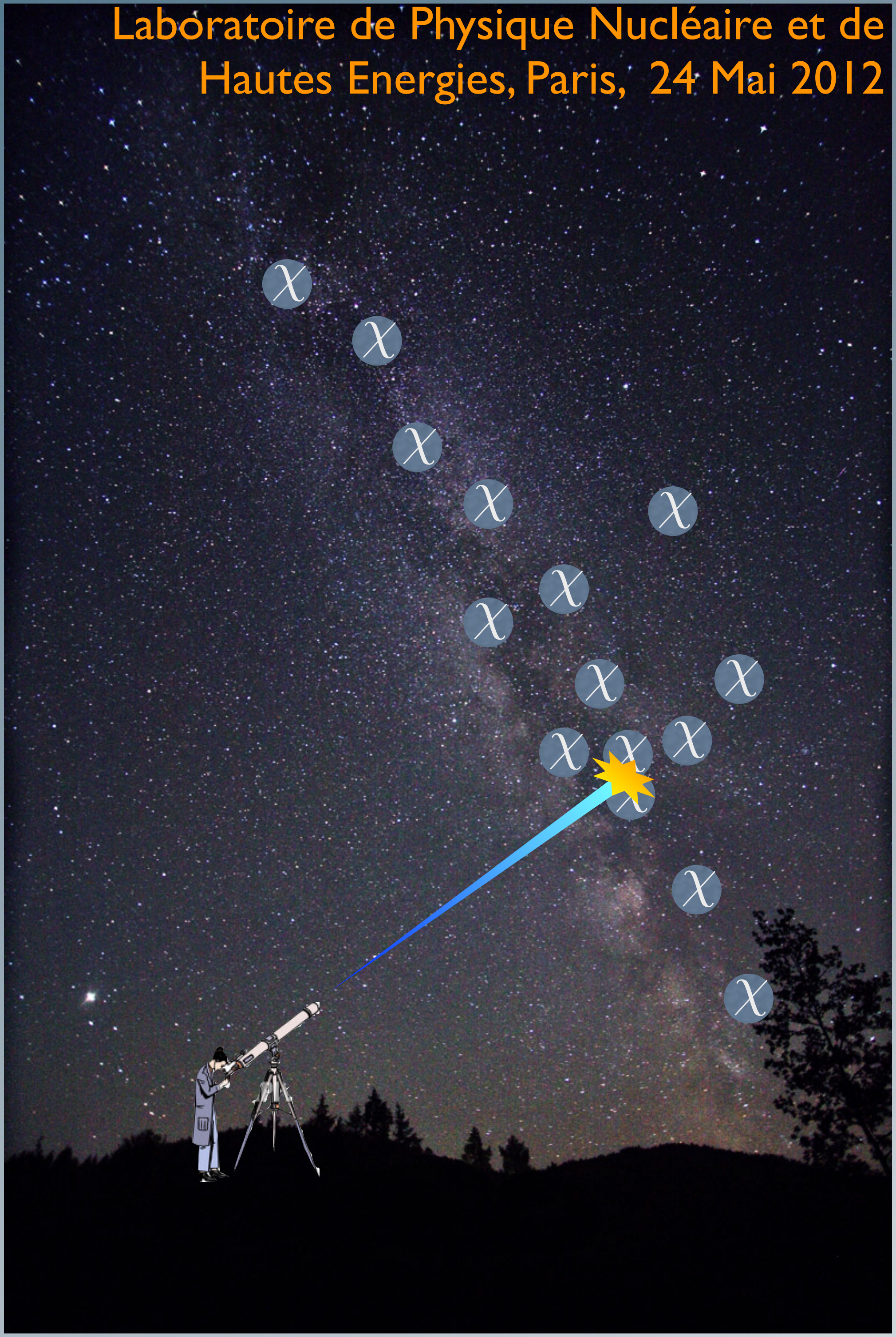


Dark Matter searches with Gamma rays:

The glimpse of a smoking gun signal?

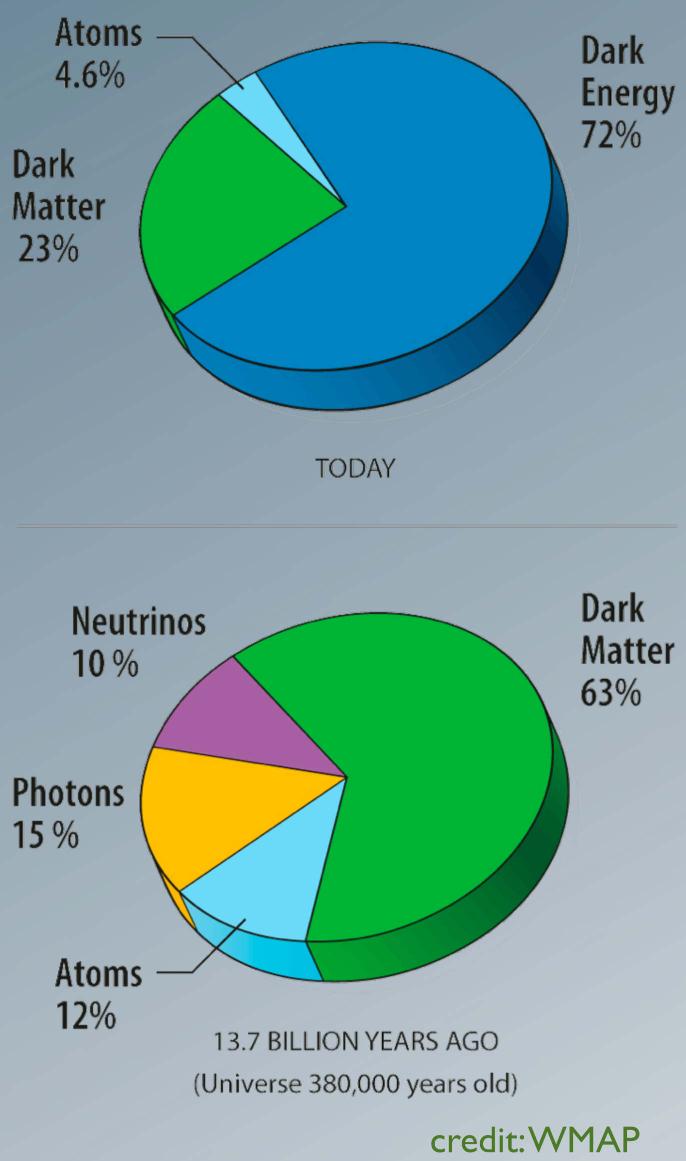
w/ Christoph Weniger, Francesca Calore, Xiaoyuan Huang, Alejandro Ibarra, Gilles Vertongen, Stefan Vogl, ...

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



- *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 Weakly Interacting Massive Particles in the early universe:

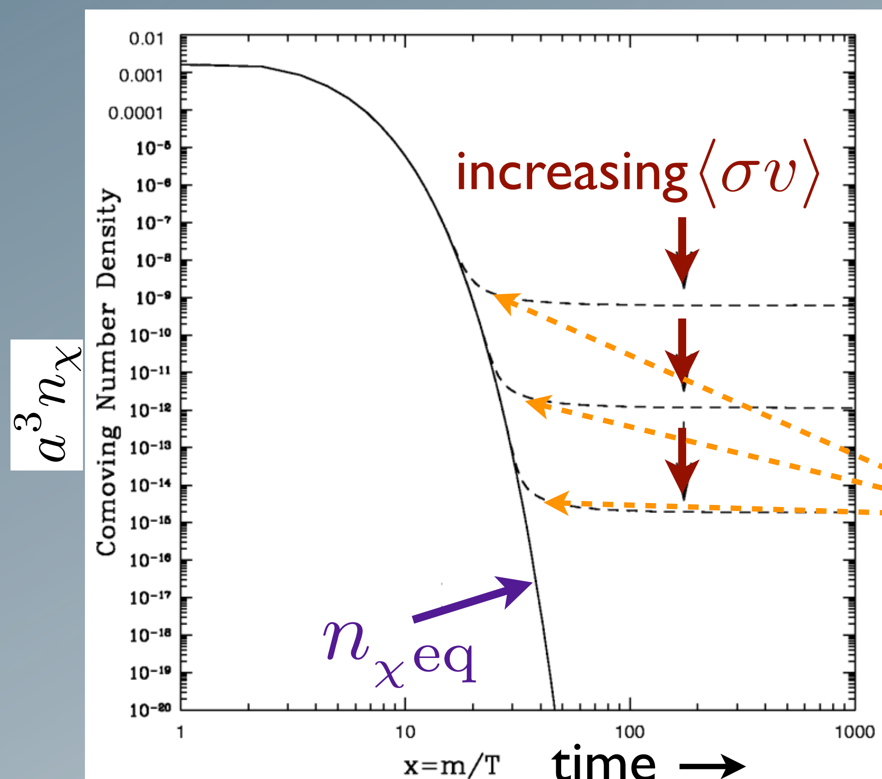


Fig.: Jungman, Kamionkowski & Griest, PR'96

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

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

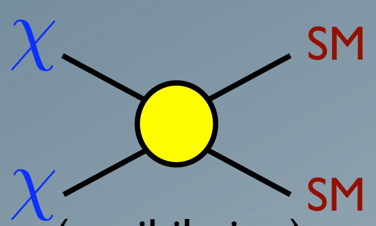
"Freeze-out" when annihilation rate falls behind expansion rate ($\to a^3 n_\chi \sim \mathrm{const.}$)

for weak-scale interactions!

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

Freeze-out ≠ decoupling !

- WIMP interactions with heat bath of SM particles:



(annihilation)

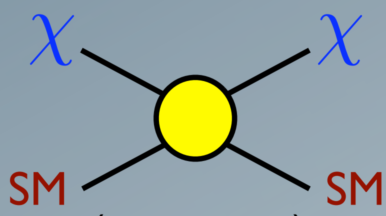
$\Downarrow$

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

chemical decoupling

$\Downarrow$

$$\Omega_\chi$$



(scattering)

$\Downarrow$

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

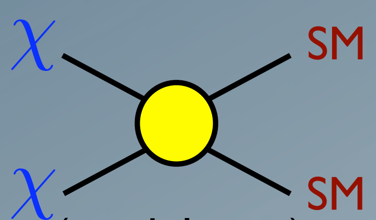
kinetic decoupling

$\Downarrow$

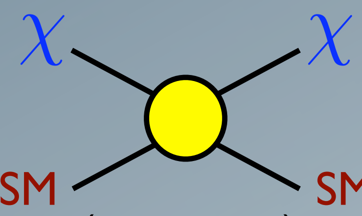
$$M_{\rm cut}$$

Freeze-out ≠ decoupling !

- WIMP interactions with heat bath of SM particles:



(annihilation)



(scattering)

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

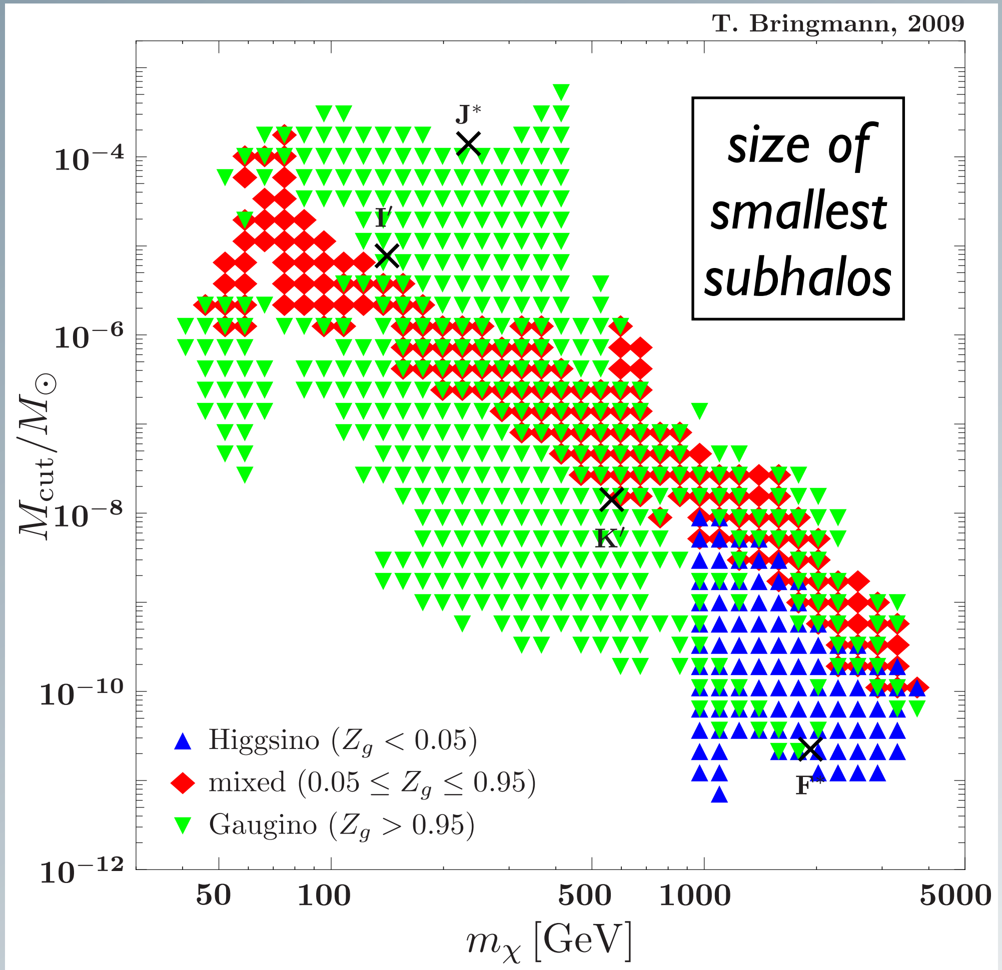
chemical decoupling

Ω_χ

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

kinetic decoupling

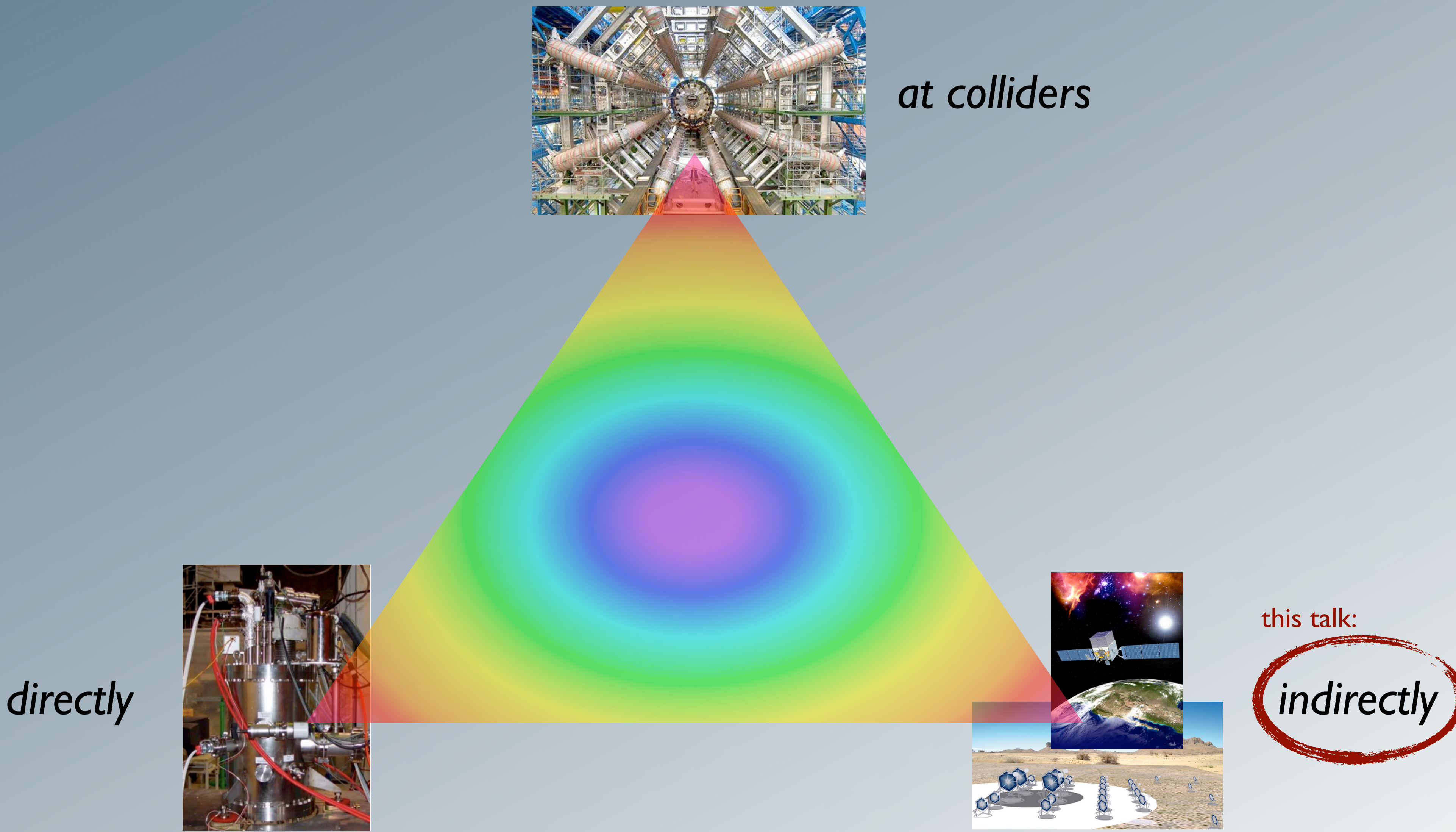
$M_{\rm cut}$



TB, NJP '09

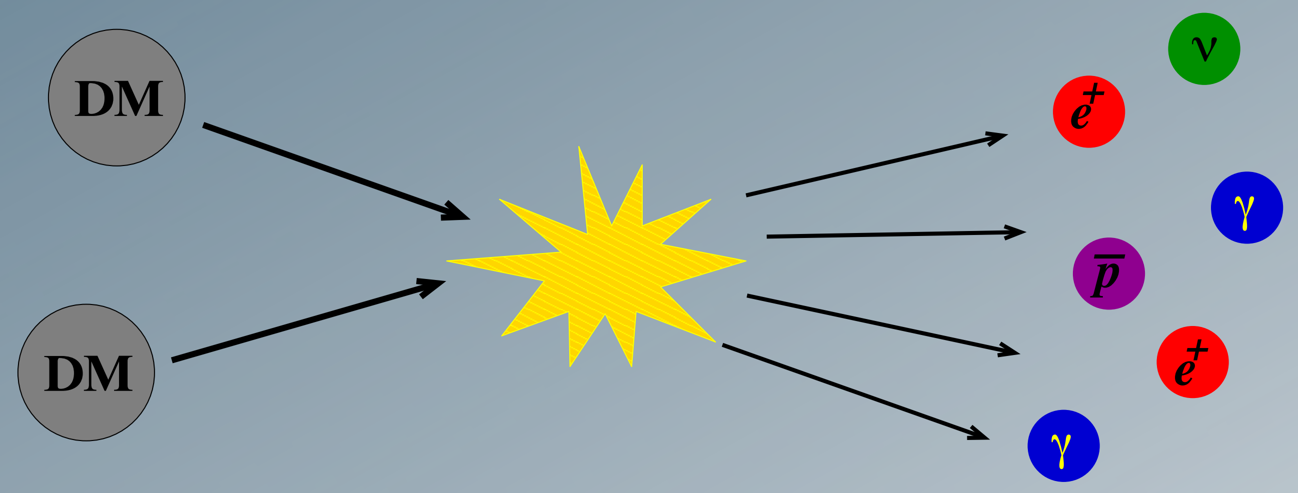
- *no "typical" $M_{\rm cut} \sim 10^{-6} M_\odot$, but highly model-dependent*
- *a window into the particle-physics nature of dark matter!*

Strategies for DM searches



➩ *all complementary!*

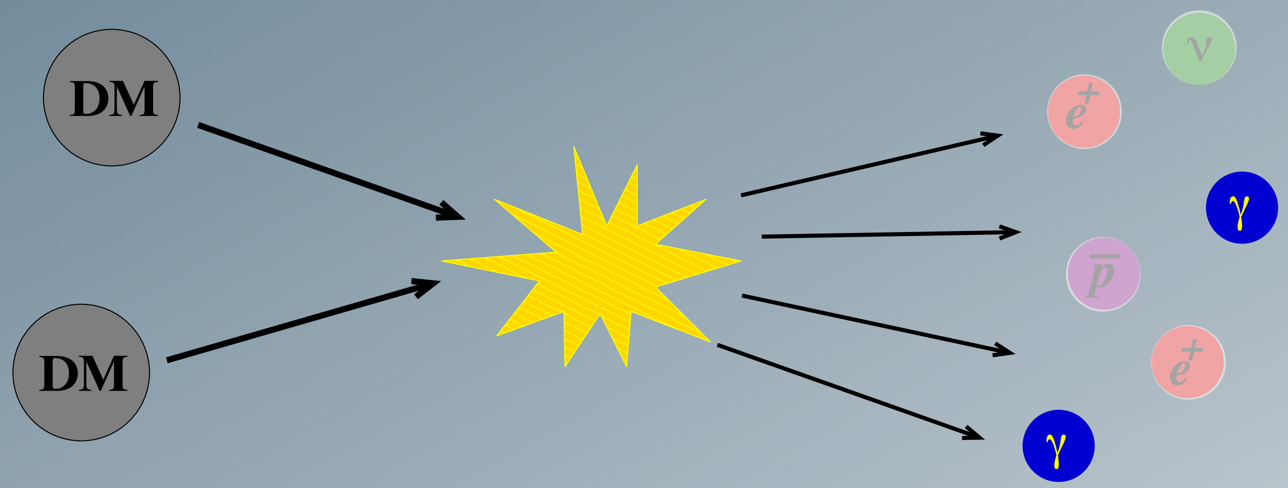
Indirect DM searches



- 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

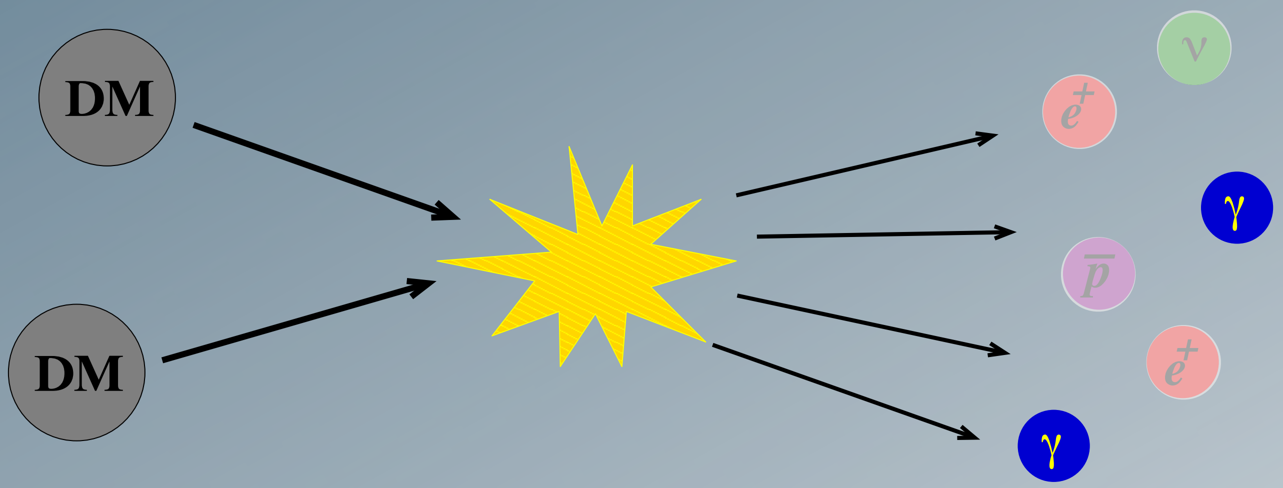
Indirect DM searches



Gamma rays:

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

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

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.

high accuracy
spectral information

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

D : distance to source

large uncertainty in
normalization

Halo profiles

<u>ΛCDM *N*-body simulations</u>

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

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

$(\alpha \approx 0.17)$

$\rightsquigarrow$ rather stable result

<u>Fits to rotation curves?</u>

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

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

$\rightsquigarrow$ 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

Substructure

- *N*-body simulations: The DM halo contains not only a smooth component, but a lot of substructure!

- Indirect detection effectively involves an averaging:

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

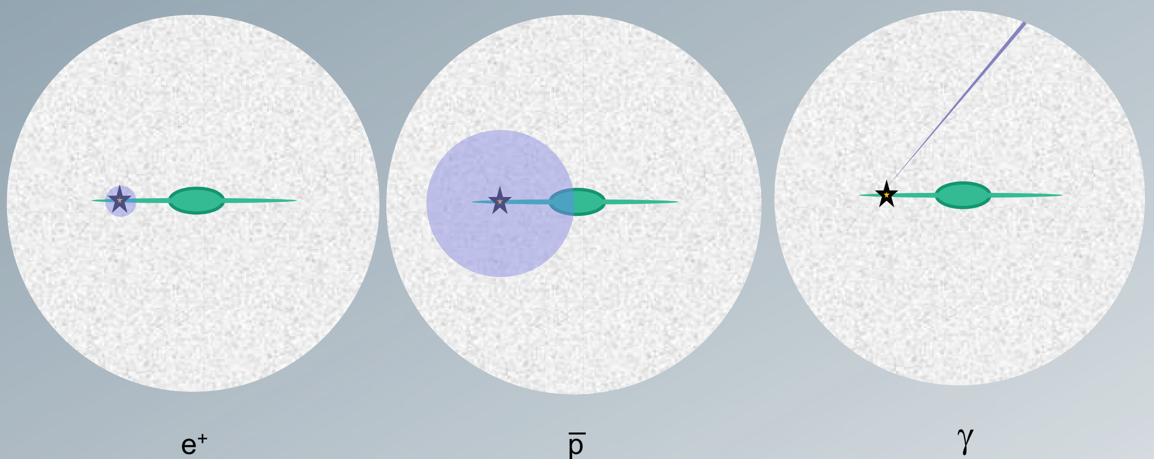


Fig.: Bergström, NJP '09

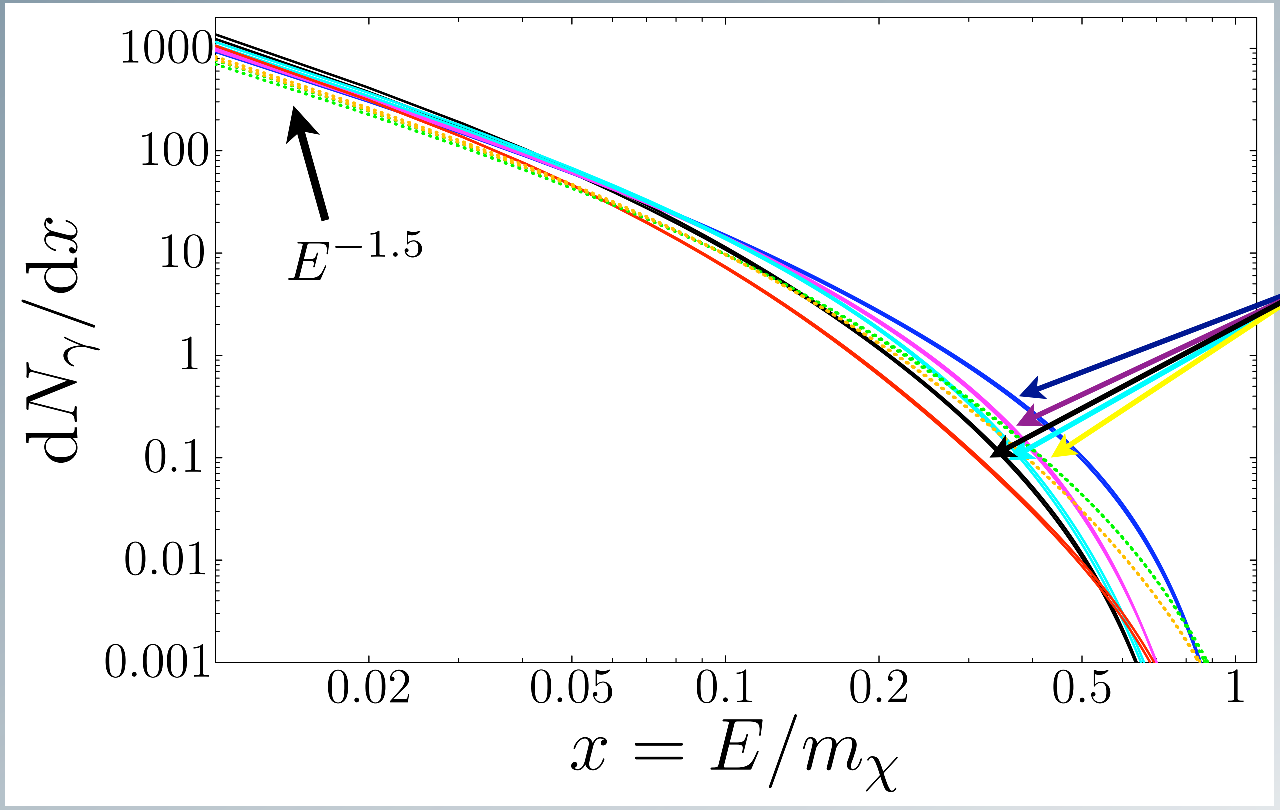
- "Boost factor"
  - each decade in $M_{\rm subhalo}$ contributes about the same

    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

- 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

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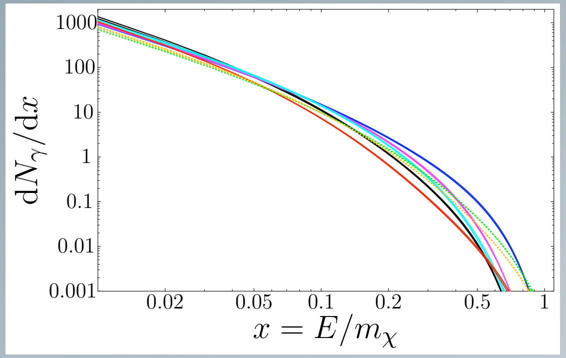
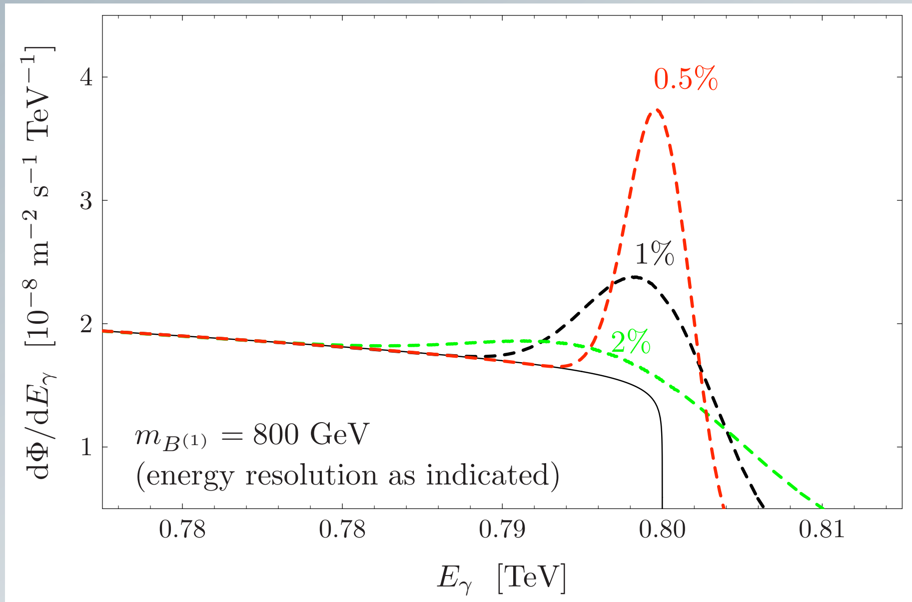


- Line signals from $\chi\chi \to \gamma\gamma, \gamma Z, \gamma H$

Bergström, Ullio & Buckley, ApJ '98

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



Bergström, TB, Eriksson & Gustafsson, JCAP '05

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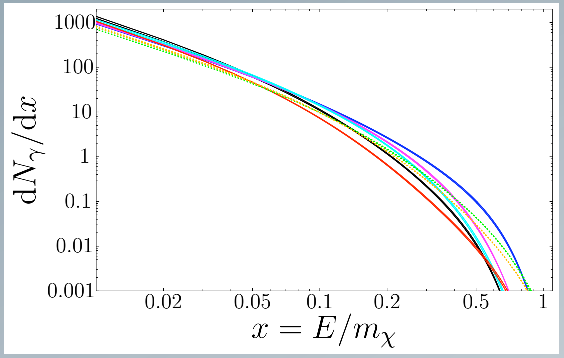

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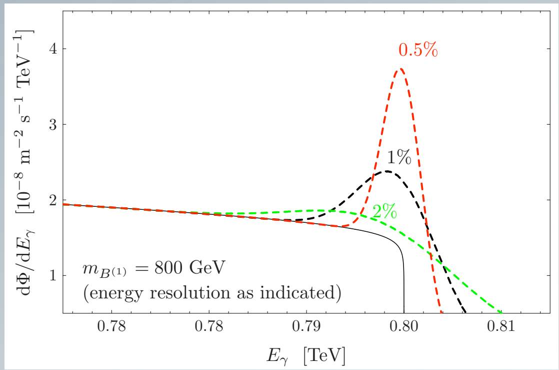
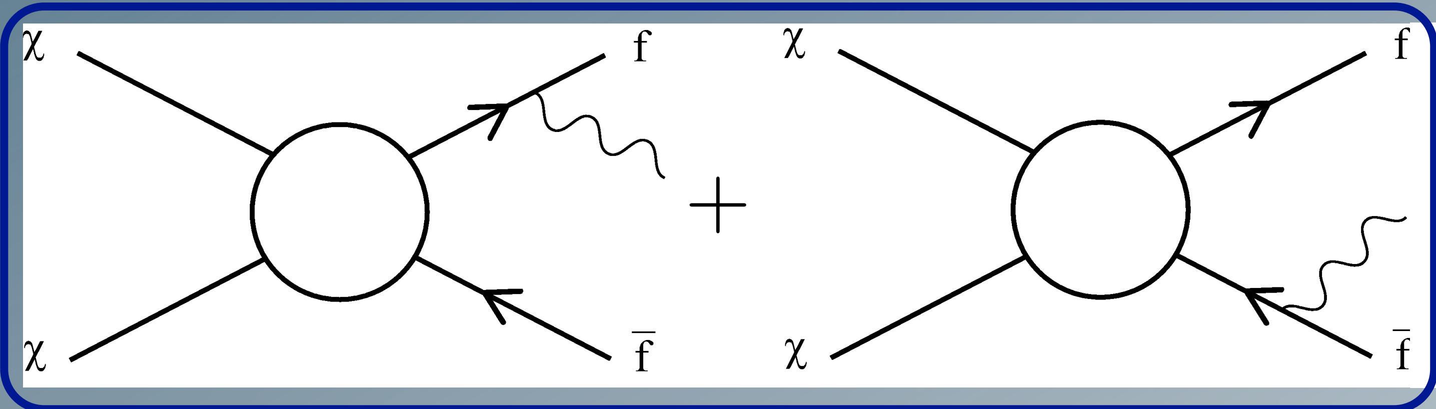
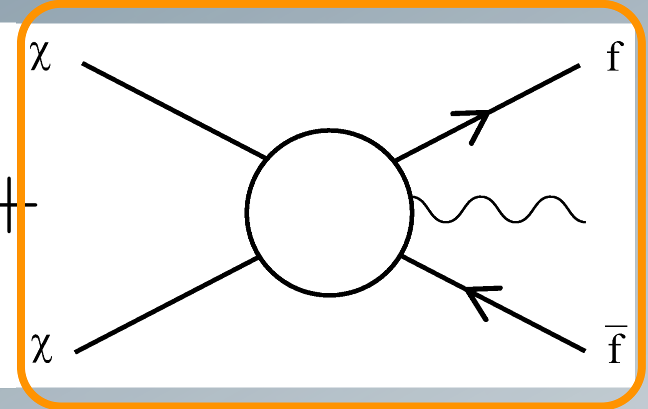


- Internal bremsstrahlung (IB)
  - whenever charged final states are present: $\mathcal{O}(\alpha)$
  - characteristic signature (details model-dependent!)
  - generically dominates at high E_γ

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

Internal bremsstrahlung





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

"Virtual" 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: $\langle \sigma v \rangle \propto \cancel{\frac{m_\ell^2}{m_\chi^2}} \quad \frac{\alpha_{\rm em}}{\pi}$

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

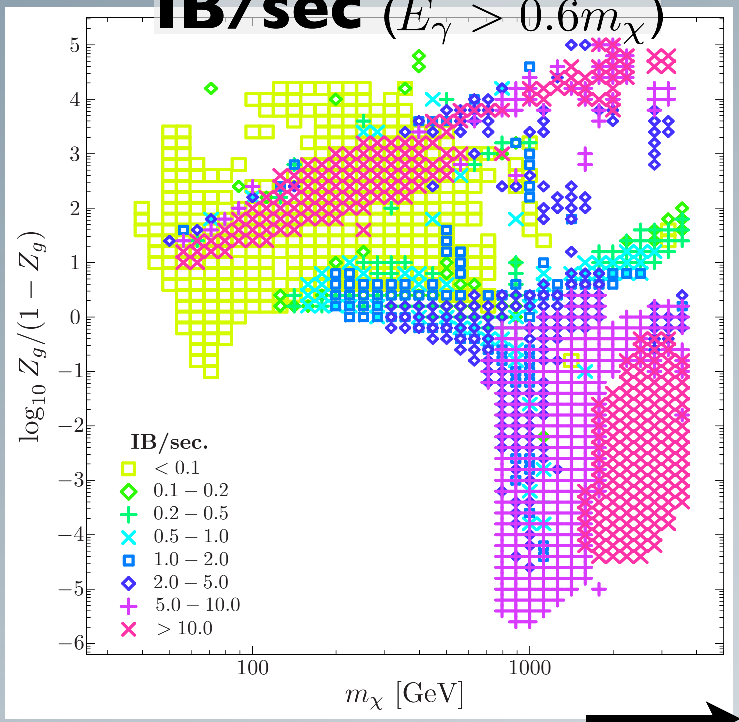
- Full implementation in DarkSUSY, scan mSUGRA and MSSM: TB, Edsjö & Bergström, JHEP '08

Gaugino ➔

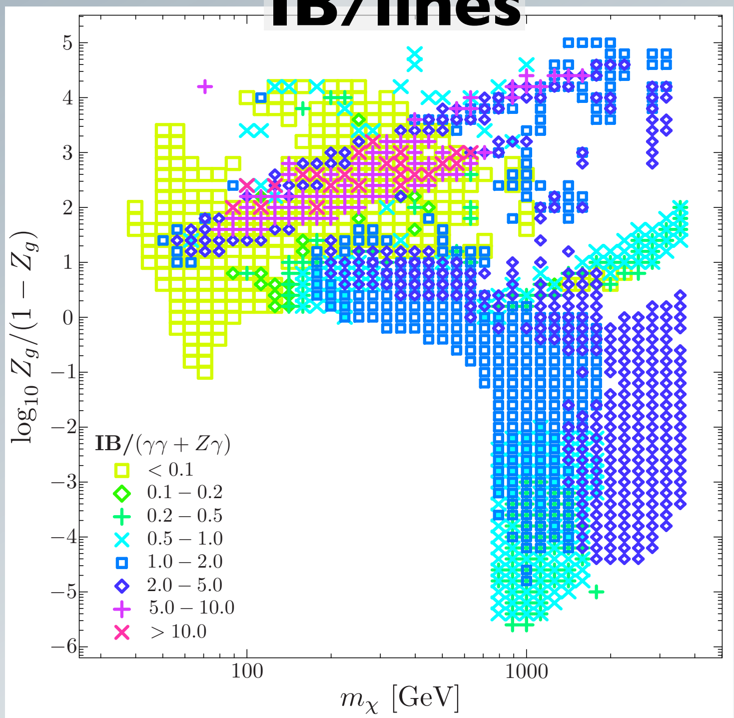
mixed ➔

Higgsino ➔

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

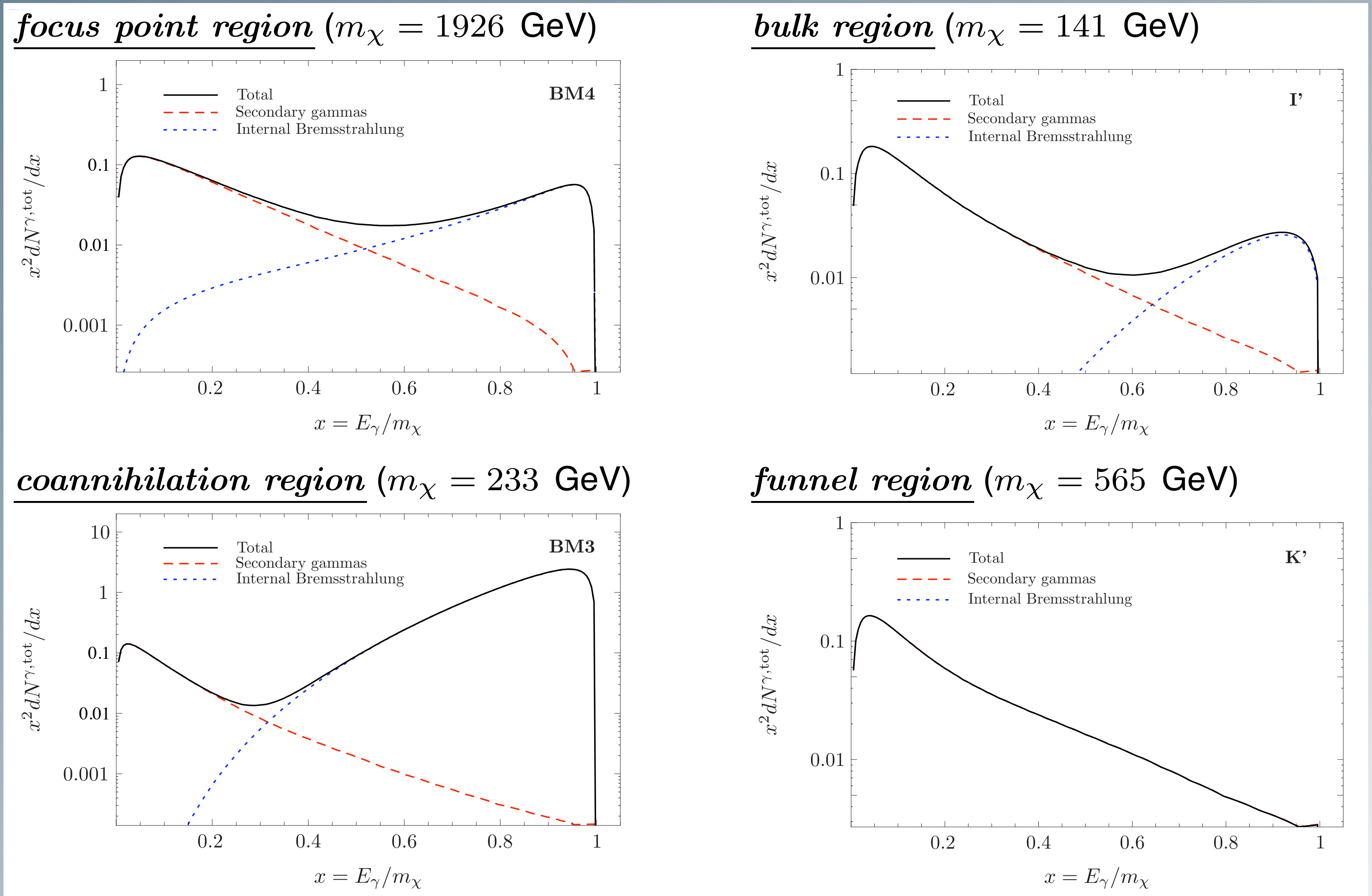


IB/lines



$\longrightarrow m_\chi$

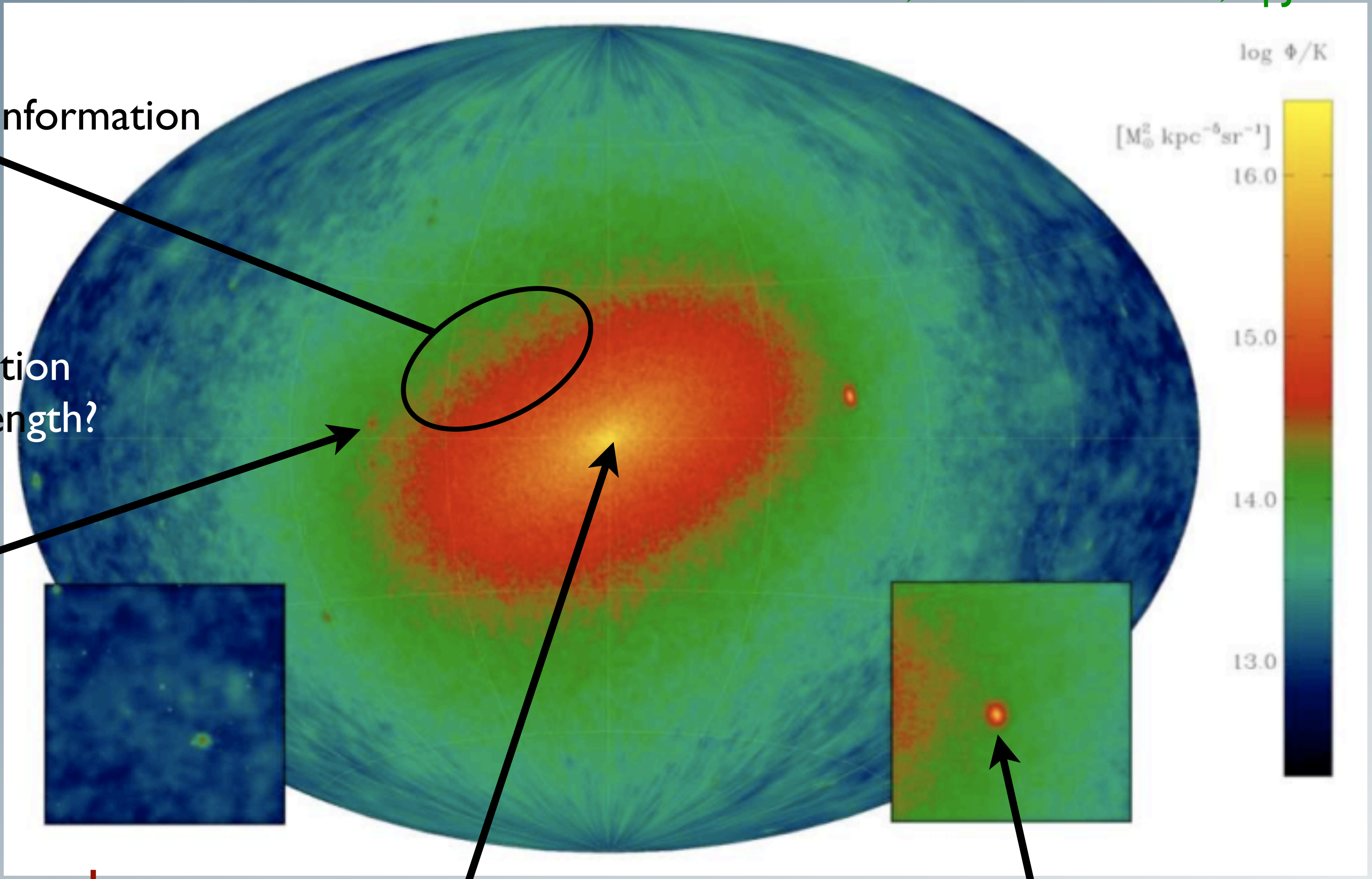
mSUGRA spectra



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

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?

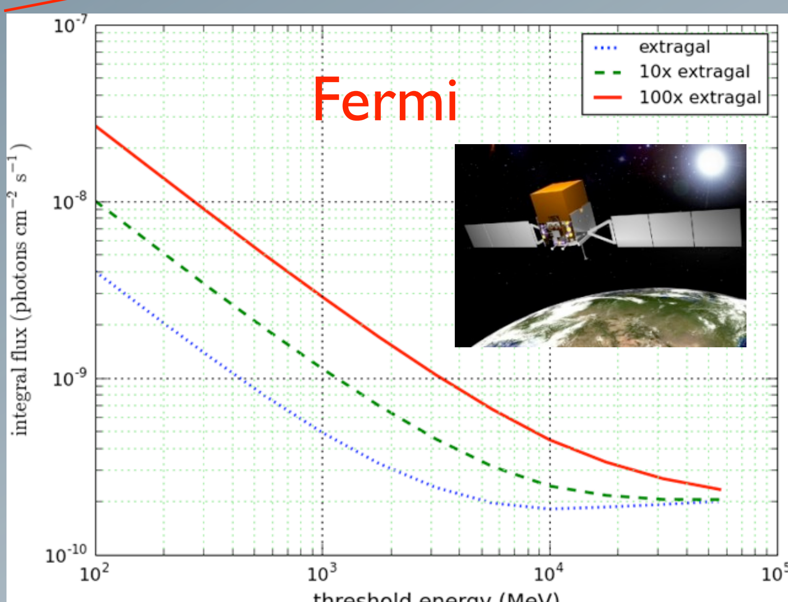
Sensitivities

Space-borne

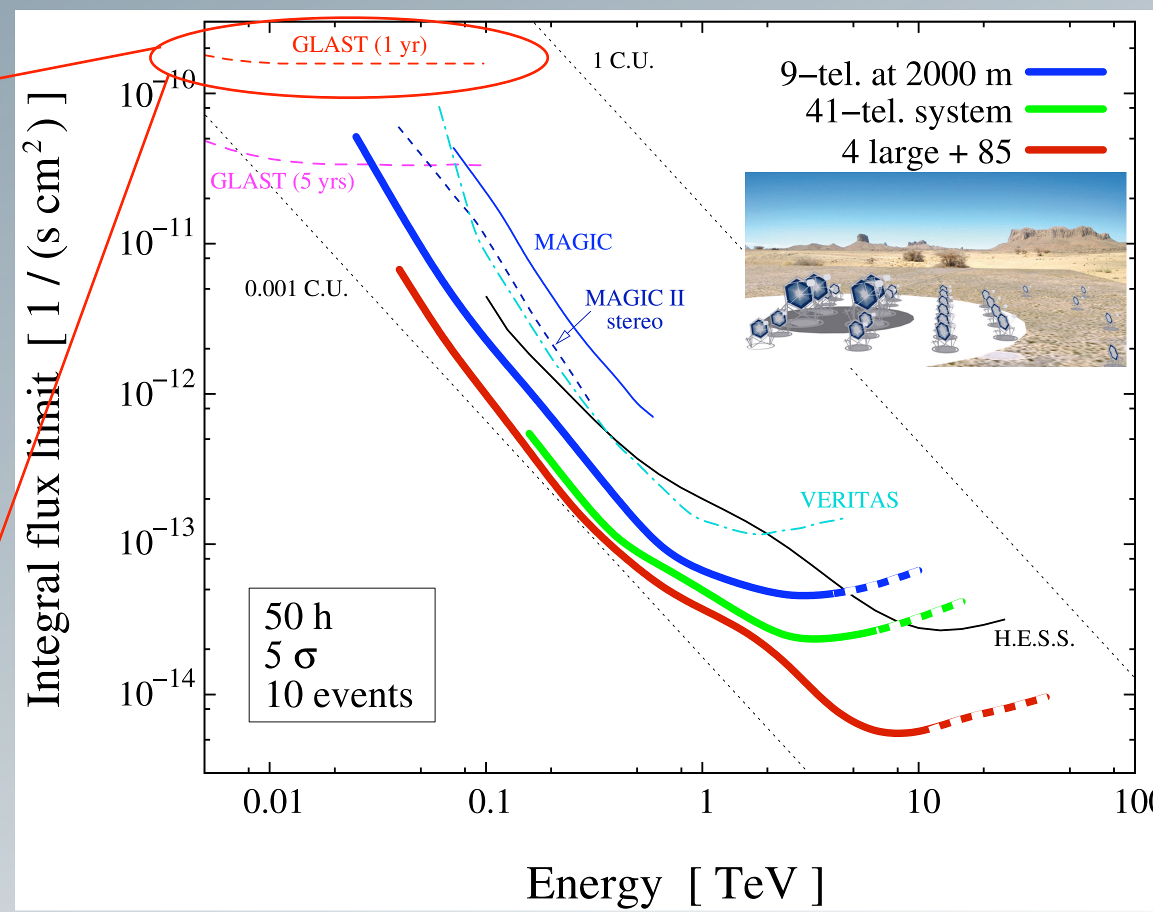
- small eff. Area (~m^2)
- large field of view
- upper bound on resolvable E_γ

Ground-based

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



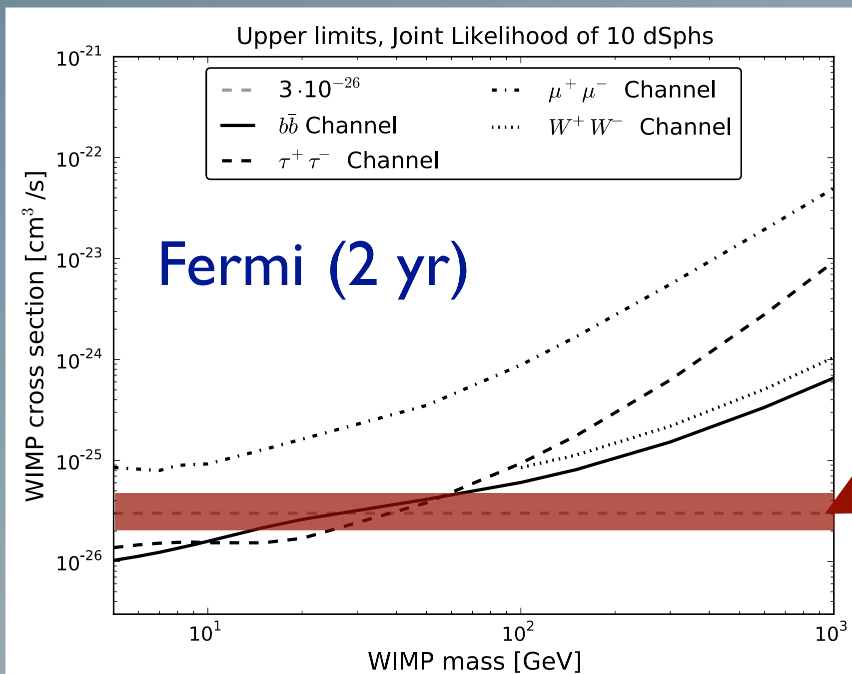
(from the LAT webpage)



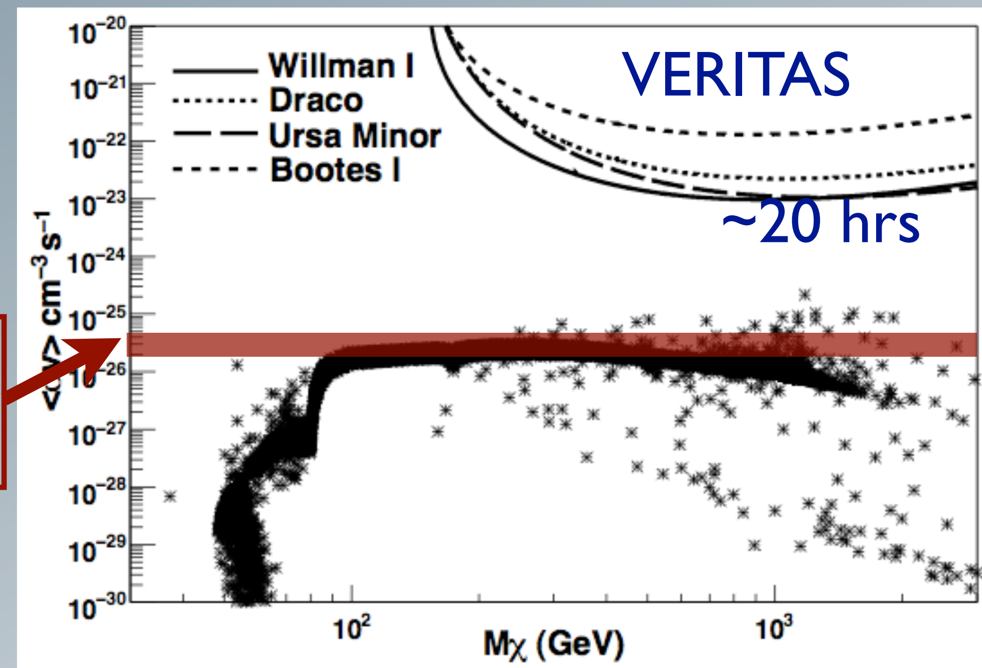
Bernlöhr et al., '07

Observational status: dwarfs

- Greatly improved recent limits from Dwarf galaxies:



standard thermal value



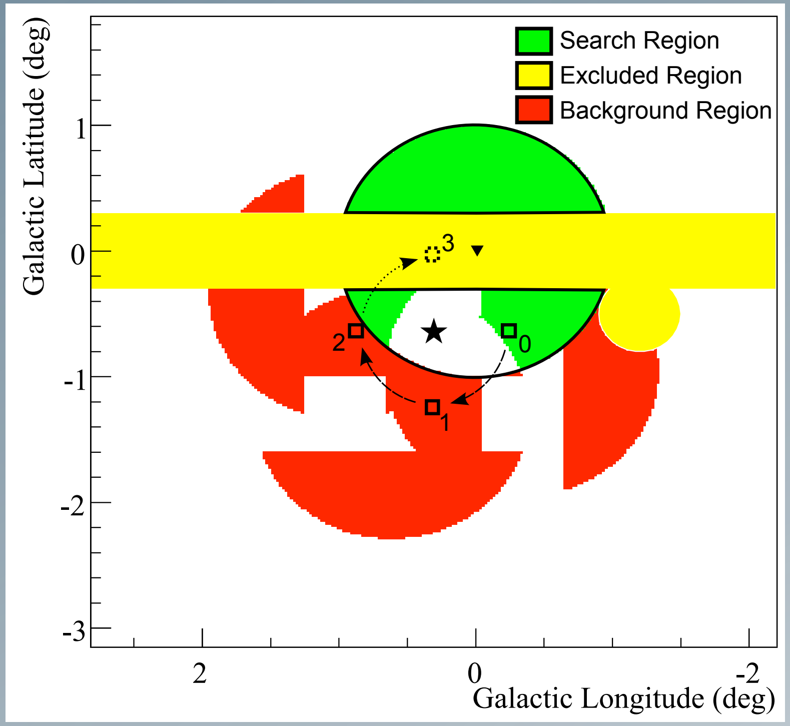
Ackermann *et al*, 1108.3546

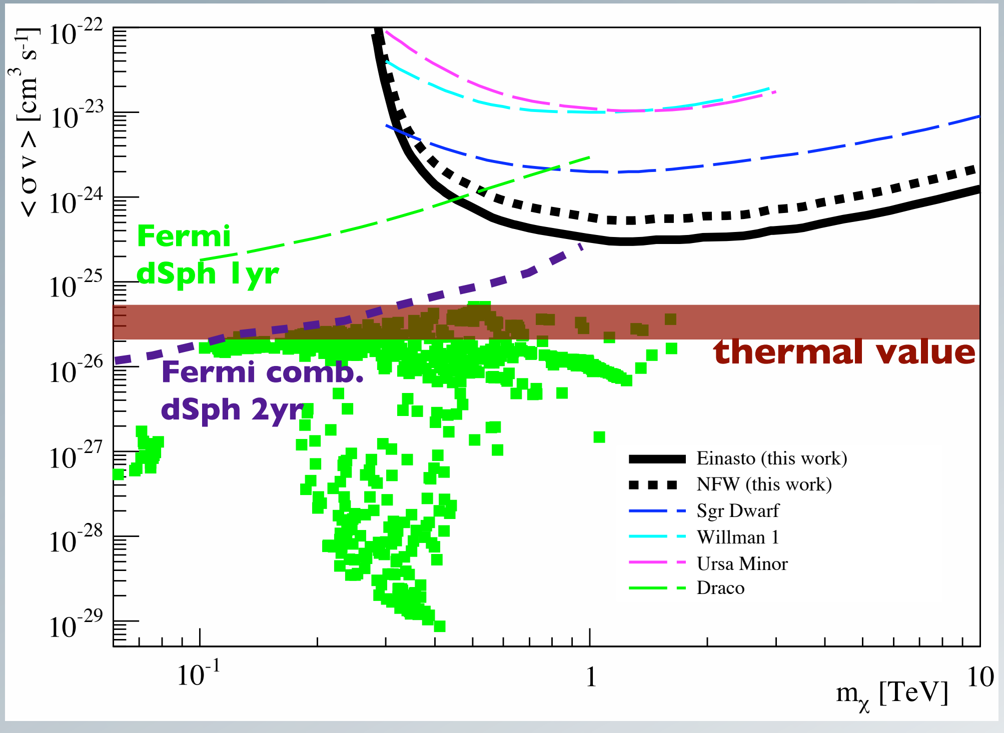
Acciari *et al*, 1006.5955

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

Galactic center

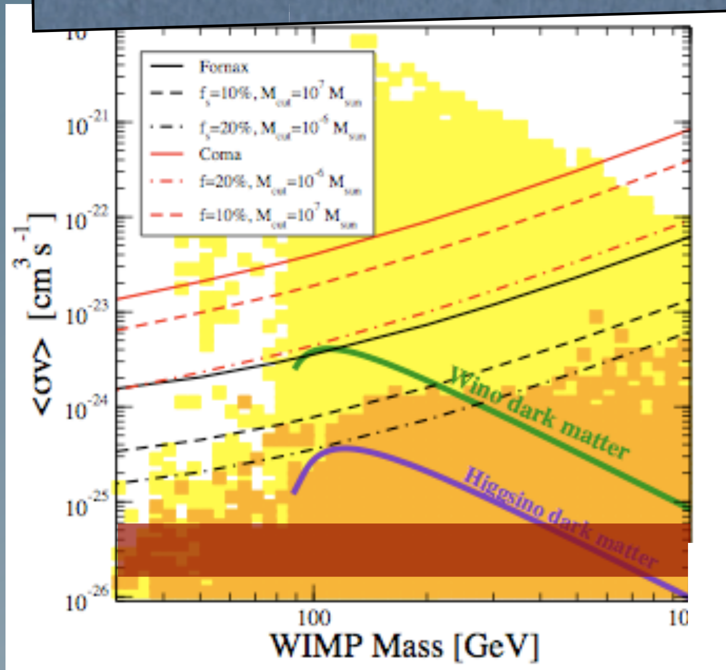
- Recent strong limits from HESS by using a clever background subtraction method: Abramowski *et al*, 1103.3266





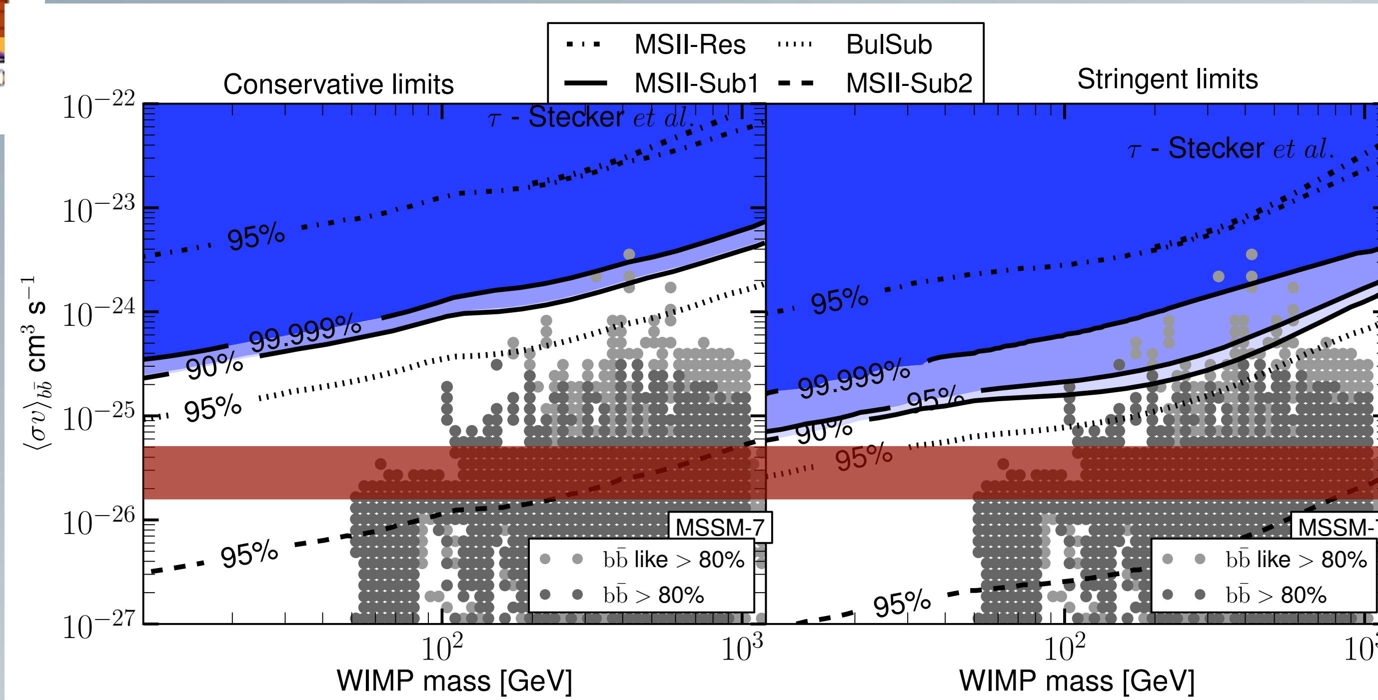
⇨ Indirect searches start to be very competitive!

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)

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

- Excellent targets for indirect detection with gamma rays

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

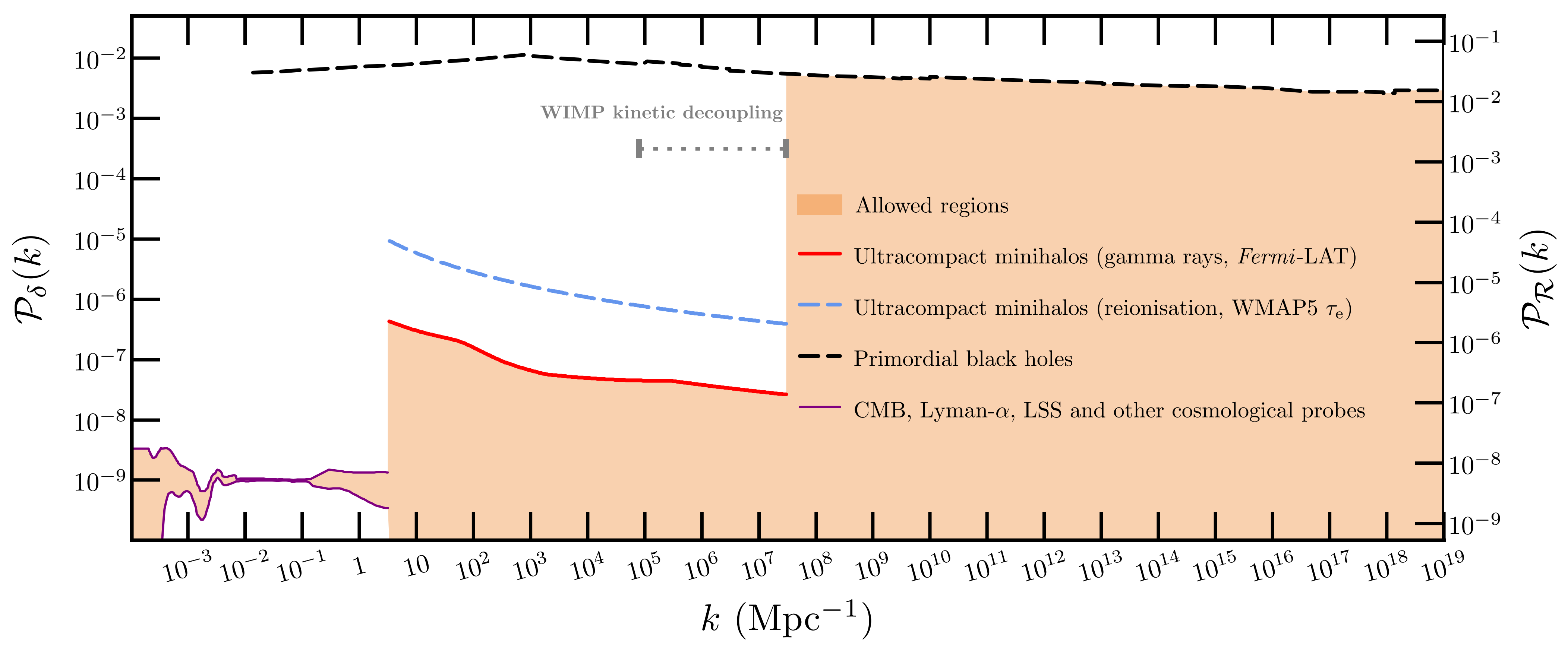
- Required density contrast at horizon entry:

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

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

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

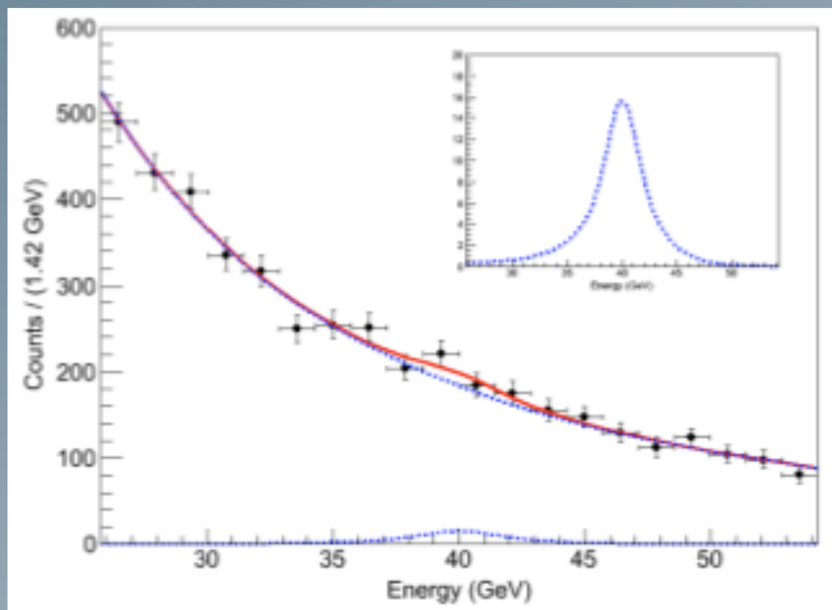
(assuming 1 TeV WIMPs annihilating into $\bar{b}b$)



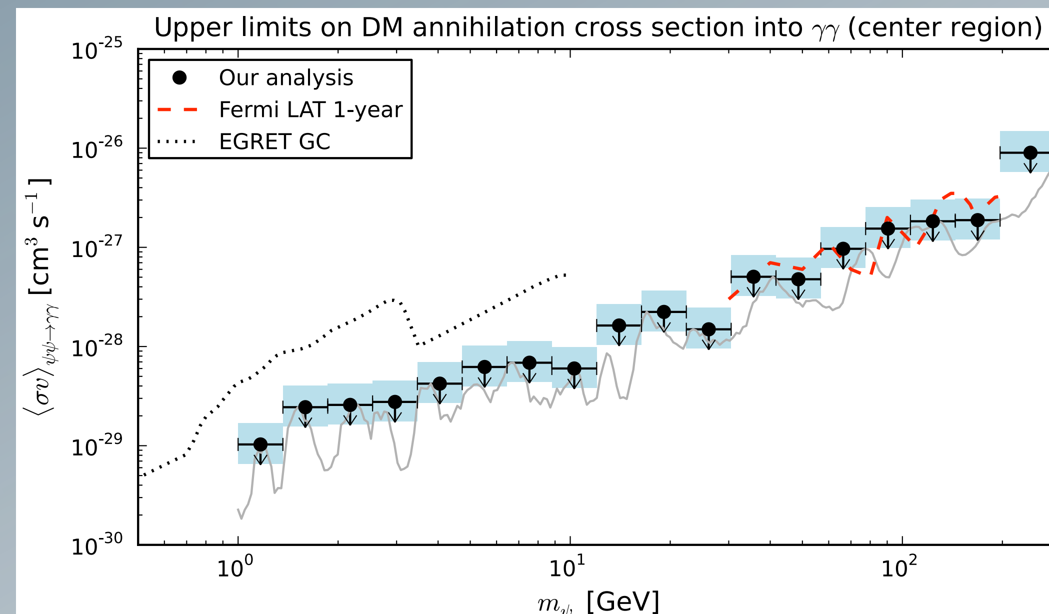
TB, Scott & Akrami, PRD '12

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

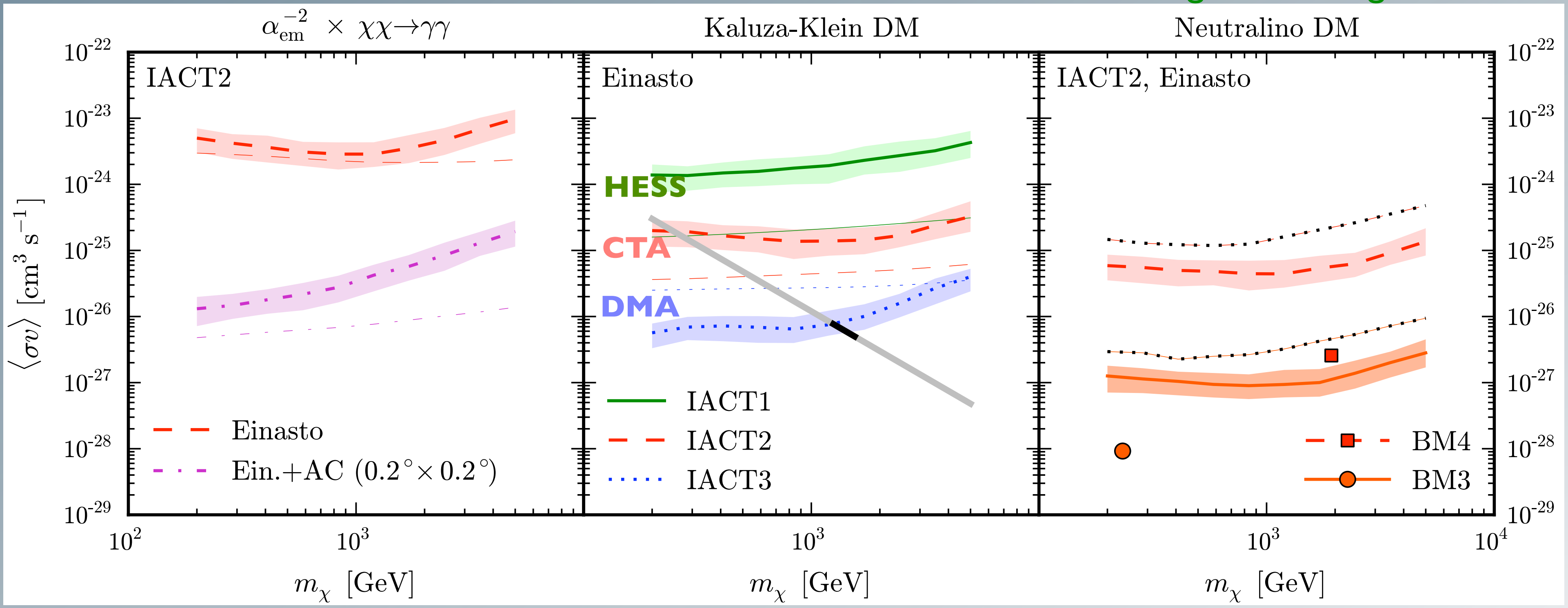
- NB: 1y data, simple choice of target region...
- No significant changes after 24 months of data...

Ackermann *et al*, 1205.2739

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)**

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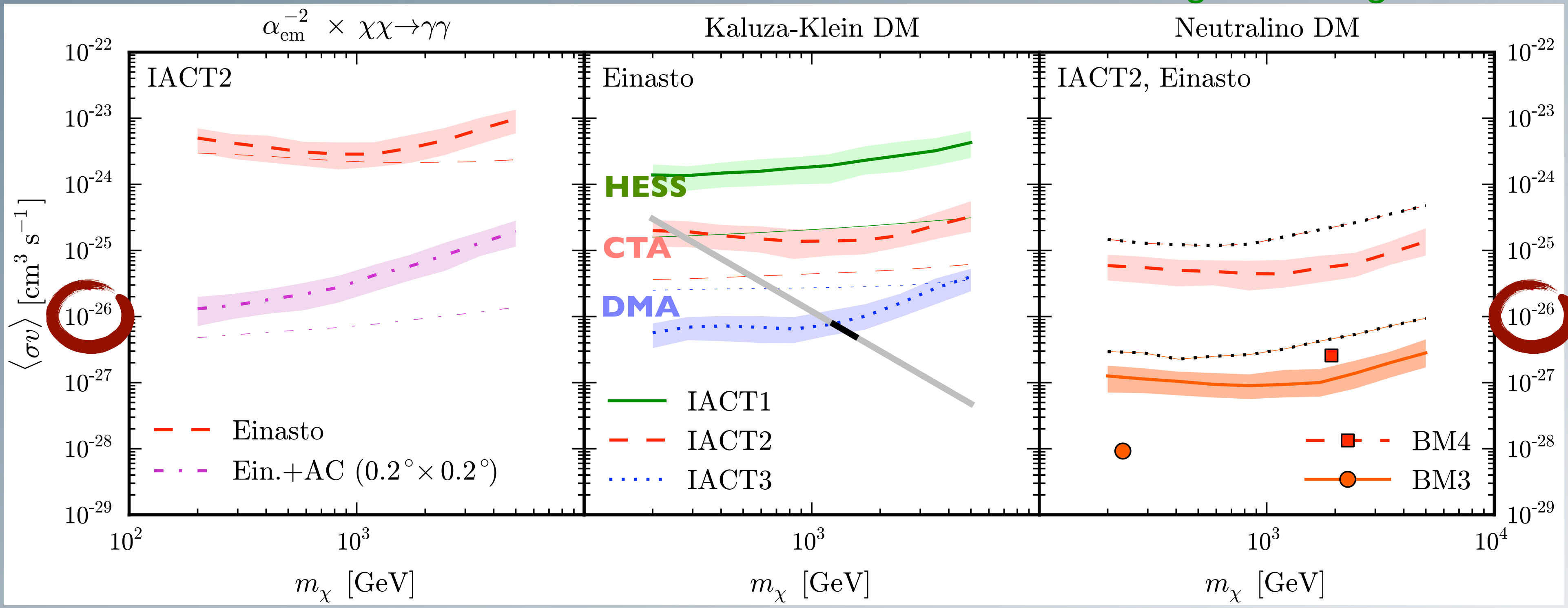
TB, Calore, Vertongen & Weniger, PRD '10



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

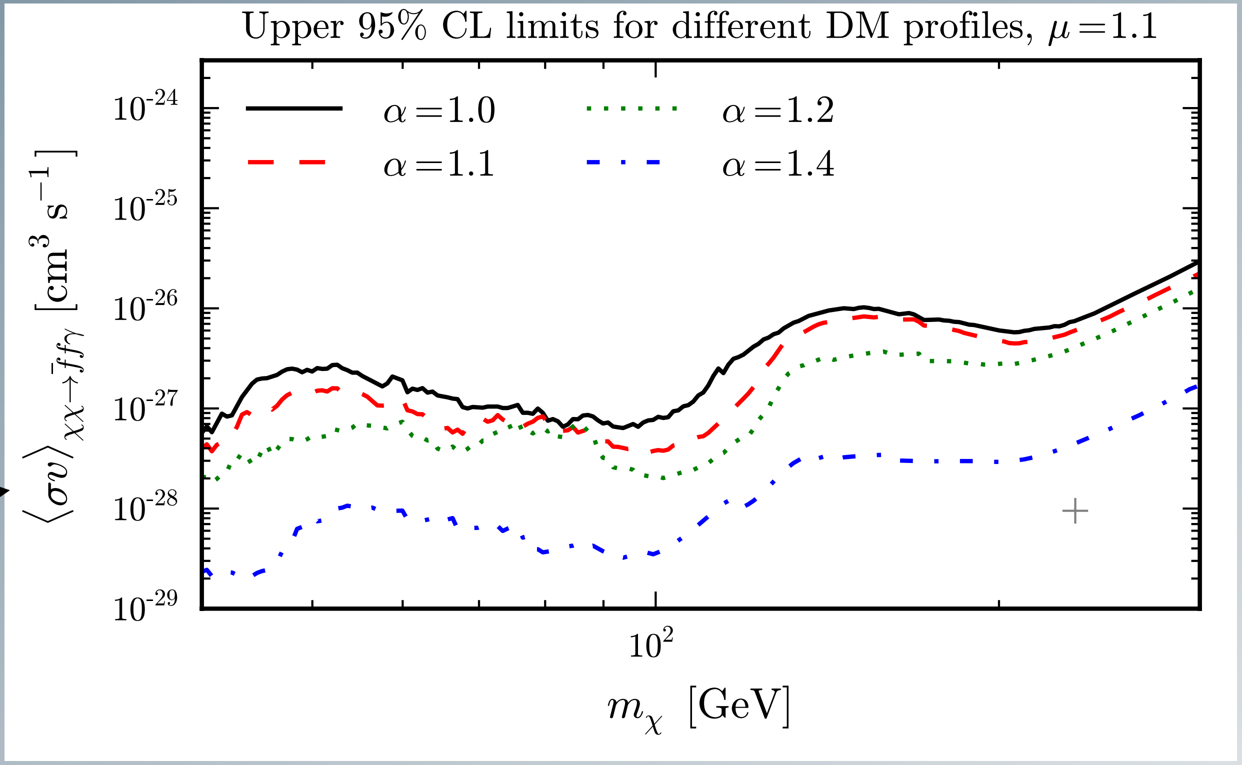
⇨ Natural cross sections well within reach for ACTs!

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…?

[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

~MSSM:

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

SU(2) singlet scalar

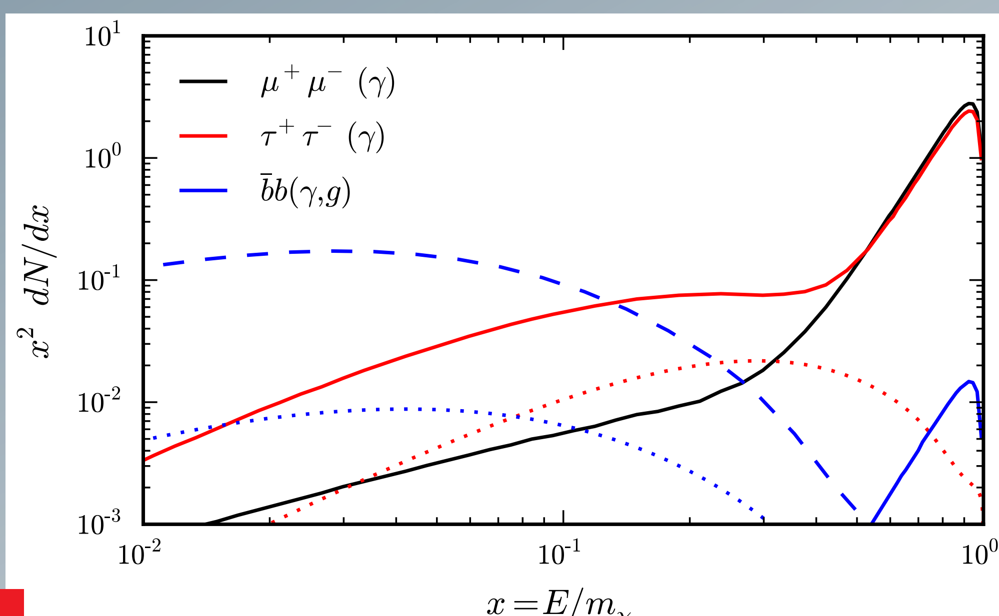
$\eta \rightarrow \tilde{f}_L, \tilde{f}_R$

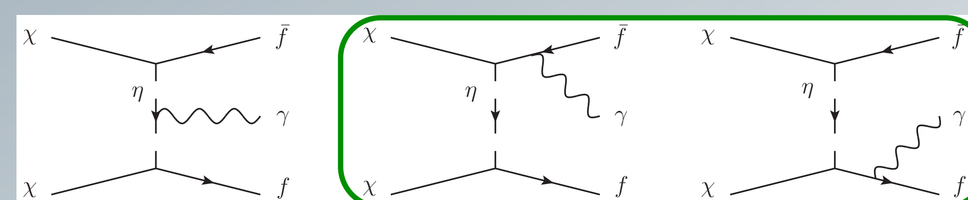
$$\mathcal{L}_{\rm int} = -y\bar{\chi}\Psi_R\eta + \mathrm{h.c.}$$

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

Yukawa interaction term

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





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 $\rightsquigarrow \quad \theta \sim 0.1^\circ - 5^\circ$
  - ~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

signal

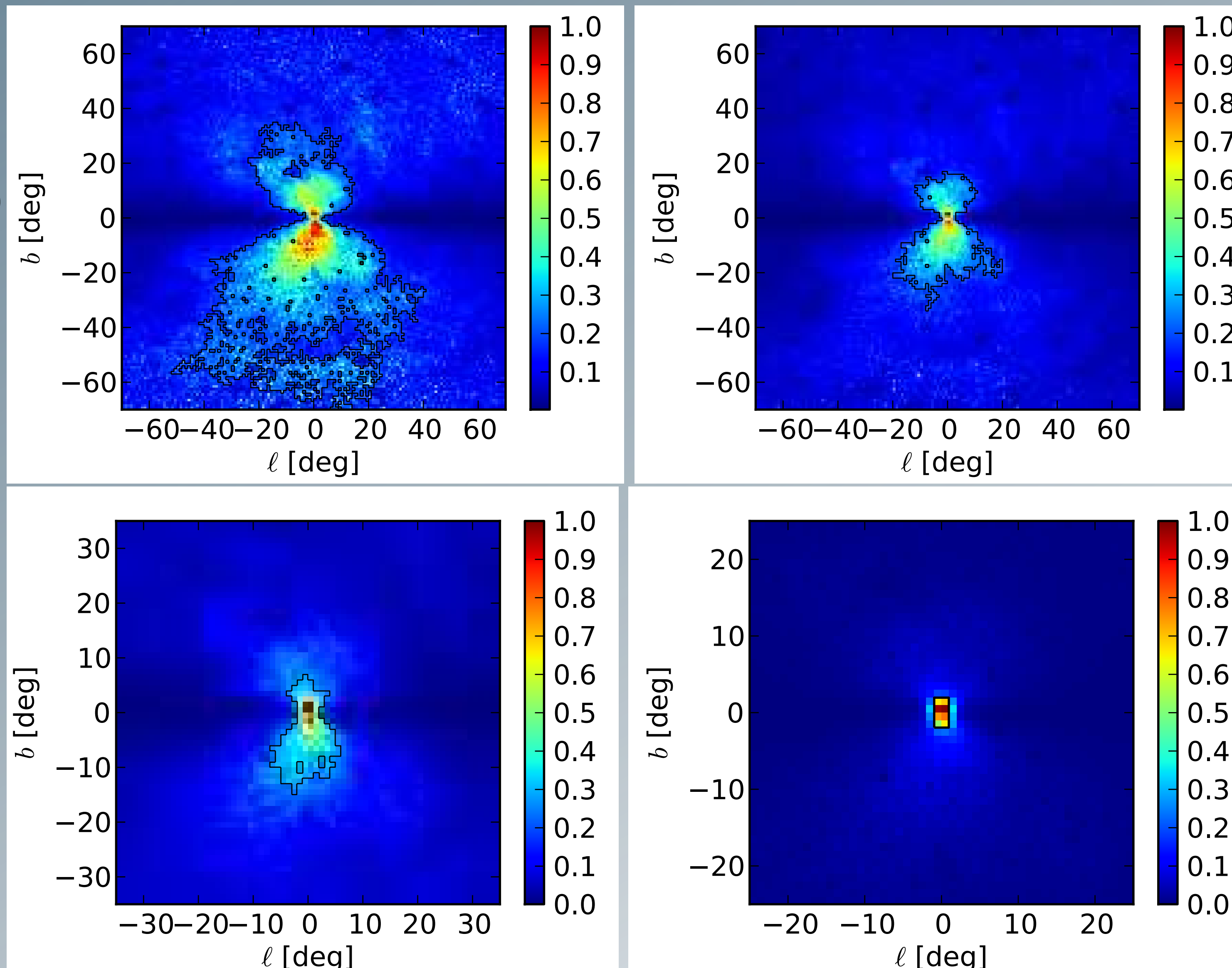
$$\boxed{\mathcal{R}_T \equiv \frac{\sum_{i\in T} \mu_i}{\sqrt{\sum_{i\in T} c_i^{E_\gamma \leq 40\,\mathrm{GeV}}}}}$$

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

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!
- Fit of 3-parameter model sufficient:

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

- 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

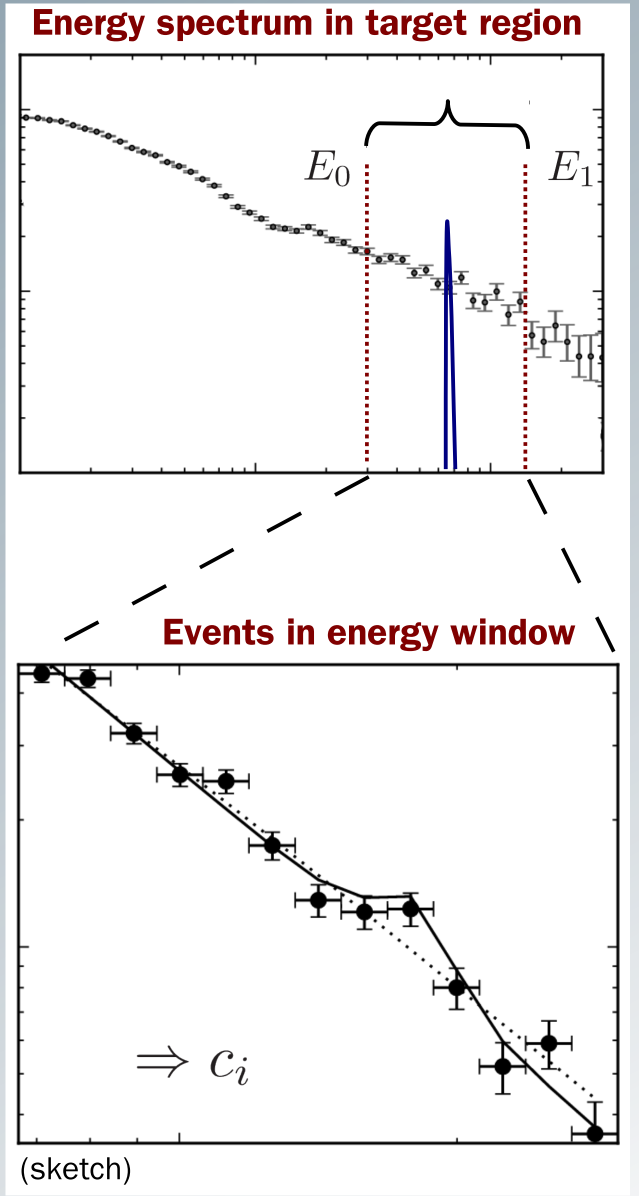


Fig.: C. Weniger

Likelihood analysis

- 'binned' likelihood
  - NB: bin size $\ll$ energy resolution $\rightsquigarrow$ same as un-binned 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　　expected

- Significance follows from value of test statistic:

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

best fit with $S \stackrel{!}{=} 0$

best fit with $S \geq 0$

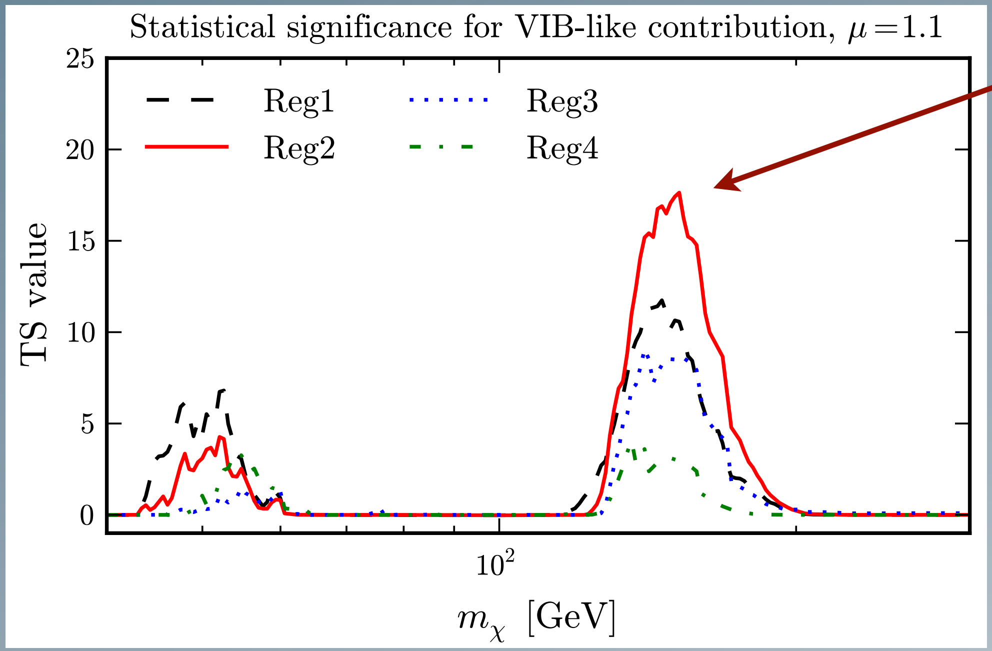
➡ significance (without trial correction): ~$\sqrt{TS}\sigma$

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

A tentative signal!

TB, Huang, Ibarra, Vogl & Weniger, 1203.1312

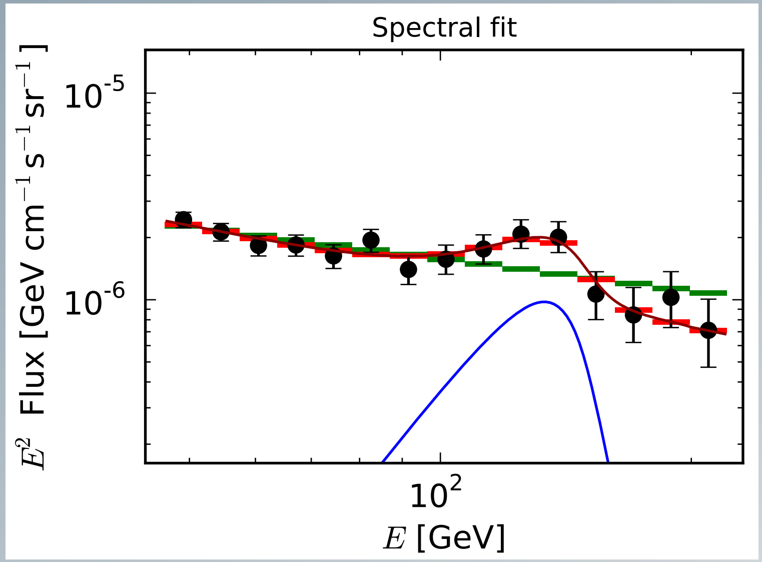
$$\rho_\chi \propto \frac{1}{r^\alpha (1 + r/r_s)^{3-\alpha}}, \qquad \alpha = 1.1$$



- 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)

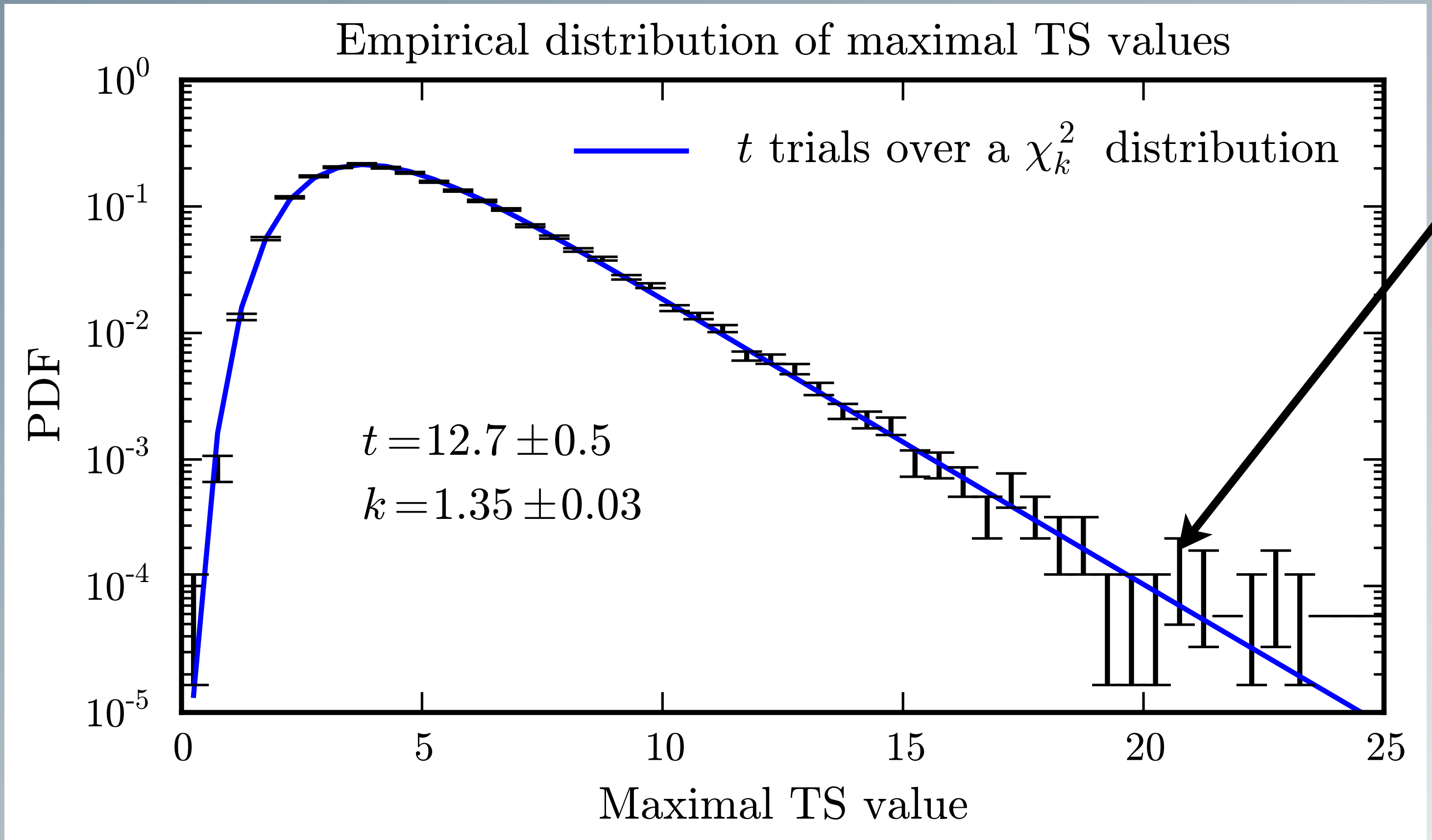
- NB: also very well fit by line with

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

Look-elsewhere effect

- Need to take into account that many independent statistical trials are performed!

[i) scan over DM mass and ii) different test regions]



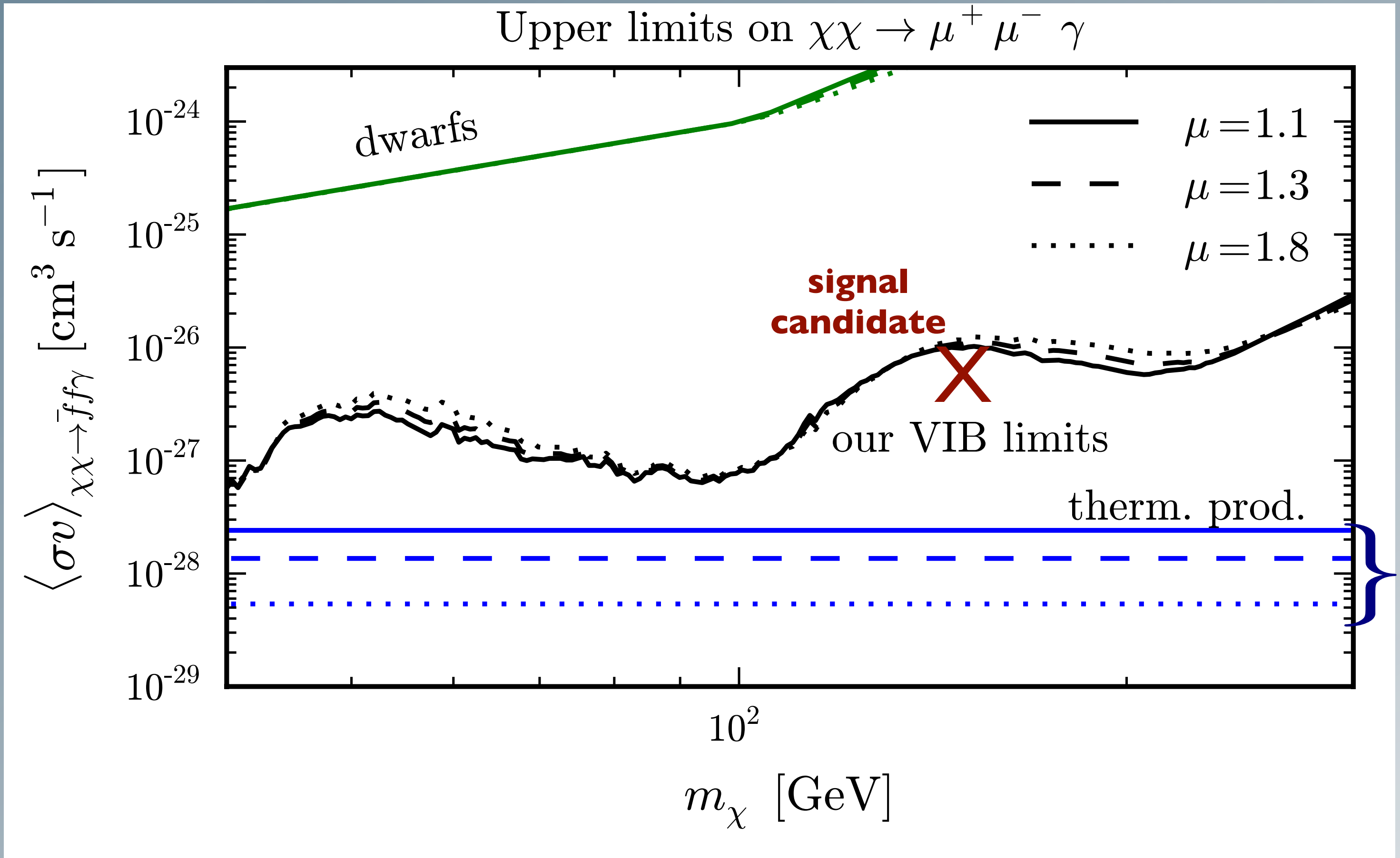
from bootstrap analysis of galactic anticenter hemisphere

solve

$$P(\chi^2_k < TS)^t = P(\chi^2_1 < \sigma^2)$$

Weniger, 1204.2797

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

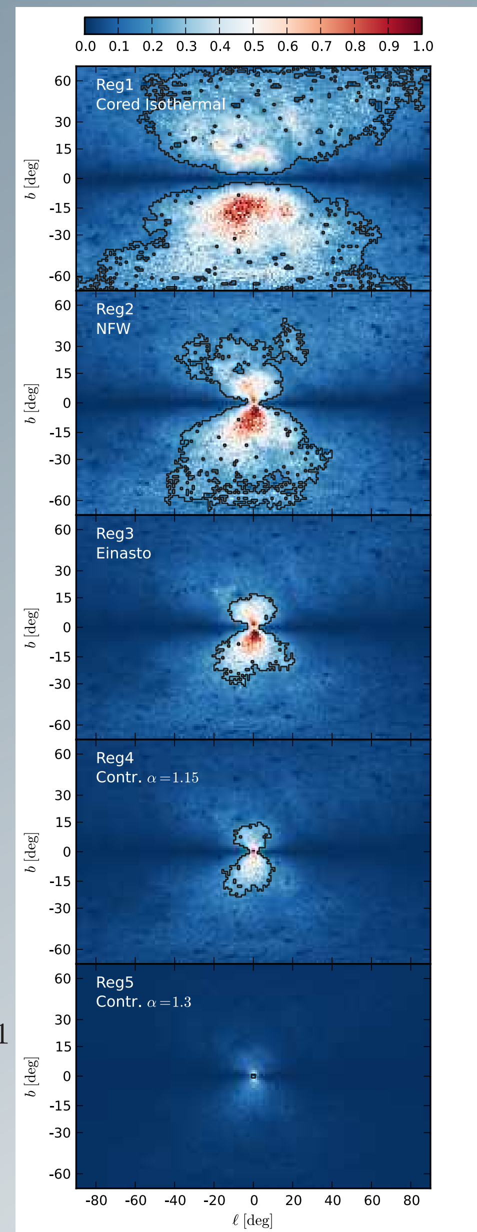
but the analysis relies of course on the public Fermi tools...

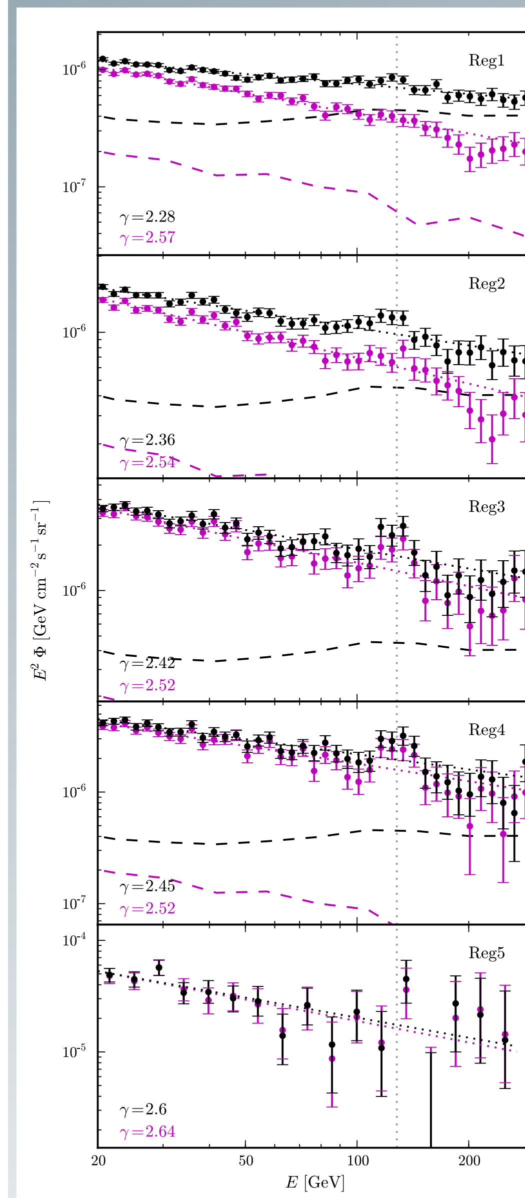
➡ need independent confirmation by collaboration!

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

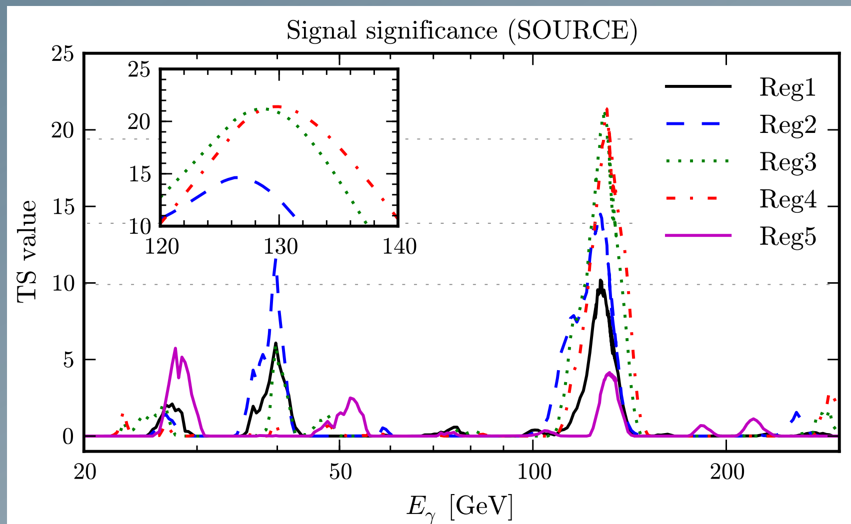


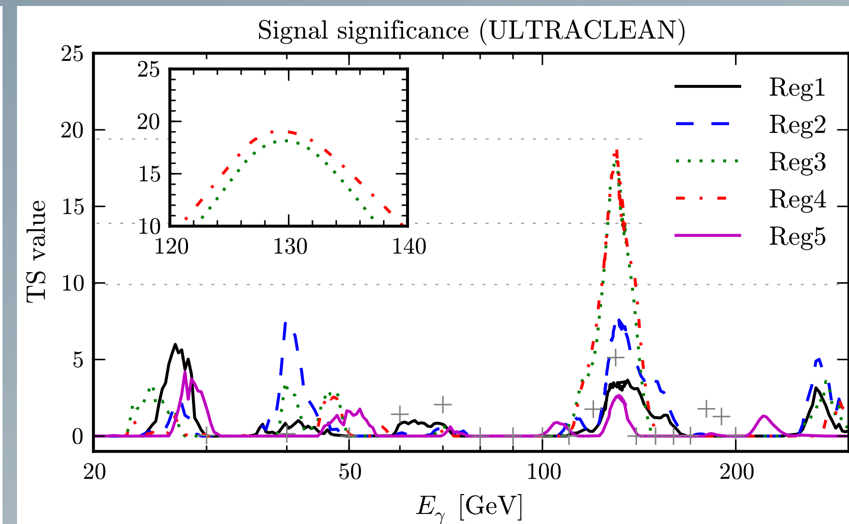


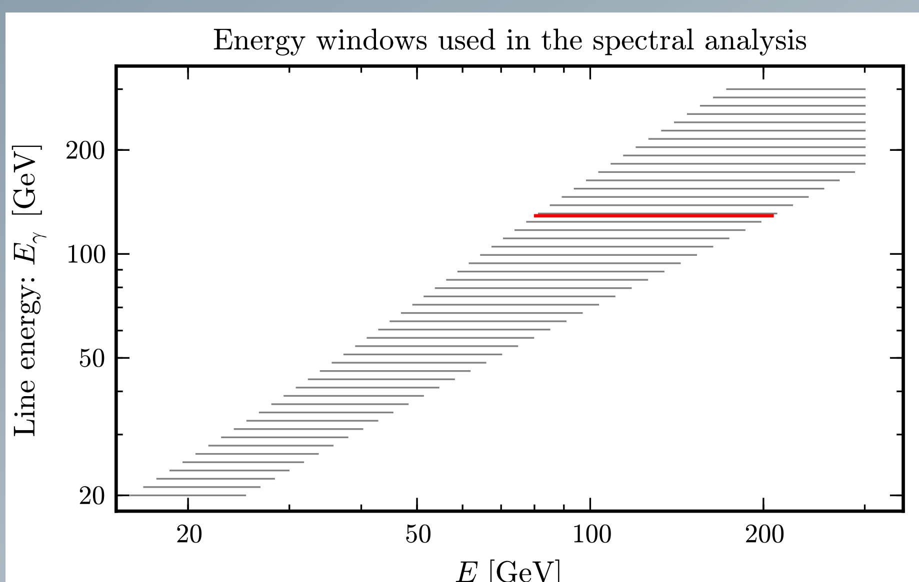
- bottom line:
  - $4.6\sigma(3.3\sigma)$ effect
  - $m_\chi = 129.8 \pm 2.4^{+7}_{-13}$ GeV
  - $\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma} = (1.27 \pm 0.32^{+0.18}_{-0.28}) \times 10^{-27}\ \mathrm{cm^3\ s^{-1}}$

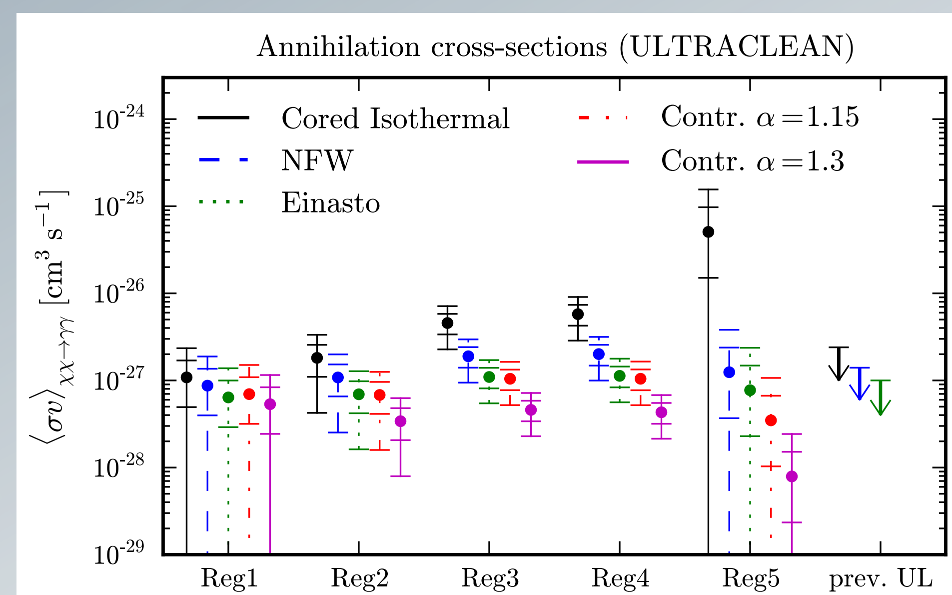
Line analysis (2)

Weniger, 1204.2797



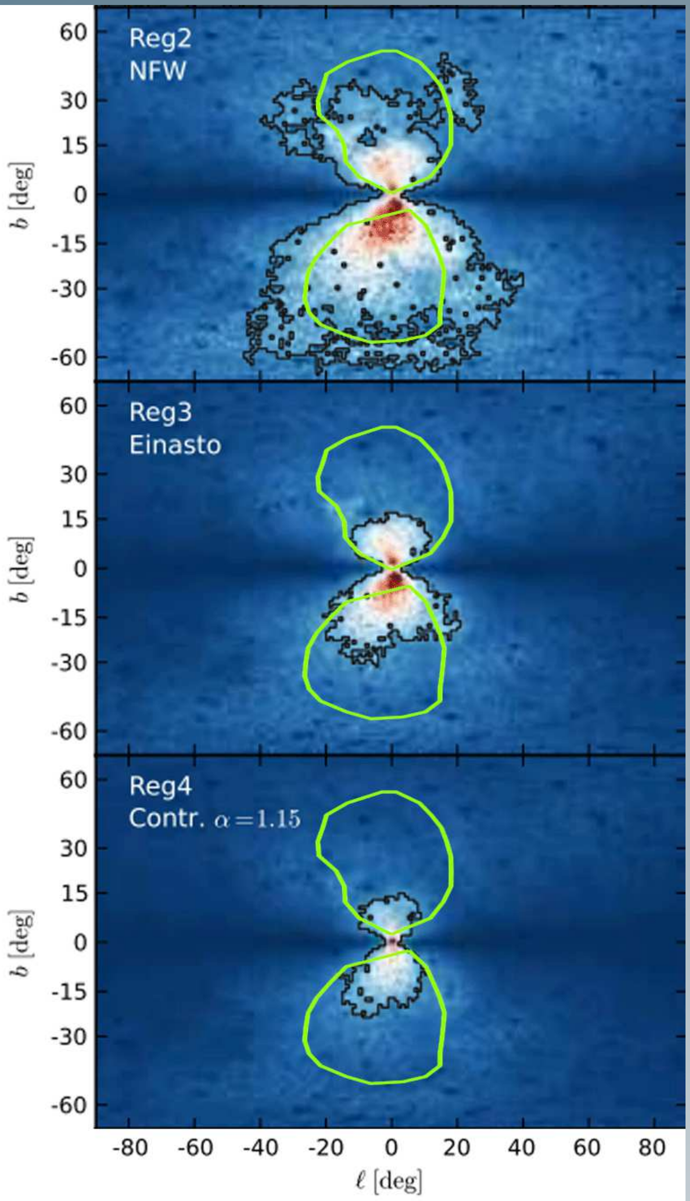


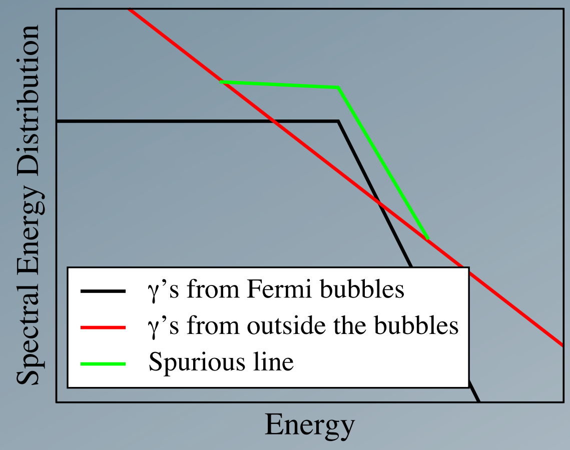


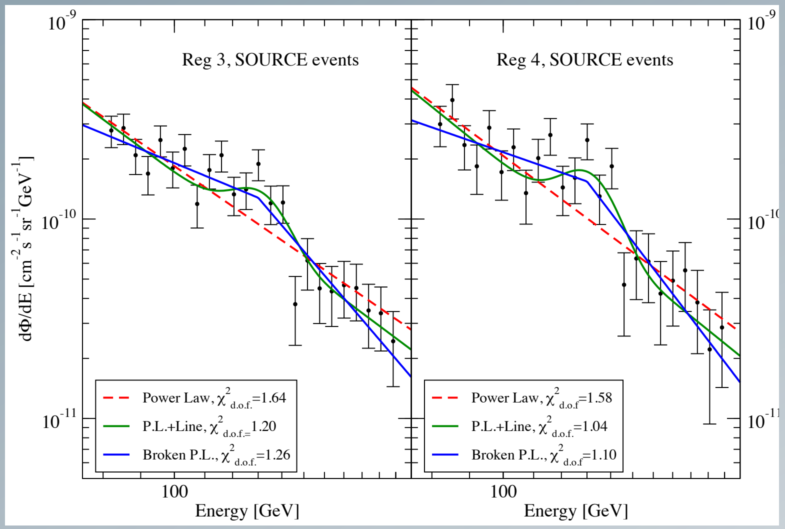


Overlap w/ Fermi bubbles ?

Profumo & Linden, 1204.6047



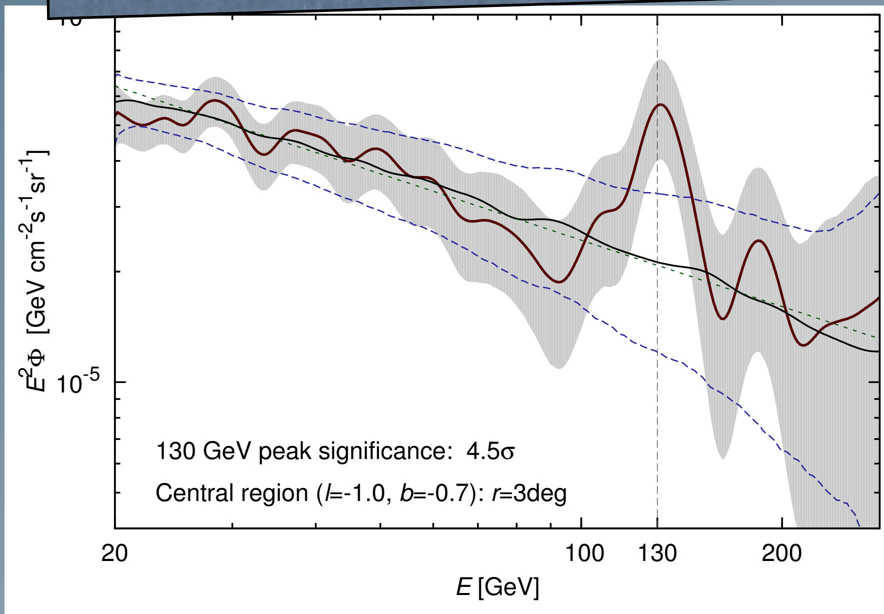


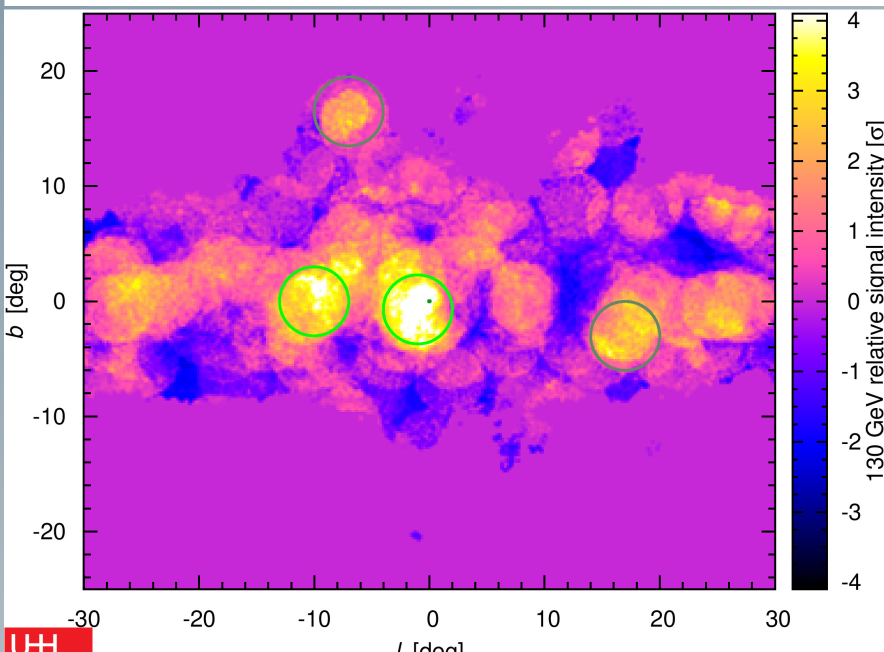


- Broken power-law also possible ***but***
  - what is the 'likely astrophysical' explanation ??
  - 'our' BG spectral index of about -2.6 is expected from CR→ISM …
  - the sketch corresponds neither to fit nor to data (NB: Bubble contribution @ 100 GeV << BG !)
  - …

➡ Shape similarity probably just a coincidence!

An independent confirmation



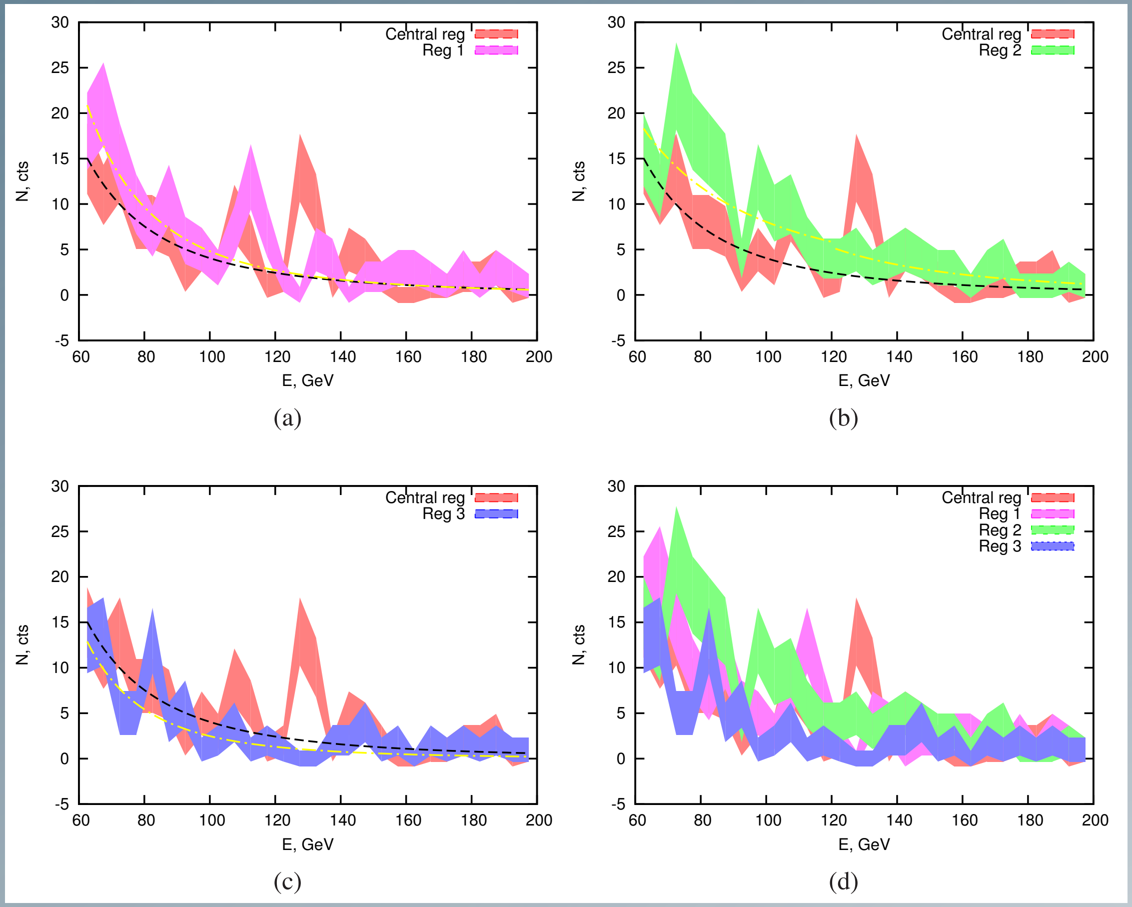


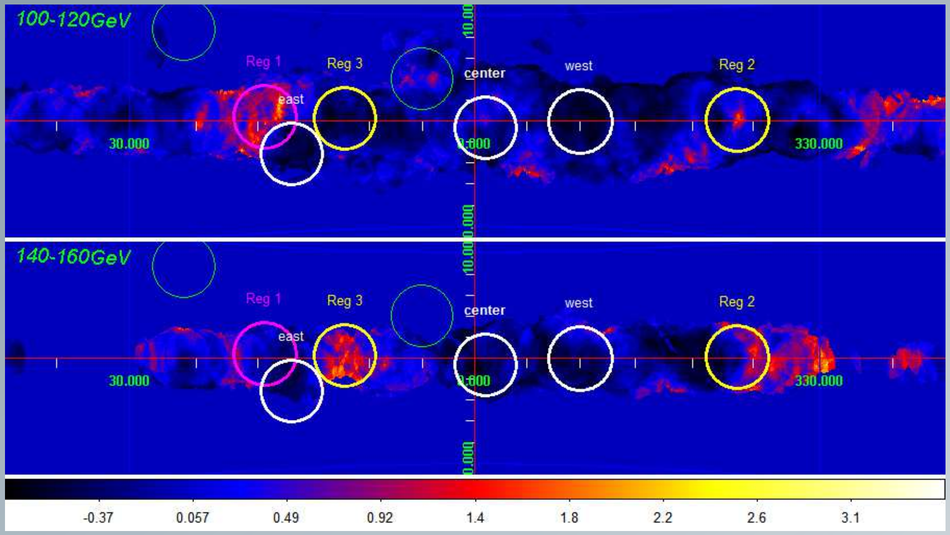
Tempel, Hektor & Raidal, 1205.1045

- Slightly different statistical technique
  - kernel smoothing instead of sliding energy window
  - wide kernel for background estimate: highly consistent with -2.6 power law
  - small adaptive kernel size to look for spectral features: line-like feature found at 130GeV!
- high significance of signal
- Identify signal regions
  - several 'hot spots'
  - no correlation with Fermi bubbles!

Look-elsewhere effect (2)

Boyarsky, Malyshev & Ruchayskiy, 1205.4700





- Disk BG not a power-law/ more spectral features in other regions?

⇨ Need to carefully quantify LEE for lines!

Future confirmation?

- ‘Tentative evidence’ based on ~50 photons

  ⇨ need a few years more data to confirm signal...

- … but maybe much faster if Fermi collaboration publishes PASS8 event selection before!

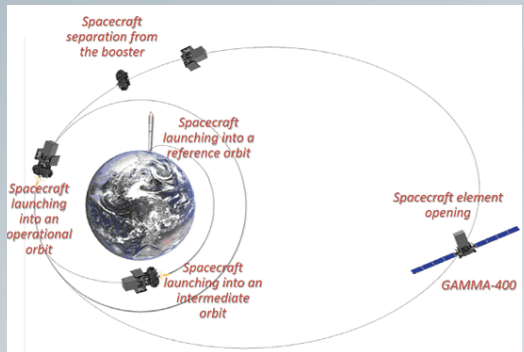
- final word possibly by GAMMA-400

  Galper *et al.*, 1201.2490

  - launch around 2018
  - greatly improved angular and energy resolution (at the expense of sensitivity)
  - $\sim 10\sigma$ signal significance possible !

    Bergström, 1205.4882

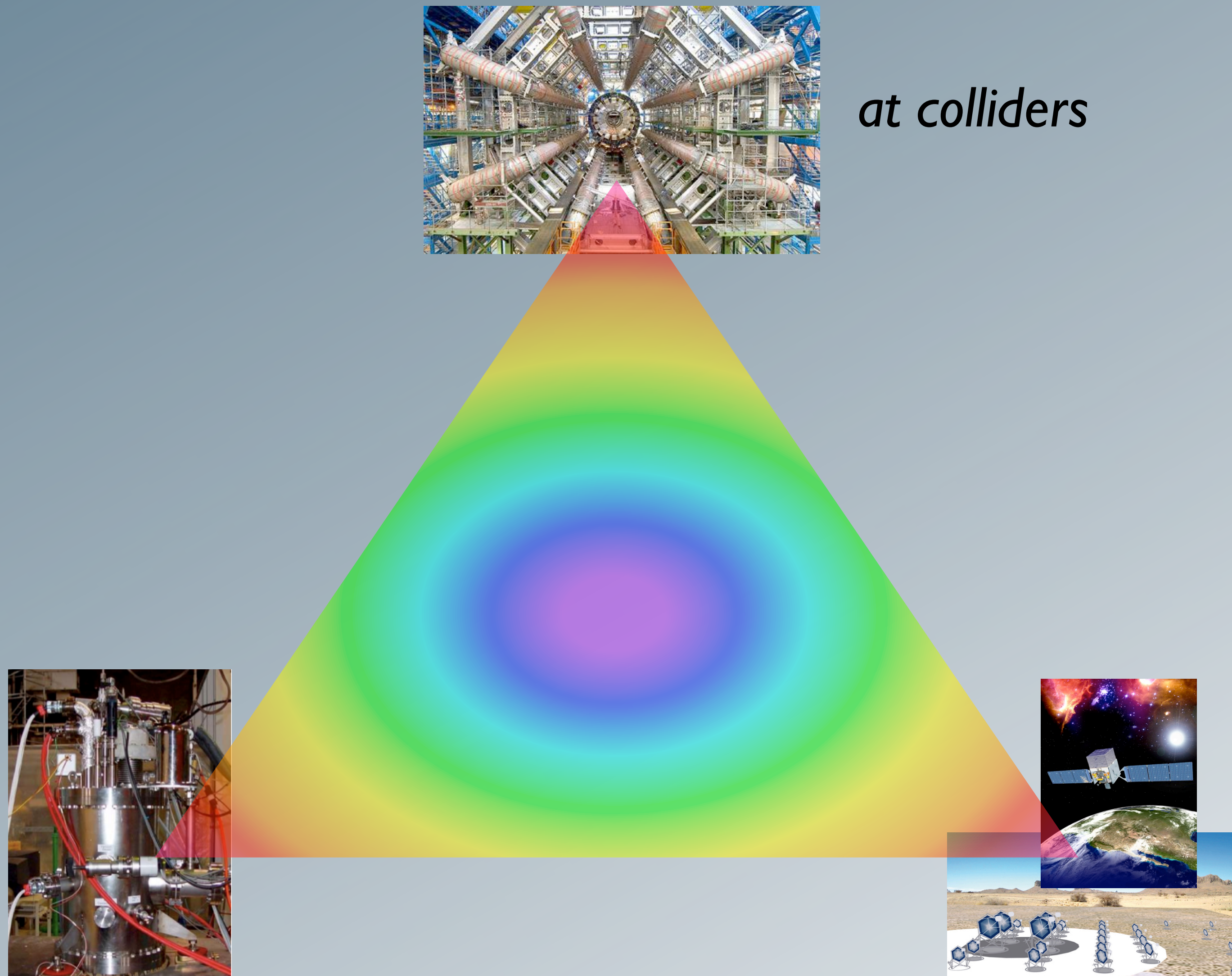
  ⇨ may also provide further information about the spectrum!



	Fermi	**GAMMA-400**	H.E.S.S.
Energy range, GeV	0.1-300	**0.1-3000**	>100
Angular resolution, deg (E_γ > 100 GeV)	0.1	**~0.01**	0.1
Energy resolution, % (E_γ > 100 GeV)	10	**~1**	15

Strategies for DM searches

at colliders



directly

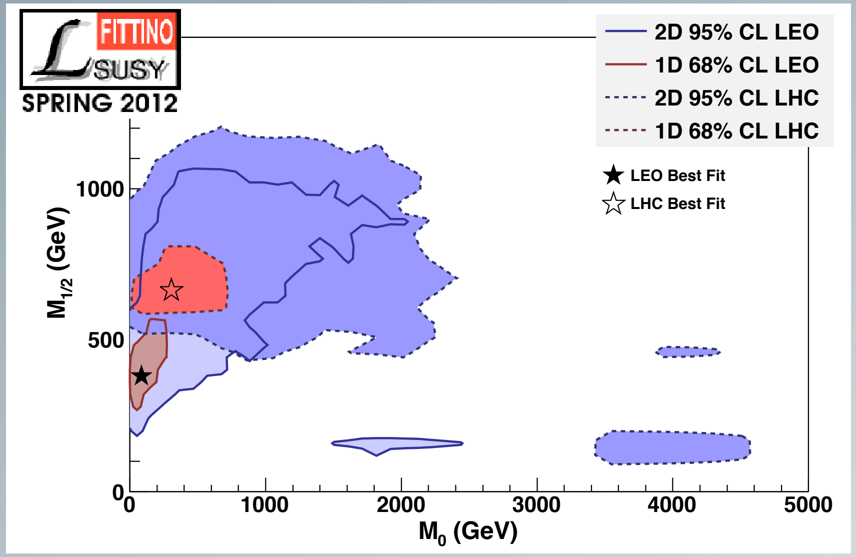
indirectly

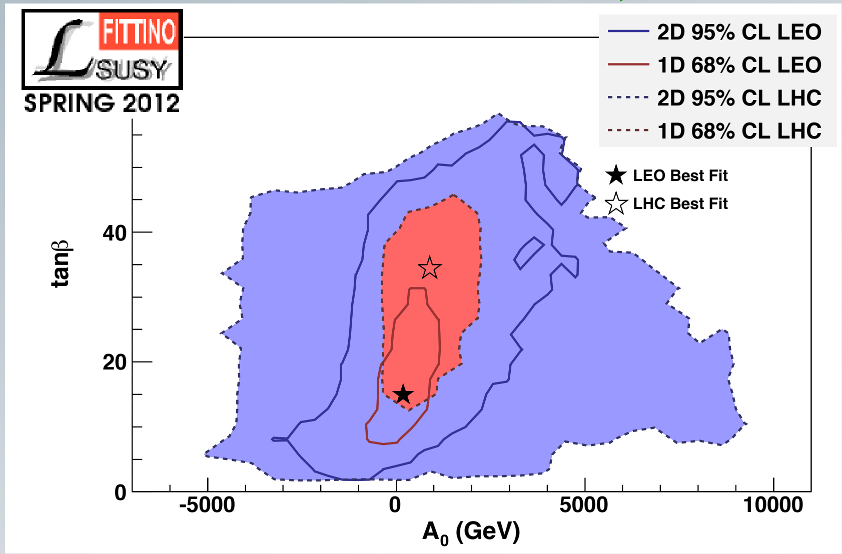
LHC implications

- 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 quite some tension with data!

Bechtle *et al.*, 1204.4199

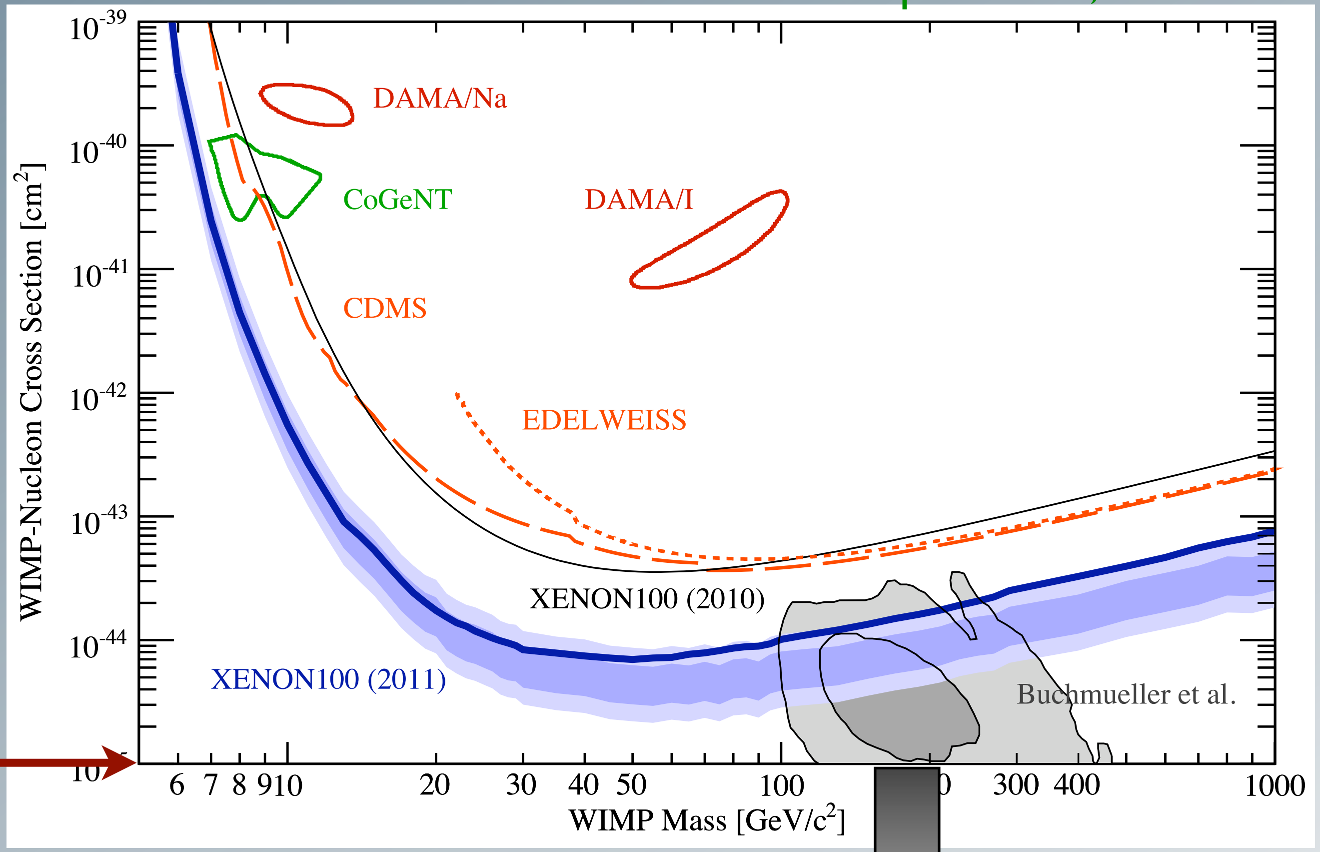




Direct searches

- Impressive improvements of direct detection limits in recent years:

Aprile *et al.*, 1104.2549



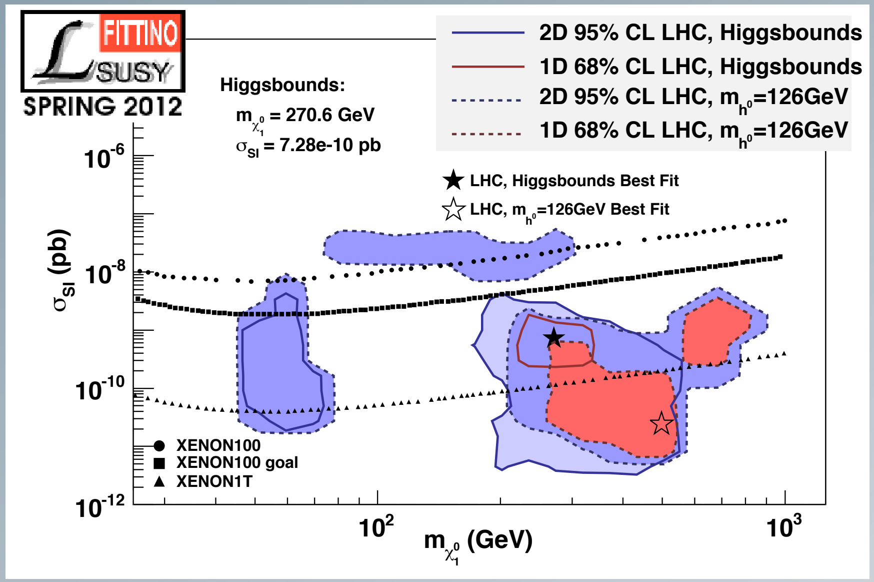
10^{-9} pb

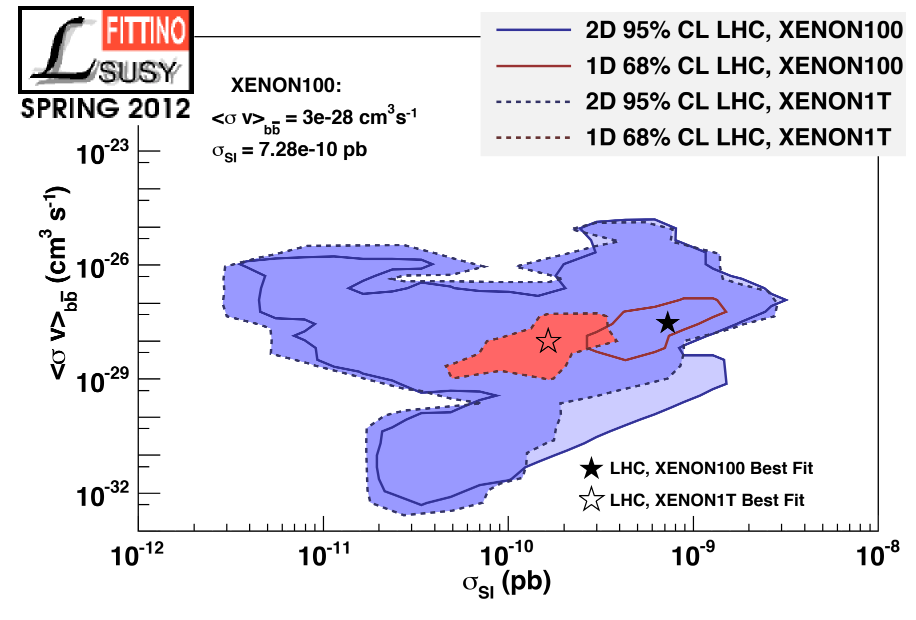
lower limit to $\sigma_{\rm SI}$?

Direct vs. indirect searches

Bechtle *et al.*, 1204.4199

Implications of a 126 GeV 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, …)

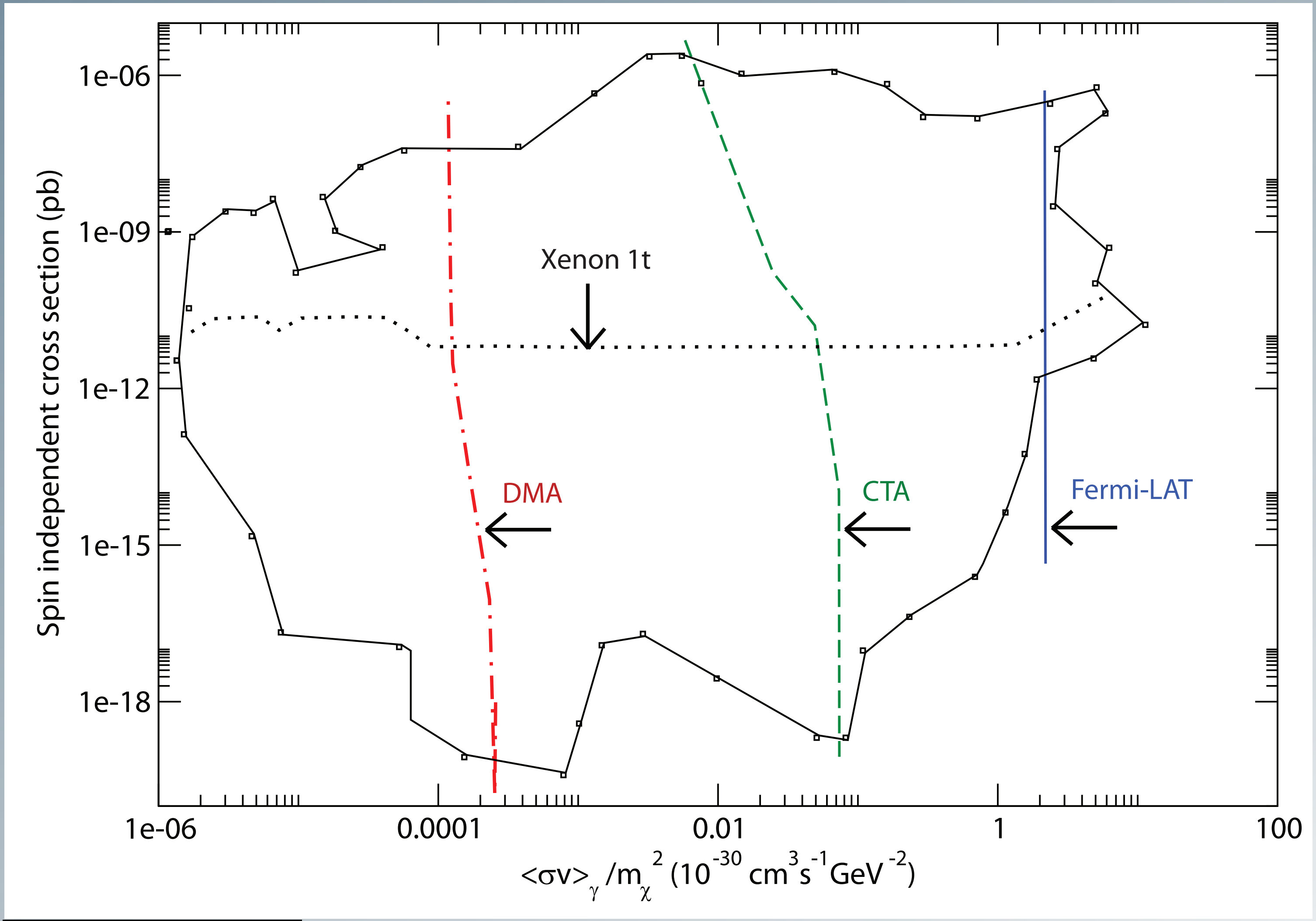
- CTA will have a greatly improved performance, but has many interesting (astrophysical) targets to observe

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

- What could a dedicated future dark matter indirect detection experiment achieve?

(Far) future of DM searches

- MSSM scan
  - relic density, collider bounds OK
- Galactic center:
  - NFW
  - no boost factor
- The "Dark Matter Array":
  - 10 x A_{eff}(CTA)
  - E > 10 GeV
  - dedicated: t_{obs} ~5000 hrs



Bergström, TB & Edsjö, PRD '11
Bergström, 1205.4882

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(50) photons $\rightsquigarrow$ need more data... !