Dark matter phenomenon: general review and indirect searches

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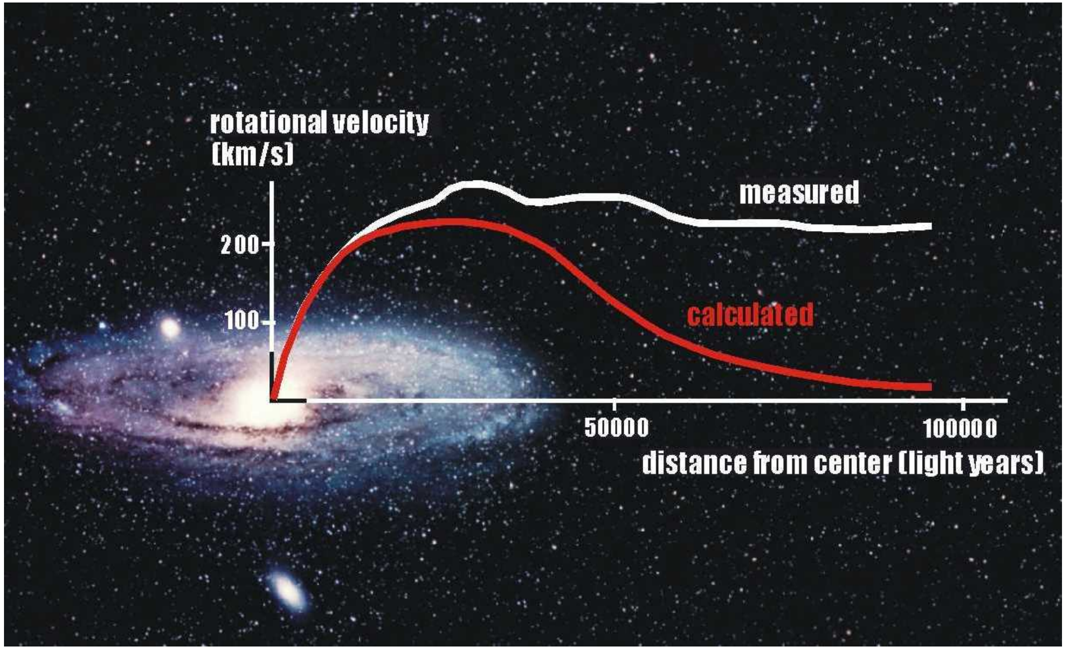
Talk outline

1. History of dark matter (DM) discovery.
2. DM in the early Universe and implications for models.
3. DM in the present Universe and implications for models.
4. Candidates for the role of DM: WIMPs, axions, sterile neutrinos, PBHs etc.
5. My work on WIMP indirect searches and constraints.
6. Future perspective.
7. Summary.

1. History of DM discovery.

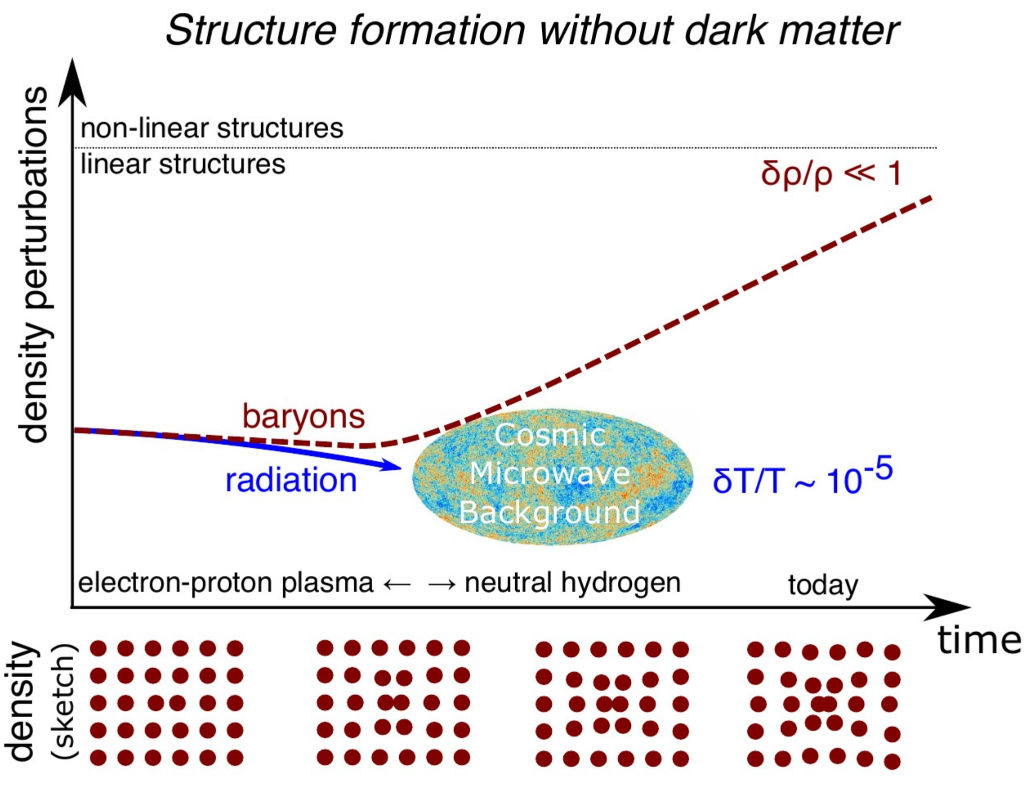
In 1930s: Fritz Zwicky found out a large difference between luminous and gravitating mass in Coma cluster, and Sinclair Smith found the same in Virgo cluster.

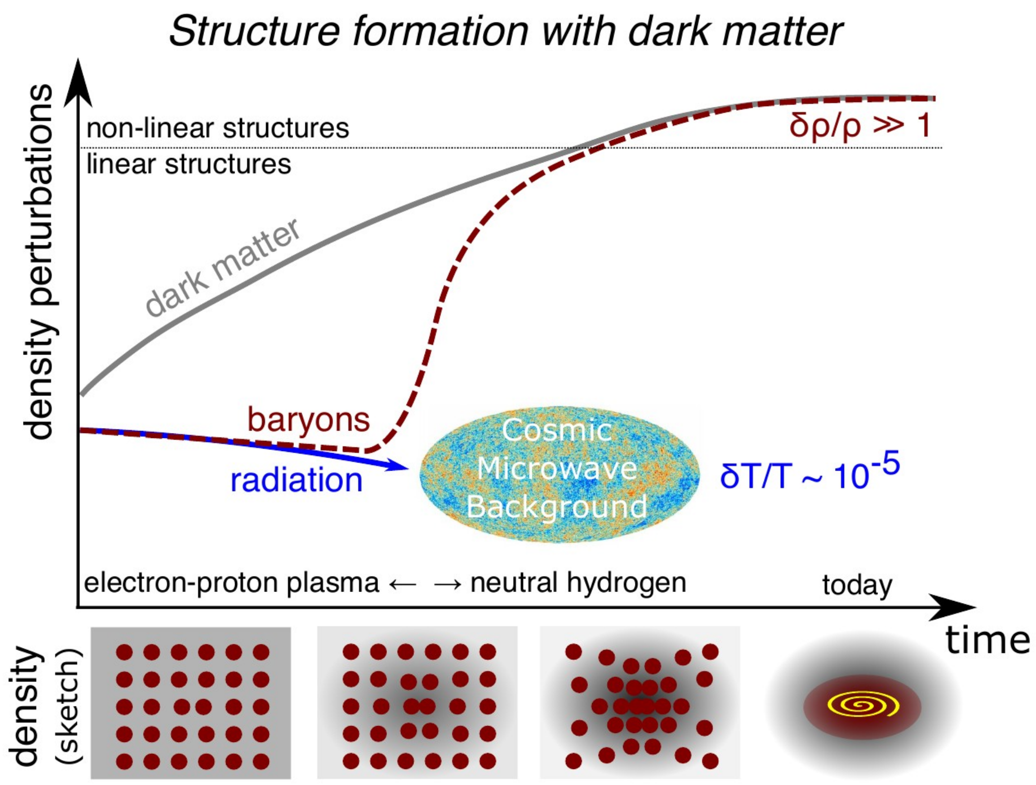


First indications of abnormally high mass-to-light ratios in galaxies were noticed back to 1930s too (Lundmark, Babcock). But wide acceptance came later in 1970s: Rubin & Ford, Freeman, Einasto et al., Bosma. Both optical and radio data played a big role.

2. Dark matter in the early Universe and implications for models.

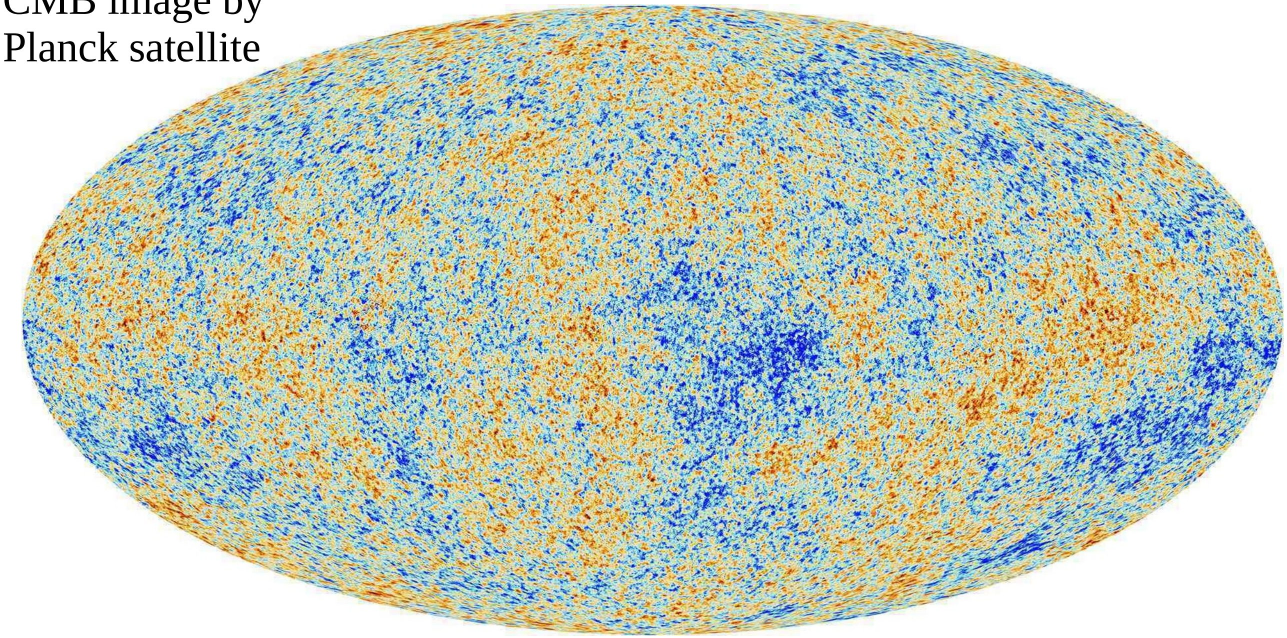
Structure formation in early Universe

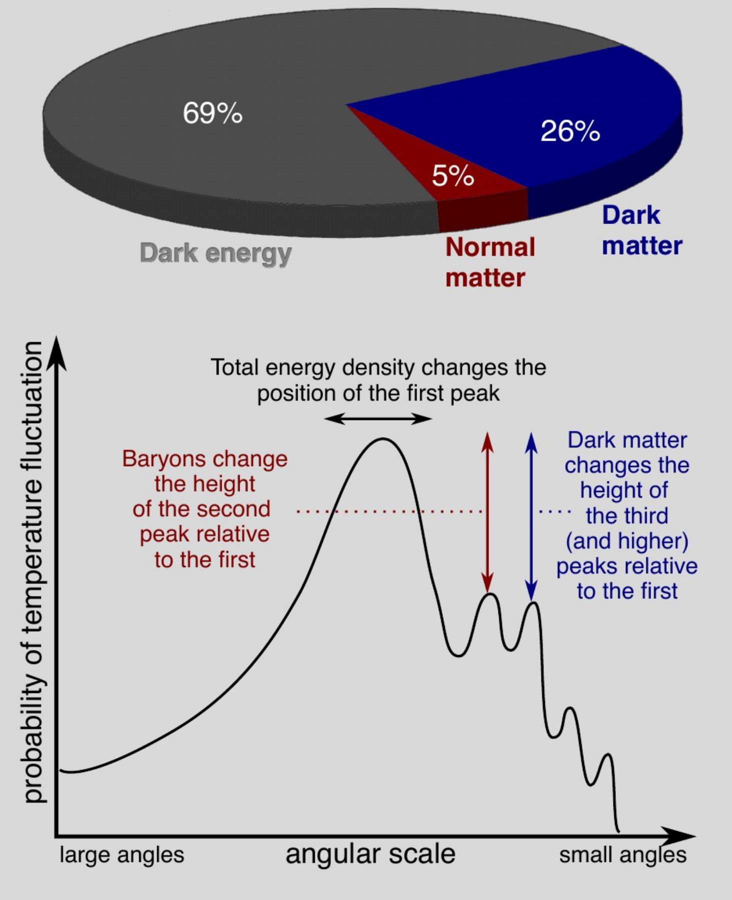




Precise cosmology from CMB measurements

CMB image by Planck satellite





Top: Composition of the present universe as inferred from CMB data. Bottom: Illustration of the effects of baryons and dark matter on the CMB temperature power spectrum.

<u>Brief history:</u>

1950-1960s – discovery of CMB;

1992 – first measurements of CMB spectrum (black body with T = 2.7 K) and anisotropies by COBE satellite;

XXI century – WMAP and Planck missions.

General DM properties from cosmology

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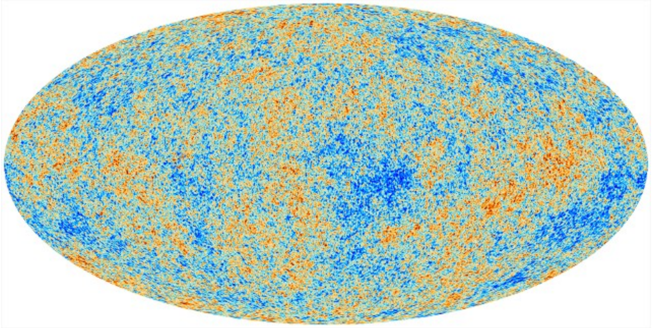
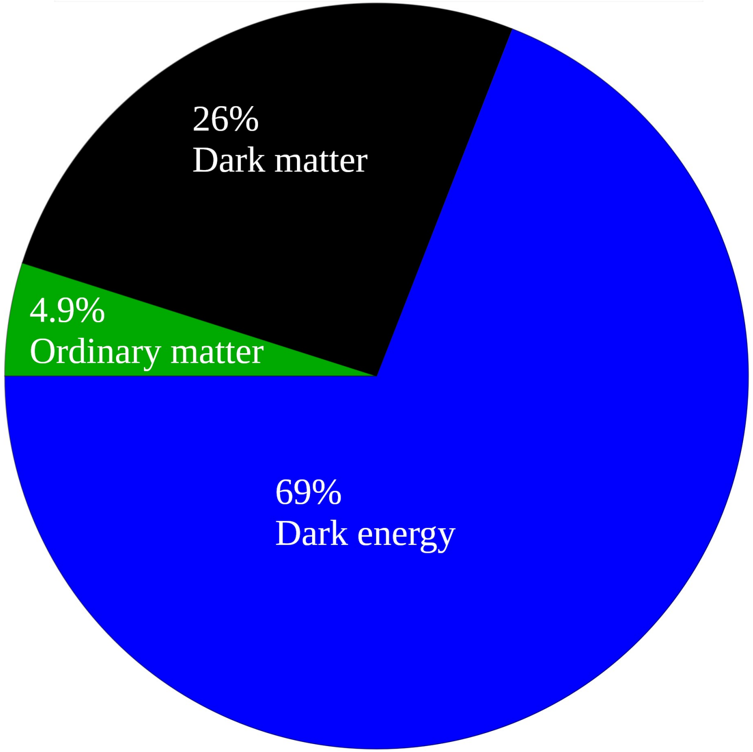




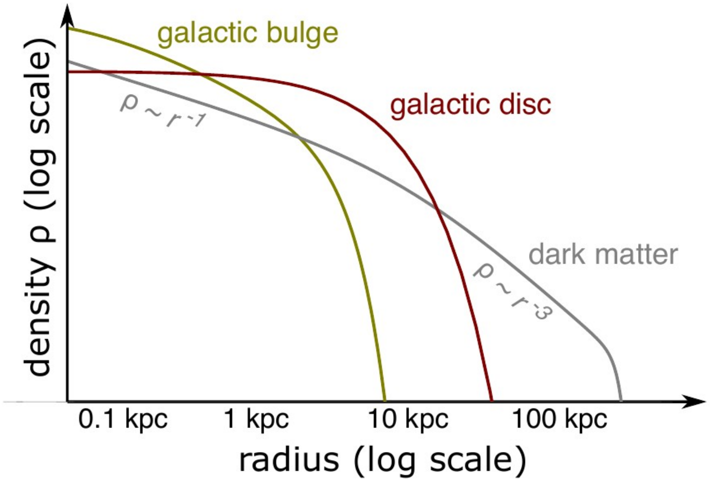
- DM bears 26% of the total energy density of Universe;
- is composed by non-SM particles most likely;
- is stable over the age of Universe;
- gravitates as usual matter;
- does not interact much through other SM forces;
- must be cold enough to form structures in the early Universe → m_x > few keV if produced thermally;
- Big Bang nucleosynthesis (BBN) independently confirms abundance and requires additionally m_x > few MeV in case of thermal production.

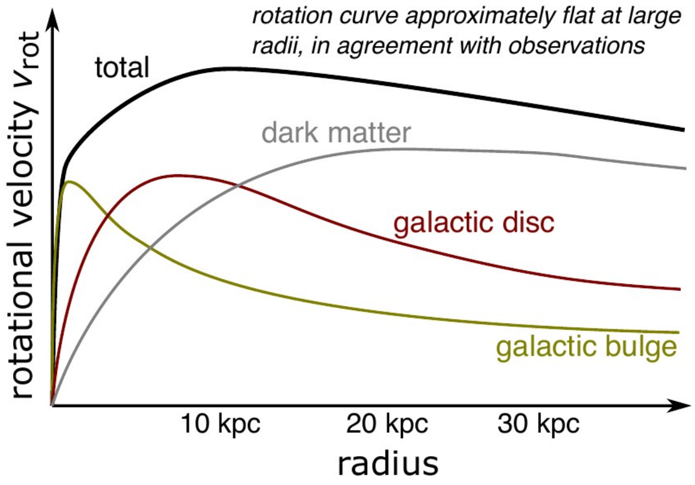
3. Dark matter in the present Universe and implications for models.

DM halos

Populate a very wide mass range from ~ 10^{-6} to 10^{15} $M_\odot$. The smallest halos are the densest and earliest. N-body CDM simulations derived *universal* halo density profiles:

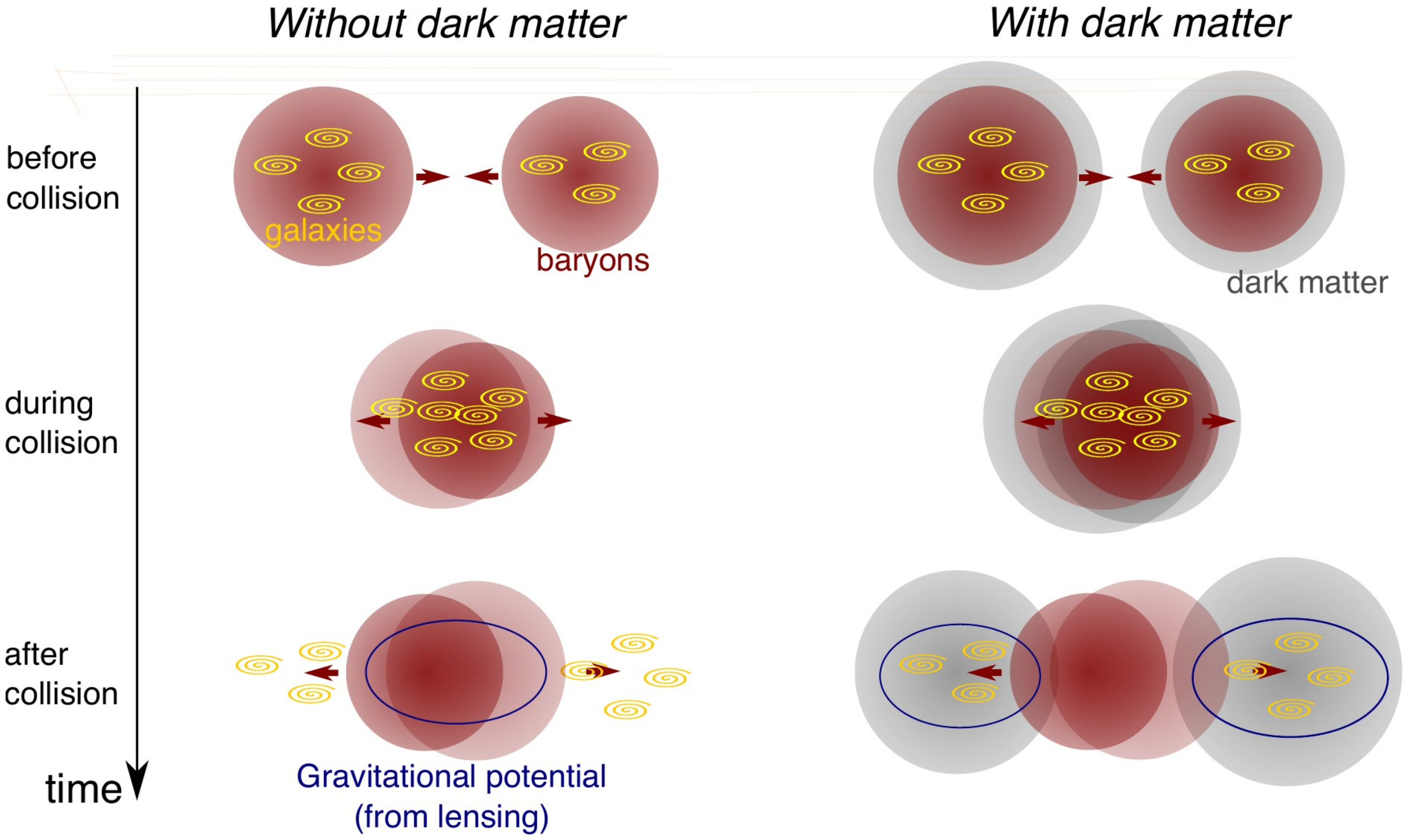
$$\rho(r) = \rho_s \frac{r_s}{r}\left(\frac{2}{1 + r/r_s}\right)^2$$ - NFW-1997.





$\rho(r_\odot = 8.4$ kpc$) \approx 0.4$ GeV/cm^3, $f(v) \propto v^2 \exp\left(-\frac{v^2}{v_0^2}\right)$, $v_0 \approx 240$ km/s, $M \approx 10^{12}$ $M_\odot$

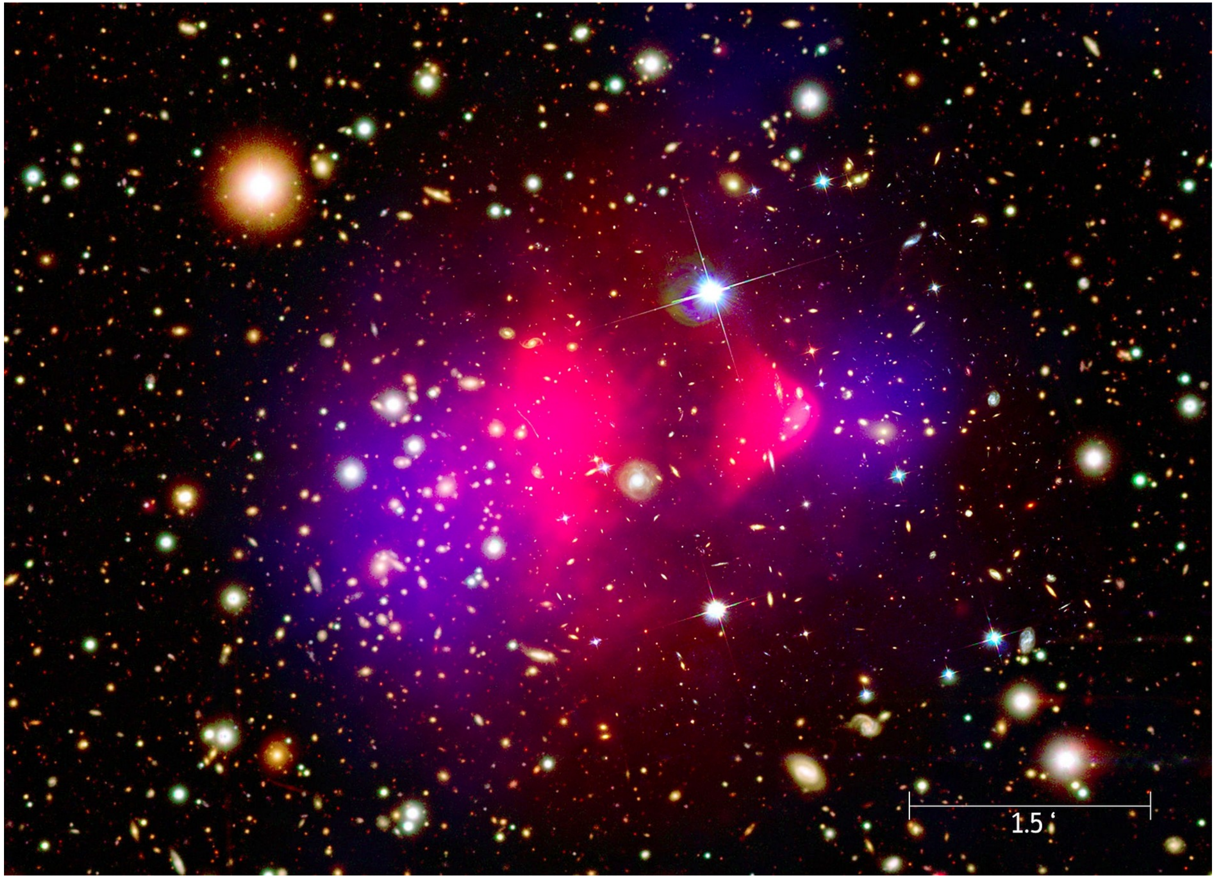
DM in galaxy clusters



Excludes MOND!

DM in galaxy clusters - 2

Bullet cluster



In general, gas temperature in clusters matches the global dark/visible matter ratio.

$$\sigma_{\rm self}/m_{\rm DM} \lesssim 2\,{\rm cm}^2\,{\rm g}^{-1}.$$

4. Candidates for the role of DM.

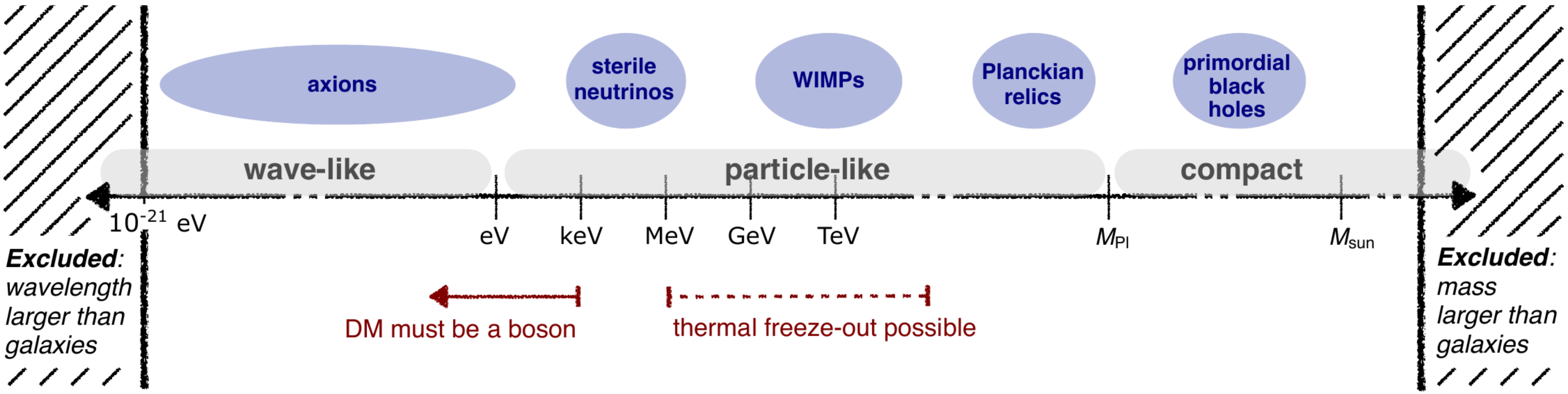
Main candidates for the role of DM

Subject of my work: Weakly Interacting Massive Particles (WIMPs)

Basic mass limits

The densest known DM entities – dwarf spheroidal galaxies (MW satellites) – provide:

- for fermionic DM $m_x \gtrsim 500$ eV – Tremaine-Gunn bound from Pauli exclusion principle (1979);
- for bosonic DM $m_x \gtrsim 10^{-21}$ eV – for de Brogile wavelength to fit the galaxy size.



WIMP DM

- Historically WIMPs have been the most probable candidate for the role of DM.
- WIMPs are a wide class of supersymmetric particles, which are spin partners of SM particles. The most motivated particle is typically the lightest **neutralino (χ)**, which is Majorana fermion.
- WIMP mass is theoretically expected to lie in the range from **few GeV up to ~ 100 TeV.**
- In a simple scenario, WIMPs were **produced thermally** in the early Universe.
- WIMPs are theoretically predicted to annihilate with each other producing SM particles:

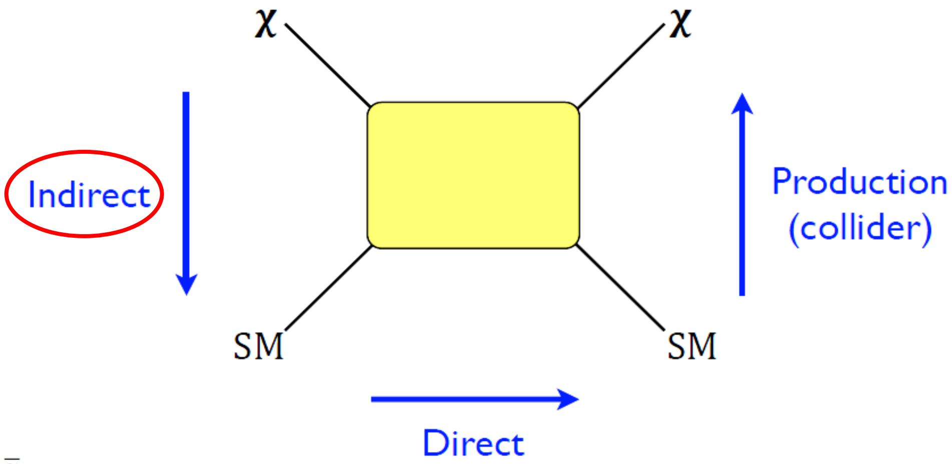
$$\chi + \chi \longleftrightarrow SM + \overline{SM}$$

- WIMP annihilation cross section is usually treated as **<σ*v*>**, since σ*v* is supposed to be velocity-independent in the first approximation ($\sigma \propto 1/v$ – Bethe law for scattering in QM).
- The cross section sets WIMP abundance in Universe in the frame of thermal production:

$$\Omega_\chi \propto 1/\langle\sigma v\rangle,\ \Omega_\chi \approx 0.3 \Leftrightarrow \langle\sigma v\rangle \approx 2\cdot 10^{-26}\ \mathrm{cm}^3/\mathrm{s}.$$

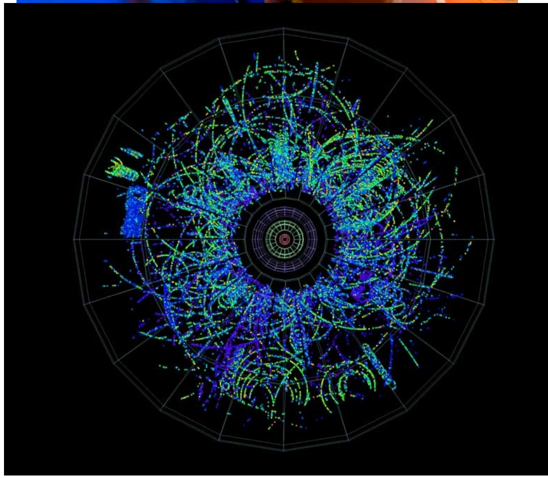
- So-called **WIMP miracle**: weak interaction cross section (assumed for annihilation) ~ necessary thermal production cross section!

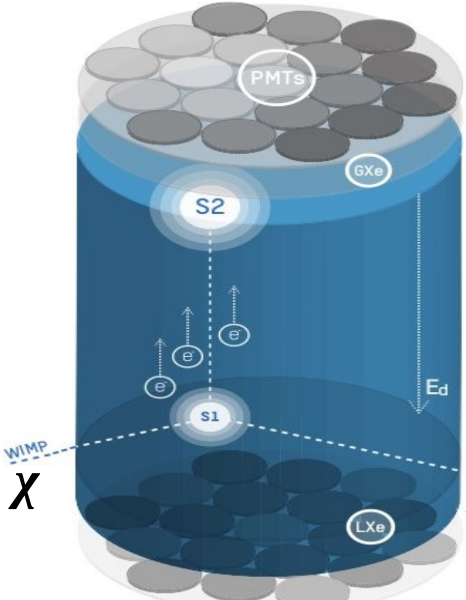
Main strategies of WIMP searches



$$\chi\chi \to e^+e^-,\ \mu^+\mu^-,\ \tau^+\tau^-,\ q\bar{q},\ c\bar{c},\ b\bar{b},\ t\bar{t},\ \gamma\gamma,\ W^+W^-,\ Z^0Z^0,\ hh,\ \nu_i\bar{\nu_i}\ \ldots$$

$$\chi\chi \to \tau^+\tau^- \to \pi^\pm + 2\pi^0 + \nu_\tau + \bar{\nu_\tau} \to \mu^\pm + \nu_\mu + \bar{\nu_\mu} + 4\gamma + \nu_\tau + \bar{\nu_\tau} \to e^\pm + 2\nu_\mu + 2\bar{\nu_\mu} + \nu_e + \bar{\nu_e} + 4\gamma + \nu_\tau + \bar{\nu_\tau}$$





Xenon dual-phase time projection chamber (invented by Dolgoshein et al. in 1970).

Axions

- Axion was originally invented by Peccei-Quinn (1977) as a solution of strong CP problem (CP conservation in QCD). Neutral boson.
- Later KSVZ & DFSZ (1980) refined the concept.
- Possible mass range relevant for (non-thermal) DM: ~ (10^{-21} – 1) eV.
- Axions participate in electromagnetic interaction: axion-photon conversion is possible in electromagnetic field (Primakoff effect).
- The latter enables wide range of search techniques: haloscopes, solar axion telescopes, spectra of gamma-ray sources.
- Maxwell's equations with axion field (Sikivie-1983, in natural units):

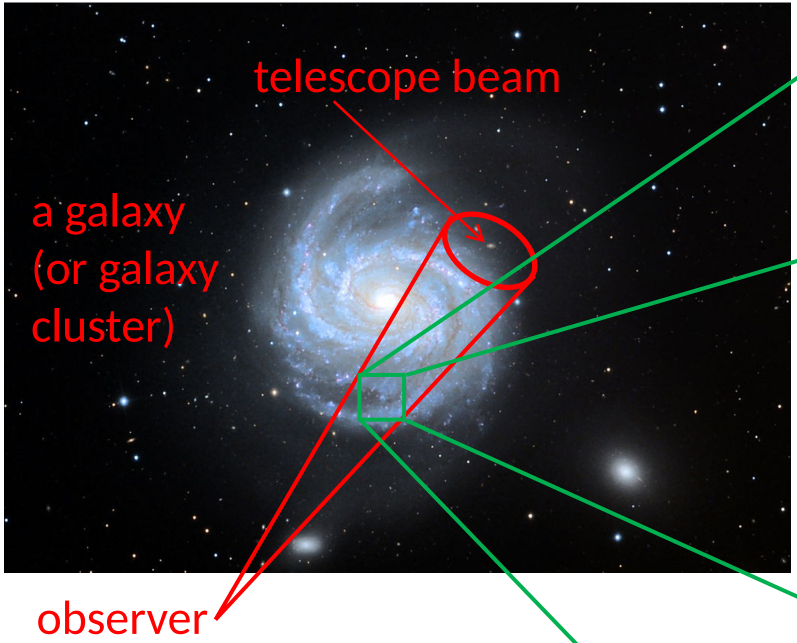
Name	Equations
Gauss's law	$\nabla \cdot \mathbf{E} = \rho - g_{a\gamma\gamma} \mathbf{B} \cdot \nabla a$
Gauss's law for magnetism	$\nabla \cdot \mathbf{B} = 0$
Faraday's law	$\nabla \times \mathbf{E} = -\dot{\mathbf{B}}$
Ampère–Maxwell law	$\nabla \times \mathbf{B} = \dot{\mathbf{E}} + \mathbf{J} + g_{a\gamma\gamma} \left(\dot{a} \mathbf{B} - \mathbf{E} \times \nabla a \right)$
Axion field's equation of motion	$\ddot{a} - \nabla^2 a + m_a^2 a = -g_{a\gamma\gamma} \mathbf{E} \cdot \mathbf{B}$

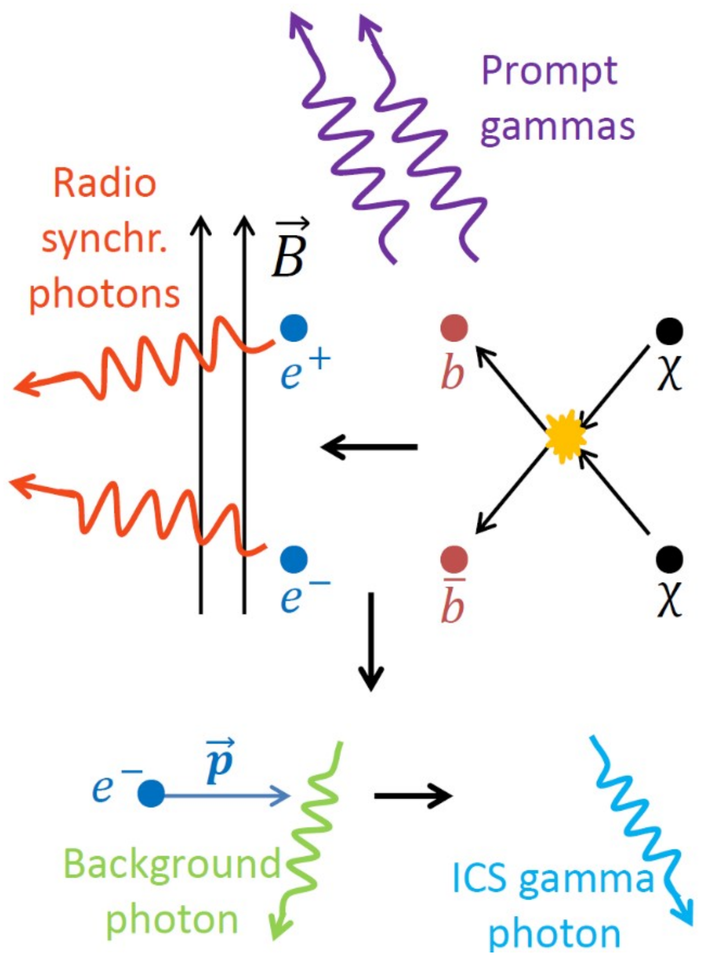
Others: sterile neutrinos, PBHs, AQNs etc.

- Sterile neutrinos: interact only via gravity, but mix with active neutrinos. Usually considered to have keV-scale mass to be DM. Decay to photons → significantly constrained by X-ray observations (famous 3.5 keV line story). Other limits severely constrain overall.
- Primordial black holes (PBHs): macro candidate from very early Universe. Currently allowed range of masses: ~ $(10^{-16} – 10^{-12})\ M_\odot$ (i.e. like a small asteroid). PBHs are strongly disfavored too.
- Axion quark nuggets (AQNs) by Zhitnitsky: besides DM, solve the baryon asymmetry problem in the Universe.
- DM particles may have self-interaction – needed to resolve ΛCDM problems.

5. My work on WIMP indirect searches and constraints.

My work: WIMP indirect (astrophysical) searches





WIMPs manifest mainly in radio and gamma-ray bands.

Primary annihilation products are unknown apriori.

Secondary emissions are more model-dependent (MF, propagation).

Intensity map on the sky:

$$S(\nu, \theta, \phi, \Delta\Omega) = \frac{1}{4\pi} \int_{\Delta\Omega} d\Omega \int_{l.o.s} j(\nu, l, \theta, \phi) dl$$

WIMP indirect (astrophysical) searches – 2

- The main goals of this work:
  1) ideally, we aim to discover WIMP, thus solving the big mystery of DM nature;
  2) at least, we can constrain WIMP properties;
  3) ultimately, we may exclude WIMP as viable DM candidate.
- The main problem: WIMP signals are faint, and normal non-thermal astrophysical emissions confuse a lot.
- Approximate dependence of the medium emissivity on the key DM parameters:

$$j \propto \langle \sigma v \rangle \left(\frac{\rho_{DM}}{m_x} \right)^2$$

  Therefore, the search sensitivity strongly increases with DM density and decreases with DM particle mass!
- And we have a prior expectation for the cross section value to be ~ the thermal.

5.1. Our DM search around Galactic center.

- Motivation. A long time ago Fermi gamma-ray telescope detected the emission excess at GeV energies with spherical morphology extending to few degrees around GC. This excess was difficult to explain by conventional astrophysical gamma-ray sources. At the same time, abnormal synchrotron emission component was identified there too in microwave band (decades of GHz) by WMAP/Planck. And very natural question arose – *could annihilating DM be responsible for both excesses?*
- Methodology – microwave band. Theoretical modeling of possible emission from annihilating DM (synchrotron from $e^{\pm}$ produced by WIMP annihilation), then separation of the observed emission components with isolation of possible DM component.

5.1. Solution of transport equation – GALPROP adaptation.

- DM emission computation. In general, for synchrotron emission modeling we need to solve the transport equation for $e^{\pm}$:

$$\frac{\partial n(\vec{R},p,t)}{\partial t} = q(\vec{R},p) + D_{\vec{R}}\Delta n - \frac{\partial}{\partial p}(\dot{p}n) + \frac{\partial}{\partial p}p^2 D_p \frac{\partial}{\partial p}\frac{n}{p^2}.$$

- DM source term:

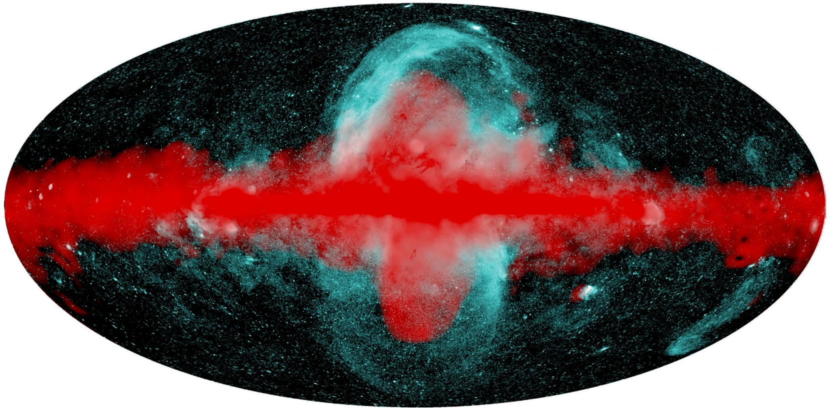
$$q(R,p) = \frac{1}{2}\langle\sigma v\rangle\left(\frac{\rho_{DM}(R)}{m_x}\right)^2 \xi(R)\frac{dN_e}{dp}.$$

annihilation cross section | DM density | WIMP mass | substructure boost | $e^{\pm}$ spectrum at injection

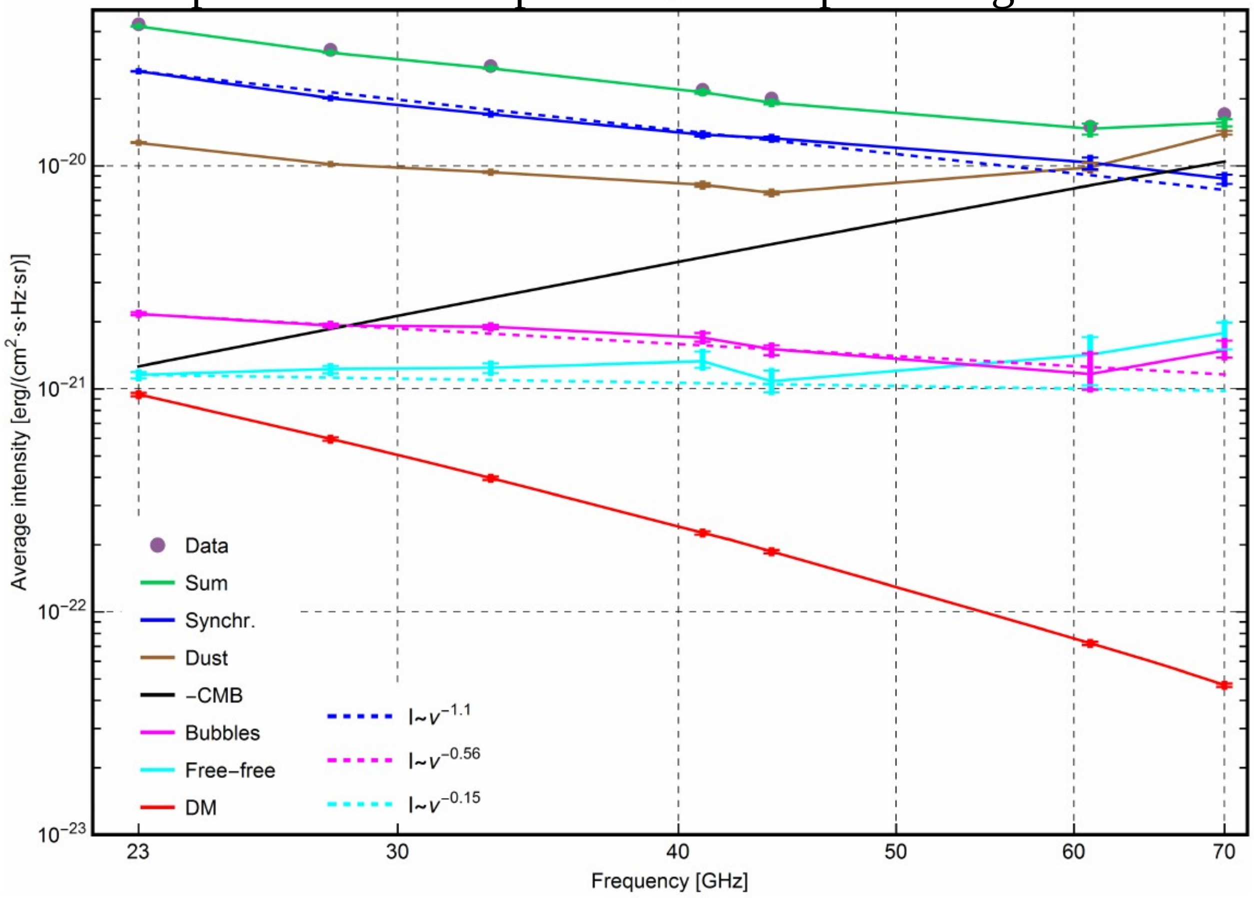
- GALPROP code (www.galprop.stanford.edu) was employed to solve the transport equation numerically and compute the synchrotron emission maps. However, the original GALPROP did not have proper DM functionality. And I developed and encoded the latter at comprehensive level. The injection spectra of DM annihilation products were taken from the results of relevant codes in particle physics (e.g. Pythia). All possible annihilation channels (i.e. primary products) were implemented.

5.1. Results of emission component separation.

Fermi (red) and eROSITA (cyan) bubbles.



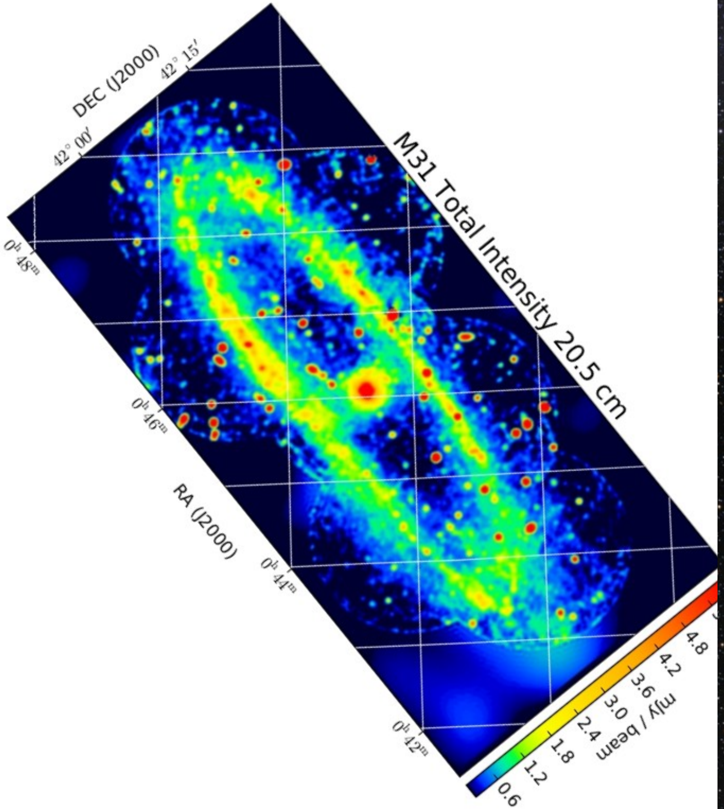
Fitted spectra of all components in the optimal region near GC



- Conclusion: excess microwave emission originates (likely) from Fermi bubbles, not from DM!

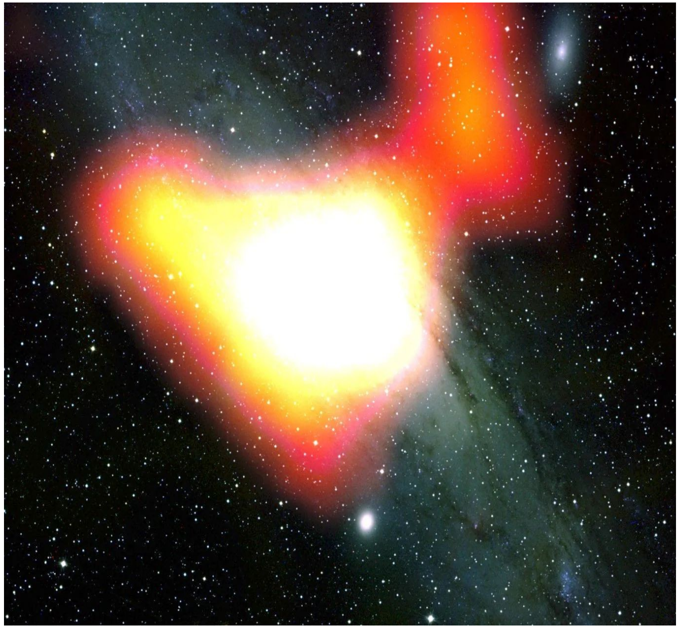
5.2. Andromeda galaxy (M31).

Radio image



Visual image

Gamma-ray image



M31 represents the closest big (hence bright) DM halo, enables detailed studies and imaging, has very quite (low “noise”) nucleus → probably, the best target for DM search in radio band.

5.2. M31 – derivation of DM radio constraints.

General methodology is similar to that for our own Galaxy Milky Way (MW, was discussed before):

- Setting DM $e^{\pm}$ spectra at production: they were taken from particle physics simulations.
- Setting DM density distribution: it has a big uncertainty in few kpc vicinity of the galactic enter (next slide).
- Setting magnetic field (MF) distribution: it's also known rather vaguely.
- Modeling DM $e^{\pm}$ cooling: it includes inverse Compton scattering (ICS) on starlight, synchrotron, bremsstrahlung, Coulomb and ionization energy losses.
- Solving the the transport equation for DM $e^{\pm}$ with the ingredients above.
- Numerical integration of the synchrotron medium emissivity along each line of sight, which yields the required emission intensity map.

Two latter points were performed by GALPROP too. However, the original GALPROP can model MW only. And I adapted it for the first time to model another galaxy – i.e., M31. This enabled precise solution of the transport equation in 2D.

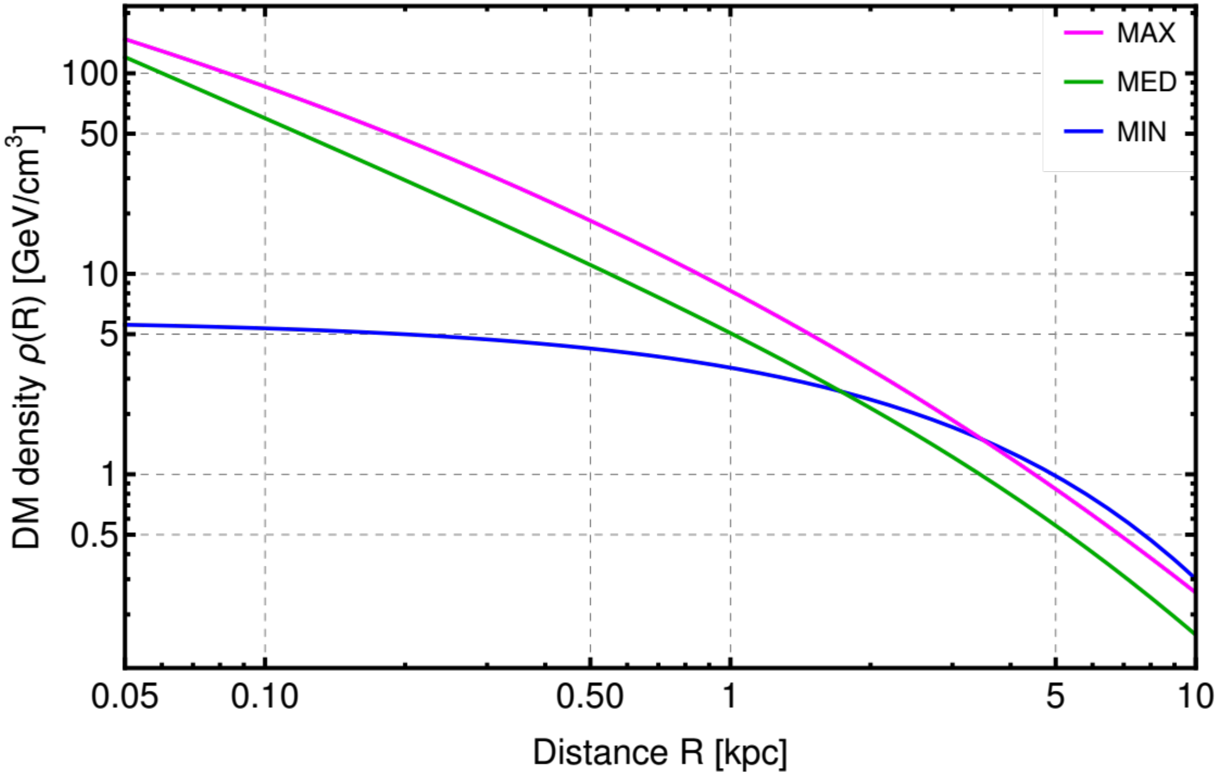
5.2. DM density distribution in M31.

- MIN, MAX DM density – Einasto profile (MAX has substructure boost):

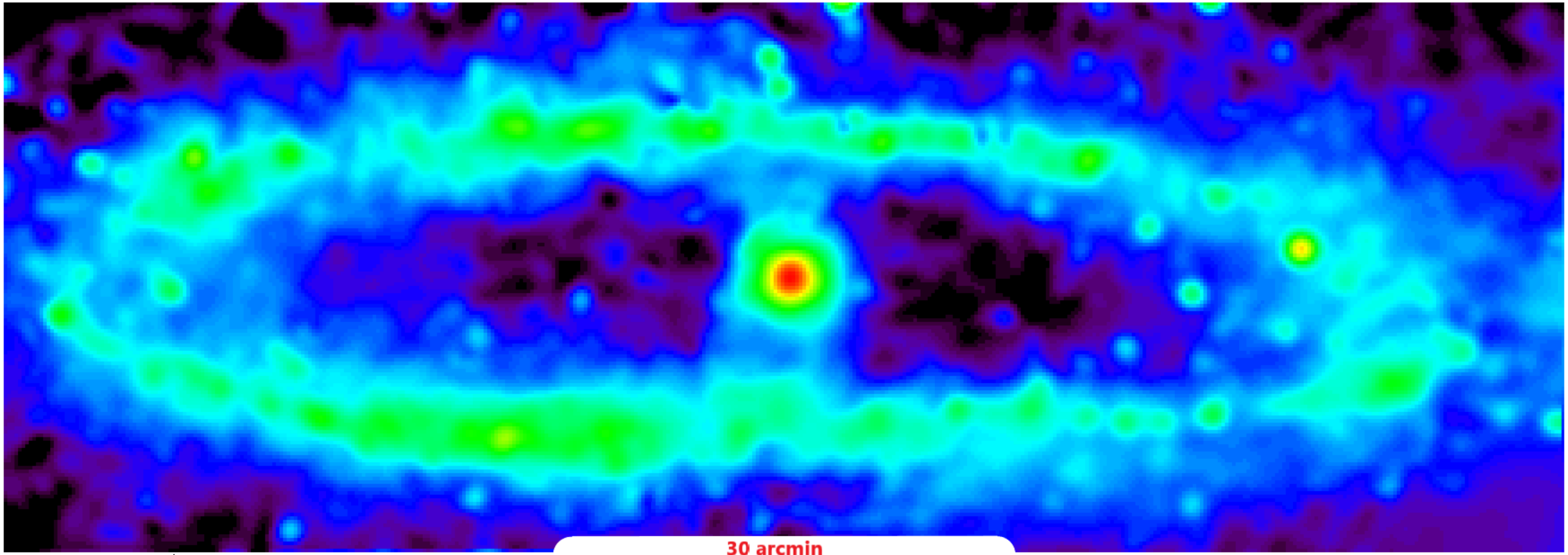
$$\rho_{\rm Ein}(R) = \rho_{-2} \exp\left(-\frac{2}{\alpha}\left(\left(\frac{R}{R_{-2}}\right)^{\alpha} - 1\right)\right)$$

- MED DM density – NFW profile (without the central singularity):

$$\rho_{\rm NFW}(R) = \frac{\rho_s}{{\rm Max}[R, R_{tr}]/R_s(1 + {\rm Max}[R, R_{tr}]/R_s)^2}$$



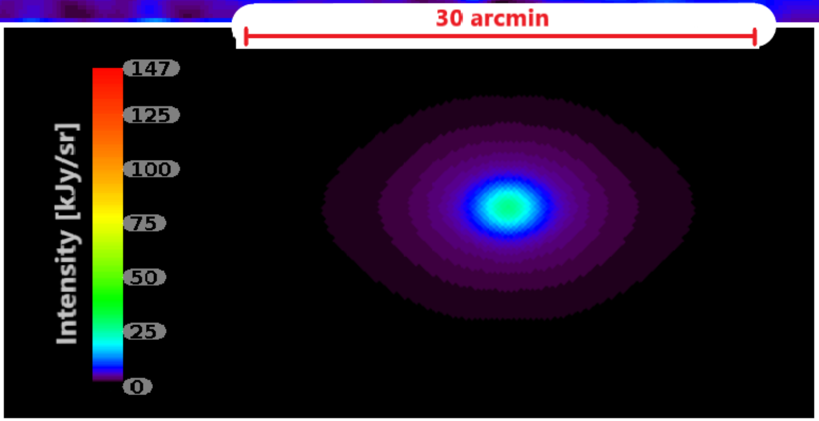
5.2. Example of obtained DM emission map – M31.



Non-thermal image:

Frequency = 1.5 GHz,

Resolution (FWHM) = 1.5 arcmin.



$\chi\chi \to 0.5 b\bar{b} + 0.5 \tau^+\tau^-$,

$m_\chi = 100$ GeV,

$\langle \sigma v \rangle_{\rm thermal} = 2.1 \cdot 10^{-26} {\rm cm}^3/{\rm s}$,

MED DM density and MF/prop.

5.2. Statistical procedure for derivation of constraints.

The likelihood function:

$$L \propto \prod_{i=1}^{8\text{freq.}} \prod_{j=1}^{\#\text{ROI}_i} \underbrace{\exp\left(-\frac{n_{ij}^2}{2\sigma_{ij}^2}\right)}_{\text{stat. uncertainty - maps' noise } n_{ij}} \times \underbrace{\exp\left(-\frac{(s_{ij}-c_{ij})^2}{2\sigma_{s,ij}^2}\right)}_{\text{systematic uncertainty of the measured intensities } c_{ij}}$$

Frequency range: 0.074-8.4 GHz.

$s_{ij} = n_{ij} + a_{ij} + w_{ij}$ - the total intensity without syst. offset (w_{ij} = DM emission intensity).

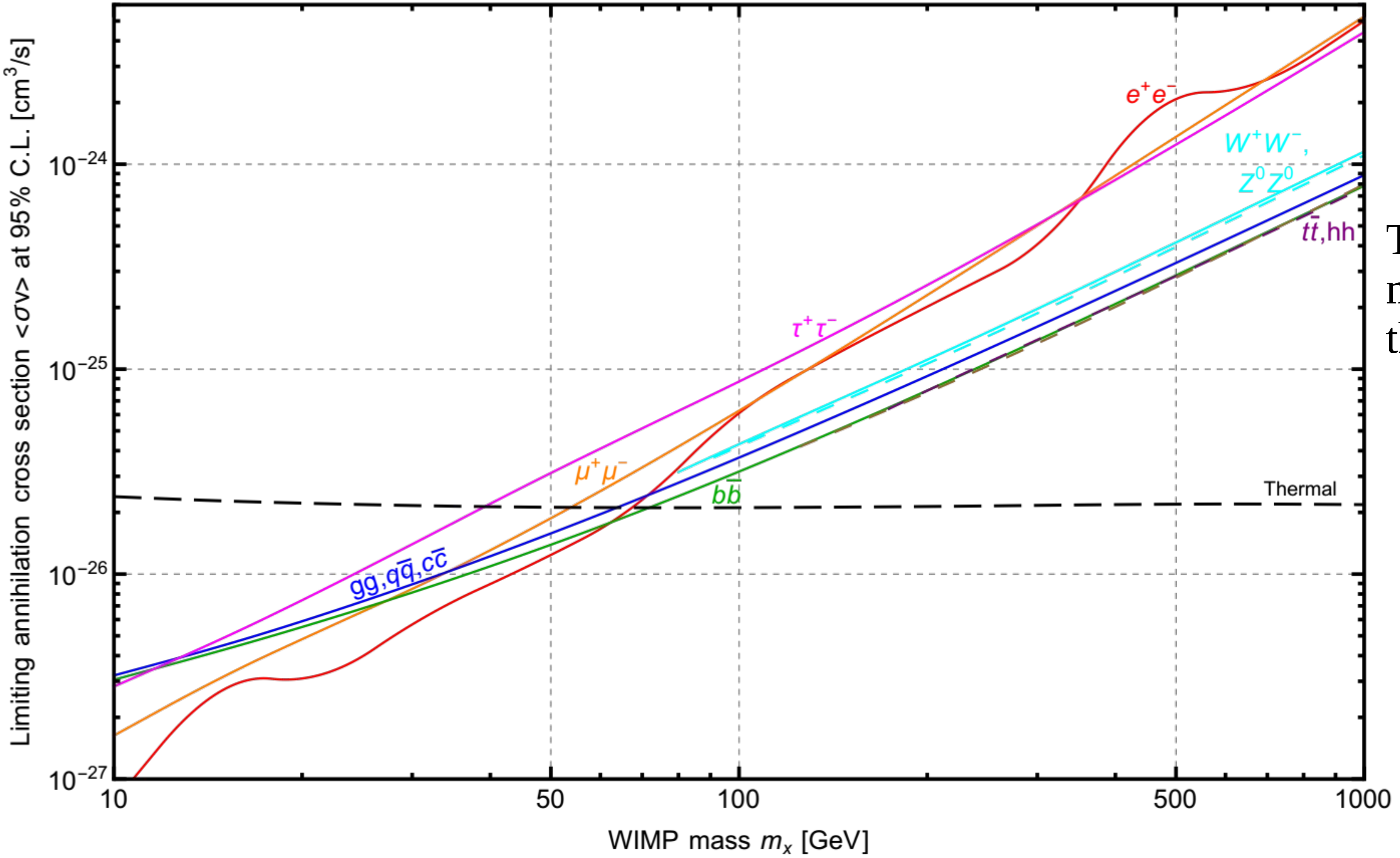
Then the probability density for $\langle\sigma v\rangle$ (1D likelihood) was derived by analytical integration:

$$L(\langle\sigma v\rangle|\vec{c}) \propto \prod_{i=1}^{8\text{freq.}} \prod_{j=1}^{\#\text{ROI}_i} \left(1 + \text{erf}\left(\frac{c_{ij} - w_{ij}(\langle\sigma v\rangle)}{\sqrt{2(\sigma_{ij}^2 + \sigma_{s,ij}^2)}}\right)\right)$$

- has 33 multipliers in total.

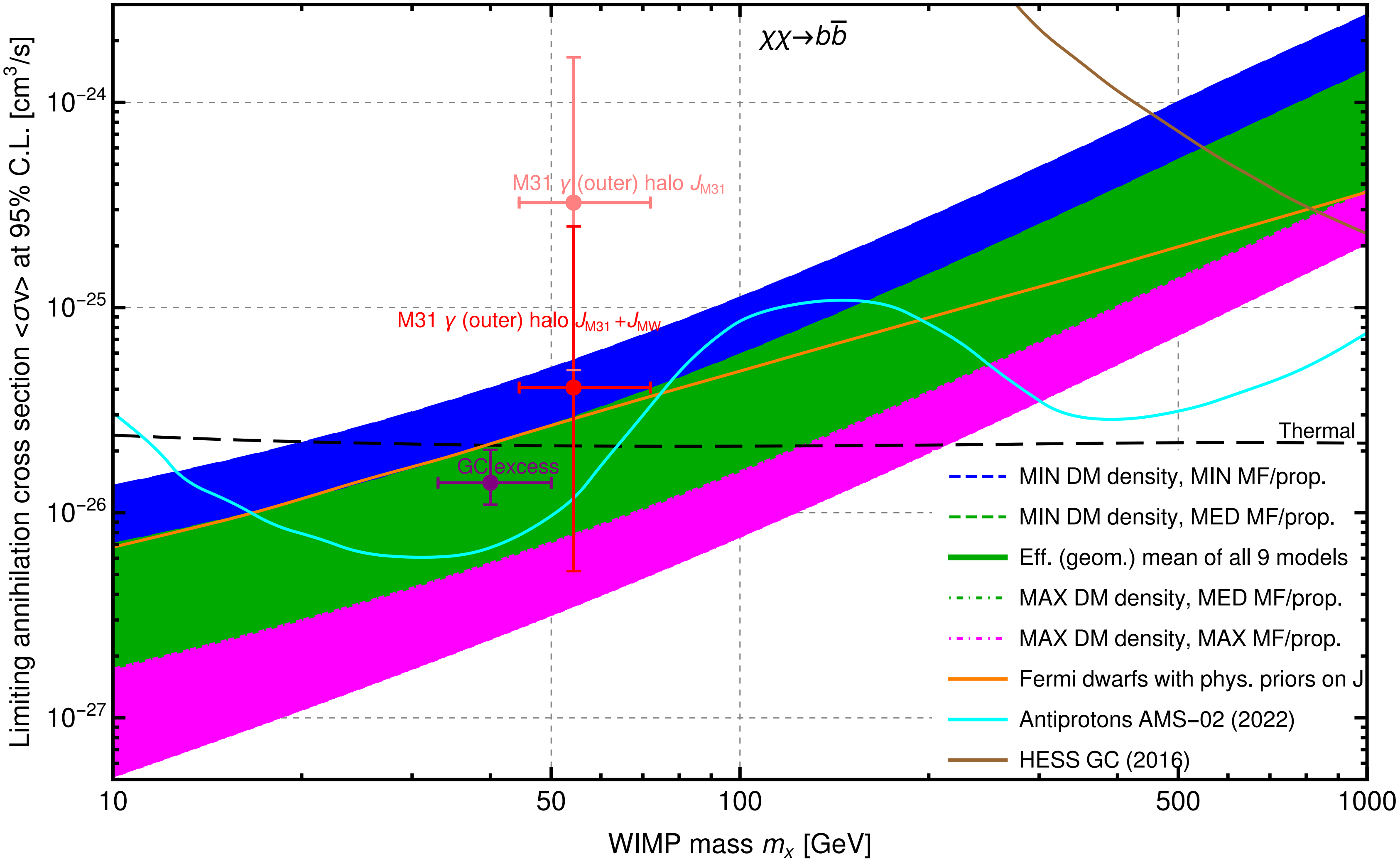
Nothing specific – i.e. the flat priors – were assumed for the intensities of usual astrophysical emission at each frequency a_{ij}. This makes the constraints rather conservative, robust and model-independent!

5.2. Derived limits – all annihilation channels.

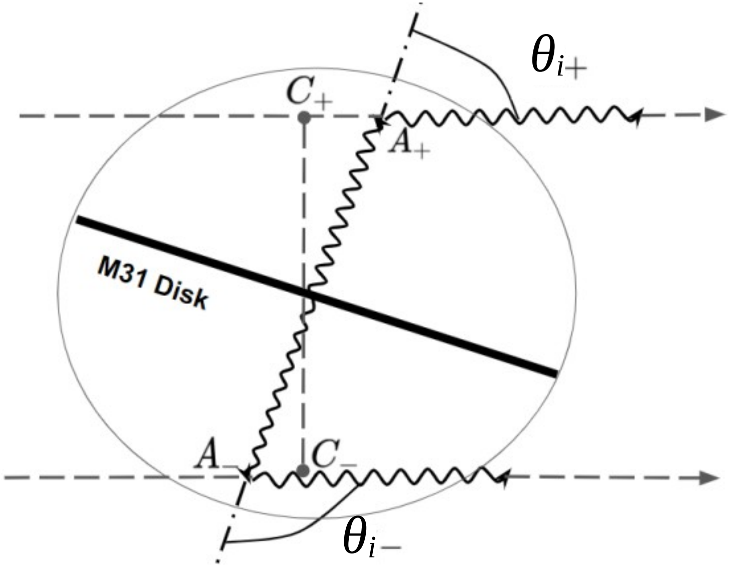


Thermal WIMP must be heavier than $\mathbf{40^{+50}_{-20}}$ GeV!

5.2. Limits for *bb** channel and relation with other results.



5.3. ICS gamma-ray emission – new effect of asymmetry.

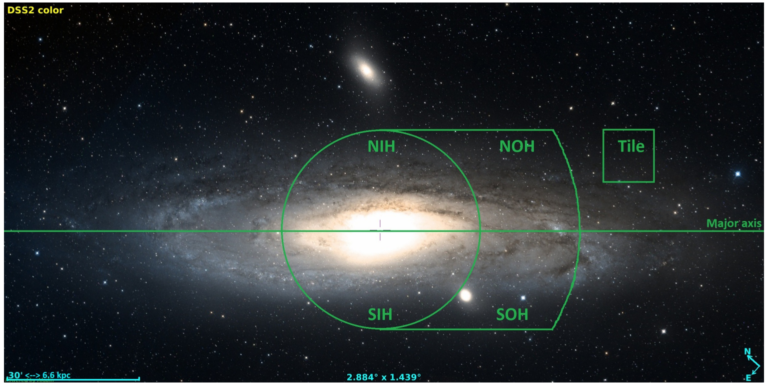


toward observer

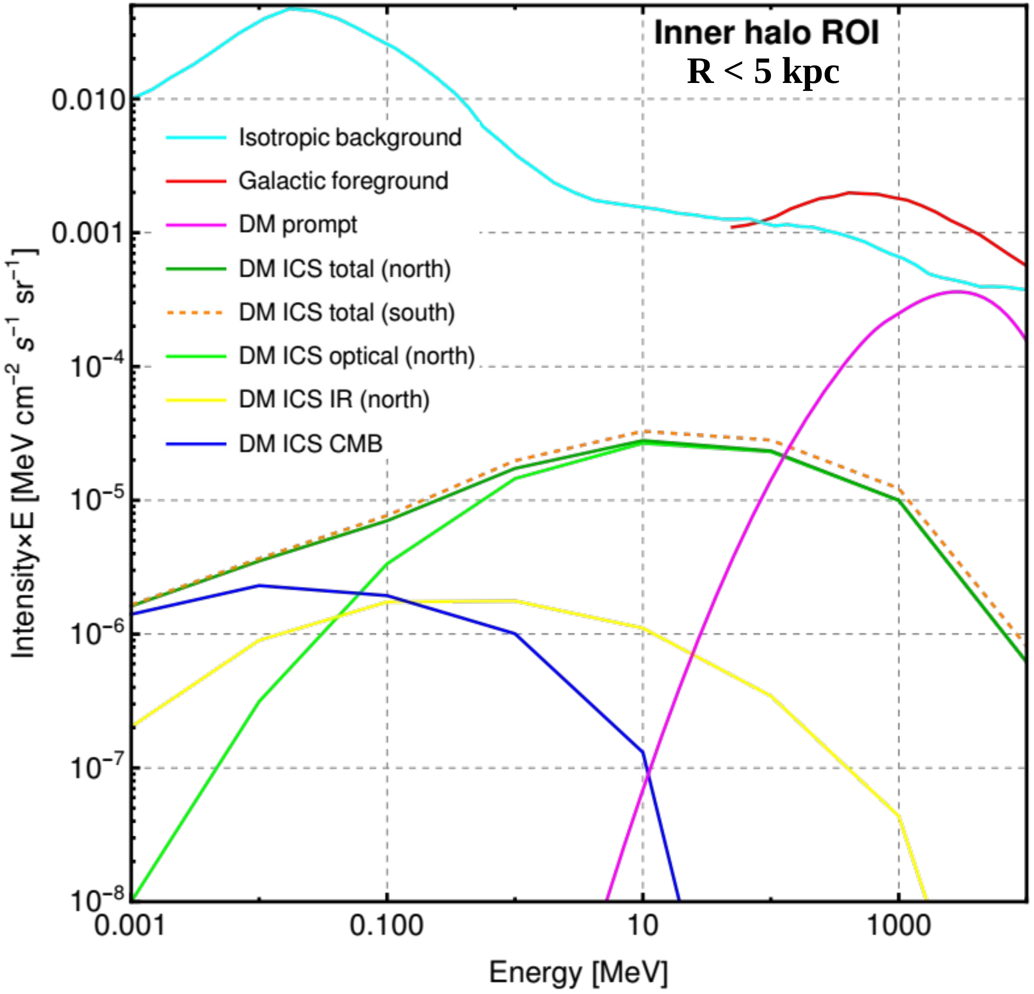
$$E_\gamma = \frac{E_{\gamma 0}(1-\beta_e\cos\theta_i)}{1-\beta_e\cos\theta_f + (1-\cos(\theta_i-\theta_f))E_{\gamma 0}/E_e}$$

$$\theta_f = 0$$

ICS emission from any $e^{\pm}$ population in inclined disk galaxy would be asymmetric on the sky with respect to the galactic major axis:



5.3. ICS emission modeling by GALPROP.



The effect of ICS emission asymmetry between galactic hemispheres on the sky was confirmed and precisely calculated by GALPROP on the trial $e^{\pm}$ produced by annihilating DM with m_x = 60 GeV. The magnitude of asymmetry, i.e. intensity difference, was obtained to be at the level of ~10%.

5.3. Observational implications.

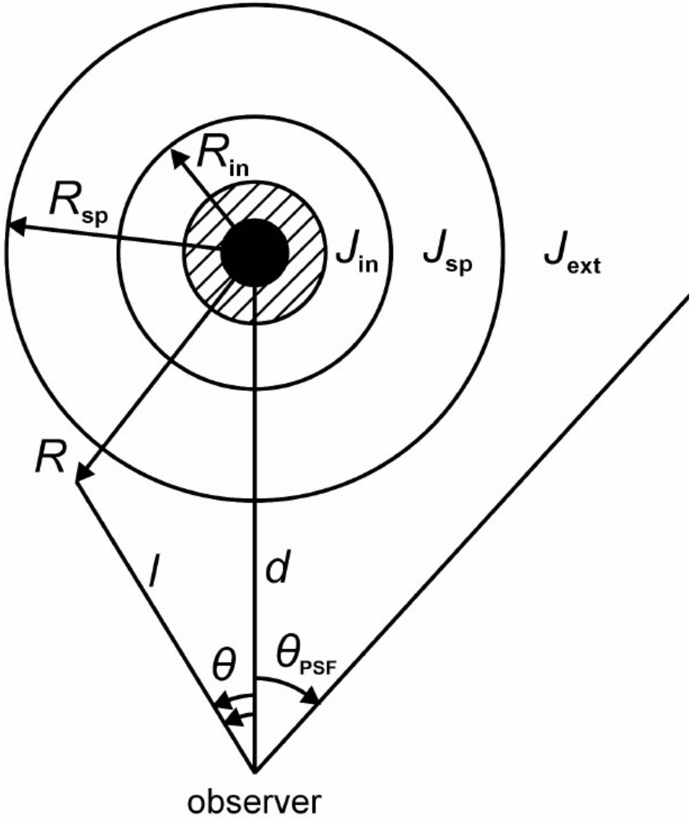
Observational detection and measurement of the gamma-ray emission asymmetry in M31 by future sensitive telescopes (e.g. COSI, e-ASTROGAM, AMS-100) may provide the following important clues for understanding the emission generation mechanism.

1. If a diffuse gamma-ray emission is absolutely symmetric at all energies with respect to the major axis of M31, this implies likely a purely hadronic emission mechanism.
2. A mild emission asymmetry at the level of few % implies likely a mixed leptonic/hadronic emission scenario.
3. A significant asymmetry at the level $\gtrsim$ 10% implies a dominance of the leptonic sources; which may include $e^{\pm}$ from CRs, DM and even probably MSPs.
4. The asymmetry from DM $e^{\pm}$ is expected to be smaller and appear over significantly narrower energy range than in the case of CR $e^{\pm}$.
5. May even help to detect DM emission component.

5.4. DM density spikes around nearby SMBHs.

- SMBHs are expected to concentrate DM by their local gravitational field and to form very dense spikes. Such spikes may provide unique opportunity to test heavy TeV-scale WIMPs.
- Emission flux density due to annihilating DM:

$$\frac{d\Phi}{dE} = \frac{\langle\sigma v\rangle}{8\pi m_x^2}\frac{dN_\gamma}{dE}(E,m_x) \times \int\limits_{\Omega_{\rm PSF}}\int\limits_{\rm LoS} \rho^2(R)d\Omega dl \equiv \frac{\langle\sigma v\rangle}{8\pi m_x^2}\frac{dN_\gamma}{dE}(E,m_x) \times J,$$



- DM density distribution around SMBH:

$$\rho(R) = \begin{cases} 0, & R < 2R_\bullet = 4GM/c^2; \\ \rho_{in}(R/R_{in})^{-\gamma_{in}}, & 2R_\bullet \leqslant R < R_{in}; \\ \rho_0(R/R_{sp})^{-\gamma}, & R_{in} \leqslant R < R_{sp}; \\ \rho_{ext}(R), & R \geqslant R_{sp}. \end{cases}$$

- Spike radius: $R_{sp} = \langle bGM/v^2\rangle = bGM/\sigma_c^2,\ b \sim 1$
- The first work on this subject was published by Gondolo&Silk in 1999.

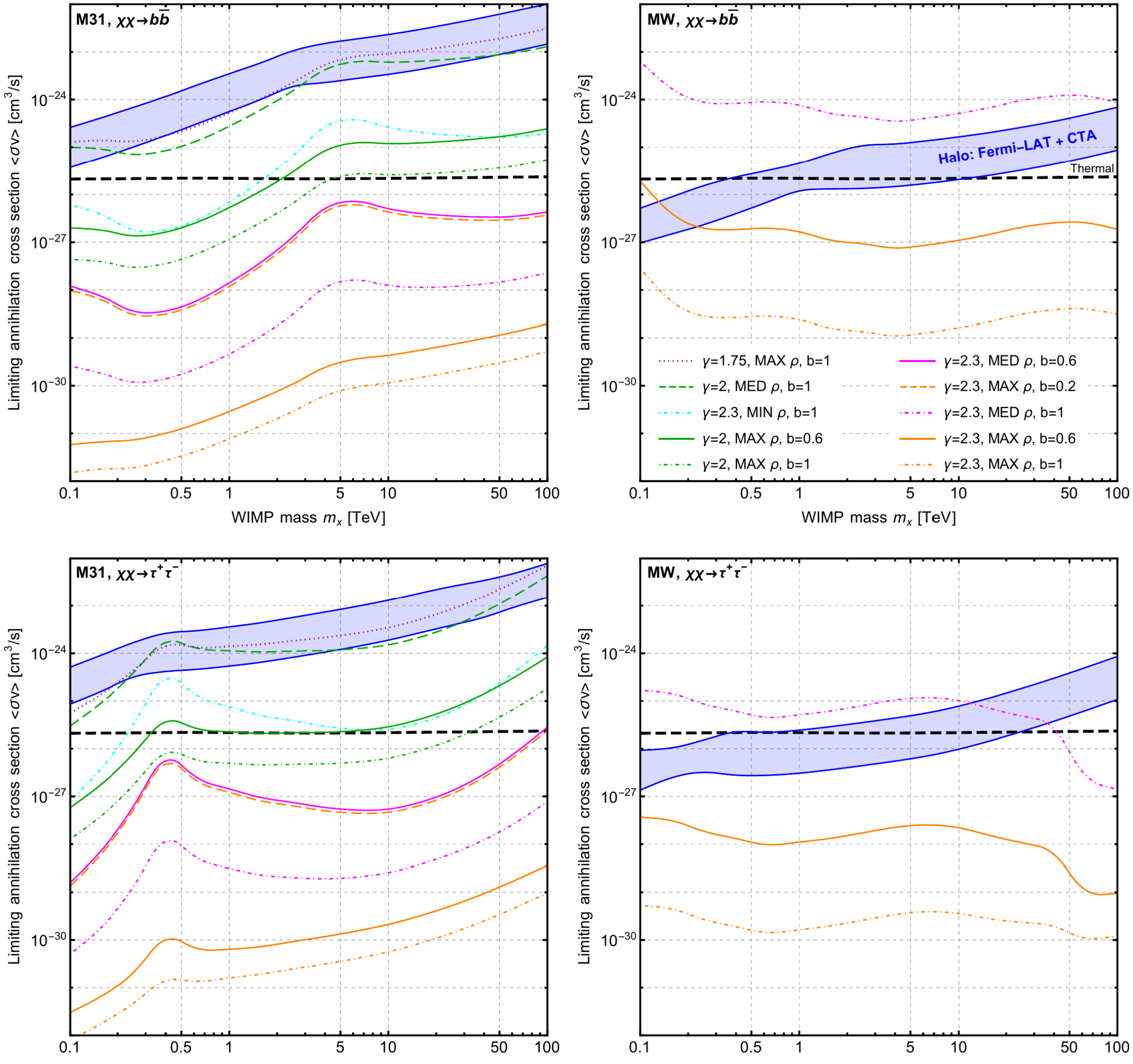
5.4. DM density spikes: the best objects.

SMBH host	d [Mpc][52]	M [$M_\odot$]	σ_c [km/s][53]	ρ_0 [GeV/cm^3]	J_{sp} [GeV^2/cm^5]
MW	0.0083 [54]	$4.3 \cdot 10^6$ [54]	130 [55]	110 [9]	$2.6 \cdot 10^{16}$
M31	0.76 [56]	$1.4 \cdot 10^8$ [57]	150	47 [47]	$8.2 \cdot 10^{15}$
NGC 3115	10	$9.6 \cdot 10^8$ [58]	260	27 [50, 59, 60]	$1.7 \cdot 10^{14}$
M104	11	$1.0 \cdot 10^9$ [61]	230	13 [62]	$7.8 \cdot 10^{13}$
M60	17	$2.1 \cdot 10^9$ [58]	330	11 [59]	$2.3 \cdot 10^{13}$
M87	17	$6.5 \cdot 10^9$ [63]	450 [51]	0.52 [64, 65]	$2.3 \cdot 10^{11}$
M84	17	$1.5 \cdot 10^9$ [58]	280	6.8 [59]	$9.0 \cdot 10^{12}$
NGC 4889	97	$2.0 \cdot 10^{10}$ [66]	390	4.7 [67]	$4.0 \cdot 10^{13}$
NGC 3842	100	$1.0 \cdot 10^{10}$ [66]	310	14 [66]	$1.7 \cdot 10^{14}$

Table 1. The list of potentially promising nearby and massive SMBHs arranged by distance. The second column contains distance, the third – mass, the fourth – stellar velocity dispersion in the center of host galaxy, the fifth – employed DM halo density at the spike border and the sixth – calculated spike J-factor. The origin of all data is provided (the first row contains default data source). MED model parameter values were used in calculation: $\gamma = 1.5$, $b = 0.6$, medium density ρ_0.

MW* and M31* are the best targets!

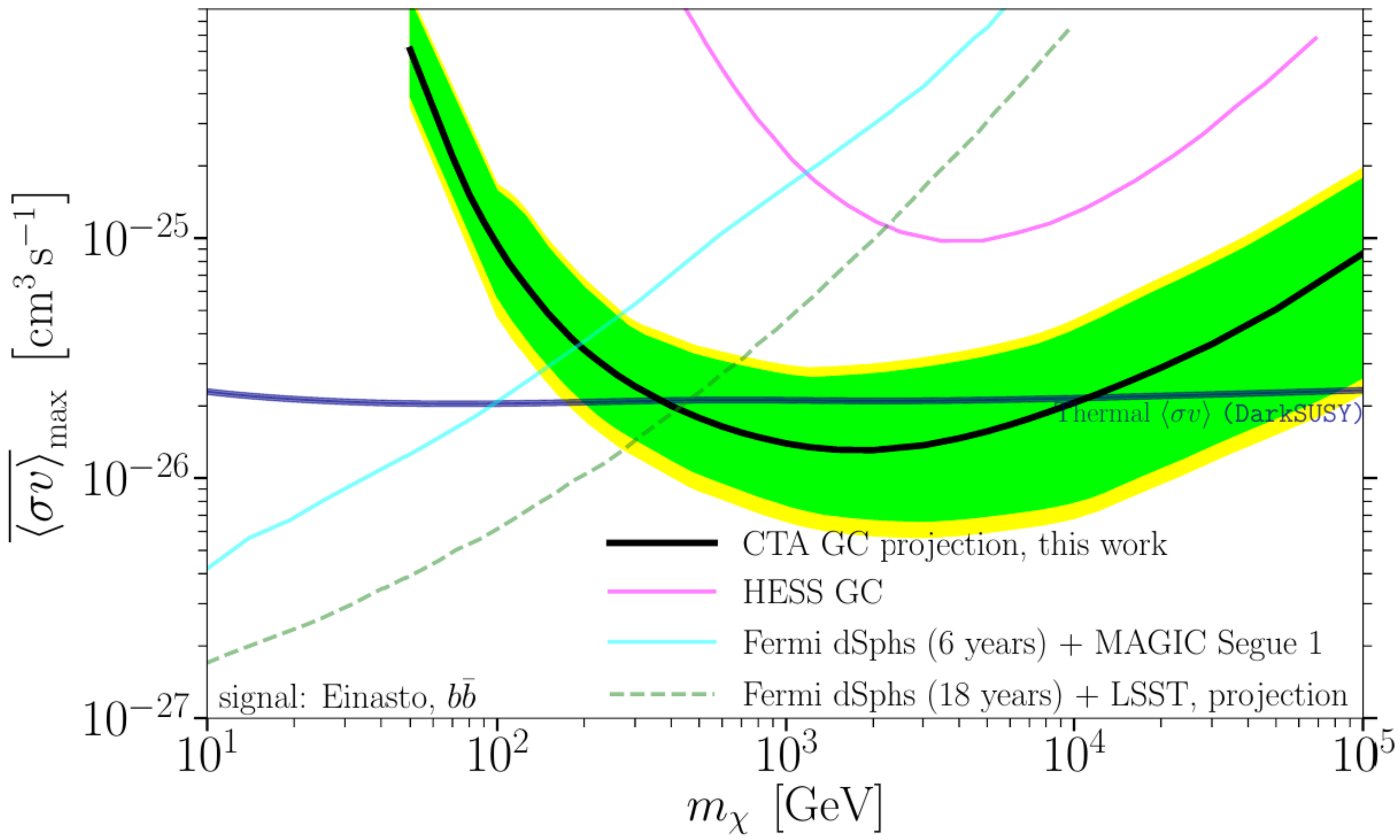
5.4. Fermi-LAT + CTA WIMP sensitivity limits in spikes.



Deep MW* and M31* observations in very high energy band may allow to probe the basic thermal s-wave annihilating WIMPs up to the highest possible mass = 100 TeV. However, it's possible only in the case of optimistic spike parameter configurations *(γ ≳ 2)*. Overall, WIMP signal predictions suffer from very large model uncertainties.

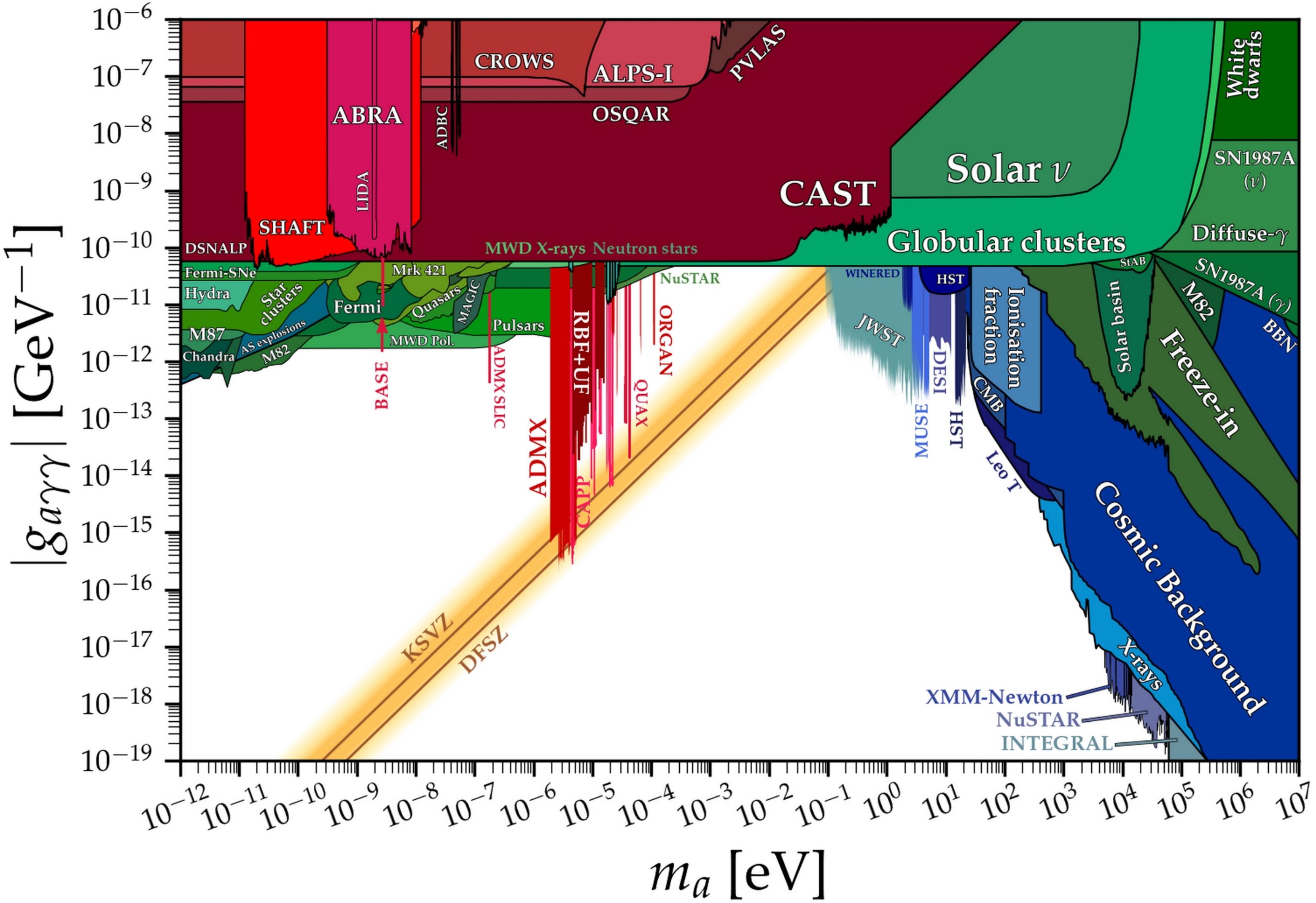
6. Future perspective.

WIMPs



- So far we have tested only light thermal WIMPs with $m_x \lesssim 100$ GeV.
- CTA will probe the range $m_x \sim$ (0.1-10) TeV *in a good case scenario.*
- The heaviest WIMPs with $m_x \sim$ (10-100) TeV are very hard to probe (SMBH?).
- Overall, this field tends to a saturation: likely, DM will be discovered either in ~10 years or never.

Axions and ALPs



7. Summary.

- Despite of almost a century of research, exact DM nature remains still unknown.
- Easily accessible candidate parameter ranges had been already tested.
- The remaining parameter regions are hard to reach due to weakness of signals in comparison with natural astrophysical backgrounds.
- Thus, WIMPs are ruled out below ~100 GeV (also by my constraints from radio observations of Andromeda galaxy), but 0.1-100 TeV range is still unexplored. And only CTA/SWGO facilities have some chances to discover such heavy WIMPs, also employing deep observations of the closest SMBHs.
- DM may not manifest at all beyond gravity.
- I bet on DM discovery either in ~10 years or never.