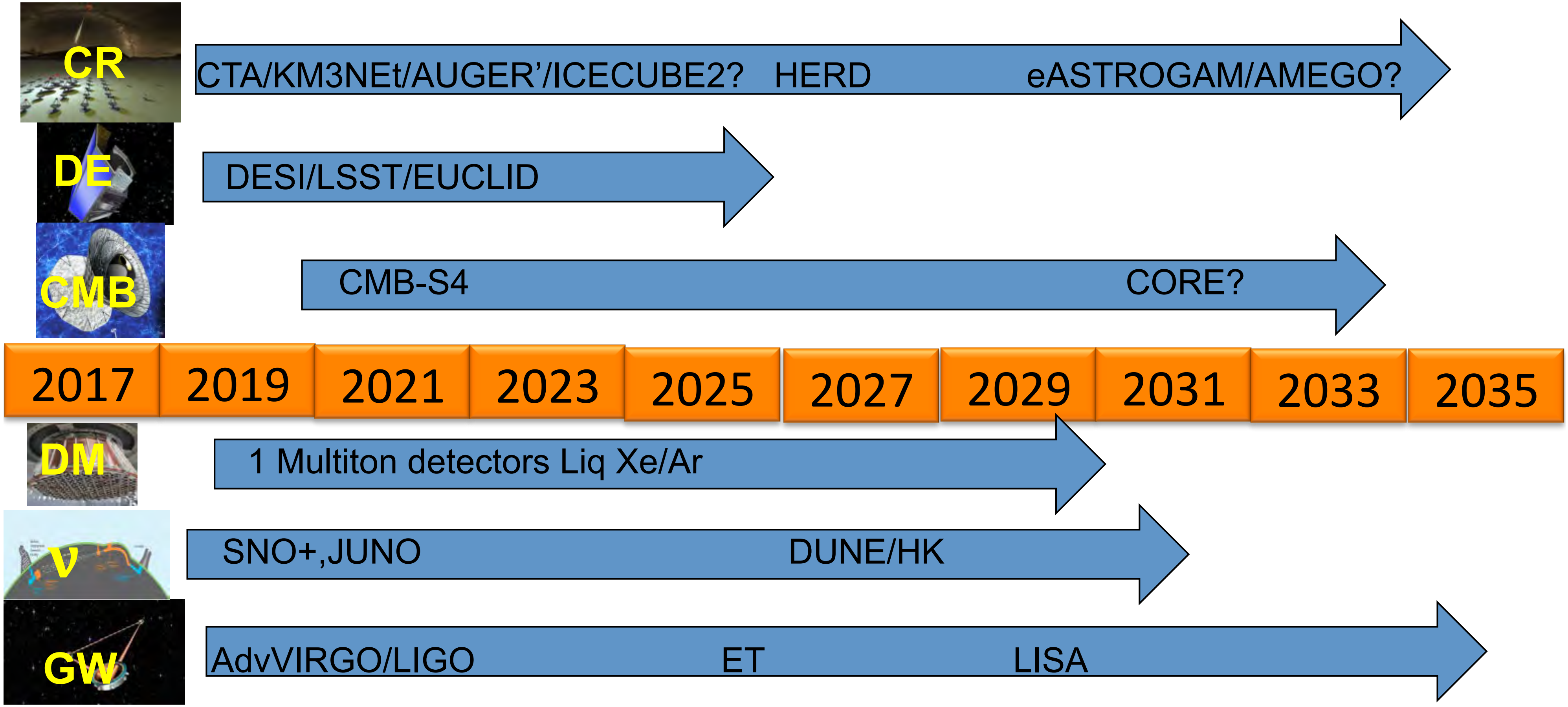
Astrophysical neutrinos
IceCube Gen-2
Km3NET?



Now 10 events/km^3/year
To make astrophysics
needs ~ 10 km^3
Or ~3 km^3 with resolution/2

instrumented volume: x 10

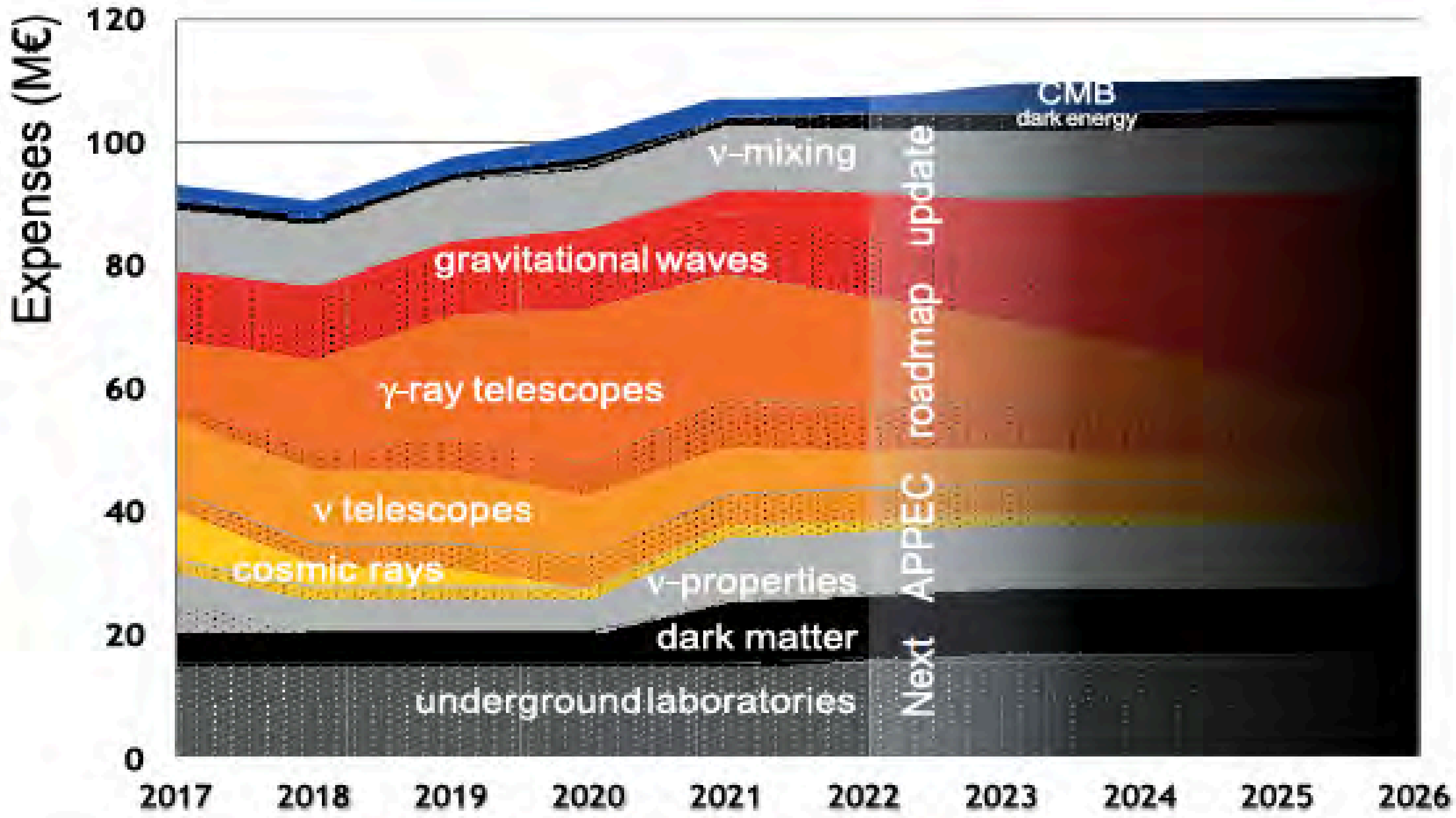
Agencies need (like?) to make plans…



…and to offer money in exchange of granted science

(budget excluding manpower, labs, regional funds, and competitive calls by NASA/ESA.)

(M/L space missions approved can be ~50 MEUR/year on top of this)



- At variance wrt accelerator physics, many experiments at different scales of funding
- Granted science in the next 10 years (fundamentality is questionable):
  - Localization of acceleration sites of cosmic rays
  - Origin of gravitational waves, and multiwavelength analysis
  - Neutrino masses and hierarchy (?)
  - …

  and the preparation of experiments capable to clarify (if possible) the problem of the energy budget of the Universe
- Fortunately, Nature is largely independent of what we (and agencies) think, and detectors and scientists are somehow as well: we can have surprises like in recent years (neutrino mass, BH mergings, structure of the Milky Way, …)


In moments of confusion like this one, we tend to follow the people who pretend to know where to go, even when they appear to be blindfolded

But maybe we should just keep an eye to the sky, and surprises might come

Thanks and see you soon in any research field…

Godel's theorem for children

- If you are inside, you can't know everything
- Ultimate limit to mathematics for explaining the Universe
- Maybe what we call fundamental symmetries are just emerging symmetries