Seminari teorici del venerdì

Naples - January 28th, 2011

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Dark Matter Electron Anisotropy:
A universal upper limit

Based on
Borriello, Maccione, and Cuoco
arXiv:10120041

Outline

...

Part 1: Dark Matter

- The content of the Universe
- Candidates
- Detection techniques

Part 2: DM Galactic Substructures

- N-body simulations
- Detectability at γ-rays energies
- Detectability at radio wavelenghts
- Angular power spectrum of γ-rays

Part 3: DM electron anisotropy

- Definition of dipole anisotropy
- Fermi LAT upper limit
- Limit cases
- Clumpiness and anisotropy
- Universality of the DM electron anisotropy upper limit

Part 4: Astrophysical implications

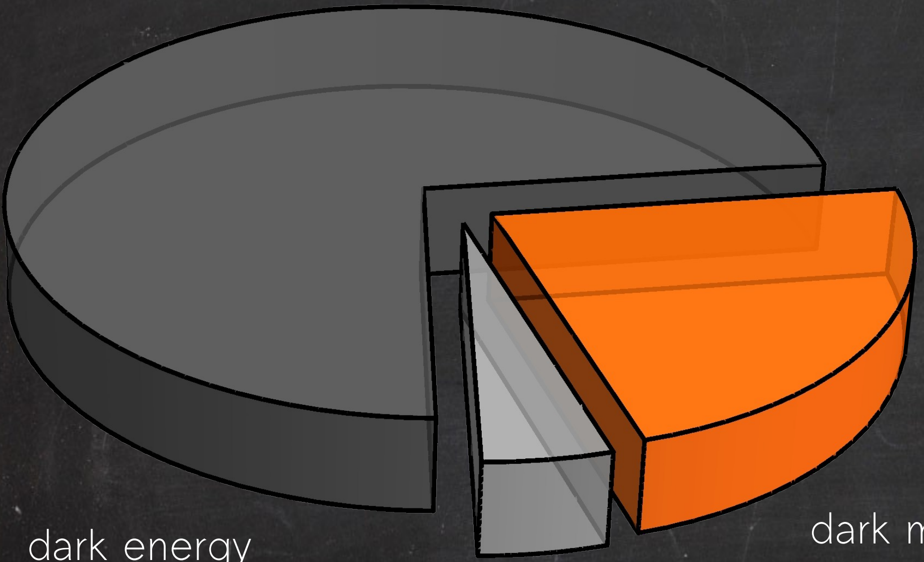
- Two possibilities
- AP dominated anisotropy scenario
- Excluding the DM interpretation of a forthcoming anisotropy detection

Part 1:
Dark Matter

Dark Matter

The content of the Universe

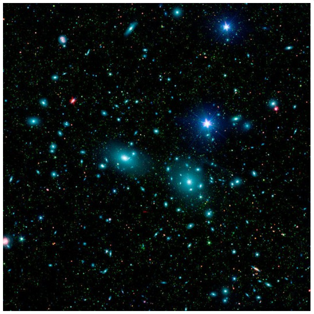
Larson et al. arXiv:1001.4635

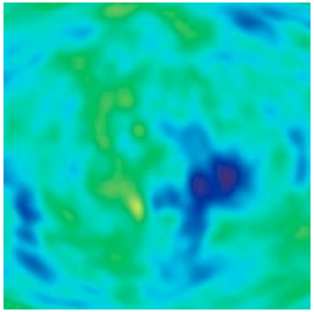


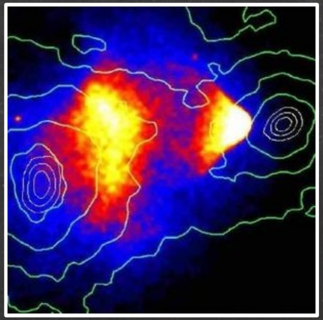
Baryonic matter 4.5 %
Atoms, ordinary matter

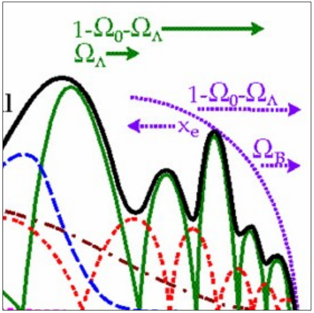
Dark matter 22.7 %.
No interaction with light
Only gravitational effect

Dark energy 72.8 %
“Anti-gravity”
accelerated expansion of he Universe









Dark Matter

Candidates

Feng arXiv:1003.0904

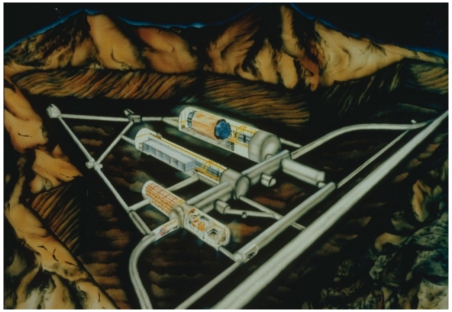
	WIMPs	SuperWIMPs	Light gravitino	Hidden DM	Sterile neutinos	Axions
Motivation	Gauge hierar. prob.	Gauge hierar. prob.	Gauge hierar. & NP flavor prob.	Gauge hierar. & NP flavor prob.	Neutino masses	Strong CP
Naturally correct Ω	Yes	Yes	No	Possible	No	No
Production mechanism	Freeze out	Decay	Thermal	Various	Various	Various
Mass range	GeV - TeV	GeV - TeV	eV - keV	GeV - TeV	keV	μeV - meV
Temperature	Cold	Cold/Warm	Cold/Warm	Cold/Warm	Warm	Cold
Collisional	✗	✗	✗	✓	✗	✗
CMB & BBN	✗	✓	✗	✓	✗	✗
Dir. detection	✓	✗	✗	✓	✗	✓
Ind. detection	✓	✓	✗	✓	✓	✗
Colliders	✓	✓	✓	✓	✗	✗

Dark Matter

Detection techniques

Direct detection

Phenomenon:	Interaction of the DM with the visible matter
Experiments:	Underground laboratories
Phys. observable:	Energy recoil of a nucleus

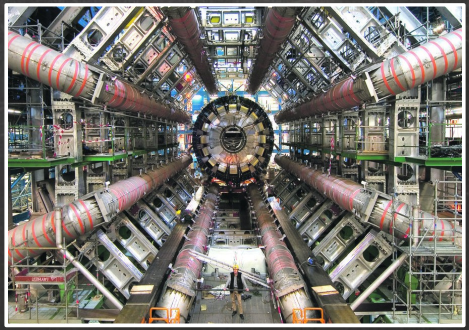


Inirect detection

Phenomenon:	DM annihilation or decay
Experiments:	Space telescopes
Phys. observable:	Cosmic ray spectrum

Colliders

Phenomenon:	Production of DM
Experiments:	Particle accelerators
Phys. observable:	Missing transverse momentum



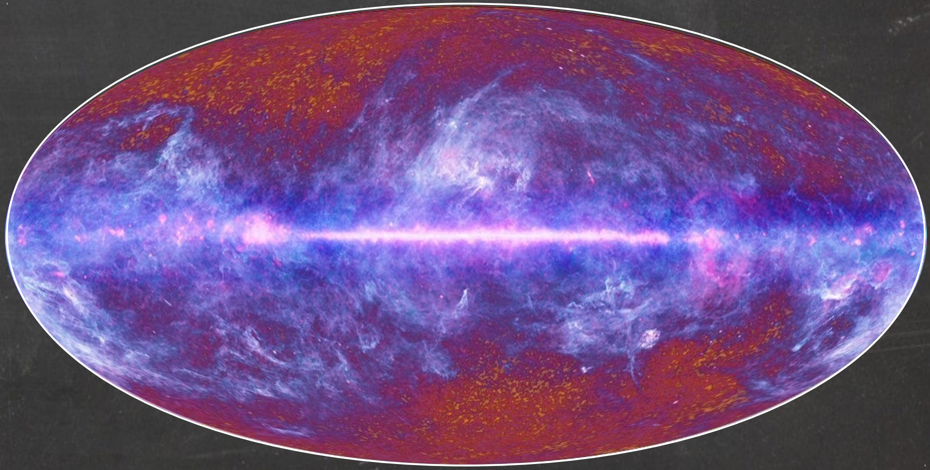
Dark Matter

Detection techniques: Indirect detection

$$\begin{tikzcd}
\chi+\chi \arrow[r] \arrow[ddddr] \arrow[dddddr] & q+\bar{q} \arrow[r] \arrow[dr] \arrow[ddr] \arrow[dddr] & \pi^{-}+\ldots \arrow[r] & \nu_{\mu}+\mu^{-} \arrow[r] & \nu_{\mu}+\bar{\nu}_{e}+e^{-} \\
 & & \pi^{0}+\ldots \arrow[r] & \gamma+\gamma & \\
 & & \bar{p}+\ldots & & \\
 & & \ldots & & \\
 & W^{+}+W^{-} & & & \\
 & \ldots & & &
\end{tikzcd}$$

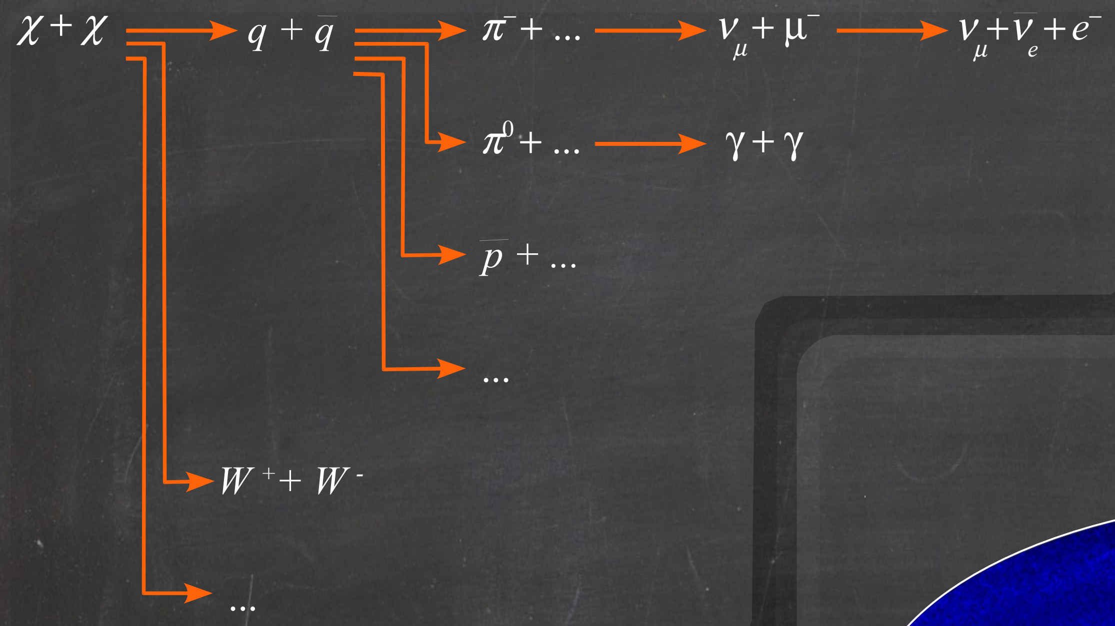
Dark matter search
in **all-sky surveys**

Planck



Dark Matter

Detection techniques: Indirect detection



$$\chi+\chi \rightarrow q+\bar{q} \rightarrow \pi^{-}+\ldots \rightarrow \nu_{\mu}+\mu^{-} \rightarrow \nu_{\mu}+\bar{\nu}_{e}+e^{-}$$

$$q+\bar{q} \rightarrow \pi^{0}+\ldots \rightarrow \gamma+\gamma$$

$$q+\bar{q} \rightarrow \bar{p}+\ldots$$

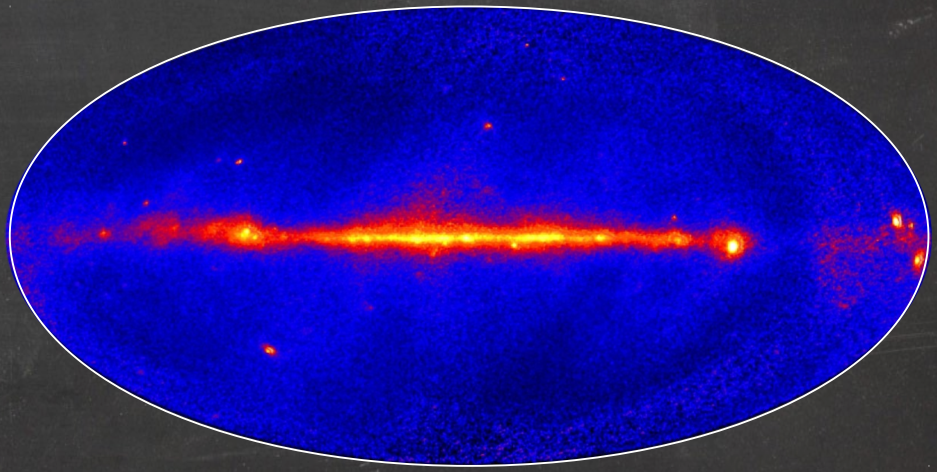
$$q+\bar{q} \rightarrow \ldots$$

$$\chi+\chi \rightarrow W^{+}+W^{-}$$

$$\chi+\chi \rightarrow \ldots$$

Dark matter search
in **all-sky surveys**

Fermi LAT



Dark Matter

Detection techniques: Indirect detection

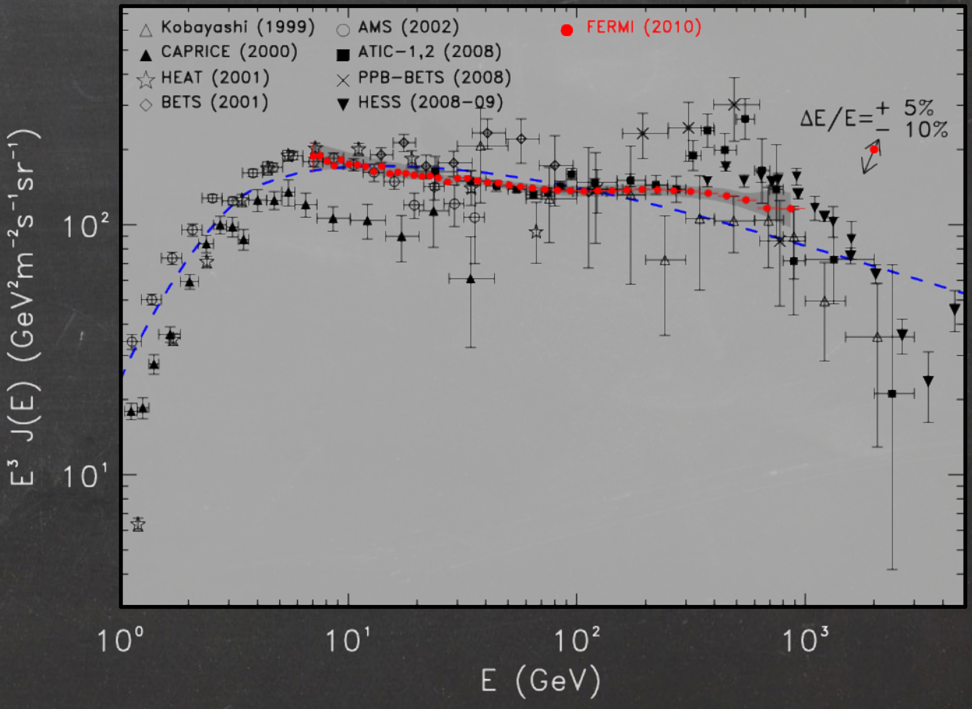
Ackermann et al. ArXiv:1008.3999

$$\begin{tikzcd}
\chi+\chi \arrow[r] \arrow[ddddr] \arrow[dddddr] & q+\bar{q} \arrow[r] \arrow[dr] \arrow[ddr] \arrow[dddr] & \pi^-+\ldots \arrow[r] & \nu_\mu+\mu^- \arrow[r] & \nu_\mu+\bar{\nu}_e+e^- \\
 & & \pi^0+\ldots \arrow[r] & \gamma+\gamma & \\
 & & \bar{p}+\ldots & & \\
 & & \ldots & & \\
 & W^++W^- & & & \\
 & \ldots & & &
\end{tikzcd}$$

$$\begin{tikzcd}
\chi+\chi \arrow[r] & \mu^++\mu^- \arrow[dr] \arrow[ddr] & \\
 & & \nu_\mu+\bar{\nu}_e+e^- \\
 & & \bar{\nu}_\mu+\nu_e+e^+
\end{tikzcd}$$

Dark matter search
in (particle) **cosmic rays**

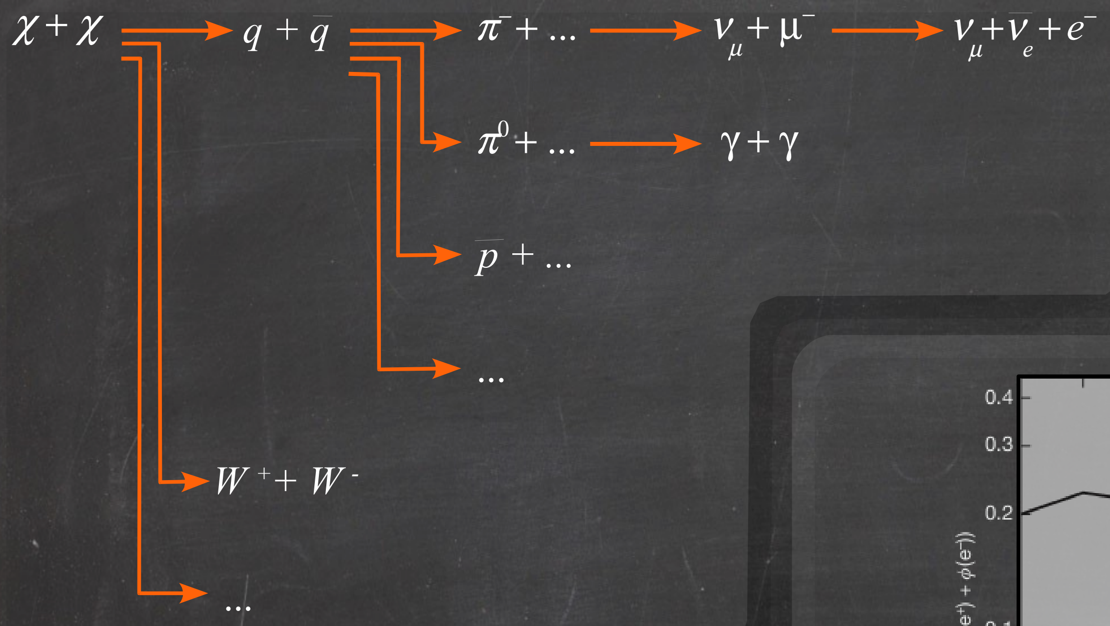
Fermi LAT



Dark Matter

Detection techniques: Indirect detection

Adriani et al. ArXiv:0810.4995



$\chi+\chi \longrightarrow q+\bar{q} \longrightarrow \pi^{-}+\ldots \longrightarrow \nu_\mu+\mu^{-} \longrightarrow \nu_\mu+\bar{\nu}_e+e^{-}$

$\pi^{0}+\ldots \longrightarrow \gamma+\gamma$

$\bar{p}+\ldots$

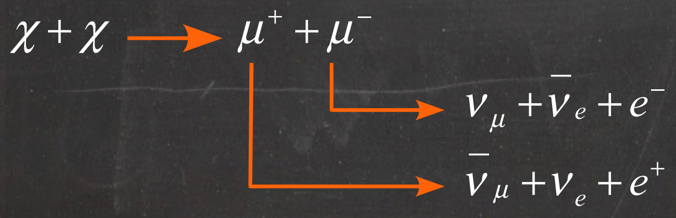
$\ldots$

$W^{+}+W^{-}$

$\ldots$

Dark matter search
in (particle) **cosmic rays**

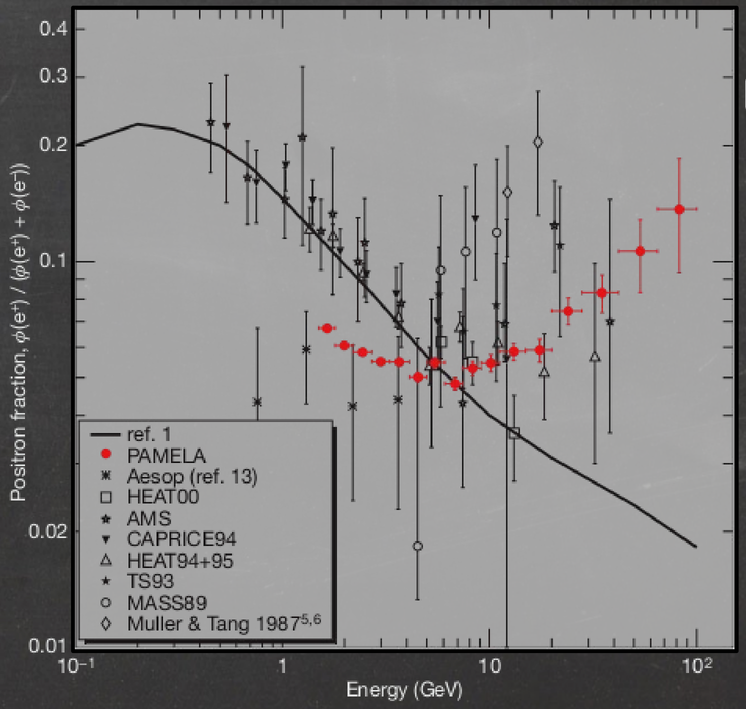
Pamela



$\chi+\chi \longrightarrow \mu^{+}+\mu^{-}$

$\nu_\mu+\bar{\nu}_e+e^{-}$

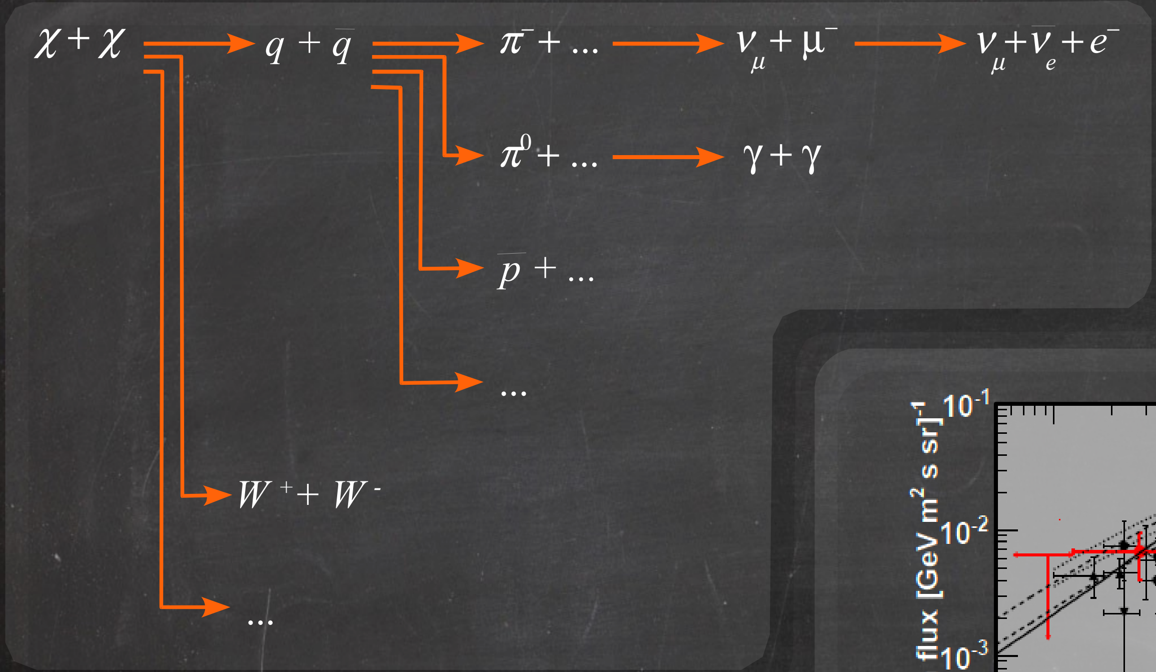
$\bar{\nu}_\mu+\nu_e+e^{+}$



Dark Matter

Detection techniques: Indirect detection

Adriani et al. ArXiv:1007.0821



$$\chi+\chi \to q+\bar{q} \to \pi^{-}+\ldots \to \nu_\mu+\mu^{-} \to \nu_\mu+\bar{\nu}_e+e^{-}$$

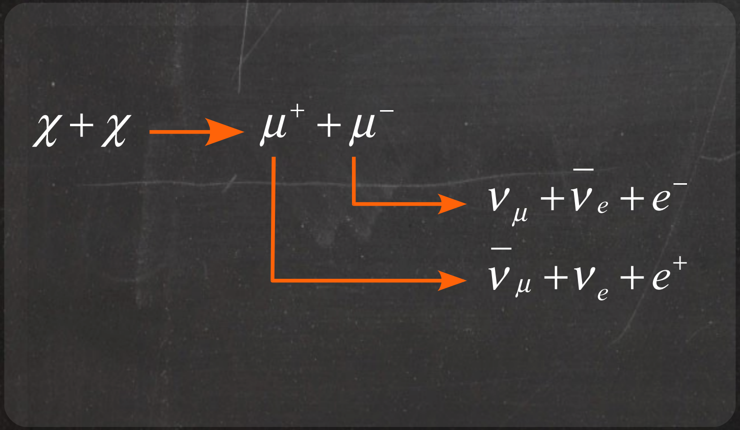
$$q+\bar{q} \to \pi^{0}+\ldots \to \gamma+\gamma$$

$$q+\bar{q} \to \bar{p}+\ldots$$

$$q+\bar{q} \to \ldots$$

$$\chi+\chi \to W^{+}+W^{-}$$

$$\chi+\chi \to \ldots$$



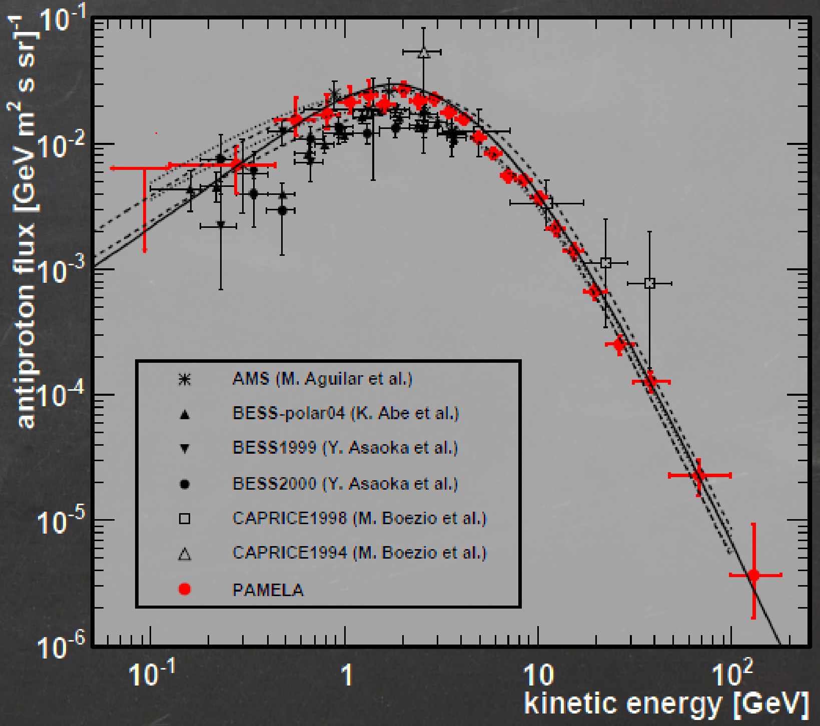
$$\chi+\chi \to \mu^{+}+\mu^{-}$$

$$\mu^{-} \to \nu_\mu+\bar{\nu}_e+e^{-}$$

$$\mu^{+} \to \bar{\nu}_\mu+\nu_e+e^{+}$$

Dark matter search
in (particle) **cosmic rays**

Pamela

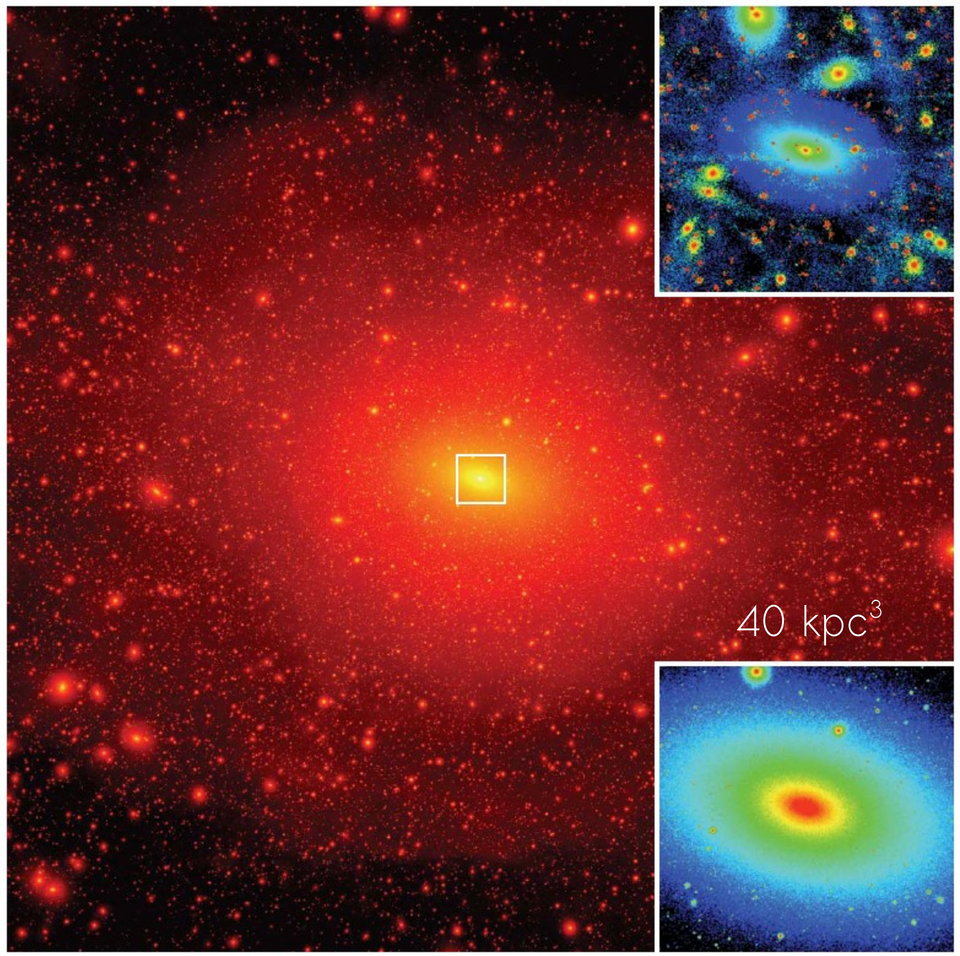


Part 2:
DM galactic substructures

DM galactic substructures

N-body simulations

Diemand et al. arXiv:0805.1244
Springer at al. arXiv:0809.0898



800 kpc^3

Numerical simulations: **smooth** and **homogeneous** Universe before a redshift of $z = 100$.

Then, the tiny **fluctuations** of the matter distribution began to **collapse** because of gravity.

The first objects to form are Earth-mass dark-matter **subhaloes.**

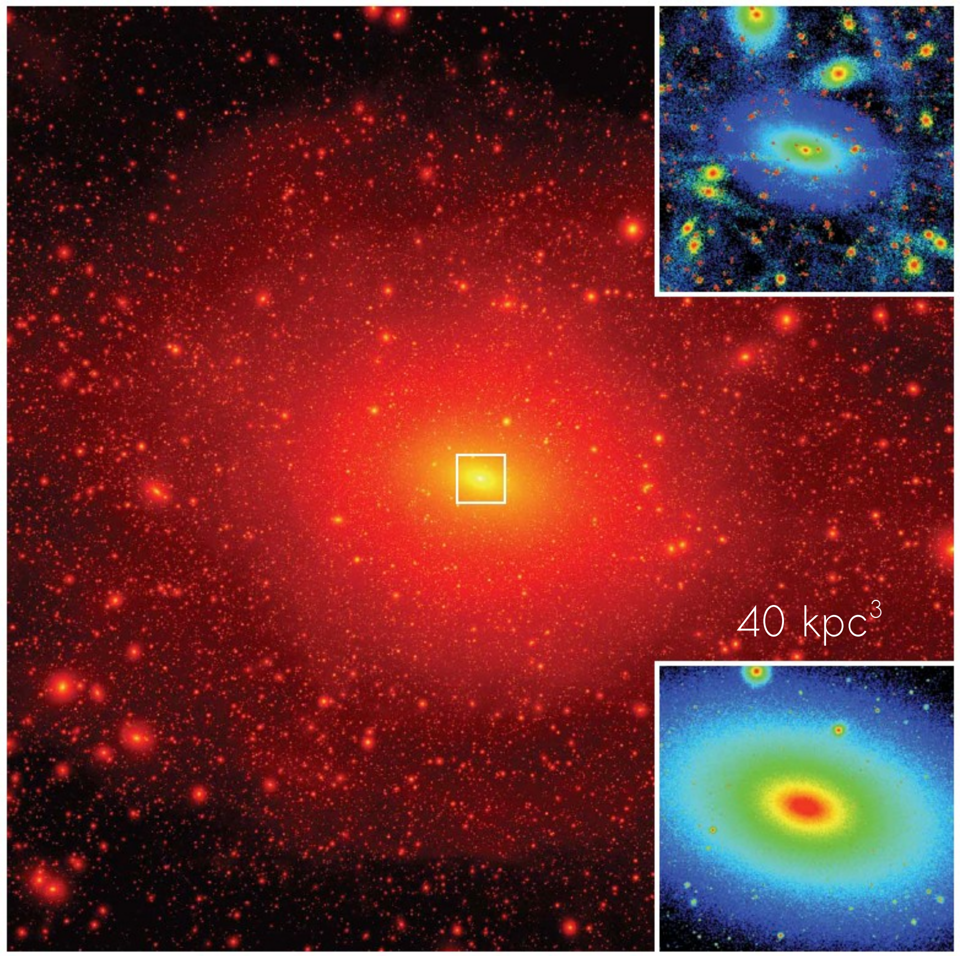
Stable against gravitational disruption: over 10^{17} clumps survive.

Mass distribution: $\sim m^{-2}$.

DM galactic substructures

N-body simulations

Diemand et al. arXiv:0805.1244
Springer at al. arXiv:0809.0898



The highest mass objects: $10^{10}\ M_\odot$ (10% of the mass of the Milky Way)-

Equipartition in mass among the smooth halo and the subhaloes distribution is found if the results are extrapolated till Earth mass substructures.

Current numerical resolution:

$10^{4.5}\ M_\odot$ Via Lactea II

$10^{4}\ M_\odot$ Aquarius

DM galactic substructures

Detectability at γ-rays energies

Pieri et al. arXiv:arXiv:0908.0195

DM particle: **Neutralino**

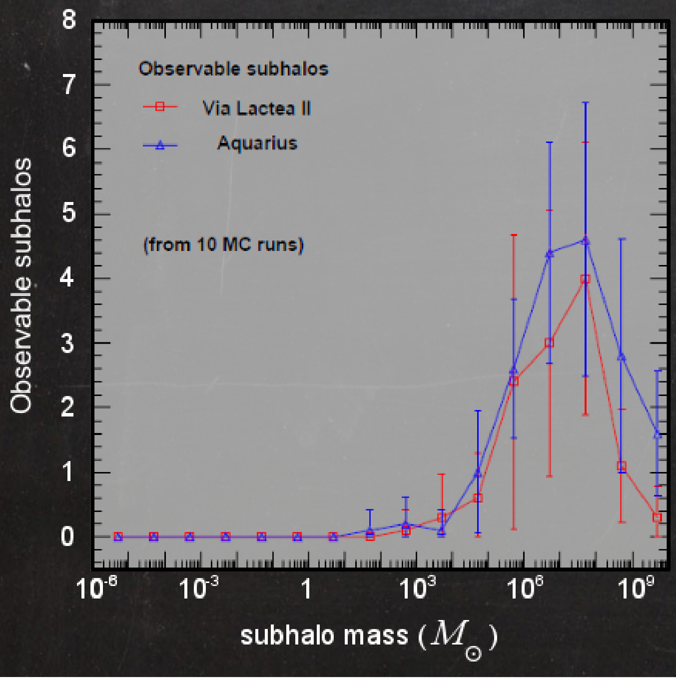
DM mass: 40 GeV

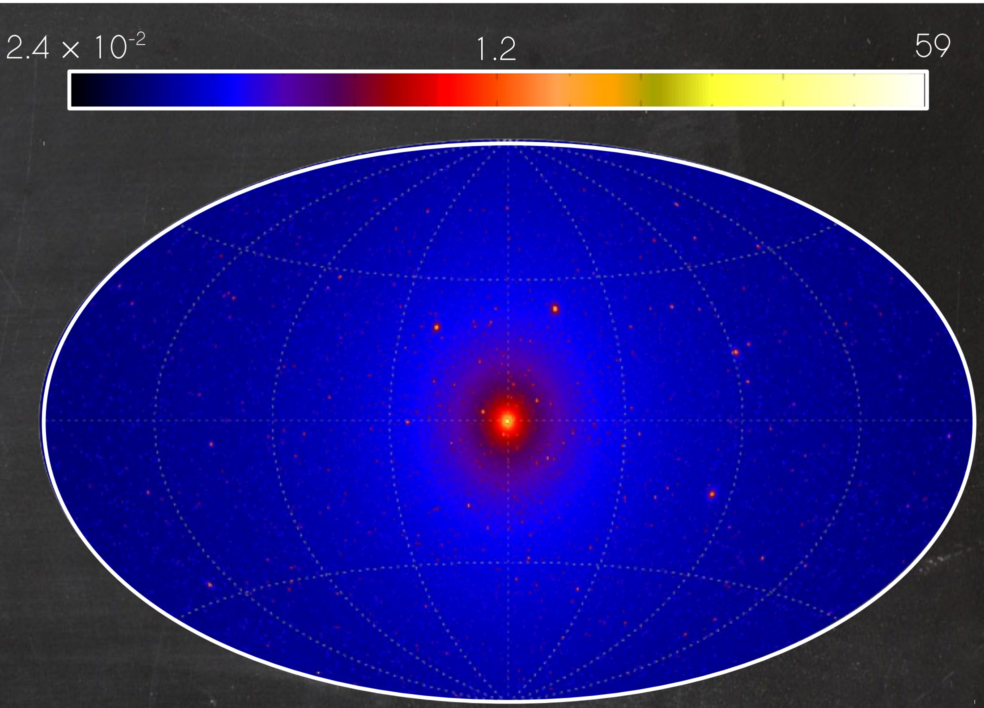
Annihilation rate: 3×10^{-26} cm^3 s^{-1}

Energy treshold: 3 GeV

Annihilation channel:

$\chi+\chi\rightarrow b$ quarks $\rightarrow\pi^0\rightarrow\gamma+\gamma$





Full sky map of the **number of photons** produced by DM annihilation

Observable clumps:

Via Lactea II 9.2 ± 2.6 at $3\,\sigma$

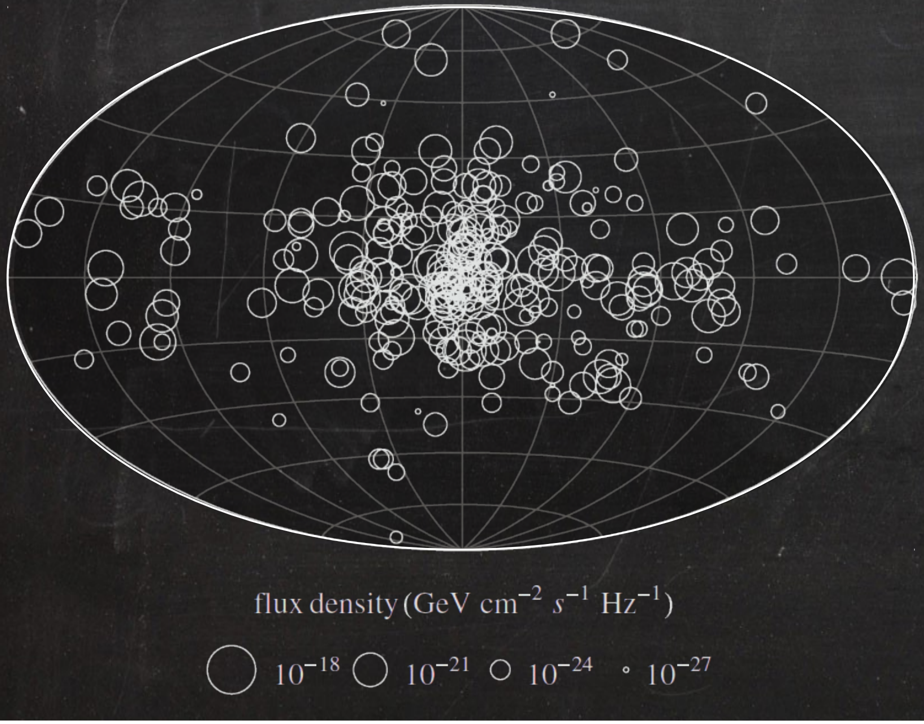
DM galactic substructures

Detectability at radio wavelenghts

Borriello et al. arXiv:arXiv:0809.2990

clump \#	distance kpc	scale rad. kpc	density par. GeV c^{-2}cm^{-3}	GMF μG	flux GeV cm^{-2}s^{-1}Hz^{-1}
1	14.2	0.180	6.51	0.0962	1.70×10^{-25}
2	4.71	0.181	6.50	0.320	4.55×10^{-23}
3	5.50	0.188	6.40	3.08	2.66×10^{-21}

Clumps from 10^7 to 10^{10} $M_{\rm sun}$

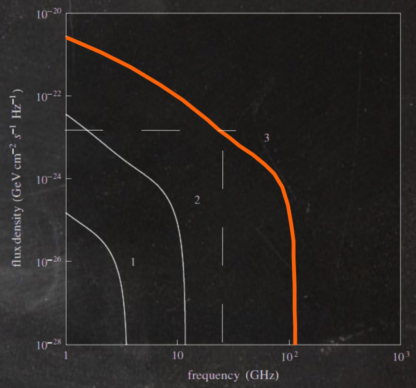


At $\nu \approx 23$ GHz (1st **WMAP** band) the flux is order 10^{-23} GeV cm^{-2}s^{-1}Hz^{-1} (100 GeV $\tilde{\chi}_1$)

$e^{\pm}$ **diffuse** in a ~1 kpc radius sphere:

$\Omega \sim 0.1$ sr

(d ~ 5 kpc)



Flux/Ω ~ 10^{-22} GeV cm^{-2}s^{-1}Hz^{-1}sr^{-1}

Experiment	**Sensitivity** GeV cm^{-2} s^{-1} Hz^{-1} sr^{-1}
WMAP	10^{-18}
ALMA	10^{-19}

DM galactic substructures

Angular power spectrum of γ-rays

Siegal-Gaskins arXiv:0807.1328

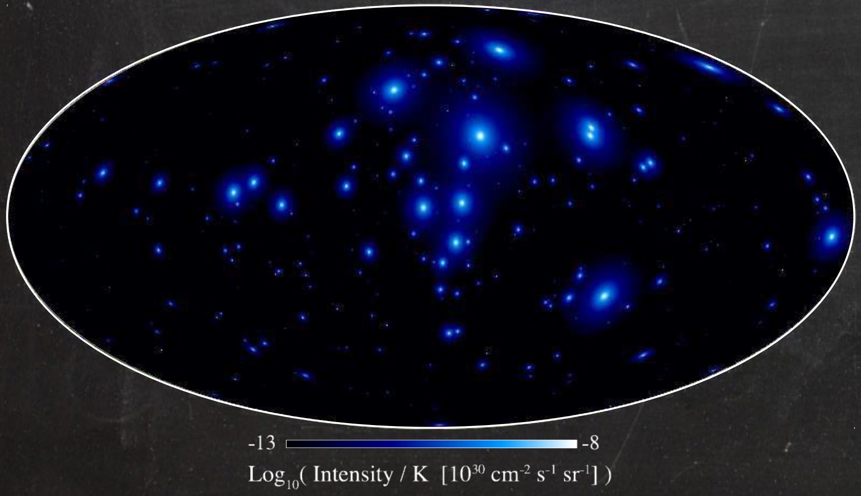
Fluctuation of the radiation intensity coming from the angular region Ω:

$$\delta I(\Omega) = \frac{I(\Omega) - \langle I \rangle}{\langle I \rangle} = \sum_{lm} a_{lm} Y_{lm}(\Omega)$$

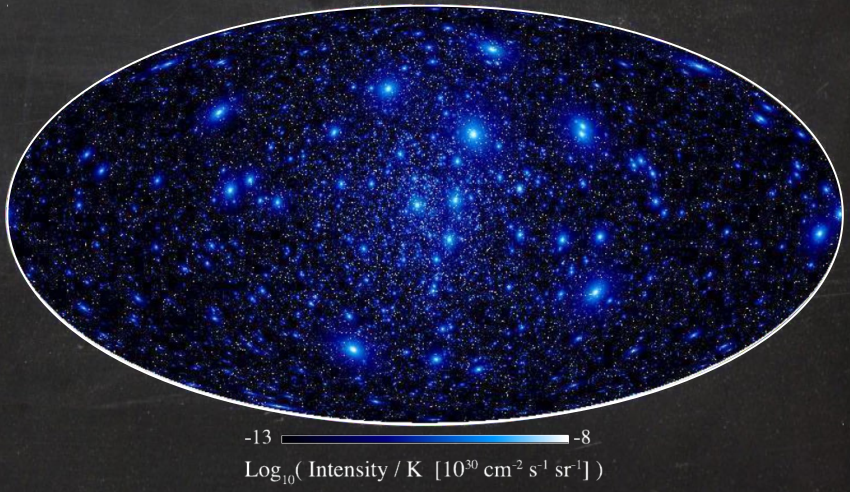
Angular power spectrum of $\delta I(\Omega)$:

$$C_l = \langle |a_{lm}|^2 \rangle = \frac{\sum_m |a_{lm}|^2}{2l+1}$$

Clumps from 10^7 to $10^{10}\ M_{\rm sun}$



Clumps from 10 to $10^{10}\ M_{\rm sun}$



DM galactic substructures

Angular power spectrum of γ-ray emission

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Angular power spectrum of $\delta I(\Omega)$:

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DM particle: **Neutralino** (MSSM)

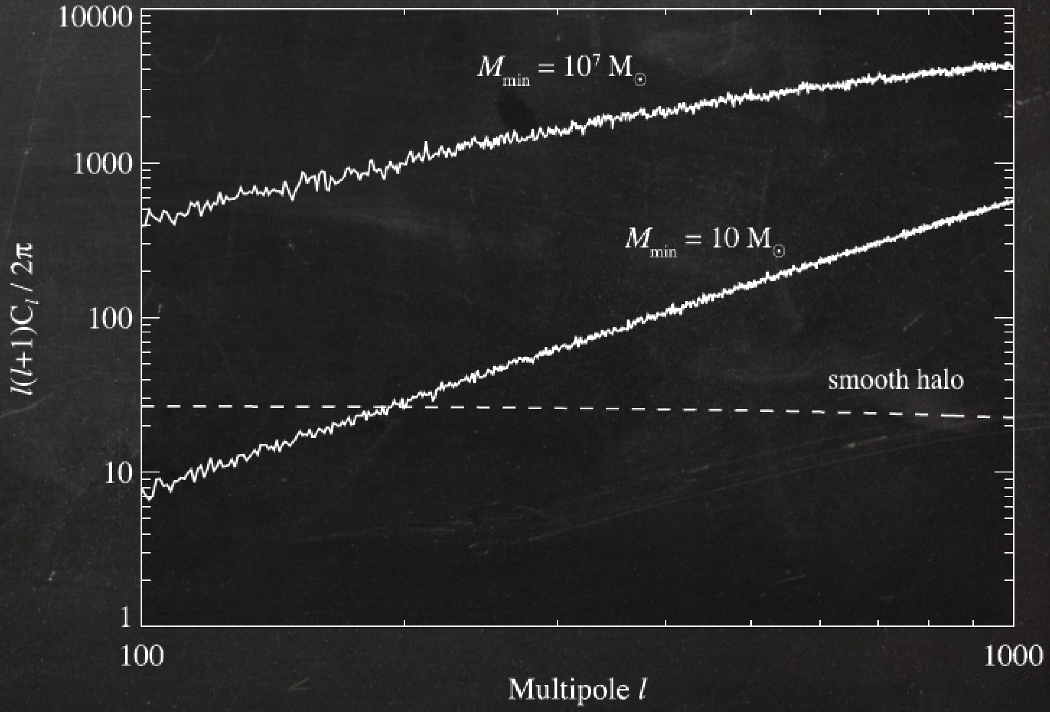
DM mass: 85 GeV

Annihilation rate: 3×10^{-26} cm^3 s^{-1}

Energy treshold: 10 GeV

Annihilation channel:

$$\chi + \chi \rightarrow \text{quarks} \rightarrow \pi^0 \rightarrow \gamma + \gamma$$



Intelude: Why electron anisotropy could be better?

A lot of uncertainty affects every attempt to detect the DM

Its **nature** (mass, rate of annihilation or decay, etc.)

Spiked or cored galactic mass **density** profile?

Smooth or clumpy distribution

etc...

DM electron intrinsic anisotropy will be defined in terms of a **ratio** in which the two term vary in a coherent way with respect to integrated unknowns. **Any multiplicative factors is simplified.**

Electrons and positrons can travel only **few kpc**. Almost no difference among spiked and cored profiles

Part 3:
Electron anisotropy

Electron anisotropy

Definition of dipole anisotropy

e.g. Berezinskii et al., North Holland, 1990

I = cosmic rays **intensity** (# of particles/sr/cm^2/s)

Total flux: $\phi(E) = \int I(E)\, d\Omega$

Diffusion in the **turbulent** GMF → almost **isotropic** flux

Residual degree of **anisotropy**:

$$\delta = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

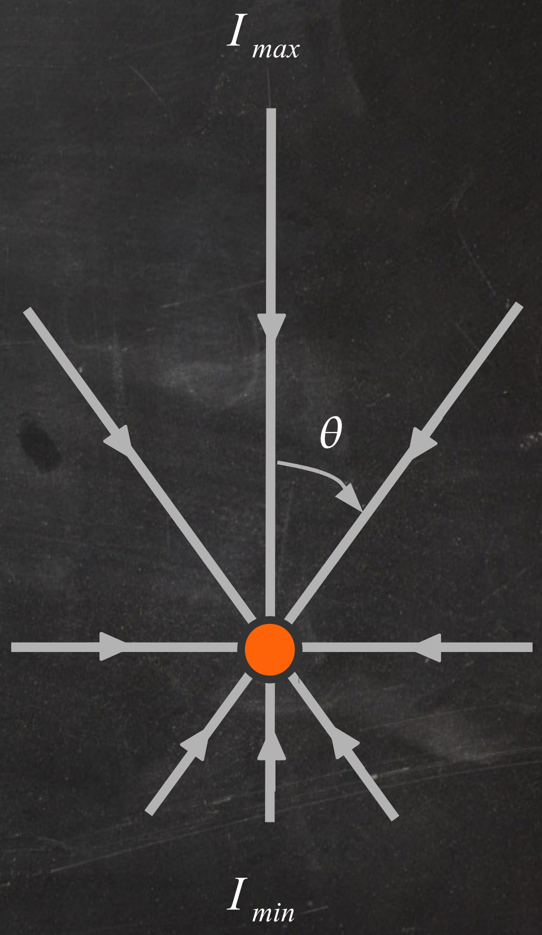
Dipole anisotropy: $I(E) = I_0(E) + I_1(E)\cos\theta$

Total flux: $\phi = 4\pi I_0 = nv$

Flux from z: $\phi_z = \frac{4\pi}{3} I_1$

Anisotropy:

$$\delta = \frac{I_1}{I_0}$$



Electron anisotropy

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Total flux: $\phi = 4\pi I_0 = nv$

Flux from z : $\phi_z = \frac{4\pi}{3} I_1$

Anisotropy:

$$\delta = \frac{I_1}{I_0}$$

In a **diffusive approach**:

$$\phi_z = -D_{zz}\frac{\partial n}{\partial z}$$

In general:

$$\vec{\delta} = \frac{3}{v}\,\frac{\mathbf{D}\cdot\vec{\nabla}\phi}{\phi}$$

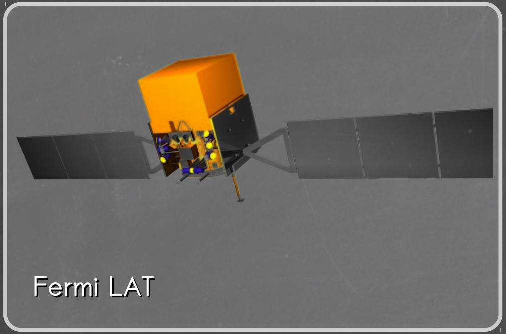
If the propagation is **isotropic**:

$$\vec{\delta} = \frac{3D(E)}{v}\,\frac{\vec{\nabla}\phi}{\phi}$$

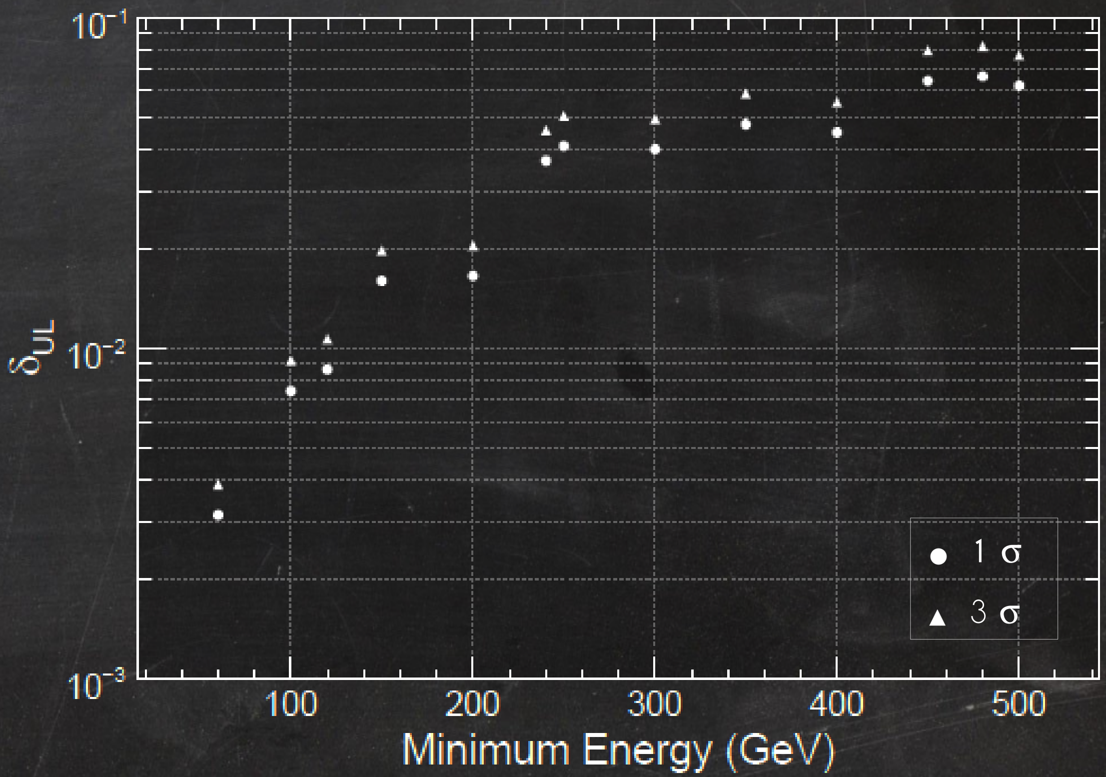
Electron anisotropy

Fermi LAT upper limit

Fermi LAT Collaboration, arXiv:1008.5119



Upper limits on the integrated **dipole anisotropy** versus the **minimum energy** for different confidence levels.



Electron anisotropy

Limit cases

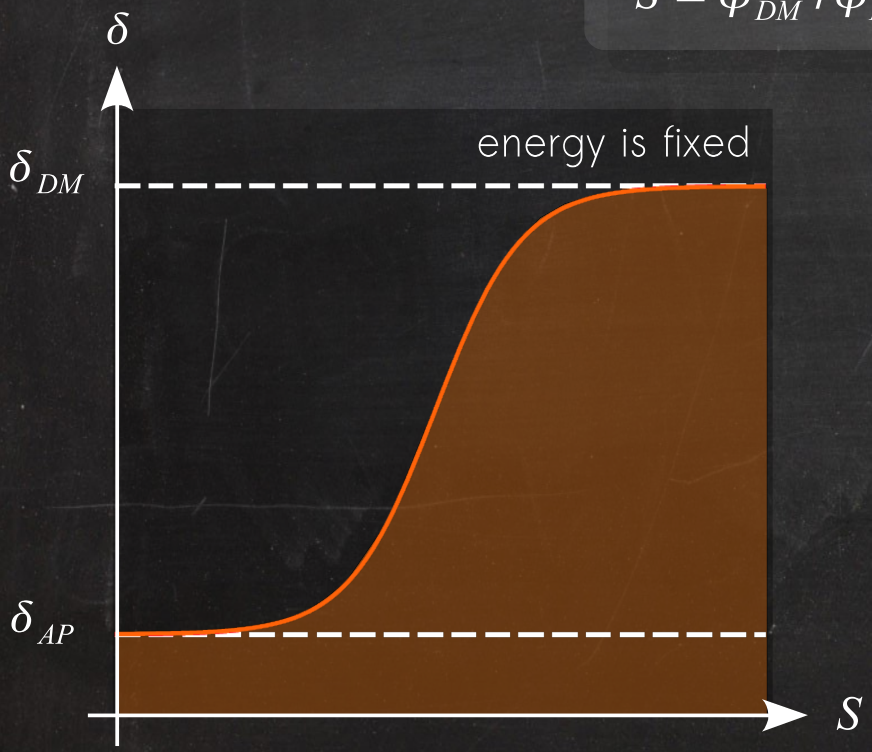
Total flux = Astrophysical flux + Dark Matter flux

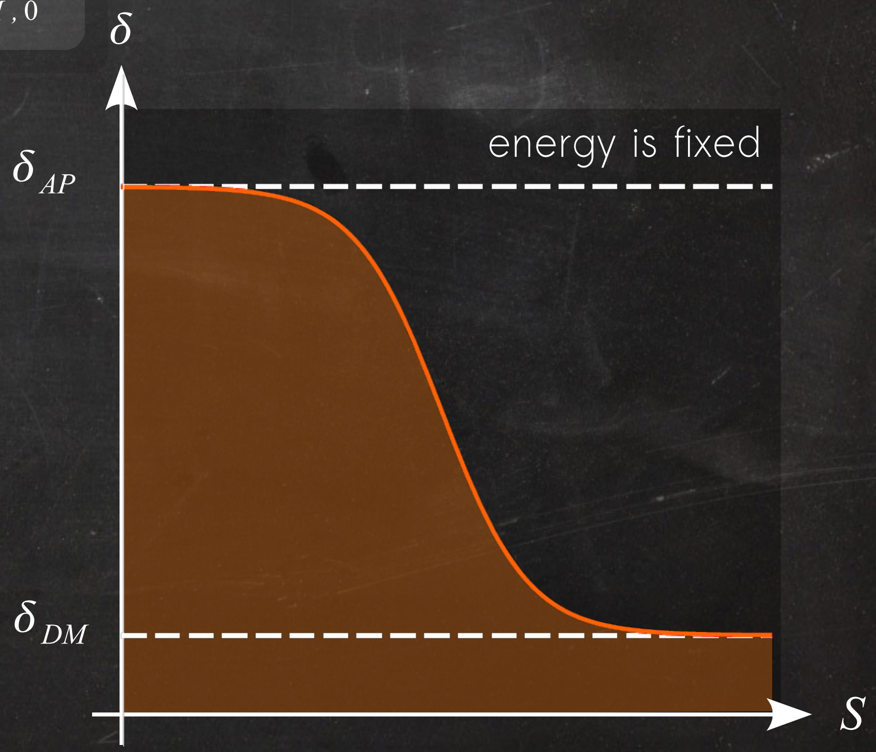
$$\delta = \frac{3D}{v}\frac{|\vec{\nabla}\phi_{AS}+\vec{\nabla}\phi_{DM}|}{\phi_{AS}+\phi_{DM}} \leqslant \frac{\delta_{AS}/\phi_{DM}+\delta_{DM}/\phi_{AS}}{1/\phi_{AS}+1/\phi_{DM}}$$

Intrinsic degree of anisotropy:

$$\delta_i = \frac{3D}{v}\frac{|\vec{\nabla}\phi_i|}{\phi_i}$$

$$S = \phi_{DM}/\phi_{DM,0}$$





Electron anisotropy

Clumpiness and anisotropy

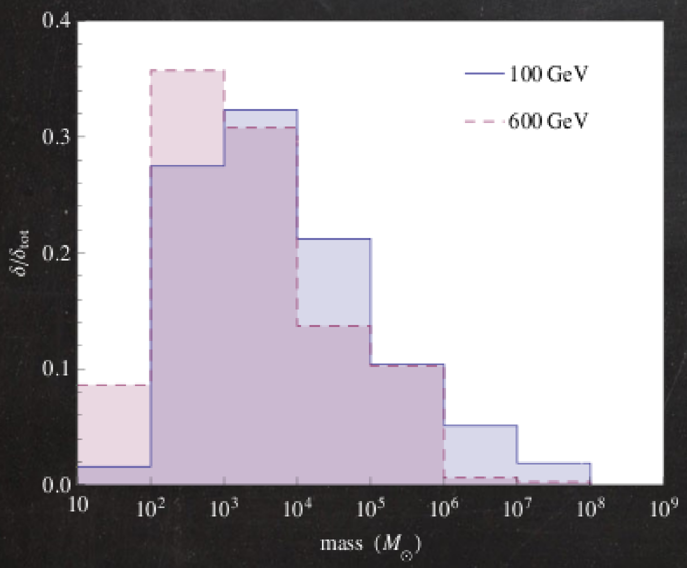
Borriello et al. arXiv:arXiv:1012.0041

The ideal case:

Several MC simulation of the distribution of substructure.

Flux from each substructure. Sum over the distribution.

Mean over the realizations.



The real case:

We are dealing with 10^{17} substructures!

We start evaluating the mean values analytically. We discover that the smooth halo and the small clumps do not contribute to the anisotropy.

10^{-6} o 10 $M_\odot$ → mean flux, **zero anisotropy**

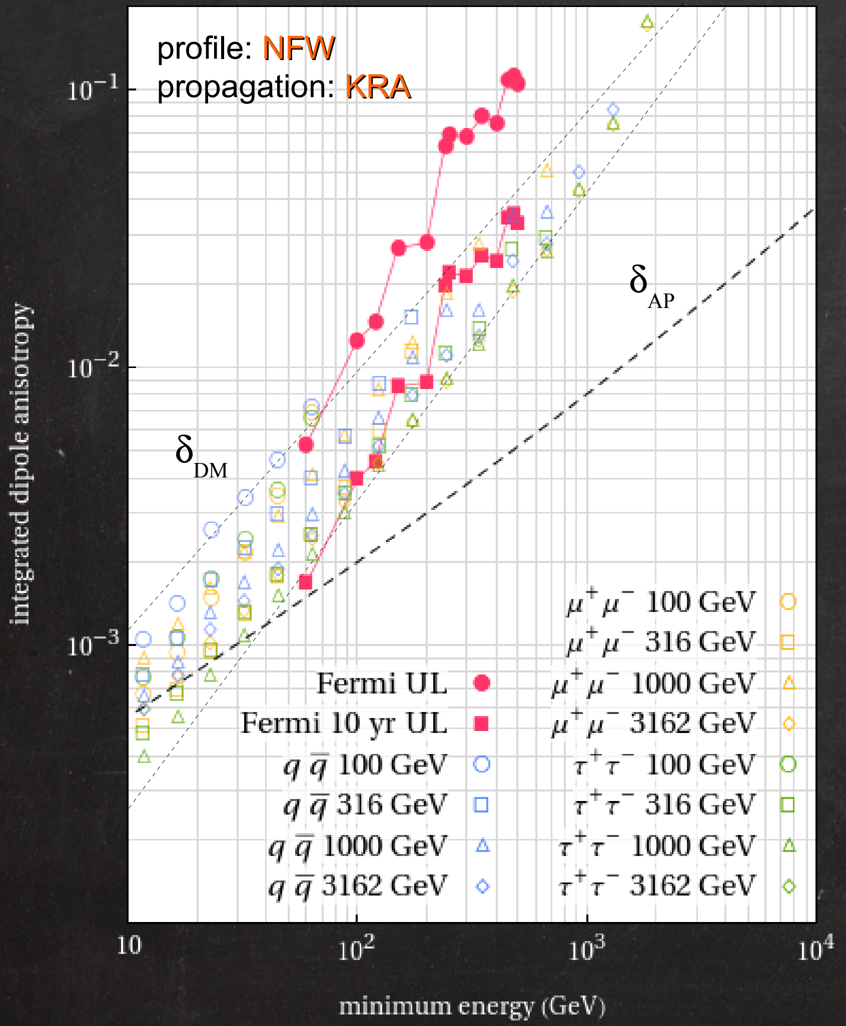
10 o 10^{10} $M_\odot$ → **100** MC realizations

$$\delta_{DM} = \frac{3\,D(E)}{v}\,\frac{|\vec{\nabla}\,\phi_{DM}^{high\,mass}|}{\phi_{DM}^{smooth}+\phi_{DM}^{low\,mass}+\phi_{DM}^{high\,mass}}$$

Electron anisotropy

Universality of the DM electron anisotropy upper limit

Borriello et al. arXiv:arXiv:1012.0041



$$\delta_{DM} = \frac{3\,D(E)}{v}\frac{|\vec{\nabla}\phi_{DM}|}{\phi_{DM}}$$

Mass:
From 100 to 3500 GeV

Annihilation models:

- quark pairs
- muon pairs
- tau particle pairs

DM mass density profile:

- NFW (spiked)
- Burkert (cored)

Annihilation rate:
Independent (by def.)

Local DM density:
Independent (by def.)

Propagation model:

- Kraichnan
- Kolmogorov

100 MC realization of the distribution of the clumps with

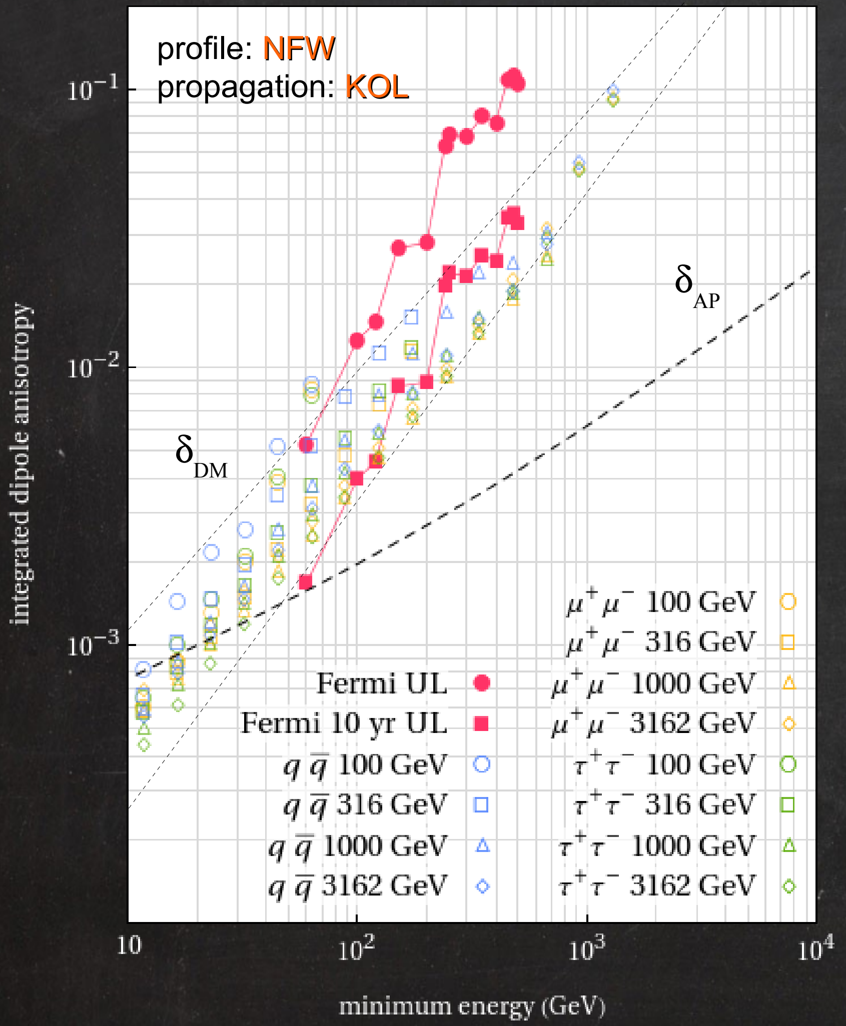
$m \in 10 \div 10^{10}\ M_\odot$

for each model

Electron anisotropy

Universality of the DM electron anisotropy upper limit

Borriello et al. arXiv:arXiv:1012.0041



$$\delta_{DM} = \frac{3\,D(E)}{v}\,\frac{|\vec{\nabla}\phi_{DM}|}{\phi_{DM}}$$

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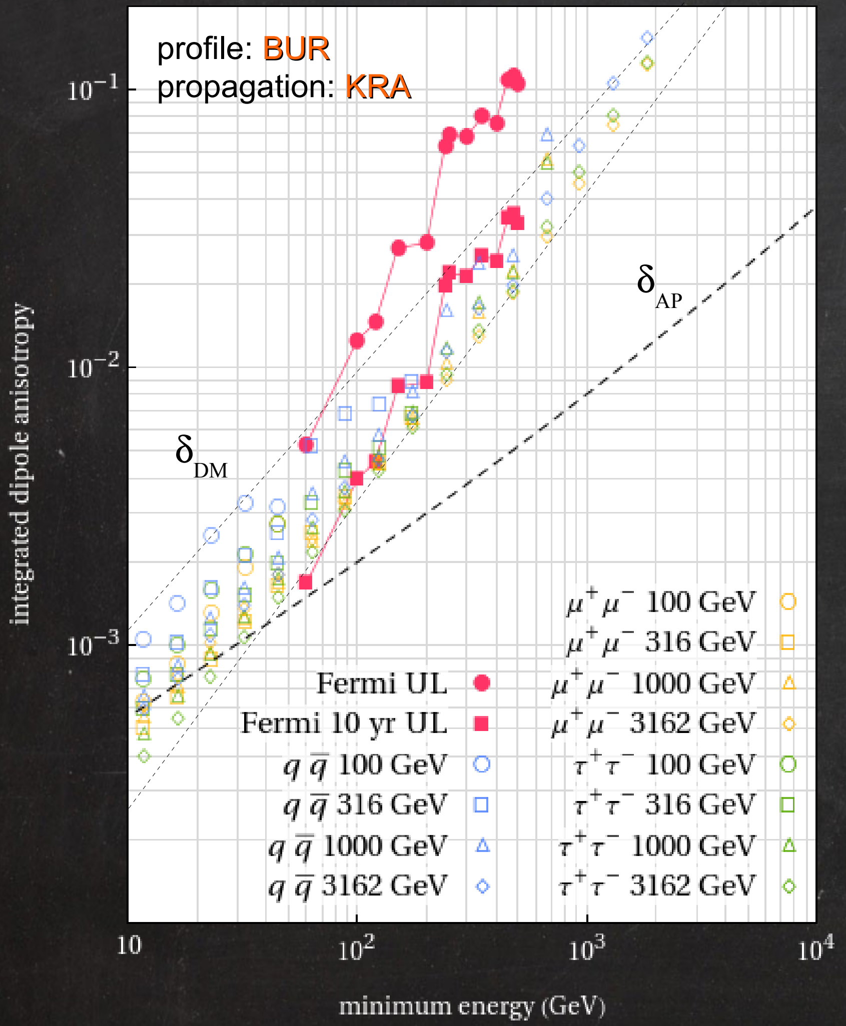
for each model

Electron anisotropy

Universality of the DM electron anisotropy upper limit

Borriello et al. arXiv:arXiv:1012.0041



$$\delta_{DM} = \frac{3\,D(E)}{v}\frac{|\vec{\nabla}\phi_{DM}|}{\phi_{DM}}$$

Mass:
From 100 to 3500 GeV

Annihilation models:
- quark pairs
- muon pairs
- tau particle pairs

DM mass density profile:
- NFW (spiked)
- Burkert (cored)

Annihilation rate:
Independent (by def.)

Local DM density:
Independent (by def.)

Propagation model:
- Kraichnan
- Kolmogorov

100 MC realization of the distribution of the clumps with

$m \in 10 \div 10^{10}\ M_\odot$

for each model

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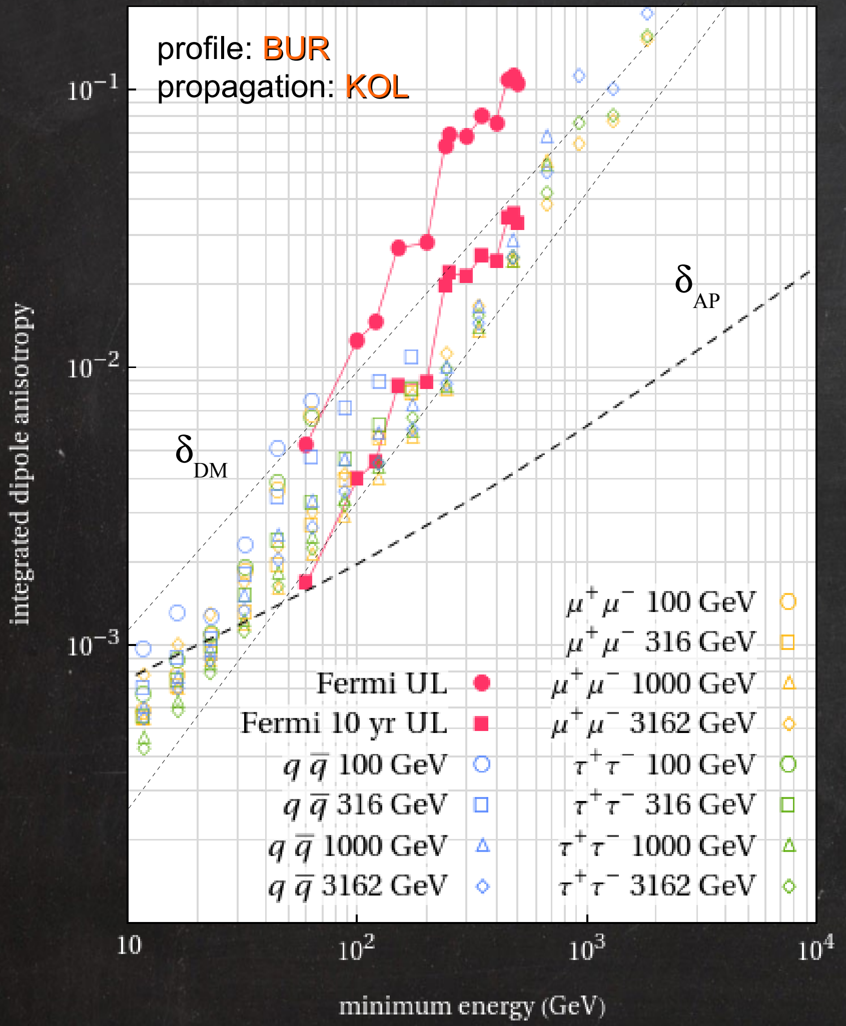

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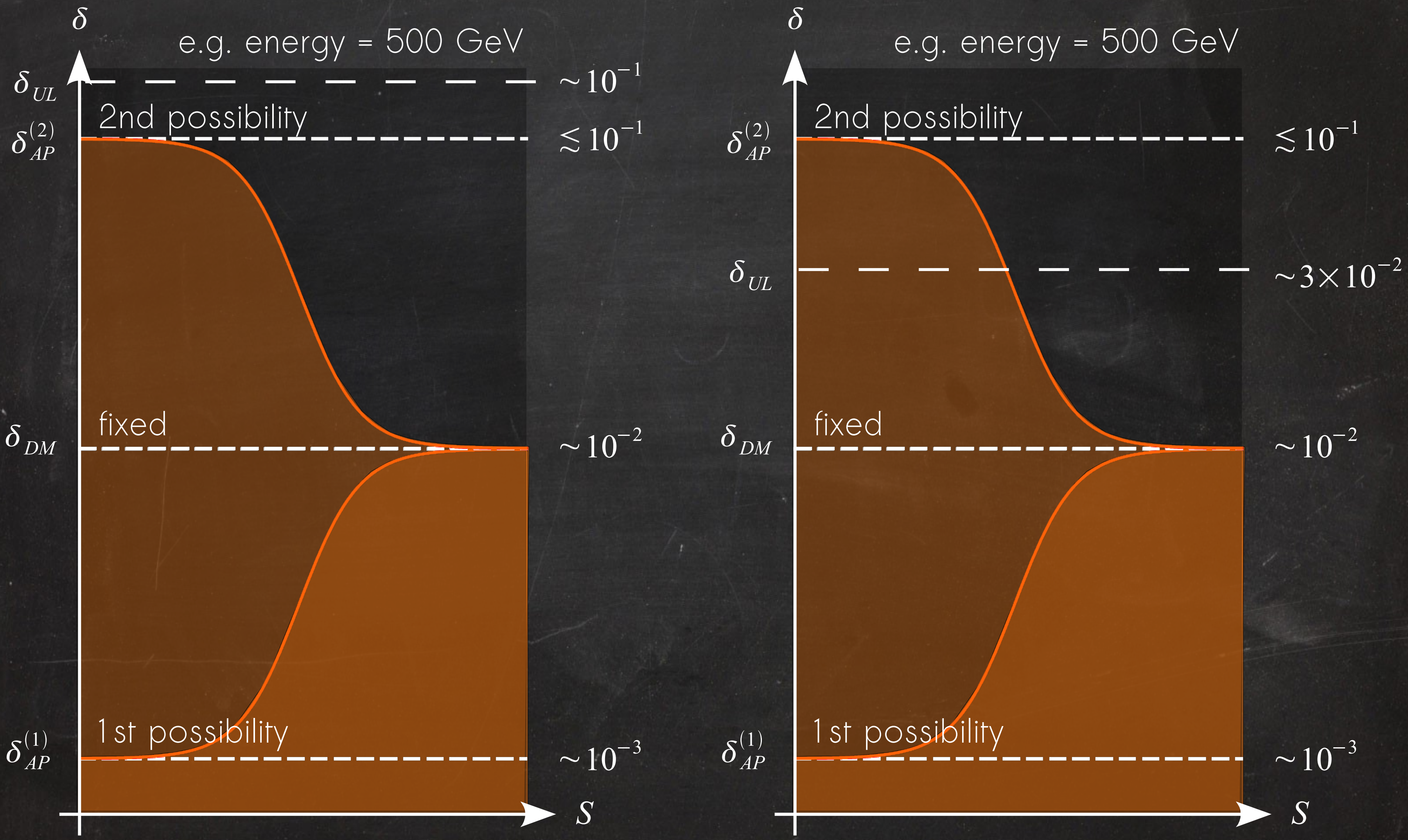
Part 4:

Astrophisical implications

Astrophysical implications

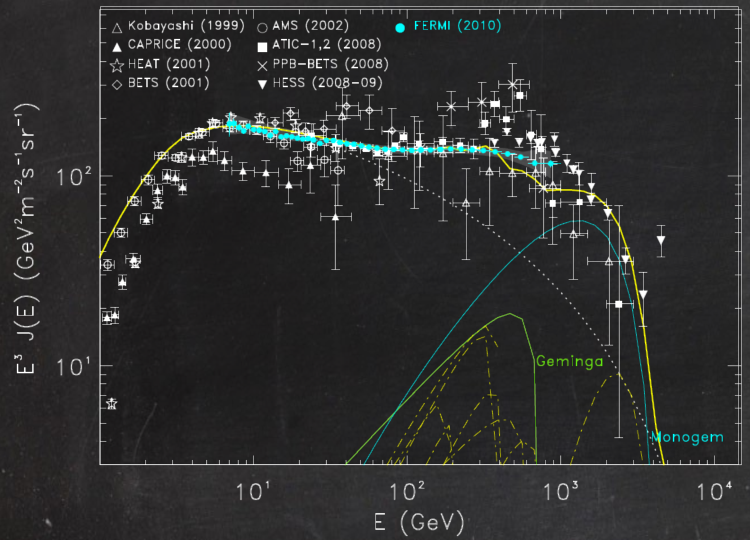
Excluding the DM interpretation of a forthcoming anisotropy detection



Astrophysical implications

AP anisotropy dominated scenario

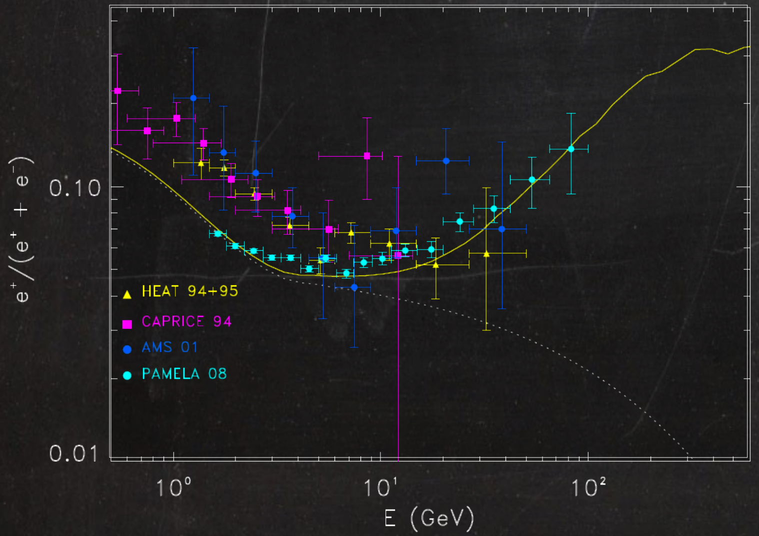
Di Bernardo et al. ArXiv:1010.0174

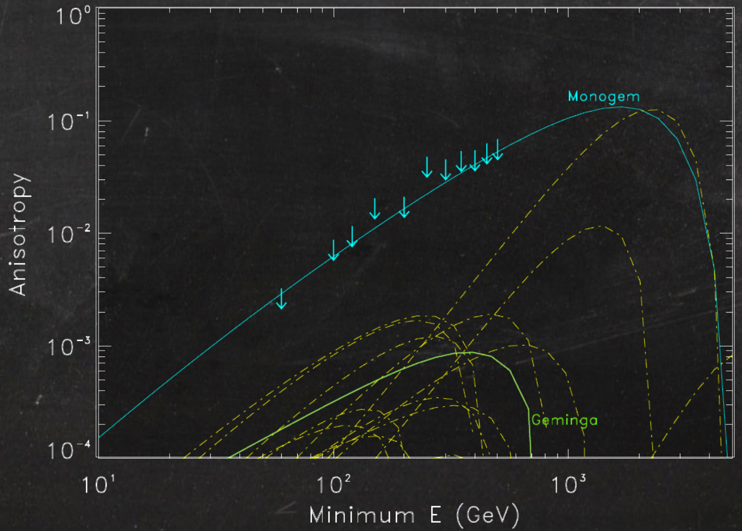


$\delta_{AP} > \delta_{DM}$

Nearby pulsars (within 2 kpc, KRA diffusion setup) contribution is able to explain the excess seen by Fermi LAT with respect to a standard electron and positron astrophysical background.

The same model is able to perfectly reproduce the **positron fraction** observed by Pamela.

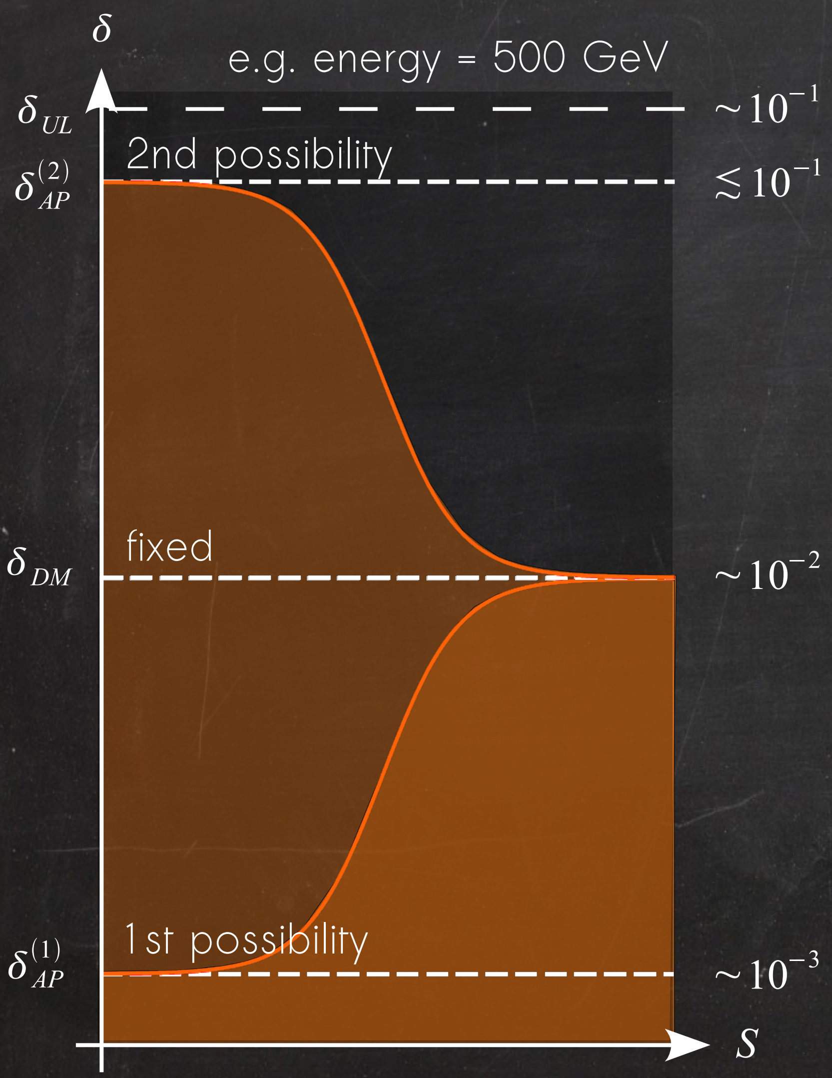


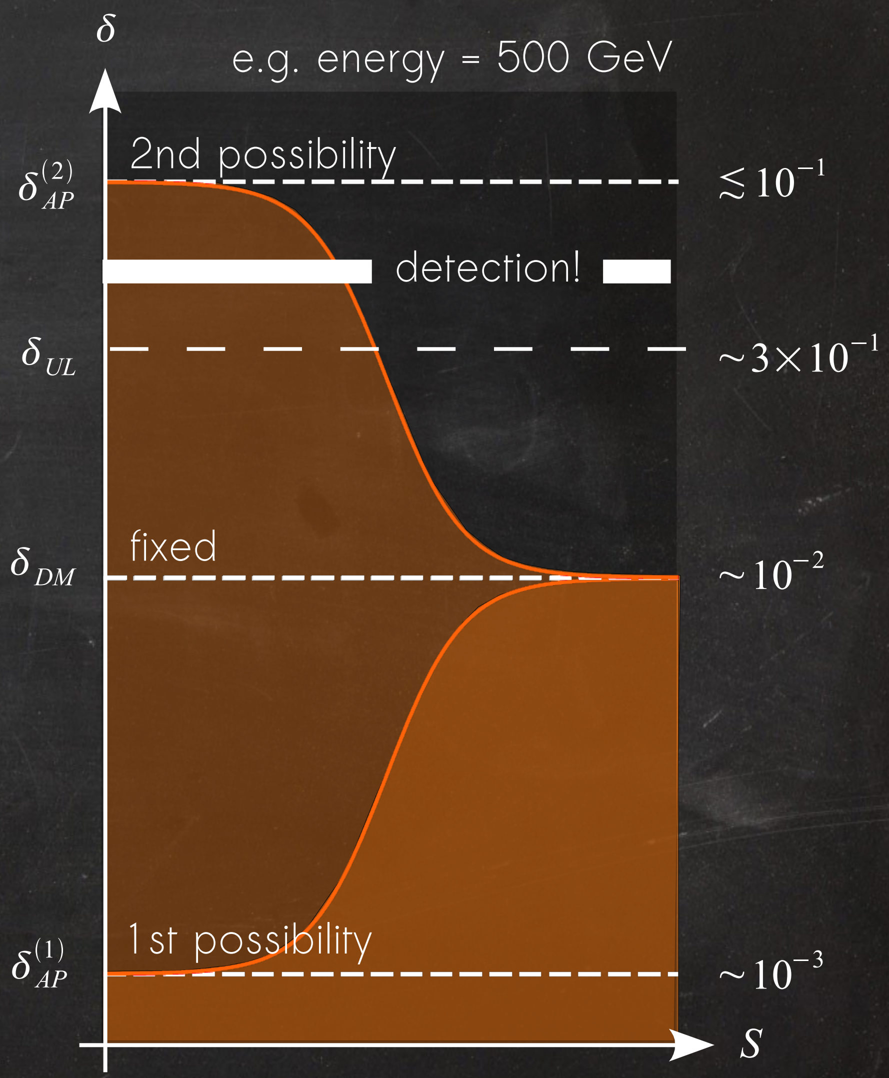


The associated electron anisotropy would be **on the verge of being detected** by Fermi LAT.

Astrophysical implications

Excluding the DM interpretation of a forthcoming anisotropy detection





Astrophysical implications

Excluding the DM interpretation of a forthcoming anisotropy detection

Conclusions:

- Dipole anisotropy can exceed the DM intrinsic upper limit only thanks to the contribution of **non-standard astrophysical sources**.
- If a detection will be made by Fermi LAT in the next ten years, then this argument could be used as a **criterion** to deduce the presence of exotic astrophysical sources.
- The possibility that such a high degree of anisotropy could be entirely due to a near DM clump is **ruled out**.