UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

Highlights on Indirect Dark Matter Detection

Farinaldo Queiroz

MPIK

“An experiment is a question which science poses to Nature, and a measurement is the recording of Nature’s answer”. Max Planck (1858-1947)

June -2016

Outline

1. *Introduction to the WIMP Paradigm*

2. *Brief review on Indirect Dark Matter Detection*

3. *GeV gamma-ray excess in the Galactic Center*

4. *3.5 KeV line emission – Galaxy Cluster and Galactic Center*

5. *Search for line emissions from dark matter annihilations*

Please Remember

1) The Dark Matter Interpretation of the Galactic Center Excess is still viable and will remain viable for several years

2) We can search for neutrinos from dark matter annihilation using gamma-ray telescopes with the potential to distinguish neutrino flavors

Evidences for Dark Matter

Galaxy Rotation Curves

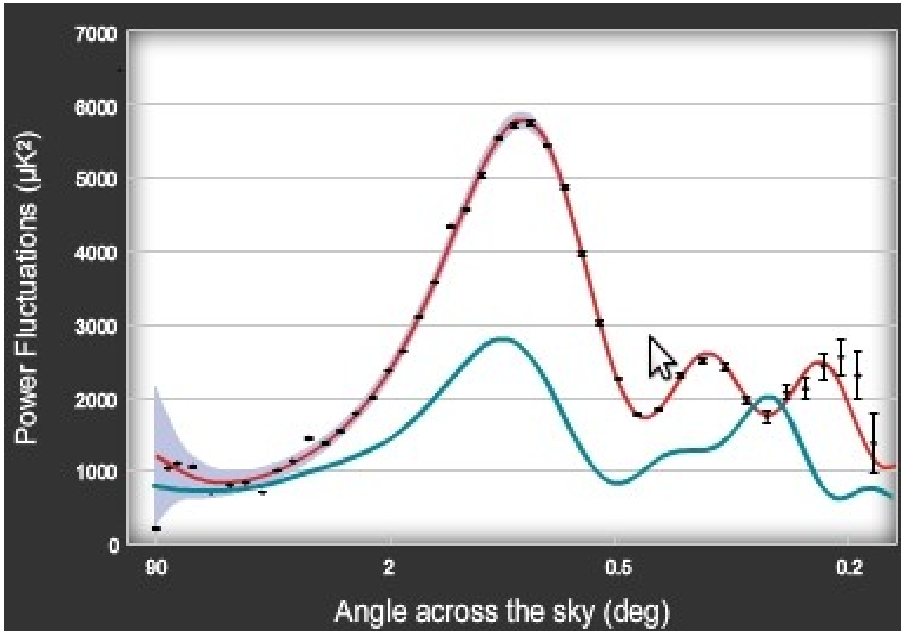
Structure Formation

Gravitational Lenses

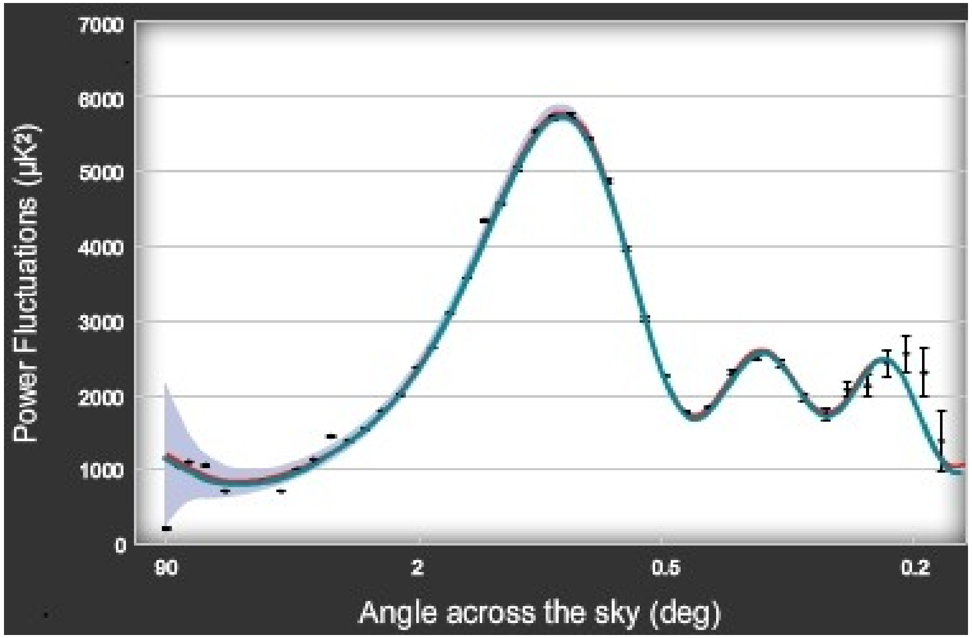
Cluster Collisions

Cosmic Microwave Background Radiation

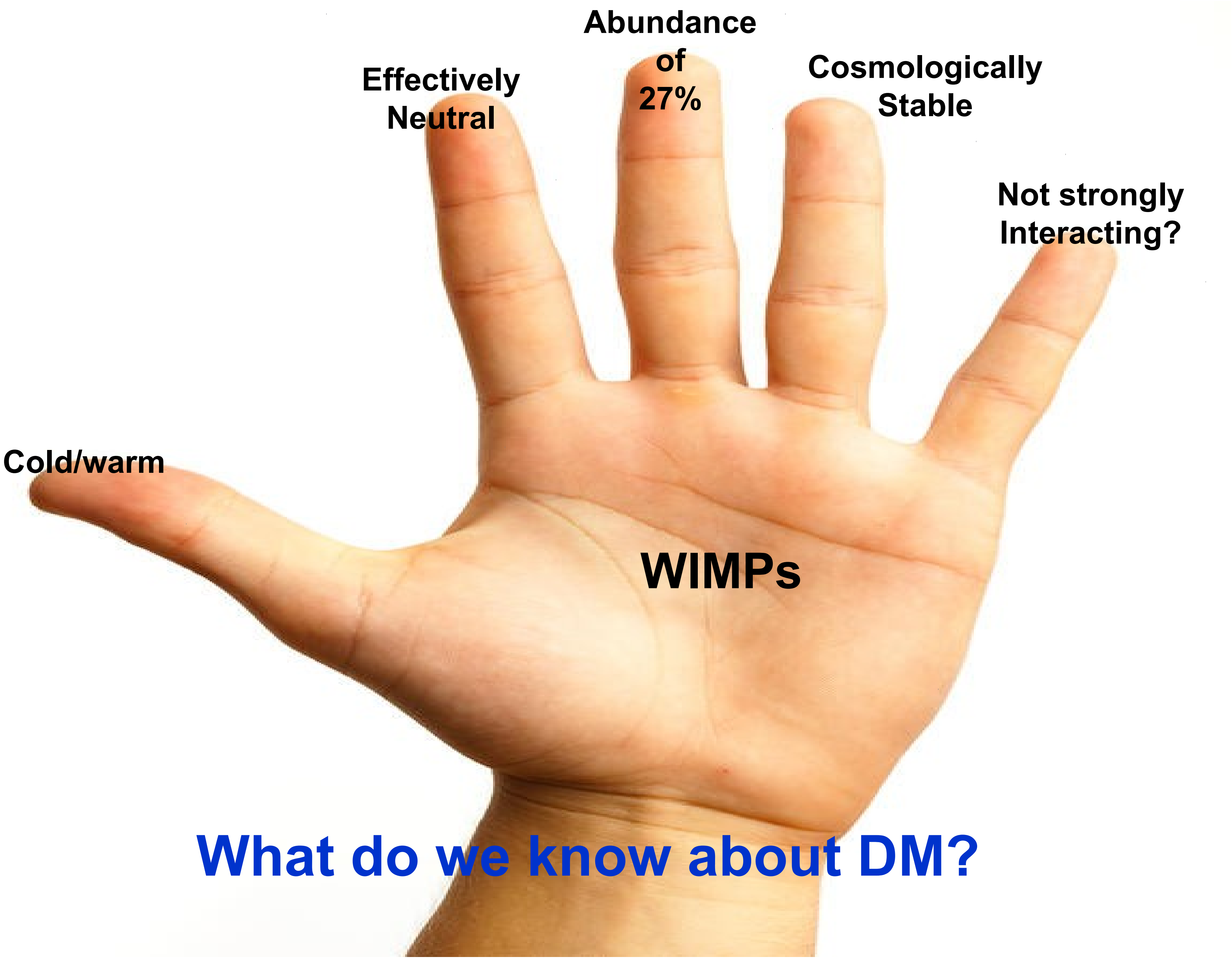
Without Dark Matter



With Dark Matter



access Planck website, it's really cool



What do we know about DM?

Basic Concepts

A. dark matter particles could interact with standard model particles and reach thermal equilibrium. Non-thermal processes are also OK.

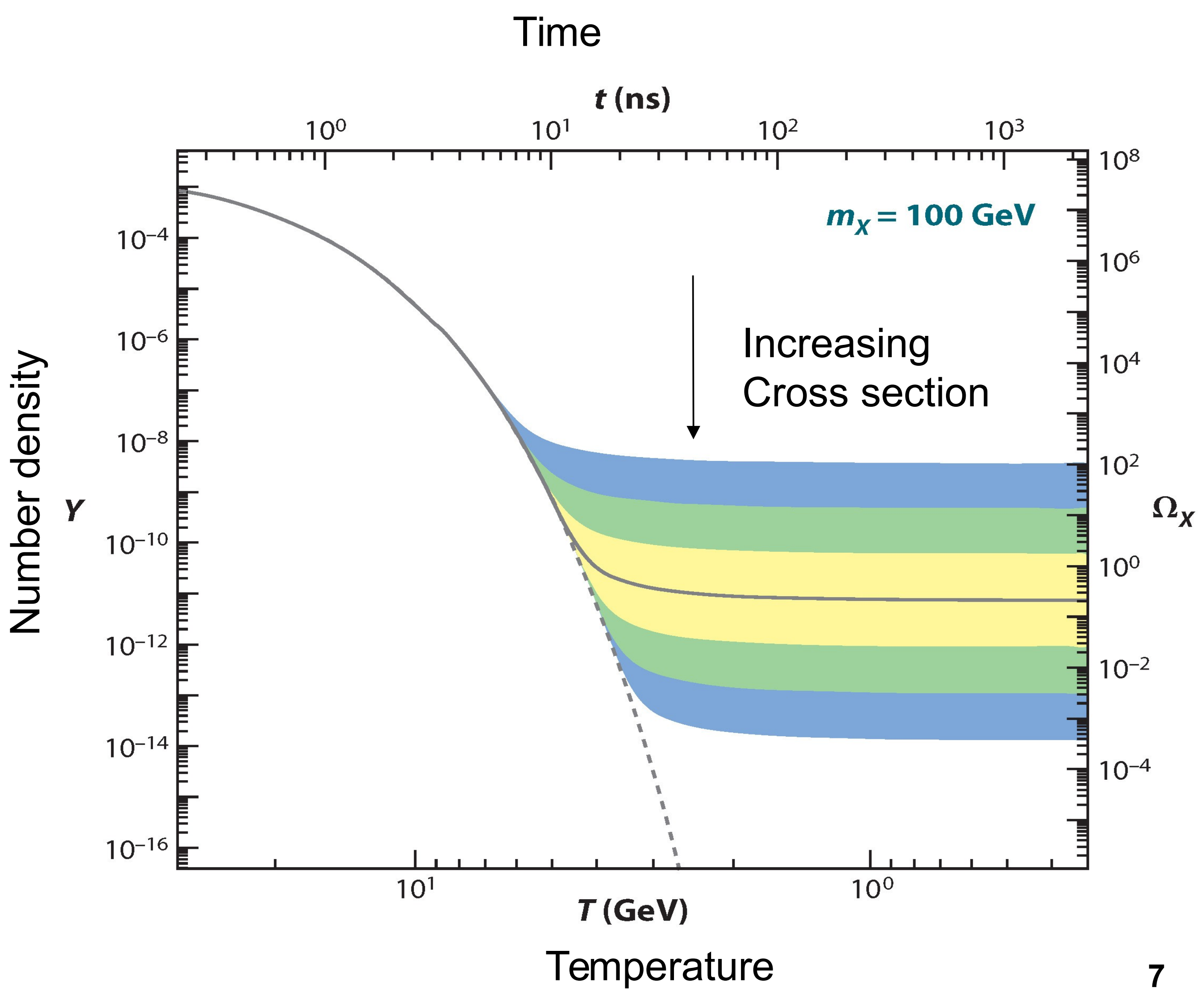
B. After the universe cooled down and expanded, eventually the expansion rate equaled the interaction rate → freeze-out.

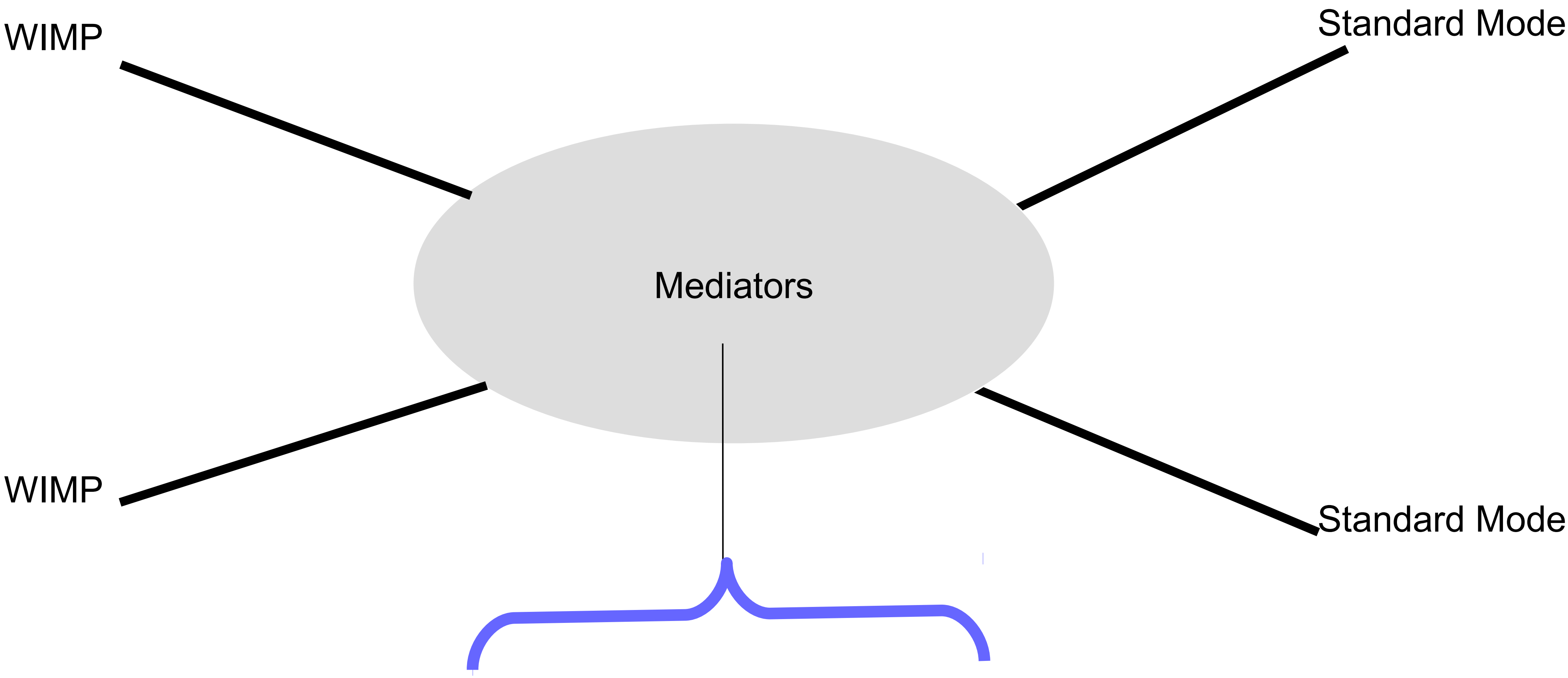
C. After the freeze-out the dark matter particles clustered forming the structures we observe today.

D. In the WIMP paradigm the abundance is connected to the annihilation cross section at freeze-out.

Dark Matter Abundance (WIMP)

Right relic abundance → Annihilation cross section at the weak scale





Higgs portal (Westhoff+ 1506.04149 , Duerr+ 1508.04418)

Dark Photon (Pospelov+ 1603.01256)

Z' portal (Berlin+ 1402.6287, Ohmer+ 1506.00954, Fairbairn+ 1605.07940)

Co-annihilation (Baker+,1510.03434)

Freeze-in (Klasen+ 1309.277)

Lindner group

I will not care about what happens in the black box

Gamma-ray searches for dark matter annihilation are based on measuring the differential gamma-ray flux

# of Photons ~ Anni. cross section x Number density squared x Volume of the sky

# of Photons ~ Anni. cross section X Number density squared X Volume of the sky

ρ^2/m_χ^2

$$\frac{d\phi}{d\Omega dE} = \frac{\langle \sigma v_{\rm rel} \rangle}{8\pi m_\chi^2} \frac{dN_\gamma}{dE} \times \int_{\rm l.o.s.} ds\ \rho(\vec{r}[s,\Omega])^2$$

# of Photons ~ Anni. cross section X Number density squared X Volume of the sky

ρ^2/m_χ^2

normalize

$$\frac{d\phi}{d\Omega dE} = \frac{\langle \sigma v_{\rm rel}\rangle}{8\pi m_\chi^2}\frac{dN_\gamma}{dE} \times \int_{\rm l.o.s.} ds\ \rho(\vec{r}[s,\Omega])^2$$

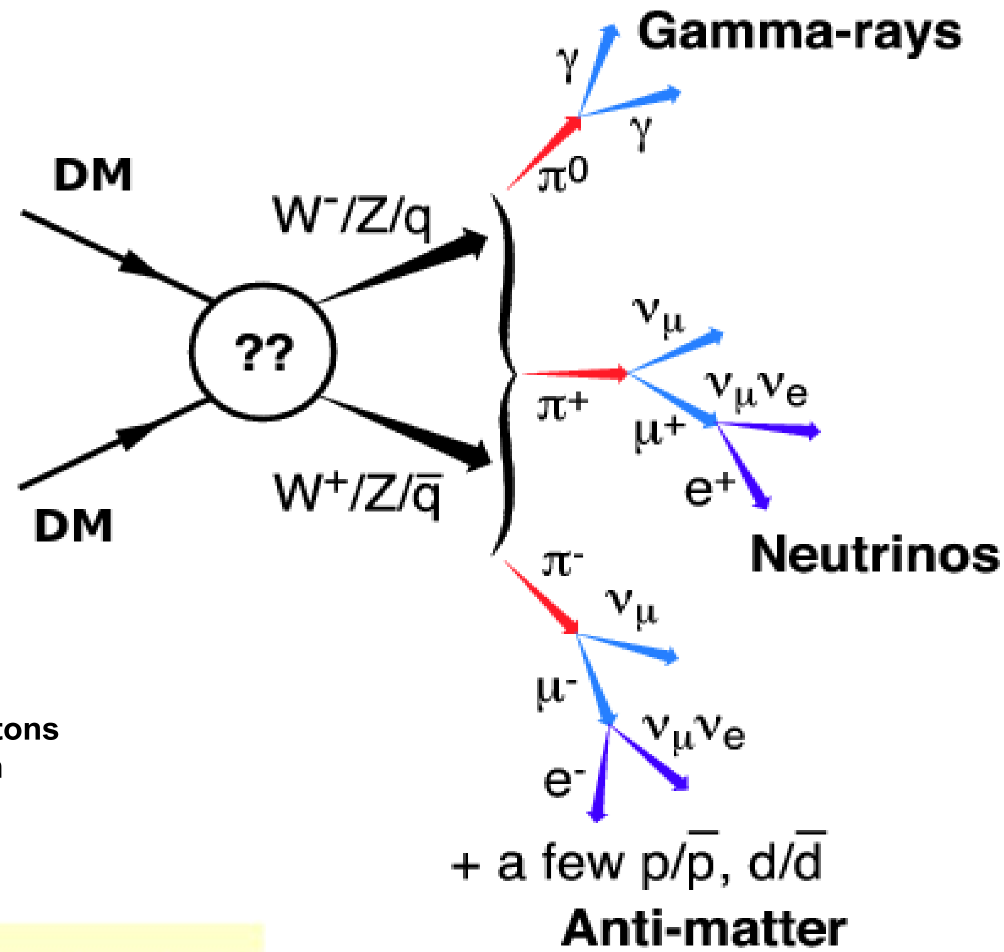
Normalization factor
(solid angle of a sphere)

Basic Concepts

Dark Matter Indirect Detection

A. The dark matter particles might still be able to interact with standard model particles and produce an observable signal.

B. We know how to account for hadronization and final state radiation well up to the dark matter mass, which can be very heavy.



Differential Flux

Annihilation cross section

Number of photons per annihilation

$$\frac{d\phi}{d\Omega dE} = \frac{\langle \sigma v_{\rm rel} \rangle}{8\pi m_\chi^2} \frac{dN_\gamma}{dE} \times \int_{\rm l.o.s.} ds \; \rho(\vec{r}[s,\Omega])^2$$

Line of sight integral

Dark matter density

Dark Matter Annihilation: Gamma-ray Excess at the Galactic Center

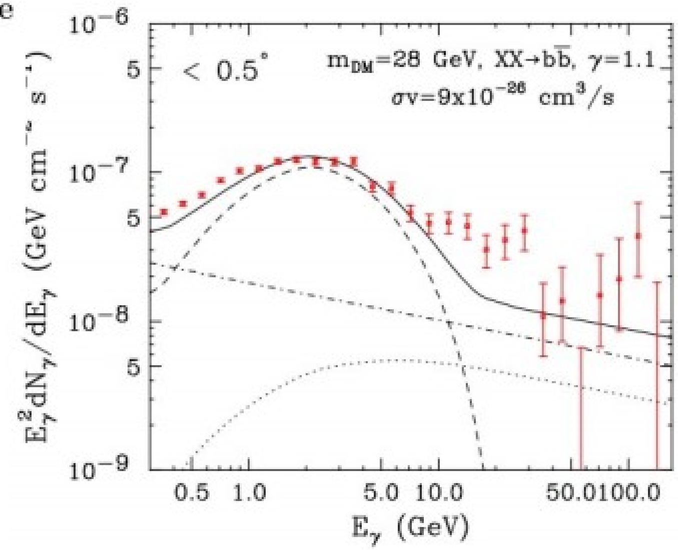
First observation (2009)

Possible Evidence For Dark Matter Annihilation In The Inner Milky Way From The Fermi Gamma Ray Space Telescope

Lisa Goodenough[1] and Dan Hooper[2,3]

[1] *Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003*
[2] *Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL 60510*
[3] *Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637*

We study the gamma rays observed by the Fermi Gamma Ray Space Telescope from the direction of the Galactic Center and find that their angular distribution and energy spectrum are well described by a dark matter annihilation scenario. In particular, we find a good fit to the data for dark matter particles with a 25-30 GeV mass, an annihilation cross section of $\sim 9 \times 10^{-26}$ cm^3/s, and that are distributed with a cusped halo profile, $\rho(r) \propto r^{-1.1}$, within the inner kiloparsec of the Galaxy. We cannot, however, exclude the possibility that these photons originate from an astro-



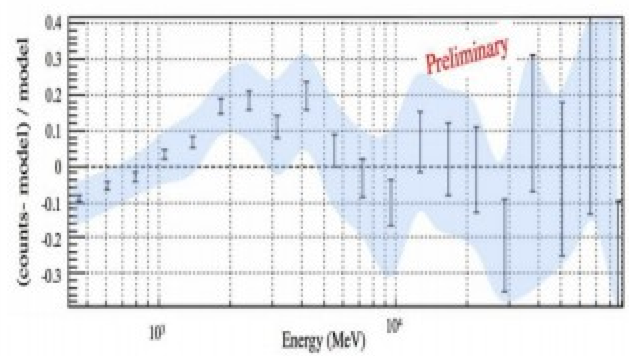
First Fermi-LAT team members – report (2009)

2009 Fermi Symposium, Washington, D.C., Nov. 2-5

Indirect Search for Dark Matter from the center of the Milky Way with the Fermi-Large Area Telescope

Vincenzo Vitale and Aldo Morselli, for the Fermi/LAT Collaboration
Istituto Nazionale di Fisica Nucleare, Sez. Roma Tor Vergata, Roma, Italy

erations, is reported. The diffuse gamma ray backgrounds and discrete sources, as we know them today, can account for the large majority of the detected gamma-ray emission from the Galactic Center. Nevertheless a residual emission is left, not accounted for by the above models.
An improved model of the Galactic diffuse emission and a careful evaluation of new (possibly unresolved) sources (or source populations) will improve the sensitivity for a DM search.



Dark Matter Annihilation: Gamma-ray Excess at the Galactic Center

Fermi–LAT OBSERVATIONS OF HIGH-ENERGY γ-RAY EMISSION TOWARD THE GALACTIC CENTRE

M. AJELLO[1], A. ALBERT[2], W. B. ATWOOD[3], G. BARBIELLINI[4,5], D. BASTIERI[6,7], K. BECHTOL[8], R. BELLAZZINI[9], E. BISSALDI[10], R. D. BLANDFORD[2], E. D. BLOOM[2], R. BONINO[11,12], E. BOTTACINI[2], T. J. BRANDT[13], J. BREGEON[14], P. BRUEL[15], R. BUEHLER[16], S. BUSON[6,7], G. A. CALIANDRO[2,17], R. A. CAMERON[2], R. CAPUTO[3], M. CARAGIULO[10], P. A. CARAVEO[18], C. CECCHI[19,20], A. CHEKHTMAN[21], J. CHIANG[2], G. CHIARO[7], S. CIPRINI[22,19,23], J. COHEN-TANUGI[14], L. R. COMINSKY[24], J. CONRAD[25,26,27], S. CUTINI[22,23,19], F. D'AMMANDO[28,29], A. DE ANGELIS[30], F. DE PALMA[10,31], R. DESIANTE[32,11], L. DI VENERE[33], P. S. DRELL[2], C. FAVUZZI[33,10], E. C. FERRARA[13], P. FUSCO[33,10], F. GARGANO[10], D. GASPARRINI[22,23,19], N. GIGLIETTO[33,10], P. GIOMMI[22], F. GIORDANO[33,10], M. GIROLETTI[28], T. GLANZMAN[2], G. GODFREY[2], G. A. GOMEZ-VARGAS[34,35], I. A. GRENIER[36], S. GUIRIEC[13,37], M. GUSTAFSSON[38], A. K. HARDING[13], J.W. HEWITT[39], A. B. HILL[40,2], D. HORAN[15], T. JOGLER[2], G. JÓHANNESSON[41], A. S. JOHNSON[2], T. KAMAE[42], C. KARWIN[43], J. KNÖDLSEDER[44,45], M. KUSS[9], S. LARSSON[46,26], L. LATRONICO[11], J. LI[47], L. LI[46,26], F. LONGO[4,5], F. LOPARCO[33,10], M. N. LOVELLETTE[48], P. LUBRANO[19,20], J. MAGILL[49], S. MALDERA[11], D. MALYSHEV[2], A. MANFREDA[9], M. MAYER[16], M. N. MAZZIOTTA[10], P. F. MICHELSON[2], W. MITTHUMSIRI[50], T. MIZUNO[51], A. A. MOISEEV[52,49], M. E. MONZANI[2], A. MORSELLI[34], I. V. MOSKALENKO[2], S. MURGIA[43,†], E. NUSS[14], M. OHNO[54], T. OHSUGI[51], N. OMODEI[2], E. ORLANDO[2], J. F. ORMES[55], D. PANEQUE[56,2], M. PESCE-ROLLINS[9,2], F. PIRON[14], G. PIVATO[9], T. A. PORTER[2,‡], S. RAINÒ[33,10], R. RANDO[6,7], M. RAZZANO[9,58], A. REIMER[59,2], O. REIMER[59,2], S. RITZ[3], M. SÁNCHEZ-CONDE[26,25], P. M. SAZ PARKINSON[3,60], C. SGRÒ[9], E. J. SISKIND[61], D. A. SMITH[62], F. SPADA[9], G. SPANDRE[9], P. SPINELLI[33,10], D. J. SUSON[63], H. TAJIMA[64,2], H. TAKAHASHI[54], J. B. THAYER[2], D. F. TORRES[47,65], G. TOSTI[19,20], E. TROJA[13,49], Y. UCHIYAMA[66], G. VIANELLO[2], B. L. WINER[67], K. S. WOOD[48], G. ZAHARIJAS[68,69], S. ZIMMER[25,26]

Draft version November 11, 2015

ABSTRACT

....

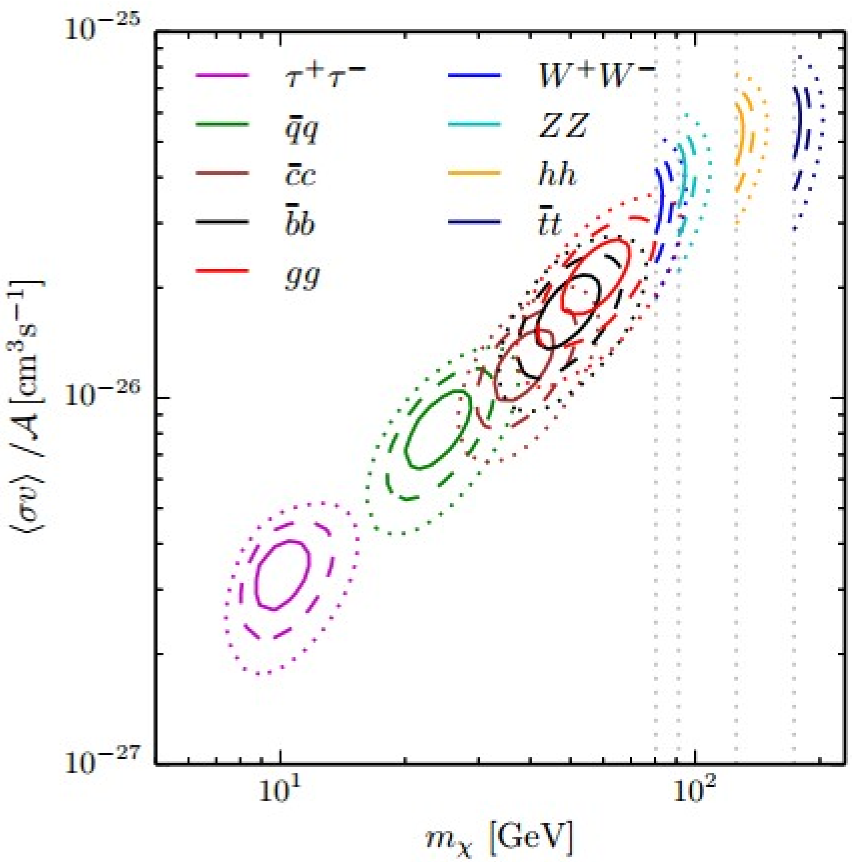
Fermi-LAT collab. has confirmed the excess

$\sim$ 1 kpc derived for the IEMs used in this paper, and comparable to the integrated brightness of the point sources in the region for energies $\gtrsim$ 3 GeV. If spatial templates that peak toward the GC are used to model the positive residual and included in the total model for the $15° \times 15°$ region, the agreement with the data improves, but they do not account for all the residual structure. The spectrum of the positive residual modelled with these templates has a strong dependence on the choice of IEM.

Gamma-ray Excess in the Galactic Center

Interpretations

Dark Matter



F. Calore et al, 1411.4647

Many dark matter models fit the Galactic excess easily, but only some are consistent with direct detection and collider bounds.

Other Sources

1. Young Pulsars

   K. N. Abazajian+, 1402.4090.
   R. Bartels+, 1506.05104;
   S. Lee+,1506.05124;

2. Collisions between gas with protons accelerated by a black holes.

   T. Linden+, 1203.3539;
   O. Macias+, 1410.1678

3. Collisions between gas with cosmic-rays (e.g. non-thermal bremsstrahlung from a population of electrons scattering off neutral molecular clouds)

   F. Yusef-Zadeh+,1206.6882

4. Series of Burst-like events during an active past of our galaxy

   E. Carlson+,1405.7685
   J. Petrovic+, 1405.7928

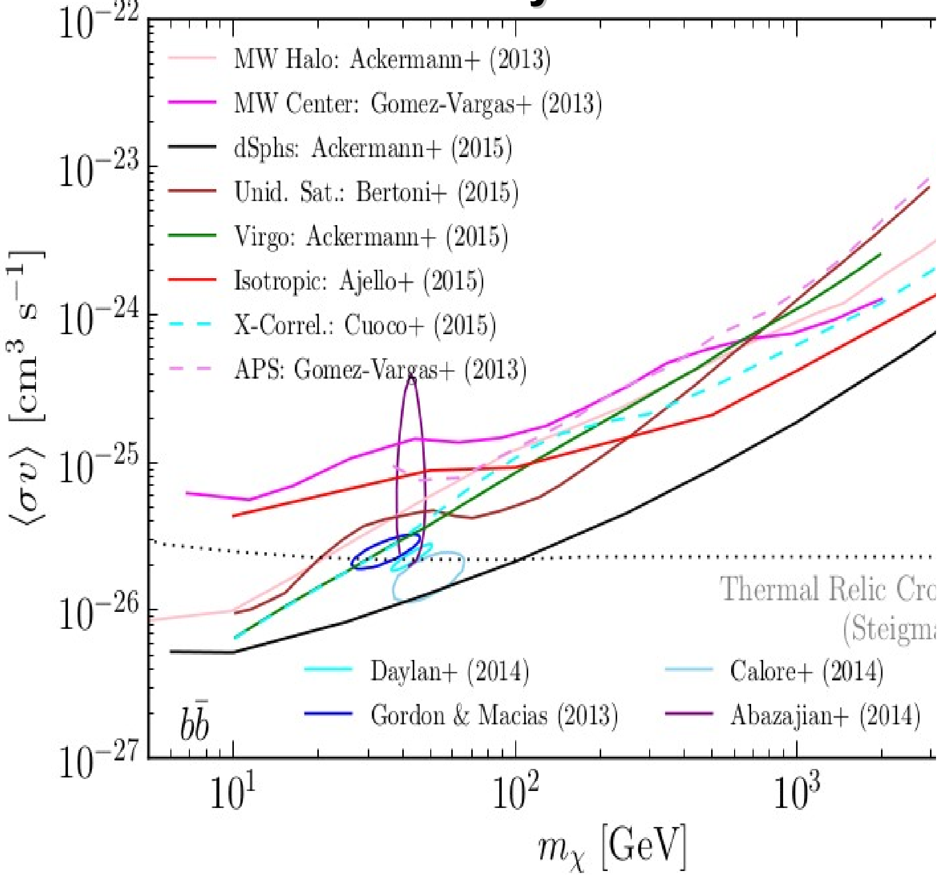
5. Different distributions of distribution cosmic-ray sources

   E. Carlson+,1510.04698
   D. Gaggero+, 1507.06129

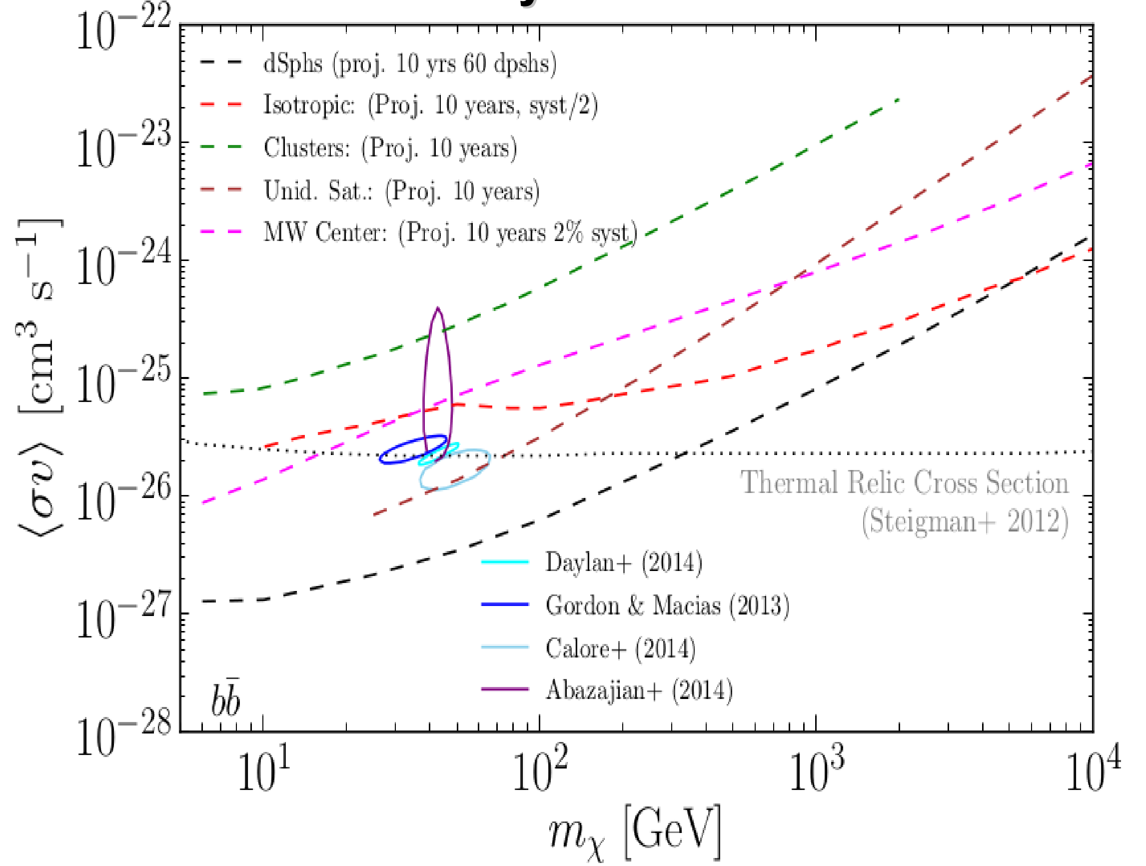
FERMI-LAT

Status of the Gamma-ray Excess in the Galactic Center

Today



3 years from now

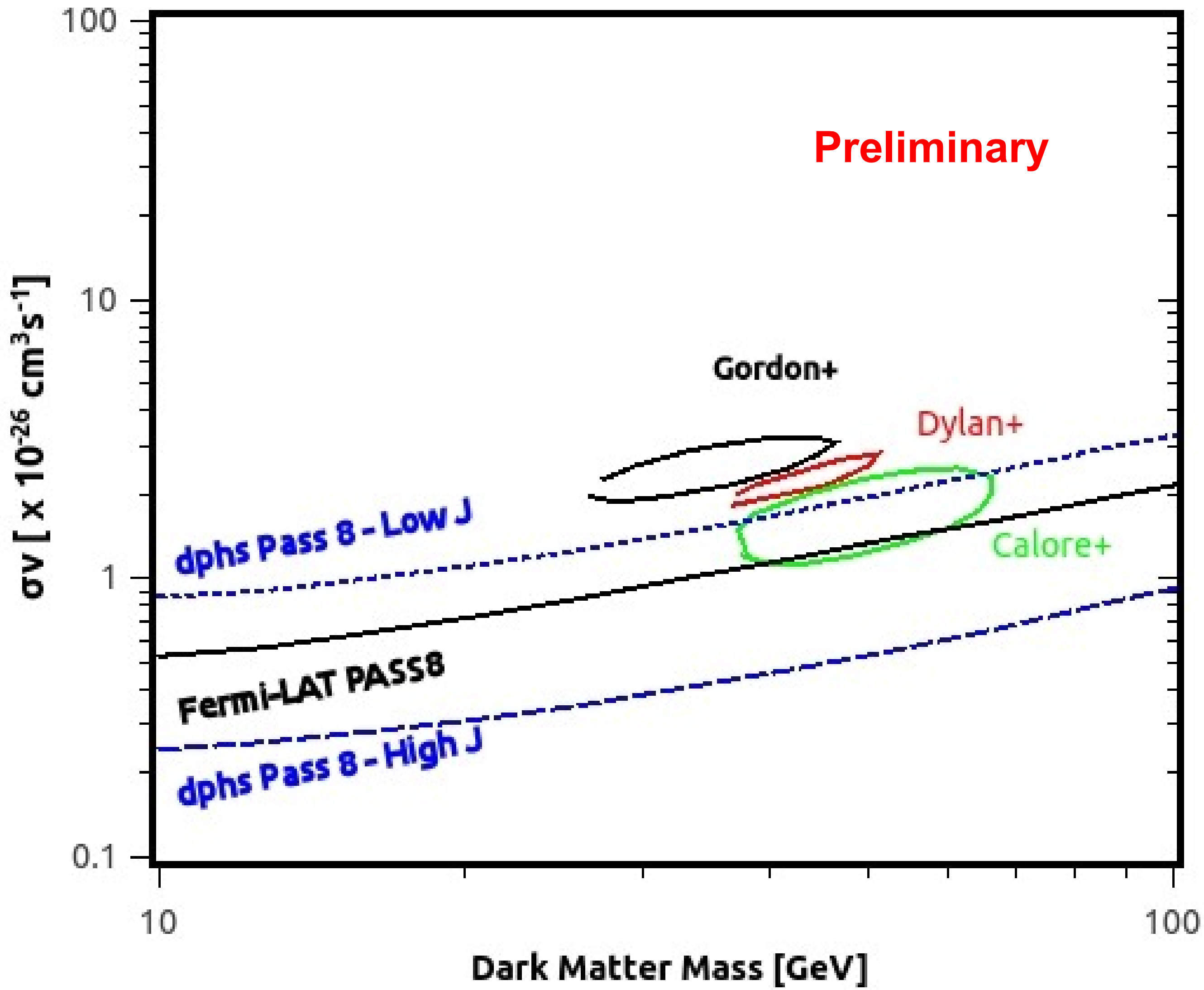


From the right panel, one could conclude that the dark matter interpretation of the galactic center excess will be decisively confirmed or ruled in the near future.

Isn't that a bit optimistic?

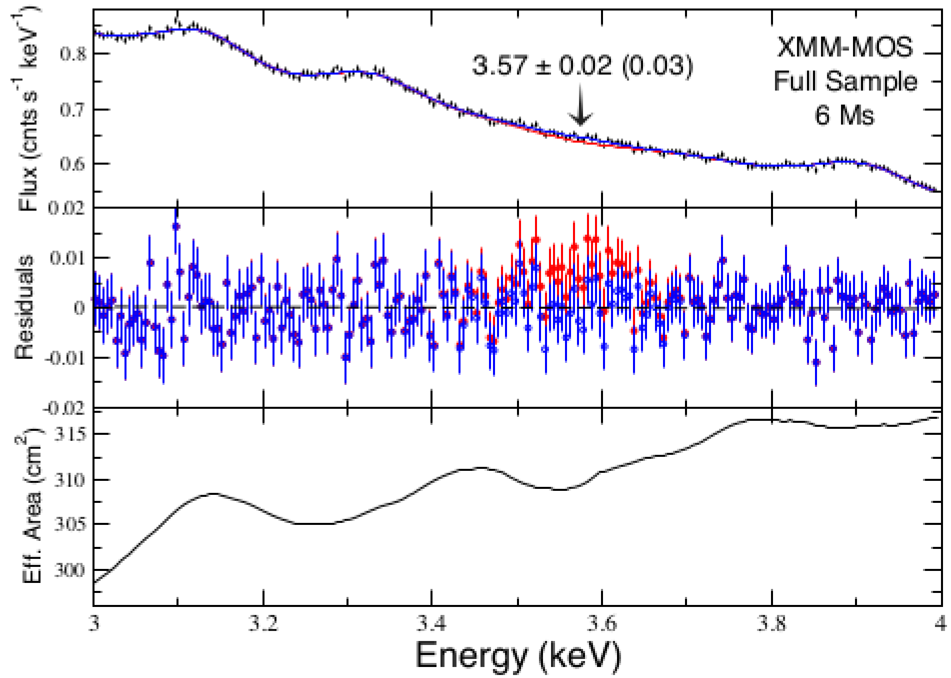
Conservative
Status of the Gamma-ray Excess in the Galactic Center

Work in progress..
Farinaldo Queiroz, Carlos Yaguna, Christoph Weniger



Dark Matter Decay: KeV Excess at the Galactic Center and Galaxy Clusters

Detection of an unidentified emission line in the stacked x-ray spectrum of 73 galaxy clusters using XMM-Newton instrument



"we argue that there should be no atomic transitions in thermal plasma at this energy"

A. Boyarsky+, 1402.4119 and 1408.2503

E. Bulbul+, 1402.2301

KeV Sterile Neutrino as dark matter

$$\Gamma_\gamma(m_s,\theta) = 1.38\times10^{-29}\ \mathrm{s}^{-1}\left(\frac{\sin^2 2\theta}{10^{-7}}\right)\left(\frac{m_s}{1\ \mathrm{keV}}\right)^5$$

Dodelson&Widrow hep-ph9303287

Dark Matter Decay: KeV Excess at the Galactic Center and Galaxy Clusters

Dark Matter Searches going bananas...

Jeltema,Profumo, 1408.1699

1.They focused on the 3-4KeV energy range, differently from previous papers

2. They a public version of the tool used to compute the line emissions, differently from previous papers

3. They found no evidence for a 3.5KeV line emission.

4. Updated limits on decaying DM are closing in

Mambrini, Profumo, **Queiroz**, 1508.06635

Follow-up observations

Observations of Draco is in tension with other observations at 95-99% C.L.

Ruchayskiy, Boyarsky+, 1512.07217

Jeltema&Profumo, 1512.01239

Stacked Analysis of Dwarf Galaxies is in strong tension with the 3.5KeV line emission

Queiroz+, work in progress...

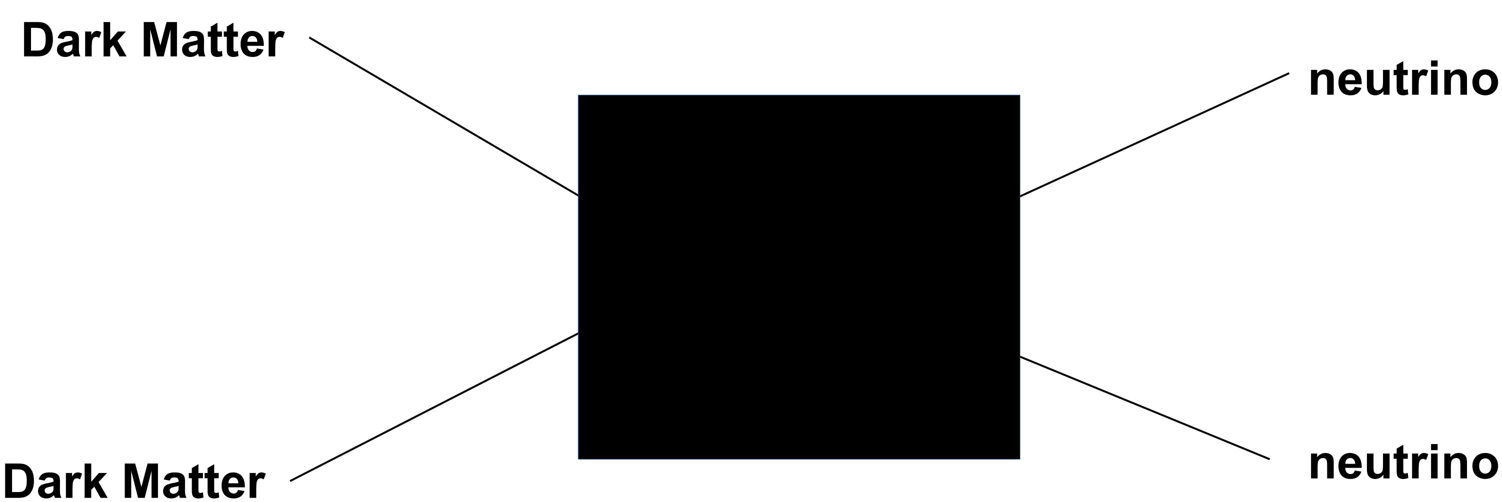
One needs to either stack dwarf galaxies or to gather much more data to clarify the origin of the KeV line emission

Thinking about neutrino lines...

Which detector would you use to search for this dark matter particle?

↓

Icecube/Antares/Super-K ?

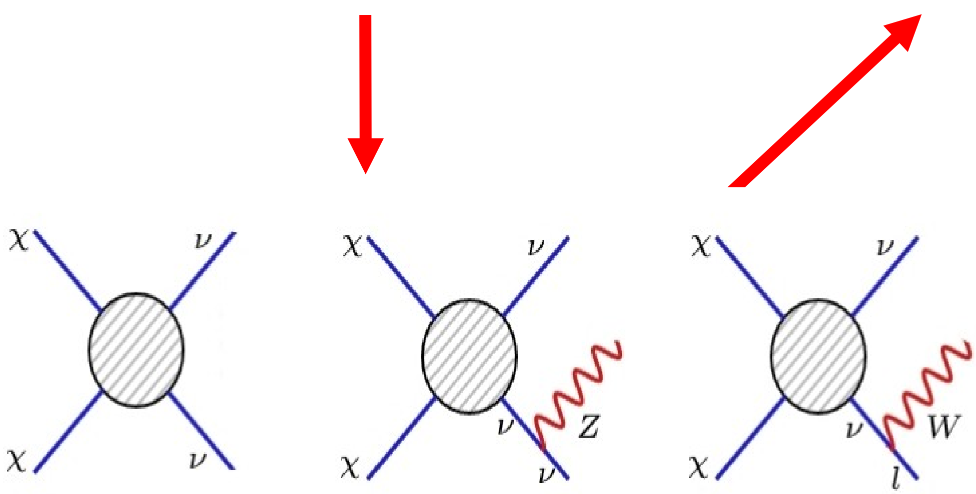


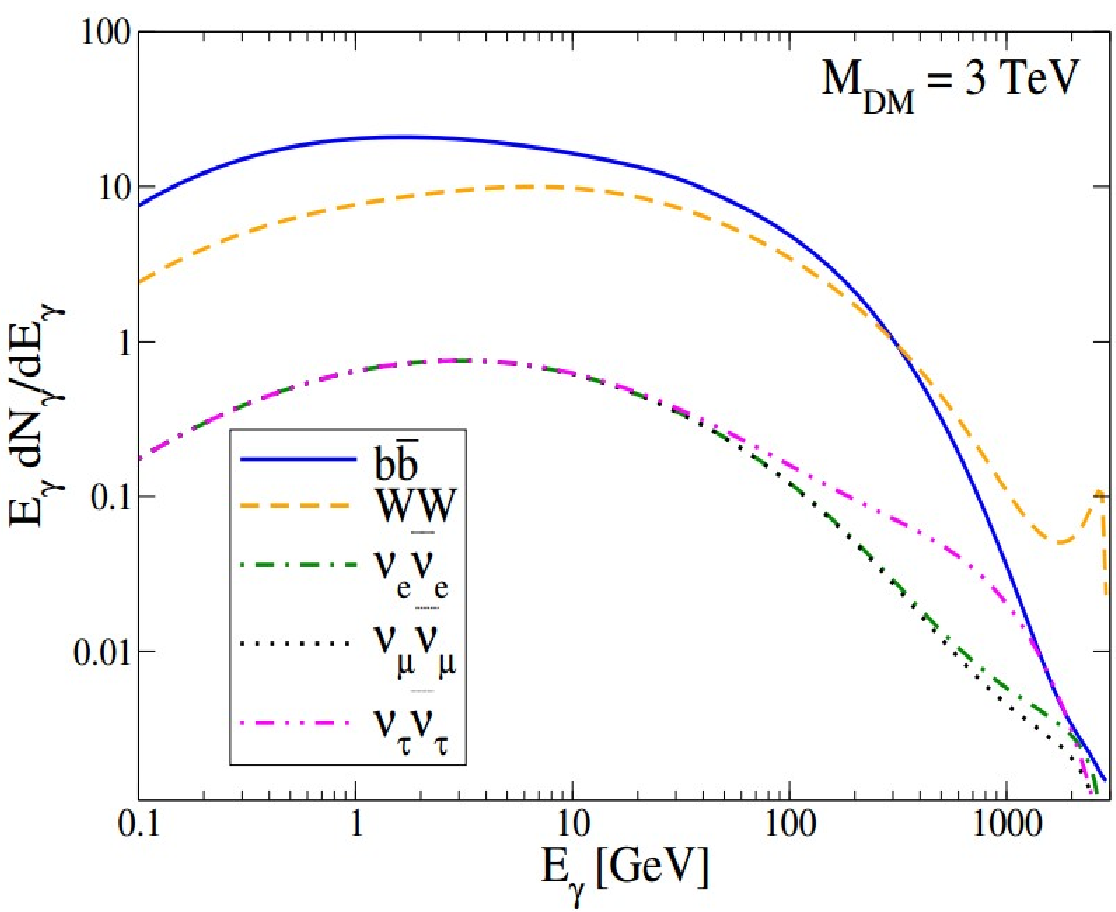
Gamma-ray Limits on Neutrino Lines

Queiroz, Yaguna, Weniger – JCAP 1605 (2016) no.05, 050- arxiv:1602.05966

Several searches for neutrinos flavors from dark matter annihilations have been conducted by Super-K, IceCube and ANTARES collaborations.

Electroweak corrections are important and a neutrino final state also gives rise to a gamma-ray emission which can be probed by Fermi-LAT/H.E.S.S. instruments.

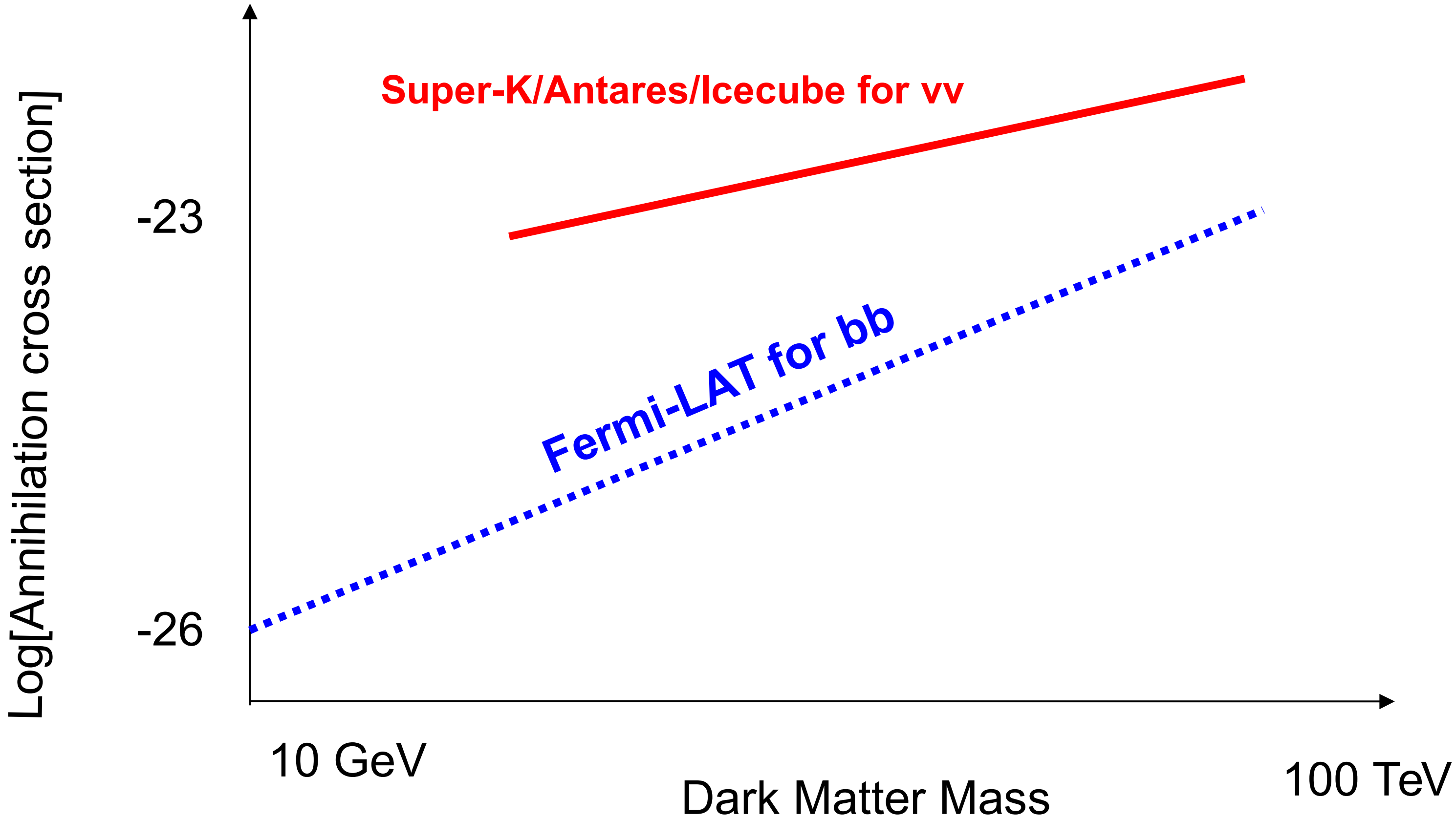




Notice that all three annihilation modes produce sizable continuous gamma-ray emission.

Gamma-ray Limits on Neutrino Lines

Queiroz, Yaguna, Weniger – JCAP 1605 (2016) no.05, 050- arxiv:1602.05966

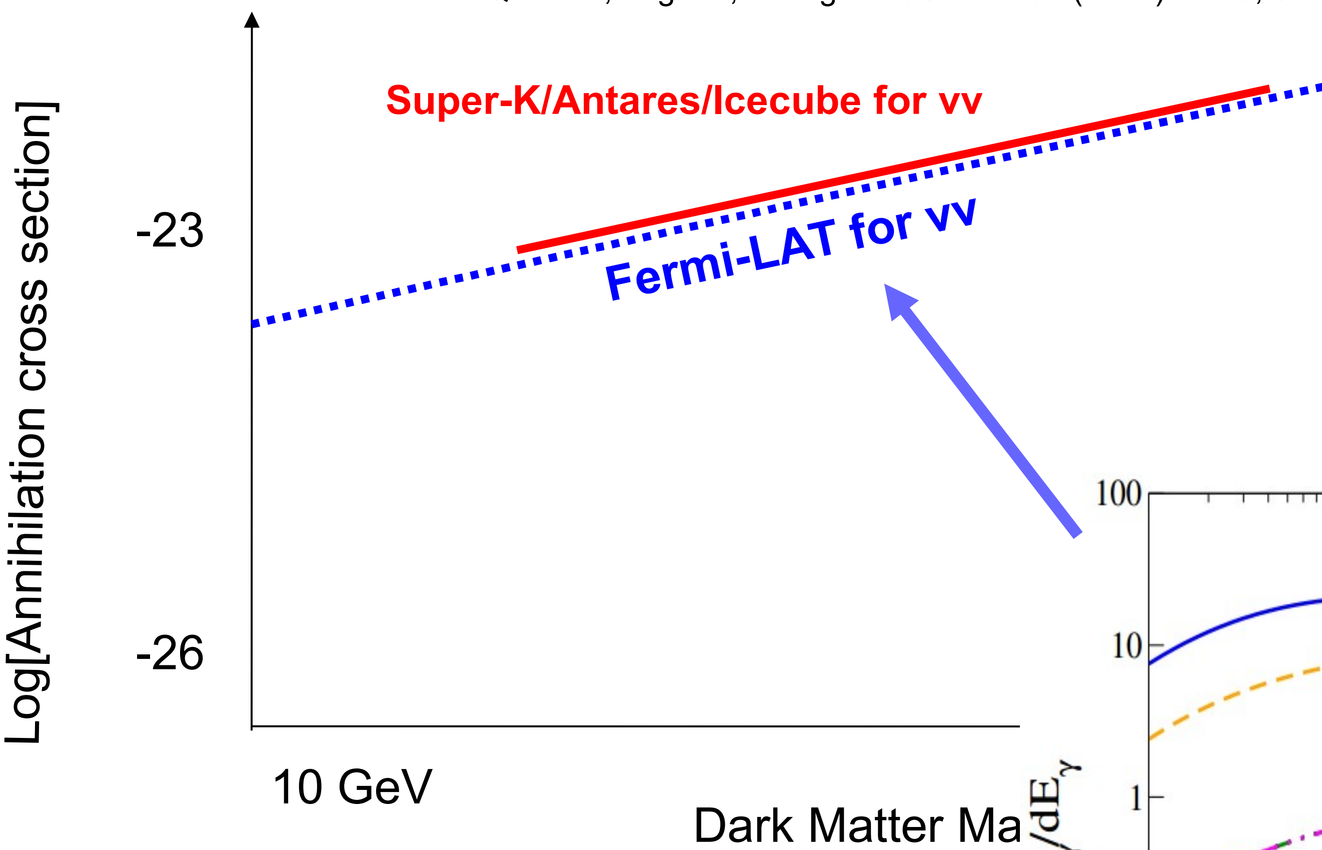


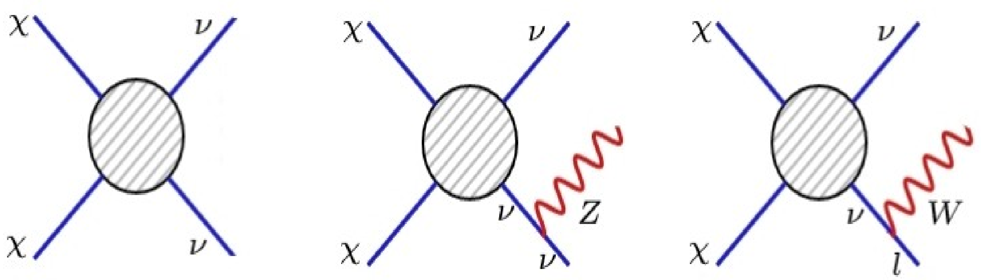
The best limits from Icecube are ~ 3 orders of magnitude weaker than best limits from Fermi-LAT.....

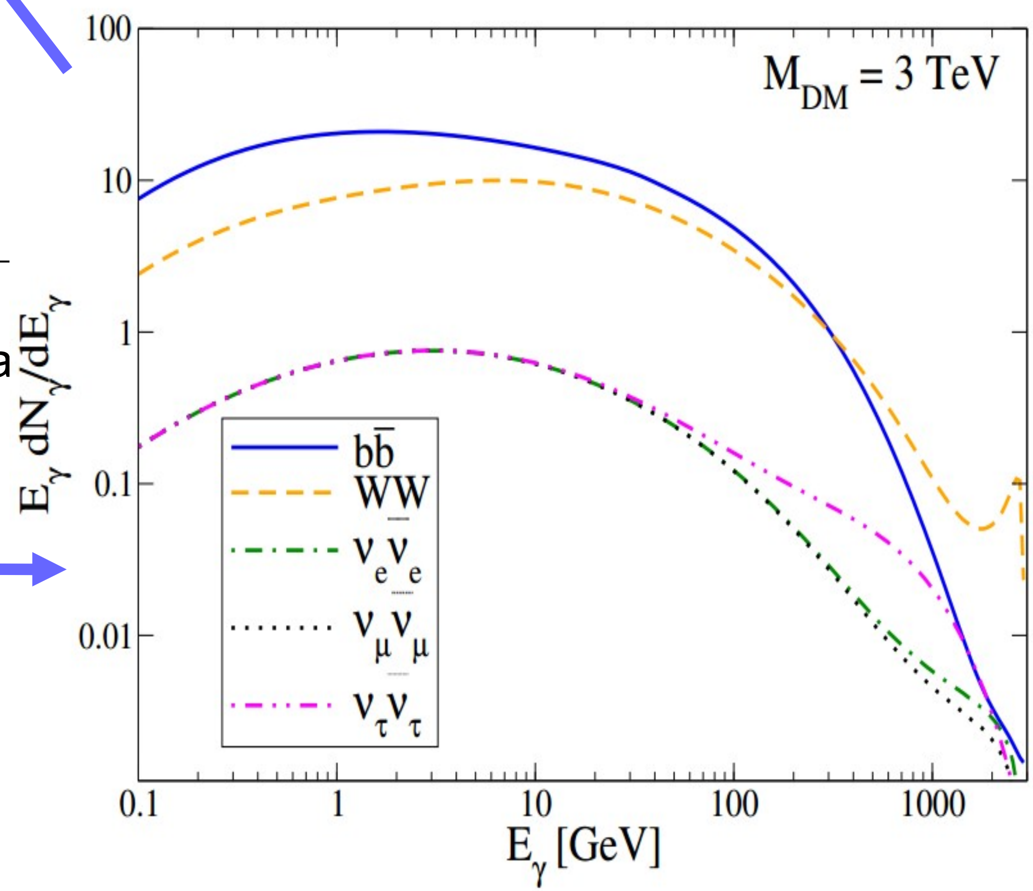
First works: Kachelriess, Serpico, 0707.0209
Bell,Dent, Jacques, Weiler, 0805.3423

Gamma-ray Limits on Neutrino Lines

Queiroz, Yaguna, Weniger – JCAP 1605 (2016) no.05, 050- arxiv:1602.05966







Cirelli+, 1012.4515

Concerning the spectrum

x= E/m   l = Log [s/m]

splitting $1 \to x + x'$	splitting function: real	and virtual
$F_{0,M} \to F_{0,M} + V_M$	$P_{F\to F} = \frac{1+x^2}{1-x} L(1-x)$	$P^{\rm vir}_{F\to F} = \frac{3\ell}{2} - \frac{\ell^2}{2}$
$F_{0,M} \to V_M + F_{0,M}$	$P_{F\to V} = \frac{1+(1-x)^2}{x} L(x)$	$P^{\rm vir}_{F\to V} = \frac{3\ell}{2} - \frac{\ell^2}{2}$
$V \to F + \bar{F}$	$P_{V\to F} = [x^2 + (1-x)^2]\ell$	$P^{\rm vir}_{V\to F} = -\frac{2\ell}{3}$
$S_M \to S_M + V_M$	$P_{S\to S} = 2\frac{x}{1-x} L(1-x)$	$P^{\rm vir}_{S\to S} = 2\ell - \frac{\ell^2}{2}$
$S_M \to V_M + S_M$	$P_{S\to V} = 2\frac{1-x}{x} L(x)$	$P^{\rm vir}_{S\to V} = 2\ell - \frac{\ell^2}{2}$
$V \to S + S'$	$P_{V\to S} = x(1-x)\ell$	$P^{\rm vir}_{V\to S} = -\frac{\ell}{6}$
$V_M \to V_M + V_M$	$P_{V\to V} = 2\left[\frac{x}{1-x} L(1-x) + \frac{1-x}{x} L(x) + x(1-x)\ell\right]$	
$V_M \to V_M + V_0$	$P'_{V\to V} = 2\left[\frac{x}{1-x}\ell + \frac{1-x}{x} L(x) + x(1-x)\ell\right]$	
$V_M \to V_0 + V_M$	$P_{V\to\gamma} = 2\left[\frac{x}{1-x} L(1-x) + \frac{1-x}{x}\ell + x(1-x)\ell\right]$	
$F \to F + S$	$P^{\rm Yuk}_{F\to F} = (1-x)\ell$	$P^{\rm Yuk,vir}_{F\to F} = -\frac{\ell}{2}$
$F \to S + F$	$P^{\rm Yuk}_{F\to S} = x\ell$	$P^{\rm Yuk,vir}_{F\to S} = -\frac{\ell}{2}$
$S \to F + F$	$P^{\rm Yuk}_{S\to F} = \ell$	$P^{\rm Yuk,vir}_{S\to F} = -\ell$

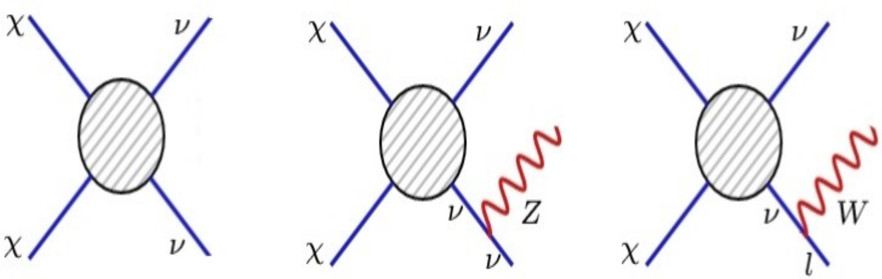
Gamma-ray Limits on Neutrino Lines

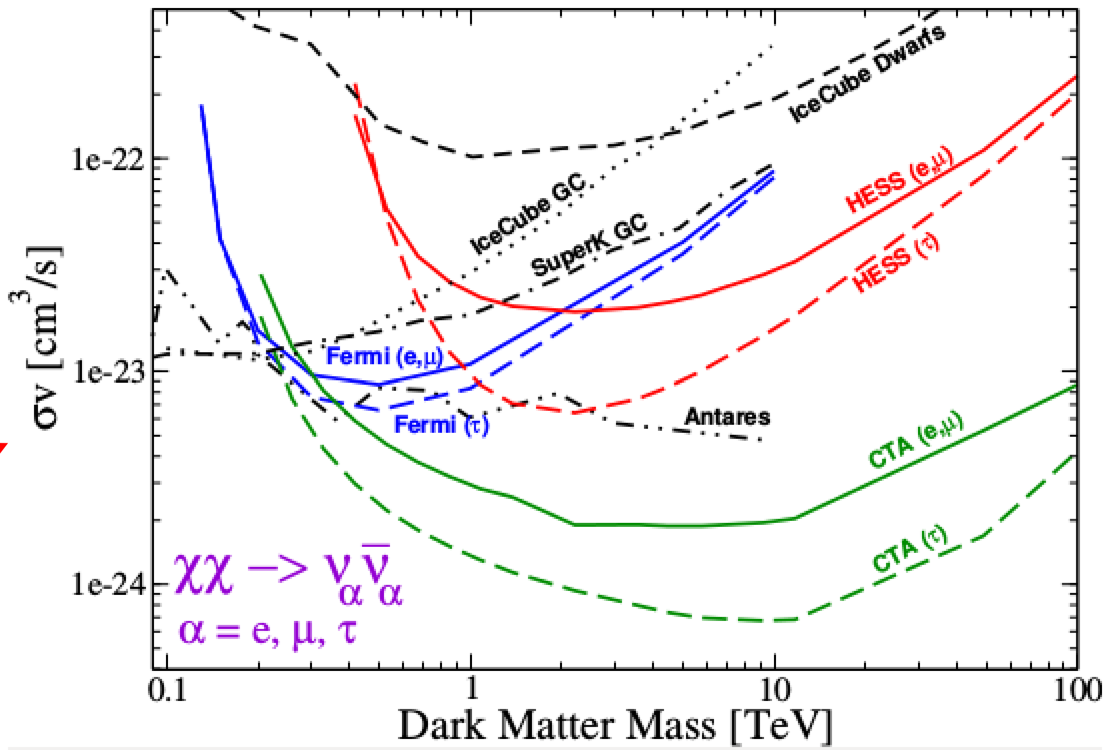
Queiroz, Yaguna, Weniger – JCAP 1605 (2016) no.05, 050- arxiv:1602.05966

A neutrino signal seen by Icecube/ANTARES/ Super-K from dark matter annihilation should also be seen by Fermi-LAT/H.E.S.S. and definitely by CTA

Several searches for neutrinos flavors from dark matter annihilations have been conducted by Super-K, IceCube and ANTARES collaborations.

Electroweak corrections are important and a neutrino final state also gives rise to a gamma-ray emission which can be probed by Fermi-LAT/H.E.S.S. instruments.





F. Queiroz, C. Yaguna, C. Weniger - arxiv:1602.05966

As for dark matter decays, gamma-ray telescopes are not very sensitive

Gamma-ray Limits on Neutrino Lines

Queiroz, Yaguna, Weniger – JCAP 1605 (2016) no.05, 050- arxiv:1602.05966

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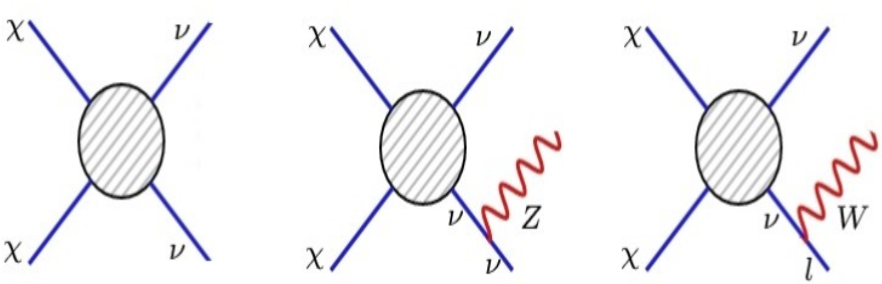
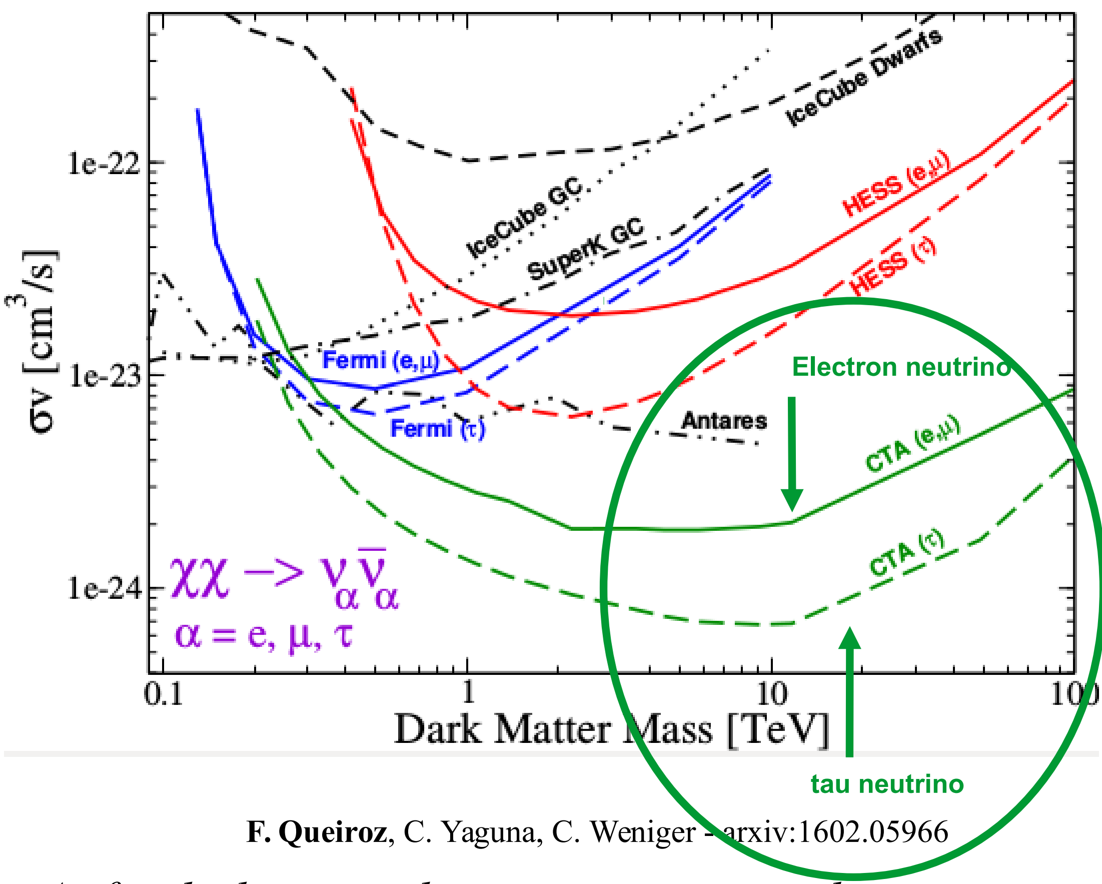


Distinguishing neutrino flavors with gamma-rays



F. Queiroz, C. Yaguna, C. Weniger - arxiv:1602.05966

As for dark matter decays, gamma-ray telescopes are not very sensitive

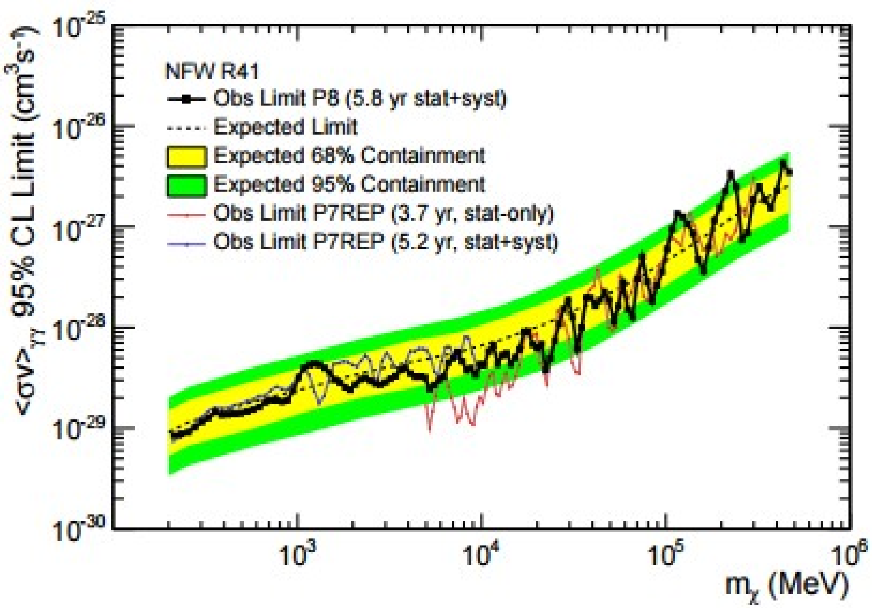
Another promising dark matter signal would be the detection of gamma-ray lines

Fermi-LAT and H.E.S.S. Telecopes have placed stringent limits on the annihilation cross section into photon pairs.

Fermi-LAT - 2015

Break at 500 GeV

~ 6 years of data – PASS 8
Energy: 200 MeV -500 GeV
CLEAN event selection
Target: Milky Way Halo

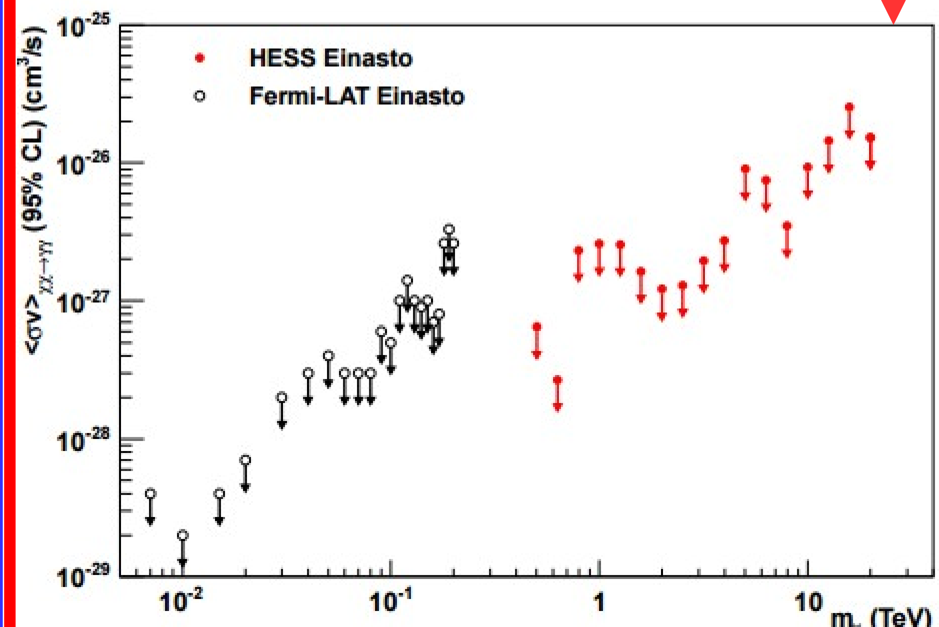


Phys.Rev. D91 (2015) no.12, 122002

H.E.S.S. - 2013

Break at 25 TeV

112 h (live time)
Energy: 500 GeV – 25 TeV
Target: Milky Way Halo



Phys.Rev.Lett. 110 (2013) 041301

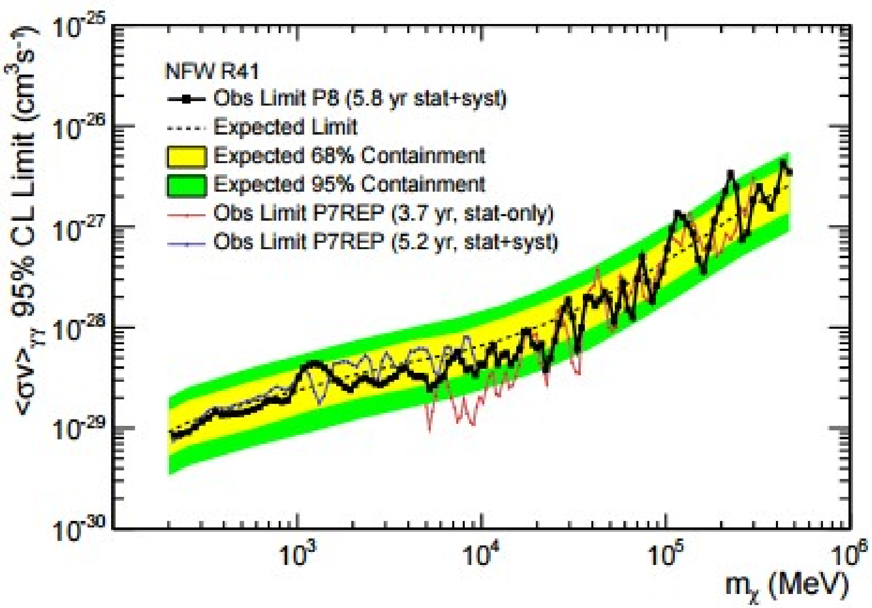
Another promising dark matter signal would be the detection of gamma-ray lines

Can we extend their limits to heavier DM masses? YES.
How? Using the continuum gamma-ray emission data.

Fermi-LAT - 2015

Break at 500 GeV

~ 6 years of data – PASS 8
Energy: 200 MeV -500 GeV
CLEAN event selection
Target: Milky Way Halo

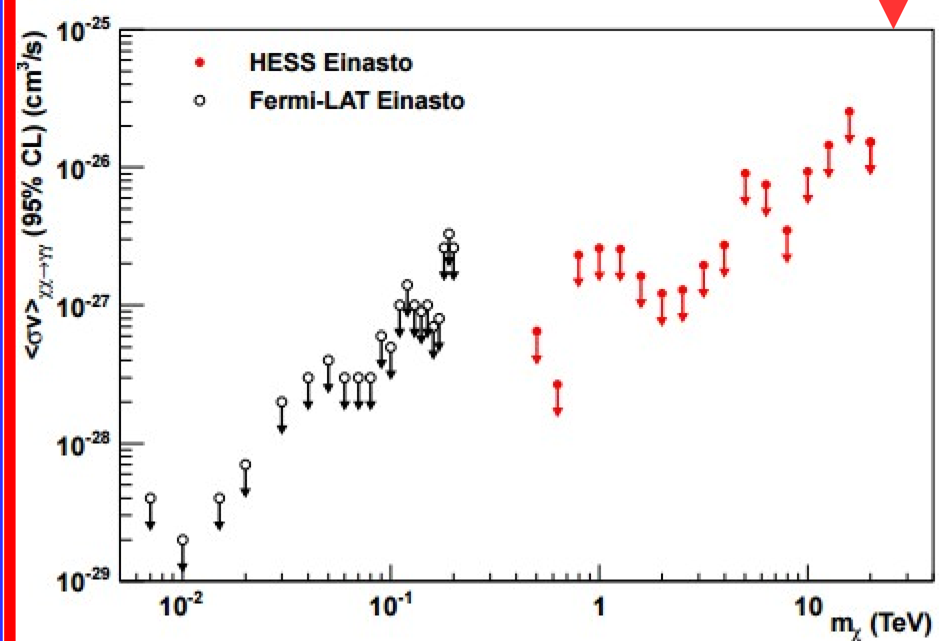


Phys.Rev. D91 (2015) no.12, 122002

H.E.S.S. - 2013

Break at 25 TeV

112 h (live time)
Energy: 500 GeV – 25 TeV
Target: Milky Way Halo



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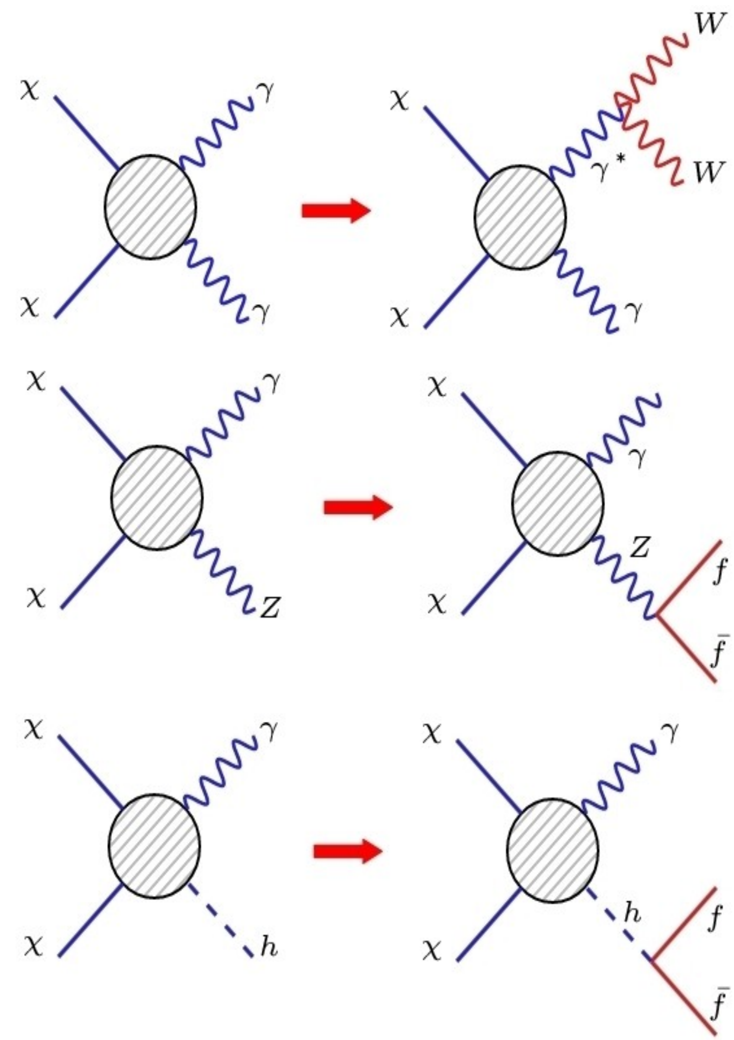
Can we extend their limits to heavier DM masses? YES.
How? Using the continuum gamma-ray emission data.

Four steps

I) Assume a 2 TeV DM particle annihilating into gamma-gamma or gamma-Z or gamma-h.

II) The process above is subject to electroweak corrections



III) The gamma-rays resulted from such processes appear at lower energies within Fermi-LAT sensitivity

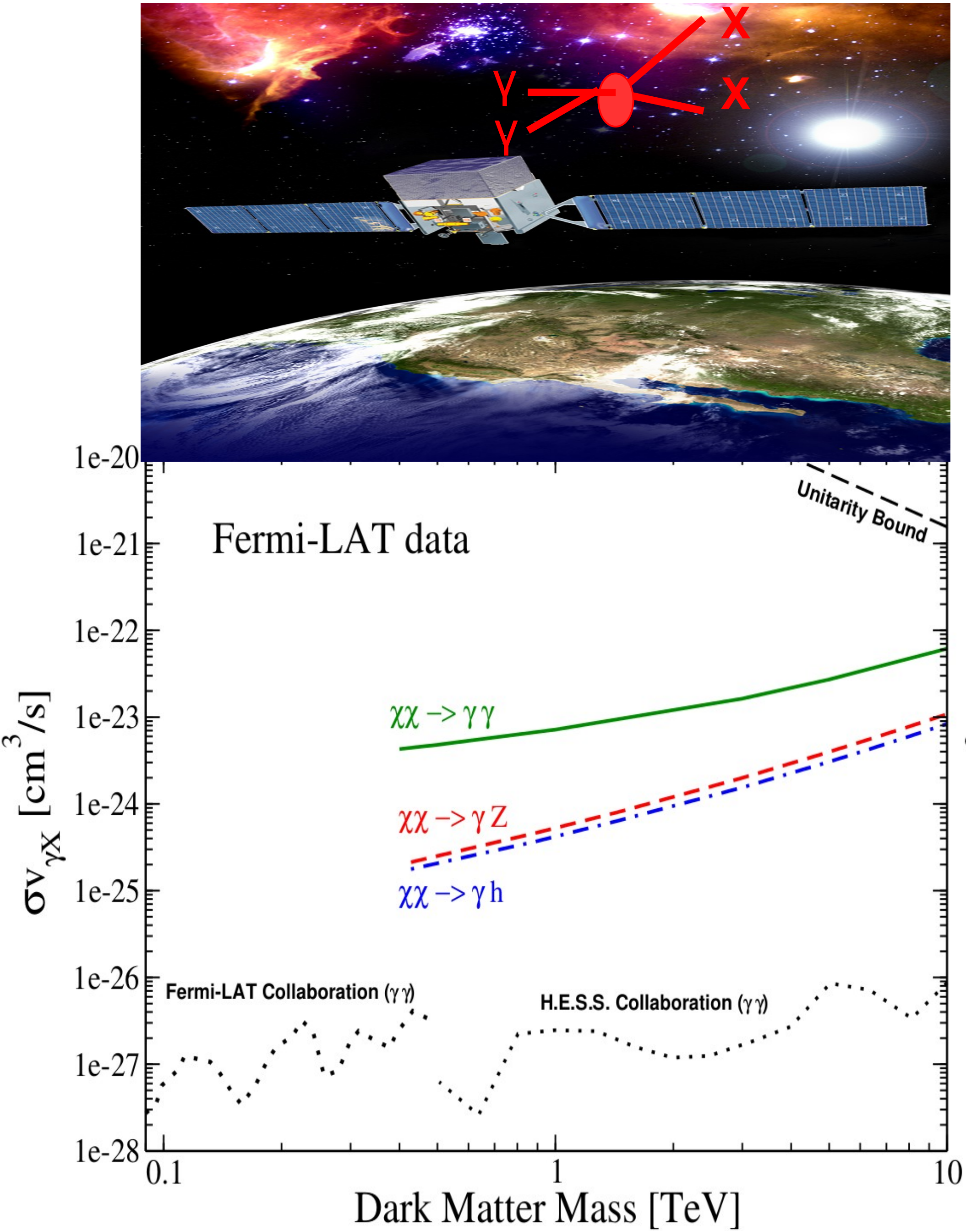
IV) The same idea can be applied for a 50 TeV particle, in reference to H.E.S.S. telescope.

Using the gamma-ray continuum emission one can extend Fermi-LAT and H.E.S.S. limits to heavier dark matter masses.

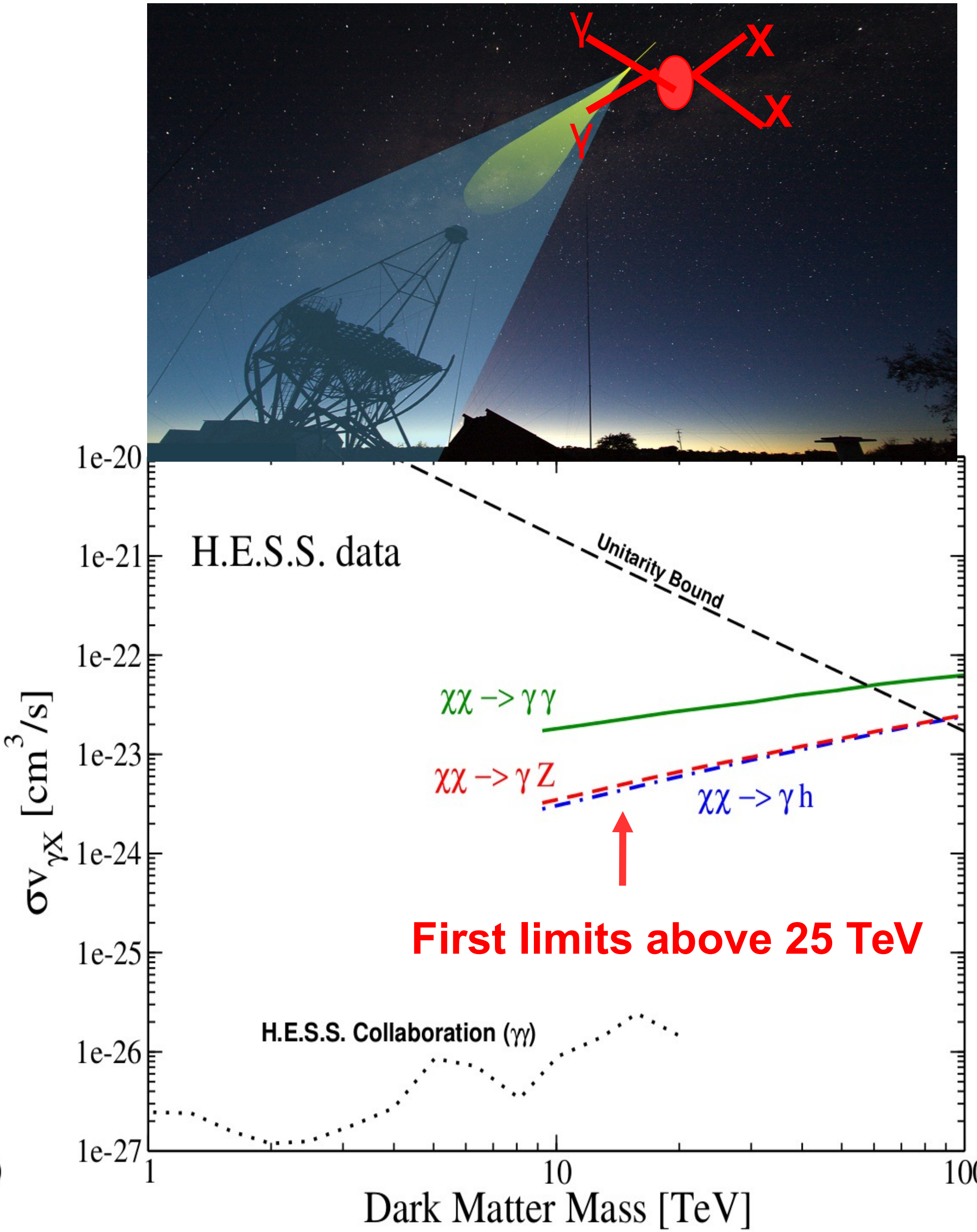
Extending Fermi-LAT and H.E.S.S. Limits on Gamma-ray Lines from Dark Matter Annihilation

Profumo, **Queiroz**, Yaguna, Submitted to MNRAS – arxiv:1602.08501

Fermi-LAT



H.E.S.S.



Please Remember

1) The Dark Matter Interpretation of the Galactic Center Excess is still viable and will remain viable for several years

2) We can search for neutrinos from dark matter annihilation using gamma-ray telescopes with the potential to distinguish neutrino flavors

Thank you