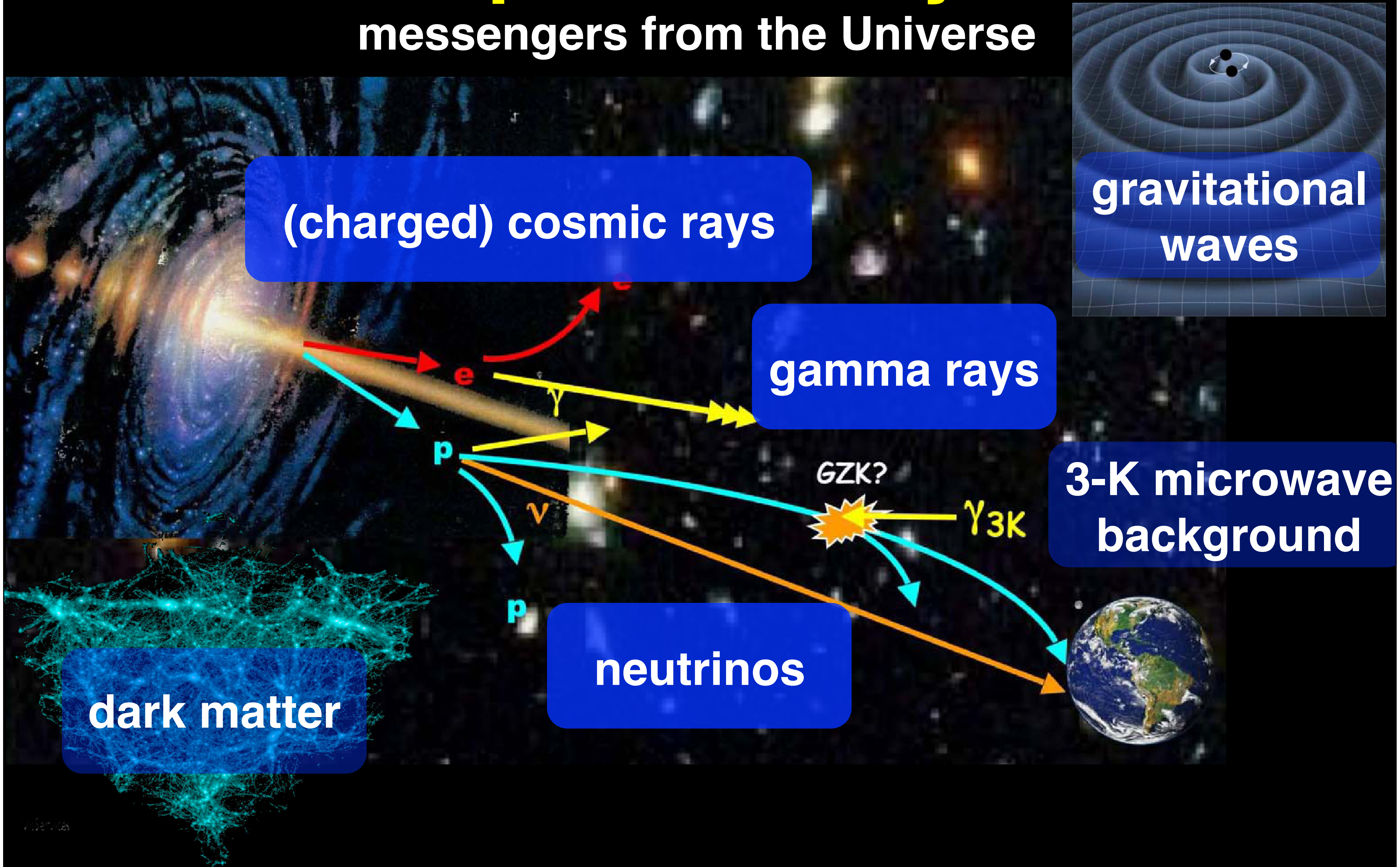
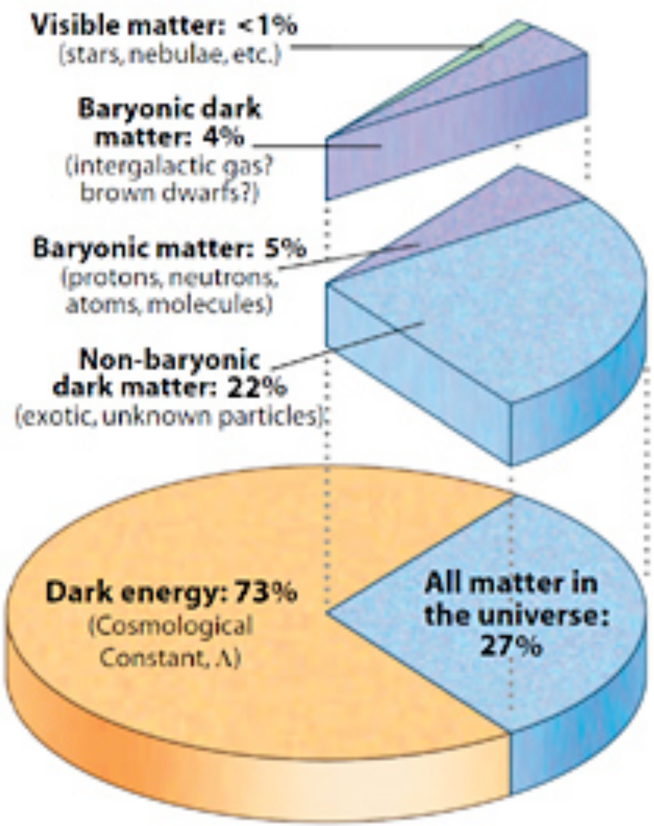
Astroparticle Physics

messengers from the Universe



Dark Matter

Dark matter is a hypothetical form of matter. It has to be postulated to describe phenomenons, which could not be explained by known forms of matter. It has to be assumed that the largest part of dark matter is made out of heavy, slow moving, electric and color uncharged, weakly interacting particles. Such a particle does not exist within the standard model of particle physics. Dark matter makes up 25 % of the energy density of the universe. The true nature of dark matter is still unknown.



Five reasons we think Dark Matter exists

1) Galaxy clusters

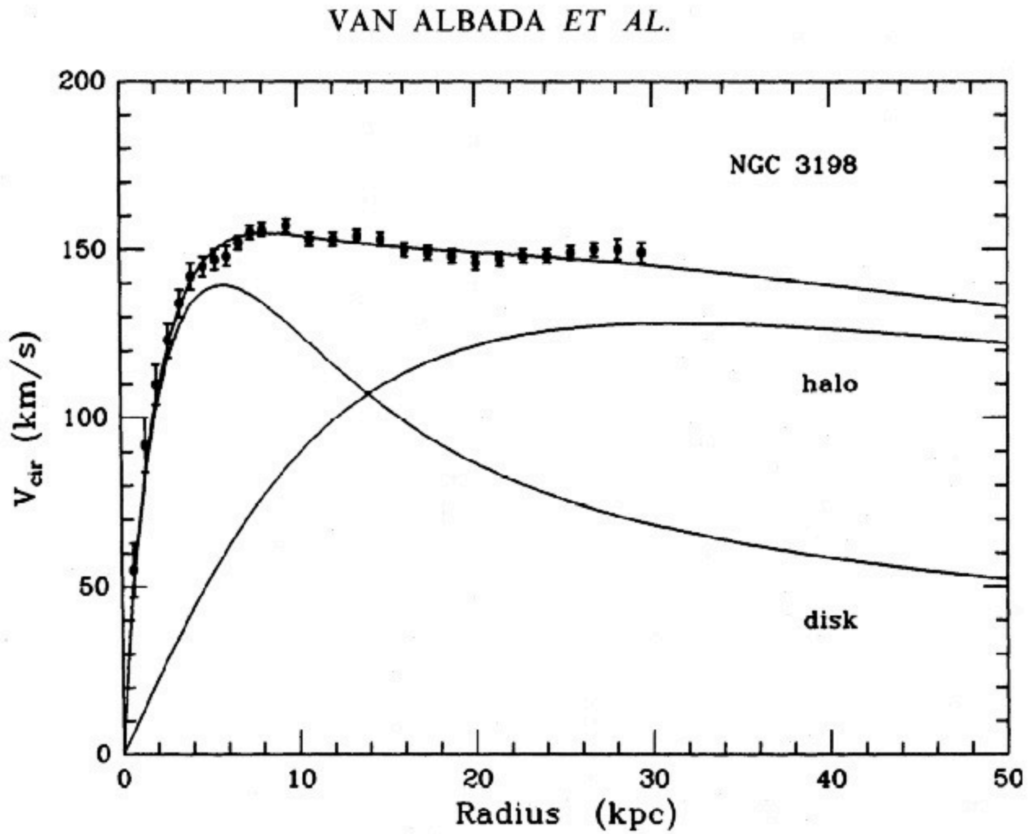
In 1933, Fritz Zwicky (above) was studying the nearest very large cluster of galaxies to us in space: the Coma cluster (left).

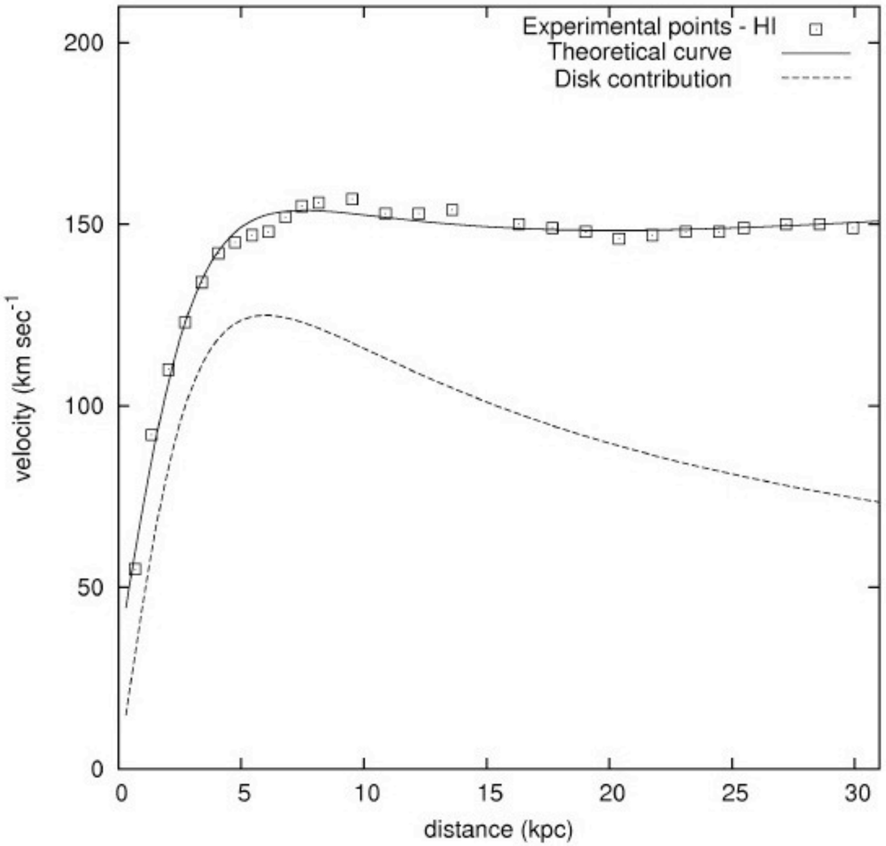
He used the virial theorem, an equation which relates the average kinetic energy of a system to its total potential energy, to infer the gravitational mass of the cluster. He then compared that to the mass inferred from the bright, luminous matter (stars and gas) in the galaxies. You'd expect those two numbers — gravitational mass and mass due to luminous matter — to match, wouldn't you? But instead, he found that the mass from the luminous matter was not enough to keep the cluster bound, and was several times smaller than the inferred gravitational mass. Assuming that the luminous matter constituted all of the mass in each galaxy, they should have been flying apart! He thus coined the term "dark matter" for the material that must therefore be present, quietly holding the galaxy cluster tightly together.

Ethan Siegel

Five reasons we think Dark Matter exists

2) Galactic rotation curves





Similar evidence was observed within galaxies themselves. From standard Newtonian dynamics, we expect the velocity of stars to fall as you move from the near the center of mass of a galaxy to its outer edges. But when studying the Andromeda galaxy in the 1960s, Vera Rubin and Kent Ford found something very different: the velocity of stars remained approximately constant, regardless of how far they were from the galactic center.

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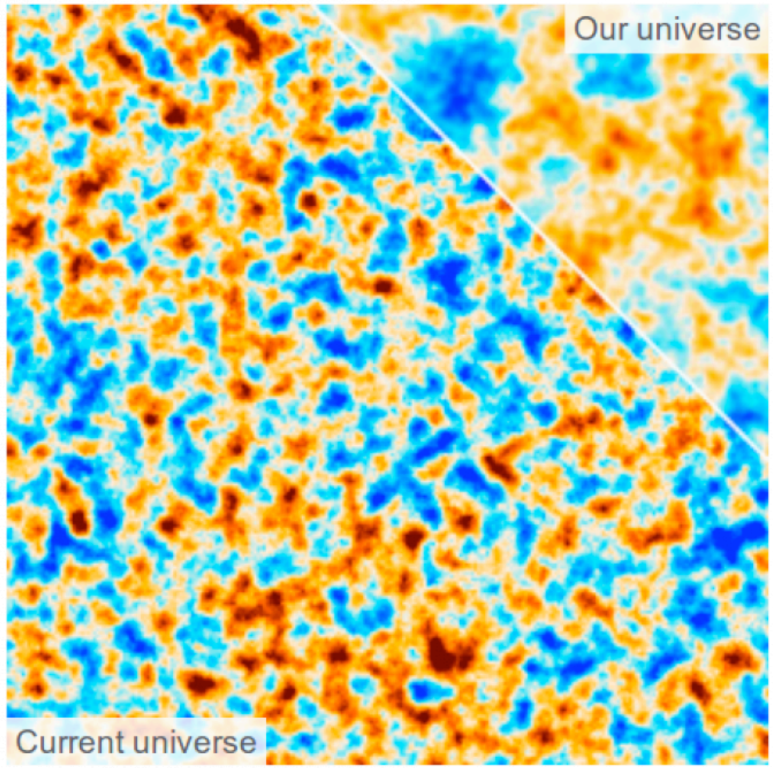
Five reasons we think Dark Matter exists

3) The cosmic microwave background

The Cosmic Microwave Background (CMB) is the earliest photograph of our Universe. The patterns that we see in observations of the CMB were set up by competition between two forces acting on matter; the force of gravity causing matter to fall inward and an outward pressure exerted by photons (or particles of light). This competition caused the photons and matter to oscillate into-and-out-of dense regions. But if the Universe consisted partially of *dark matter* in addition to normal matter, that pattern would be affected dramatically. The existence of dark matter leaves a characteristic imprint on CMB observations, as it clumps into dense regions and contributes to the gravitational collapse of matter, but is unaffected by the pressure from photons.



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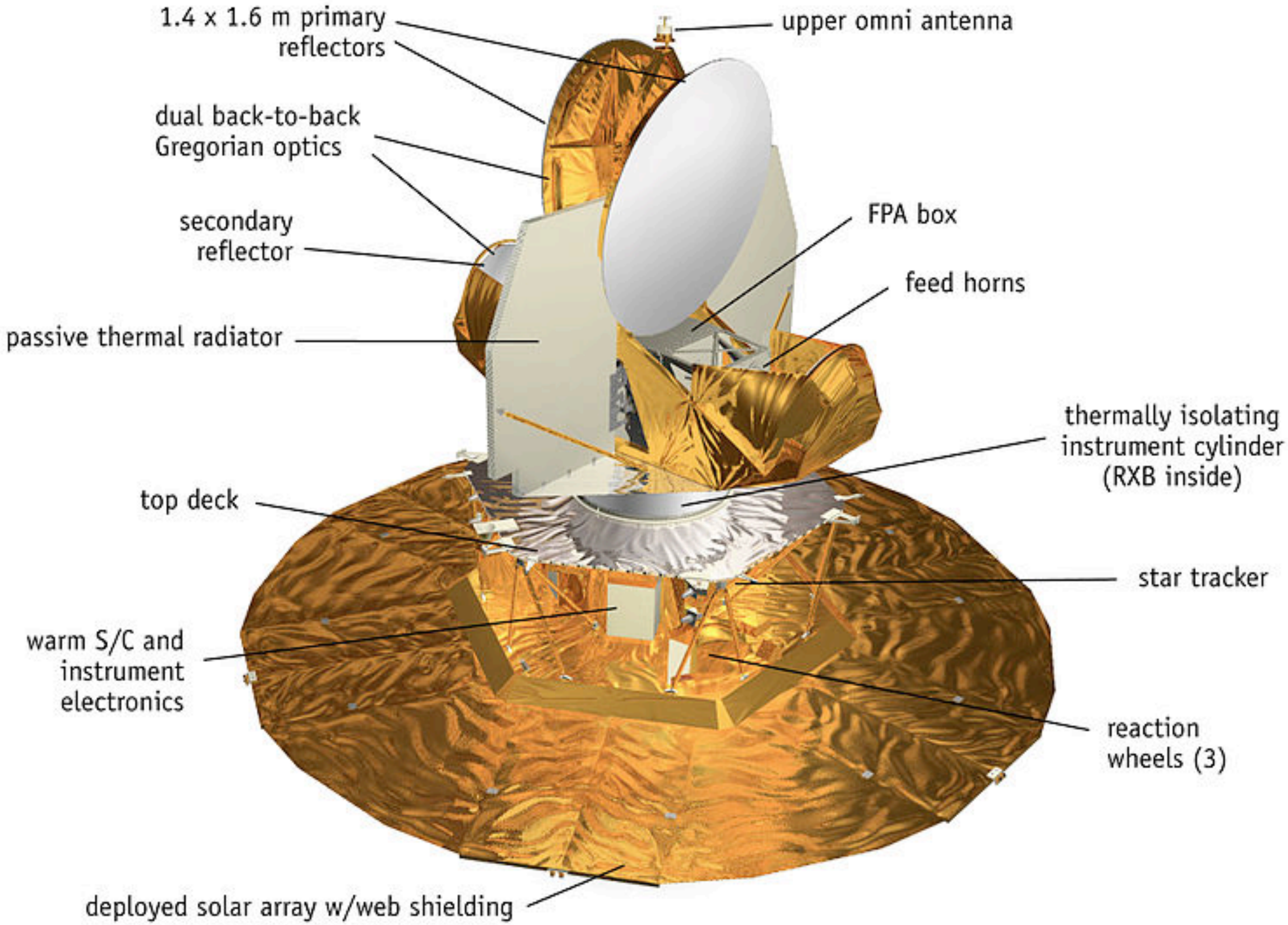
Five reasons we think Dark Matter exists

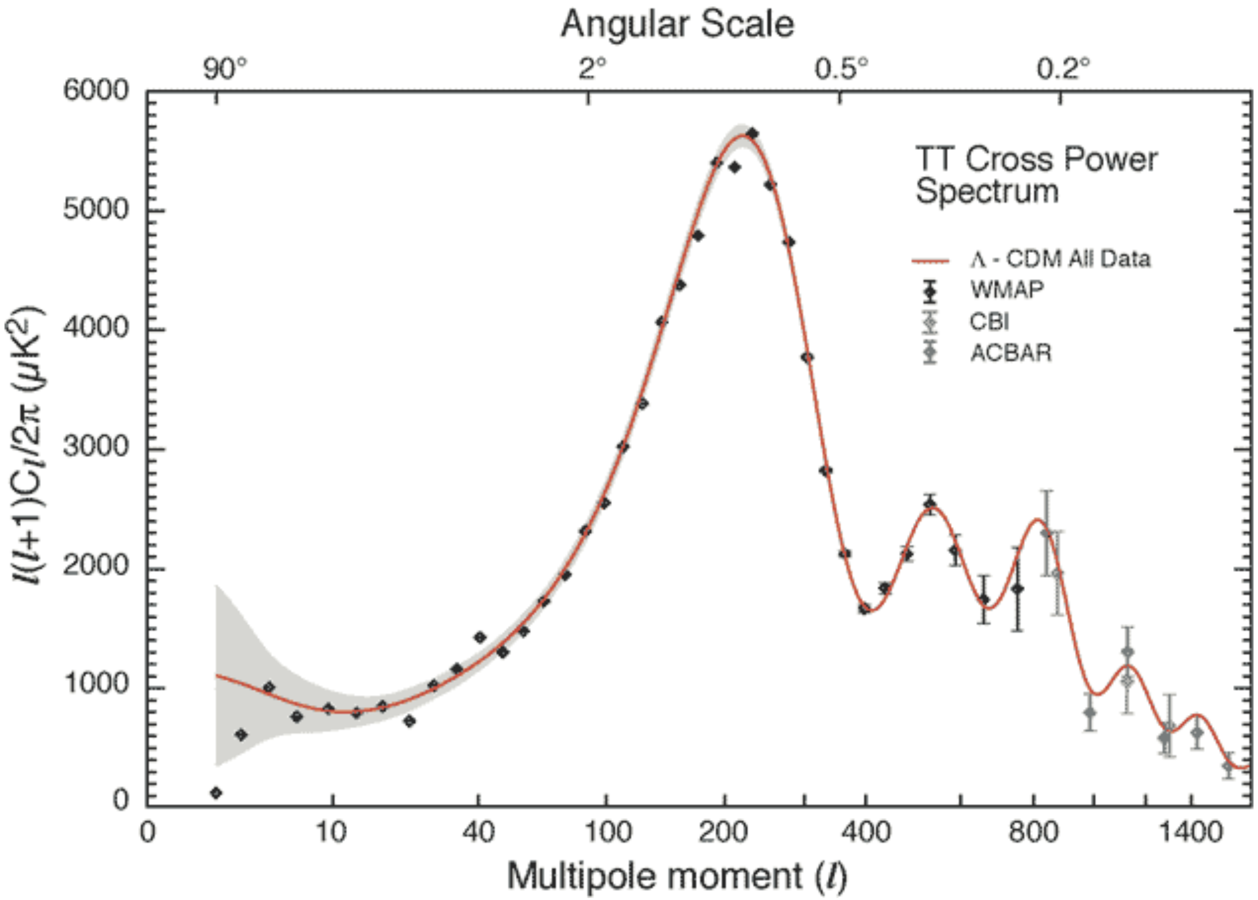
3) The cosmic microwave background



Five reasons we think Dark Matter exists

3) The cosmic microwave background

We can predict these oscillations in the CMB with and without dark matter, which we often present in the form of a *power spectrum*. The power spectrum of the CMB shows us the strength of oscillations at different sizes of the photons and matter. The Wilkinson Microwave Anisotropy Probe (WMAP) was the first instrument to measure the CMB power spectrum through the first peak of oscillations, and showed that the existence of dark matter is favored.



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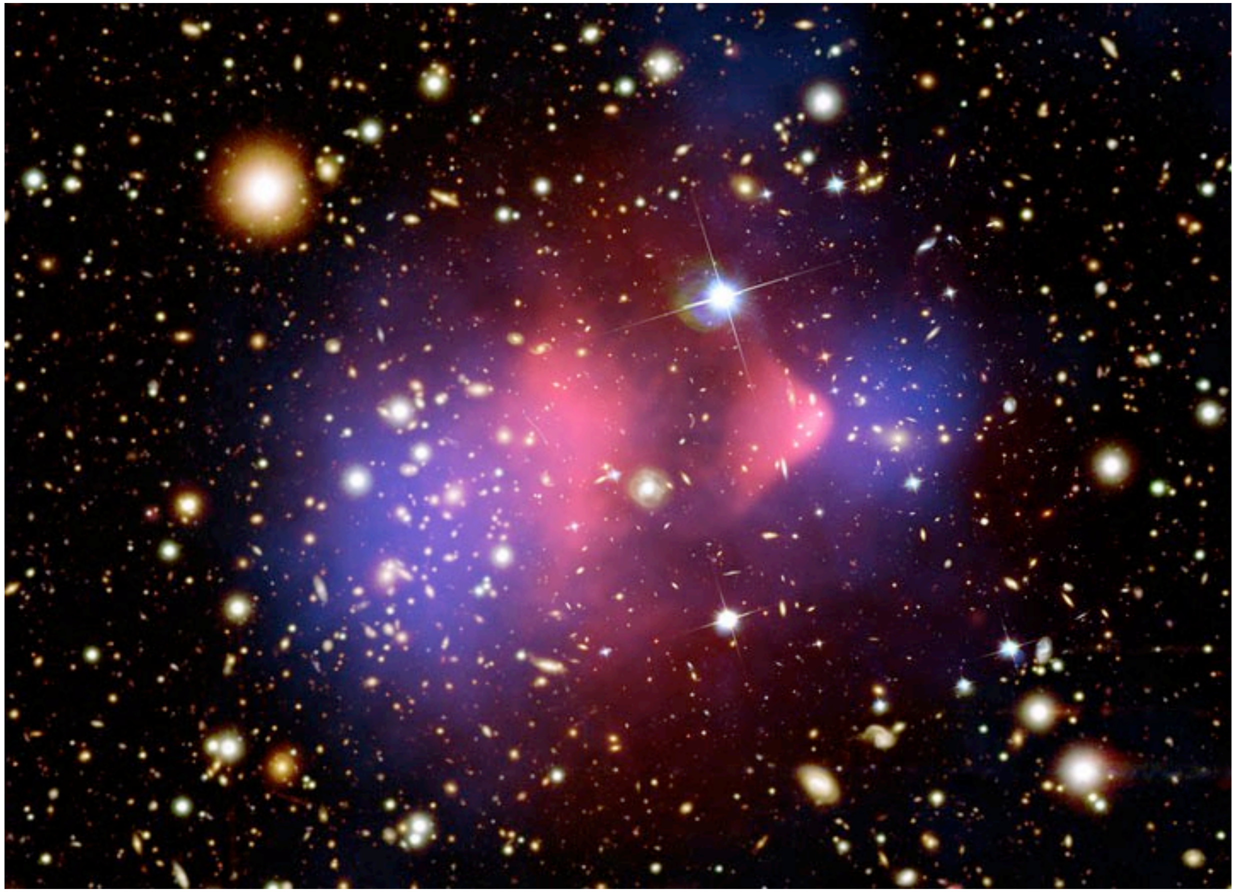
Five reasons we think Dark Matter exists

4) The Bullet cluster



In 2006, astronomers working on the Hubble Space Telescope and the Chandra X-ray Observatory released exciting information about an object known as the bullet cluster. This cluster is actually two galaxy clusters which have recently undergone a high-speed collision, forcing the contents of each cluster to merge together. Observations from the two telescopes allowed us to measure the location of the cluster mass after the collision using two methods: optical observations of X-ray emission and gravitational lensing.

One way we can tell two clusters have just collided is through X-ray astronomy. An extremely hot gas of particles pervades the space between each galaxy in a cluster, which accounts for for about 90% of the mass from ordinary matter (rather than stars). When two galaxy clusters collide, the gas particles become even hotter from crashing into each other, causing an increase in brightness of the X-ray emission. From this we can tell how energetic the gas is and where it is located.

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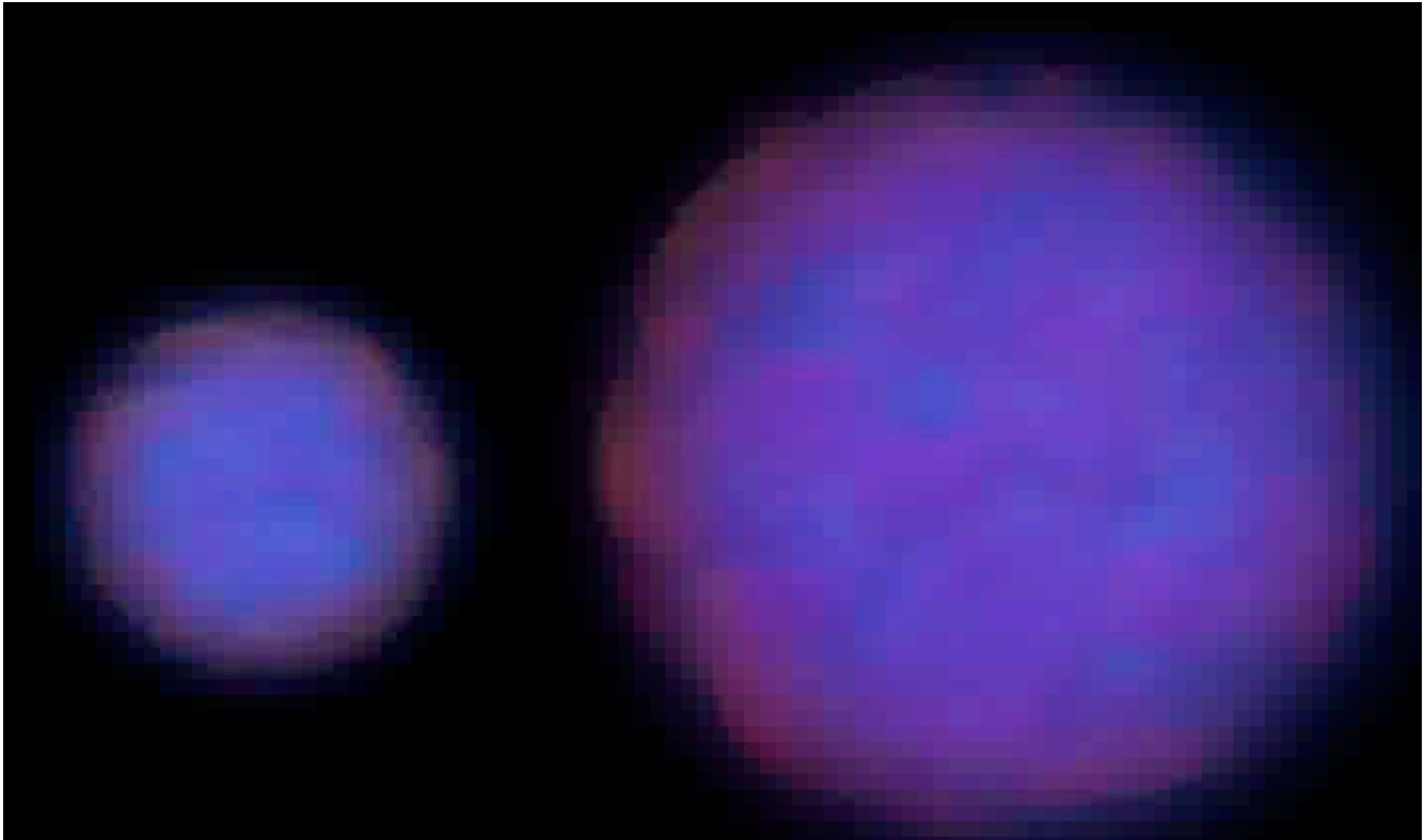
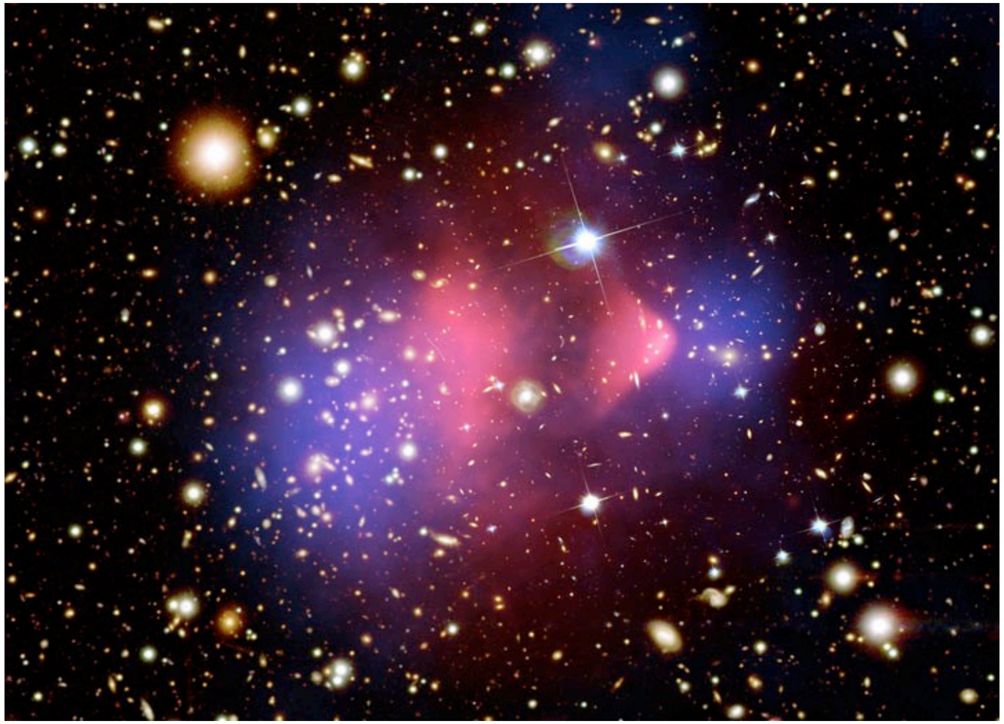


This animation shows an artist's representation of the huge collision in the bullet cluster. Hot gas, containing most of the normal matter in the cluster, is shown in red and dark matter is in blue. During the collision the hot gas in each cluster is slowed and distorted by a drag force, similar to air resistance. A bullet-shaped cloud of gas forms in one of the clusters. In contrast, the dark matter is not slowed by the impact, because it does not interact directly with itself or the gas except through gravity, and separates from the normal matter. The animation ends by dissolving into an image showing the hot gas seen with Chandra (pink) and the cluster mass as inferred by gravitational lensing (blue), which is mostly dark matter.

Five reasons we think Dark Matter exists

4) The Bullet cluster



Gravitational lensing occurs because matter isn't the only thing that feels the effects of gravity: light does as well. This means that a massive object can act as a lens; a background source that emits light in all directions will have some of that light focused if it passes by a massive object. By measuring these focused images, we can infer the location and mass of the lens between us and the source.

If the clusters were entirely comprised of ordinary matter, the location of mass from the optical observations and the location calculated from gravitational lensing in the bullet cluster should overlap. Instead, the observations showed a glaring inconsistency. The optically visible matter told us the mass should be concentrated near the center of the image shown, highlighted in red. The mass distribution from gravitational lensing, highlighted in blue, shows that the concentration of mass is actually in two pieces, just outside of the luminous matter in the galaxy! Invoking dark matter, this behavior is easy to explain as follows:

a.) Dark matter interacts with its surroundings significantly less frequently than ordinary matter.
b.) During the cluster collision, the dark matter of one cluster would have slipped through all of the objects in the other cluster with relative ease.
c.) The luminous matter, on the other hand, would have bounced off of other particles around it, causing it to slow and separate from the dark matter.

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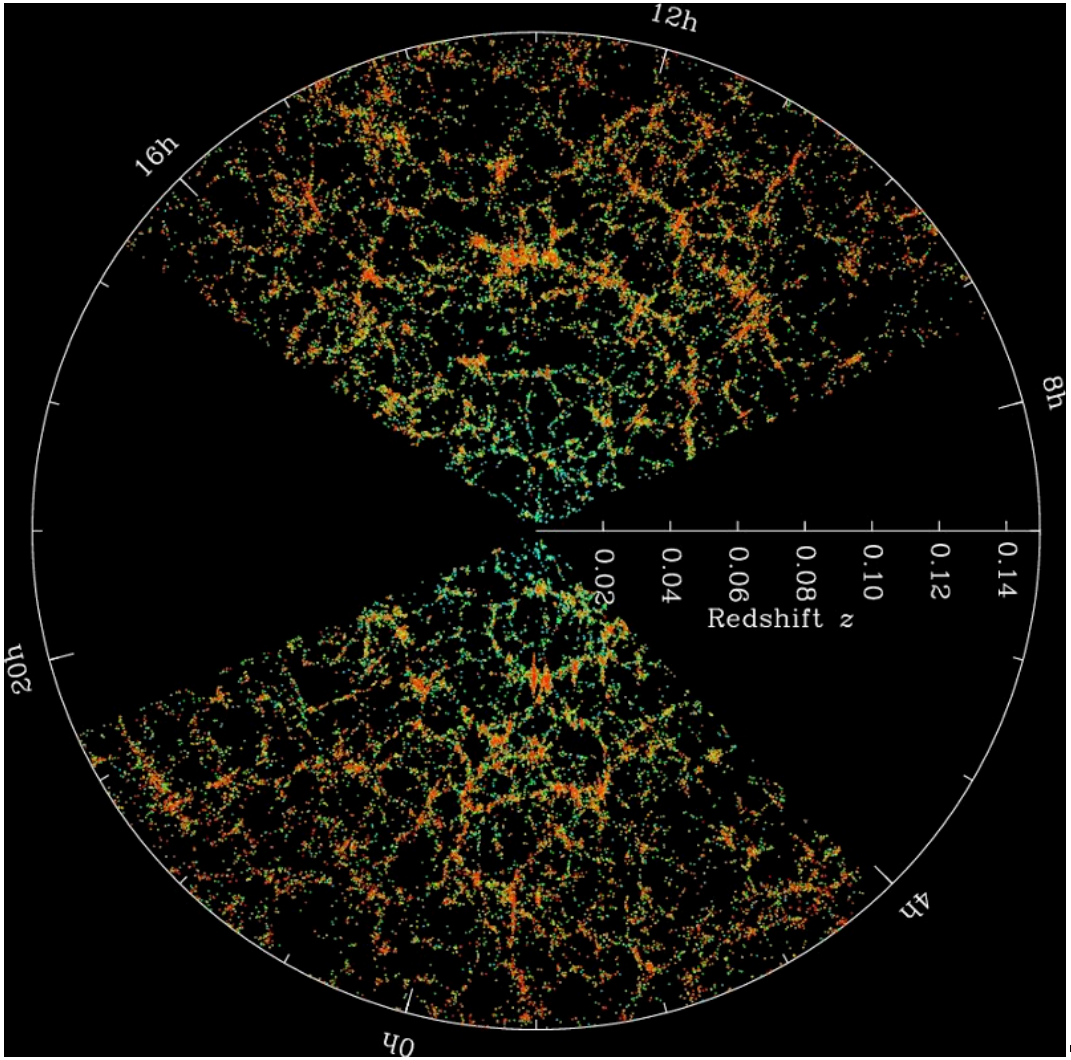
Five reasons we think Dark Matter exists

5) Large-scale structure formation

When telescopes like the Sloan Digital Sky Survey map the locations the galaxies in the Universe, with the biggest features being referred to as large-scale structure, it sees a set of patterns that *couldn't* happen with only the gravity due to ordinary matter at work. We know that before the CMB, ordinary matter wasn't able to efficiently clump into dense objects due to the oscillations from the competing forces of gravity and pressure from radiation. The structure we observe is much more advanced in its evolution given the amount of time available for objects to gravitationally collapse after the time of the CMB.



Instead, dark matter provides a reasonable explanation. Because dark matter didn't undergo the same oscillations with matter and light, it was free to collapse on its own to form dense regions that helped structure formation get a head start, and allowed the distribution of galaxies and clusters to be what we observe today.

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These five independent pieces of evidence, when taken all together, provide a compelling reason that dark matter must exist. Reading through each explanation again, there is a common theme: gravity. Each piece of the puzzle relies on the way dark matter affects things around it via the gravitational force.

An Alternative

Since we haven't measured it directly yet, and the evidence for dark matter's existence centers on its gravitational interactions, a responsible scientific community would ask "what if we just don't understand gravity as well as we think we do?"
Some research groups have been tackling that question, investigating theories like MOND (MOdified Newtonian Dynamics), which are often grouped together under the umbrella "modified gravity." So far, these theories have had successes in describing one of these peculiarities: galactic rotation curves, but have not yet provided an explanation for the complete set of observations like dark matter does.

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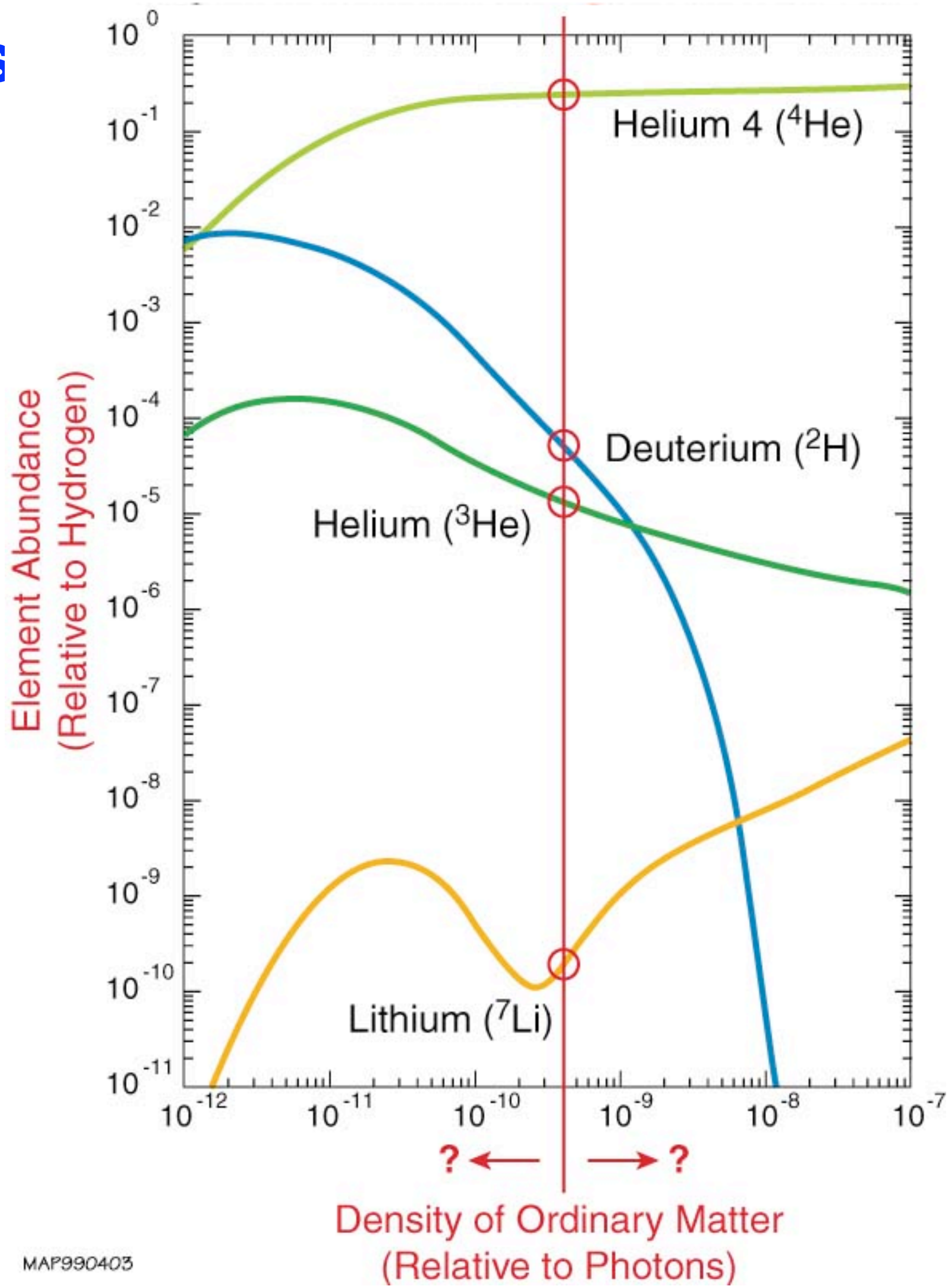
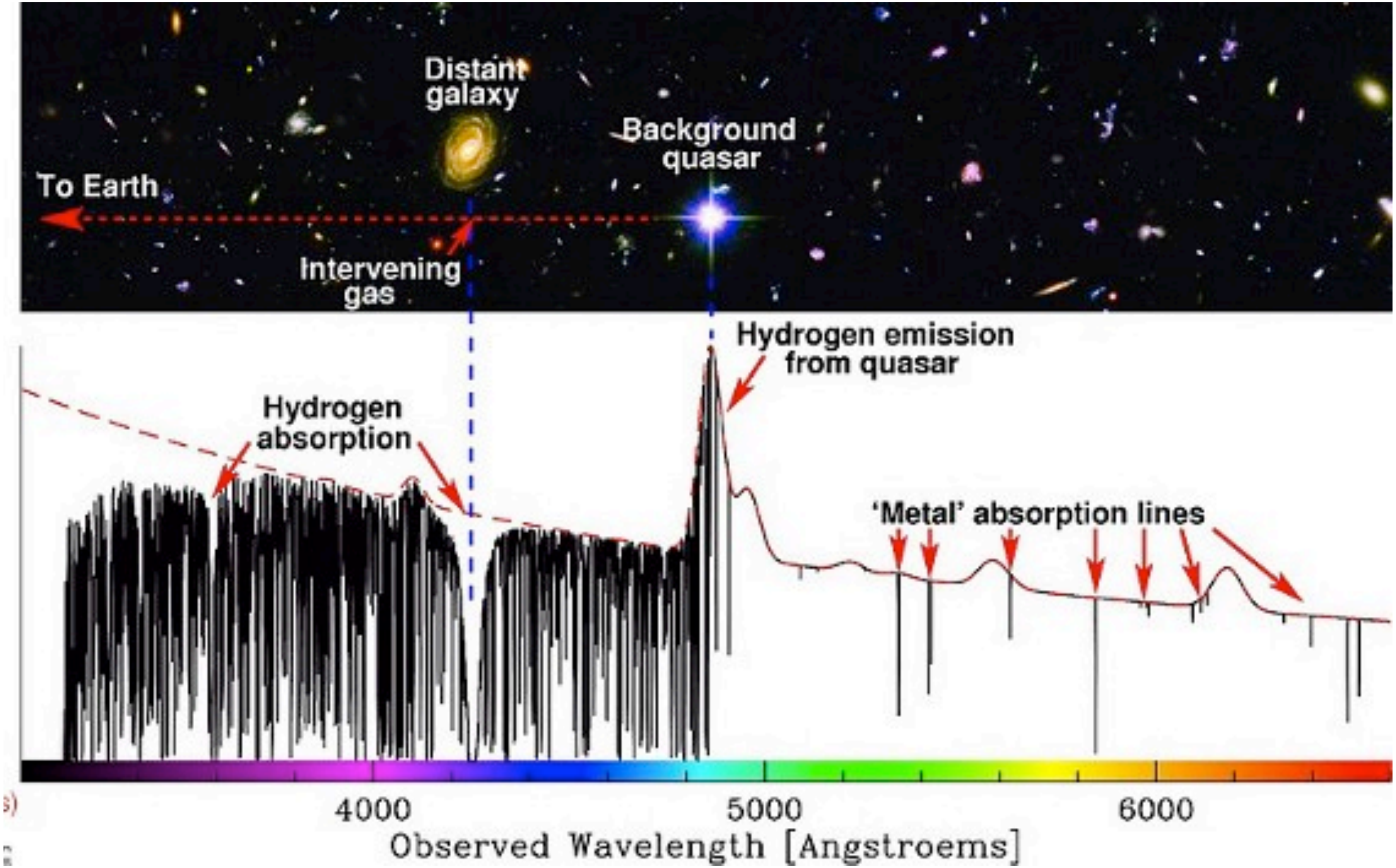
Big-Bang nucleosynthes

These five reasons don't constitute the total observational evidence we have for dark matter. Big Bang Nucleosynthesis (BBN), which explains the way light elements such as Helium were formed fractions of a second after the Big Bang, tells us abundance of baryonic matter doesn't account for the total matter content of the Universe inferred from other observations, and that dark matter can't be just be things like protons and neutrons.



Light absorption by molecular clouds

Observations of molecular clouds — neutral hydrogen gas — absorbing light from background galaxies and quasars, known as the Lyman-alpha forest, gives us information about the location of dark matter clumps as well as how much energy dark matter particles are allowed to have.



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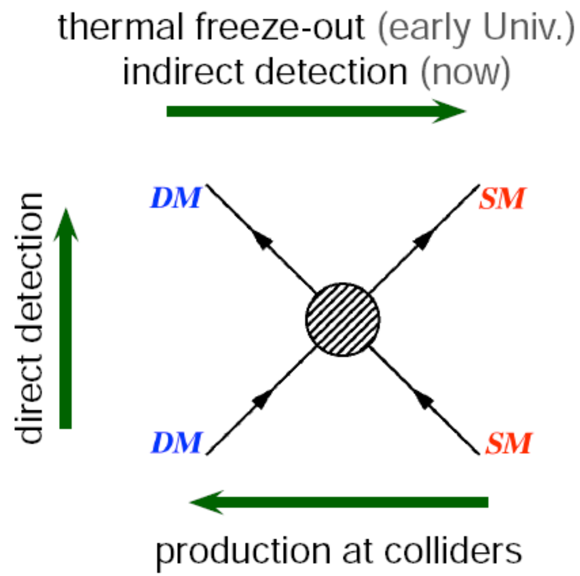
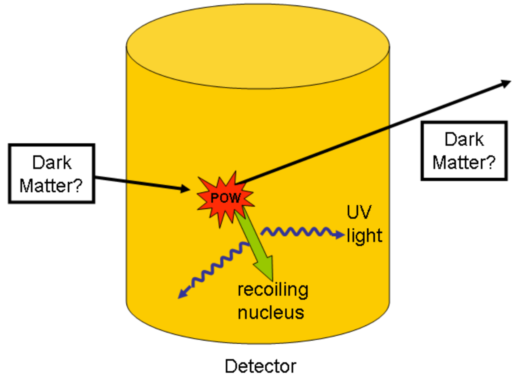
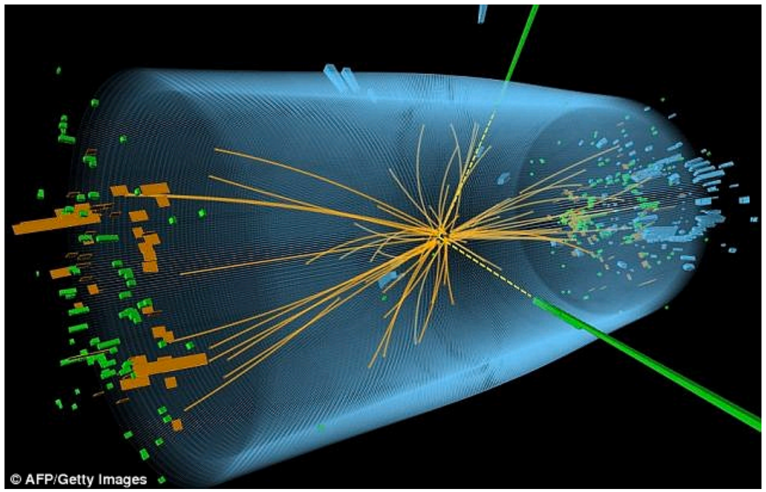
How to find DM?
What do we know?

The hunt for dark matter particles

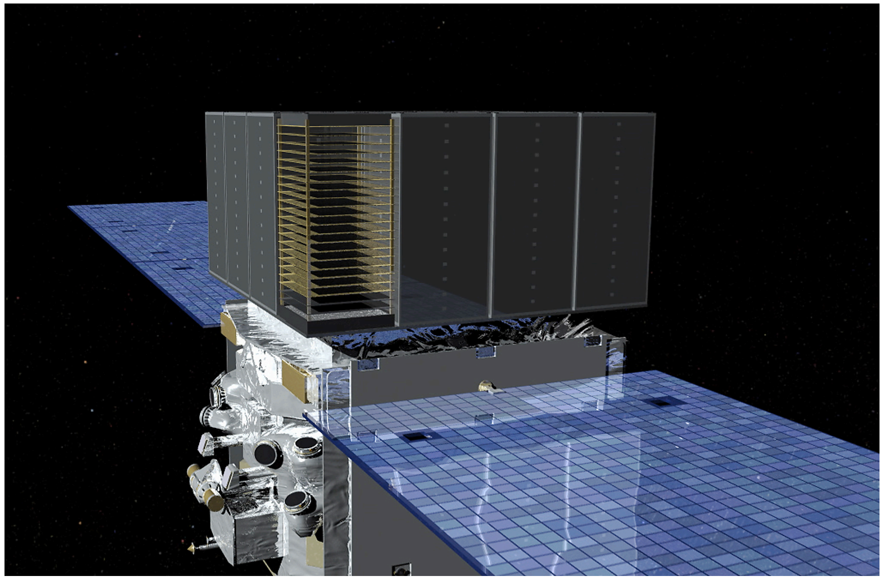


direct searches





collider searches



indirect searches

We don't know yet what DM is... but we do know many of its properties

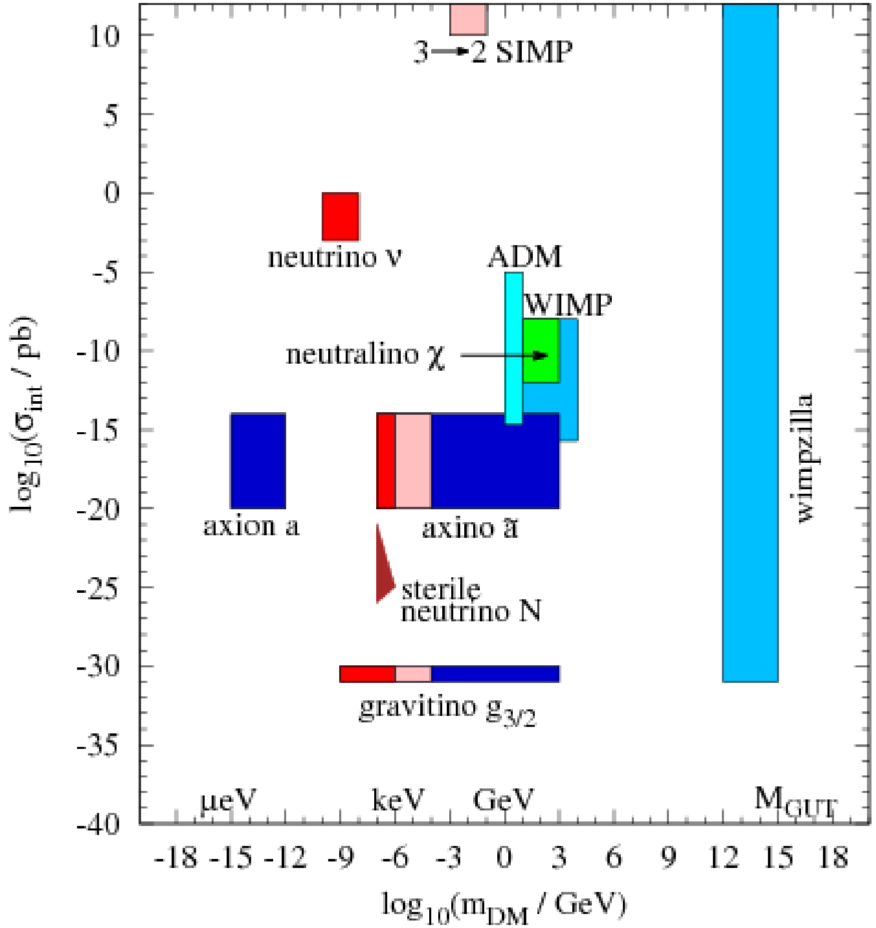
Good candidates for Dark Matter have to fulfil the following conditions

- Neutral
- Stable on cosmological scales
- Reproduce the correct relic abundance
- Not excluded by current searches
- No conflicts with BBN or stellar evolution

Many candidates in Particle Physics

- Axions
- Weakly Interacting Massive Particles (WIMPs)
- SuperWIMPs and Decaying DM
- WIMPzillas
- Asymmetric DM
- SIMPs, CHAMPs, SIDMs, ETCs...

Baer et al. 2014



... they have very **different** properties

Current challenges for DARK MATTER

- **Experimental detection:**
  Does DM feel other interactions apart from Gravity?
  Is the Electro-Weak scale related somehow related to DM?
  How is DM distributed?

- **Determination of the DM particle parameters:**
  Mass, interaction cross section, etc…

- **What is the theory for Physics beyond the SM:**
  DM as a window for new Physics
  Can we identify the DM candidate?

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Supersymmetry is a well motivated extension of the SM

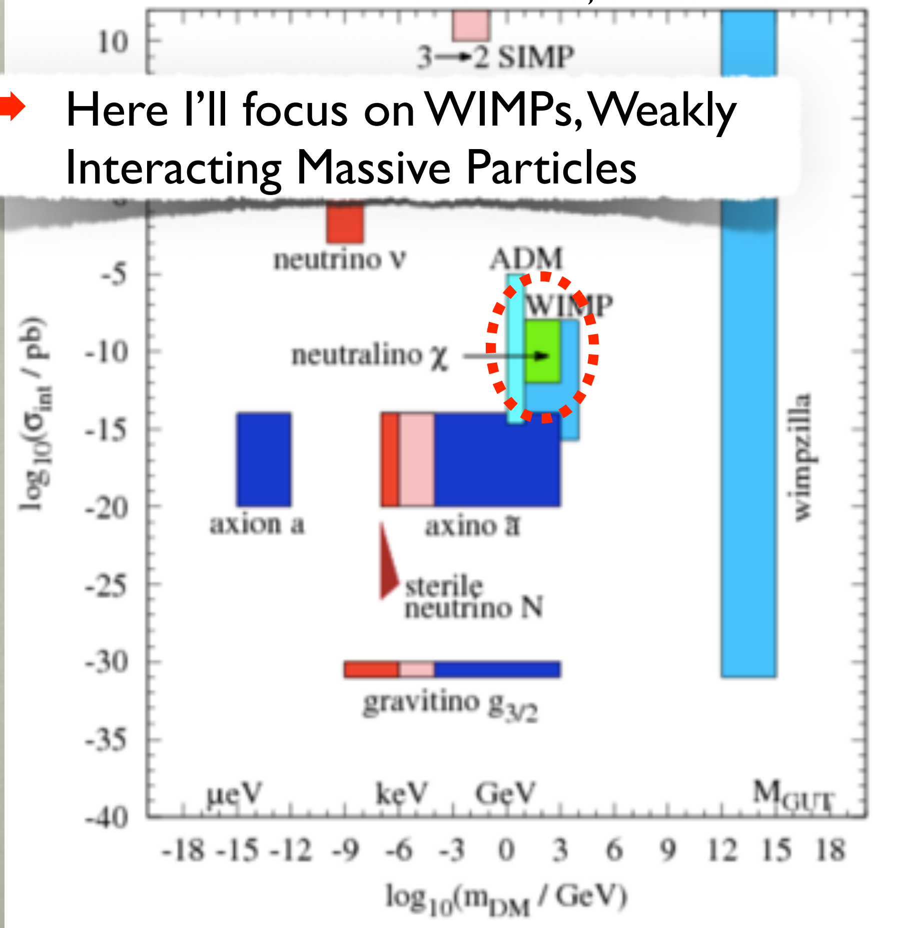
- **Solution to the hierarchy problem?** Low mass Higgs with SM-like couplings

- **Dark Matter candidates**

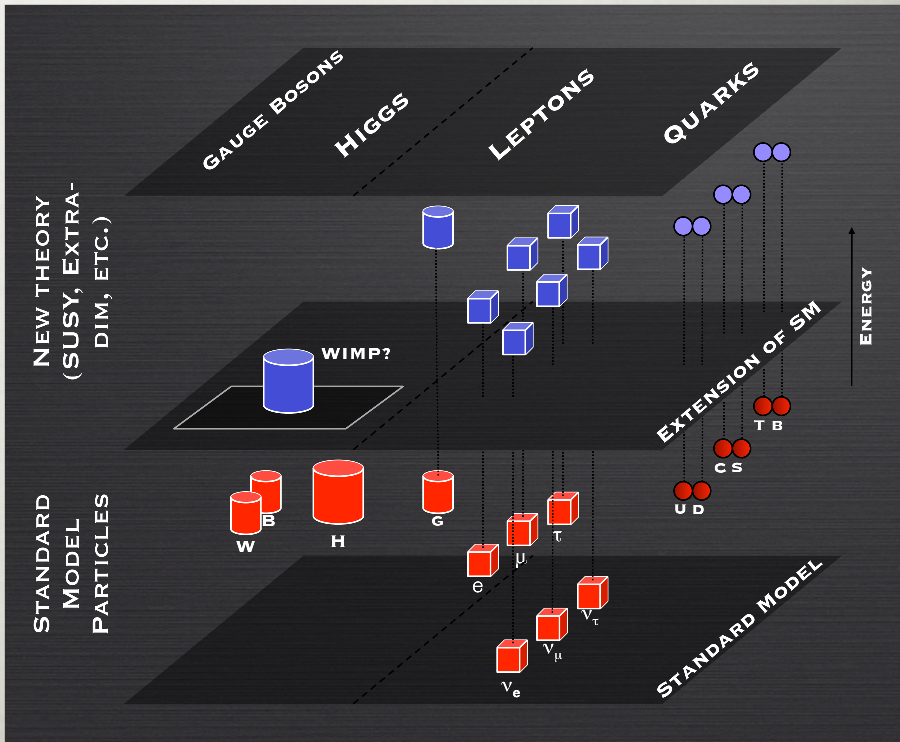
Dark Matter Candidates

- Several beyond the Standard Model of particle physics scenarios have been proposed that naturally predict the existence of new particles that are excellent dark matter candidates

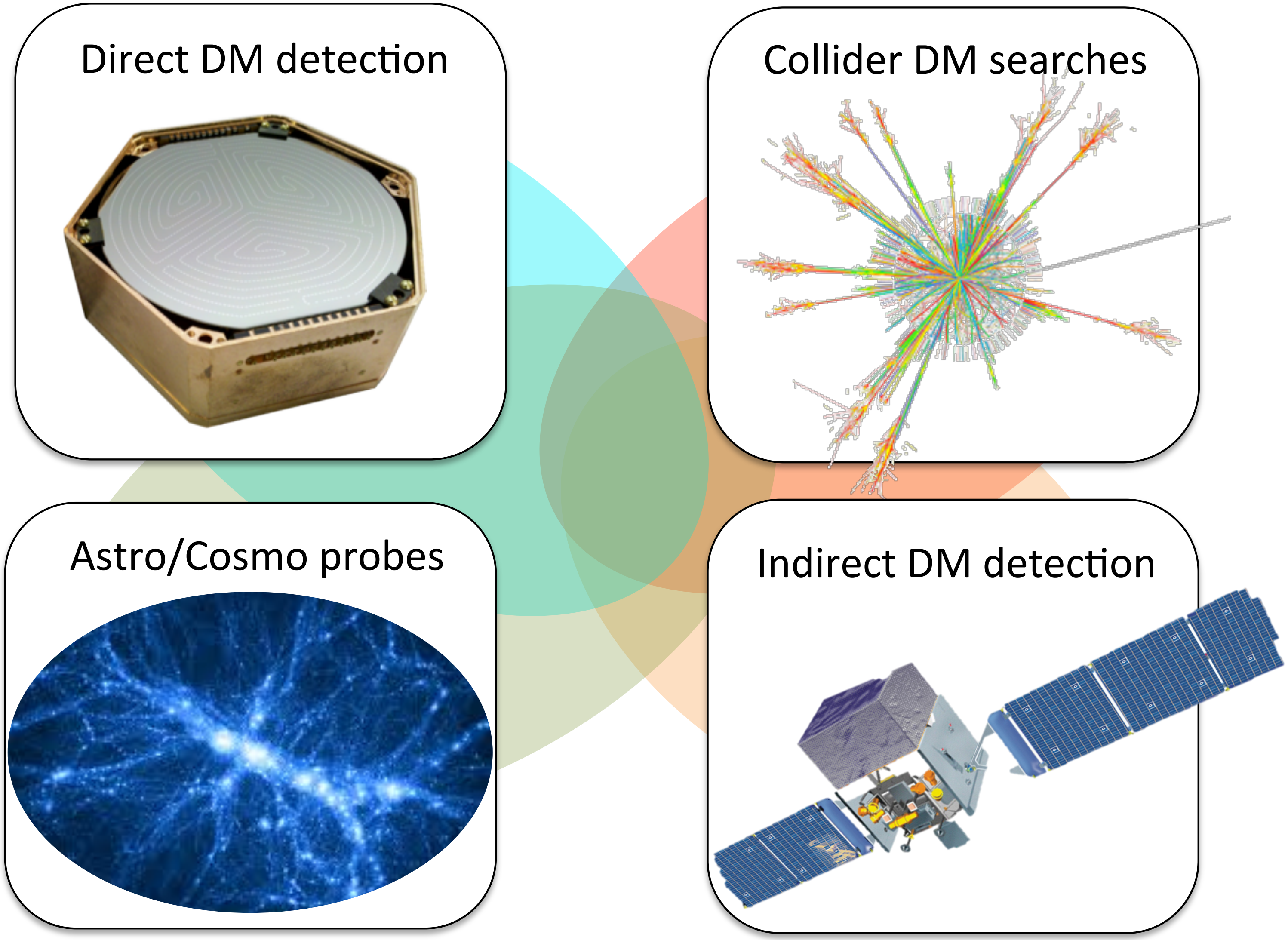
H. Baer et al, arXiv:1407.0017



Here I'll focus on WIMPs, Weakly Interacting Massive Particles

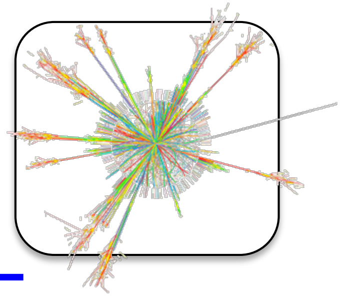


Dark matter MUST BE searched for in different ways…

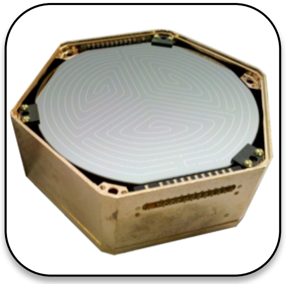


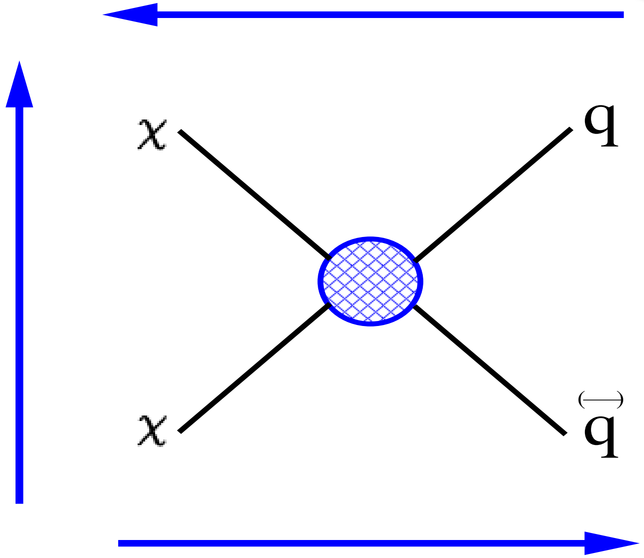
... probing DIFFERENT aspects of their interactions with ordinary matter

Accelerator Searches (production)



Direct Detection
(scattering)

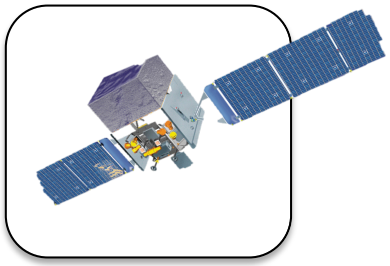




Constraints in one sector affect observations in the other two.

"**Redundant**" detection can be used to extract DM properties.

Indirect Detection
(annihilation or decay)



In the past ~20 yrs we have had numerous potential signatures for DM. Some remain unexplained while many have been attributed to backgrounds or statistical fluctuations.

These are shaping our theoretical approach to the DM problem making us look in (often conflicting) directions

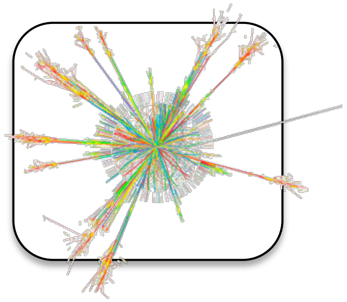
Astro/Cosmo Probes

Warm DM (Simulations)

Self-interacting DM

3.5 keV line

LHC



Diphoton at 750 GeV

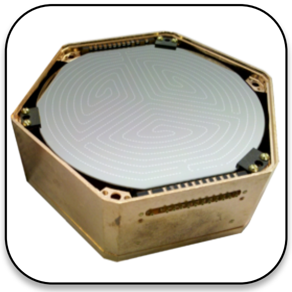
Indirect Detection

PAMELA-AMS

Fermi-LAT:
- Galactic Centre
- 135 gamma line

511 eV emission

Direct Detection



DAMA annual modulation

Low-mass craze (CDMS, CoGeNT, CRESST)

A Tentative Gamma-Ray Line from Dark Matter Annihilation at the Fermi Large Area Telescope

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Abstract. The observation of a gamma-ray line in the cosmic-ray fluxes would be a smoking-gun signature for dark matter annihilation or decay in the Universe. We present an improved search for such signatures in the data of the Fermi Large Area Telescope (LAT), concentrating on energies between 20 and 300 GeV. Besides updating to 43 months of data, we use a new data-driven technique to select optimized target regions depending on the profile of the Galactic dark matter halo. In regions close to the Galactic center, we find a 4.6σ indication for a gamma-ray line at $E_\gamma \approx 130$ GeV. When taking into account the look-elsewhere effect the significance of the observed excess is 3.2σ. If interpreted in terms of dark matter particles annihilating into a photon pair, the observations imply a dark matter mass of $m_\chi = 129.8 \pm 2.4^{+7}_{-13}$ GeV and a partial annihilation cross-section of $\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma} = \left(1.27 \pm 0.32^{+0.18}_{-0.28}\right) \times 10^{-27}$ cm^3 s^{-1} when using the Einasto dark matter profile. The evidence for the signal is based on about 50 photons; it will take a few years of additional data to clarify its existence.

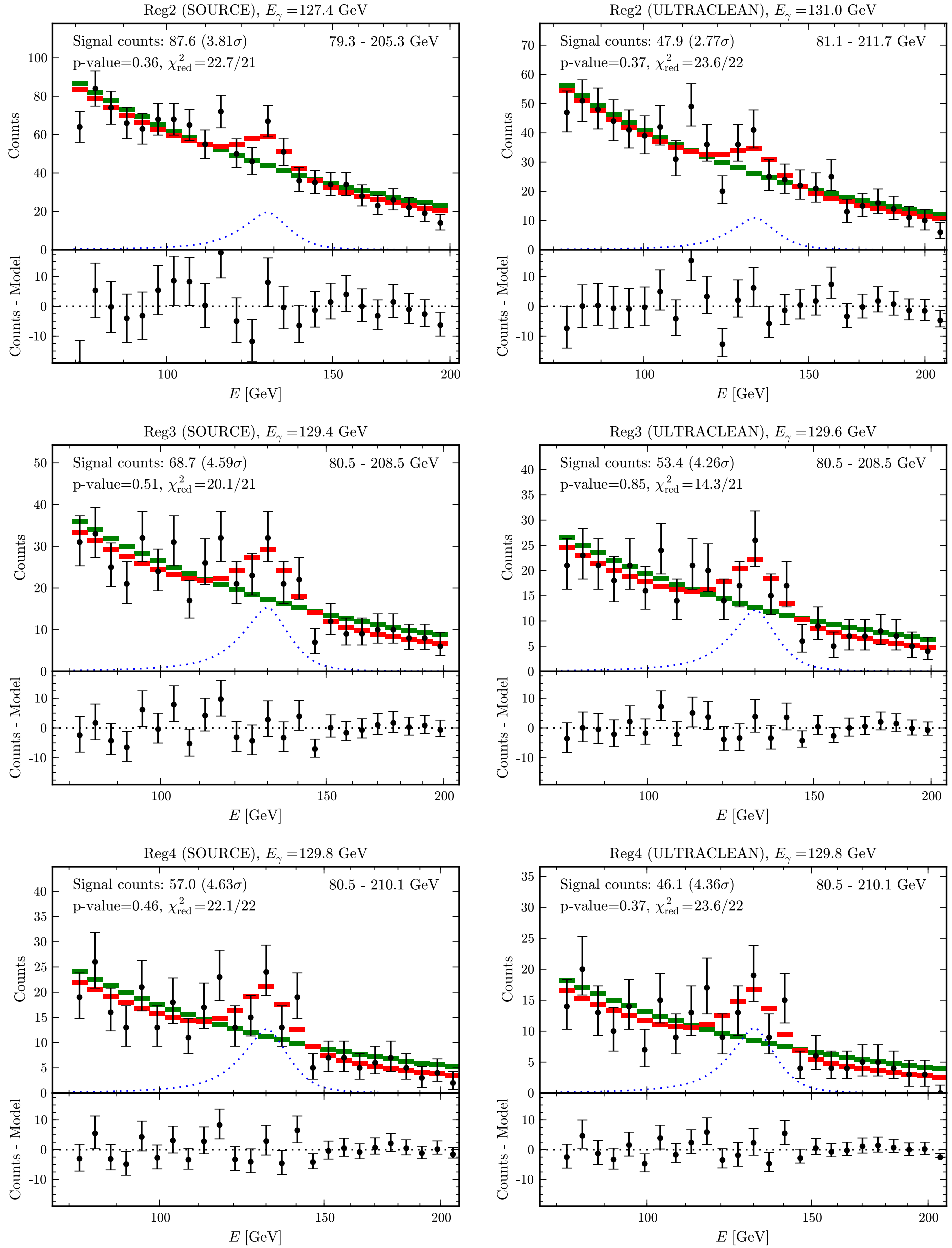
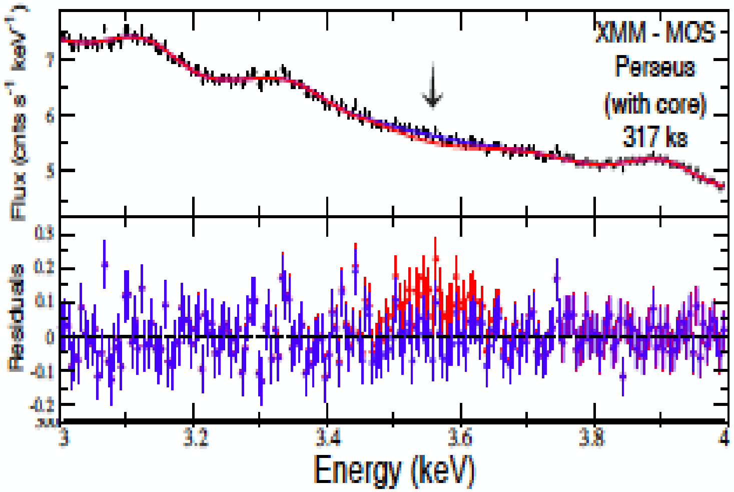


Figure 4. *Upper sub-panels:* the measured events with statistical errors are plotted in *black*. The *horizontal bars* show the best-fit models with (*red*) and without DM (*green*), the *blue dotted line* indicates the corresponding line flux component alone. In the *lower sub-panel* we show residuals after subtracting the model with line contribution. Note that we rebinned the data to fewer bins after performing the fits in order to produce the plots and calculate the p-value and the reduced $\chi^2_r \equiv \chi^2/\text{dof}$. The counts are listed in Tabs. 1, 2 and 3.

The 3.5 keV Line

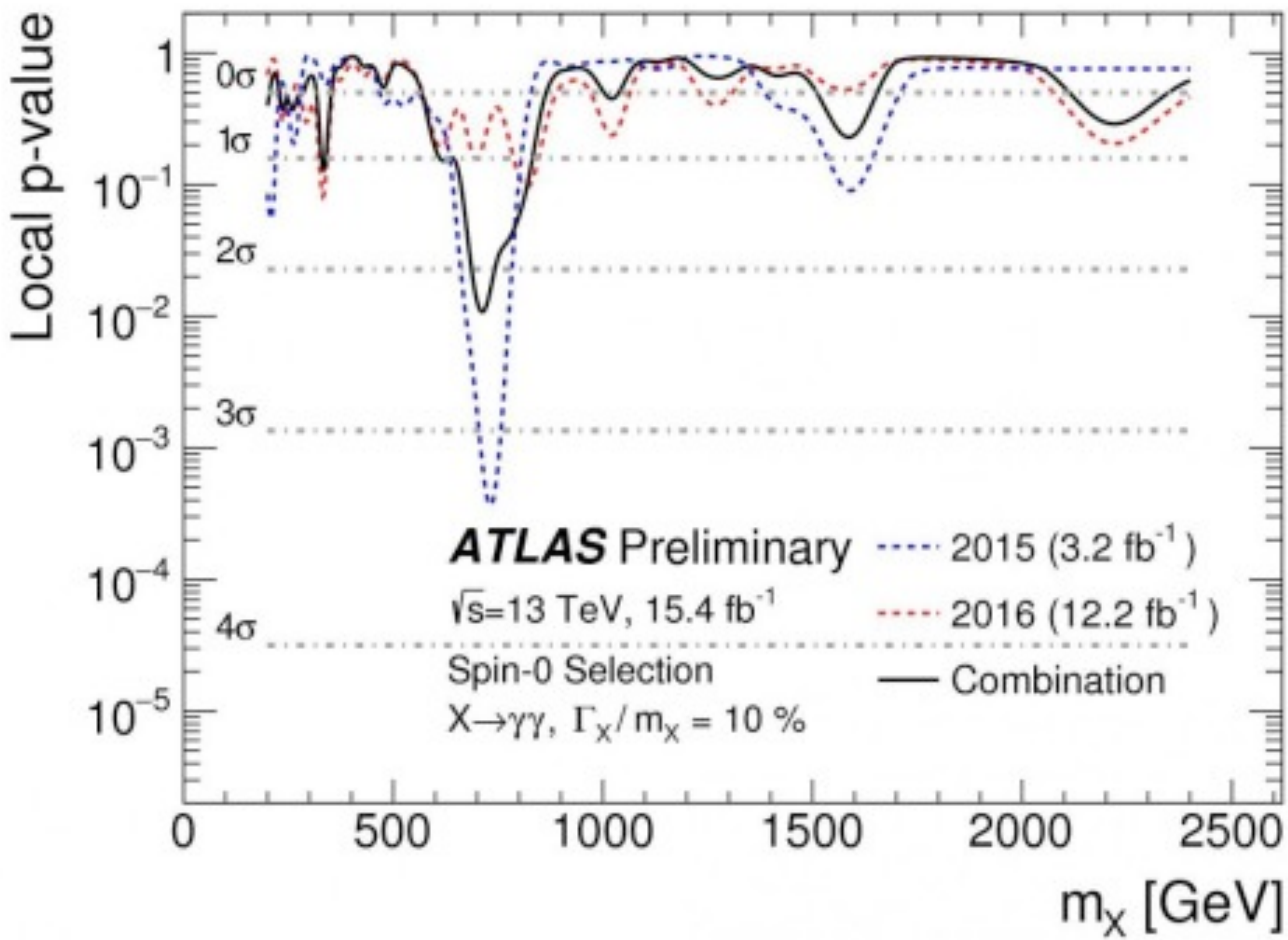
Detected, with **mild significance** (~4σ) with **XMM** and Chandra observations of **Perseus**, **M31**, stacked clusters (Balbul et al. 2014, Boyarsky et al. 2014)



Bulbul et al. 2014

These papers argue that the line is not explained by **astrophysical** lines, and may stem from **DM decay**

- **A simple DM decay picture is inconsistent with non-detection in Draco and Galactic Center morphology**
- **There are plausible astrophysical explanations**



hints for new particle at 750 GeV in 2015 data?
not confirmed by 2016 data

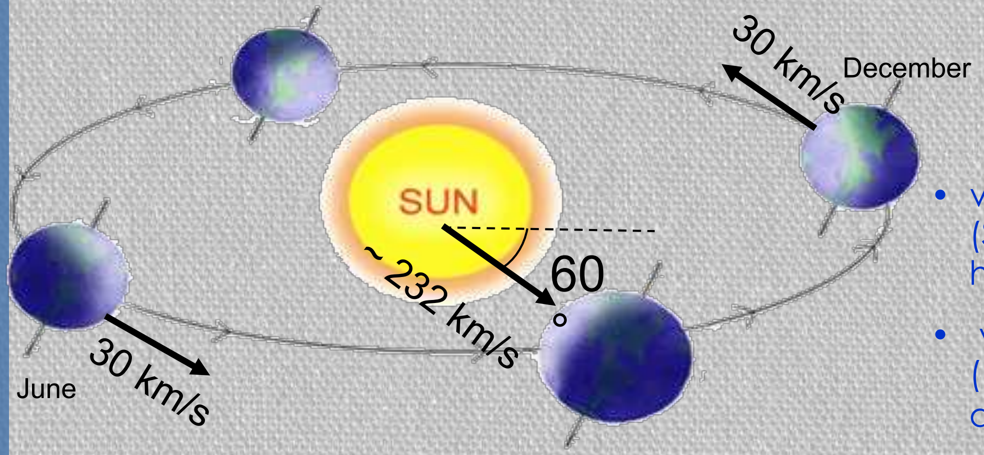
The DM annual modulation: a model independent signature to investigate the DM particles component in the galactic halo

With the present technology, the annual modulation is the main model independent signature for the DM signal. Although the modulation effect is expected to be relatively small a suitable large-mass, low-radioactive set-up with an efficient control of the running conditions can point out its presence.

Requirements of the DM annual modulation

1) Modulated rate according cosine
2) In a definite low energy range
3) With a proper period (1 year)
4) With proper phase (about 2 June)
5) Just for single hit events in a multi-detector set-up
6) With modulation amplitude in the region of maximal sensitivity must be <7% for usually adopted halo distributions, but it can be larger in case of some possible scenarios

Drukier, Freese, Spergel PRD86; Freese et al. PRD88



- v_{sun} ~ 232 km/s (Sun vel in the halo)
- v_{orb} = 30 km/s (Earth vel around the Sun)
- $\gamma = \pi/3$, $\omega = 2\pi/T$, T = 1 year
- $t_0 = 2^{nd}$ June (when $v_\oplus$ is maximum)

$$v_\oplus(t) = v_{sun} + v_{orb} \cos\gamma \cos[\omega(t-t_0)]$$

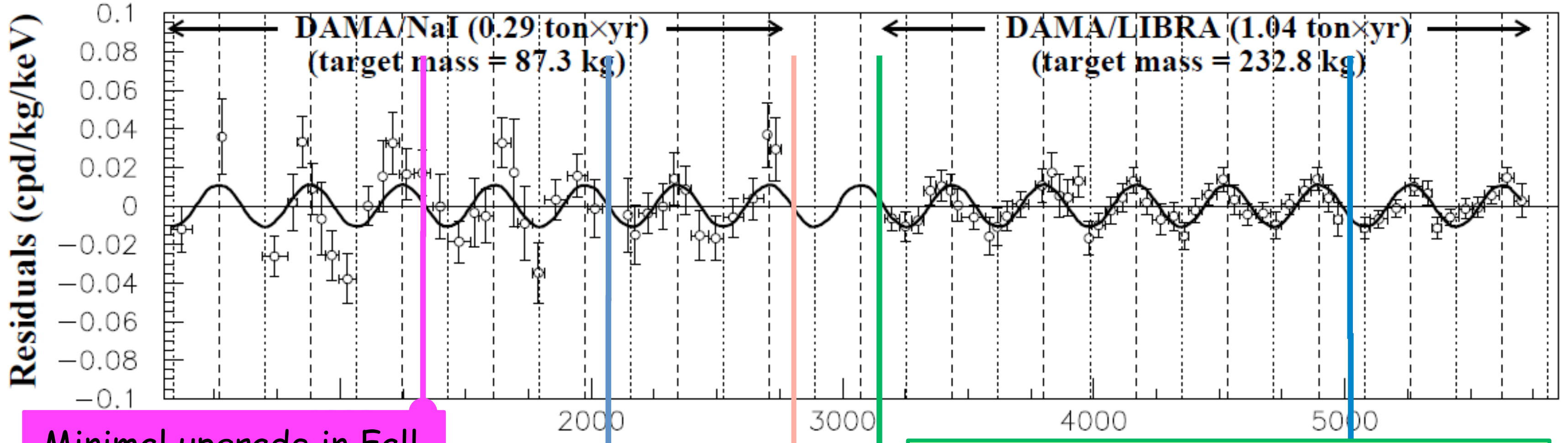
$$S_k[\eta(t)] = \int_{\Delta E_k} \frac{dR}{dE_R} dE_R \cong S_{0,k} + S_{m,k} \cos[\omega(t-t_0)]$$

the DM annual modulation signature has a different origin and peculiarities (e.g. the phase) than those effects correlated with the seasons

To mimic this signature, spurious effects and side reactions must not only - obviously - be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements

DAMA/NaI & DAMA/LIBRA main upgrades and improvements

single-hit residual rate vs time



Minimal upgrade in Fall

PHASE2

July 2000 new DAQ and new electronic chain installed (MULTIPLEXER removed, now one TD channel for each detector): (i) TD VXI Tektronix; (ii) Digital Unix DAQ system; (iii) GPIB-CAMAC.

On 2003 DAMA/LIBRA has begun first operations (one TD channel for each PMT; two for each detector)

Sept.-Oct. 2008 – DAMA/LIBRA upgrade:

(i) one detector has been recovered by replacing a broken PMT
(ii) new optimization of some PMTs and HVs performed
(iii) All TD replaced with new ones
(iv) new DAQ with optical read-out installed

July 2002 DAMA/NaI data taking completed

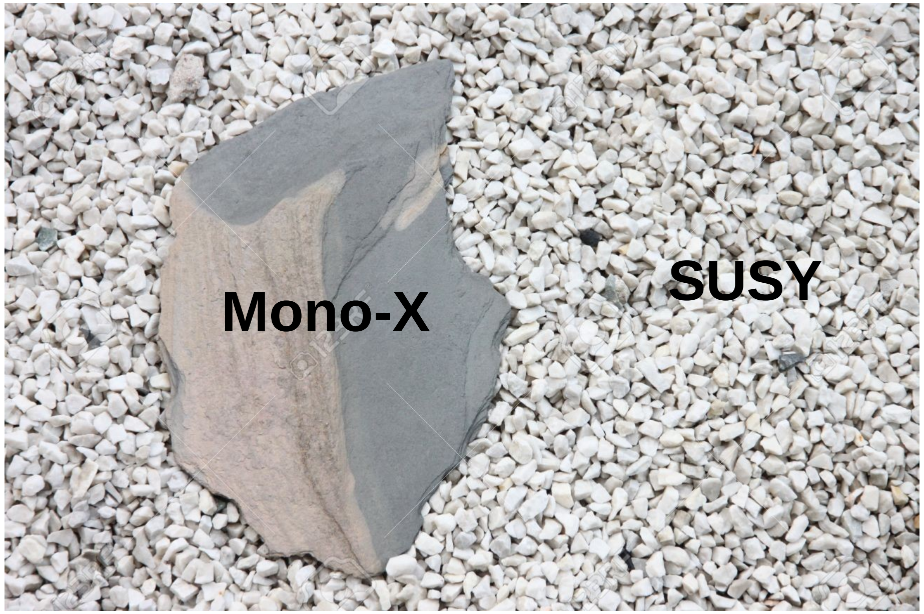
The second DAMA/LIBRA upgrade in Fall 2010: replacement of all the PMTs with higher Q.E. ones (+ new preamplifiers in fall 2012 & other developments in progress)

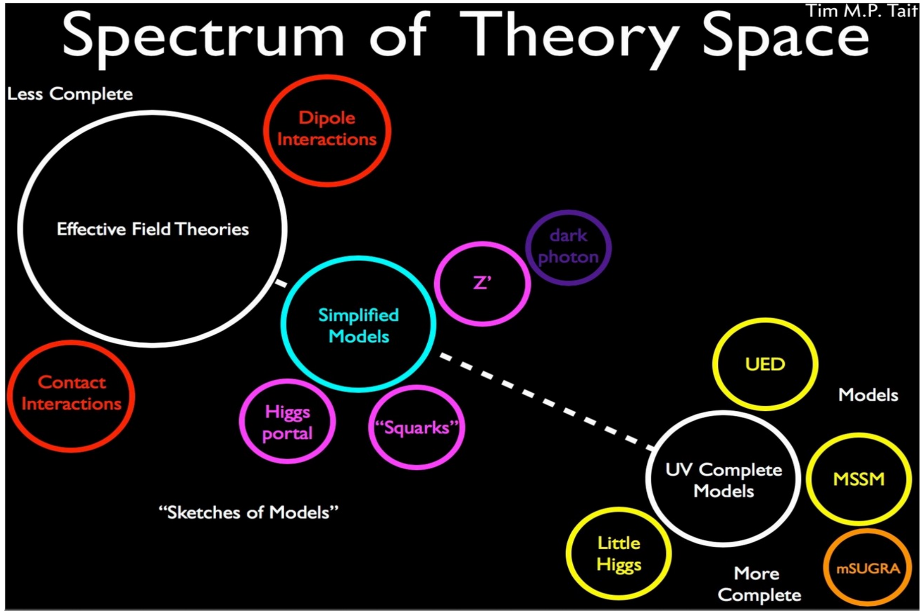
DAMA/LIBRA-phase2 *in data taking*

Collider searches

Many BSM models provide WIMP candidates

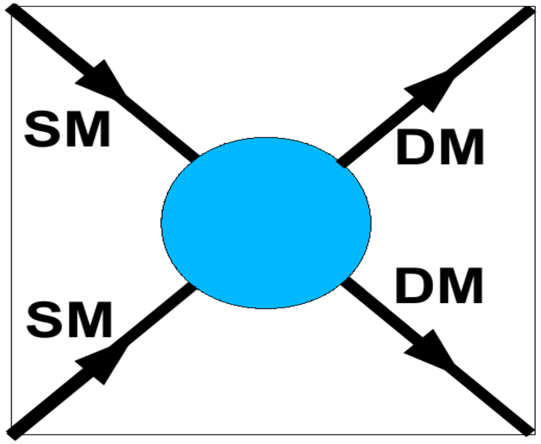
- Eg: SUSY (nMSSM, cMSSM, …), UED/ADD, Little Higgs …
- Large numbers of parameters, wide range of phenomenology





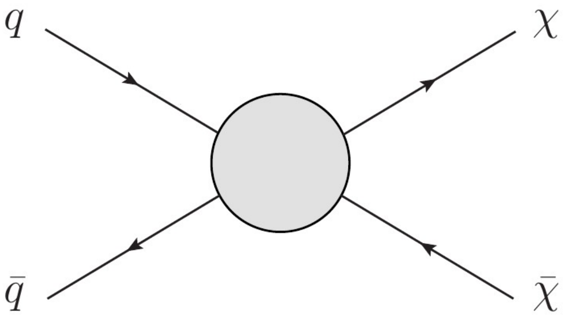
Alternatively, <u>take a general approach</u> :

- Perform broad searches based on general DM phenomenology
- Use "models" that are simple as possible, even if they are incomplete
- Turn as large a stone as possible … mono-X!



Mono-X

In reality, could not observe this at ATLAS & CMS …



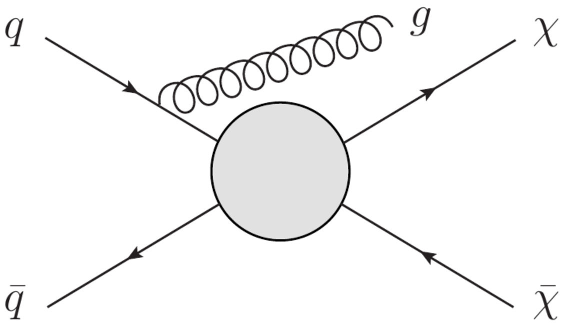
Dark Matter is **DARK**

- Leaves no activity in the detector
- Nothing to reconstruct in diagram above

DM must instead recoil against *something* to become “visible”

“Mono-X” (or “MET+X”) includededs “X” for viable detection

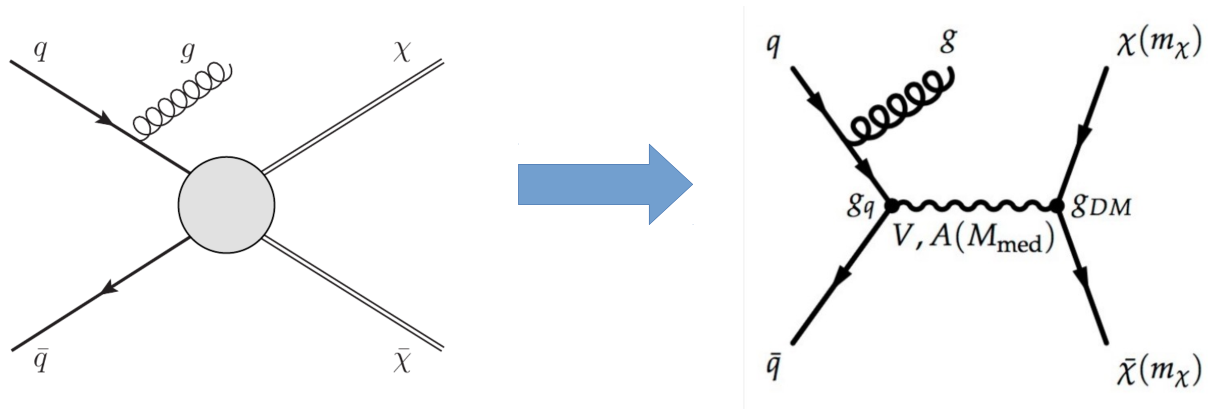
- X: quarks/gluons, photons, W/Z …



Simplified Models

More complete, somewhat more complicated …

- Include explicit DM mediator & SM,DM mediator couplings



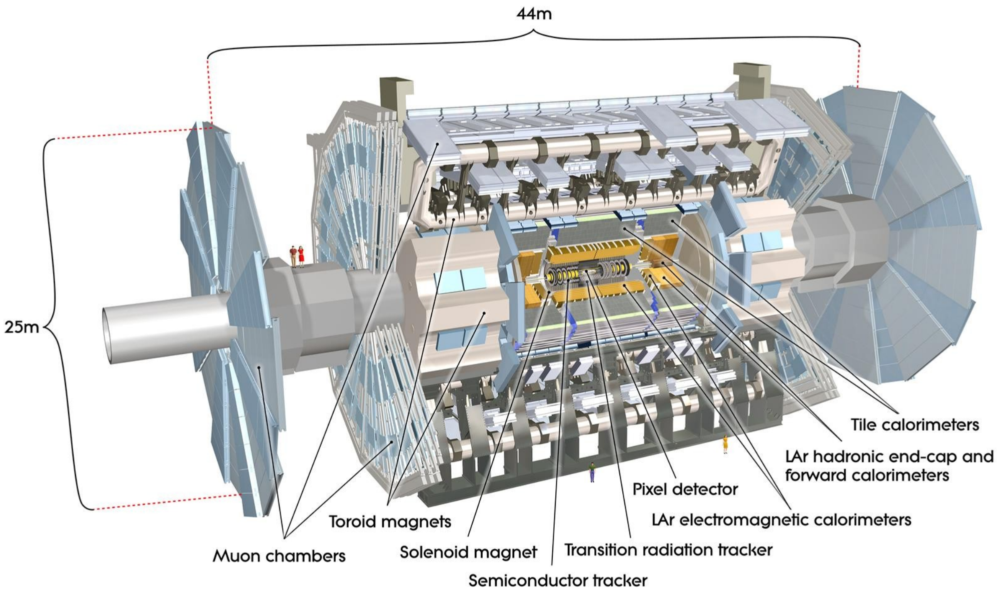
- Now additional parameters (gDM, gSM, mDM, mMed), but still compact representation of the important pheno.

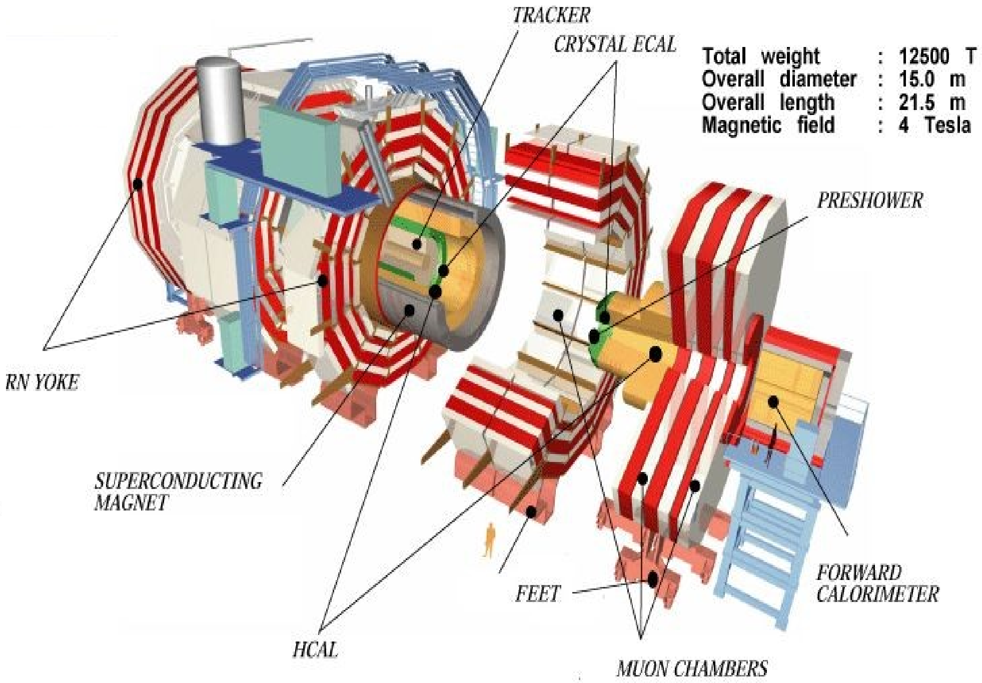
SMs → EFTs in limit of large (~10 TeV) mMed, couplings

- But accurately describe kinematics, rates, etc over full range of model parameters

See talk from Ning Zhou

(10 kiloTonne!) DM Detectors





ATLAS & CMS are DM discovery experiments!

Nearly all detector capabilities utilized in DM searches

- Vertexing, tracking, calorimetry, muons …
- Reveal the invisible by measuring the visible!

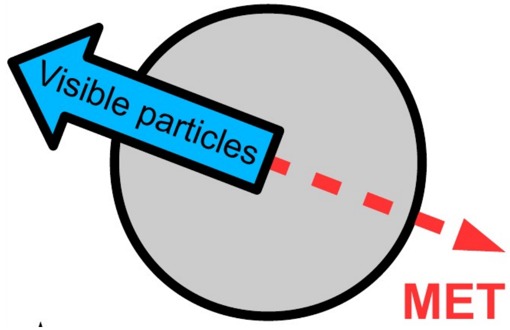
Missing Transverse Energy (MET, E_t^{miss}, $\not{E}_T$)

Non-interacting particles escape the detector

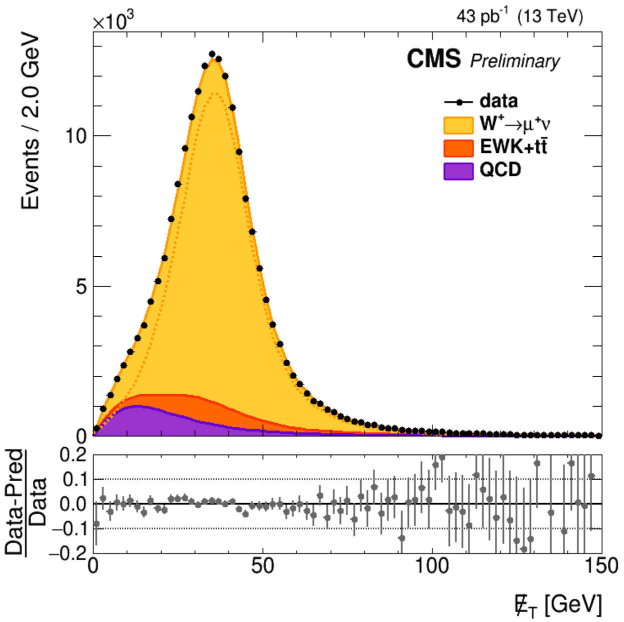
- Their presence inferred from energy/momentum imbalance

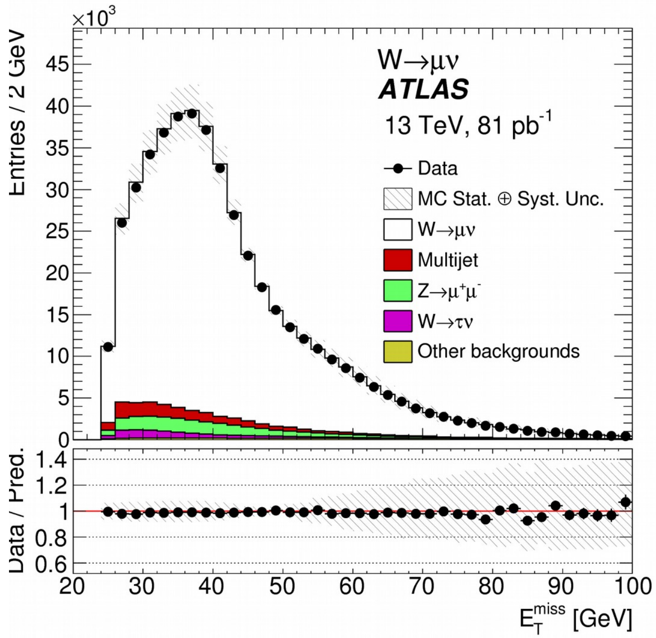
Missing energy not an ideal observable …

- Some final state particles lost in the beampipe
- Missing <u>Transverse</u> Energy much more useful
  - Negative vector sum of all visible energy



$$\not{E}_T \equiv -\sum_i E_T^i \hat{n}_i = -\sum_{all\ visible} \vec{E}_T$$

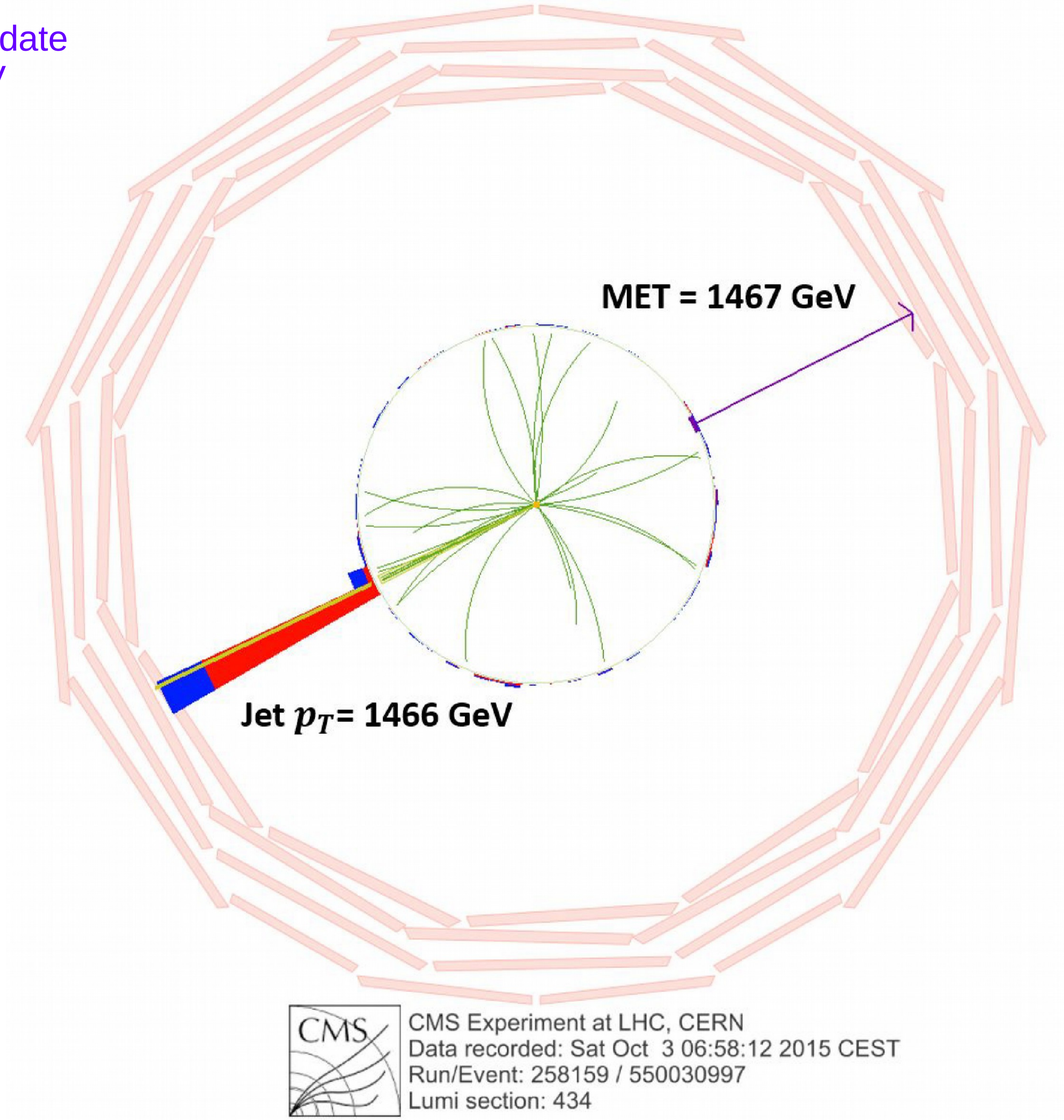




A well understood collider observable

- Wide use in SM measurements

Monojet candidate
at $\sqrt{s}$ = 13 TeV



Interpretation

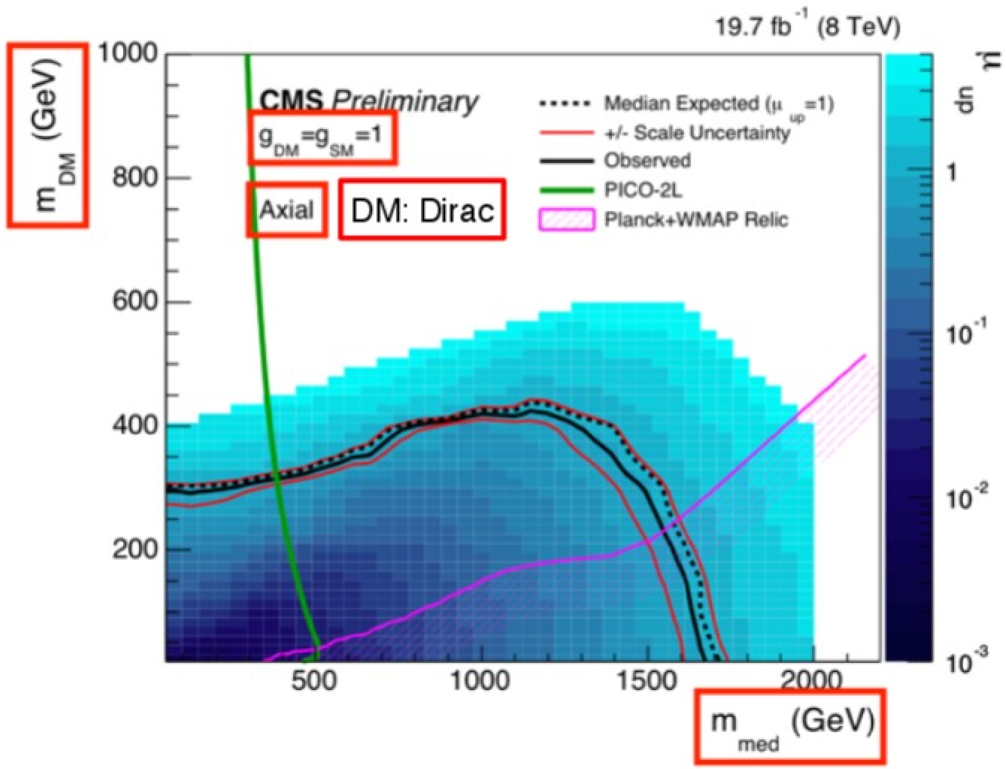
Extraction of potential DM signals …

In absence of excess: limit setting, model constraints

- NB: 95% CLs lmits are standard in collider world

m(Med)-m(DM) plane: provides natural representation of collider results

- Results shown as limit on signal cross section or on signal strength ($\mu = \sigma_{obs}/\sigma_{th}$)
- Fix gDM & gSM
- Label all assumptions (eg: mediator & DM type)



upper limits from searches for
- monojets (missing transverse energy)
- mono Z
- mono photon
- mono Higgs
- mono bottom/top

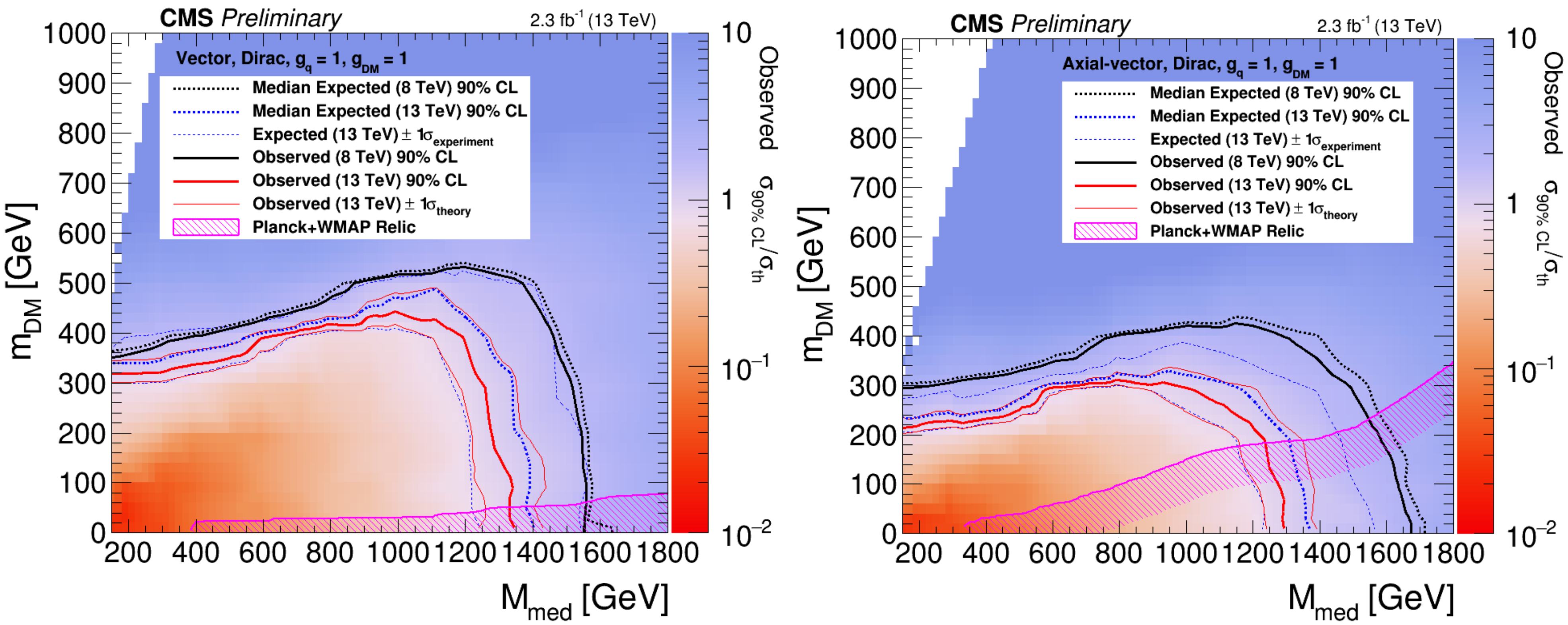
-> upper limits established
-> no discovery (yet)

CMS Monojet Results @ 13 TeV (2)

CMS-PAS-EXO-16-013

Limits set in mMed-mDM plane

- Both vector & axial couplings considered
- NB: gSM=1, 90% CL limits …
- 13 TeV results presently less constraining w.r.t 8 TeV

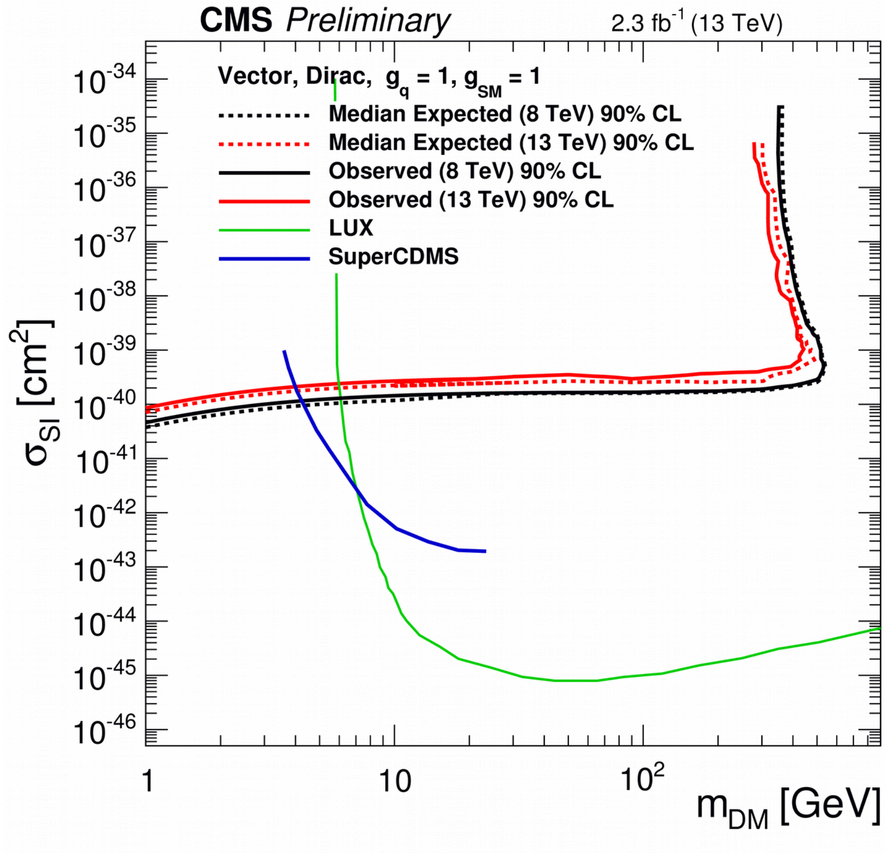


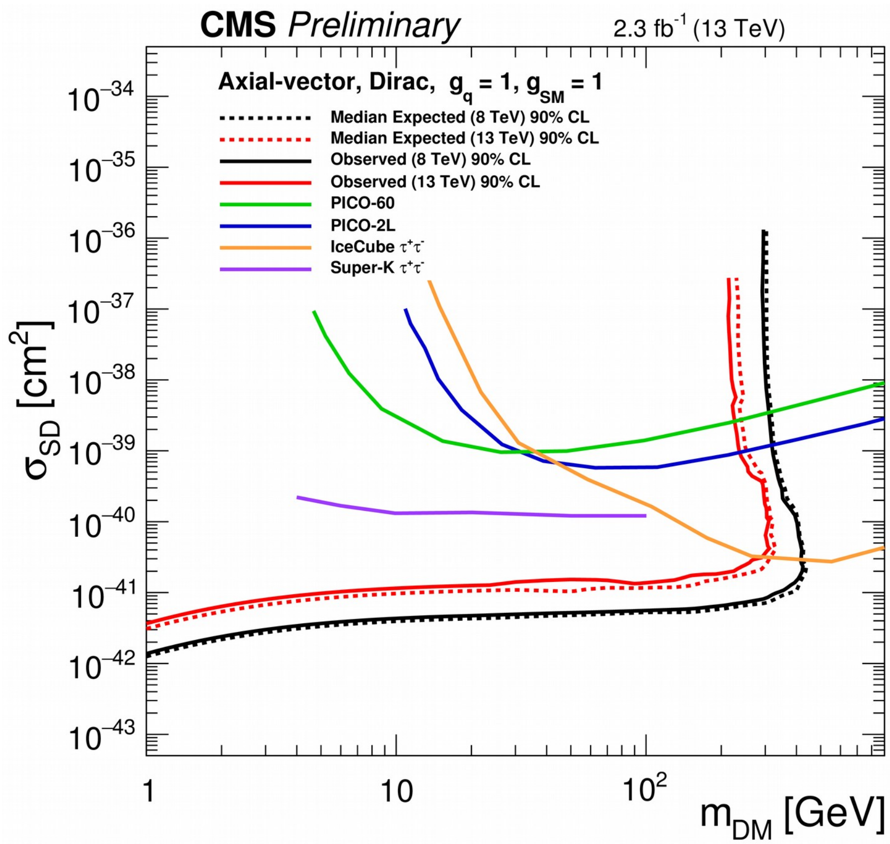
CMS Monojet Results @ 13 TeV (3)

CMS-PAS-EXO-16-013

Translation of limits to SI & SD planes

- Low mDM reach complements capabilites of direct detection!





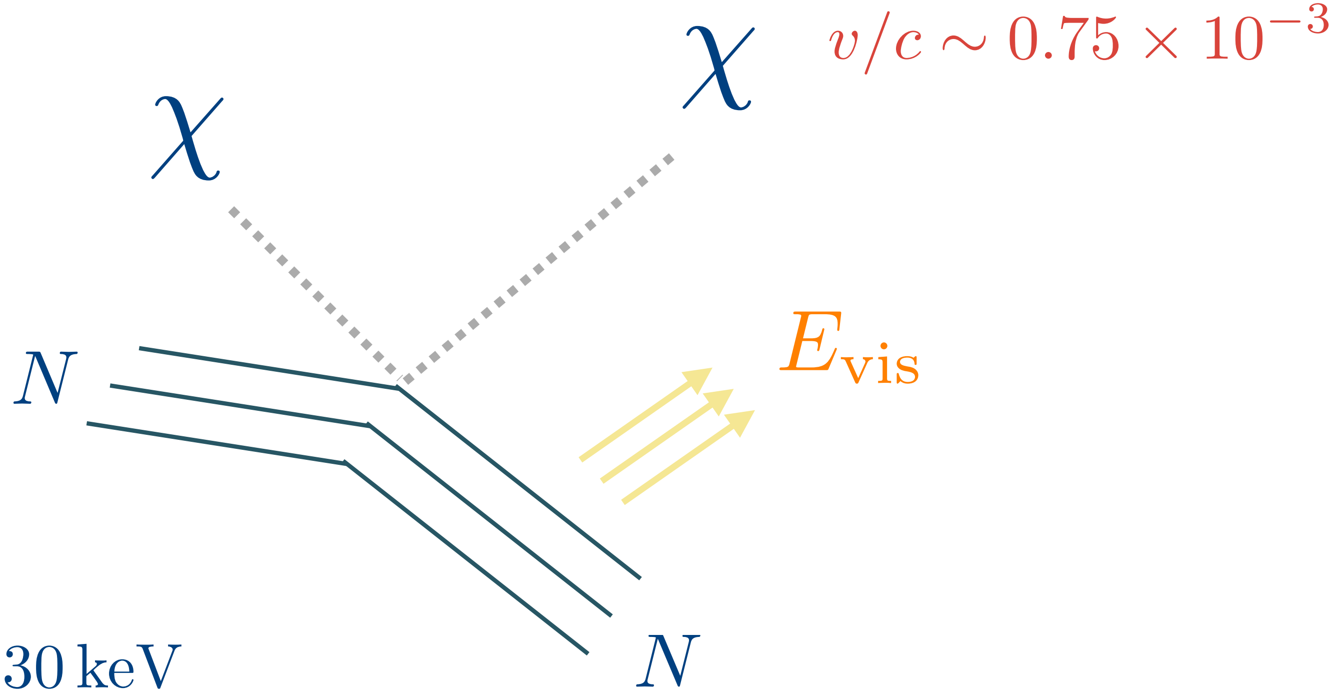
Direct detection

Physics aim of direct detection experiments

Observe WIMP dark matter via elastic scattering off atomic nuclei

Momentum transfer ~ few tens of MeV

Energy deposited in the detector ~ few keV - tens of keV

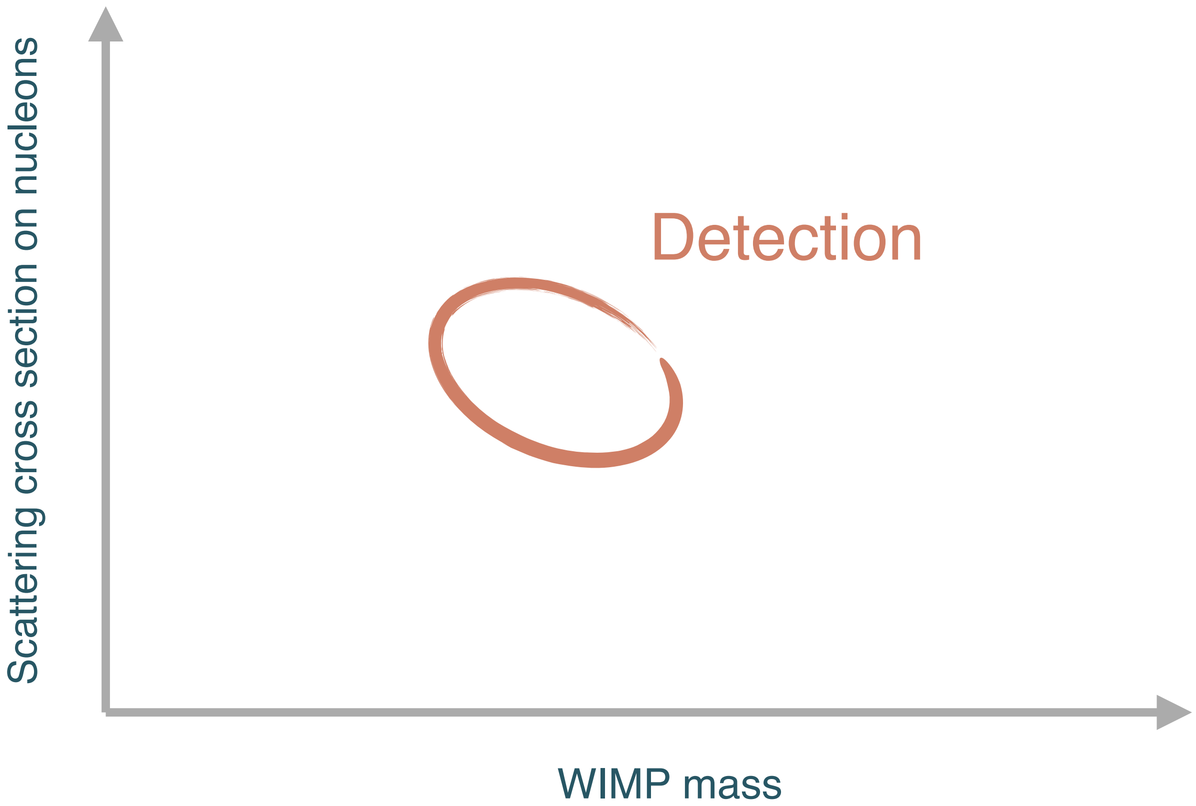


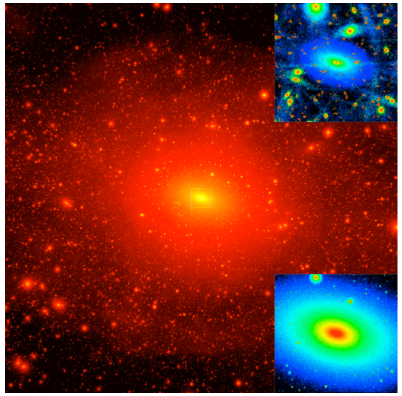
$$E_R = \frac{q^2}{2m_N} < 30\,\mathrm{keV}$$

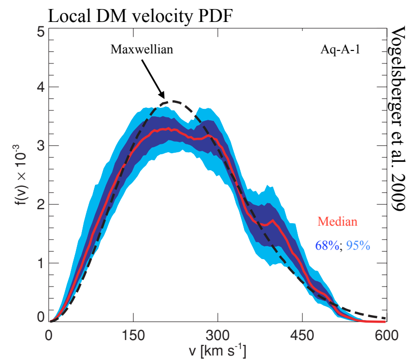
What can we learn about WIMPs?

- Constraints on the mass and scattering cross section

$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{v_{min}}^{v_{max}} dv f(v) v \frac{d\sigma}{dE_R}$$







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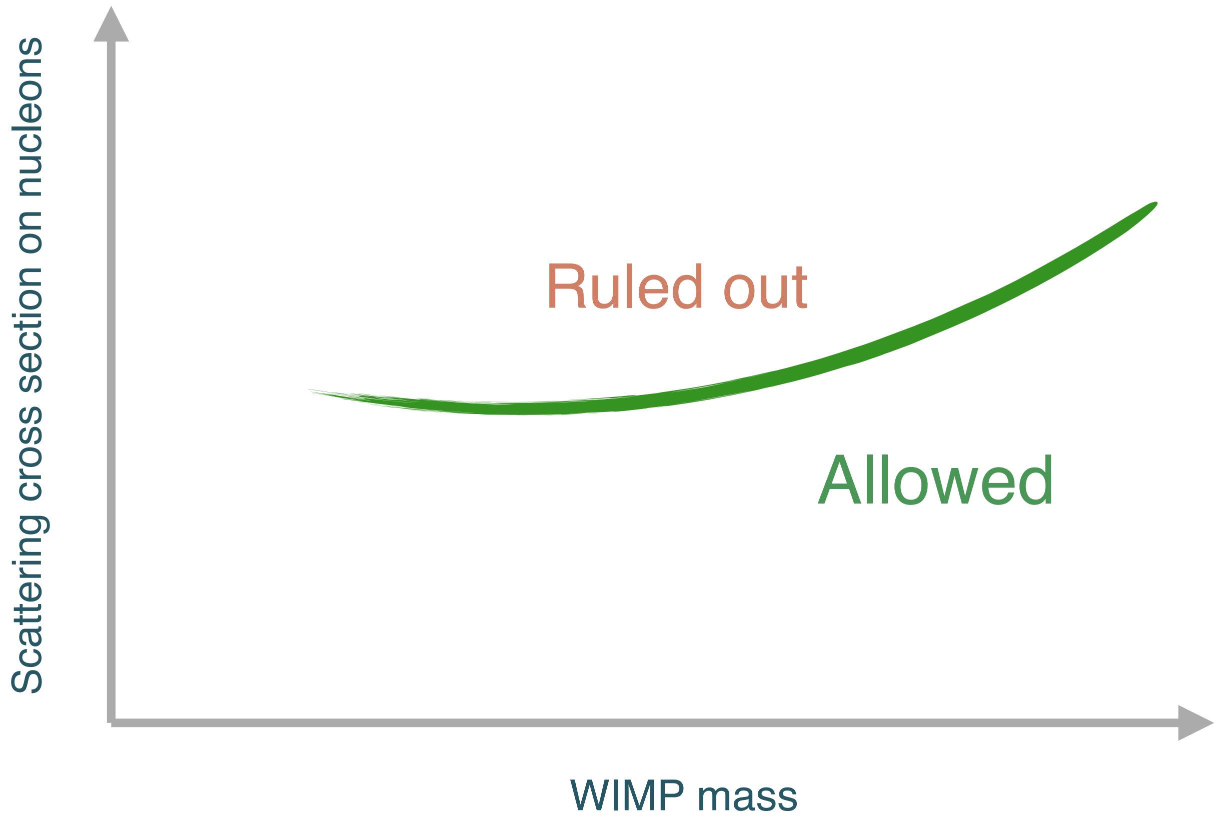
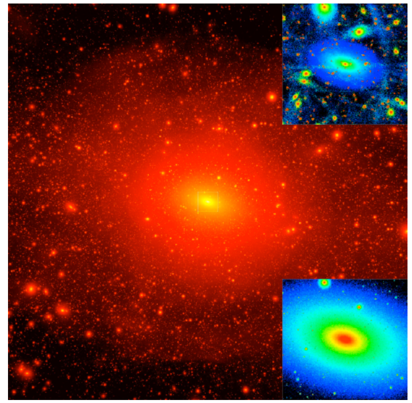
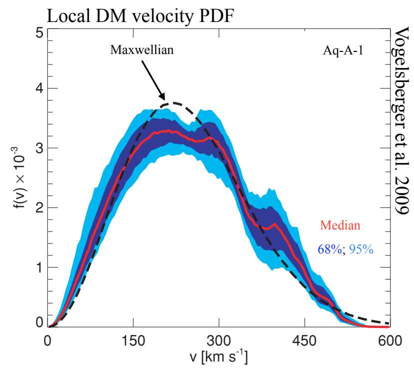
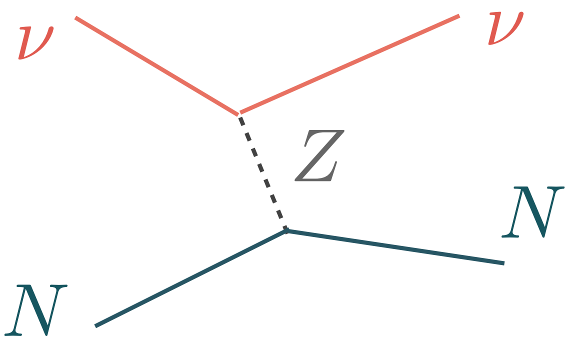


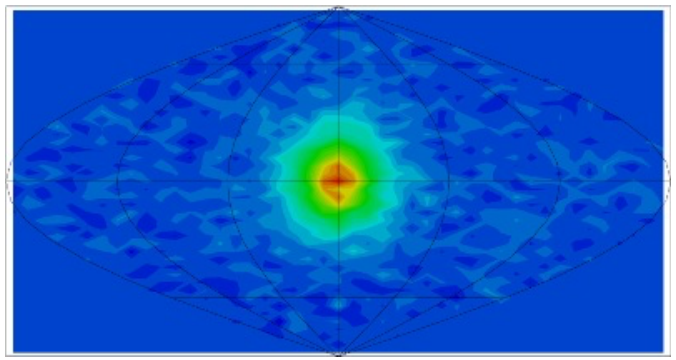


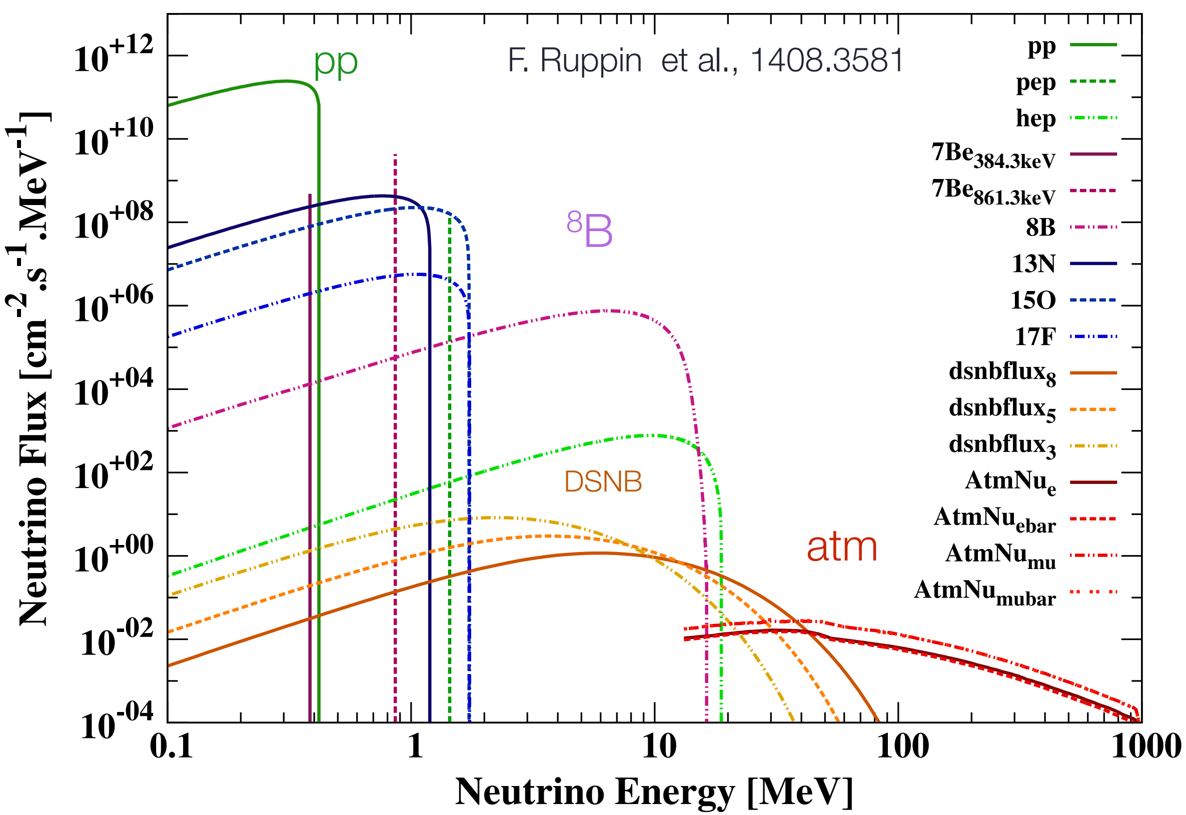


Backgrounds

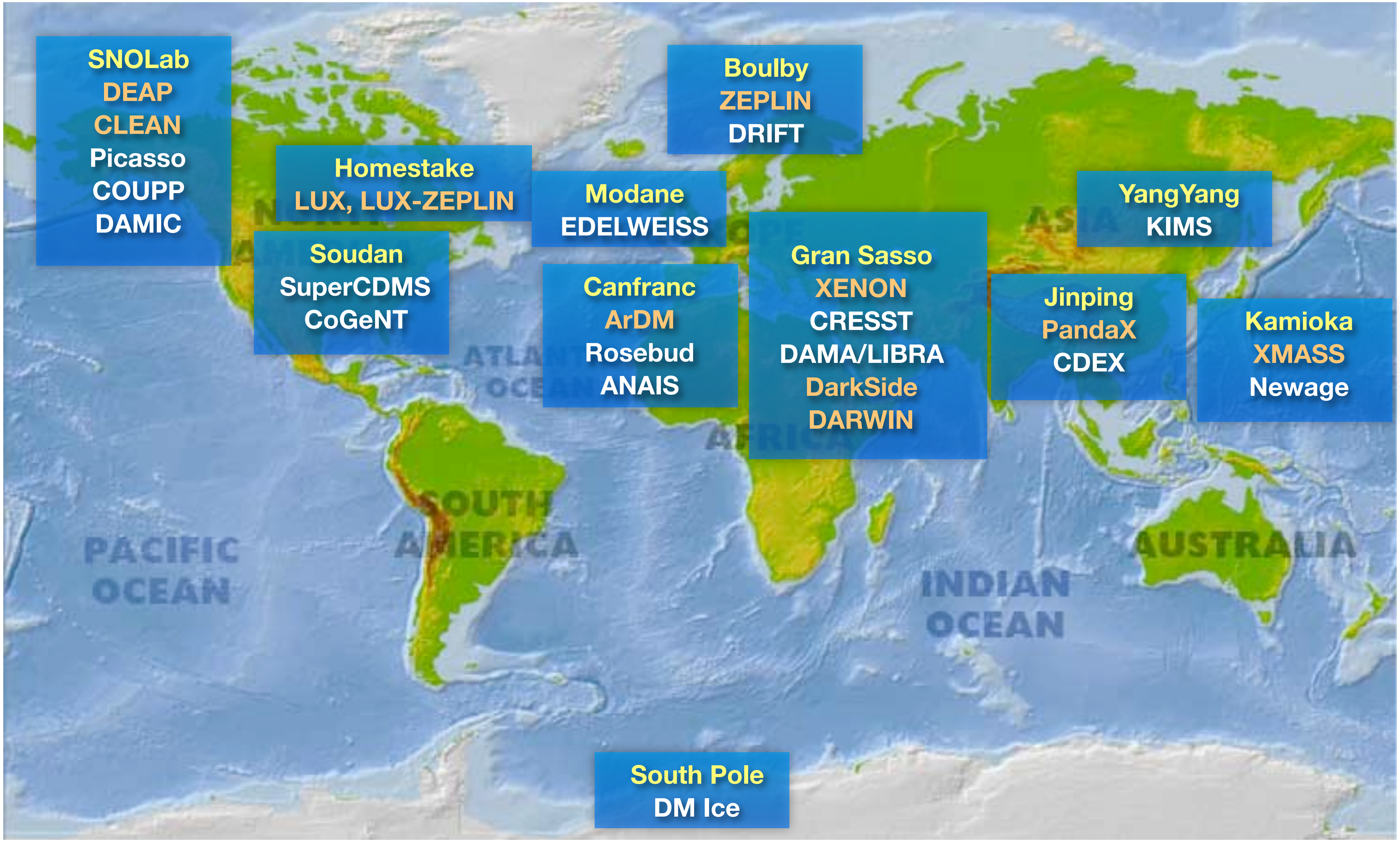
- Cosmic rays & cosmic activation of detector materials
- Natural (^{238}U, ^{232}Th, ^{40}K) & anthropogenic (^{85}Kr, ^{137}Cs) radioactivity: γ, e^-, n, α
- Ultimately: **neutrino-nucleus scattering (solar, atmospheric and supernovae neutrinos)**



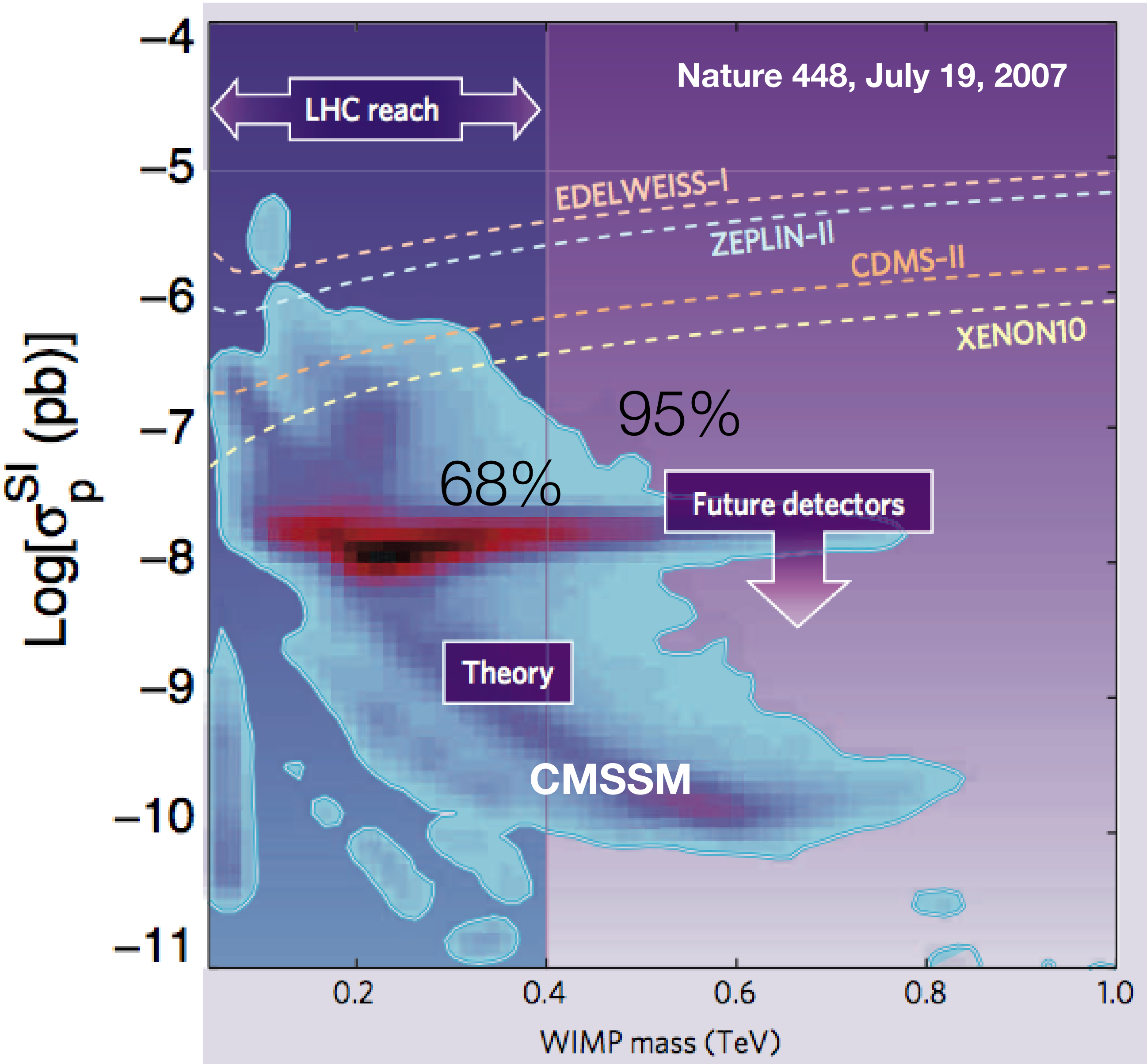




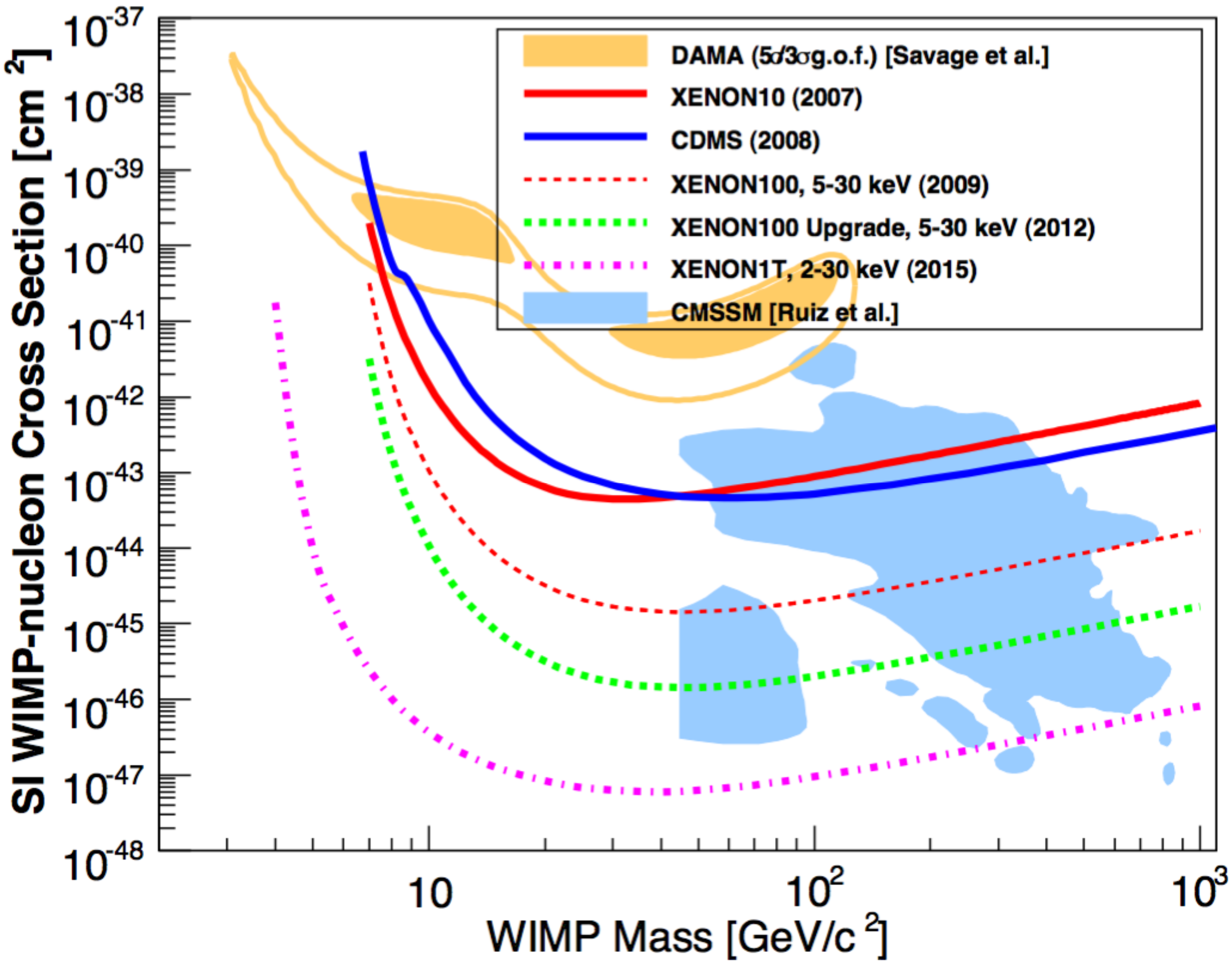
A world-wide effort to search for WIMPs



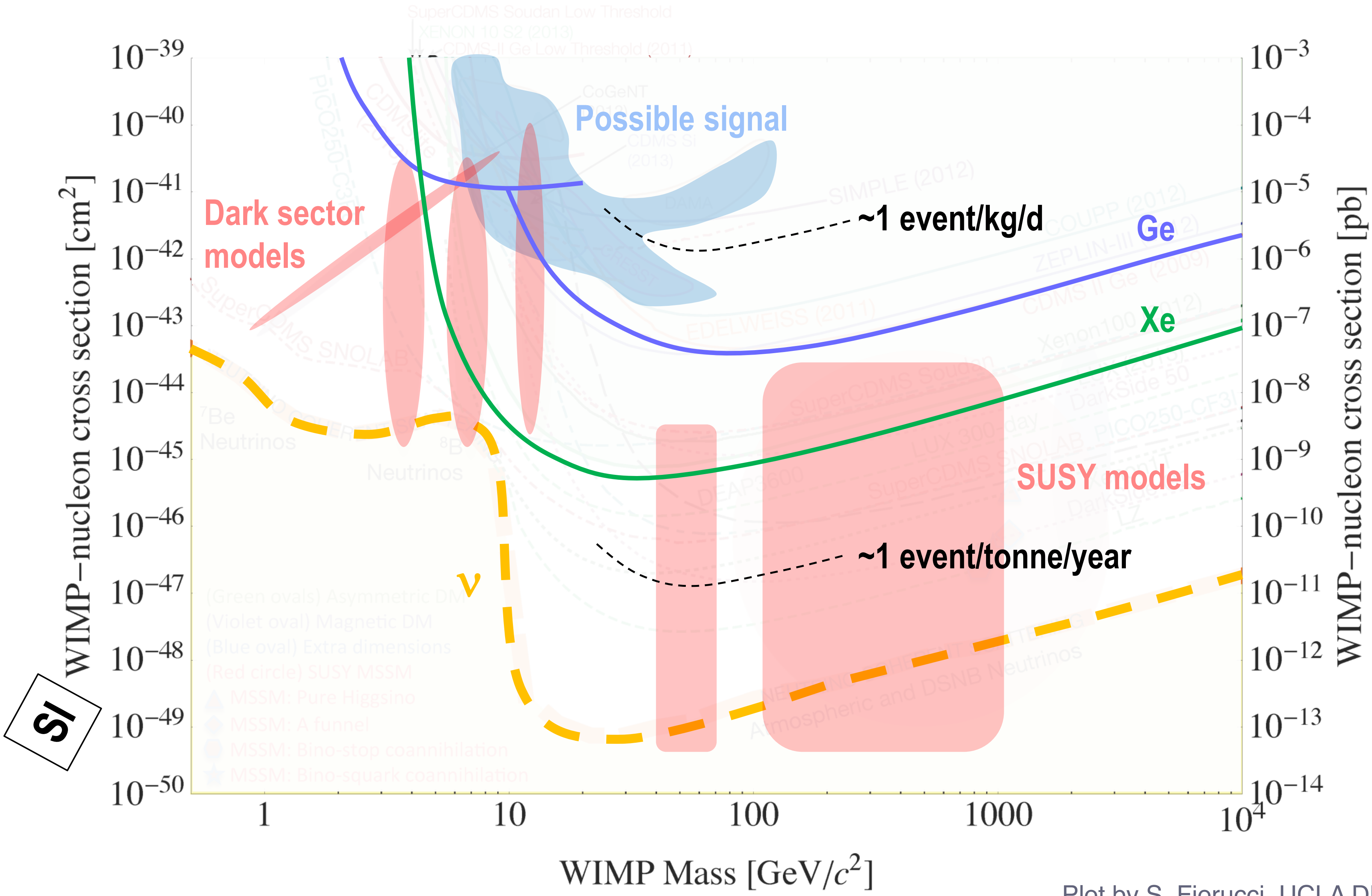
The WIMP landscape in 2007



The WIMP landscape in 2009



The WIMP landscape today



Plot by S. Fiorucci, UCLA DM2016

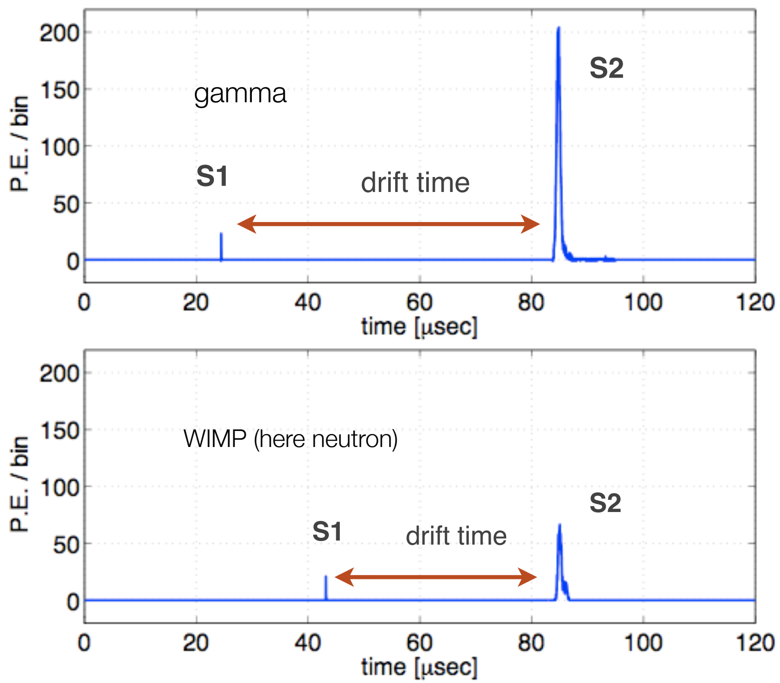
Why noble gases for direct dark matter detection?

- Dense, homogeneous target with self-shielding; fiducialisation
- Large detector masses feasible at moderate costs
- High light (40 photons/keV) and charge (W_{LAr} = 24 eV, W_{LXe} = 15 eV) yields

Properties [unit]	**Xe**	**Ar**	**Ne**
Atomic number:	54	18	10
Mean relative atomic mass:	131.3	40.0	20.2
Boiling point T_b at 1 atm [K]	165.0	87.3	27.1
Melting point T_m at 1 atm [K]	161.4	83.8	24.6
Gas density at 1 atm & 298 K [$\mathrm{g\,l^{-1}}$]	5.40	1.63	0.82
Gas density at 1 atm & T_b [$\mathrm{g\,l^{-1}}$]	9.99	5.77	9.56
Liquid density at T_b [$\mathrm{g\,cm^{-3}}$]	2.94	1.40	1.21
Dielectric constant of liquid	1.95	1.51	1.53
Volume fraction in Earth's atmosphere [ppm]	0.09	9340	18.2

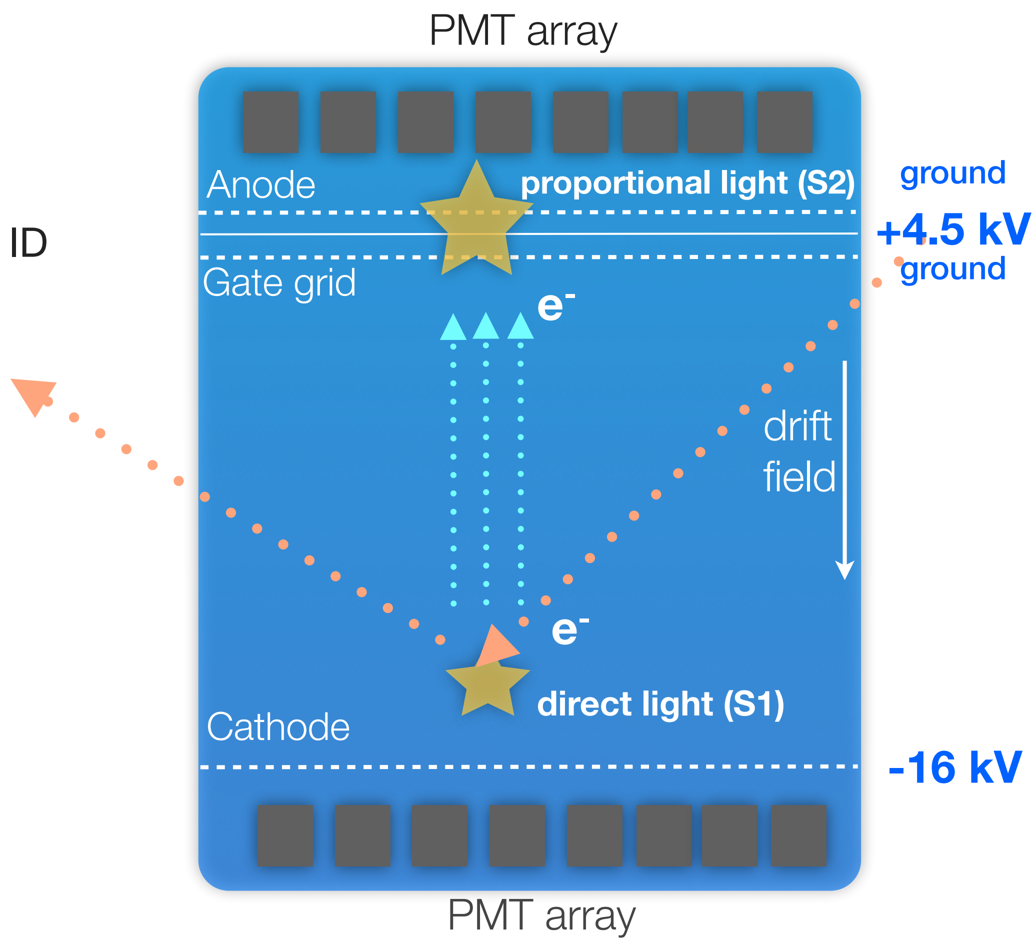
The Double-Phase Detector Concept

- Particle interaction in the active volume produces *prompt scintillation light (S1)* and ionisation electrons
- Electrons drift to interface (E= 0.53 kV/cm) where they are extracted and amplified in the gas. Detected as *proportional scintillation light (S2)*
    - $(S2/S1)_{WIMP} \ll (S2/S1)_{Gamma}$
    - 3-D position sensitive detector with particle ID



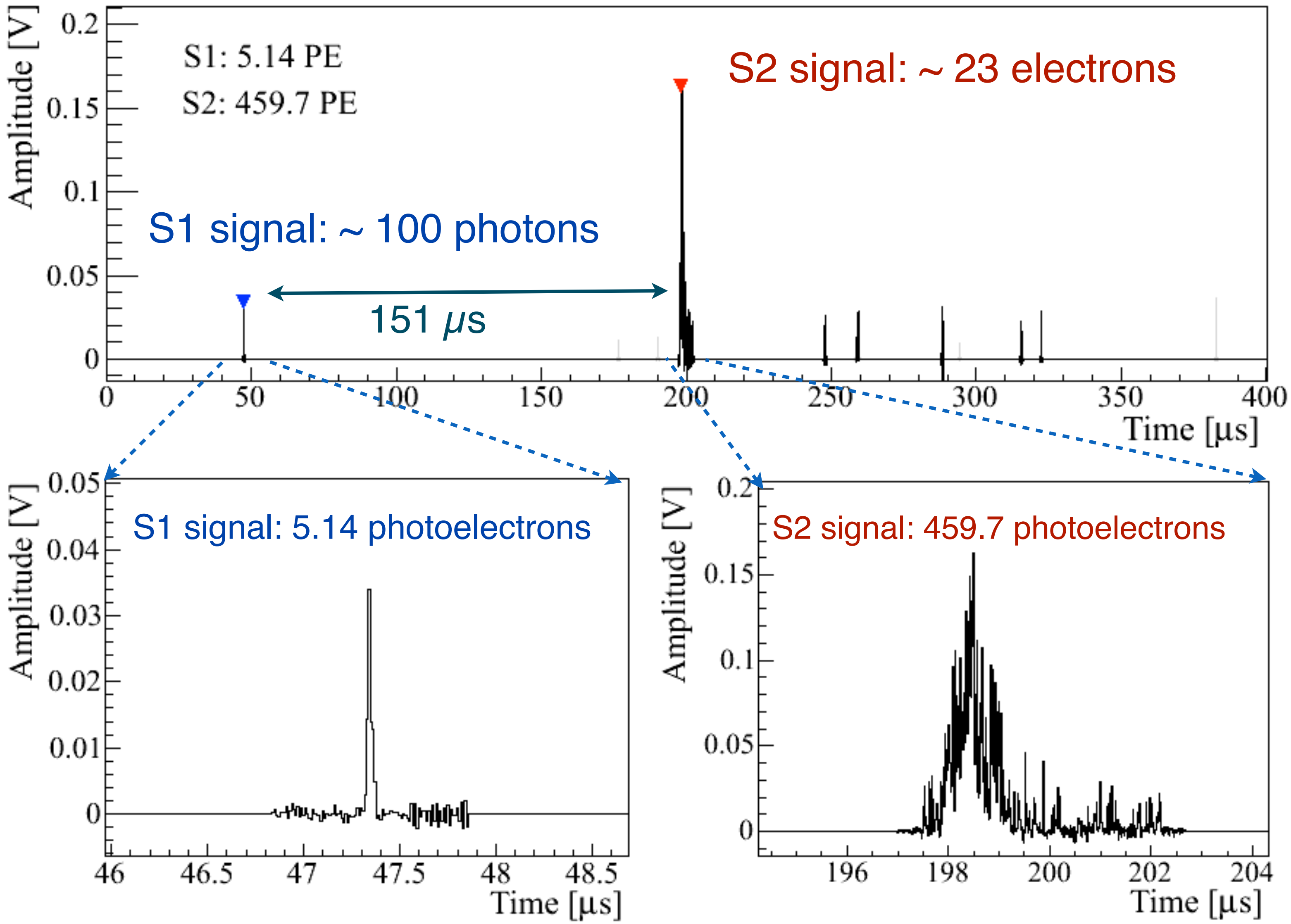
position resolution:

<3mm in x-y; < 0.3 mm in z



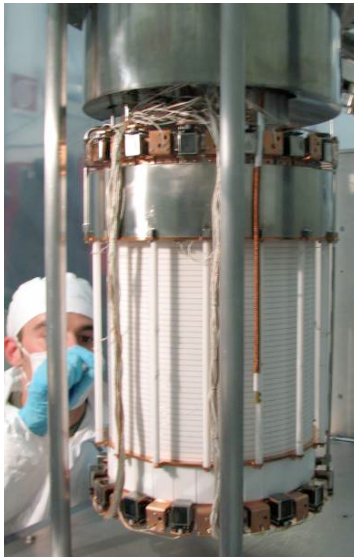
Example of a low-energy event in XENON100

The maximum electron drift time at 0.53 kV/cm is 176 μs



Time projection chambers: xenon

See talk by L. Bütikofer



XENON100 at LNGS:

161 kg LXe
(~50 kg fiducial)

242 1-inch PMTs

results from run II
calibration data (YBe, ^{83m}Kr, CH_3T, ^{220}Rn) etc

S. Fiorucci, Patras 2016

LUX at SURF:

350 kg LXe
(100 kg fiducial)

122 2-inch PMTs

re-analysis of 2013 data (run 3)
first result from run 4 by the end of this year

X. Ji, UCLA DM 2016

PandaX at Jinping:

500 kg LXe
(306 kg fiducial)

110 3-inch PMTs

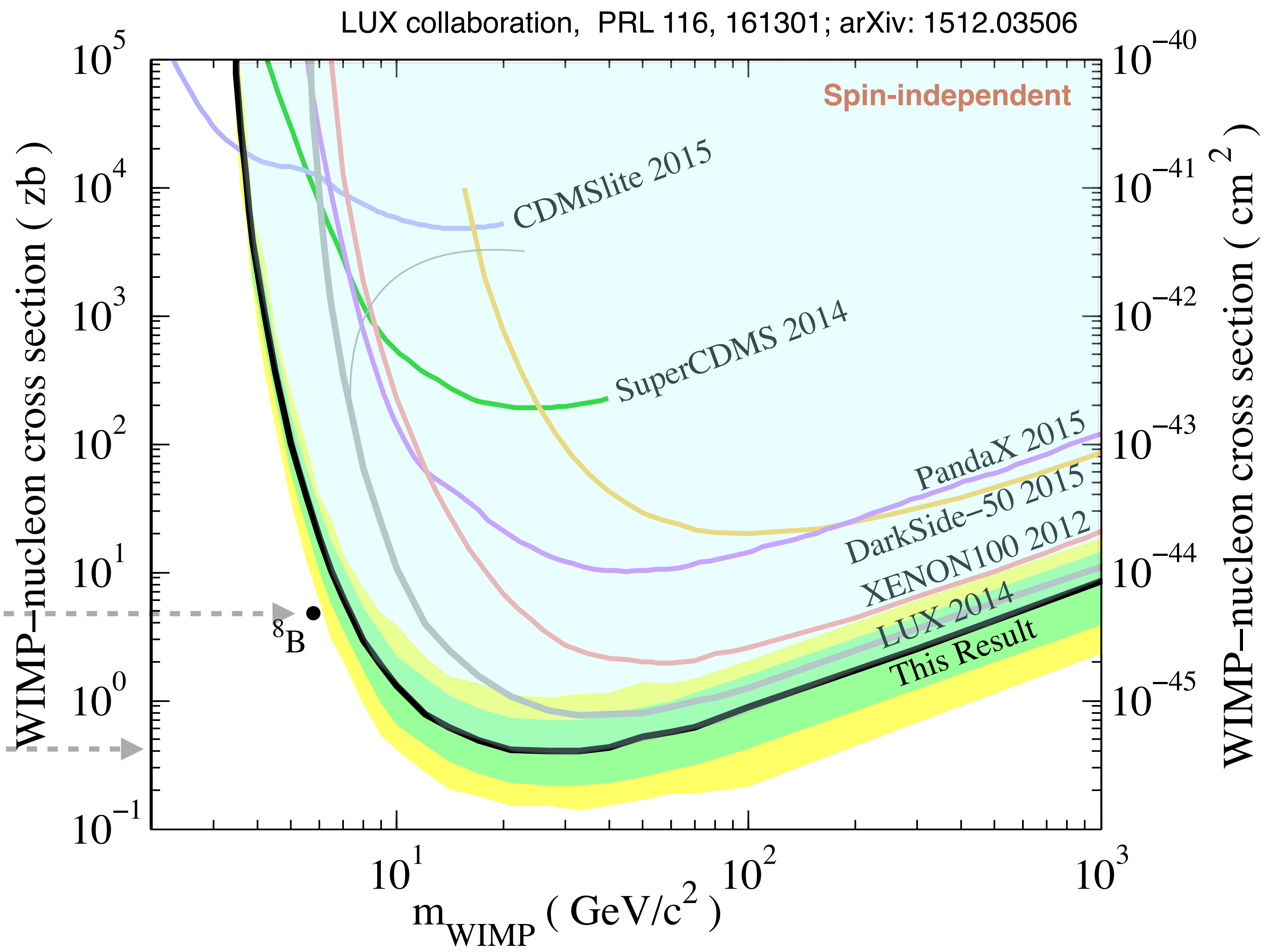
first commissioning run
science data since spring 2016

Recent results: no evidence (yet) for WIMPs

LUX:
95 d x 145 kg
1.1 keV threshold

Expected events
from ^{8}B neutrinos

Minimum at 0.4 zb

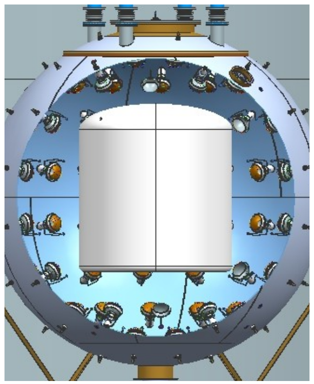


1 b = 10^{-24} cm^2 z=Zepto 10^{-21}

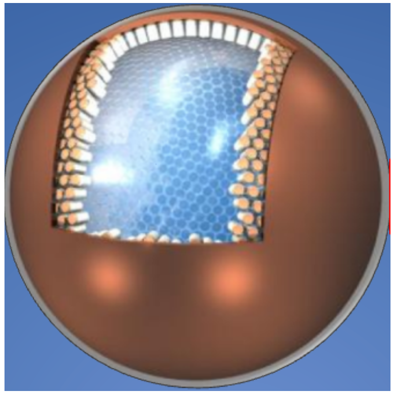
New and future noble liquid detectors

- **Under commissioning: XENON1T (3.5 t LXe) at Gran Sasso**
- Planned LXe: LUX-ZEPLIN 7t, XENONnT 7t, XMASS 6t
- Proposed LAr: DarkSide 20 t, DEAP 50 t
- Design & R&D stage: DARWIN 50 t LXe; ARGO 300 t LAr

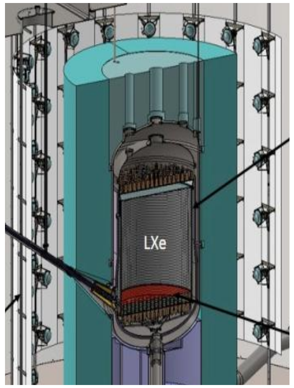
XENONnT: 7t LXe



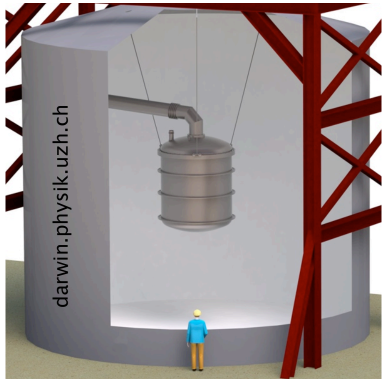
DarkSide: 20 t LAr



XMASS: 6t LXe



LZ: 7t LXe



DARWIN: 50 t LXe

The XENON1T experiment

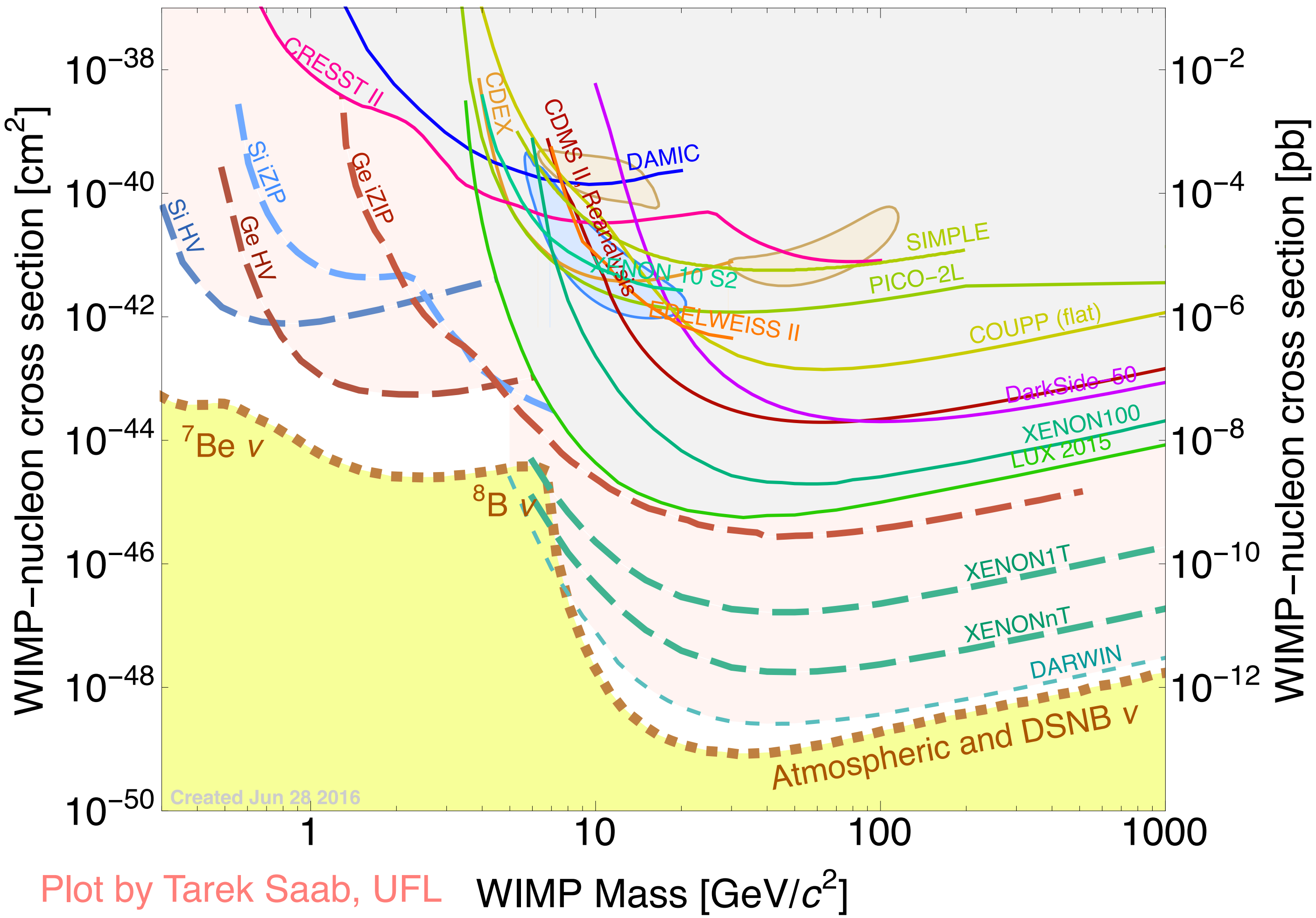
See talk by P. Pakarha

- Total (active) LXe mass: 3.5 t (2 t), 1 m electron drift, 248 3-inch PMTs in two arrays
- Background goal: 100 x lower than XENON100 ~ 5×10^{-2} events/(t d keV)

The end

Of course, "the probability of success is difficult to estimate, but if we never search, the chance of success is zero"

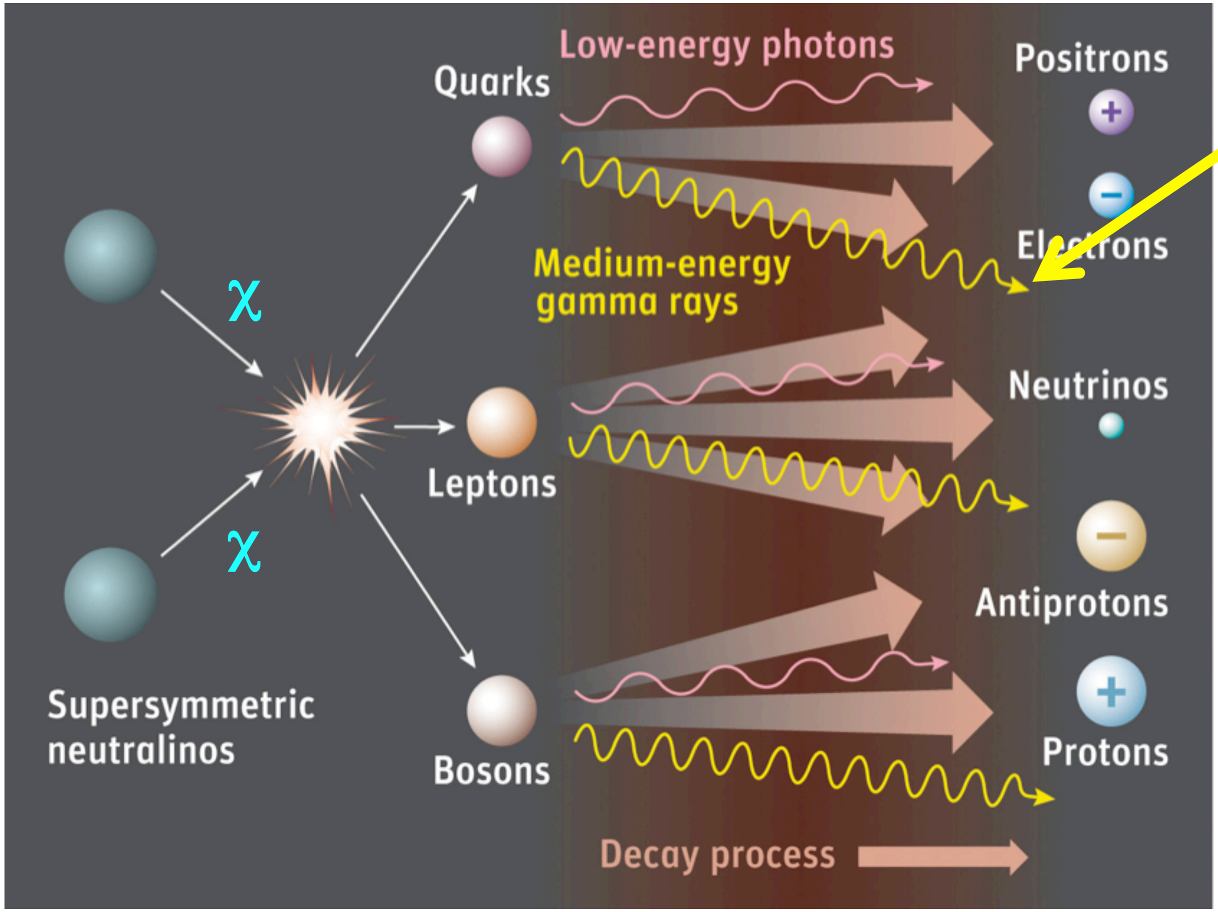
G. Cocconi & P. Morrison, Nature, 1959



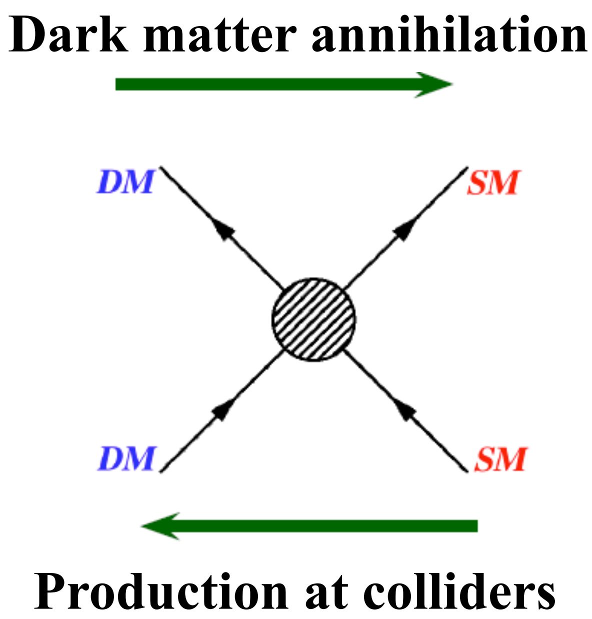
Plot by Tarek Saab, UFL

Indirect/astrophysical searches

Indirect Dark Matter Searches



Detect gamma rays



Advantage: Neutral cosmic rays (gamma-rays) are not affected by interstellar & intergalactic magnetic fields (point back to source)

Complementary to indirect dark matter searches at colliders

Dark Matter Annihilation/Decay search

Expected gamma-ray flux:

$$\frac{d\Phi_\gamma}{dE} = \frac{d\Phi_\gamma^{PP}}{dE} J(\Omega)$$

Particle Physics factor:
photons per annhilation/decay

Astrophysical factor:
line-of-site integral of Dark Matter distribution

Annihilation

$$\frac{d\Phi_\gamma^{PP}}{dE} = \frac{\langle \sigma_{ann} v \rangle}{8\pi m_{DM}^2} \frac{dN_\gamma}{dE}$$

$$J(\Omega) = \int_\Omega \int_{los} \rho^2(r)\, dr\, d\Omega$$

Decay

$$\frac{d\Phi_\gamma^{PP}}{dE} = \frac{1}{4\pi m_{DM} \tau_{DM}} \frac{dN_\gamma}{dE}$$

$$J(\Omega) = \int_\Omega \int_{los} \rho(r)\, dr\, d\Omega$$

Perform a likelihood fit on the measured gamma-ray flux

Produce 95% CL limits on:

- $<\sigma_{ann}\, v>$: thermally averaged annihilation cross section
- τ_{DM} : DM particle decay life-time

as a function of the dark matter particle mass m_{DM}