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Dark Matter searches with astrophysics

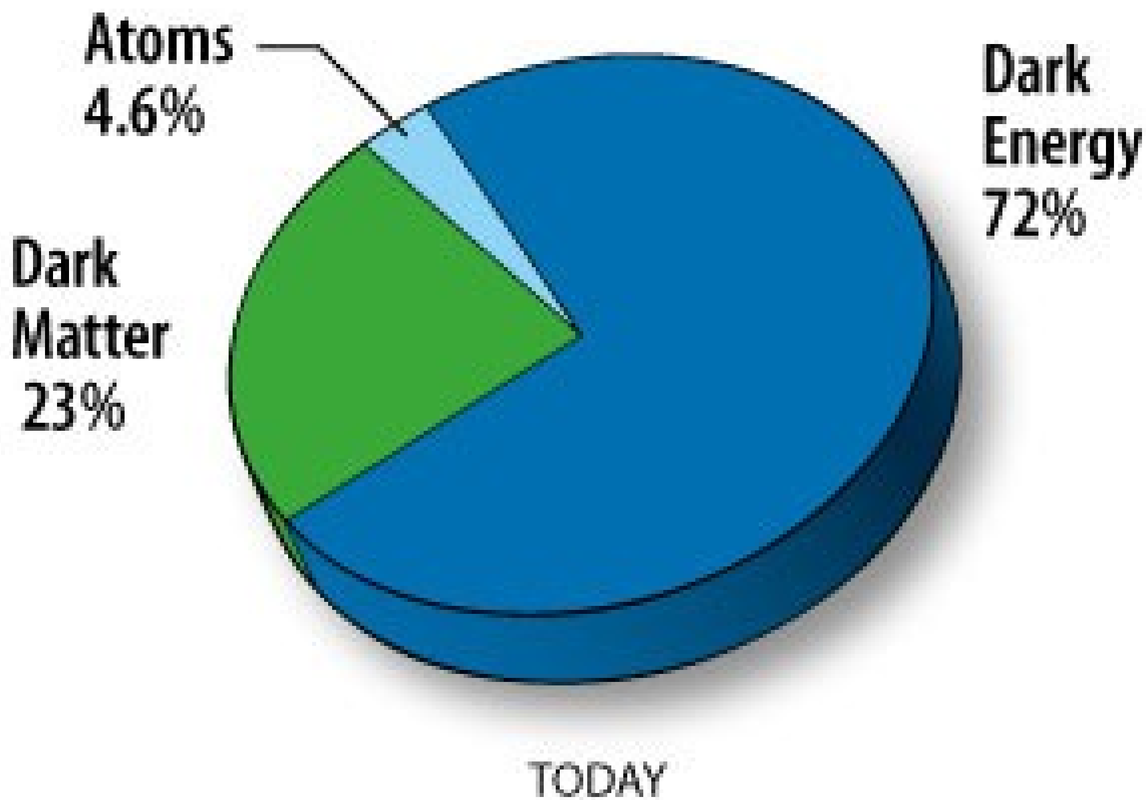
IAP

24 February 2013

The cosmological pie

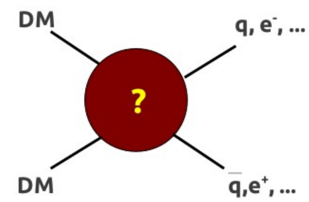
Non baryonic Dark Matter dominates the matter content of the Universe

Motivation to search for new physics beyond the Standard Model



Weakly Interacting Massive Particles

WIMPs annihilate in the early Universe and decouple from thermal bath when they are non relativistic



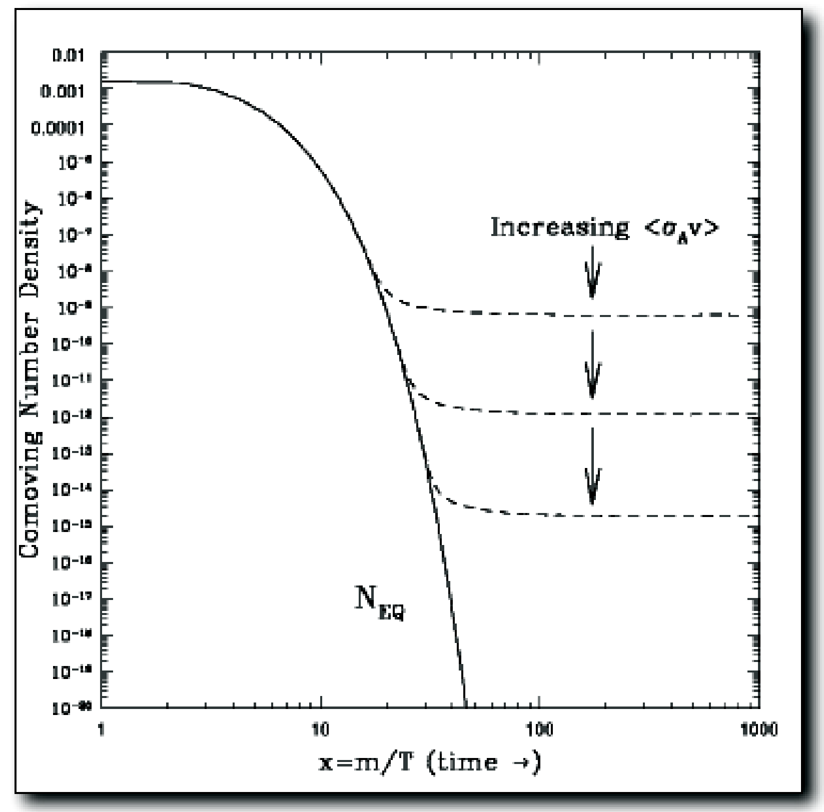
Relic density with standard cosmology:

$$\Omega h^2 \sim 0.1 \; \frac{3\times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}}{\langle \sigma v \rangle}$$

Electroweak cross-sections are in the correct range

$$\langle \sigma v \rangle \sim \frac{\alpha^2}{100\ \mathrm{GeV}^2} \sim 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

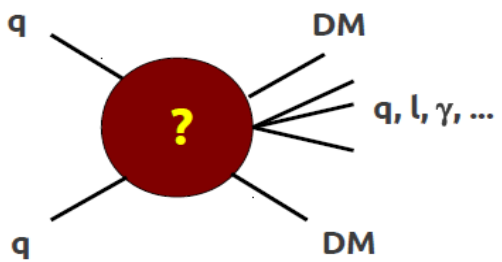
WIMPs arises in many extensions of the Standard Model at the EW scale



Hunting WIMPs

Colliders

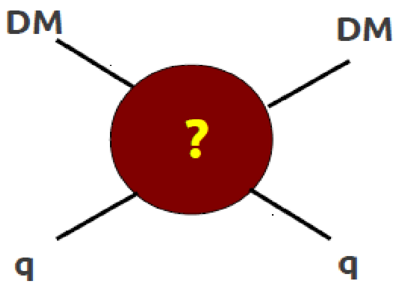
Missing energy signature at LHC



Direct Detection

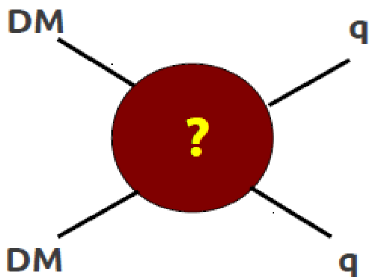
DM scattering off detectors in

underground laboratories



Indirect detection

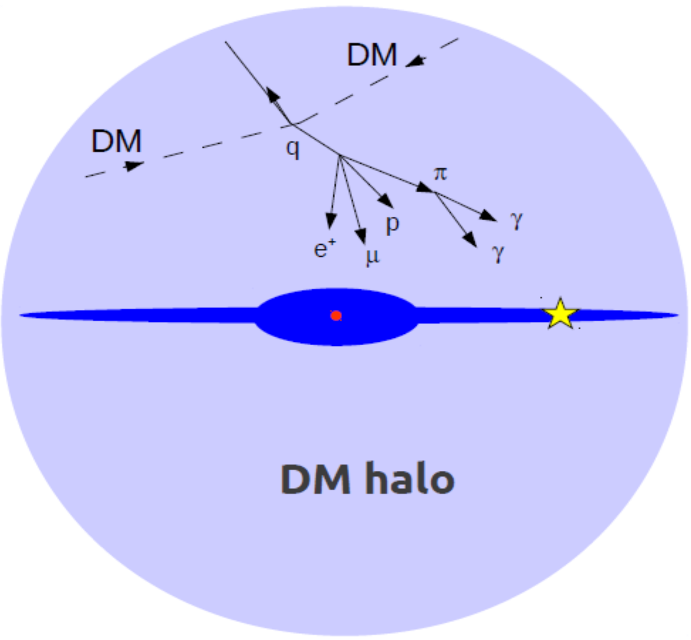
Signature of DM annihilations in space



Hunting WIMPs with astrophysics

WIMPs inside halos annihilate into Standard Model particles.

Generically these processes lead to fluxes of



- **photons**

  Typically gamma-rays since WIMPs masses lie

  in the GeV-TeV range

- **Antimatter**

  antiproton, positrons, antideuterium

- **neutrinos**

Plan of the talk

- **Searches of DM with gamma-rays**

  Brief discussion about recent results on gamma-ray lines

  Implications for models of DM

- **Radio**

  Bounds from radio data and searches of extragalactic sources

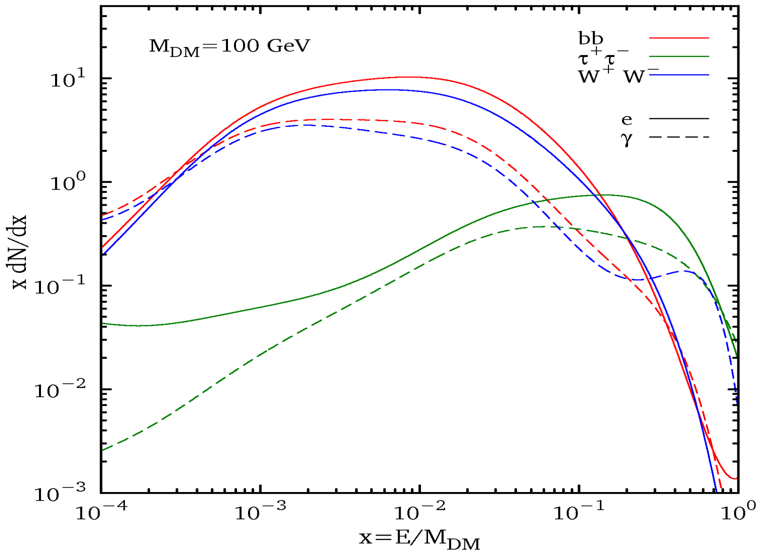
Annihilation spectra

$$\frac{d\Phi}{dE_\gamma} = \frac{1}{8\pi} \boxed{\frac{(\sigma v)}{M_\chi^2} \sum_i B_f \frac{dN^f}{dE_\gamma}} \times \boxed{\int ds d\Omega \;\; \rho_\chi^2(s,\Omega)}$$

DM annihilates into SM particle which eventually hadronize/decay and produce photons, neutrinos, anti-protons, positrons...

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

$$\pi^0 \to \gamma\gamma$$



Continuum featureless photon spectrum

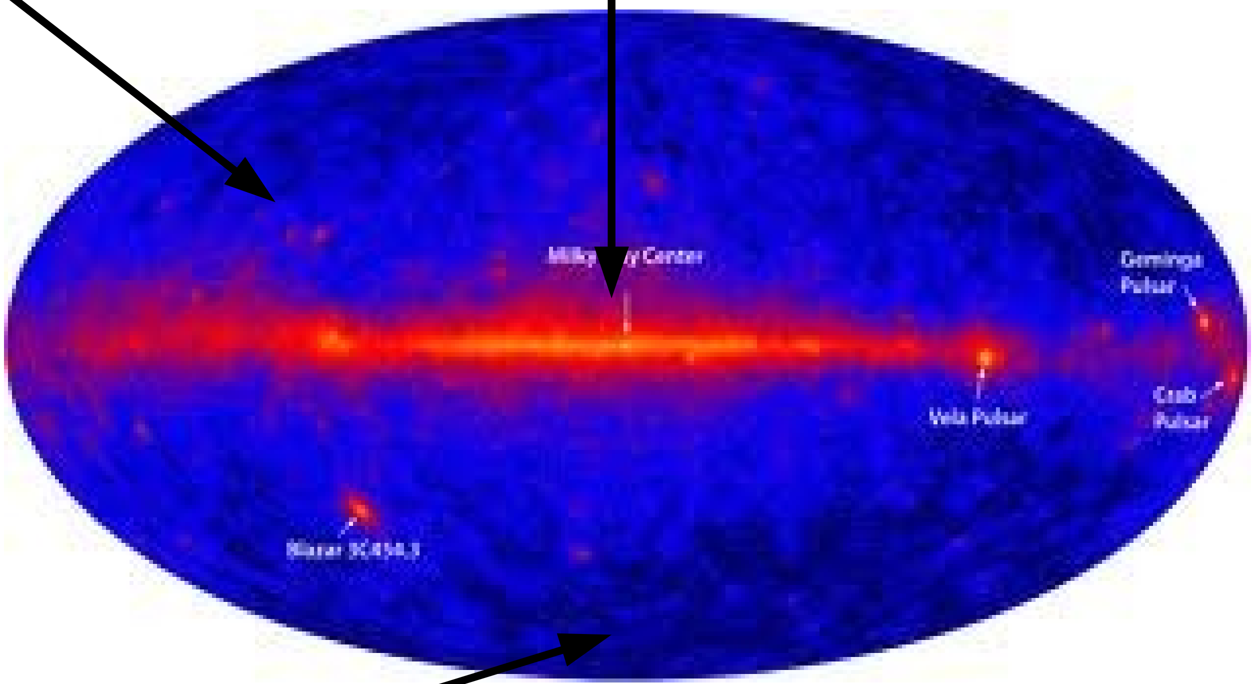
Difficult to distinguish from astrophysical background

Where to look for DM

Dwarf galaxies

Galactic center

Cluster of galaxies

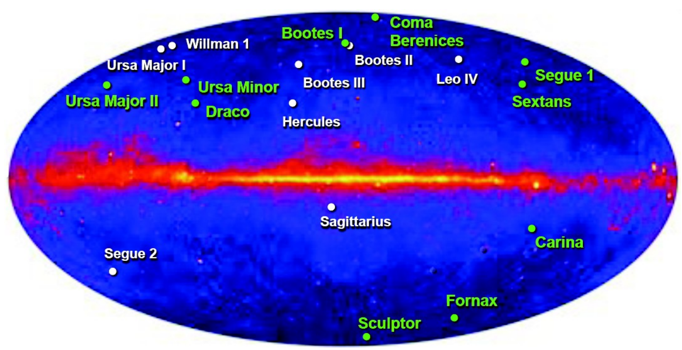


Extragalactic emission

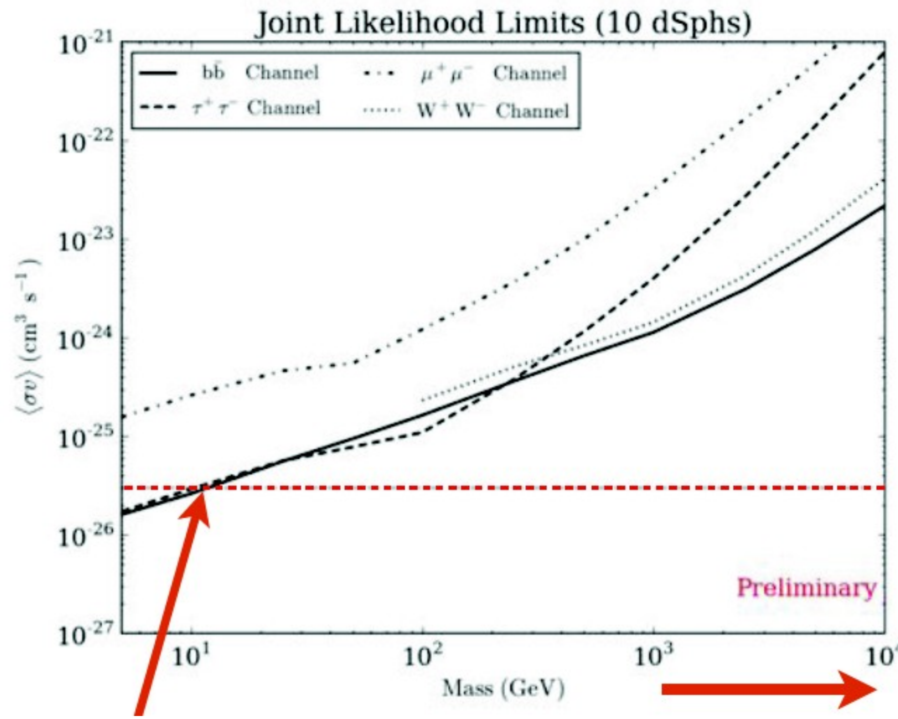
clumps

Diffuse Halo

Dwarf galaxies



From Drlica-Wagner, Fermi Symposium 2012



Thermal cross-section

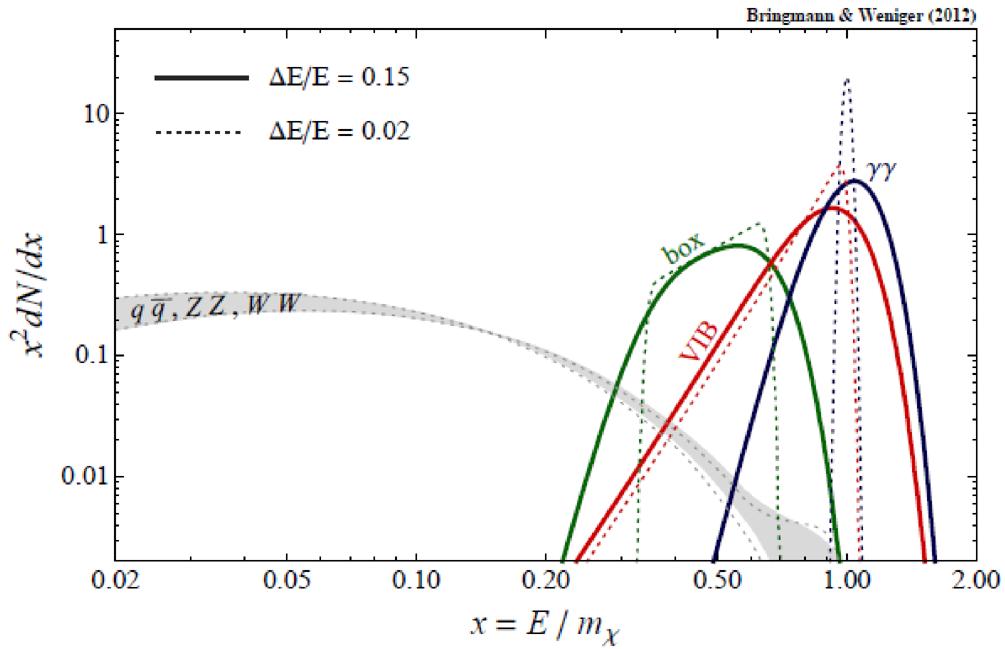
DM dominated objects, large M/L ratios

Nearby

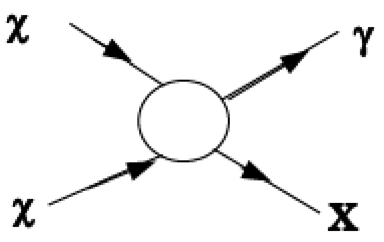
DM density distribution from stellar velocity distribution

Strong bounds on DM annihilations

Spectral features



Bringmann, Weniger 2012



Gamma-ray lines are induced at loop-level : O(α^2) suppression

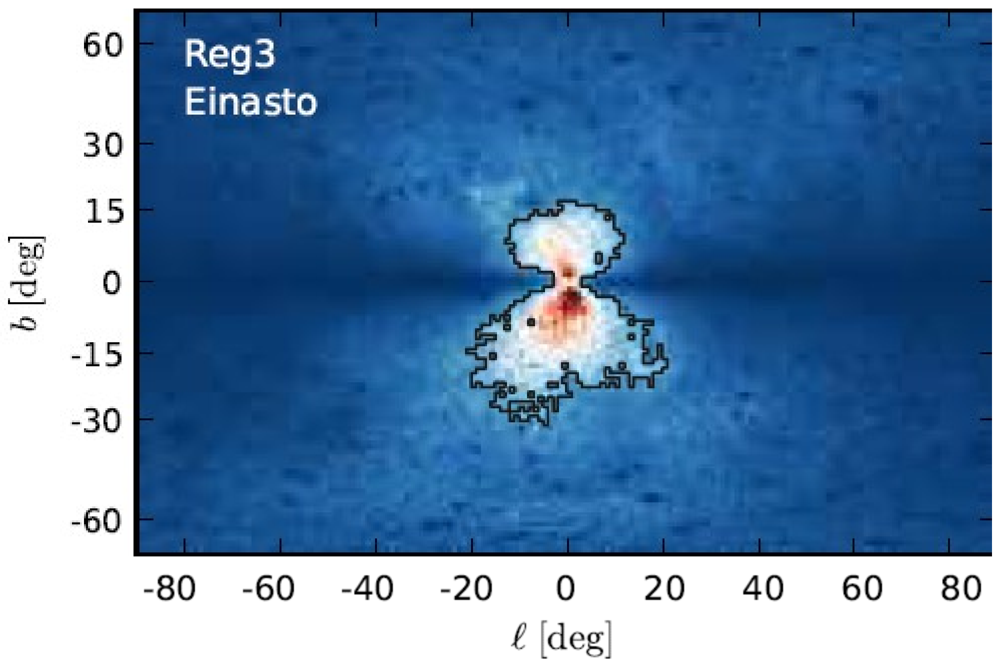
Hard spectrum can arise from radiative corrections

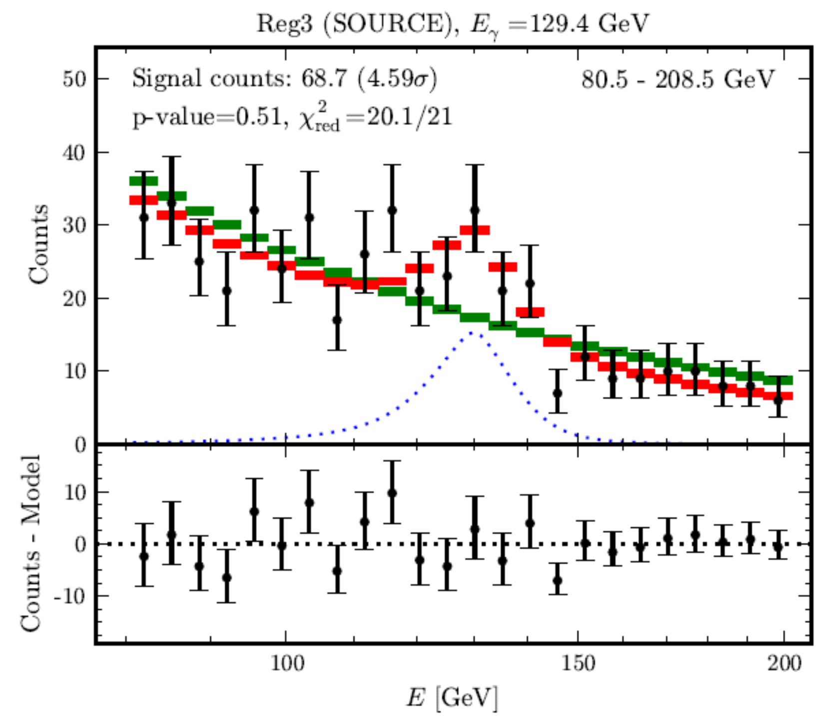
Internal Bremsstrahlung

$$\chi\chi \to f\bar{f}\gamma$$

Fermi Lines

Weniger 2012





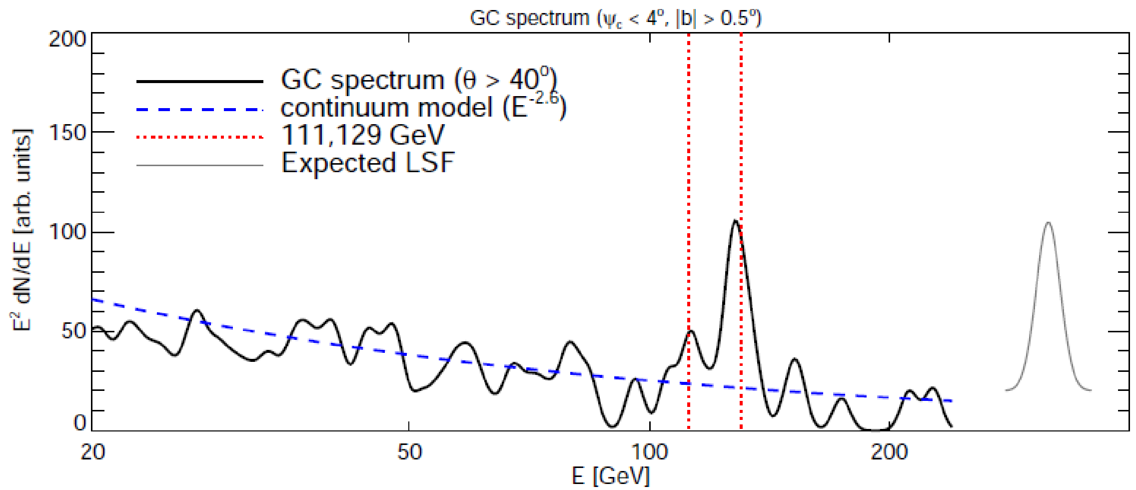
Optimized target region around the galactic center & excluding most of the disk

“Sliding energy window”: search in a small energy range around the line.

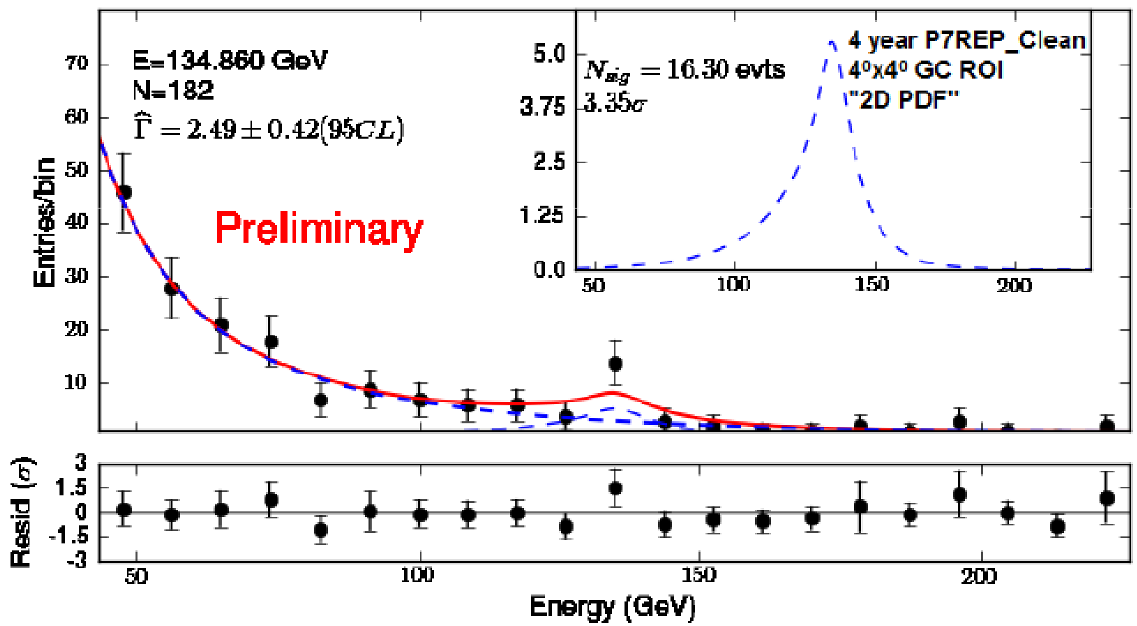
Astro bkg as a power law

Line at 130 GeV with Local significance of 4.6 sigma (Global significance 3.2 sigma)

Fermi Lines



Su, Finkbeiner arXiv:1206.1616



Talk by A. Albert, Fermi Symposium 2012

News from Fermi-Collaboration

Results from Fermi Collaboration with reprocessed data + improved energy resolution

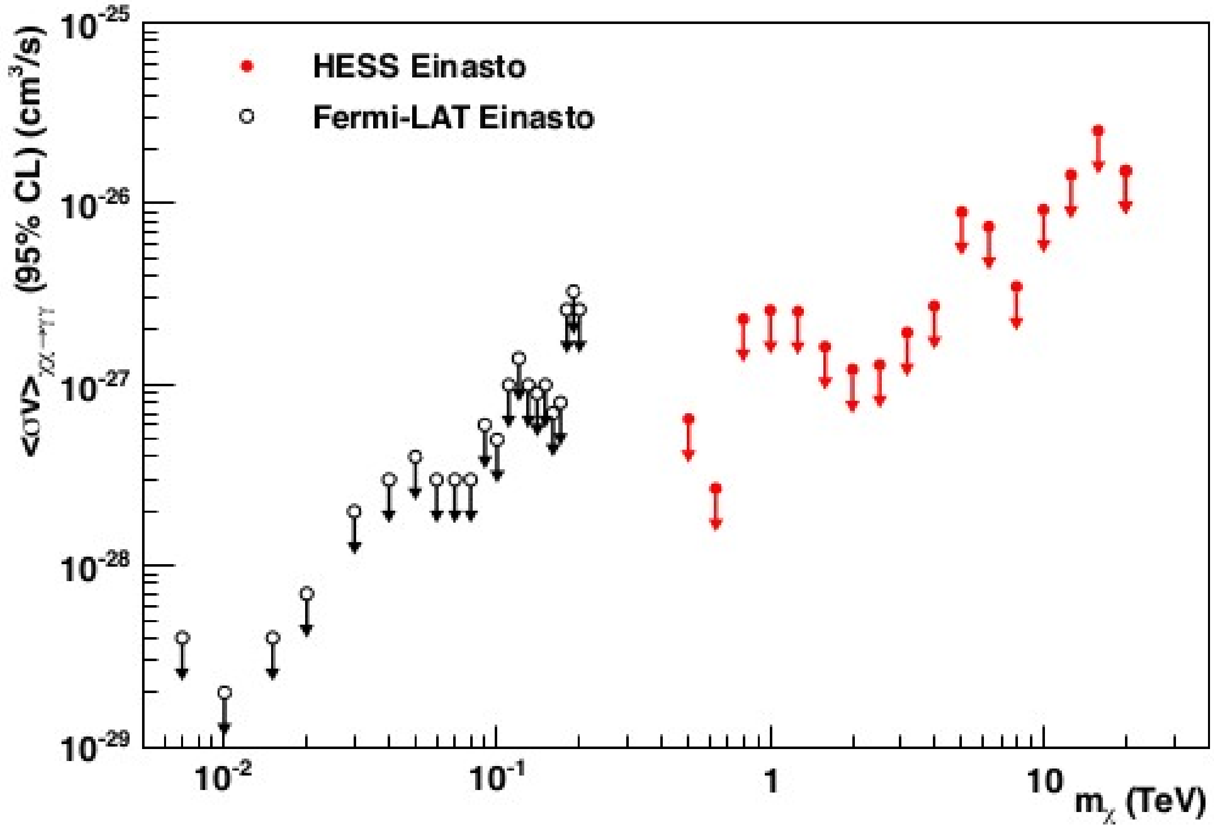
The peak move to 135 GeV and the significance drops below 2 sigma

Search for systematics effects. Look at control regions away from GC

Feature detected in the Earth Limb photons

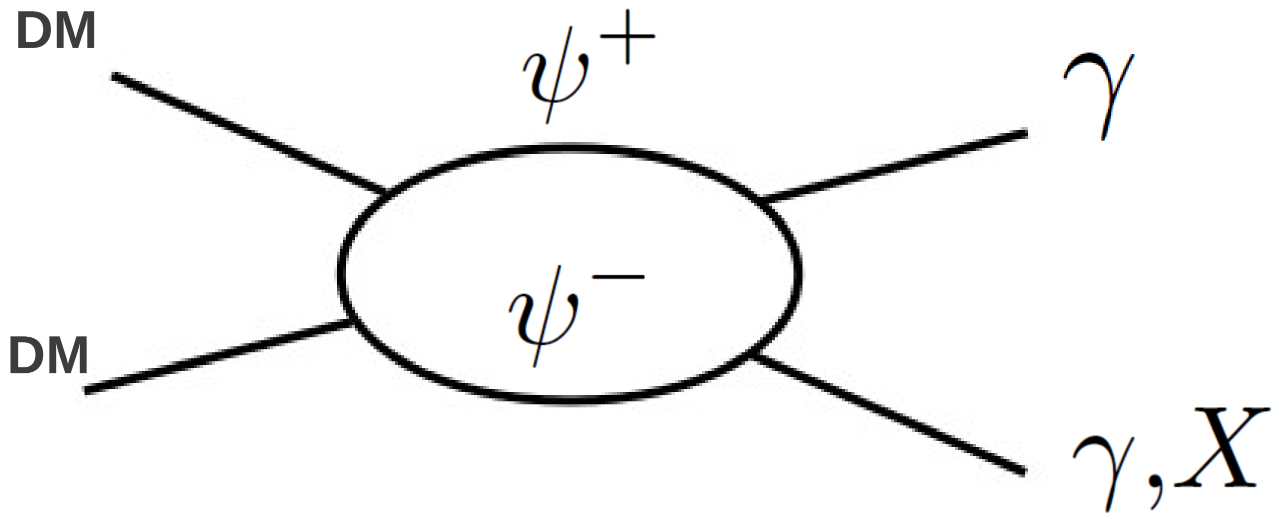
Maybe also in other control regions, see Finkbeiner,Su,Weniger 2012, Whiteson 2013

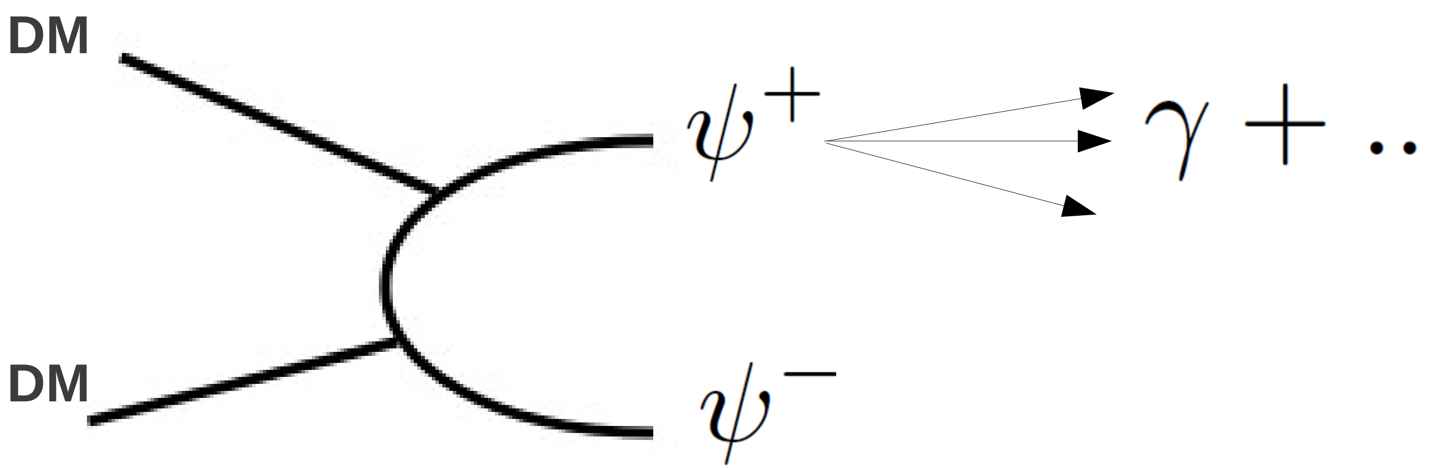
Limits on gamma-rays Lines



Hess collaboration 2013, arXiv:1301.1173

Implications for models





Implications for models

Sensitivity of FERMI-LAT to lines around 100 GeV $$(\sigma v)_{\gamma\gamma} \sim 10^{-27}\ \mathrm{cm}^3/\mathrm{s}$$

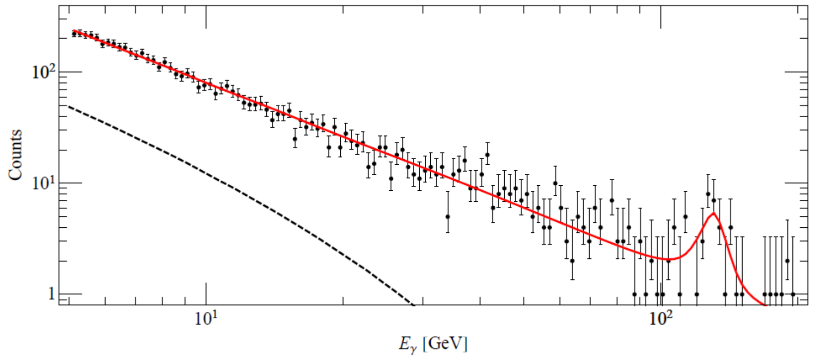
From dwarfs for hadronic channels & M around 100 GeV $$(\sigma v)_{WW,f\bar{f}} \lesssim 10^{-25}\ \mathrm{cm}^3/\mathrm{s}$$

From the shape of the spectrum bounds

on the continuum

$$\frac{(\sigma v)_{WW,f\bar{f}}}{(\sigma v)_{\gamma\gamma}} \lesssim 10$$

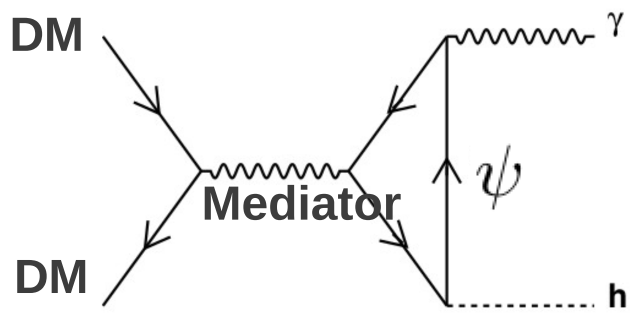
Cohen, Lisanti,Slatyer, Wacker 2012



Loop suppression is typically larger!

Summarizing: not straightforward to accommodate such signal in DM models

Forbidden channel scenario



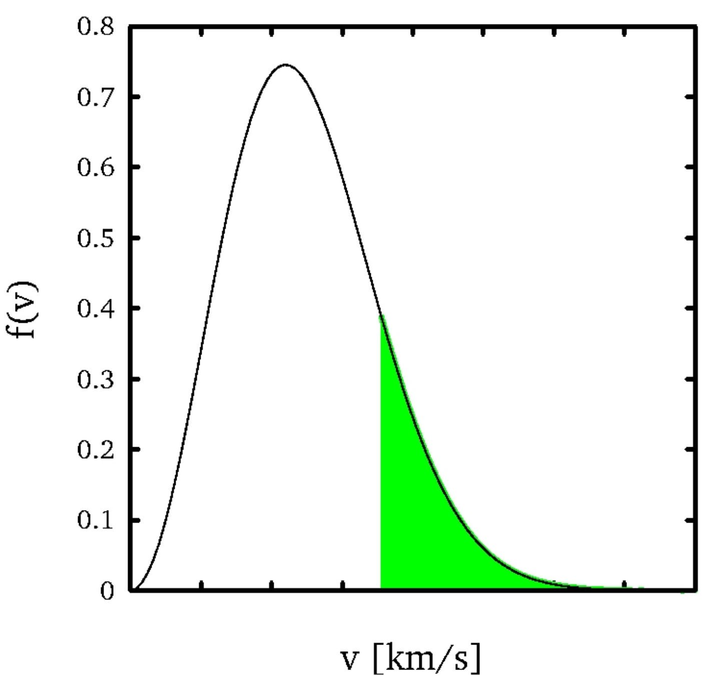
DM has large couplings to new charged particles ψ via a mediator

$M_{DM} \lesssim M_{\psi}$ annihilations kinematically forbidden today since DM has small velocities

$$v/c \sim 10^{-3}$$

Annihilations can occur in the early Universe

$$v/c \sim 10^{-1}$$

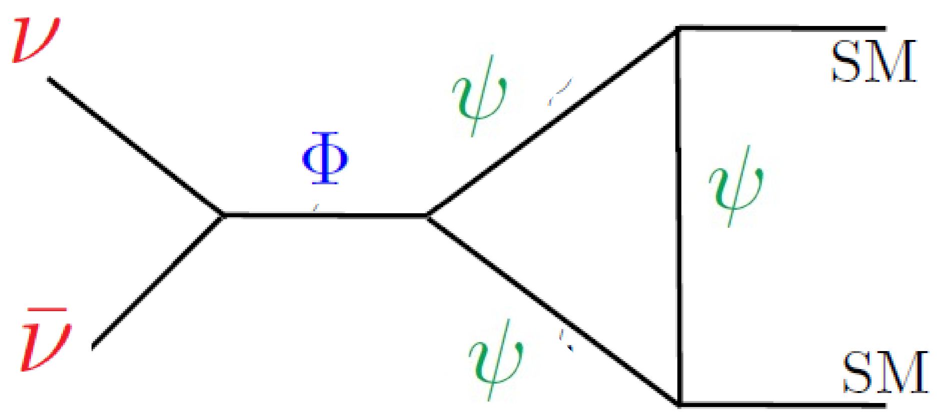


Simple recipe

The dark sector contains **DM** $\mathcal{V}$ + **scalar** Φ + **charged fermions** ψ

SM gauge group $(SU(3),\ SU(2),\ U(1))$

- $(1,\ 2,\ 1/2)$: $\psi_{1/2} = (\psi^+, \psi^0)$;
- $(1,\ 2,\ \text{-}3/2)$: $\psi_{-3/2} = (\psi^-, \psi^{--})$;
- $(1,\ 1,\ \text{-}1)$: $\psi_{-1} = \psi^-$.



1-loop annihilations

$\gamma\gamma$

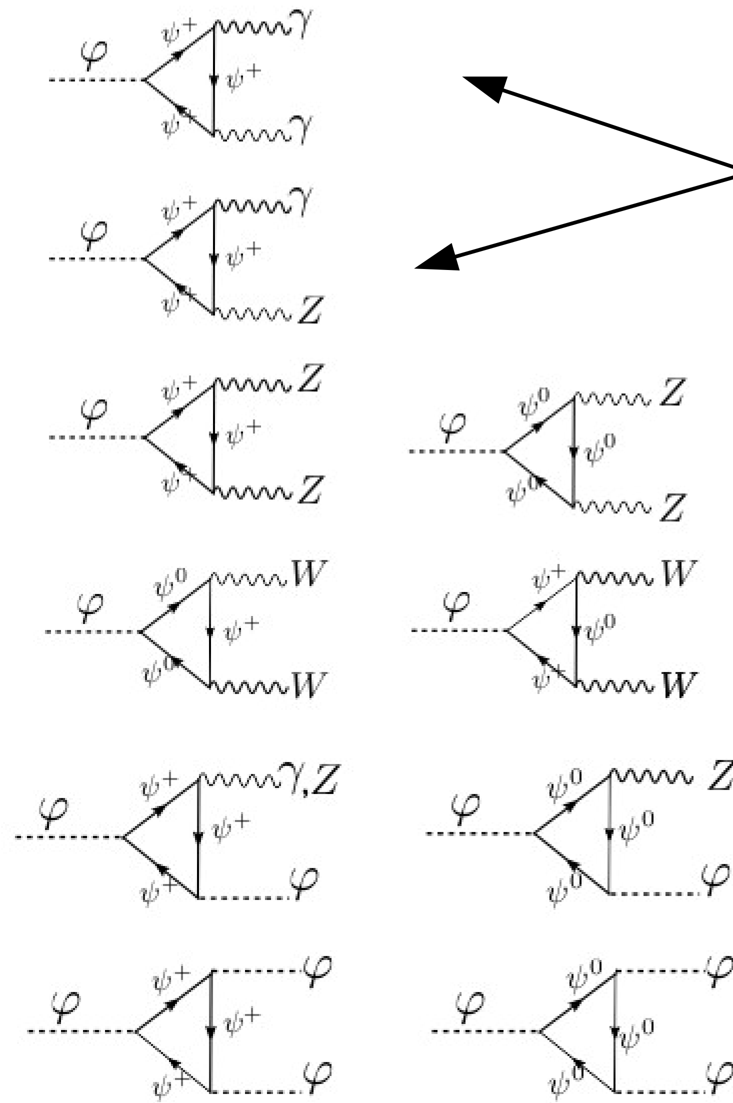
γZ

ZZ

WW

$\gamma\varphi, Z\varphi$

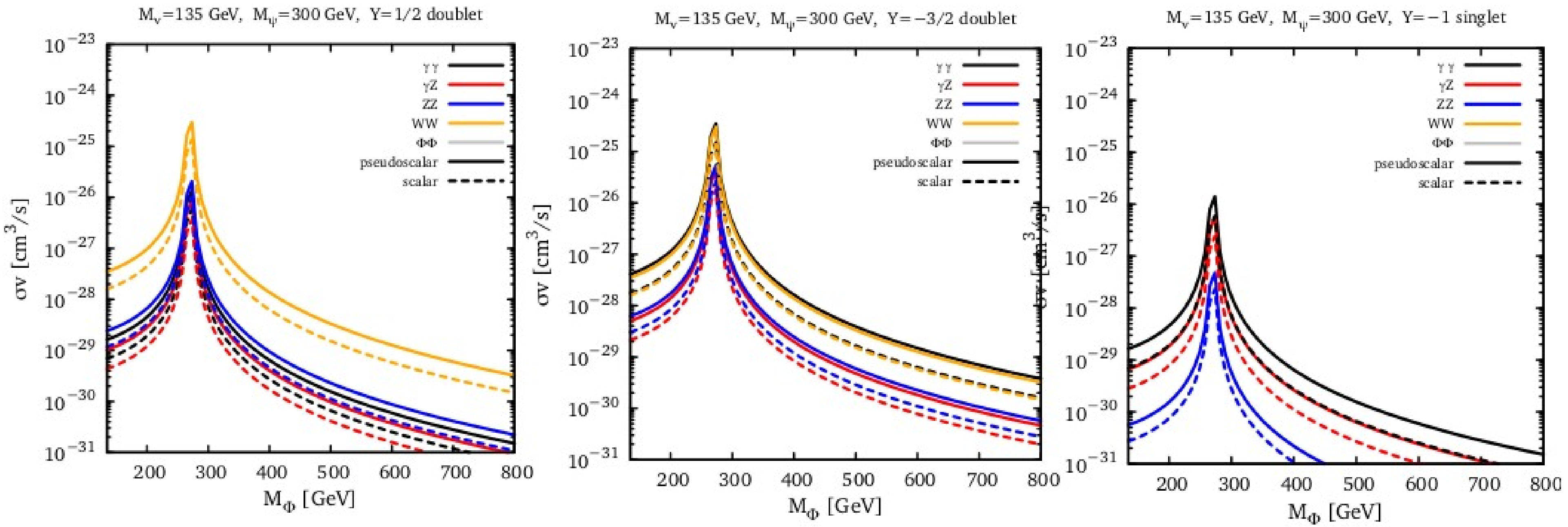
$\varphi\varphi$



More than 1 line!

=0

1-loop annihilations



- (1, 2, 1/2): $\psi_{1/2} = (\psi^+, \psi^0)$;
- (1, 2, -3/2): $\psi_{-3/2} = (\psi^-, \psi^{--})$;
- (1, 1, -1): $\psi_{-1} = \psi^-$.

	ψ_{-1}	$\psi_{-3/2}$	$\psi_{1/2}$
$\sigma_{\gamma Z}/\sigma_{cont}$	10	0.5	0.02
$\sigma_{\gamma\gamma}/\sigma_{cont}$	30	1	0.04

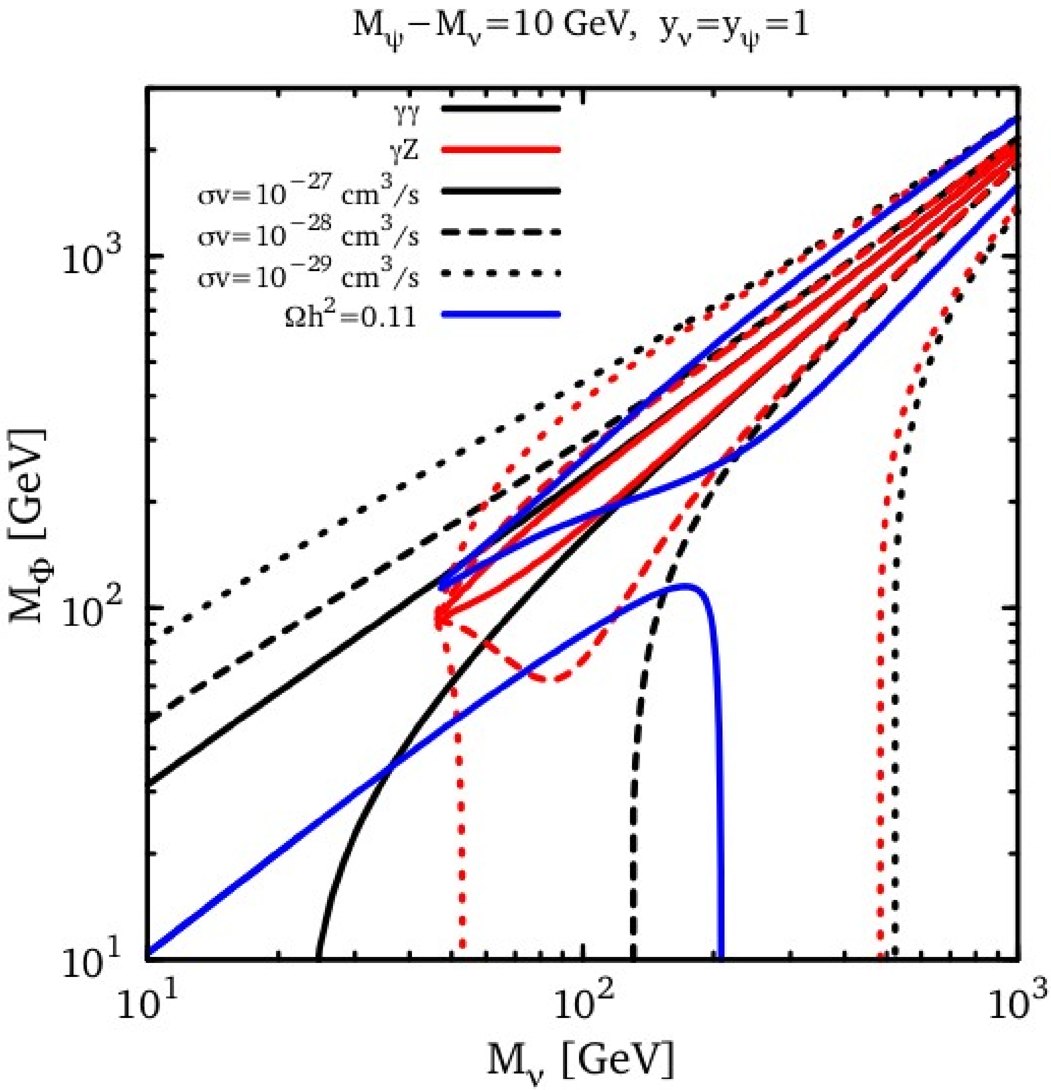
Jackson, Servant, Shaughnessy, Tait, MT. 2013

Relic density

$$\bar{\nu}\nu \to \mathrm{SM\ SM} \qquad \text{via } \Phi - H \text{ mixing}$$

$$\bar{\nu}\nu \to \bar{\psi}\psi$$

$$\bar{\nu}\nu \to \Phi\Phi$$



Top connection

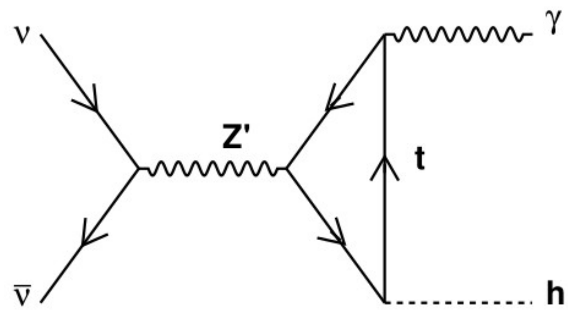
The charged particle ψ might be the SM top quark **Jackson, Servant, Shaughnessy, Tait, MT. 2010**

It is the only one SM fermion with a mass in right ballpark

Dark sector which couples more to large particles with heavier particles are motivated

in models of composite Higgs and fermions and & Randall Sundrum extra-dimensions

Simple UV completion



$$\boxed{yH\bar{\hat{Q}}_3\hat{t}_R} + \boxed{\mu\bar{\psi}_L\psi_R} + \boxed{Y\Phi\bar{\psi}_L\hat{t}_R}$$

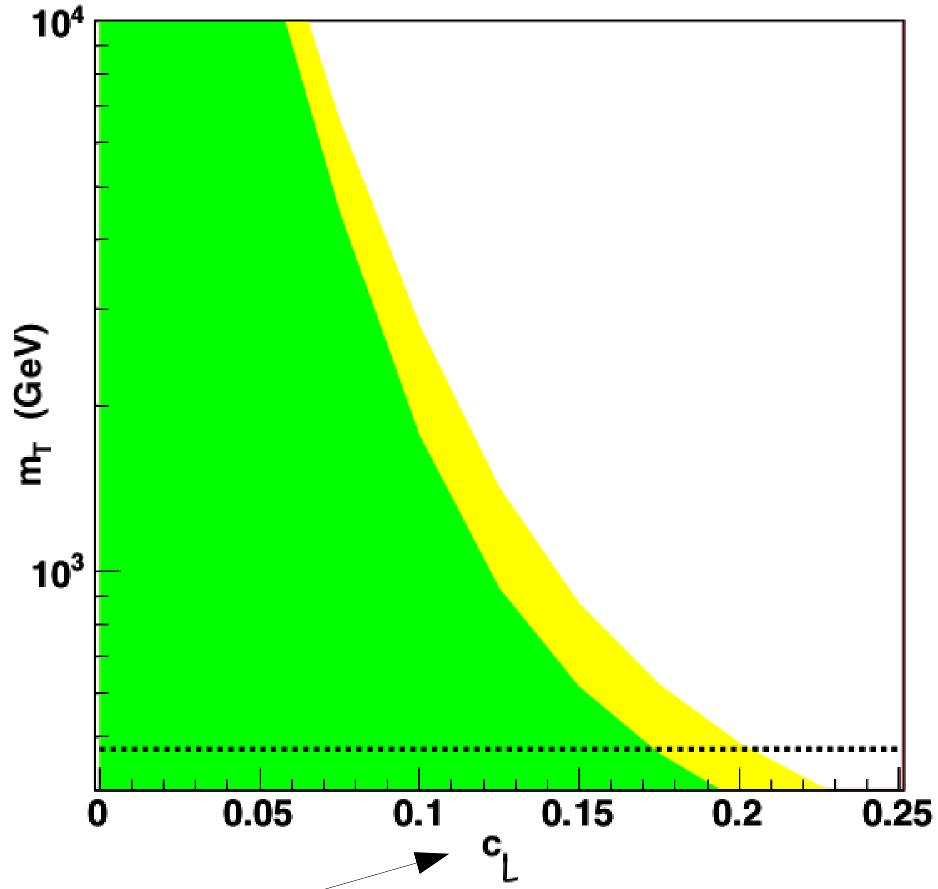
SM top mass **mass new fermion** **Mixing**

Top quark (t) and extra fermion (T) are superposition of initial fermions

$$\begin{pmatrix} t_{R/L} \\ T_{R/L} \end{pmatrix} = \begin{pmatrix} -\sin\theta_{R/L} & \cos\theta_{R/L} \\ \cos\theta_{R/L} & \sin\theta_{R/L} \end{pmatrix} \begin{pmatrix} \hat{t}_{R/L} \\ \Psi_{R/L} \end{pmatrix}$$

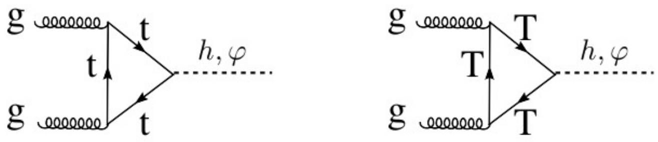
Mixing angle functions of initial parameters

Electroweak Precision Tests

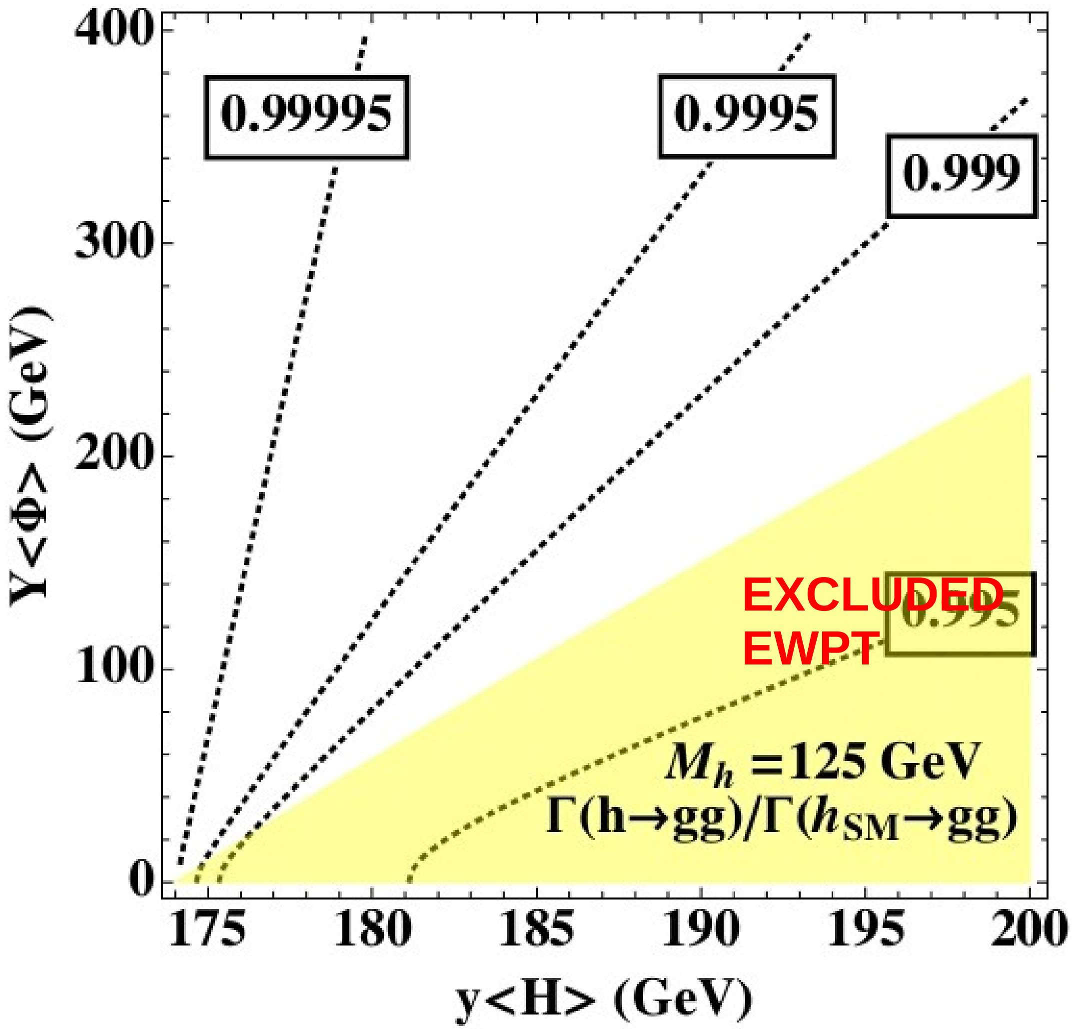


The mixing between the top quark and the new fermion is constrained by precision measurements at colliders

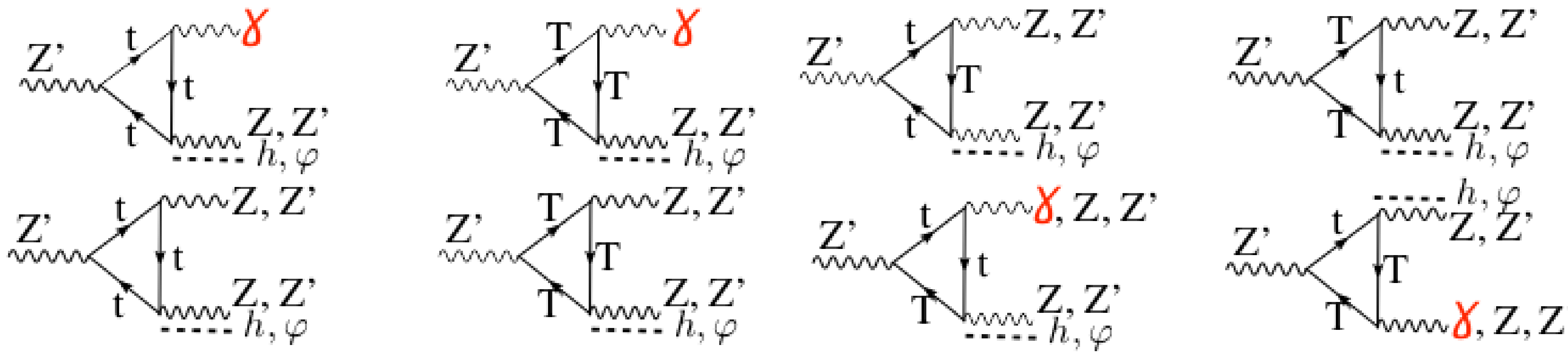
Higgs Physics

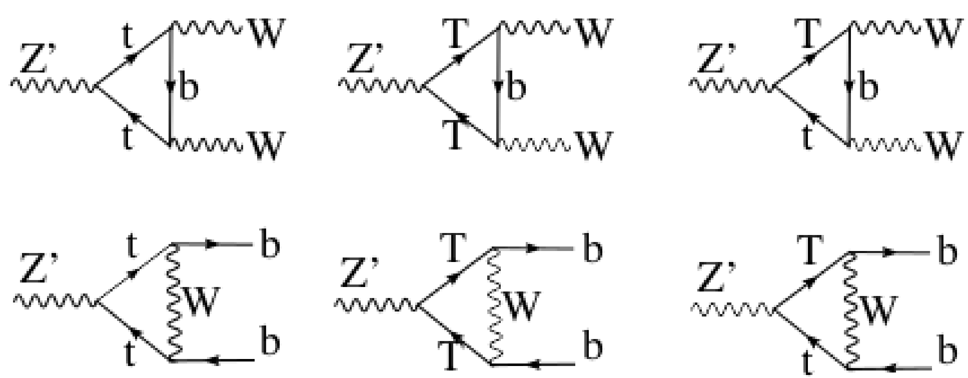


Like SM !

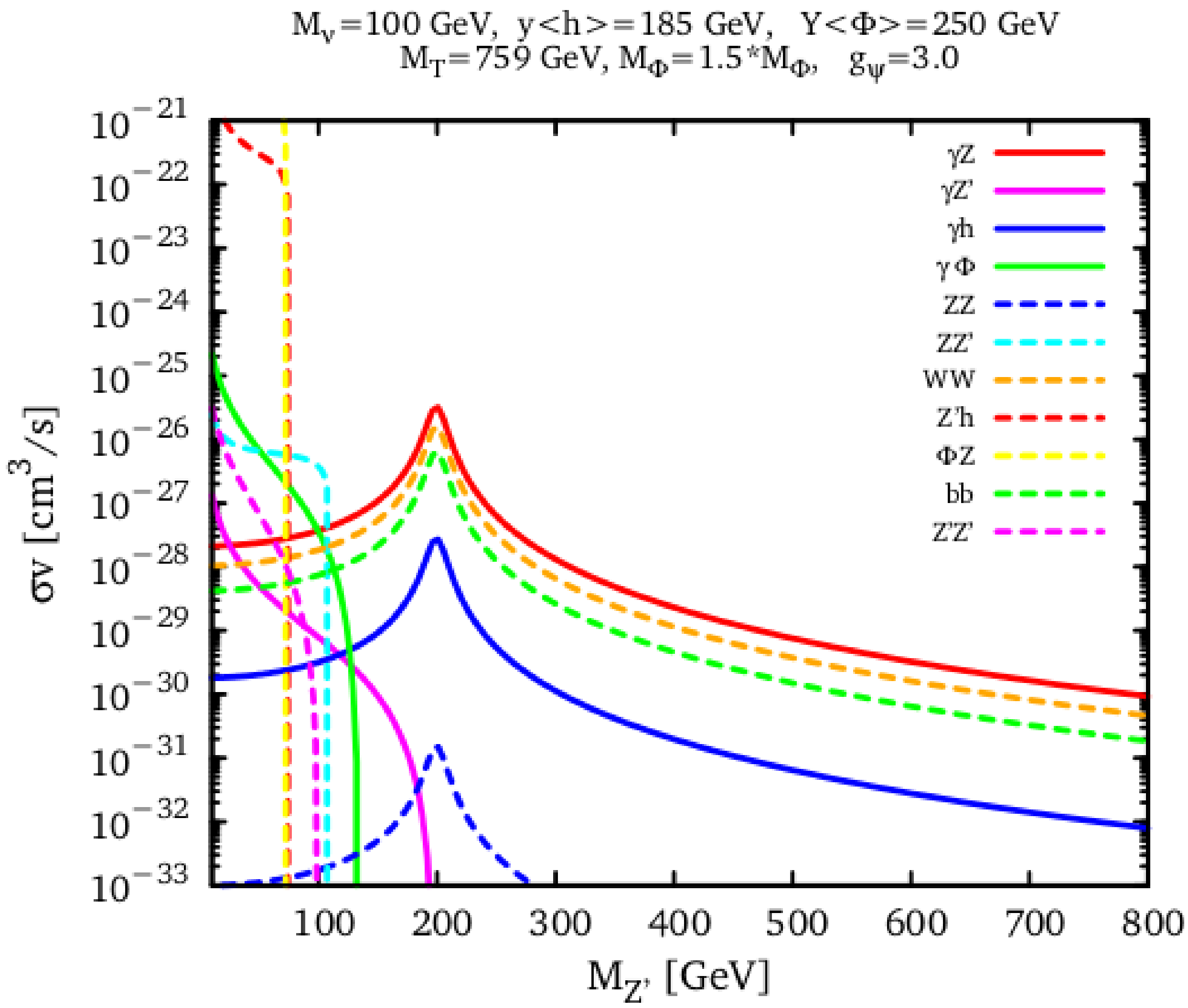


1-loop diagrams

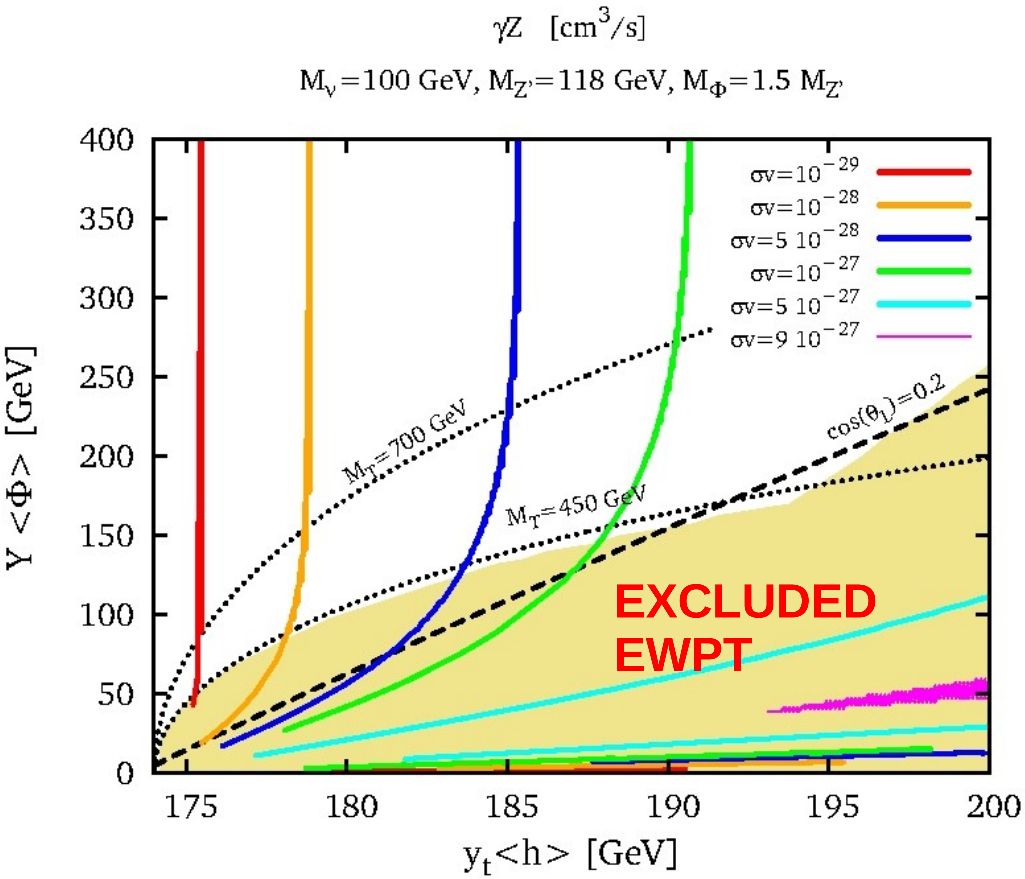


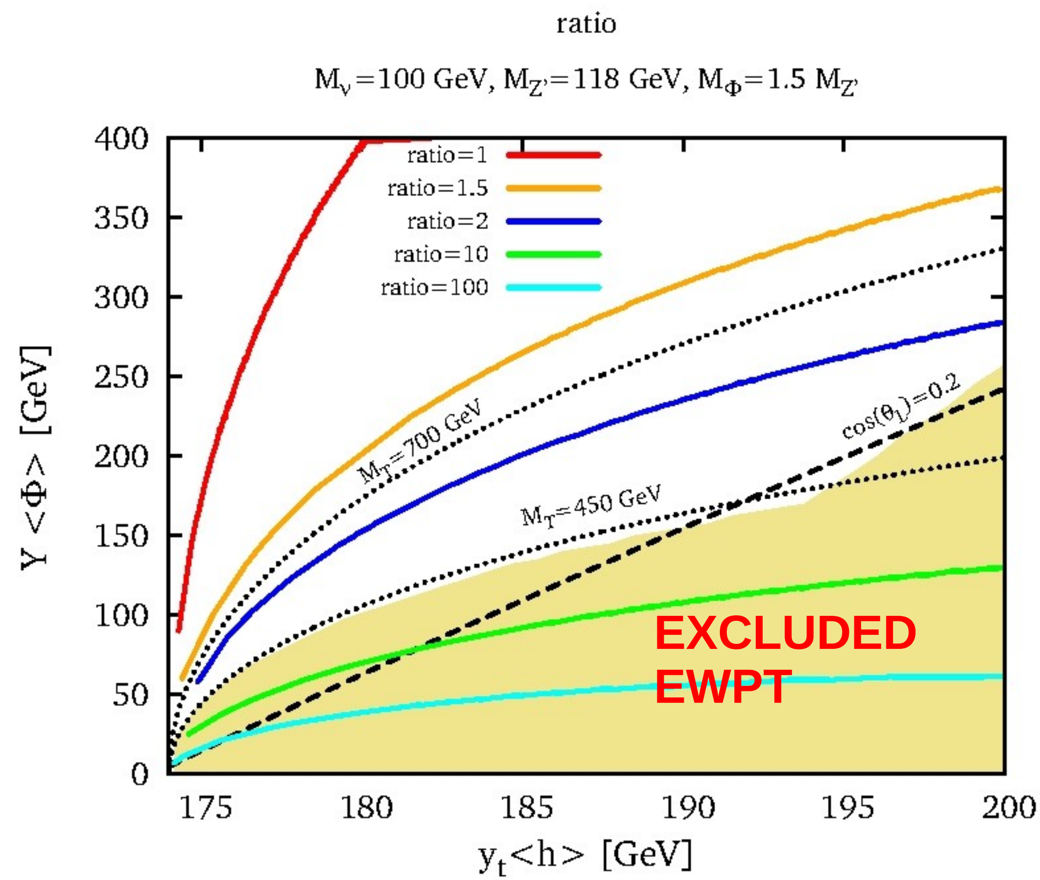


1-loop x-sections



Lines





Large Line signals with small continuum is possible!

Jackson, Servant, Shaughnessy, Tait, MT. In preparation

Summary

Large line signals can arise in models where annihilations are enhanced by resonant effects and the continuum emission is forbidden/depressed

These features can be captured by simple models with vector/scalar mediators & possibly with mass mixing with the SM top

Gamma-ray line signals are precious probes of DM annihilations

We need to single out the DM theories which can be tested

Other wavelengths

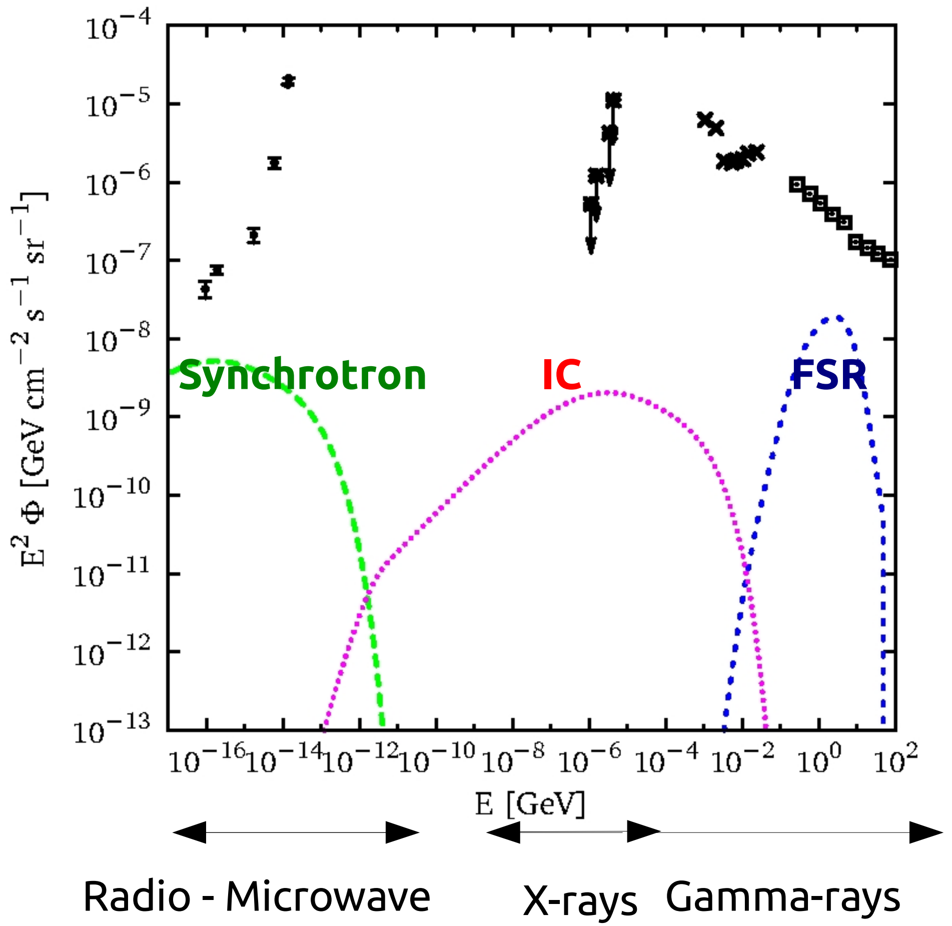
Gamma-rays are primary messengers of WIMPs annihilations

Can we look for DM signals at other wave-lengths?

- **Radio**

  Bounds from radio and searches of extragalactic sources

Secondary emissions

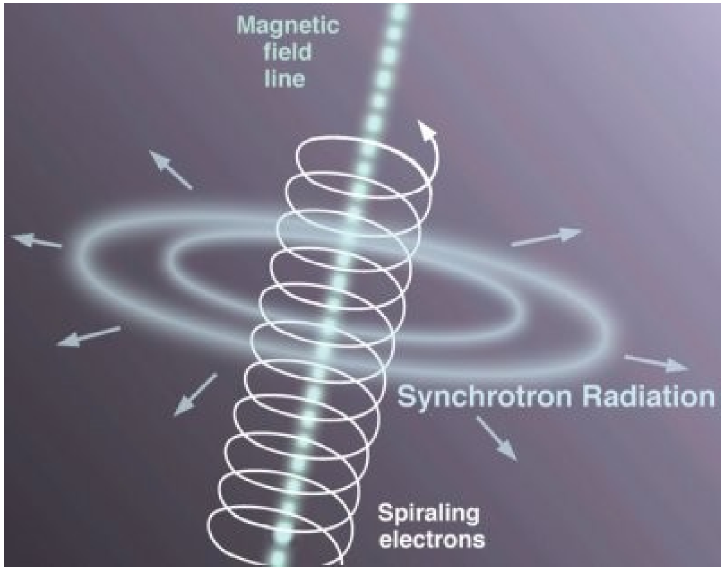


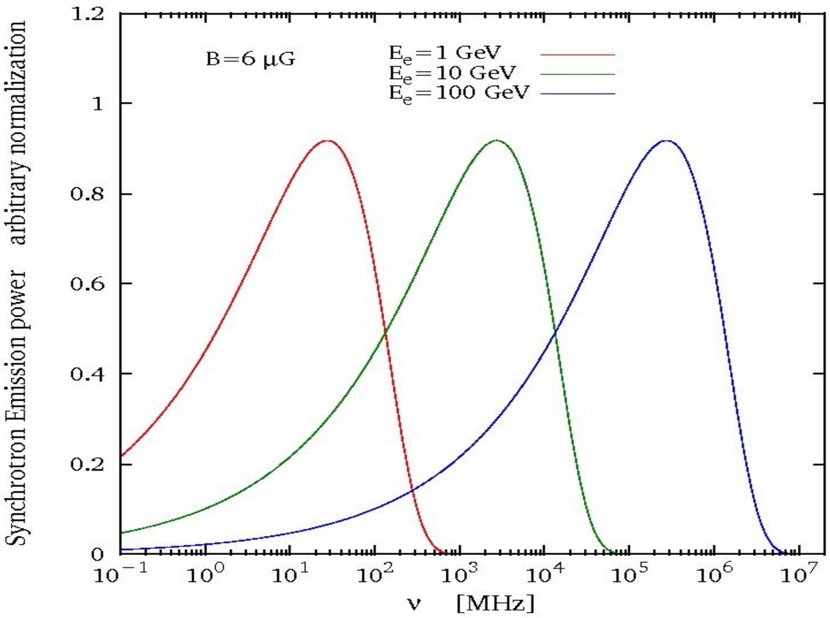
Final state radiation $\chi\chi \to q\bar{q} \to \pi^0 + \ldots \quad \pi^0 \to \gamma\gamma$

Inverse Compton $e^{\pm}\gamma \to e^{\pm}\gamma'$

Synchrotron emission from interactions of electrons with magnetic fields

Synchrotron radiation



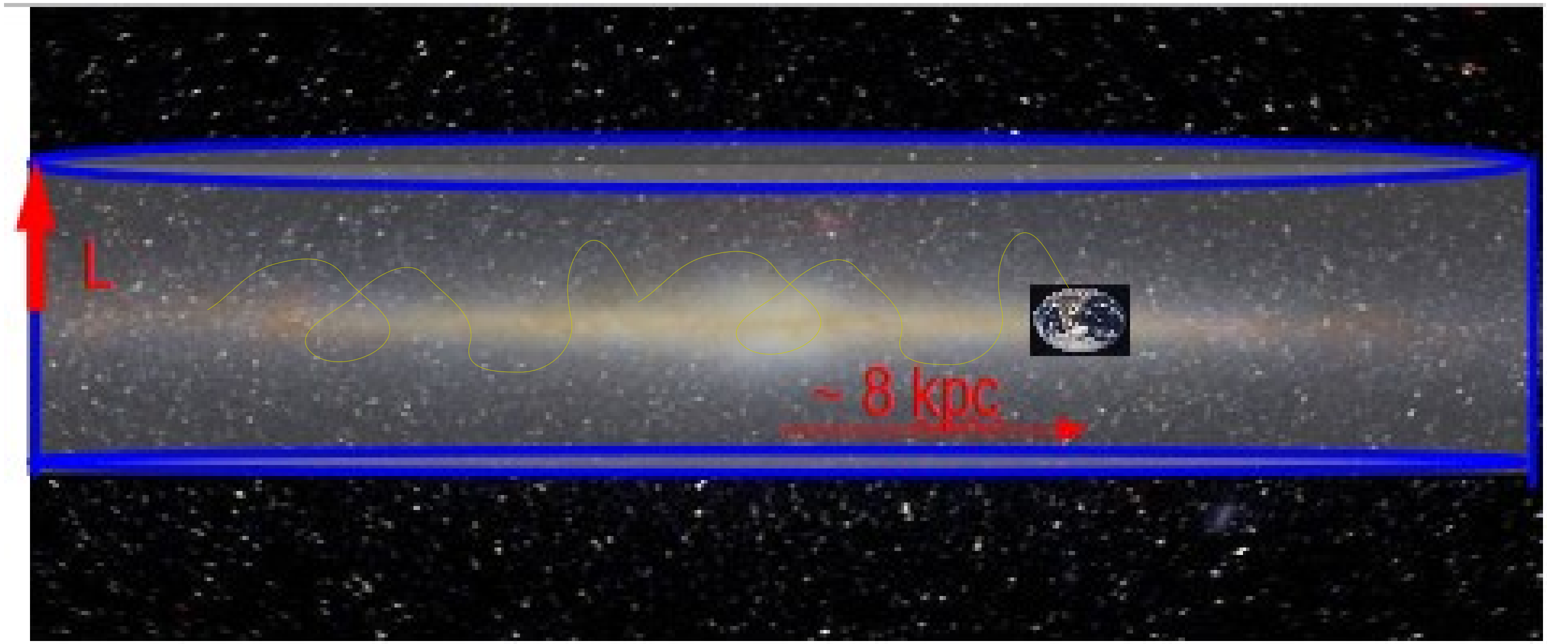


Synchrotron emission from interactions of electrons with magnetic fields

Typical values for the synchrotron peak:

$$\nu \sim 30\ \mathrm{MHz}\ \frac{B}{6\mu G}\left(\frac{E_e}{1GeV}\right)^2$$

Propagation of charged particles



Propagation of charged cosmic-rays described by transport equation which describes energy losses, diffusion accelerations, convection

$$\partial_t \mathcal{N} - \boldsymbol{\nabla} \cdot \{K(E) \boldsymbol{\nabla} \mathcal{N}\} + \partial_E \left\{ \frac{dE}{dt} \mathcal{N} \right\} = \mathcal{Q}(E, \boldsymbol{x}, t)$$

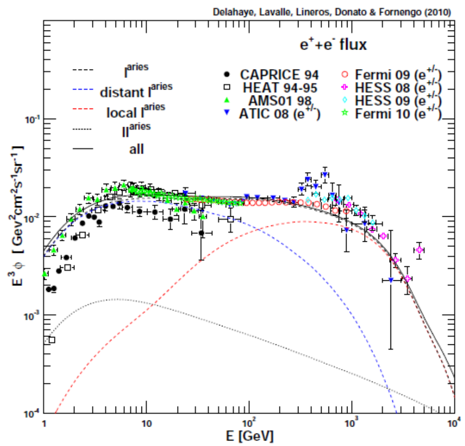
diffusion

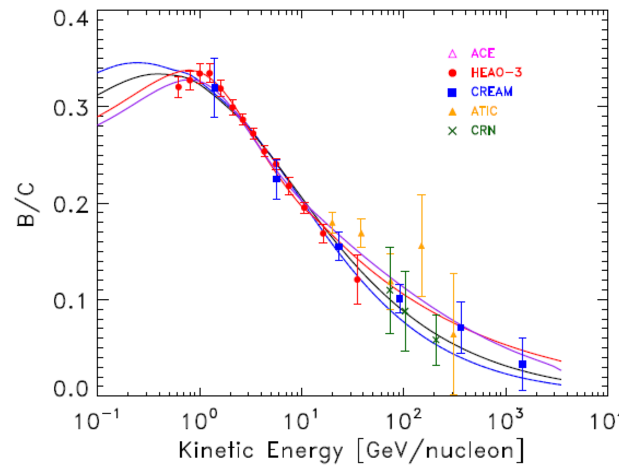
energy losses

distribution of sources

Local cosmic-rays

Delahaye et al. 2010





Di Bernardo et al. 2012

Astrophysical sources can explain data under reasonable assumptions

Sources of leptonic CRs:

1) primary electrons from sources (Supernova Remnants)

2) secondaries electrons and positrons from hadronic CRs interactions

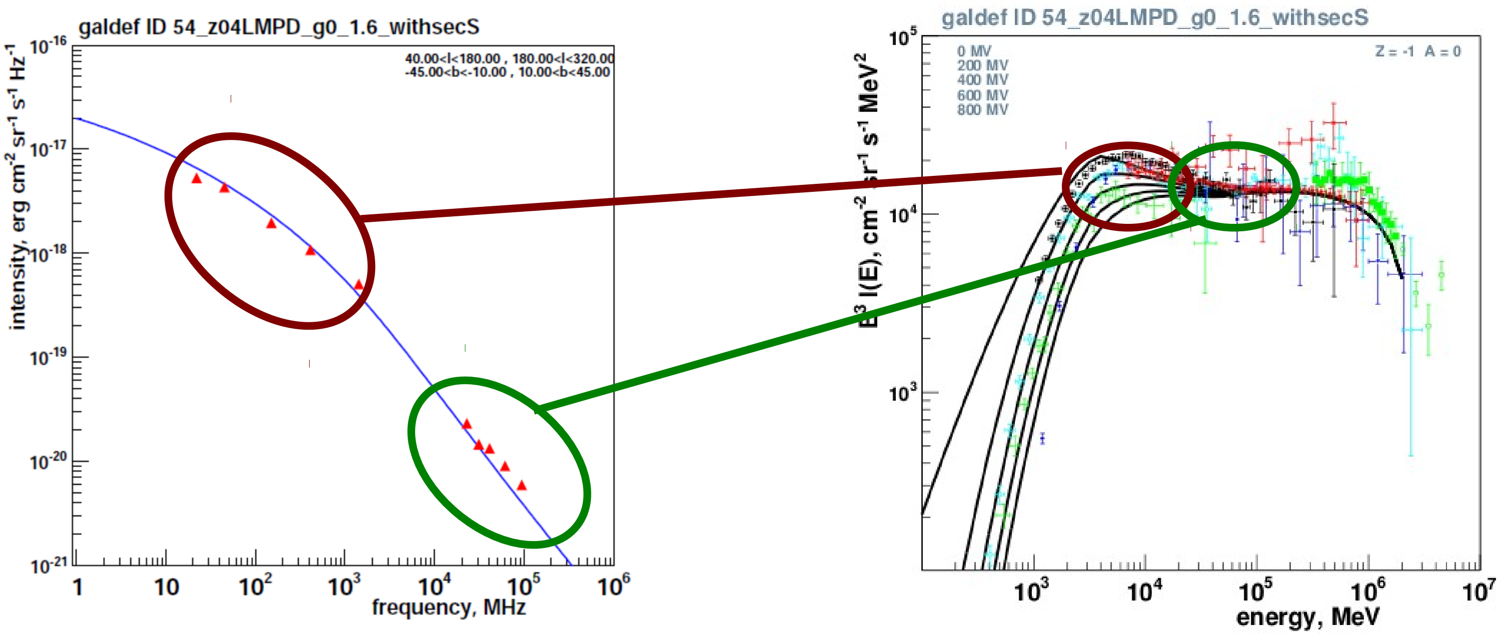
3) extra population of electrons and positrons (likely pulsars).

Propagation models tuned against data, notably B/C, radioactive isotopes, protons

This leaves degeneracies among the propagation parameters

Additional info should be used

Constrain CRs and B with radio



Strong, Orlando, Jaffe 2011

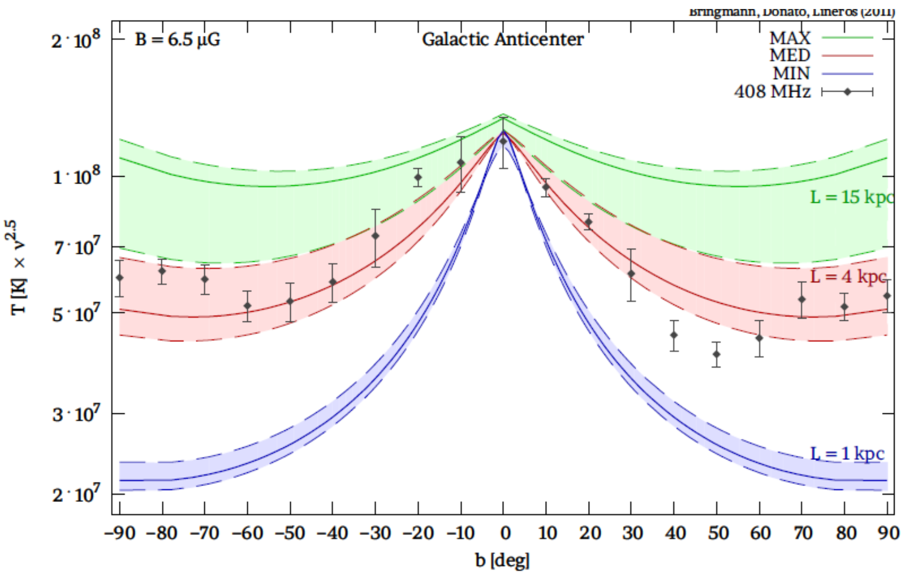
Magnetic fields are constrained by Faraday rotation measurements of sources

Radio surveys constrain the synchrotron emission from CR electrons

Low/high frequency surveys probe different parts of the interstellar electron

Constrain CRs and B with radio

Bringmann, Donato, Lineros 2011



Morphology and normalization of synchrotron emission (+ info on Magnetic fields)

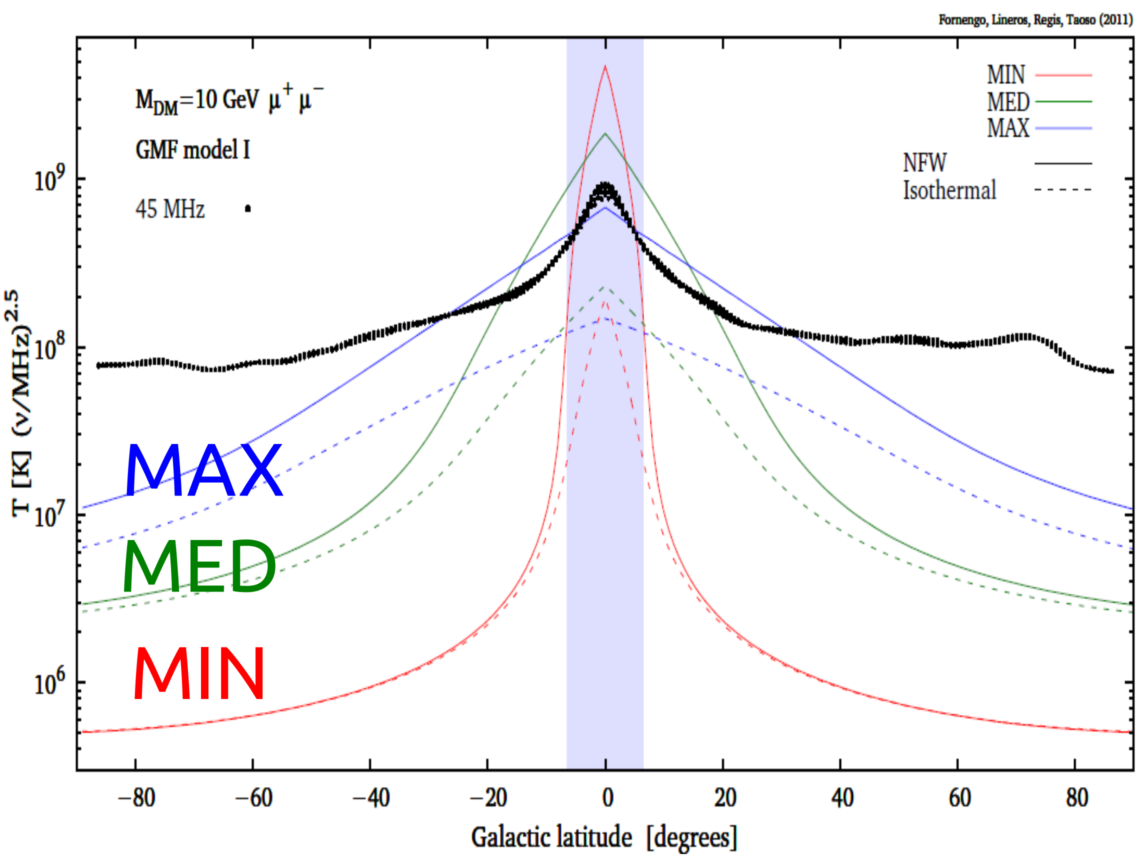
constrain the parameter of propagation models

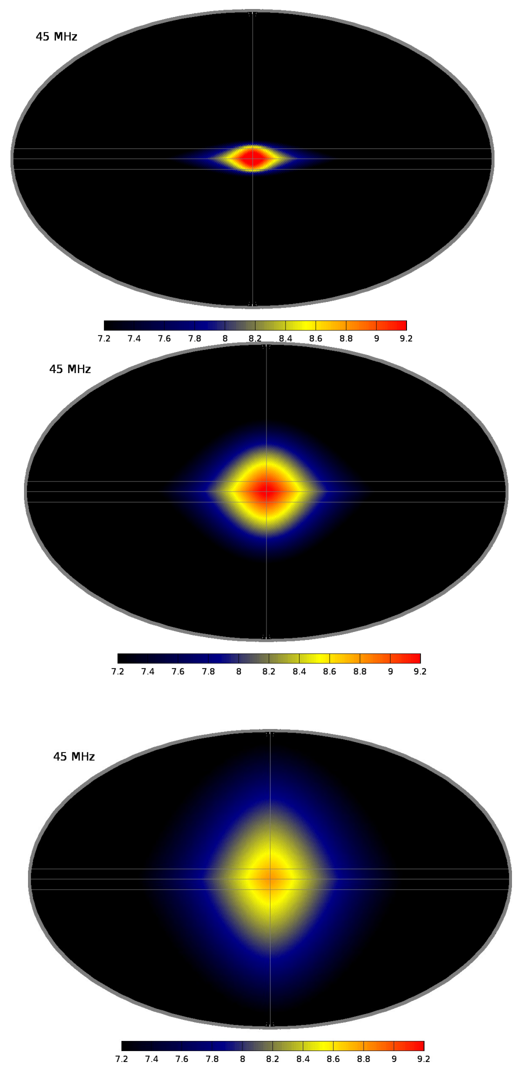
Models with small scale-height of the diffusion regions are disfavored

Similar conclusions arises from analysis of the diffuse gamma-ray emission from Fermi-LAT

Gamma-ray diffuse from interactions of protons with gas and IC and Brem. of electrons

Synchrotron from DM



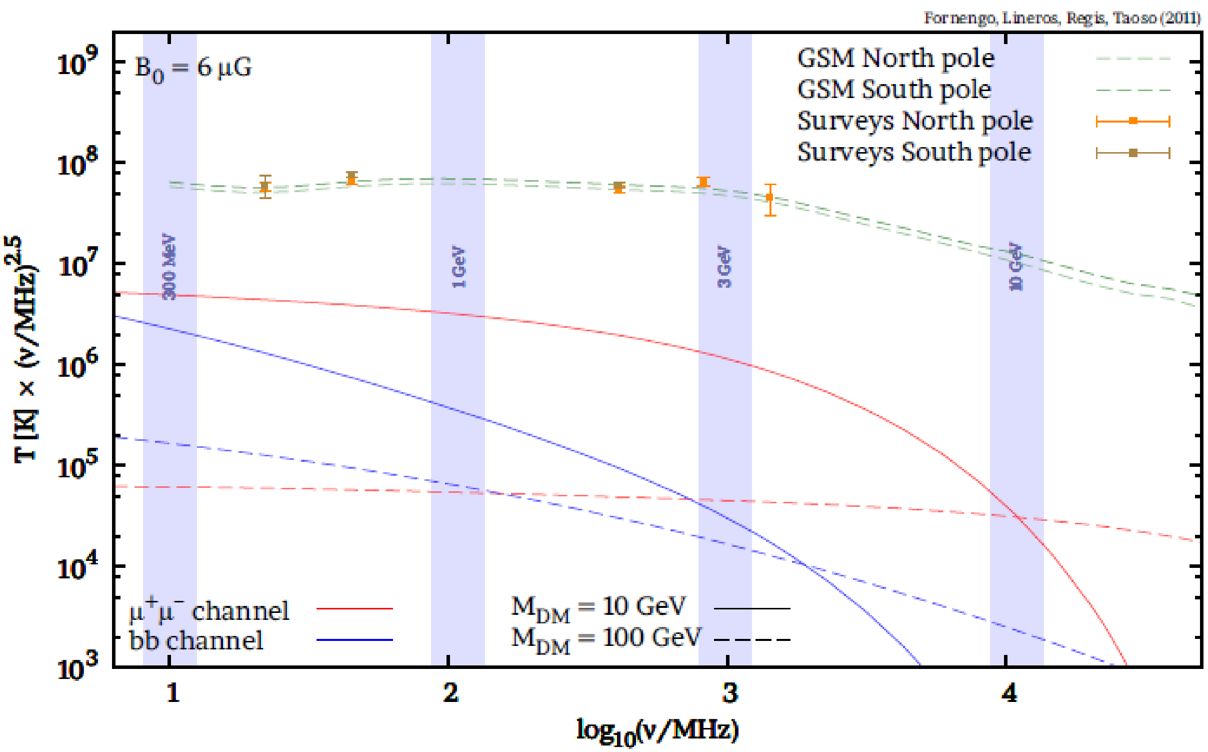


Propagation models allowed by cosmic-rays data

MIN MED MAX bracket the uncertainties.

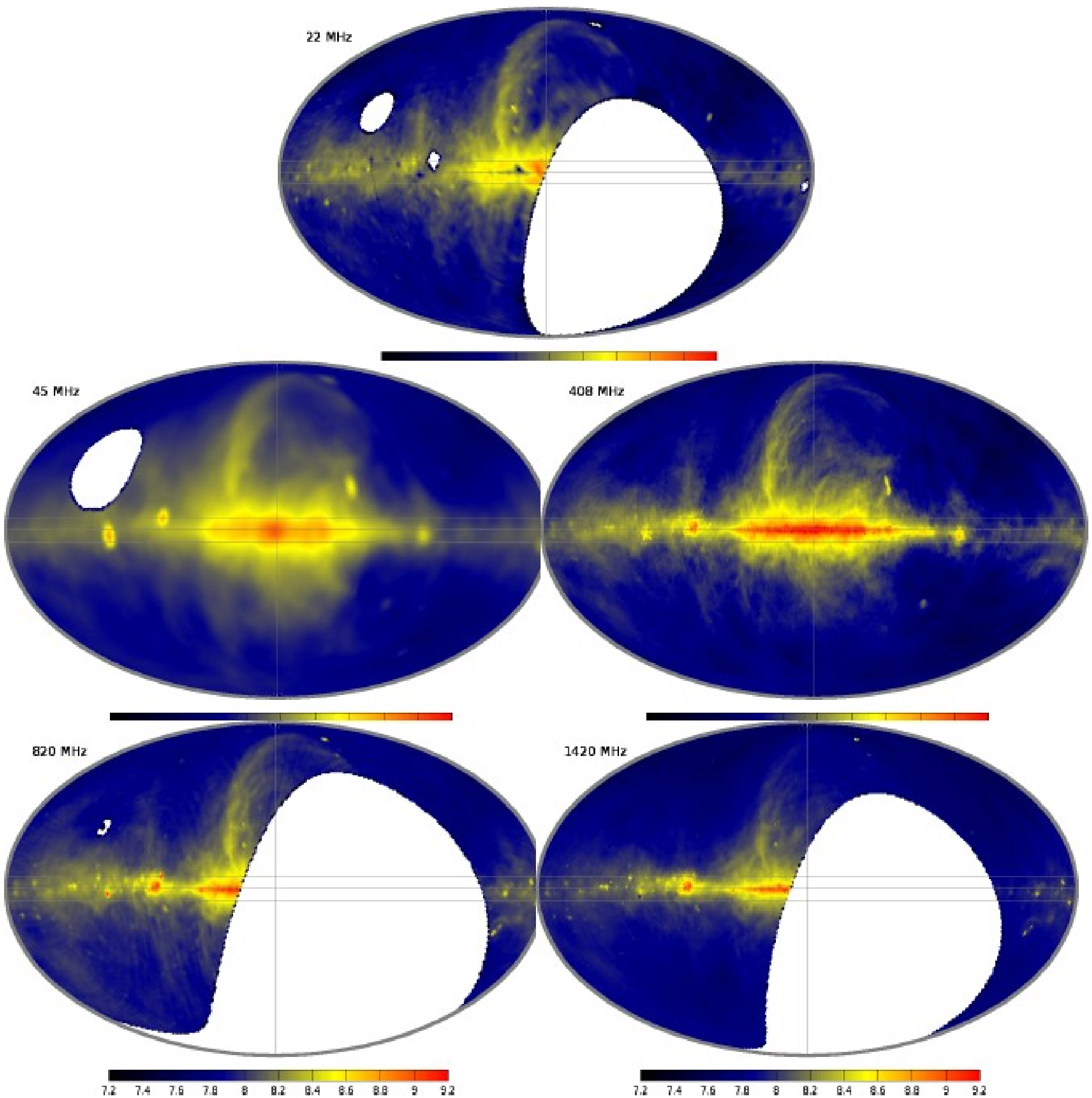
However extreme modes (MIN) are disfavored from shape of diffuse radio and gamma emissions!

Synchrotron from DM



Low radio frequencies particularly suitable to constrain light DM

Radio surveys from 22 MHz to 1420 MHz



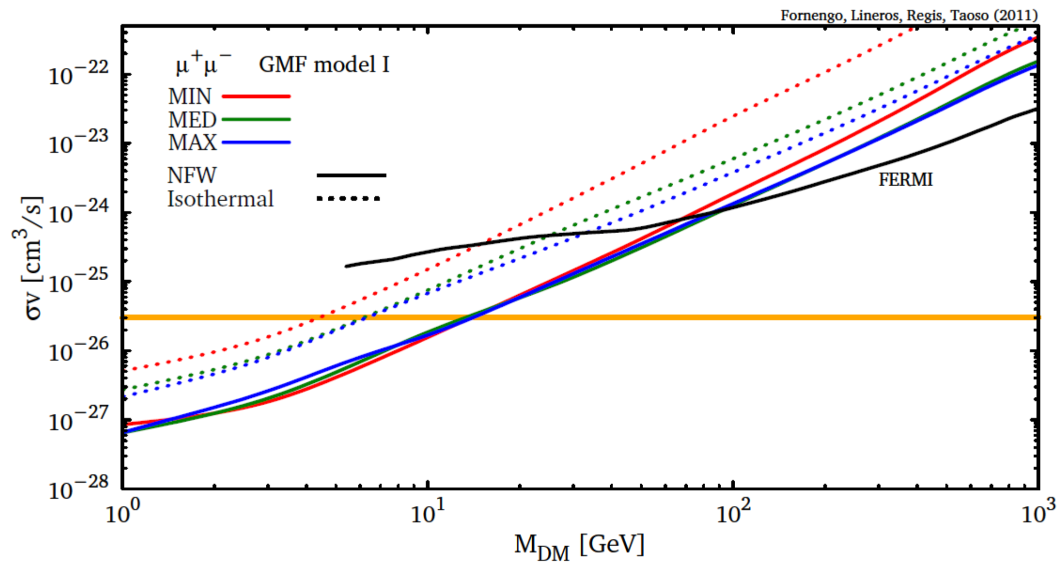
Constraints on DM

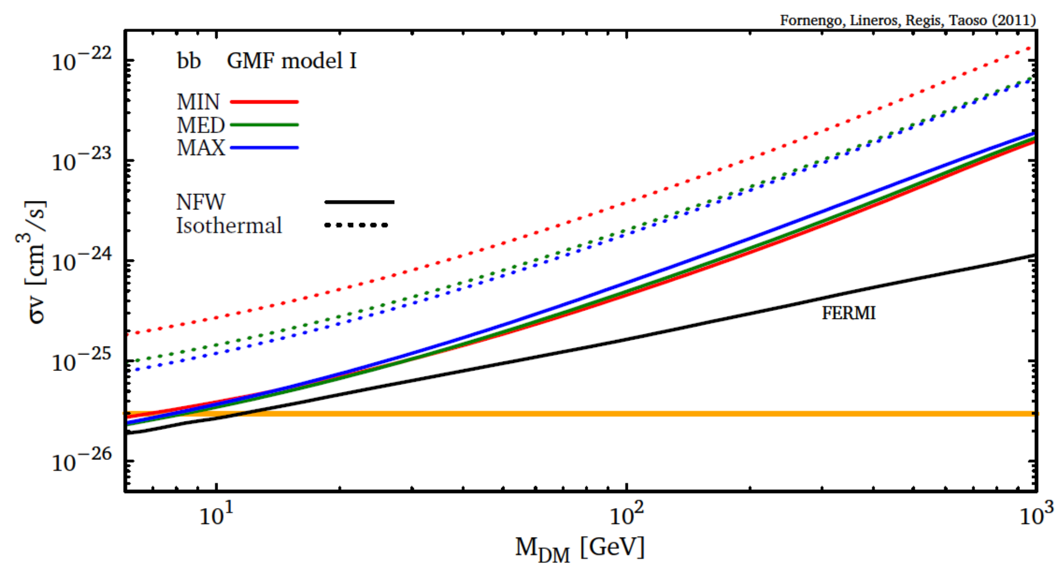
Bounds are better/worst than those from gamma-rays for leptonic/hadronic channels

The dependence on the scale-height and on the propagation parameters is not dramatic

Bounds depend somewhat on the dark matter density profile

N.Fornengo, R.Lineros, M.Regis, M.T. 2011





Constraints on DM

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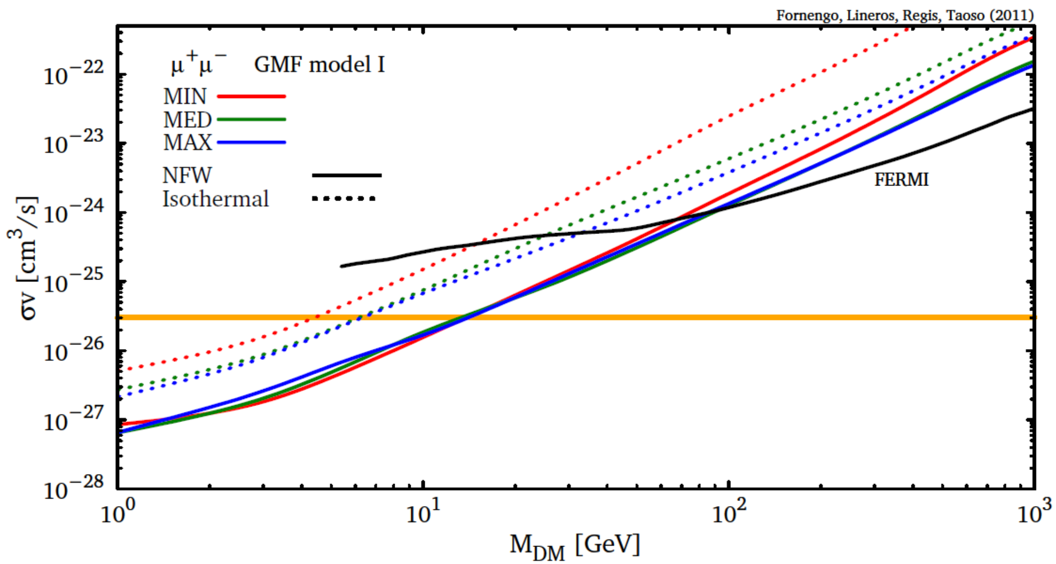
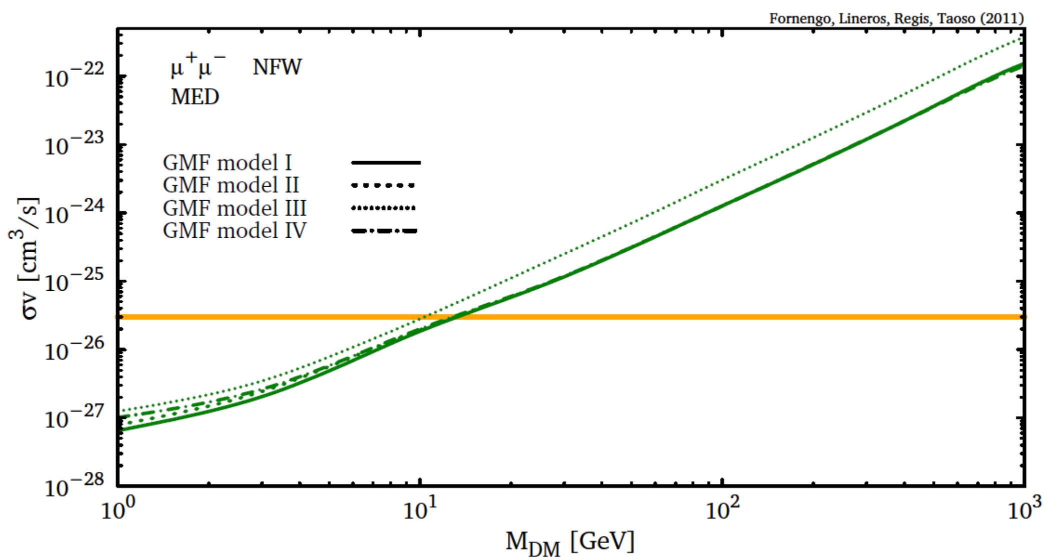
The dependence on the scale-height and on the propagation parameters is not dramatic

Bounds depend somewhat on the dark matter density profile



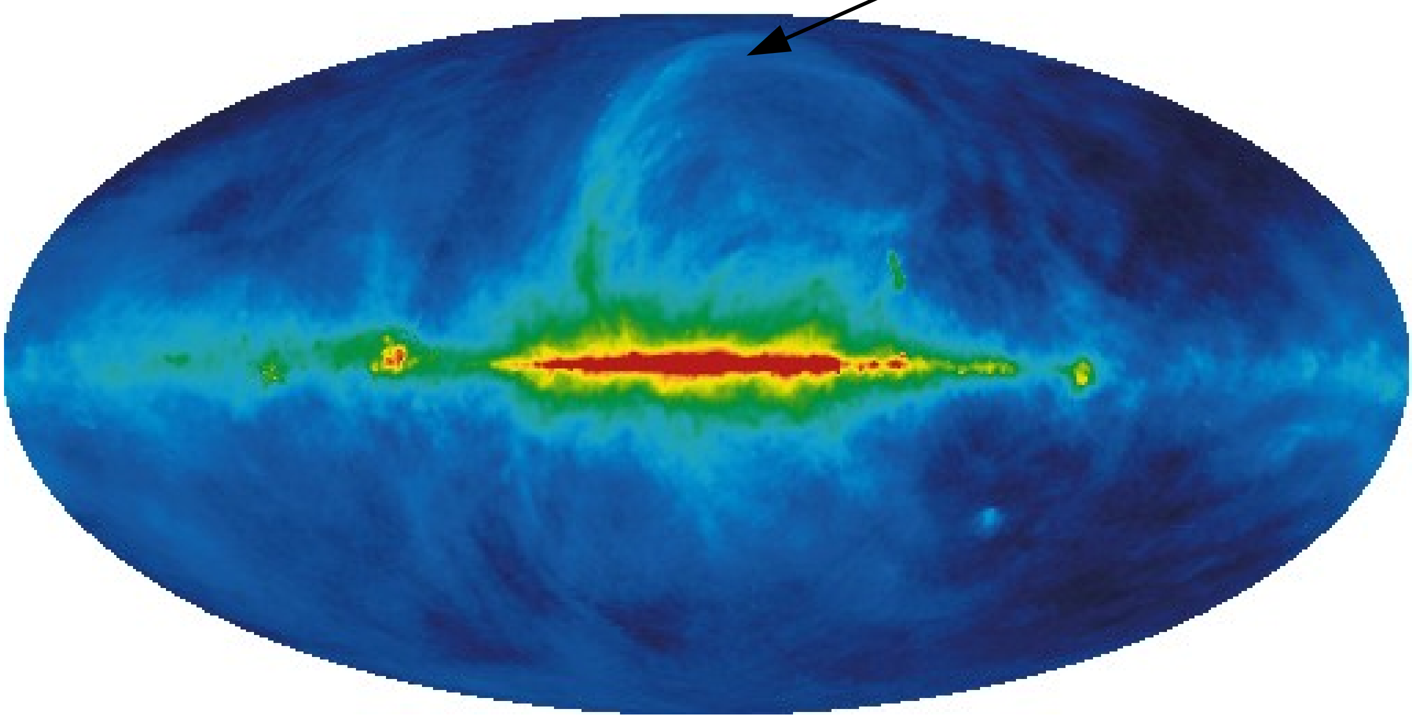


Isotropic radio background

Isotropic radio background emission can be extracted from radio maps looking at high latitude and after subtraction of a galactic model. Delicate jobs !!!

Used to study populations of radio sources.

Can be useful to look for dark matter signals?



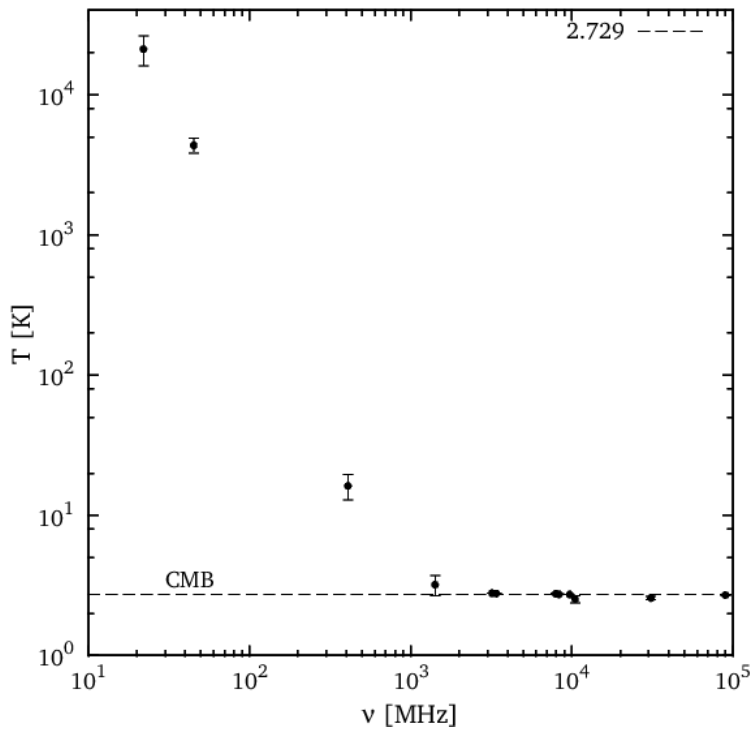
ARCADE-II excess

Data from low frequency surveys 22 MHz 45 MHz 408 MHz 1420 MHz + ARCADE-2 3.2 GHz – 90 GHz **Fixen et al. 2009**

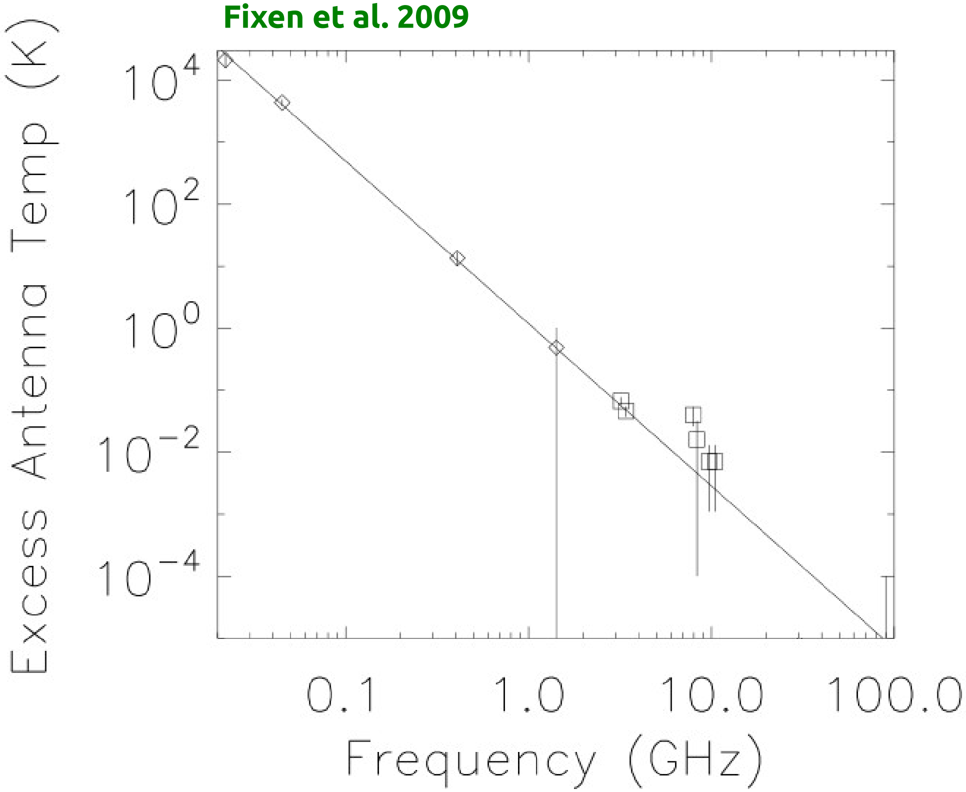
Galactic emission estimated with 2 methods:

plane parallel model & correlation of radio maps with CII map (tracer of galactic emission)

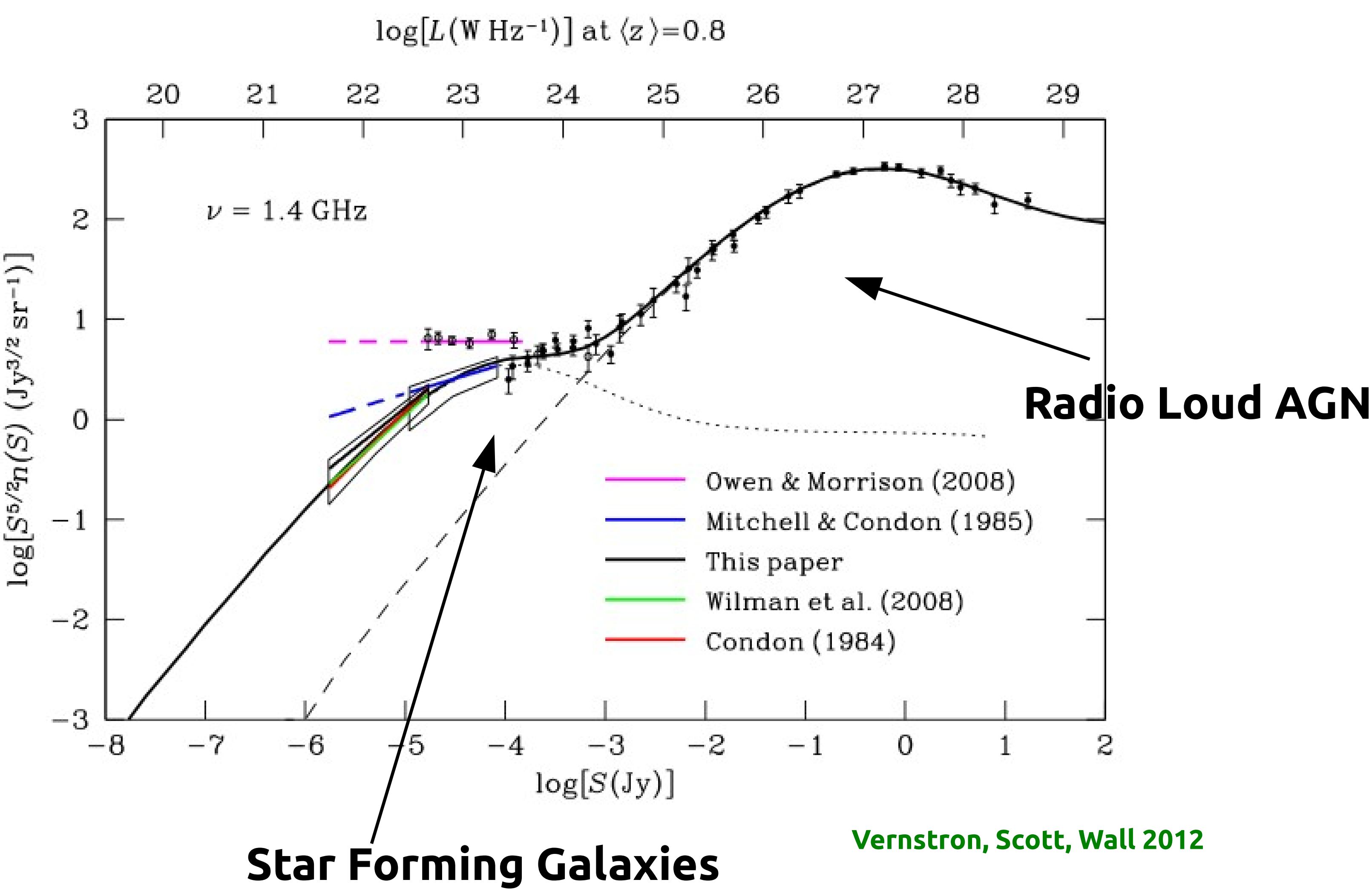
After CMB monopole is removed data an isotropic background is detected <10 GHz



Fixen et al. 2009



Number counts of sources



Vernstron, Scott, Wall 2012

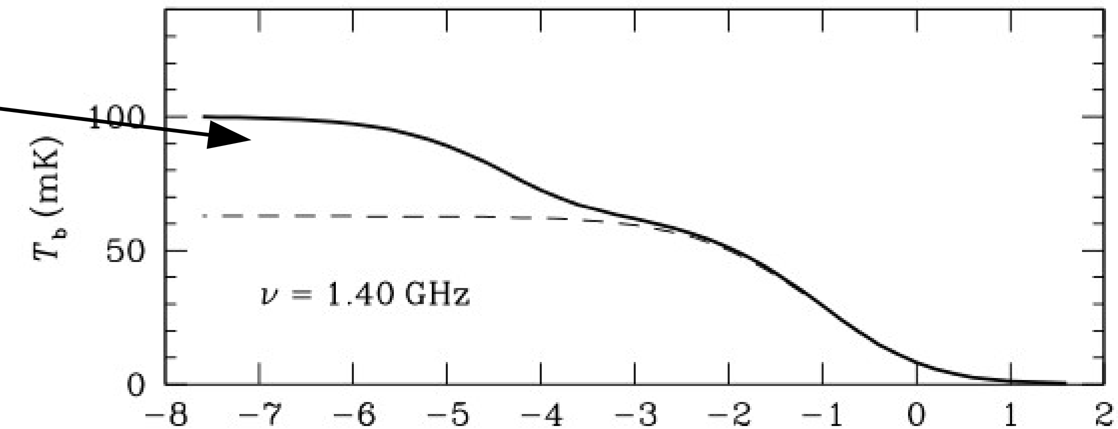
ARCADE-II excess

Isotropic extra galactic radio background inferred by ARCADE is 480 mK !

Vernstron, Scott, Wall 2012

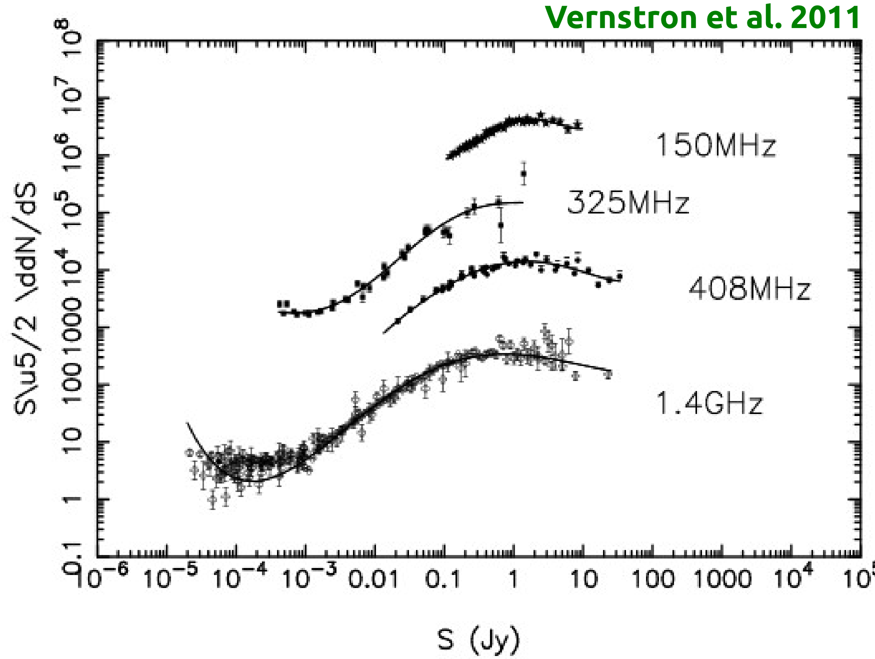
Expected contribution of

radio sources

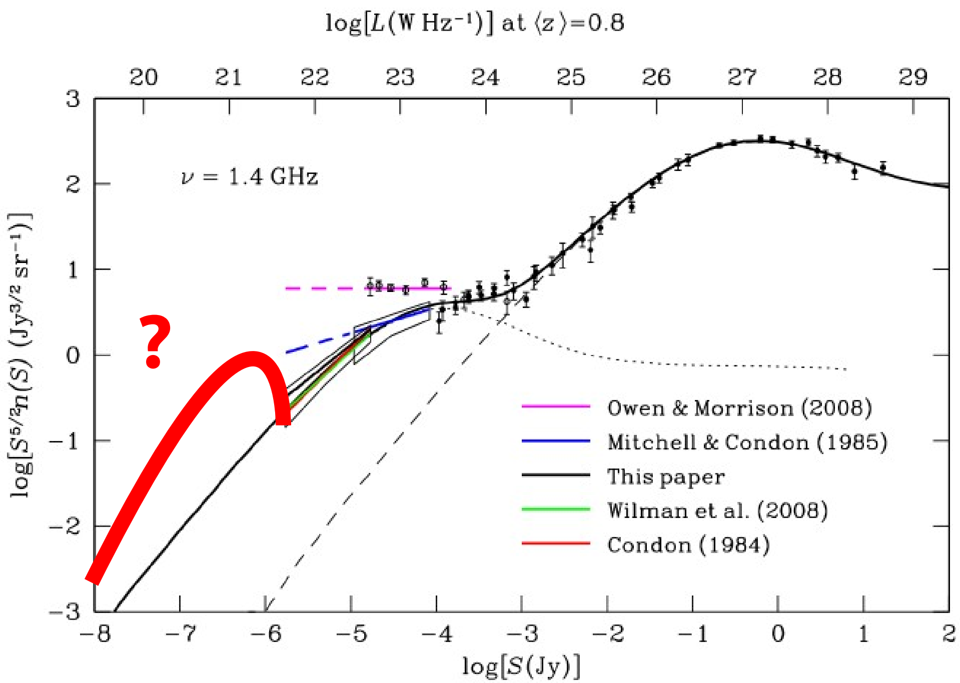


Vernstron et al. 2011

Excess confirmed at other frequencies



Possible explanations



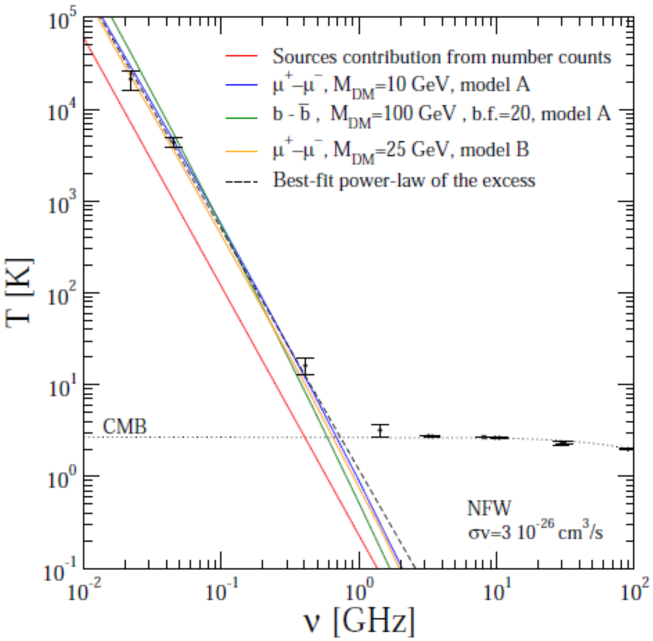
The excess calls for an undetected population of radio sources at fluxes below micro-Jy

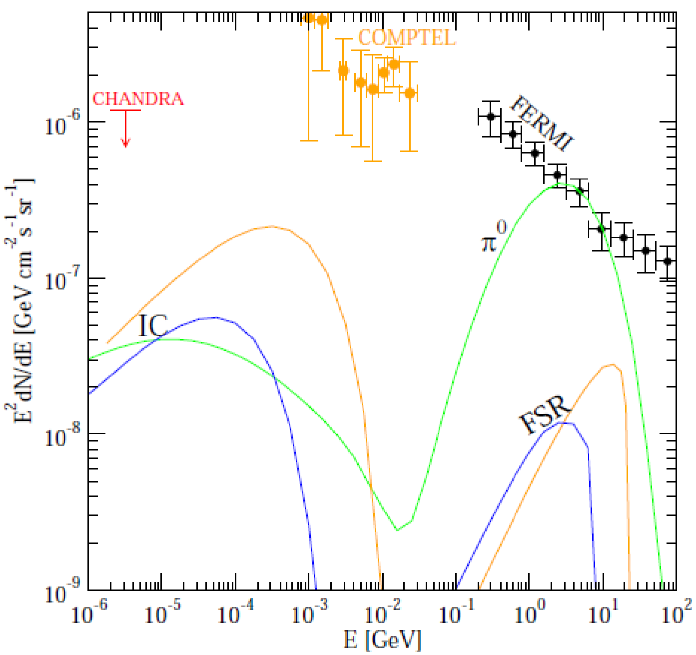
Interpretations in terms of known astro- sources are challenged by multi-wavelength constraints: gamma-rays, X-rays (diffuse intragalactic emission), IR (star forming galaxies).

Singal et al. 2010, Lacki 2010, Ponente 2010, ...

Can DM explain these data?

N.Fornengo, R.Lineros, M.Regis, M.T. 2011





Synchrotron emission in extra-galactic halos can explain the excess

Only leptonic channels are viable

Constraints from gamma and X rays are ok for lepto-philic and light DM

DM is in principle a viable option but there isn't any striking signature of DM into the signal!!!

Options

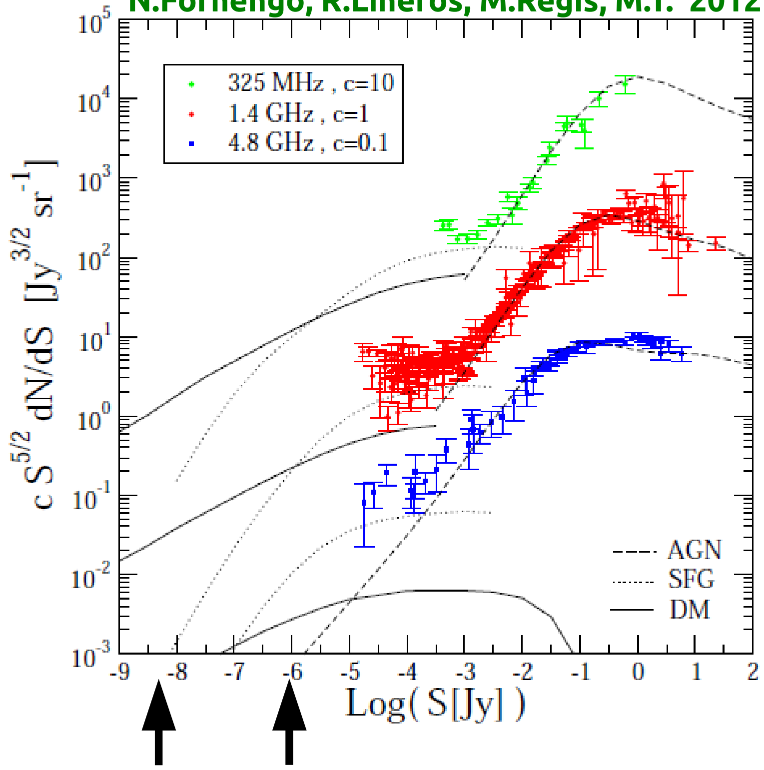
1) The radio background estimated by ARCADE-2 collaboration is off because it is contaminated by galactic foreground.

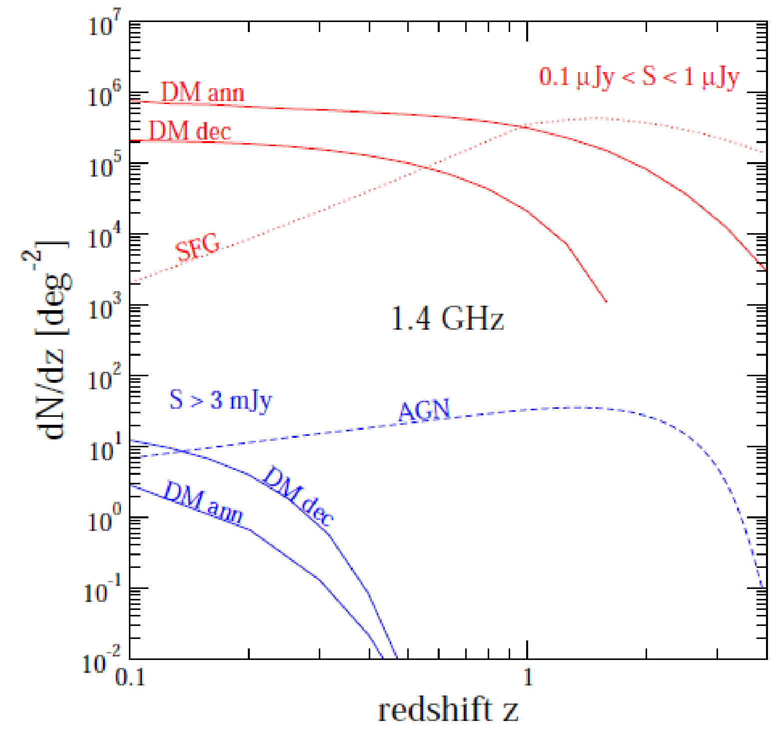
Different methods to test the robustness of this estimation

2) There is an undetected small population of faint and numerous radio sources with faint emissions at other wavelengths.

Forecast for future experiments

N.Fornengo, R.Lineros, M.Regis, M.T. 2012





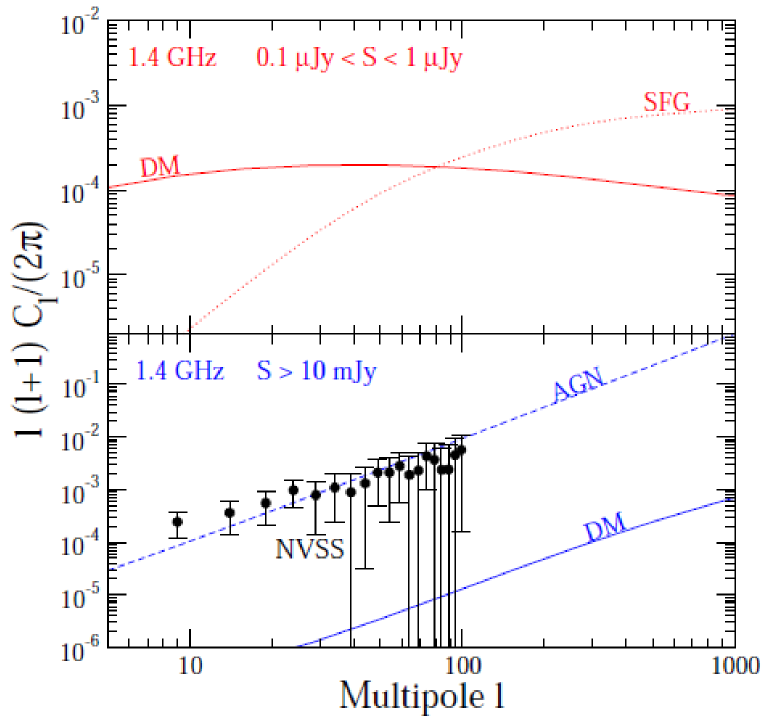
DM sources can dominate the number counts of sources at sub micro-Jy fluxes

These fluxes are at the reach of future radio telescopes:

EVLA and ASKAP soon, SKA (long term project)

Redshift evolution of DM sources different from that of Star Forming galaxies

Forecast for future experiments



Present data on angular correlations are not relevant: too large fluxes

They can becomes relevant probes for DM sources at low fluxes

Caution: predictions are affected by large astro-uncertainties

See **N.Fornengo, R.Lineros, M.Regis, M.T. 2012** for more details

Summary

Gamma-ray line signals are precious probes of DM annihilations

We need to single out the DM theories which can be tested

DM annihilations typically produce a multi-wavelength spectrum

From Radio data we can constrain the dark properties

Future surveys might say something about extragalactic DM radio sources

THANKS