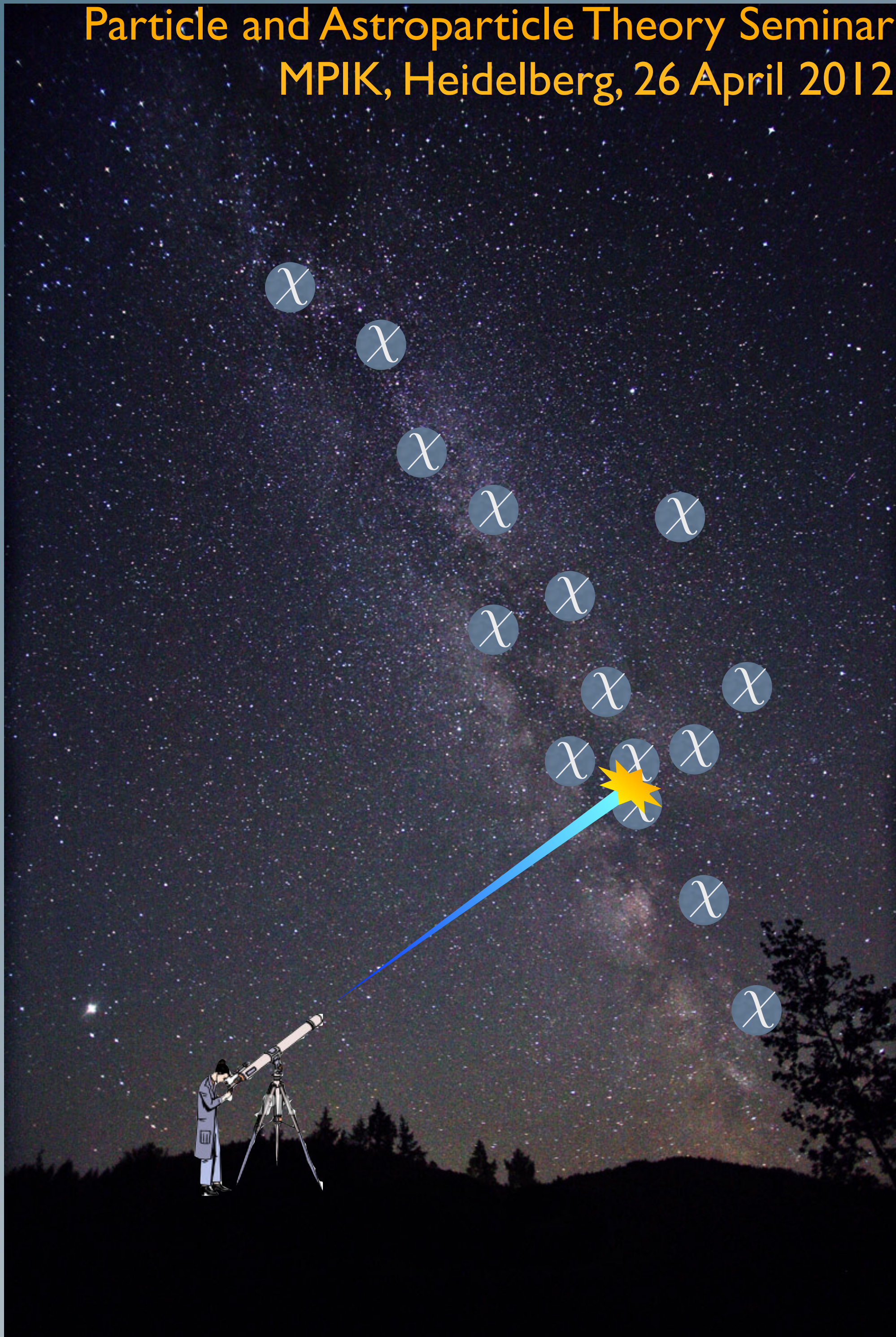


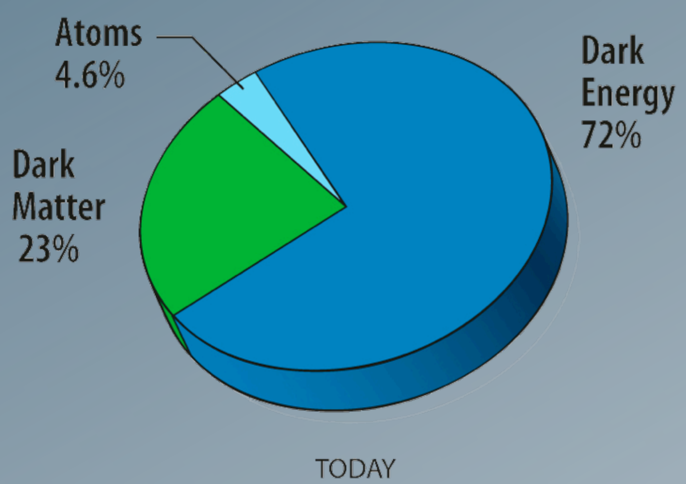
Dark Matter searches with Gamma rays

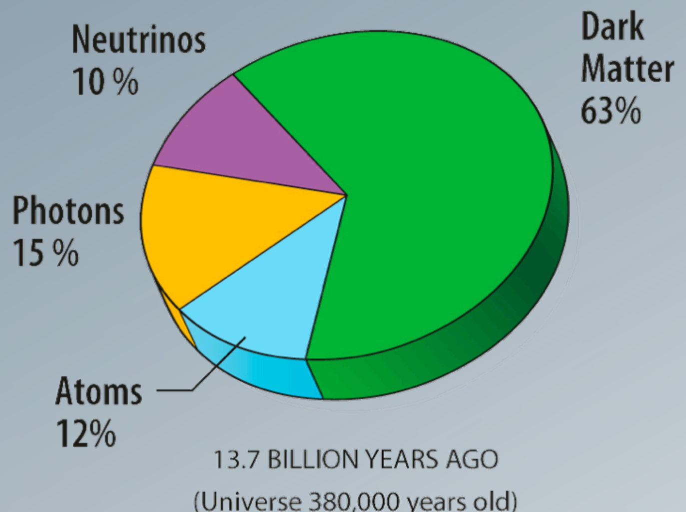
Torsten Bringmann,
University of Hamburg

Emmy Noether-Programm
Deutsche Forschungsgemeinschaft DFG

Collaborative Research Centre 676
Particles, Strings, and the Early Universe
The Structure of Matter and Space-Time
Deutsche Forschungsgemeinschaft DFG

Dark matter

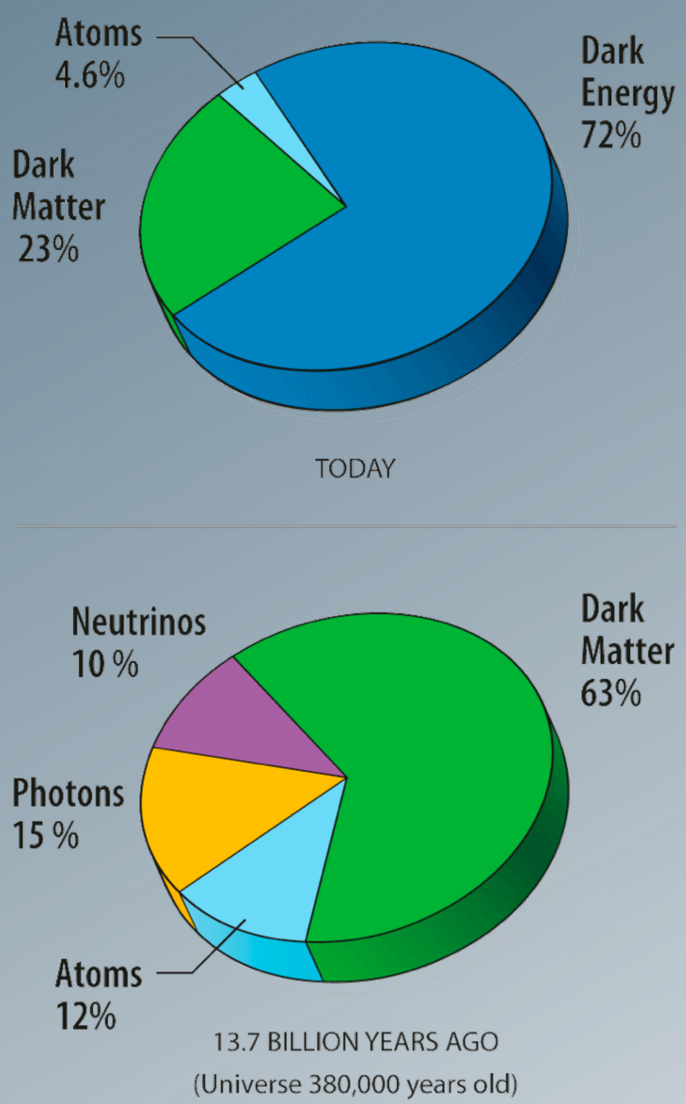




credit: WMAP

- *Existence* by now (almost) impossible to challenge!
  - $\Omega_{\mathrm{CDM}} = 0.233 \pm 0.013$ (WMAP)
  - electrically neutral (dark!)
  - non-baryonic (BBN)
  - cold – dissipationless and negligible free-streaming effects (structure formation)
  - collisionless (bullet cluster)

Dark matter



credit: WMAP

- *Existence* by now (almost) impossible to challenge!
  - $\Omega_{\mathrm{CDM}} = 0.233 \pm 0.013$ (WMAP)
  - electrically neutral (dark!)
  - non-baryonic (BBN)
  - cold – dissipationless and negligible free-streaming effects (structure formation)
  - collisionless (bullet cluster)
- *WIMPS* are particularly good candidates:
  - ✓ well-motivated from particle physics [SUSY, EDs, little Higgs, ...]
  - ✓ thermal production "automatically" leads to the right relic abundance

The WIMP "miracle"

- The number density of **W**eakly **I**nteracting **M**assive **P**articles in the early universe:

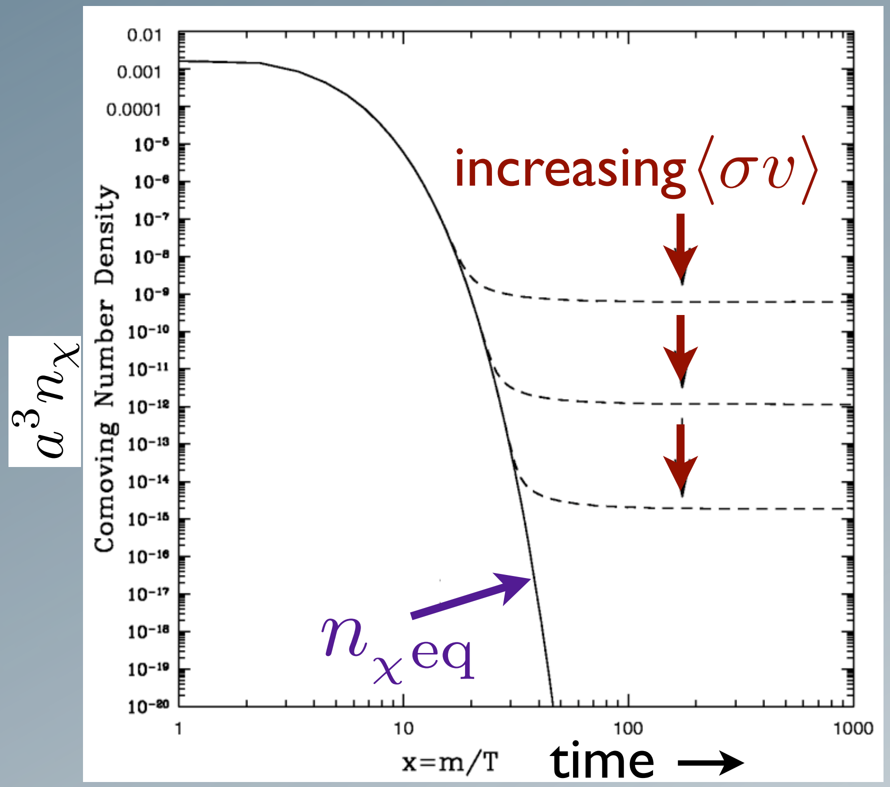


Fig.: Jungman, Kamionkowski & Griest, PR'96

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - n_{\chi\,\mathrm{eq}}^2\right)$$

$\langle\sigma v\rangle$: $\chi\chi \to \mathrm{SM\ SM}$ (thermal average)

The WIMP "miracle"

- The number density of Weakly Interacting Massive Particles in the early universe:

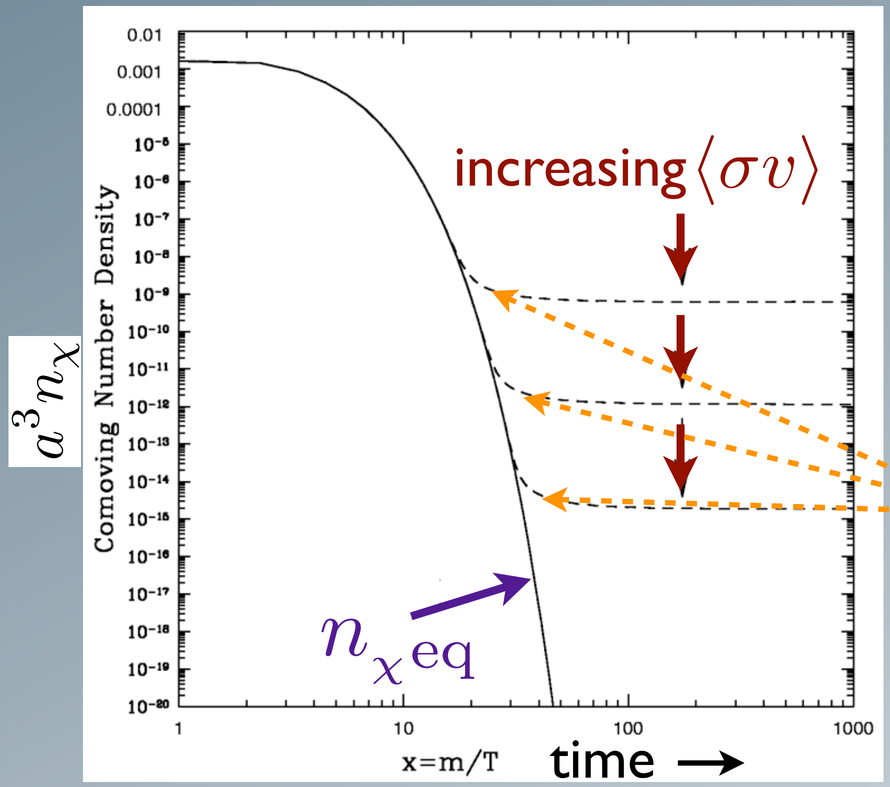


Fig.: Jungman, Kamionkowski & Griest, PR'96

$$\boxed{\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle \left(n_\chi^2 - n_{\chi \mathrm{eq}}^2 \right)}$$

$\langle \sigma v \rangle$: $\chi\chi \to \mathrm{SM\ SM}$ (thermal average)

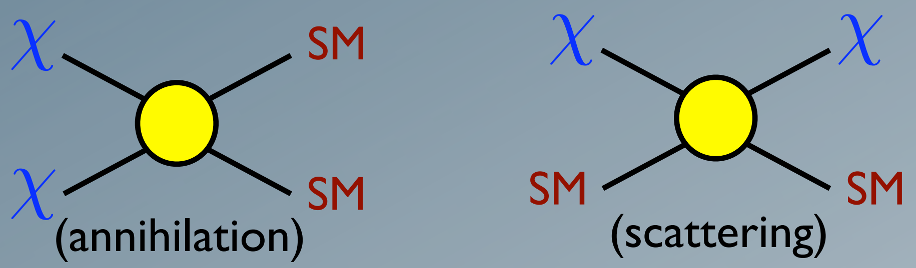
"Freeze-out" when annihilation rate falls behind expansion rate ($\to a^3 n_\chi \sim \mathrm{const.}$)

- Relic density (today): $\Omega_\chi h^2 \sim \frac{3 \cdot 10^{-27} \mathrm{cm}^3/\mathrm{s}}{\langle \sigma v \rangle} \sim \mathcal{O}(0.1)$

for weak-scale interactions!

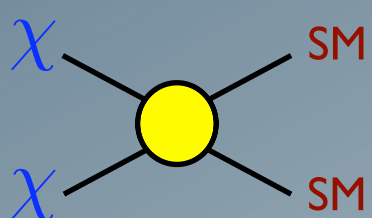
Freeze-out ≠ decoupling !

- WIMP interactions with heat bath of SM particles:

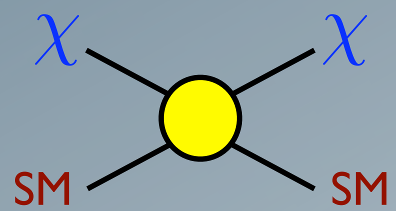


Freeze-out ≠ decoupling !

- WIMP interactions with heat bath of SM particles:



(annihilation)



(scattering)

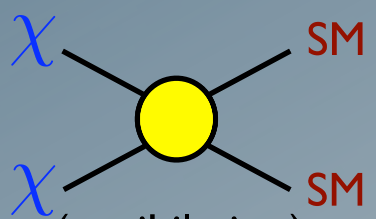
$$\boxed{T_{\rm cd} \sim m_\chi / 25}$$

chemical decoupling

$$\Omega_\chi$$

Freeze-out ≠ decoupling !

- WIMP interactions with heat bath of SM particles:



(annihilation)

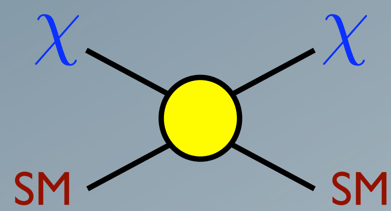
$\Downarrow$

$\boxed{T_{\rm cd} \sim m_\chi/25}$

chemical decoupling

$\Downarrow$

$$\Omega_\chi$$



(scattering)

$\Downarrow$

$\boxed{T_{\rm kd} \sim m_\chi/(10^2..10^5)}$

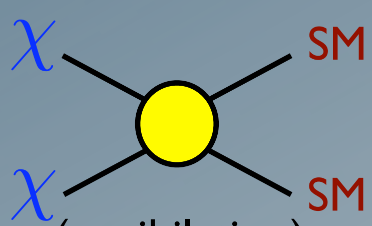
kinetic decoupling

$\Downarrow$

$$M_{\rm cut}$$

Freeze-out ≠ decoupling !

- WIMP interactions with heat bath of SM particles:

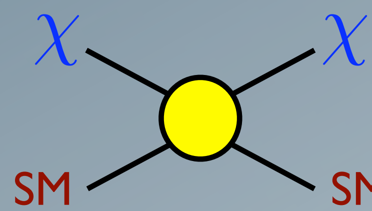


(annihilation)

$T_{\rm cd} \sim m_\chi/25$

chemical decoupling

Ω_χ

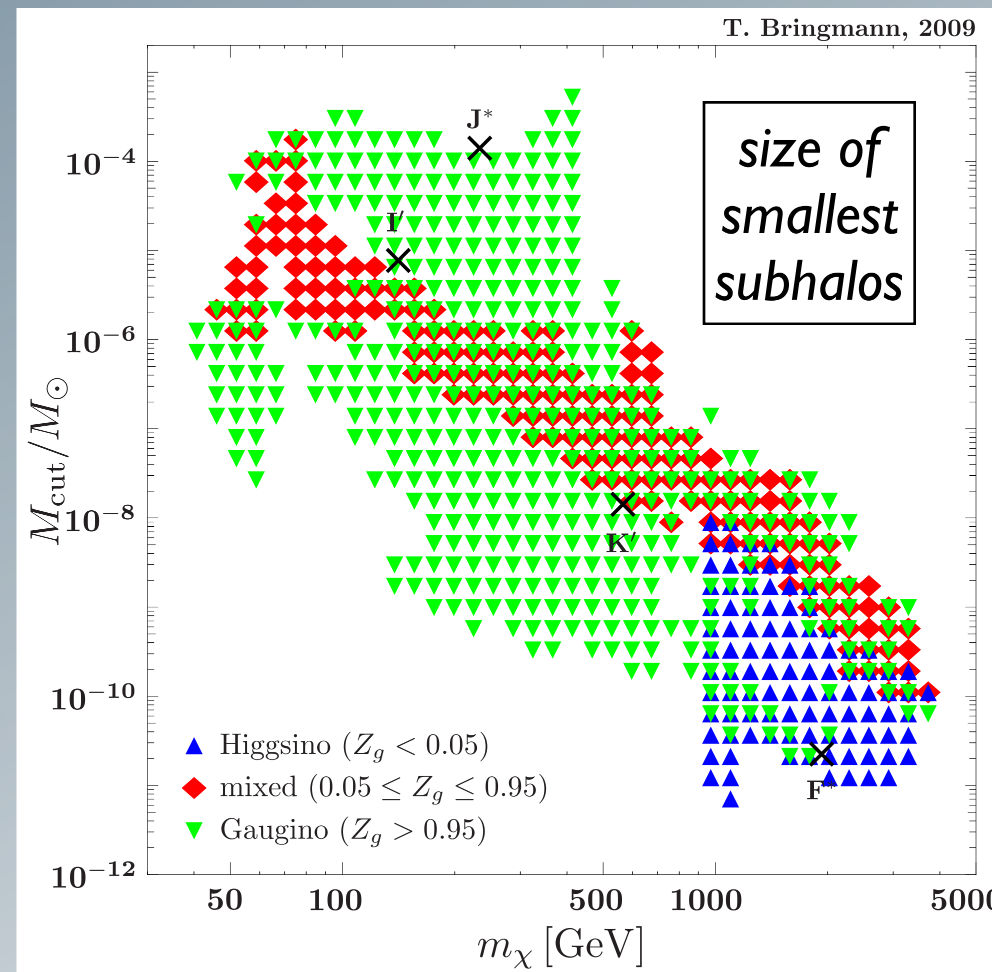


(scattering)

$T_{\rm kd} \sim m_\chi/(10^2..10^5)$

kinetic decoupling

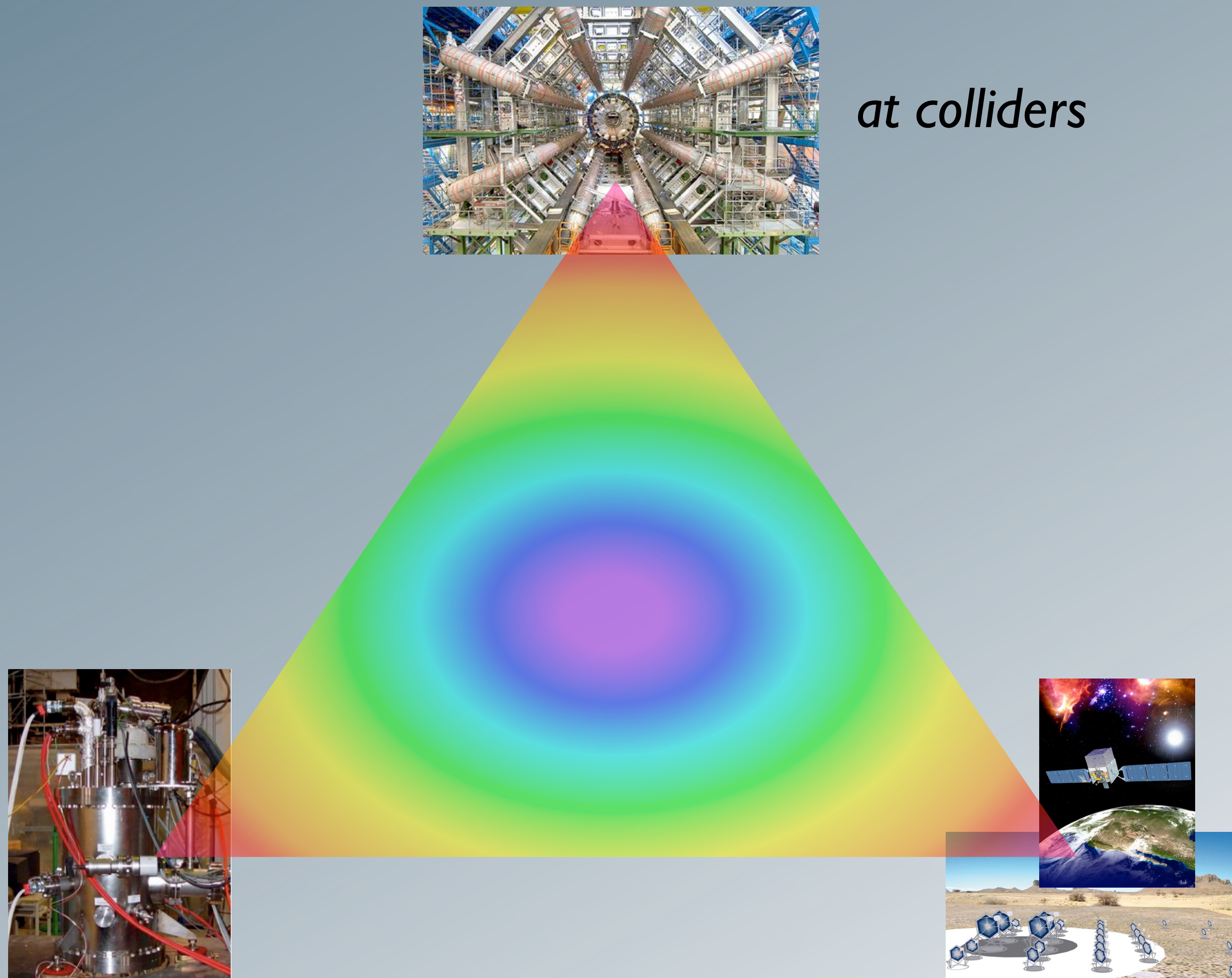
$M_{\rm cut}$



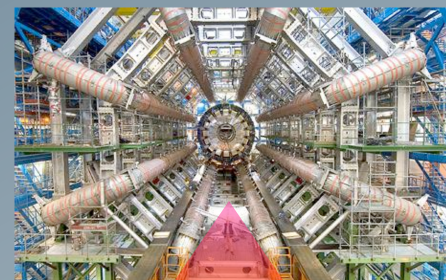
TB, NJP '09

- *no "typical" $M_{\rm cut} \sim 10^{-6} M_\odot$, but highly model-dependent*
- *a window into the particle-physics nature of dark matter!*

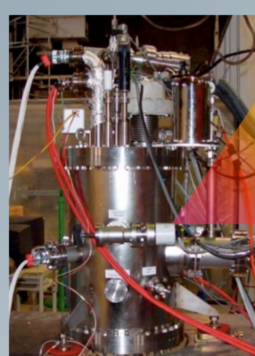
Strategies for DM searches



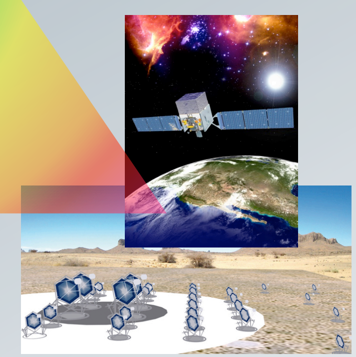
Strategies for DM searches



at colliders



directly

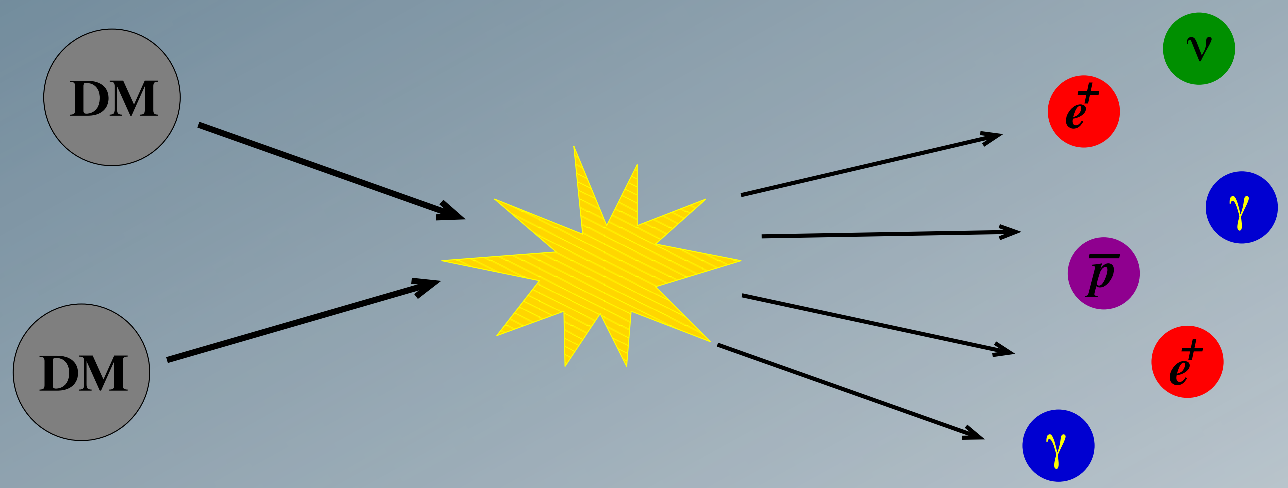


this talk:

indirectly

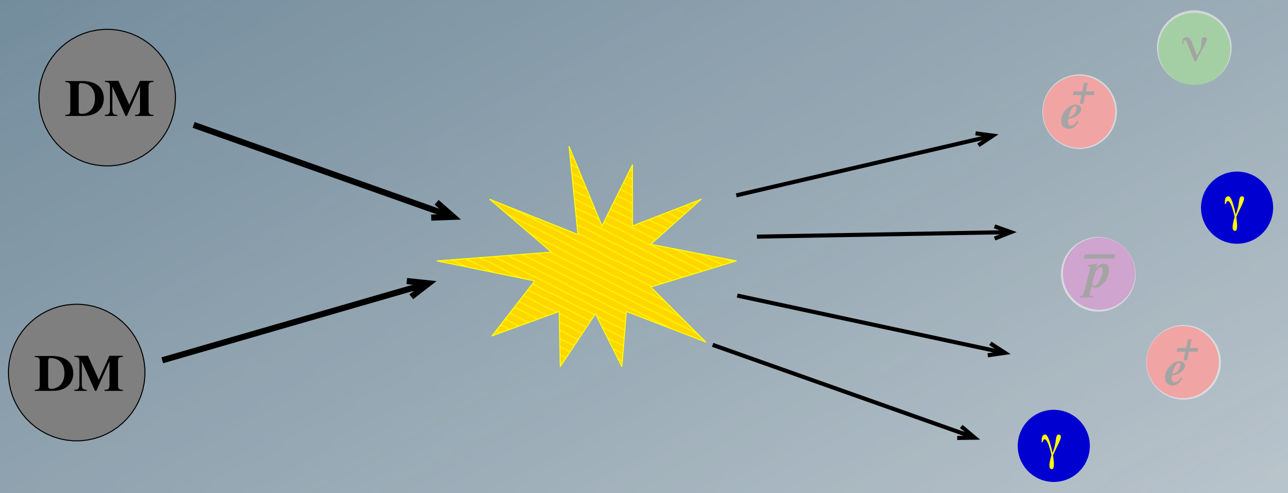
➩ *all complementary!*

Indirect DM searches



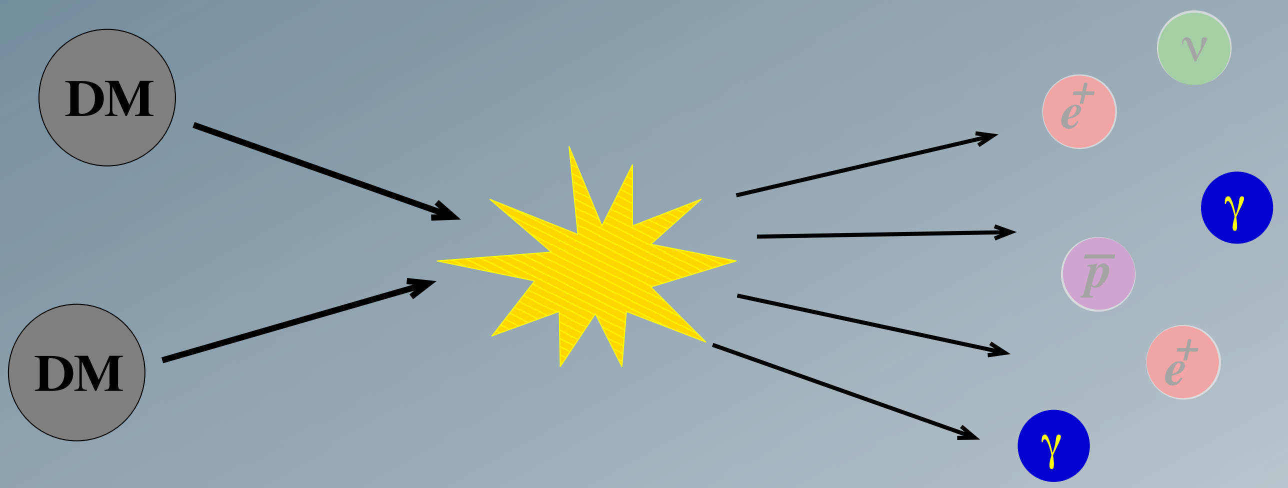
- DM has to be (quasi-)stable against decay...
- … but can usually pair-annihilate into SM particles
- Try to spot those in cosmic rays of various kinds
- The challenge: i) absolute rates
  $\rightsquigarrow$ regions of high DM density
  ii) discrimination against other sources
  $\rightsquigarrow$ low background; clear signatures

Indirect DM searches



Gamma rays:

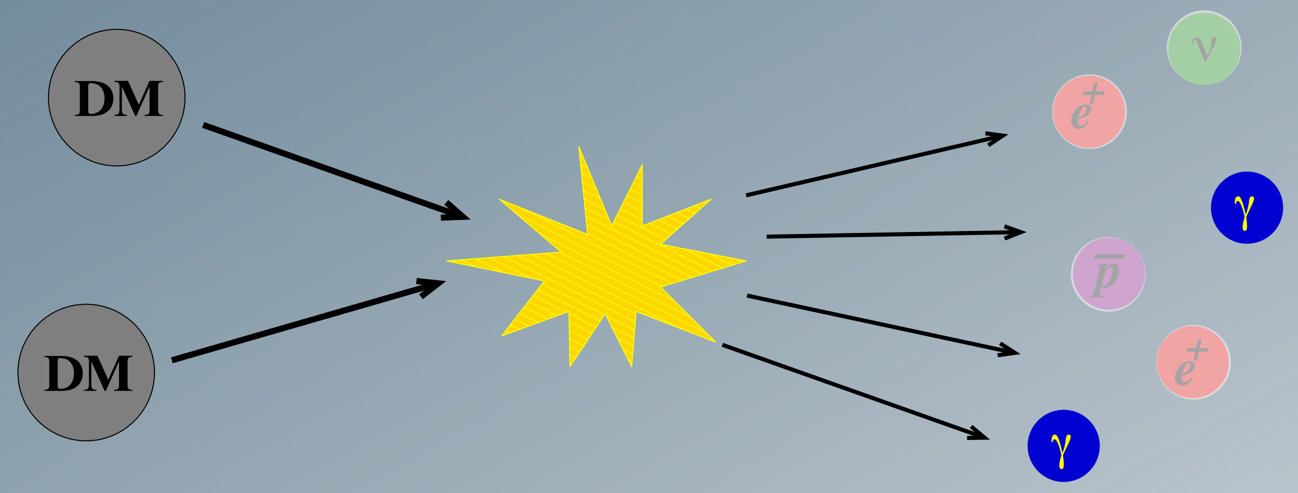
Indirect DM searches



Gamma rays:

- Rather high rates
- No attenuation when propagating through halo
- No assumptions about diffuse halo necessary
- Point directly to the sources: clear spatial signatures
- Clear spectral signatures to look for

Indirect DM searches



Gamma rays:

- Rather high rates
- No attenuation when propagating through halo
- No assumptions about diffuse halo necessary
- Point directly to the sources: clear spatial signatures
- Clear spectral signatures to look for ⇦ maybe most important!

Gamma-ray flux

The expected gamma-ray flux [GeV^{-1}cm^{-2}s^{-1}sr^{-1}] from a source with DM density ρ is given by

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\Delta\psi) = \frac{\langle\sigma v\rangle_{\rm ann}}{8\pi m_\chi^2}\sum_f B_f \frac{dN_\gamma^f}{dE_\gamma}\cdot\int_{\Delta\psi}\frac{d\Omega}{\Delta\psi}\int_{\rm l.o.s} d\ell(\psi)\rho^2(\mathbf{r})$$

Gamma-ray flux

The expected gamma-ray flux [$\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$] from a source with DM density ρ is given by

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\Delta\psi) = \boxed{\frac{\langle\sigma v\rangle_{\mathrm{ann}}}{8\pi m_\chi^2}\sum_f B_f \frac{dN_\gamma^f}{dE_\gamma}} \cdot \int_{\Delta\psi}\frac{d\Omega}{\Delta\psi}\int_{\mathrm{l.o.s}} d\ell(\psi)\rho^2(\mathbf{r})$$

particle physics

$\langle\sigma v\rangle_{\mathrm{ann}}$: total annihilation cross section

m_χ : WIMP mass $(50\,\mathrm{GeV} \lesssim m_\chi \lesssim 5\,\mathrm{TeV})$

B_f : branching ratio into channel f

N_γ^f : number of photons per ann.

Gamma-ray flux

The expected gamma-ray flux [GeV^{-1}cm^{-2}s^{-1}sr^{-1}] from a source with DM density ρ is given by

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \Delta\psi) = \boxed{\frac{\langle\sigma v\rangle_{\rm ann}}{8\pi m_\chi^2} \sum_f B_f \frac{dN_\gamma^f}{dE_\gamma}} \cdot \boxed{\int_{\Delta\psi} \frac{d\Omega}{\Delta\psi} \int_{\rm l.o.s} d\ell(\psi)\rho^2(\mathbf{r})}$$

particle physics   astrophysics

$\langle\sigma v\rangle_{\rm ann}$: total annihilation cross section

m_χ : WIMP mass $(50\,\mathrm{GeV} \lesssim m_\chi \lesssim 5\,\mathrm{TeV})$

B_f : branching ratio into channel f

N_γ^f : number of photons per ann.

for point-like sources:
$\simeq (D^2\Delta\psi)^{-1} \int d^3r\, \rho^2(\mathbf{r})$

$\Delta\psi$: angular res. of detector

D : distance to source

Gamma-ray flux

The expected gamma-ray flux [$\mathrm{GeV^{-1}cm^{-2}s^{-1}sr^{-1}}$] from a source with DM density ρ is given by

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\Delta\psi) = \boxed{\frac{\langle\sigma v\rangle_{\rm ann}}{8\pi m_\chi^2}\sum_f B_f\frac{dN_\gamma^f}{dE_\gamma}}\cdot\boxed{\int_{\Delta\psi}\frac{d\Omega}{\Delta\psi}\int_{\rm l.o.s}d\ell(\psi)\rho^2(\mathbf{r})}$$

particle physics

astrophysics

for point-like sources:

$\simeq \left(D^2\Delta\psi\right)^{-1}\int d^3r\,\rho^2(\mathbf{r})$

$\langle\sigma v\rangle_{\rm ann}$: total annihilation cross section

m_χ : WIMP mass $(50\,\mathrm{GeV}\lesssim m_\chi\lesssim 5\,\mathrm{TeV})$

B_f : branching ratio into channel f

N_γ^f : number of photons per ann.

$\Delta\psi$: angular res. of detector

D : distance to source

high accuracy

spectral information

Gamma-ray flux

The expected gamma-ray flux [GeV^{-1}cm^{-2}s^{-1}sr^{-1}] from a source with DM density ρ is given by

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \Delta\psi) = \underbrace{\boxed{\frac{\langle\sigma v\rangle_{\rm ann}}{8\pi m_\chi^2} \sum_f B_f \frac{dN_\gamma^f}{dE_\gamma}}}_{\text{particle physics}} \cdot \underbrace{\boxed{\int_{\Delta\psi} \frac{d\Omega}{\Delta\psi} \int_{\rm l.o.s} d\ell(\psi) \rho^2(\mathbf{r})}}_{\text{astrophysics}}$$

for point-like sources:
$\simeq \left(D^2 \Delta\psi\right)^{-1} \int d^3 r\, \rho^2(\mathbf{r})$

$\langle\sigma v\rangle_{\rm ann}$: total annihilation cross section

m_χ : WIMP mass $(50\,\mathrm{GeV} \lesssim m_\chi \lesssim 5\,\mathrm{TeV})$

B_f : branching ratio into channel f

N_γ^f : number of photons per ann.

→ high accuracy spectral information

$\Delta\psi$: angular res. of detector

D : distance to source

→ large uncertainty in normalization

Halo profiles

ΛCDM *N*-body simulations

$$\rho_{\rm NFW} = \frac{c}{r(a+r)^2}$$

$$\rho_{\rm Einasto}(r) = \rho_s\, e^{-\frac{2}{\alpha}\left[\left(\frac{r}{a}\right)^\alpha - 1\right]}$$

$$(\alpha \approx 0.17)$$

$\rightsquigarrow$ rather stable result

Fits to rotation curves?

$$\rho_{\rm Burkert} = \frac{c}{(r+a)(a^2+r^2)}$$

$$\rho_{\rm iso} = \frac{c}{(a^2+r^2)}$$

$\rightsquigarrow$ conflicting observational claims

Halo profiles

ΛCDM *N*-body simulations

$$\rho_{\rm NFW} = \frac{c}{r(a+r)^2}$$

$$\rho_{\rm Einasto}(r) = \rho_s\, e^{-\frac{2}{\alpha}\left[\left(\frac{r}{a}\right)^\alpha - 1\right]}$$

$$(\alpha \approx 0.17)$$

$\rightsquigarrow$ rather stable result

Fits to rotation curves?

$$\rho_{\rm Burkert} = \frac{c}{(r+a)(a^2+r^2)}$$

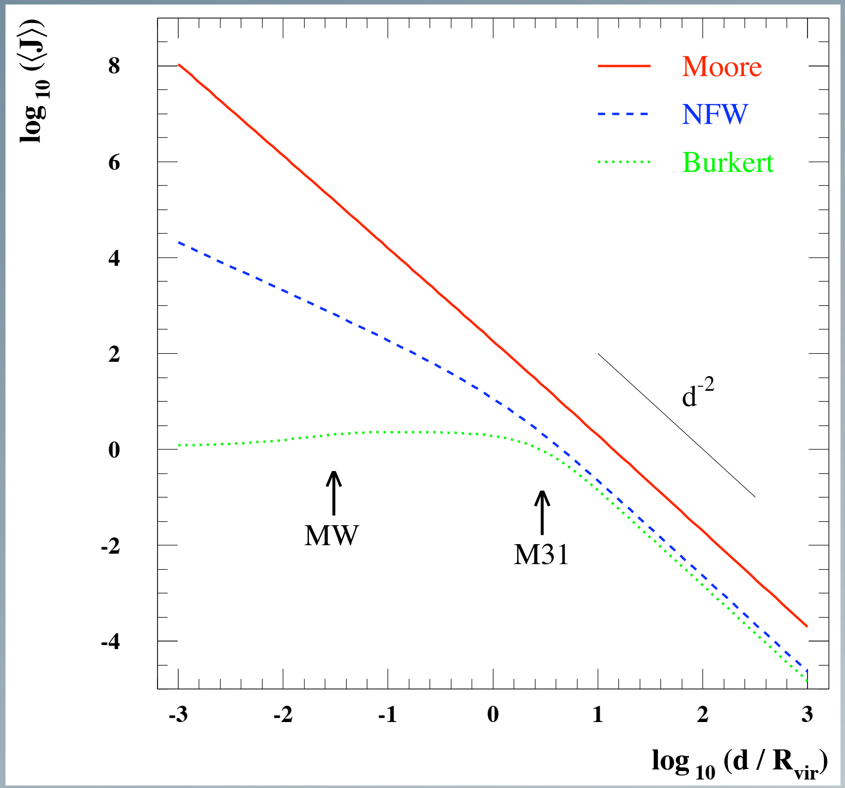
$$\rho_{\rm iso} = \frac{c}{(a^2+r^2)}$$

$\rightsquigarrow$ conflicting observational claims

- Situation a bit unclear; effect of baryons?
  (But could also lead to a steepening of the profile!)
- Difference in annihilation flux several orders of magnitude for the galactic center
- Situation much better for e.g. dwarf galaxies

Halo profiles

$\left\langle \int_{\rm los} \rho^2 d\ell \right\rangle \propto$ signal strength

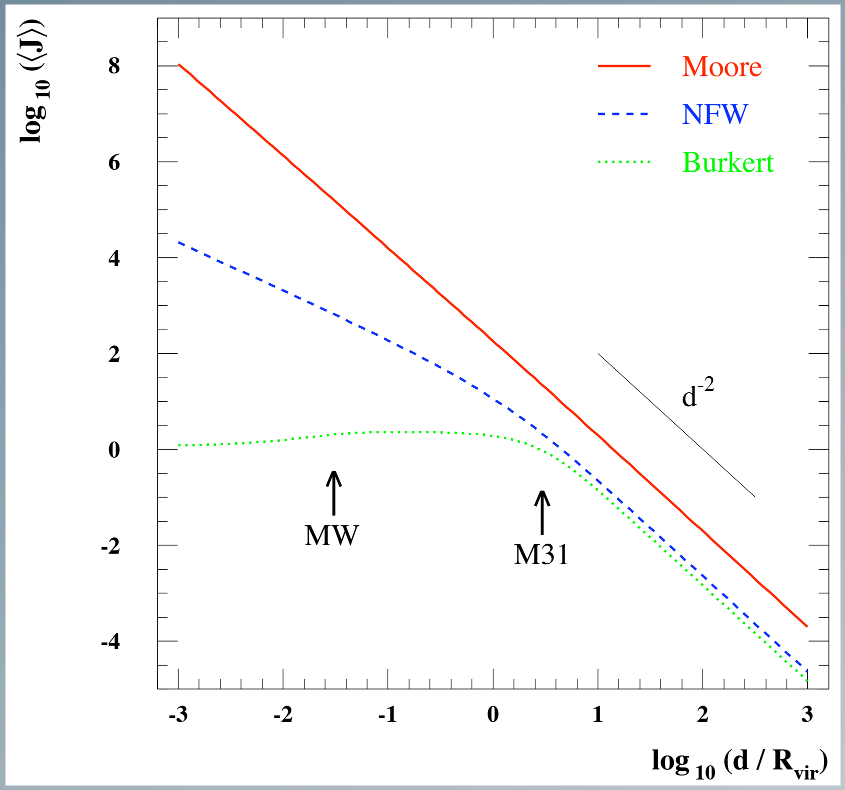


Ullio, Bergström & Edsjö, PRD '02

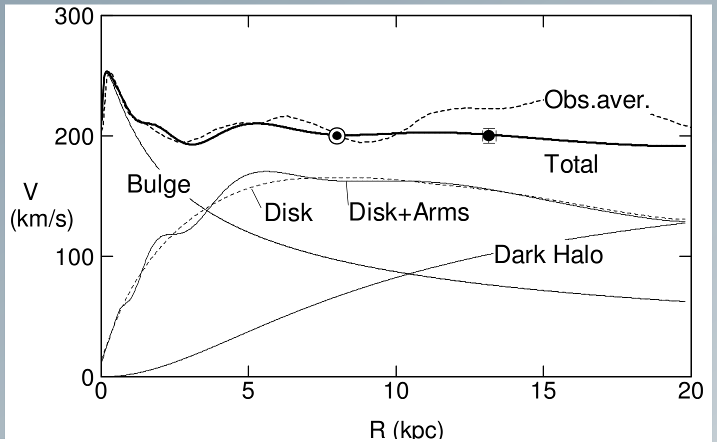
Large uncertainties "only" in the very central region.

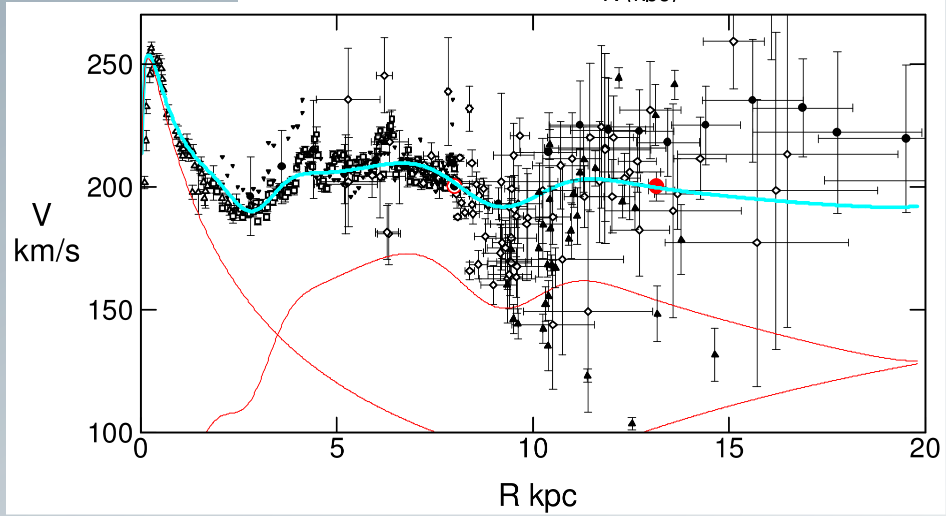
Halo profiles

$$\left\langle \int_{\rm los} \rho^2 d\ell \right\rangle \propto$$ signal strength



Ullio, Bergström & Edsjö, PRD '02





Sofue, Honma & Omodaka, 0811.0859

Large uncertainties "only" in the very central region.

Observational determination of (inner) DM profile for the *Milky Way* essentially impossible.

Local DM density

standard value:

$$\rho_{\odot}^{\rm DM} \sim 0.3\,\frac{\rm GeV}{\rm cm^3}$$

0.30 ± 0.05

Wydrow, Pim & Dubinski, ApJ '08

0.39 ± 0.03

Catena & Ullio, JCAP '10

0.43 ± 0.11 ± 0.10

Salucci et al, A&A '10

• • •

Local DM density

standard value:

$$\rho_{\odot}^{\mathrm{DM}} \sim 0.3\,\frac{\mathrm{GeV}}{\mathrm{cm}^3}$$

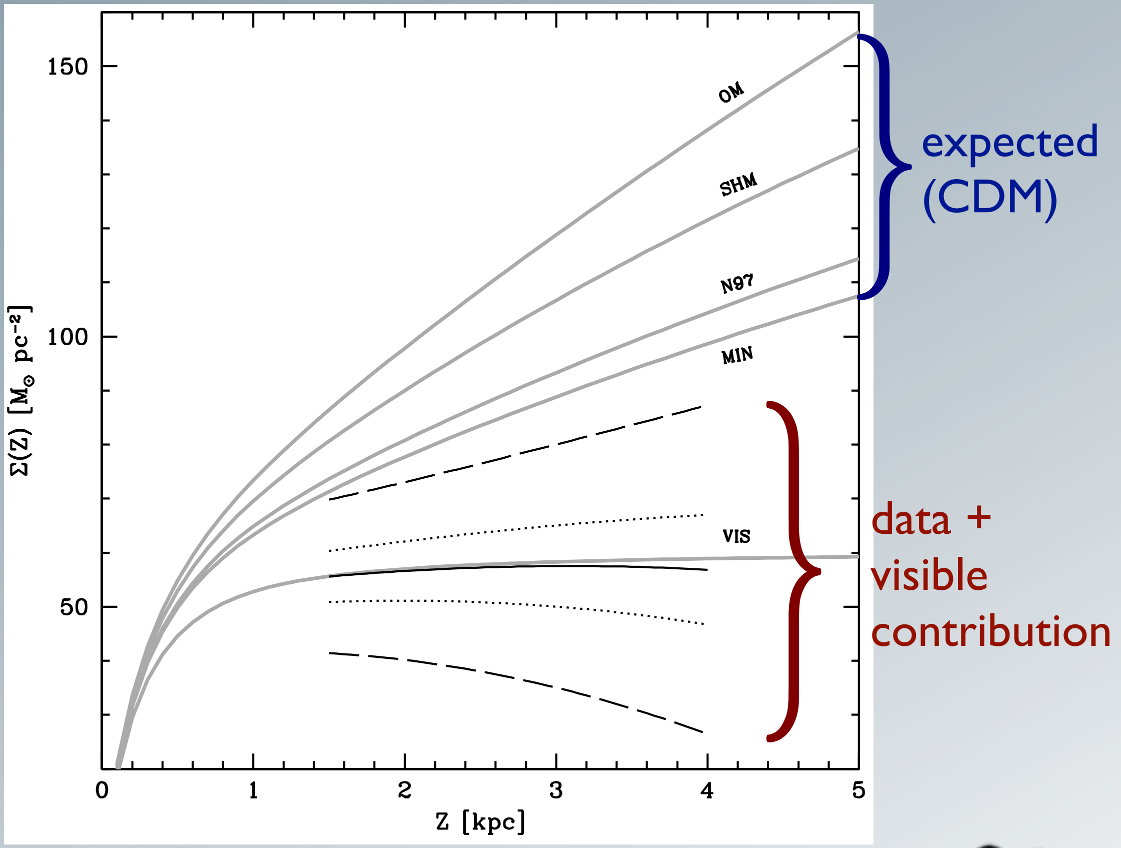
0.30 ± 0.05
Wydrow, Pim & Dubinski, ApJ '08

0.39 ± 0.03
Catena & Ullio, JCAP '10

0.43 ± 0.11 ± 0.10
Salucci et al, A&A '10

...

or 'no' local DM at all???



Bidin et al, 1204.3924 (ApJ acc.)

Substructure

- *N*-body simulations: The DM halo contains not only a smooth component, but a lot of substructure!
- Indirect detection effectively involves some averaging:

$$\Phi_{\rm SM} \propto \langle \rho_\chi^2 \rangle = (1 + {\rm BF}) \langle \rho_\chi \rangle^2$$

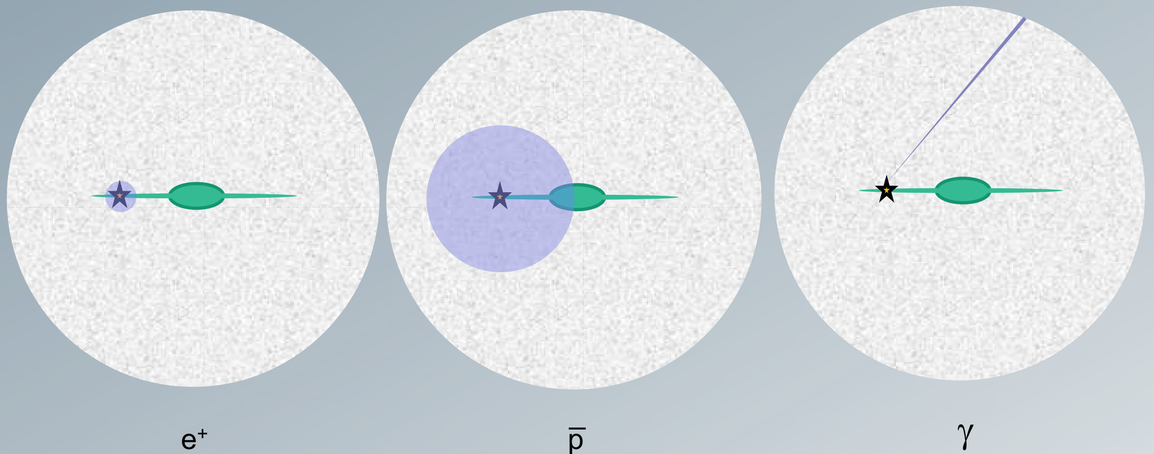


Fig.: Bergström, NJP '09

Substructure

- *N*-body simulations: The DM halo contains not only a smooth component, but a lot of substructure!
- Indirect detection effectively involves some averaging:

$$\Phi_{\rm SM} \propto \langle \rho_\chi^2 \rangle = (1 + {\rm BF}) \langle \rho_\chi \rangle^2$$

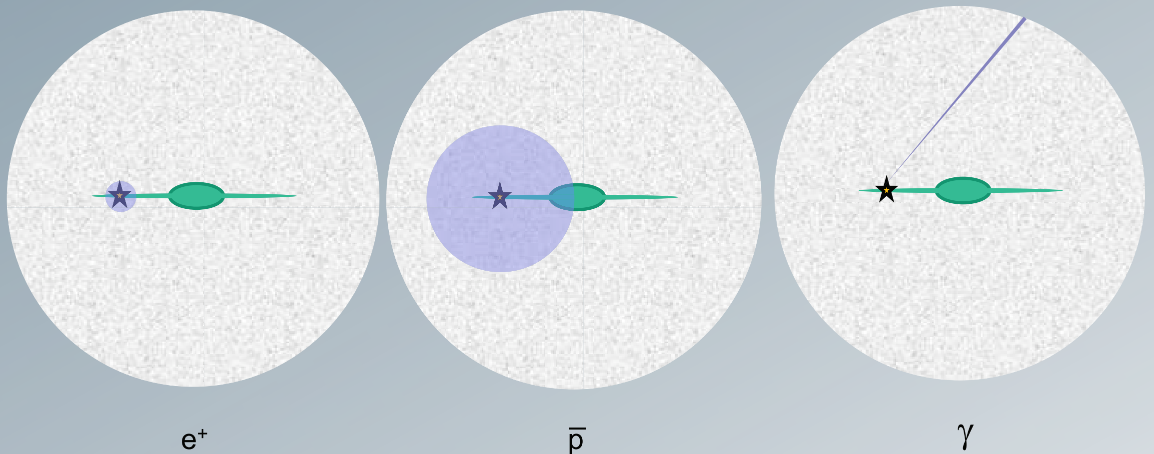


Fig.: Bergström, NJP '09

- "Boost factor"
  - each decade in $M_{\rm subhalo}$ contributes about the same

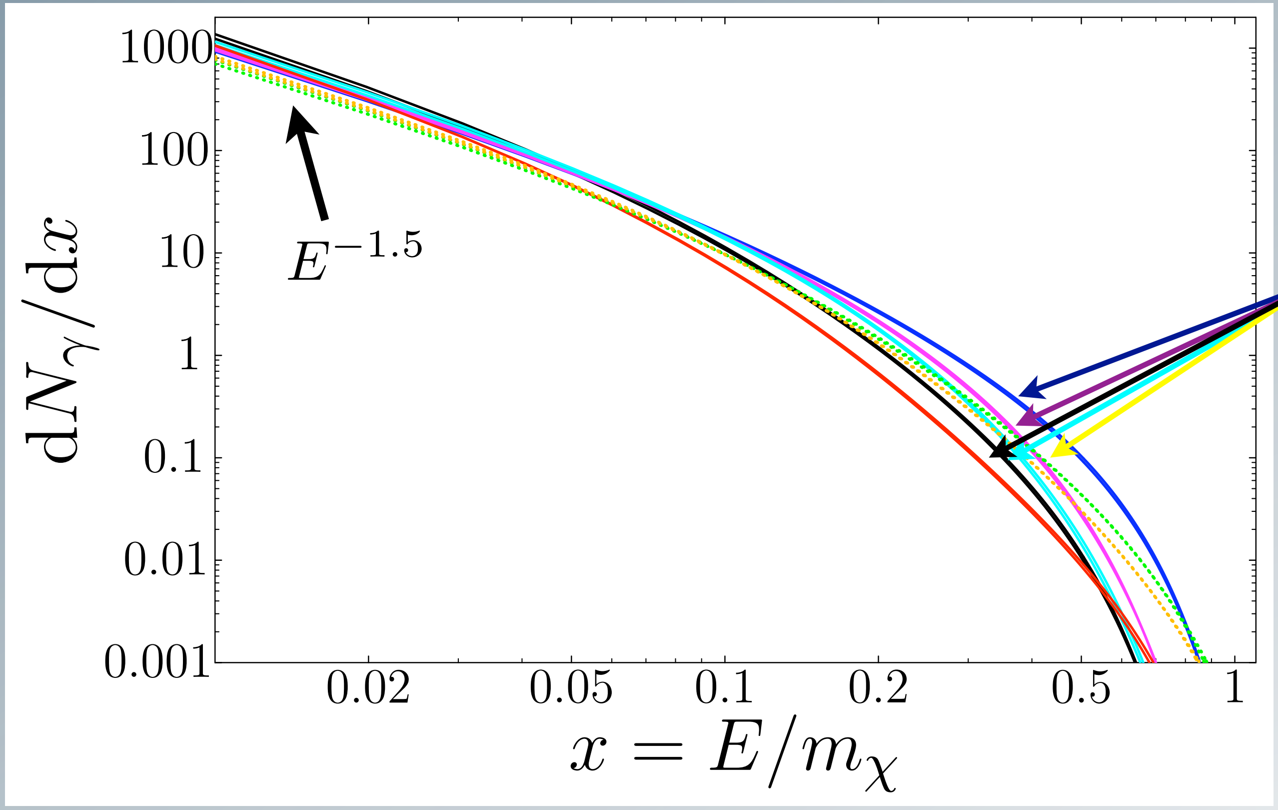
    e.g. Diemand, Kuhlen & Madau, ApJ '07

    ⇨ *important to include realistic value for* $M_{\rm cut}$ *!*
  - depends on uncertain form of microhalo profile ($c_{\rm V}$ ...) and dN/dM (large extrapolations necessary!)

DM annihilation spectra

DM annihilation spectra

- Secondary photons from fragmentation
  - mainly from $\pi^0 \to \gamma\gamma$
  - result in a rather featureless, model-independent spectrum

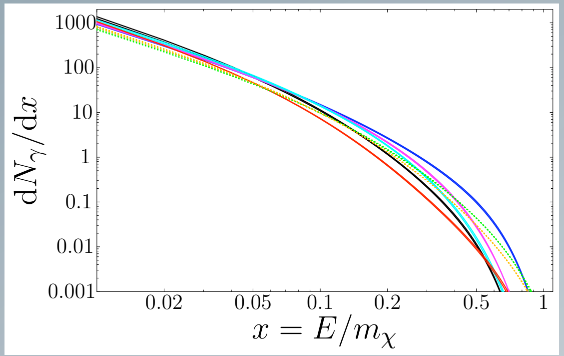


various (gauge boson and quark) final states

Bertone et al., astro-ph/0612387

DM annihilation spectra

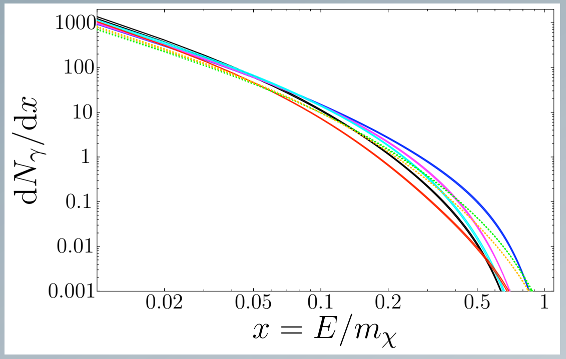
- Secondary photons from fragmentation
  - mainly from $\pi^0 \to \gamma\gamma$
  - result in a rather featureless, model-independent spectrum



- Line signals from $\chi\chi \to \gamma\gamma, \gamma Z, \gamma H$
  Bergström, Ullio & Buckley, ApJ '98
  - necessarily loop suppressed: $\mathcal{O}(\alpha^2)$
  - smoking-gun signature

DM annihilation spectra

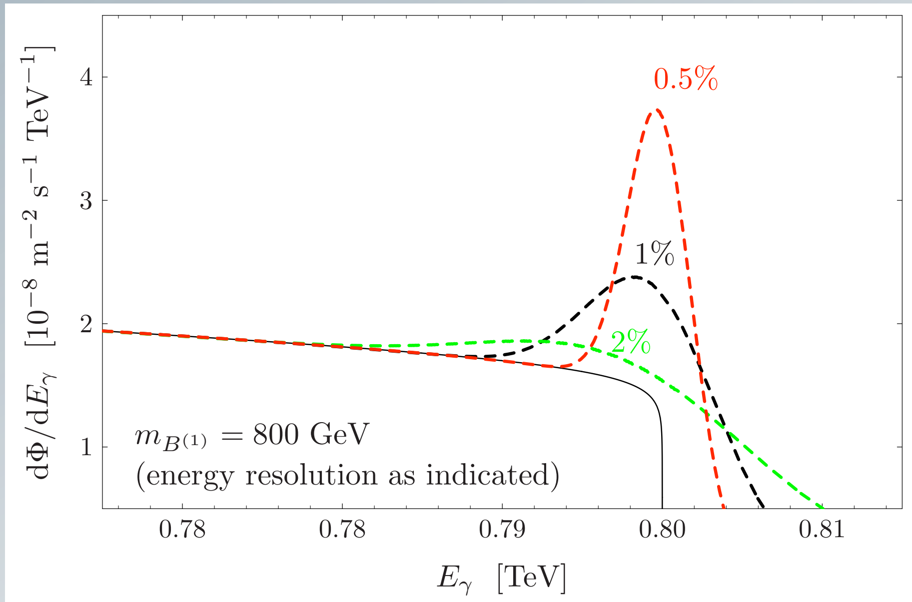
- Secondary photons from fragmentation
  - mainly from $\pi^0 \to \gamma\gamma$
  - result in a rather featureless, model-independent spectrum



- Line signals from $\chi\chi \to \gamma\gamma, \gamma Z, \gamma H$

Bergström, Ullio & Buckley, ApJ '98

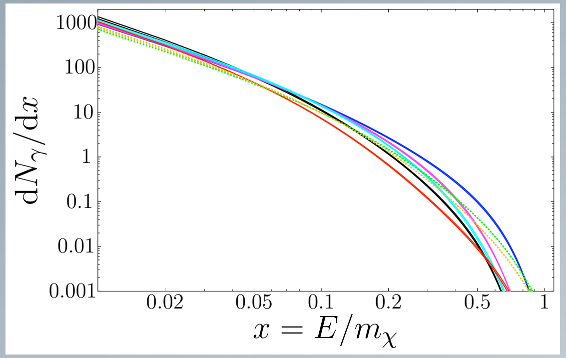
  - necessarily loop suppressed: $\mathcal{O}(\alpha^2)$
  - smoking-gun signature



Bergström, TB, Eriksson & Gustafsson, JCAP '05

DM annihilation spectra

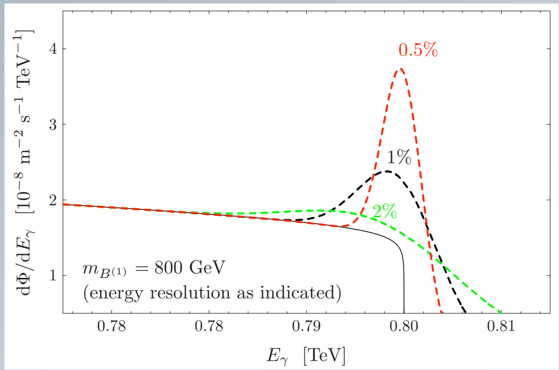
- Secondary photons from fragmentation
  - mainly from $\pi^0 \to \gamma\gamma$
  - result in a rather featureless, model-independent spectrum



- Line signals from $\chi\chi \to \gamma\gamma, \gamma Z, \gamma H$

Bergström, Ullio & Buckley, ApJ '98

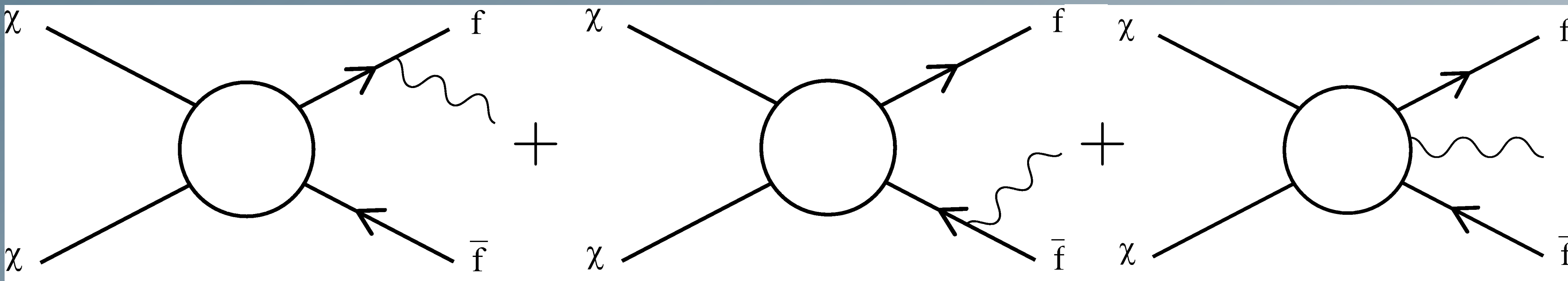
  - necessarily loop suppressed: $\mathcal{O}(\alpha^2)$
  - smoking-gun signature



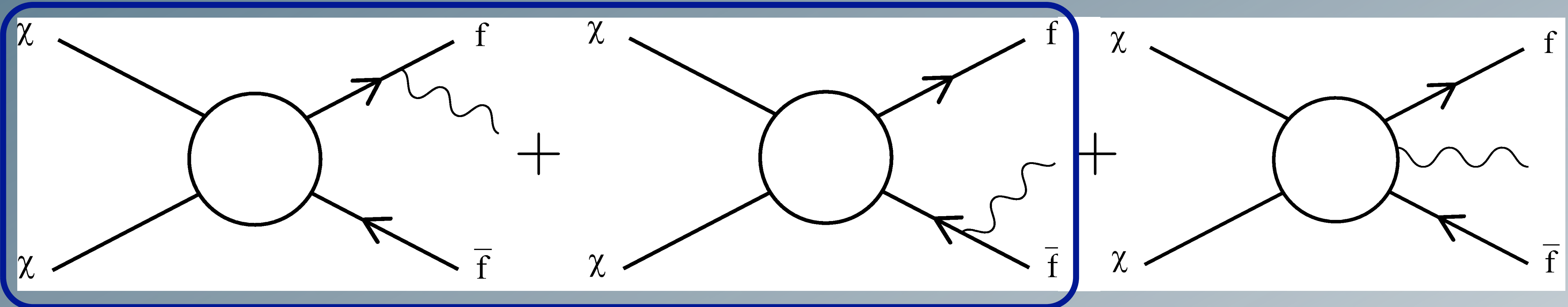
- Internal bremsstrahlung (IB)
  - whenever charged final states are present: $\mathcal{O}(\alpha)$
  - characteristic signature (details model-dependent!)
  - generically dominates at high E_γ

Birkedal, Matchev, Perelstein & Spray, hep-ph/0507194
TB, Bergström & Edsjö, JHEP '08

Internal bremsstrahlung



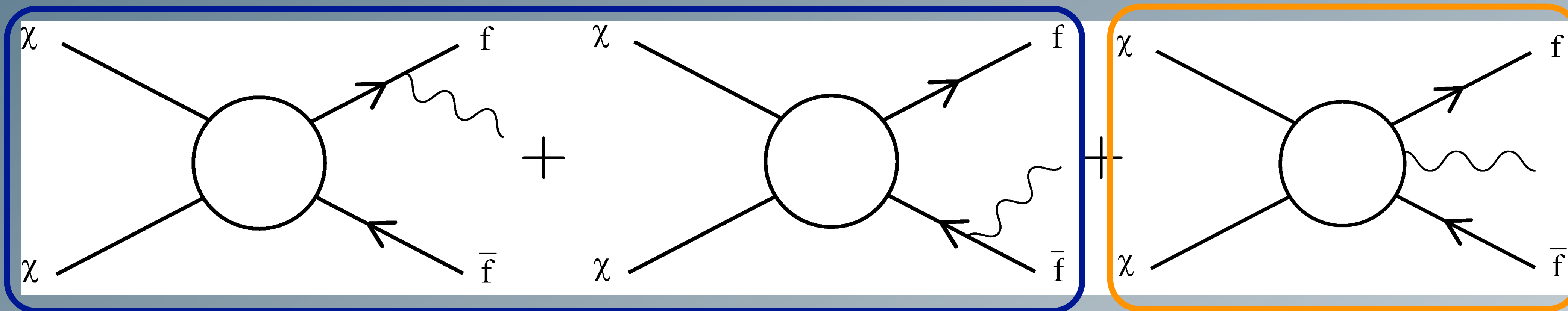
Internal bremsstrahlung



Final state radiation

- usually dominant for $m_\chi \gg m_f$
- mainly collinear photons
  $\rightsquigarrow$ model-independent spectrum
  Birkedal, Matchev, Perelstein & Spray, hep-ph/0507194
- important for high rates into leptons, e.g. Kaluza-Klein or “leptophilic” DM

Internal bremsstrahlung



Final state radiation

- usually dominant for $m_\chi \gg m_f$
- mainly collinear photons
  $\rightsquigarrow$ model-independent spectrum
  Birkedal, Matchev, Perelstein & Spray, hep-ph/0507194
- important for high rates into leptons, e.g. Kaluza-Klein or "leptophilic" DM

"Vitual" IB

- dominant in two cases:
  i) f bosonic and *t*-channel mass degenerate with m_χ
  Bergström, TB, Eriksson & Gustafsson, PRL'05
  ii) symmetry restored for 3-body state Bergström, PLB '89
- model-dependent spectrum
- important e.g. in mSUGRA

IB and SUSY

- Neutralino annihilation helicity suppressed: $\langle \sigma v \rangle \propto \frac{m_\ell^2}{m_\chi^2}$

IB and SUSY

- Neutralino annihilation ~~helicity~~ suppressed: $\langle\sigma v\rangle \propto \cancel{\frac{m_\ell^2}{m_\chi^2}} \quad \frac{\alpha_{\rm em}}{\pi}$

  ➜ $\langle\sigma v\rangle_{3-\mathrm{body}} \gg \langle\sigma v\rangle_{2-\mathrm{body}}$ *possible!*

IB and SUSY

- Neutralino annihilation ~~helicity~~ suppressed: $\langle \sigma v \rangle \propto \cancel{\frac{m_\ell^2}{m_\chi^2}}$ $\frac{\alpha_{\rm em}}{\pi}$

  ➜ $\langle \sigma v \rangle_{3-\rm body} \gg \langle \sigma v \rangle_{2-\rm body}$ *possible!*

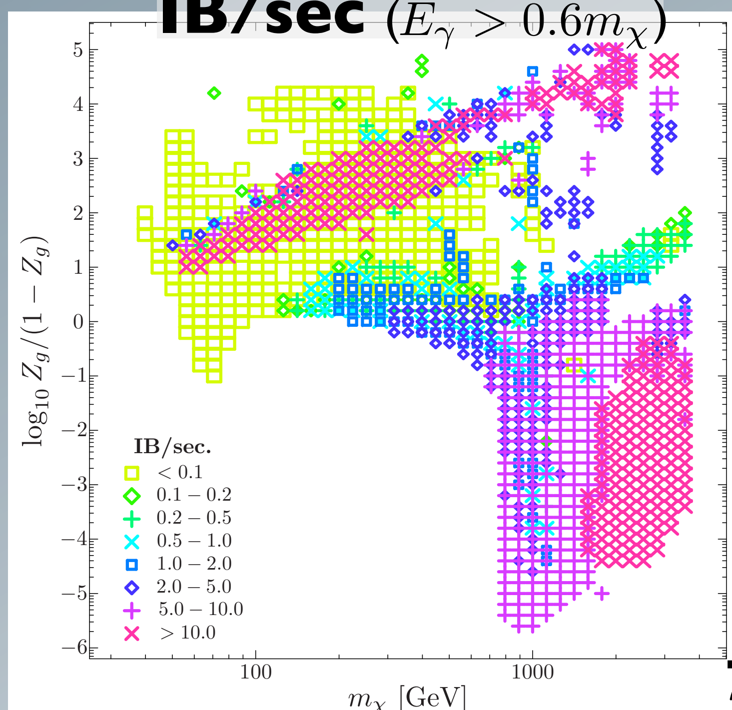
- Full implementation in DarkSUSY, scan mSUGRA and MSSM: TB, Edsjö & Bergström, JHEP '08

Gaugino →

mixed →

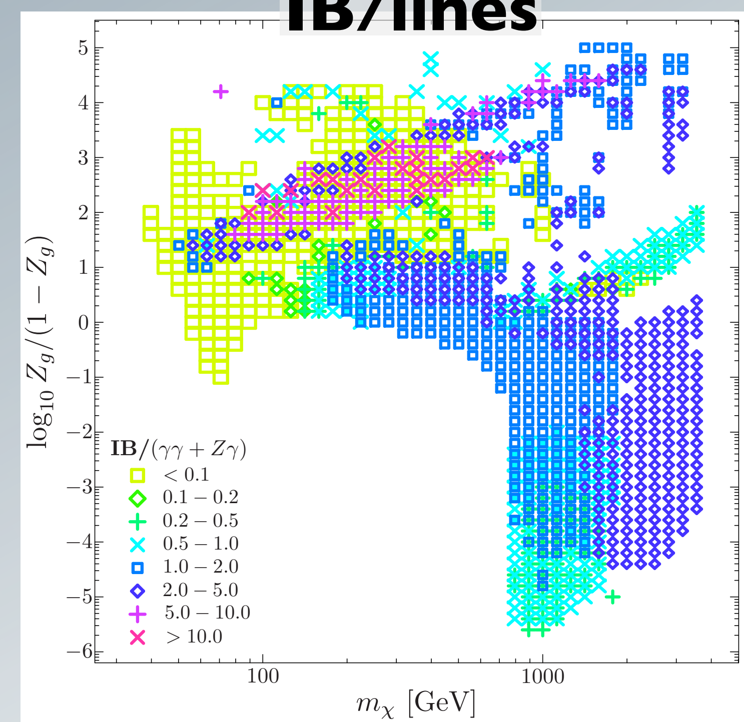
Higgsino →

IB/sec $(E_\gamma > 0.6 m_\chi)$

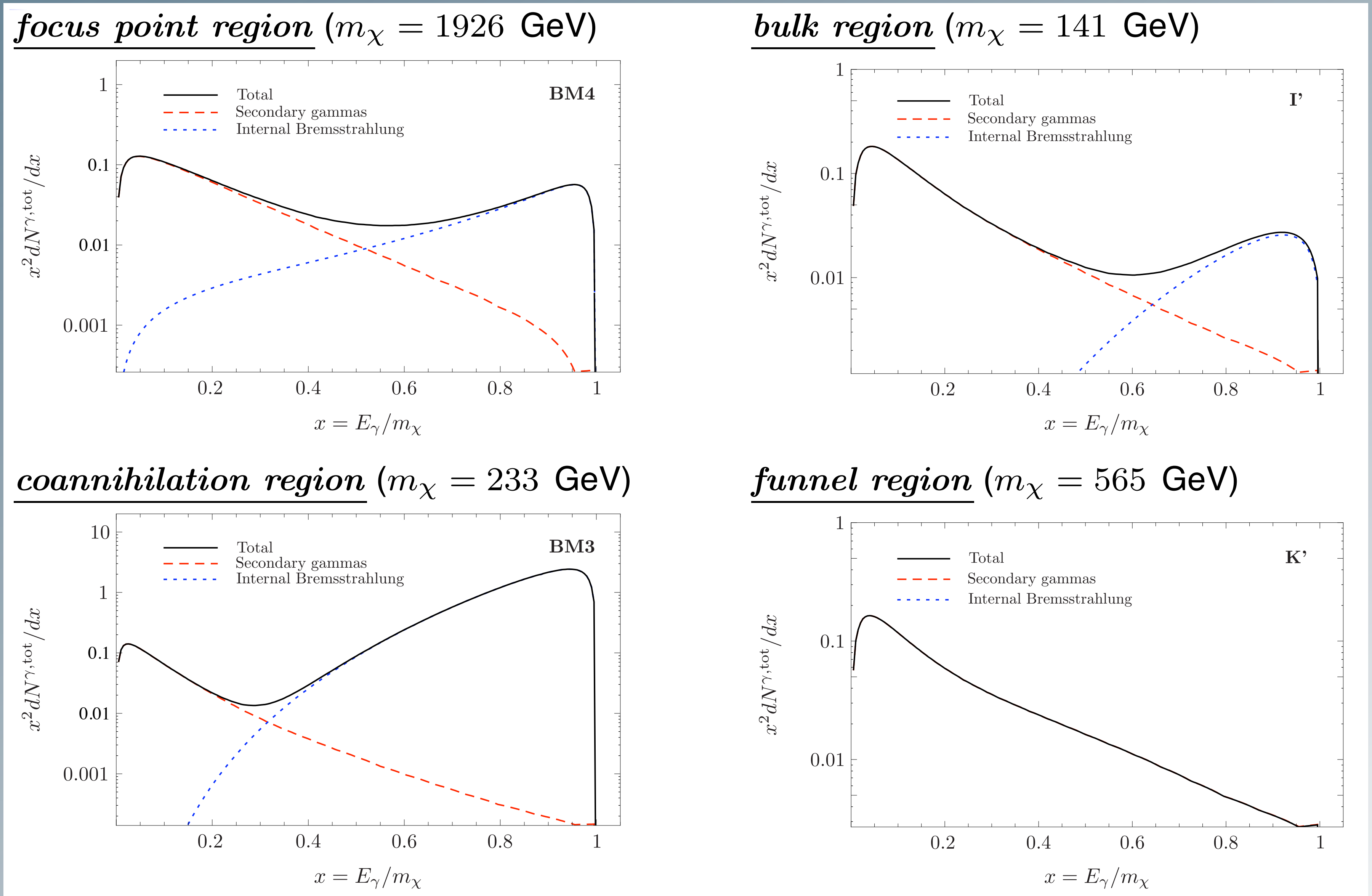


$\longrightarrow m_\chi$

IB/lines



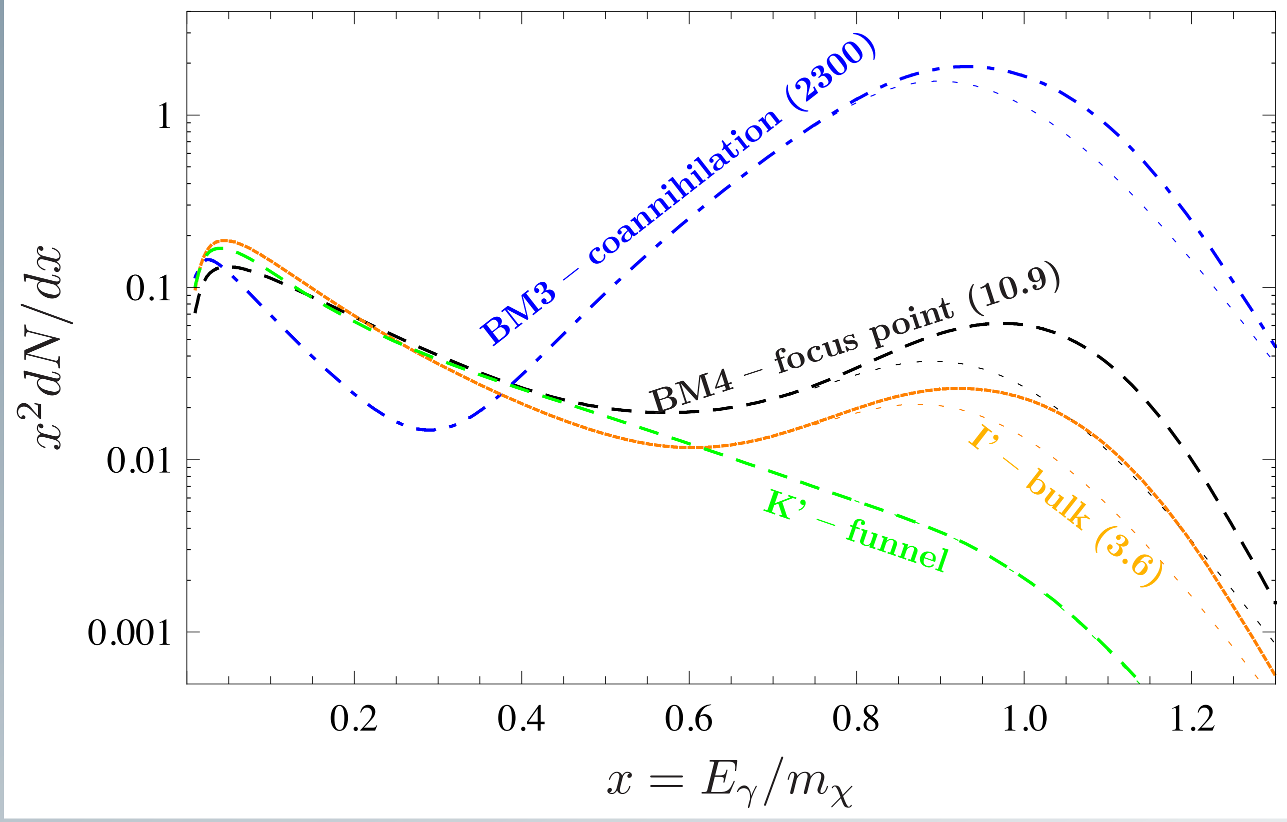
mSUGRA spectra



(benchmarks taken from TB, Edsjö & Bergström, JHEP '08 and Battaglia et al., EPJC '03)

Comparing DM spectra

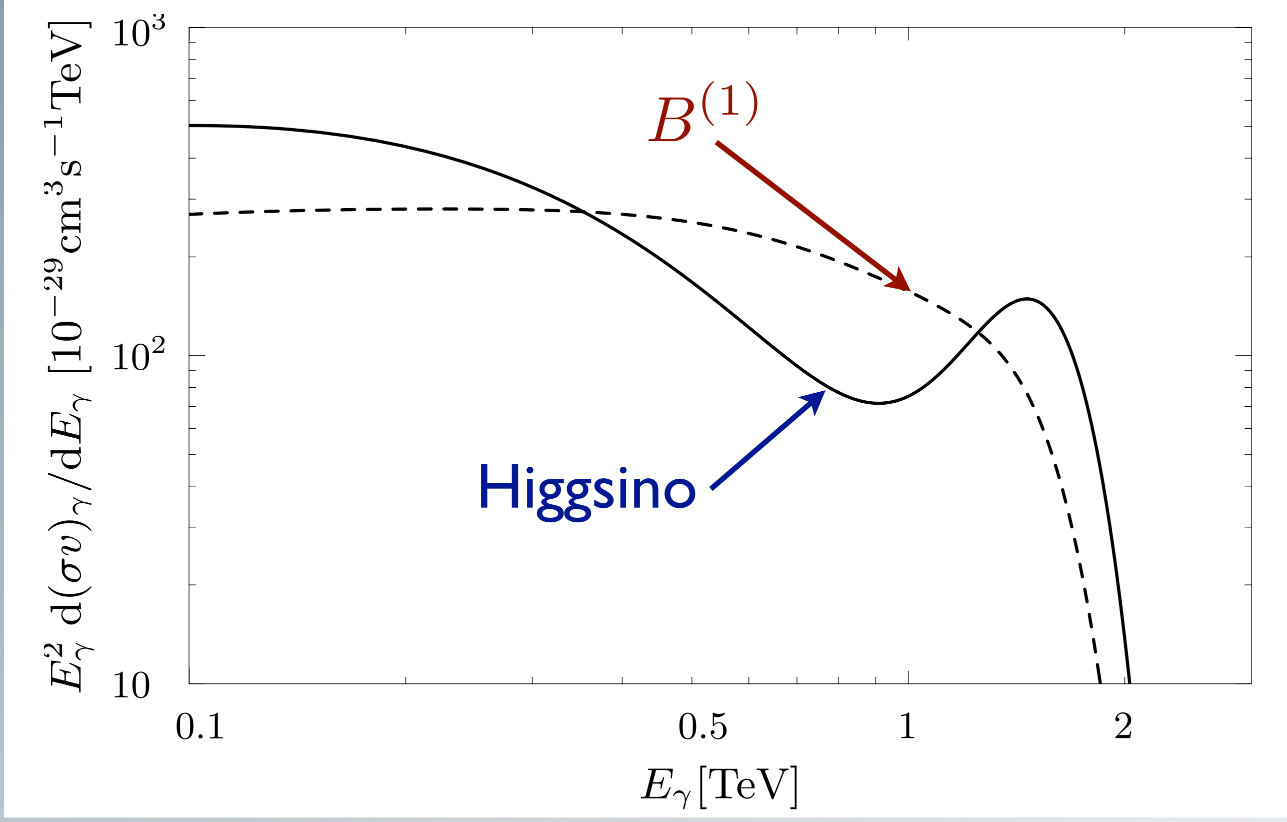
- (Very) pronounced cut-off at $E_\gamma = m_\chi$
- Further features at slightly lower energies
- Could be used to distinguish DM candidates!
  - Example: mSUGRA benchmarks (assume energy resolution of 10%)



TB, PoS '08

Comparing DM spectra

- (Very) pronounced cut-off at $E_\gamma = m_\chi$
- Further features at slightly lower energies
- Could be used to distinguish DM candidates!
  - Example: Higgsino vs KK-DM (about same mass; assume $\Delta E = 15\%$)



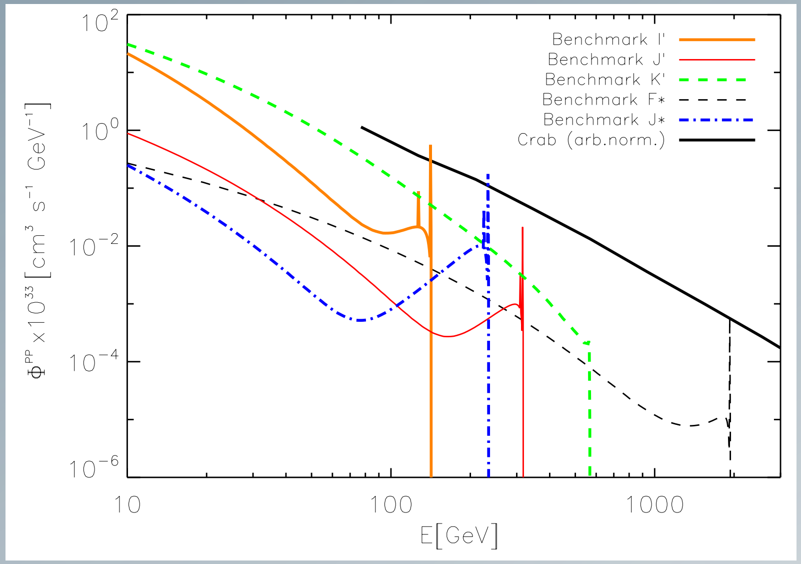
Bergström *et al.*, '06

IB: total flux enhancement

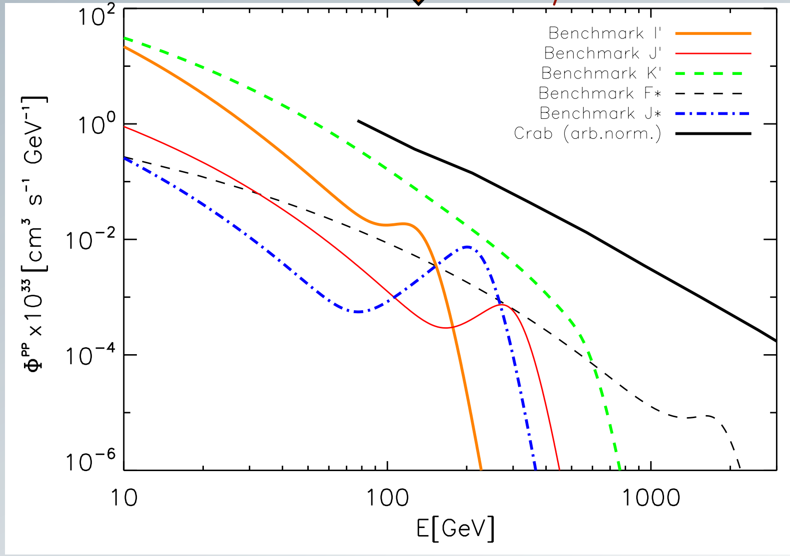
- IB contributions important at high energies
  $\rightsquigarrow$ this is where Air Cherenkov Telescopes are most sensitive!

IB: total flux enhancement

- IB contributions important at high energies
  ⇝ this is where Air Cherenkov Telescopes are most sensitive!
- Example: Dwarf galaxies
  - IB boosts effective sensitivity by a factor of up to ~10
    TB, Doro & Fornasa, JCAP '09
    Cannoni et al., PRD '10
  - CTA could see a DM signal from Willman 1 for a large class of models (less optimistic prospects for Draco)



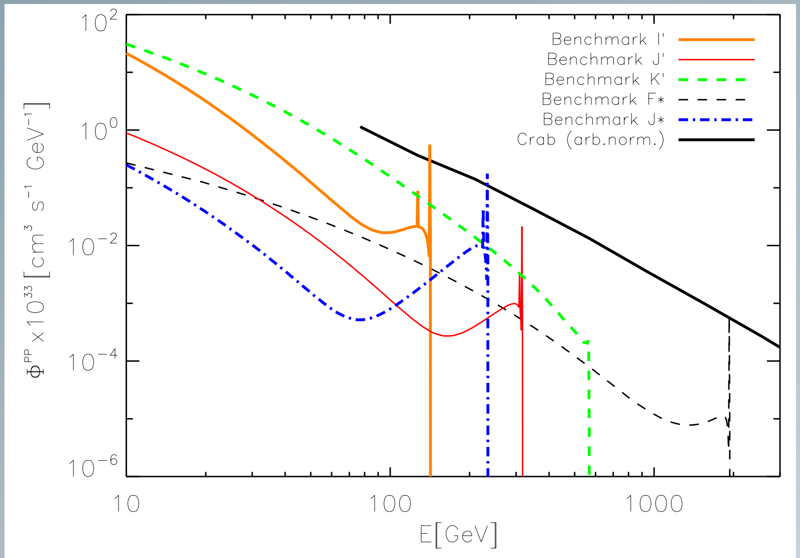
$\Delta E/E = 10\%$



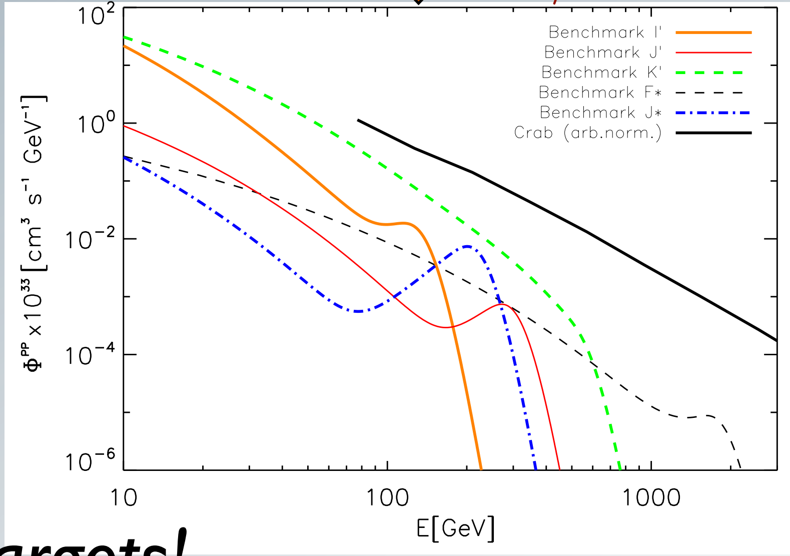
TB, Doro & Fornasa, JCAP '09

IB: total flux enhancement

- IB contributions important at high energies
  ⇝ this is where Air Cherenkov Telescopes are most sensitive!



$\Delta E/E = 10\%$



TB, Doro & Fornasa, JCAP '09

- Example: Dwarf galaxies
  - IB boosts effective sensitivity by a factor of up to ~10

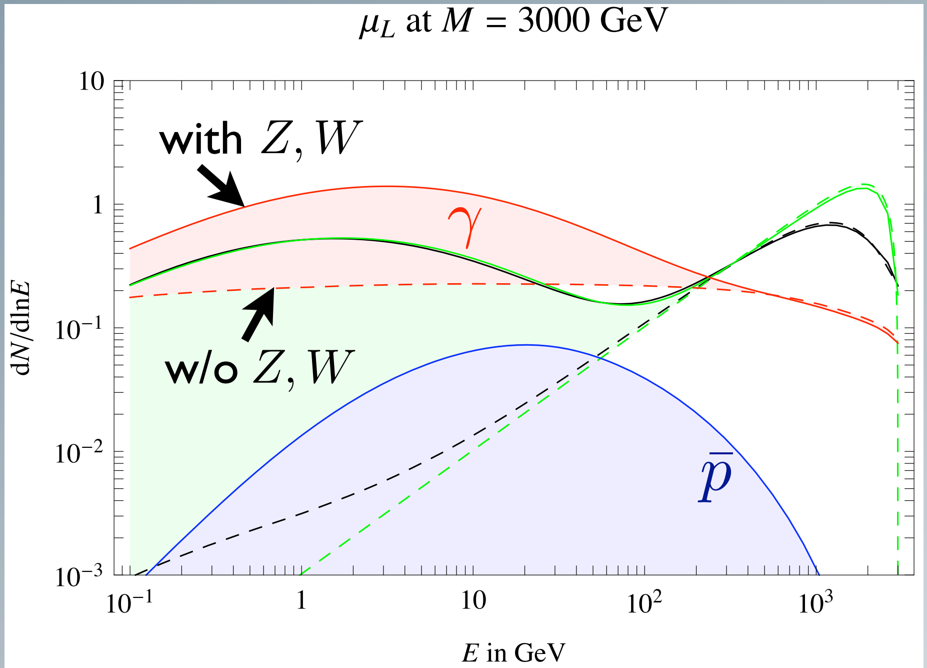
    TB, Doro & Fornasa, JCAP '09
    Cannoni et al., PRD '10
  - CTA could see a DM signal from Willman 1 for a large class of models (less optimistic prospects for Draco)

⇨ *important to include also for other targets!*

Electroweak corrections

- FSR of Z and $W^{\pm}$:
  - can open new channels like $\bar{p}$ ($\rightsquigarrow$ leptophilic models!)
  - sizable changes in spectrum for large m_χ (mostly at small E_γ)

Bell, Dent, Jacques & Weiler, PRD '08
Kachelriess, Serpico & Solberg, PRD '09
Ciafaloni & Urbano, PRD '10

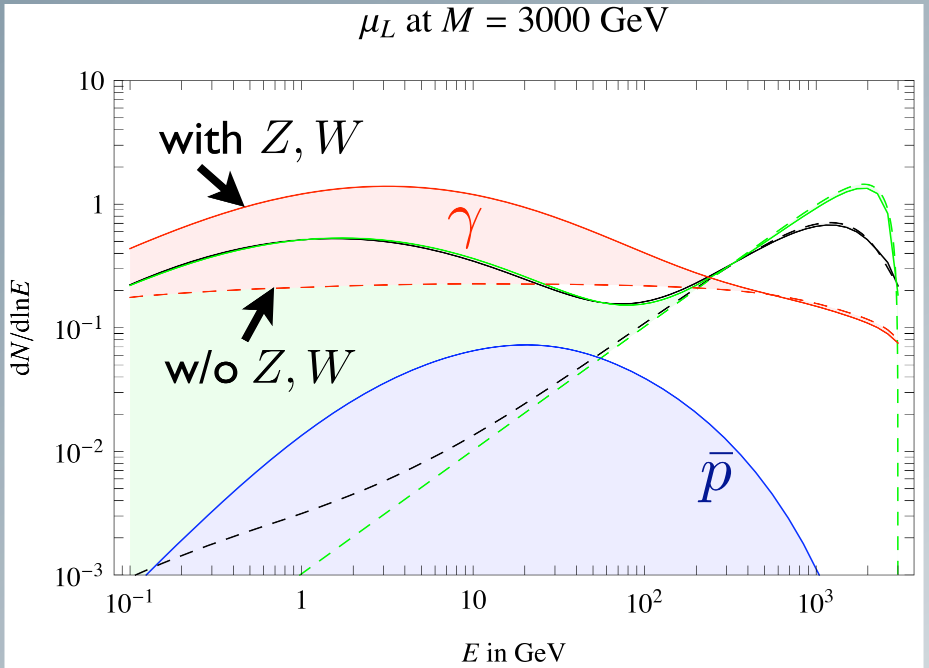


Ciafaloni *et al.*, 1009.0224

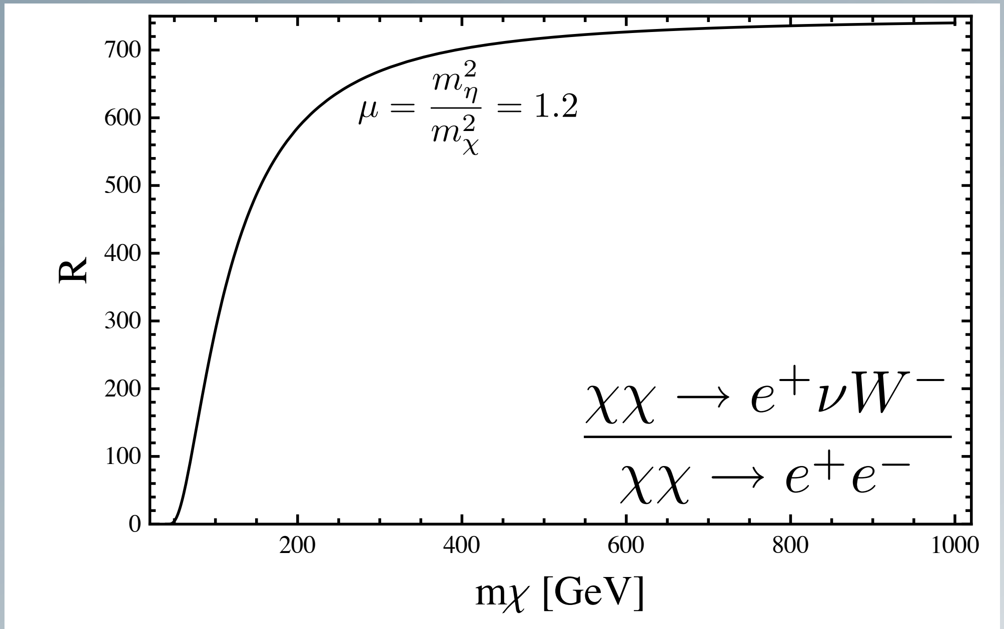
Electroweak corrections

- FSR of Z and $W^{\pm}$:
  - can open new channels like $\bar{p}$ ($\rightsquigarrow$ leptophilic models!)
  - sizable changes in spectrum for large m_χ (mostly at small E_γ)

Bell, Dent, Jacques & Weiler, PRD '08
Kachelriess, Serpico & Solberg, PRD '09
Ciafaloni & Urbano, PRD '10



Ciafaloni *et al.*, 1009.0224

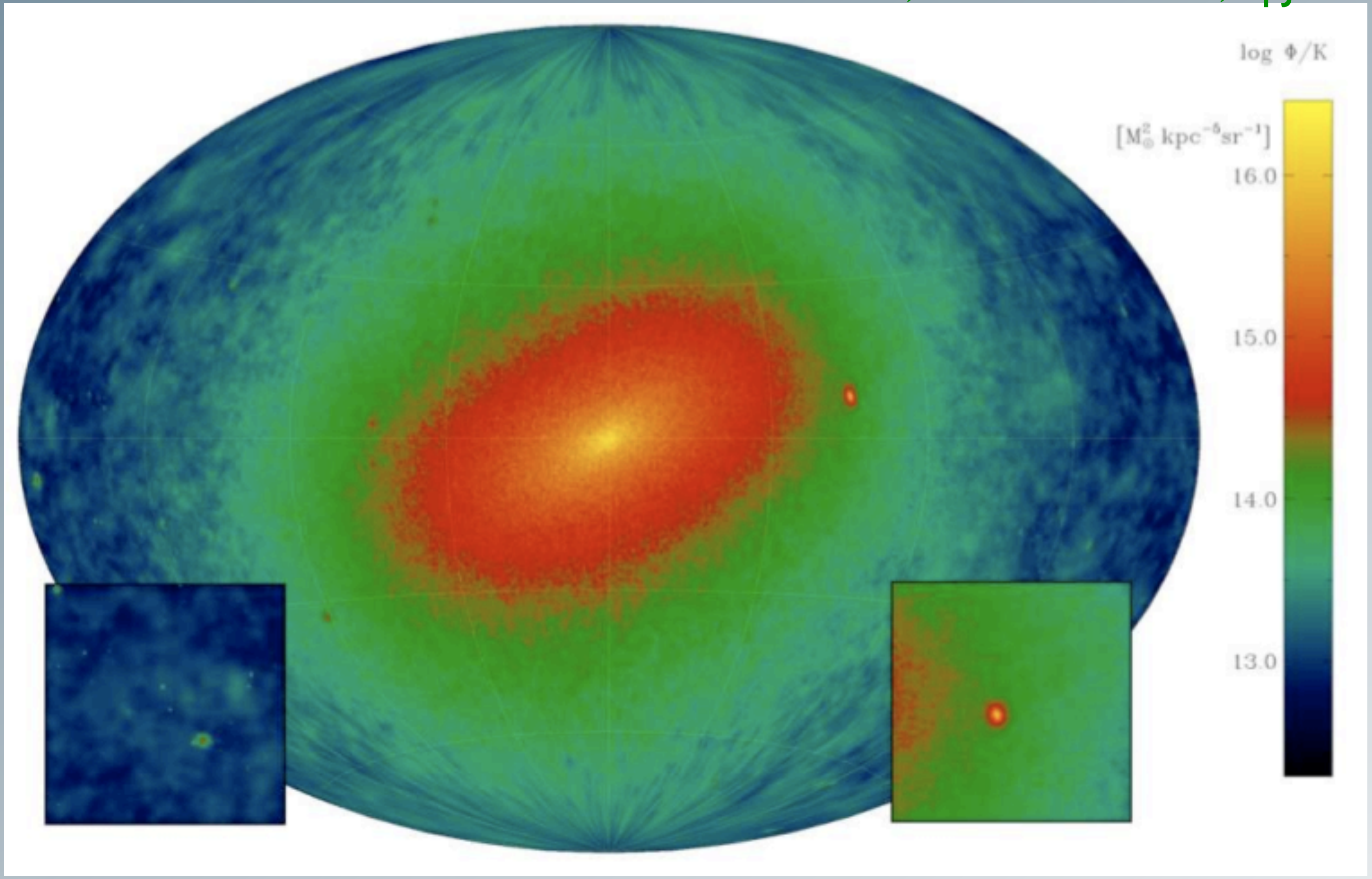


- VIB lifts helicity or v^2 suppression (just like for photons, but numerically larger effect!)

Ciafaloni *et al.*, 1104.2996
Bell *et al.*, 1104.3823

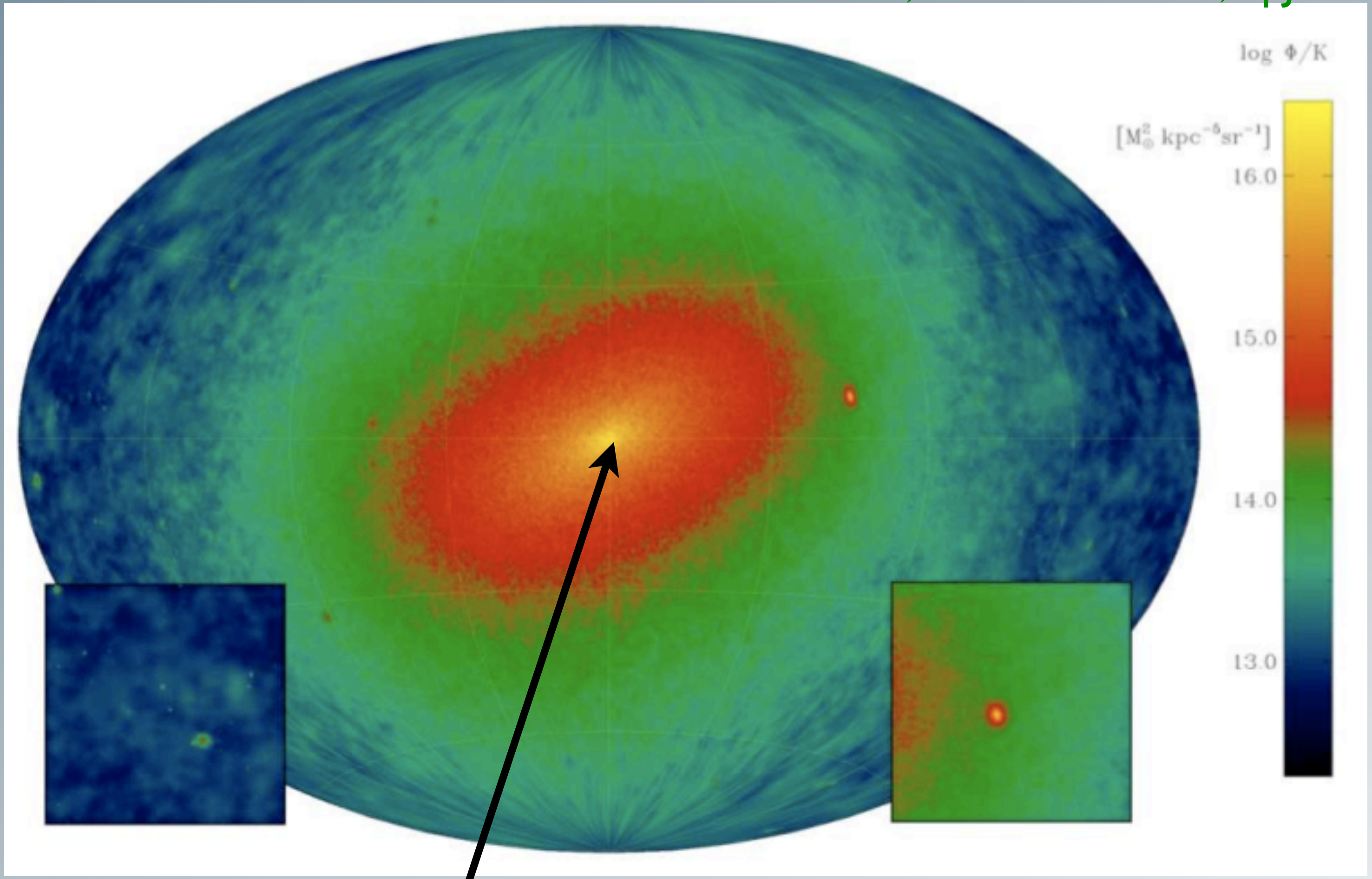
Where to look

Diemand, Kuhlen & Madau, ApJ '07



Where to look

Diemand, Kuhlen & Madau, ApJ '07

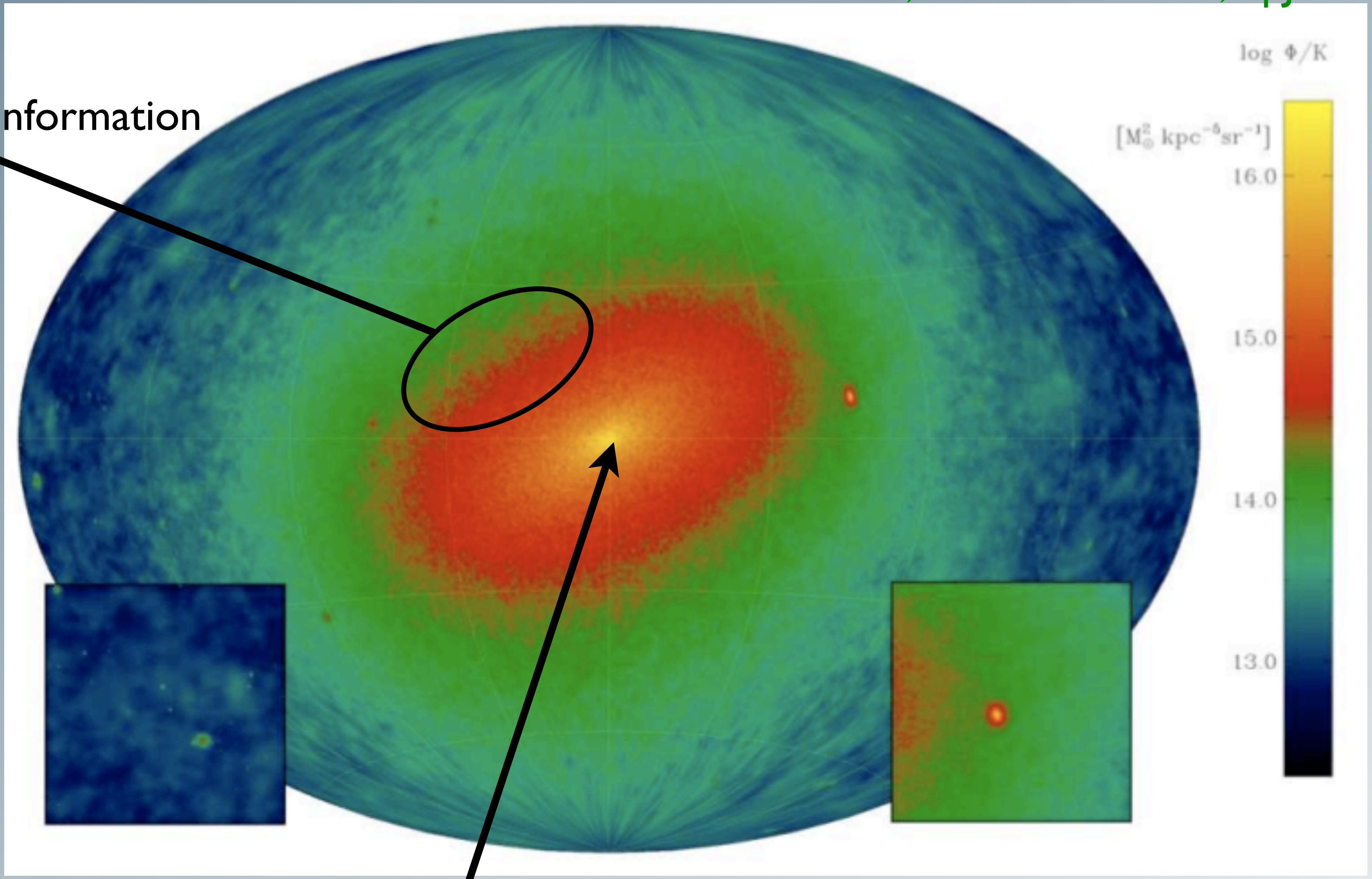


Galactic center

- brightest DM source in sky
- large background contributions

Where to look

Diemand, Kuhlen & Madau, ApJ '07



Galactic halo

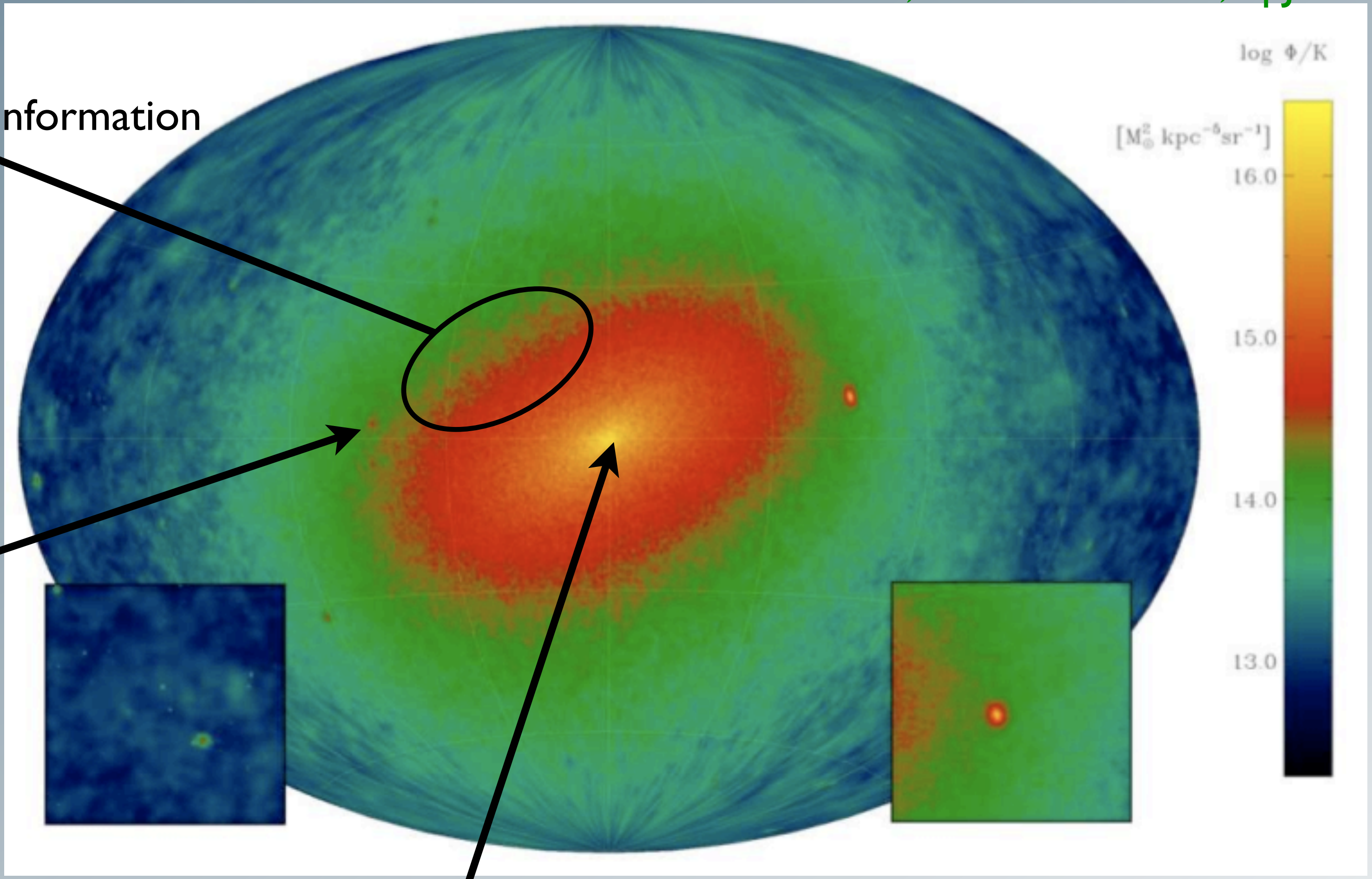
- good statistics, angular information
- galactic backgrounds?

Galactic center

- brightest DM source in sky
- large background contributions

Where to look

Diemand, Kuhlen & Madau, ApJ '07



Galactic halo

- good statistics, angular information
- galactic backgrounds?

Dwarf Galaxies

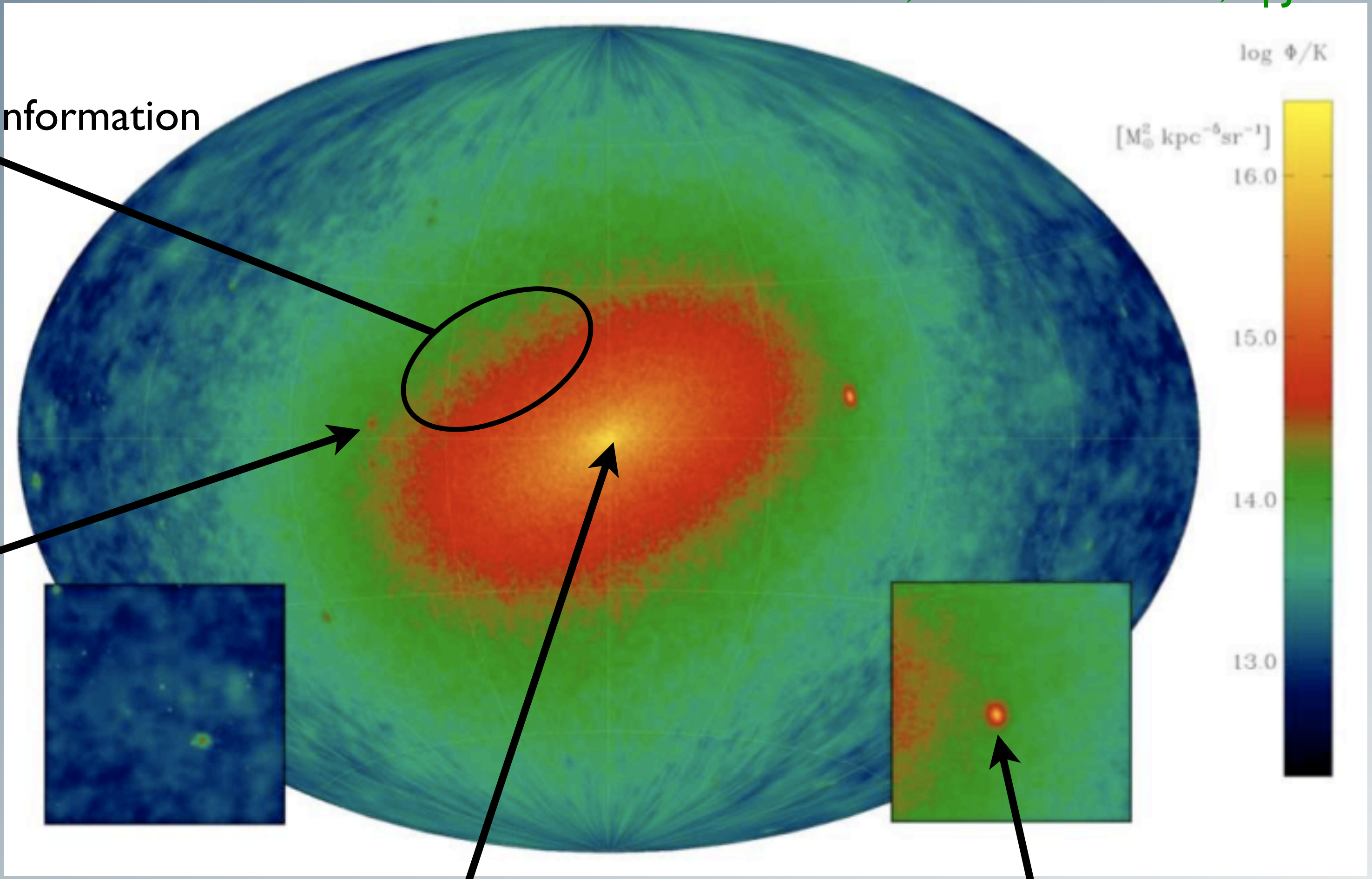
- DM dominated, M/L~1000
- fluxes soon in reach!

Galactic center

- brightest DM source in sky
- large background contributions

Where to look

Diemand, Kuhlen & Madau, ApJ '07



Galactic halo

- good statistics, angular information
- galactic backgrounds?

Dwarf Galaxies

- DM dominated, M/L~1000
- fluxes soon in reach!

Galactic center

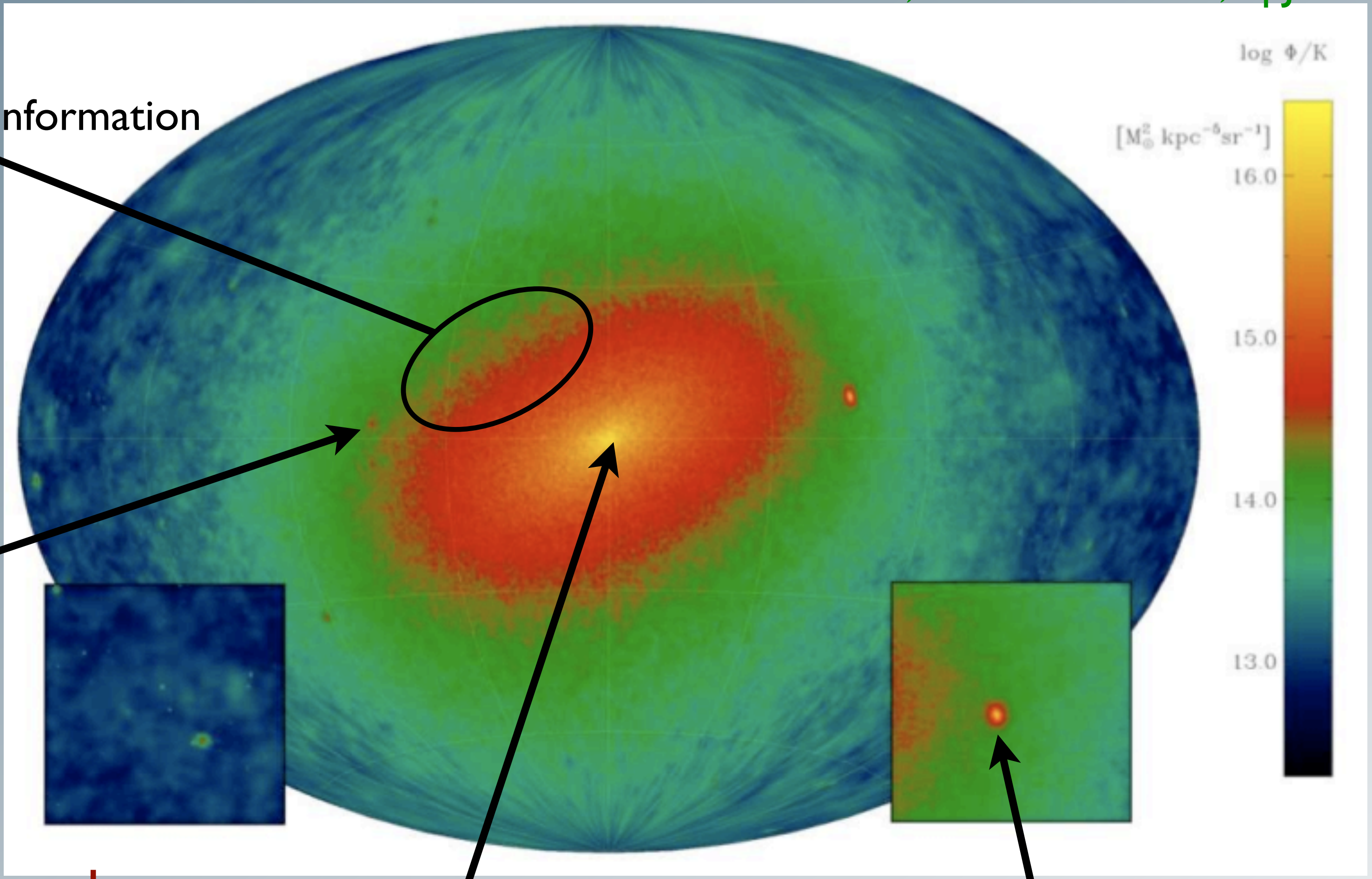
- brightest DM source in sky
- large background contributions

DM clumps

- easy discrimination (once found)
- bright enough?

Where to look

Diemand, Kuhlen & Madau, ApJ '07



Galactic halo

- good statistics, angular information
- galactic backgrounds?

Dwarf Galaxies

- DM dominated, M/L~1000
- fluxes soon in reach!

Extragalactic background

- DM contribution from all z
- background difficult to model

Galactic center

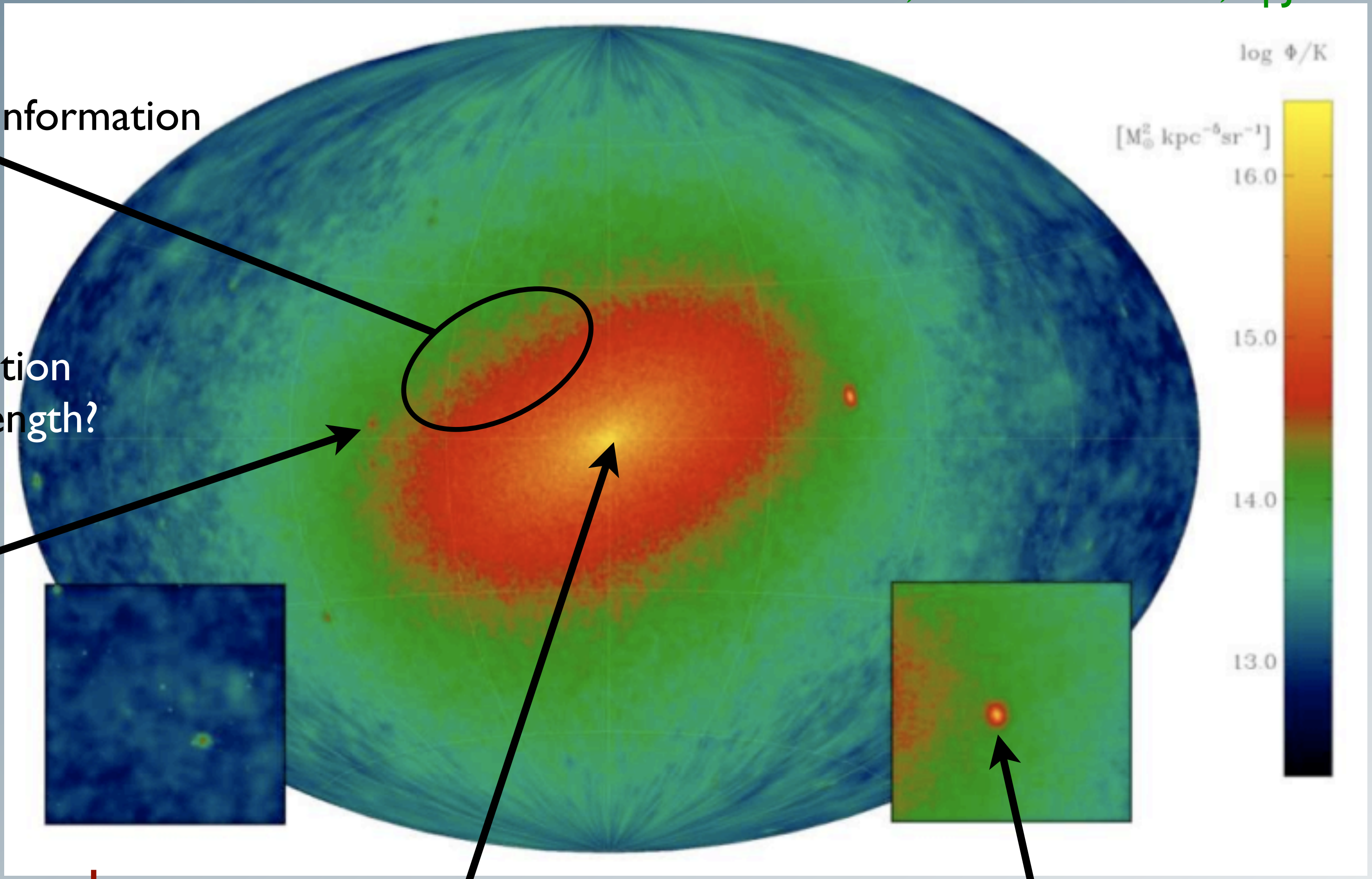
- brightest DM source in sky
- large background contributions

DM clumps

- easy discrimination (once found)
- bright enough?

Where to look

Diemand, Kuhlen & Madau, ApJ '07



Galactic halo

- good statistics, angular information
- galactic backgrounds?

Galaxy clusters

- cosmic ray contamination
- better in multi-wavelength?

Dwarf Galaxies

- DM dominated, M/L~1000
- fluxes soon in reach!

Extragalactic background

- DM contribution from all z
- background difficult to model

Galactic center

- brightest DM source in sky
- large background contributions

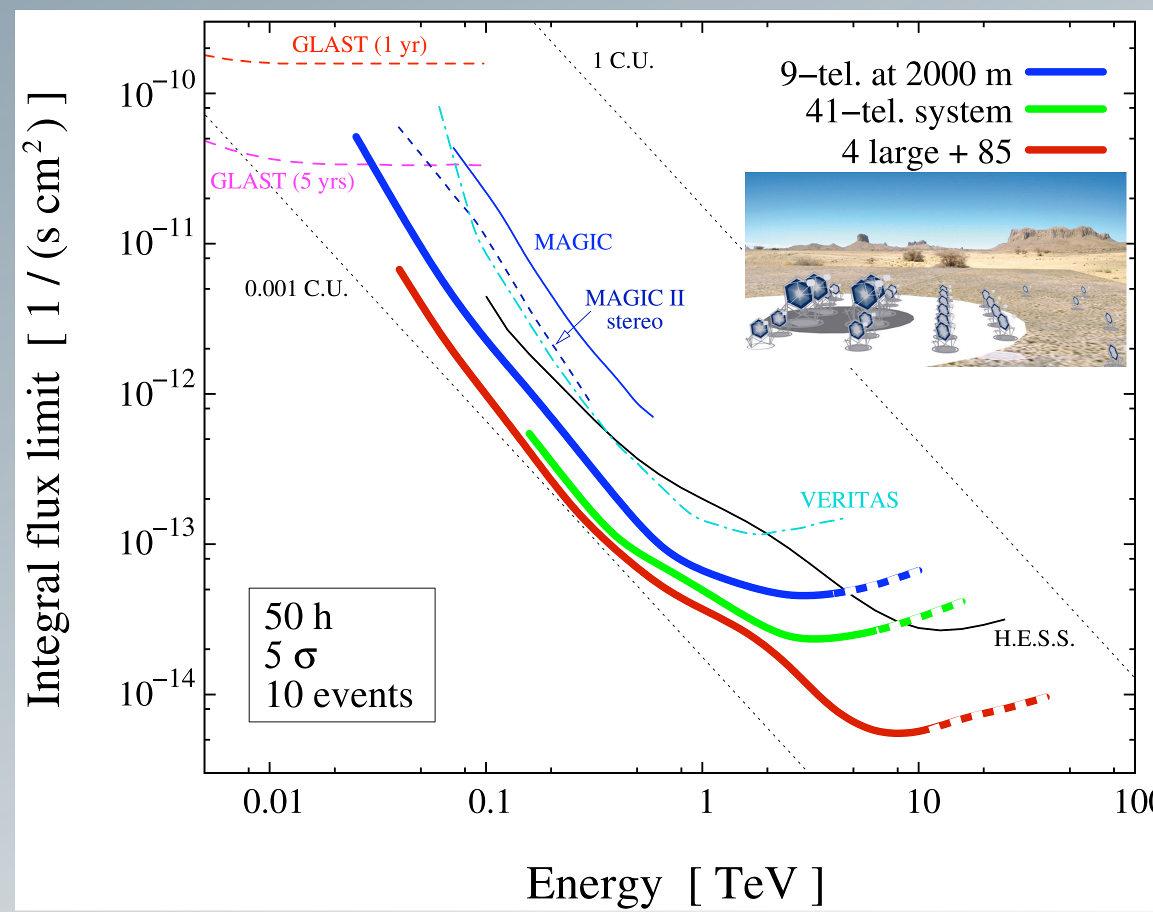
DM clumps

- easy discrimination (once found)
- bright enough?

Sensitivities

Ground-based

- large eff. Area (~km^2)
- small field of view
- lower threshold $\gtrsim$ 40 GeV



Bernlöhr et al., '07

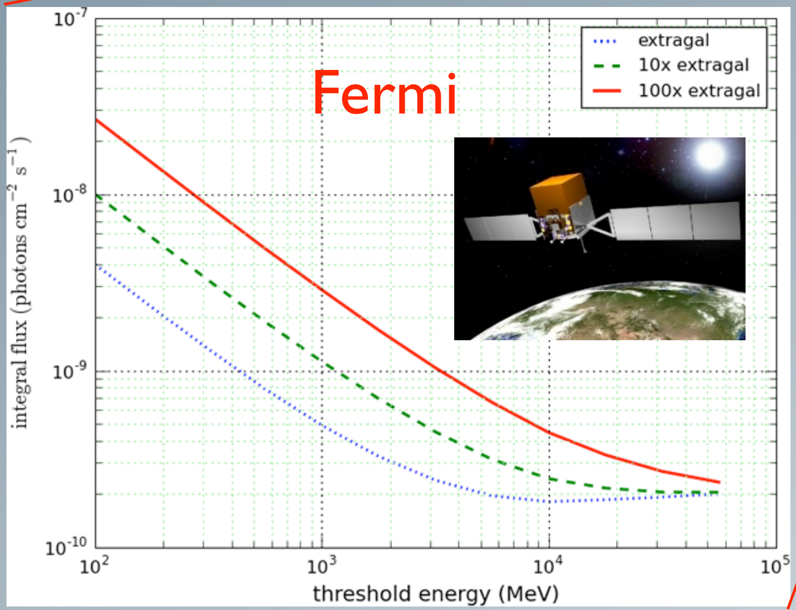
Sensitivities

Space-borne

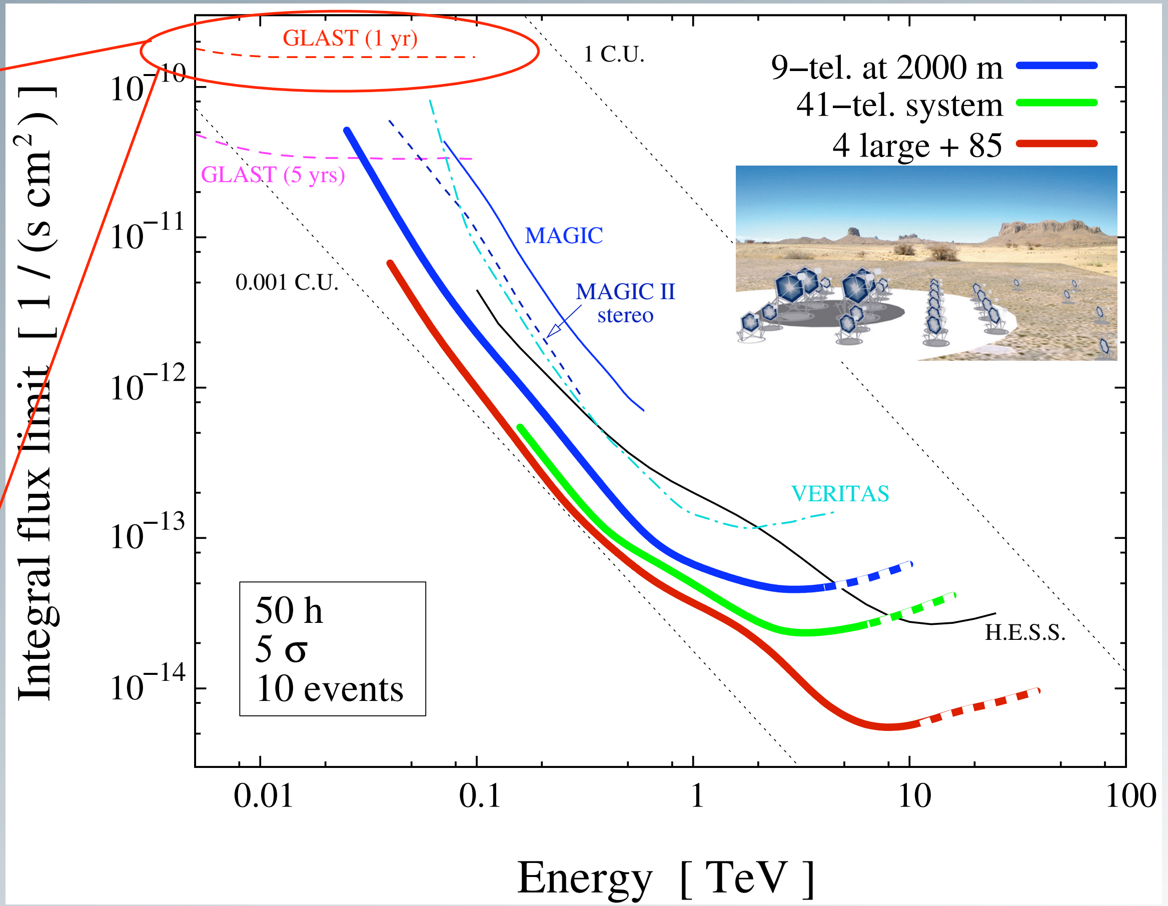
- small eff. Area (~m^2)
- large field of view
- upper bound on resolvable E_γ

Ground-based

- large eff. Area (~km^2)
- small field of view
- lower threshold $\gtrsim$ 40 GeV



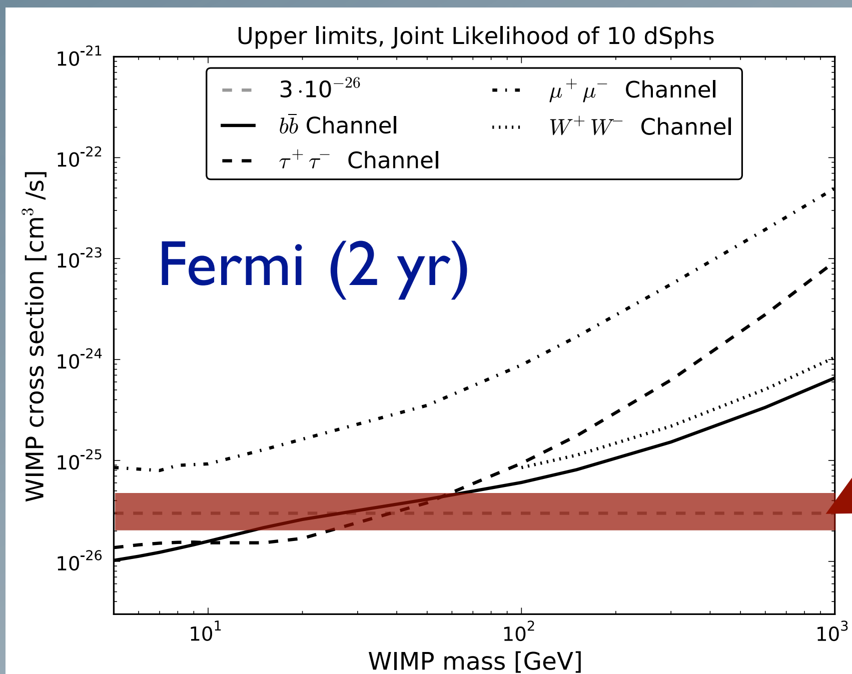
(from the LAT webpage)



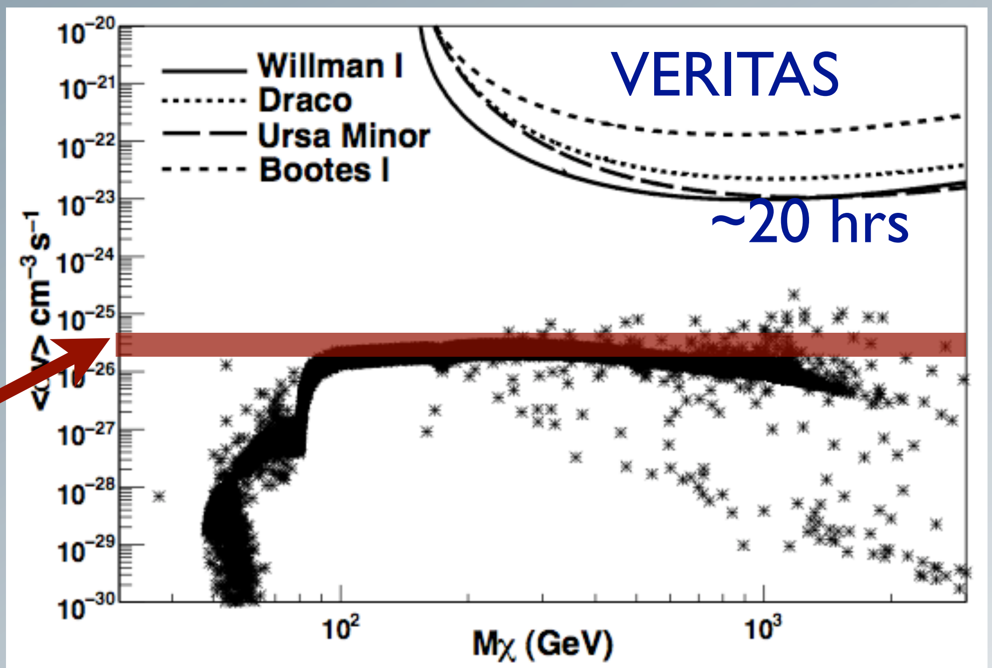
Bernlöhr et al., '07

Observational status: dwarfs

- Greatly improved recent limits from Dwarf galaxies:



standard thermal value



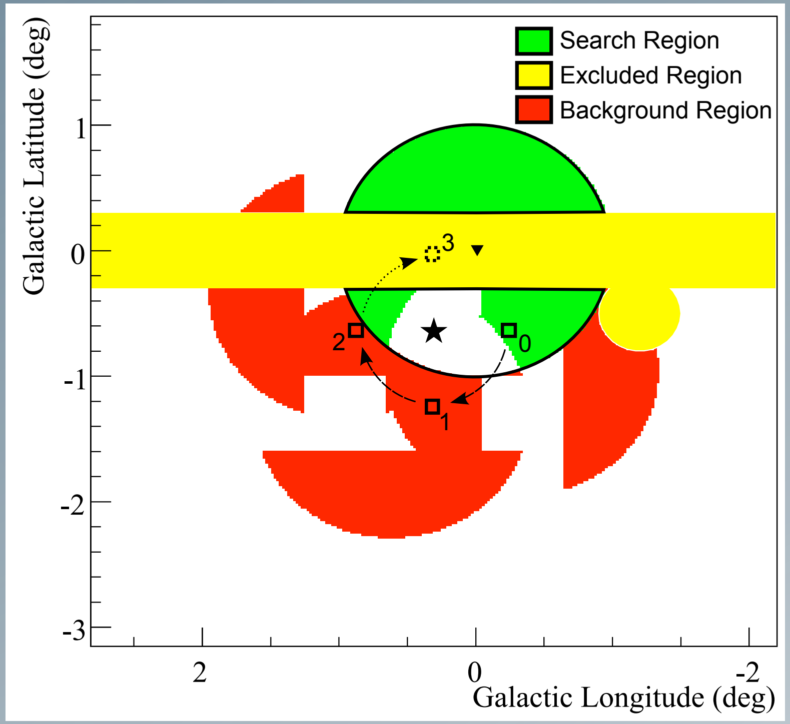
Ackermann *et al*, 1108.3546

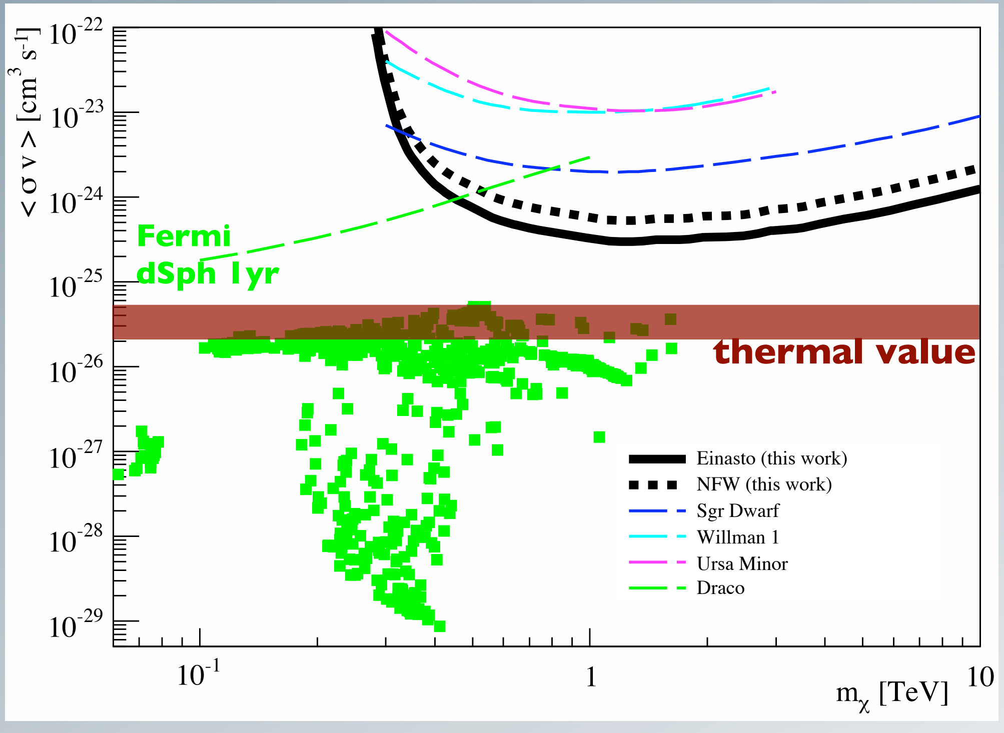
Acciari *et al*, 1006.5955

- So far no (unambiguous) DM signals seen
- Limits will improve with increased exposure

Galactic center

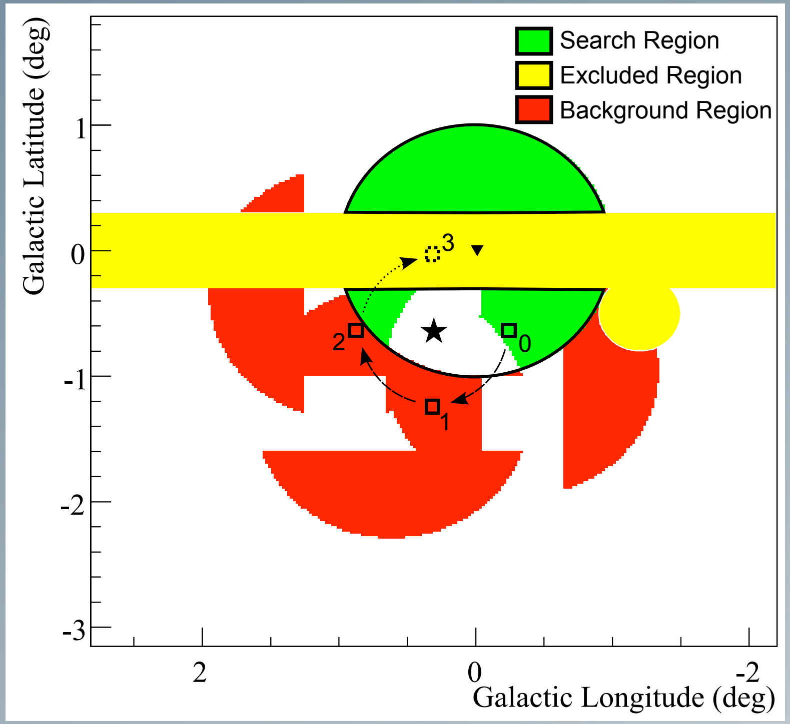
- Recent strong limits from HESS by using a clever background subtraction method: Abramowski *et al*, 1103.3266

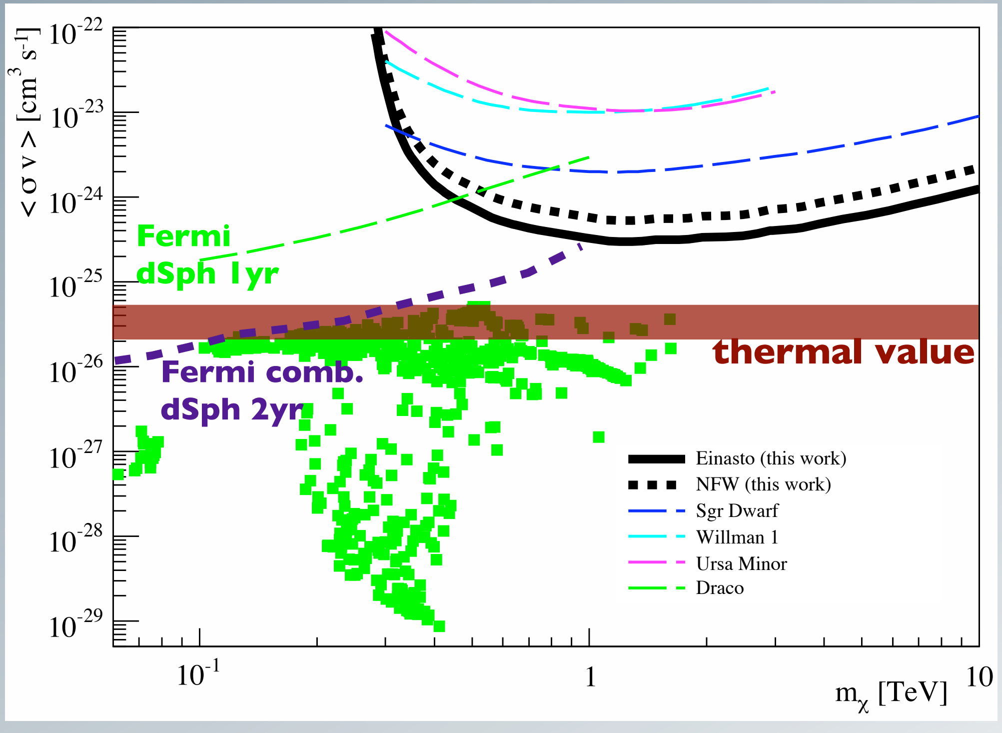




Galactic center

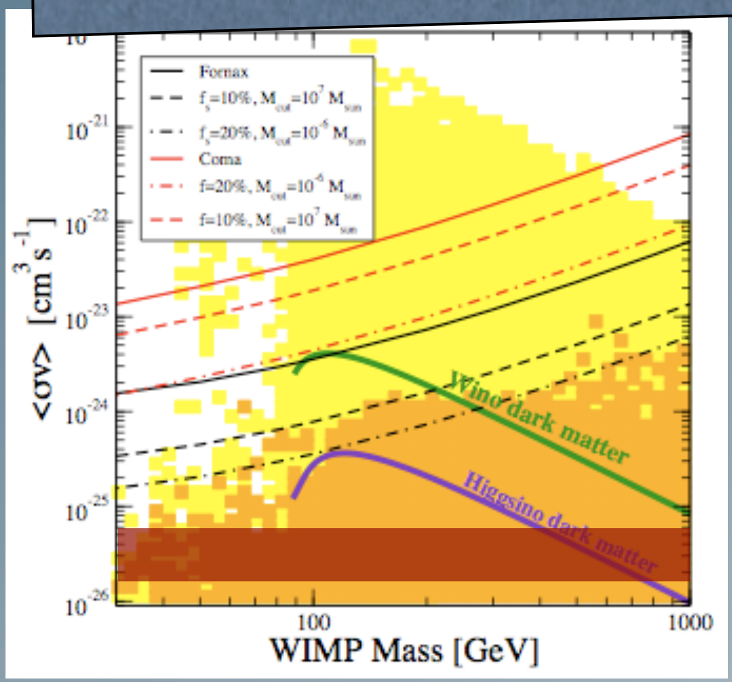
- Recent strong limits from HESS by using a clever background subtraction method: Abramowski *et al*, 1103.3266





⇨ Indirect searches start to be very competitive!

Galaxy clusters & diff. BG

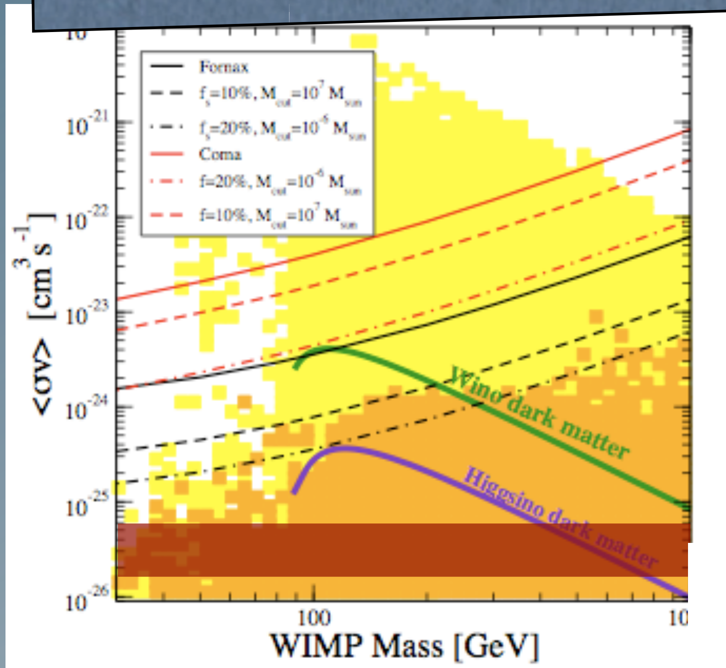


Almost as constraining: galaxy clusters

(NB: much better discovery potential!)

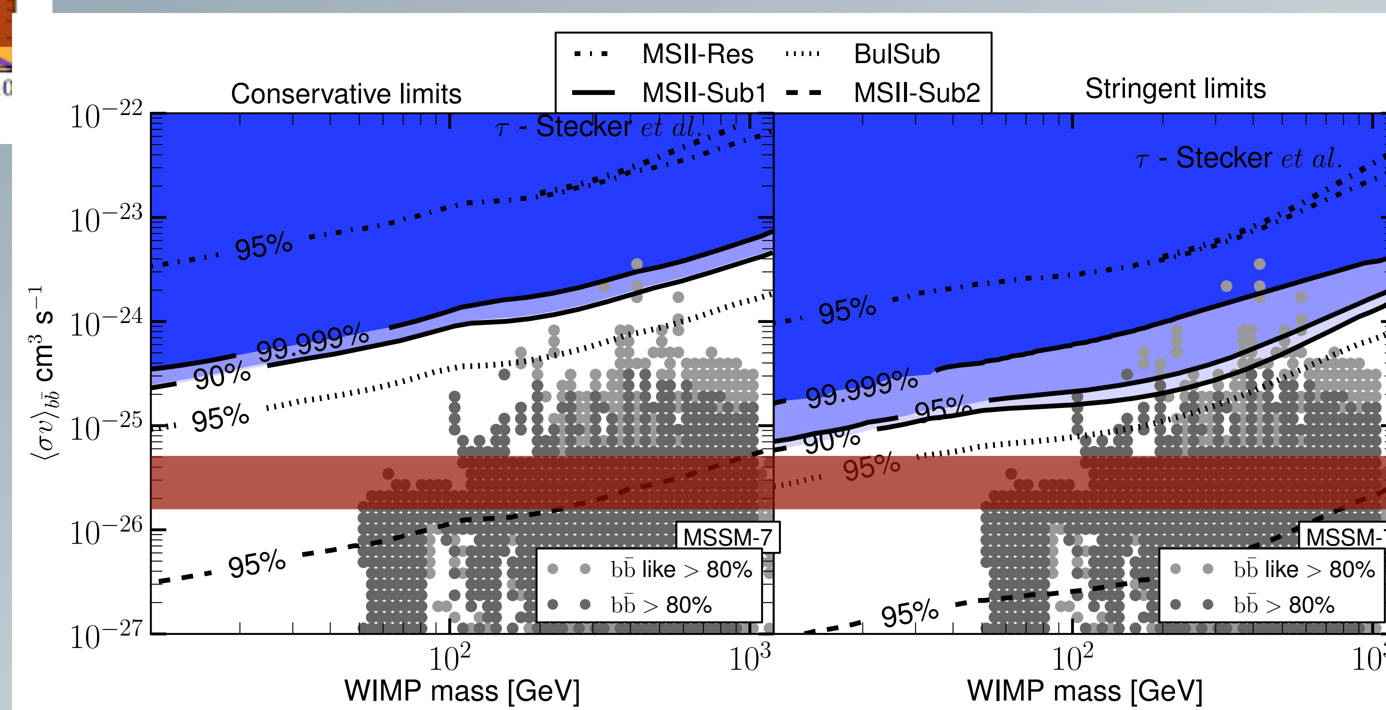
Ackermann *et al*, 1001.4531 [Fermi-LAT collaboration]

Galaxy clusters & diff. BG



Constraints from the diffuse gamma-ray background depend strongly on subhalo model

Abdo *et al*, 1001.4531
[Fermi-LAT collaboration]



Almost as constraining:
galaxy clusters
(NB: much better discovery potential!)

Ackermann *et al*, 1001.4531
[Fermi-LAT collaboration]

UCMHs

- Ultracompact Minihalos are DM halos that form shortly after matter-radiation equality Ricotti & Gould, ApJ '09
  - isolated collapse
  - formation by radial infall (Bertschinger, ApJS '95)

$$\longrightarrow \qquad \rho \propto r^{-9/4}$$

UCMHs

- Ultracompact Minihalos are DM halos that form shortly after matter-radiation equality Ricotti & Gould, ApJ '09
  - isolated collapse
  - formation by radial infall (Bertschinger, ApJS '95)

$$\longrightarrow \qquad \rho \propto r^{-9/4}$$

- Excellent targets for indirect detection with gamma rays

Scott & Sivertsson, PRL '09
Lacki & Beacom, ApJ '10

UCMHs

- Ultracompact Minihalos are DM halos that form shortly after matter-radiation equality   Ricotti & Gould, ApJ '09
  - isolated collapse
  - formation by radial infall (Bertschinger, ApJS '95)

$$\longrightarrow \quad \rho \propto r^{-9/4}$$

- Excellent targets for indirect detection with gamma rays

Scott & Sivertsson, PRL '09
Lacki & Beacom, ApJ '10

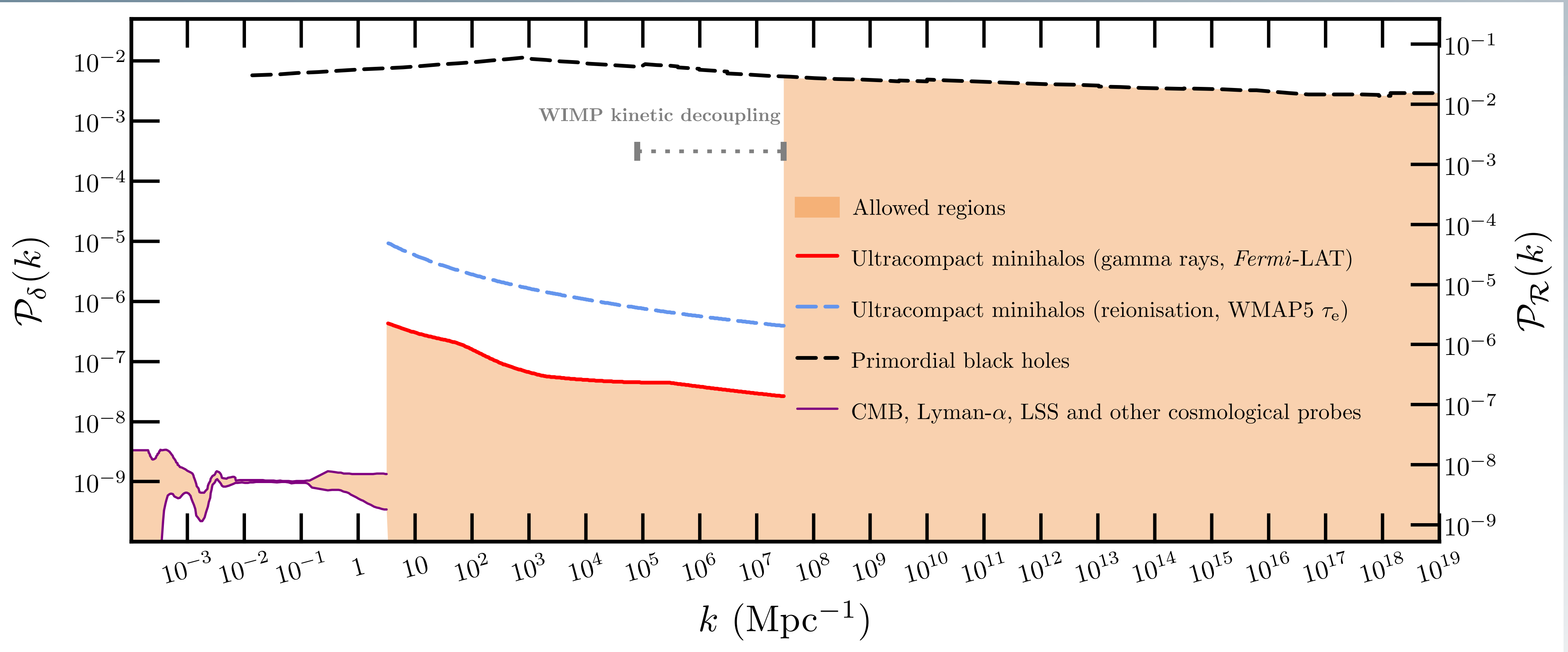
- Required density contrast at horizon entry:

$$\boxed{\delta \equiv \frac{\Delta\rho}{\rho} \sim 10^{-3} \quad @ \quad z \gg z_{\rm eq}}$$

  - PBH: $\delta \gtrsim 0.3$
  - typical observed value: $\delta \sim 10^{-5}$ at 'large' scales

New constraints on $\mathcal{P}(k)$:

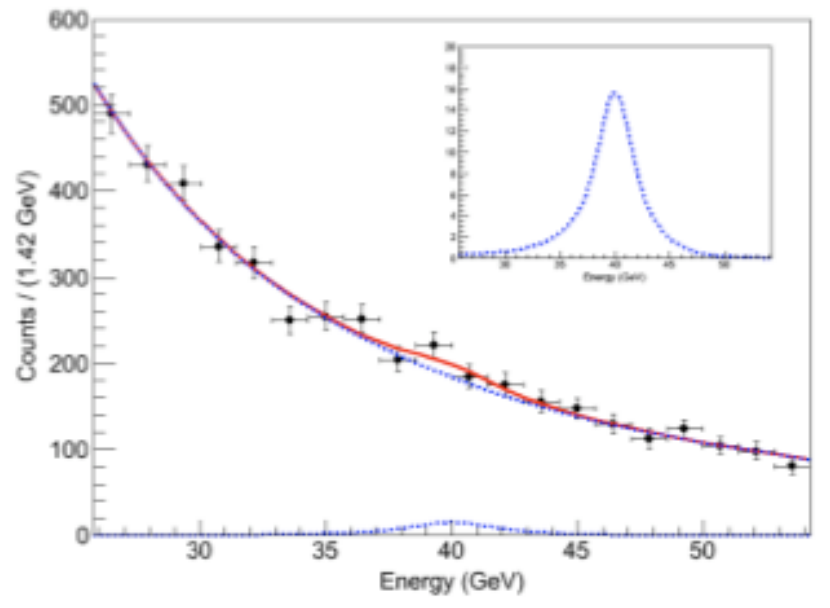
(assuming 1 TeV WIMPs annihilating into $\bar{b}b$)



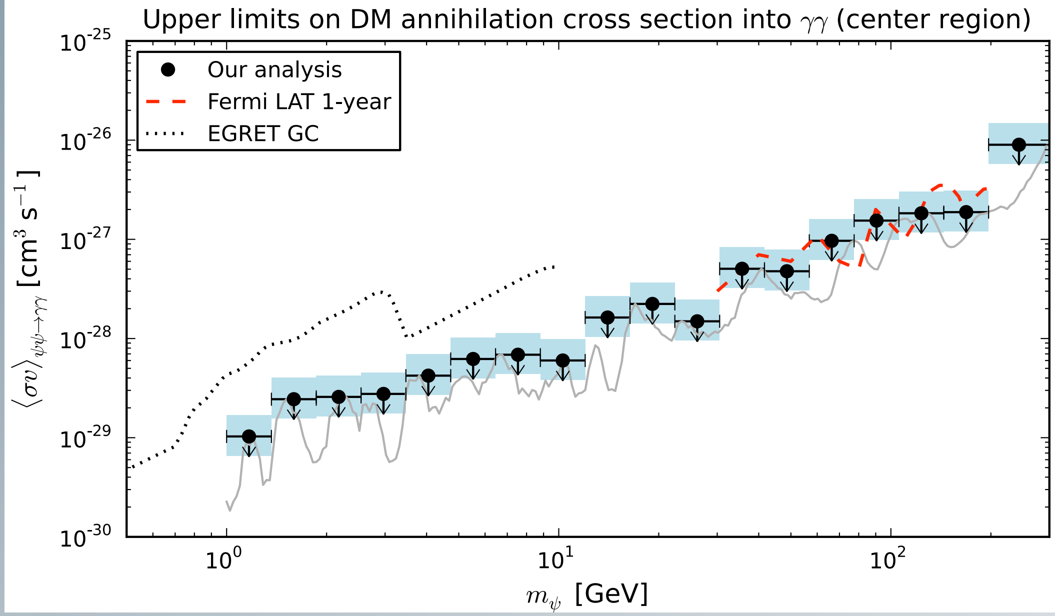
TB, Scott & Akrami, 1110.2484

Line signals@ 2011

- Fermi all-sky search for line signals:



Abdo *et al*, 1001.4836



Vertongen & Weniger, JCAP 2011

- not (yet) probing too much of WIMP parameter space

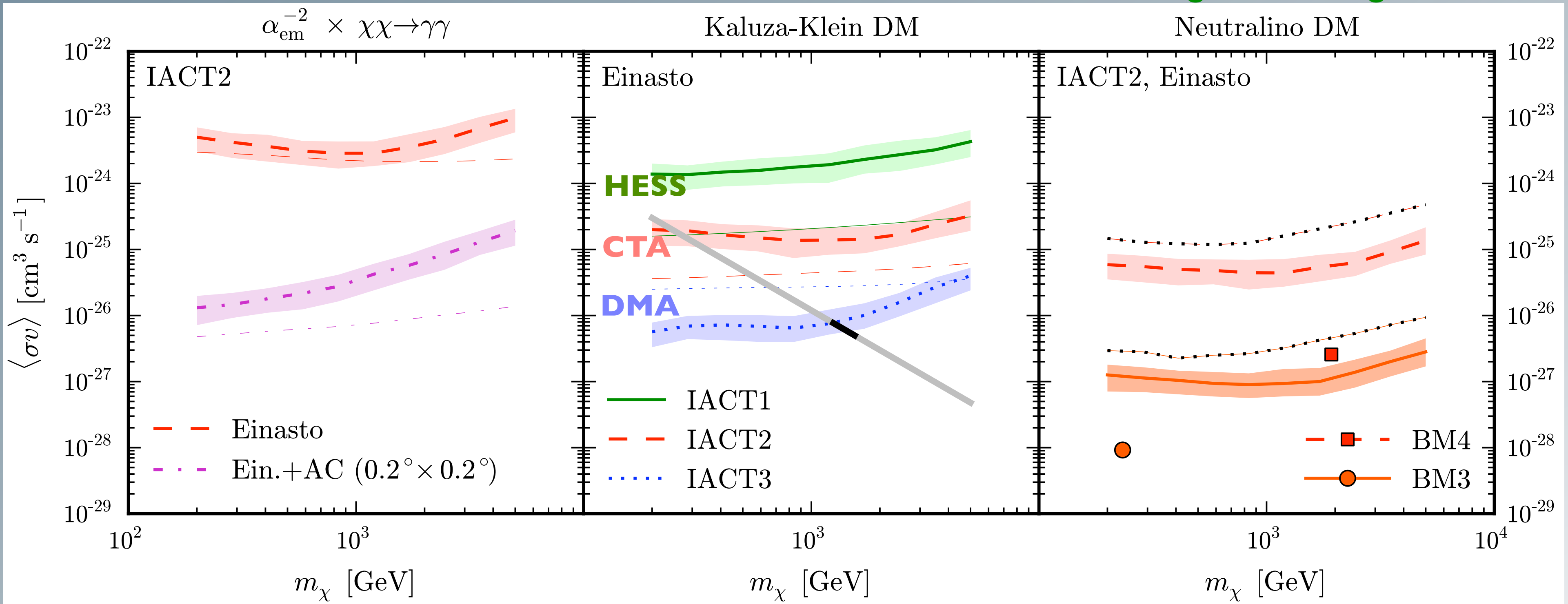
(NB: natural expectation $\langle\sigma v\rangle_{\gamma\gamma} \sim \alpha_{\rm em}^2 \langle\sigma v\rangle_{\rm therm} \simeq 10^{-30}{\rm cm}^3{\rm s}^{-1}$)

- NB: 1y data, simple choice of target region...

Other spectral features

- Searching for other signatures like sharp steps or IB "bumps" may well be more promising:

TB, Calore, Vertongen & Weniger, PRD '10

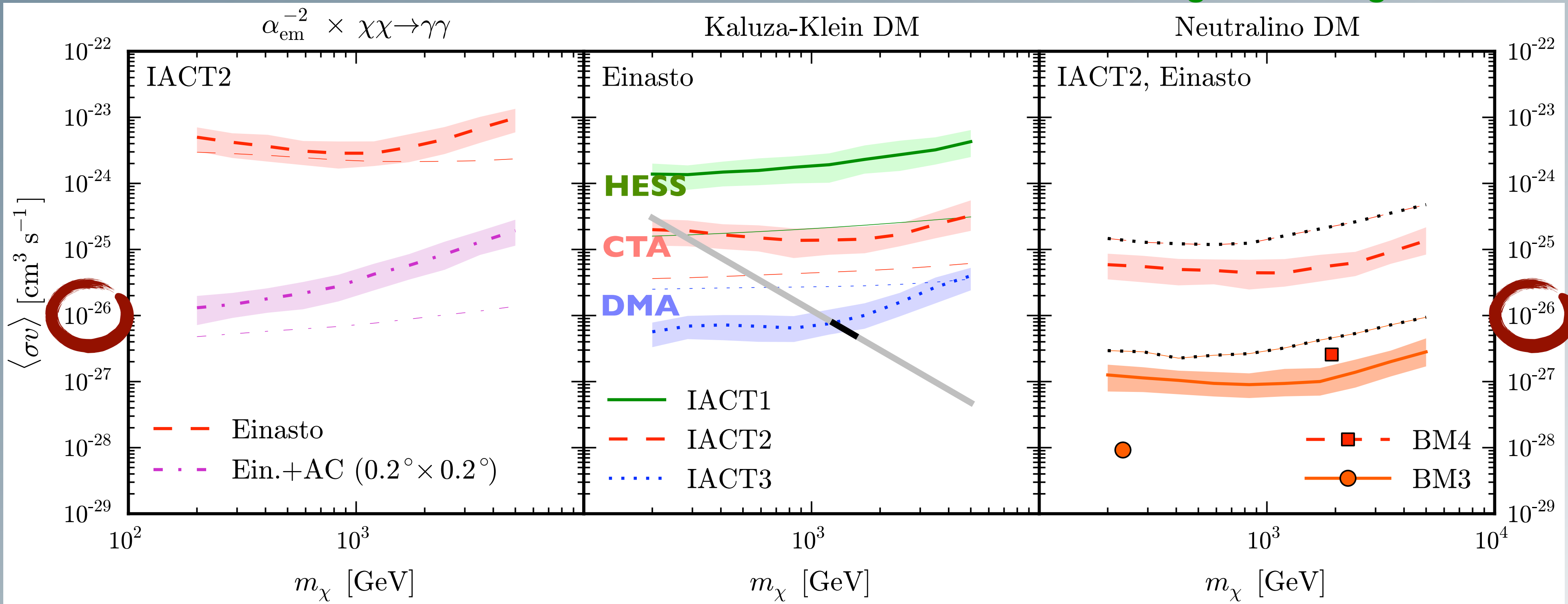


Line signals **Kaluza-Klein DM (step)** **Neutralino DM (IB bump)**

Other spectral features

- Searching for other signatures like sharp steps or IB "bumps" may well be more promising:

TB, Calore, Vertongen & Weniger, PRD '10



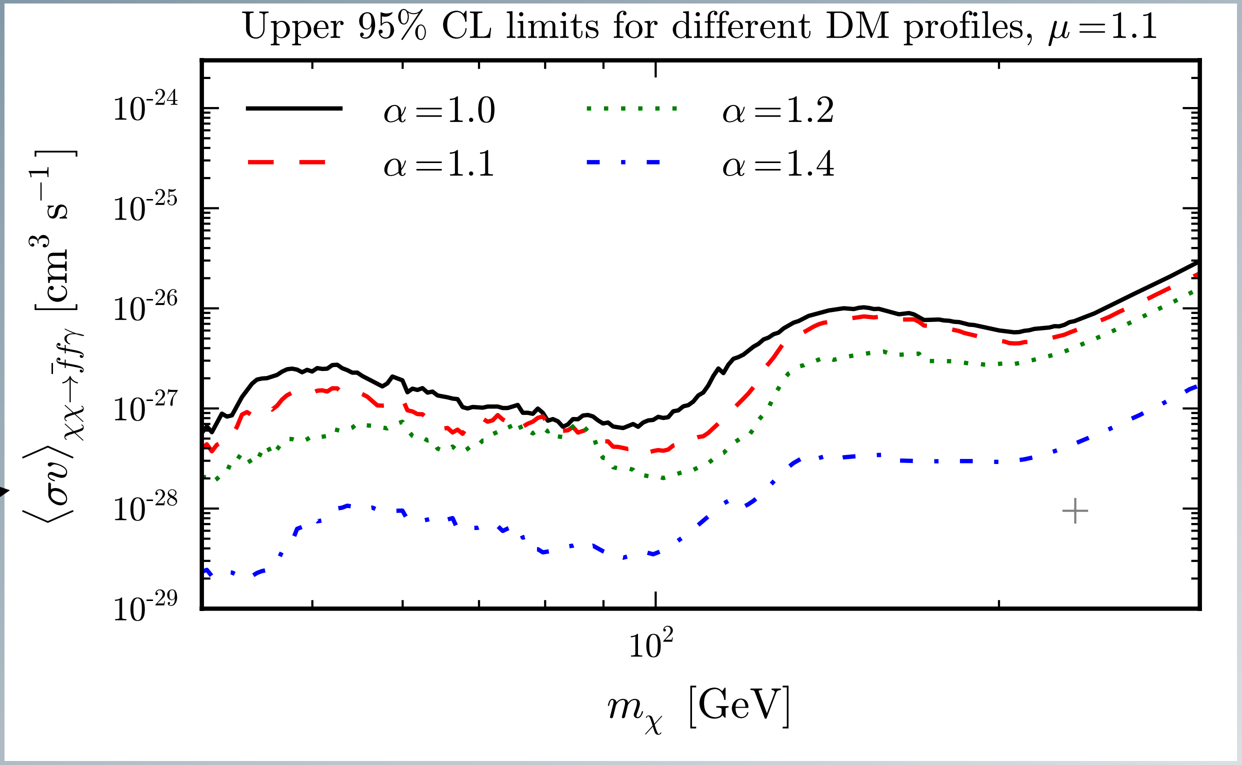
Line signals **Kaluza-Klein DM (step)** **Neutralino DM (IB bump)**

⇨ Natural cross sections well within reach for ACTs!

IB features with Fermi?

TB, Huang, Ibarra, Vogl & Weniger, 1203.1312

- Introduce simplified toy model with minimal field content to get strong IB signals
  - (~same as sfermion co-annihilation region in SUSY)



NB: 3-body x-section!

GC and halo region

$$\rho_\chi \propto r^{-\alpha}$$

- limits on $\ell^+\ell^-(\gamma)$ much stronger than for Fermi dwarfs!

Even more constraints…

Even more constraints…?

[bored]

The model...

TB, Huang, Ibarra, Vogl & Weniger, 1003.1312

$$\mathcal{L}_\chi = \frac{1}{2}\bar{\chi}^c i\partial\!\!\!/\chi - \frac{1}{2}m_\chi\bar{\chi}^c\chi$$

Majorana DM particle

$$\mathcal{L}_\eta = (D_\mu\eta)^\dagger(D^\mu\eta) - m_\eta^2\eta^\dagger\eta$$

SU(2) singlet scalar

$$\mathcal{L}_{\mathrm{int}} = -y\bar{\chi}\Psi_R\eta + \mathrm{h.c.}$$

Yukawa interaction term

$\bar{b}bg$

The model...

TB, Huang, Ibarra, Vogl & Weniger, 1003.1312

$$\mathcal{L}_\chi = \frac{1}{2}\bar{\chi}^c i\partial\!\!\!/\chi - \frac{1}{2}m_\chi\bar{\chi}^c\chi$$

Majorana DM particle

$$\mathcal{L}_\eta = (D_\mu\eta)^\dagger(D^\mu\eta) - m_\eta^2\eta^\dagger\eta$$

SU(2) singlet scalar

$$\mathcal{L}_{\mathrm{int}} = -y\bar{\chi}\Psi_R\eta + \mathrm{h.c.}$$

Yukawa interaction term

τ, μ, b

$\bar{b}bg$

The model...

TB, Huang, Ibarra, Vogl & Weniger, 1003.1312

$$\mathcal{L}_\chi = \frac{1}{2}\bar{\chi}^c i\partial\!\!\!/\chi - \frac{1}{2}m_\chi\bar{\chi}^c\chi$$

Majorana DM particle

~MSSM:

$$\mathcal{L}_\eta = (D_\mu\eta)^\dagger(D^\mu\eta) - m_\eta^2\eta^\dagger\eta$$

SU(2) singlet scalar

$\eta \rightarrow \tilde{f}_L, \tilde{f}_R$

$$\mathcal{L}_{\rm int} = -y\bar{\chi}\Psi_R\eta + \text{h.c.}$$

Yukawa interaction term

couplings $y_{R,L}$ ***fixed!***

$\Psi \rightarrow \tau, \mu, b$

$\bar{b}bg$

The model...

TB, Huang, Ibarra, Vogl & Weniger, 1003.1312

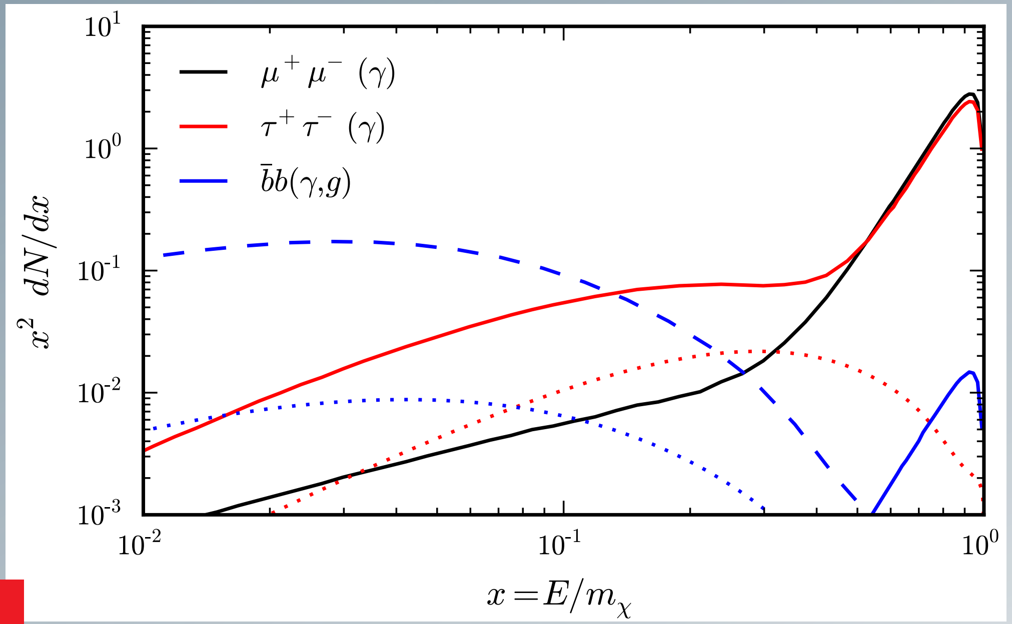
$$\mathcal{L}_\chi = \frac{1}{2}\bar{\chi}^c i\not{\partial}\chi - \frac{1}{2}m_\chi\bar{\chi}^c\chi$$ Majorana DM particle

~MSSM:

$$\mathcal{L}_\eta = (D_\mu\eta)^\dagger(D^\mu\eta) - m_\eta^2\eta^\dagger\eta$$ SU(2) singlet scalar $\eta \to \tilde{f}_L, \tilde{f}_R$

$$\mathcal{L}_{\rm int} = -y\bar{\chi}\Psi_R\eta + \text{h.c.}$$ Yukawa interaction term **couplings** $y_{R,L}$ ***fixed!***

$\Psi \to \tau, \mu, b$



$\bar{b}bg$

The model...

TB, Huang, Ibarra, Vogl & Weniger, 1003.1312

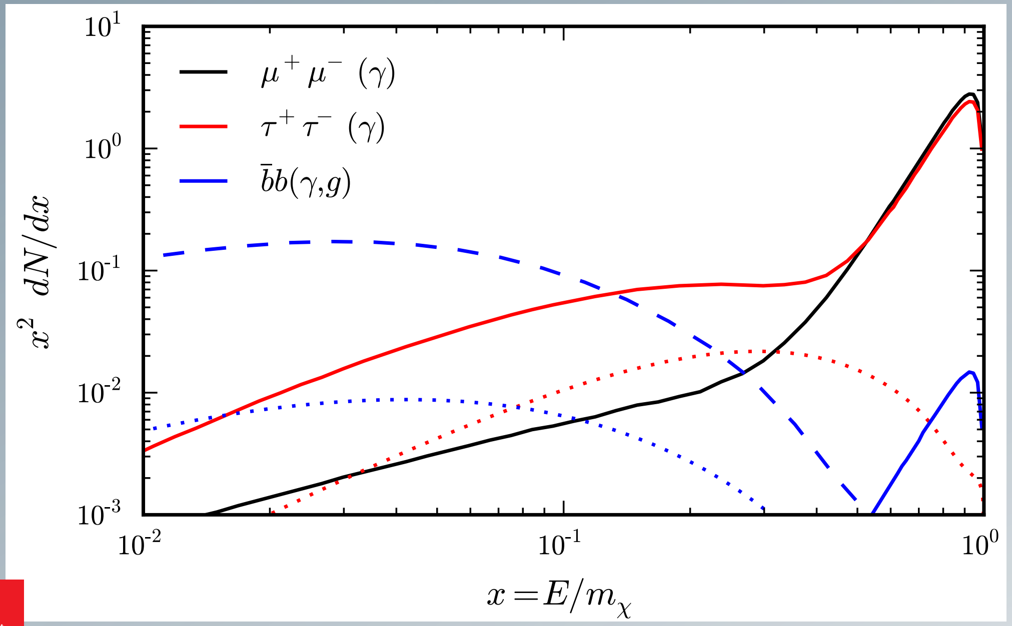
$$\mathcal{L}_\chi = \frac{1}{2}\bar{\chi}^c i\partial\!\!\!/\chi - \frac{1}{2}m_\chi\bar{\chi}^c\chi$$ Majorana DM particle

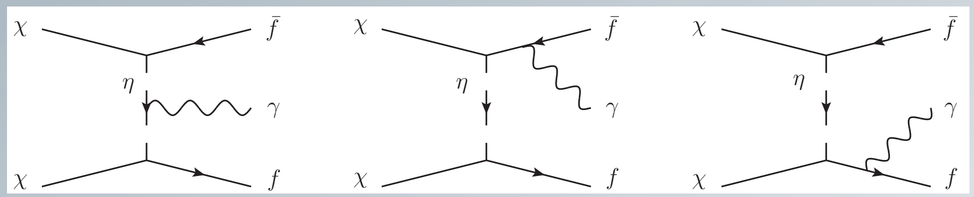
~MSSM:

$$\mathcal{L}_\eta = (D_\mu\eta)^\dagger(D^\mu\eta) - m_\eta^2\eta^\dagger\eta$$ SU(2) singlet scalar $\eta \rightarrow \tilde{f}_L, \tilde{f}_R$

$$\mathcal{L}_{\rm int} = -y\bar{\chi}\Psi_R\eta + \mathrm{h.c.}$$ Yukawa interaction term **couplings $y_{R,L}$ *fixed!***

τ, μ, b





solid: full 3-body

$\bar{b}bg$

The model...

TB, Huang, Ibarra, Vogl & Weniger, 1003.1312

$$\mathcal{L}_\chi = \frac{1}{2}\bar{\chi}^c i\partial\!\!\!/\chi - \frac{1}{2}m_\chi\bar{\chi}^c\chi$$ Majorana DM particle

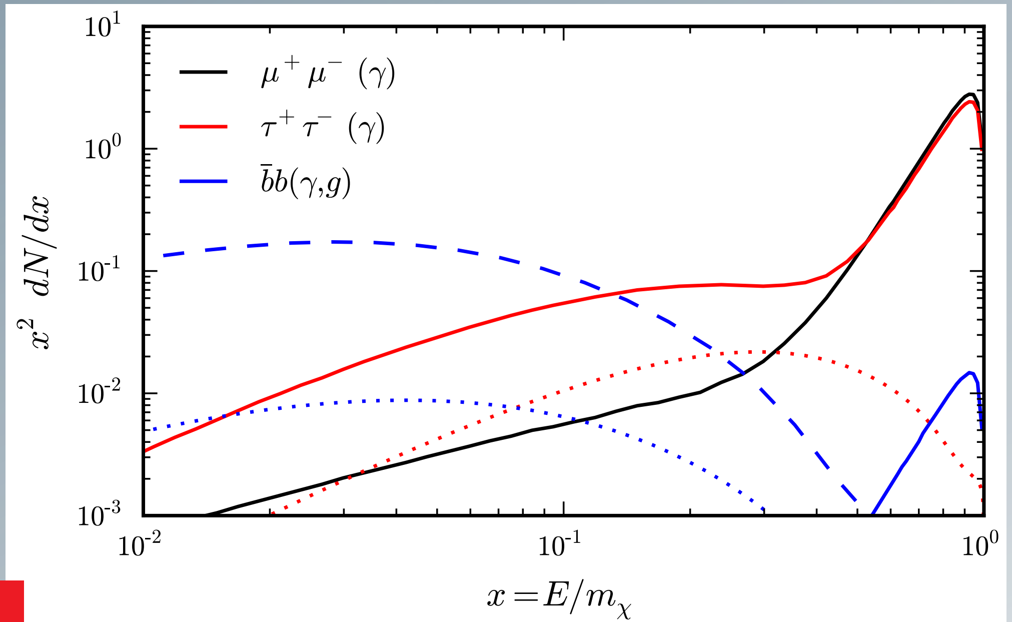
~MSSM:

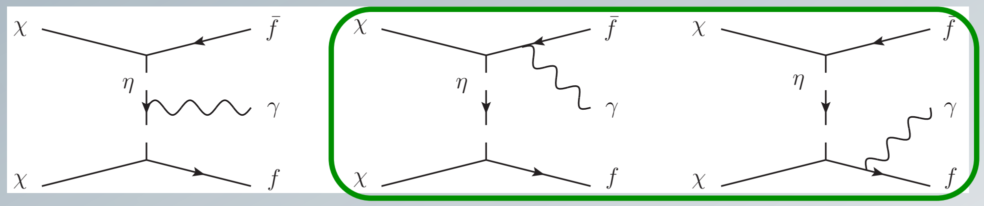
$$\mathcal{L}_\eta = (D_\mu\eta)^\dagger(D^\mu\eta) - m_\eta^2\eta^\dagger\eta$$ SU(2) singlet scalar $\eta \to \tilde{f}_L, \tilde{f}_R$

$$\mathcal{L}_{\rm int} = -y\bar{\chi}\Psi_R\eta + \mathrm{h.c.}$$ Yukawa interaction term

couplings $y_{R,L}$ fixed!

$\Psi \to \tau, \mu, b$





solid: full 3-body

dotted: 2-body + FSR

(dashed: photons from $\bar{b}bg$)

Target selection

- Galactic center by far brightest source of DM annihilation radiation
- Need strategy for large astrophysical backgrounds:
  - early focus on innermost region (but now: strong HESS source)
  - define optimal (S/N) cone around GC $\rightsquigarrow$ $\theta \sim 0.1^\circ - 5^\circ$
  - ~same, but for annulus (excluding the GC)
  - exclude galactic plane
  - ...

Target selection

- Galactic center by far brightest source of DM annihilation radiation
- Need strategy for large astrophysical backgrounds:
  - early focus on innermost region (but now: strong HESS source)
  - define optimal (S/N) cone around GC $\rightsquigarrow$ $\theta \sim 0.1^\circ - 5^\circ$
  - ~same, but for annulus (excluding the GC)
  - exclude galactic plane
  - ...
- New idea: data-driven approach
  - estimate background distribution from observed LAT *low-energy* photons $1\,\mathrm{GeV} \leq E_\gamma \leq 40\,\mathrm{GeV}$
  - Define grid with $1^\circ \times 1^\circ$
  - Optimize total S/N pixel by pixel:

TB, Huang, Ibarra, Vogl & Weniger, 1203.1312

$$\boxed{\mathcal{R}_T \equiv \frac{\sum_{i\in T}\mu_i}{\sqrt{\sum_{i\in T} c_i^{E_\gamma \leq 40\,\mathrm{GeV}}}}}$$

signal

$\rho_\chi \propto r^{-\alpha}$

target region

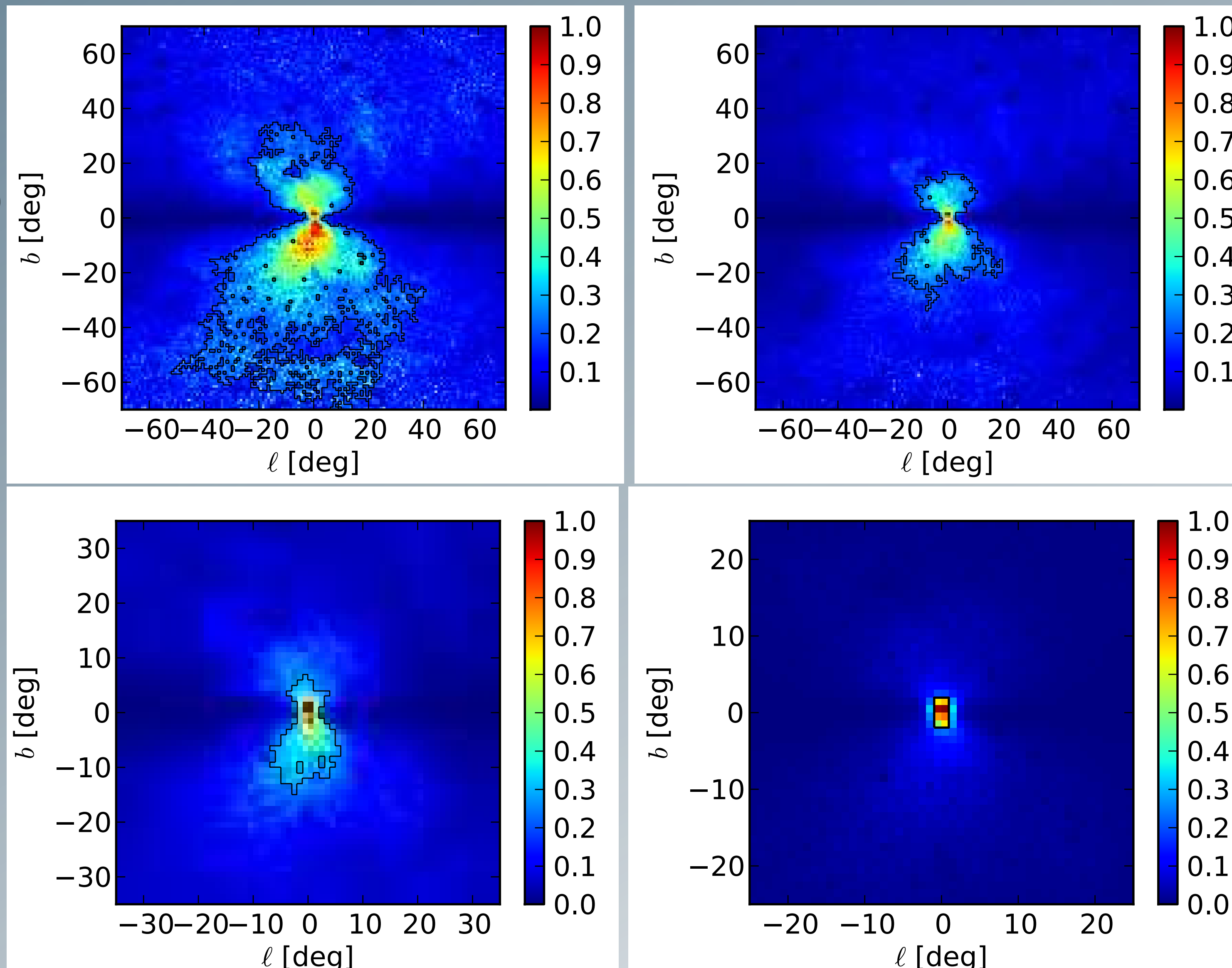
Optimal target regions

TB, Huang, Ibarra, Vogl & Weniger, 1203.1312

$\rho_\chi \propto r^{-1.0}$

'NFW'

$\rho_\chi \propto r^{-1.1}$



$\rho_\chi \propto r^{-1.2}$

$\rho_\chi \propto r^{-1.4}$

'adiabatic contraction'

Color scale: signal to *background*

Method

- Sliding energy window technique
  - standard in line searches
  - window size: few times energy resolution
  - main advantage: background can well be estimated by power law!

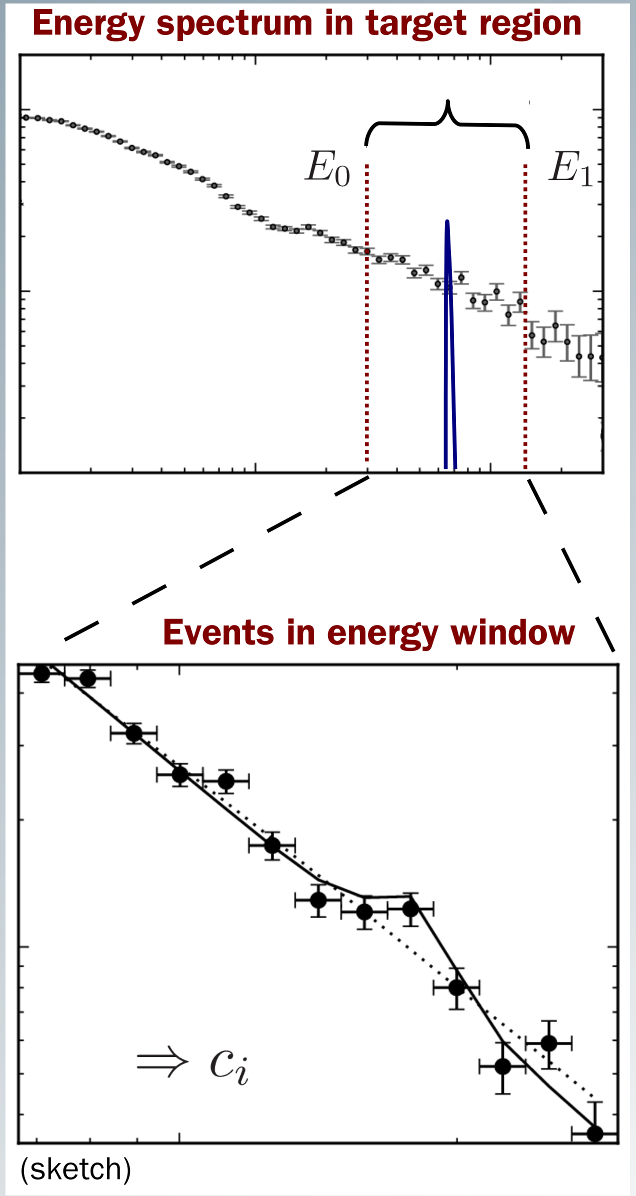


Fig.: C. Weniger

Method

- Sliding energy window technique
  - standard in line searches
  - window size: few times energy resolution
  - main advantage: background can well be estimated by power law!
- Fit of 3-parameter model sufficient:

$$\frac{dJ}{dE} = S\frac{dN^{\mathrm{signal}}}{dE} + \beta E^{-\gamma}$$

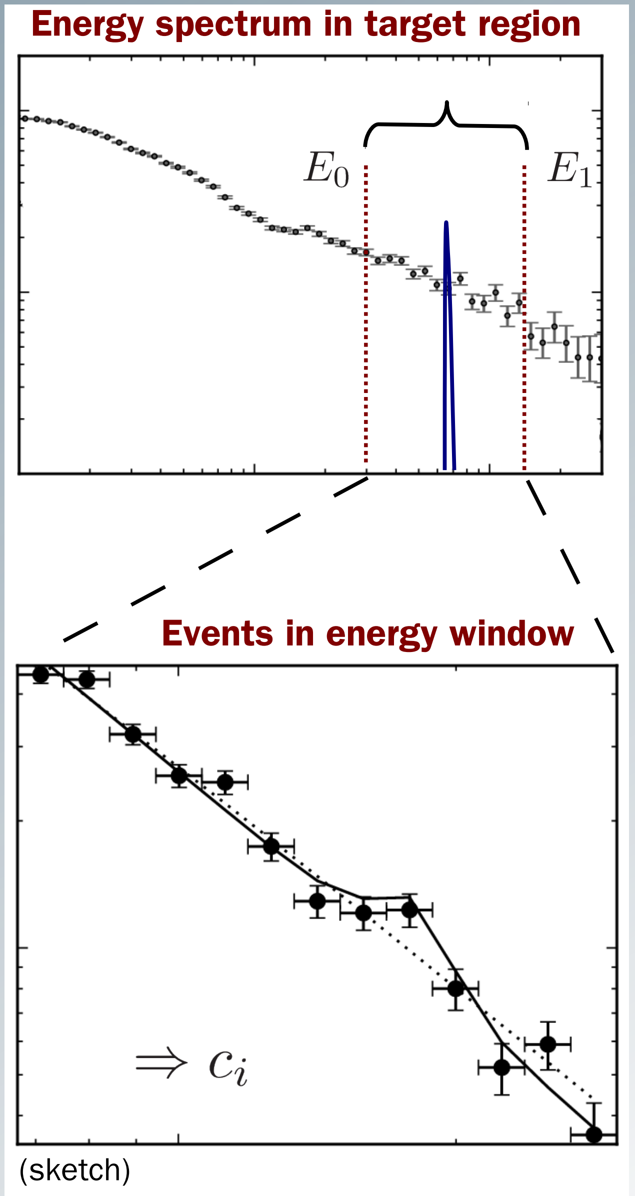


Fig.: C.Weniger

Method

- Sliding energy window technique
  - standard in line searches
  - window size: few times energy resolution
  - main advantage: background can well be estimated by power law!
- Fit of 3-parameter model sufficient:

$$\frac{dJ}{dE} = S\frac{dN^{\rm signal}}{dE} + \beta E^{-\gamma}$$

- expected events:

$$\mu_i = \int_{E_0}^{E_1} dE \int dE'\, \mathcal{D}(E,E')\mathcal{E}(E')\frac{dJ}{dE'}$$

LAT energy resolution

LAT exposure

here: 43 months

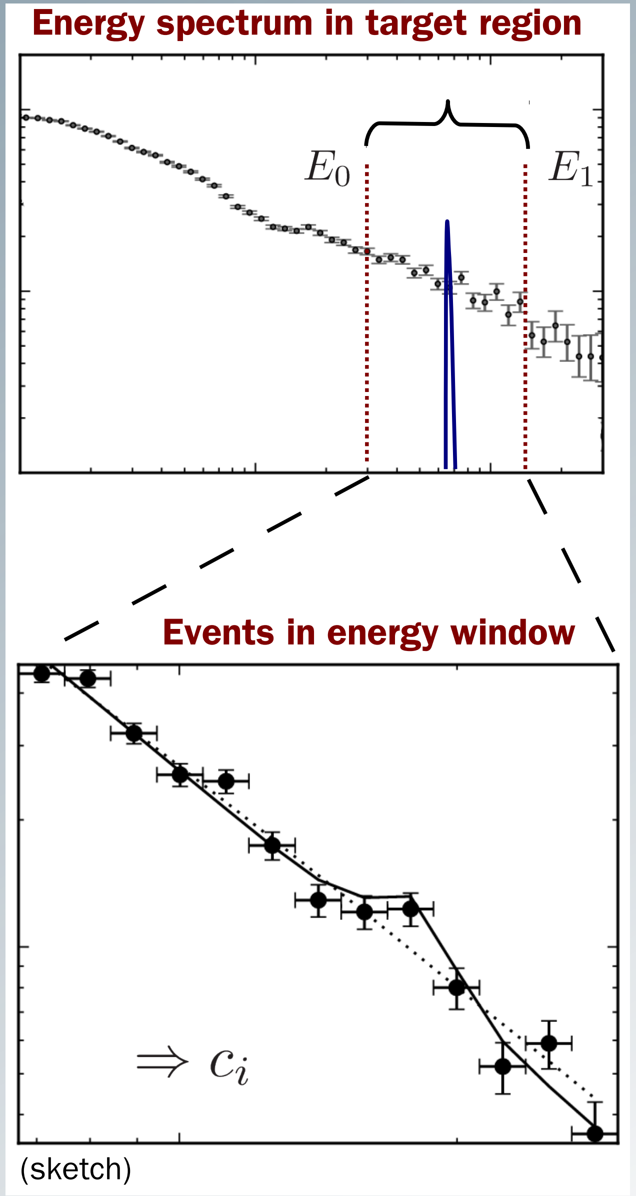


Fig.: C. Weniger

Likelihood analysis

- 'binned' likelihood
  - NB: bin size $\ll$ energy resolution $\rightsquigarrow$ same as unbinned analysis!

$$\boxed{\mathcal{L} = \prod_i P(c_i|\mu_i)}$$

observed **expected**

$$P(c_i|\mu_i) = \frac{\mu_i^{c_i} e^{-\mu_i}}{c_i!}$$

Likelihood analysis

- 'binned' likelihood
  - NB: bin size $\ll$ energy resolution $\rightsquigarrow$ same as unbinned analysis!

$$\boxed{\mathcal{L} = \prod_i P(c_i|\mu_i)} \qquad P(c_i|\mu_i) = \frac{\mu_i^{c_i} e^{-\mu_i}}{c_i!}$$

observed (c_i) **expected** (μ_i)

- Significance follows from *TS* value:

$$\boxed{TS \equiv -2\ln\frac{\mathcal{L}_{\rm null}}{\mathcal{L}_{\rm DM}}}$$

best fit with $S \stackrel{!}{=} 0$ ($\mathcal{L}_{\rm null}$)

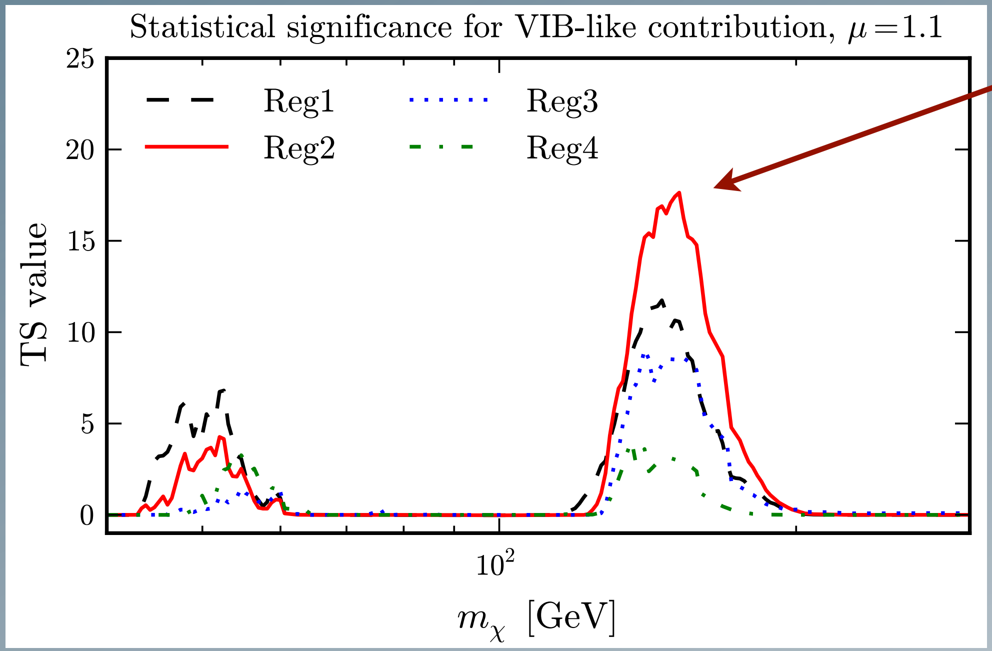
best fit with $S \geq 0$ ($\mathcal{L}_{\rm DM}$)

⇨ significance (without trial correction): $\sqrt{TS}\sigma$

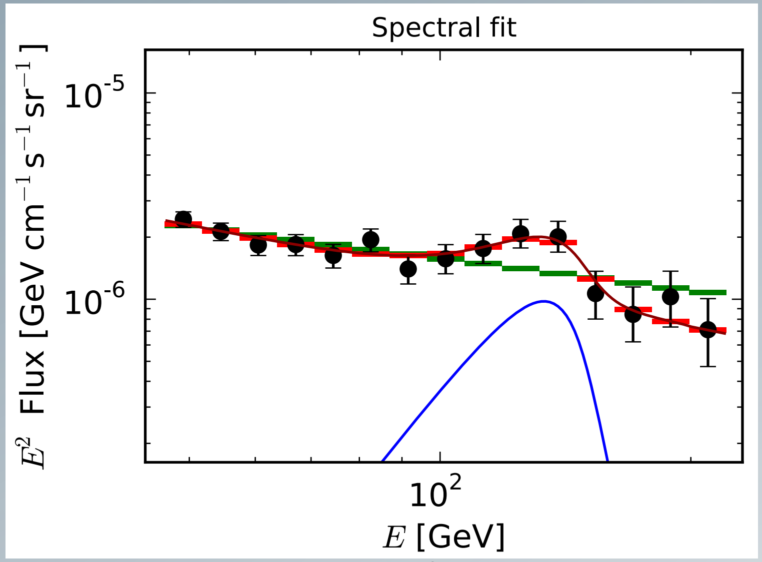
(95% *Limits* derived by profile likelihood method: increase S until $\Delta(-2\ln\mathcal{L}) = 2.71$, while refiting/ 'profiling over' the other parameters)

A tentative signal!

TB, Huang, Ibarra, Vogl & Weniger, 1203.1312

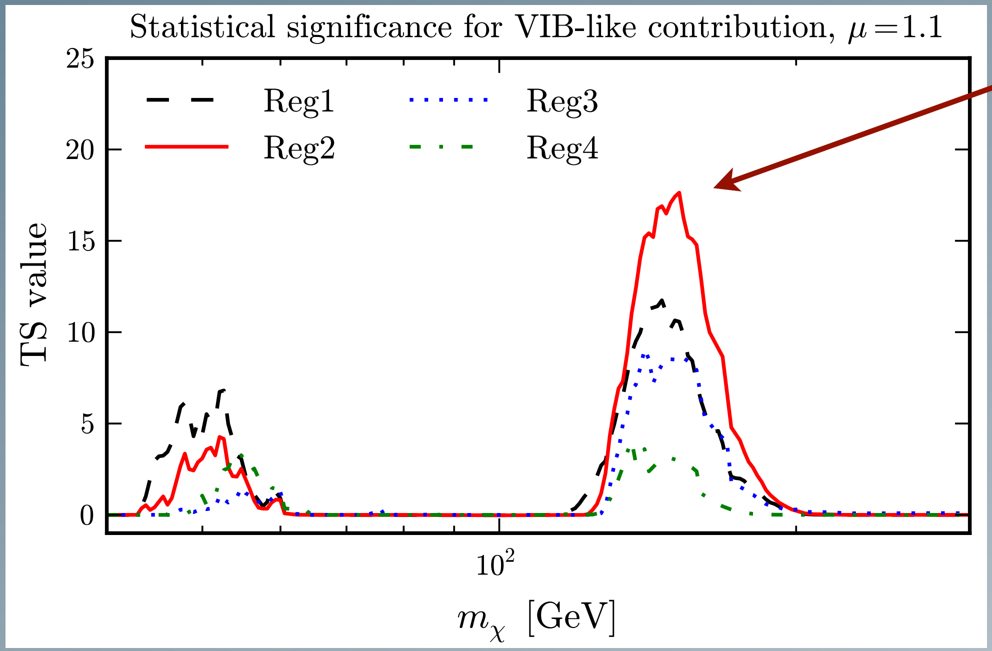


$$\rho_\chi \propto \frac{1}{r^\alpha (1 + r/r_s)^{3-\alpha}}, \quad \alpha = 1.1$$



A tentative signal!

TB, Huang, Ibarra, Vogl & Weniger, 1203.1312



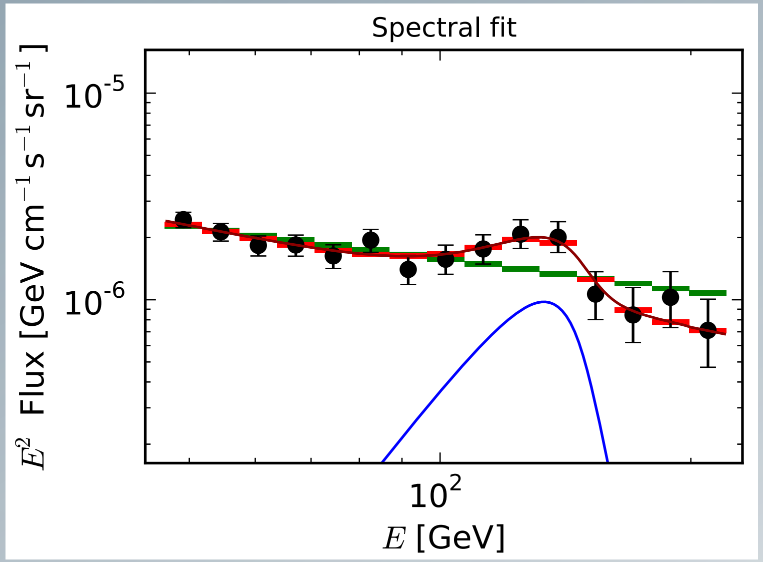
$$\rho_\chi \propto \frac{1}{r^\alpha (1 + r/r_s)^{3-\alpha}}, \qquad \alpha = 1.1$$

- Best-fit values:

$$\boxed{m_\chi = 149 \pm 4 \; {}^{+8}_{-15} \text{ GeV}}$$

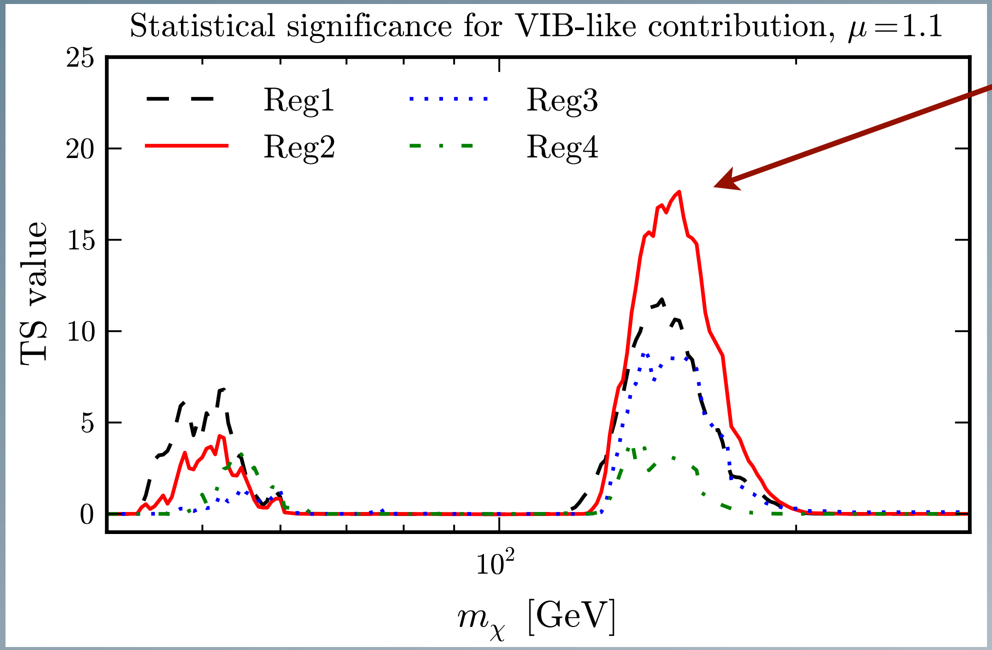
$$\boxed{\langle \sigma v \rangle_{\chi\chi \to \bar{f} f \gamma} = (5.7 \pm 1.4 \; {}^{+0.7}_{-1.0}) \times 10^{-27} \text{cm}^3 \text{s}^{-1}}$$

- Signal significance:
  - 4.3σ (without LEE)
  - 3.1σ (taking into account LEE)



A tentative signal!

TB, Huang, Ibarra, Vogl & Weniger, 1203.1312

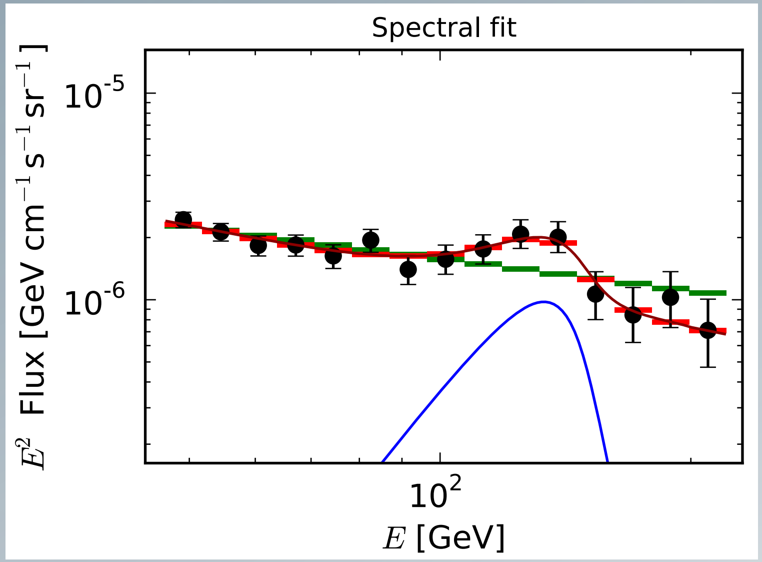


$$\rho_\chi \propto \frac{1}{r^\alpha (1 + r/r_s)^{3-\alpha}}, \qquad \alpha = 1.1$$

- Best-fit values:

$$\boxed{m_\chi = 149 \pm 4 \ {}^{+8}_{-15} \ \mathrm{GeV}}$$

$$\boxed{\langle \sigma v \rangle_{\chi\chi \to \bar{f} f \gamma} = (5.7 \pm 1.4 \ {}^{+0.7}_{-1.0}) \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}}$$

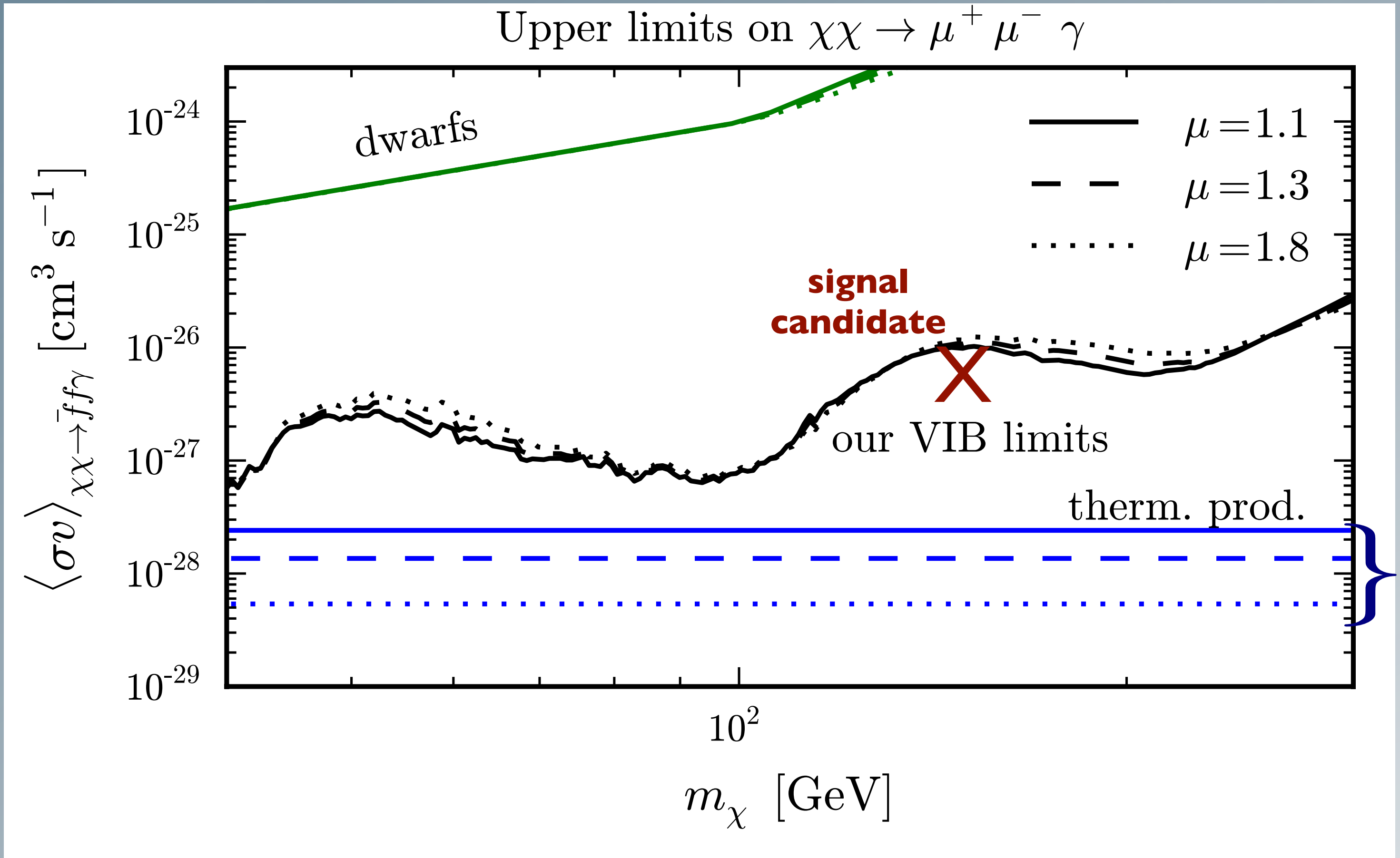


- Signal significance:
  - 4.3σ (without LEE)
  - 3.1σ (taking into account LEE)

- NB: also very well fit by line with

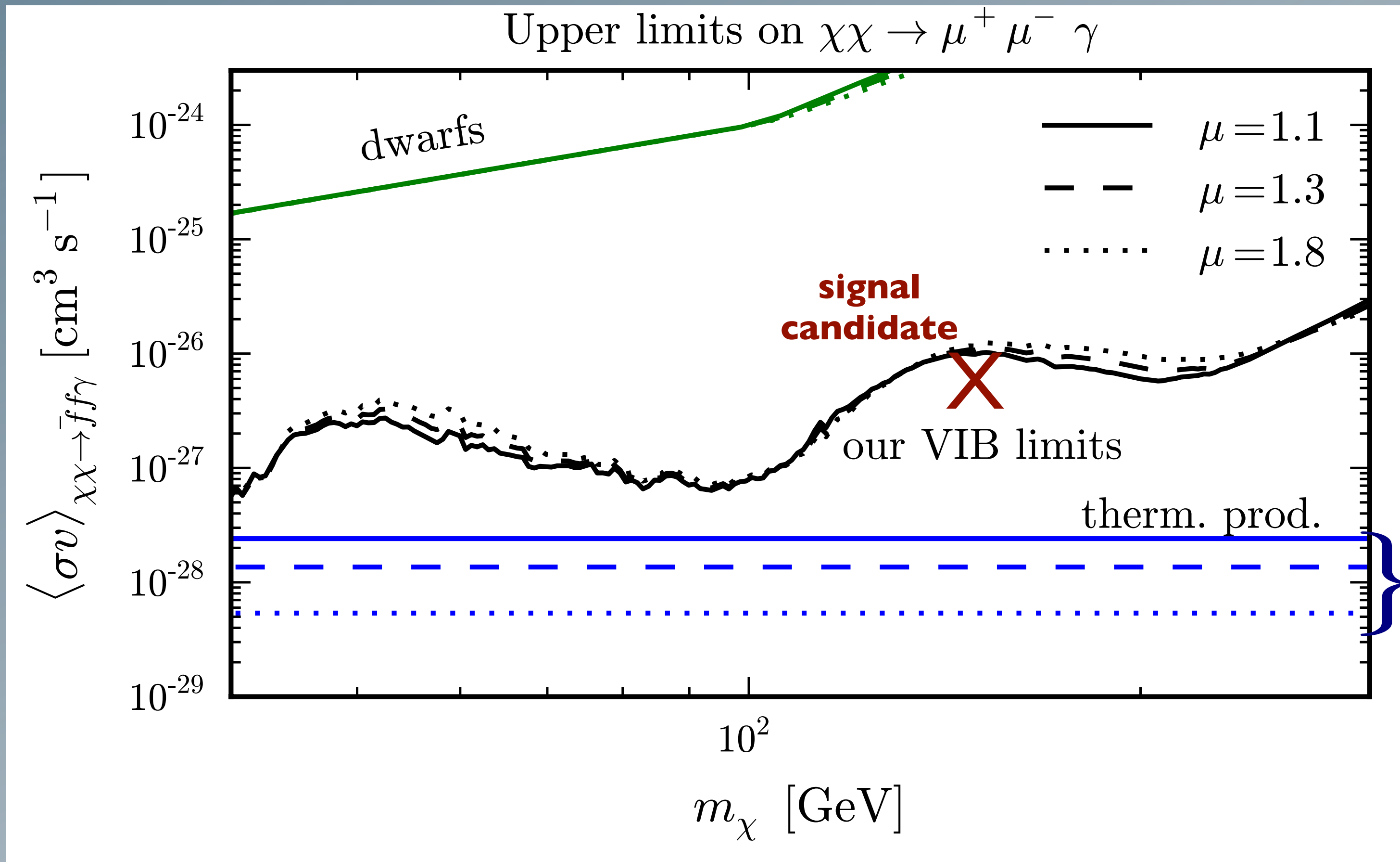
$$m_\chi \sim 130 \, \mathrm{GeV}, \langle \sigma v \rangle \sim 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}$$

Relic density?



relic density strongly depends on mass splitting

Relic density?



relic density strongly depends on mass splitting

- Signal a factor of $\gtrsim 20$ too large for thermal production
  - co-annihilation would further reduce expected signal
  - larger rates possible for destructive interference w/ s-channel diagrams, non-thermal production, boost-factor due to clumps...

Systematics?

- Signal appears independently in all parts of the templates for the optimal target region(s)...
- but disappears completely when shifted by ~10° away from the GC
- bootstrap analysis of *TS* distribution in galactic anticenter region $\rightsquigarrow$ χ^2 distribution as expected
- signal grows, on average, with time

Systematics?

- Signal appears independently in all parts of the templates for the optimal target region(s)...
- but disappears completely when shifted by ~10° away from the GC
- bootstrap analysis of *TS* distribution in galactic anticenter region $\leadsto$ χ^2 distribution as expected
- signal grows, on average, with time

but the analysis relies of course on the public Fermi tools...

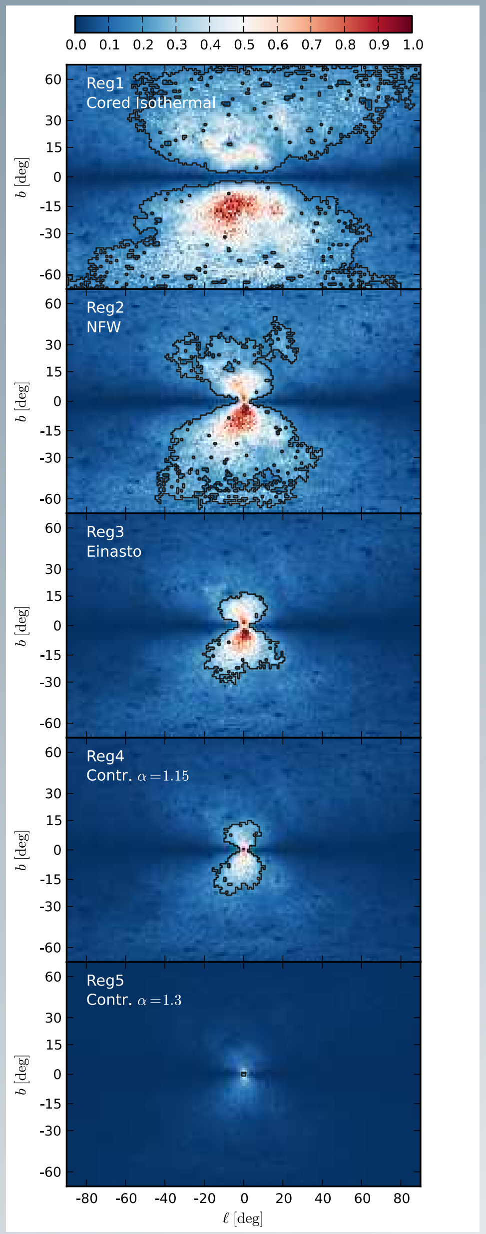
$\Rightarrow$ need independent confirmation by collaboration!

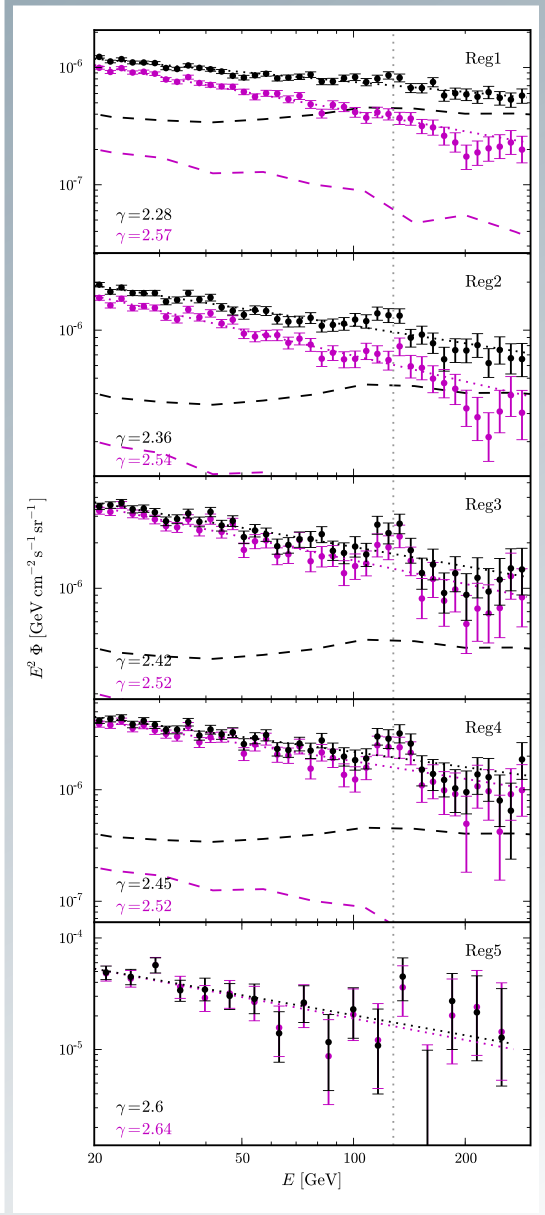
Line analysis

Weniger, 1204.2797

- "A tentative gamma-ray line from DM @ Fermi LAT"
  - same data: 43 months Fermi LAT
  - very nice and extended description of (~same) method
  - extended discussion

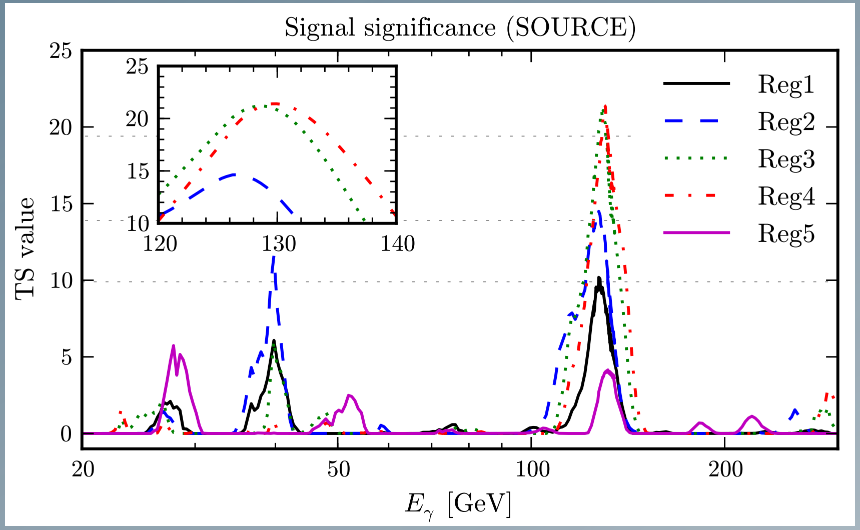
- bottom line:
  - $4.6\sigma\,(3.3\sigma)$ effect
  - $m_\chi = 129.8 \pm 2.4\,^{+7}_{-13}$ GeV
  - $\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma} = (1.27 \pm 0.32\,^{+0.18}_{-0.28}) \times 10^{-27}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$

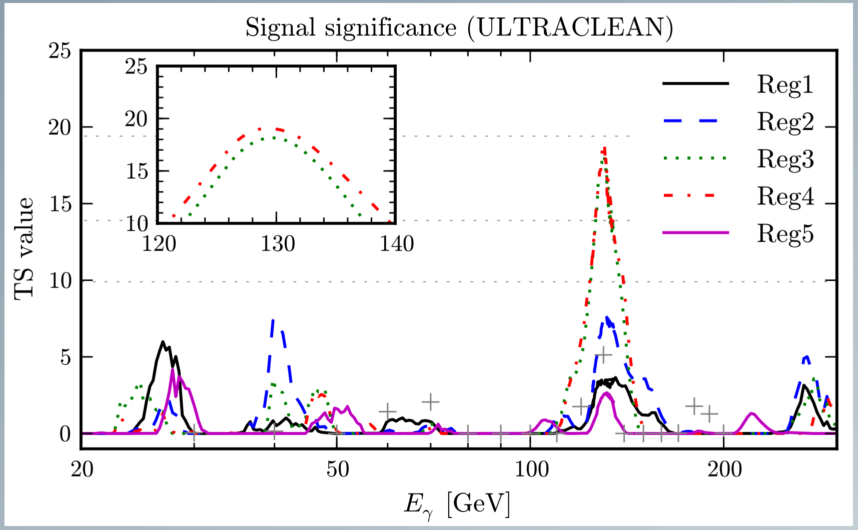


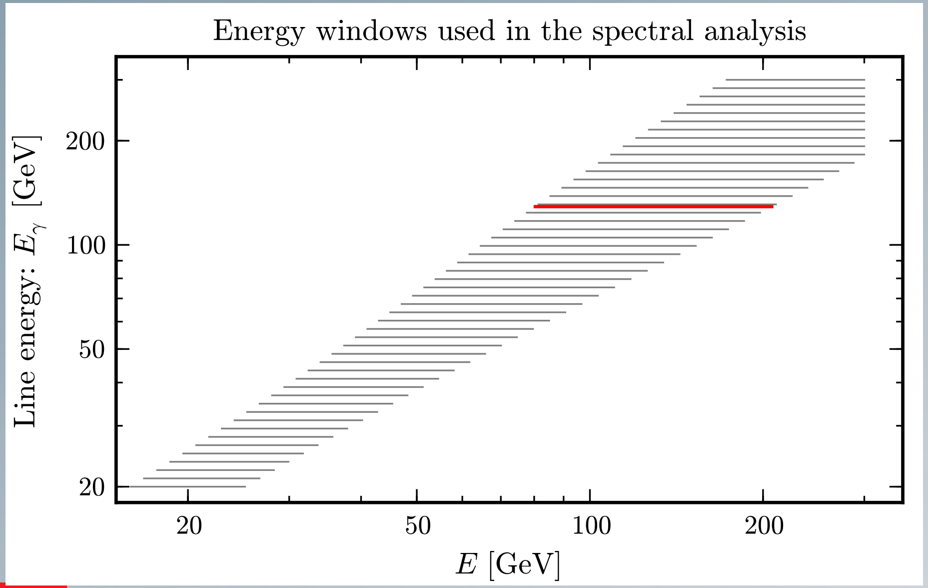


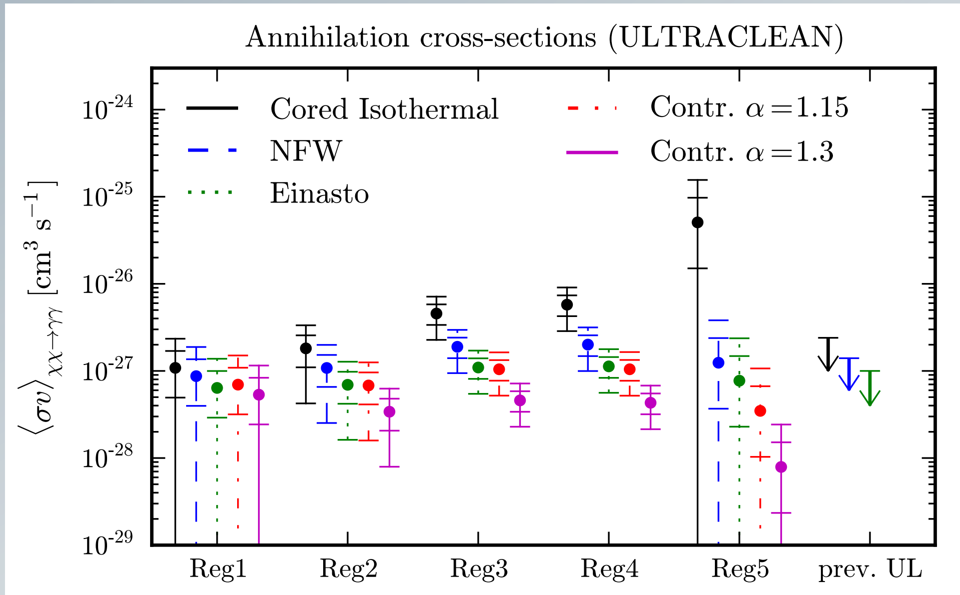
Line analysis (2)

Weniger, 1204.2797

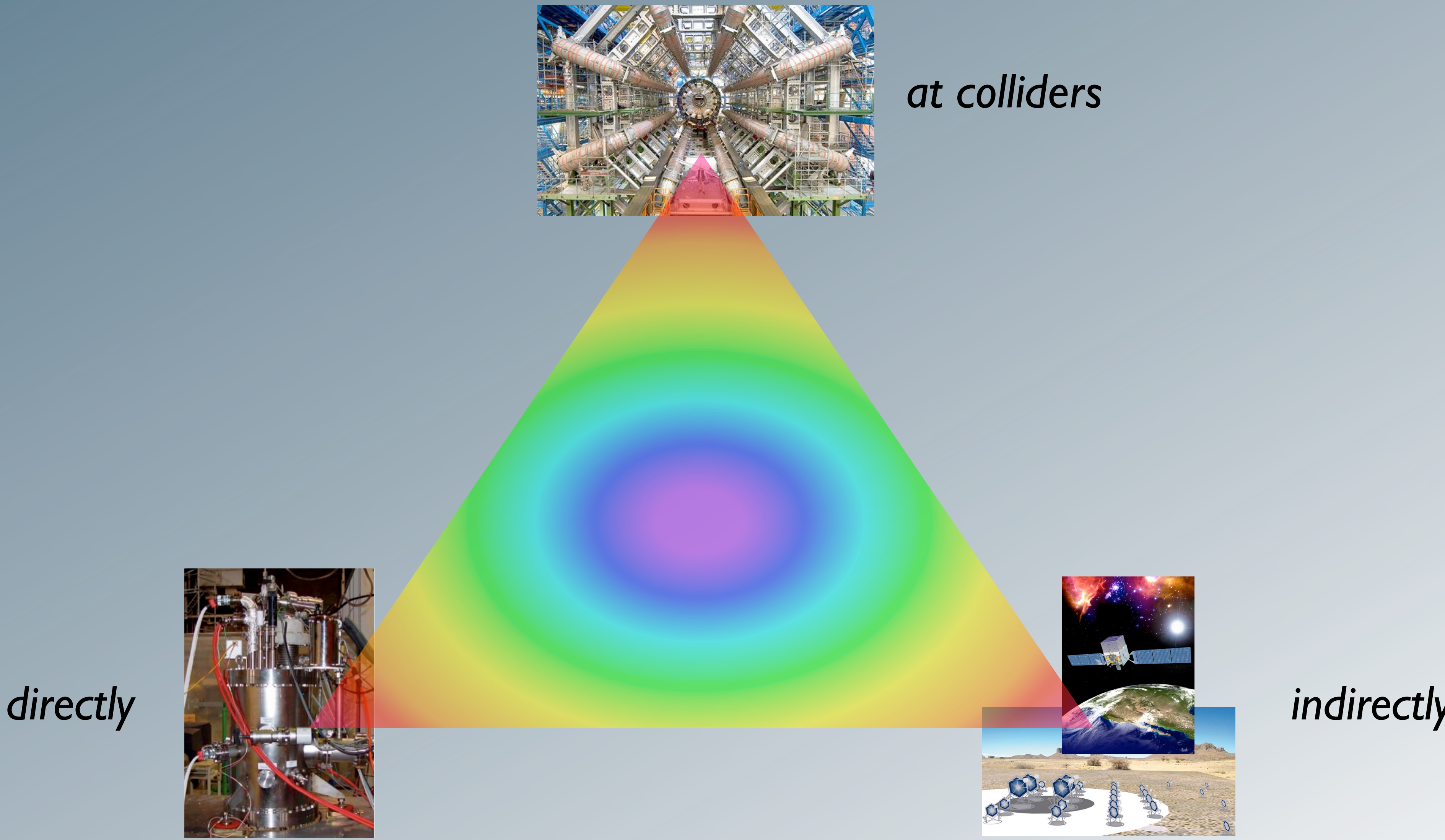








Strategies for DM searches



LHC implications

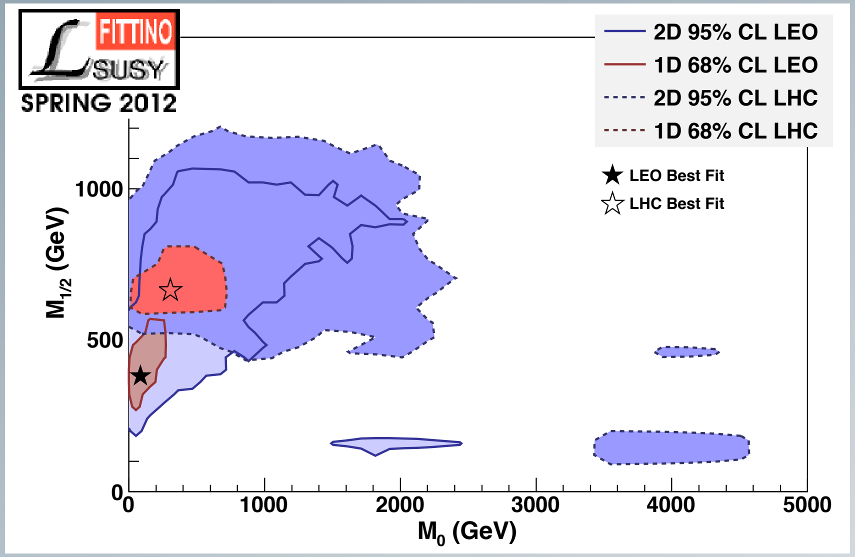
- LHC limits on sparticles and possible Higgs around 126 GeV indicate heavy colored new states
- Low-energy observables, in particular $g-2$, indicate necessity of light new states coupling to leptons

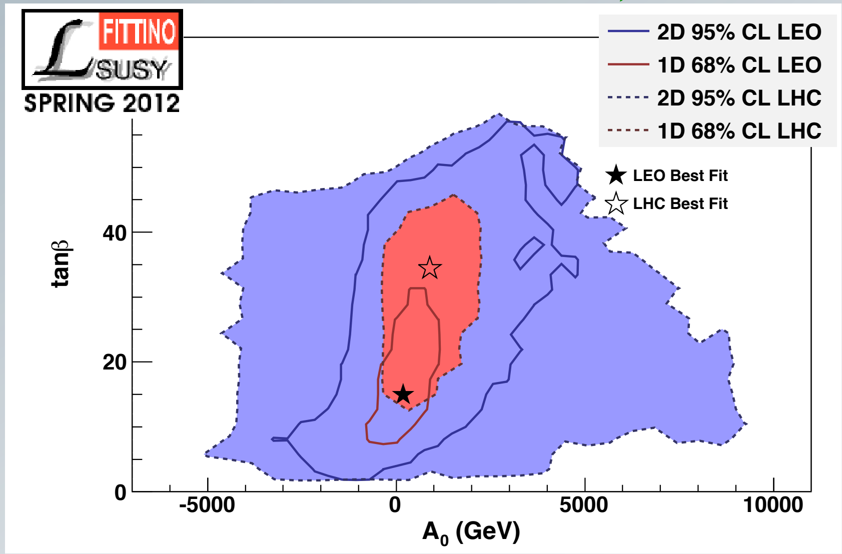
LHC implications

- LHC limits on sparticles and possible Higgs around 126 GeV indicate heavy colored new states
- Low-energy observables, in particular g−2, indicate necessity of light new states coupling to leptons

➜ *constrained* SUSY scenarios already in some tension with data!

Bechtle *et al.*, 1204.4199

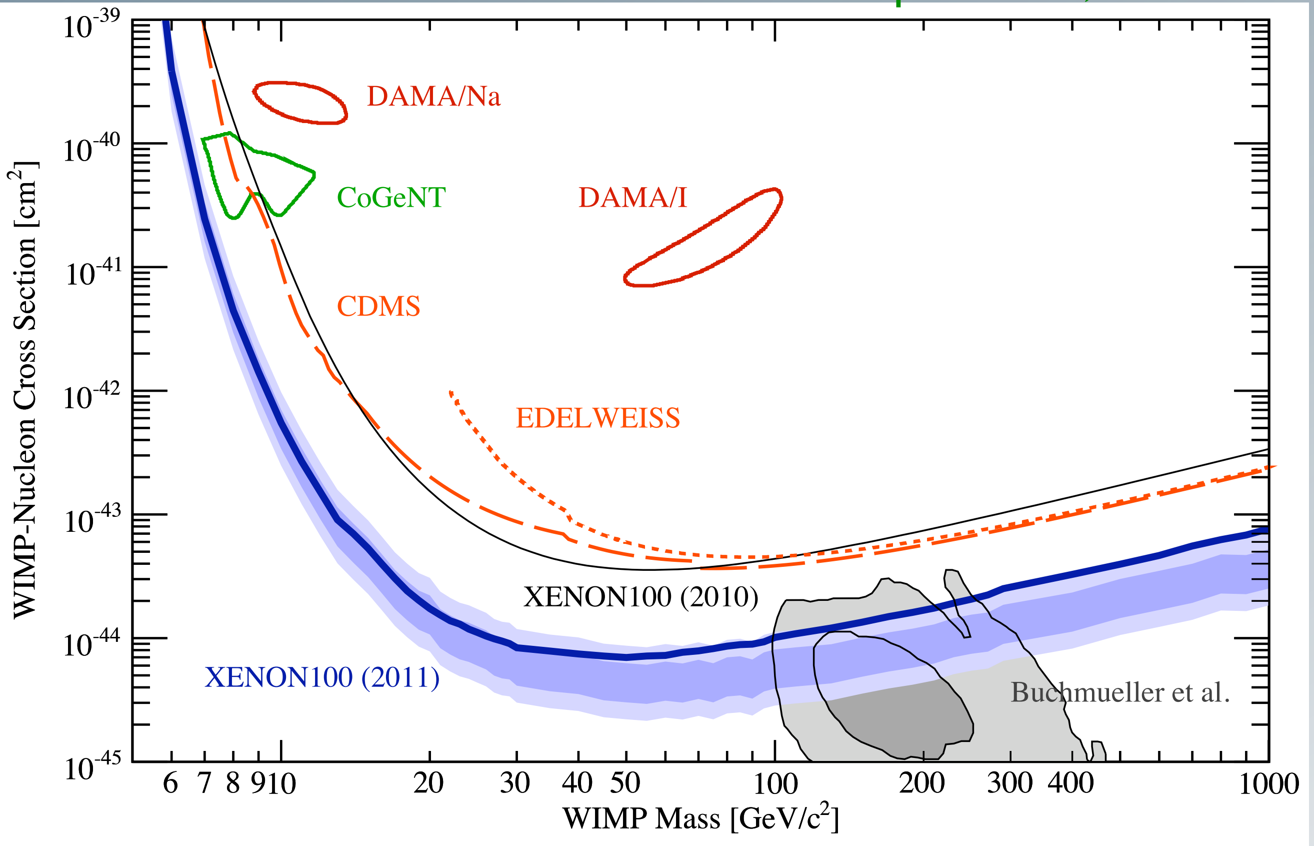




Direct searches

- Impressive improvements of direct detection limits in recent years:

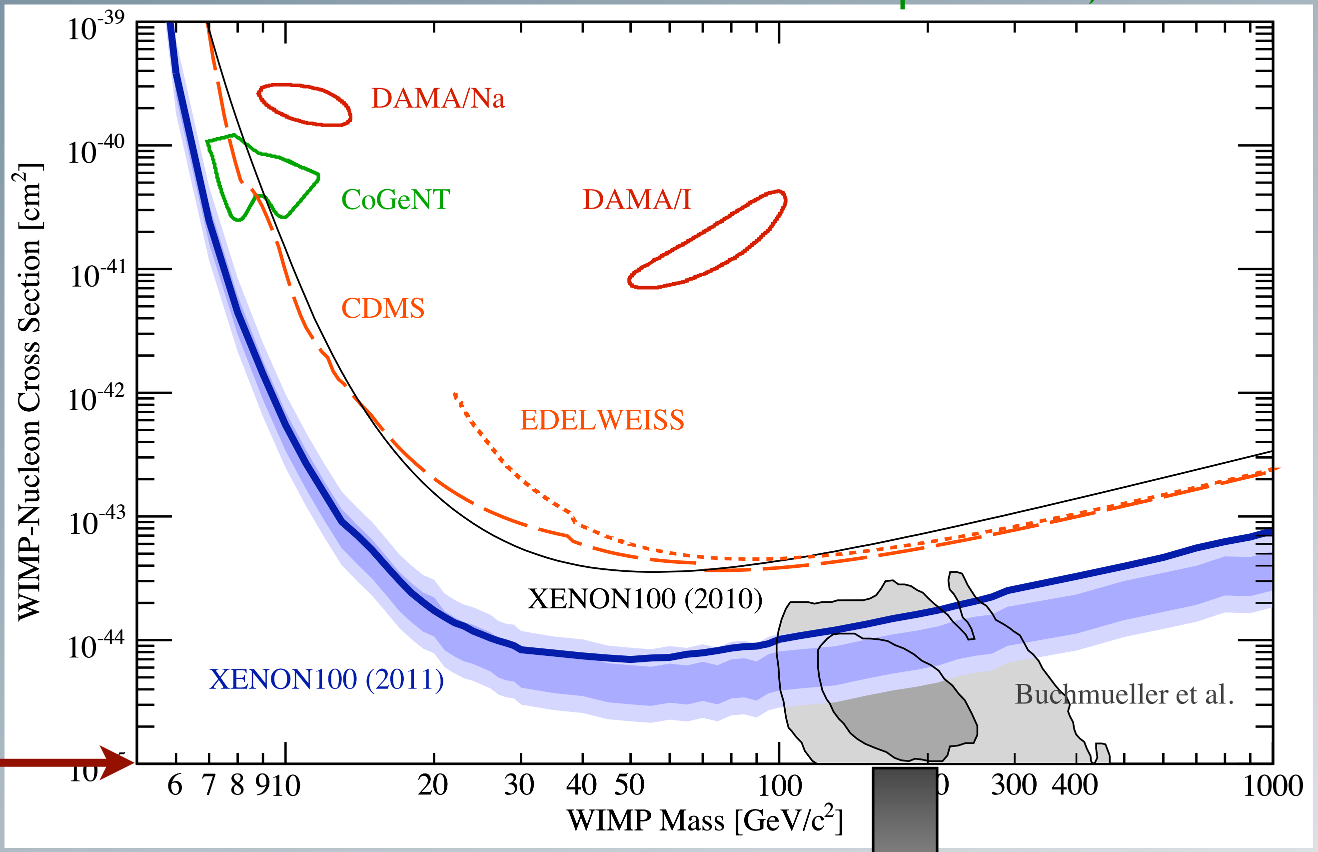
Aprile *et al.*, 1104.2549



Direct searches

- Impressive improvements of direct detection limits in recent years:

Aprile *et al.*, 1104.2549



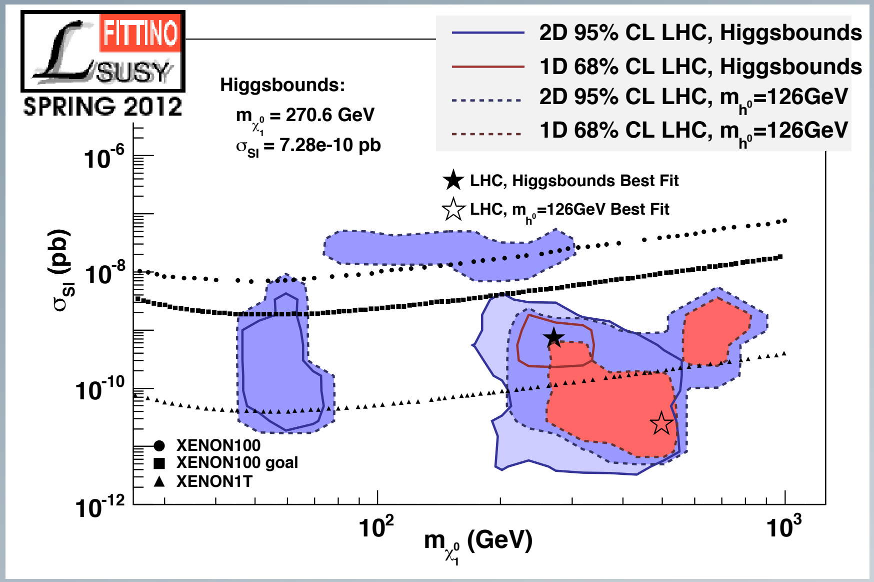
10^{-9} pb

lower limit to $\sigma_{\rm SI}$?

Direct vs. indirect searches

Bechtle *et al.*, 1204.4199

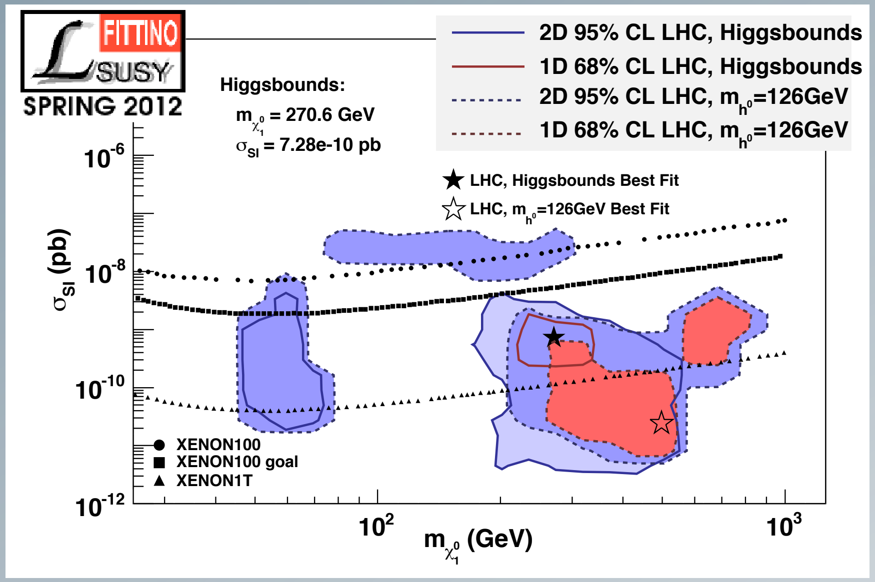
Implications of a heavy Higgs:

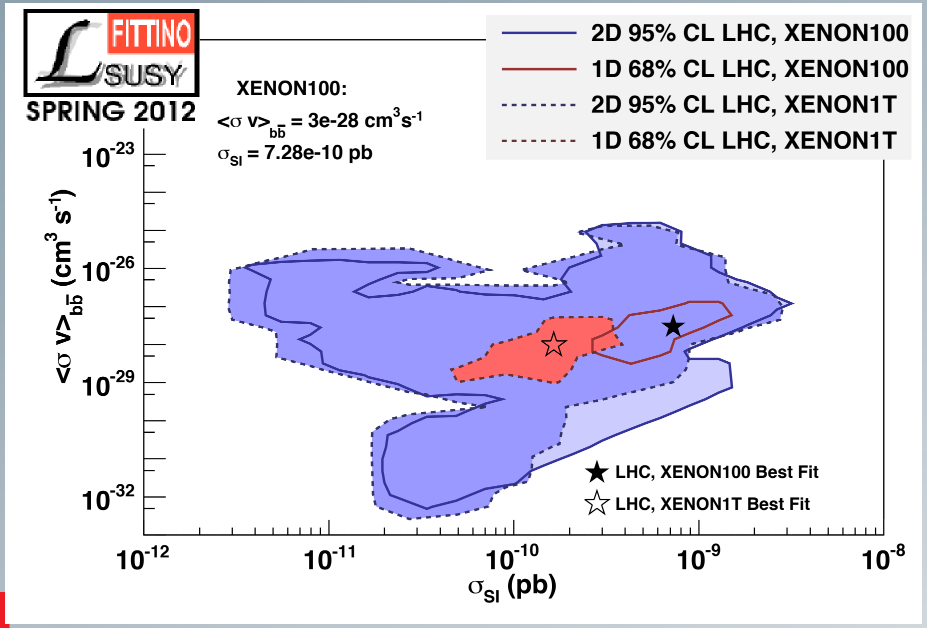


Direct vs. indirect searches

Bechtle *et al.*, 1204.4199

Implications of a heavy Higgs:





Fermi Dwarfs limits just start to touch this area from above

➡ *complementarity of direct and indirect searches!*

IDMS – How far can we go?

- Potential of indirect searches not yet fully capitalized:
  - small eff. areas (Fermi)
  - relatively short observation times (HESS, VERITAS, MAGIC, …)

- CTA will have a greatly improved performance, but has many interesting (astrophysical) targets to observe

  $\rightsquigarrow$ access to observation time will continue to be an issue

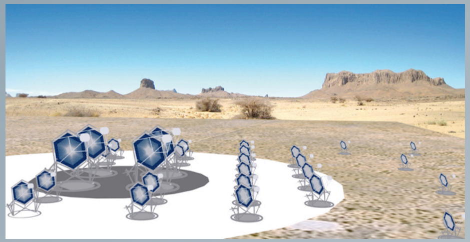
IDMS – How far can we go?

- Potential of indirect searches not yet fully capitalized:
  - small eff. areas (Fermi)
  - relatively short observation times (HESS, VERITAS, MAGIC, …)
- CTA will have a greatly improved performance, but has many interesting (astrophysical) targets to observe
  $\rightsquigarrow$ access to observation time will continue to be an issue
- What could a dedicated future dark matter indirect detection experiment achieve?

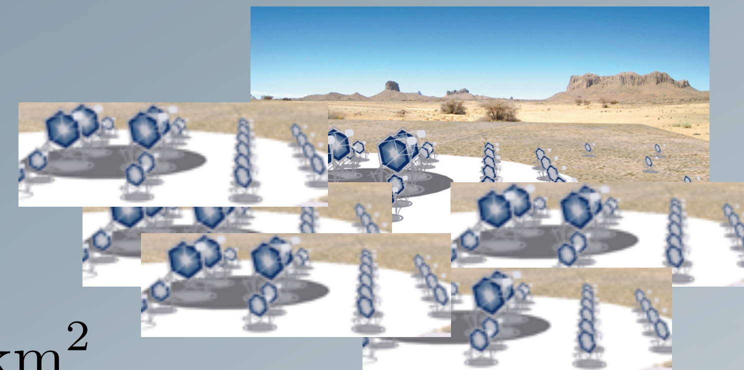
➪ *Let's think BIG…!*

The Dark Matter Array

- Focus on a CTA-like design with a large array of Cherenkov Telescopes

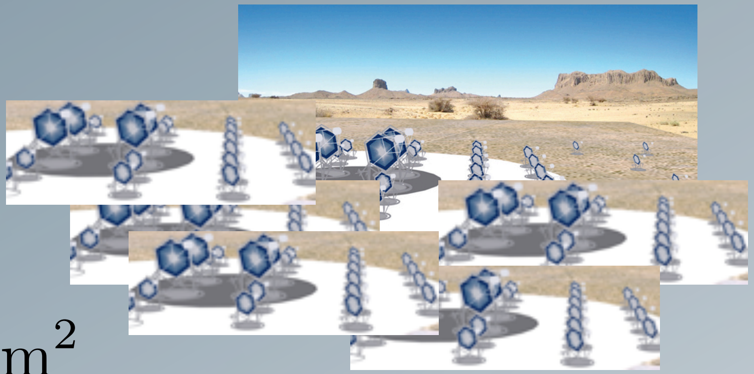


The Dark Matter Array



- Focus on a CTA-like design with a large array of Cherenkov Telescopes
  - ➔ aim at $A^{\rm eff}_{\rm DMA} \sim 10 \times A^{\rm eff}_{\rm CTA} \gtrsim 10\,{\rm km}^2$

The Dark Matter Array

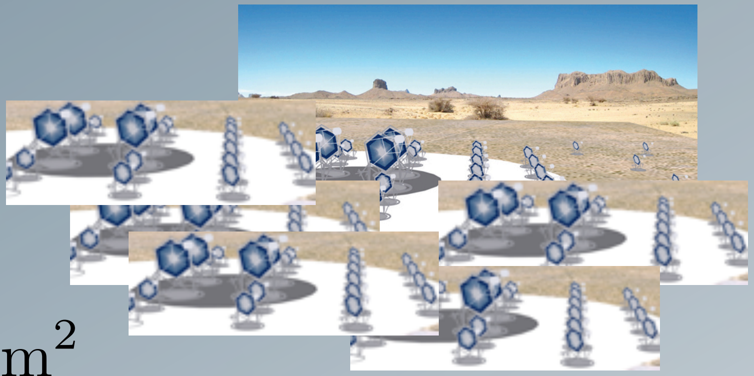


- Focus on a CTA-like design with a large array of Cherenkov Telescopes
  ➡ aim at $A^{\rm eff}_{\rm DMA} \sim 10 \times A^{\rm eff}_{\rm CTA} \gtrsim 10\,{\rm km}^2$

- Best achievable energy threshold?

The Dark Matter Array

- Focus on a CTA-like design with a large array of Cherenkov Telescopes
  - ➔ aim at $A^{\rm eff}_{\rm DMA} \sim 10 \times A^{\rm eff}_{\rm CTA} \gtrsim 10\,{\rm km}^2$



ELSEVIER

Astroparticle Physics 15 (2001) 335–356

Astroparticle Physics

www.elsevier.nl/locate/astropart

5@5 – a 5 GeV energy threshold array of imaging atmospheric Cherenkov telescopes at 5 km altitude

F.A. Aharonian [a,*], A.K. Konopelko [a], H.J. Völk [a], H. Quintana [b]

"5@5"

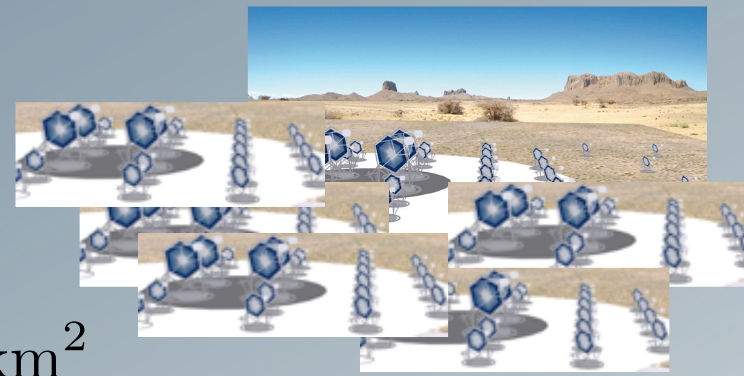
Abstract

We discuss the concept and the performance of a powerful future ground-based astronomical instrument, 5@5 – a **5** GeV energy threshold stereoscopic array of several large imaging atmospheric Cherenkov telescopes (IACTs) installed **at** a very high mountain elevation of about **5** km a.s.l. – for the study of the γ-ray sky at energies from approximately 5 to 100 GeV, where the capabilities of both the current space-based and ground-based γ-ray projects are quite limited.

astronomy photon statistics. The existing technological achievements in the design and construction of multi(1000)-pixel, high resolution imagers, as well as of large, 20 m diameter class multi-mirror dishes with rather modest optical requirements, would allow the construction of such a detector in the foreseeable future, although in the longer terms from the point of view of ongoing projects of 100 GeV threshold IACT arrays like HESS which is in the build-up phase. An ideal site for such an instrument could be a high-altitude, 5 km a.s.l. or more, flat area with a linear scale of about 100 m in a very arid mountain region in the Atacama desert of Northern Chile.

The Dark Matter Array

- Focus on a CTA-like design with a large array of Cherenkov Telescopes
  - ➡ aim at $A^{\rm eff}_{\rm DMA} \sim 10 \times A^{\rm eff}_{\rm CTA} \gtrsim 10\,{\rm km}^2$



ELSEVIER

Astroparticle Physics 15 (2001) 335–356

Astroparticle Physics

www.elsevier.nl/locate/astropart

5@5 – a 5 GeV energy threshold array of imaging atmospheric Cherenkov telescopes at 5 km altitude

F.A. Aharonian [a,*], A.K. Konopelko [a], H.J. Völk [a], H. Quintana [b]

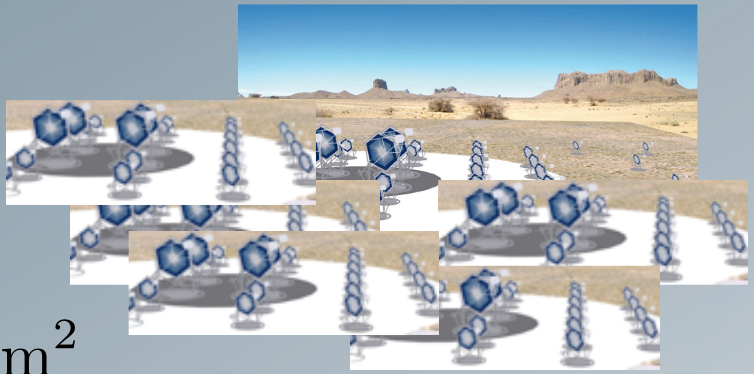
“5@5”

Abstract

We discuss the concept and the performance of a powerful future ground-based astronomical instrument, 5@5 – a **5** GeV energy threshold stereoscopic array of several large imaging atmospheric Cherenkov telescopes (IACTs) installed **at** a very high mountain elevation of about **5** km a.s.l. – for the study of the γ-ray sky at energies from approximately 5 to 100 GeV, where the capabilities of both the current space-based and ground-based γ-ray projects are quite limited.

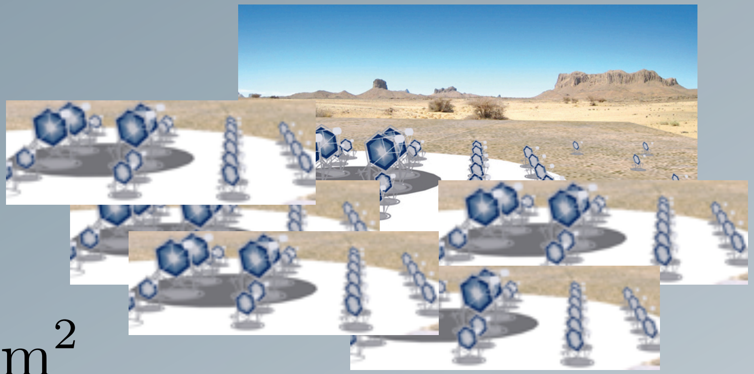
astronomy photon statistics. The existing technological achievements in the design and construction of multi(1000)-pixel, high resolution imagers, as well as of large, 20 m diameter class multi-mirror dishes with rather modest optical requirements, would allow the construction of such a detector in the foreseeable future, although in the longer terms from the point of view of ongoing projects of 100 GeV threshold IACT arrays like HESS which is in the build-up phase. An ideal site for such an instrument could be a high-altitude, 5 km a.s.l. or more, flat area with a linear scale of about 100 m in a very arid mountain region in the Atacama desert of Northern Chile.

The Dark Matter Array



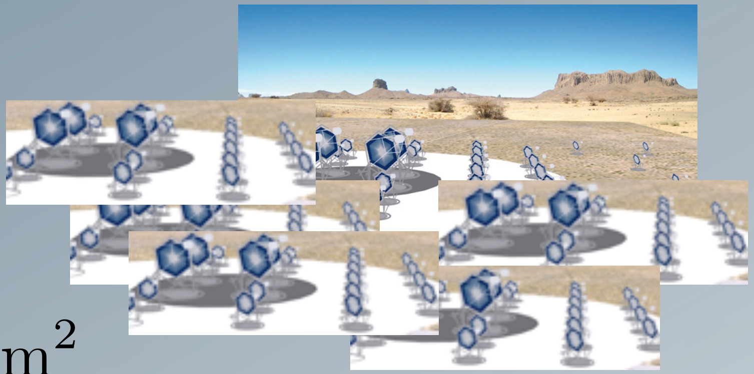
- Focus on a CTA-like design with a large array of Cherenkov Telescopes
  - ➡ aim at $A_{\mathrm{DMA}}^{\mathrm{eff}} \sim 10 \times A_{\mathrm{CTA}}^{\mathrm{eff}} \gtrsim 10\,\mathrm{km}^2$
- Best achievable energy threshold?
  - ➡ aim at $E_{\mathrm{DMA}}^{\mathrm{thr}} \approx 10\,\mathrm{GeV}$ (cf. “5@5”)

The Dark Matter Array



- Focus on a CTA-like design with a large array of Cherenkov Telescopes
  - ➪ aim at $A^{\mathrm{eff}}_{\mathrm{DMA}} \sim 10 \times A^{\mathrm{eff}}_{\mathrm{CTA}} \gtrsim 10\,\mathrm{km}^2$
- Best achievable energy threshold?
  - ➪ aim at $E^{\mathrm{thr}}_{\mathrm{DMA}} \approx 10\,\mathrm{GeV}$ (cf. “5@5”)
- Dedicated for DM searches
  - ➪ aim at $t^{\mathrm{obs}}_{\mathrm{DMA}} = 5000\,\mathrm{h} \lesssim 5\,\mathrm{y}$

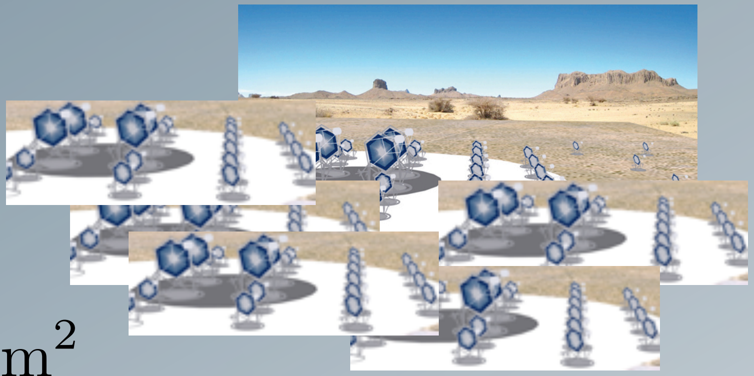
The Dark Matter Array



- Focus on a CTA-like design with a large array of Cherenkov Telescopes
  - ➩ aim at $A^{\rm eff}_{\rm DMA} \sim 10 \times A^{\rm eff}_{\rm CTA} \gtrsim 10\,{\rm km}^2$
- Best achievable energy threshold?
  - ➩ aim at $E^{\rm thr}_{\rm DMA} \approx 10\,{\rm GeV}$ (cf. "5@5")
- Dedicated for DM searches
  - ➩ aim at $t^{\rm obs}_{\rm DMA} = 5000\,{\rm h} \lesssim 5\,{\rm y}$

➩ *Science fiction?*

The Dark Matter Array



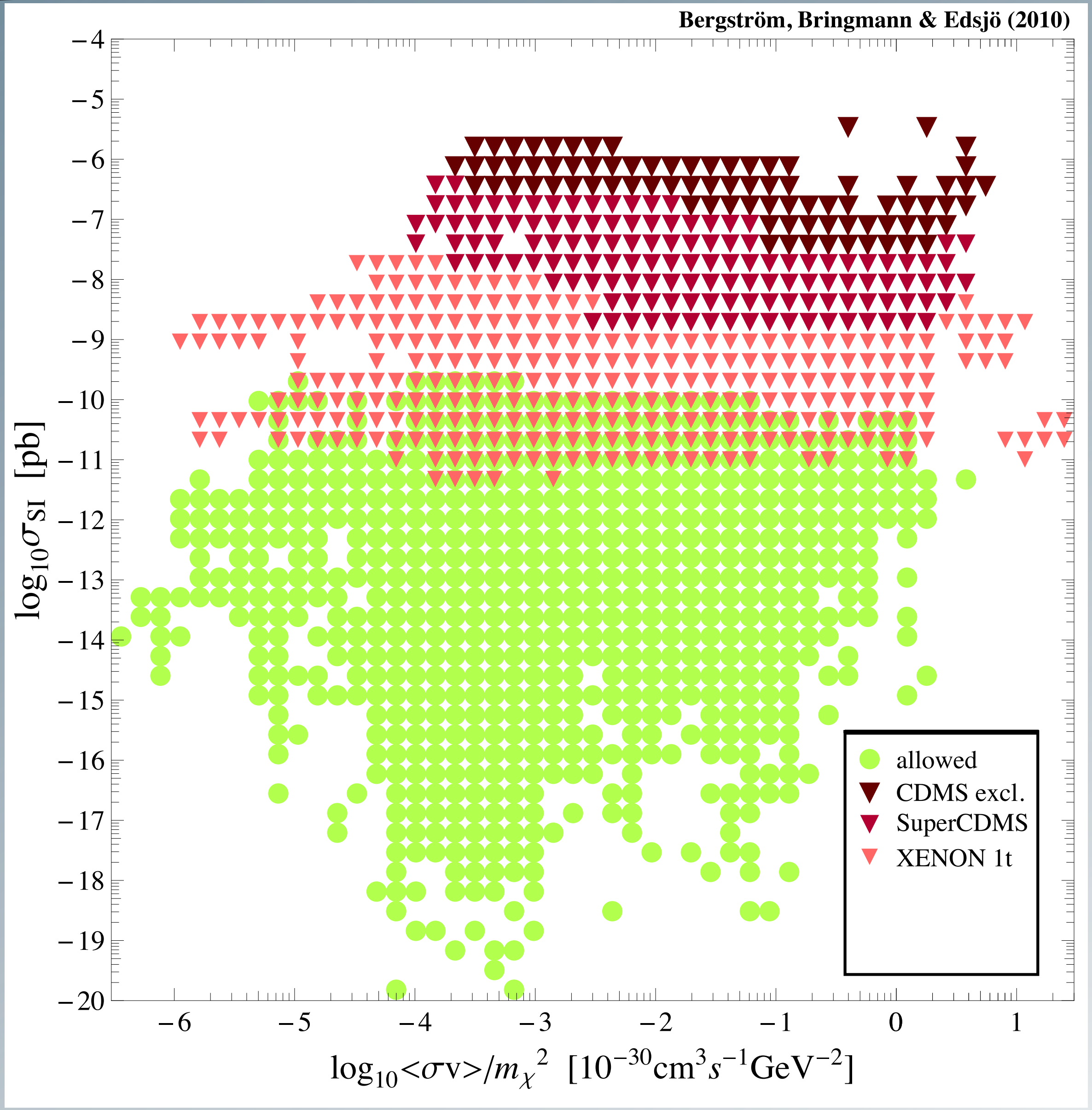
- Focus on a CTA-like design with a large array of Cherenkov Telescopes
  - ➔ aim at $A^{\rm eff}_{\rm DMA} \sim 10 \times A^{\rm eff}_{\rm CTA} \gtrsim 10\,{\rm km}^2$
- Best achievable energy threshold?
  - ➔ aim at $E^{\rm thr}_{\rm DMA} \approx 10\,{\rm GeV}$ (cf. “5@5”)
- Dedicated for DM searches
  - ➔ aim at $t^{\rm obs}_{\rm DMA} = 5000\,{\rm h} \lesssim 5\,{\rm y}$

➔ *Science fiction?*

Maybe…
But let’s see what is possible for the sake of argument!

Direct vs. indirect detection

MSSM+mSUGRA scan:
~10^6 models, 3σ WMAP,
all collider bounds OK

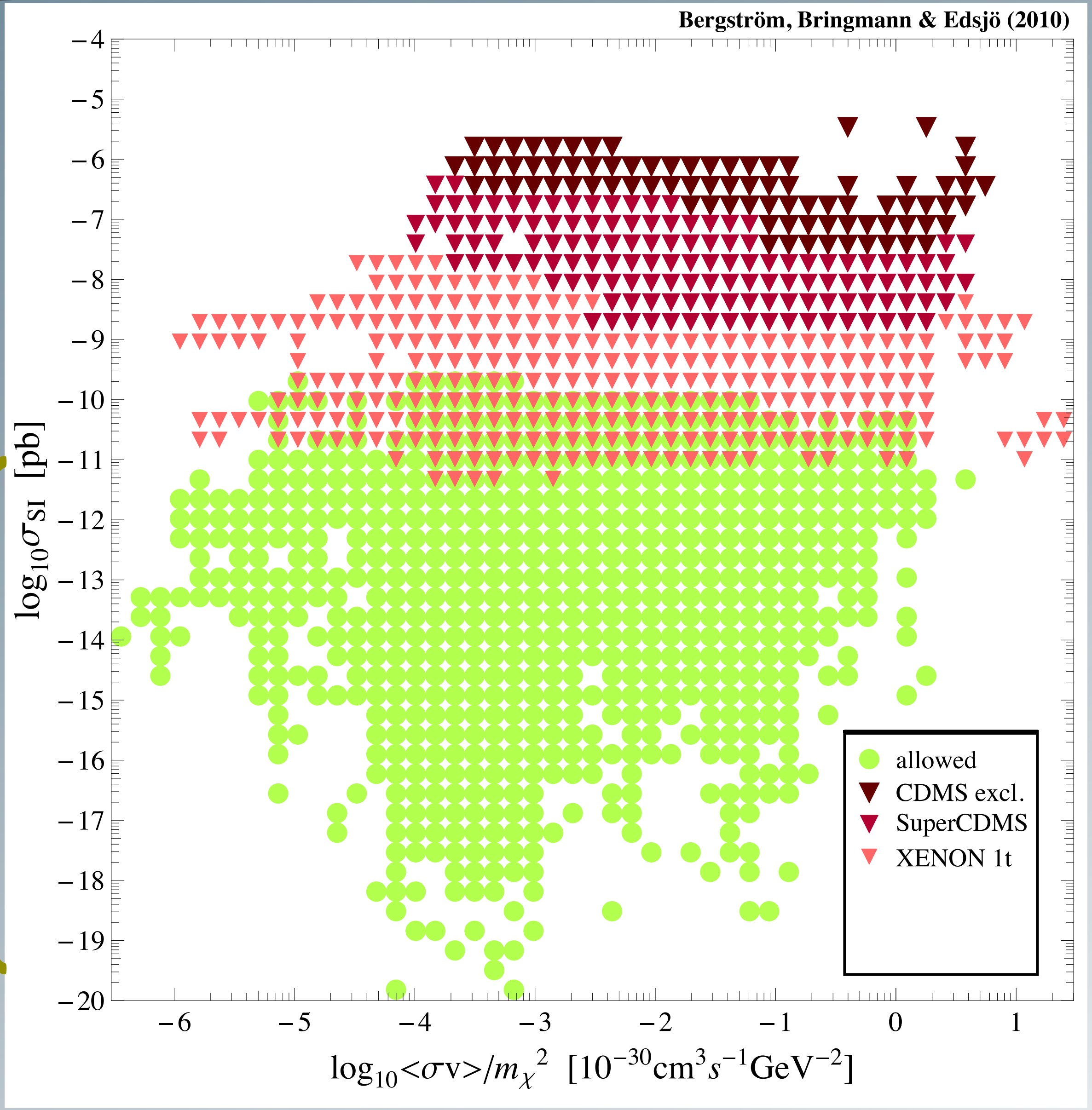


(Bergström, TB & Edsjö, PRD '11)

Direct vs. indirect detection

MSSM+mSUGRA scan:
~10^6 models, 3σ WMAP,
all collider bounds OK

almost 10 orders of magnitude often "missing" in exclusion plots from direct detection!



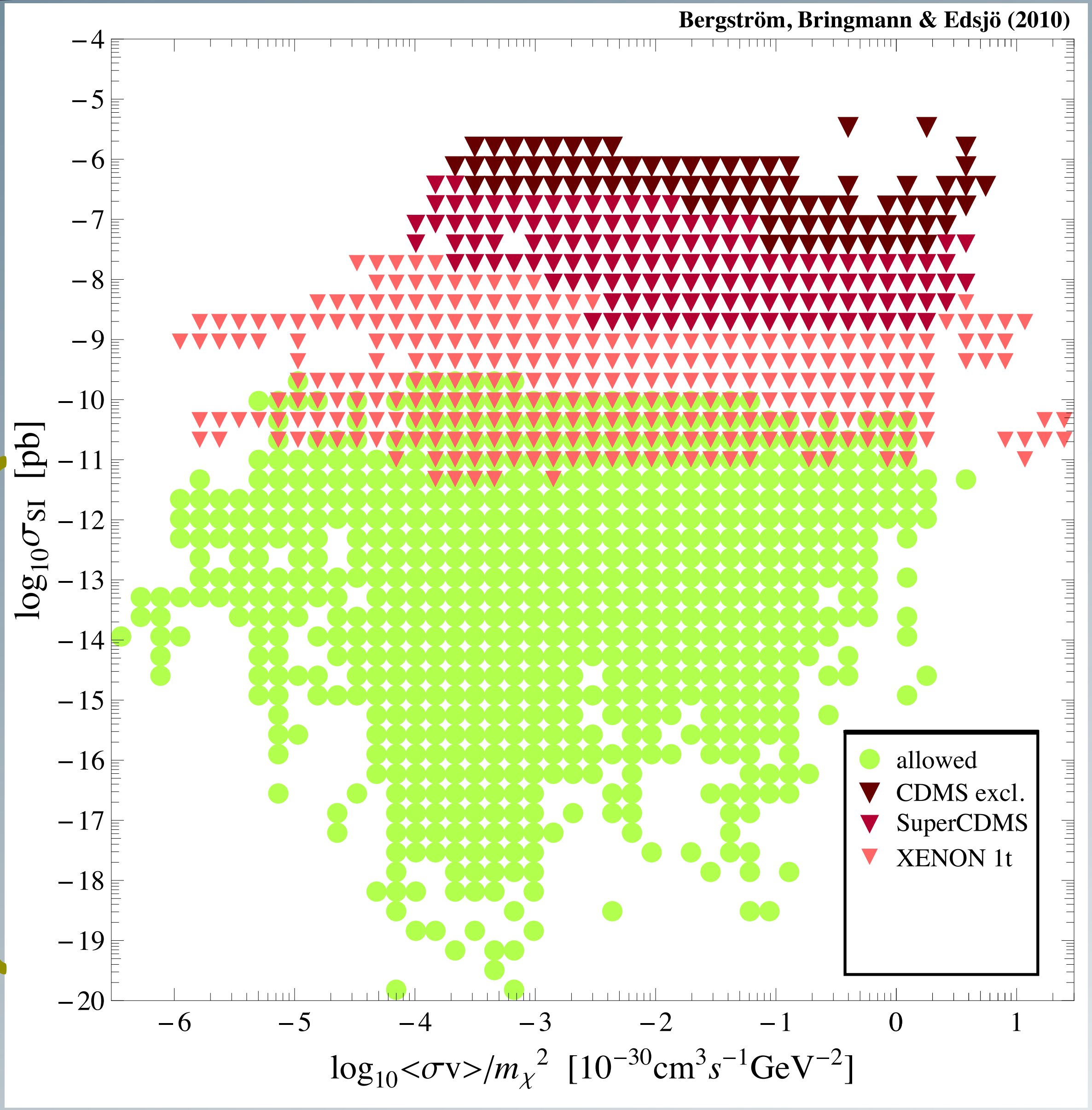
(Bergström, TB & Edsjö, PRD '11)

Direct vs. indirect detection

DarkSUSY

MSSM+mSUGRA scan:
~10^6 models, 3σ WMAP, all collider bounds OK

almost 10 orders of magnitude often "missing" in exclusion plots from direct detection!



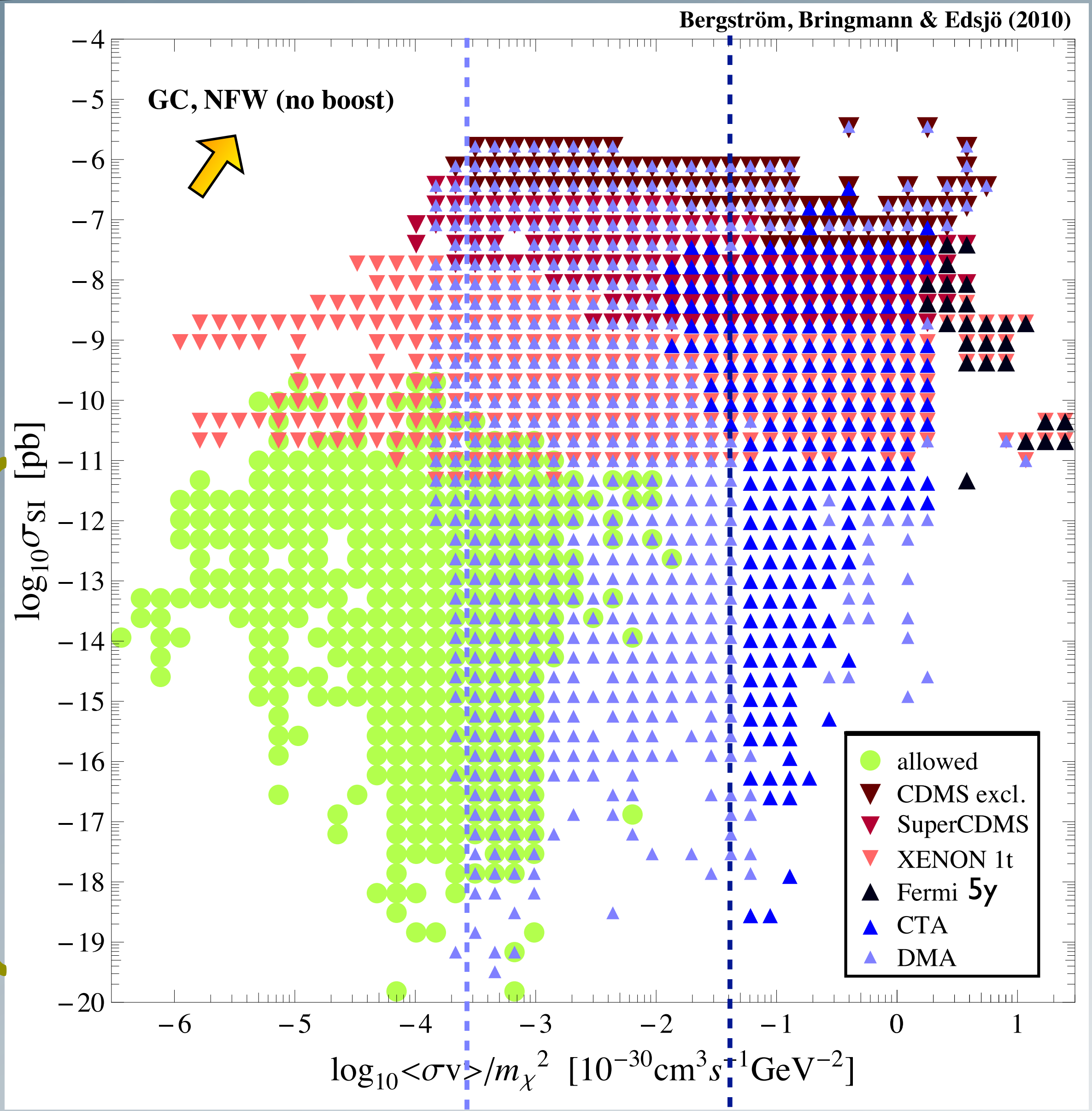
CTA/DMA: assume that angular resolution is good enough to distinguish HESS source from GC; take Fermi background model

(Bergström, TB & Edsjö, PRD '11)

Direct vs. indirect detection

MSSM+mSUGRA scan:
~10^6 models, 3σ WMAP,
all collider bounds OK

almost 10 orders of magnitude often "missing" in exclusion plots from direct detection!



DMA CTA

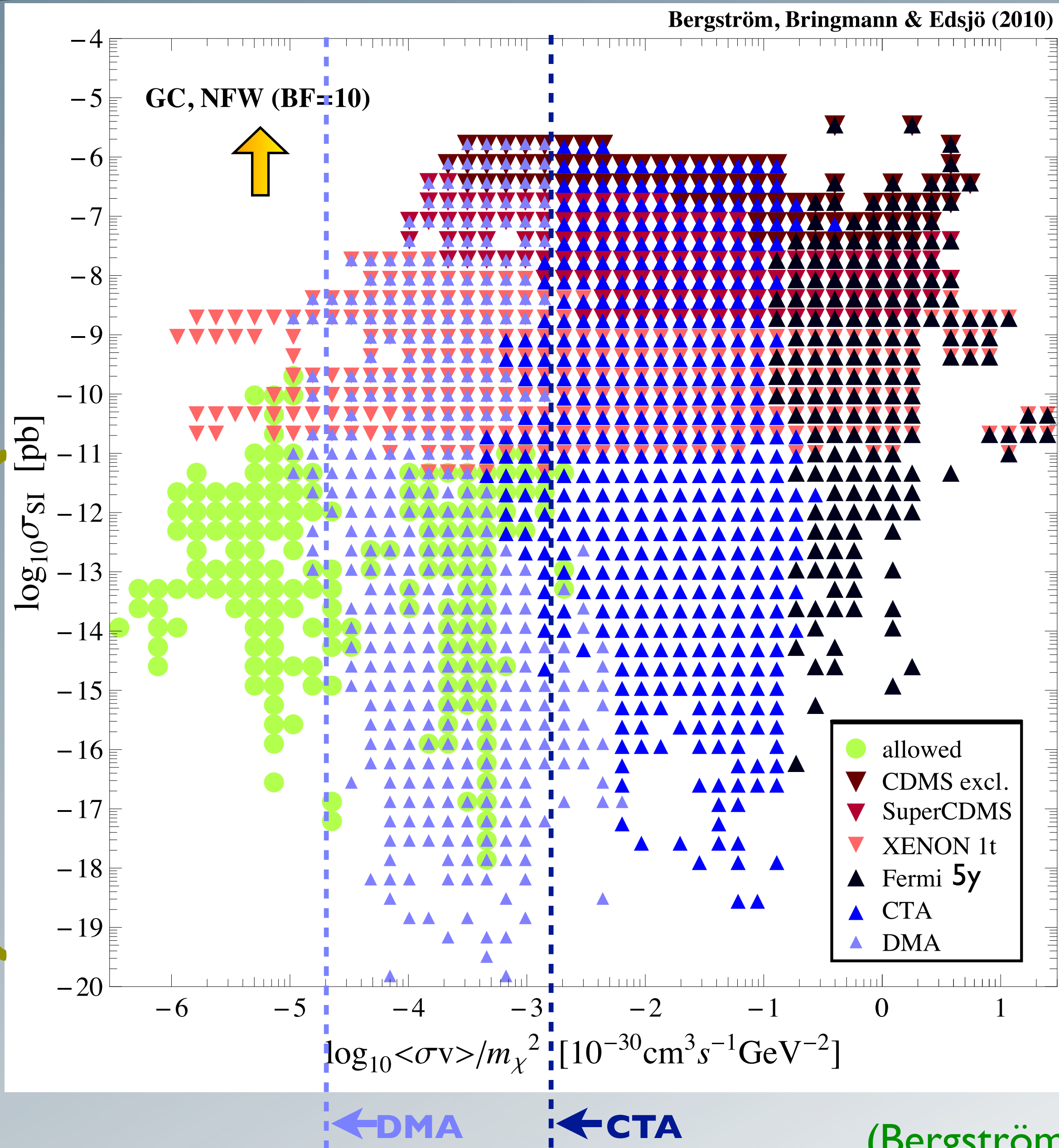
CTA/DMA: assume that angular resolution is good enough to distinguish HESS source from GC; take Fermi background model

(Bergström, TB & Edsjö, PRD '11)

Direct vs. indirect detection

MSSM+mSUGRA scan:
~10^6 models, 3σ WMAP,
all collider bounds OK

almost 10 orders of magnitude often "missing" in exclusion plots from direct detection!



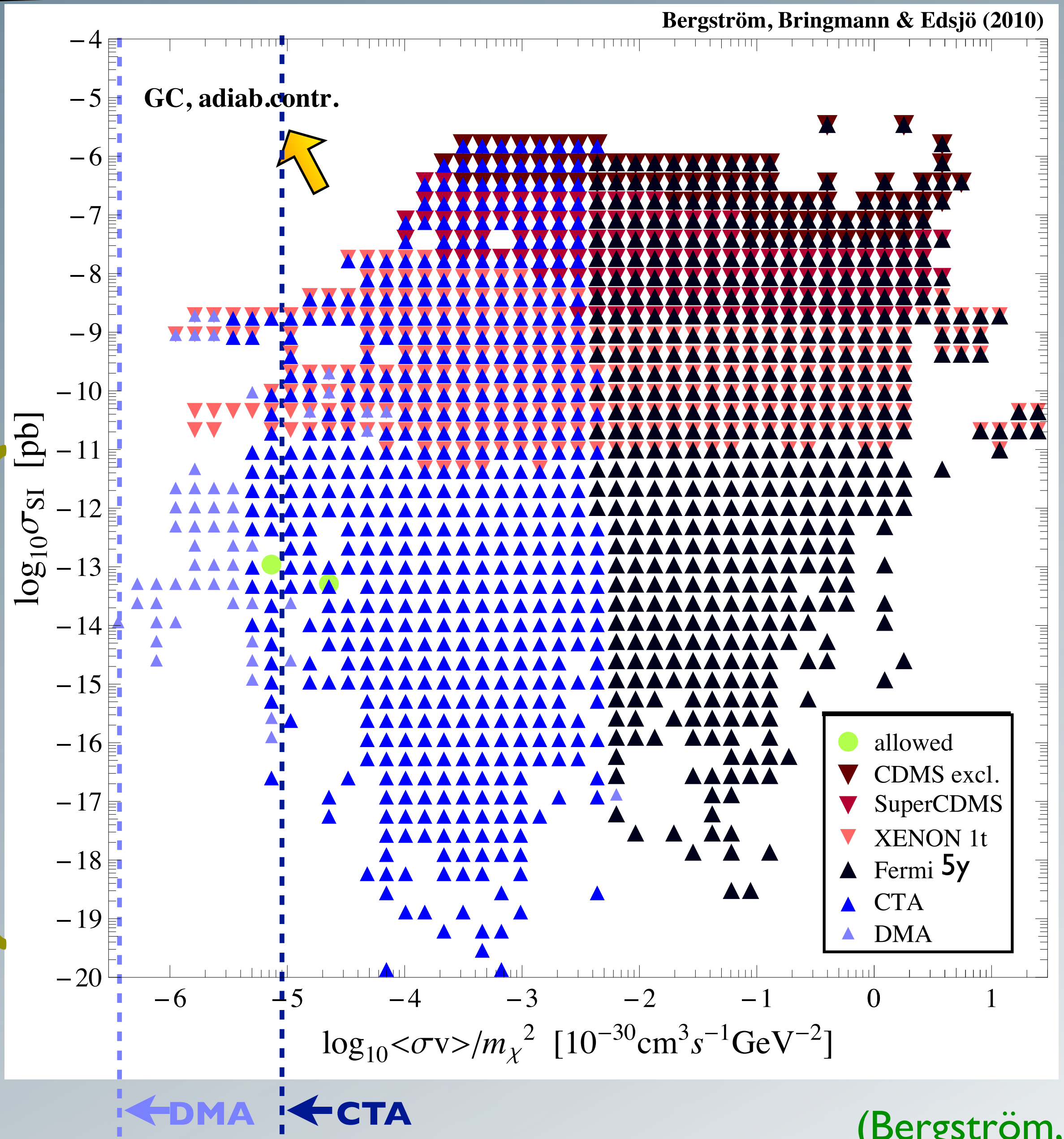
CTA/DMA: assume that angular resolution is good enough to distinguish HESS source from GC; take Fermi background model

(Bergström, TB & Edsjö, PRD '11)

Direct vs. indirect detection

MSSM+mSUGRA scan:
~10^6 models, 3σ WMAP,
all collider bounds OK

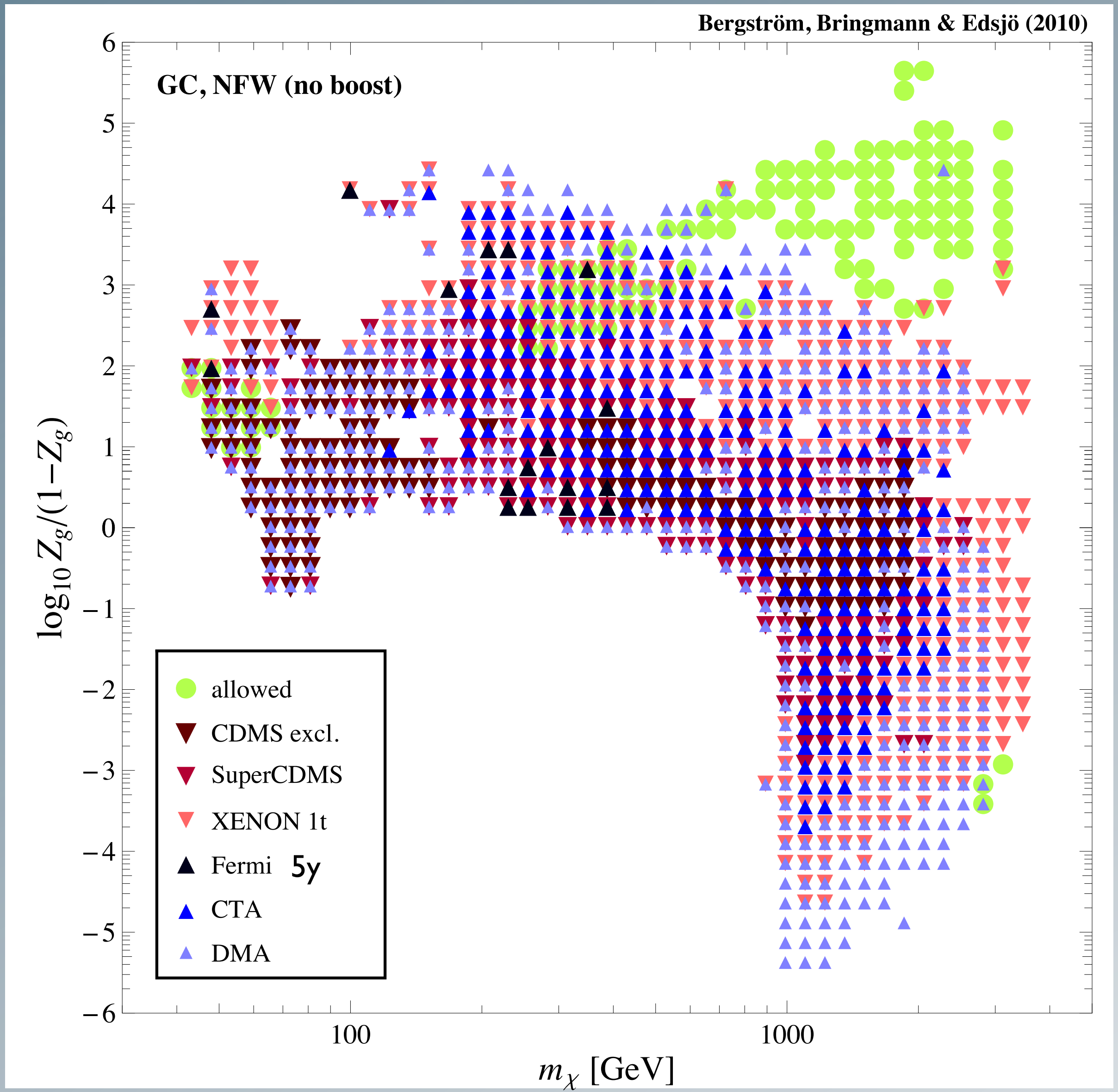
almost 10 orders of magnitude often "missing" in exclusion plots from direct detection!



CTA/DMA: assume that angular resolution is good enough to distinguish HESS source from GC; take Fermi background model

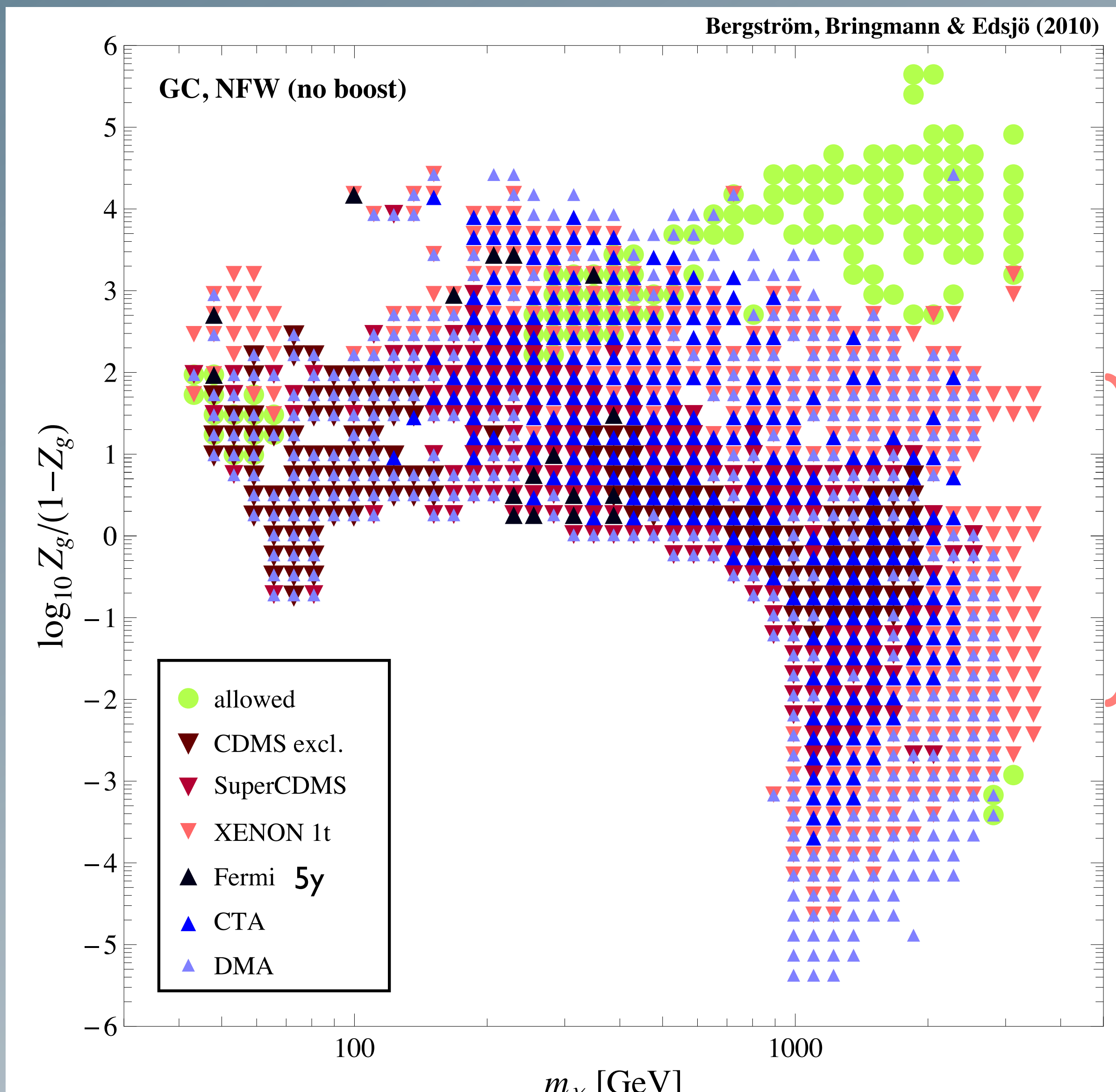
(Bergström, TB & Edsjö, PRD '11)

Direct vs. indirect detection



(Bergström, TB & Edsjö, PRD '11)

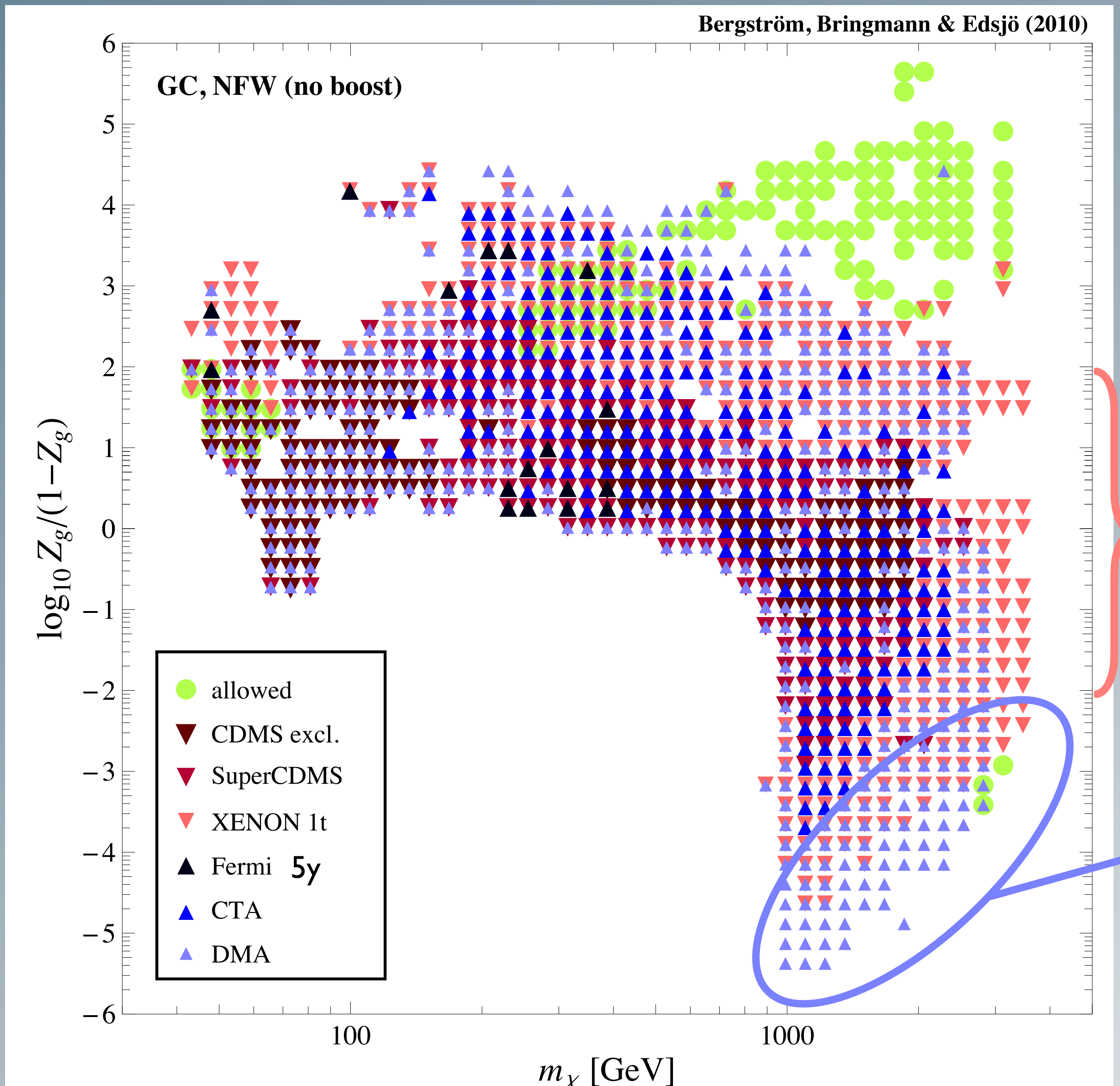
Direct vs. indirect detection



mixed neutralinos:
well suited for direct searches

(Bergström, TB & Edsjö, PRD '11)

Direct vs. indirect detection

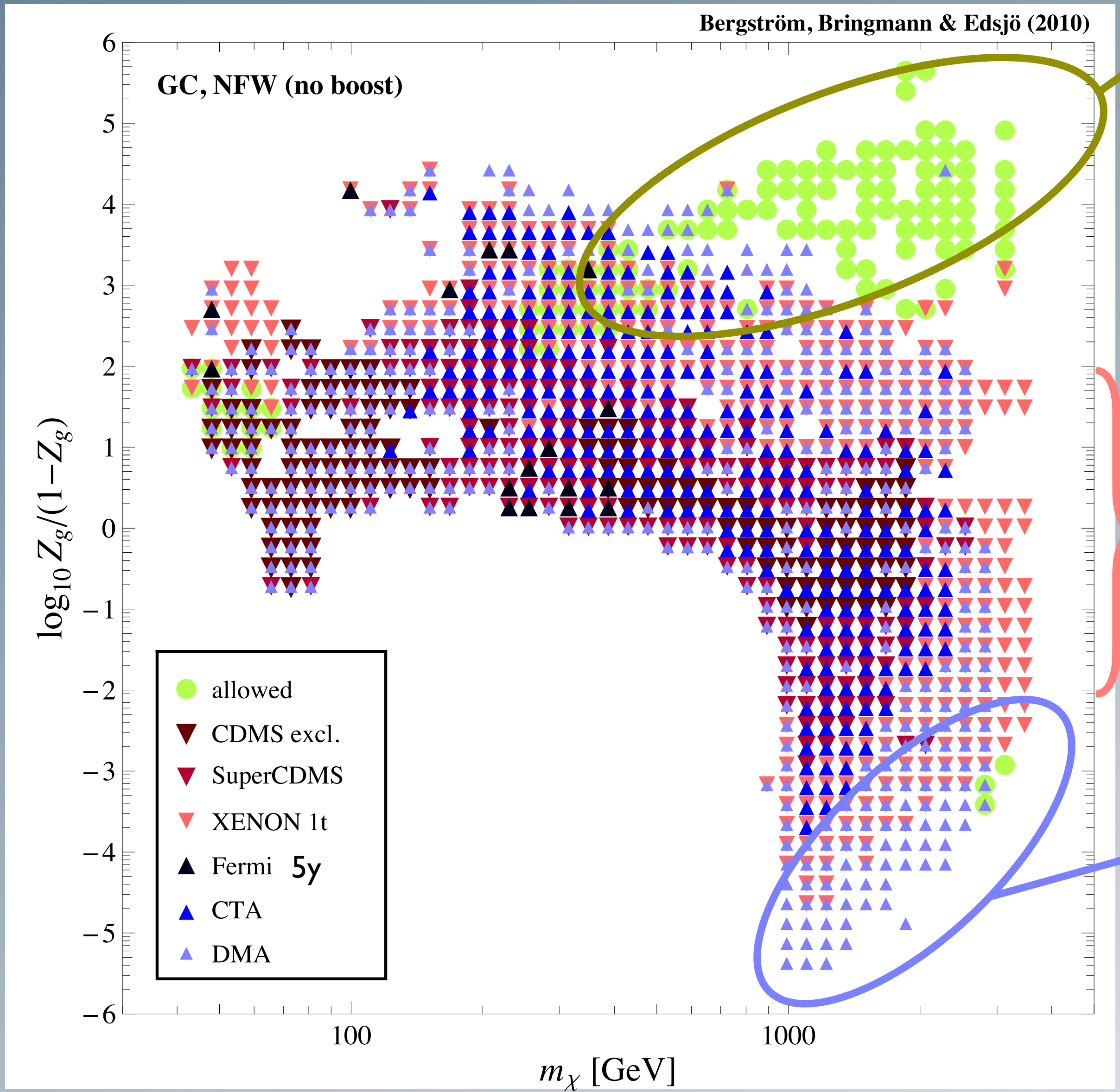


mixed neutralinos:
well suited for direct searches

pure Higgsinos:
accessible by indirect searches (DMA!)

(Bergström, TB & Edsjö, PRD '11)

Direct vs. indirect detection



high-mass Gauginos:

more difficult, but indirect searches OK for favorable DM distributions

NB! Sommerfeld effects not yet included...

mixed neutralinos:

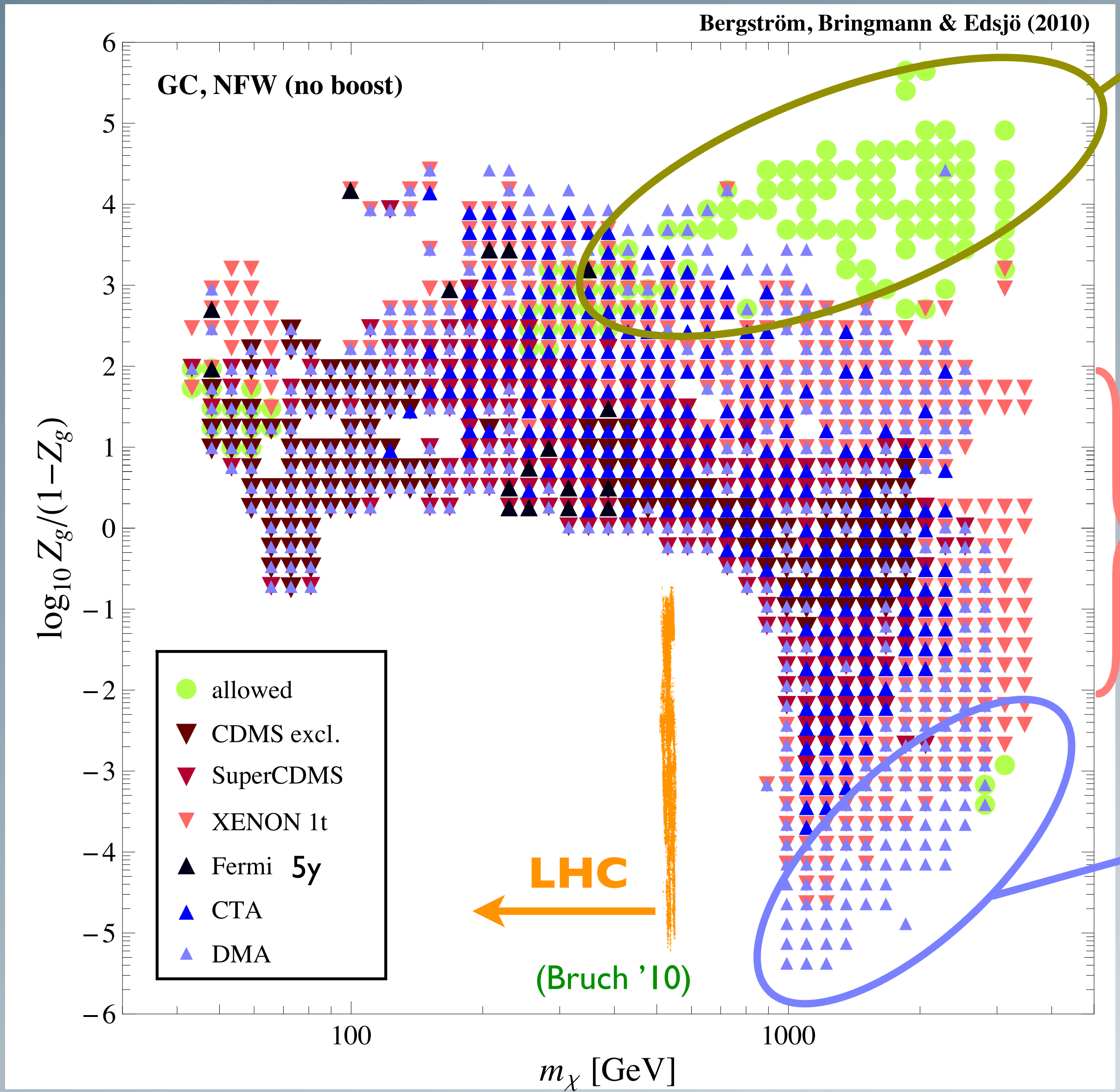
well suited for direct searches

pure Higgsinos:

accessible by indirect searches (DMA!)

(Bergström, TB & Edsjö, PRD '11)

Direct vs. indirect detection



high-mass Gauginos:
more difficult, but indirect searches OK for favorable DM distributions

NB! Sommerfeld effects not yet included...

mixed neutralinos:
well suited for direct searches

pure Higgsinos:
accessible by indirect searches (DMA!)

(Bergström, TB & Edsjö, PRD '11)

Conclusions and Outlook

Conclusions and Outlook

- Indirect detection experiments seriously start to probe the parameter space of realistic WIMP models

Conclusions and Outlook

- Indirect detection experiments seriously start to probe the parameter space of realistic WIMP models
- A dedicated dark matter experiment (like DMA)
  - could fully exploit the potential of indirect searches (especially when combined with multiwavelength/-messenger techniques)
  - would be truly ***complementary*** to direct and accelerator searches!

Conclusions and Outlook

- Indirect detection experiments seriously start to probe the parameter space of realistic WIMP models
- A dedicated dark matter experiment (like DMA)
  - could fully exploit the potential of indirect searches (especially when combined with multiwavelength/-messenger techniques)
  - would be truly ***complementary*** to direct and accelerator searches!
- Distinct spectral features in gamma rays
  - help to identify a DM annihilation signal
  - could reveal a lot about the nature of the DM particles

  ⇨ discovery (rather than exclusion) channel!

Conclusions and Outlook

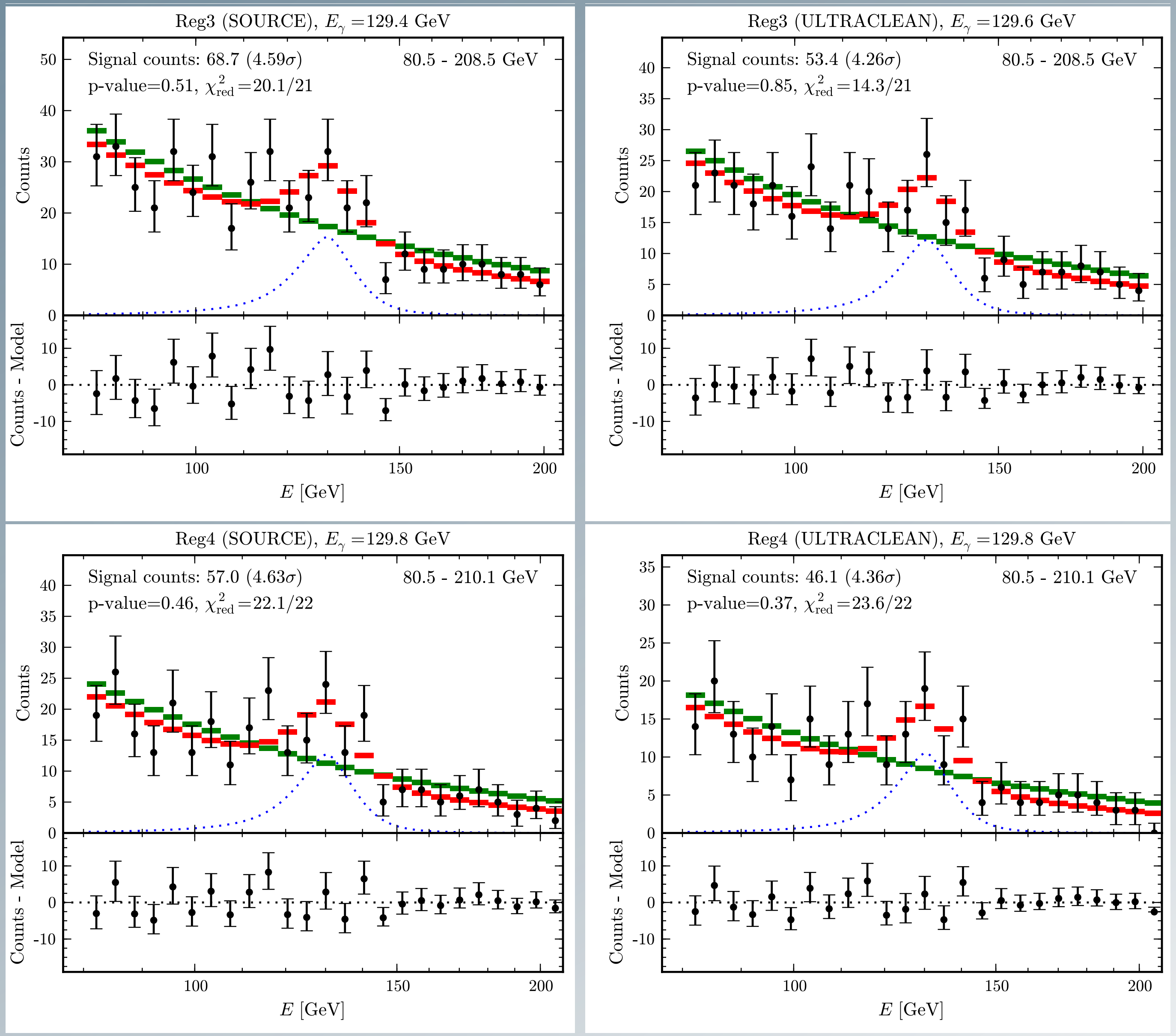
- Indirect detection experiments seriously start to probe the parameter space of realistic WIMP models
- A dedicated dark matter experiment (like DMA)
  - could fully exploit the potential of indirect searches (especially when combined with multiwavelength/-messenger techniques)
  - would be truly ***complementary*** to direct and accelerator searches!
- Distinct spectral features in gamma rays
  - help to identify a DM annihilation signal
  - could reveal a lot about the nature of the DM particles

  ⇨ discovery (rather than exclusion) channel!
- Have we already seen a signal?
  - based on O(100) photons $\rightsquigarrow$ need a few years' more data...

Backup slides

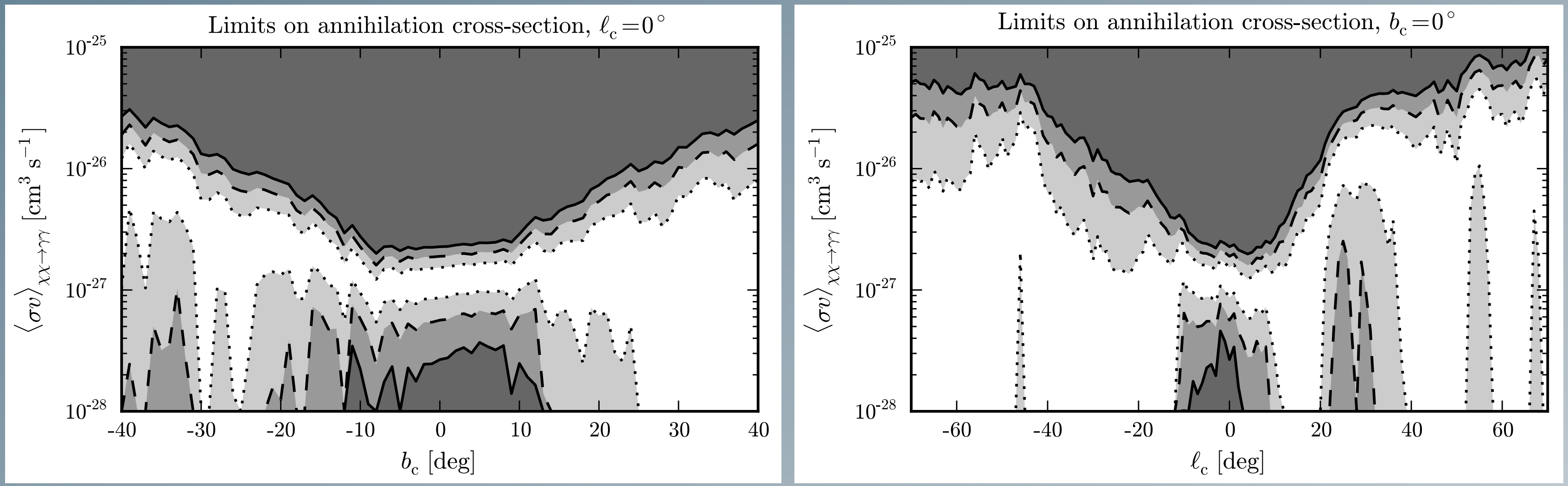
Line analysis (3)

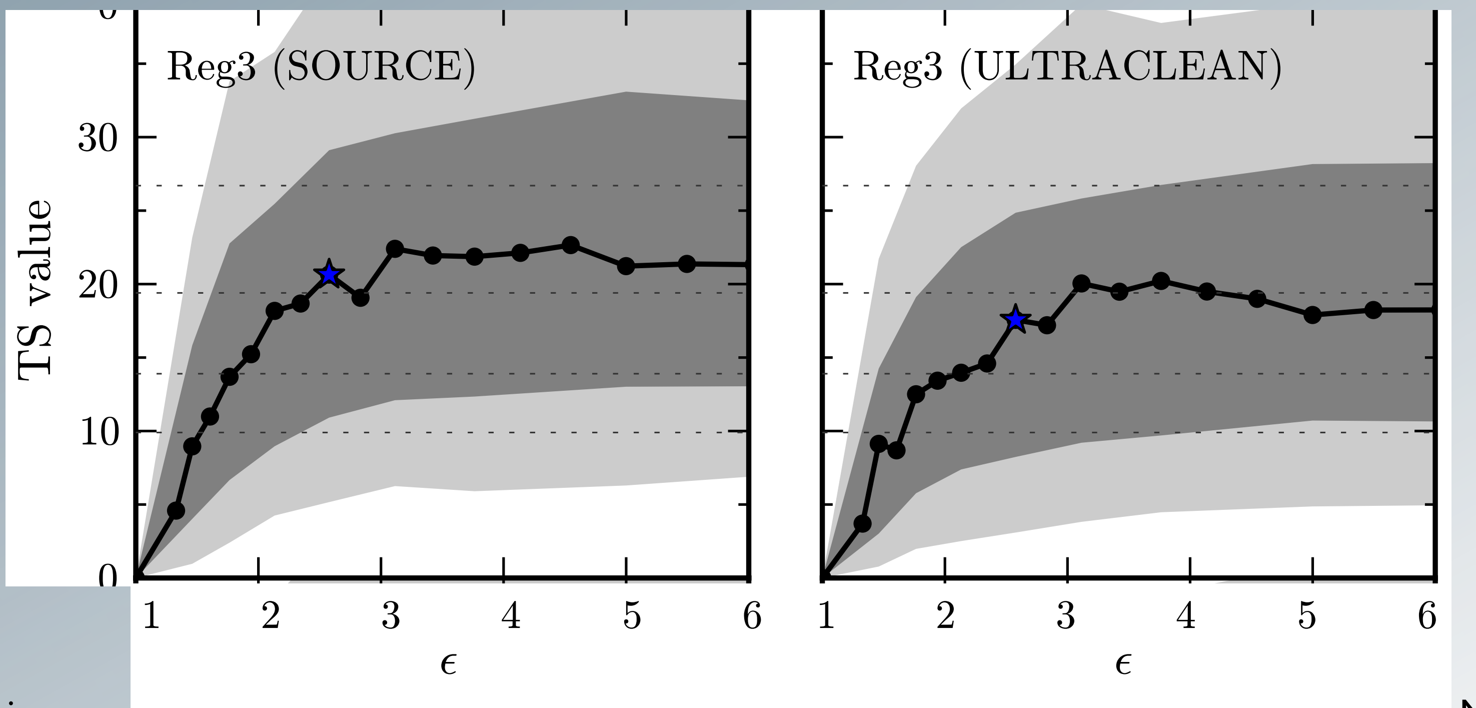
Weniger, 1204.2797



Line analysis (3)

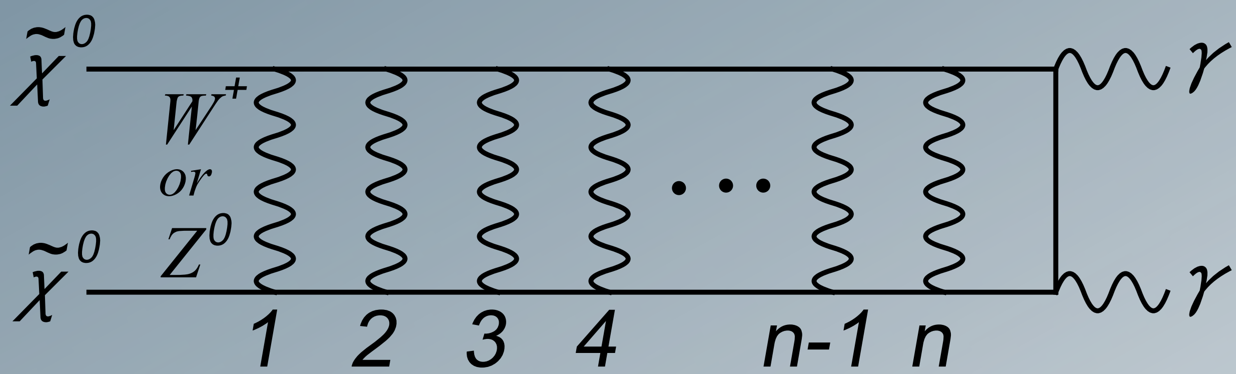
Weniger, 1204.2797

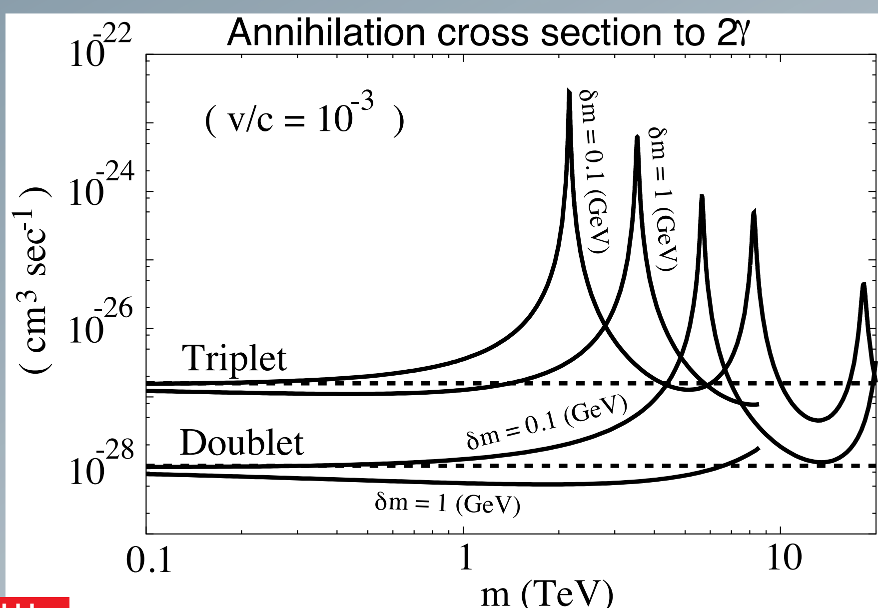




Sommerfeld enhancement

Relevance of non-perturbative effects for DM annihilations pointed out long before PAMELA:





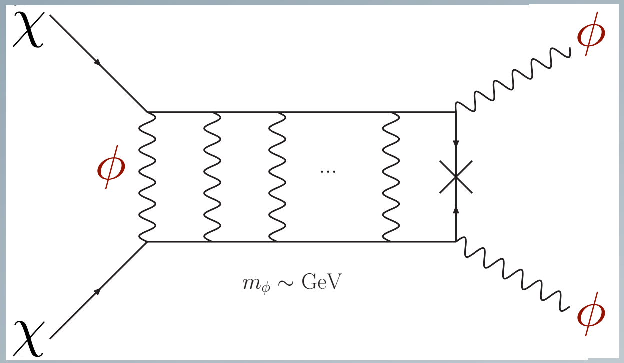
➡ *considerable enhancement of annihilation rates possible!*

Hisano, Matsumoto, Nojiri, Saito, … '03 - '06

“A theory of dark matter”

Arkani-Hamed, Finkbeiner, Slatyer & Weiner, PRD ’09

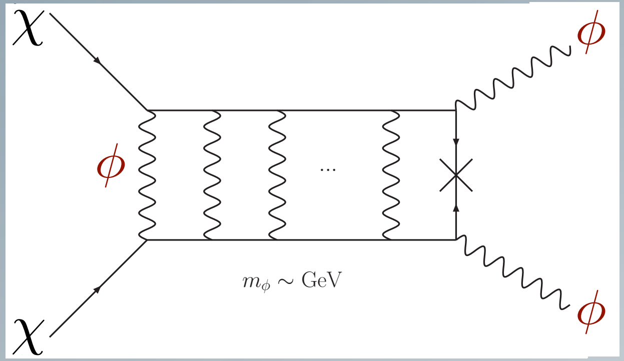
- ***idea***: introduce new force in dark sector, with $m_\phi \lesssim 1\,\mathrm{GeV}$
  - large annihilation rates (Sommerfeld enhancement)
  - later decay: $\phi \to e^+e^-$ or $\mu^+\mu^-$ (kinematics!)



"A theory of dark matter"

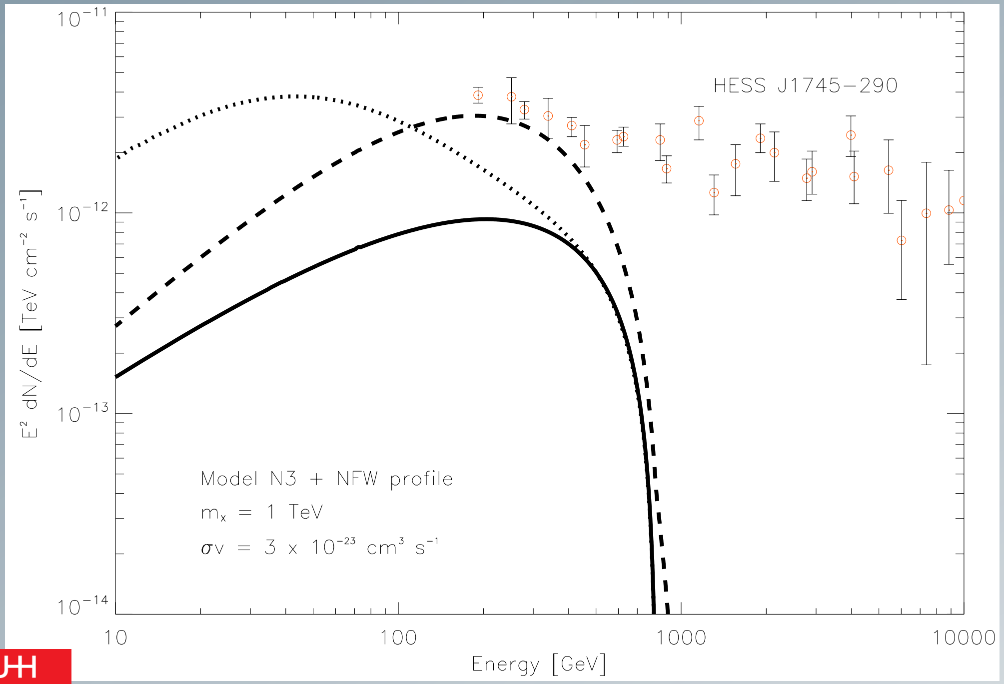
Arkani-Hamed, Finkbeiner, Slatyer & Weiner, PRD '09

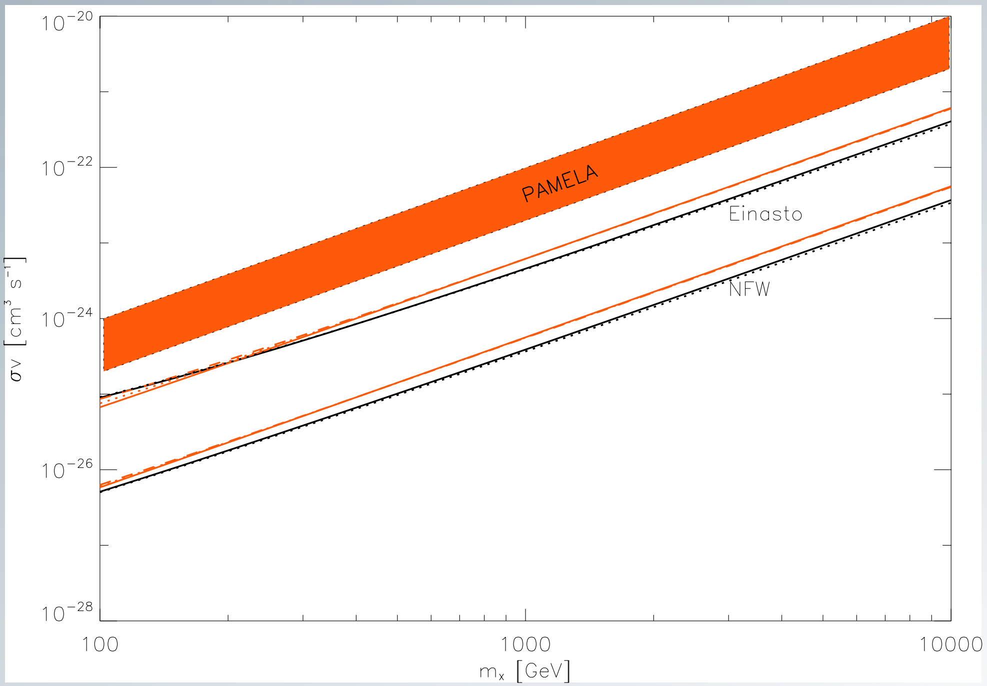
- ***idea***: introduce new force in dark sector, with $m_\phi \lesssim 1\,\mathrm{GeV}$
  - large annihilation rates (Sommerfeld enhancement)
  - later decay: $\phi \to e^+e^-$ or $\mu^+\mu^-$ (kinematics!)



- ***but***: strong constraints from γ (IB) and radio (synchroton)!

Bertone, Bergström, TB, Edsjö & Taoso, PRD '09

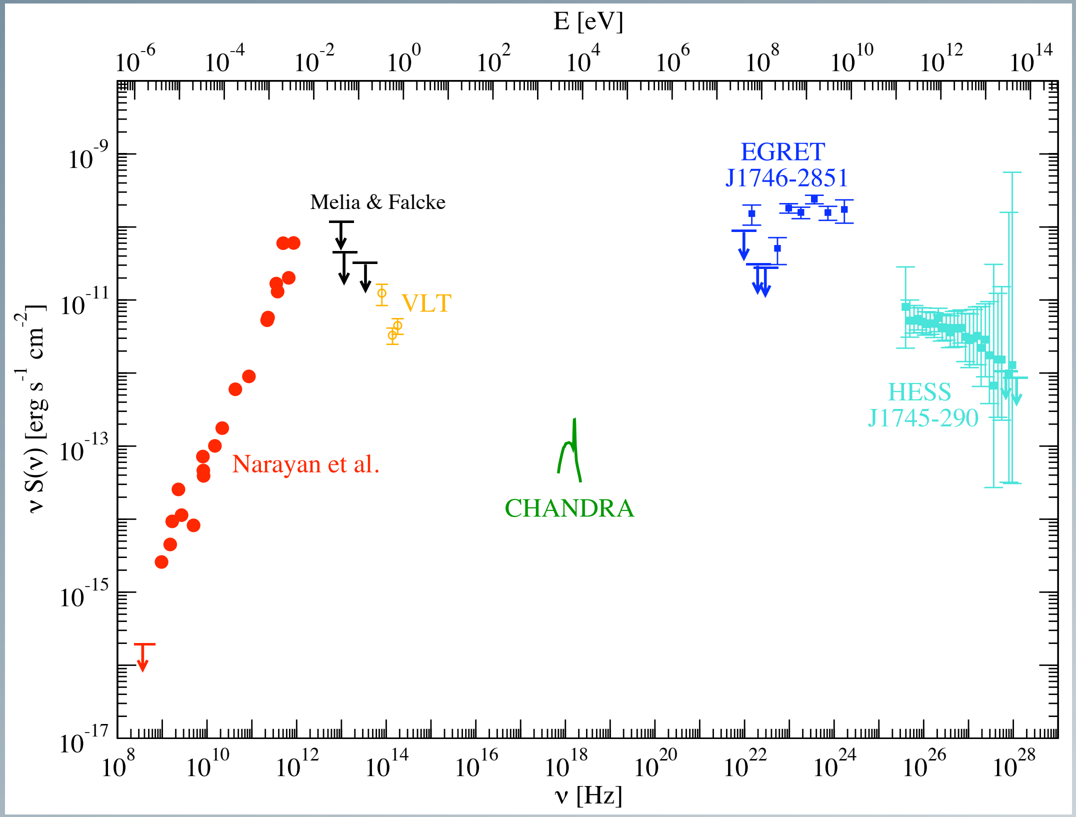


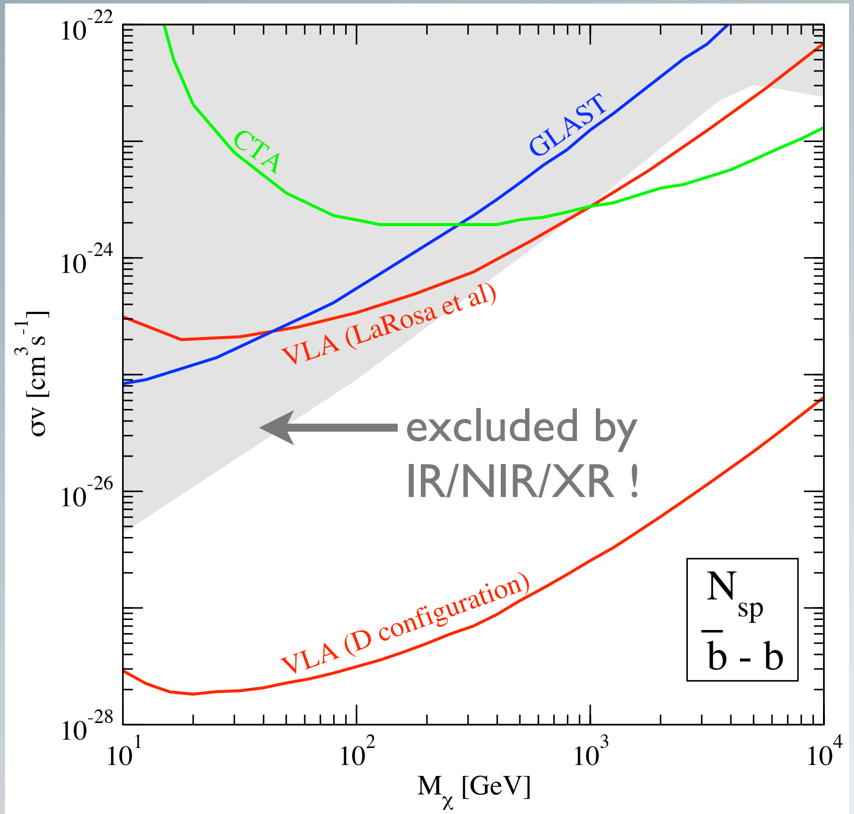


Multi-Wavelength

- E.g. the Galactic Center: An interesting target for multi-wavelength searches!

Regis & Ullio, PRD '08



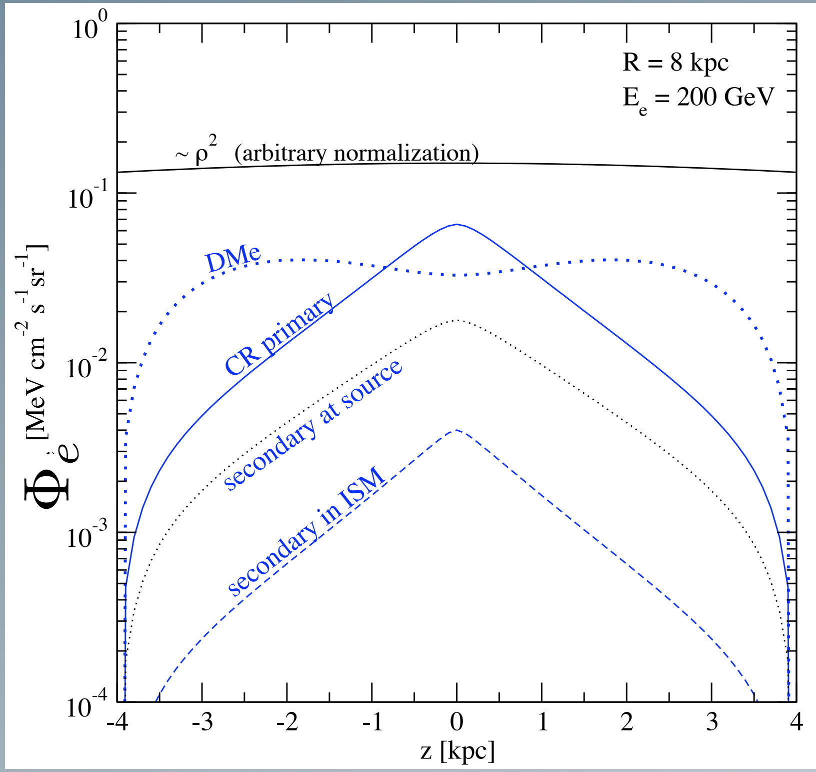


→ Gamma rays not necessarily most constraining!

Galactic diffuse emission

- A more conservative approach relies only on local observations and quantities

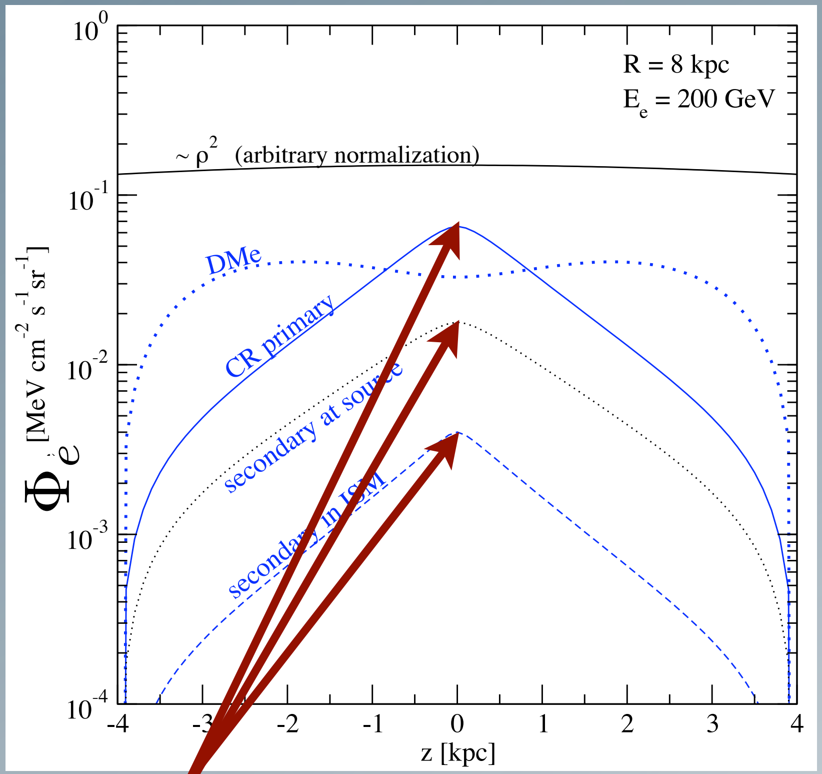
Regis & Ullio, PRD '09



Galactic diffuse emission

- A more conservative approach relies only on local observations and quantities

Regis & Ullio, PRD '09

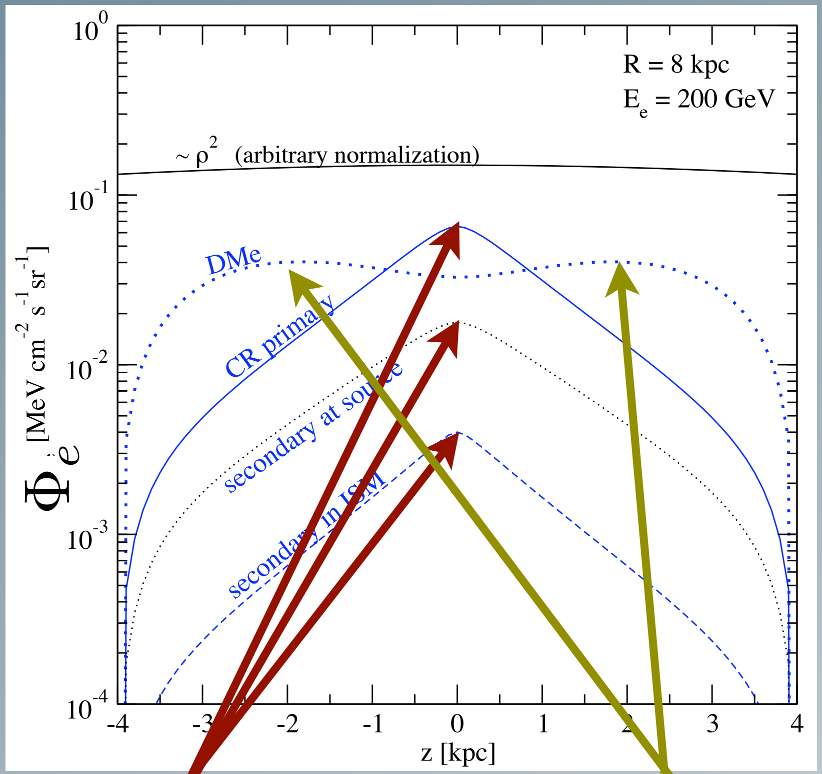


Primary/secondary astrophysical source localized at z=0

Galactic diffuse emission

- A more conservative approach relies only on local observations and quantities

Regis & Ullio, PRD '09



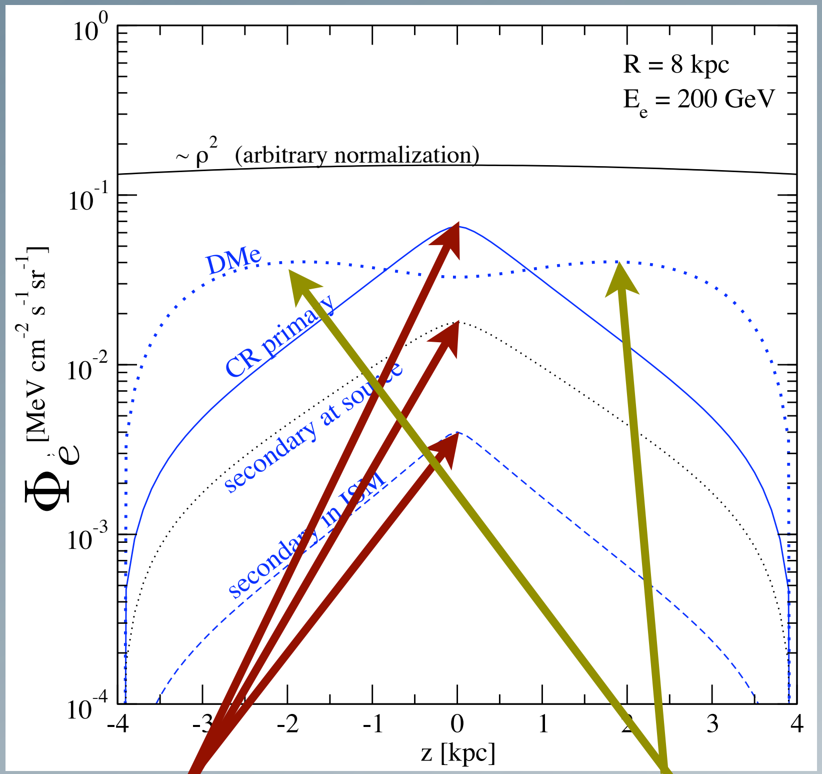
Primary/secondary astrophysical source localized at z=0

DM contribution extended

Galactic diffuse emission

- A more conservative approach relies only on local observations and quantities

Regis & Ullio, PRD '09



Primary/secondary astrophysical source localized at z=0

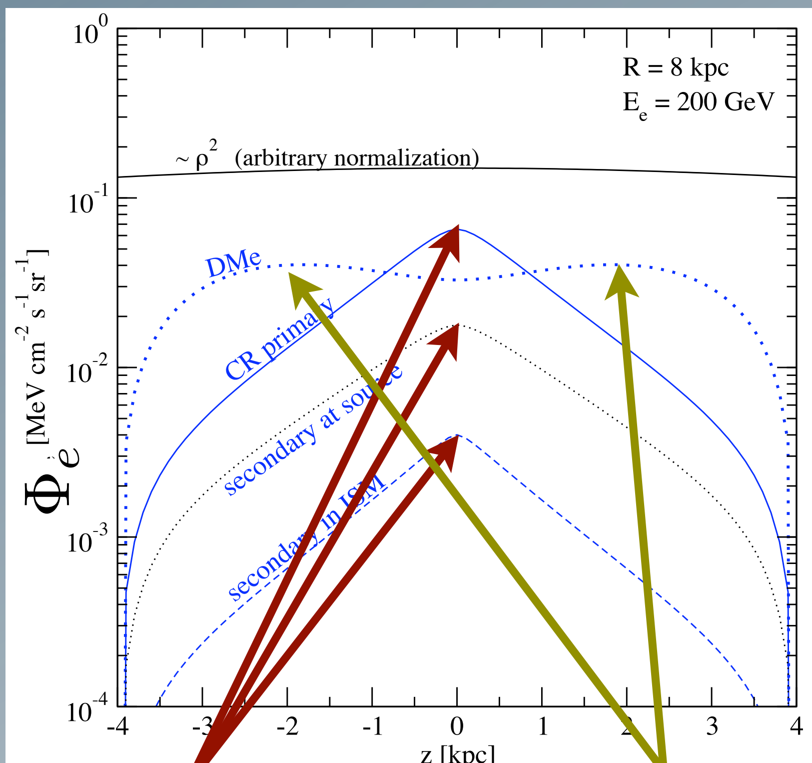
DM contribution extended

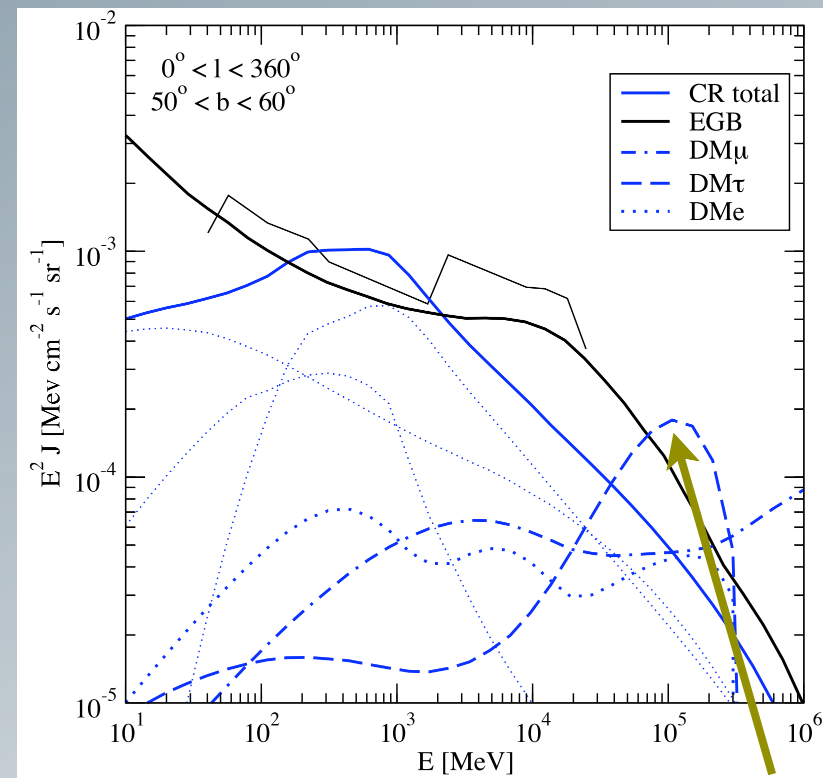
⇨ handle on this by Fermi/Planck !?

Galactic diffuse emission

- A more conservative approach relies only on local observations and quantities

Regis & Ullio, PRD '09





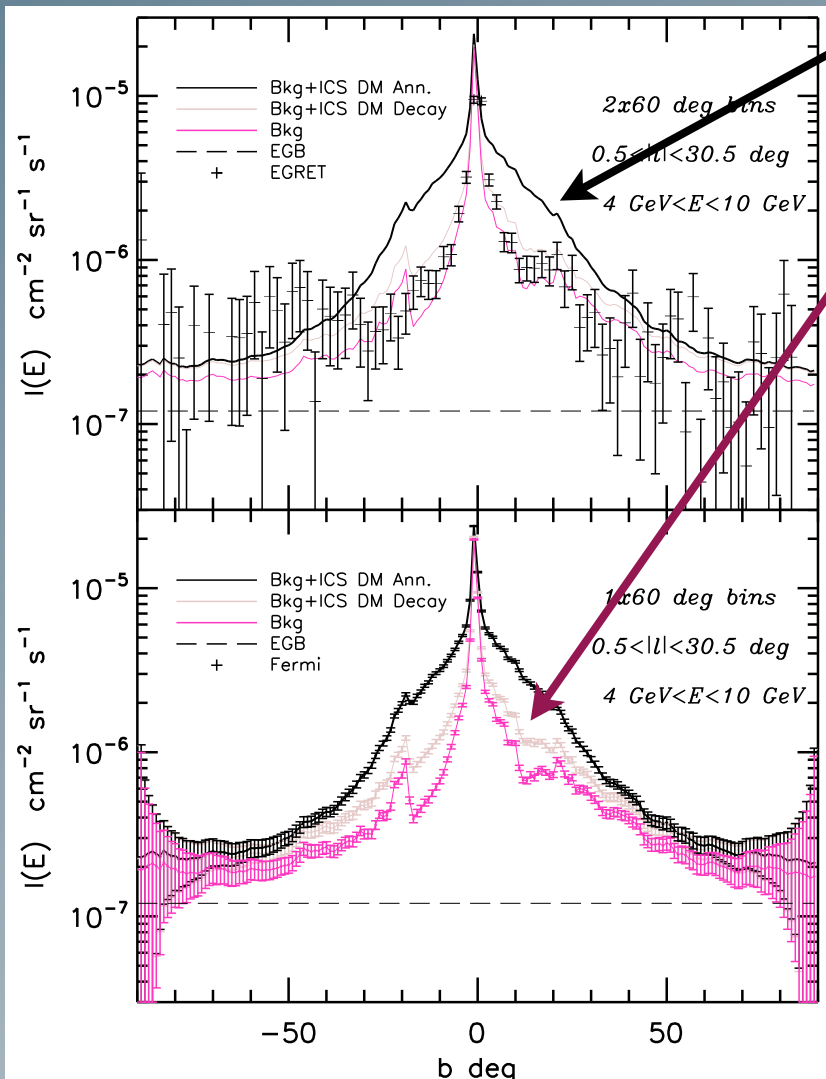
Primary/secondary astrophysical source localized at z=0

DM contribution extended

⇨ handle on this by Fermi/Planck !?

IC+FSR emission from DM component could be seen against diffuse background

Diffuse γ-ray constraints

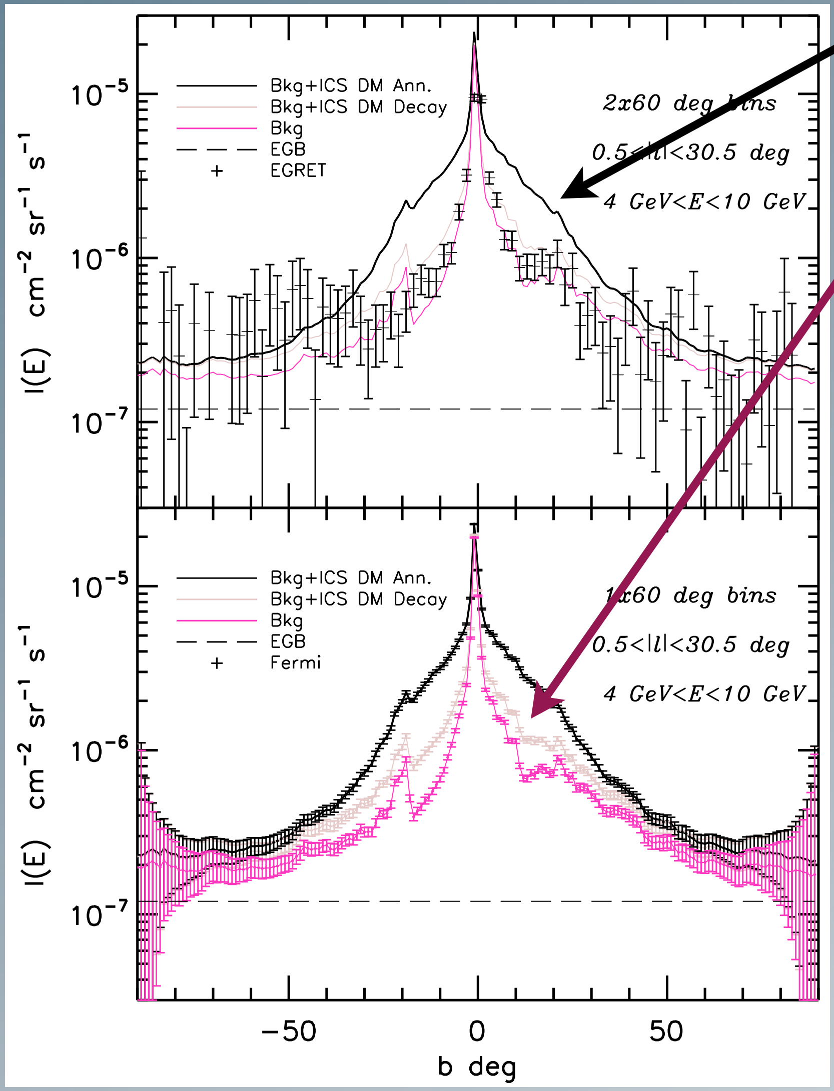


Borriello, Cuoco & Miele, PRL '09

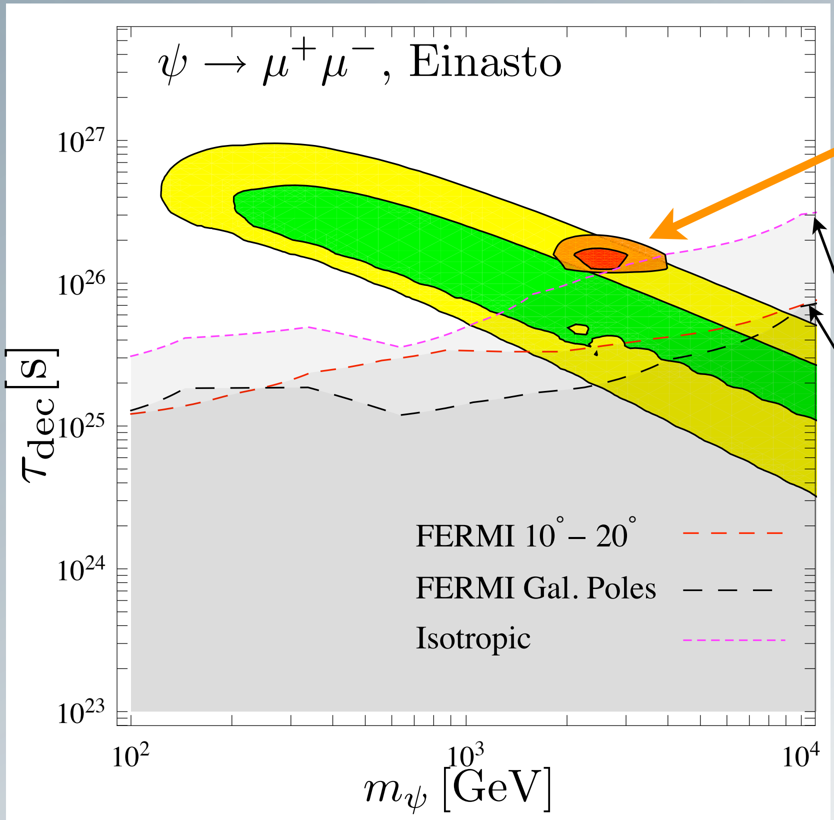
- Already EGRET data in some tension with annihilating WIMP explanation of PAMELA
- Prediction for Fermi:
  even decaying DM could be excluded!

Diffuse γ-ray constraints

- Already EGRET data in some tension with annihilating WIMP explanation of PAMELA
- Prediction for Fermi:
even decaying DM could be excluded!



Borriello, Cuoco & Miele, PRL '09



Cirelli, Panci & Serpico, 0912.0663