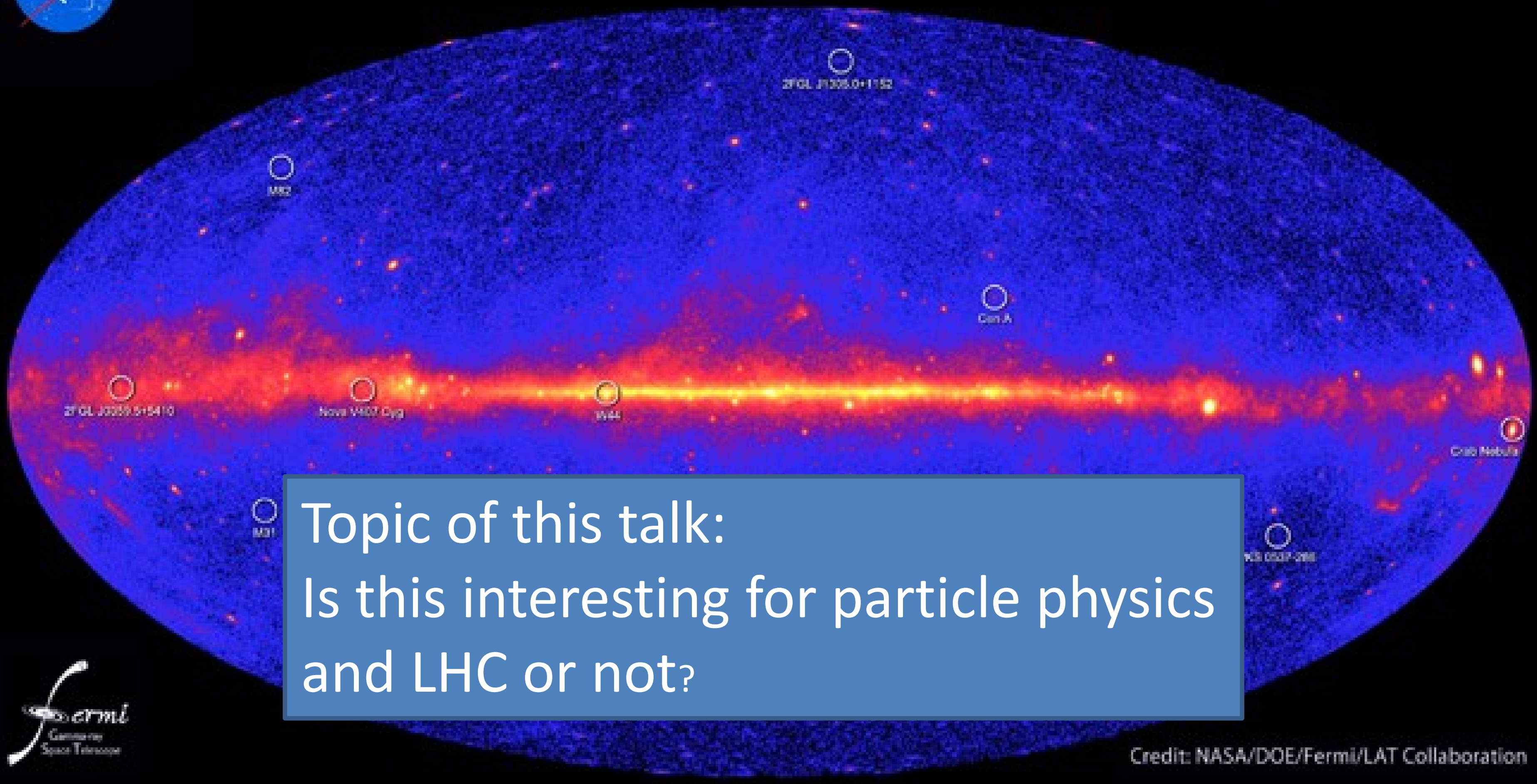
Is Dark Matter WIMPy? Connecting Geneva with the Galactic Center

Sascha Caron
(Nikhef and RU Nijmegen)

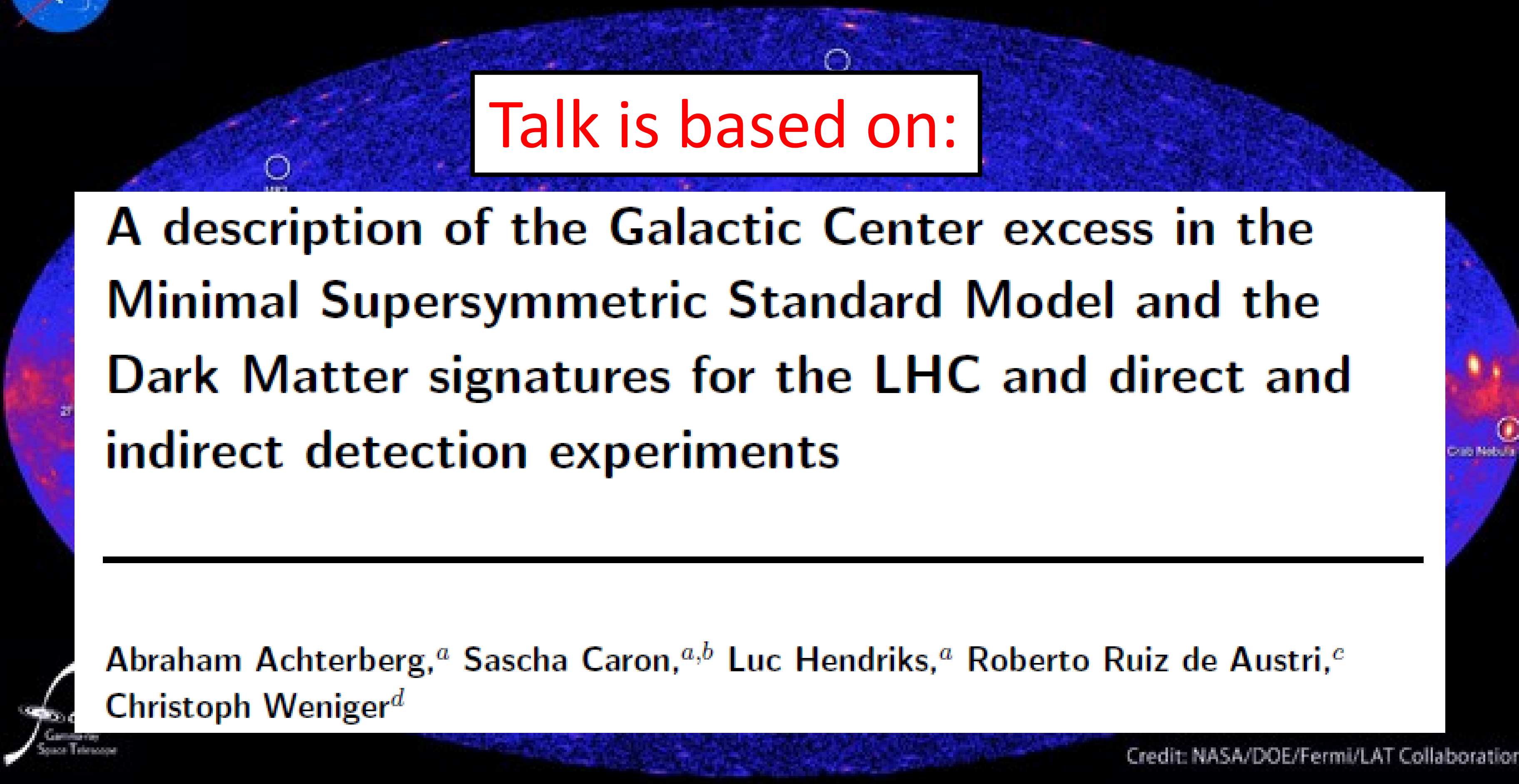
Fermi two-year all-sky map



Topic of this talk:
Is this interesting for particle physics and LHC or not?

Sky map at photon energies at GeV energies
visible light has 2-3 eV

Fermi two-year all-sky map



Talk is based on:

A description of the Galactic Center excess in the Minimal Supersymmetric Standard Model and the Dark Matter signatures for the LHC and direct and indirect detection experiments

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Abraham Achterberg,[a] Sascha Caron,[a,b] Luc Hendriks,[a] Roberto Ruiz de Austri,[c] Christoph Weniger[d]

Sky map at photon energies at GeV energies
visible light has 2-3 eV

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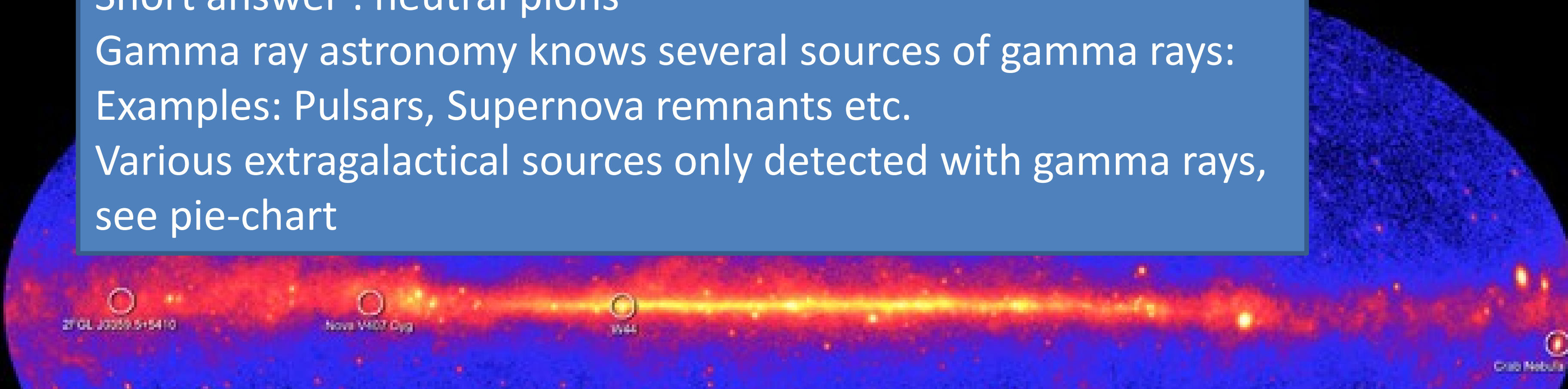
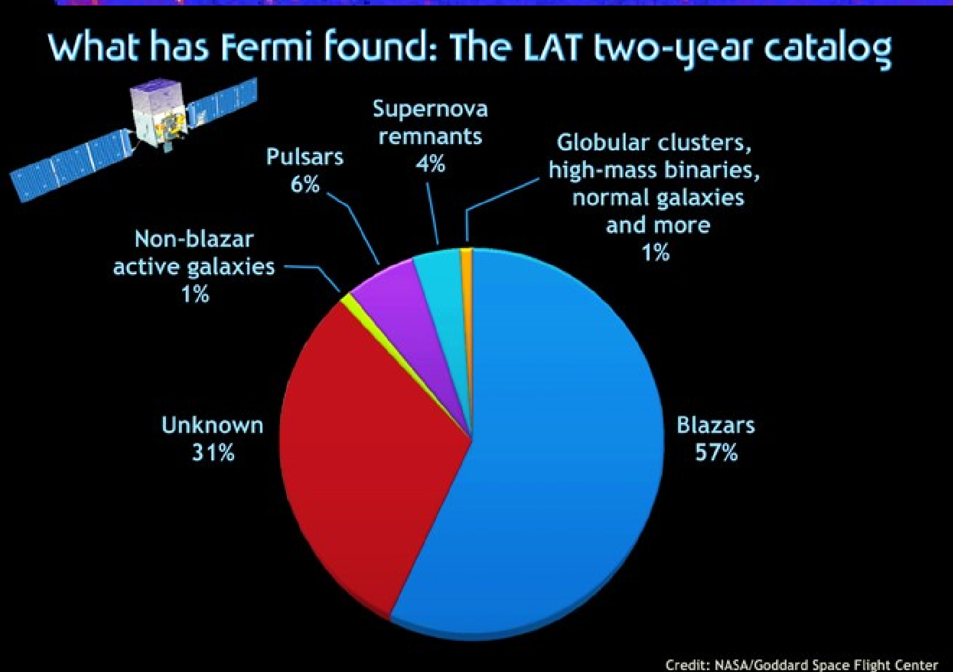
Fermi two-year all-sky map

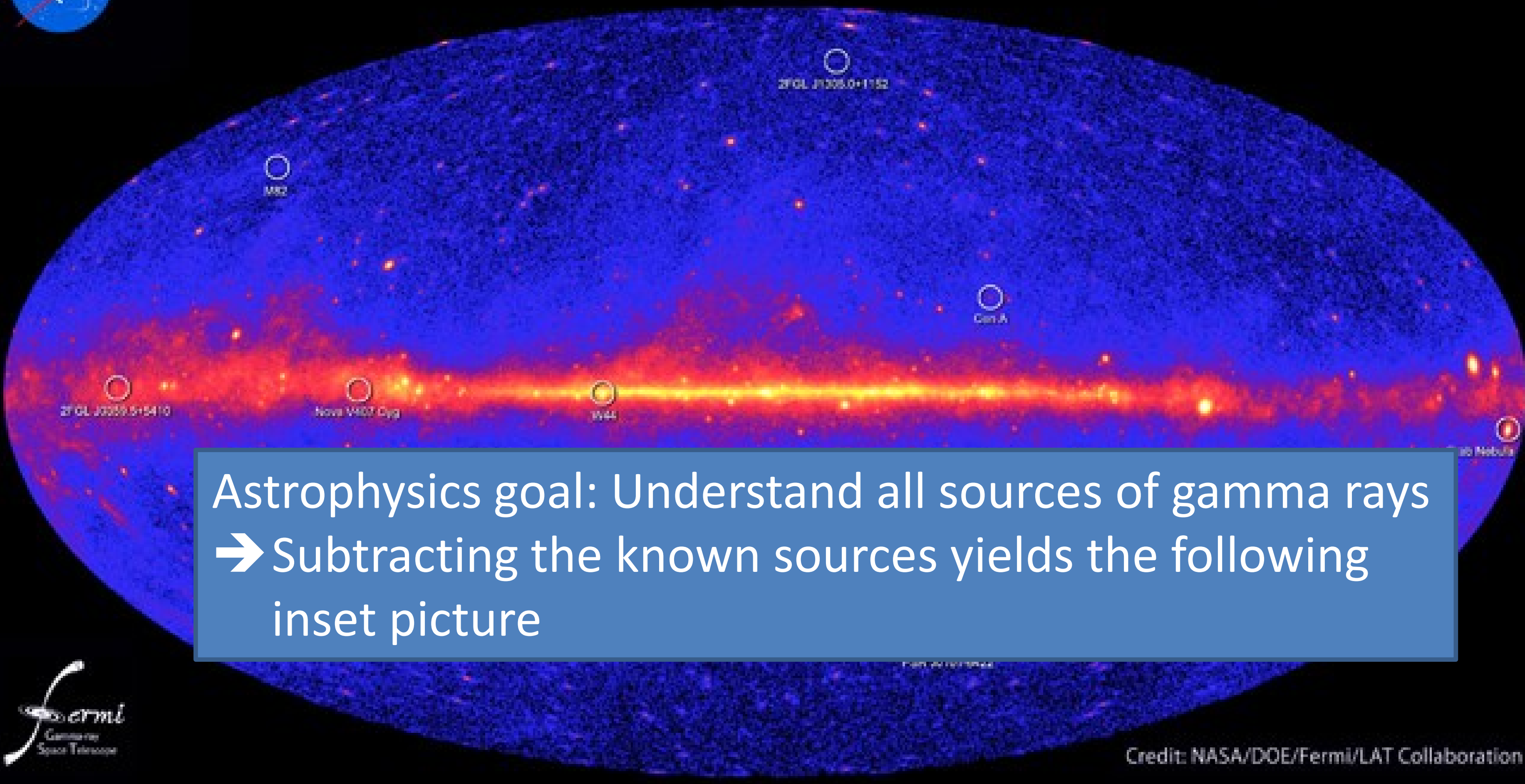
Where do GeV photons come from ?
Short answer : neutral pions
Gamma ray astronomy knows several sources of gamma rays:
Examples: Pulsars, Supernova remnants etc.
Various extragalactical sources only detected with gamma rays, see pie-chart





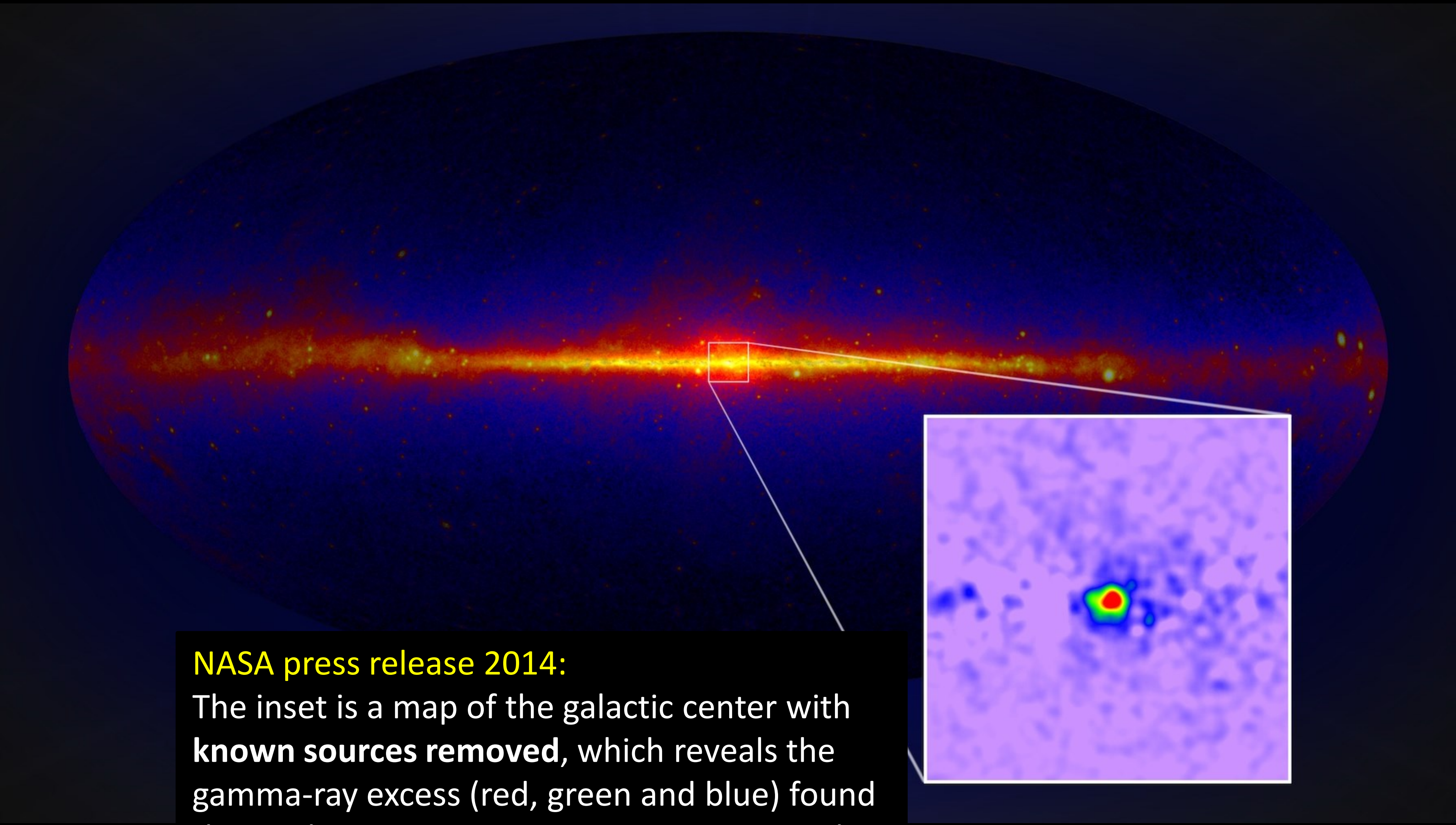
Pulsar: rapidly rotating neutron star (very dense)
Supernova remnant:
Remnant of star collapse

Fermi two-year all-sky map

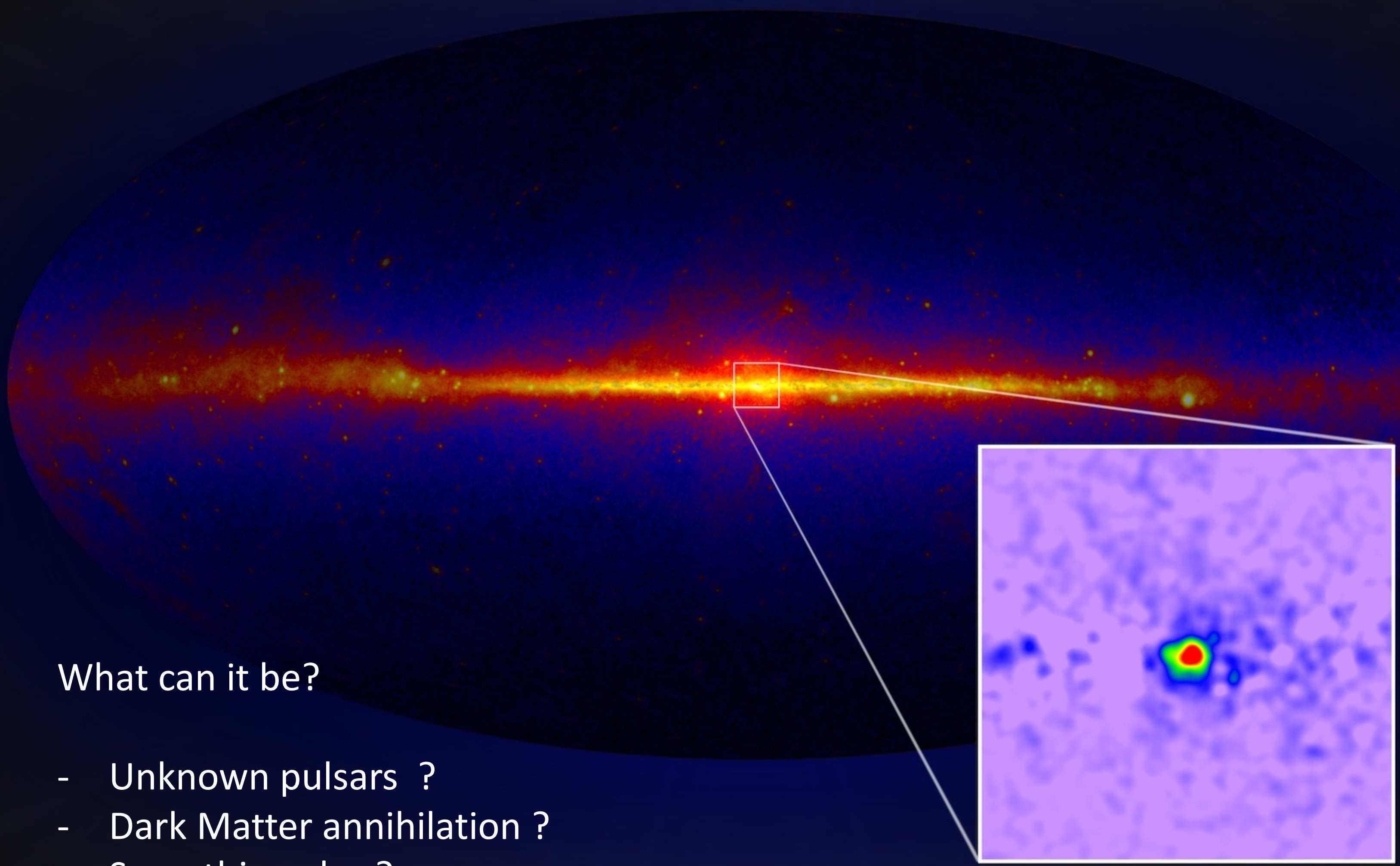


Astrophysics goal: Understand all sources of gamma rays
→ Subtracting the known sources yields the following inset picture

Sky map at photon energies at GeV energies
visible light has 2-3 eV



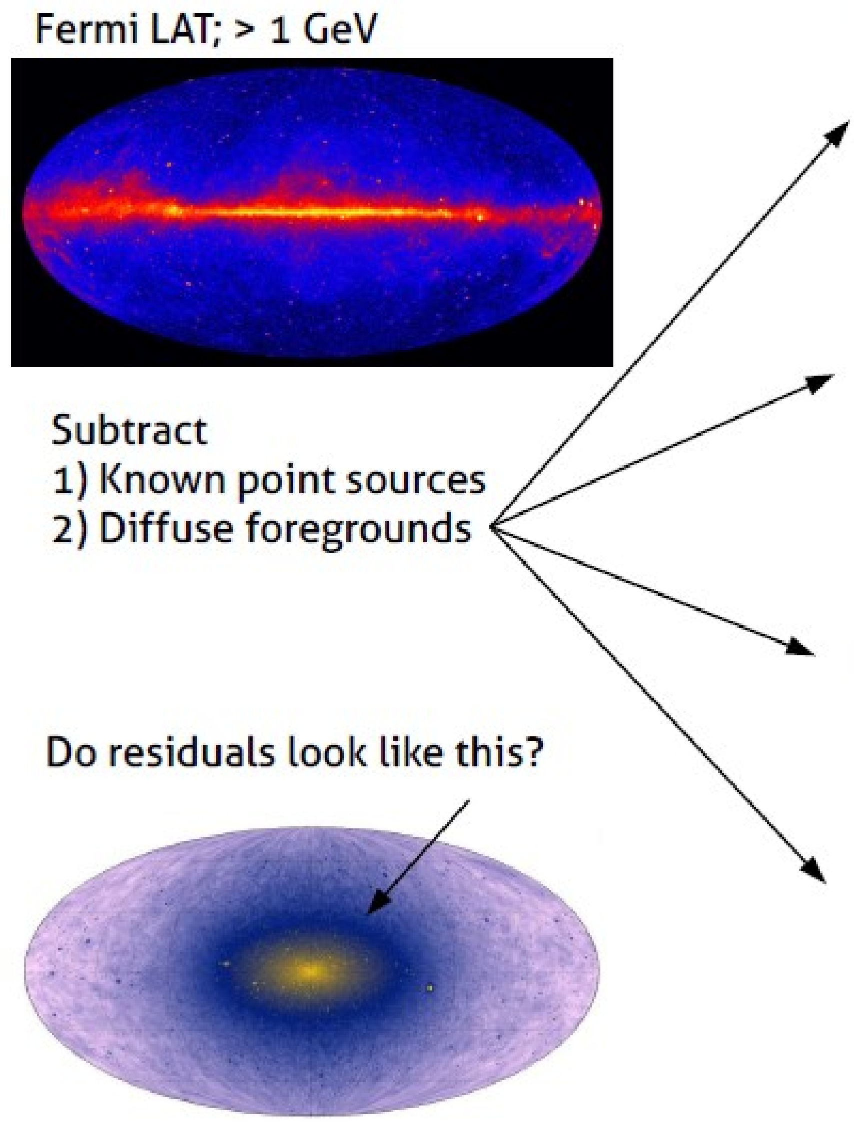
NASA press release 2014:
The inset is a map of the galactic center with **known sources removed**, which reveals the gamma-ray excess (red, green and blue) found there. This excess emission is consistent with annihilations from some hypothesized forms of dark matter. Credit: NASA/DOE/Fermi LAT Collaboration and T. Linden (Univ. of Chicago)

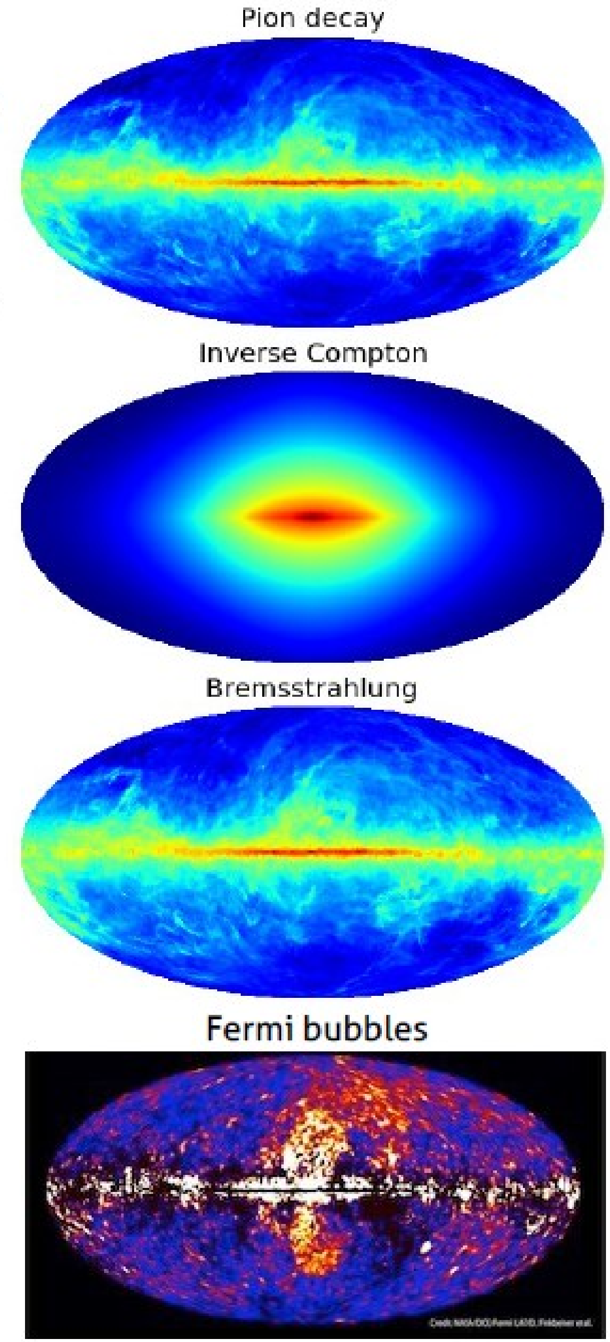


What can it be?

- Unknown pulsars ?
- Dark Matter annihilation ?
- Something else ?

DM searches in the inner Galactic region with Fermi LAT





By Ch. Weniger (UvA)

Fermi GC excess: First appearance in 2009

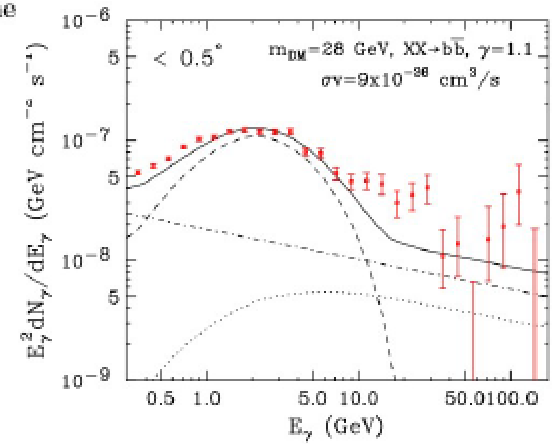
First clear statements about properties of *excess* emission (morphology, spectrum etc, subject to some changes in later analyses):

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



First very cautious comments by the LAT team, without any detailed characterization of the *residual*:

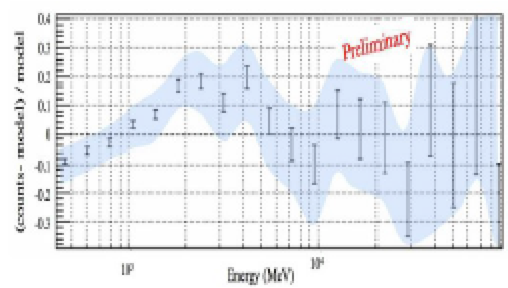
2009 Fermi Symposium, Washington, D.C., Nov. 2-5

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

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.

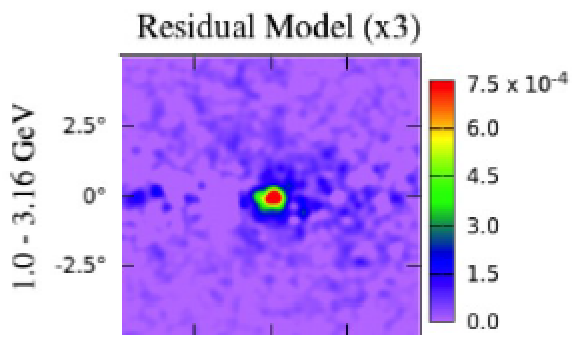


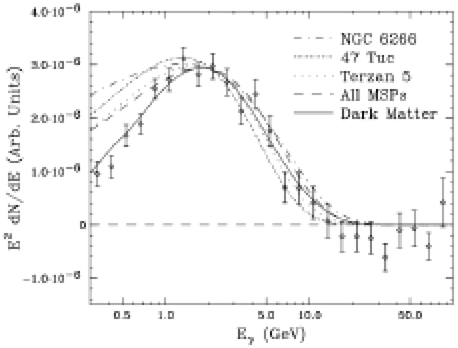
By Ch. Weniger (UvA)

Follow-up studies

At the Galactic center (roughly 7deg x 7deg)

Goodenough & Hooper 2009
Hooper & Goodenough 2011
Hooper & Linden 2011
Boyarsky+ 2011
Abazajian & Kaplinghat 2012
Gordon & Macias 2013
Macias & Gordon 2014
Abazajian+ 2014
Daylan+2014

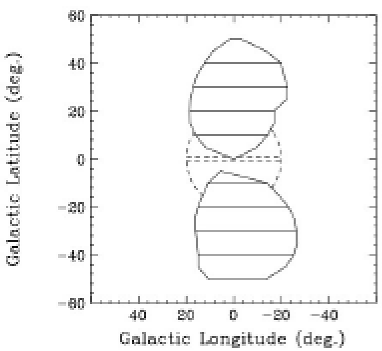


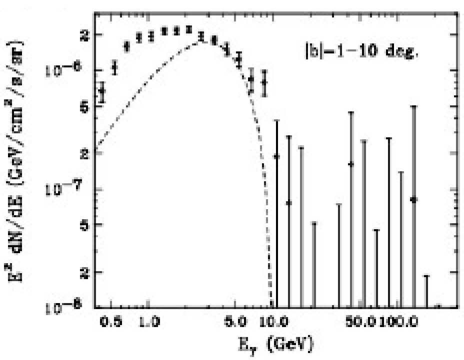


[Daylan+ 2014]

In the inner Galaxy (roughly |b|>1 deg to tens of deg)

Hooper & Slatyer 2013
Huang+ 2013
Zhou+ 2014
Daylan+ 2014





[Hooper & Slatyer 2013]

Gamma excess signal extraction

We adopt here the results from Calore,Cholis,Weniger where the excess emission was studied at latitudes above 2 degree. This region is very sensitive to a dark matter signal, but avoids the much more complicated Galactic center region.

F. Calore, I. Cholis, and C. Weniger, Background model systematics for the Fermi GeV excess, ArXiv e-prints (Aug., 2014) [arXiv:1409.0042].

Phenomenological tasks

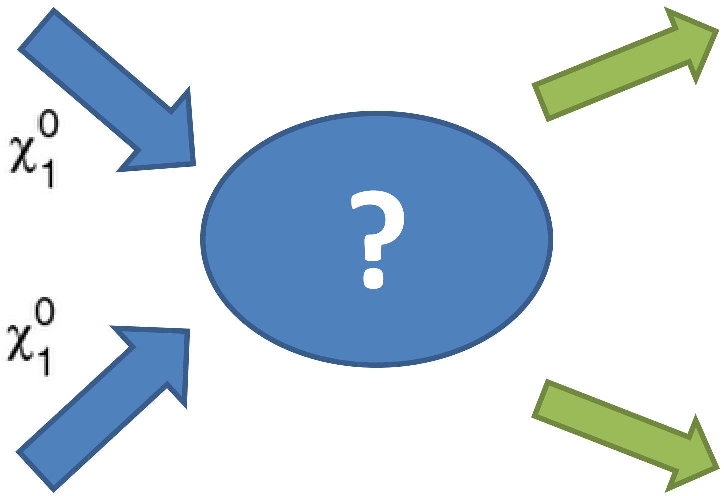
Astronomy:

➔ *Can it be explained by unknown pulsars or other astrophysics source?*

Particle Physics:

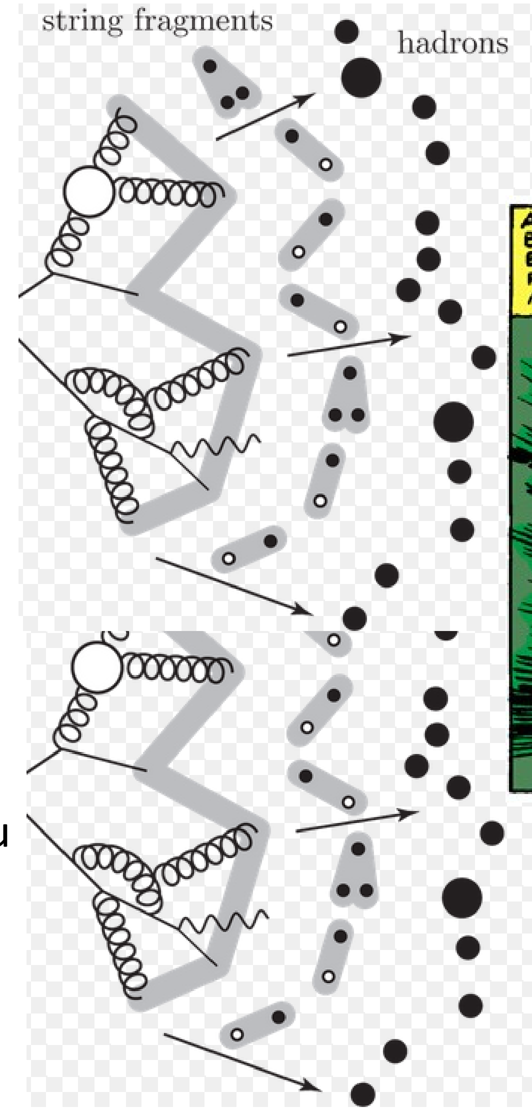
➔ *Is it possible that this is really DM annihilation?*

DM Signal Modelling



q
tau
?

q
tau
?



Pi0 => gamma gamma

Pi0 => gamma gamma

Model building

- It (early days) it seemed to be that the signal could be described by **DM DM => bb or tautau**

  with a DM mass of **20-40 GeV**

  => Pythia spectrum nicely in agreement with data
- Such process are **not** possible within 'minimal

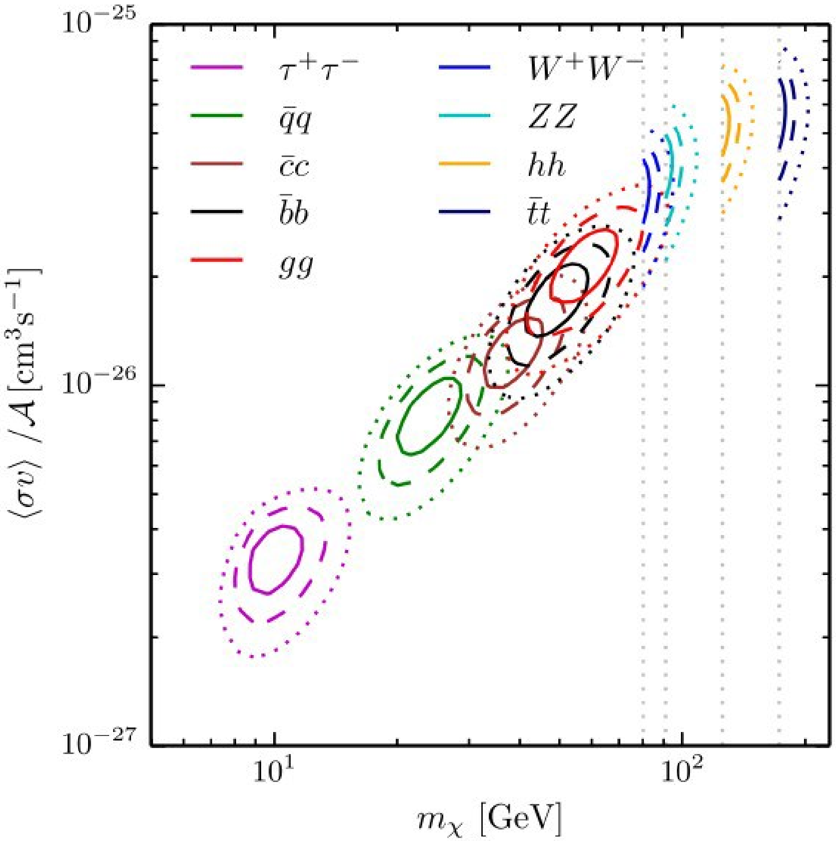
  SUSY models due to limits on staus and sbottoms

(need to be in nMSSM etc., such DM particles hard to test at LHC since they need to be mixed

such that they have escaped detection e.g. at LEP)

- It seems to be that such processes have also difficulties from recent dwarf limits on DM => gamma rays also;: P. Agrawal, B. Batell, P. J. Fox, and R. Harnik, WIMPs at the Galactic Center, arXiv:1411.2592.

Model building



Channel	$\langle\sigma v\rangle$ (10^{-26} cm^3 s^{-1})	m_χ (GeV)	χ^2_{min}	p-value
$\bar{q}q$	$0.83^{+0.15}_{-0.13}$	$23.8^{+3.2}_{-2.6}$	26.7	0.22
$\bar{c}c$	$1.24^{+0.15}_{-0.15}$	$38.2^{+4.7}_{-3.9}$	23.6	0.37
$\bar{b}b$	$1.75^{+0.28}_{-0.26}$	$48.7^{+6.4}_{-5.2}$	23.9	0.35
$\bar{t}t$	$5.8^{+0.8}_{-0.8}$	$173.3^{+2.8}_{-0}$	43.9	0.003
gg	$2.16^{+0.35}_{-0.32}$	$57.5^{+7.5}_{-6.3}$	24.5	0.32
W^+W^-	$3.52^{+0.48}_{-0.48}$	$80.4^{+1.3}_{-0}$	36.7	0.026
ZZ	$4.12^{+0.55}_{-0.55}$	$91.2^{+1.53}_{-0}$	35.3	0.036
hh	$5.33^{+0.68}_{-0.68}$	$125.7^{+3.1}_{-0}$	29.5	0.13
$\tau^+\tau^-$	$0.337^{+0.047}_{-0.048}$	$9.96^{+1.05}_{-0.91}$	33.5	0.055
[$\mu^+\mu^-$	$1.57^{+0.23}_{-0.23}$	$5.23^{+0.22}_{-0.27}$	43.9	0.0036]$_{\mathrm{ICS}}$

- Actually more parameter space seems to be allowed…
- No MSSM solution… somehow difficult to for model building…

Fermi-LAT detector

- Formerly known as GLAST
- Particle physics detector
- Photon Conversion

⇒ Silicon Tracker for pointing resolution

⇒ Calorimeter for energy measurement

Anticoincidence Detector to remove unwanted charged cosmics

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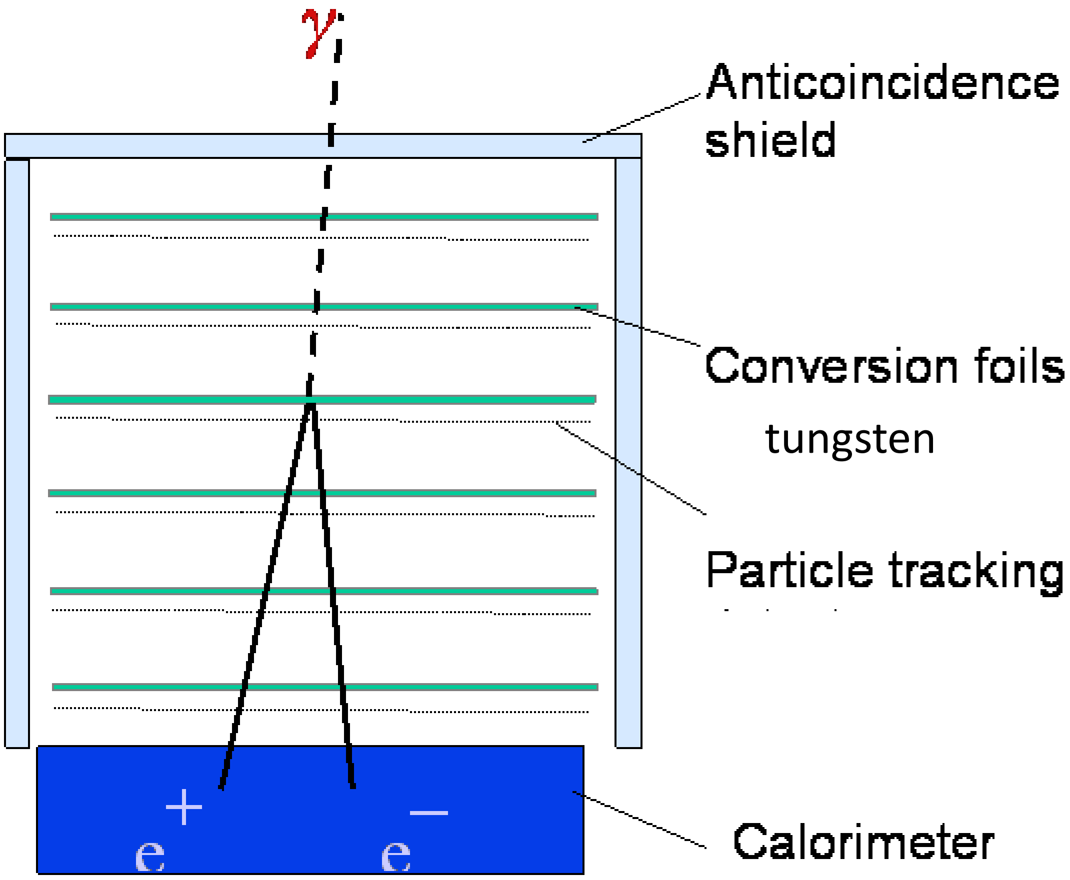


Energy Calibration

- http://arxiv.org/pdf/1206.1896v2.pdf

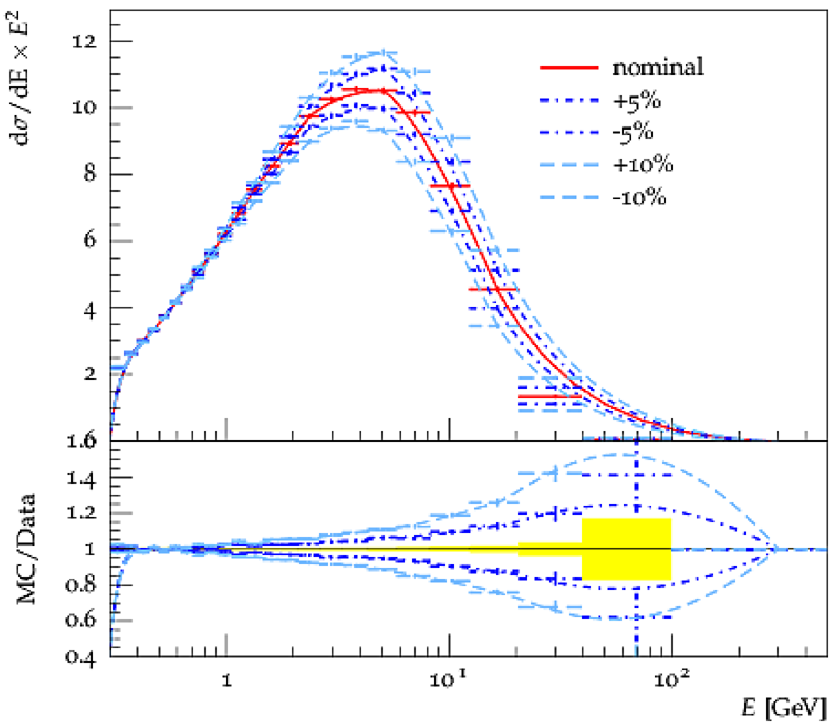
- **9% shift measured** in test beams not yet understood
- 2-5% shift measured in range 6-13 GeV with

- Fermi-LAT conclusion:

"Based on the full body of information currently available
 we conclude that that the energy scale for the
LAT is correct to +20- 50%
of the energy
resolution of the LAT at a given energy. This corresponds
to an uncertainty of 2-5%
on energy scale over the range 10-100 GeV, and
increases to 4-10%
below 100 MeV and above 300 GeV."

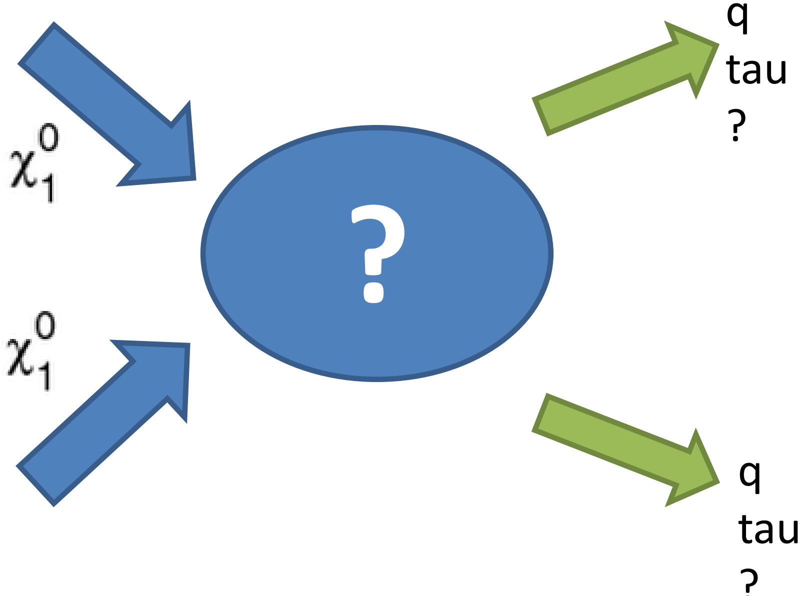
==> So assuming 5% for the unmeasured region at 3-4 GeV seems reasonable.

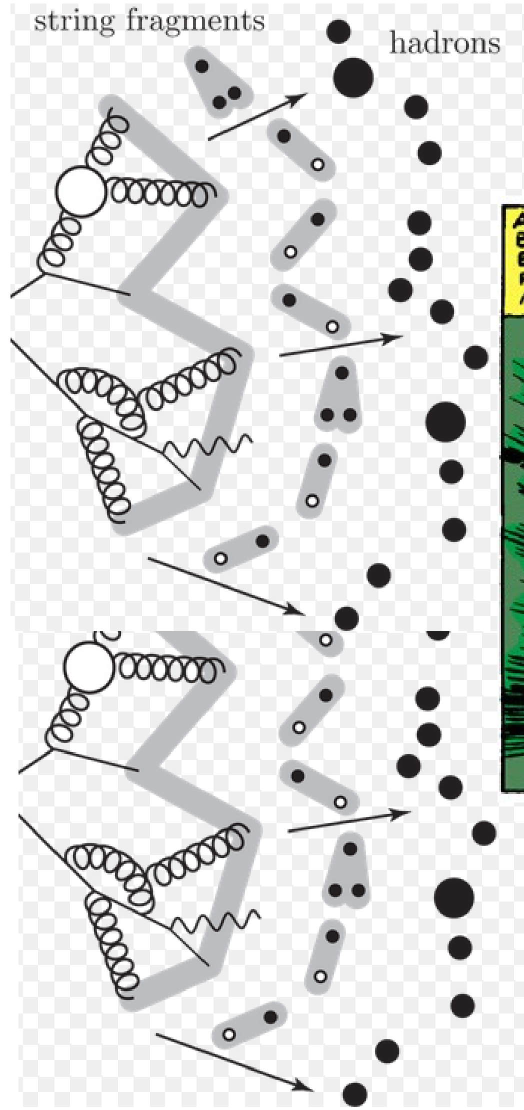
➔ We derived effect on energy spectrum, shape changes by up to 20%



➔ Shape uncertainty 3-10%

DM Signal Modelling





Pi0 => gamma gamma

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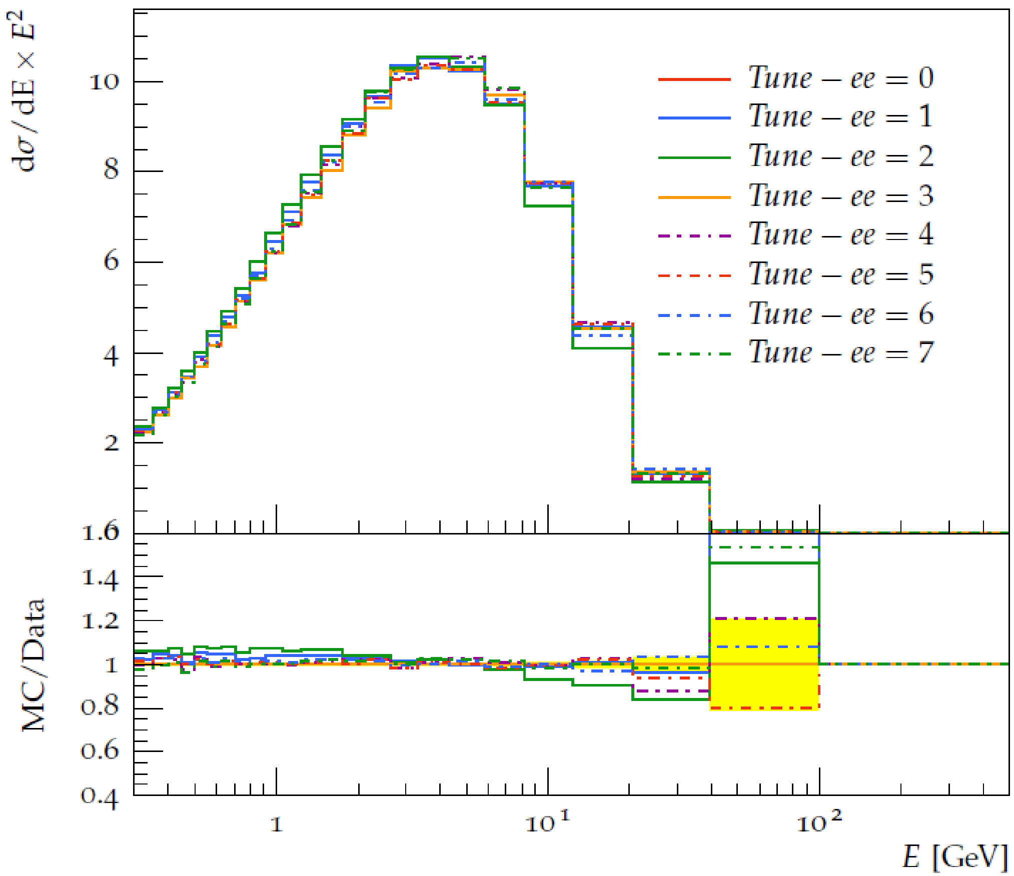
Signal Modelling

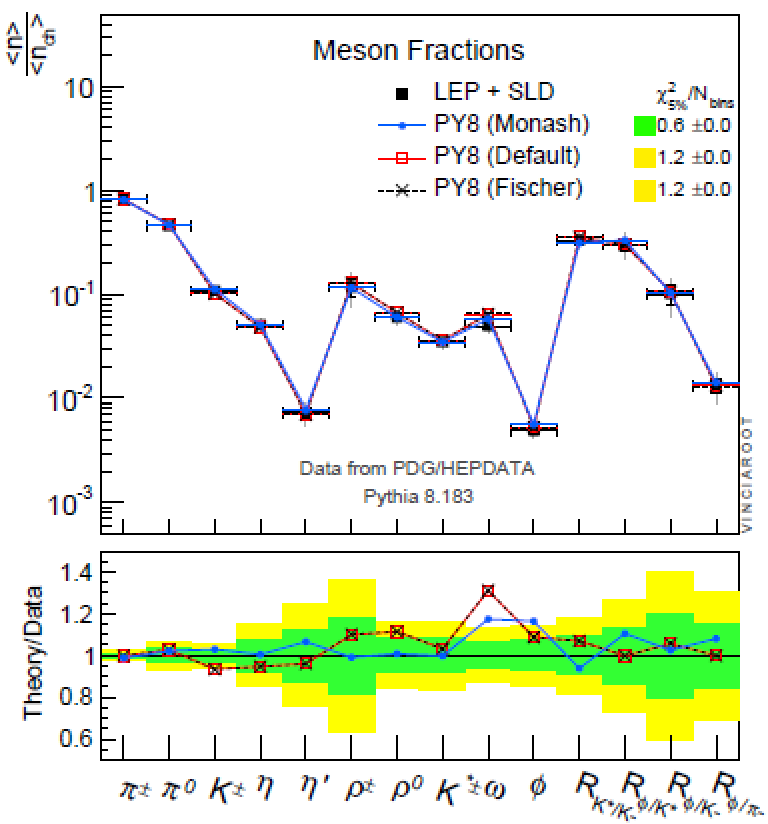


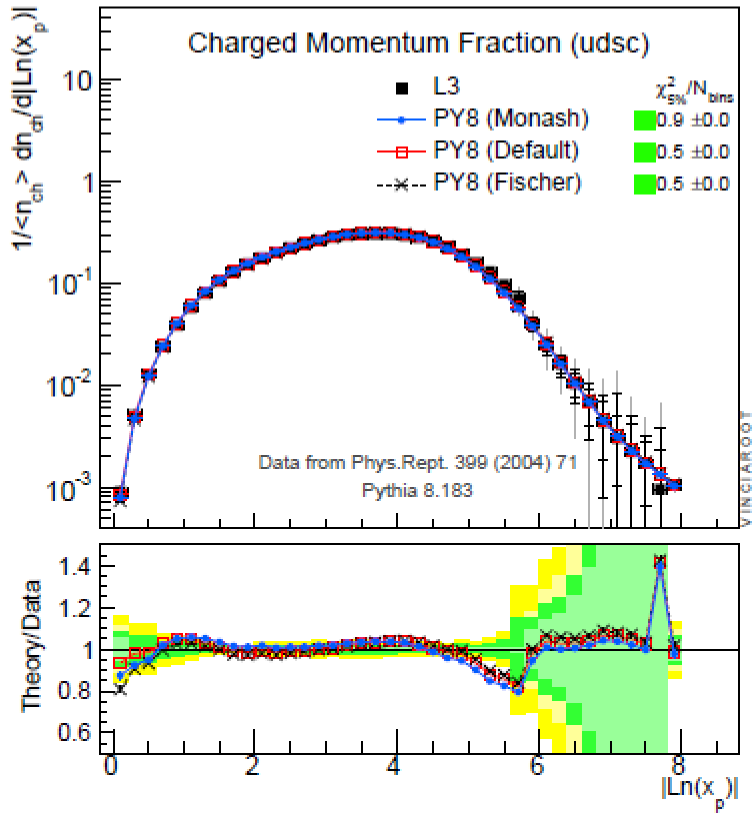
Minimal modelling again uncertainty 5-10% !

Tunes from here:

http://home.thep.lu.se/~torbjorn/pythia81html/Welcome.html http://arxiv.org/pdf/1404.5630v1.pdf

Signal Modelling





- Variation of Pythia8 tunes seems to **underestimate** true uncertainty (pi0 production, charge distribution)

Signal Modelling

Adding both effects (MC modelling
and energy scale) in squares yields

a minimal modelling
uncertainty (outside Astronomical uncertainties)
of 8-15%

Changing e.g. only the shape from nominal E to -5% * E
changes p-value for fit from 0.035 to 0.09

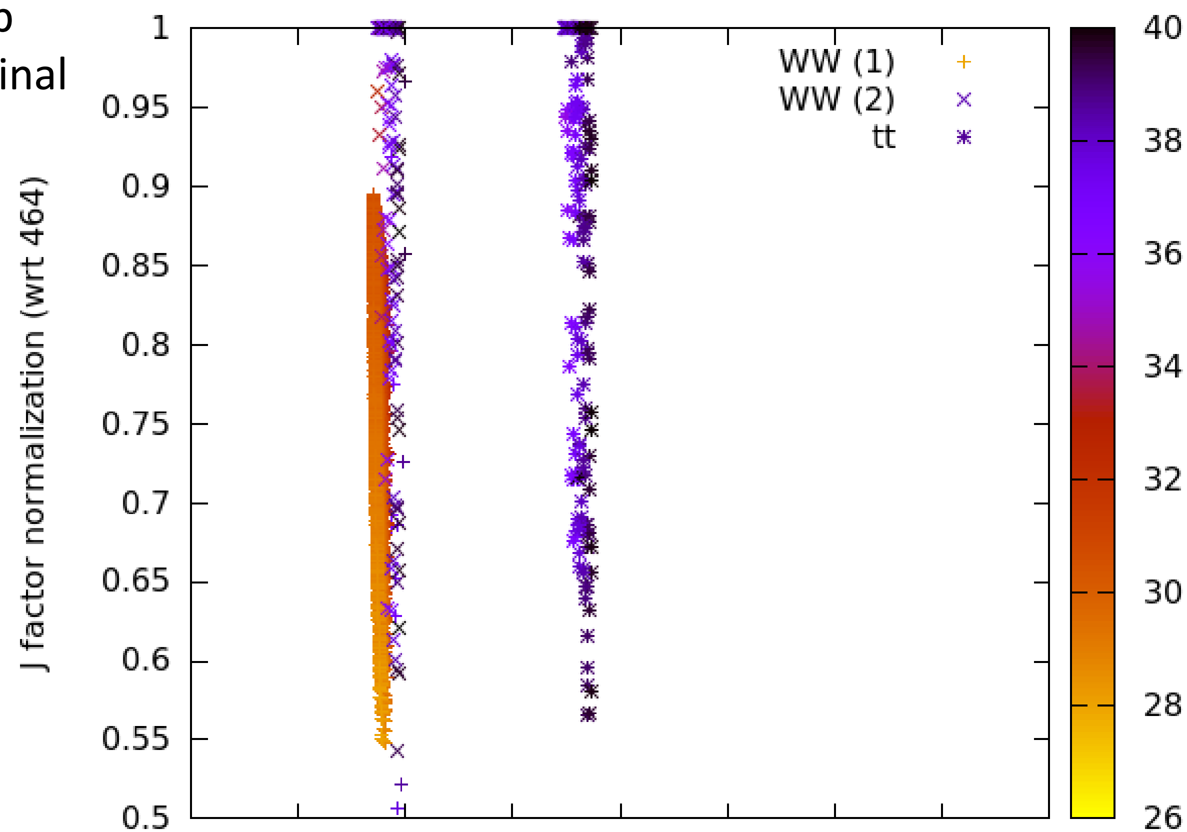
Signal normalization

$$\frac{\mathrm{d}\Phi_\gamma(E_\gamma)}{\mathrm{d}E_\gamma \mathrm{d}\Omega} = \frac{\langle \sigma v \rangle}{8\pi m_{\mathrm{DM}}^2} \frac{\mathrm{d}N_\gamma}{\mathrm{d}E} \int \mathrm{d}s \, \rho_{\mathrm{DM}}^2(r(s\,,\,\theta))$$

2 sigma up
from nominal

DM density^2
has large uncertainties..

Need to be taken into
account



About 1 sigma up

Is there really no minimal Supersymmetry solution ?

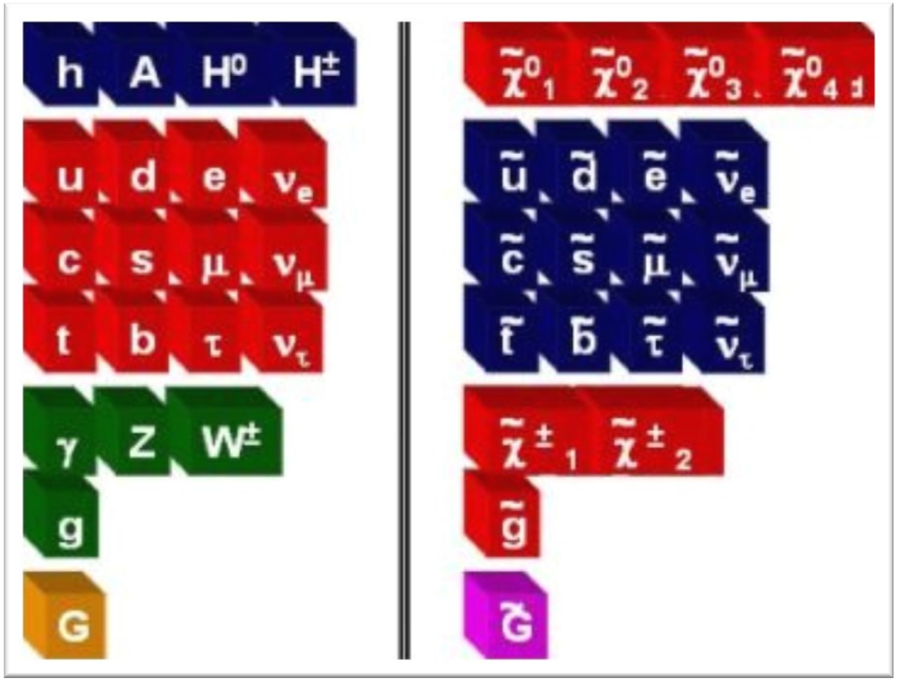
The Minimal SUSY SM

Remember: This is for almost everybody the most general version you know (126 parameters)….

We are just assuming this:

The MSSM is still the most promising framework for WIMP dark matter.

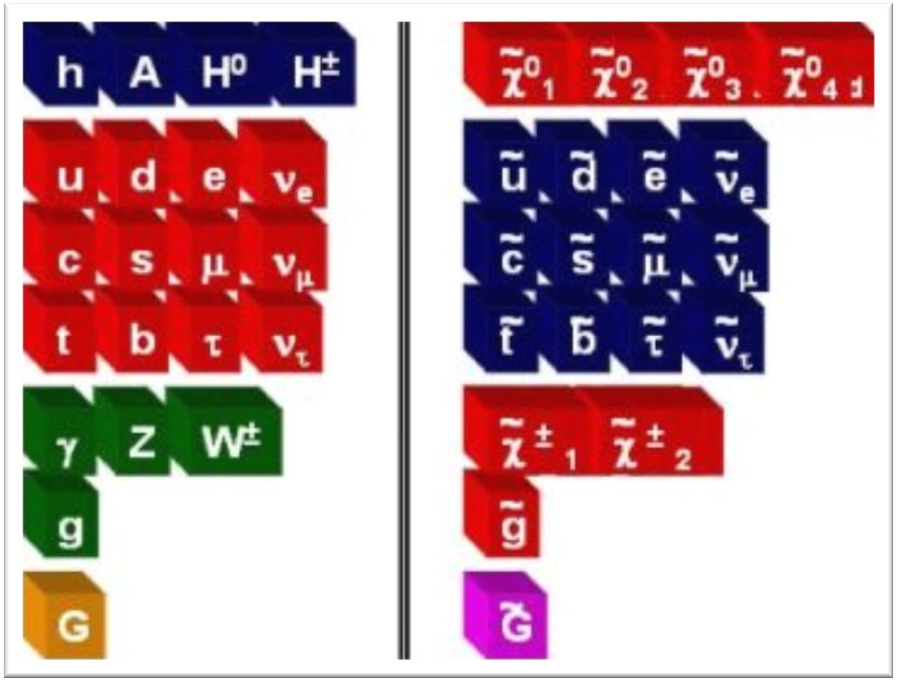
It is the first to study in my mind.



The Minimal SUSY SM

126 parameters can be reduced to 19 which are phenomelogically relevant for DM and direct searches at LHC

In this scheme, one assumes that: (i) All the soft SUSY-breaking parameters are real, therefore the only source of CP-violation is the CKM matrix.
(ii) The matrices of the sfermion masses and the trilinear couplings are diagonal, in order to avoid FCNCs at the tree-level.
(iii) First and second sfermion generation universality to avoid severe constraints, for instance, from K 0 mixing.

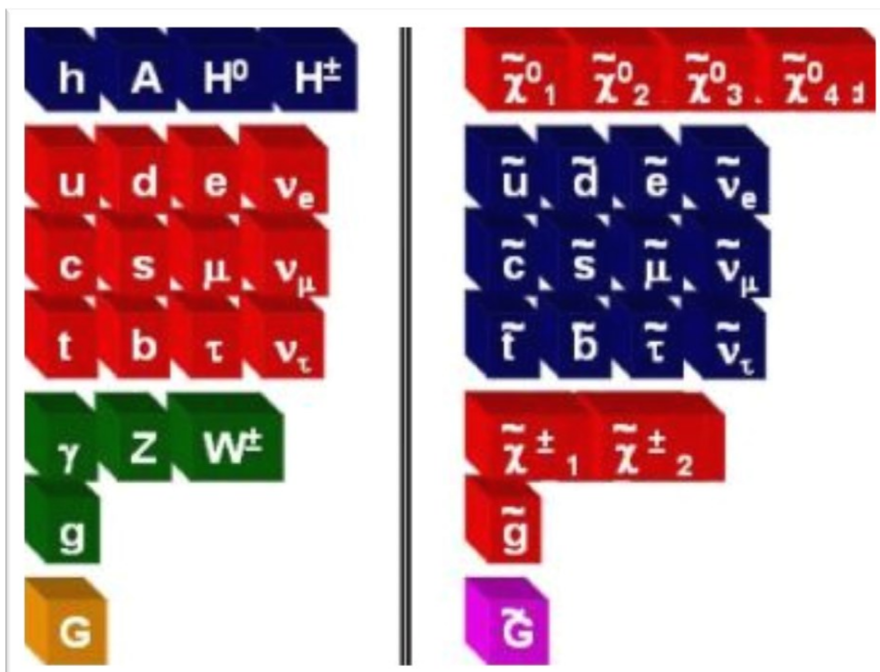


The Minimal SUSY SM

126 parameters can be reduced to 19 which are phenomelogically relevant for DM and direct searches at LHC

The 19 remaining parameters are 10 sfermion masses,[1] 3 gaugino masses $M_{1,2,3}$, the ratio of the Higgs vacuum expectation values $\tan\beta$, the Higgsino mixing parameter μ, the mass m_A of the CP-odd Higgs-boson A^0 and 3 trilinear scalar couplings $A_{b,t,\tau}$.

[1] $\tilde{Q}_1$, $\tilde{Q}_3$, $\tilde{L}_1$, $\tilde{L}_3$, $\tilde{u}_1$, $\tilde{d}_1$, $\tilde{u}_3$, $\tilde{d}_3$, $\tilde{e}_1$ and $\tilde{e}_3$.



Scanning ? How?

Need Luc Hendriks

- How to search for a solution?

- => Try random sampling
- Found no solution…

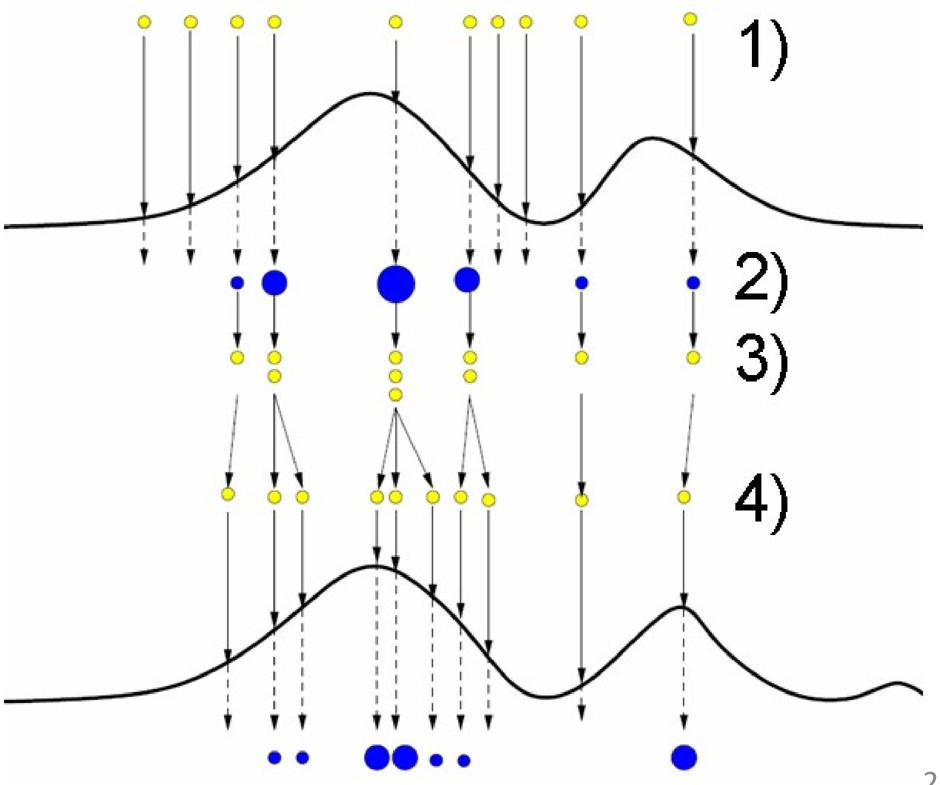
- Idea: Try something more sophisticated…

Iterative Particle Filtering

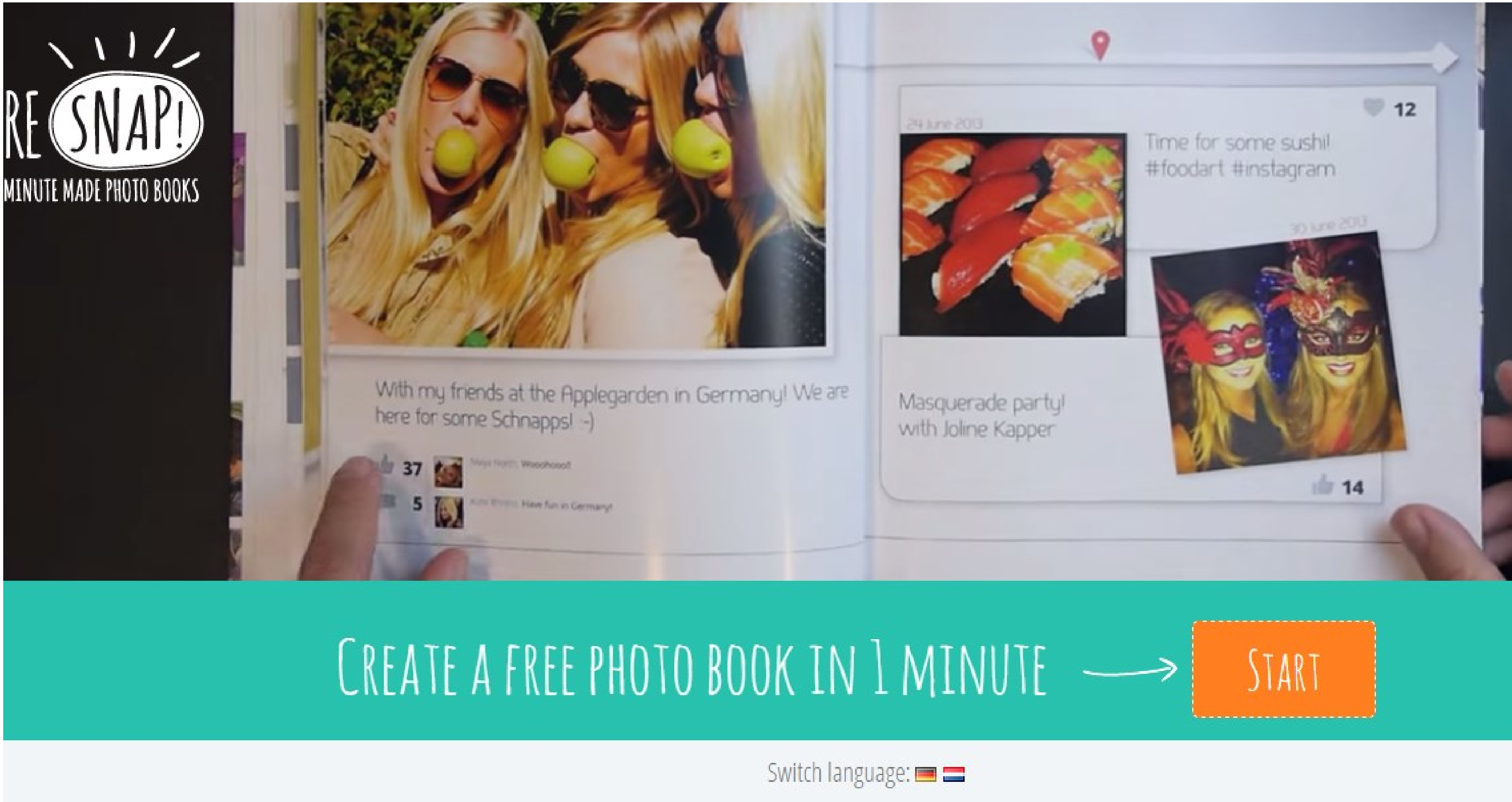
A filter algorithm (you know the Kalman filter)
Usually used for e.g. “tracking objects” (your new car or drone)
Idea: importance sampling
➔ *Generate recursively more points in interesting regions*

Set of particles
(parameter points)
to represent the
posterior density.
➔ Particles sampled
in regions of higher
likelihood…

➔ Have a look at the MSSM
solutions to see how good this
actually works…



“Valorisatie”



www.resnap.com

What do we exactly do ?

- Use full machinery of SUSY codes, i.e. Suspect, MicroMegas, DarkSUSY, etc.
- Lightest Neutralino is required to be DM candidate
- LEP limits on the mass of the lightest chargino
- 122 GeV < mass(Higgs) < 128 GeV

  (allowing for SUSY code uncertainty of 3 GeV)

- Upper limits from the LUX experiment on the spin-independent cross section.
- Upper limits from the IceCube experiment with the 79 string configuration on the spin-dependent cross section , assuming that neutralinos annihilate exclusively to W+W- pairs.

GC chi2 test

We train the particle filter **only** with the chi2 which compares the GC data with the generated GC spectrum

$$\chi^2 = \sum_{i,j} (d_i - m_i)(\Sigma_{ij})^{-1}(d_j - m_j)$$

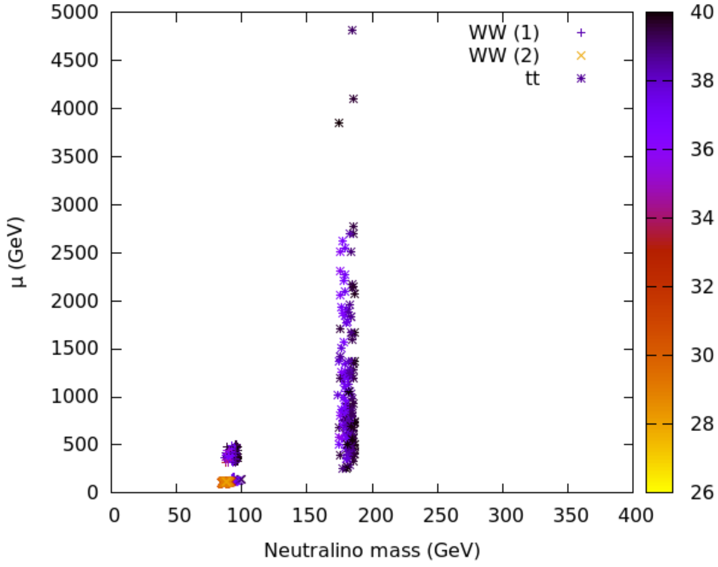
Σ_{ij} is the covariance matrix with statistical and systematic uncertainties

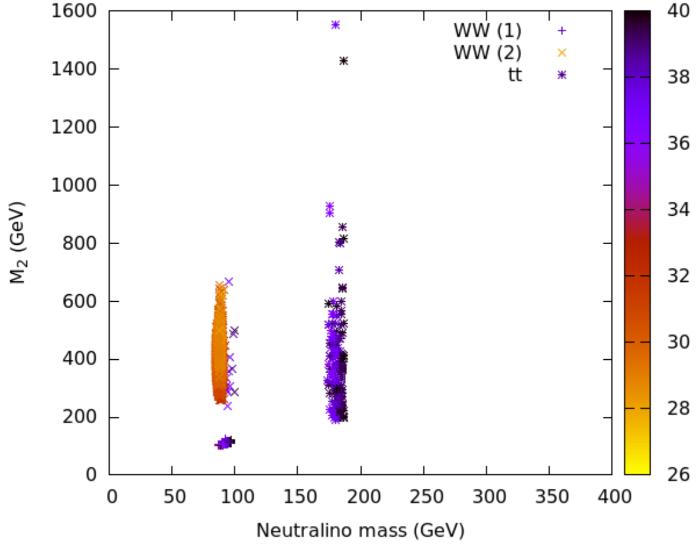
Includes the "highly correlated" Astro uncertainties **+ 10% additional uncertainty for modelling the spectrum (see before)**

After finding first good fits we constrain the parameter space further to the relevant parameters:

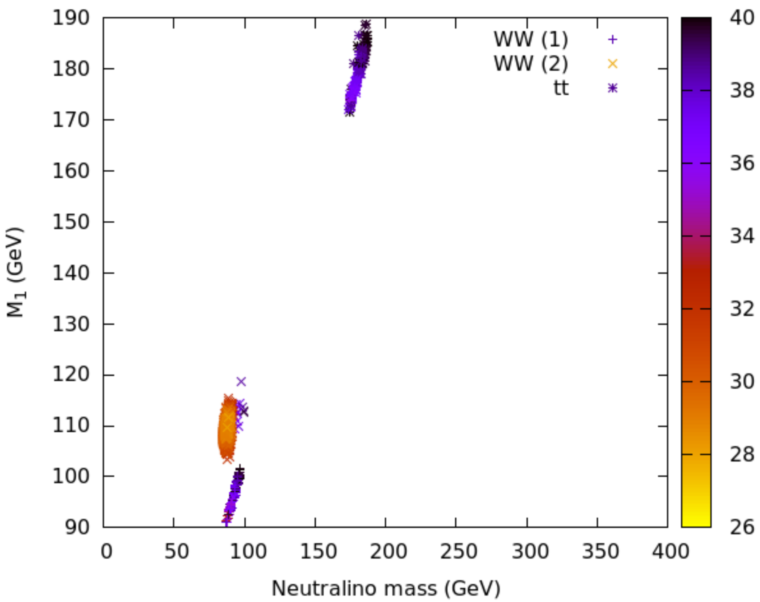
$$M_1, M_2, \mu, \tan\beta, M_A, \tilde{d}_3, \tilde{Q}_3, A_t.$$

Solutions…

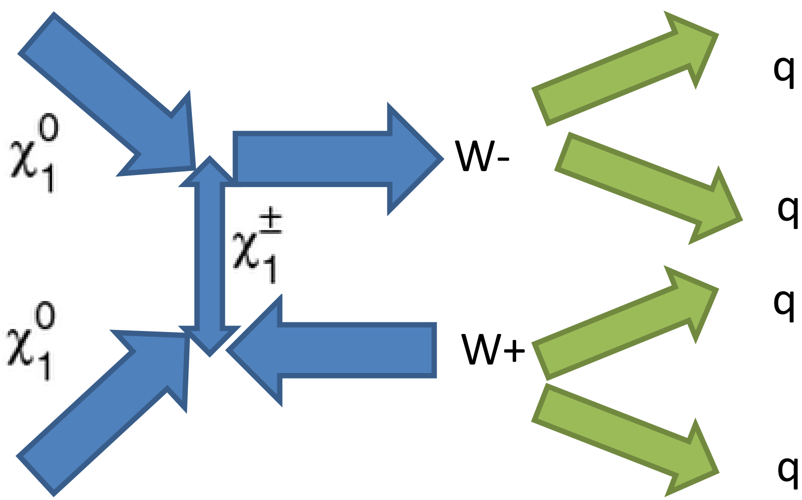


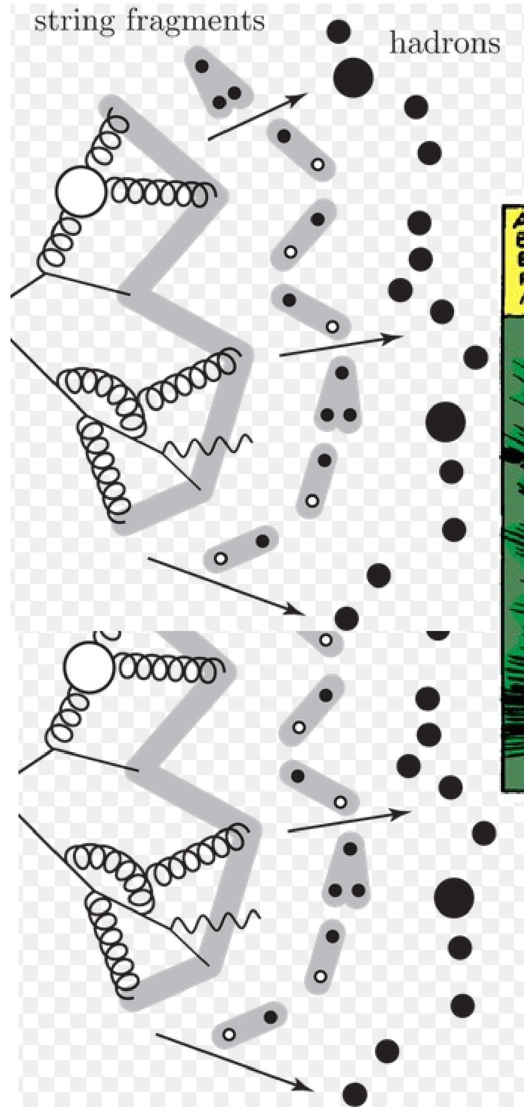


24 degrees of freedom

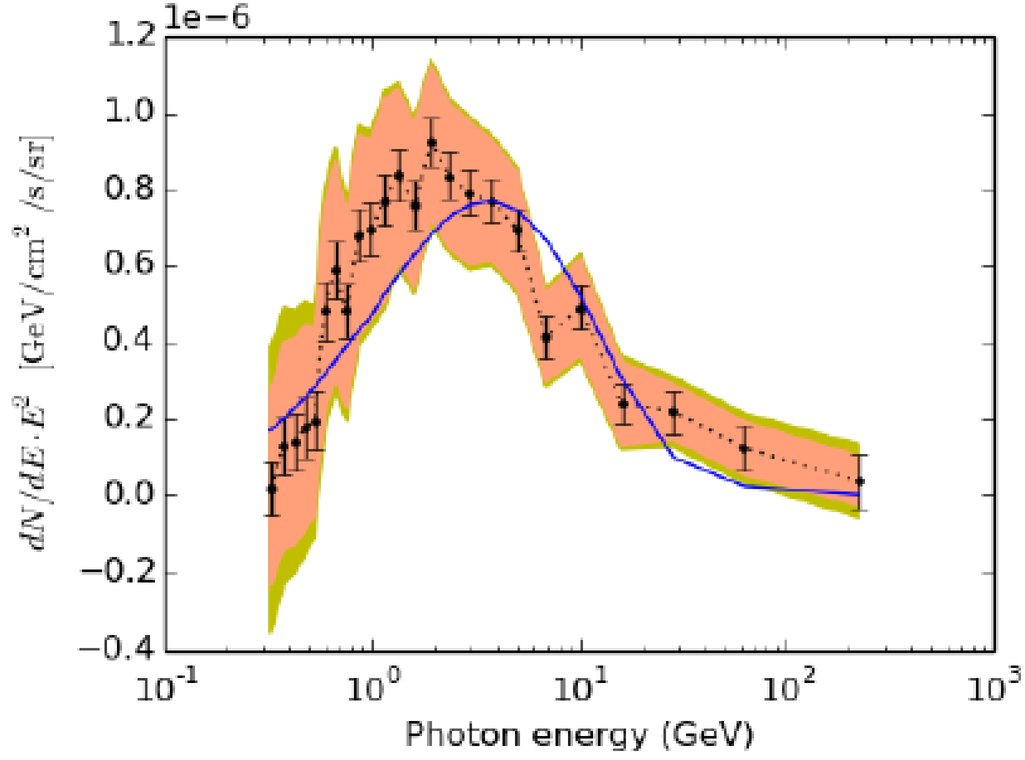


Signal Modelling





Signal Modelling



Shown are only Astronomy uncertainties which are highly correlated.

➔ P-value of this fit : **0.3-0.4**

3 solutions

A) Maximum P-value = 0.35: A Bino-Higgsino neutralino with mass 84-92 GeV as DM annihilating into W+W-

B) Maximum P-value ≈ 0.13: A Bino-Wino-Higgsino neutralino with mass 85-100 GeV as DM annihilating into W+W-

C) Maximum P-value ≈ 0.05: A (mainly) Bino neutralino with mass about 170-200 GeV as DM annihilating into top pairs

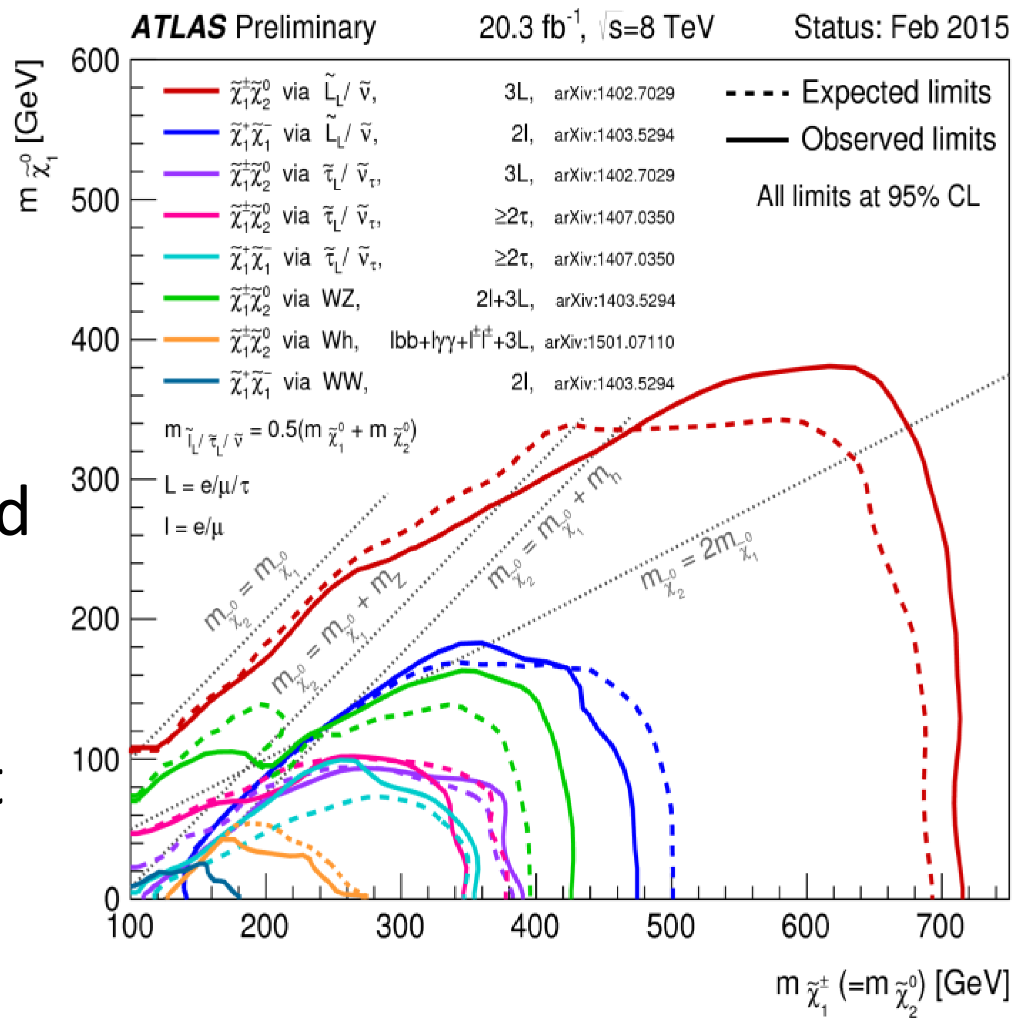
OK, they must have been excluded already by LHC searches?

No !!!

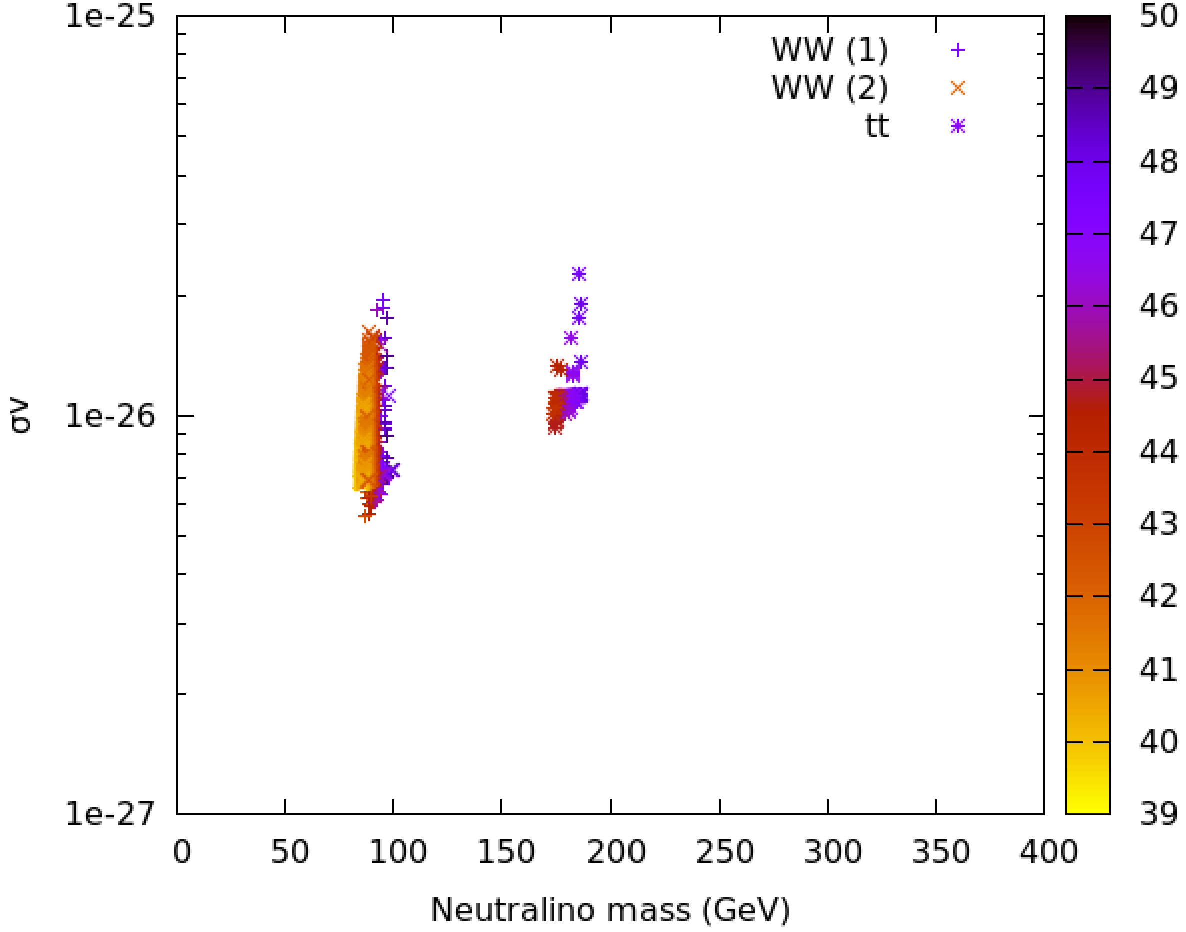
Carefully checked
All 3 solutions !

None of them is excluded by LHC

Solutions also consistent with all precision measurements

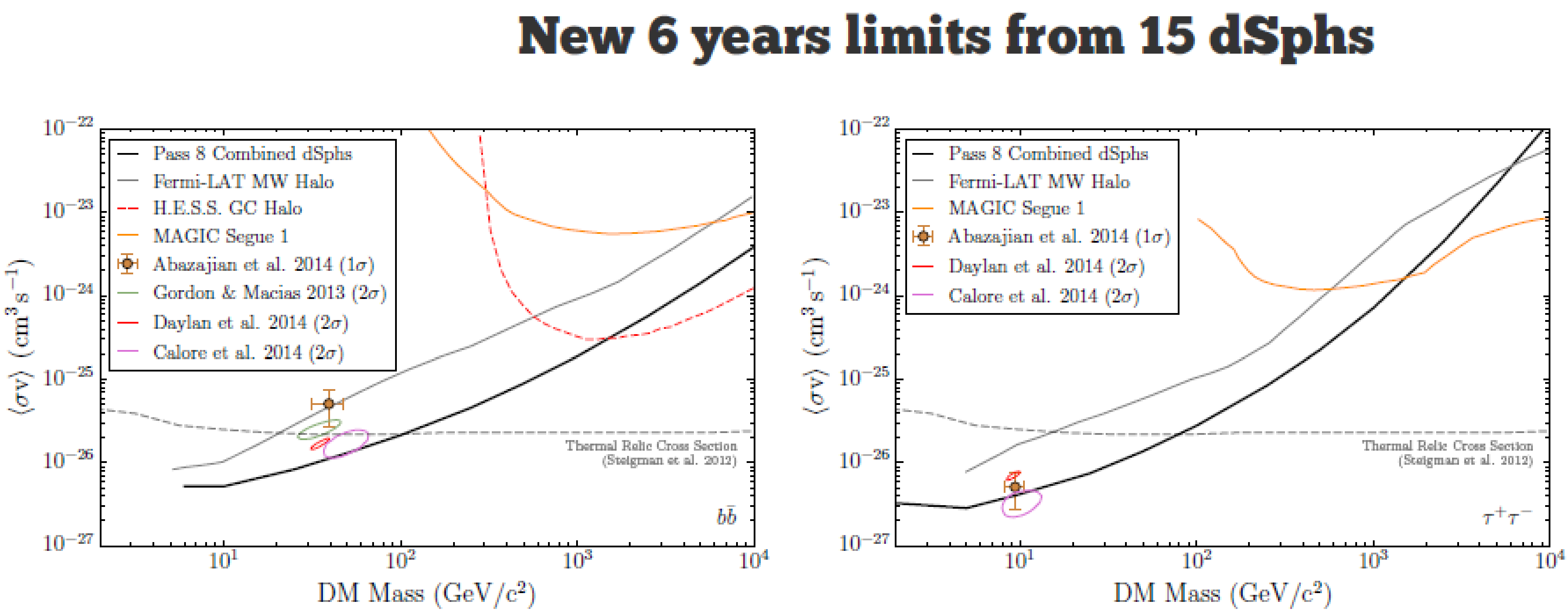


OK, let's look at more properties

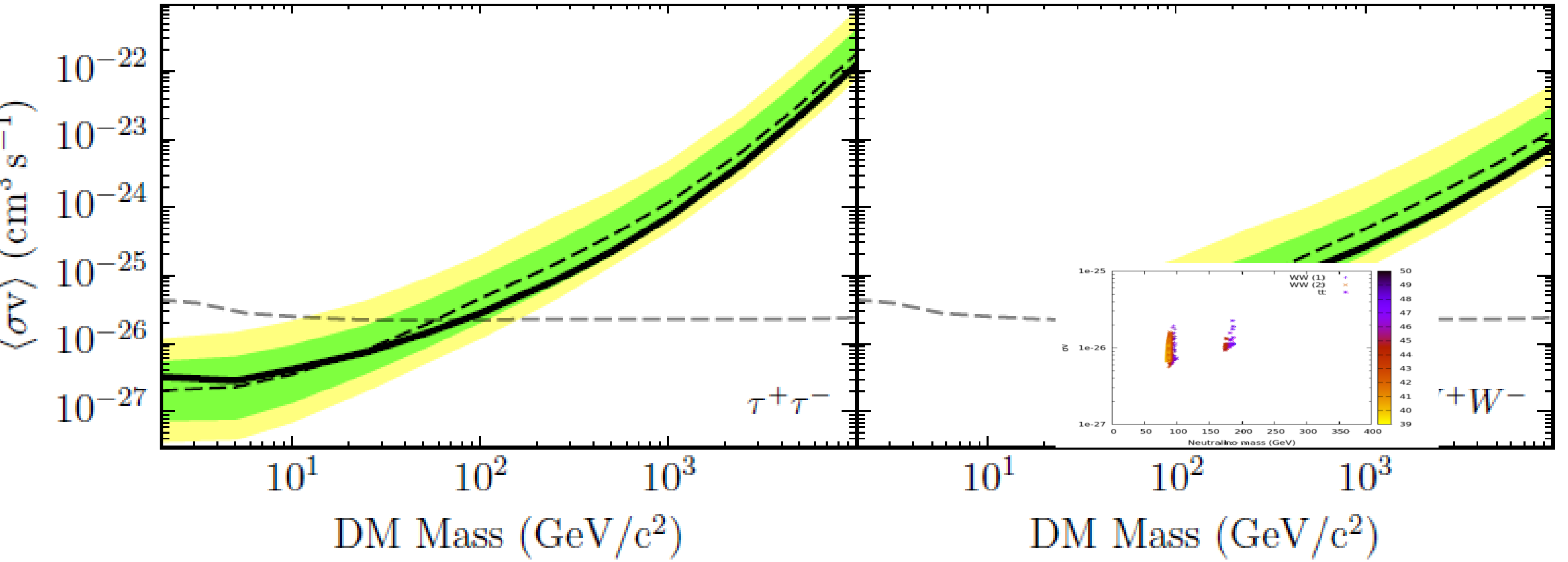


WW (1)
WW (2)
tt
σv
1e-25
1e-26
1e-27
0
50
100
150
200
250
300
350
400
Neutralino mass (GeV)
50
49
48
47
46
45
44
43
42
41
40
39

Dwarf galaxies…



http://arxiv.org/pdf/1503.02641v1.pdf



G. 8. DM annihilation cross-section constraints derived from the combined 15-dSph analysis for various channel

Our solutions are **not** excluded…

Relic Density MSSM

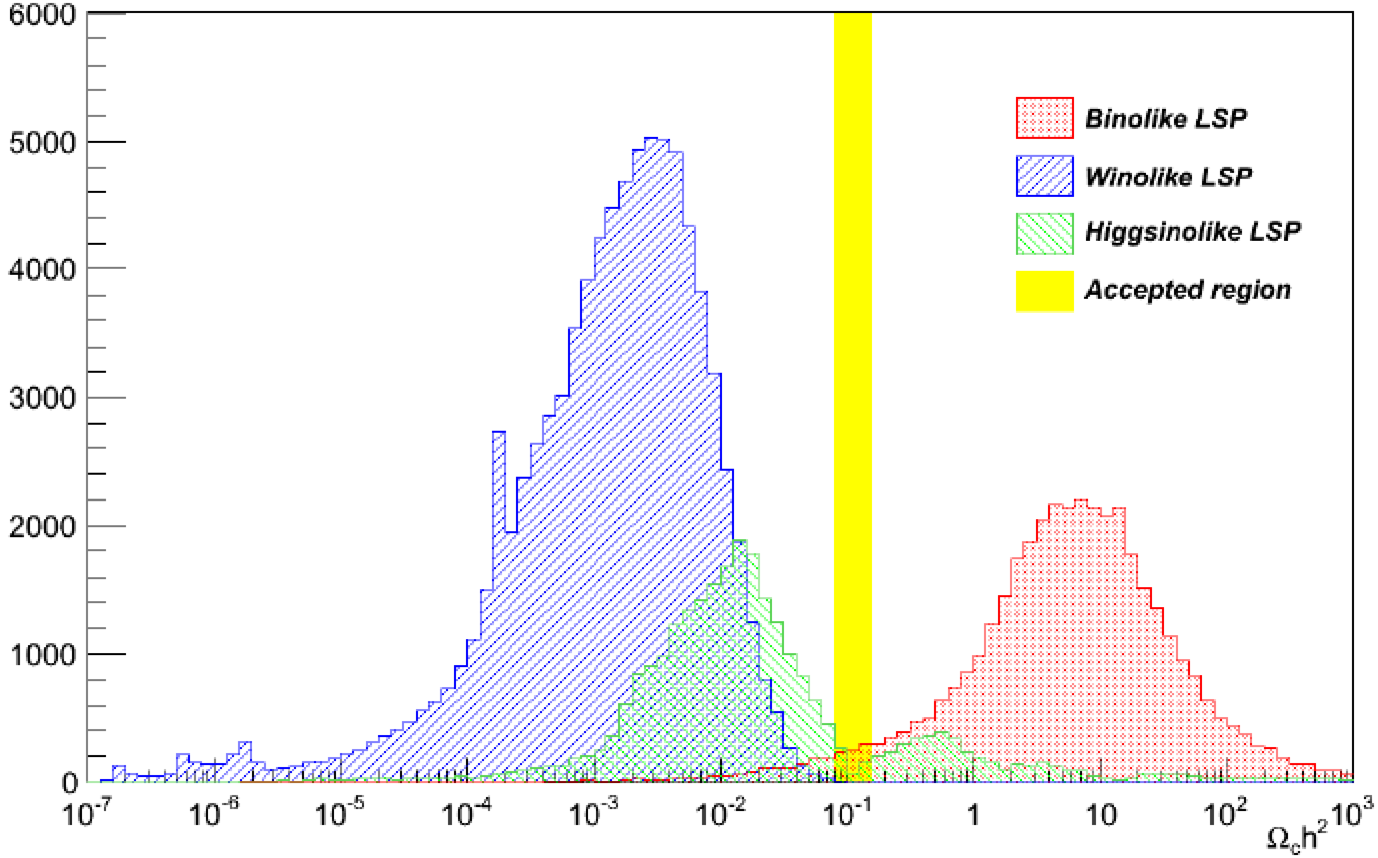
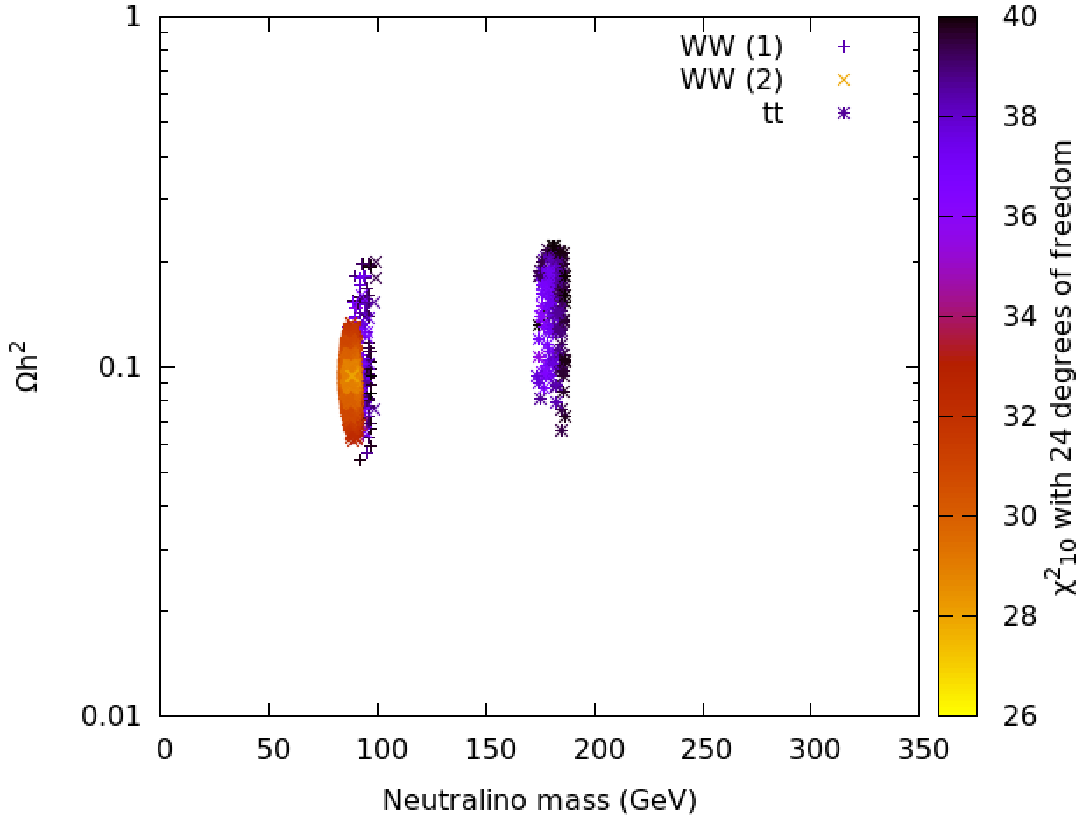


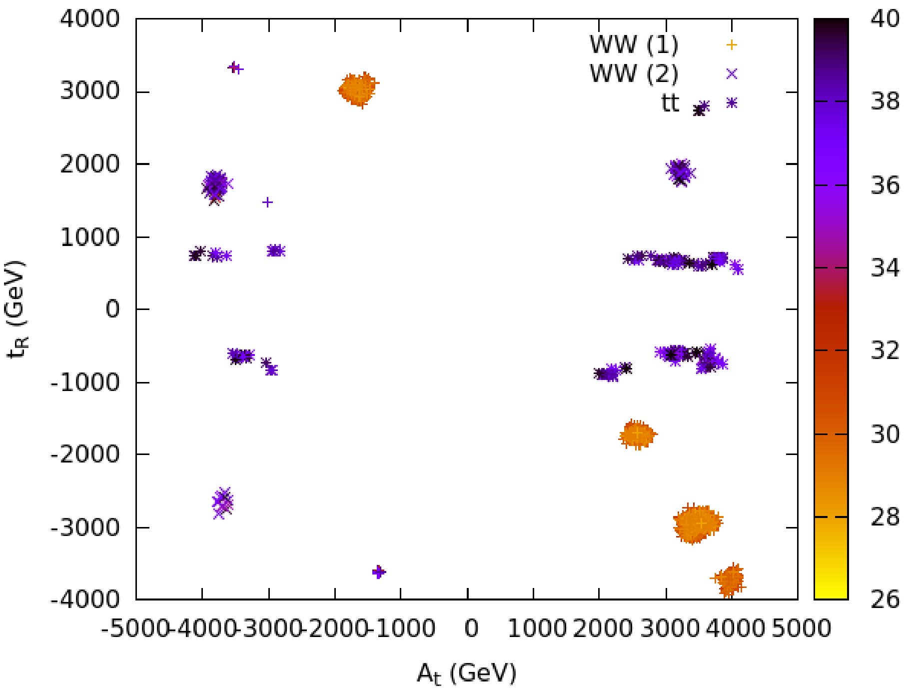
Figure 2: Dark Matter relic density $\Omega_c h^2$ obtained from the 19 parameter pMSSM models compared with the accepted region. The number of models is shown as a function of $\Omega_c h^2$.

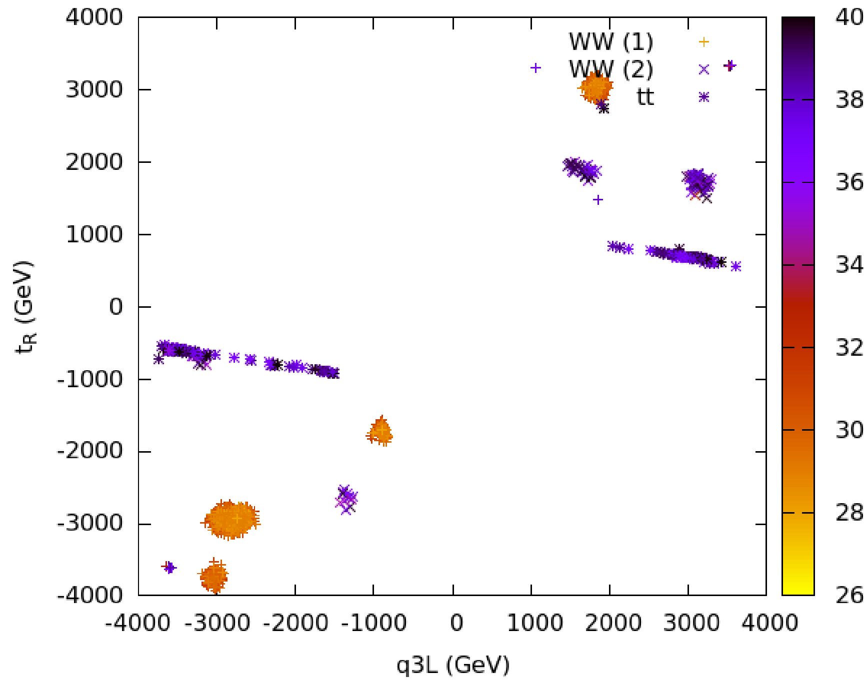
Relic Density best fit points



…. My legs became a bit shaky to be honest…we did not include this in the fit !

Stop parameters …



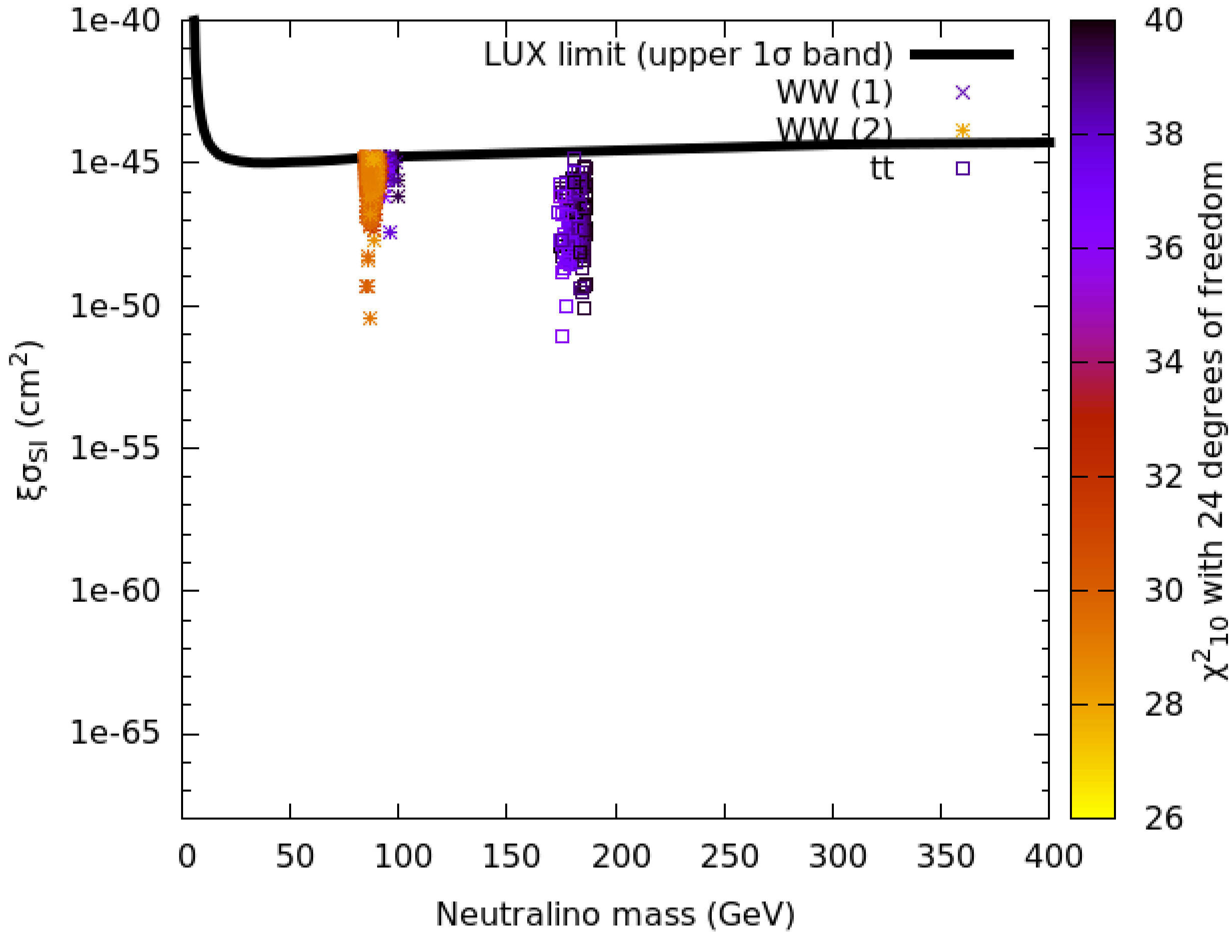


Impressive to find such located solutions… constrained by Higgs mass…
Particle Filter locates regions which are 10^{-20} of phase space

What can we do now?

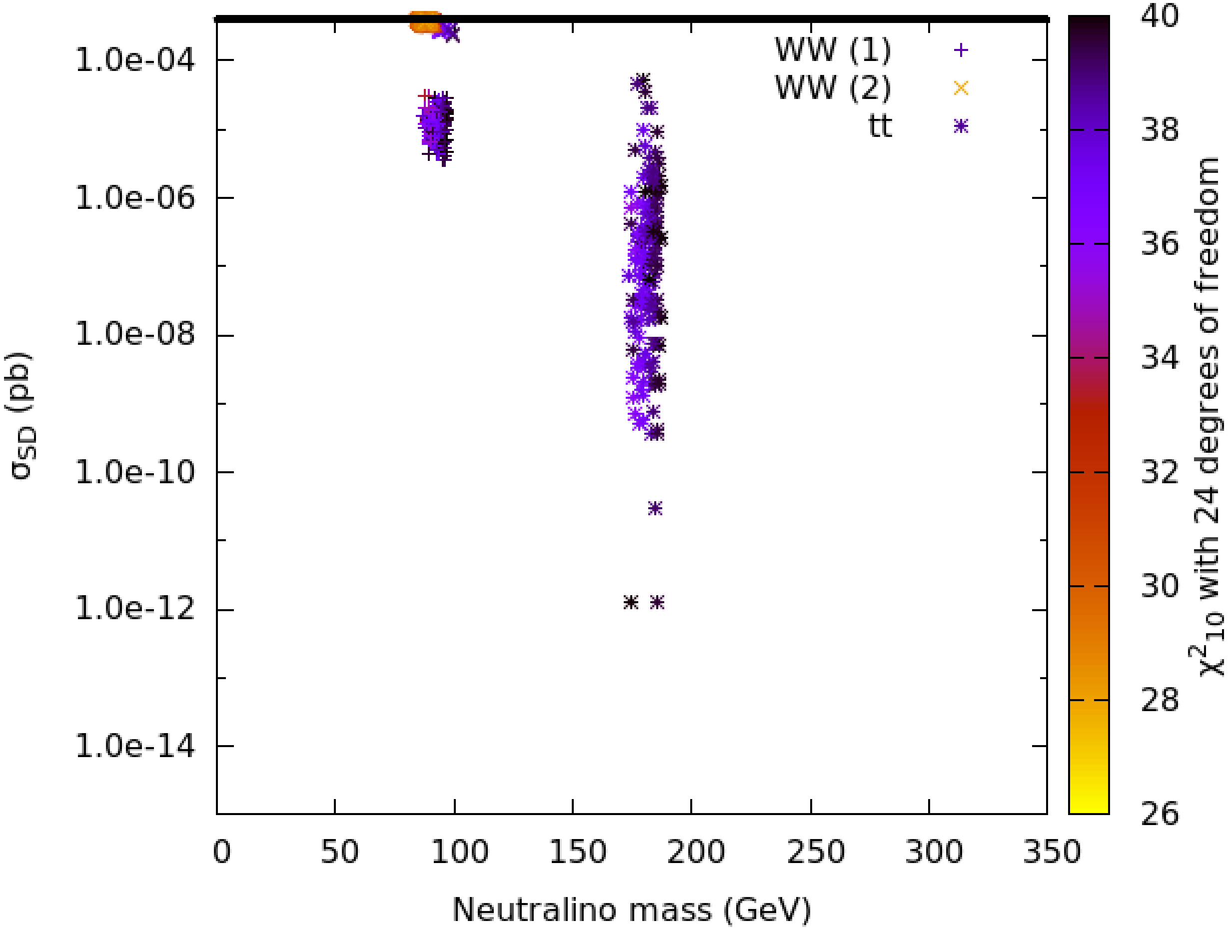
LUX ?

Xenon1T?



What can we do now?

Best WW Solution will be **tested** with Icecube upgrade



What can we do now?

- All 3 solutions give extremely precise forecasts for LHC

Monojets

Higgs+DM

Monojets

- Bino Higgsino
  ➔ Should be testable with 50fb-1 at 14 TeV
- Bino Wino Higgsino
  ➔ Difficult… but almost only chance, need to check
- Stop pairs…?

➔ Better new dedicated search dedicated to small (but not too small) compression, e.g. soft leptons + Monojet ?

Higgs + DM

- Both WW solutions have very constrained neutralino/chargino parameters…

Heavy neutralino 3 and 4 will be 400-600 GeV and decay via Z , **Higgs** or W + DM

➔Strengthen
Higgs + DM searches

Higgs, di-Higgs and tri-Higgs production via SUSY processes at the LHC with 14 TeV

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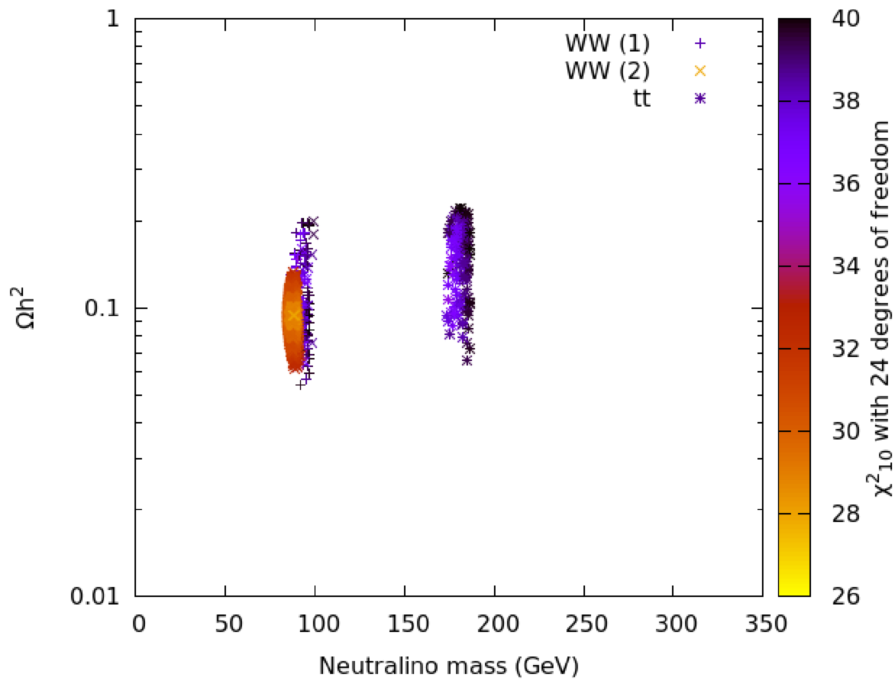
Summary:

Is this all
by pure chance?

LHC can tell
us… if we try…

Need manpower



Extra Slides

For massless quarks, the longitudinal component of the energy carried by a hadron formed in the string-breaking process $\mathrm{string} \to \mathrm{hadron} + \mathrm{string}'$ is governed by the Lund symmetric fragmentation function:

$$f(z) \propto \frac{z^{(a_i - a_j)}(1-z)^{a_j}}{z} \exp\left(\frac{-bm_\perp^2}{z}\right) \ , \tag{3}$$

where z is the energy carried by the newly formed (ij) hadron, expressed as a fraction of the (light-cone) energy of the quark (or antiquark) endpoint, i, of the fragmenting string. (The remaining energy fraction, $(1-z)$, goes to the new string' system, from which another hadron can be split off in the same manner, etc., until all the energy is used up.) The transverse mass of the produced (ij) hadron is defined by $m_\perp^2 = m_{\mathrm{had}}^2 + p_{\perp,\mathrm{had}}^2$, hence heavier hadrons have harder spectra. The proportionality sign in eq. (3) indicates that the function is to be normalized to unity.

New gamma projects in space

- **AstroGam** 300 KeV- GeV (Proposal to ESA for M4)
- **Gamma-light** (Proposed to ESA but not approved)

http://agenda.infn.it/getFile.py/access?contribId=67&resId=0&materialId=slides&confId=4267

- **Gamma-400** launch foreseen by 2020

100 MeV - 3 TeV, an approved Russian γ-ray satellite. Energy resolution (100 GeV) ~ 1 %. Effective area ~ 0.4 m^2. Angular resolution (100 GeV) ~ 0.01°.

Science with Gamma-400 Workshop http://cdsagenda5.ictp.it/full_display.php?ida=a1311

- **DAMPE**: Satellite of similar performance as Gamma-400. An approved Chinese γ-ray satellite. Planned launch 2015-16.

- **HERD**: Instrument on the planned Chinese Space Station.

Energy resolution (100 GeV) ~ 1 %. Effective area ~ 1 - 2 m2. Angular resolution (100 GeV) ~ 0.01°. Planned launch around 2020.

- **PANGU**: suggested as a candidate for the joint small mission between the European Space Agency (ESA) and the Chinese Academy of Science (CAS)

arXiv:1407.0710 (performances similar to Gamma-Light)