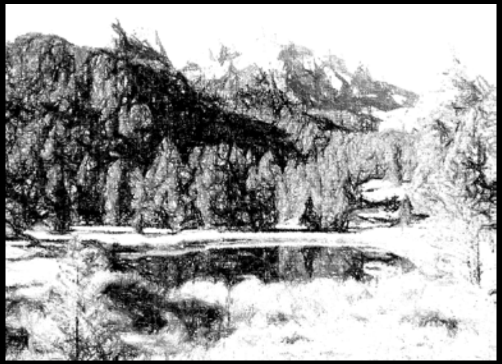
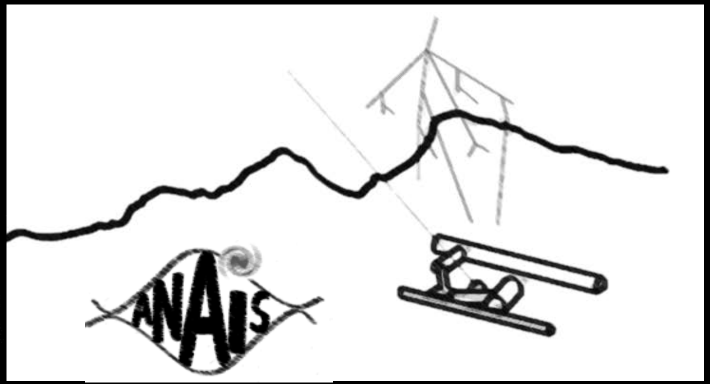


Dark Matter Review

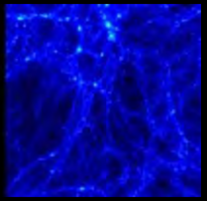
M.L. Sarsa

Centro de Astropartículas y Física de Altas Energías, UNIVERSIDAD DE ZARAGOZA



MultiDark

Multimessenger Approach for Dark Matter Detection



XLVIII International Meeting on Fundamental Physics

BENASQUE, 7 September 2021

LSC Laboratorio Subterráneo de Canfranc

CAPA Centro de Astropartículas y Física de Altas Energías Universidad Zaragoza

ACKNOWLEDGMENTS

The Review of Particle Physics (2021)

P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020) and 2021 update

Direct Detection of Dark Matter - APPEC Committee Report

arXiv:2104.07634v1 [hep-ex] 15 Apr 2021

EPS-HEP2021 & TAUP2021 speakers and organizers:

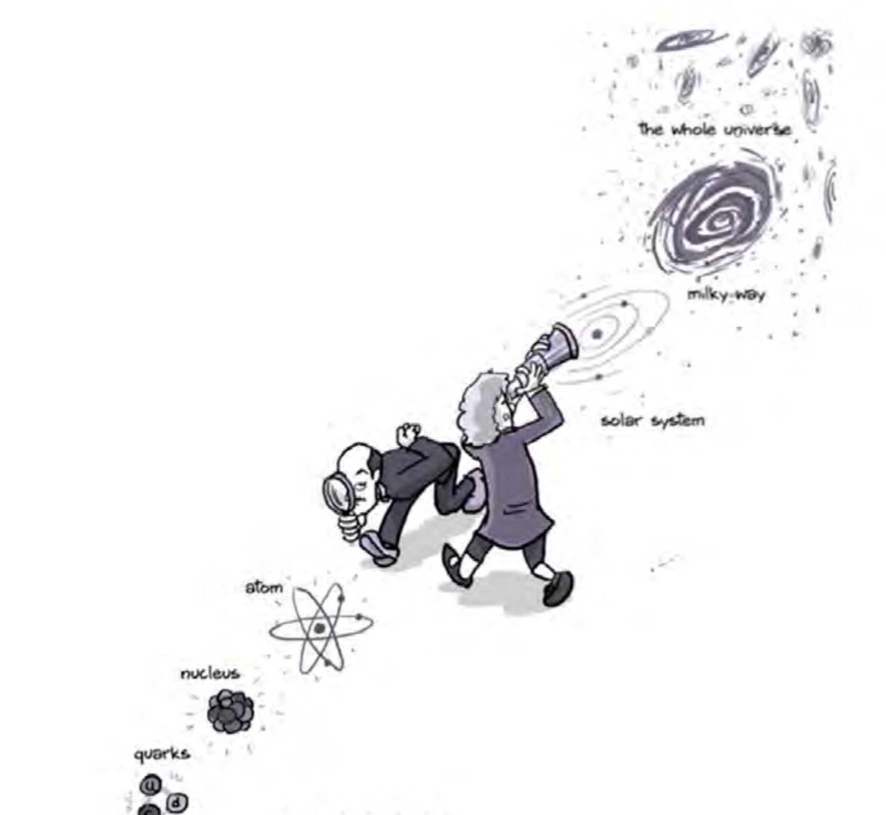
ANAIS collaborators (M. Martínez in particular)

DISCLAIMER

Broad field to review

Topics and experiments' selection strongly biased by my background and knowledge (or lack of it)

I apologize for all the omissions and flaws in the following



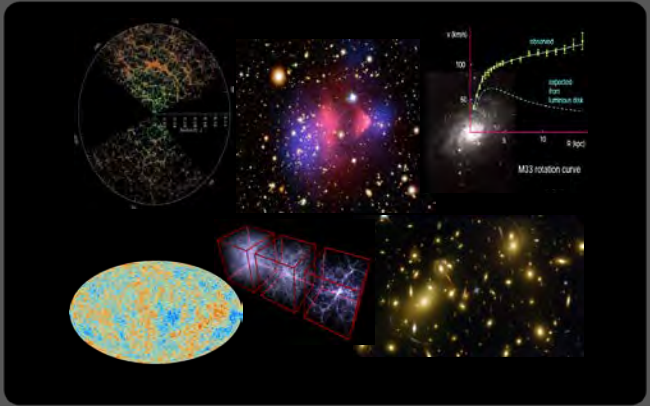
Credit: PHD COMICS

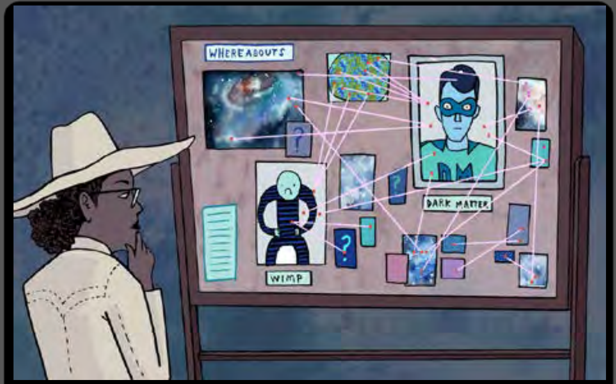
REVIEW - OUTLINE

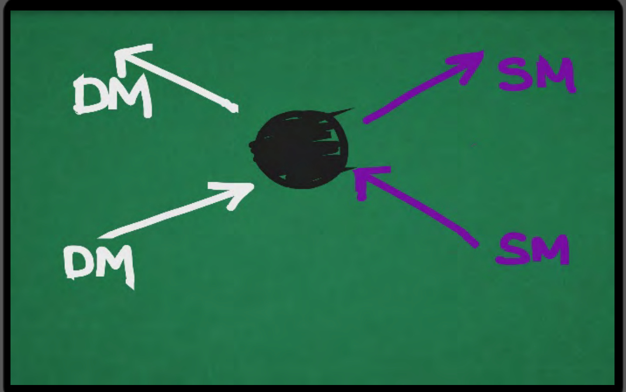
Multimessenger Astroparticle Physics Review

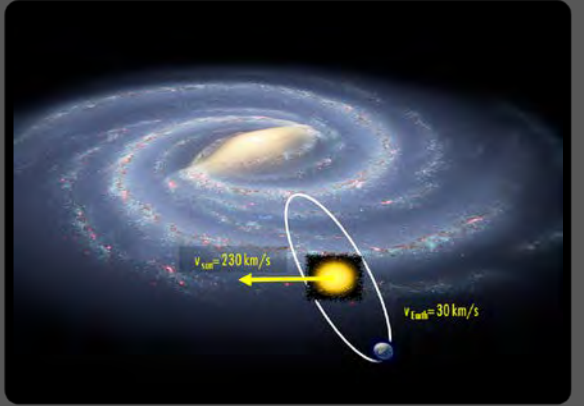
Gamma Rays and Cosmic Rays Summary

Neutrino Physics Review









Evidences on DARK MATTER

Cosmology review

BSM Physics

DARK MATTER CANDIDATES

Focus on Particle Physics Candidates

Mainly WIMPs / axions

STRATEGIES TO SEARCH FOR DARK MATTER

Focus on Direct Detection techniques for WIMPs

Axion Searches

ANNUAL MODULATION SEARCHES

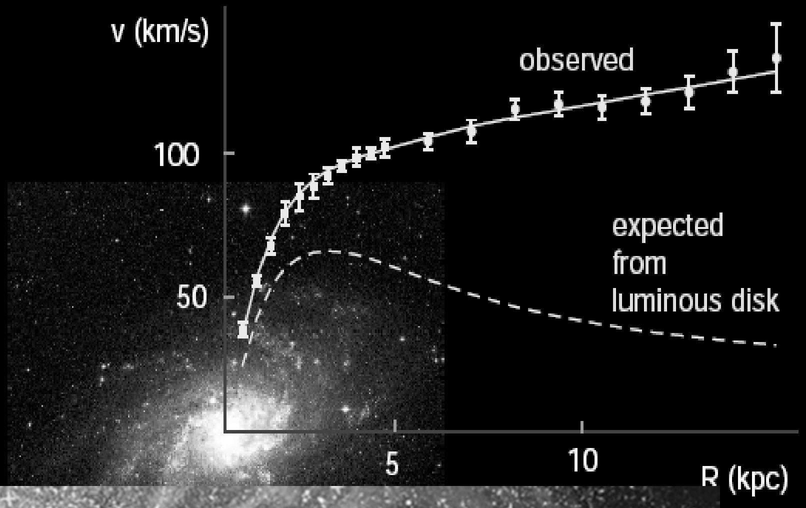
Focus o recent ANAIS results

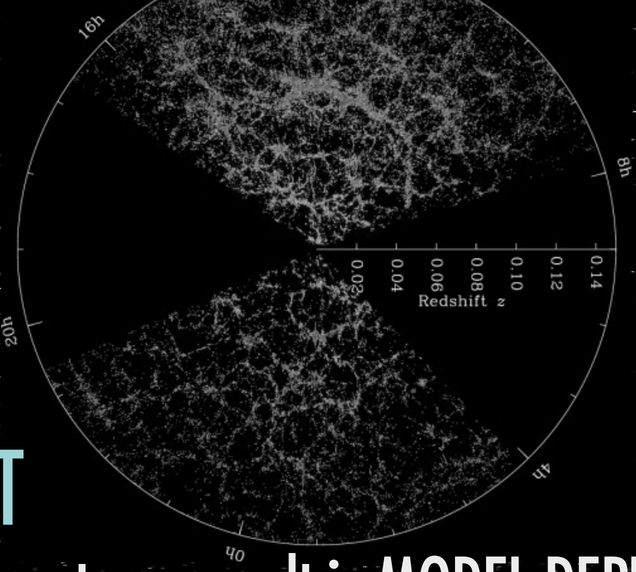
Future Large Facilities

EVIDENCES ON DARK MATTER

From observing the only Universe at reach

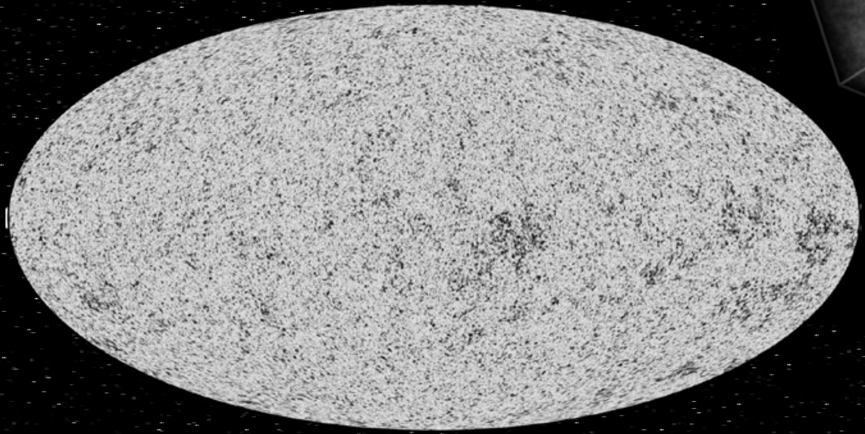
We cannot do experiments but fitting models to data

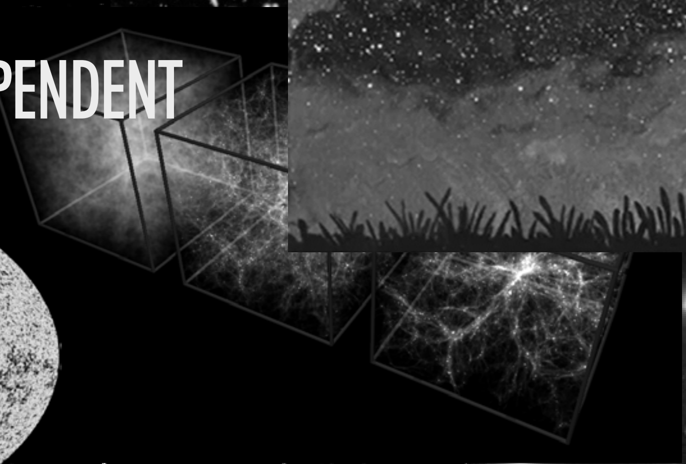




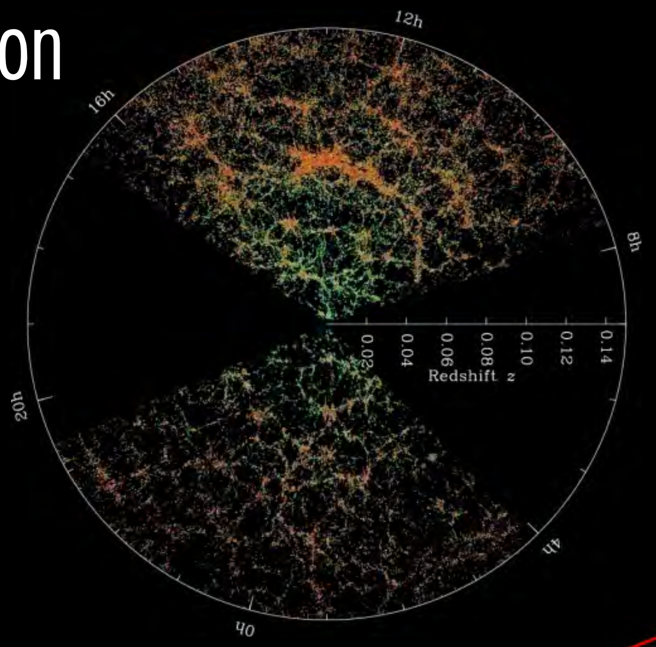
CAVEAT

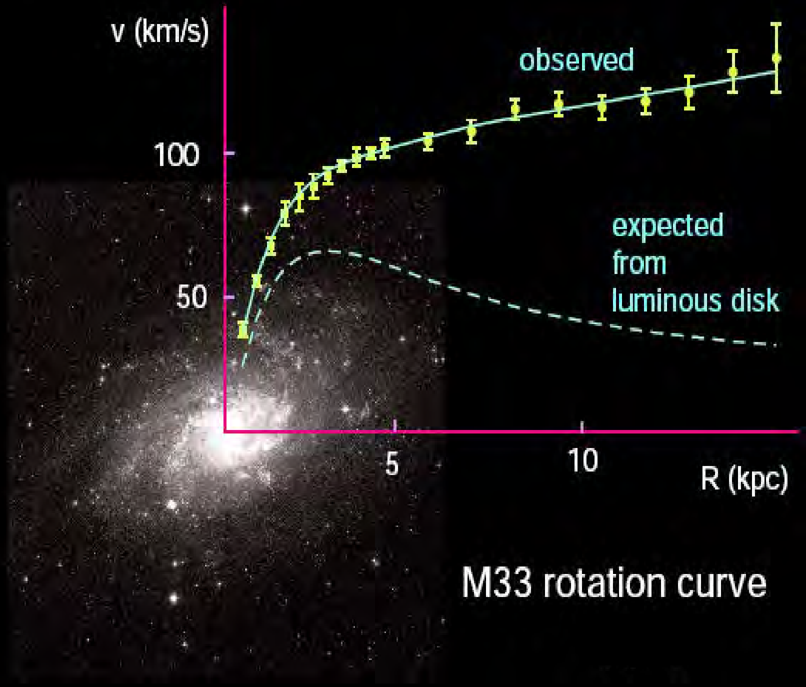
Almost any result is MODEL DEPENDENT

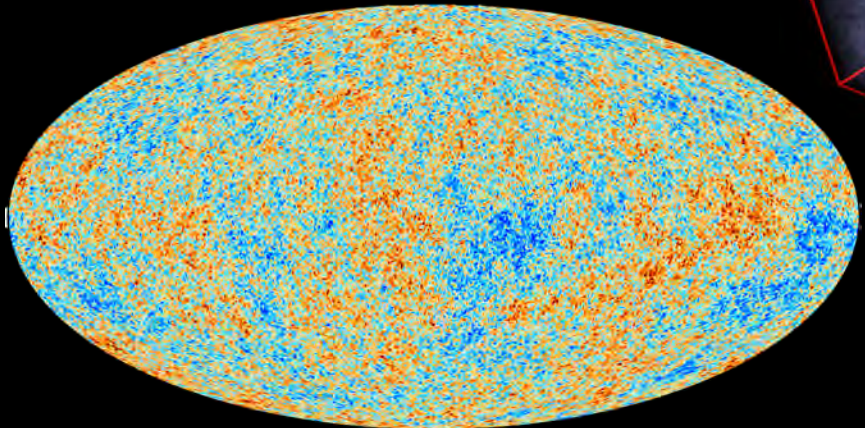


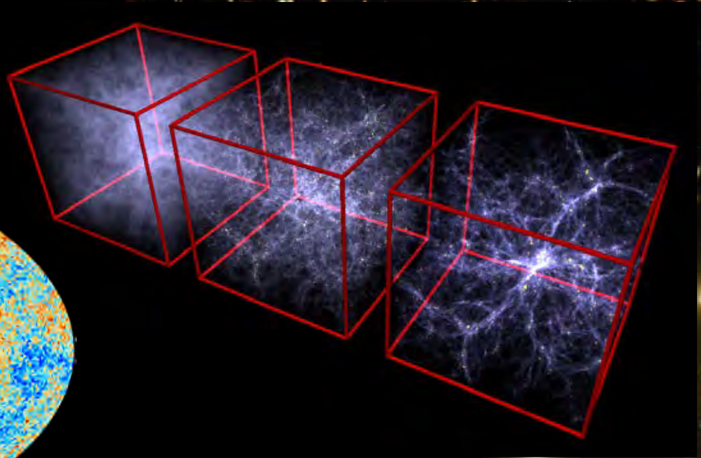


Dark Matter evidences come from very different observational techniques, from different scales and times of the Universe evolution





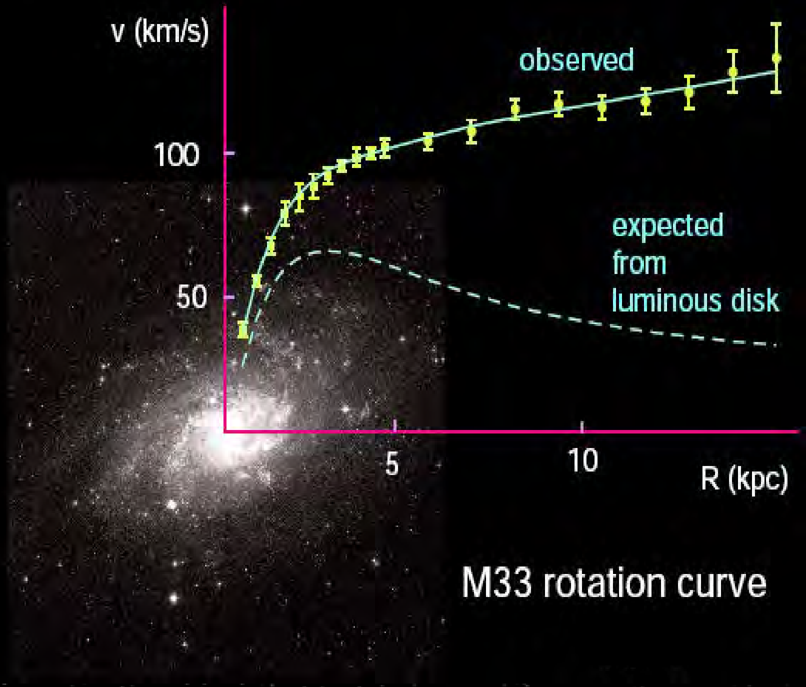




EVIDENCES ON DARK MATTER

Spiral Galaxies Rotation Curves

since the seventies of the XXth century
by using visible and radio wavelengths
observations from stars and dust clouds
redshift measurements



M33 rotation curve

EVIDENCES ON DARK MATTER

Galaxy Clusters matter content larger than expected from luminosity

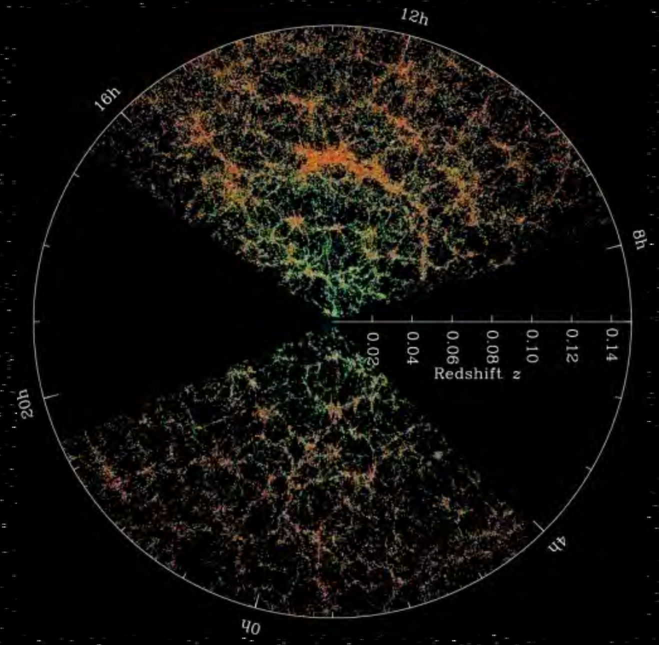
since the thirties of XXth century by using virial theorem and velocity dispersions mesurements

More recently by gravitational lensing effect – reconstruction of matter profile

EVIDENCES ON DARK MATTER

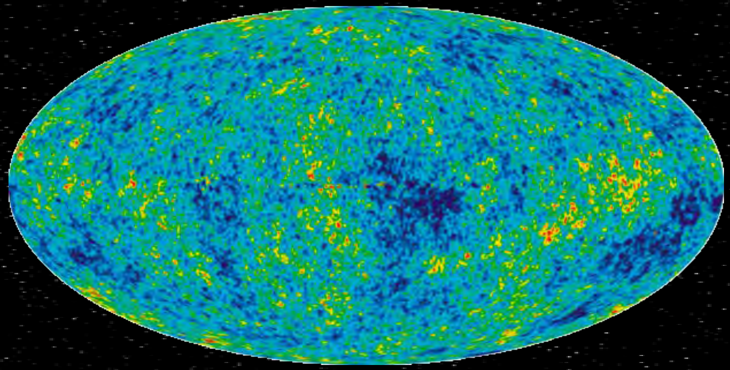
Galaxy Clusters dynamics – BULLET CLUSTER
from 2006
by combining information from optical, X-ray and matter distribution reconstruction by gravitational lensing effect

EVIDENCES ON DARK MATTER



Large Scale Structure

Distribution of galaxies (not only position, but properties)



Cosmic Microwave Background Radiation Anisotropies

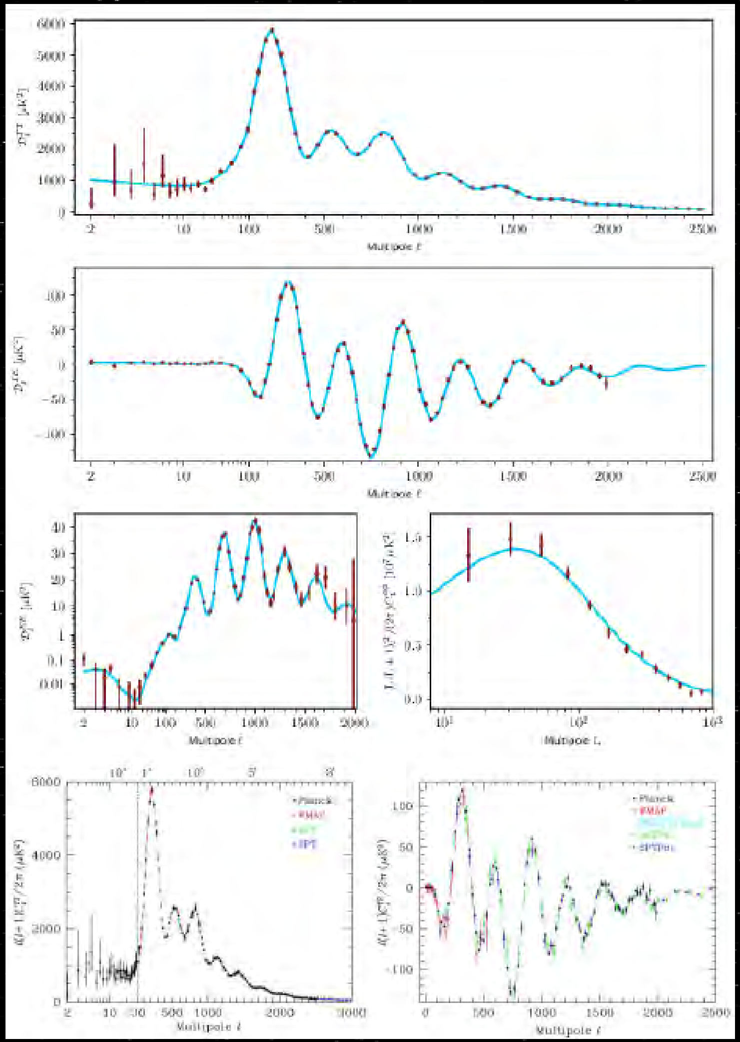
Picture of the early Universe (photon-baryon fluid) @ recombination

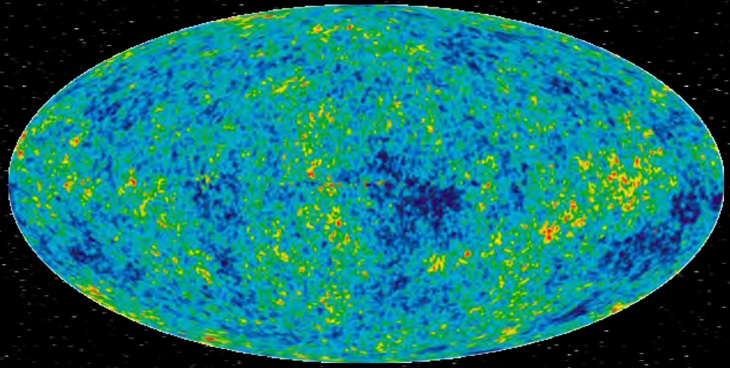
EVIDENCES ON DARK MATTER

PRECISION COSMOLOGY

PLANCK Collaboration results
Temperature and polarization anisotropies in CMBR, and more…

Fitting parameters in ΛCDM model difficult to improve precision further…





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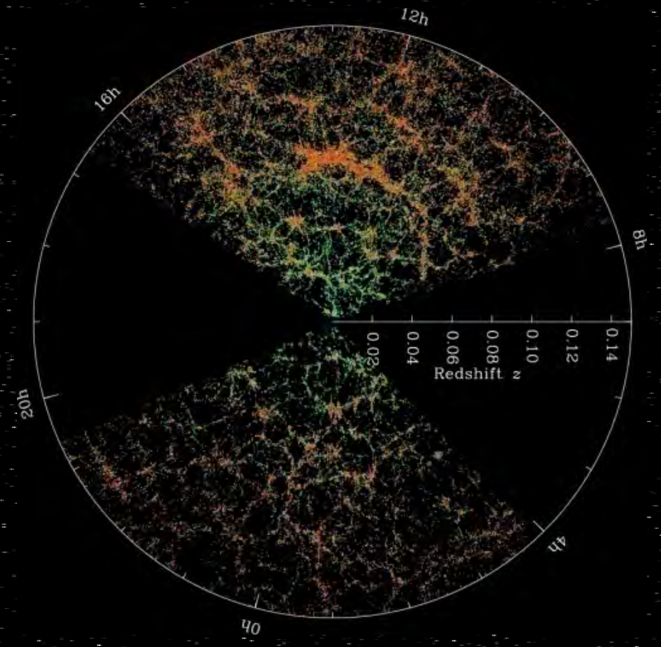
Picture of the early Universe (photon-baryon fluid) @ recombination

EVIDENCES ON DARK MATTER

PRECISION COSMOLOGY



Large Scale Structure

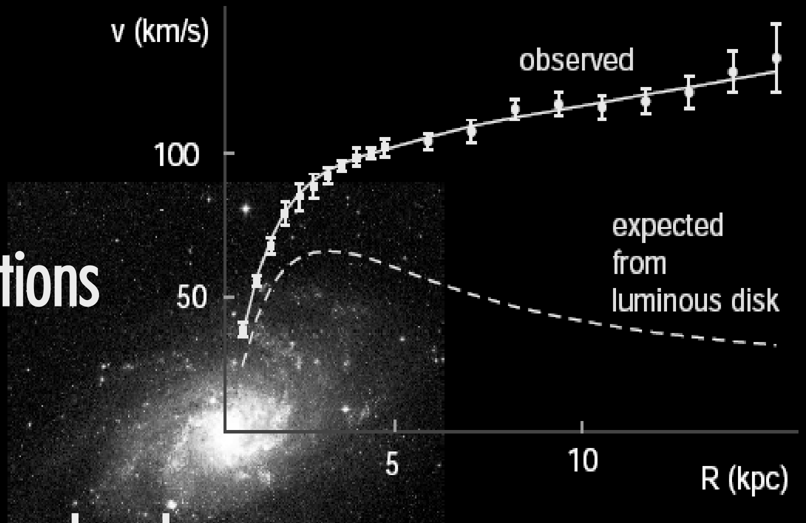
Distribution of galaxies (not only position, but properties)

Recent results from KiDS, DES yr3, and eBOSS

Large efforts on massive surveys will help to understand: inflation, neutrino masses, nature of dark matter, etc.

L. Verde @ TAUP2021: "All detectable galaxies will be mapped by ~2061"

EVIDENCES ON DARK MATTER

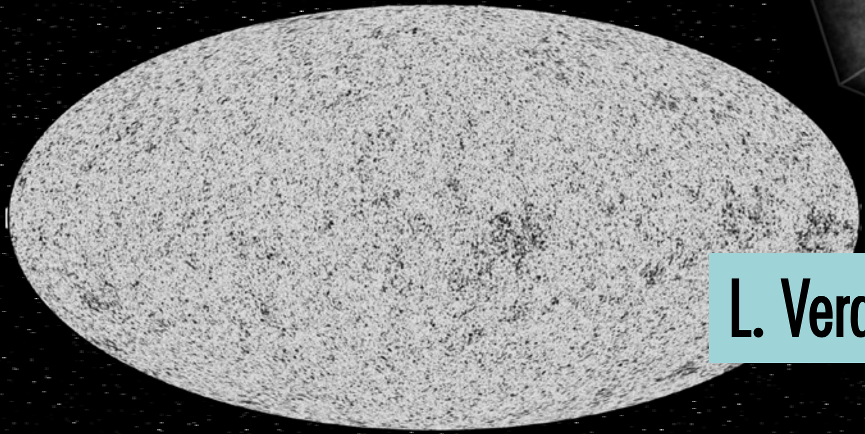


M33 rotation curve

ΛCDM cosmology has been impressively successful explaining all the observations

Some conflict between $\sigma 8$ and H_0 between LSS surveys and CMB data still to solve, but alternative theories of gravity have difficult to explain so many things as ΛCDM model explains:

-oscillations in the baryon distribution
-dwarfs galaxies without dark matter and dwarfs galaxies dominated by dark matter

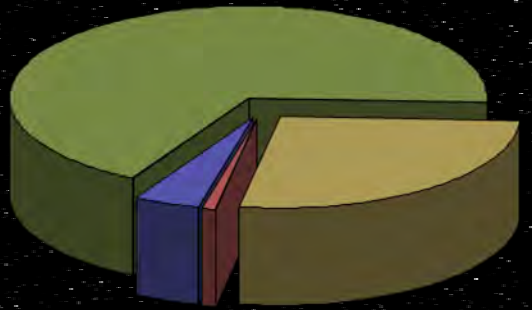


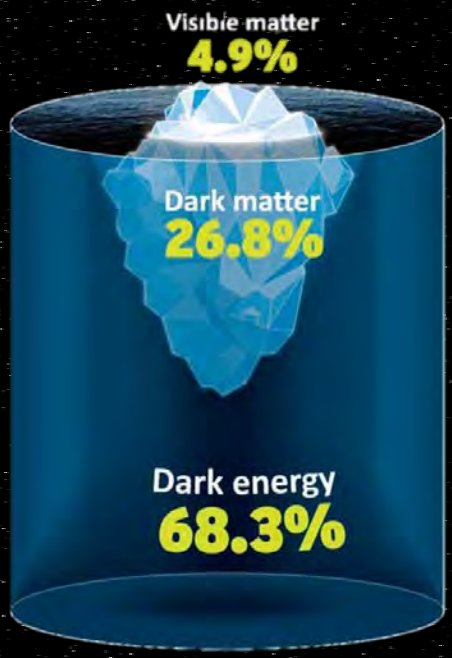
L. Verde @ TAUP2021: “Concordance, vanila ΛCDM still rules”

QUANTIFYING THE DARK MATTER CONTENT

In ΛCDM cosmology frame the Universe recipe is still composed of:

$\Omega \sim 1$



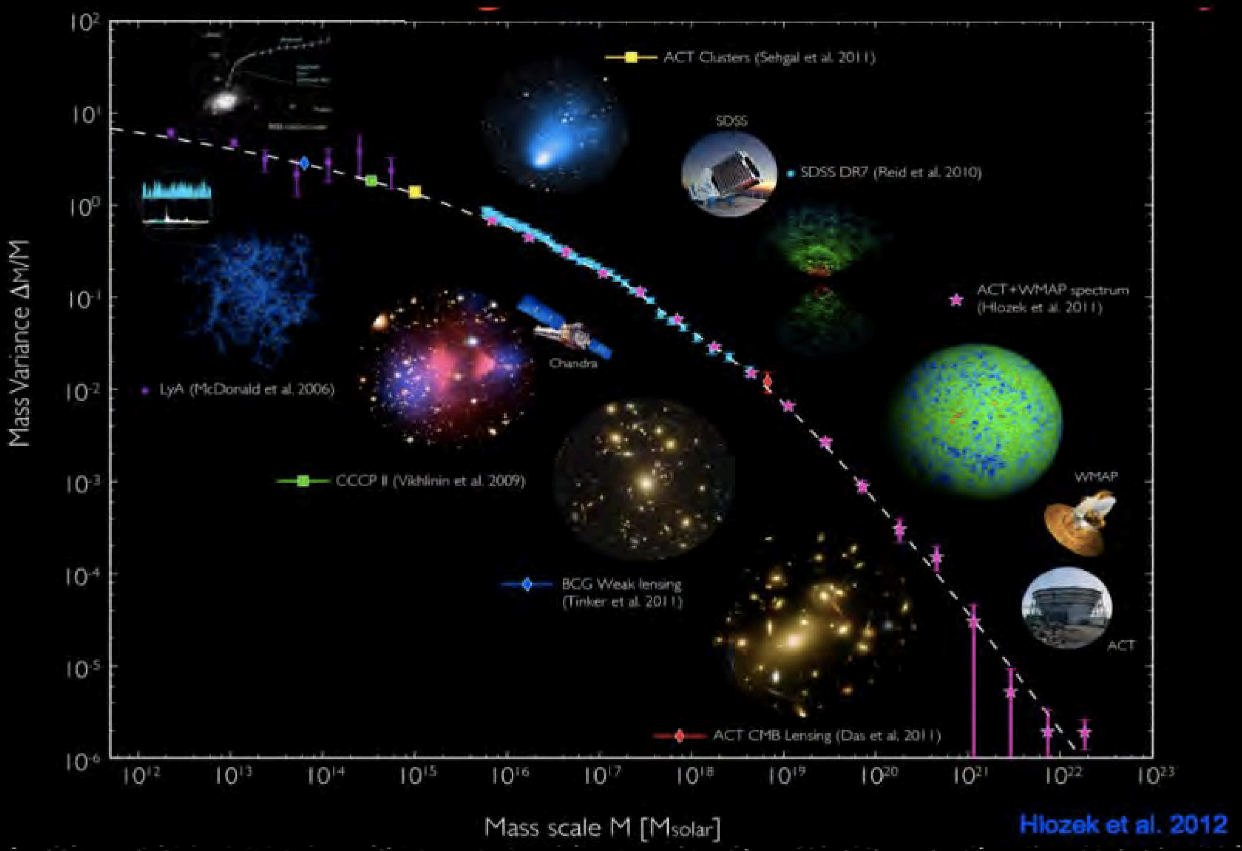


AND ABOUT THE DARK MATTER NATURE?

There is no unambiguous proof of the particle nature
Very loose bounds on mass and properties
Other options: MACROSCOPIC DM (primordial black holes, topological and non-topological solitons, DM clumps, etc.) …

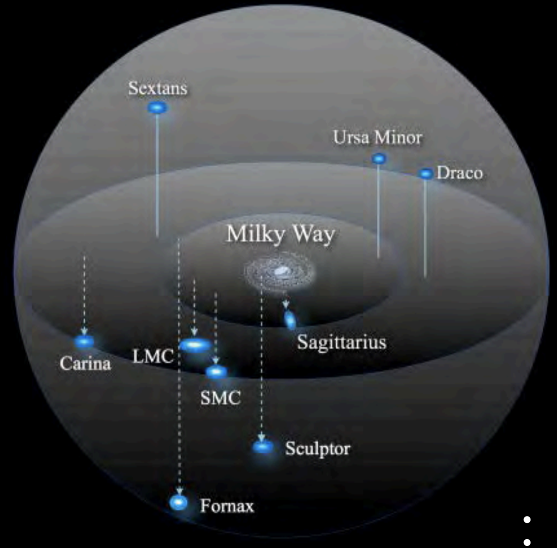
HOW COLD IS THE DARK MATTER

ΛCDM: successful at large scales



But small scale controversies introduced **WDM**

Weinberg+14



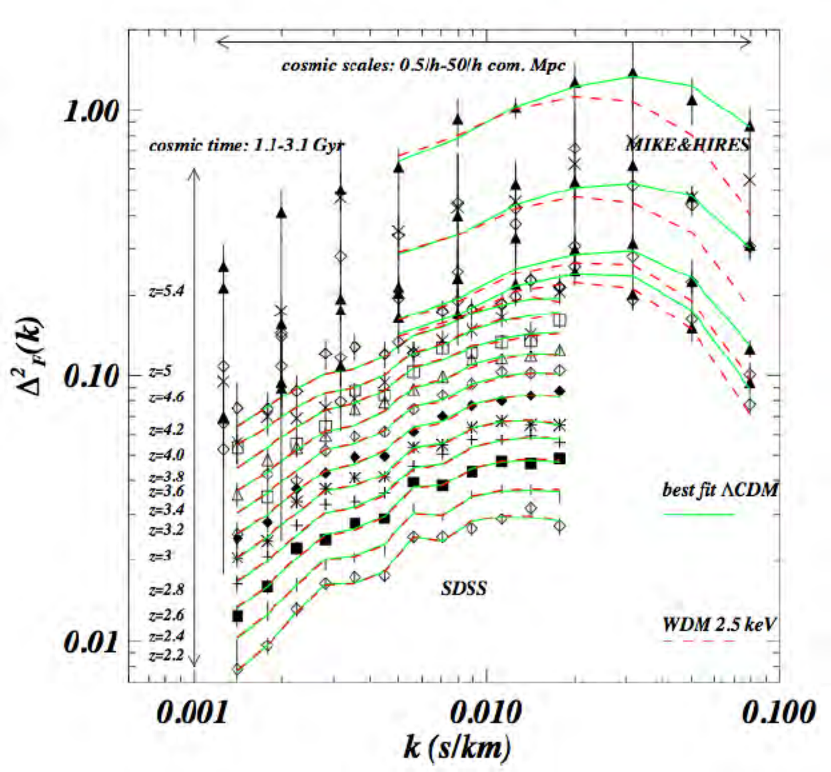
Too big to fail problem
Missing satellites problem
Cusp-core problem
Amplitude of power spectrum too low

Baryonic Physics could solve the question, but also DM Physics

HOW COLD IS THE DARK MATTER

But, recent IGM (Intergalactic Medium) data (Lyman-alpha forest) provide tight constraints on other than CDM candidates

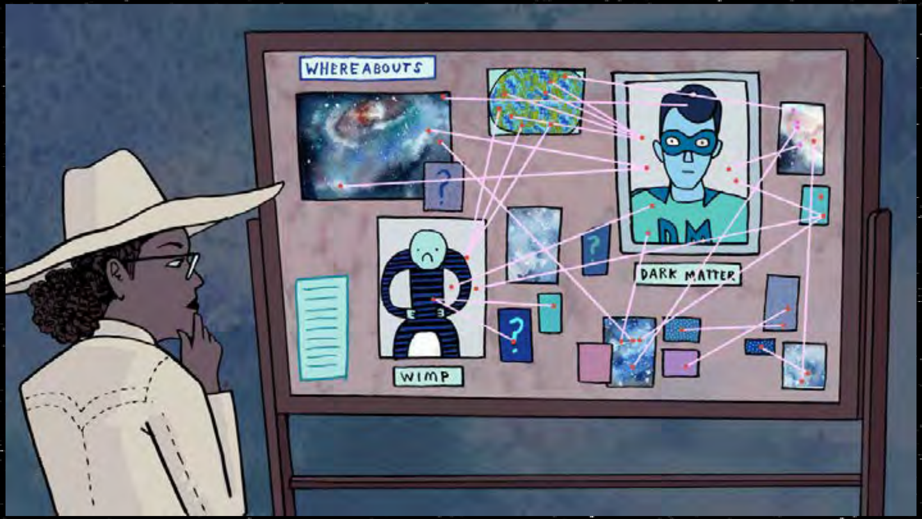
-thermal WDM
-sterile neutrinos
-ultralight boson DM



$M_{\text{thermal WDM}} > 3.5$ keV (2σ C.L.)

Masses able to solve the small-scale crisis of ΛCDM "are at odds" with Ly-α forest data pointing at a cold cosmic web
(M. Viel @ TAUP2021)

PARTICLE DARK MATTER CANDIDATES



Credit:Artwork by Sandbox Studio, Chicago with Corinne Mucha

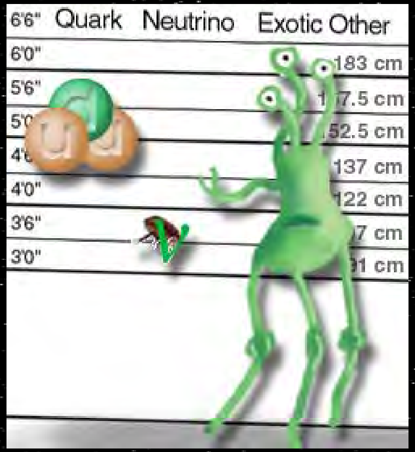
Many DM candidates are on scene

Covering many orders of magnitude in mass and cross section

A few "generic" properties:

- massive
- non-baryonic
- neutral (or milli-charged)
- stable (or very long lived)
- non relativistic when structures formed (cold/warm)
- only gravitationally interacting or very weakly interacting

(non necessarily EW nature – new couplings)



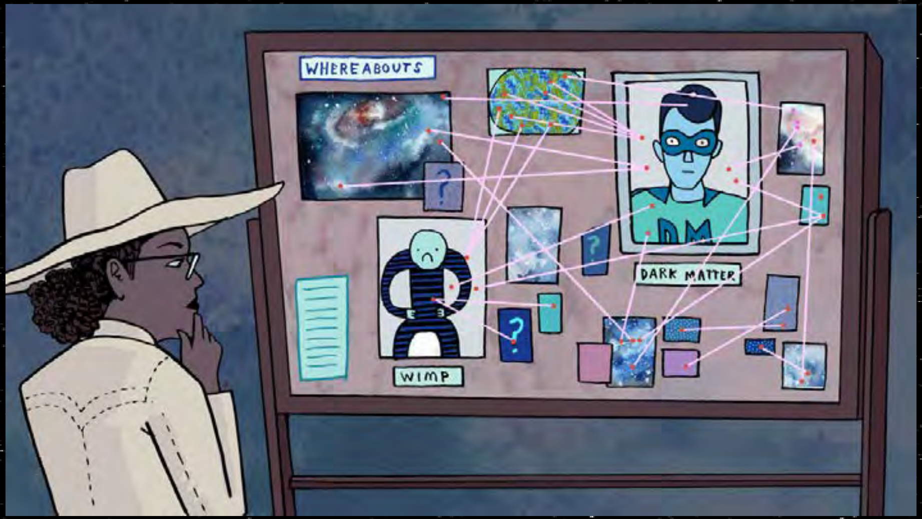
Beyond the Standard Model of Particle Physics

PARTICLE DARK MATTER CANDIDATES

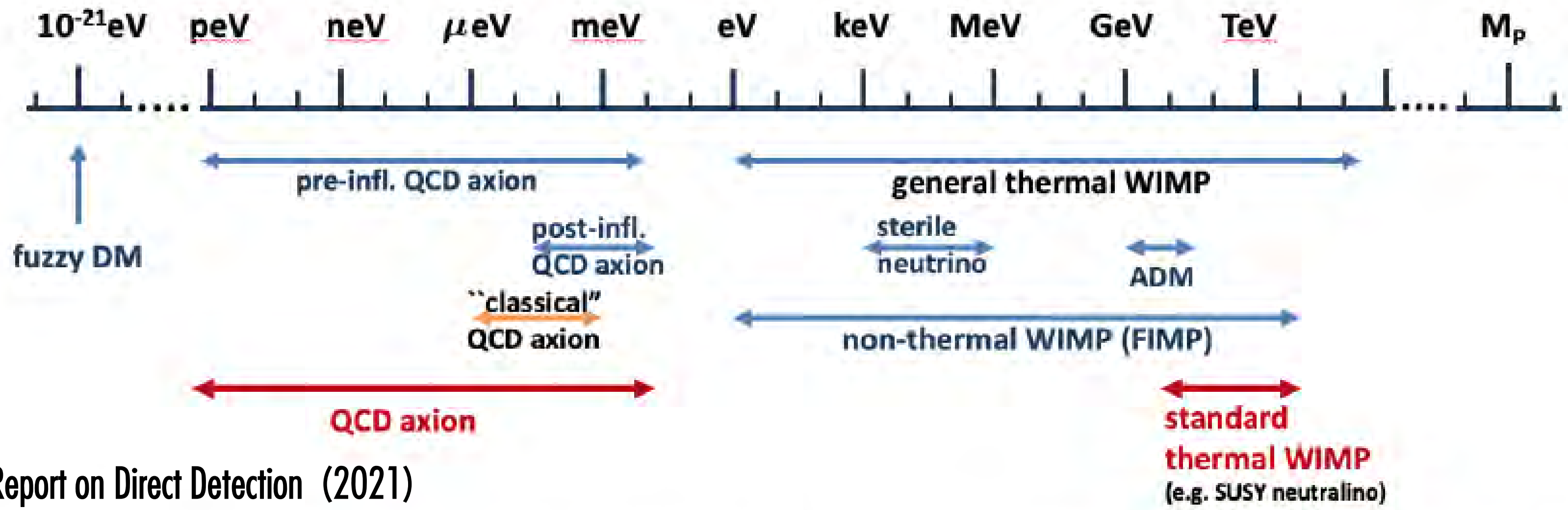
Many DM candidates are on scene

Covering many orders of magnitude in mass and cross section

Many frameworks beyond SM contain viable DM candidates:
complete theories / ad-hoc extensions / …

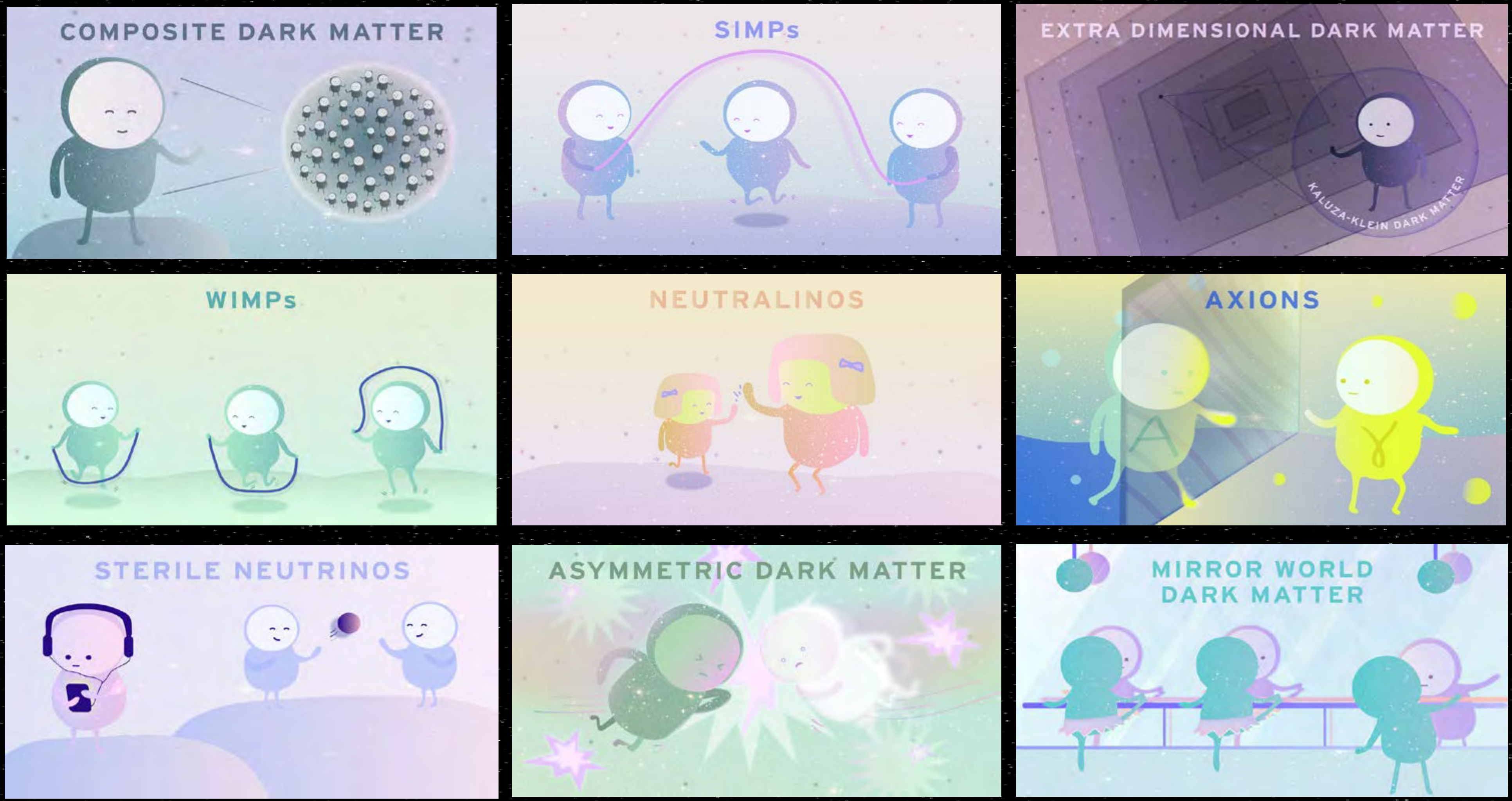


Credit:Artwork by Sandbox Studio, Chicago with Corinne Mucha



Credit: APPEC Report on Direct Detection (2021)

PARTICLE DARK MATTER CANDIDATES



Credit:Artwork by Sandbox Studio, Chicago

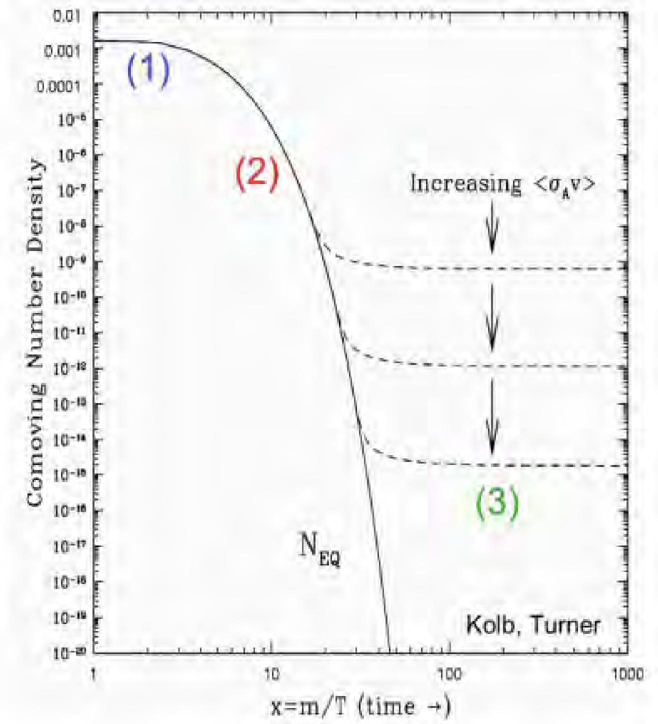
PARTICLE DARK MATTER CANDIDATES: Thermal WIMPs

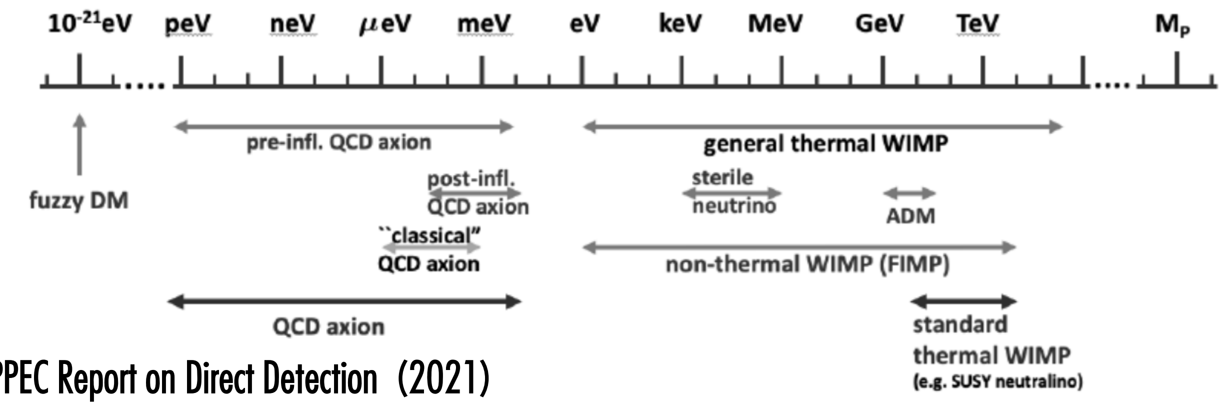
Thermal WIMPs are well motivated CDM candidates

-WIMP MIRACLE: assuming thermal production, electroweak scale cross-sections for a GeV particle produce the correct relic density

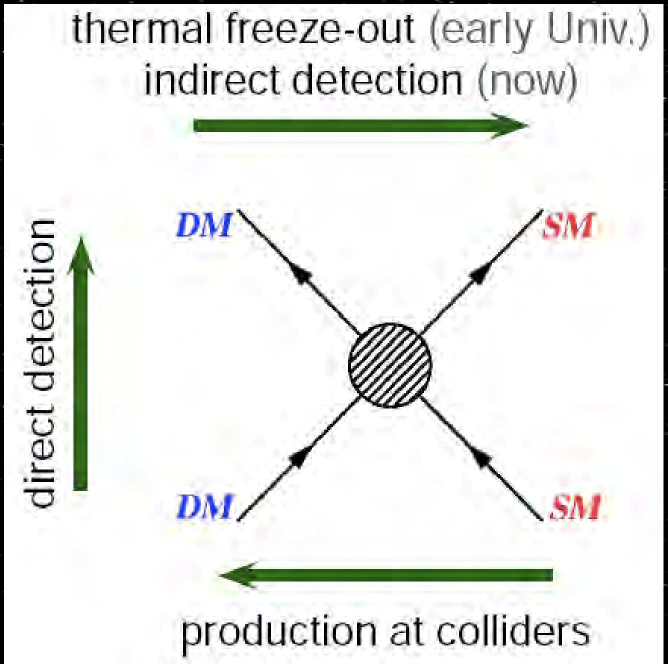
-WIMP detection can be envisaged -> Direct and Indirect Detection Approaches and production at colliders

-Easy to find in SM-extensions as SUSY, KK, etc.





Credit: APPEC Report on Direct Detection (2021)



PARTICLE DARK MATTER CANDIDATES: Thermal WIMPs

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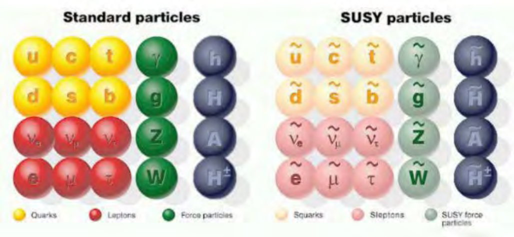
-Easy to find in SM-extensions as SUSY, KK, etc.

Recent change of paradigm
Beyond standard thermal WIMPs



Conservation of R-parity implies that the Lightest Supersymmetric Particle (LSP) is stable -> **DM** !!

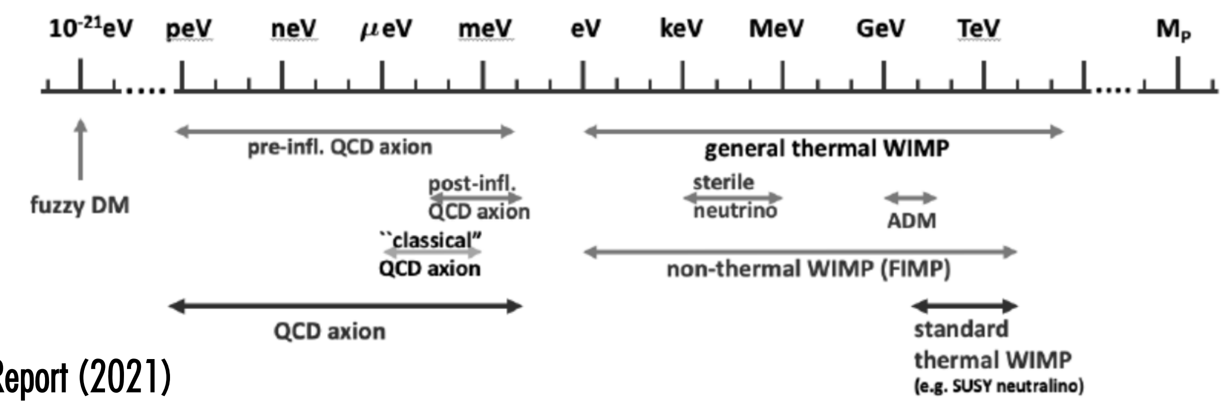
The lightest KK particle (**LKP**) is stable and cannot decay into standard model particles -> Convenient DM candidate!!

Credit:Artwork by Sandbox Studio, Chicago

PARTICLE DARK MATTER CANDIDATES according the DM Genesis

At early times of Universe evolution, for $T \gg m_{DM}$

- $N_{DM}/N_\gamma \sim 1$ -> Thermal Equilibrium because of sizeable DM interaction rates with SM particles and at freeze-out the right relic density for weak scale — Thermal WIMPs
- $N_{DM}/N_\gamma \ll 1$ -> Very small DM interaction rates, never in equilibrium, produced by decay of parent WIMPs or thermal leakage of other fields: gravitinos, sterile neutrinos, etc. — Super-WIMPs
- $N_{DM}/N_\gamma \gg 1$ -> Bosonic DM, very light, almost non-interacting: axions and other light scalar fields — Super-cold DM



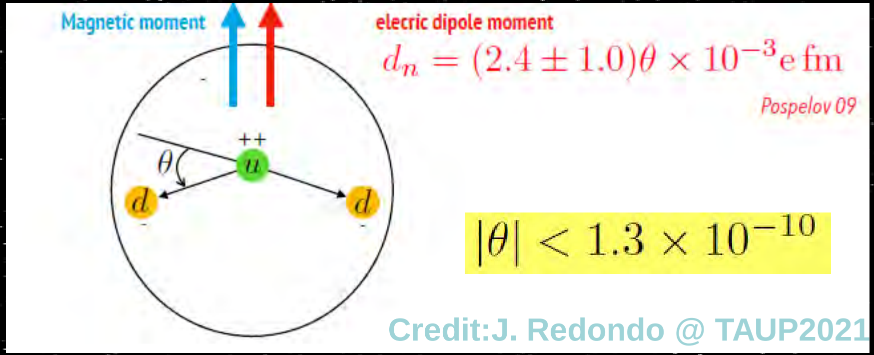
APPEC Report (2021)

PARTICLE DARK MATTER CANDIDATES: Axions and ALPs

Axions and ALPs are also very robust DM candidates

Axion would solve the strong CP problem: CP is not violated by strong interactions while the QCD lagrangian does

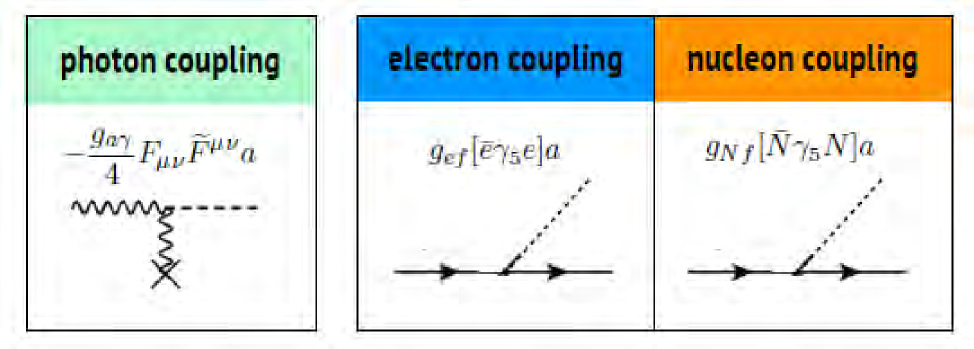
$$\mathcal{L}_{\rm QCD} = \underbrace{-\frac{1}{4}G_{\mu\nu a}G^{\mu\nu}_{a} + \sum_q i\bar{q}\gamma^\mu D_\mu q - \bar{q}mq}_{\text{P,T conserving}} + \underbrace{\frac{\alpha_s}{8\pi}\theta G_{\mu\nu a}\tilde{G}^{\mu\nu}_{a}}_{\text{P,T violating}}$$



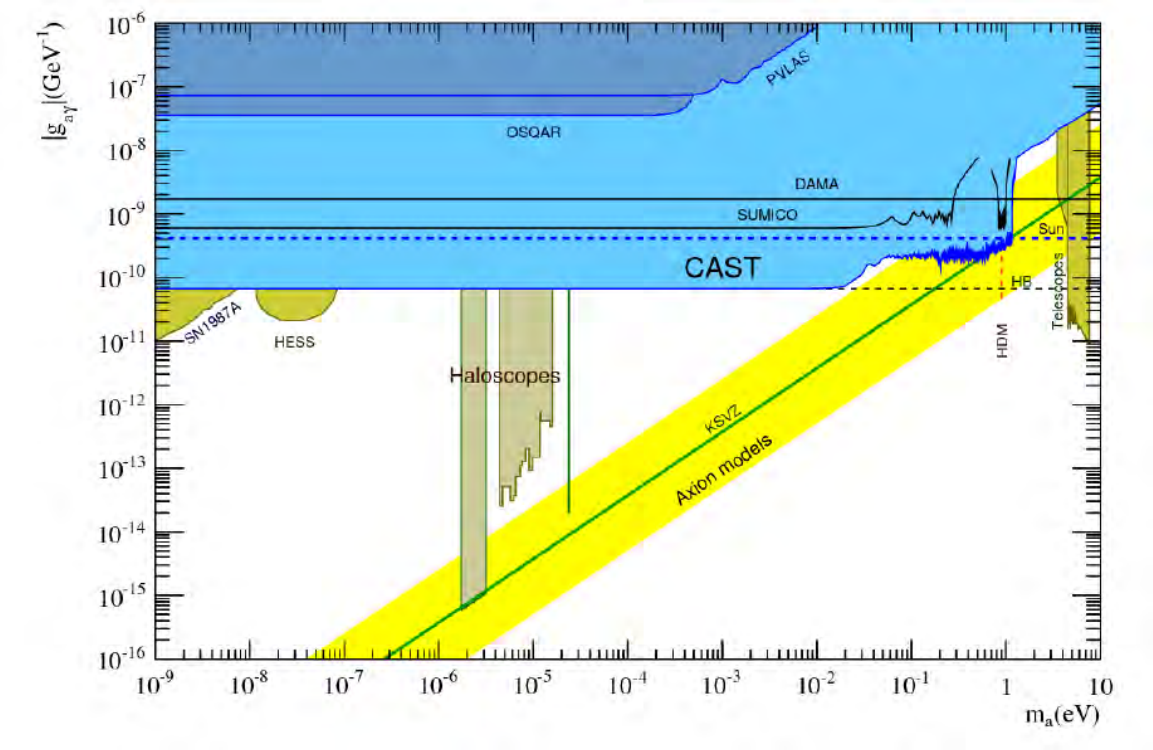
Is the Goldstone boson associated to a global U(1) symmetry spontaneously broken

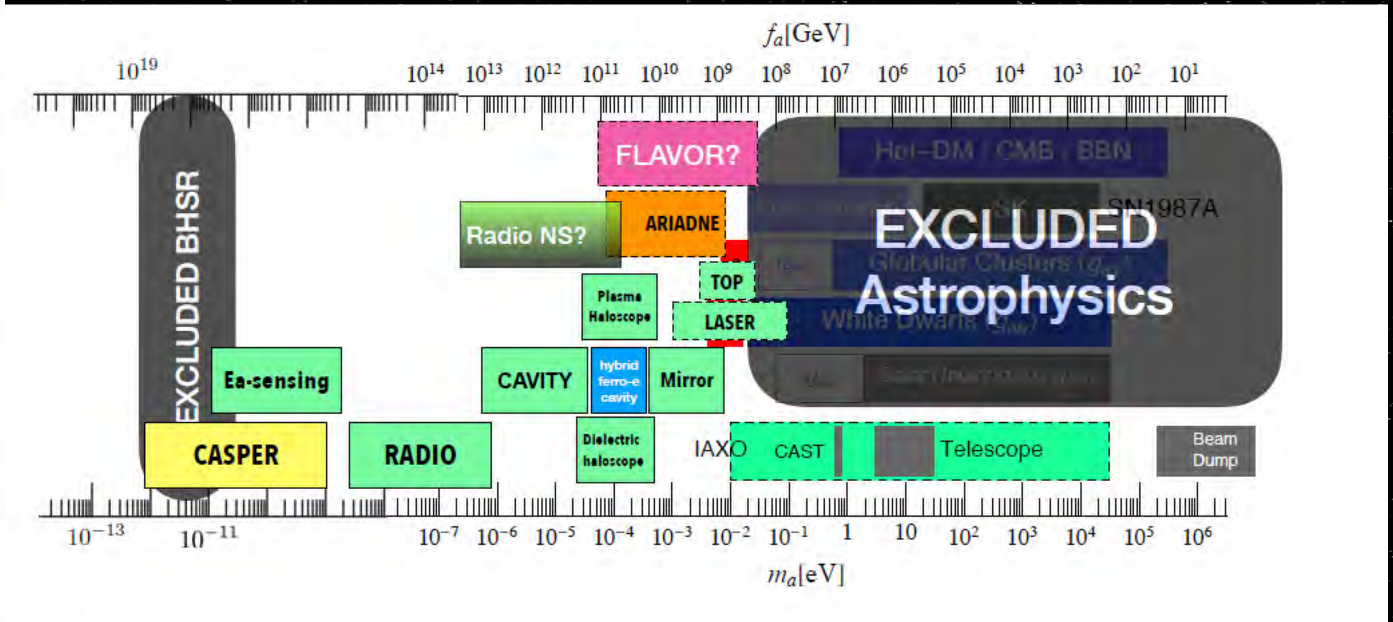
- Pseudoscalar
- Very light
- Neutral

Axions and ALPS are generic DM candidates and compatible with SUSY, GUTs and String Theories



PARTICLE DARK MATTER CANDIDATES: Axions and ALPs





Axion Searches Talk
(Thursday)

PARTICLE DARK MATTER CANDIDATES: Others…

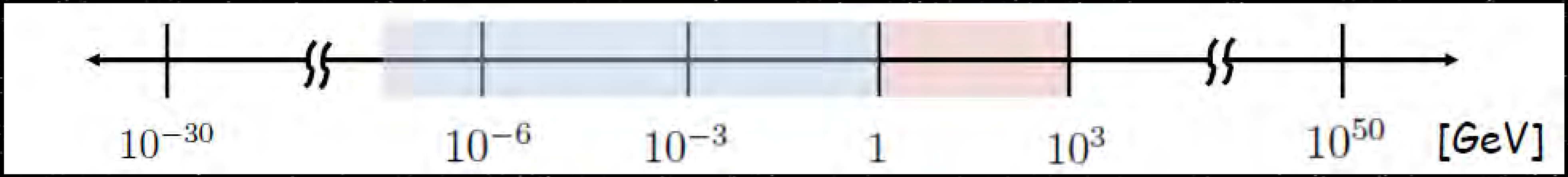
Sterile neutrinos

Sterile neutrinos (Ni) are a natural ingredient of the most popular mechanism to generate neutrino masses: the seesaw mechanism

Sterile neutrinos are neutral leptons with no ordinary weak interactions except those induced by mixing with active neutrinos

But could have interactions involving new physics

PARTICLE DARK MATTER CANDIDATES: Others…



New Theory Ideas

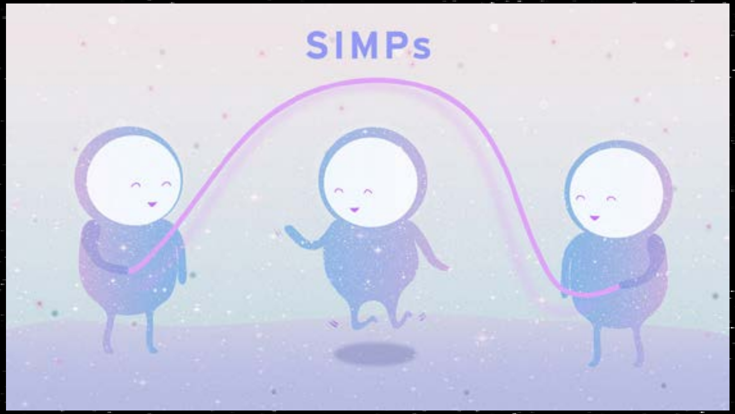
- ……
- Weakly coupled WIMPs [Pospelov, Ritz, Voloshin 2007; Feng, Kumar 2008]
- Asymmetric dark matter [Kaplan, Luty, Zurek, 2009]
- Freeze-in dark matter [Hall, Jedamzik, March-Russell, West, 2009]
- SIMPs [**YH**, Kuflik, Volansky, Wacker, 2014; **YH**, Kuflik, Murayama, Volansky, Wacker, 2015]
- ELDERs [Kuflik, Perelstein, Rey-Le Lorier, Tsai, 2016 & 2017]
- Forbidden dark matter [Griest, Seckall, 1991; D'Agnolo, Ruderman, 2015]
- Co-decaying dark matter [Dror, Kuflik, Ng, 2016]
- Co-scattering dark matter [D'Agnolo, Pappadopulo, Ruderman, 2017]
- ……

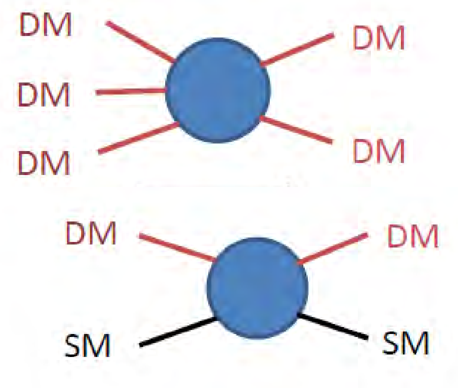
… Are abundant

By no means a comprehensive list

YH @ TAUP 2021

Credit: Y. Hochberg @ TAUP2021





$$\langle \sigma v^2 \rangle_{3\to 2} \equiv \frac{\alpha^3}{m_{\rm DM}^5}$$

$$m_{\rm DM} \sim \alpha \times 100 \text{ MeV}$$

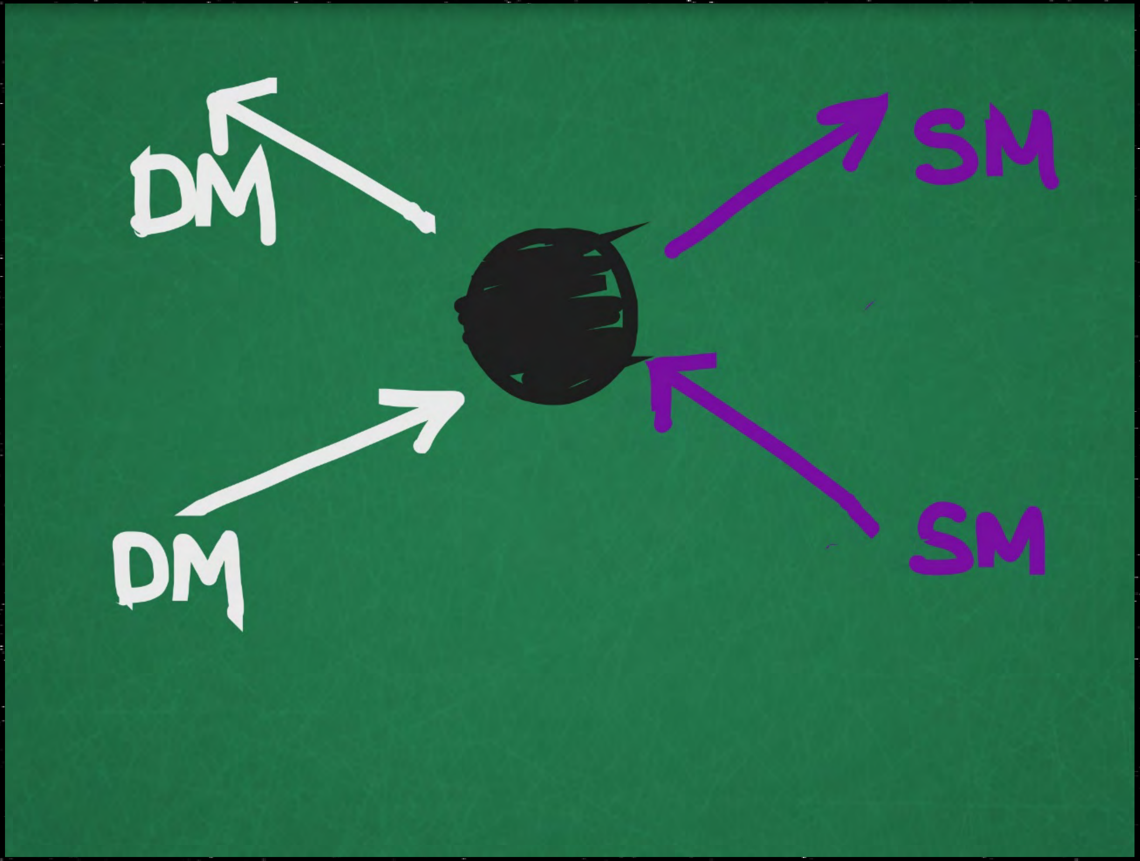
STRATEGIES FOR UNRAVELLING THE NATURE OF DARK MATTER

Without assumptions on the coupling between DM and SM particles

-Searching for new particles at accelerators

-Indirect detection of the products coming from DM annihilation or decay

-Direct detection of the galactic dark matter



COMPLEMENTARY – RESULTS FROM THE THREE APPROACHES SHOULD BE COMBINED … BUT STRONG MODEL-DEPENDENCIES

STRATEGIES FOR UNRAVELLING THE NATURE OF DARK MATTER

Without assumptions on the coupling between DM and SM particles

-Searching for new particles at accelerators

-Indirect detection of the products coming from DM annihilation or decay

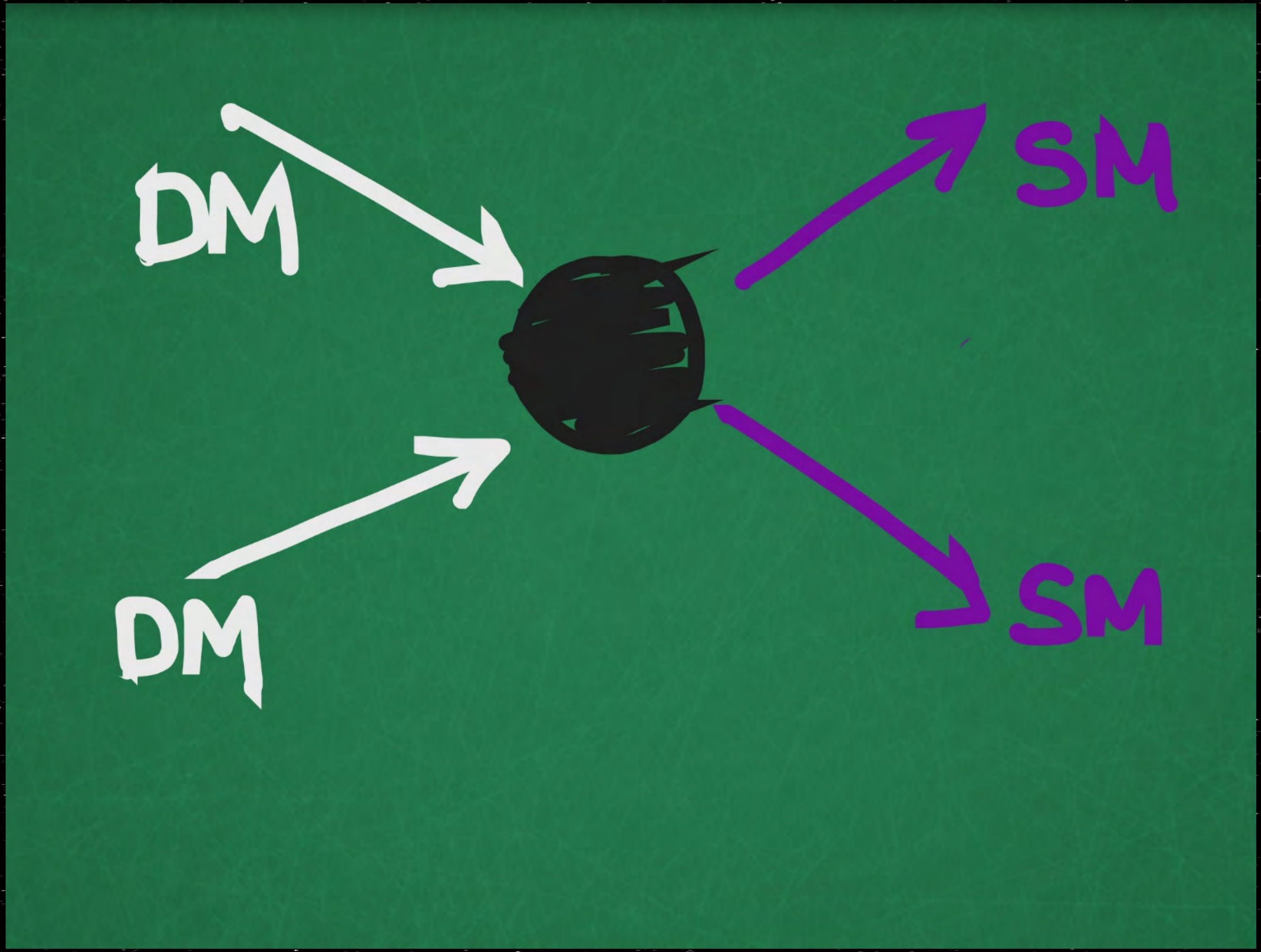
-Direct detection of the galactic dark matter

To decouple unknown and uncertainties in DM searches is mandatory

- Multimessenger approach
- Multitarget and multi-technique strategy

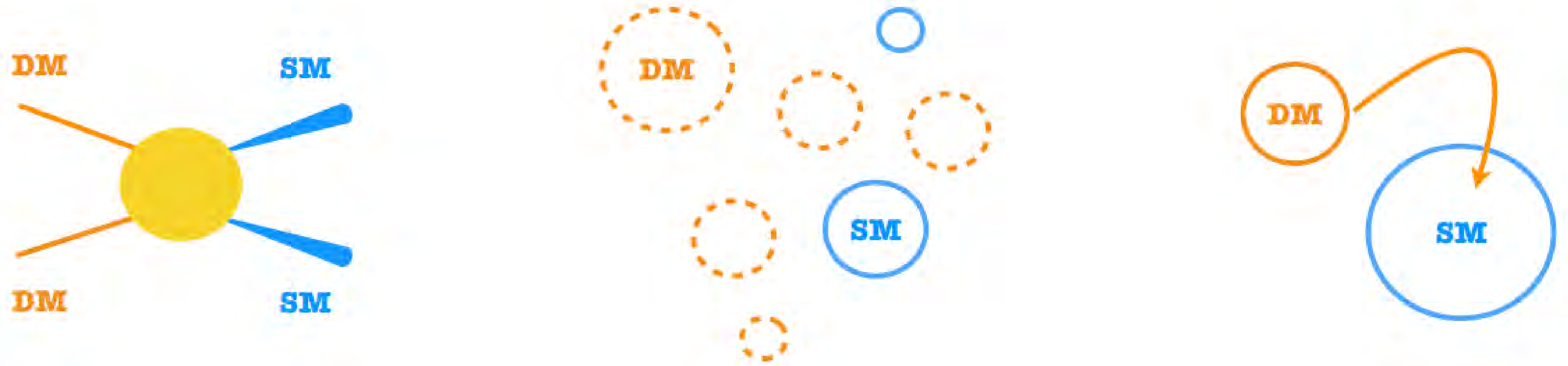
COMPLEMENTARY – RESULTS FROM THE THREE APPROACHES SHOULD BE COMBINED … BUT STRONG MODEL-DEPENDENCIES

INDIRECT DETECTION OF DARK MATTER



INDIRECT DETECTION OF DARK MATTER

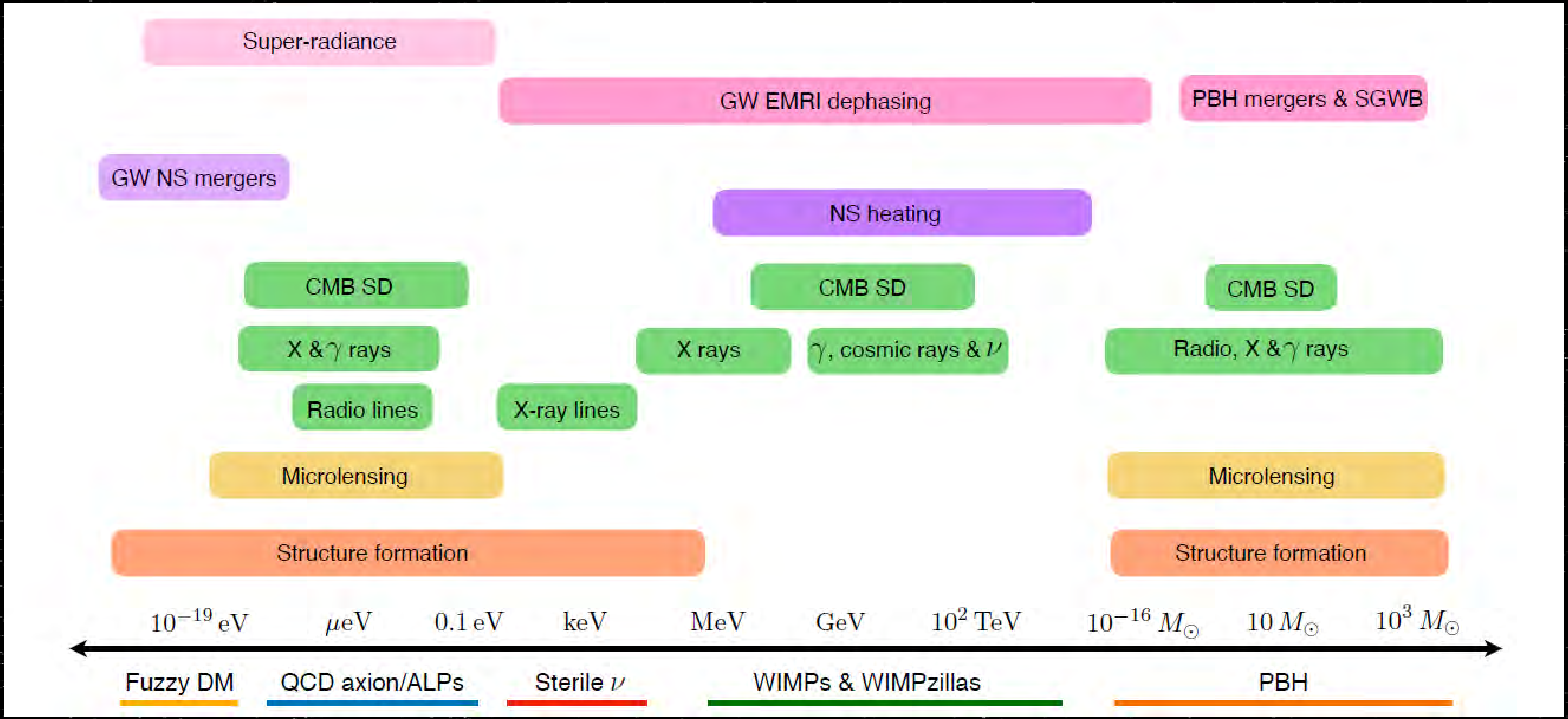
What can DM do



Energy/particle injection | *Gravitational interaction* | *Capture/scattering/accretion in/onto astrophysical objects*

INDIRECT DETECTION OF DARK MATTER

What can we observe

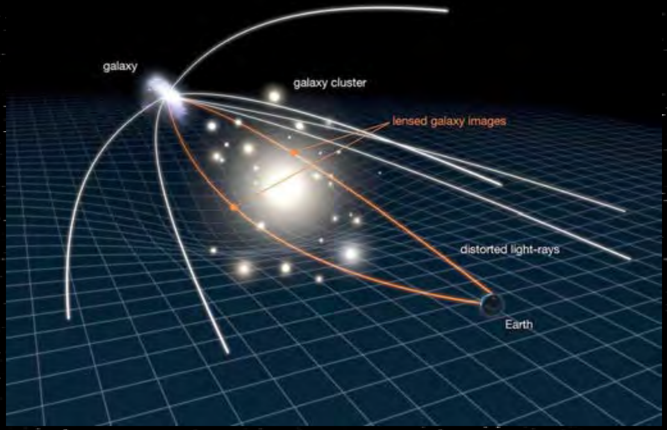


Gravitational Waves

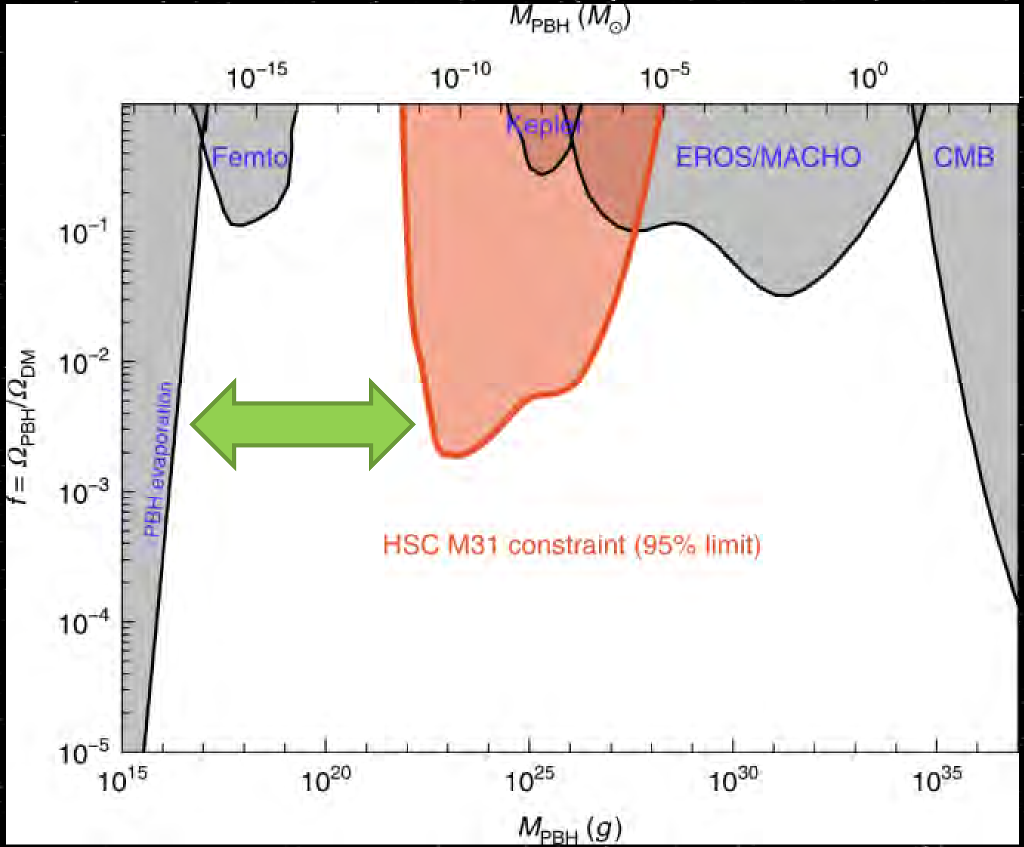
Travelling messengers

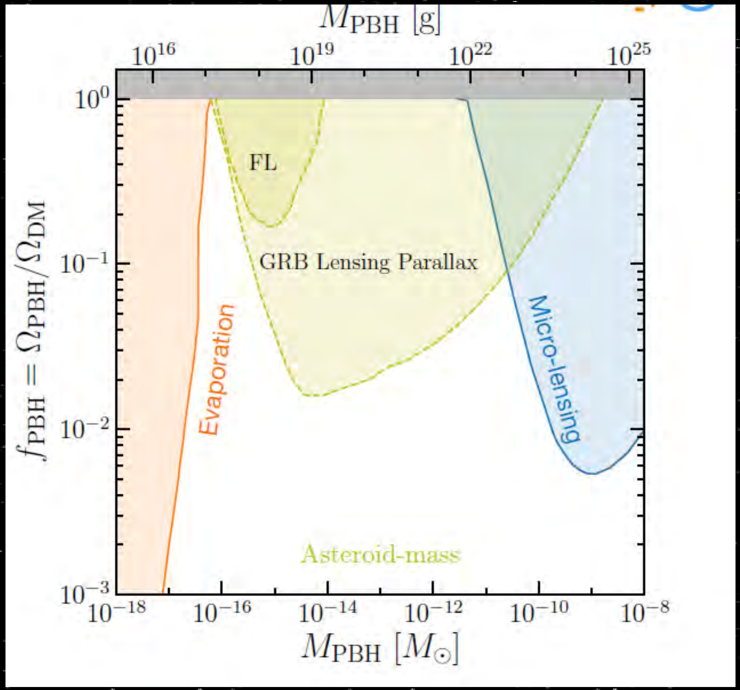
Cosmic Surveys

COSMIC SURVEYS



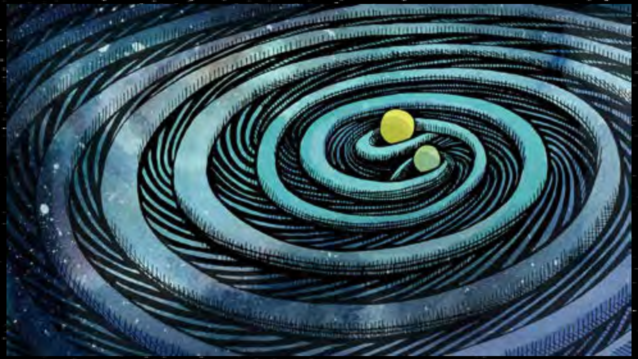
Can detect/constrain PRIMORDIAL BLACK HOLES by micro-lensing
(also other DM substructures)





EUCLID and
Vera Rubin Obsr.

GRAVITATIONAL WAVES



Could inform on PBH, which would produce stochastic GW background

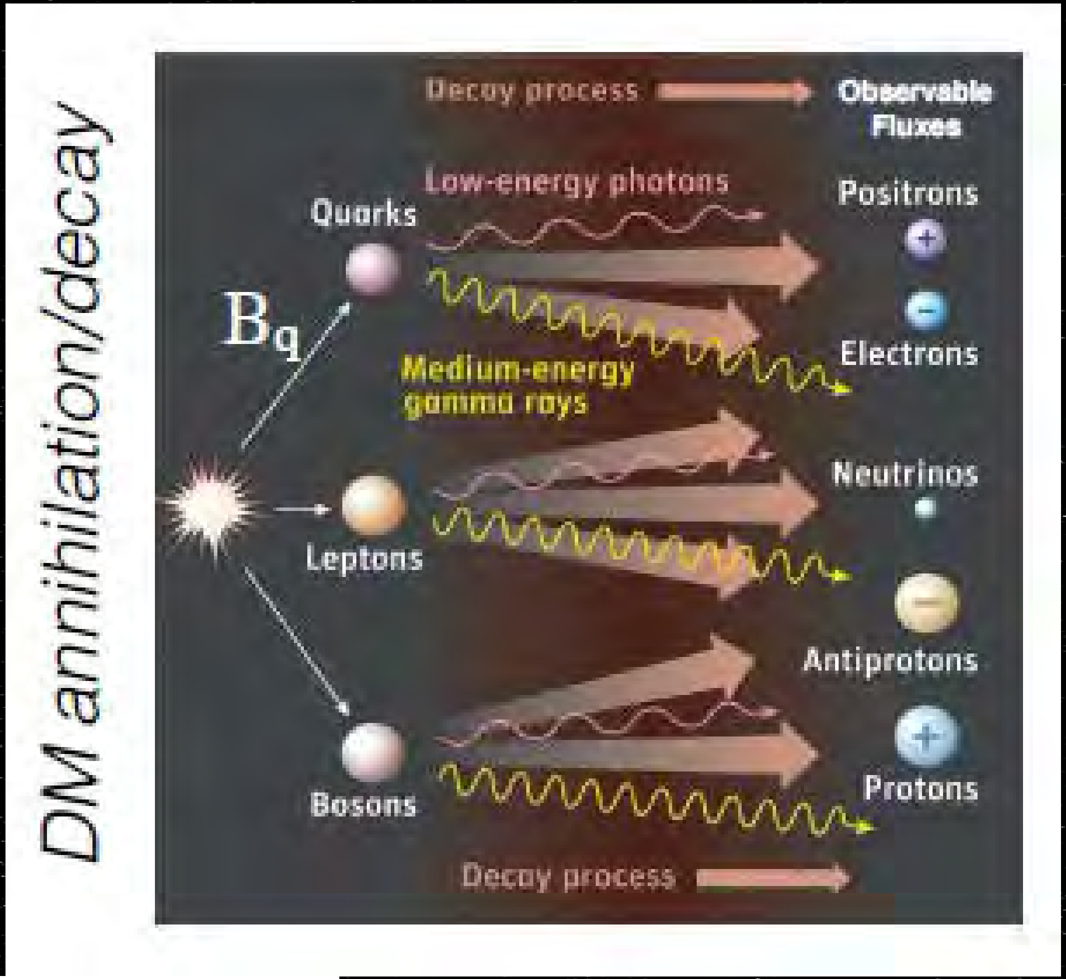
DM could be accreted on black holes and neutron stars inducing some specific GW signatures

DM could form exotic compact objects that would emit GW in mergers

…

SIGNALS FROM DM ANNIHILATIONS / DECAY

Different channels to be considered / Different detection strategy



Relevant dependences on the Particle Physics Model

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, s, \Delta\Omega) = \frac{\langle \sigma v \rangle}{2m_{\rm DM}^2} \sum_i B_i \frac{dN_\gamma^i}{dE_\gamma} \frac{1}{4\pi} \int_0^{\Delta\Omega} d\Omega \int_{\rm l.o.s} \rho_{\rm DM}^2(s) ds$$

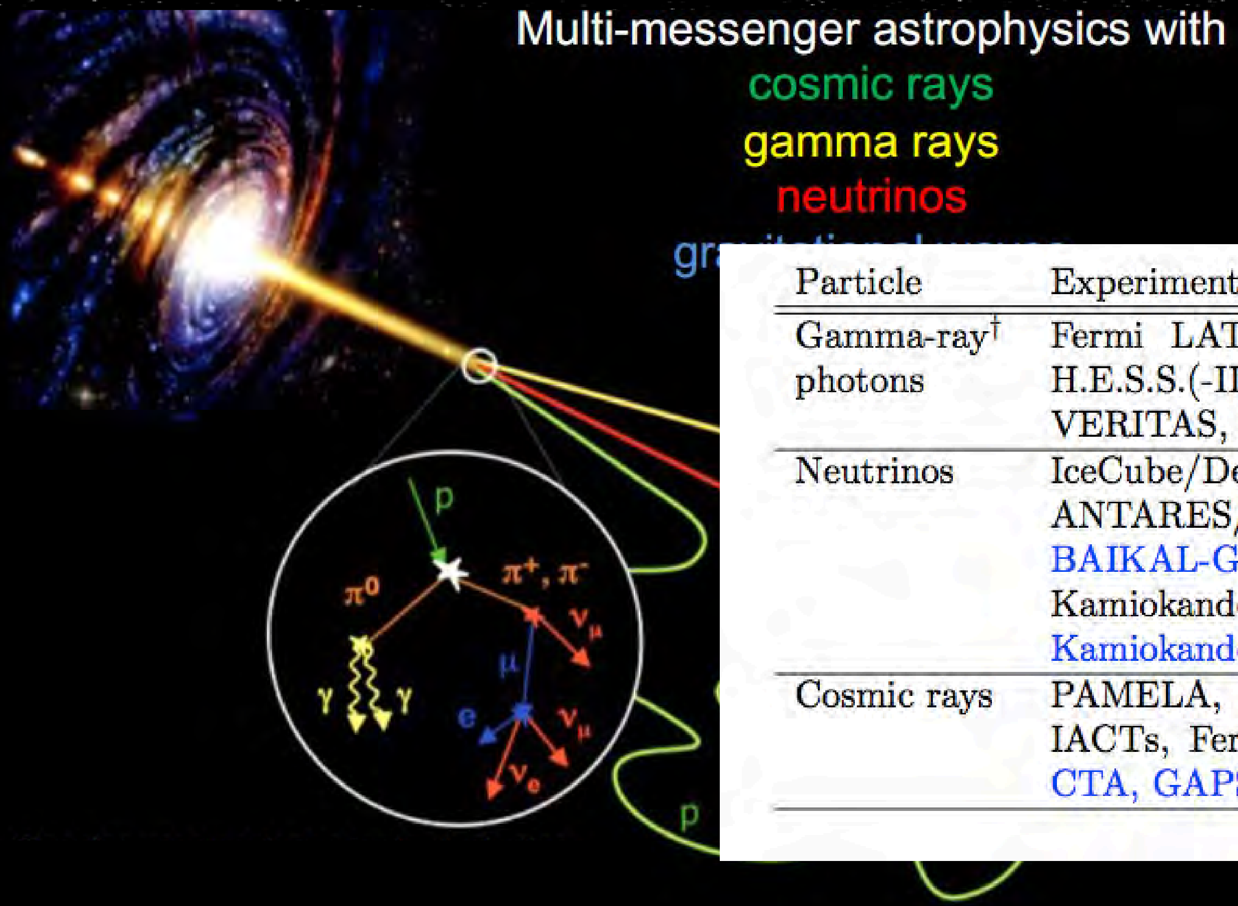
Differential gamma-ray flux produced by DM annihilation
Prompt emission

… and on the DM distribution

It is also posible "secondary radiative emission" -> inverse compton scattering or synchrotron

SIGNALS FROM DM ANNIHILATIONS / DECAY

Different channels to be considered / Different detection strategy



But also, many other astrophysical backgrounds to be taken into consideration

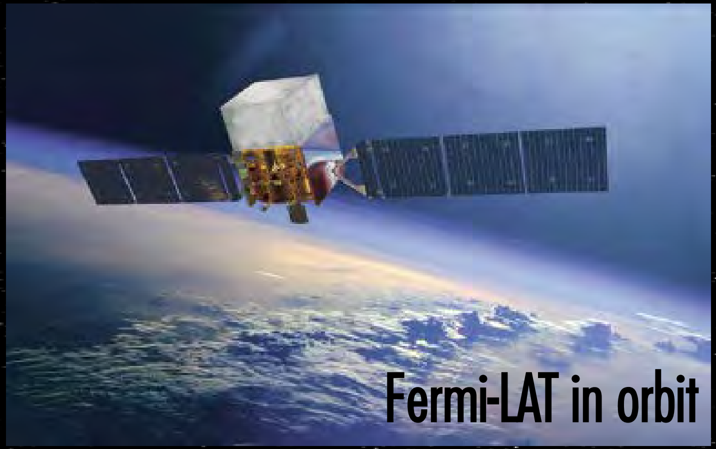
Particle	Experiments	Advantages	Challenges
Gamma-ray† photons	Fermi LAT, GAMMA-400, H.E.S.S.(-II), MAGIC, VERITAS, HAWC, CTA	point back to sources, spectral signatures	backgrounds, attenuation
Neutrinos	IceCube/DeepCore/PINGU, ANTARES/KM3NET, BAIKAL-GVD, Super-Kamiokande/Hyper-Kamiokande	point back to sources, spectral signatures	backgrounds, low statistics
Cosmic rays	PAMELA, AMS-02, ATIC, IACTs, Fermi LAT, Auger, CTA, GAPS	spectral signatures, low backgrounds for antimatter searches	diffusion, do not point back to sources

J. Gaskins, Contemporary Physics 2016

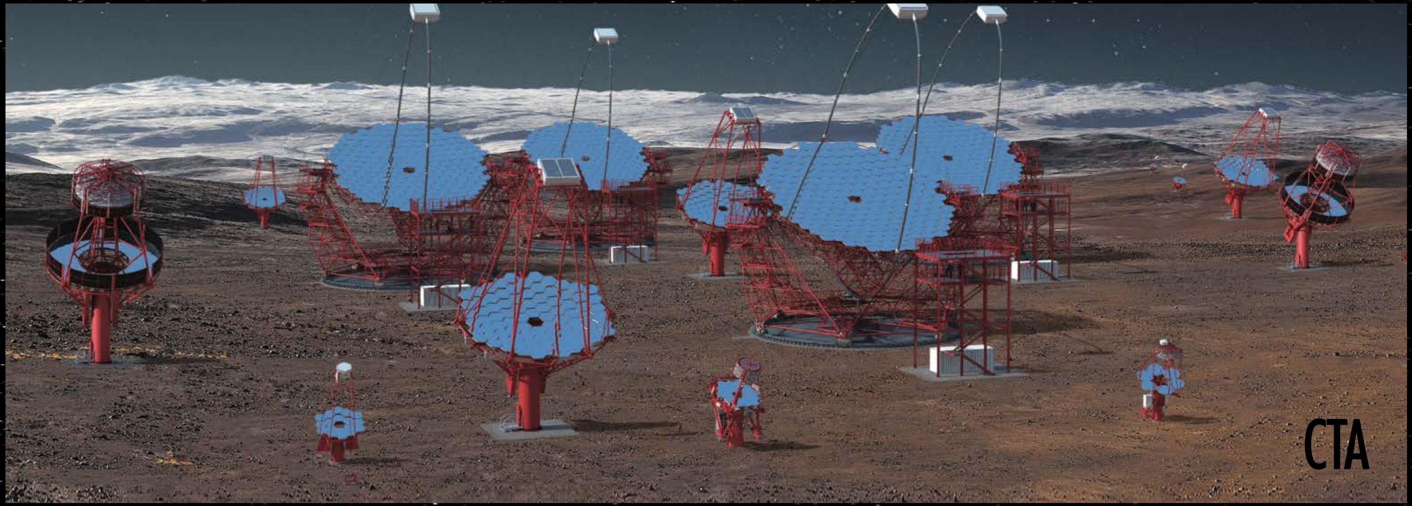
GAMMA RAY SEARCHES

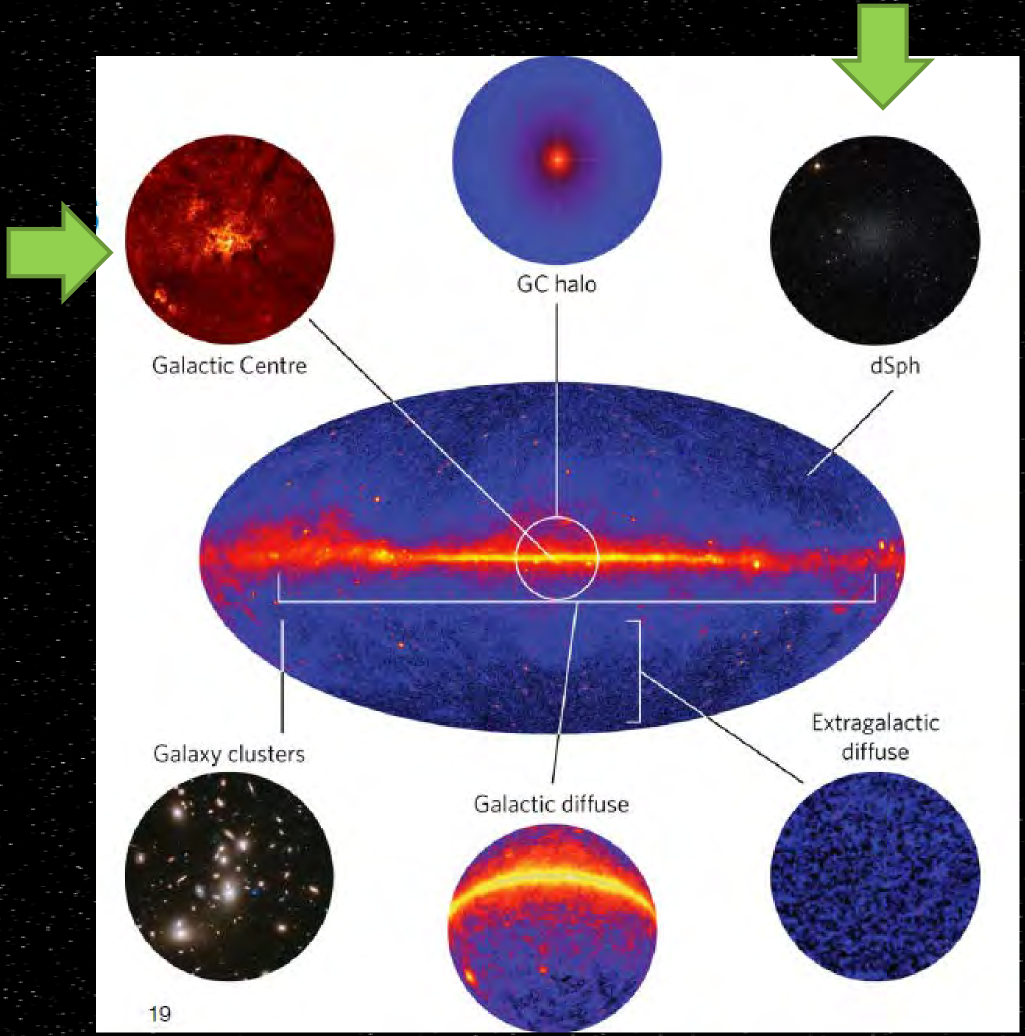
Dedicated searches for gamma lines
Study of different targets

Instruments in Space



Instruments on Ground





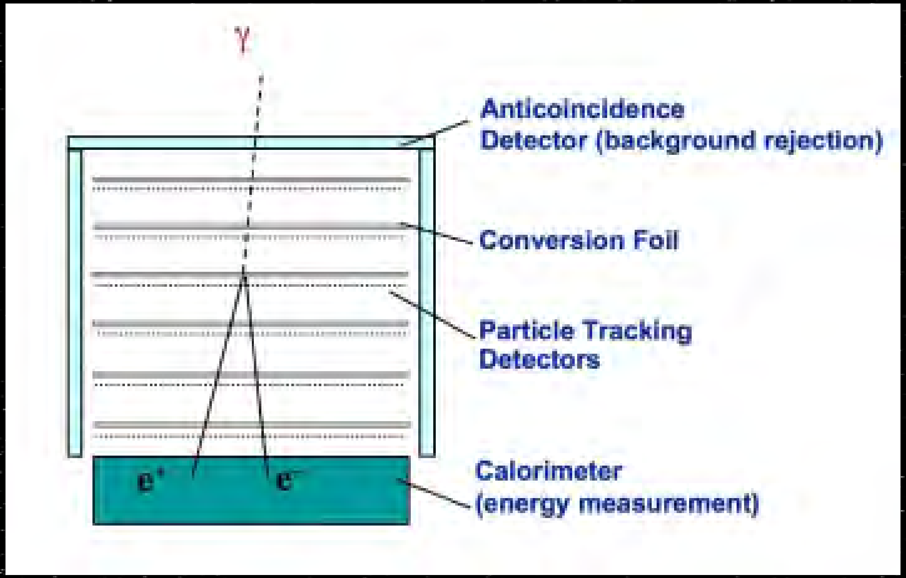
Fermi-LAT

In operation since 2008

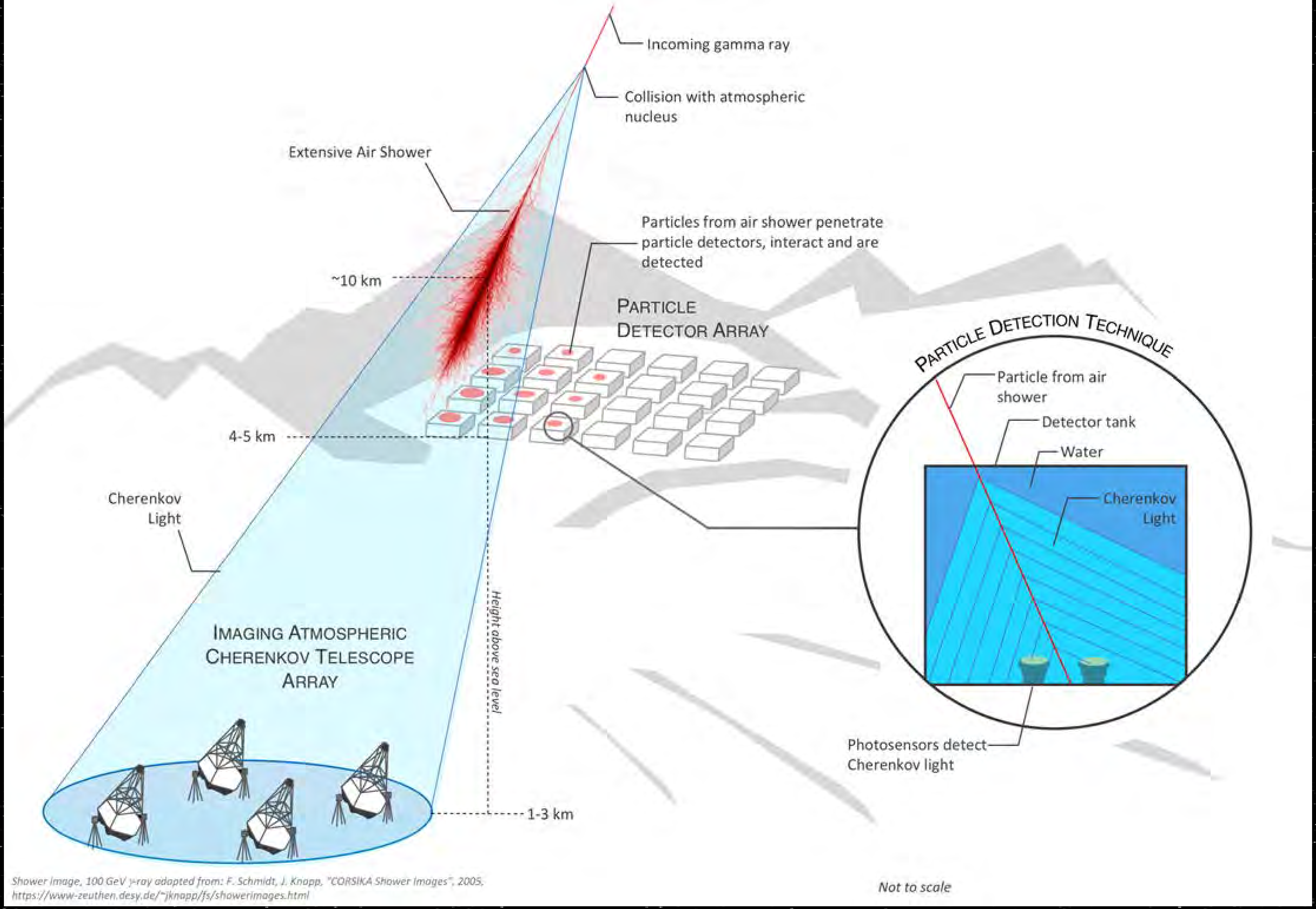
Detecting gammas from 20 MeV to 300 GeV

Field of view about 20% of the sky

Every 3 hours scans the whole sky!



Gamma ray detection on surface



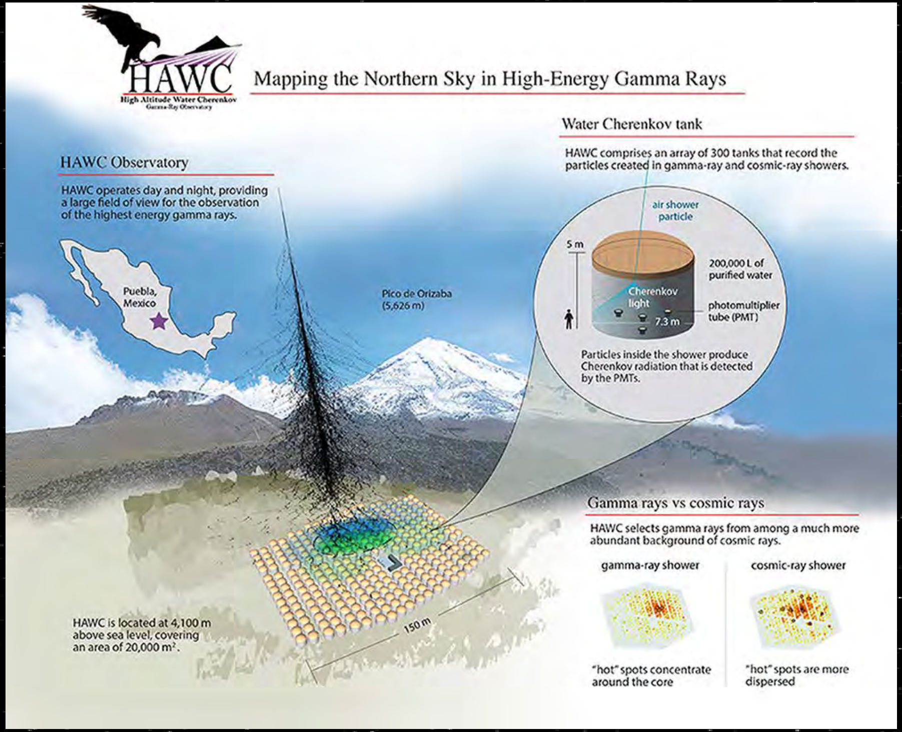
HAWC

In operation since 2013

Array of Water Cherenkov detectors @ Puebla, México (4100 m)

Energies from 300 GeV to 100 TeV

Field of view about 15% of the sky



H.E.S.S.

In operation since 2003 (phase 1) – 2012 (phase 2)

Array of five Cherenkov Telescopes @ Namibia (1800 m)

Energies from 30 GeV to 100 TeV

Field of view ~ 5% of the sky

MAGIC

In operation since 2004 (1st telescope) – 2009 (2nd telescope)

Two 17-m Cherenkov Telescopes @ La Palma, Spain (2200 m)

Energies from 50 GeV to 50 TeV

Field of view ~ 3.5% of the sky

VERITAS

In operation since 2007

Array of four Cherenkov Telescopes @ Arizona, US (1300m)

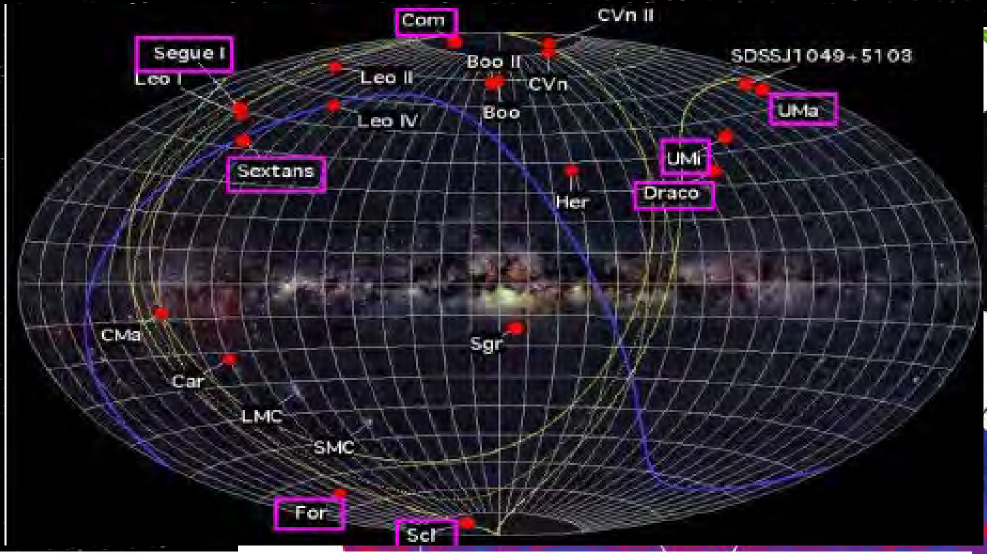
Energies from 100 GeV to 30 TeV

Field of view ~ 3.5% of the sky

COMBINED ANALYSIS for dSph

D. Kerszberg @ TAUP2021

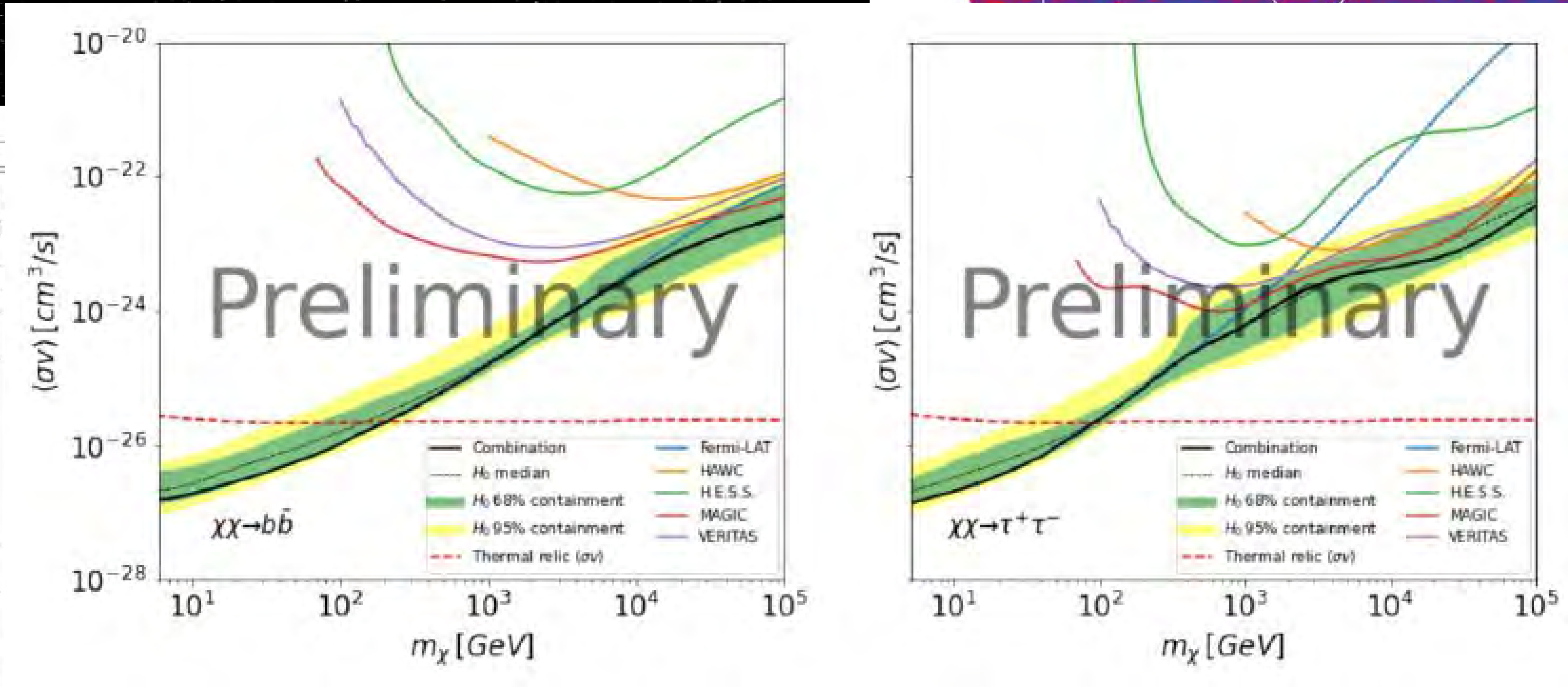
Negligible astrophysical gamma background
Large data sets available / combined likelihood and systematics analysis



- In this project we use a list of 20 dwarf galaxies for which individual collaborations already published results
- In total, 44 different data sets used

Source name
Boötes I
Canes Venatici I
Canes Venatici II
Carina
Coma Berenices
Draco
Fornax
Hercules
Leo I
Leo II
Leo IV
Leo V
Leo T
Sculptor
Segue I
Segue II
Sextans
Ursa Major I
Ursa Major II
Ursa Minor

4.1 — VERITAS 35 − 45 60.4

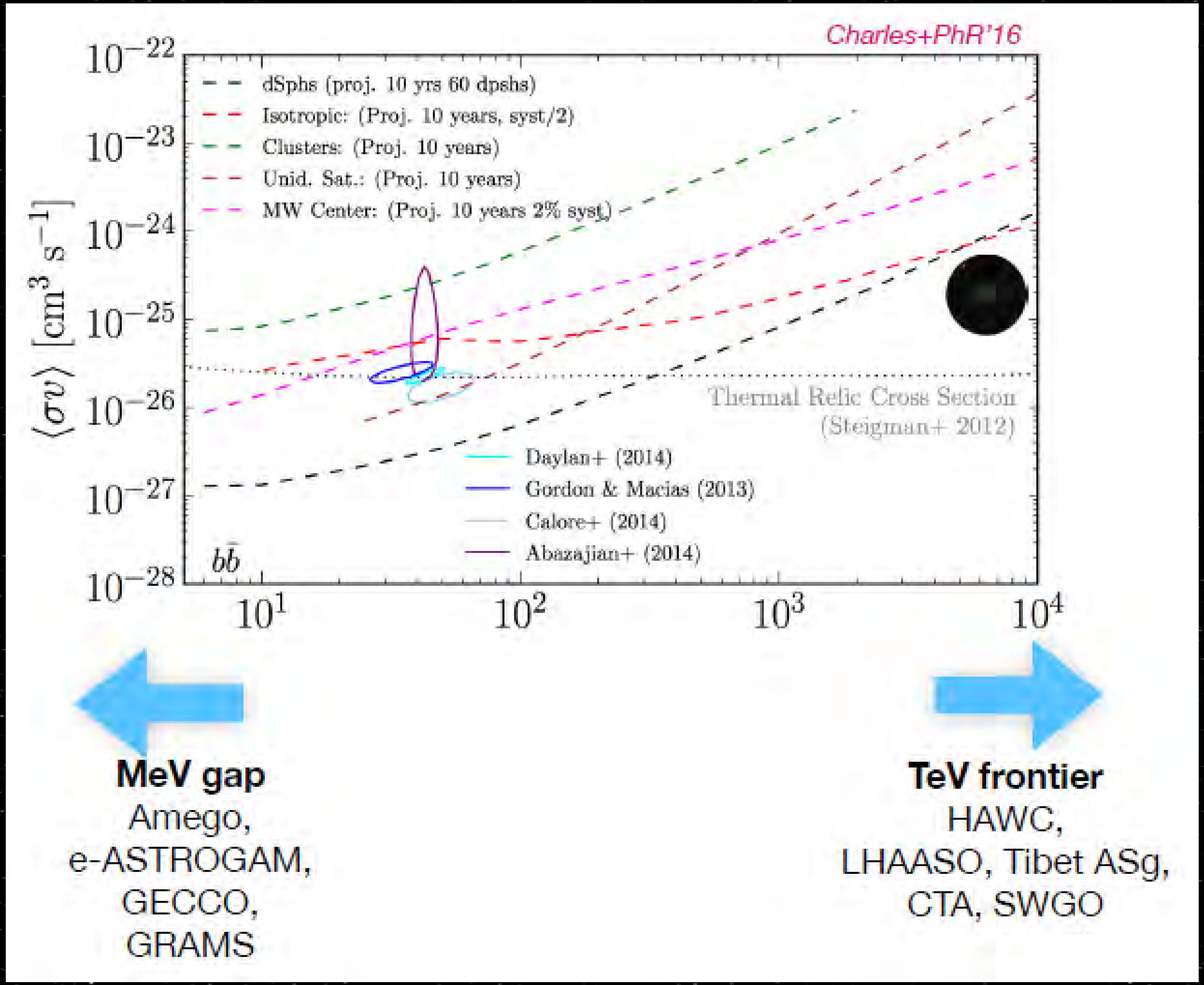


FUTURE PROSPECTS

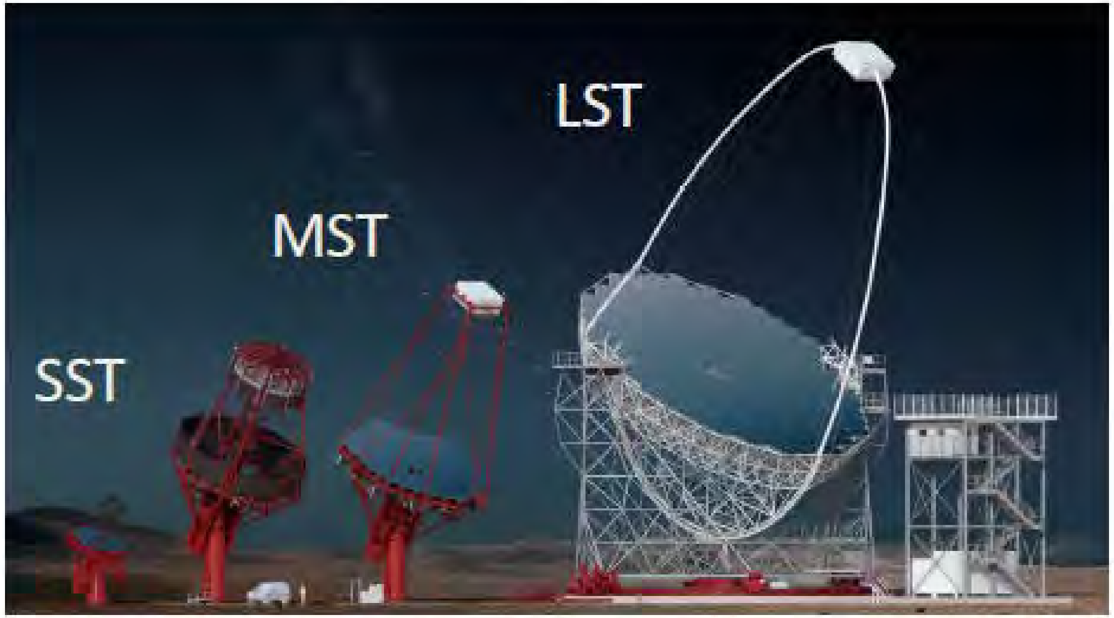
F. Calore @ TAUP2021

Some longstanding excesses are not yet resolved: DM interpretation is challenged by astrophysical alternatives

Great progress at multiple wavelengths/messengers will provide opportunity for discovery

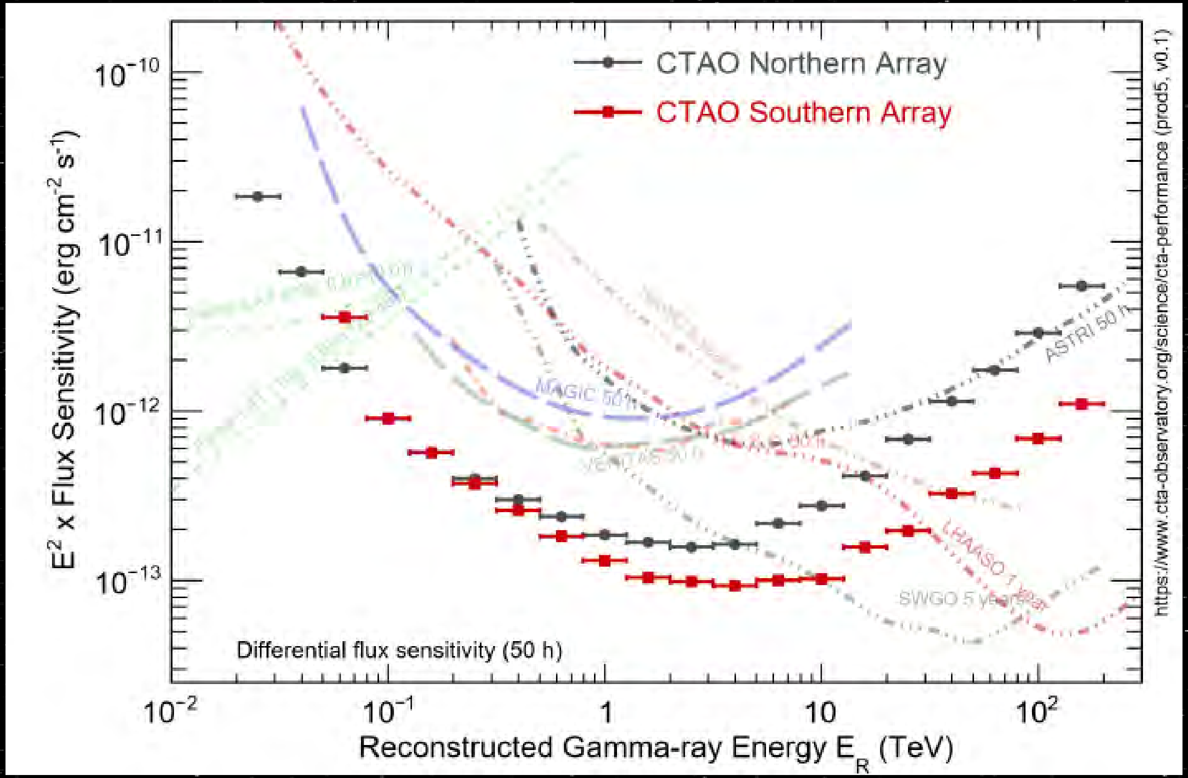


CTA: CHERENKOV TELESCOPE ARRAY



- CTA is the next-generation observatory for gamma-ray astronomy in the **very-high energy band (>20 GeV)**
- Concept: **Cherenkov telescopes** of different sizes deployed over an area of O(km^2)
- Order of magnitude better sensitivity than existing facilities
- June 25th 2021: design and costbook of first CTA phase ("Alpha configuration") approved by the Board of governmental representatives $\Rightarrow$ green light for construction

CTA: CHERENKOV TELESCOPE ARRAY



LST-1 TELESCOPE FINISHING COMMISSIONING @ La Palma

First results, already competitive for specific physics cases

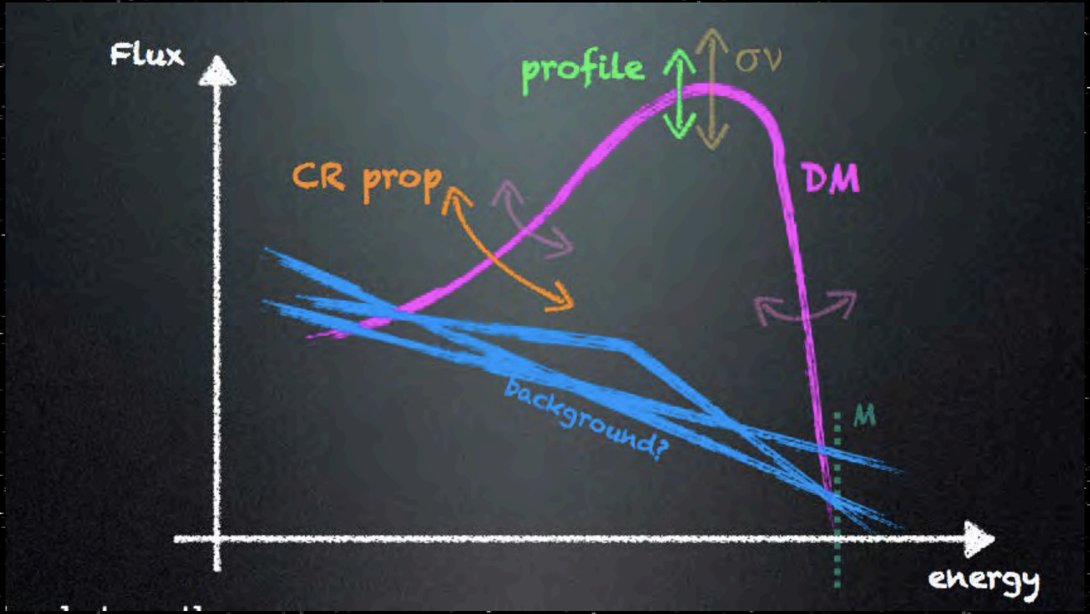
It will ouperform all existing IACT arrays

A. MORALEJO @ TAUP2021

CHARGED PARTICLES SEARCHES

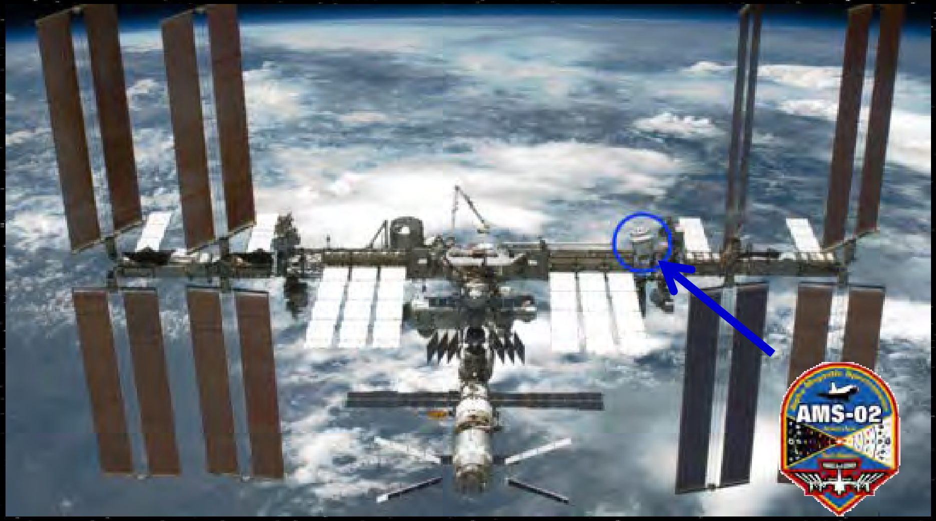
Still many uncertainties on sources of cosmic rays, and propagation

Strongly dependent on modelling of backgrounds to extract information from DM annihilation



Instruments in Space

PAMELA

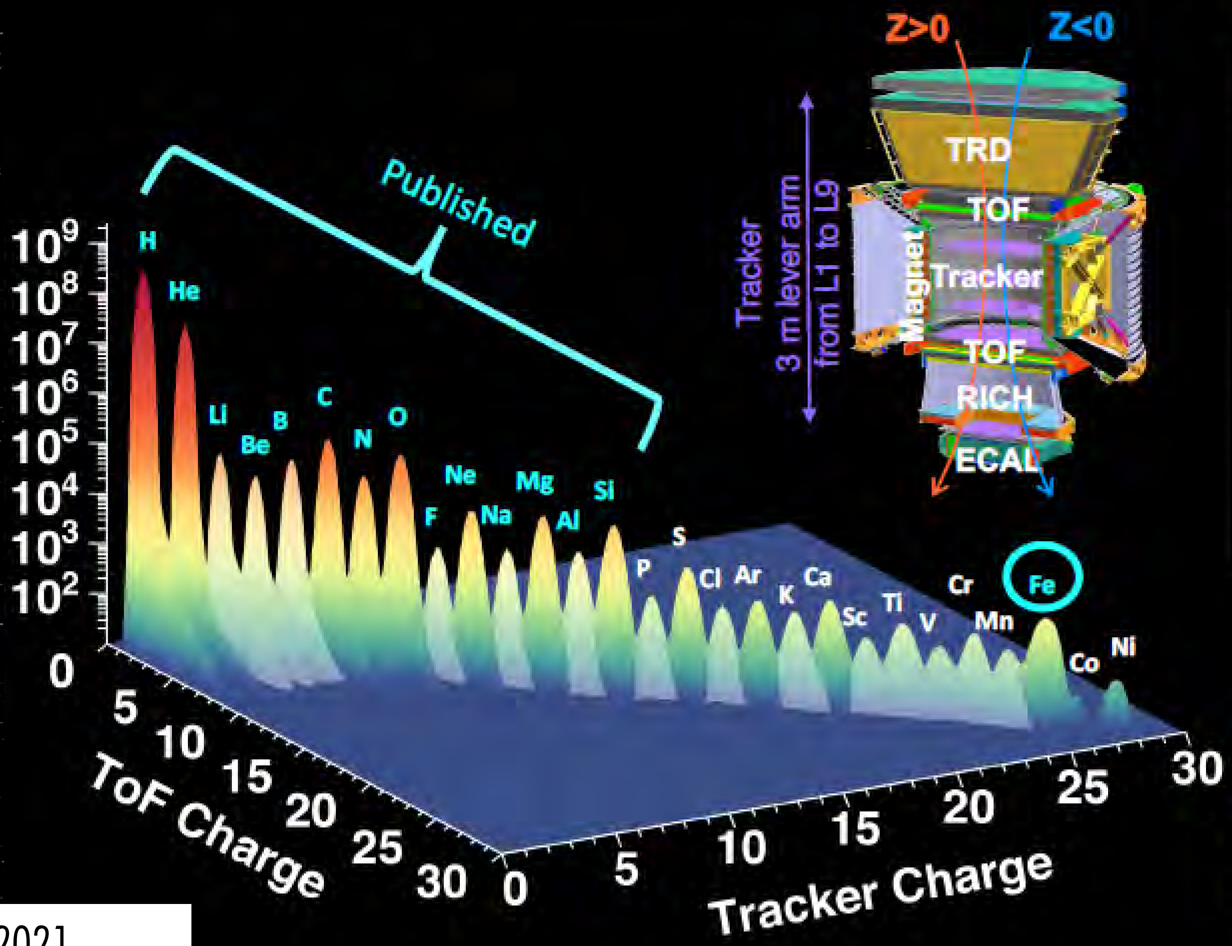


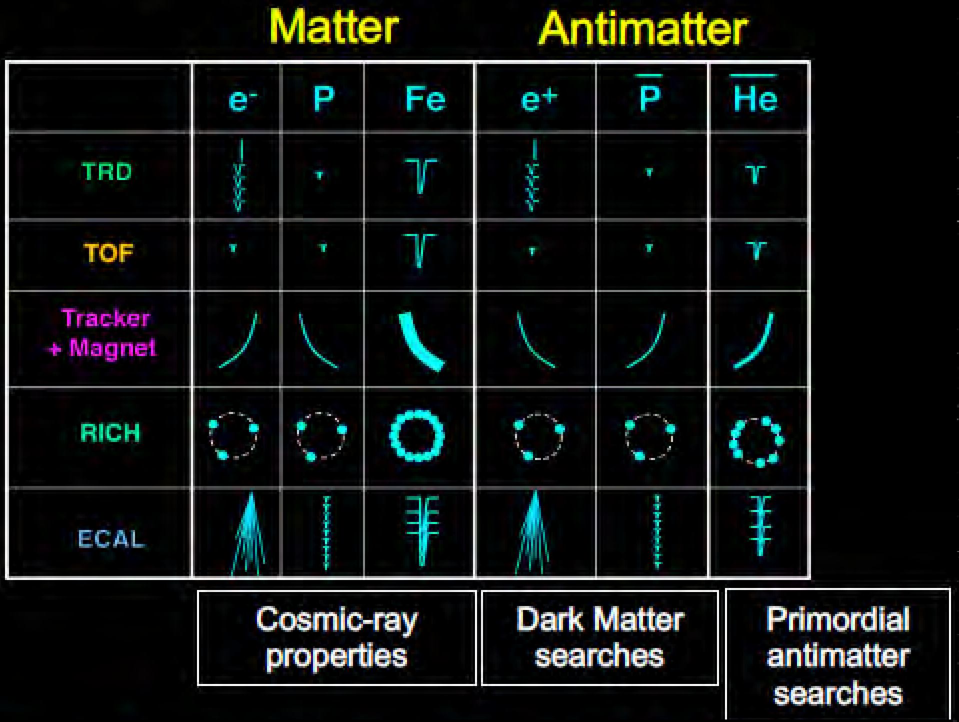
AMS-02 @ ISS

AMS-02: a TeV precision magnetic spectrometer @ ISS

AMS-02: particle and nuclei identification

Redundant measurements of particle charge (Z) and Energy (R=p/Z, velocity)





M. Paniccia @ TAUP2021

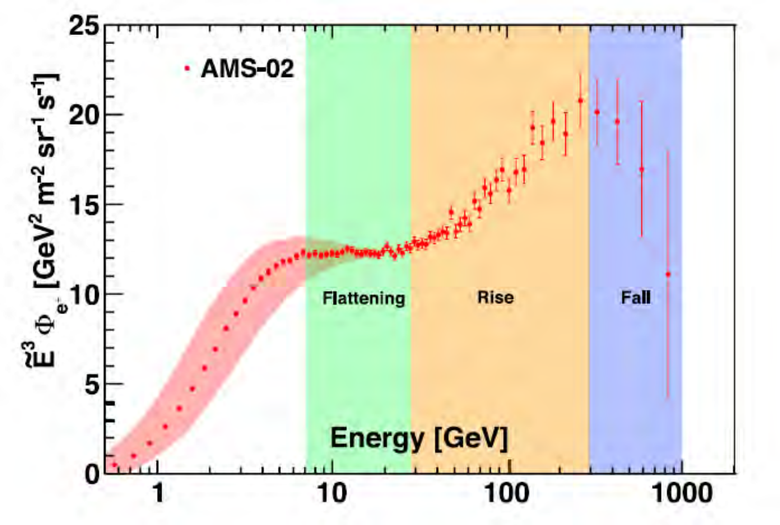
AMS-02: a TeV precision magnetic spectrometer @ ISS

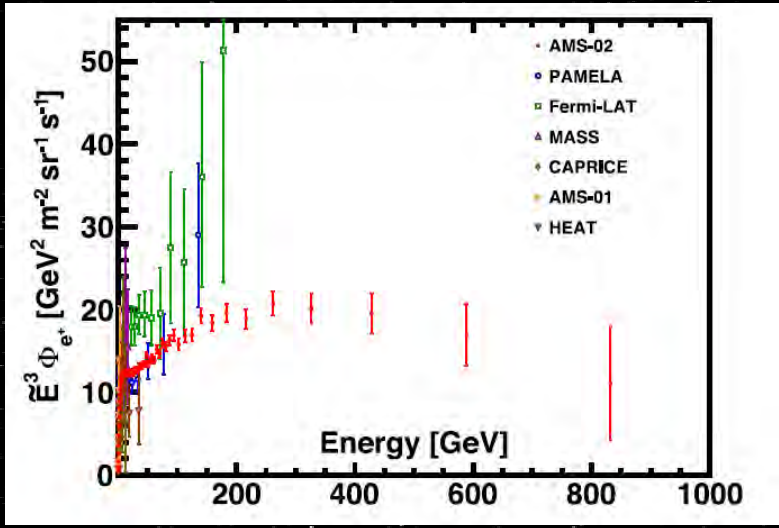
POSITRON EXCESS

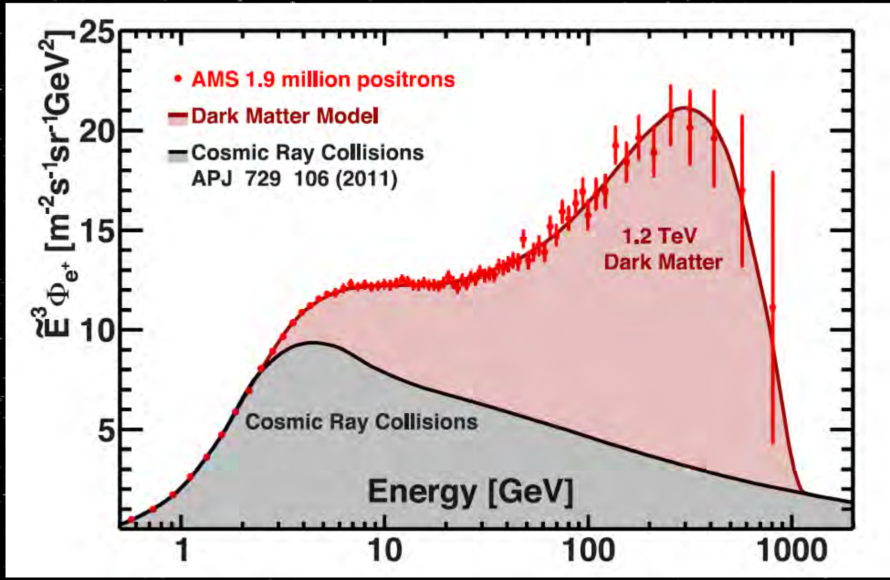
First hints by HEAT and AMS-1

Confirmed by PAMELA from 10-100 GeV & Fermi up to 200 GeV

AMS-02 confirms a hardening of the positron spectrum and steep descent that could be related to a cutoff from DM annihilation





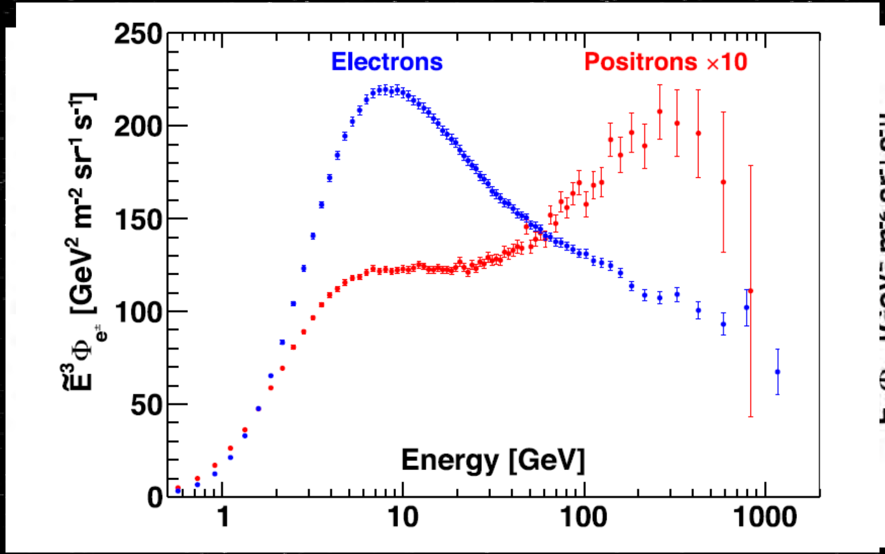


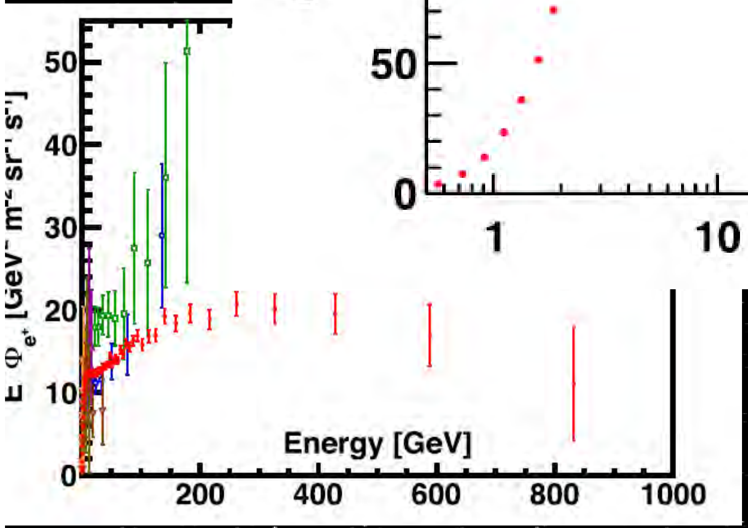
M. Aguilar et al., Physics Reports 894 (2021) 1

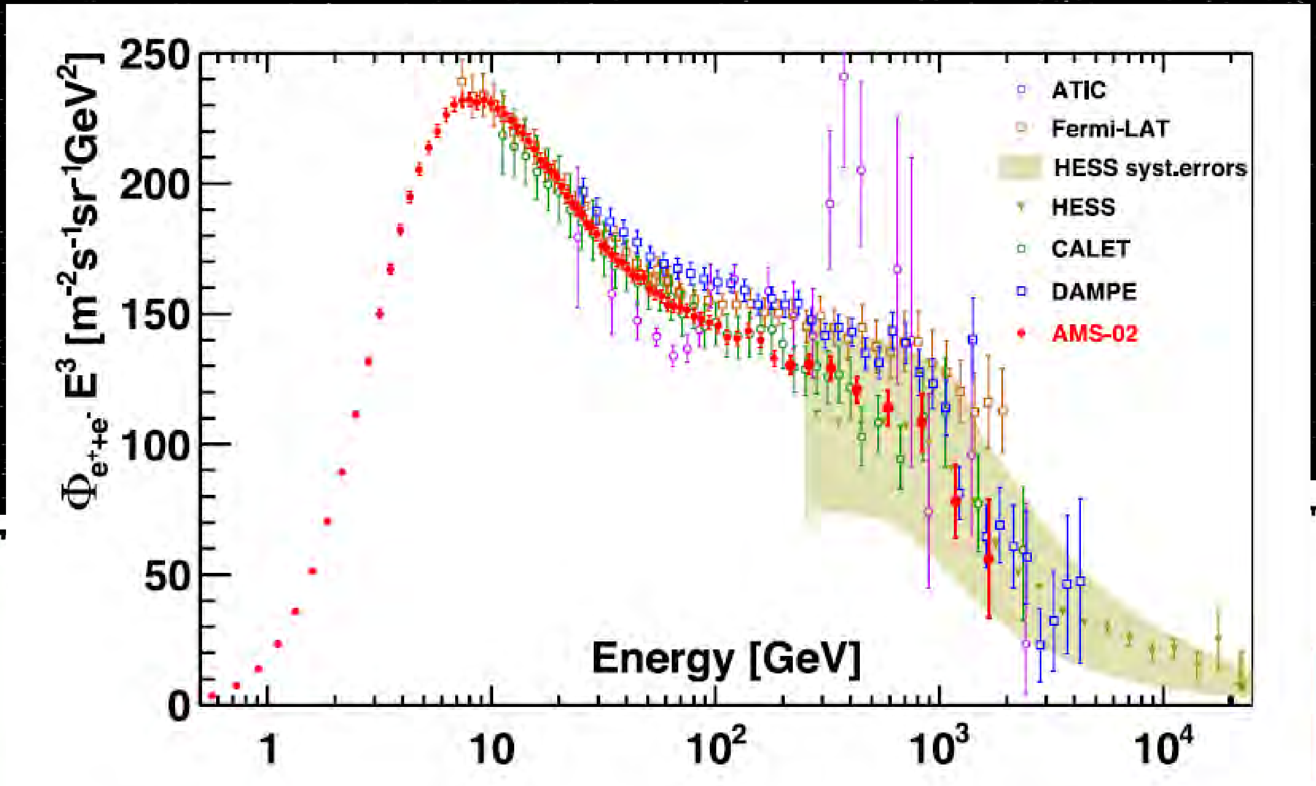
AMS-02: a TeV precision magnetic spectrometer @ ISS

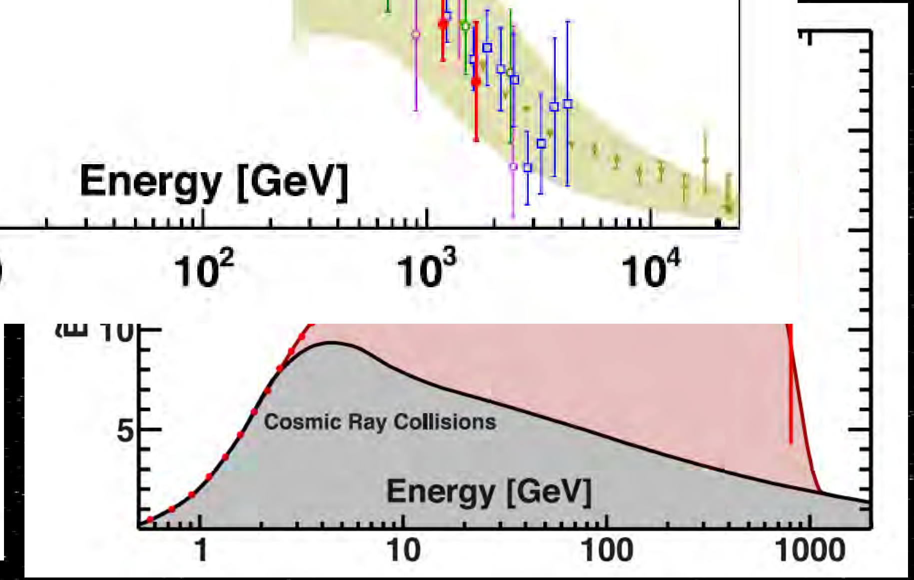
POSITRON EXCESS

Combined electron and positron flux







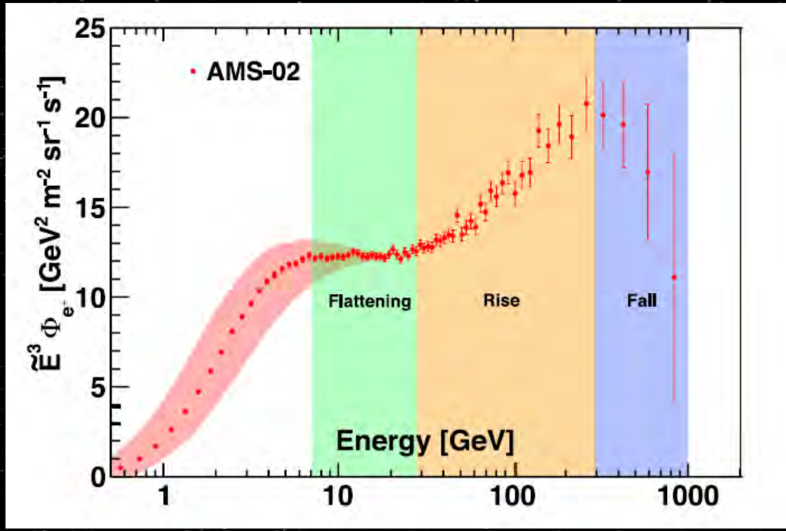


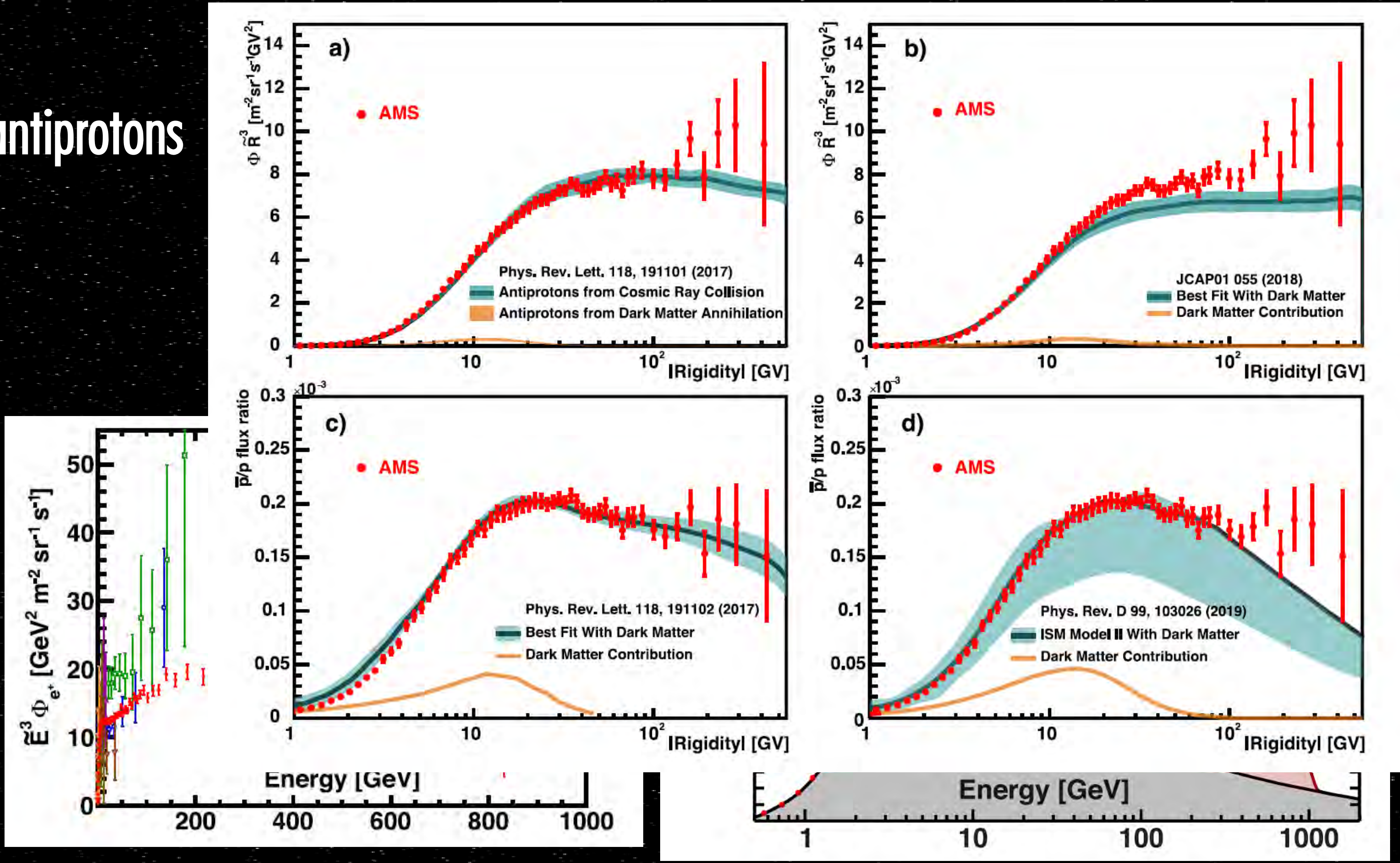
M. Aguilar et al., Physics Reports 894 (2021) 1

AMS-02: a TeV precision magnetic spectrometer @ ISS

POSITRON EXCESS

No extra-contributions are visible in antiprotons (too many uncertainties)





M. Aguilar et al., Physics Reports 894 (2021) 1

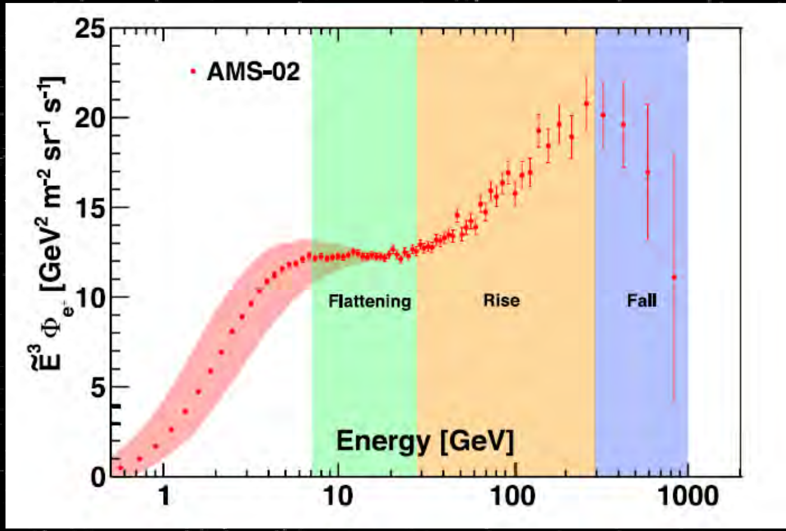
AMS-02: a TeV precision magnetic spectrometer @ ISS

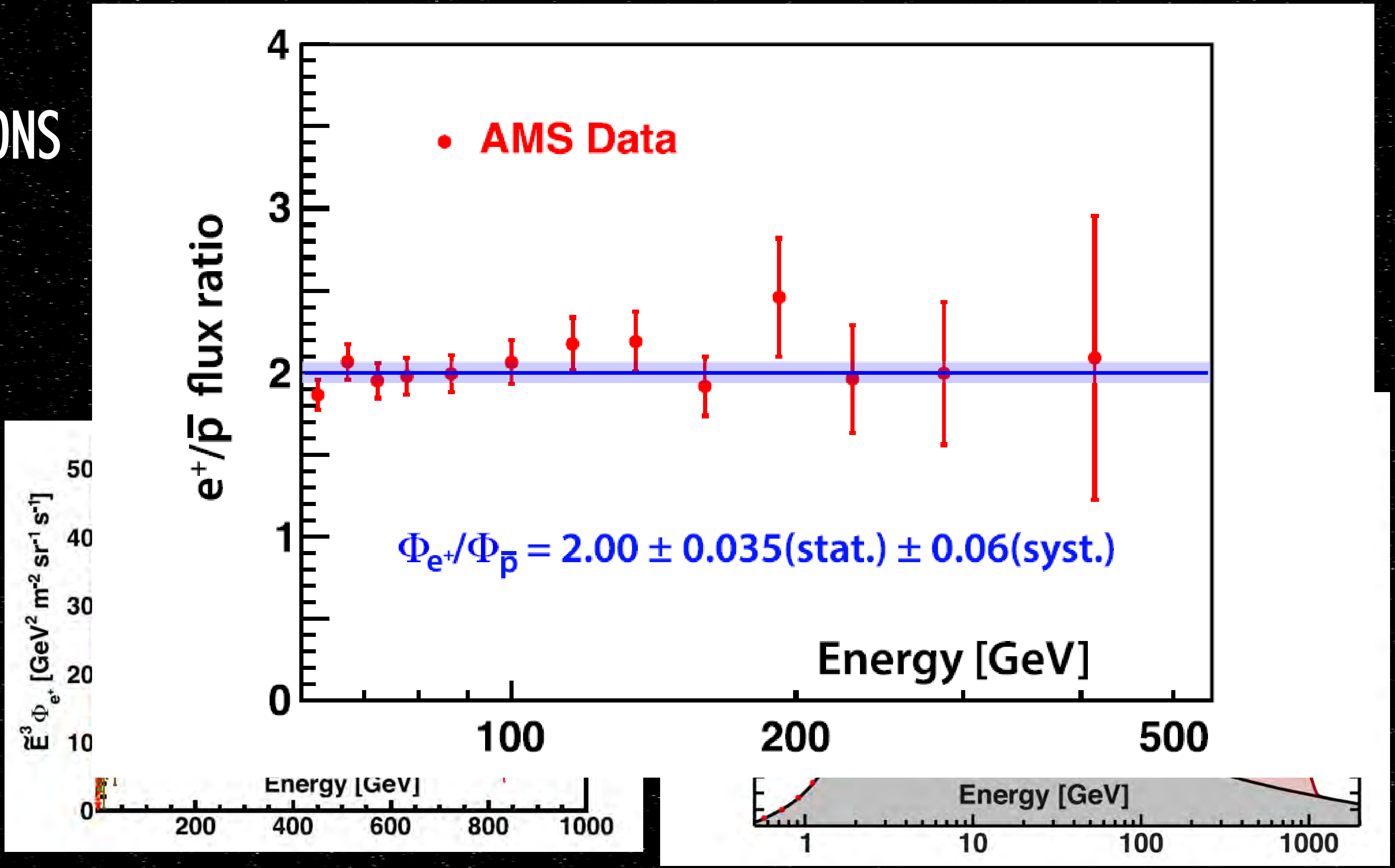
POSITRON EXCESS

CONSTANT RATIO BETWEEN POSITRONS AND ANTIPROTONS

Interesting puzzle

(V. Formato @ TAUP2021)



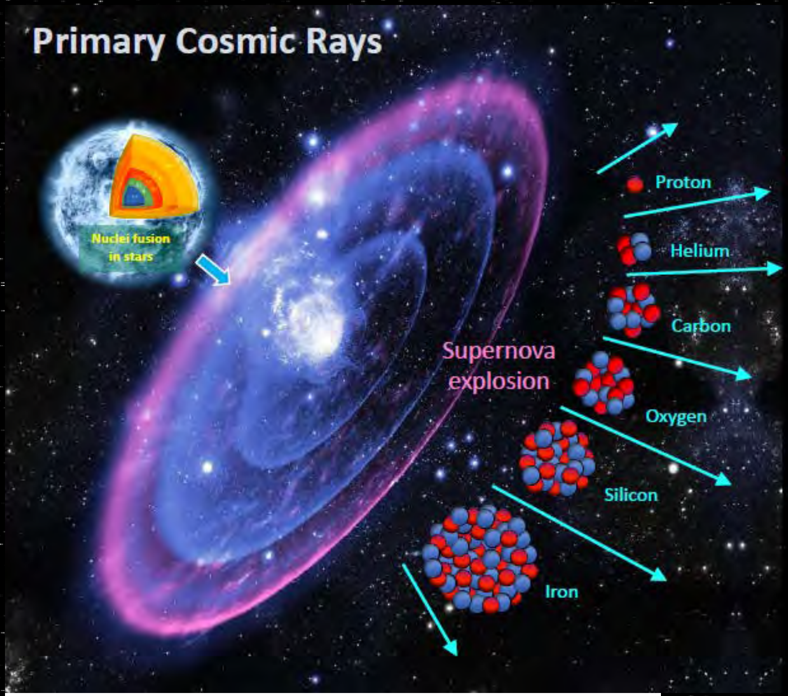


M. Aguilar et al., Physics Reports 894 (2021) 1

AMS-02: a TeV precision magnetic spectrometer @ ISS

DM Interpretation of the positron excess is difficult to match with models

Still astrophysical explanation is possible



Primary elements,
protons, He, C, O, Ne, Mg, Si..., Fe nuclei
are produced
during the lifetime of stars.

They are accelerated in
supernovae explosions
and
expelled in the interstellar medium
where they propagate diffusively
through the galaxy.

M. Paniccia and others @ TAUP2021

Enormous information on sources, acceleration and propagation processes will be provided in next years

Required to improve interpretation of a possible DM signal

DAMPE

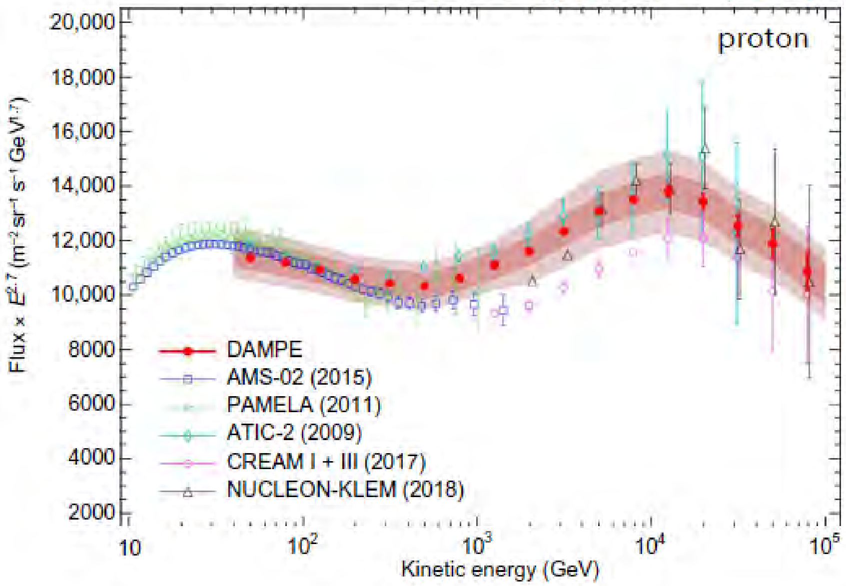
DAMPE RECENT RESULTS on protons and helium show a “bump” -> new feature

-could be an individual source

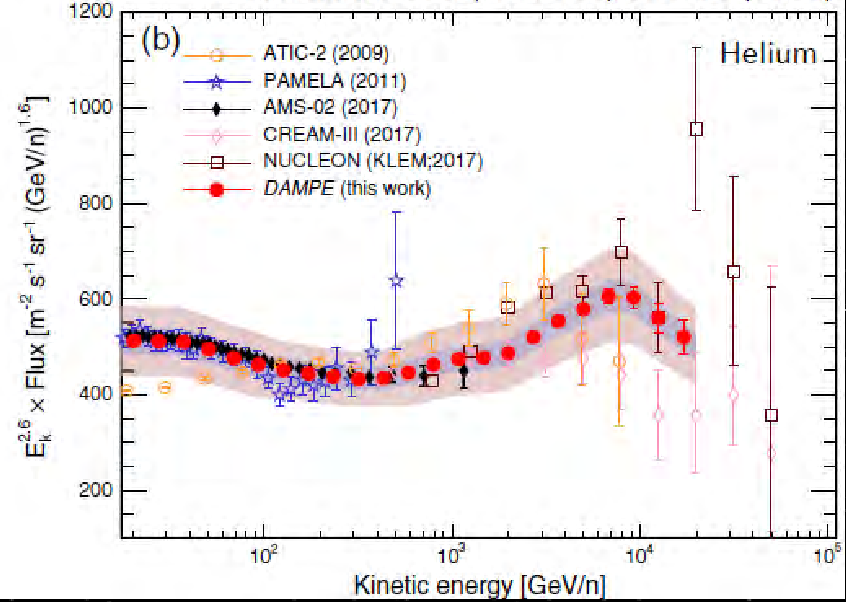
-could be a new population of CRs

(V. Formato @ TAUP2021)

Q. An et al., Sci. Adv. 5 (2019) 9

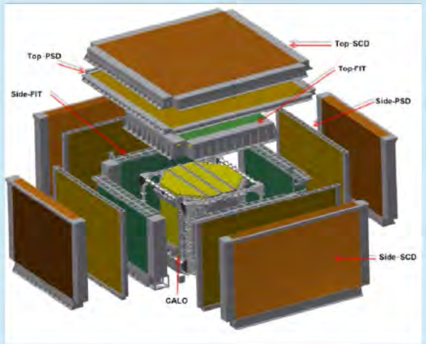


F. Alemanno et al., PRL 126, 201102 (2021)

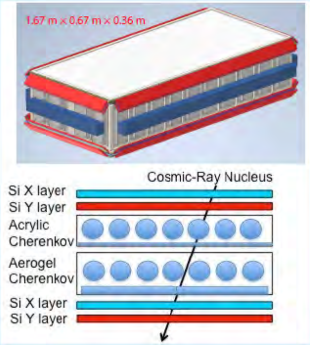


THE (NEAR) FUTURE

HERD
3D LYSO calorimeter
Expected ~2027 on the CSS
Nuclei to the PeV region
Leptons to ~100 TeV

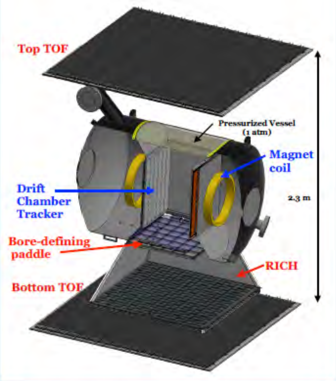


TIGERISS
Evolution of SuperTIGER
Expected on the JEM on the ISS
Nuclei 5 < Z < 86

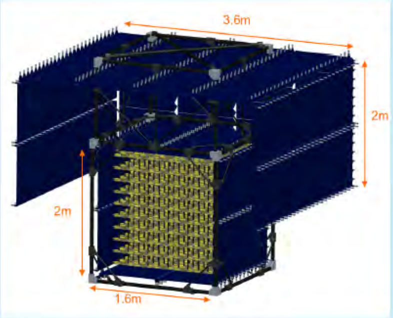


Space stations

HELIX
Superconducting spectrometer
Long duration balloon flight expected in 2022
Isotopic composition up to 10 GeV/n



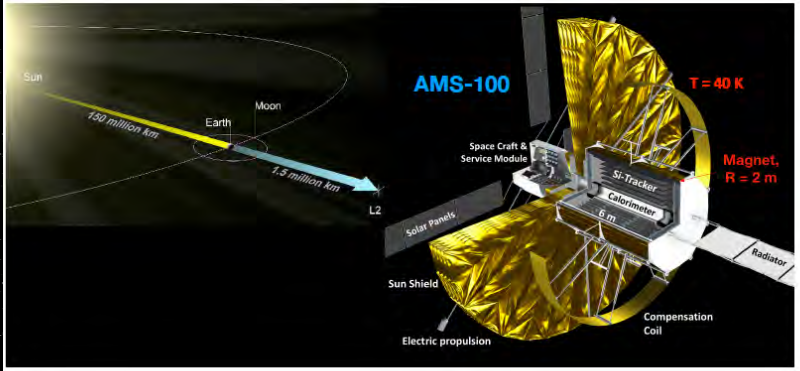
GAPS
Search for antideuterons at low energy using a exotic atom technique
Long duration balloon flight expected in late 2022



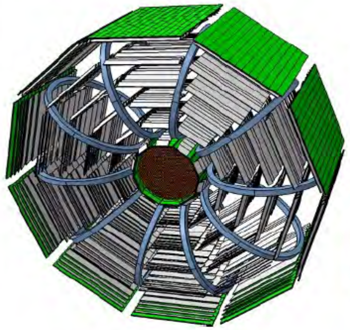
Balloons

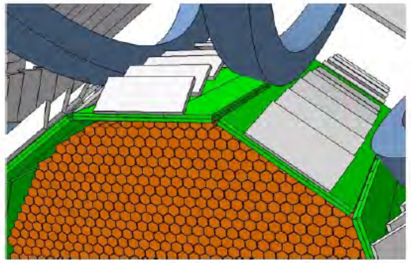
THE (FAR) FUTURE

AMS-100
Lagrange point 2
1 Tesla magnetic, (6 × 2) m
Tracker, MDR = 100 TV
Central calorimeter (reverse-collider layout)
Goals: e+, e-, nuclei (beyond the knee), antinuclei



ALADInO
Lagrange point 2
Spectrometer: MDR = 20 TV
Hexagonal-prysm calorimeter
Goals: e+, e-, nuclei, antinuclei



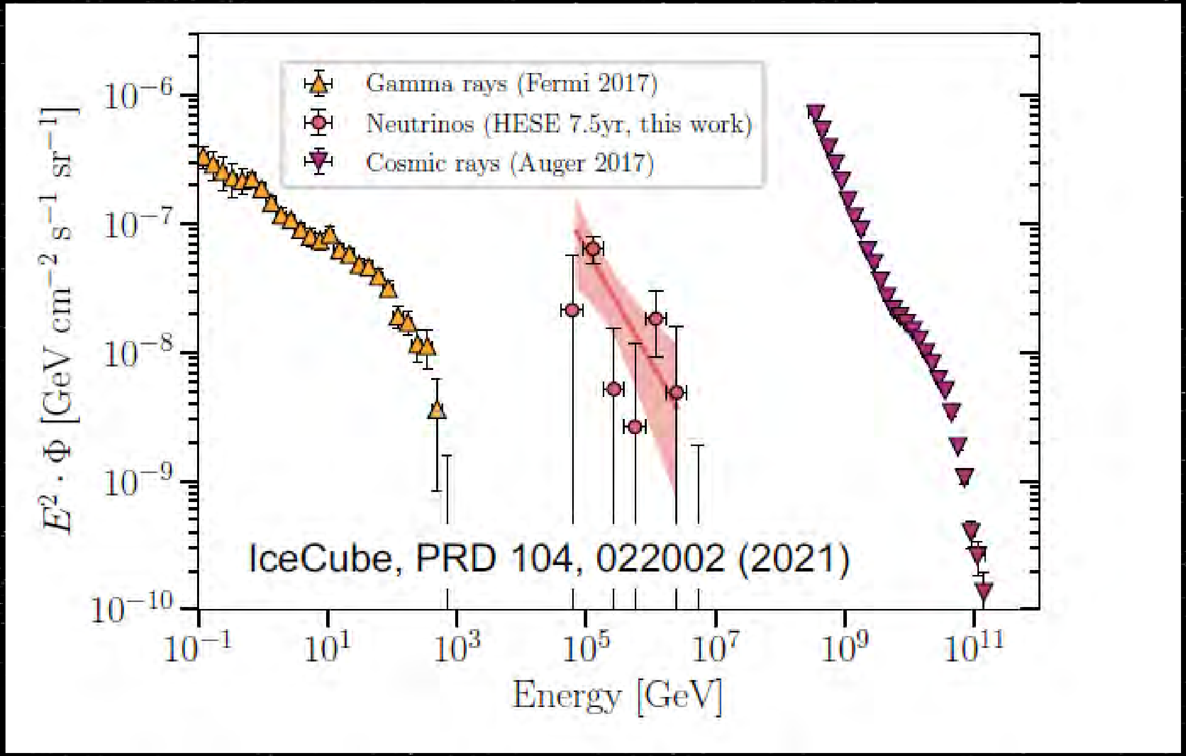


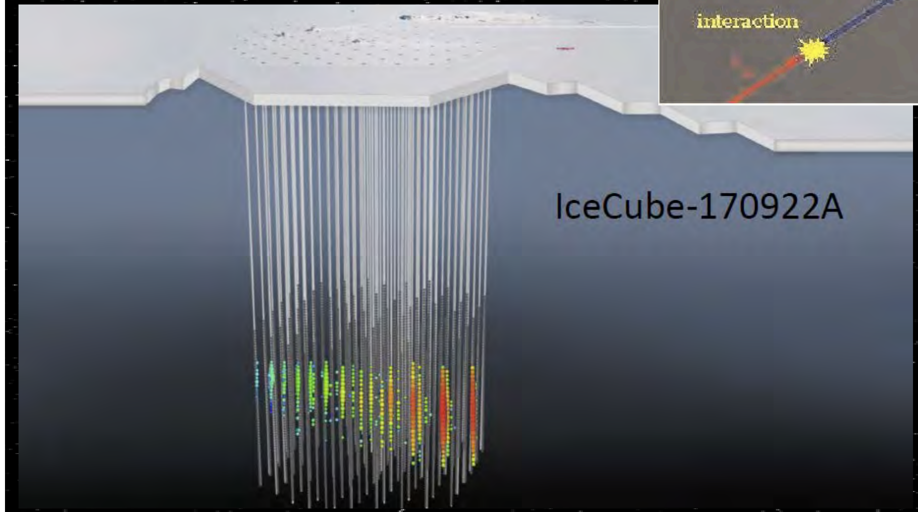
V. Formato @ TAUP2021

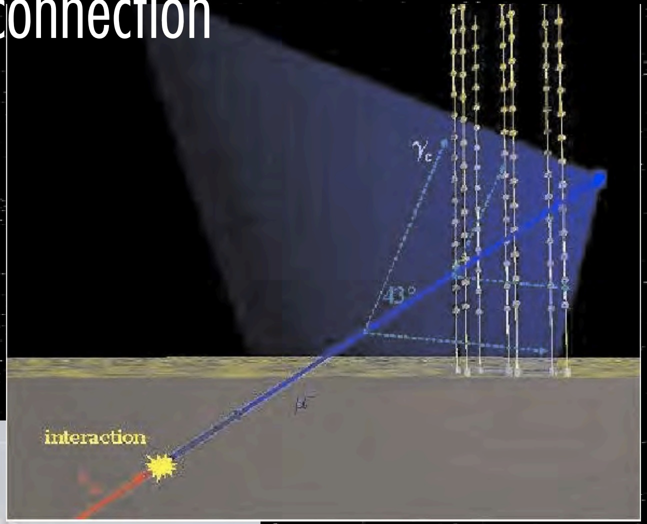
NEUTRINO SEARCHES

Neutrinos are very interesting to understand CR sources character (neutrinos point to hadronic origin)

Sky is very different in each messenger, but energy density is similar for all -> Deep connection (J. Vandenbroucke @ TAUP2021)





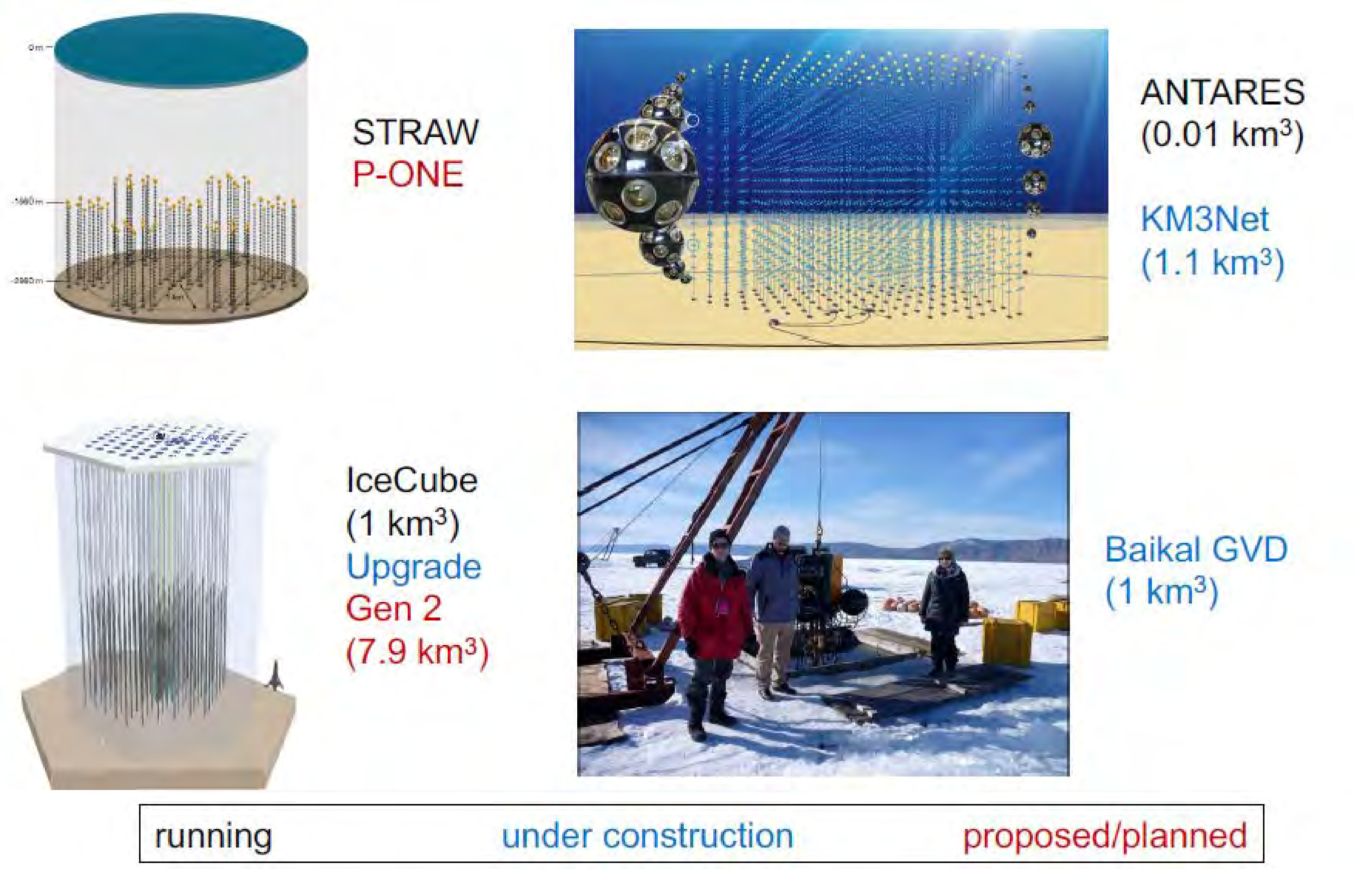


NEUTRINO SEARCHES

ANTARES
(Under Mediterranean Sea)

ICECUBE (South Pole)

Large Cherenkov detectors under-ice or under-water



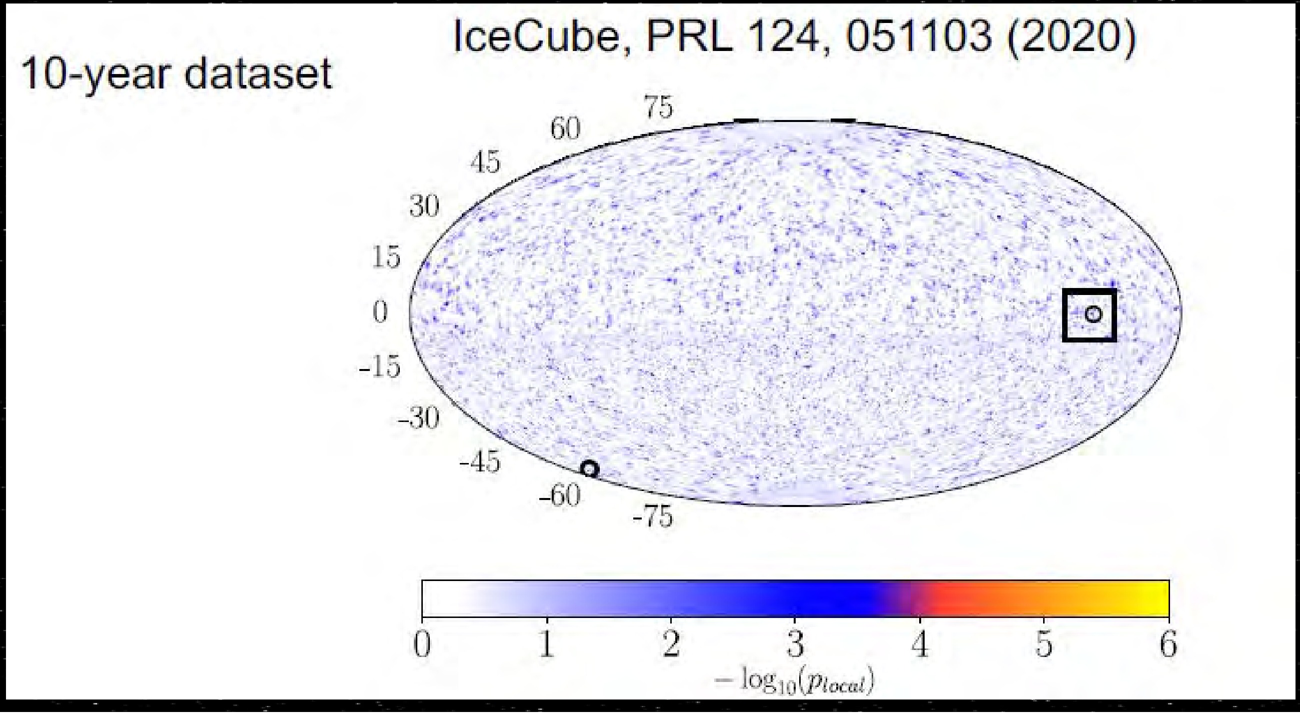
J. Vandenbroucke @ TAUP2021

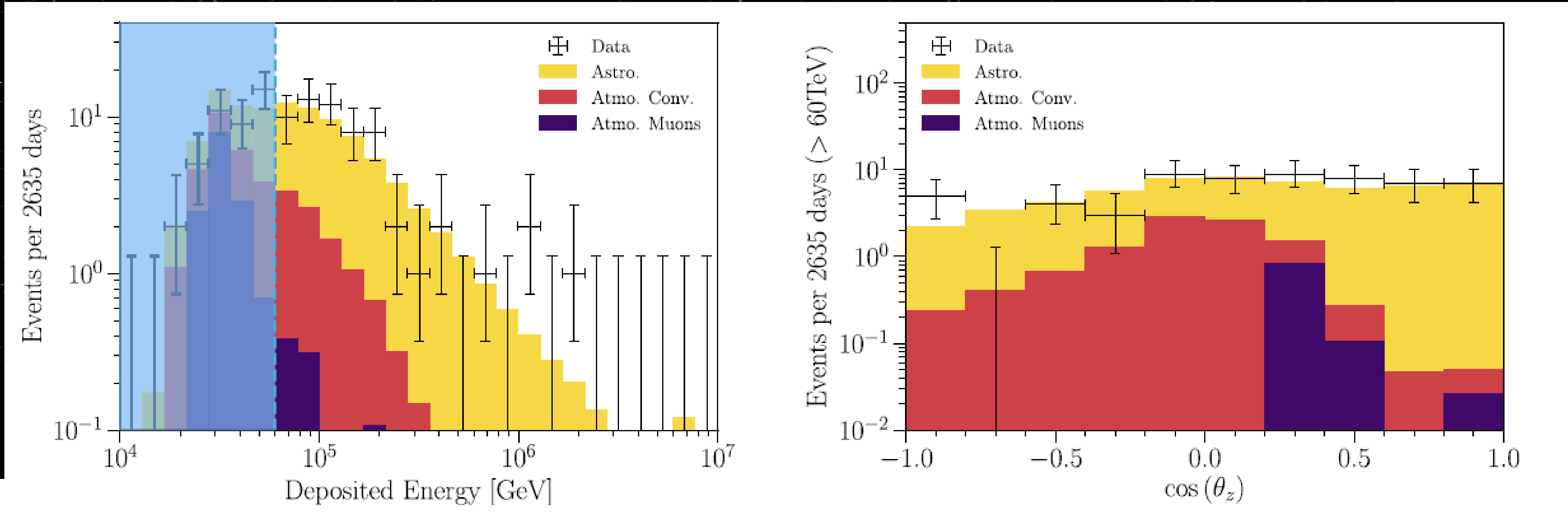
Credit: J. Vandenbroucke @ TAUP2021

NEUTRINO SEARCHES

Neutrino flux is isotropic

VHE neutrinos clearly identified
E > 60 TeV (up to PeV)





PRD104 (2021) 022002

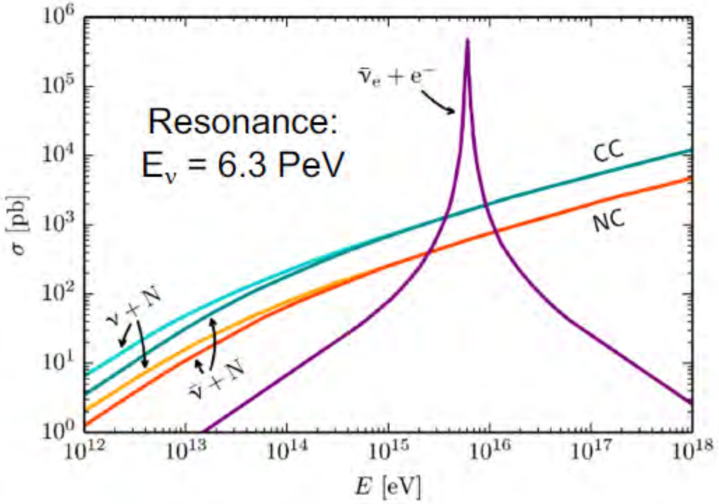
J. Vandenbroucke @ TAUP2021

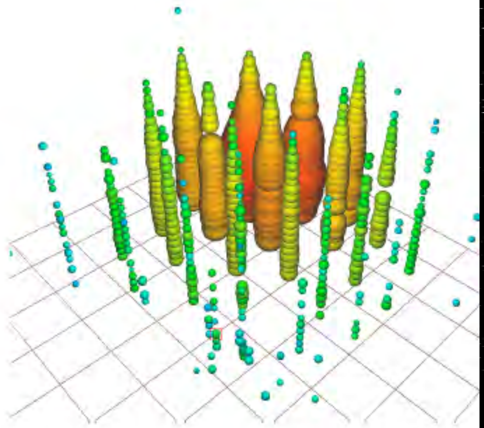
NEUTRINO SEARCHES

Large potential of multimessenger astronomy
Shown by observation of blazar TXS 0506+056

+ GWs
+ Gamma searches
+CRs

& other surprises





- Event not contained: identified in partially contained PeV search (PEPE)
- IceCube, 1710.01191 (ICRC)
- 6.05 ± 0.72 PeV visible energy

IceCube, Nature 591, 220-224 (2021)