9th APCTP - BLTP JINR Joint Workshop at Kazakhstan

*Modern problems of nuclear and elementary particle physics*

June 27 - July 4, 2015, Almaty, Kazakhstan

# THE MODERN STATUS OF THE DARK MATTER

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# OUTLOOK

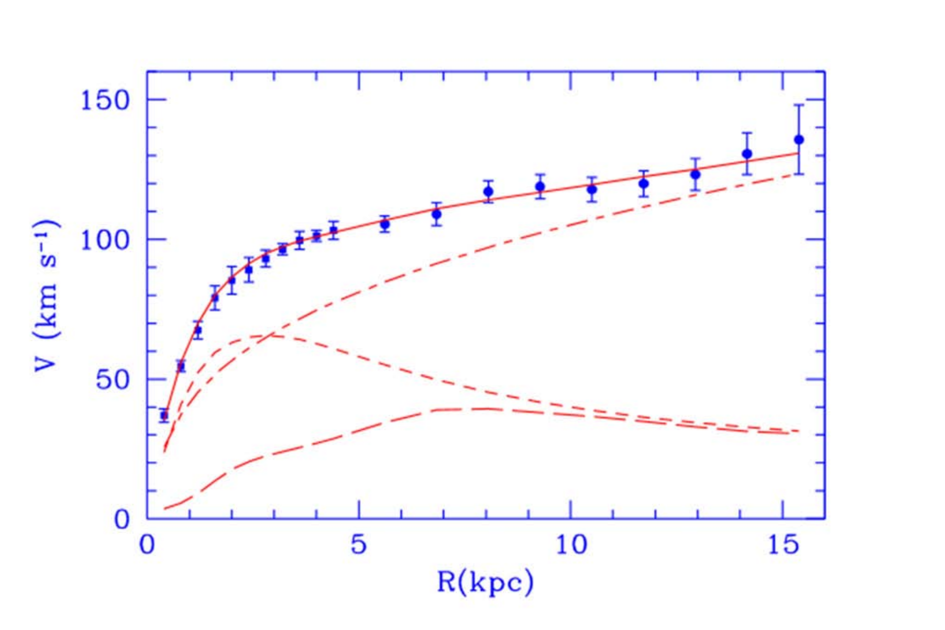
- Evidence for the Dark Matter
- Dark Matter candidates
- Supersymmetry
- Dark Matter experiments
  - Indirect detection
  - Direct detection
- Exclusion limits on DM – nucleon scattering cross-sections and future experiments
- Conclusion

# EVIDENCE FOR THE DARK MATTER

- The Dark Matter is a kind of matter which does not emit or absorb light and cannot be seen even with a telescope
- We can only detect it with its gravitational effects
- The nature of the Dark matter is one of the most intriguing puzzles in fundamental physics and cosmology

# EVIDENCE FOR THE DARK MATTER

- Orbital velocities of galaxies in clusters ("missing mass", Zwicky, 1933)
- Flat rotation curves of spiral galaxies: stars at high radius are faster than expected (Babcock,1939; Rubin, 1970s)

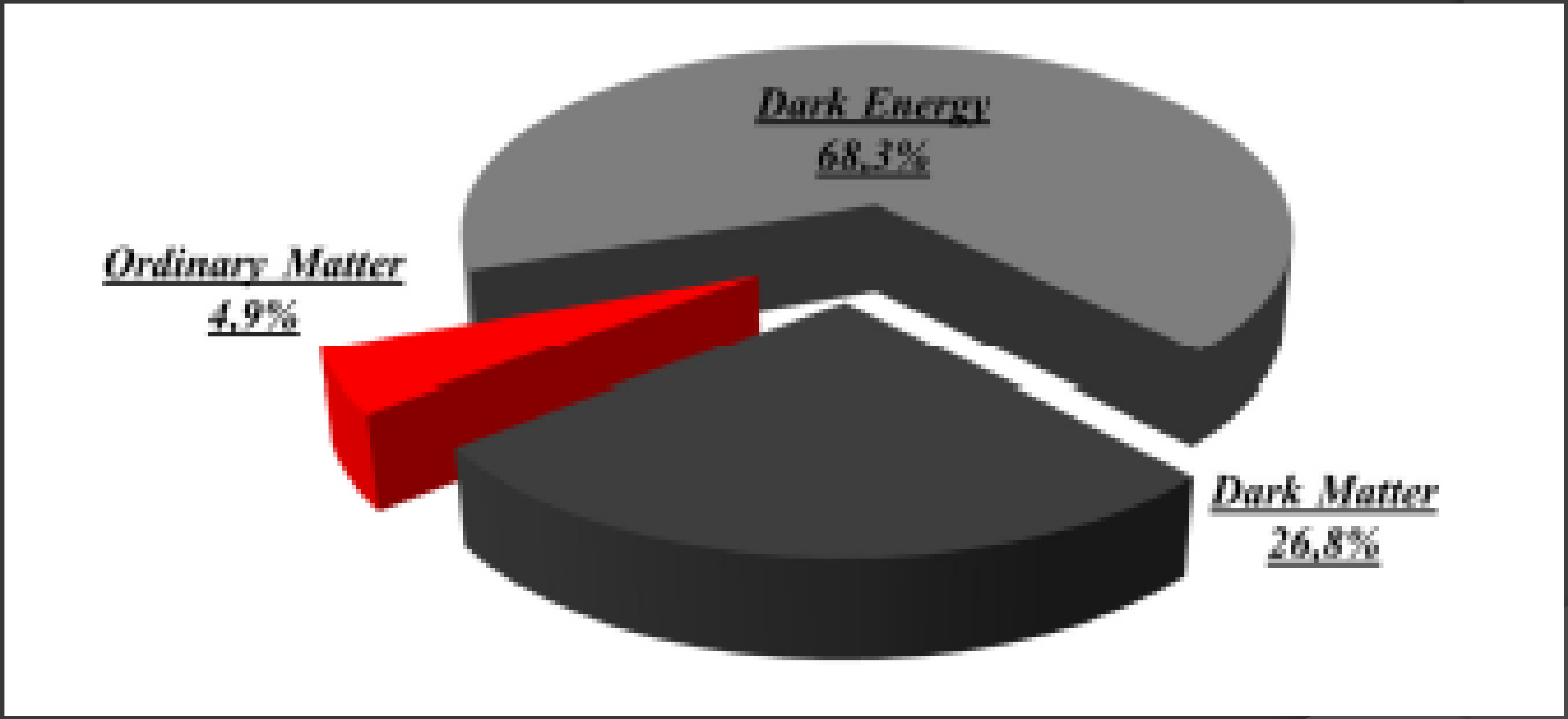


# EVIDENCE FOR THE DARK MATTER

- Gravitational lensing background objects by clusters of galaxies
- The temperature distribution of the hot gas in galaxies and clusters of galaxies

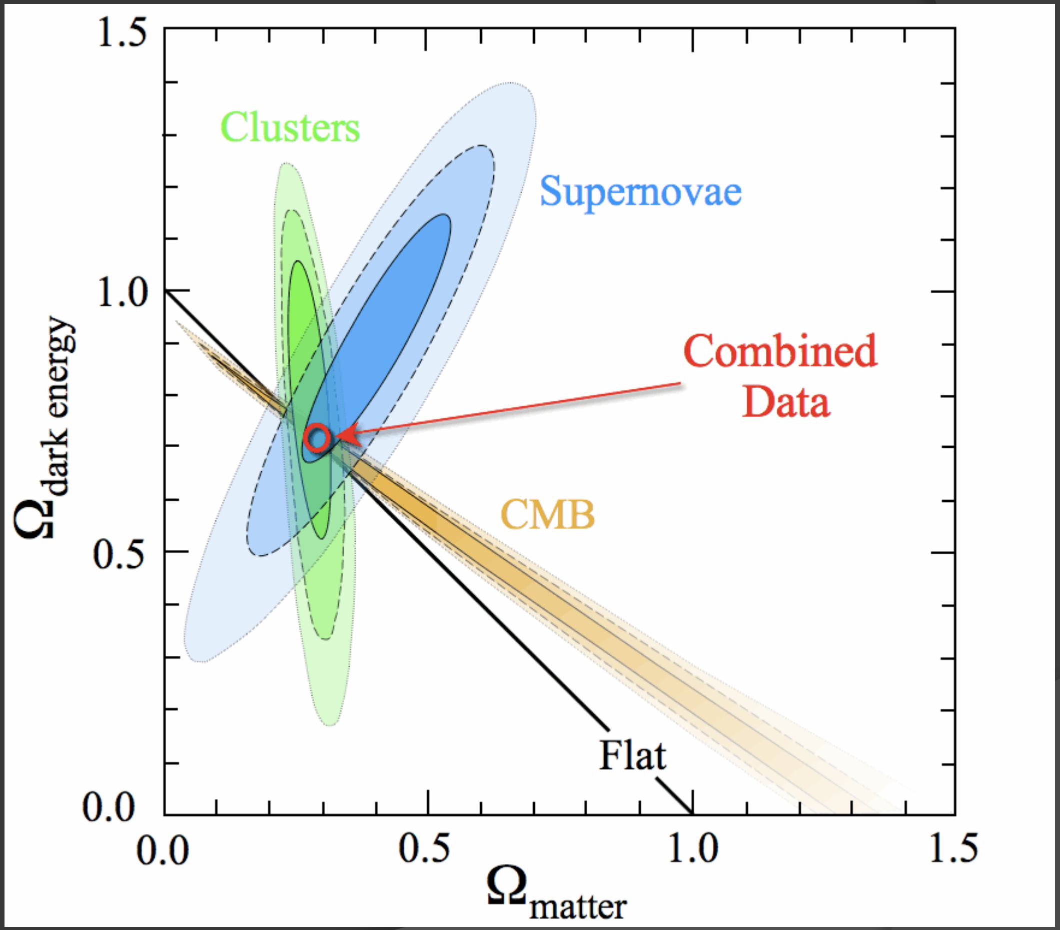
- Large scale structure formation
- Anisotropies in cosmic microwave background

# EVIDENCE FOR THE DARK MATTER



# EVIDENCE FOR THE DARK MATTER

- The Standard Cosmological Model (ΛCDM)
- The fit to data of different experiments tells us $\Omega_{DM} = 0.27$



# DARK MATTER CANDIDATES

- Particles of the Standard Model
- Particles of extensions of the Standard Model (heavy neutrinos, Higgs, axion, etc.)
- Supersymmetric particles (neutralino, axino, gravitino, sneutrino, etc.)
- Non-particle candidates, e.g. Massive compact halo objects – MACHO
- New physics mimicking the Dark Matter, e.g. Modified Newtonian Dynamics – MOND

# DARK MATTER CANDIDATES

- Constraints on the particle candidate from astrophysics and new particle searches
  - No electric charge
  - No colour charge
  - Weakly interacting
  - No strong self-interactions
  - Non-relativistic
  - Stable or very long-lived
- Weakly interacting massive particle (WIMP)

# DARK MATTER CANDIDATES

- In the Standard Model there are no particles obeying these constraints
- MACHOs mostly ruled out
- MOND has problems with weak lensing and cosmic microwave background

- The most popular candidate – predicted supersymmetric particle neutralino

# SUPERSYMMETRY

- Consistency of Grand Unification theory: unification of gauge coupling constants
- Solution to the hiearchy problem
- Radiative electroweak symmetry breaking. The Higgs boson mass is calculable.
- Supersymmetry populates «The Great Desert»: it predicts new particles and their spectrum
- Supersymmetry suggest a solution of the Dark Matter problem
- Supersymmetry can be tested experimentally

| | Bosons | Fermions | SU(3) | SU(2) | U(1) |
|---|---|---|---|---|---|
| **Matter fields** | | | | | |
| $L_i$ | | leptons $L_i = \begin{pmatrix} \nu \\ e \end{pmatrix}_L$ | 1 | 2 | -1 |
| $E_i$ | | $E_i = e_R$ | 1 | 1 | 2 |
| $Q_i$ | | quarks $Q_i = \begin{pmatrix} u \\ d \end{pmatrix}_L$ | 3 | 2 | 1/3 |
| $U_i$ | | $U_i = u_R$ | 3* | 1 | -4/3 |
| $D_i$ | | $D_i = d_R$ | 3* | 1 | 2/3 |
| **Gauge fields** | | | | | |
| $G^a$ | gluons $g^a$ | | 8 | 0 | 0 |
| $V^k$ | $W^{\pm}, Z$-bosons | | 1 | 3 | 0 |
| $V'$ | photon $\gamma$ | | 1 | 1 | 0 |
| **Higgs field** | | | | | |
| $H$ | Higgs boson $H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$ | | 1 | 2 | -1 |
| | | | | | |

| | Bosons | Fermions | SU(3) | SU(2) | U(1) |
|---|---|---|---|---|---|
| **Matter fields** | | | | | |
| $L_i$ | sleptons $\tilde{L}_i = \begin{pmatrix} \tilde{\nu} \\ \tilde{e} \end{pmatrix}_L$ | leptons $L_i = \begin{pmatrix} \nu \\ e \end{pmatrix}_L$ | 1 | 2 | -1 |
| $E_i$ | $\tilde{E}_i = \tilde{e}_R$ | $E_i = e_R$ | 1 | 1 | 2 |
| $Q_i$ | squarks $\tilde{Q}_i = \begin{pmatrix} \tilde{u} \\ \tilde{d} \end{pmatrix}_L$ | quarks $Q_i = \begin{pmatrix} u \\ d \end{pmatrix}_L$ | 3 | 2 | 1/3 |
| $U_i$ | $\tilde{U}_i = \tilde{u}_R$ | $U_i = u_R$ | 3* | 1 | -4/3 |
| $D_i$ | $\tilde{D}_i = \tilde{d}_R$ | $D_i = d_R$ | 3* | 1 | 2/3 |
| **Gauge fields** | | | | | |
| $G^a$ | gluons $g^a$ | gluino $\tilde{g}^a$ | 8 | 0 | 0 |
| $V^k$ | $W^{\pm}, Z$ - bosons | wino $\tilde{W}^{\pm}$, zino $\tilde{Z}$, | 1 | 3 | 0 |
| $V'$ | photon $\gamma$ | photino $\tilde{\gamma}$ | 1 | 1 | 0 |
| **Higgs fields** | | | | | |
| $H_1$ | Higgs boson $H_1 = \begin{pmatrix} H_1^+ \\ H_1^0 \end{pmatrix}$ | higgsino $\tilde{H}_1 = \begin{pmatrix} \tilde{H}_1^+ \\ \tilde{H}_1^0 \end{pmatrix}$ | 1 | 2 | -1 |
| $H_2$ | Higgs boson $H_2 = \begin{pmatrix} H_2^0 \\ H_2^- \end{pmatrix}$ | higgsino $\tilde{H}_2 = \begin{pmatrix} \tilde{H}_2^0 \\ \tilde{H}_2^- \end{pmatrix}$ | 1 | 2 | 1 |

# Neutralino – SUSY Dark Matter

- Neutralino – a mixture of superpartners of photon, Z-boson and neutral Higgs bosons

$$\tilde{\chi}^0 = N_1 \tilde{\gamma} + N_2 \tilde{z} + N_3 \tilde{H}_1^0 + N_4 \tilde{H}_2^0$$

  - Neutral (no electric charge, no colour)
  - Weakly interacting (due to SUSY)
  - Stable (!) if R-parity is conserved
  - Heavy enough to account for cold non-baryonic DM
  - Annihilation cross sections are known

$$R = (-1)^{3(B-L)+2S}$$

$$R_p = +1, \; R_{\tilde{p}} = -1$$

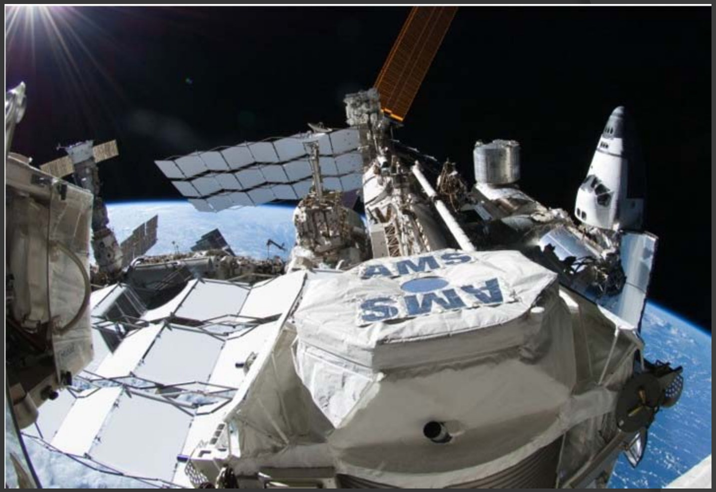
- Perfect candidate for dark matter particle

# DARK MATTER EXPERIMENTS

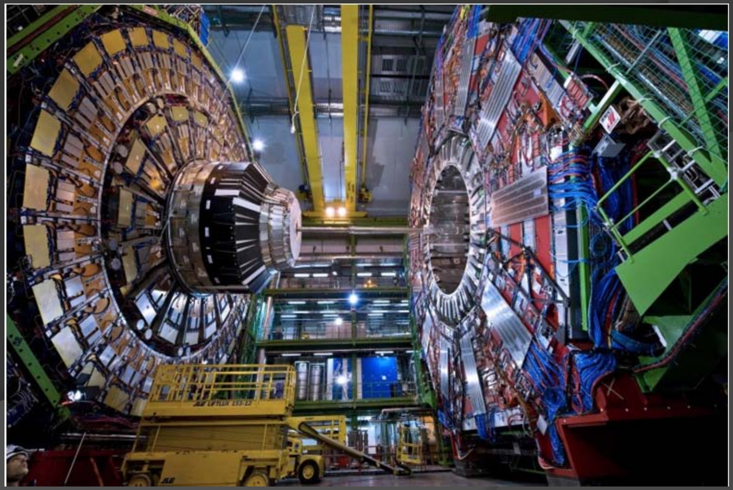
- If the Dark Matter is made up of WIMPs, then millions / billions of WIMPs must pass through every square centimeter of the Earth and its surroundings each second
- Direct detection: search for scattering processes in deep underground laboratory detectors

# DARK MATTER EXPERIMENTS

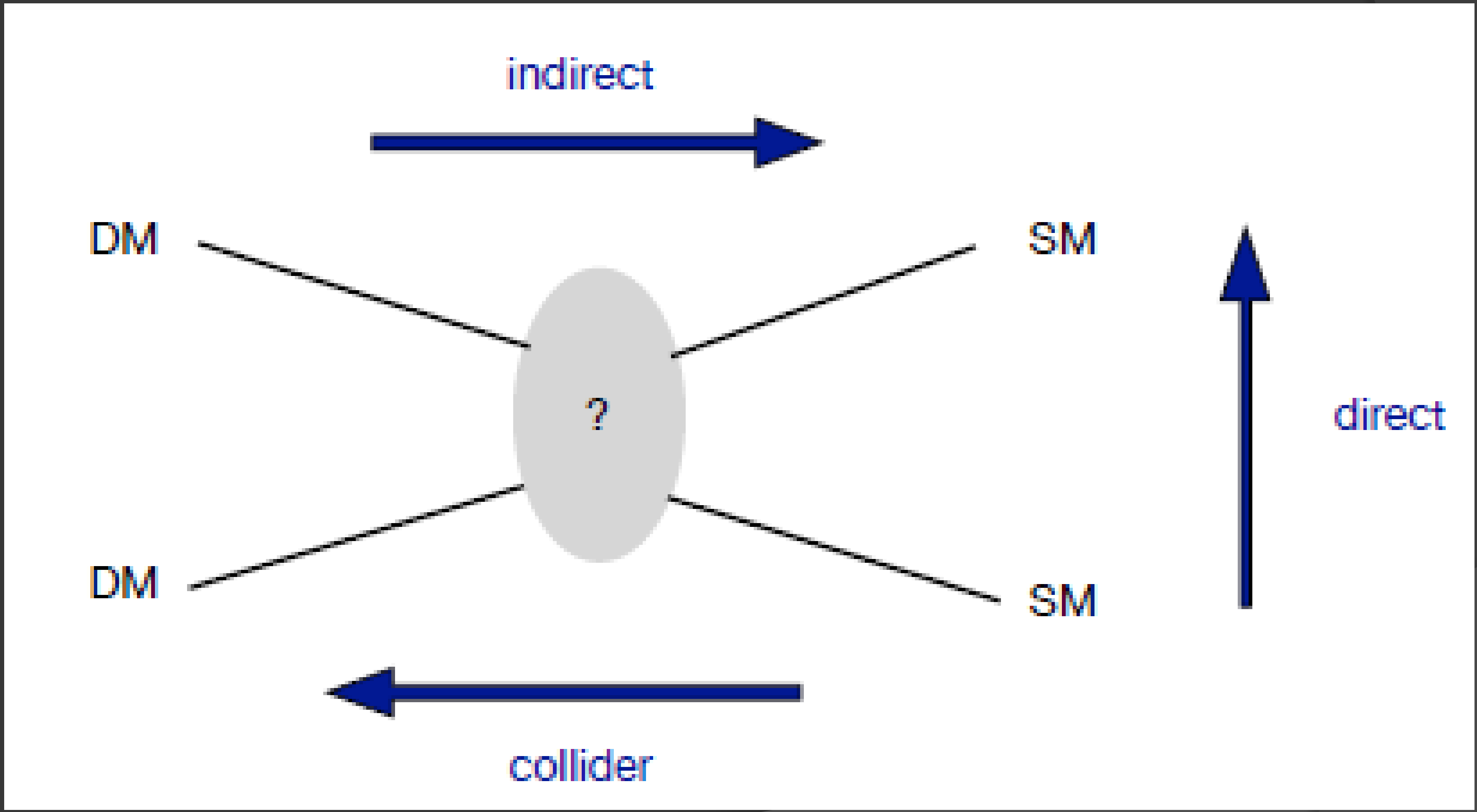
- Indirect detection: searches for processes of WIPMs annihilation (e.g. in cosmic space)




- Accelerator detection: creating WIMPs at colliders and study their properties



# DARK MATTER EXPERIMENTS



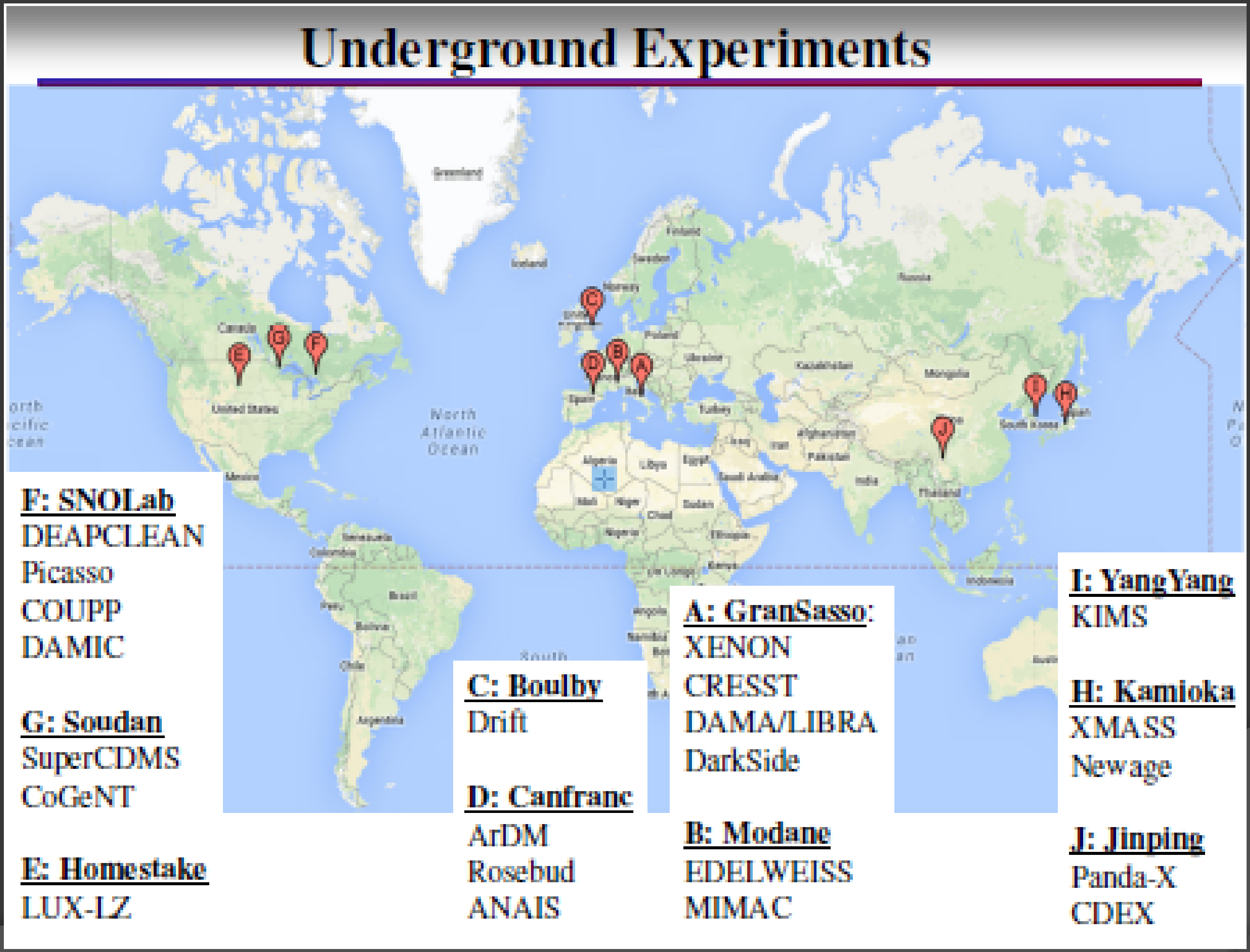
# DIRECT DARK MATTER DETECTION

- Cryogenic detectors, working at temperatures below 100mK, detect the heat produced when a particle hits an atom in a crystal absorber such as germanium
  - CDMS
  - CRESST
  - EDELWEISS
  - EURECA

# DIRECT DARK MATTER DETECTION

- Noble liquid experiments detect the flash of scintillation light produced by a particle collision in liquid xenon or argon
  - ZEPLIN
  - XENON
  - ArDM
  - WARP,
  - DarkSide
  - PandaX
  - LUX

# DIRECT DARK MATTER DETECTION

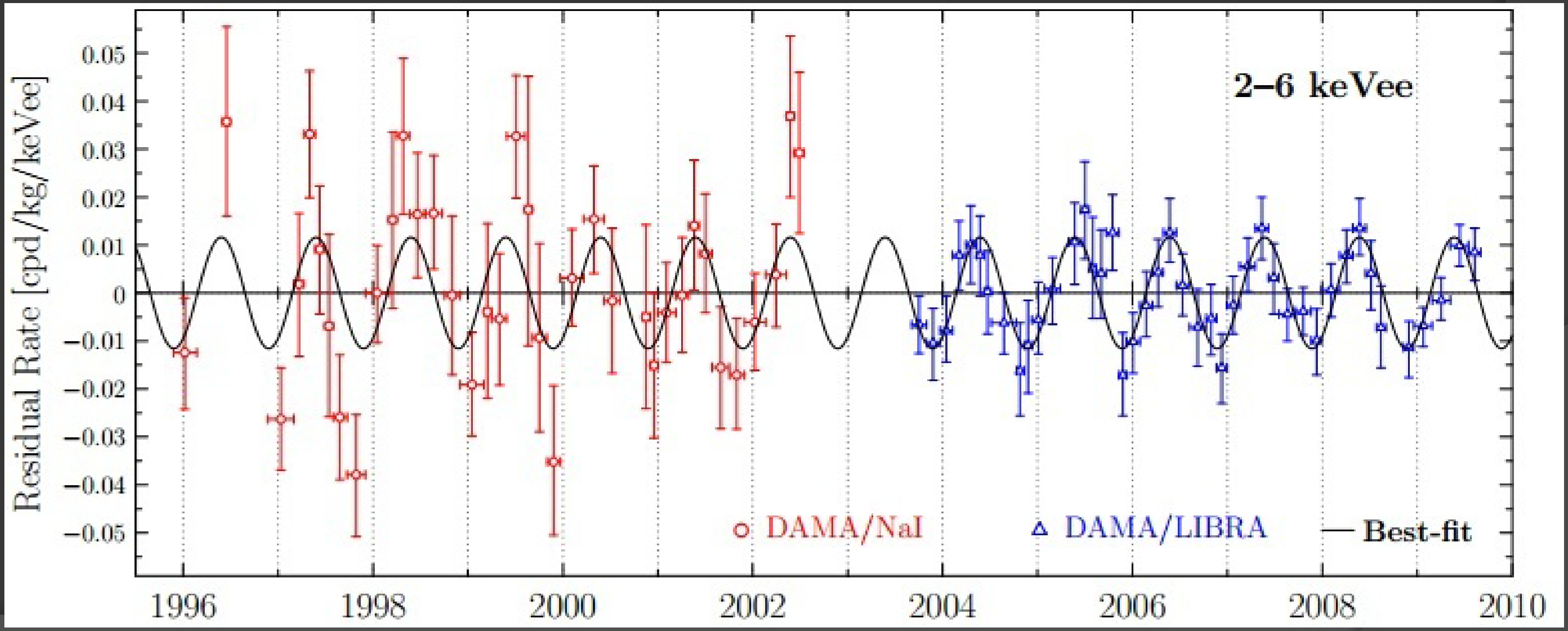


# DAMA/NaI, DAMA/LIBRA EXPERIMENT

- The DAMA/NaI, DAMA/LIBRA is a particle detector experiment designed to detect dark matter using the direct detection approach by using a scintilation NaI(Tl) detector
- DAMA/NaI detected an annual modulation in the event rate, which they claimed is due to dark matter particles

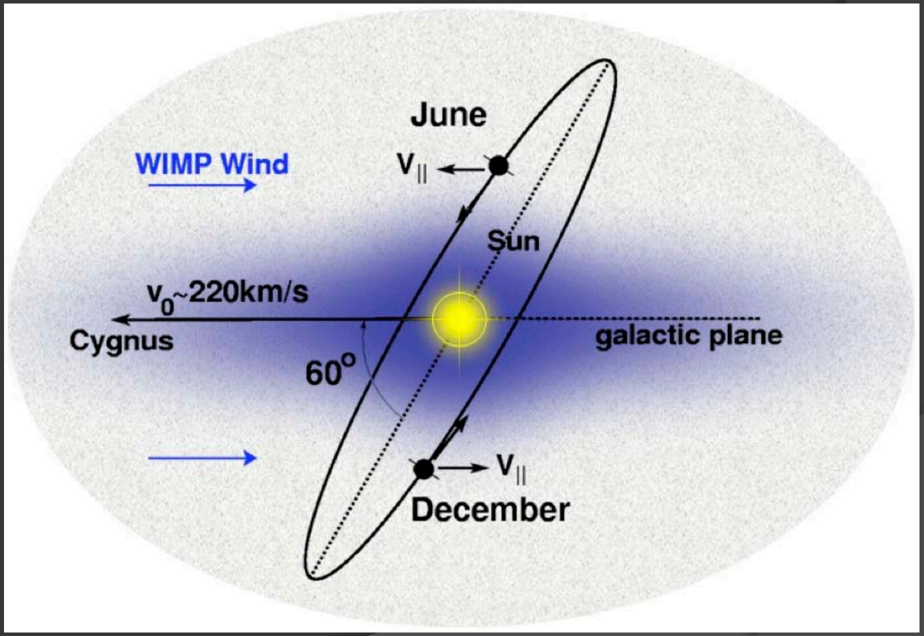
# DAMA/NaI, DAMA/LIBRA EXPERIMENT

- Final phase 1 results of DAMA/LIBRA were published in 2013, confirming an annual modulation

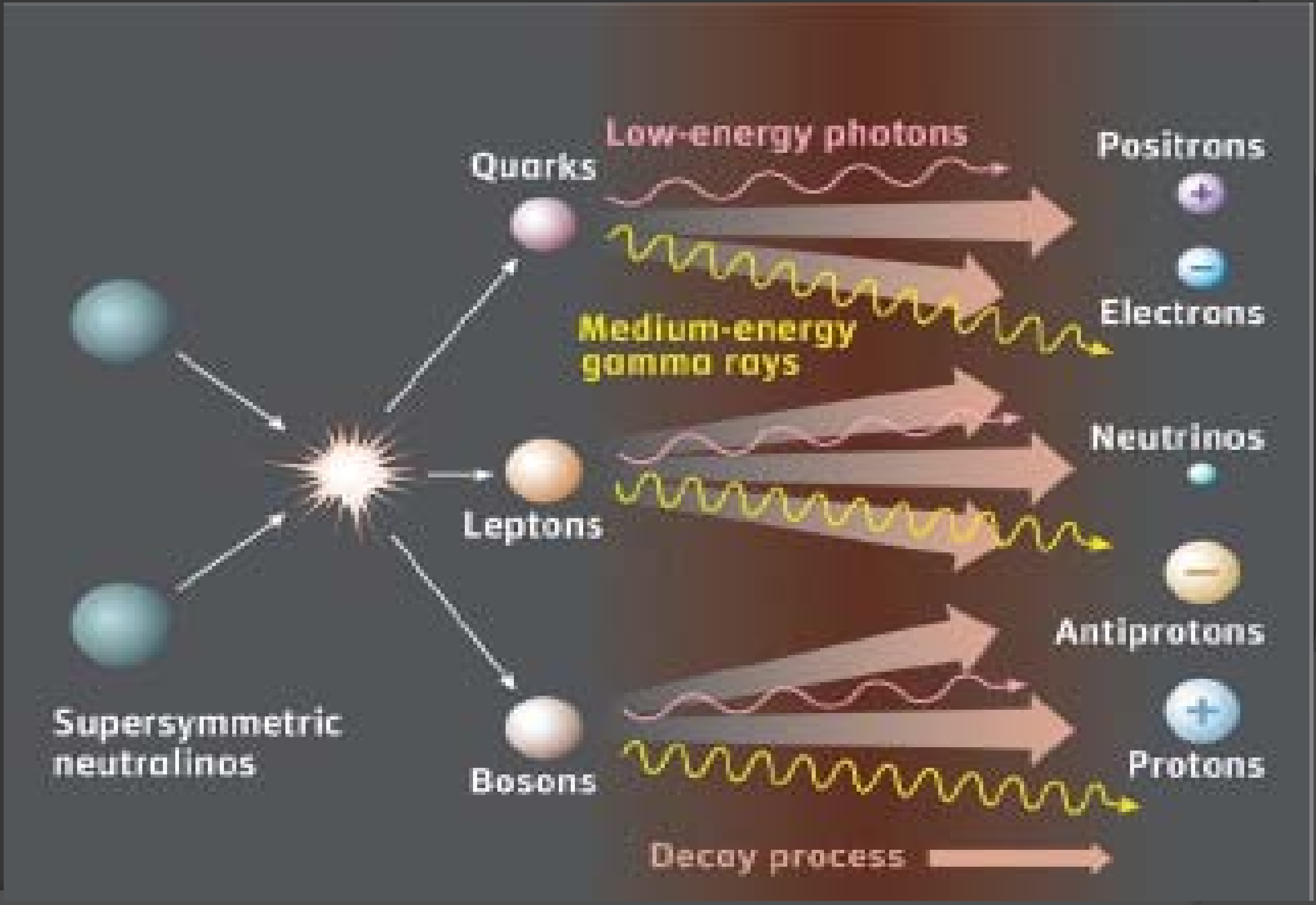


# DAMA/NaI, DAMA/LIBRA EXPERIMENT

- Possible explanation of the annual modulation is due to the variation of the velocity of the detector relative to the Dark Matter halo as the Earth orbits the Sun
- CoGeNt experiment also observes a similar modulation

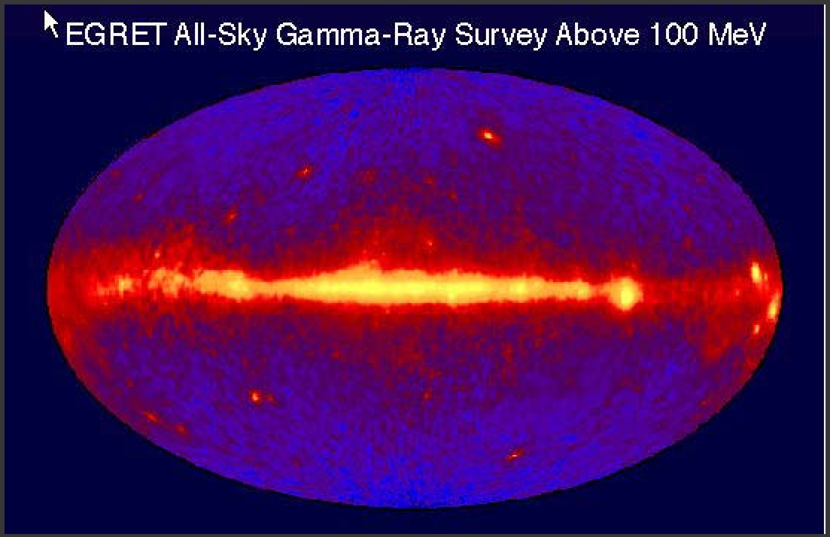


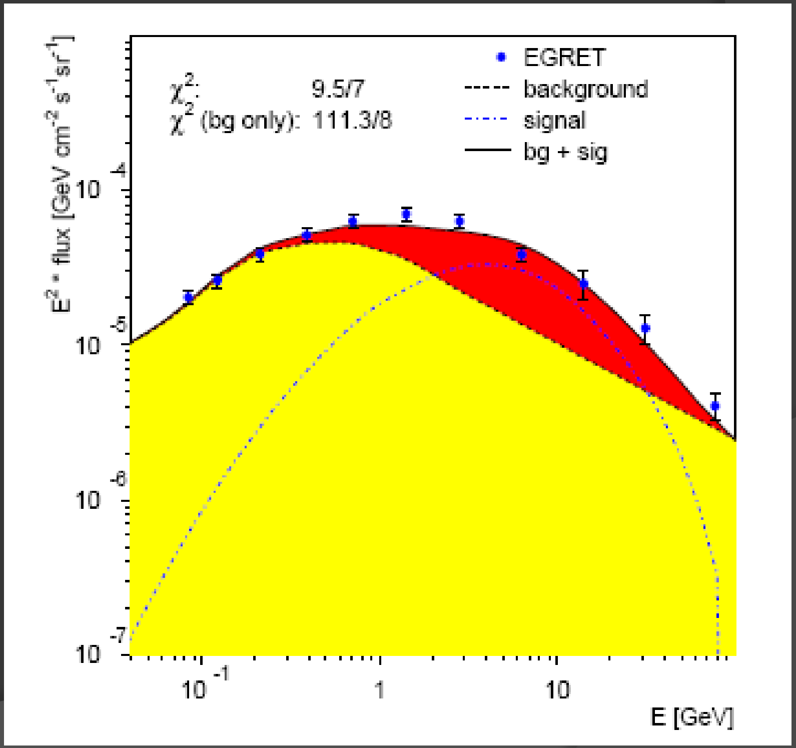
# INDIRECT DARK MATTER DETECTION



# EGRET EXPERIMENT

- EGRET Data on diffuse Gamma Rays show excess in all sky directions with the same energy spectrum

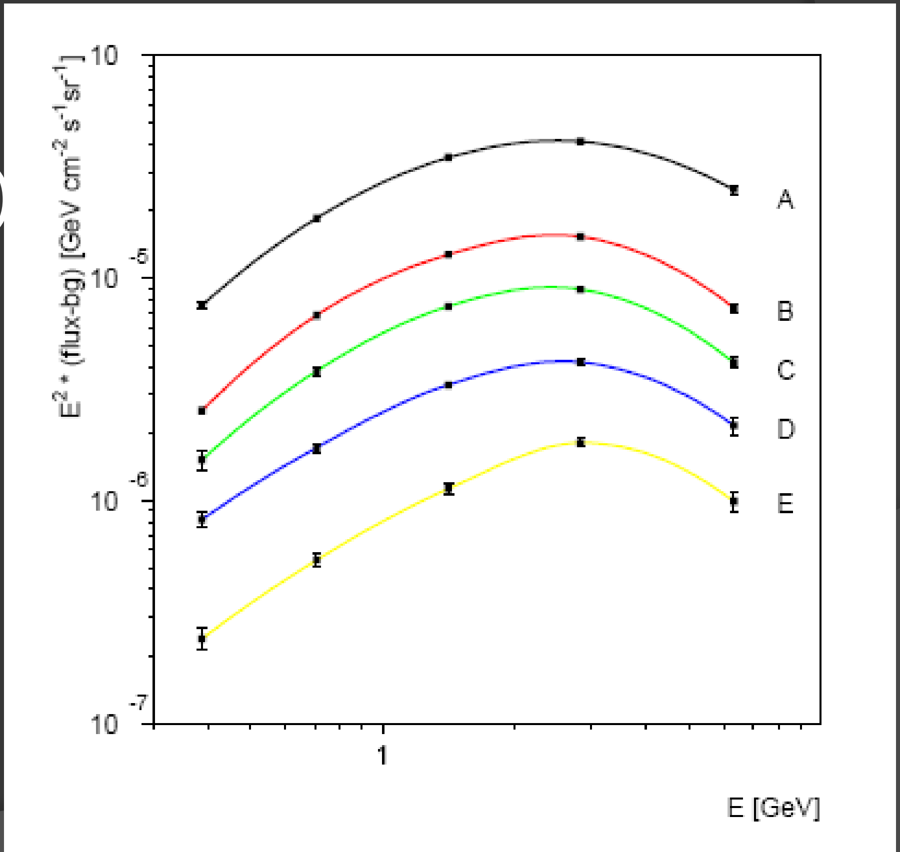


# EGRET Excess

A: Inner Galaxy (l=±30$^0$, |b|<5$^0$)
B: Galactic plane avoiding A (30-330$^0$)
C: Outer Galaxy (90-270$^0$)
D: Low latitude (10-20$^0$)
E: Intermediate lat. (20-60$^0$)
F: Galactic poles (60-90$^0$)

Excess has the same shape implying the same source

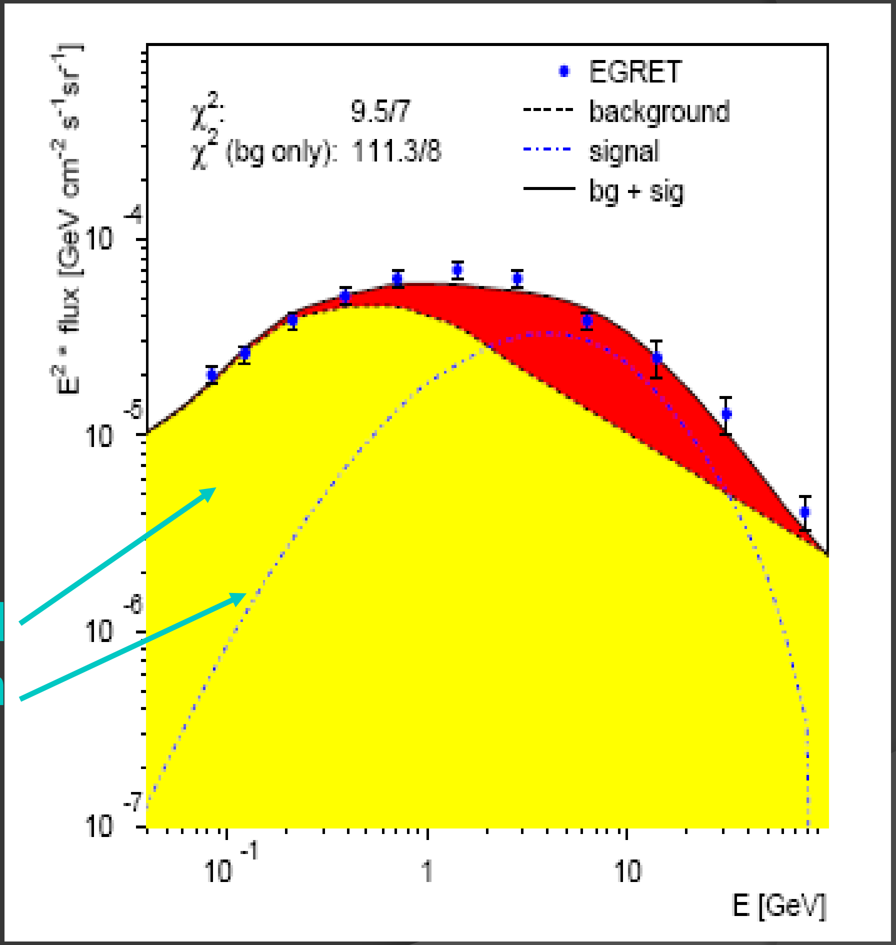


# EGRET data vs WIMP annihilation

- The excess of diffuse gamma rays is compatible with WIMP mass of 50 - 100 GeV

Background

WIMP contribution




- Region A: inner Galaxy ($l=\pm 30^0$, $|b|<5^0$)

# EGRET data vs WIMP annihilation

A: inner Galaxy ($l = \pm 30^0$, $|b| < 5^0$)
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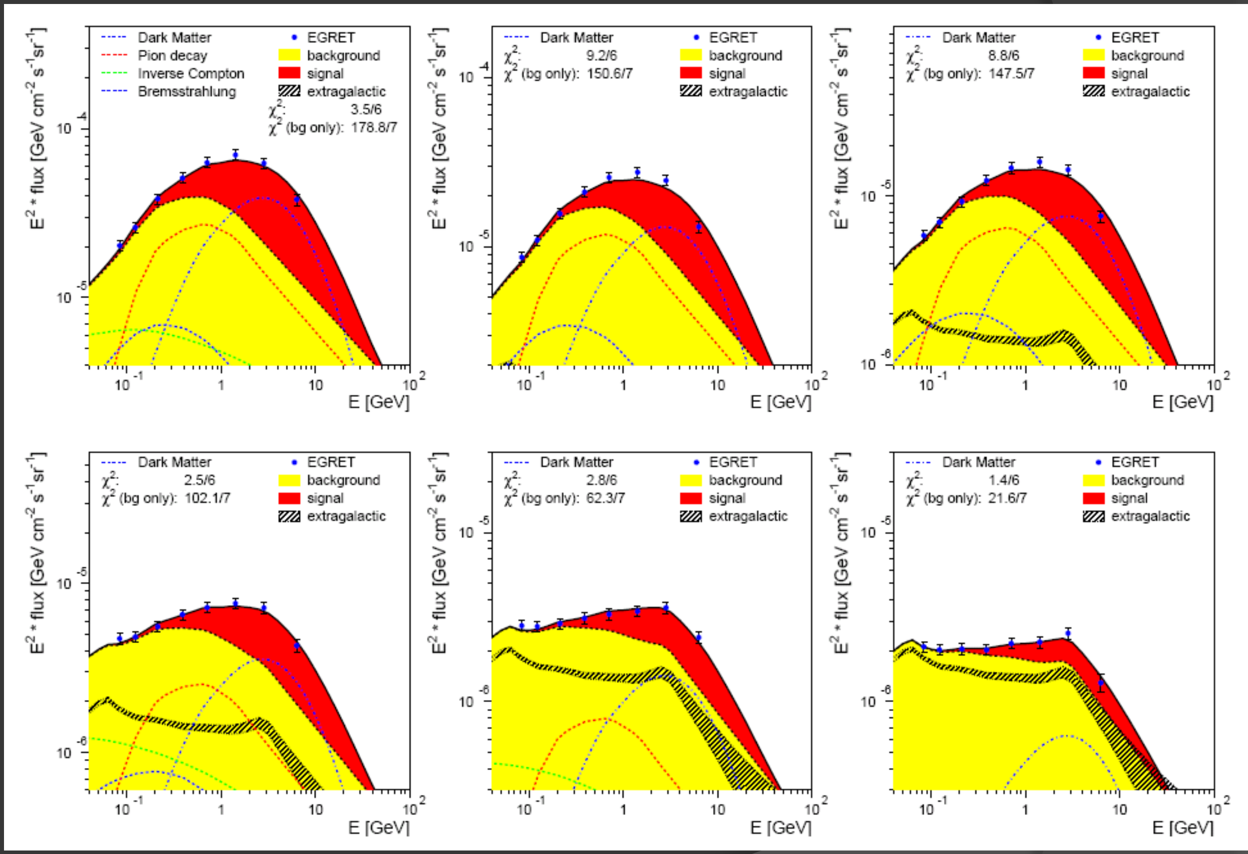


# Determination of halo profile

- The possible enhancement of DM density in the disc was parametrized by Gaussian rings in the galactic plane in addition to the expected triaxial profile. Ring parameters can be determined from a fit to the data.

$$\rho_\chi(\tilde{r}) = \rho_0 \left(\frac{R_0}{\tilde{r}}\right)^\gamma \left[\frac{1+\left(\frac{\tilde{r}}{a}\right)^\alpha}{1+\left(\frac{R_0}{a}\right)^\alpha}\right]^{\frac{\gamma-\beta}{\alpha}} + \sum_{n=1}^{N} \rho_n \exp\left(-\frac{(\tilde{r}_{gc}-R_n)^2}{2\sigma_{R_n}^2} - \frac{(z_n)^2}{2\sigma_{z_n}^2}\right)$$

=2

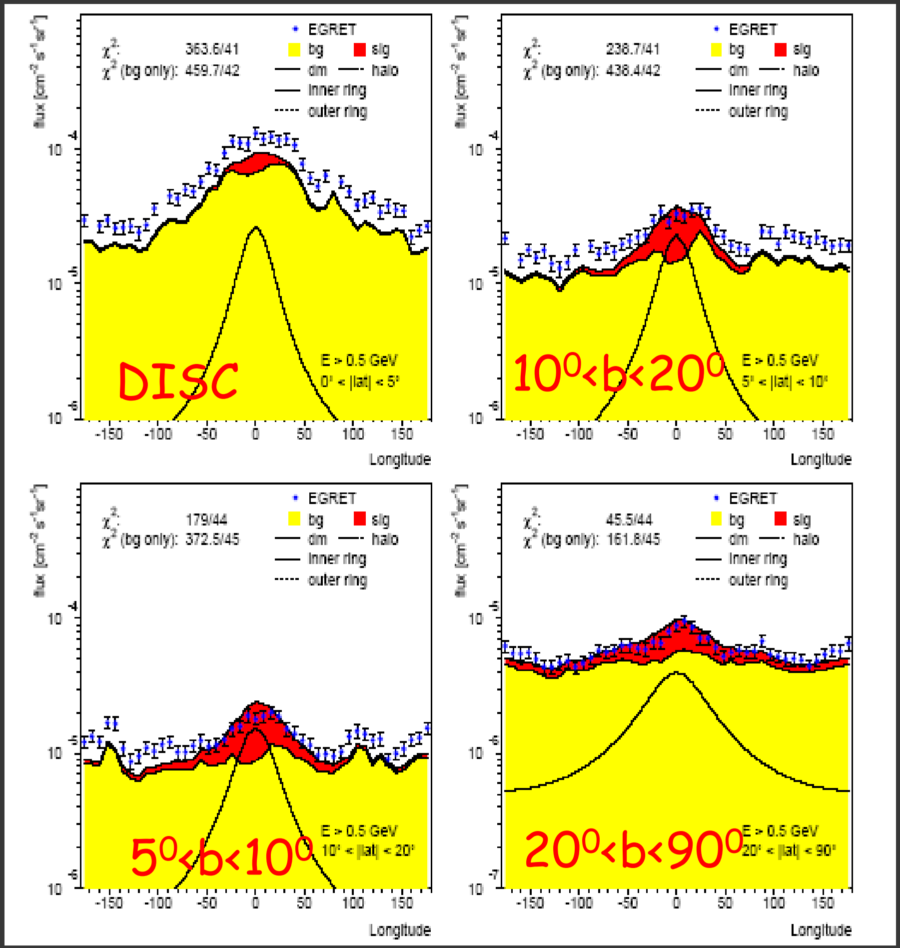
$\propto$ 1/r²

2 Gaussian ovals

$$\tilde{r} = \sqrt{\frac{x^2}{a^2}+\frac{y^2}{b^2}+\frac{z^2}{c^2}}, \qquad \tilde{r}_{gc} = \sqrt{\frac{x^2}{\tilde{a}^2}+\frac{y^2}{\tilde{b}^2}},$$

# Fits for $1/r^2$ profile with/without rings

WITHOUT rings



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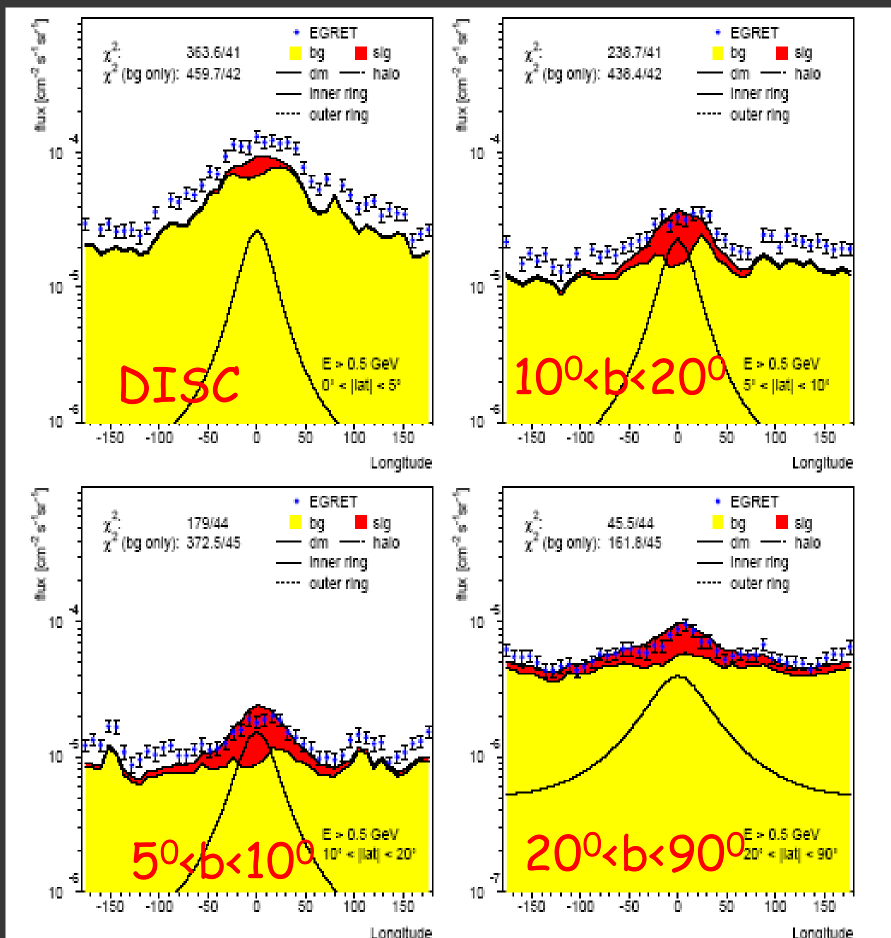
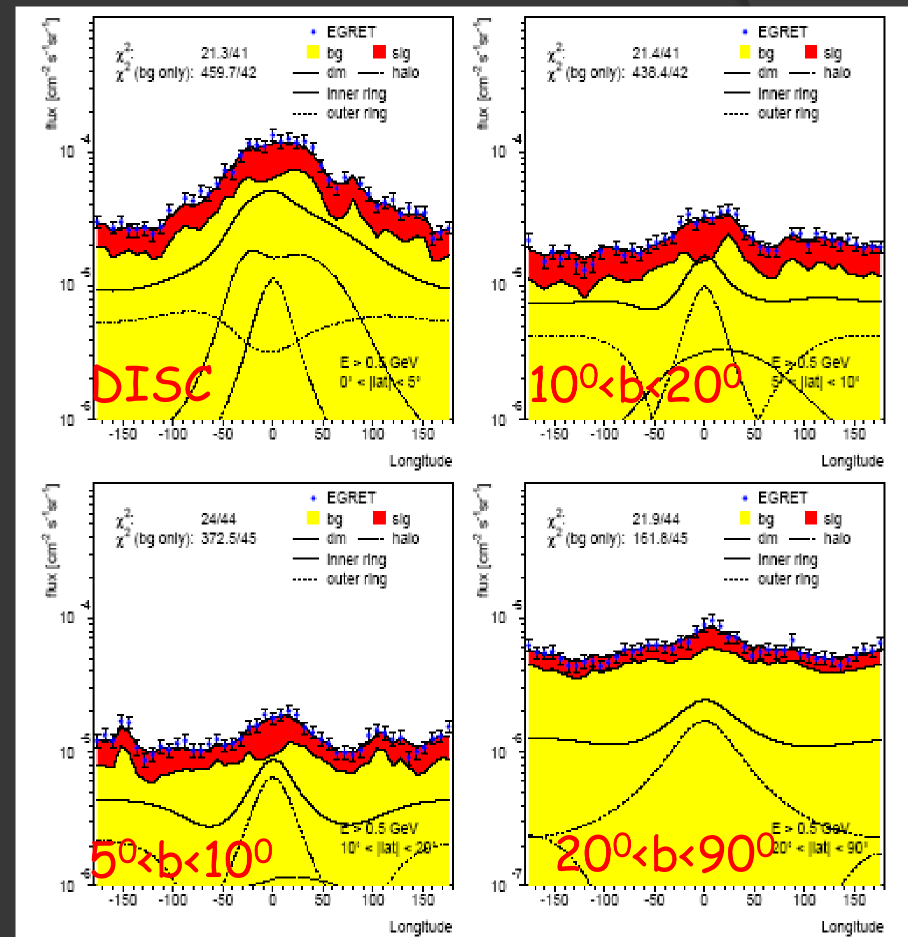


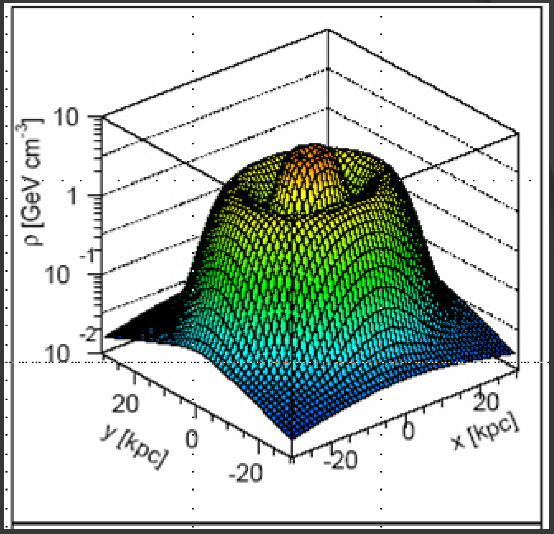

WITH 2 rings



# Fit results for halo profile

Fit results of halo parameters

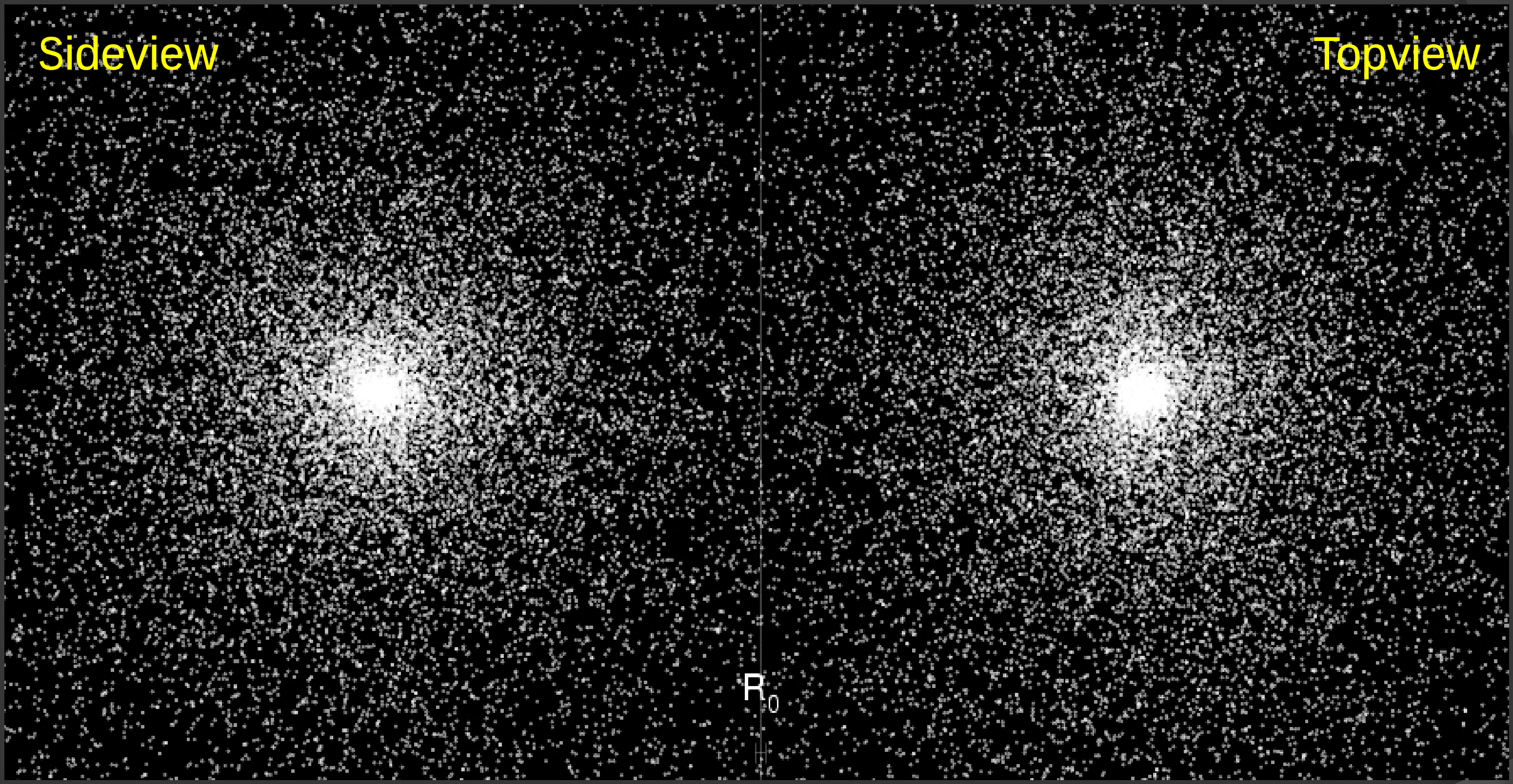
| Parameter | Value | Parameter | Value |
|---|---|---|---|
| $\alpha$ | 2 | $R_a$ | $4.3\ kpc$ |
| $\beta$ | 2 | $\sigma_{R,a}$ | $3.4\ kpc$ |
| $\gamma$ | 0 | $\sigma_{z,a}$ | $0.3\ kpc$ |
| $R_0$ | 8.5 kpc | $\rho_b$ | 1.2-2.1 GeV $\text{cm}^{-3}$ |
| $a$ | 4 kpc | $R_b$ | $14\ kpc$ |
| $\rho_0$ | 0.42 GeV $\text{cm}^{-3}$ | $\sigma_{R,b}$ | $2.1\ kpc$ |
| $\rho_a$ | 1.8-3.3 GeV $\text{cm}^{-3}$ | $\sigma_{z,b}$ | $1.3\ kpc$ |
| $b/a$ | 0.9 | $c/a$ | 0.8 |



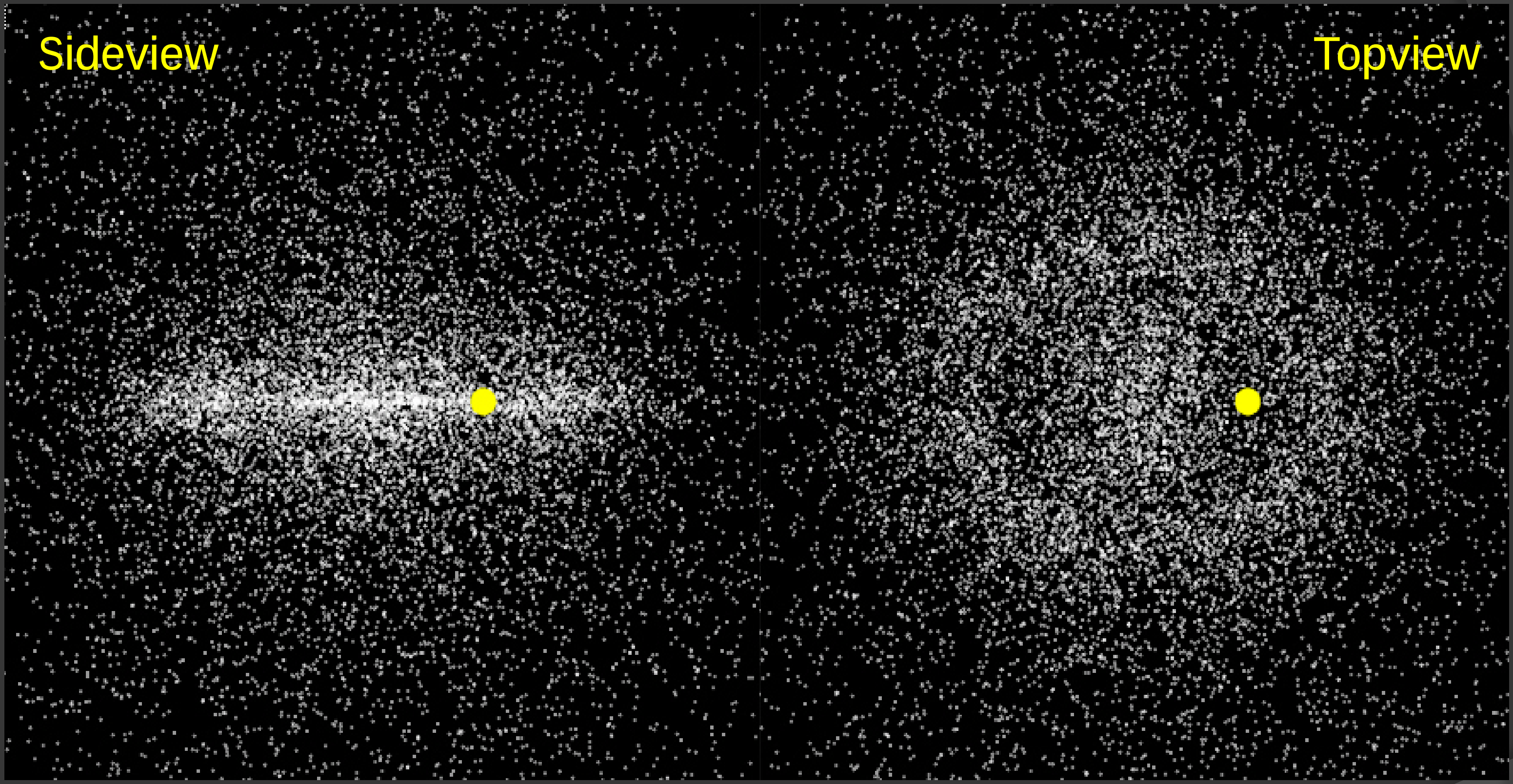

Enhancement of rings over $1/r^2$ profile 2 and 7, respectively.

Mass in rings 1.6% and 0.3% of total Dark Matter

# Halo density at 300 kpc



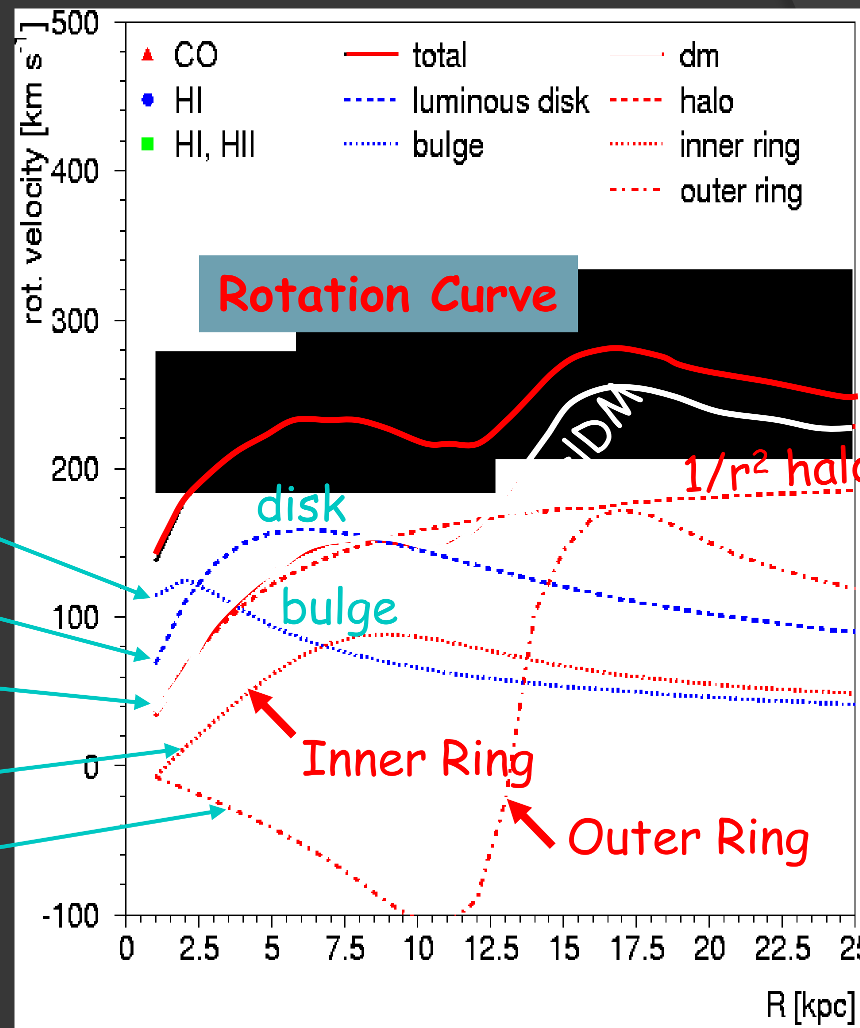
# Halo density at 30 kpc




Ring halo substructure. R ~ 4 and 14 kpc.

# The Milky Way rotation curve

- Contributions to the rotation curve of the Milky Way
  - Visible bulge
  - Visible disk
  - Dark halo
  - Inner dark ring
  - Outer dark ring



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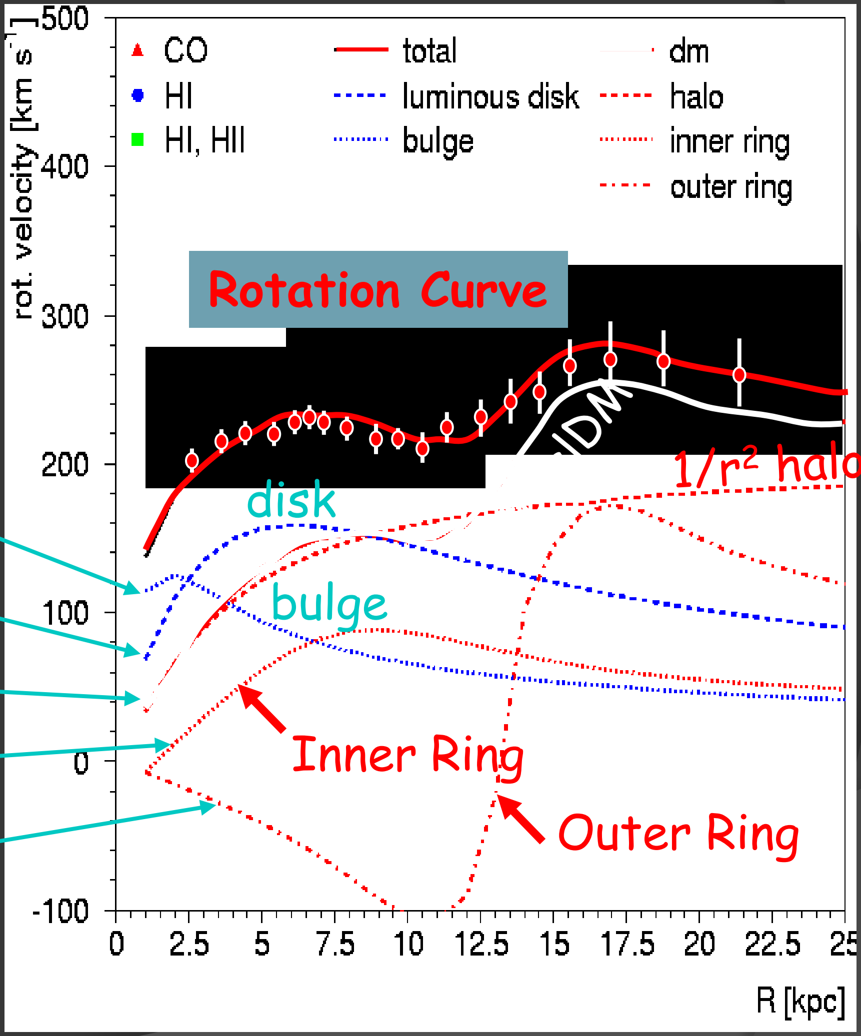
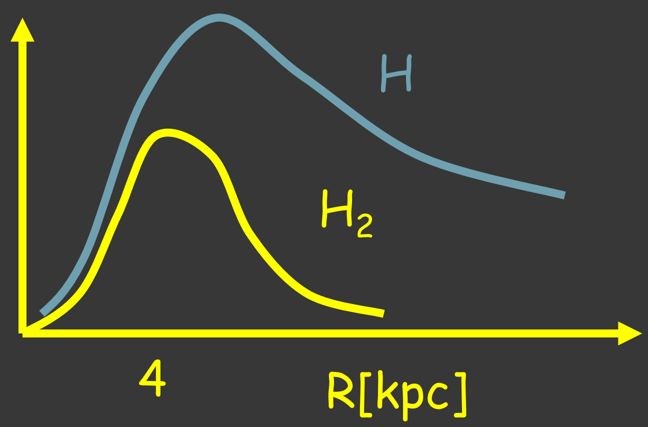
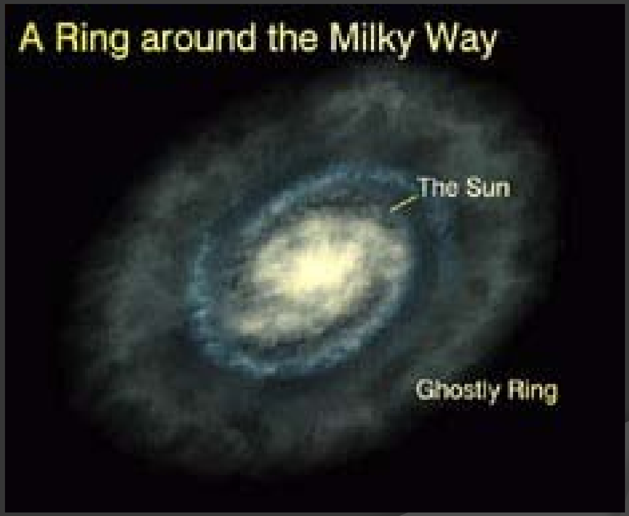


# Ring structures in the Milky Way

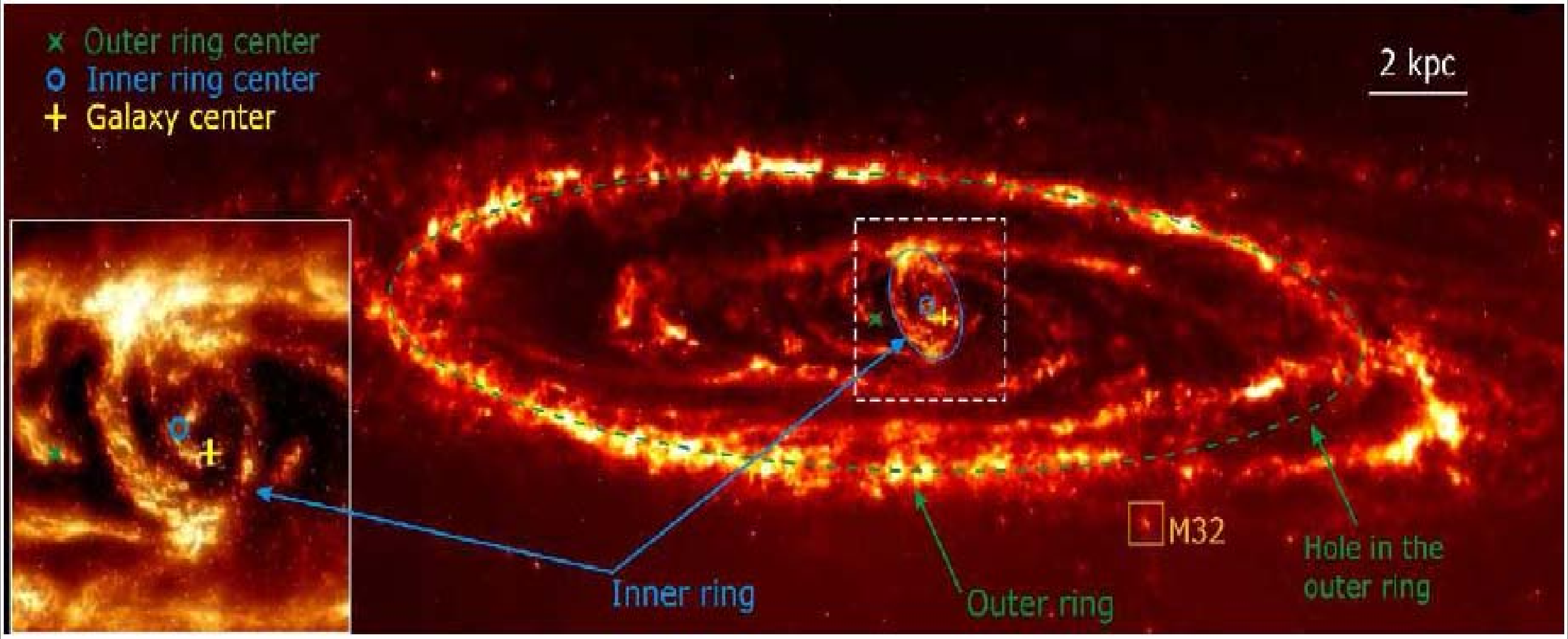
- 14 kpc coincides with ring of stars at 14-18 kpc due to infall of dwarf galaxy (Yanny, Ibata, ….., 2003)
- 4 kpc coincides with ring of neutral hydrogen molecules!



# Ring structure in Andromeda M31

- Astronomers observe ring structures in M31
- Outer ring (radius 10 kpc)
- Inner ring (elliptical 1 – 1.5 kpc)



# XENON EXPERIMENT

- XENON 10 (March 2006)
  - 25 kg of liquid Xe
  - limits on spin independent WIMP-nucleon cross sections down to $10^{-43}$ $cm^2$ for a 30 GeV WIMP
- XENON 100 (2008)
  - 165 kg of liquid Xe
  - most stringent limit on WIMP-nucleon cross section in 2012, $2.0 \times 10^{-45}$ $cm^2$ for a 65 GeV WIMP
  - Results constrain interpretations of signals in other experiments as dark matter interactions, and rule out exotic models

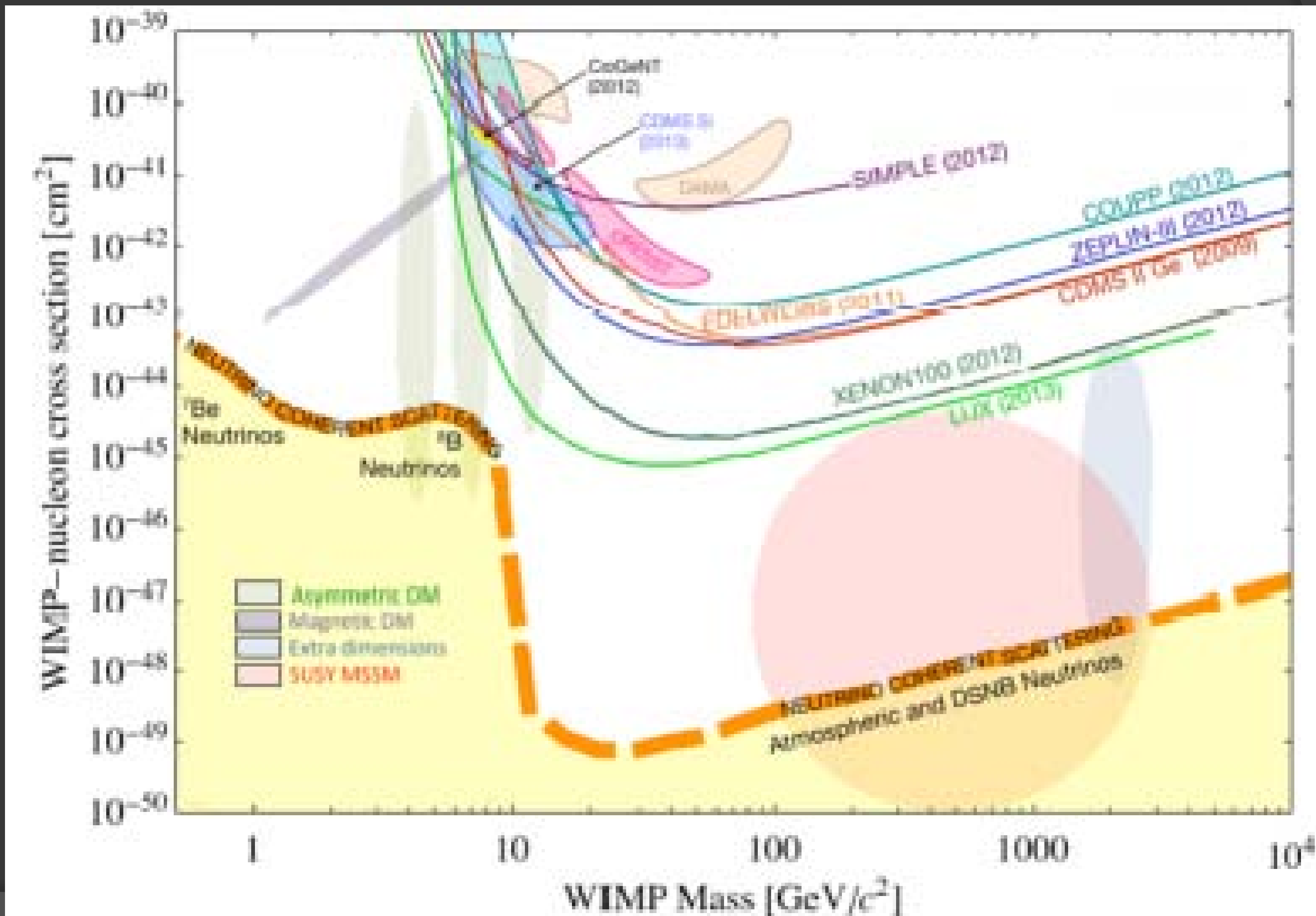
# XENON EXPERIMENT

- XENON 1T (construction started in 2014, operation planned for autumn 2015)
  - 3500 kg of liquid Xe
  - Predicted sensitivity is $2.0\times10^{-47}$ cm$^2$ for a 50 GeV WIMP (100 times lower than the XENON100 current limit)

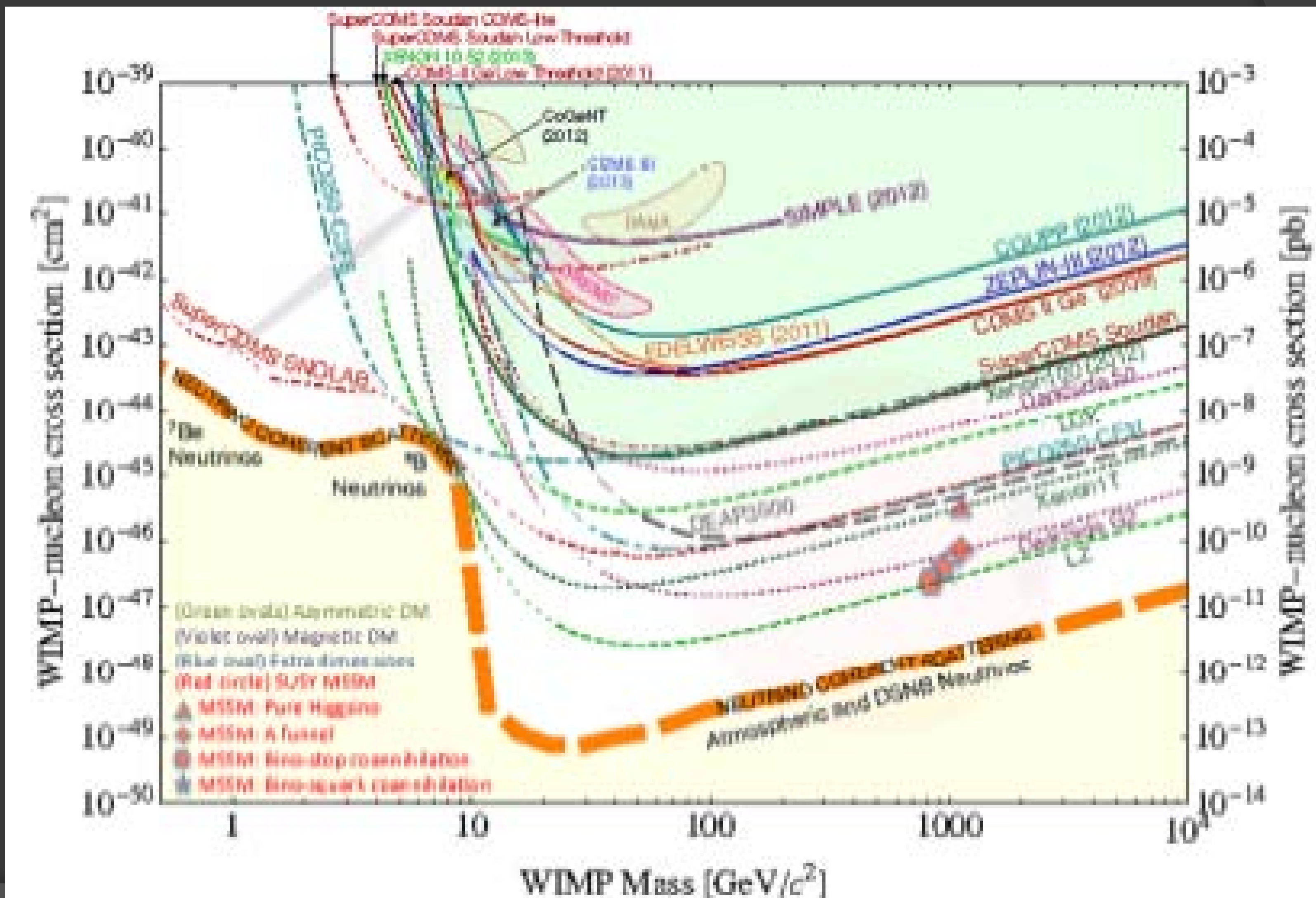
# LUX-ZEPLIN (LZ) EXPERIMENT

- LZ is a next generation dark matter experiment
- 30 institutes in the US, UK, Portugal, Russia
- 7000 kg of liquid Xe
- April 2016 – start of construction
- Feb 2019 – start of commisioning
- Projected sensitivity
  $2.0\text{x } 10^{-48}$ $cm^2$ for 50 GeV WIMP
  is expected to be finally limited by neutrino-induced `background’

# CURRENT STATUS



# CURRENT / FUTURE STATUS



# CONCLUSIONS

- We know from different observation that there is an invisible thing, interacting only gravitationally, we call it the Dark Matter
- We know from combination of different data the amount of the Dark matter: $\Omega_{DM} = 0.27$
- The candidate for the Dark Matter particle – WIMP (weakly interacting massive particle) with necessary properties
- One of the best WIMP candidate – neutralino

# CONCLUSIONS

- Annual modulation (DAMA, CoGeNt). The possible explanation is the change of the flux of WIMPs
- Direct detection experiments have excluded WIMP-nucleon cross-sections down to $10^{-8}$ pb = $10^{-44}$ cm$^2$
- Excess of the photons, positrons, antiprotons could be in principle explained as an effect of WIMP annihilation

# CONCLUSIONS

- By now, no unambiguous discovery of Dark Matter has been made
- The Dark Matter still remains a big mystery
- The future experiments will hopefully lower the exclusion limits for WIMP-nucleon cross-sections down almost to $10^{-12}$ pb = $10^{-48}$ cm$^2$
- Or we will detect it directly …
- Or we discover supersymmetry …