PAMELA's Dark Matter Legacy

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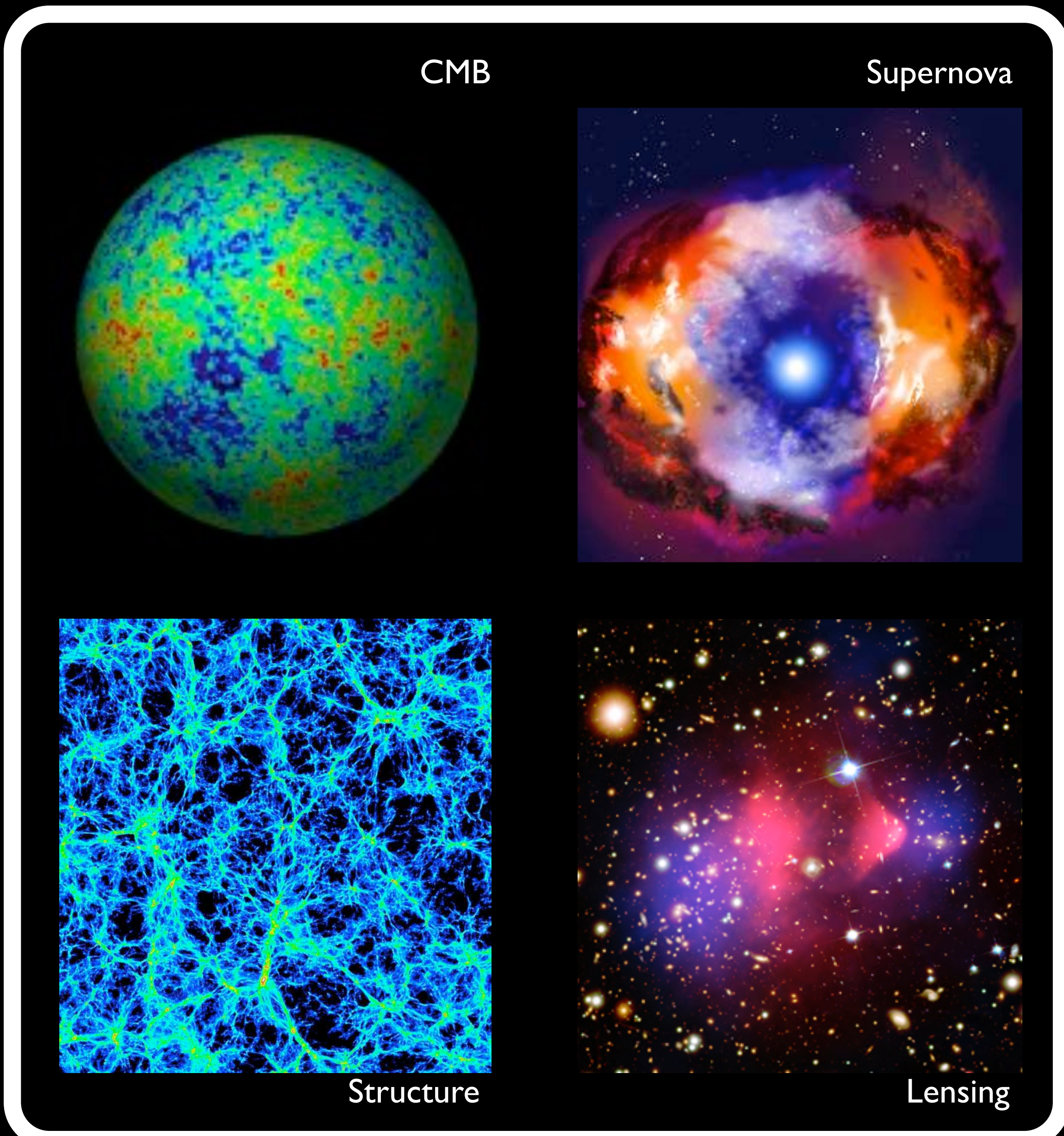
10 Years of PAMELA
Villa Mondragone
June 15, 2016

Outline

- Dark Matter
    - Particle Searches for Dark Matter
    - Indirect Detection
- PAMELA's Unique Capabilities
    - Anti-protons
    - Positrons
- Legacy and the Future

Dark Matter

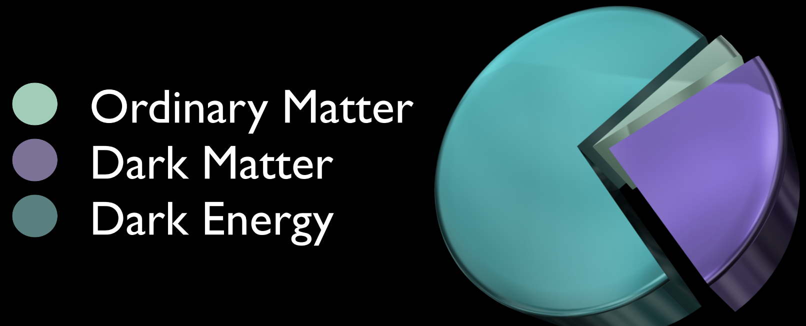
Dark Matter

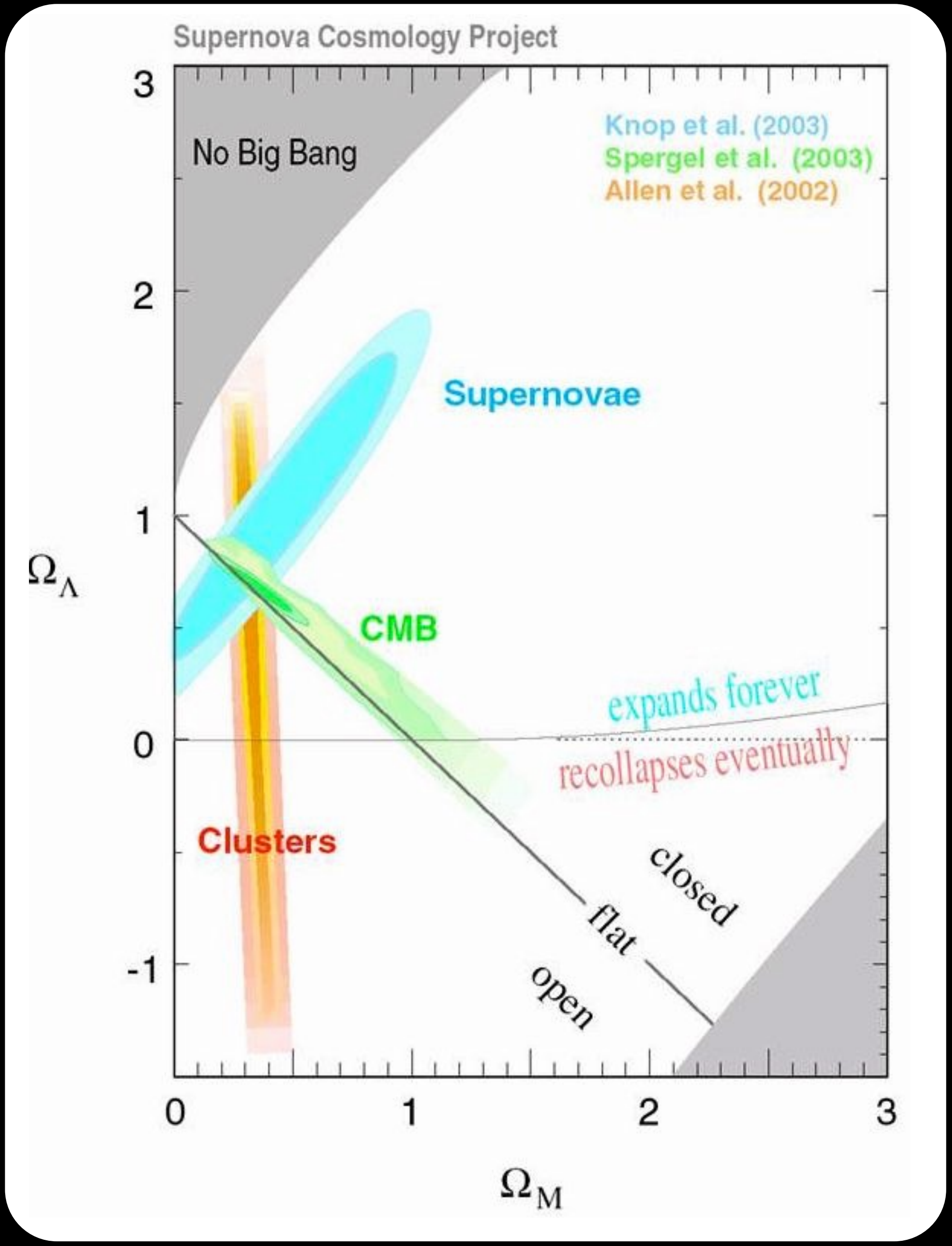


- Measurements on many length scales, ranging from cosmological distances to the scale internal to galaxies, inform us as to how our Universe evolves.
- Combined with Einstein's theory of gravity, these measurements can be used to infer the quantities of energy, matter, and radiation that the Universe contains.

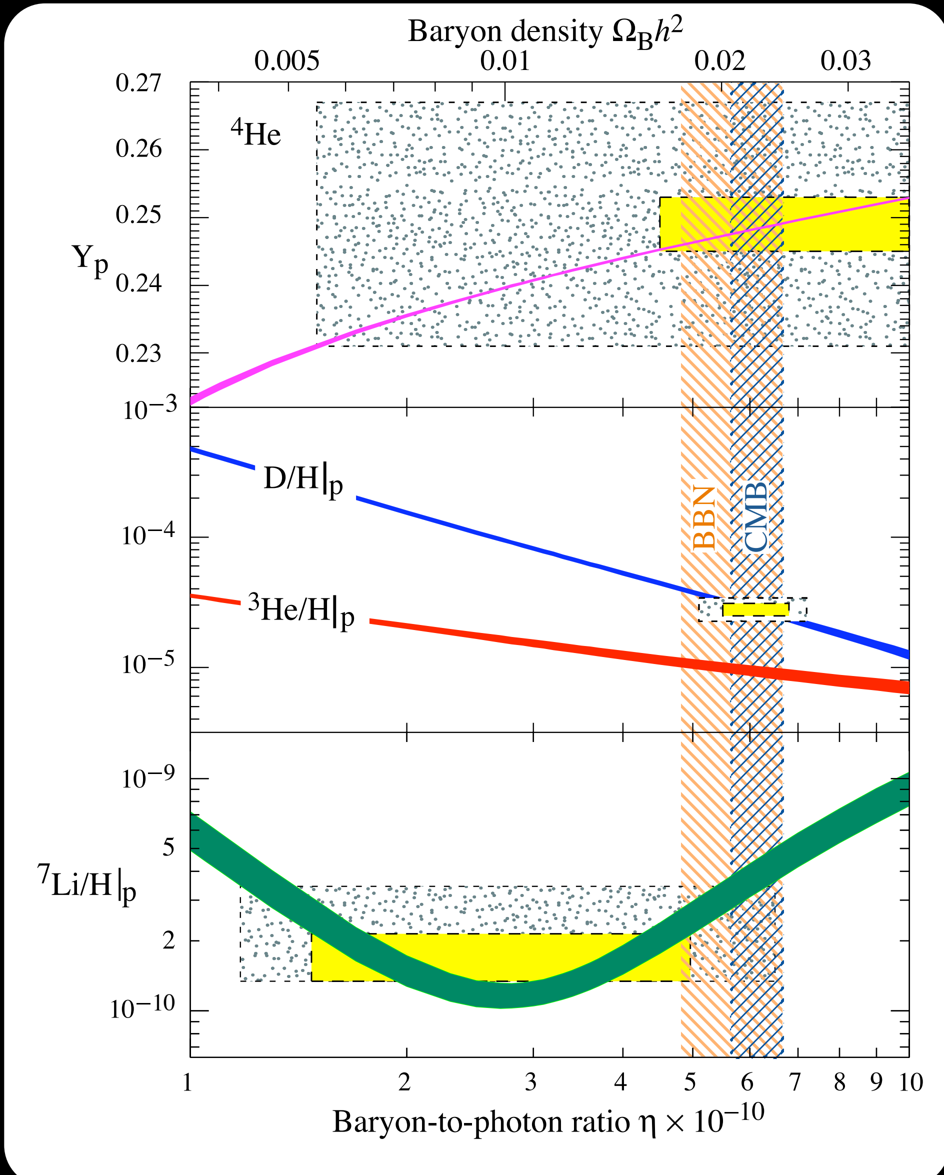
Dark Matter

- This variety of measurements leads to a strikingly consistent picture of a Universe which today is dominated by about 70% vacuum energy, 30% matter, and a small amount of radiation.
- The consistency of the measurements is a triumph of modern cosmology, indicating a very precise understanding of our Universe.

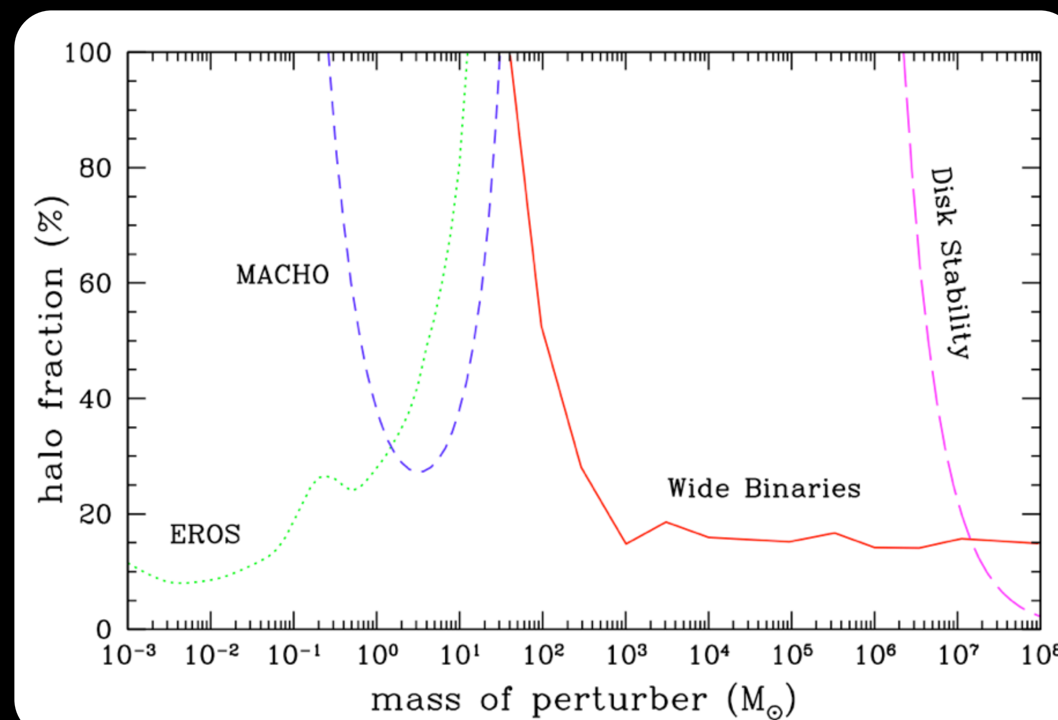




Not Ordinary Matter



The abundance of light elements allows us to independently measure the fraction of the matter that is in the form of baryons (protons and neutrons). The measurements indicate that only about 1/5 of the matter in the Universe is in this form. The remainder is something more exotic: dark matter!



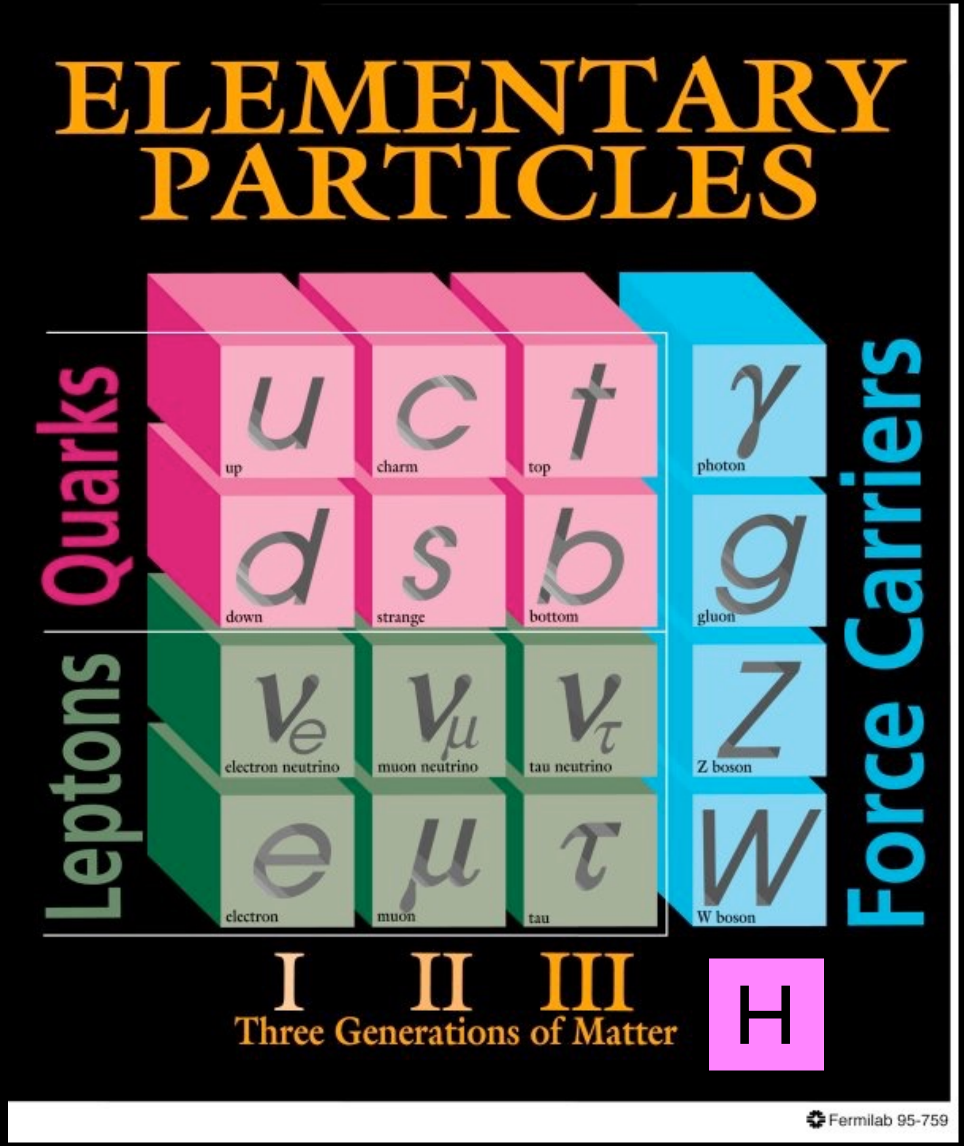
Primordial black holes remain a possible candidate, but would need some kind of mechanism to explain their production and mass distribution.

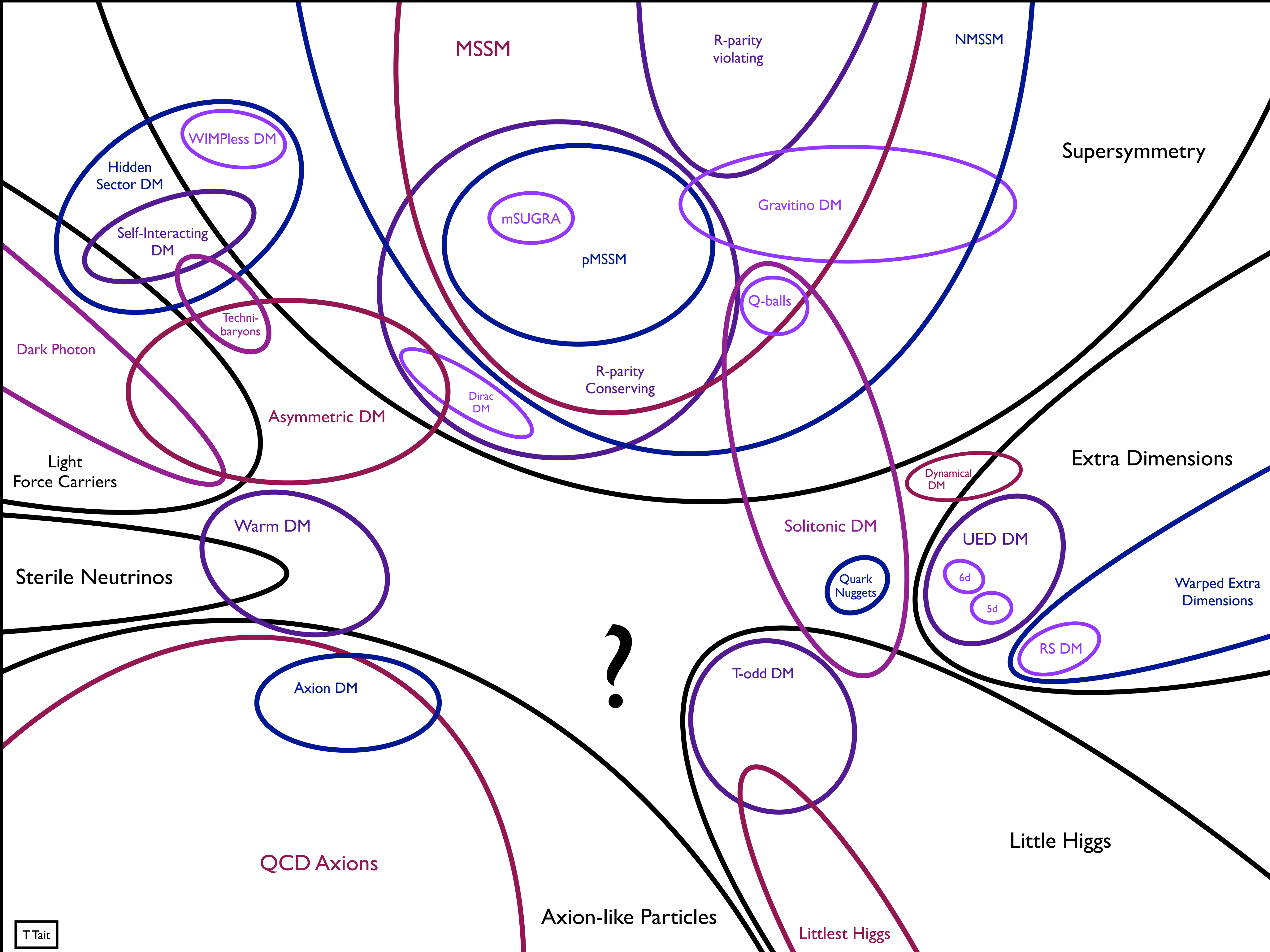
So what is Dark Matter?

- It's remarkable that measurements on very different scales all indicate a self-consistent picture of a Universe containing dark matter.
- As a particle physicist I want to know how dark matter fits into a particle description.
- What do we know about it?
  - Dark (neutral)
  - Massive
  - Still around today (stable or with a lifetime of the order of the age of the Universe itself).

Physics Beyond the SM

- The Standard Model has nothing with the right properties:
  - Photons, leptons, Ws, hadrons all shine too brightly.
  - Neutrinos are too light.
  - Ws, Zs, and Higgs bosons are all too short-lived.
- Dark matter is a manifestation of physics beyond the Standard Model.
- Without knowing what it is and how it fits into the table, our understanding of particle physics is woefully incomplete. But what is it?




MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
mSUGRA
pMSSM
Gravitino DM
Q-balls
Techni-baryons
Dark Photon
Asymmetric DM
Dirac DM
R-parity Conserving
Light Force Carriers
Extra Dimensions
Dynamical DM
Warm DM
Solitonic DM
UED DM
Sterile Neutrinos
Quark Nuggets
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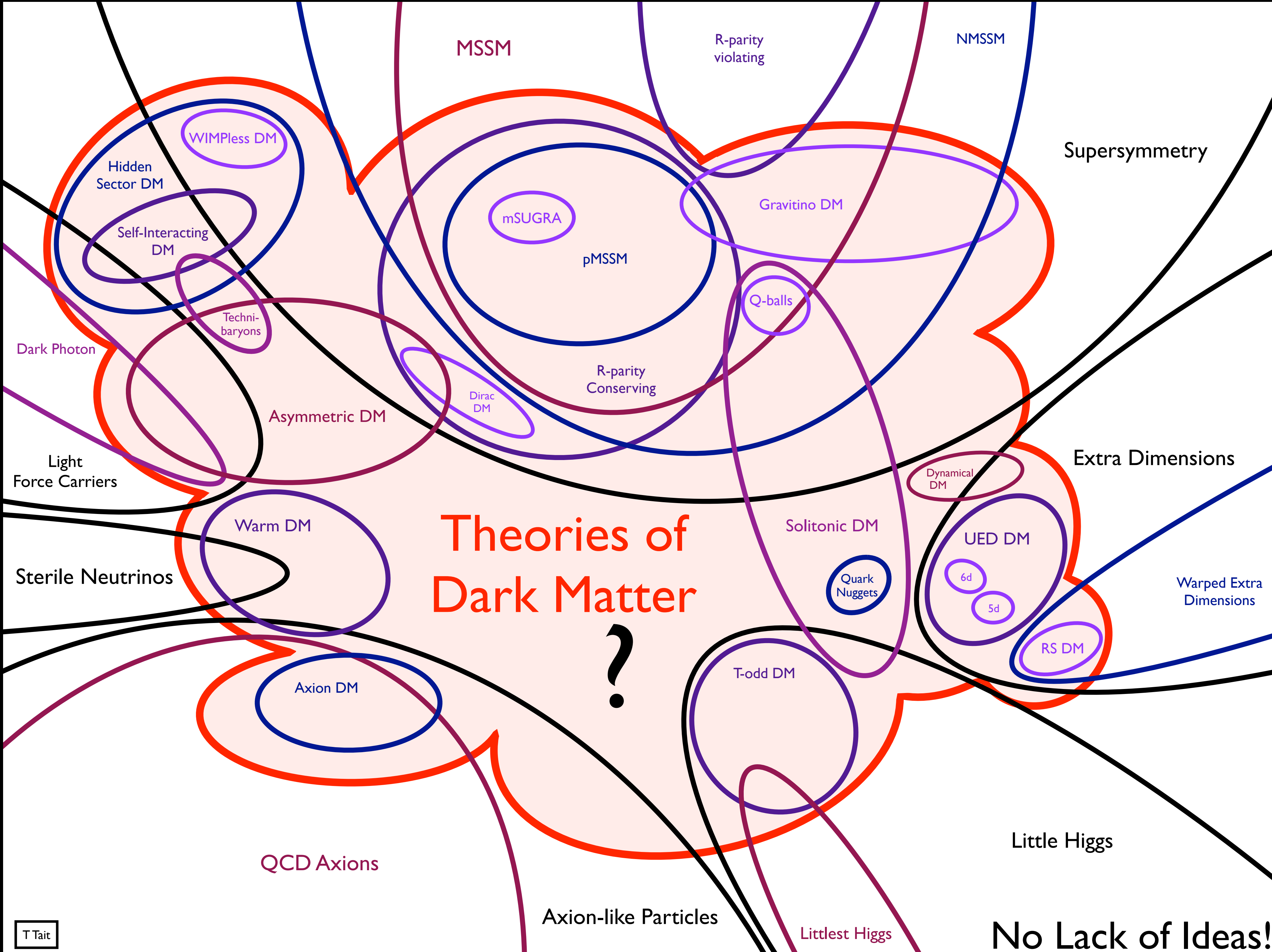
QCD Axions
Little Higgs
Axion-like Particles
Littlest Higgs
T Tait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Dark Matter
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RS DM
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait
No Lack of Ideas!

The Dark Matter Questionnaire

- [ ] Mass: _______
- [ ] Spin : _______
- [ ] Stable?
  - [ ] Yes
  - [ ] No

Couplings:

- [x] Gravity
- [ ] Weak Interaction?
- [ ] Higgs?
- [ ] Quarks / Gluons?
- [ ] Leptons?

Thermal Relic?

- [ ] Yes
- [ ] No

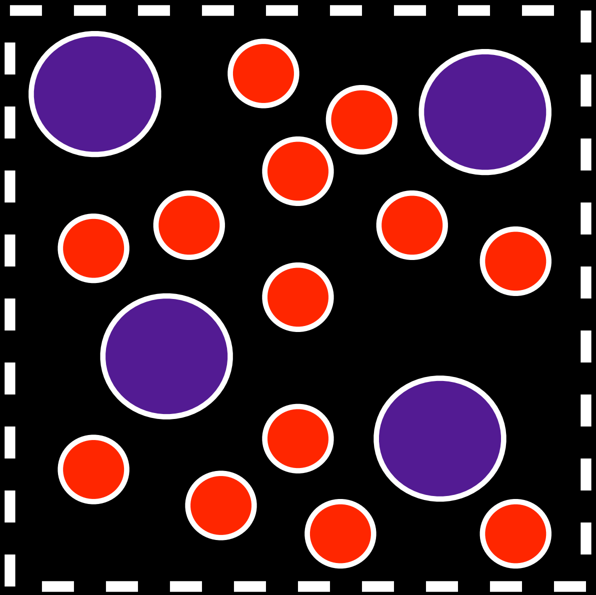
WIMPs

- One of the most attractive proposals for dark matter is that it is a Weakly Interacting Massive Particle.
  - WIMPs naturally can account for the amount of dark matter we observe in the Universe.
  - WIMPs automatically occur in many models of physics beyond the Standard Model, such as supersymmetric extensions with R-parity.
- In addition to their nice theoretical motivations, WIMPs are a form of dark matter which we can search for using particle physics detectors — such as PAMELA!

$59.99 for 20 servings

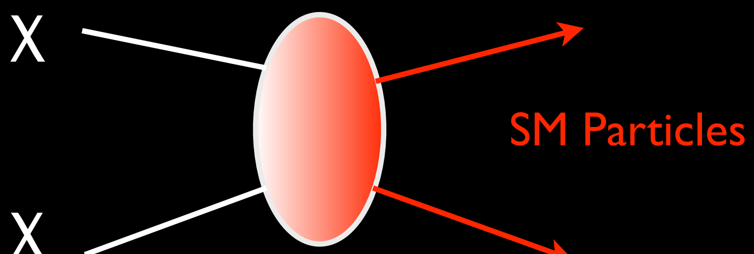
Available in Blue Raspberry, Fruit Punch, and Grape flavors....

The WIMP Miracle



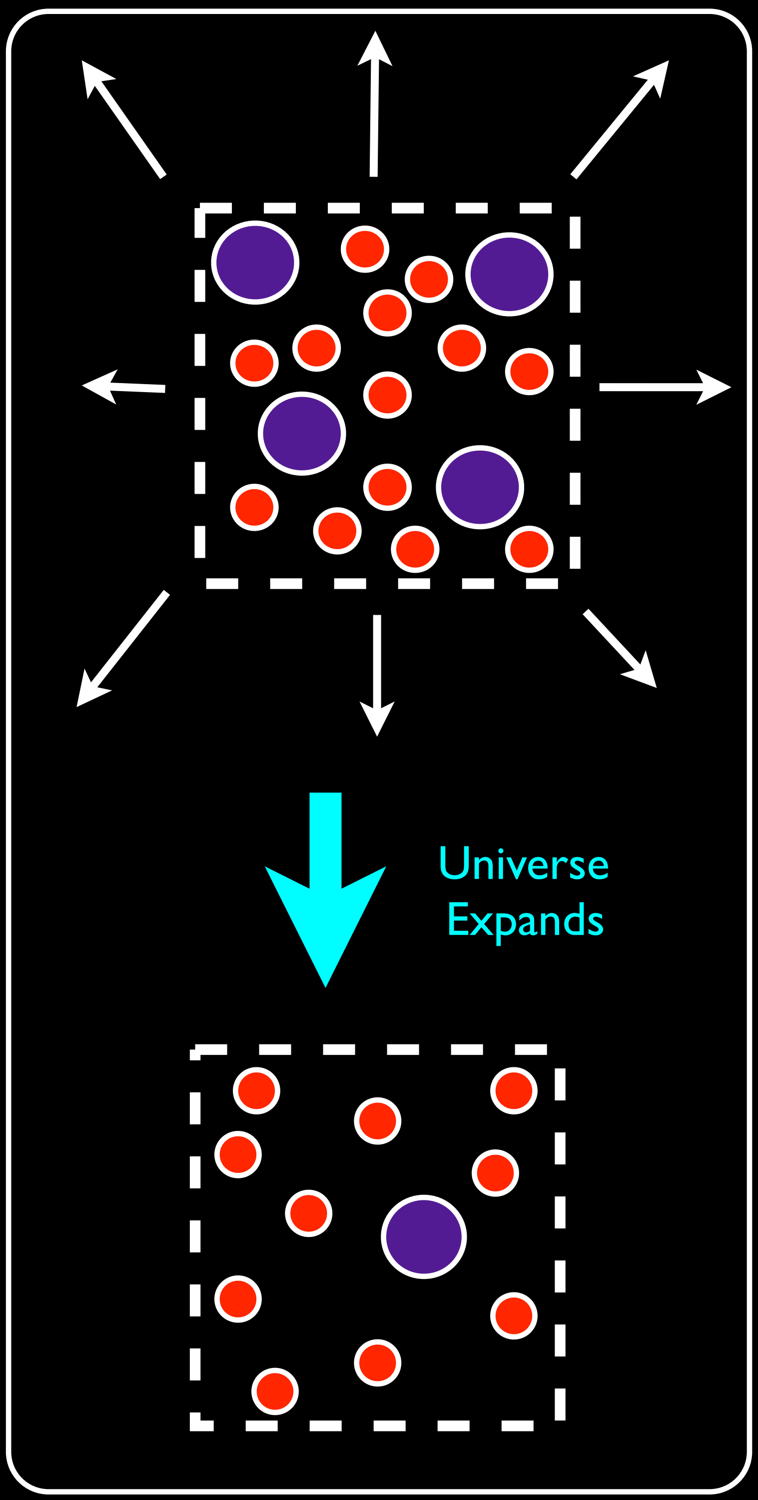
- One of the primary motivations for WIMPs is the "WIMP miracle", an attractive picture explaining the density of dark matter in the Universe today.
- The picture starts out with the WIMP in chemical equilibrium with the Standard Model plasma at early times.
- Equilibrium is maintained by scattering of WIMPs into SM particles, $\chi\chi$ -> SM.
- While in equilibrium at temperatures below its mass, the WIMP number density follows the Boltzmann distribution:

$$n_{eq} = g\left(\frac{mT}{2\pi}\right)^{3/2} \mathrm{Exp}\left[-m/T\right]$$

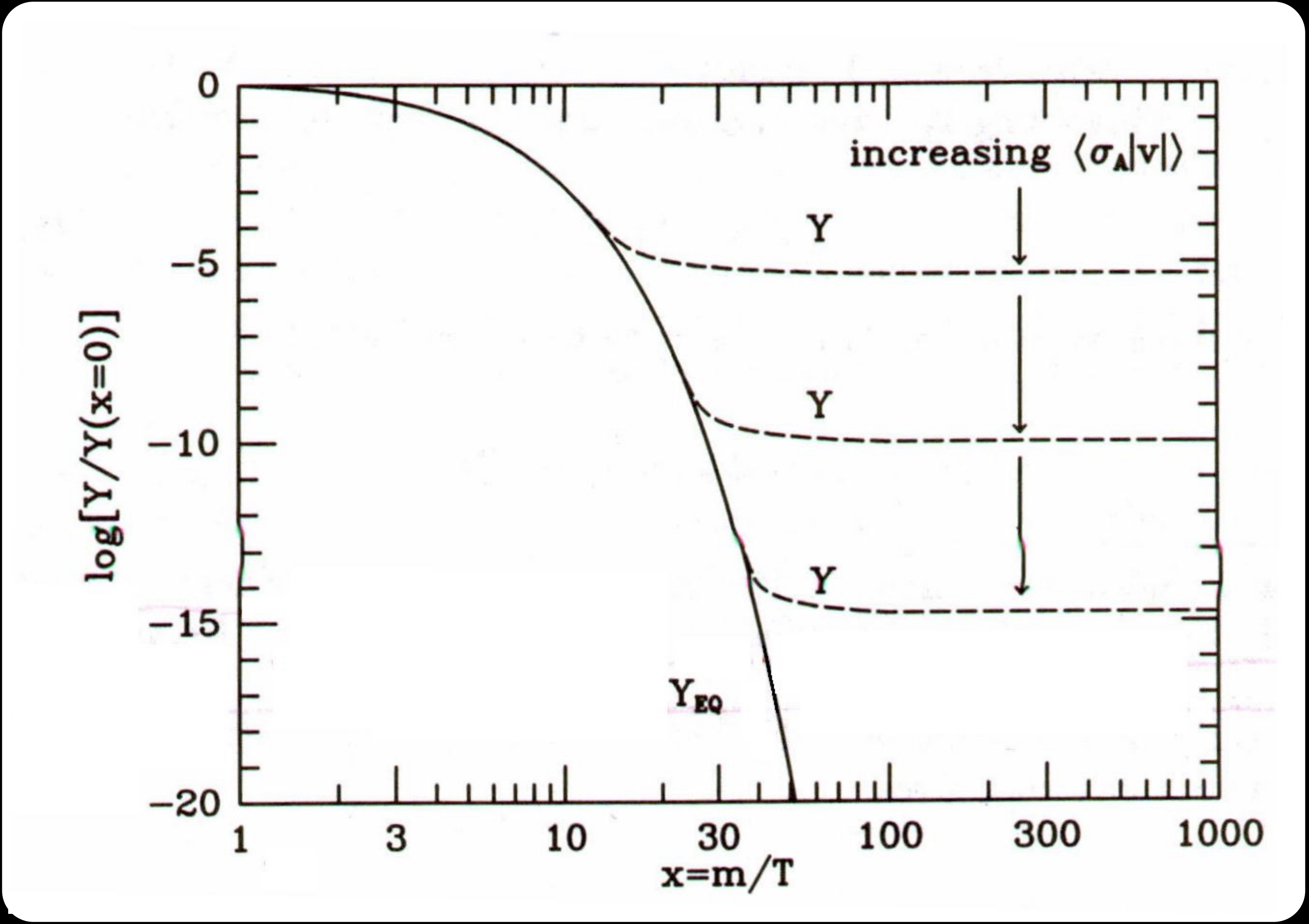


Freeze-Out

- If this were the whole story, the dark matter would just keep diluting as the Universe cools, and would be irrelevant today.
- However, the expansion of the Universe eventually results in a loss of equilibrium.
- At the "freeze-out" temperature, the WIMPs are sufficiently diluted that they can no longer find each other to annihilate and they cease tracking the Boltzmann distribution.
- The temperature at which this occurs depends quite sensitively on σ(χχ -> SM): more strongly interacting WIMPs will stay in equilibrium longer, and thus end up with a smaller relic density than more weakly interacting WIMPs.



Relic Density

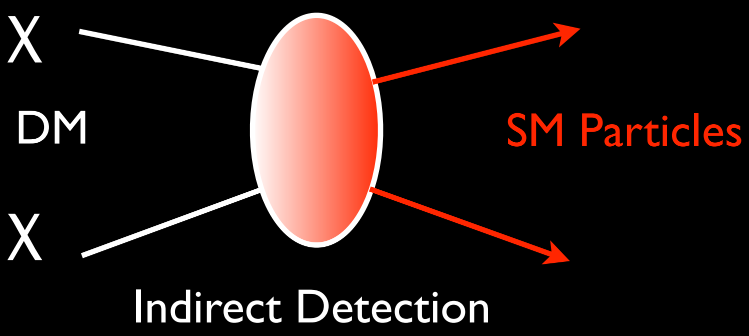


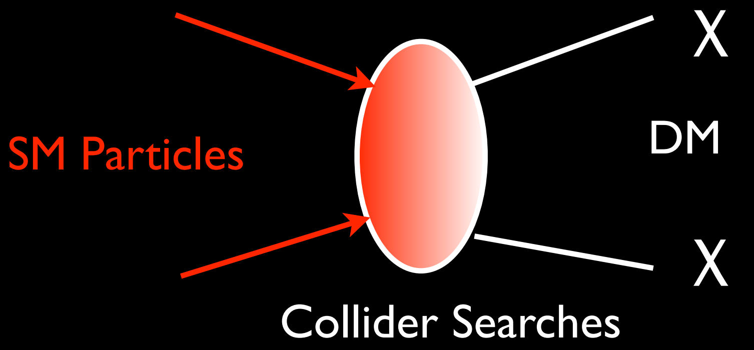
x=m/T increasing
is
T decreasing
is
time increasing

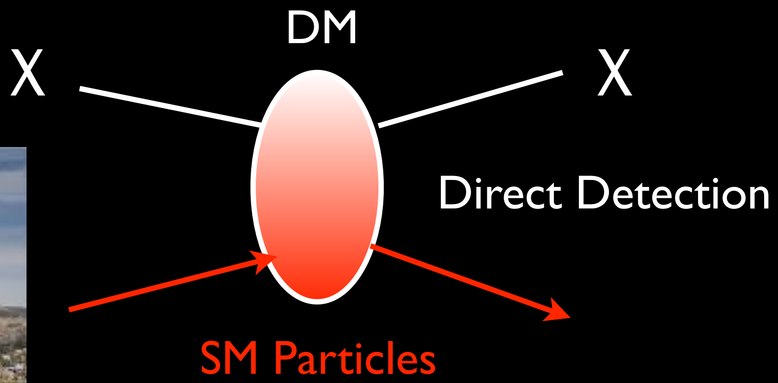
- The observed quantity of dark matter is suggestive of a cross section for annihilation into the thermal bath (the SM + ...).

Searching for Dark Matter with PAMELA

Particle Probes of DM



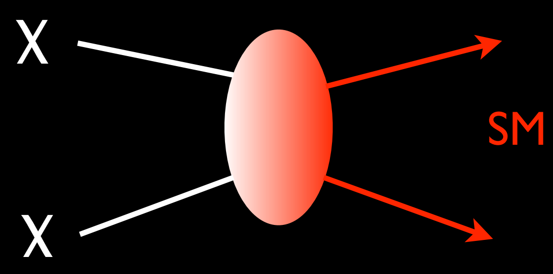


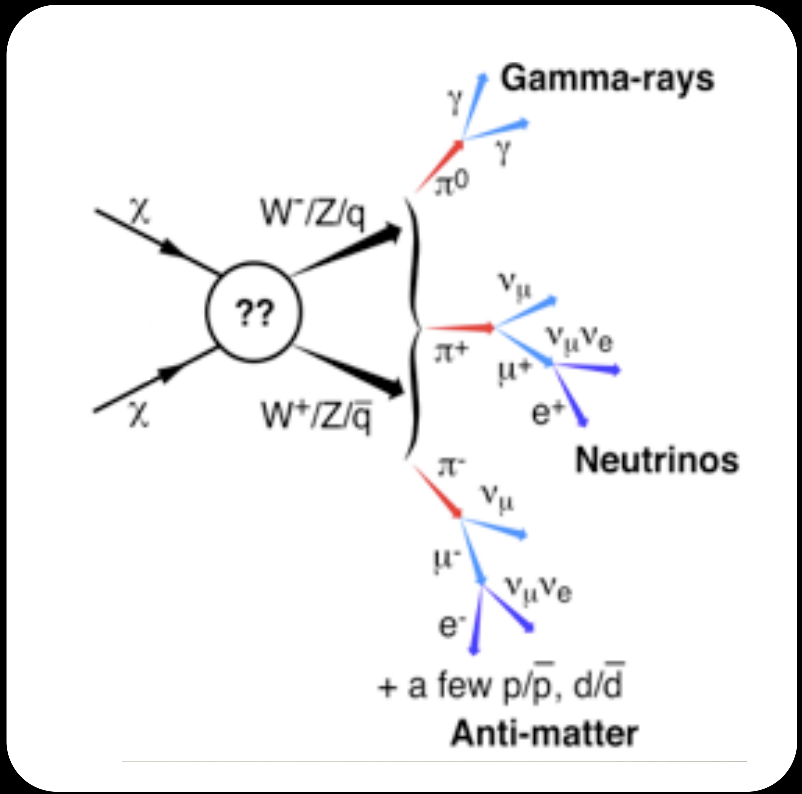


- The common feature of particle searches for WIMPs is that what they could see is determined by how dark matter interacts with the Standard Model.

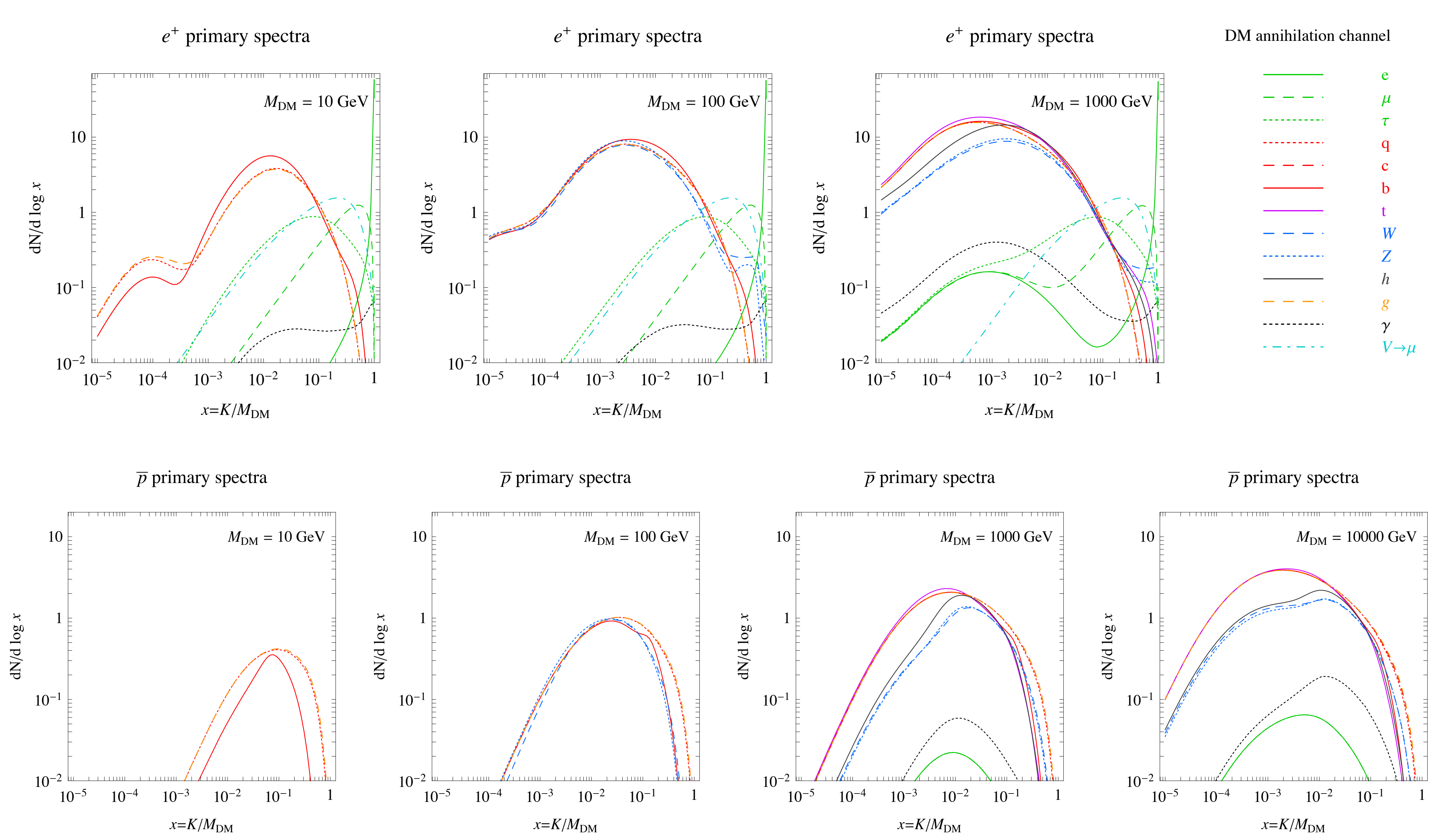
Indirect Detection

- Indirect detection tries to see dark matter annihilating.
- Dark Matter particles in the galaxy can occasionally encounter one another, and annihilate into SM particles which can make their way to the Earth where we can detect them.
- Photons and neutrinos interact sufficiently weakly with the interstellar medium, and might be detected on the Earth with directional information.
- Charged particles will generally be deflected on their way to us, but high energy anti-matter particles are rare enough that an excess of them would be noticeable.





Anti-Matter from DM



Cirelli et al, 1012.4515

Indirect Detection

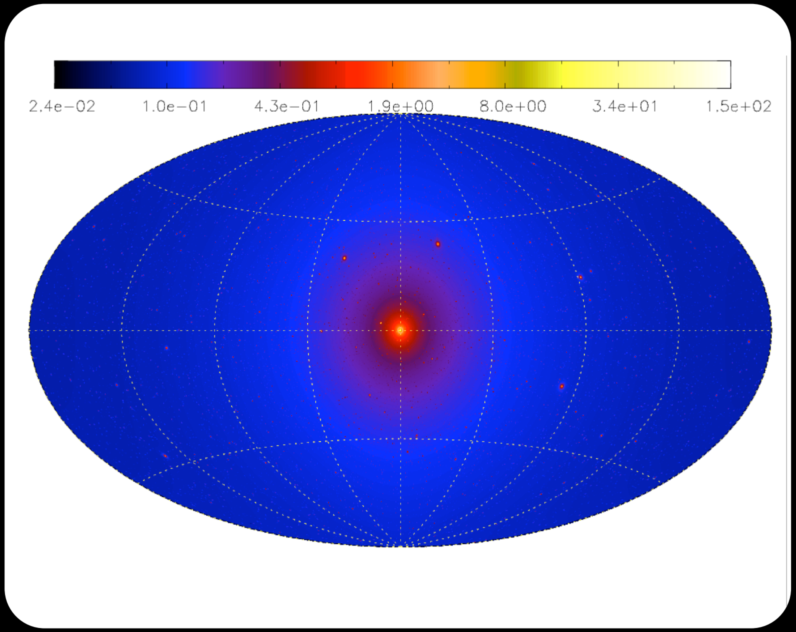
- The rate in a detector is described by a cross section which depends on the WIMP model, and the density of WIMPs squared, at the place where they are annihilating.

Microphysics

Distance along line of sight

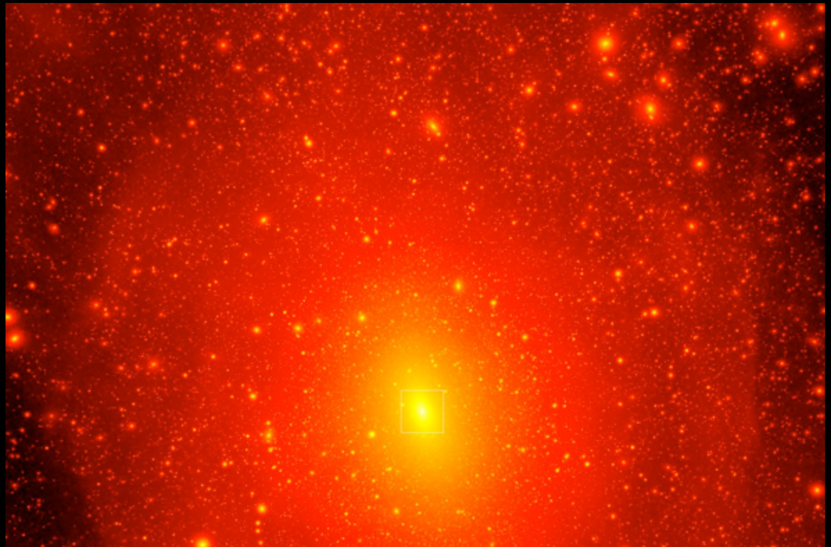
DM density

$$\frac{dN}{dE} = \frac{d\langle\sigma v\rangle}{dE} \int dl \; \rho_{DM}^2(l)$$



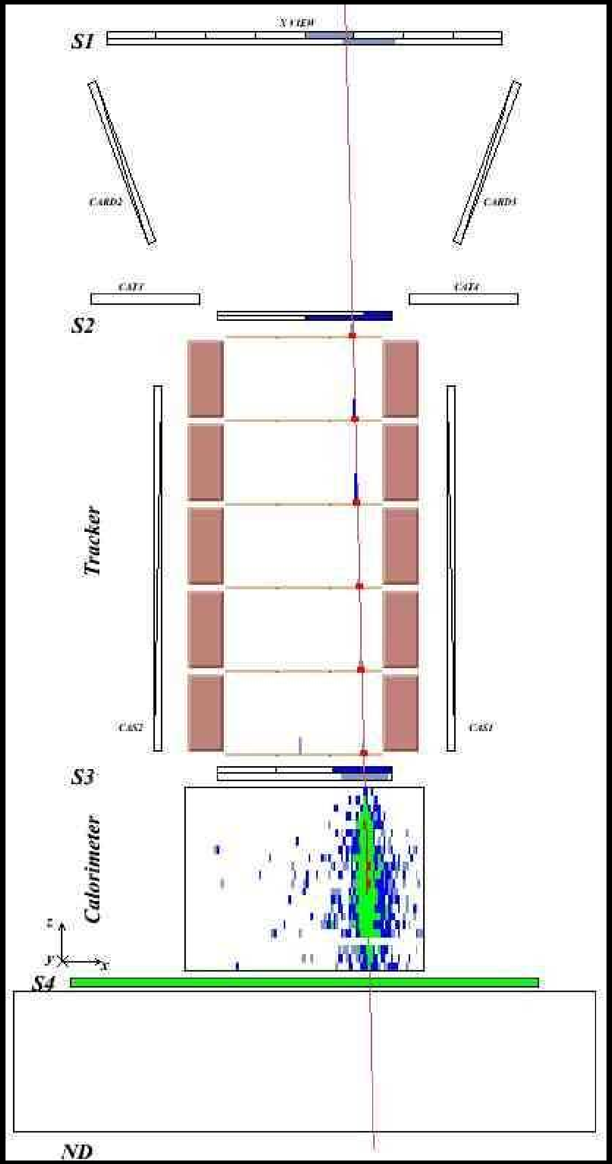
Pieri et al arXiv:0908.0195

- Models of galaxy formation suggest which directions to look as well as the magnitude of the line of sight integral, (with some uncertainty).



PAMELA and Dark Matter

- As we have already heard earlier, PAMELA combines excellent particle identification with precise measurement of kinetic energy.
- This gives it an excellent ability to identify anti-matter particles at high energies.
- If the dark matter annihilates into (anti-)quarks and/or anti-leptons, or particles which decay into them (such as weak bosons), it can see an excess of such particles over the expected rate from high energy astro-physical processes.
- Because of galactic magnetic fields, the direction to the origin of such particles is very difficult to determine.



Adriani et al 0810.4995

The Dark Matter Questionnaire

- ☐ Mass: ________
- ☐ Spin : ________
- ☐ Stable?
  - ☐ Yes ☐ No

Couplings:

- ☑ Gravity
- ☐ Weak Interaction?
- ☐ Higgs?
- ☐ Quarks / Gluons?
- ☐ Leptons?

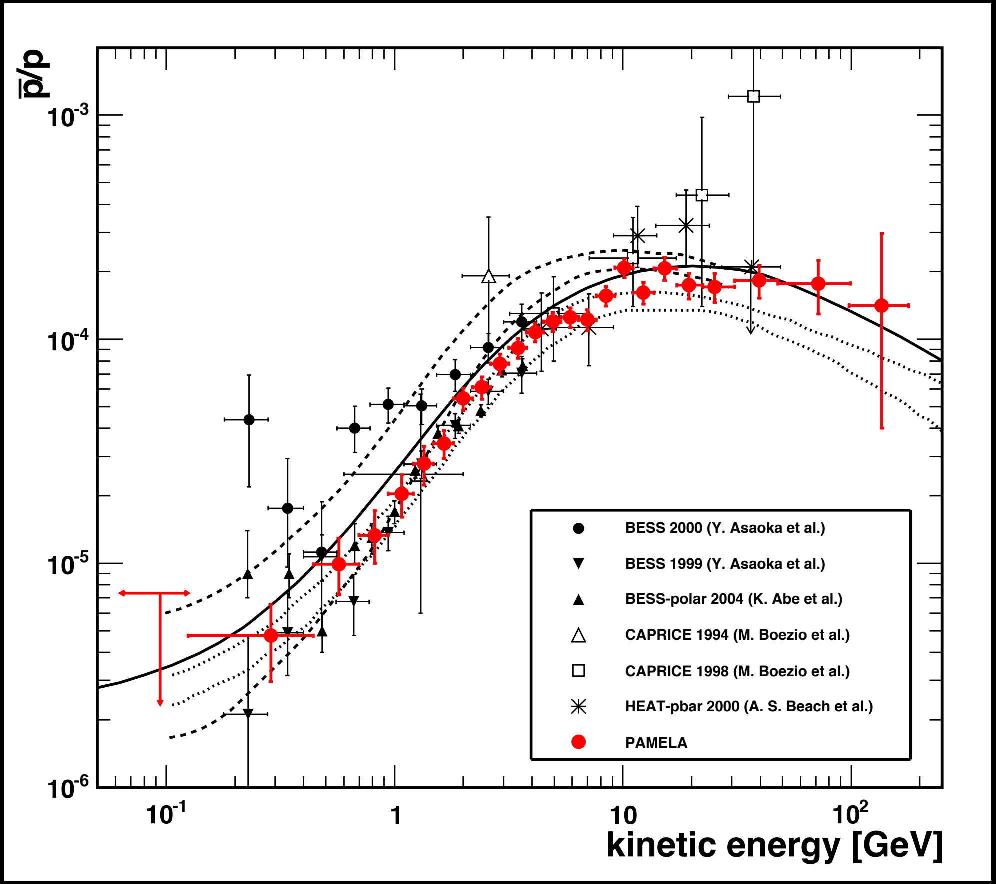
Thermal Relic?

- ☐ Yes ☐ No

PAMELA can help us understand these properties!

Anti-Protons

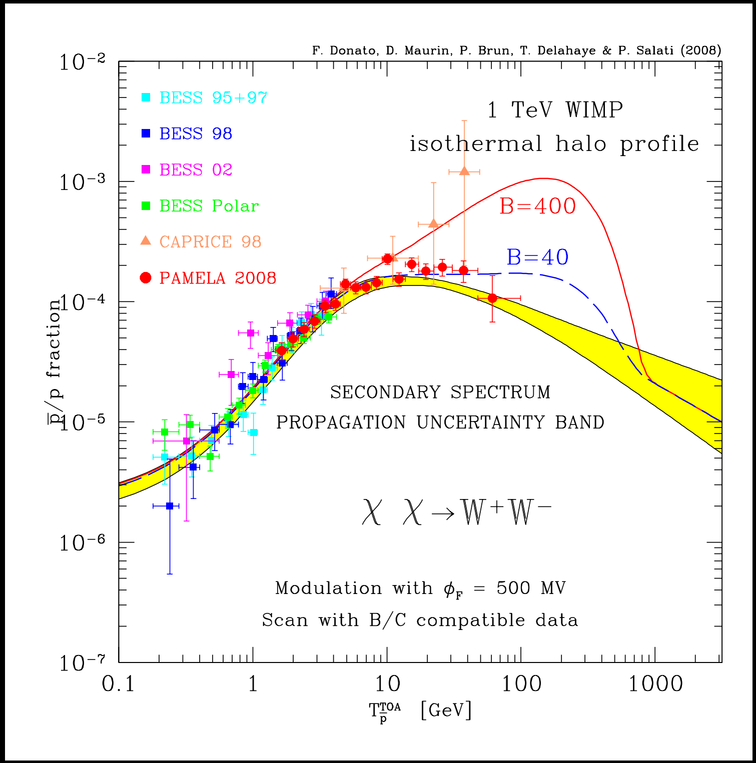
- Anti-protons are relatively rarely produced in high energy astrophysical processes.
- Because they are relatively heavy, they retain their directional information longer than e.g. positrons.
- A signal from DM annihilation producing anti-protons could reasonably be observed by PAMELA.
- Beautifully measured points as a function of kinetic energy are in reasonable agreement with previous measurements (extending them dramatically in energy), and consistent with expectations from astrophysical production as secondaries.



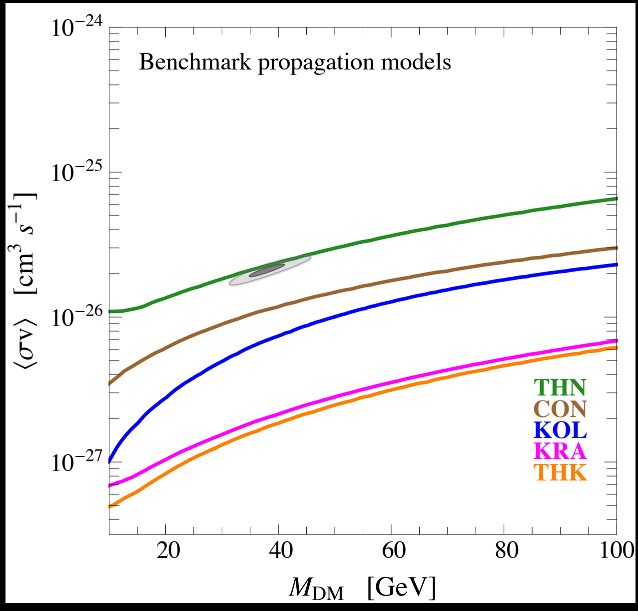
Adriani et al 1007.0821

Constraints & Impact

- Lack of an anti-proton signal is currently a powerful constraint on any dark matter particle which annihilates into quarks or gauge bosons.
- For example, there is currently an excess of ~GeV γ rays observed by the Fermi LAT from the direction of the galactic center. E.g. Hooper & Goodenough 1010.2752
- A hypothesis which fits the data is dark matter of mass ~40 GeV annihilating into bottom quarks, which ultimately result in γ rays (as well as anti-protons!)
- For many propagation models, anti-proton limits strongly constrain this DM interpretation.



Donato et al 0810.5292



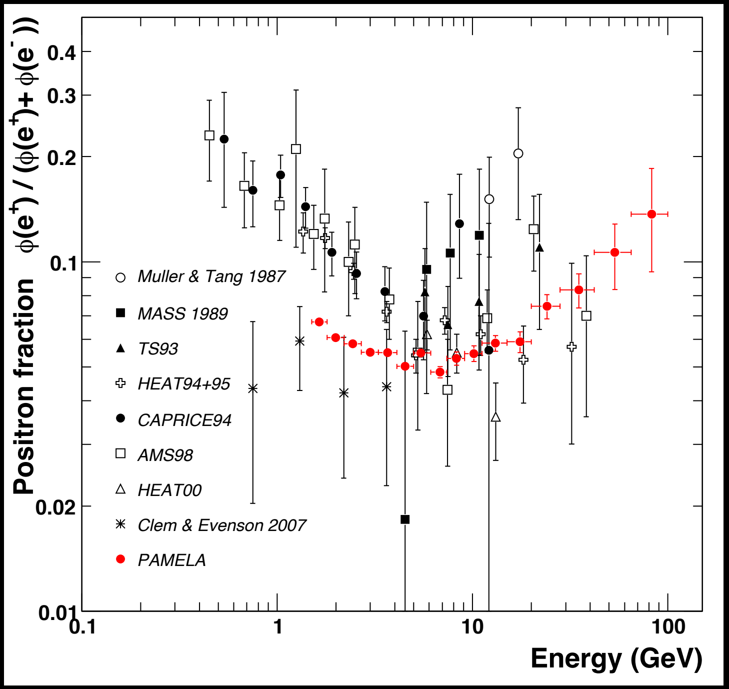
Cirelli et al 1407.2173

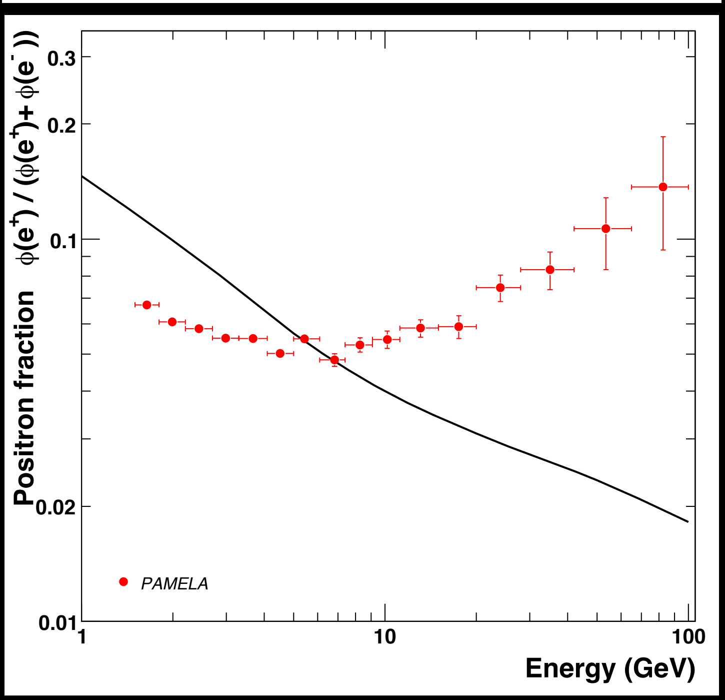
Positrons: The Anticipation

- After the launch, the dark matter community waited with bated breath to hear what it had to say about positrons…
- The anticipation was so intense that it was actually the subject of a practical joke by particle theorists!
- A fake text message claiming to leak an advance result in which the spectrum rose with higher energy (rather than falling with energy as expected) was sent to a prominent particle theorist…
- This lead to an all-night party at a conference hosted by the Kavli Institute of Theoretical Physics as particle theorists tried to understand what this would imply for theories of dark matter!
- When the joke was revealed, the anticipation did not waver…

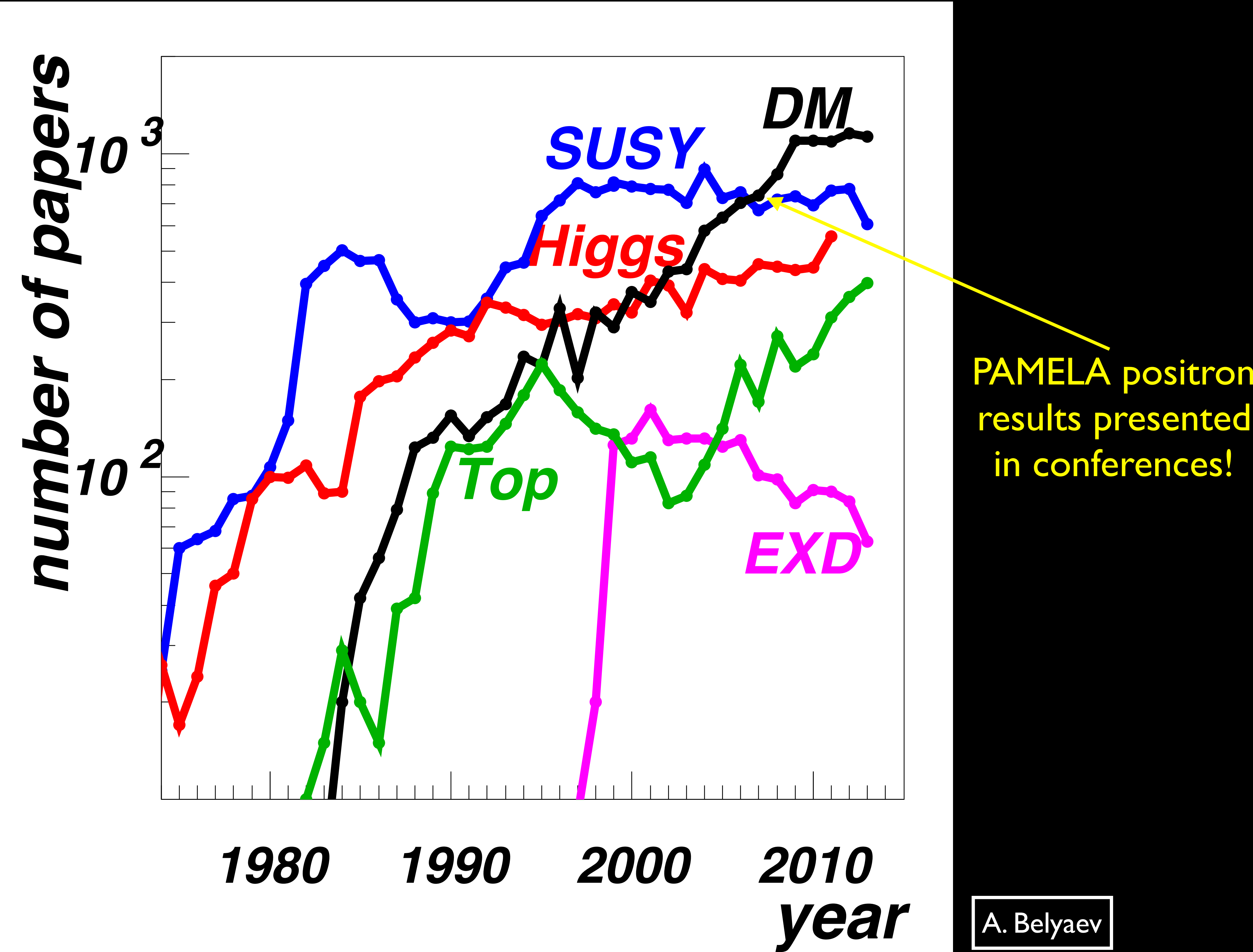
Positrons: The Reality

- And of course when the results were first shown at conferences, they lived up to this speculation and more!
- The data showed an unexpected rise beginning around 10 GeV (where the effects of solar modulation die out) and rising steadily up to the largest energies for which the initial data set had statistics, ~ 100 GeV.
- Expectations from the (admittedly uncertain) background were for the fraction to fall off at higher energies.
- A photo of the plot taken by a particle theorist during a conference talk "went viral" and became an oft-referenced object in theory papers until official plots were available.





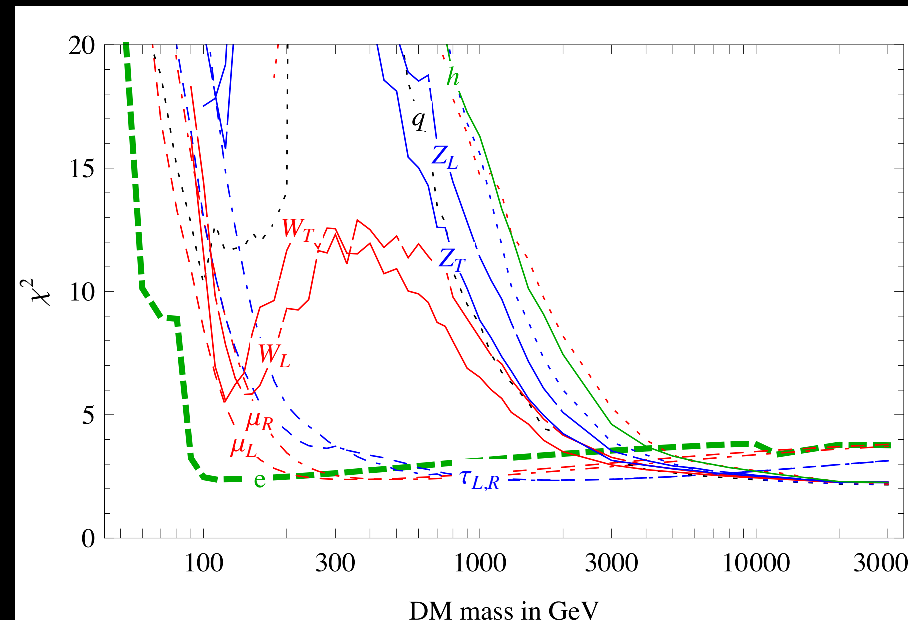
Adriani et al 0810.4995

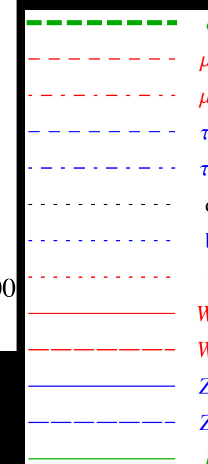

number of papers
10^3
10^2
SUSY
DM
Higgs
Top
EXD
1980
1990
2000
2010
year
PAMELA positron
results presented
in conferences!

A. Belyaev

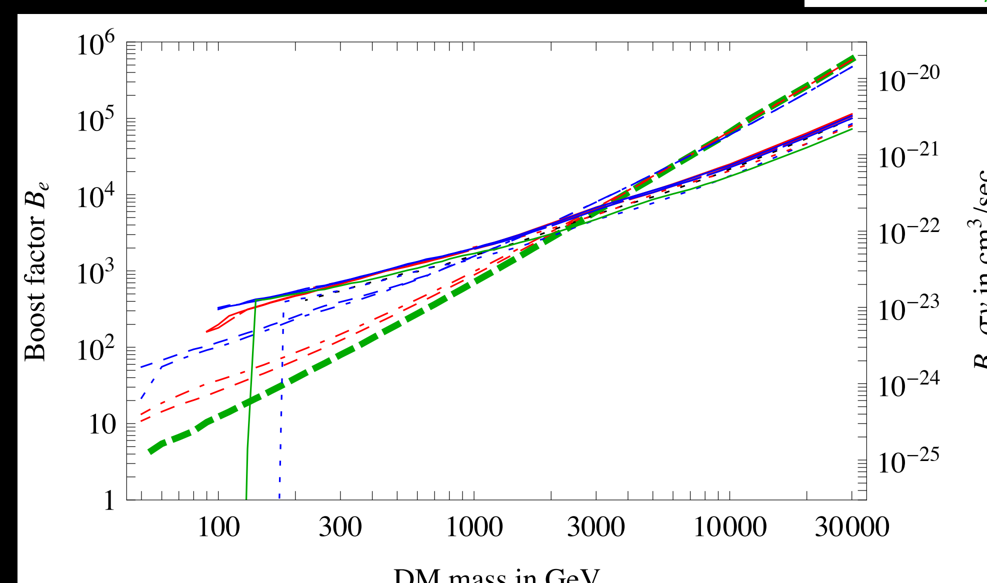
A Puzzling Signal…

- While intriguing and exiting, this signal was also very puzzling.
- Because of the magnetic fields, we can only reasonably hope for positrons produced within about 1 kpc to reach us.
- The magnitude of the PAMELA positron fraction suggests that if dark matter is its origin, either there is a large clump of dark matter very close to the solar system (which simulations indicate is unlikely), or its cross section for annihilation must be enormous, inconsistent with the cross section necessary for a thermal relic.



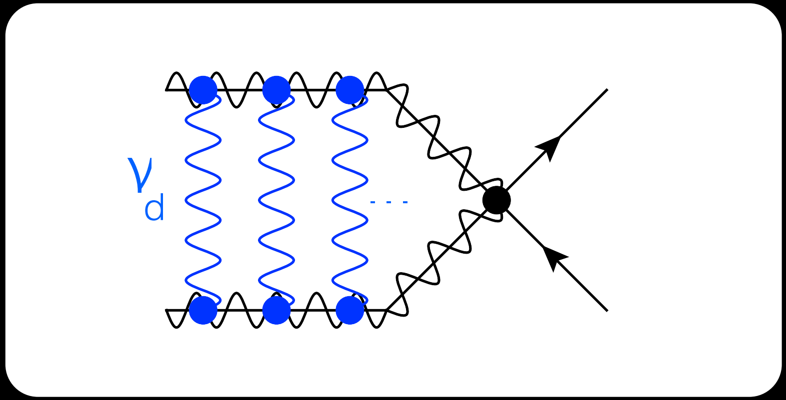


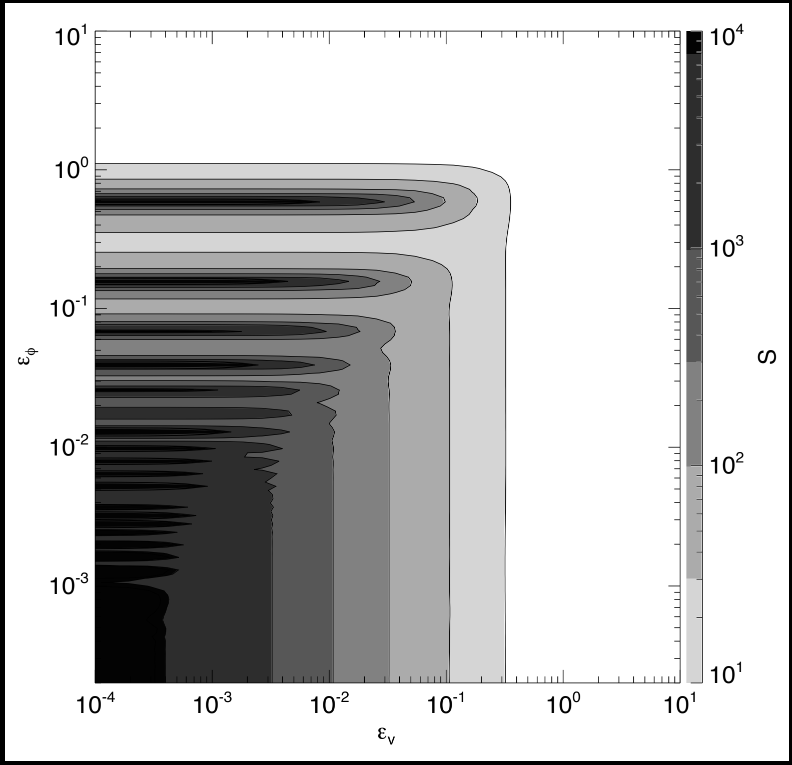
Cirelli et al 0809.2409



…Leads to New Directions in Model-Building!

- The intriguing signal prompted particle theorists to look into previously under-explored corners of dark matter theory space.
- One very interesting possibility that has since received much attention is the idea that there could be a light force carrier with large interactions with the dark matter.
- This leads to large Sommerfeld-like enhancements in the annihilation cross section due to a mutually attractive potential between the two dark matter particles.
- Cross sections roughly consistent with a thermal relic can be consistent!

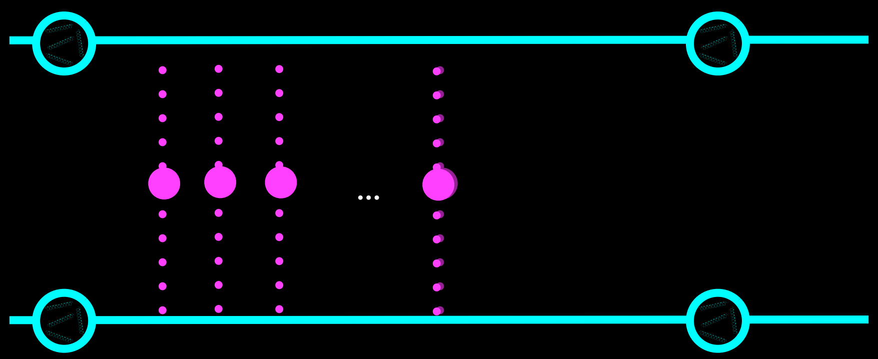




$$\epsilon_\phi \equiv \frac{m}{\alpha M} \qquad \epsilon_v \equiv \frac{v}{\alpha}$$

Cirelli, Kadastik, Raidal, Strumia 0809.2409
Arkani-Hamed, Finkbeiner, Slatyer, Weiner 0810.0713
...

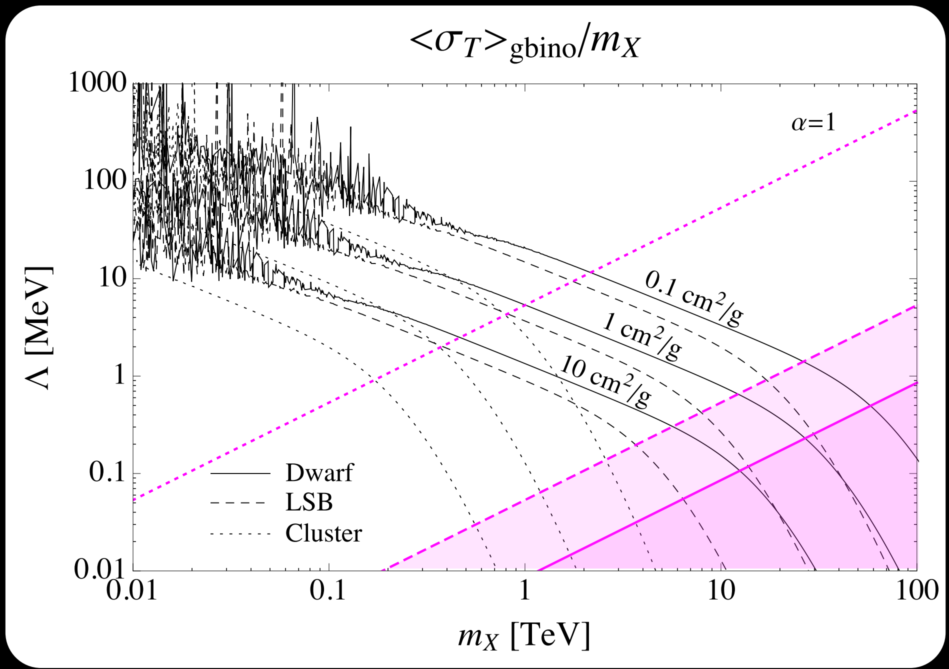
Light Dark Forces



- A light (low mass) dark force carrier is now part of the standard tool kit for dark matter model-building.
- In addition to the Sommerfeld enhancement for annihilation, such a particle can lead to enhanced self-scattering of the dark matter.
  - A large scattering cross section may even be suggested by small scale measurements of dark matter distributions!
- In general, it reveals our ignorance about the possibility of very low mass particles which are very weakly coupled to the Standard Model.

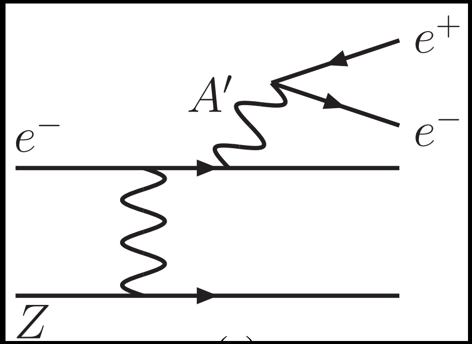
Object	Typical v
Clusters	700-1000 km/s
LSB	50-130 km/s
Dwarf	20-50 km/s

Boddy, Feng, Kaplinghat, TMPT 1402.3629

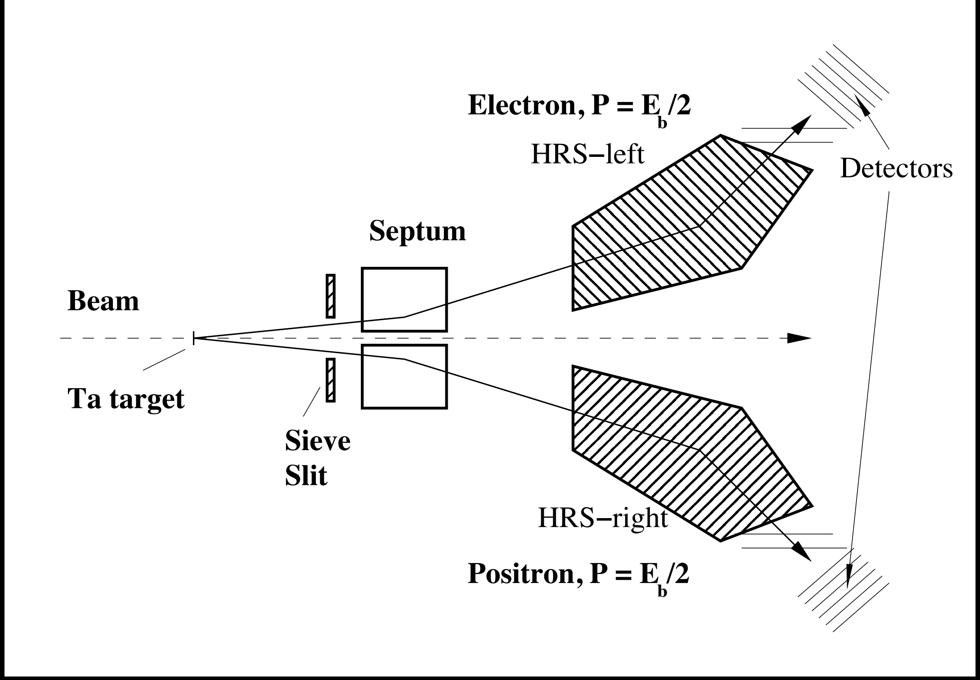


A New Experimental Frontier!

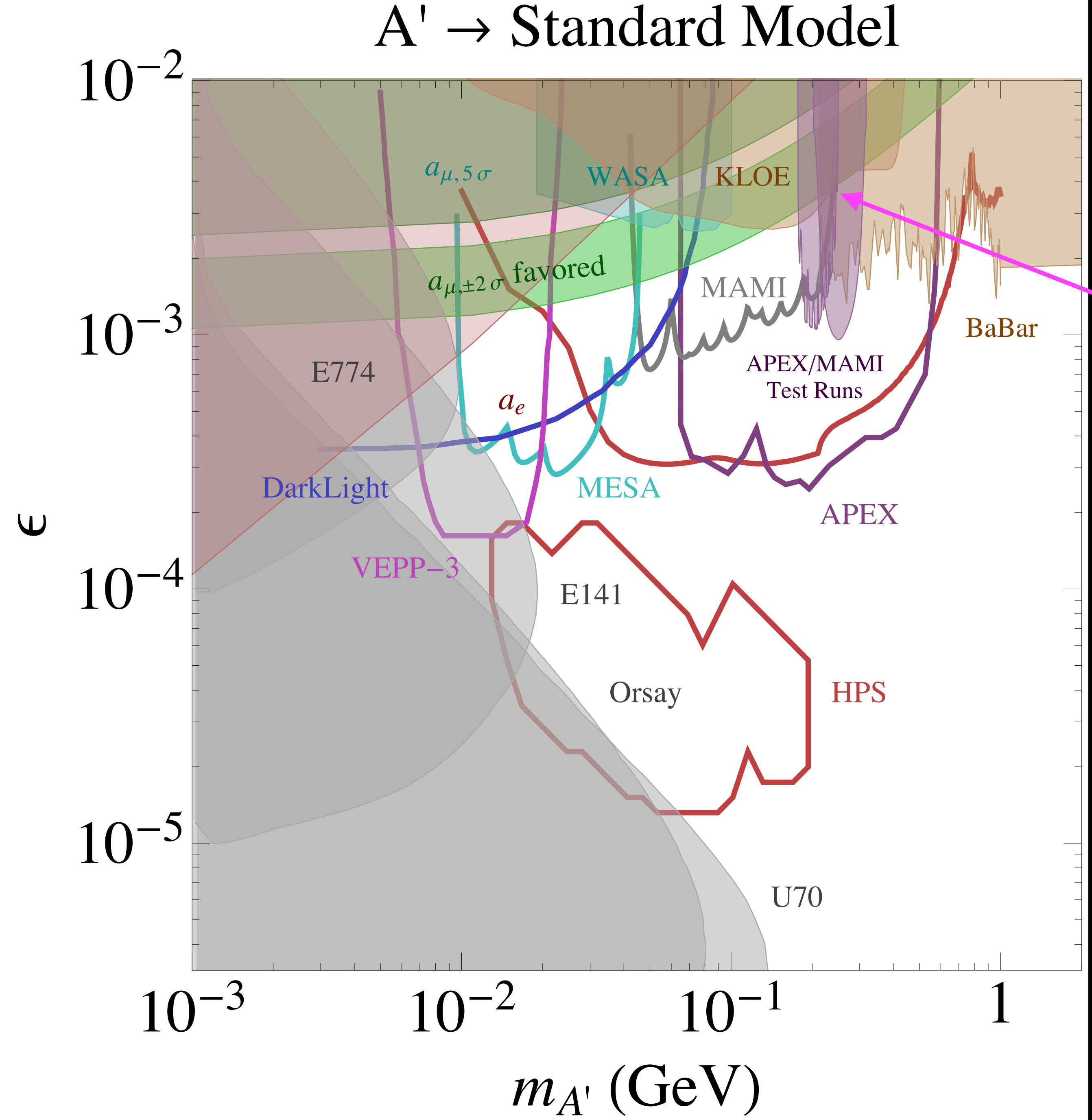
- Once people realized that light dark force carriers were interesting and under-explored, they began to devise experiments to search for them.
- Since the target parameter space has low masses and very weak couplings, often low energy, high luminosity facilities provide the best limits.
- High luminosity electron accelerators can produce the dark force carrier, which eventually decays into e+e- or in some cases the dark matter itself.
- There is now a whole family of experiments aimed at exploring different regions of mass / coupling.



Abrahamyan et al, APEX 1108.2750



Dark Photon Searches



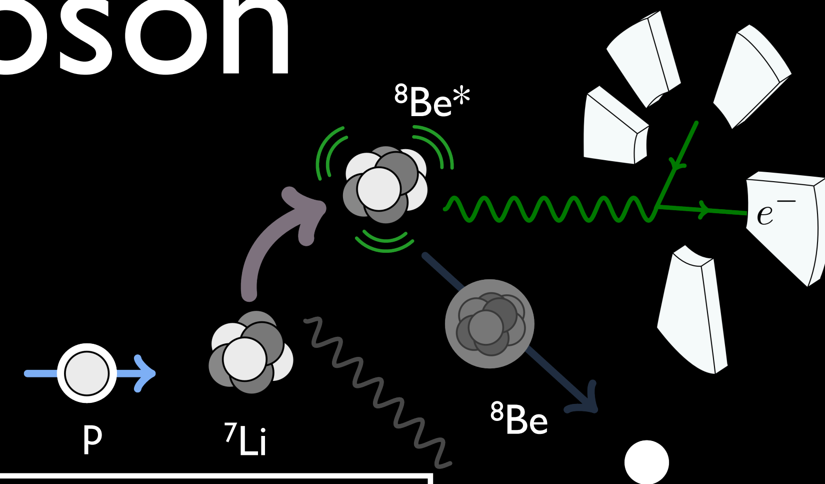
Test runs of APEX and MAMI already place new bounds on parameter space!

ε parameterizes the coupling, which is εeQ in "dark photon" models.

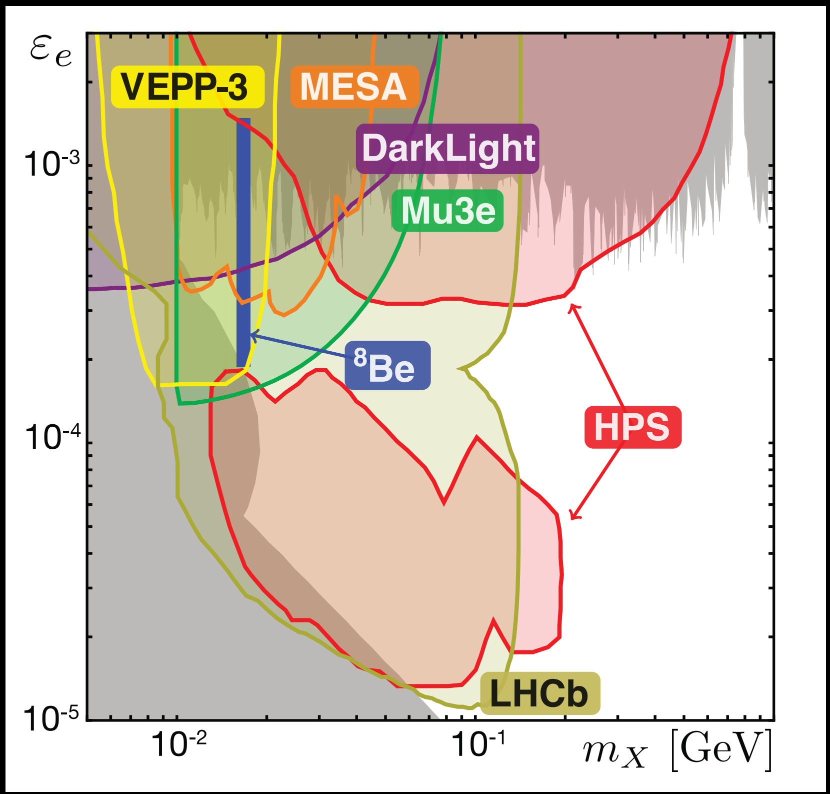
Snow mass Intensity Frontier Report 1401.6077

17 MeV Boson

- These data fill in gaps in our knowledge, and have proven to be important in unexpected places.
- For example, there has recently been interest in a ^{8}Be transition which appears to have a resonance in its decay to e+e- at around 17 MeV.
- While it remains possible that this result is due to experimental bias or unknown nuclear physics, it could also be a sign of new physics!
- The wealth of understanding we have about such objects is entirely due to the interest in studying them which followed from the PAMELA result!

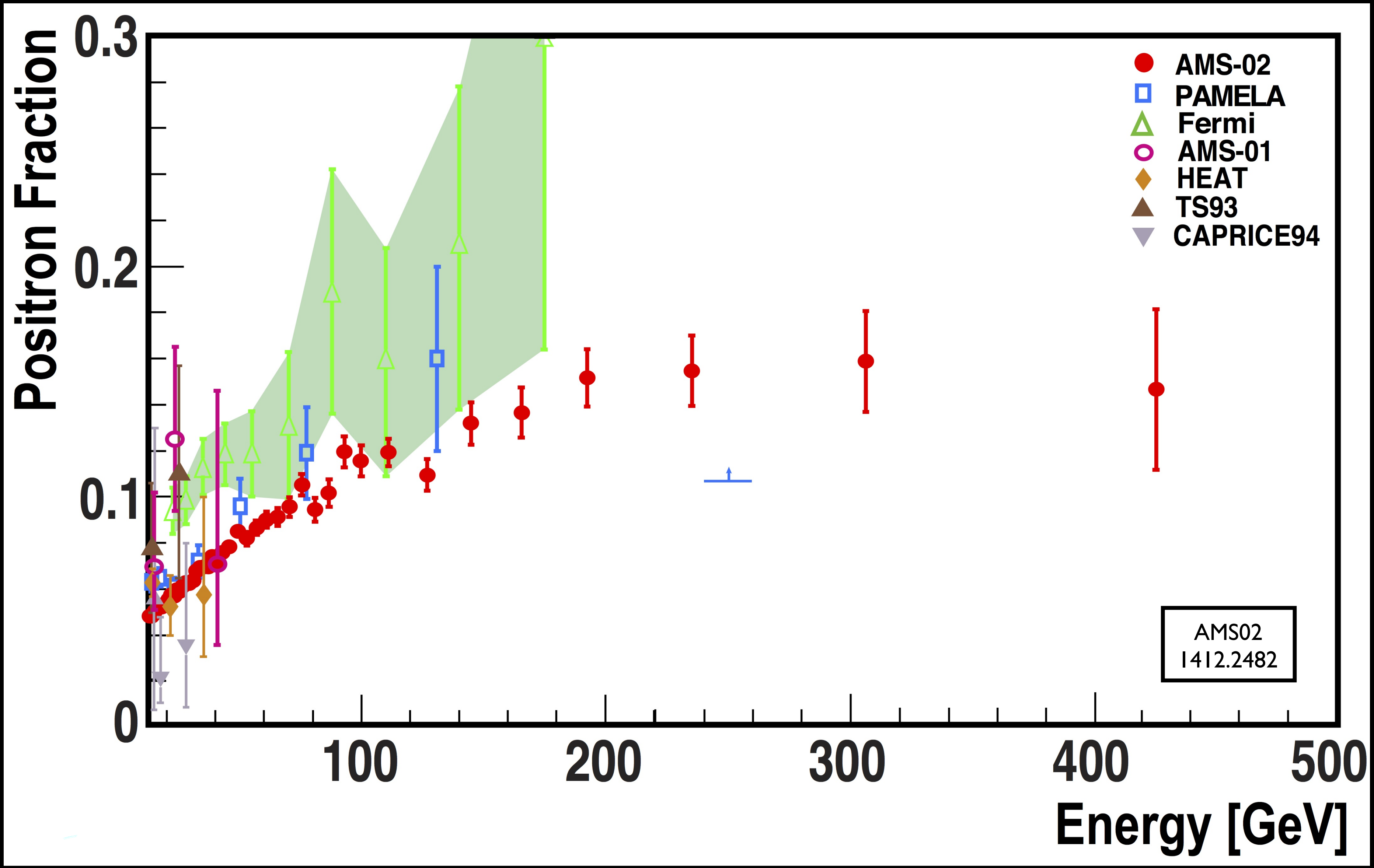


Krasznahorkay et al 1504.01527 & PRL



Feng, Fornal, Galon, Gardner, Smolinsky, TMPT, Tanedo 1604.07411

AMS-02 Weighs In



PAMELA has now passed the torch to AMS, which illustrates the high quality of the earlier PAMELA results and extends a little higher in energy.

The PAMELA Legacy

- Looking at its accomplishments in 10 years, PAMELA's impact on the science of dark matter strikes me as encapsulating the best aspects of the scientific process and international scientific collaboration.
    - First, there is the signal itself, which is reproducible by other experiments and is clearly telling us something extremely interesting, even if it ultimately turns out not to be dark mater.
    - Of course, this signal could turn out to be the first sign of particle dark matter. To establish this probably requires seeing a correlated signal in some other experiment to help convince us it is due to dark matter.
- The signal has motivated theoretical particle physicists to think outside of the standard paradigms, leading to the discovery of beautiful and interesting models which were not widely considered before.
- New directions in theory have lead to an entire program of searching for dark force carriers in a variety of channels at different facilities.
- The PAMELA legacy for dark matter research is profound and endures!

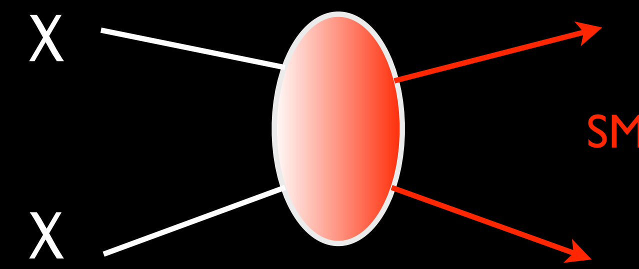
To echo what Igor Said:

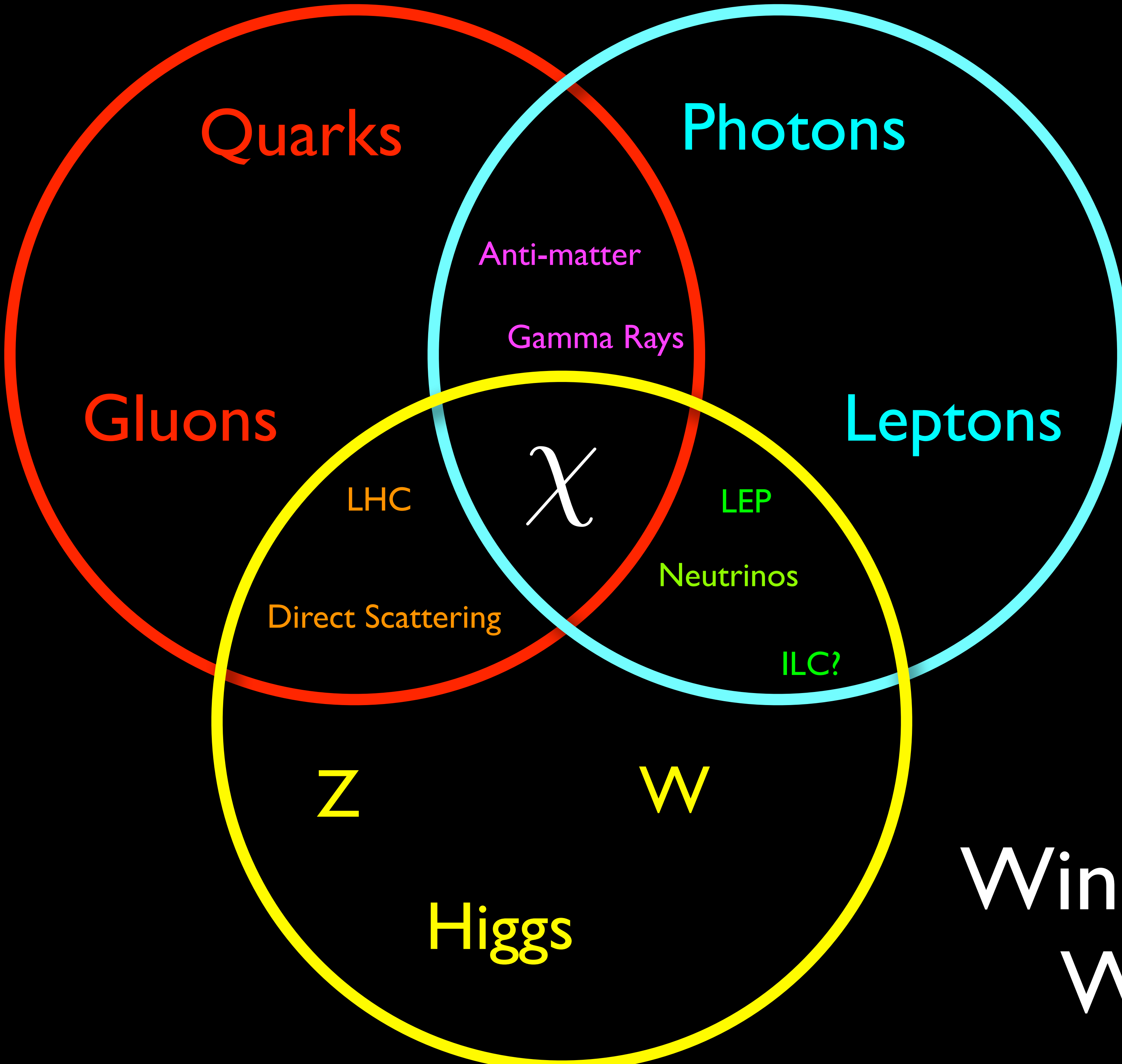
"Brilliant Job!
Congratulations, PAMELA!"

Bonus Material

SM Interactions

- Ideally, we would like to measure WIMP interactions with the Standard Model, allowing us to compute $\sigma(\chi\chi$ -> SM particles) and check the relic density.
  - If our predictions "check out" we have indirect evidence that our extrapolation backward to higher temperatures is working.
  - If not, we will look for new physics to explain the difference.
- The first step is to actually rediscover dark matter by seeing it interact through some force other than gravity.
- That tells us which SM particles it likes to talk to and in some cases something about its spin, mass, etc.

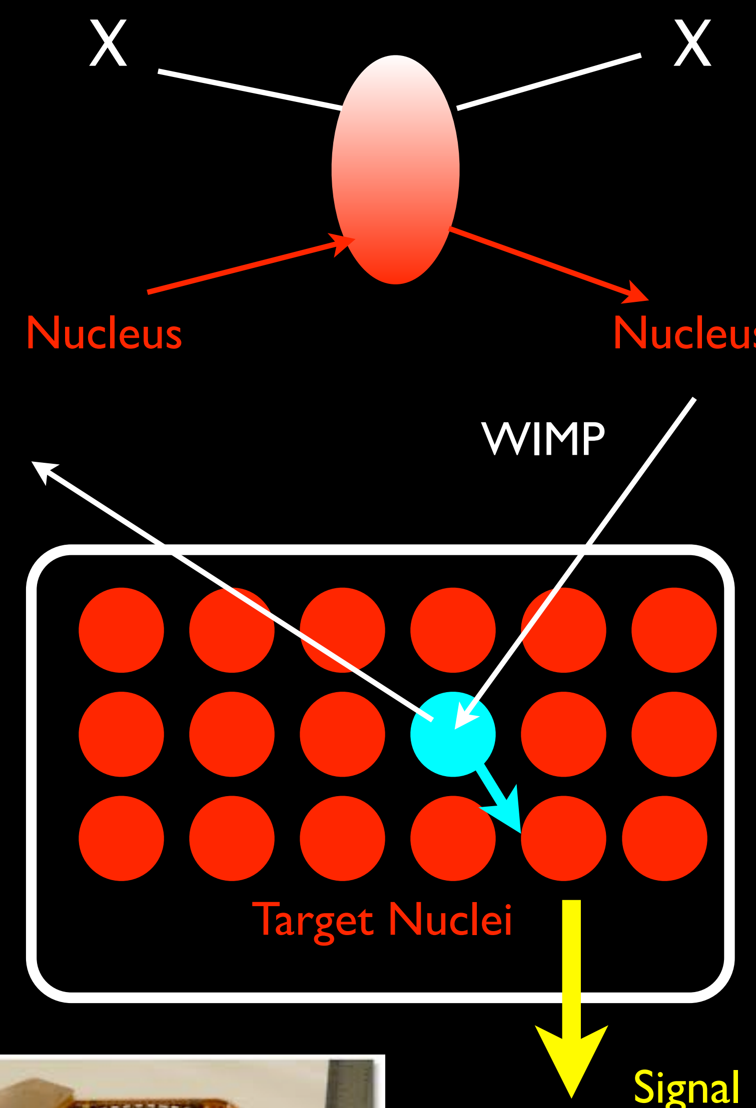


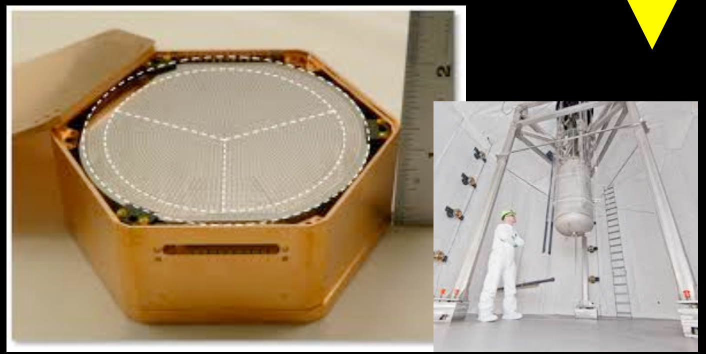


Windows on WIMPS

Direct Detection

- The basic strategy of direct detection is to look for the low energy recoil of a heavy nucleus when dark matter brushes against it.
- Direct detection looks for the dark matter in our galaxy's halo, and a positive signal would be a direct observation.
- Heavy shielding and secondary characteristics of the interaction, such as scintillation light or timing help filter out backgrounds.
- These searches are rapidly advancing, with orders of magnitude improvements in sensitivity every few years!





Direct Detection

- The rate of a direct detection experiment depends on one power of the WIMP density (close to the Earth).

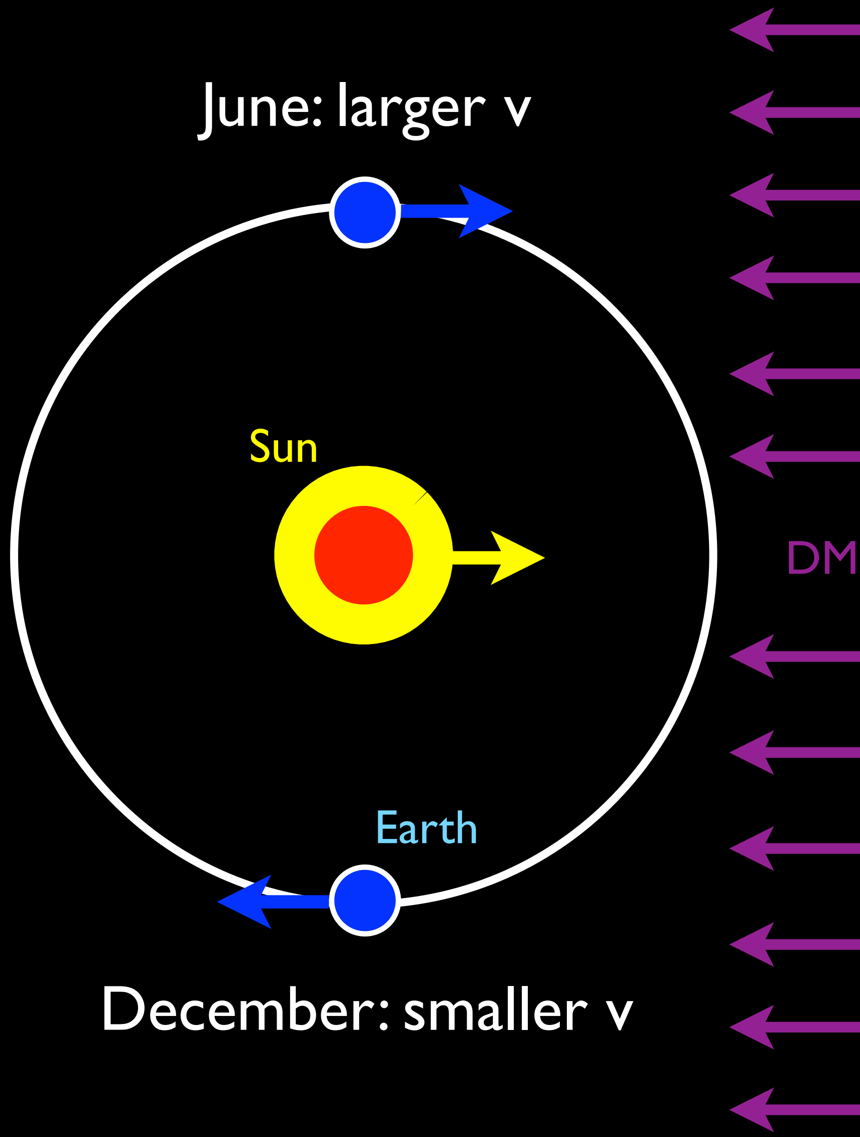
$$\frac{dN}{dE} = \sigma_0 \, \frac{\rho}{m} \int dv \, f(v) \, F(E)$$

DM density

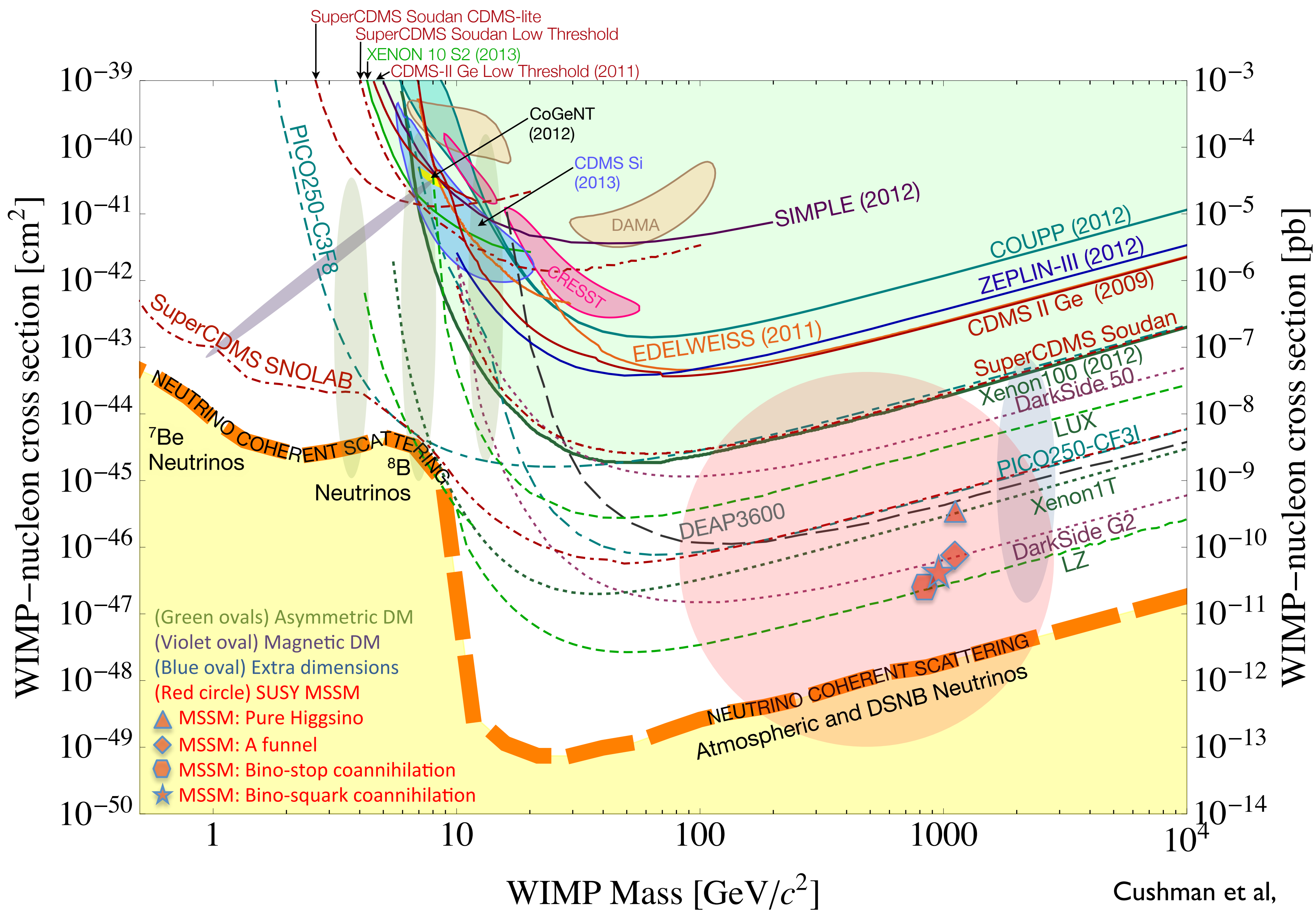
Nuclear Physics

DM velocity distribution

- The energy spectrum of the recoiling nucleus depends on the WIMP mass, its coupling to quarks, and nuclear physics.
- The cross section is dominated by the effective WIMP interactions with quarks and gluons.
- An interesting handle on the signal is an expected annual modulation.



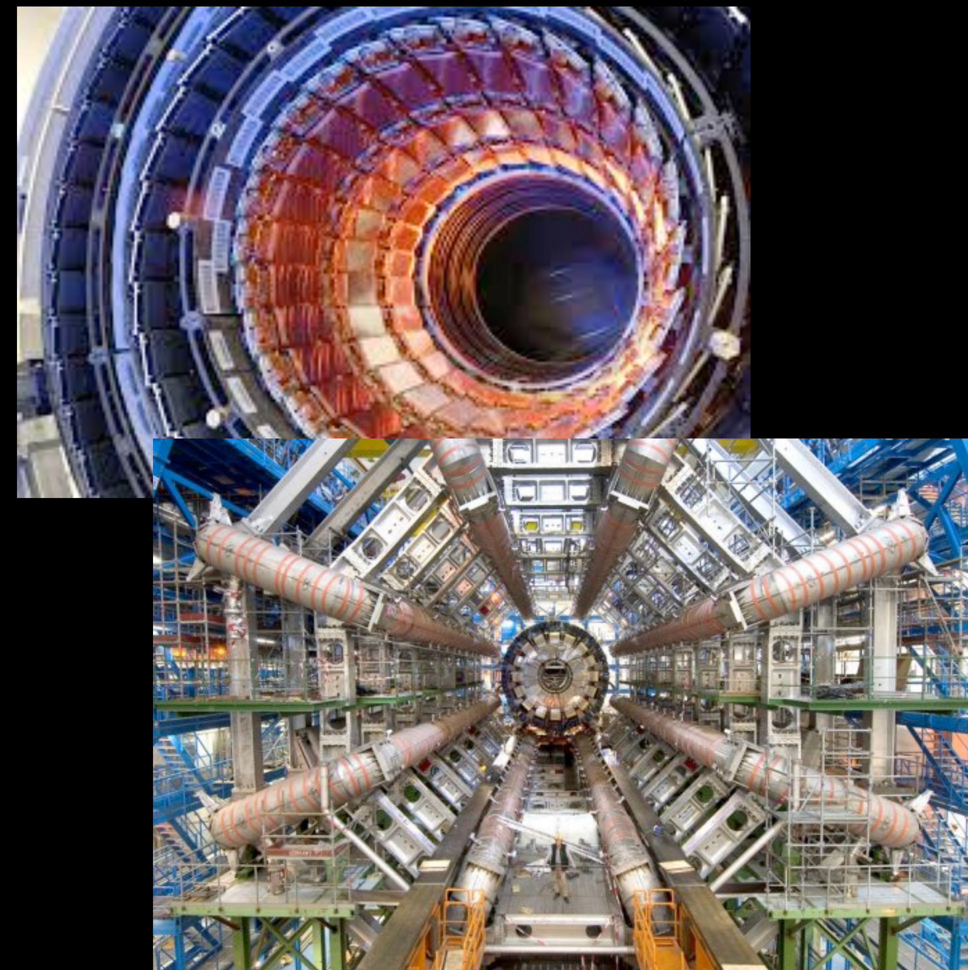
Lots of Activity



Cushman et al,
Snowmass CF1 Report

Collider Production

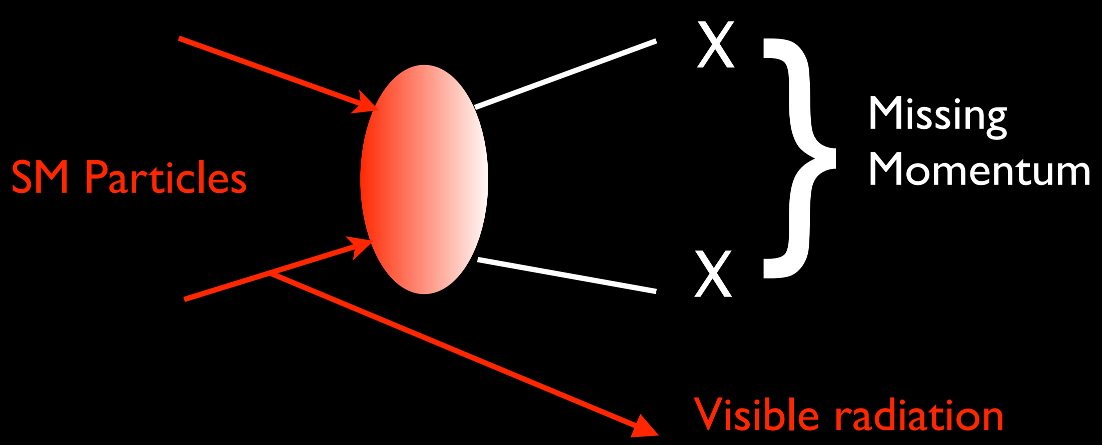
- If dark matter couples to quarks or gluons, we should also be able to produce it at high energy colliders.
- By studying its production in collisions of SM particles, we are seeing the inverse of the process which kept the WIMPs in equilibrium in the early Universe.
- Provided they have enough energy to produce them, colliders may allow us to study other elements of the "dark sector", which are no longer present in the Universe today.



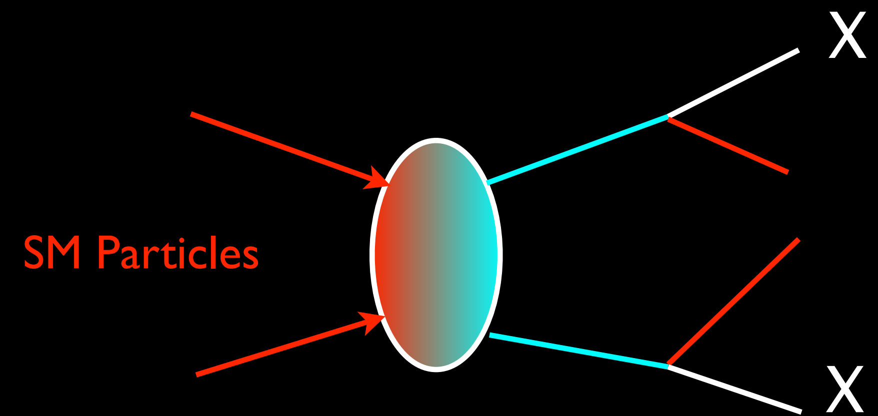
Very sophisticated devices with many, many (many!) subsystems: But no WIMP detectors.

Seeing the Invisible?

- Dark matter is expected to interact so weakly that it is expected to pass through the detector components without any significant interaction, making them effective invisible (much like neutrinos).
- We can try to "see" it nonetheless:



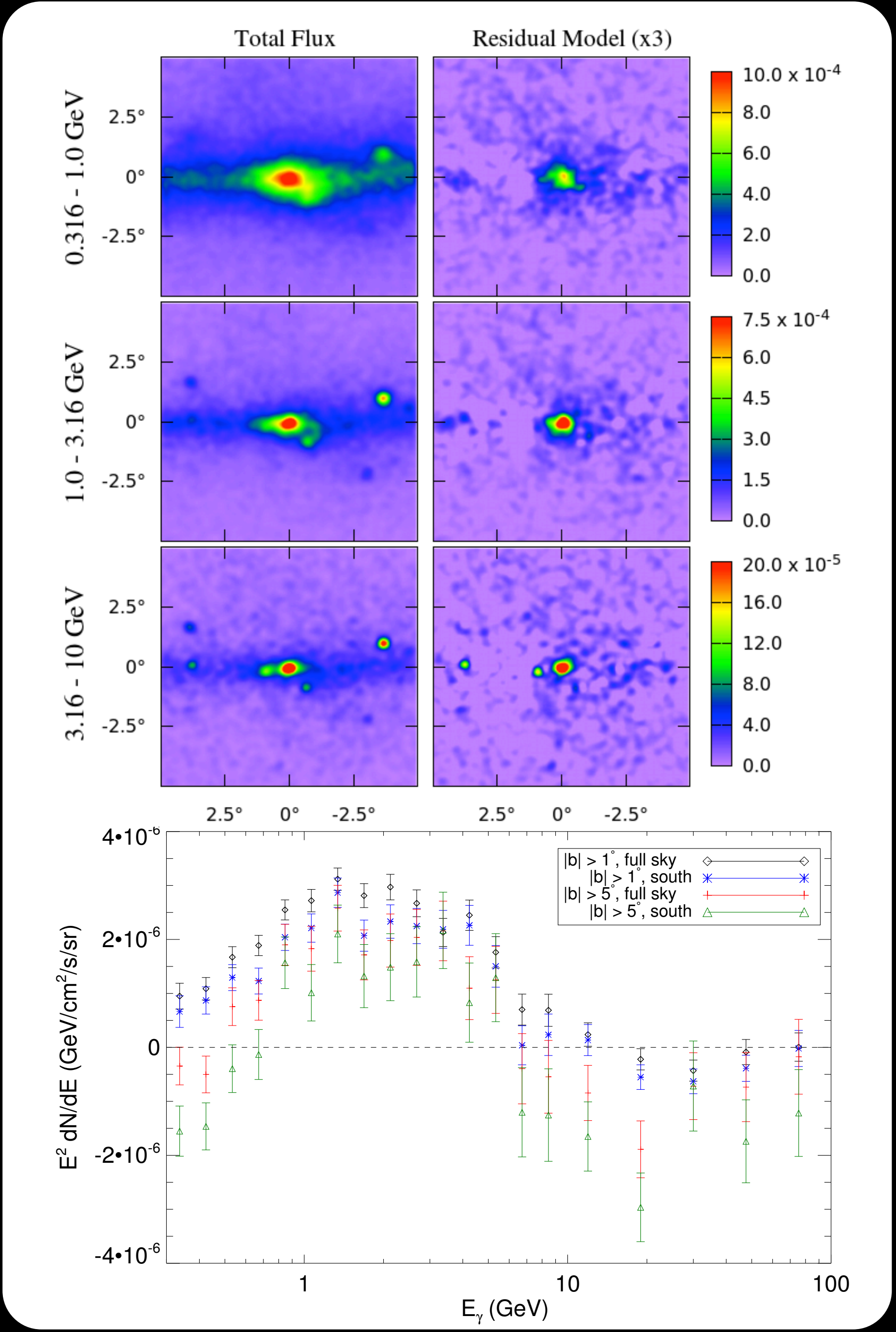
Radiation from the SM side of the reaction.



Production of "partners" which decay into WIMPS + SM particles.

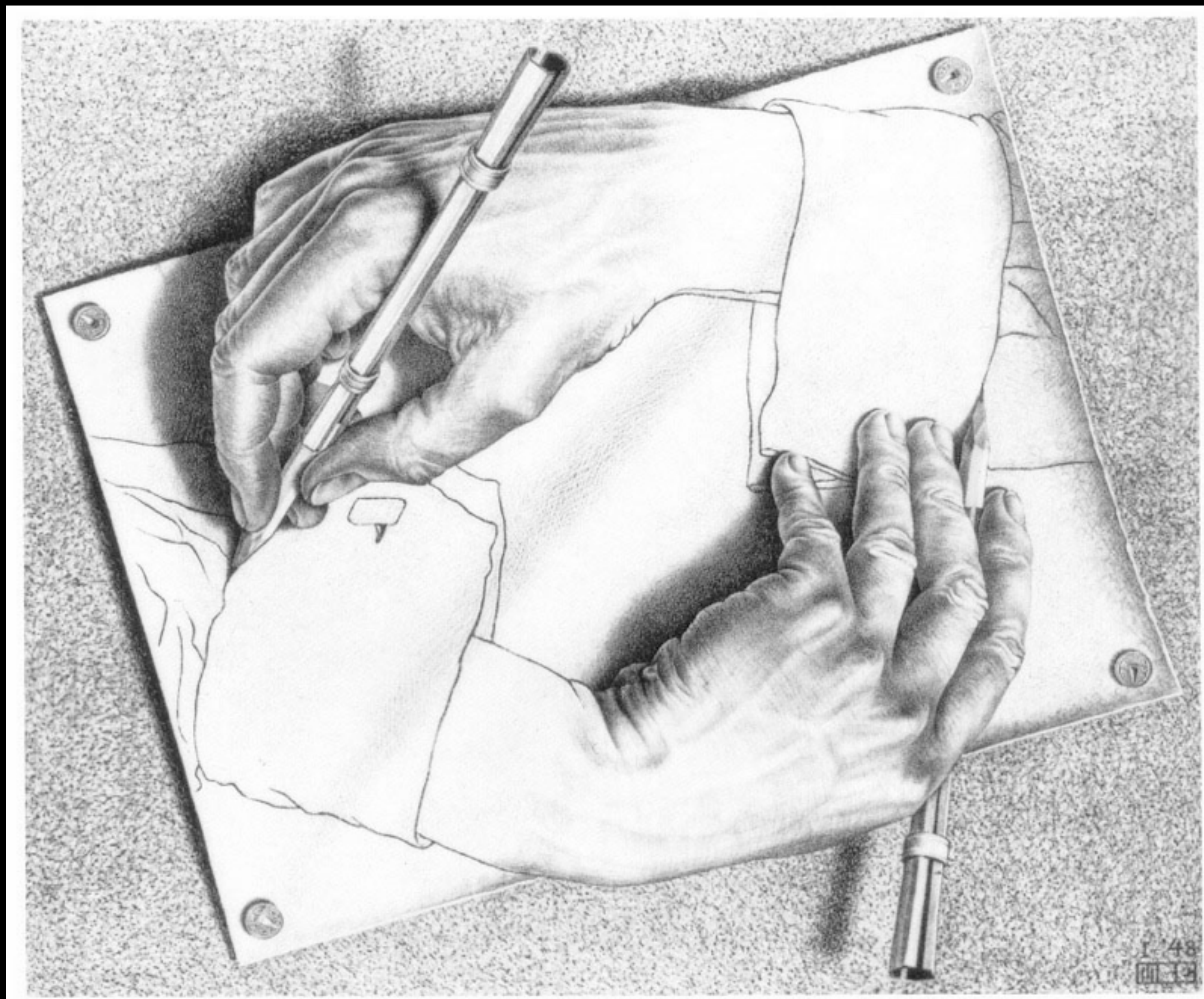
Gamma Ray GeV Excess

- A simplified model allows us to put a (possible) discovery into context and ask what a theory that could explain it should look like.
- As an example: there are hints for what could be a dark matter signal in the Fermi data from the galactic center.
- After subtracting models of the diffuse gamma ray emission, known point sources, etc, an excess remains with a distribution peaking around a few GeV, consistent with the expectations of a 40 GeV dark matter particle annihilating into bottom quarks.



Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, Slatyer 1402.6703
see also: Abazajian, Canac, Horiuchi, Kaplinghat 1402.4090
Talk by Simona Murgia, Fermi Symposium 2014

From Sketch to Life



Sketches of <u>....</u> <u>......</u>