Intriguing hints from indirect dark matter searches

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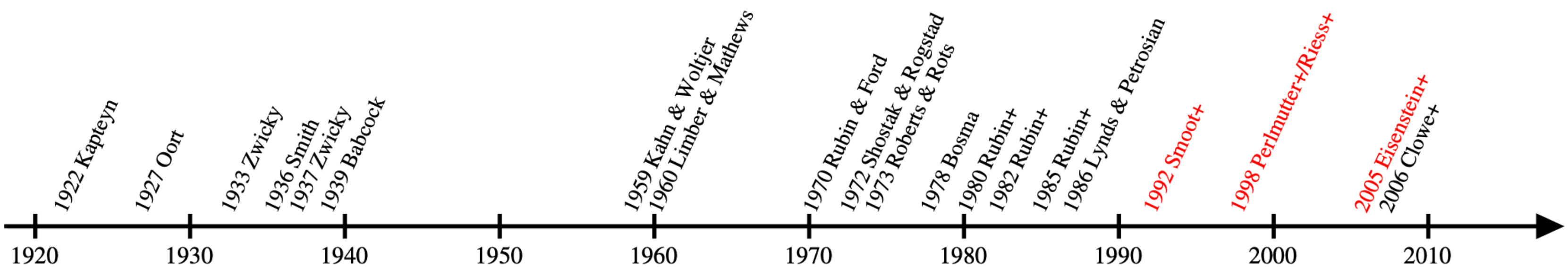
I. BRIEF HISTORICAL PERSPECTIVE

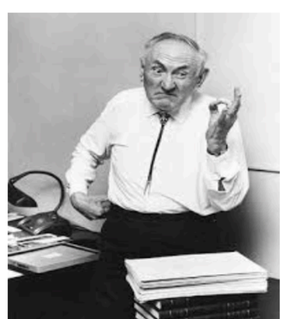
The evidence for dark matter gradually mounted throughout the 20th century, and by now we are convinced that our universe is filled with dark matter at various scales. Note that all evidence for dark matter is of gravitational origin; non-gravitational evidence is yet to be discovered.



We can identify four key revolutions in the history of dark matter:

1. dark matter is first mentioned by Kapteyn;
2. dark matter is found in the Coma cluster by Zwicky;
3. dark matter is found in spiral galaxies by Rubin & Ford; and
4. dark matter is found at cosmological scales by many.

Slide M. Pato



What do we know about dark matter ?

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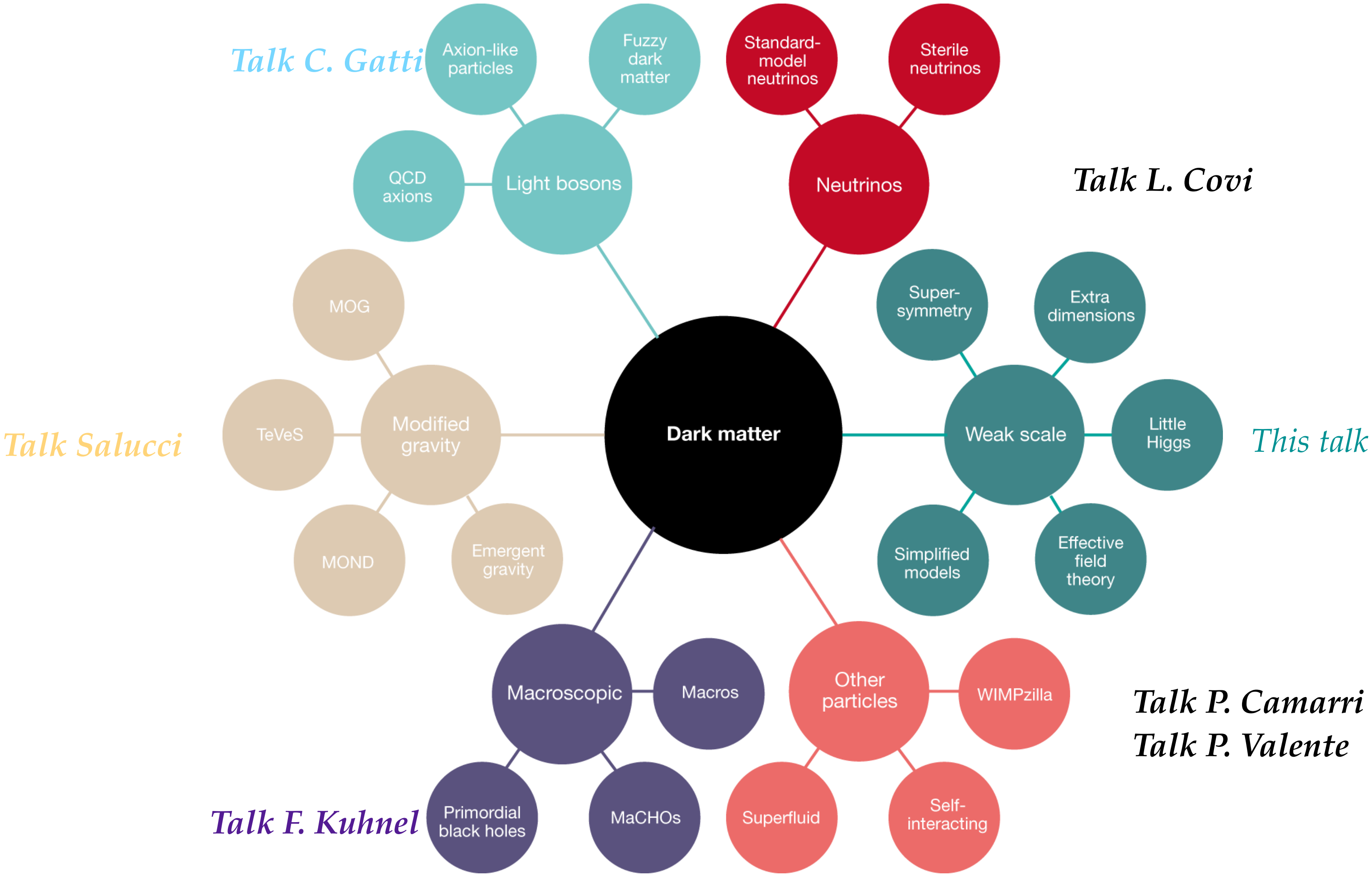
- Strong and long-standing evidence for dark matter at both astrophysical and cosmological scales.
  - It does not absorb/scatter/emit light.
  - It does interact gravitationally, so it does have mass.
  - It constitutes about 84% of the universe's matter.
  - Structure formation numerical simulations indicate that it forms the underlying structure for the visible universe.
  - It forms large clouds or halos around galaxies.
  - It interacts feebly with other particles, or not at all (only gravity).

What is dark matter made of ?

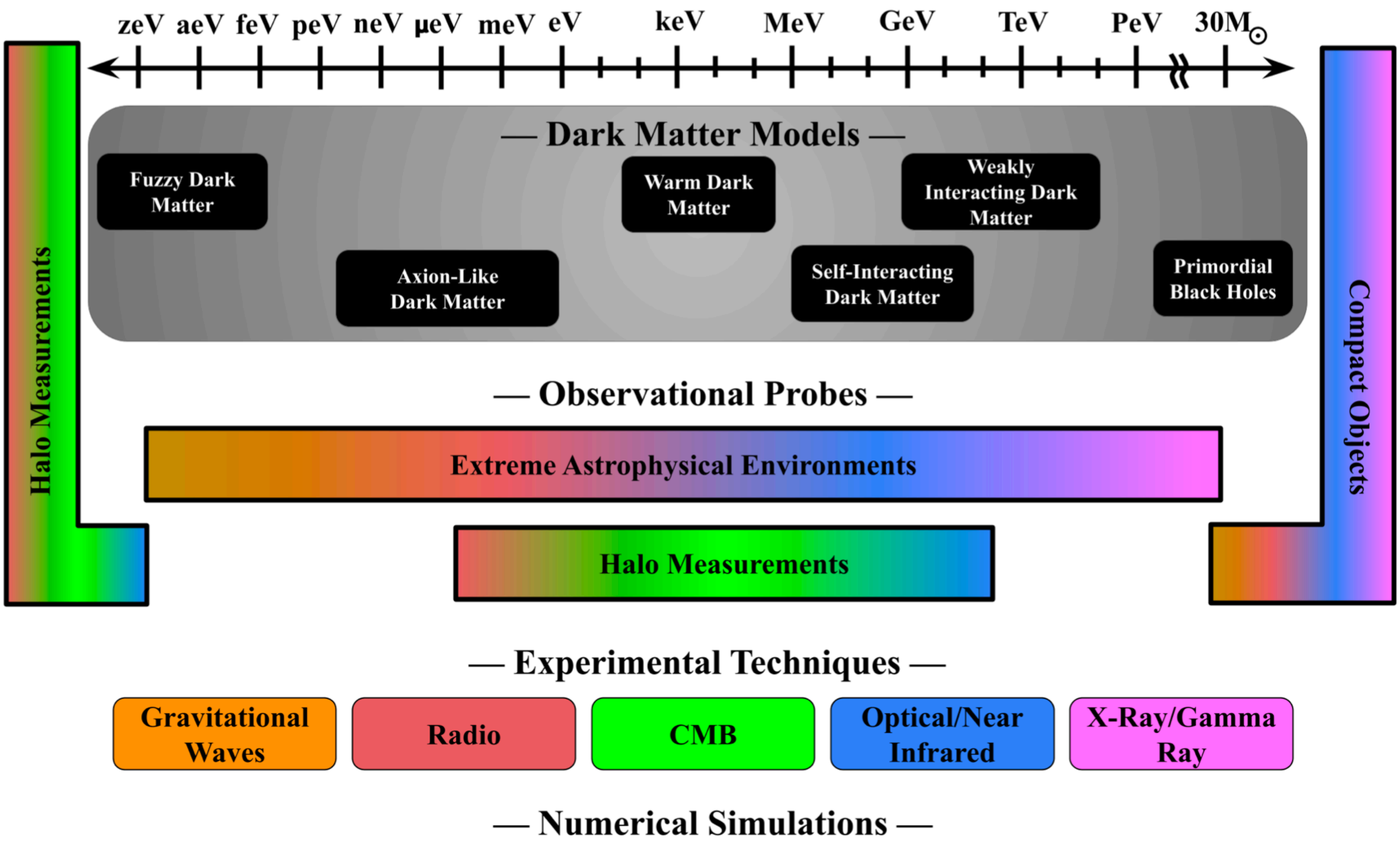
G. Bertone and T. M. P. Tait, Nature 562, 51-56 (2018).

What is dark matter made of ?



G. Bertone and T. M. P. Tait, Nature 562, 51-56 (2018).

Dark matter candidates



A. Drlica-Wagner et al SNOWMASS Cosmic Probes arxiv: 2209.08215

Some particle dark matter candidates

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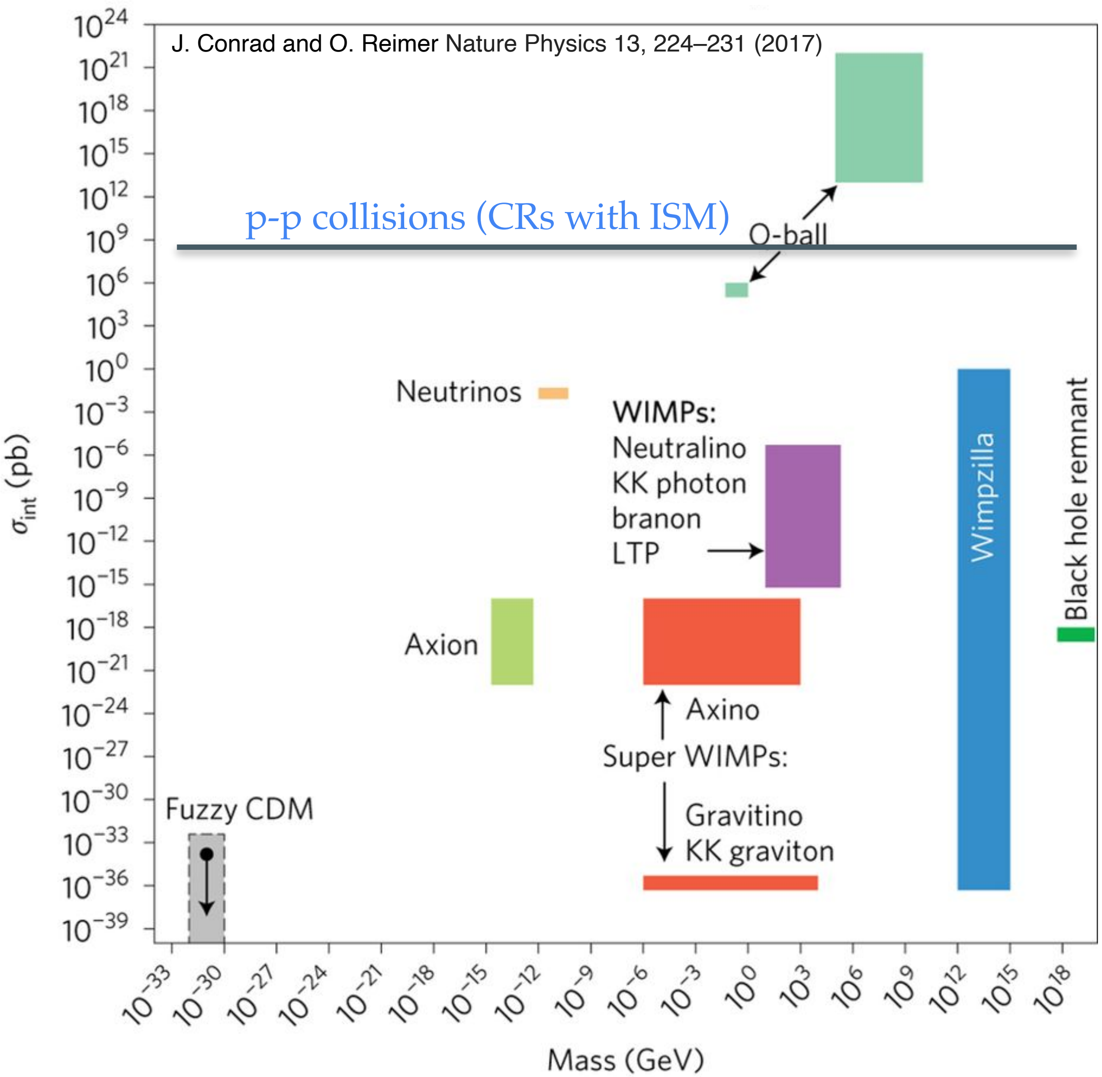

Particle Dark Matter Search Strategies

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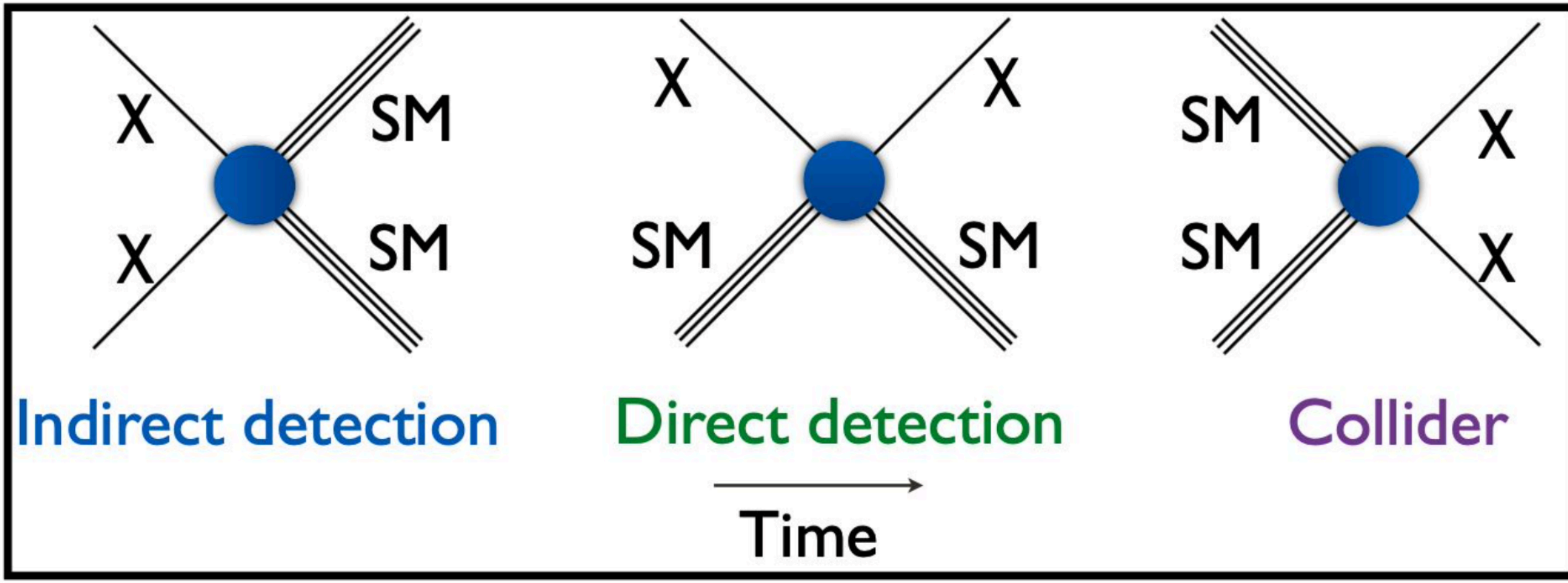


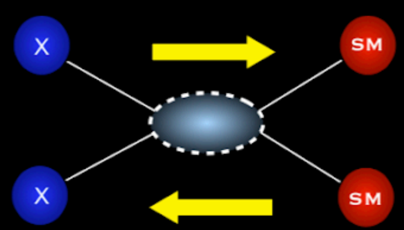
- Indirect detection: look for Standard Model particles - electrons/positrons, photons, neutrinos, protons/antiprotons - produced when dark matter particles collide or decay.
- Direct detection: look for atomic nuclei "jumping" when struck by dark matter particles, using sensitive underground detectors. *See M. Selvi on Monday*
- Colliders: produce dark matter particles in high-energy collisions, look at visible particles produced in the same collisions, check for apparent violation of energy/momentum conservation. *See E. Skorda on Friday*

Slide by Tracy Slatyer

WIMPs

By far the most studied class of dark matter candidates.

The WIMP paradigm is based on a simple yet powerful idea:



$$\frac{dn_\chi}{dt} - 3Hn_\chi = -\langle\sigma v\rangle\left[n_\chi^2 - (n_\chi^{eq})^2\right]$$

Weak-scale cross sections can reproduce observed relic density

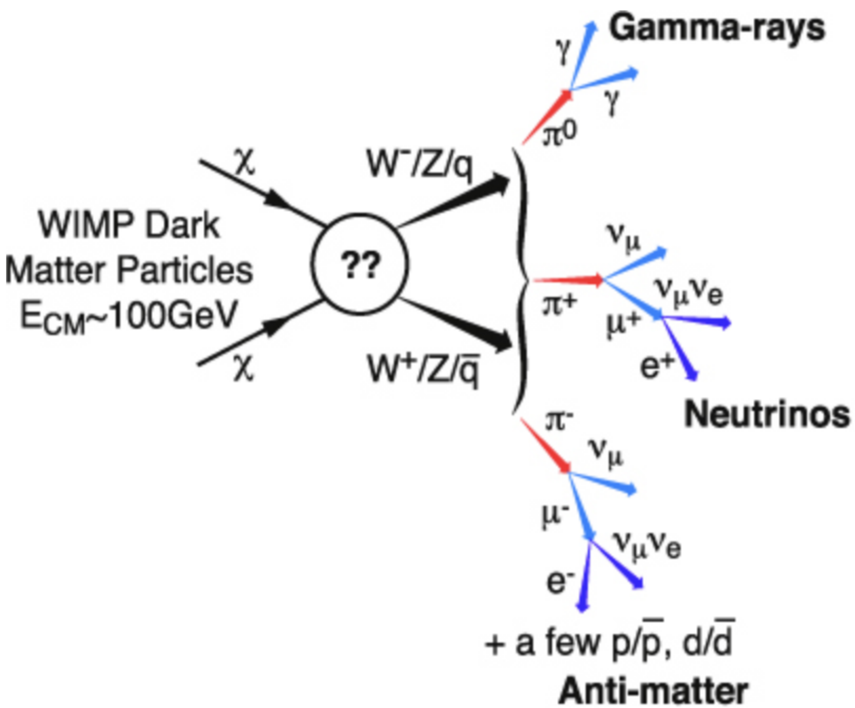
$$\Omega h^2 \approx \frac{3\times10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{<\sigma v>}$$

'WIMP miracle': new physics at ~1TeV solves at same time fundamental problems of particle physics (*hierarchy problem*) AND DM

Slide G. Bertone

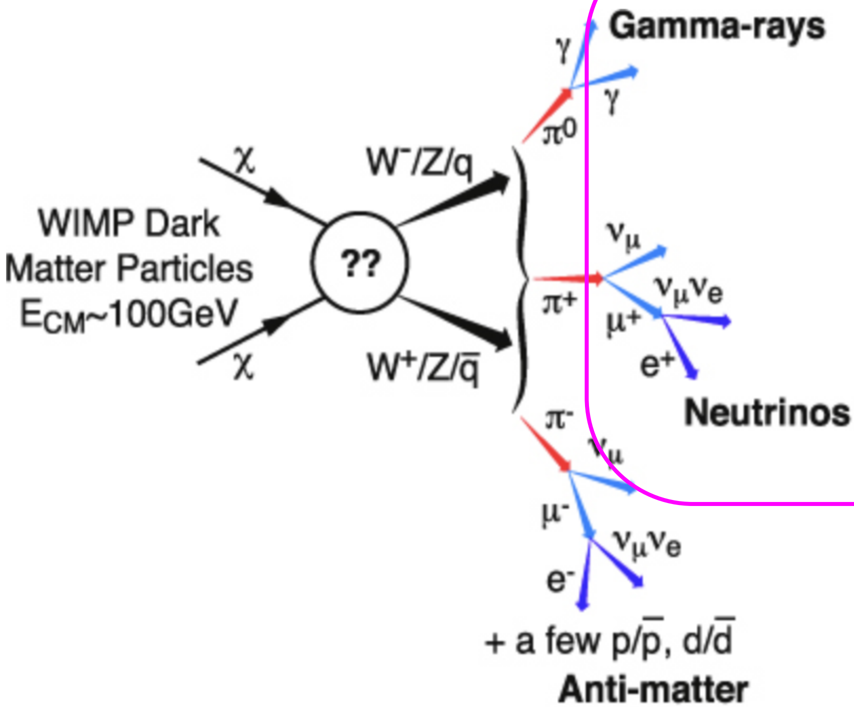
Indirect WIMP Searches

Weakly interacting massive particles (WIMPs) were created in the early universe and they are predicted in supersymmetric extensions of the Standard Model.

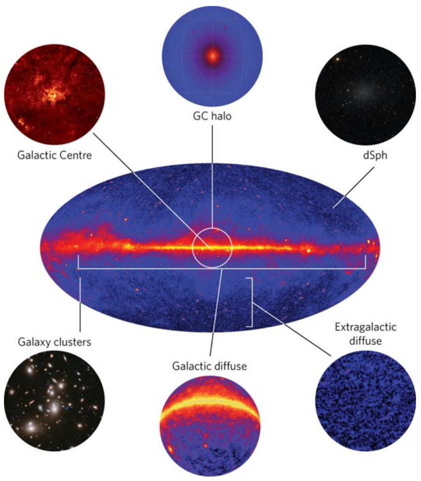


Adapted from E. A. Baltz et al, J. Cosmol. Astropart. Phys. JCAP07 (2008) 013

Indirect WIMP Searches



Neutral messengers



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Indirect WIMP Searches

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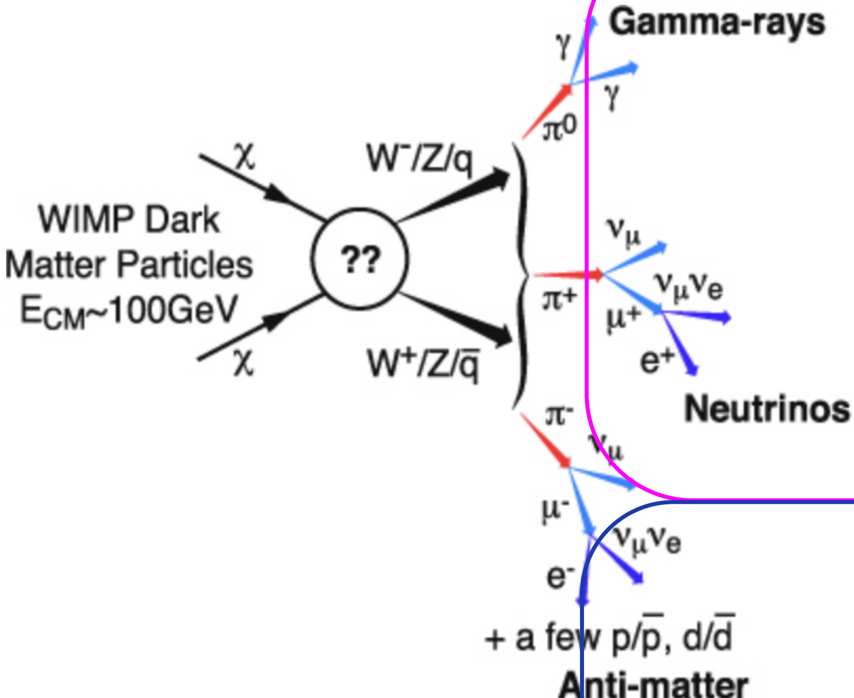
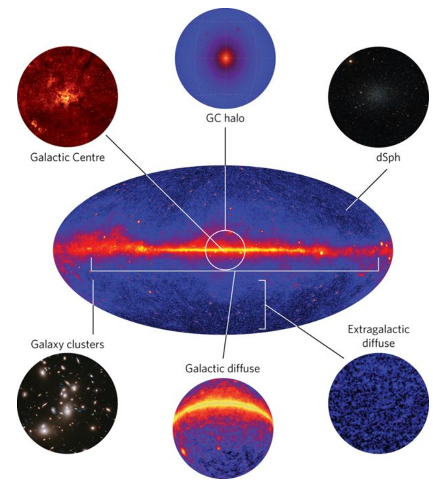
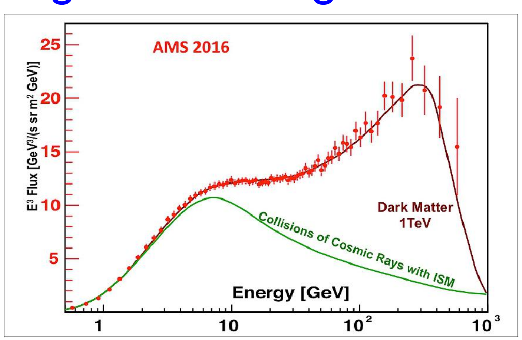


Neutral messengers



Charged messengers



A dark matter signal would appear as a distortion in the expected flux.

Adapted from E. A. Baltz et al, J. Cosmol. Astropart. Phys. JCAP07 (2008) 013

Intriguing hints

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Several intriguing hints for excesses over expected backgrounds emerged in the past decade, which could potentially have a dark matter origin.

Astrophysical excesses include:

- **the Galactic Center GeV gamma-ray excess**
- **the cosmic-ray antiproton** and positron excesses

In this talk

Direct detection excesses include:

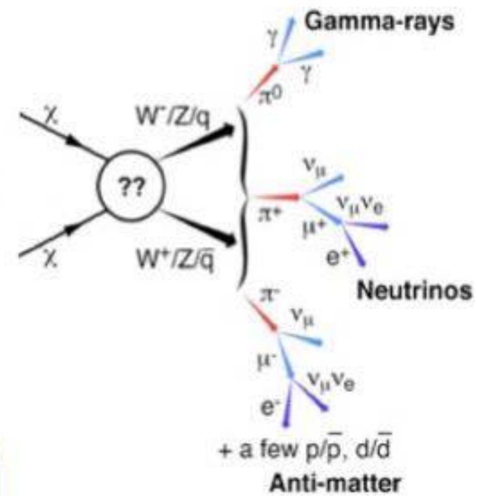
- the DAMA/LIBRA annual modulation signal
- the XENON1T excess

WIMP searches with gamma rays

Gamma-Ray Flux
(signal in data)

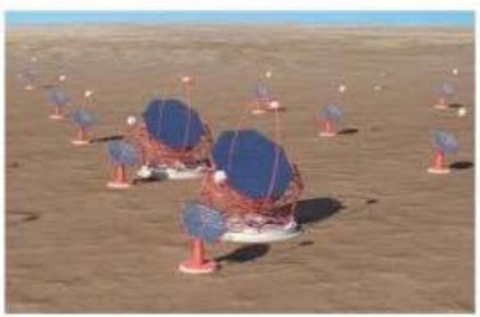
Particle Physics
(particles per annihilation)

$$\frac{d\Phi}{dE}(E,\phi,\theta) = \frac{1}{4\pi}\frac{\langle\sigma_{ann}v\rangle}{2m_{\mathrm{DM}}^2}\sum_f \frac{dN^f}{dE}B_f$$



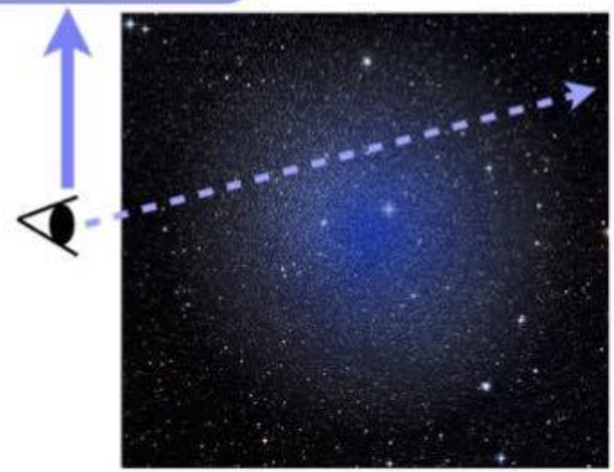
$$\times$$

$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$



Dark Matter Distribution
(line-of-sight integral)

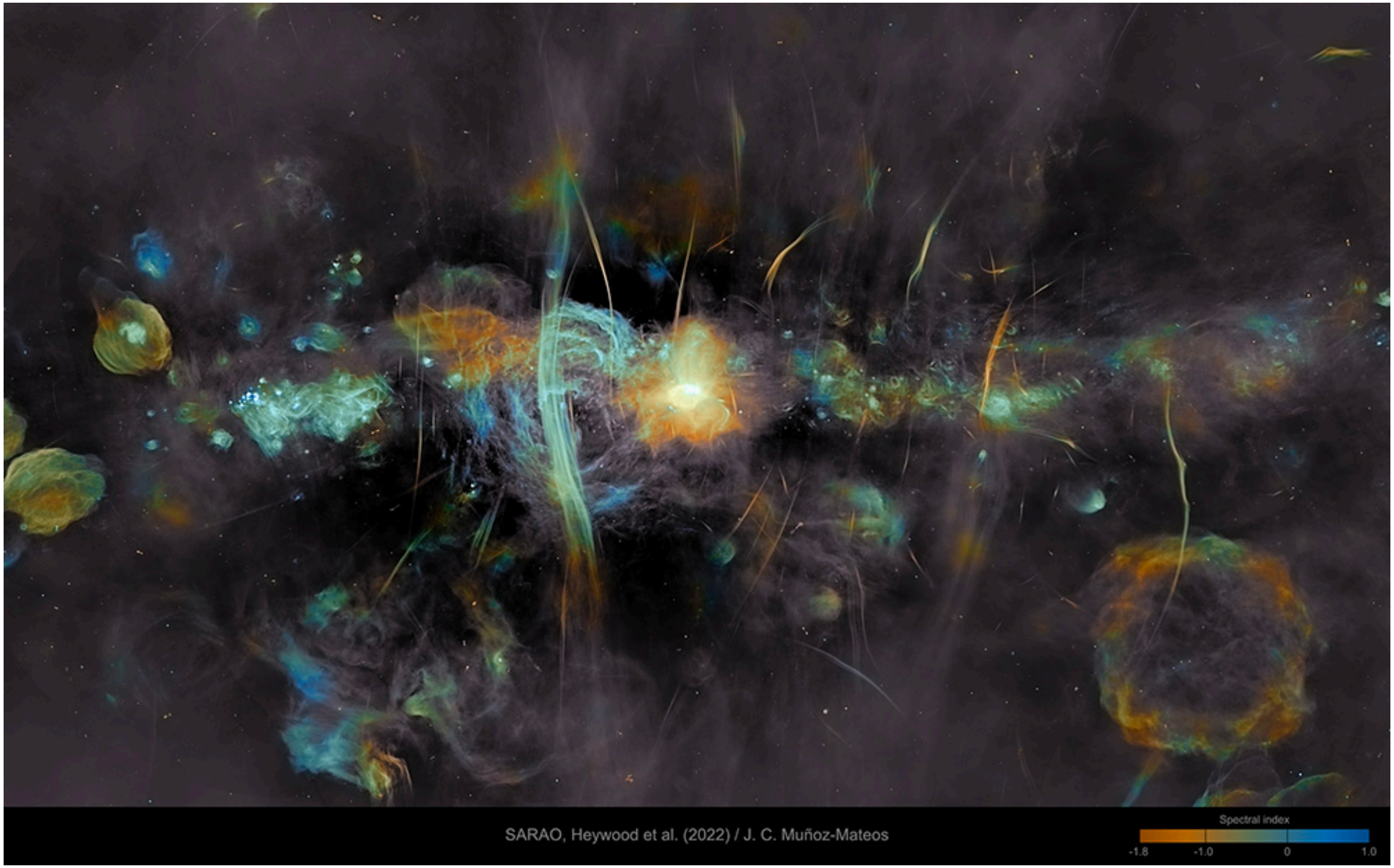
Talk F. Saturni



The galactic center excess (aka GCE)

MeerKAT view of the Galactic Center

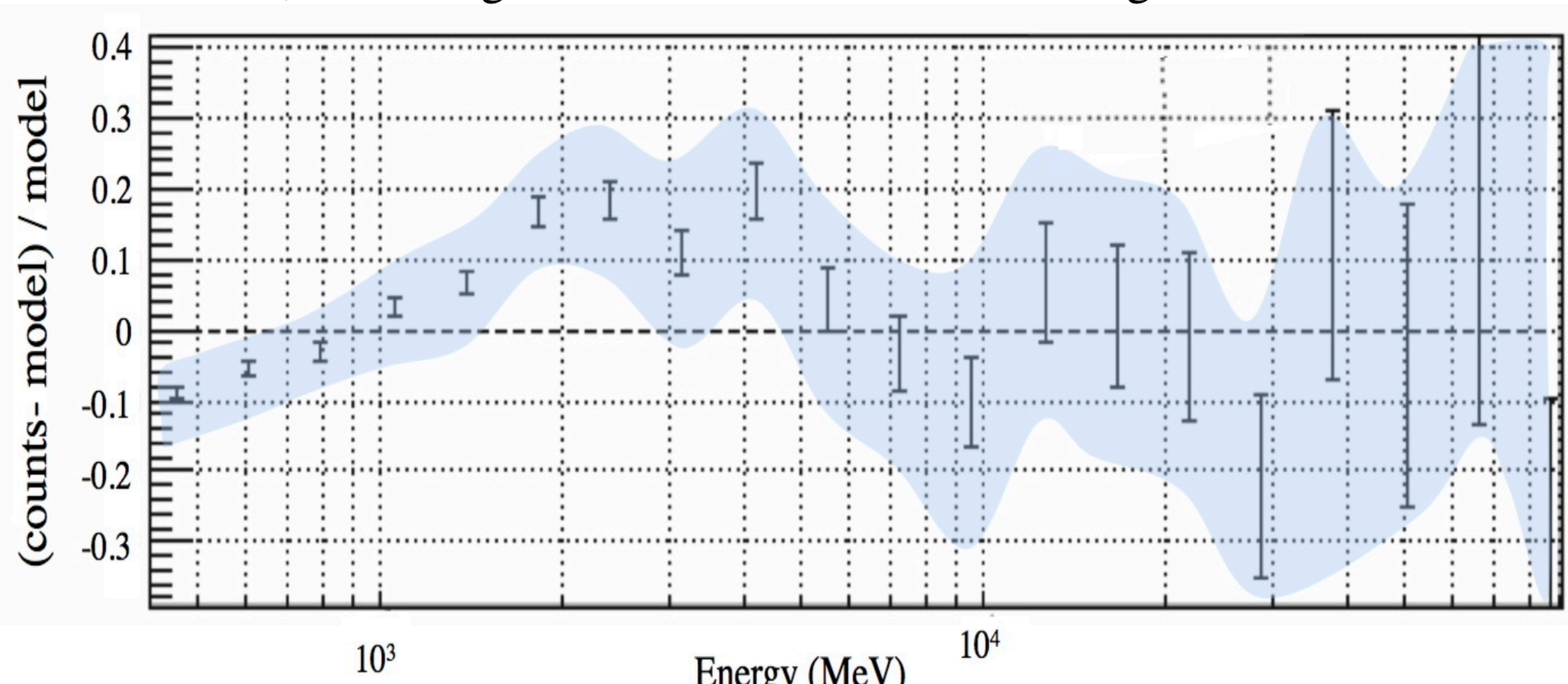
A region crowded with powerful astrophysical sources, including SNRs and pulsars



The GeV excess 7° x7° region centered on the Galactic Center

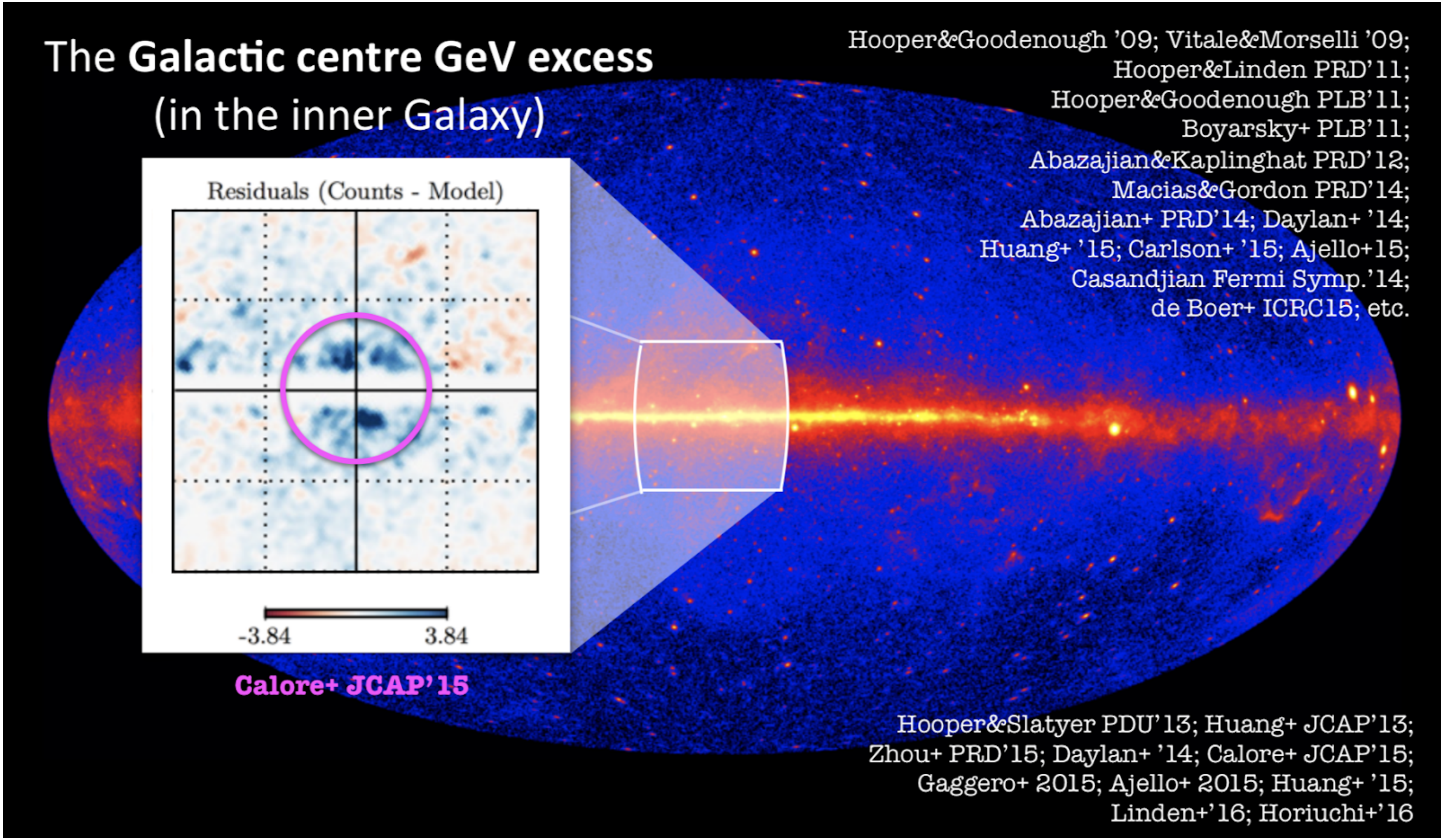
11 months of data, E >400 MeV, front-converting events analyzed with binned likelihood analysis)

- The systematic uncertainty of the effective area (blue area) of the LAT is ~10% at 100 MeV, decreasing to 5% at 560 MeV and increasing to 20% at 10 GeV



V.Vitale, A.Morselli, Fermi Coll. 2009 arXiv:0912.3828 Fermi Symposium eConf Proceedings C091122

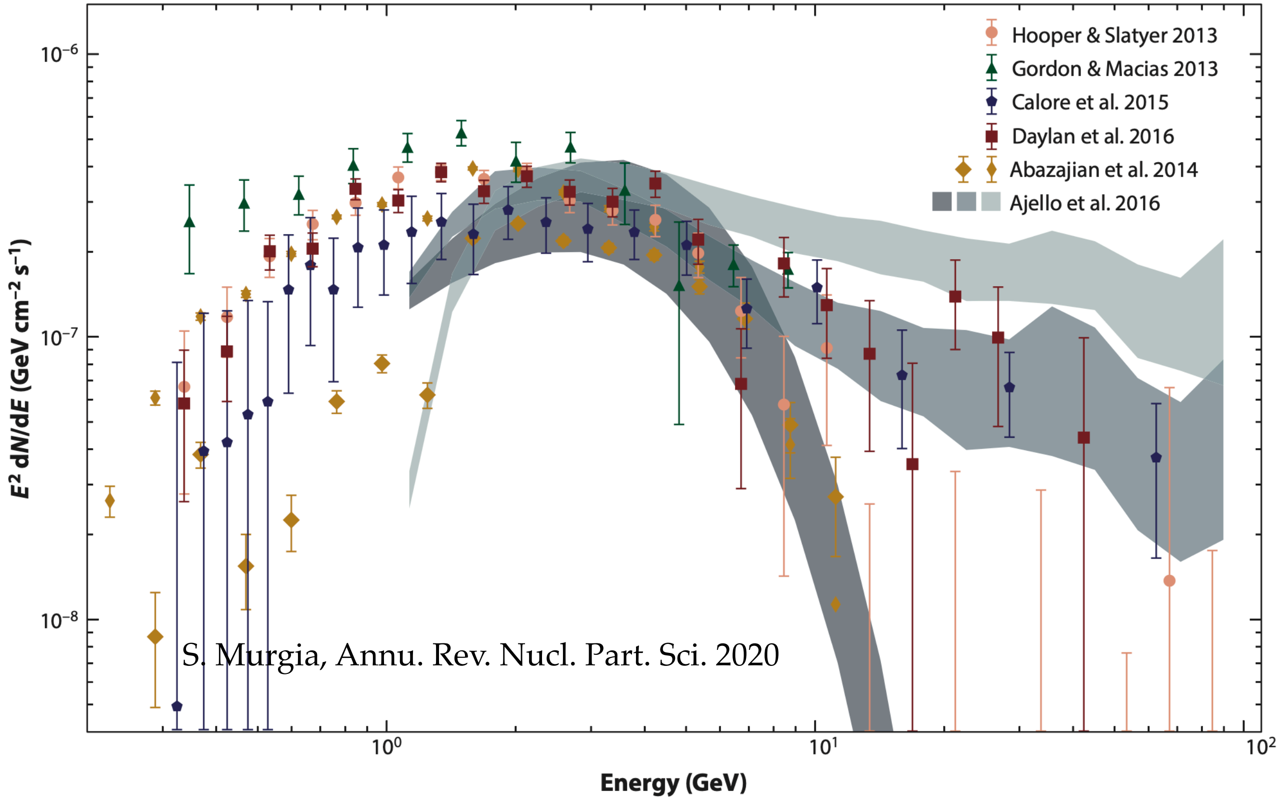
The Fermi-LAT GeV excess



Slide from F. Calore

The GCE spectrum

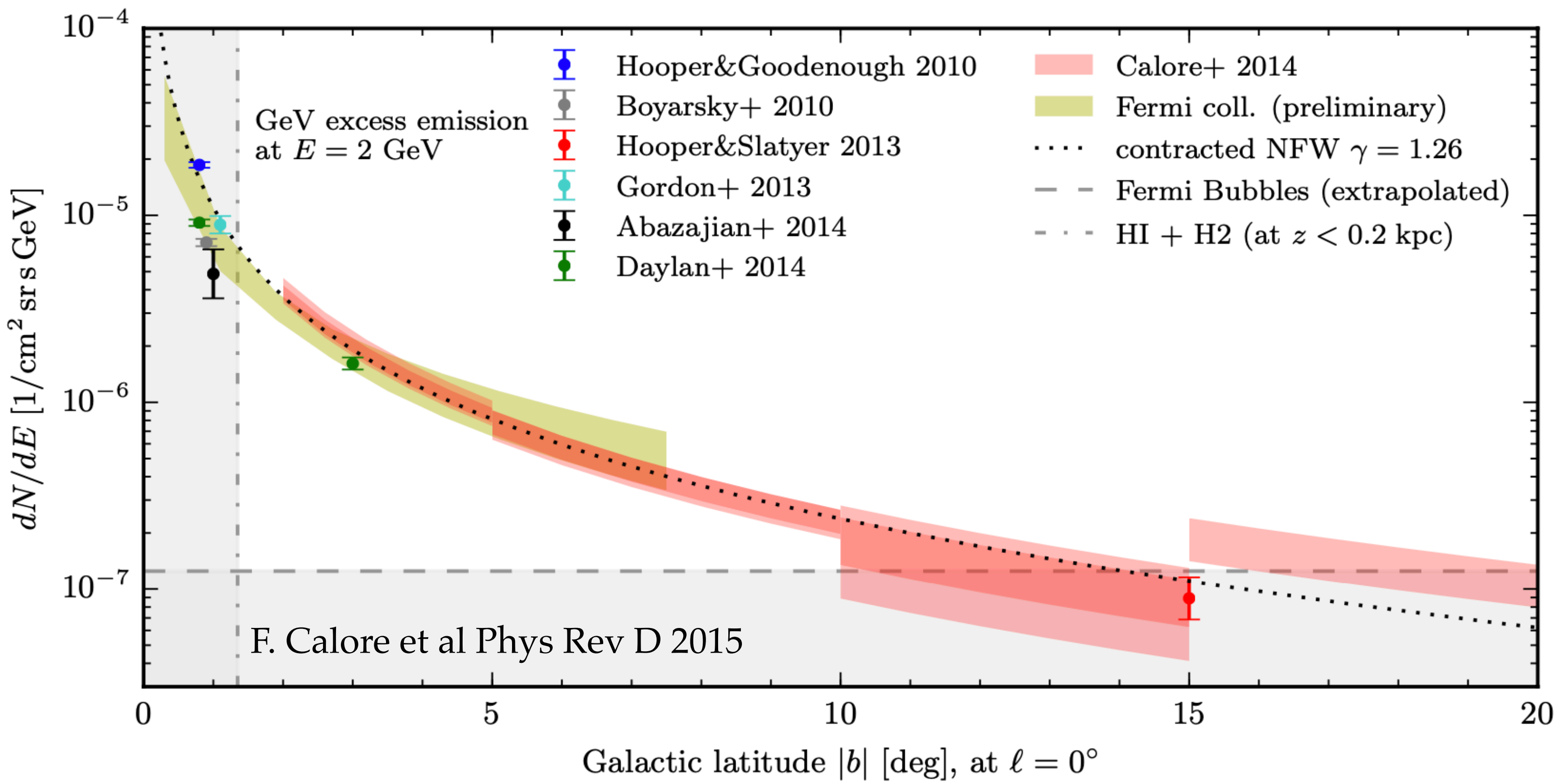
- The statistical significance of this "Galactic Center Excess" is well-established, however its origin is still controversial.
- Leading explanations are either WIMP dark matter, or a new population of gamma-ray emitting pulsars.
- Prominent feature (peak) around 3 GeV. Uncertain extension up to 10 GeV.



S. Murgia, Annu. Rev. Nucl. Part. Sci. 2020

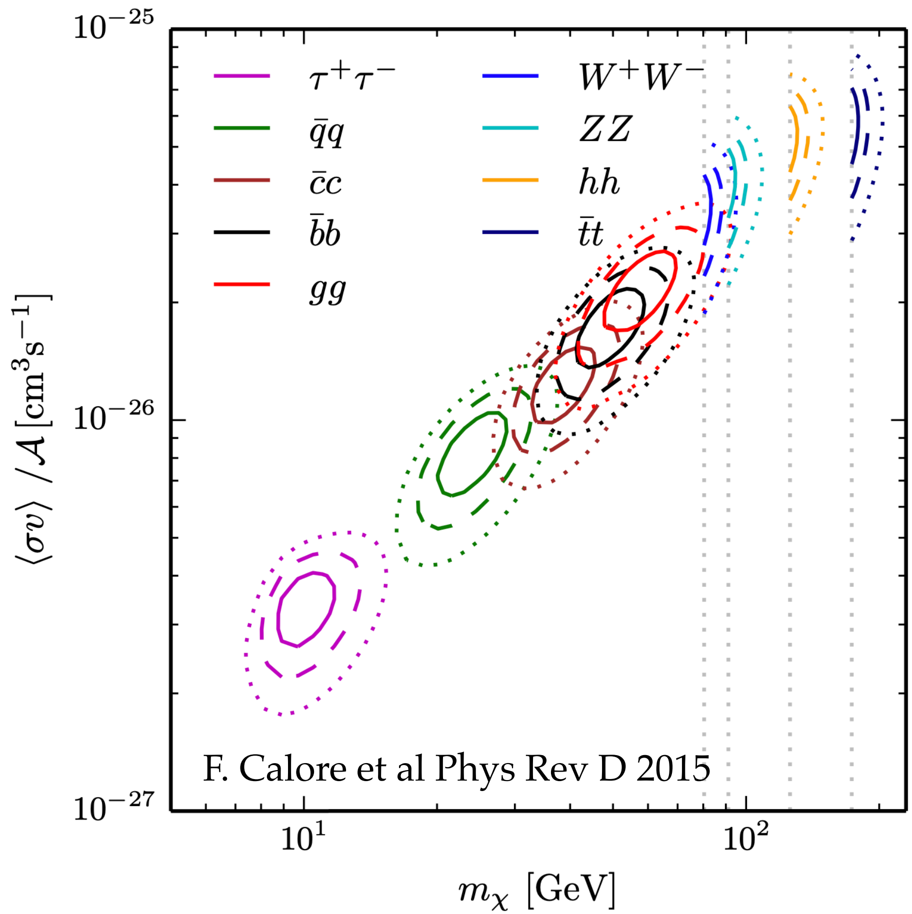
The GCE morphology

- Morphology is generally consistent with spherical symmetry which is brightest towards the GC.
- This distribution is consistent with an emission originating from DM (NFW).



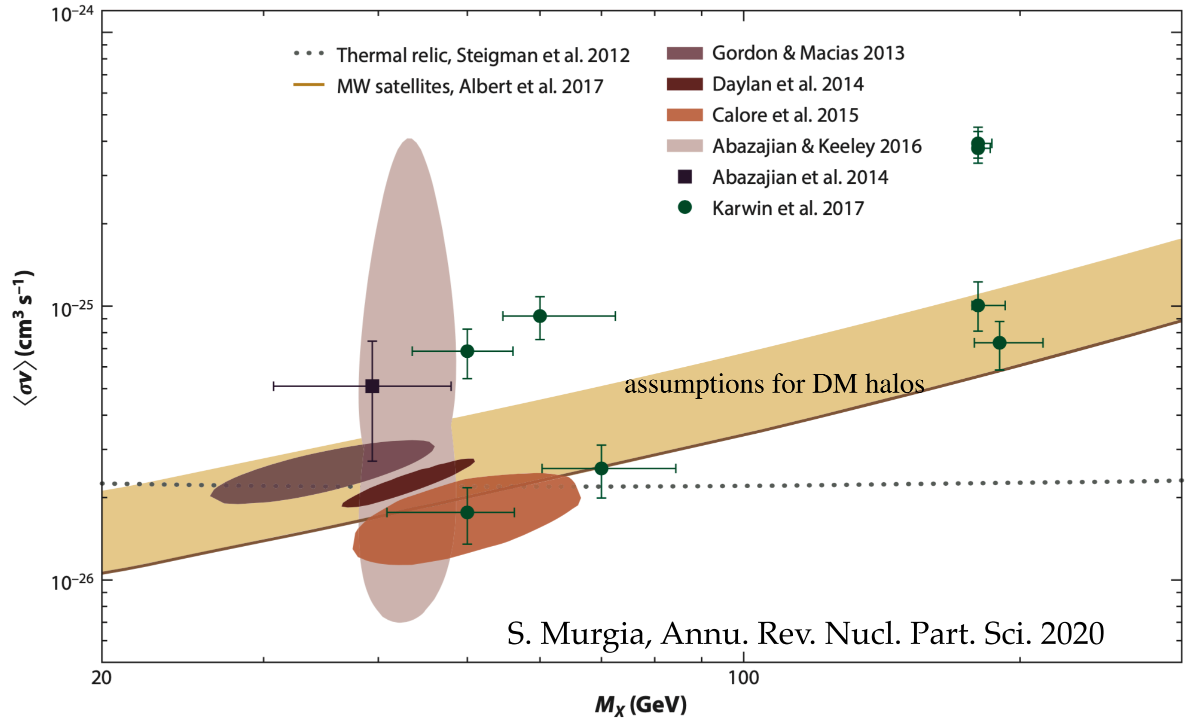
DM bounds from the GCE

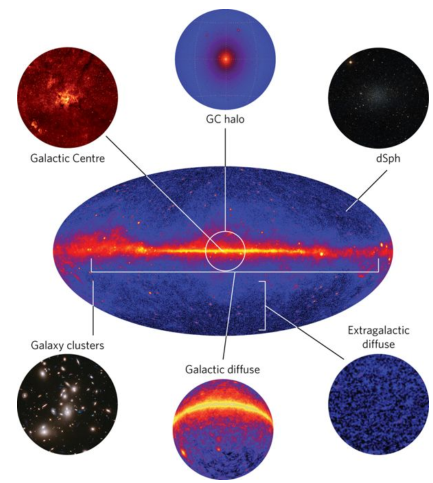
- Spectrum well fit by a DM particle with 20-60 GeV mass, annihilating into hadronic final states, with the right thermal relic cross section.



Constraining the GCE with astrophysical data

- Dwarf spheroidal galaxies [talk F. Saturni] are known to be the most dark matter dominated objects in the universe. They are low luminosity objects with no gamma-ray emission expected of astrophysical origin.
- These targets are less susceptible to the limitations in the modelling of the astrophysical background.
- DM searches from Dwarf spheroidal galaxies provide the most stringent limits to date (together with antiprotons).



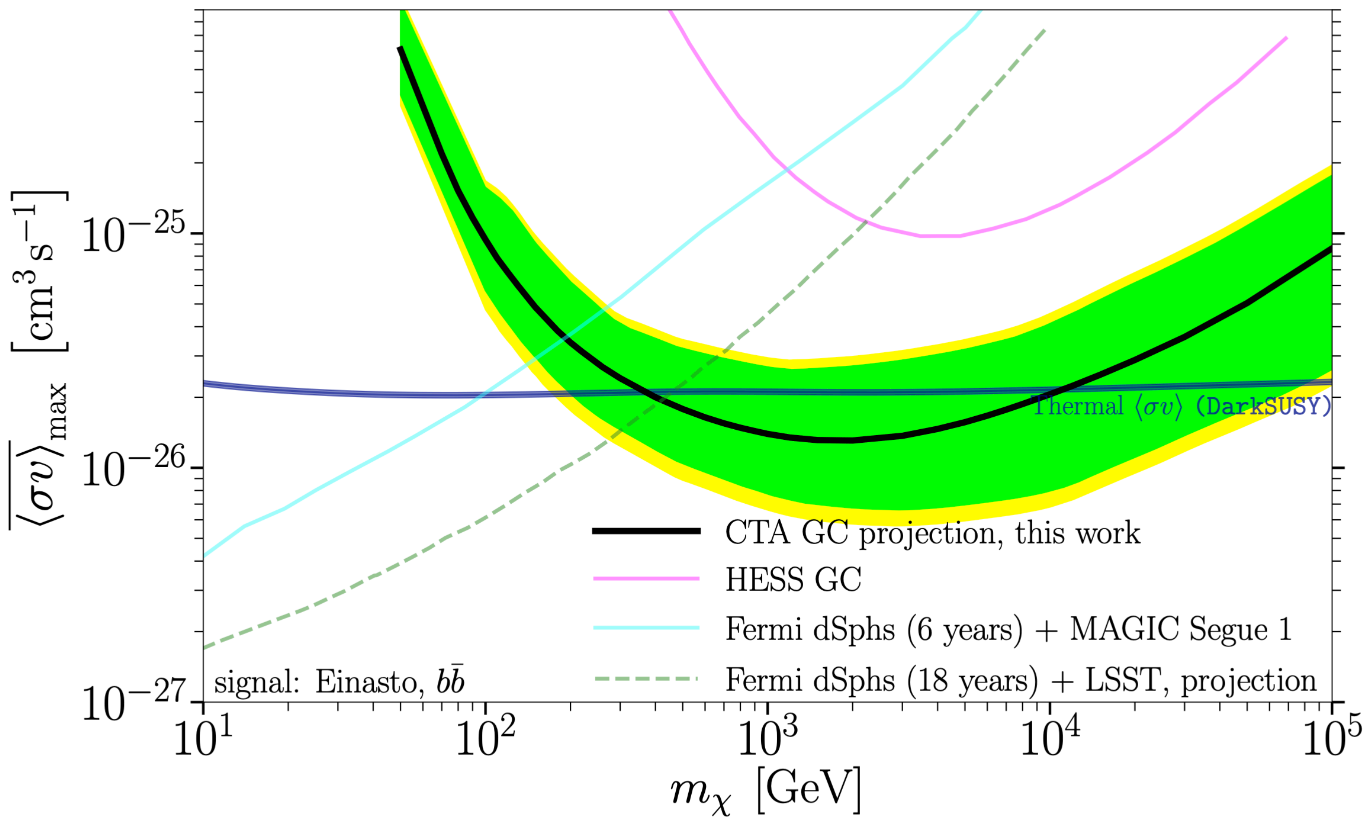


Galactic center with CTA

See talk from F. Longo

CTA will be able to probe the thermal relic cross-section with 525 h.

JCAP01(2021)057



Summary on the GCE

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- The statistical significance of this “Galactic Center Excess” is well-established, however its origin is still controversial.
- Leading explanations are either weak-scale annihilating dark matter, or a new population of gamma-ray emitting pulsars.
- An accurate model for the Galactic diffuse gamma-ray foreground is currently the key factor to understand the nature of this excess.
- Complementary discovery avenues include improved modeling strategies, and improved fitting and characterization methods.
- Even more important, a better angular resolution is the key to investigate the presence of possible unresolved gamma-ray emitters in the GC region. CTA and future space missions will provide essential information.

The cosmic-ray antiprotons excess

Antimatter in cosmic rays

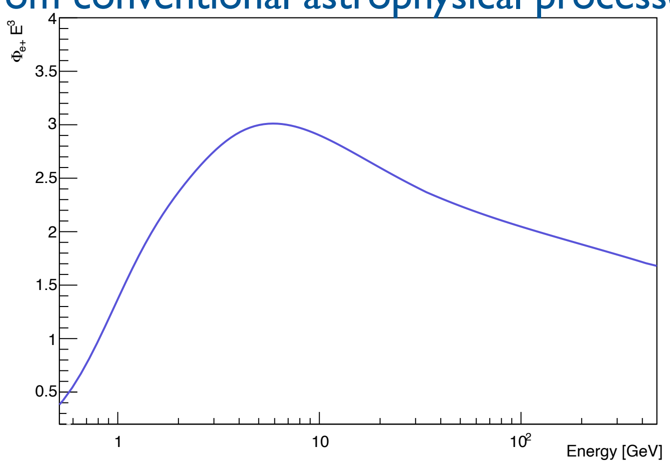
Positrons and antiprotons are known to be secondary particles produced as a consequence of the interaction of primary cosmic rays with the interstellar medium ($p+p_{ISM}$, $p+He_{ISM}$, $He+He_{ISM}$).

$$p + p_{\rm ism} \rightarrow \pi^+ + \ldots$$
$$\hookrightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

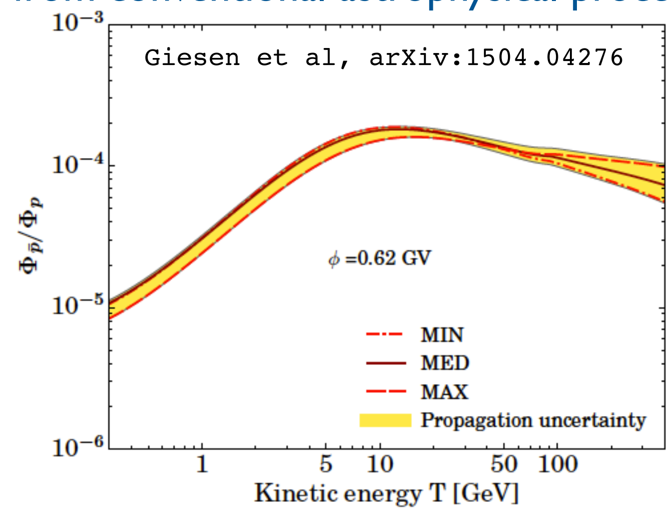
$$p + p \longrightarrow \bar{p} + X$$

- Tiny component: in the GeV-TeV region the e+/e- ~ 0.1, while anti-p/p ~ 10^{-4}
- dark matter signal would appear as a distortion in the expected flux, estimated from conventional mechanisms.

Positron flux
from conventional astrophysical processes

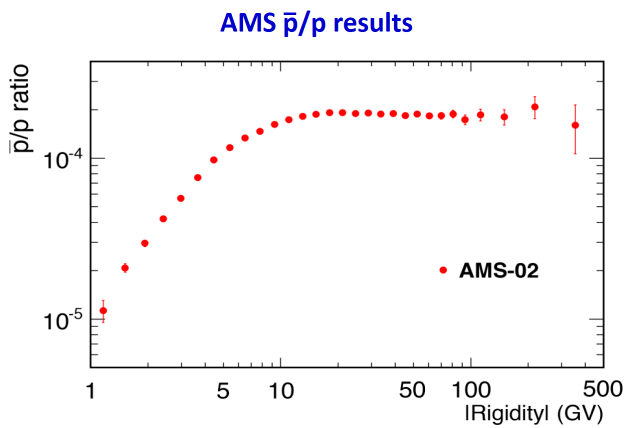


Antiproton-to-proton ratio
from conventional astrophysical processes



INDIRECT DM SEARCH WITH CHARGED CRS

Measured antimatter flux



Background:
protons, S/N ~10^{-4}

=

Particle Physics
(annihilation channels)

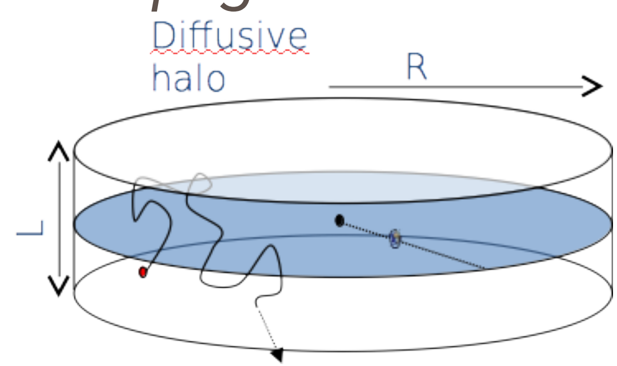
$$\frac{<\sigma_{ann} v>}{2m^2_{WIMP}} \sum_f \frac{dN^f_{e^+}}{dE_{e^+}} B$$

×

Dark matter density

×

Propagation effects



Claims from antiprotons

- A Robust Excess in the Cosmic-Ray Antiproton Spectrum: Implications for Annihilating Dark Matter, *I. Cholis et al Phys. Rev. D (2019)*
- Scrutinizing the evidence for dark matter in cosmic-ray antiprotons, *A. Cuoco, et al Phys.Rev.D* (2019)
- Investigating the dark matter signal in the cosmic ray antiproton flux with the machine learning method, *S. Lin et el Phys. Rev. D (2019)*

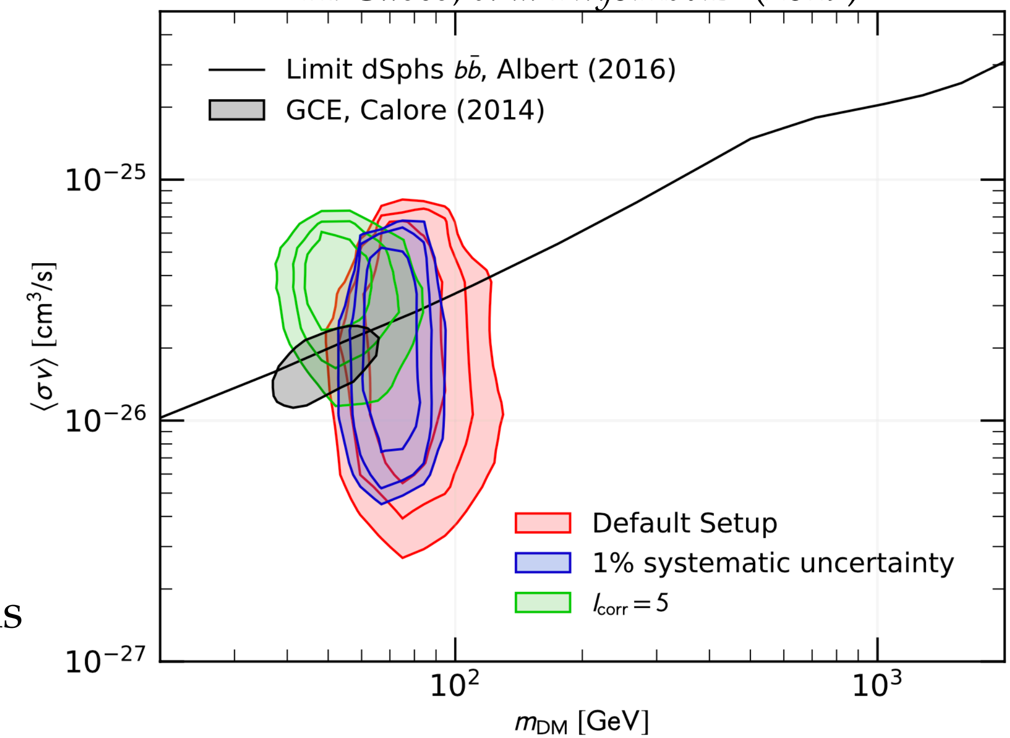
Common conclusions of the papers:

- Antiproton excess around 10 GeV.
- Can be explained by ~ 100 GeV DM particle annihilating into b quarks with thermal cross-section.
- Consistent with other gamma ray galactic center excess reported by many groups.

Common concerns of the community:

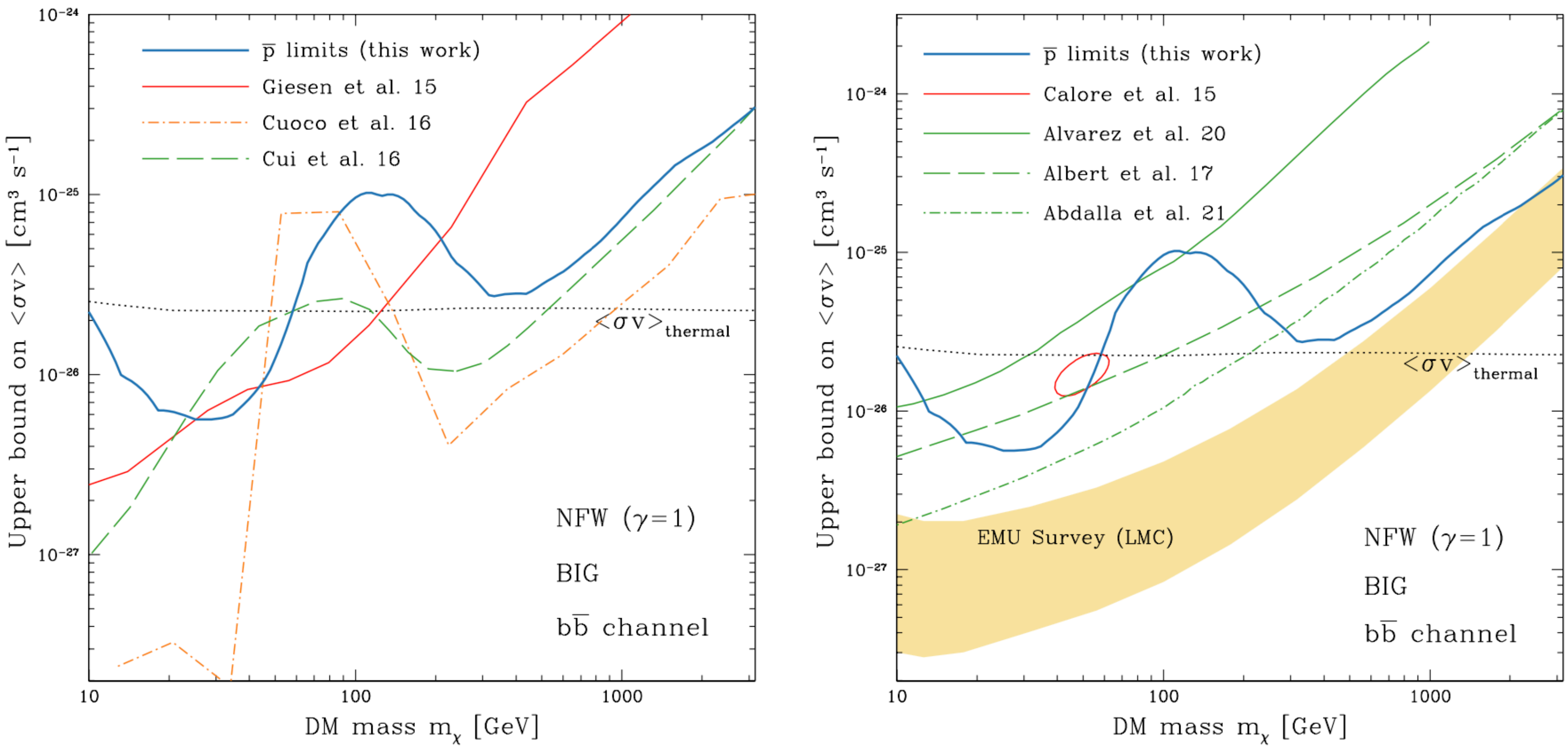
- Antiproton production cross-sections
- Solar modulation
- Systematic uncertainties

A. Cuoco, et al Phys.Rev.D (2019)



More conservative approach

- Hints of a DM signal are not statistically significant; an adequate treatment of errors is crucial for credible conclusions.
- Antiproton bounds on DM annihilation are among the most stringent ones, probing thermal DM up to the TeV scale.



F. Calore et al SciPost Phys. 12 (2022)

Summary on cosmic-ray antiprotons

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- An excess of GeV cosmic-ray antiprotons in the AMS-02 observations has been identified by several groups.
- If a signal of dark matter annihilation, it requires similar mass, cross section and annihilation channels to those required to explain the GCE.
- To establish the robustness of this excess, the underlying correlations of the AMS-02 systematic errors are needed.
- The observation of antideuteron or antihelium nuclei by AMS-02 and future missions (e. g. GAPS) will be an unambiguous signal of new physics.
- Antiproton and antinuclei dark matter searches will benefit from future production cross-section measurements from inelastic hadronic collisions, and from further reduction of the astrophysical cosmic-ray propagation modeling uncertainties.

Summary: Intriguing hints

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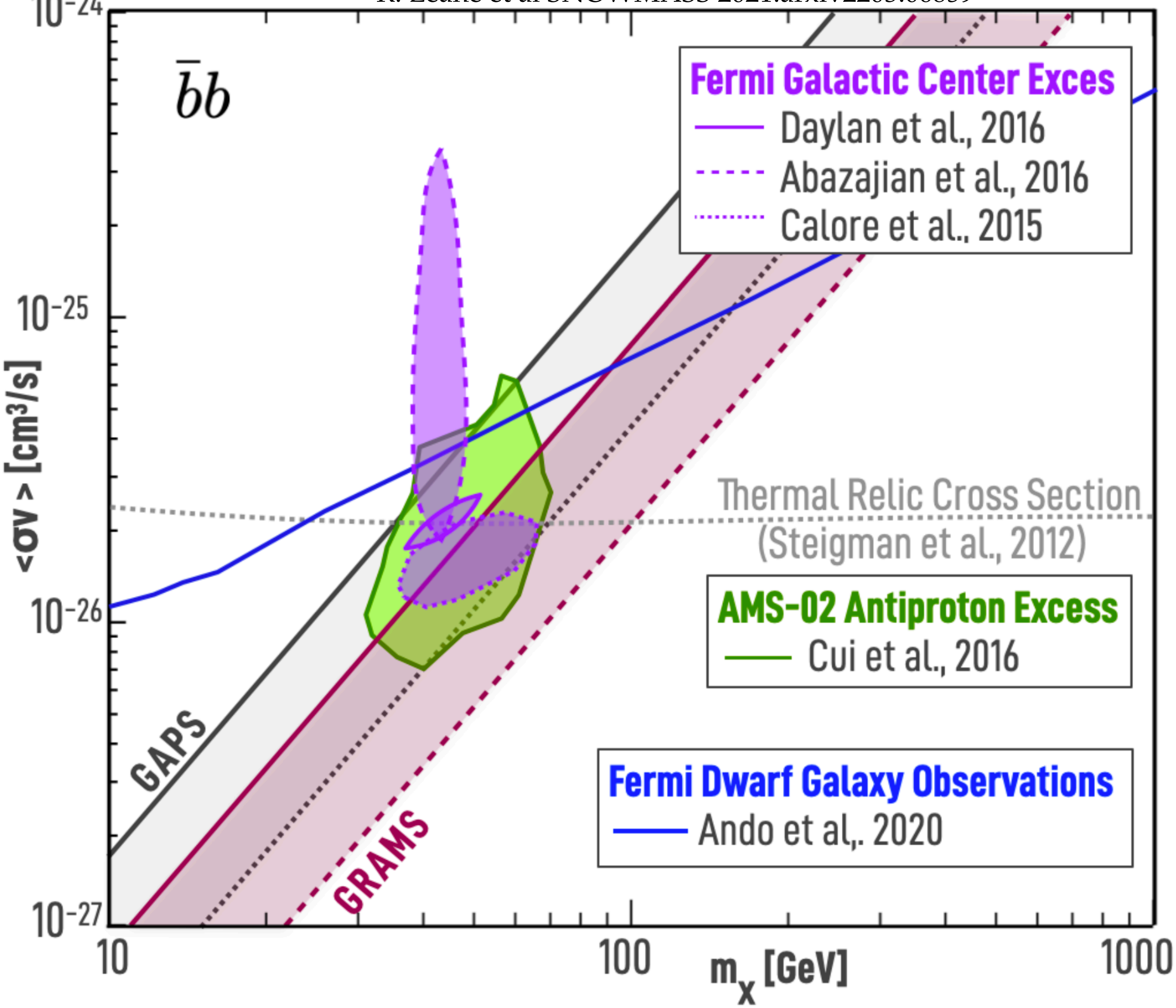
R. Leane et al SNOWMASS 2021:arxiv2203.06859



Stay tuned ! Talk by V. Gammaldi

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