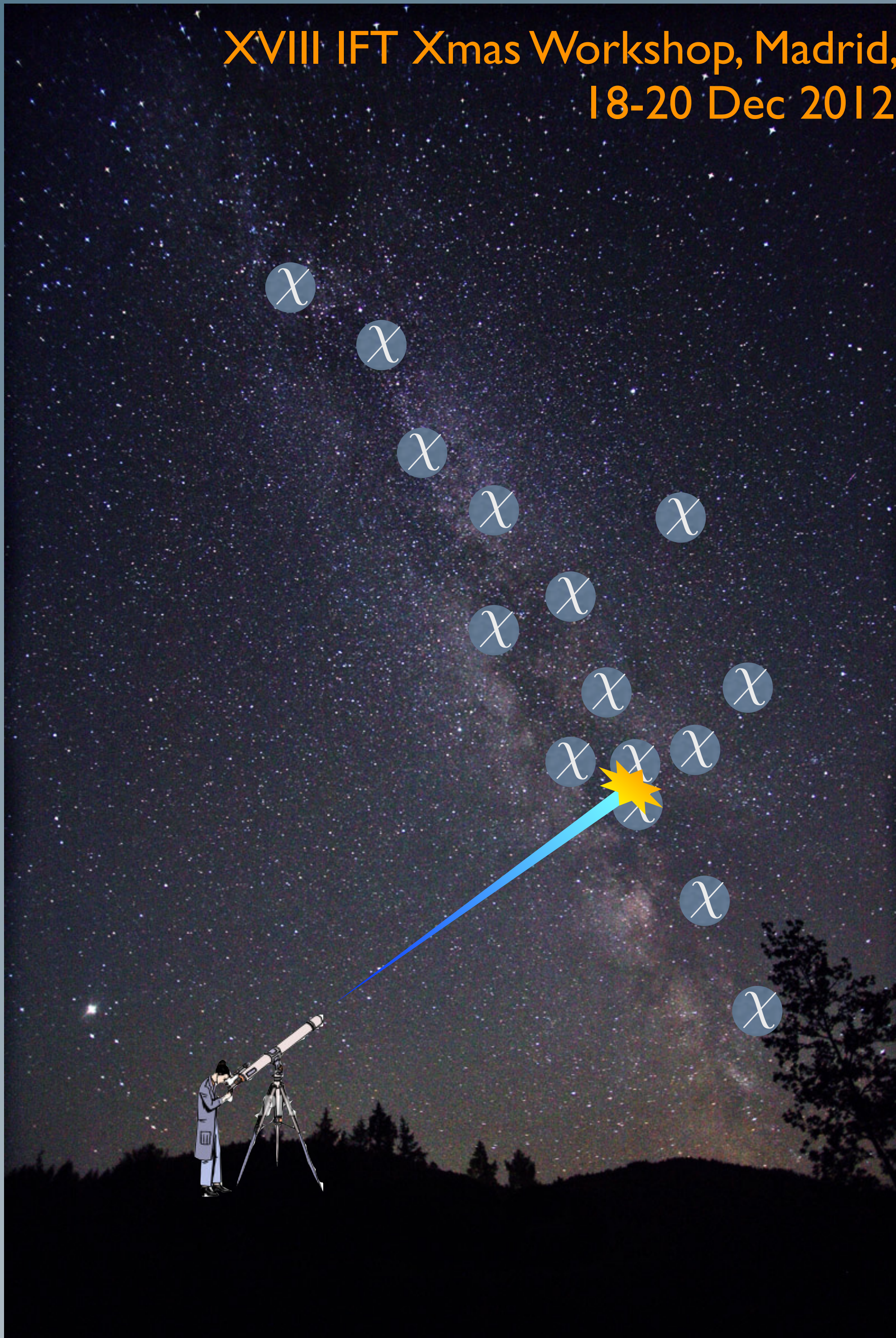

Gamma Ray Signals from Dark Matter

Concepts, Status and Prospects

see also **review**:

T. Bringmann & C. Weniger, Physics of the Dark Universe **1**, 194 (2012) [1208.5481]

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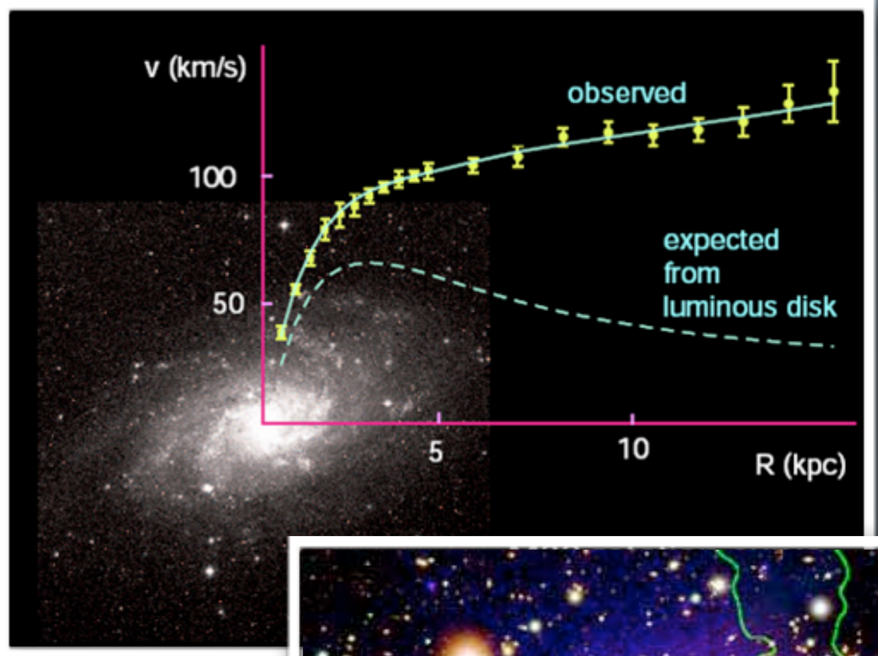
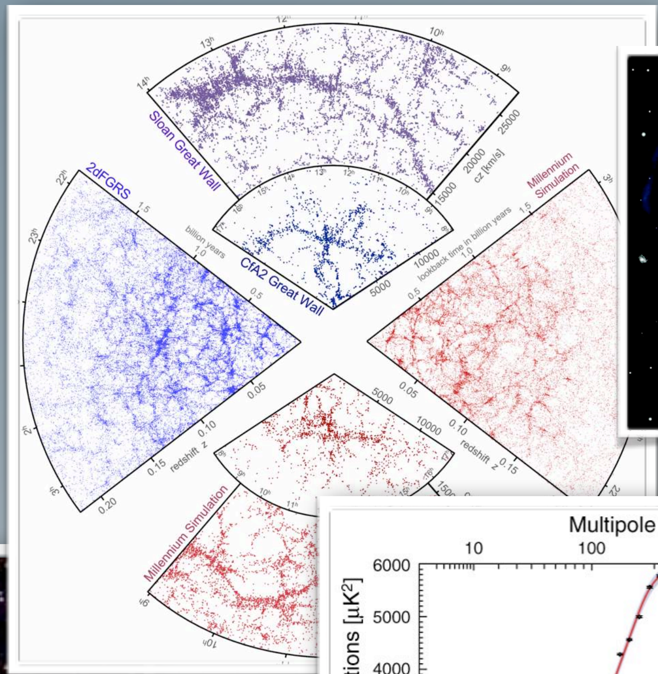
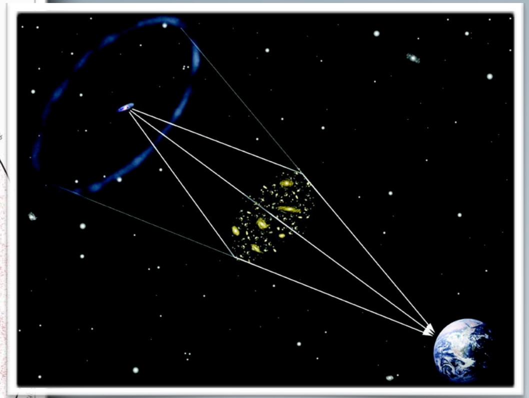
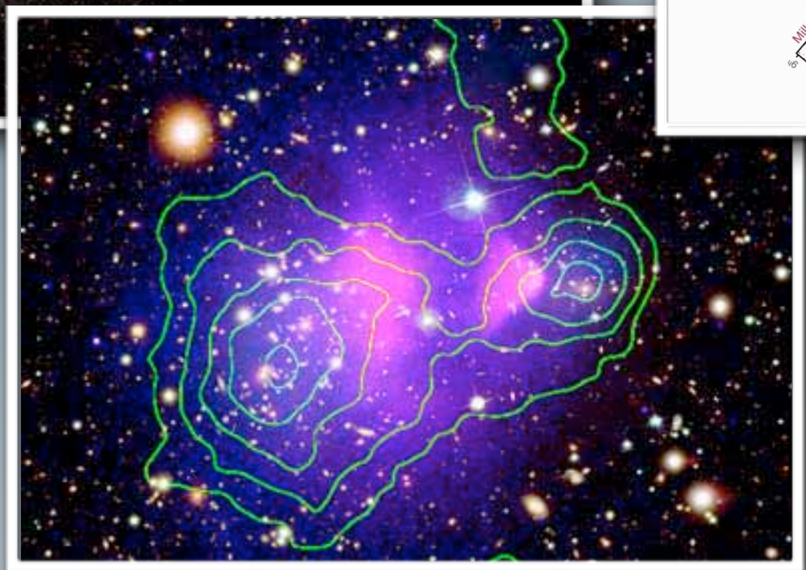
Collaborative Research Centre 676
Particles, Strings, and the Early Universe
The Structure of Matter and Space-Time
Deutsche Forschungsgemeinschaft DFG

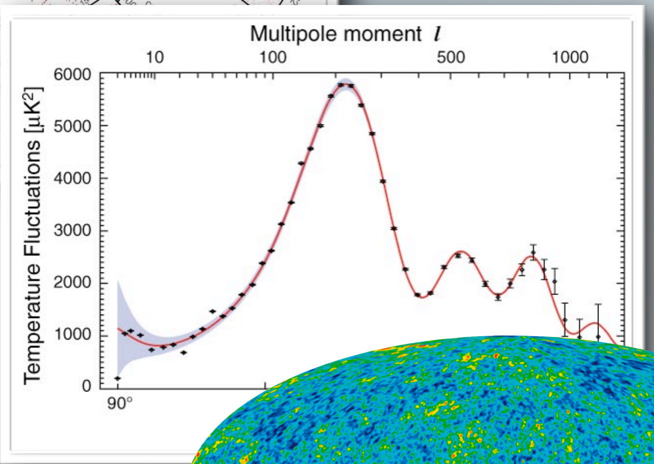
Dark matter all around

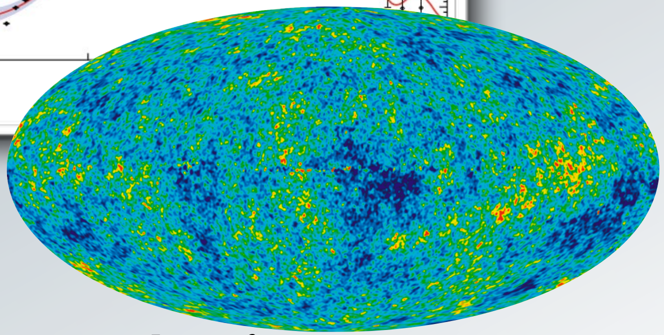






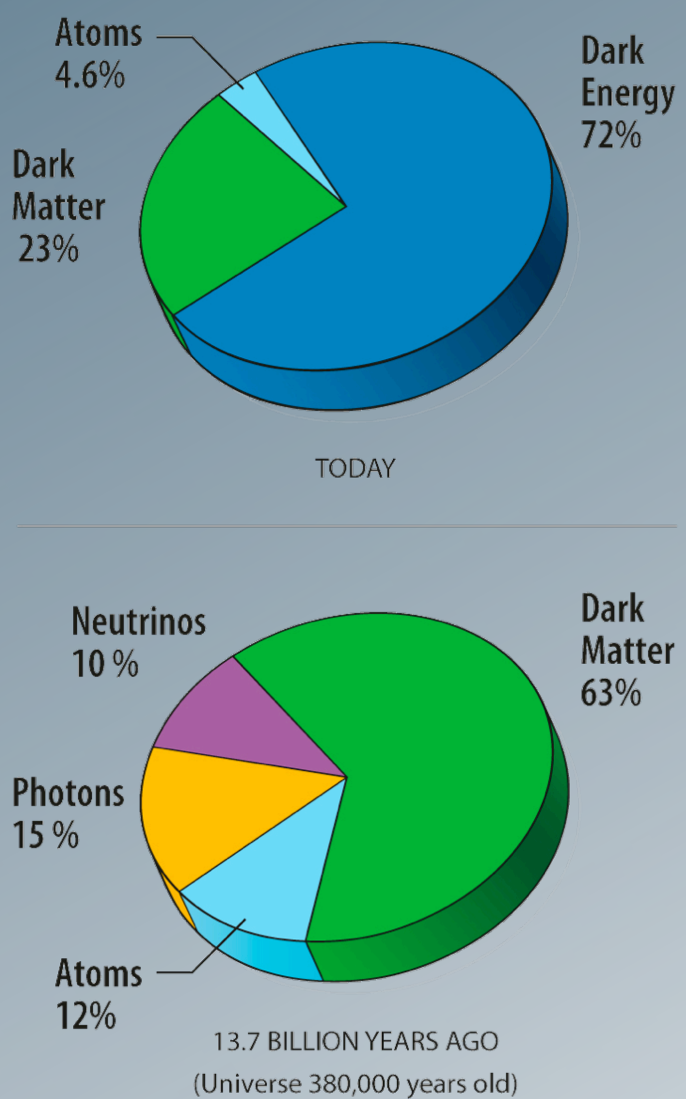






→ *overwhelming evidence on all scales!*

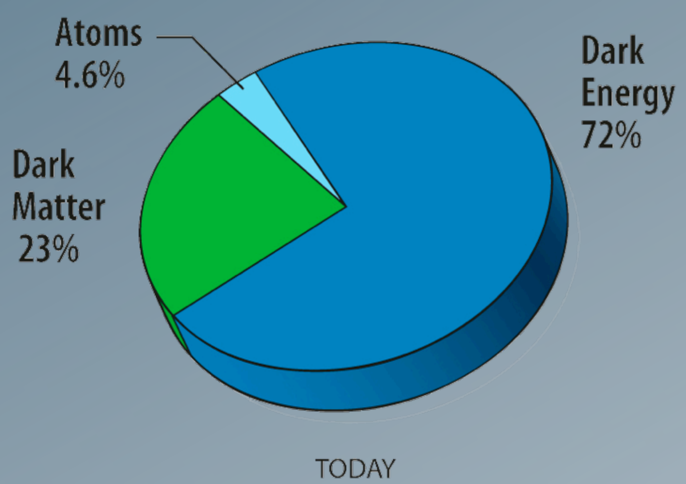
Dark matter

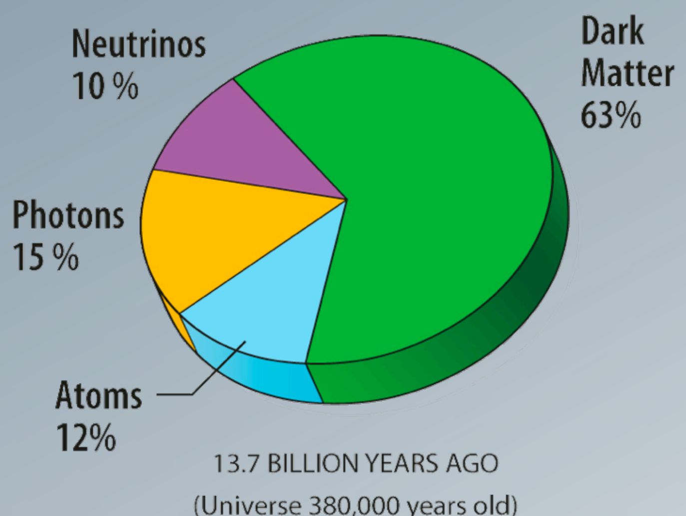


credit: WMAP

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

Dark matter





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  - 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:

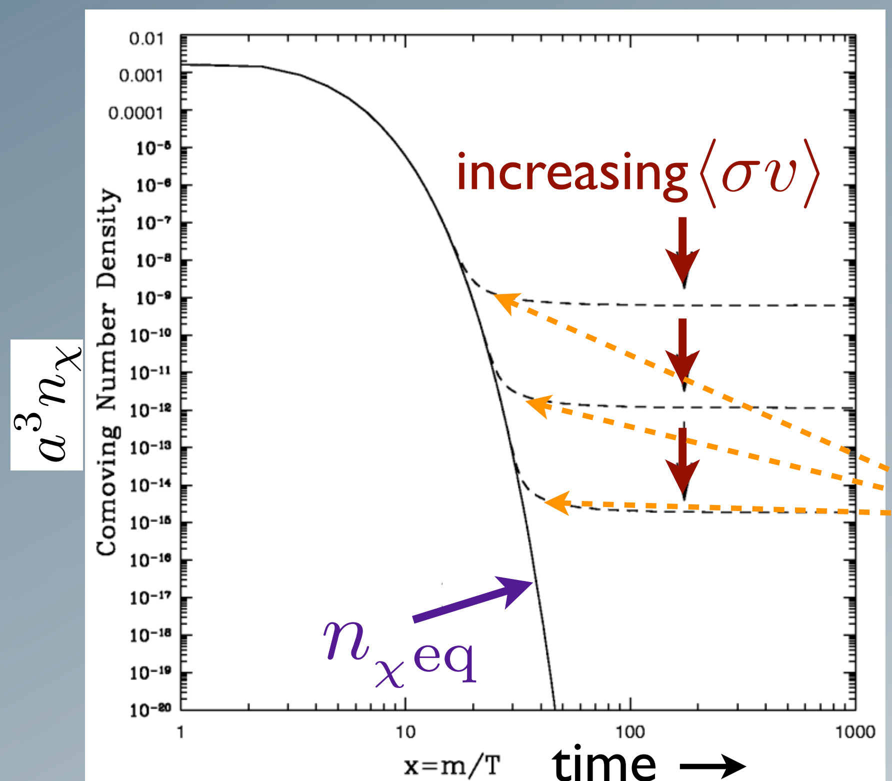


Fig.: Jungman, Kamionkowski & Griest, PR'96

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

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

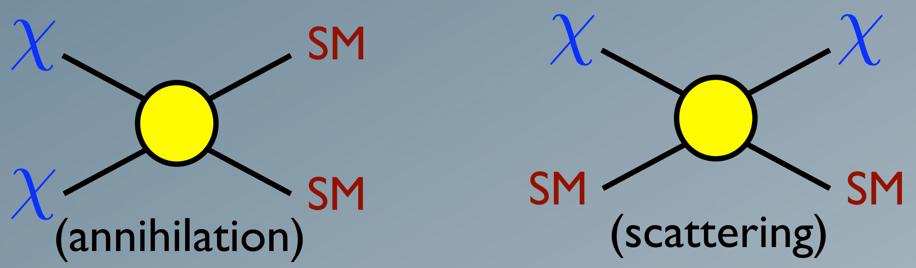
"Freeze-out" when annihilation rate falls behind expansion rate ($\to a^3 n_\chi \sim \mathrm{const.}$)

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:



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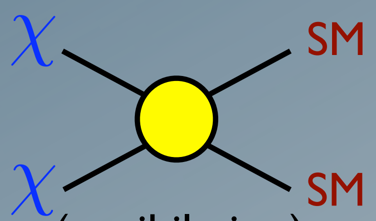
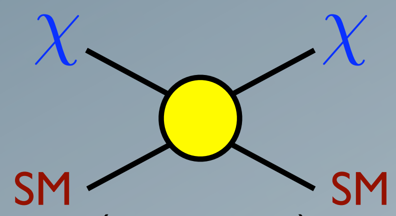


(annihilation)



(scattering)

⇩

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

chemical decoupling

⇩

$$\Omega_\chi$$

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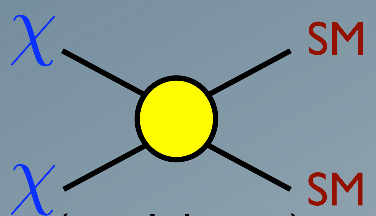

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$\Downarrow$

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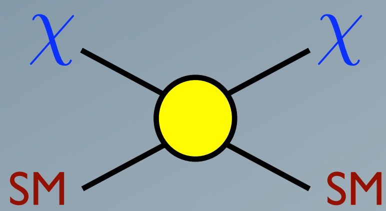
$$\Omega_\chi$$



(scattering)

$\Downarrow$

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

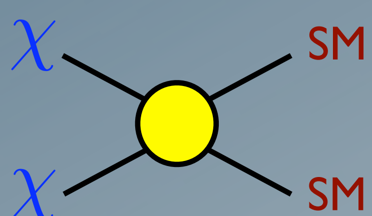
kinetic decoupling

$\Downarrow$

$$M_{\rm cut}$$

Freeze-out ≠ decoupling !

- WIMP interactions with heat bath of SM particles:



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⇩

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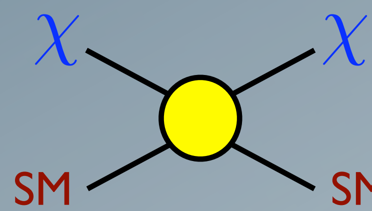
⇩

Ω_χ



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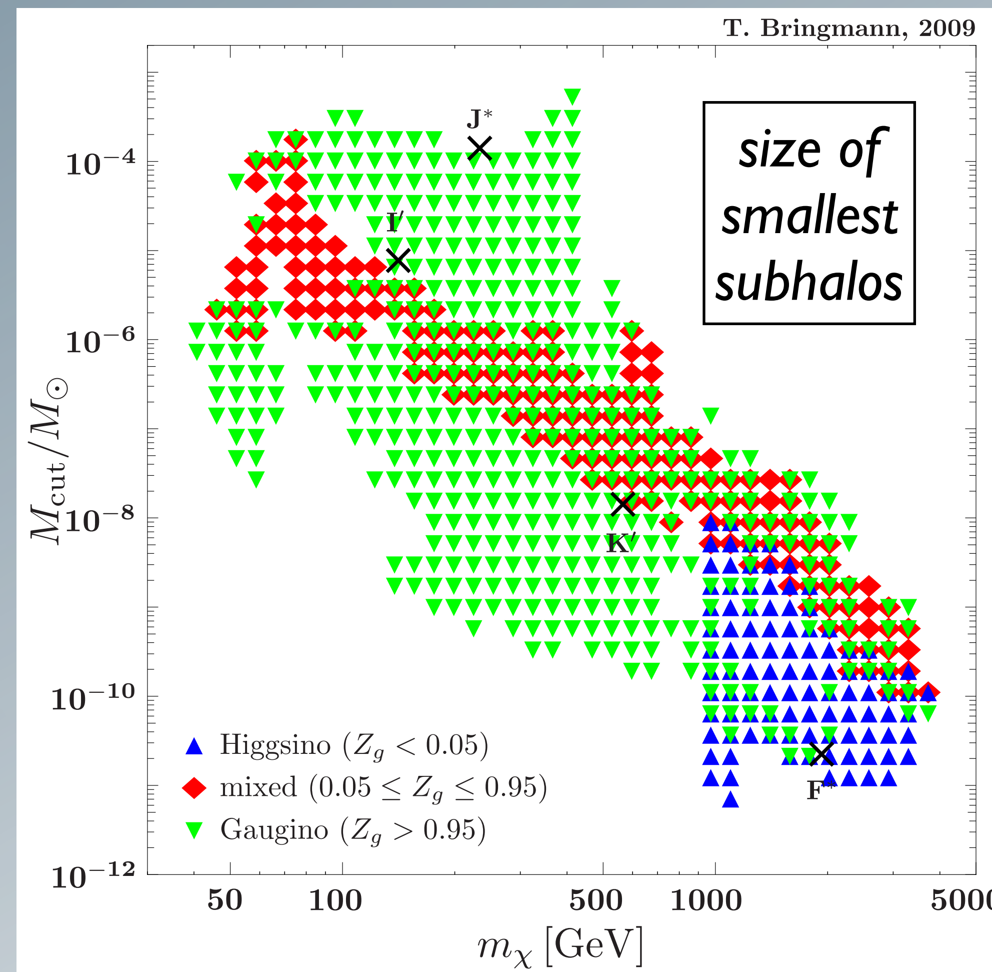
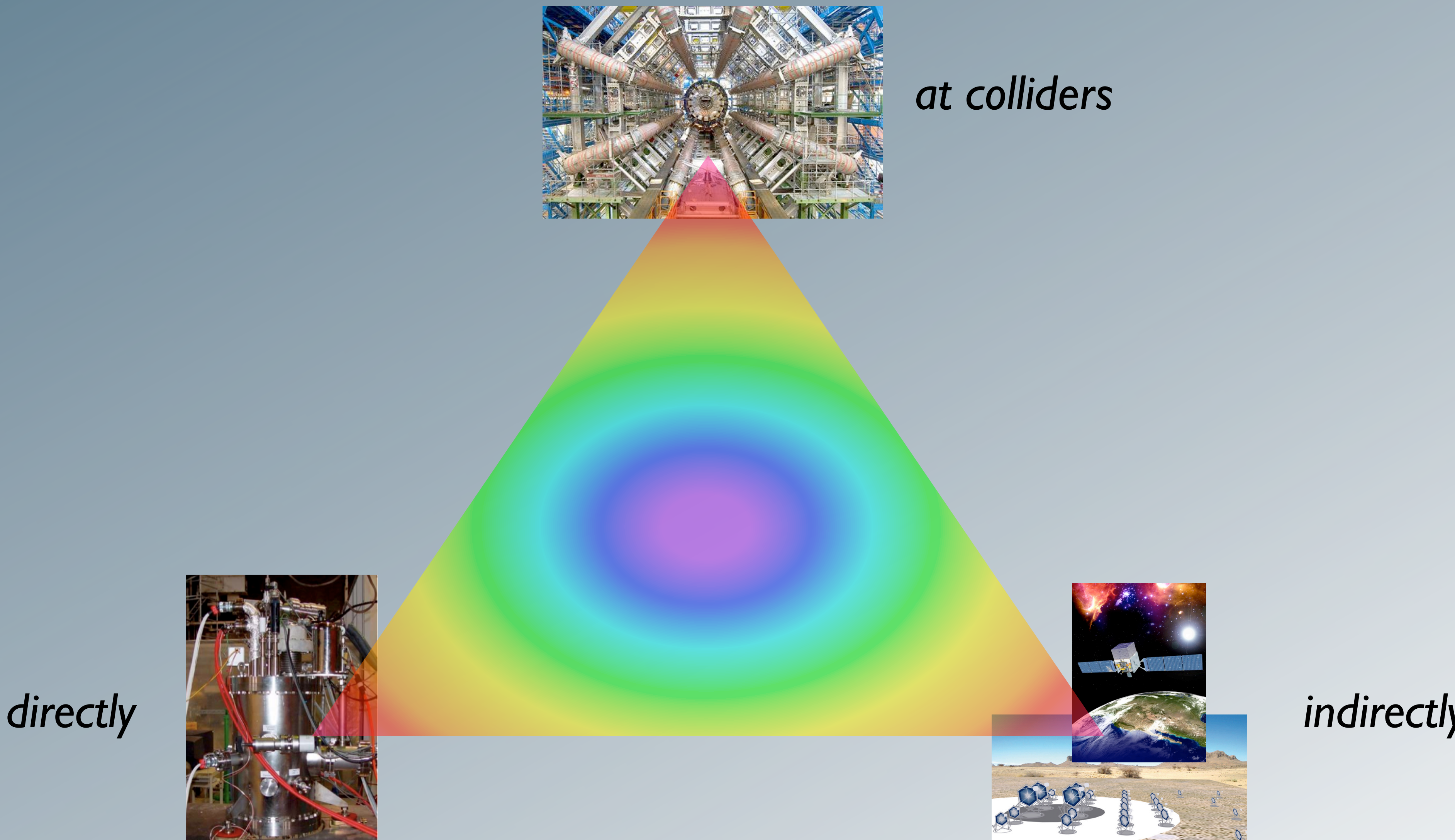
$M_{\rm cut}$



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



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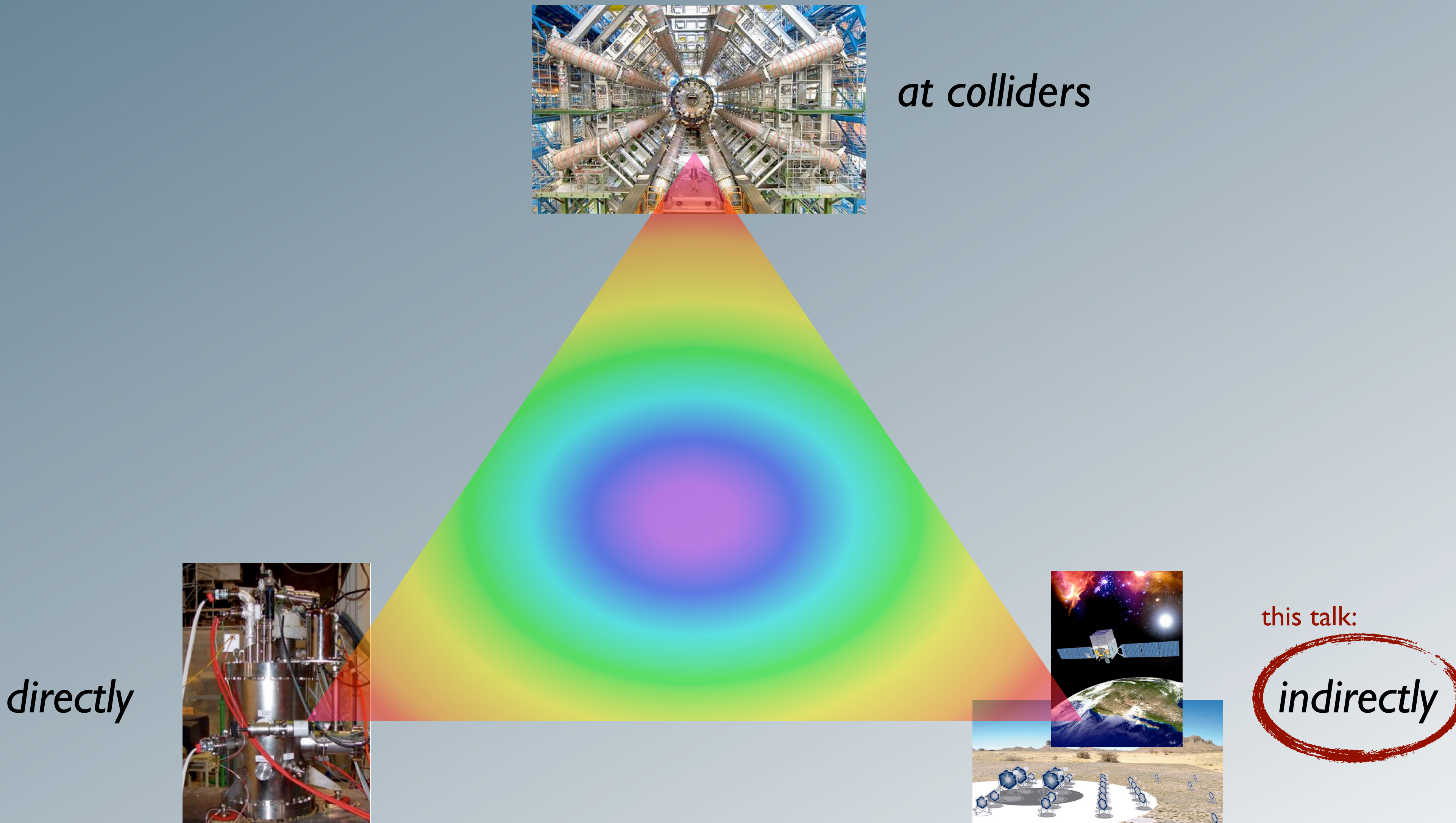
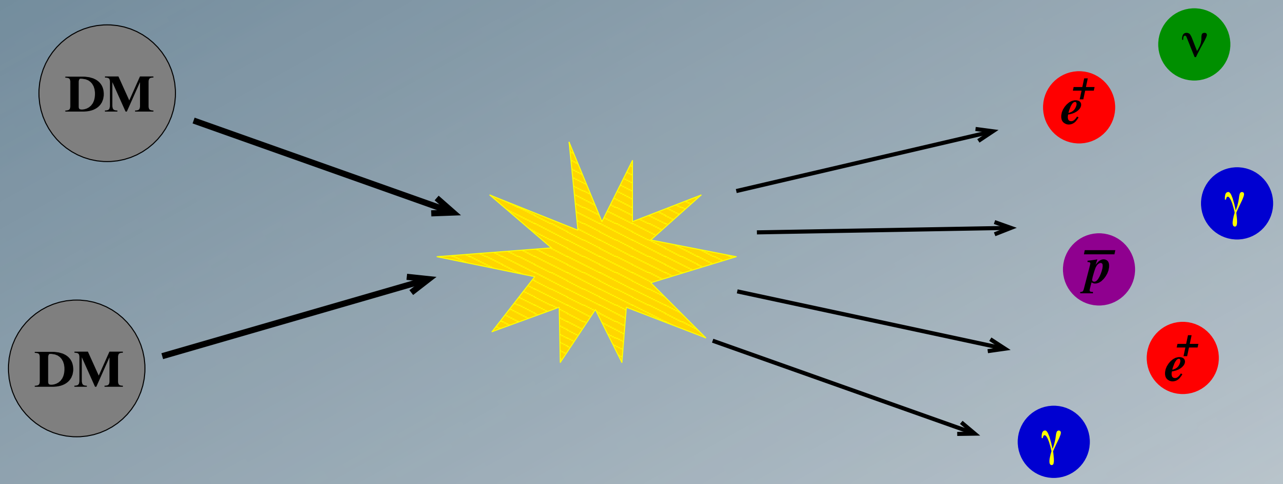


➔ *all complementary!*

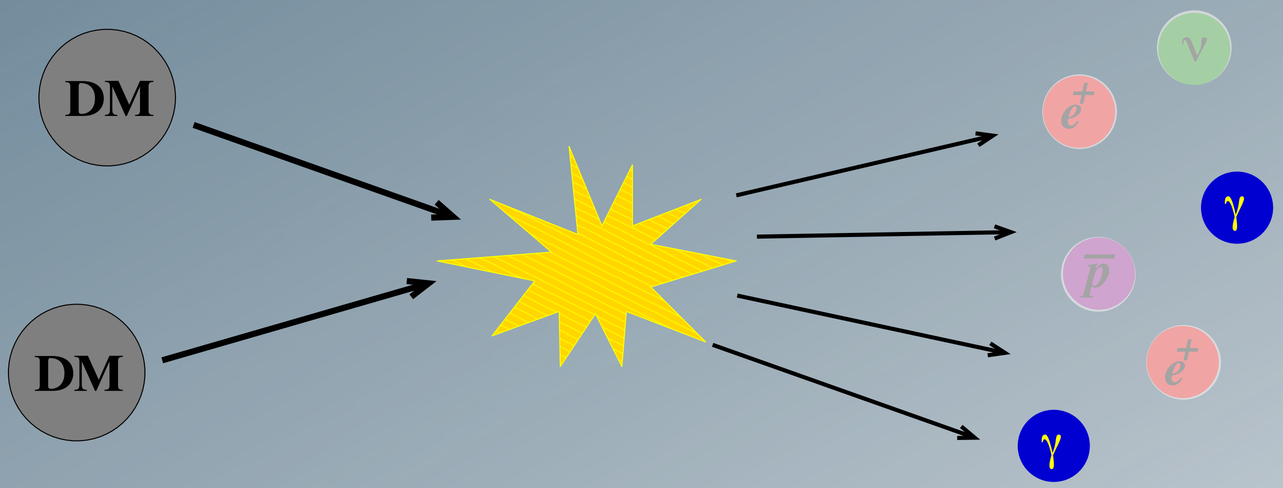
Indirect DM searches



- 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

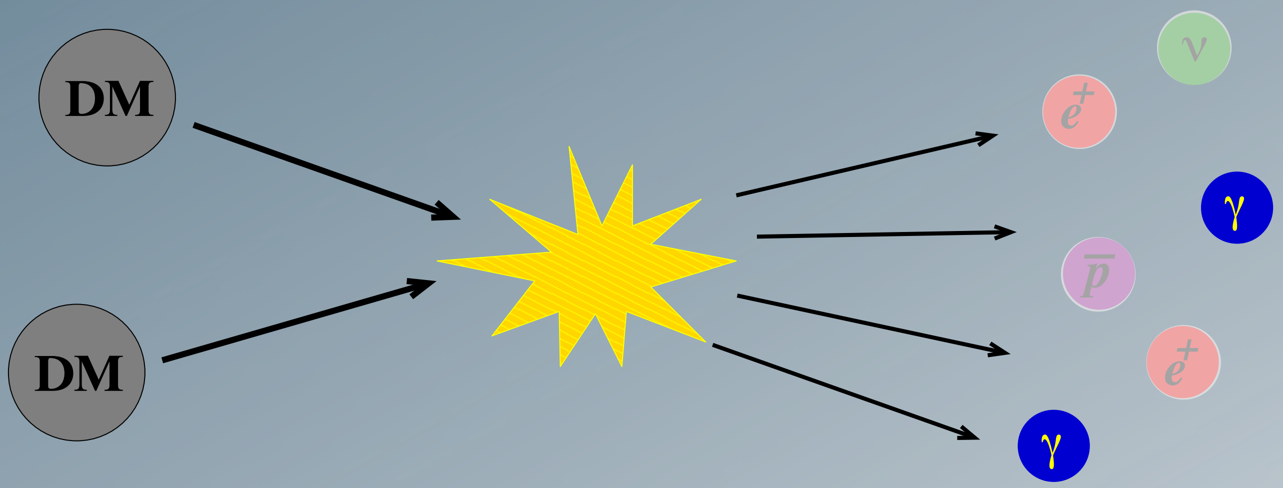
- The challenge: i) absolute rates
  $\leadsto$ regions of high DM density
  ii) discrimination against other sources
  $\leadsto$ low background; clear signatures

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

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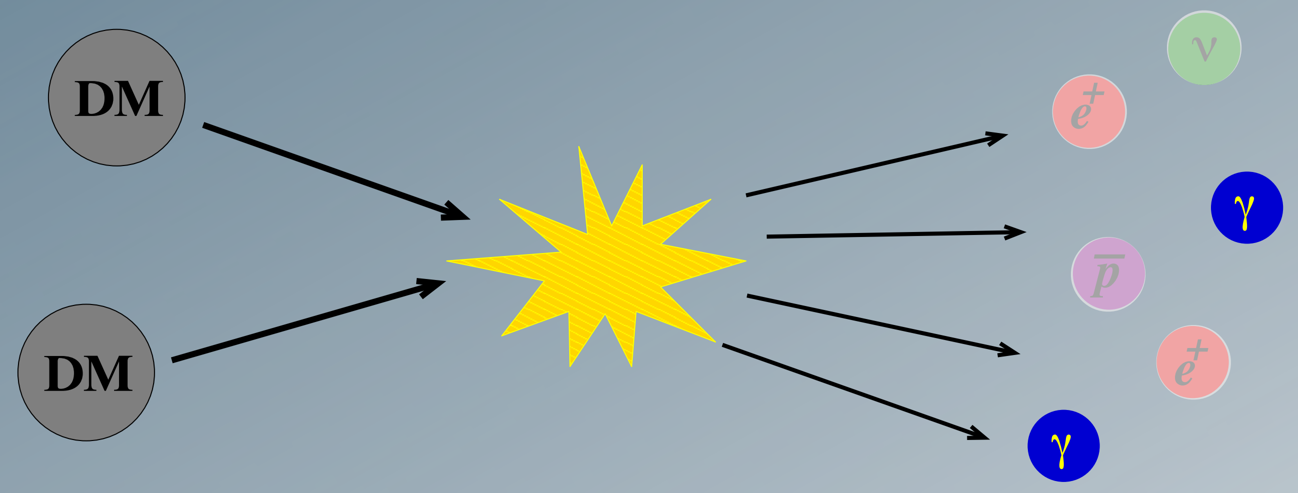

Gamma rays:

- Rather high rates
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- 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

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

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particle physics

$\langle\sigma v\rangle_{\rm ann}$: 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

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particle physics — astrophysics

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

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high accuracy
spectral information

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

D : distance to source

angular information

+ rather uncertain

normalization

Halo profiles

<u>ΛCDM *N*-body simulations</u>

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

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

$$(\alpha \approx 0.17)$$

$\rightsquigarrow$ rather stable result

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

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

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

$\rightsquigarrow$ conflicting observational claims

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$\rightsquigarrow$ 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:

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

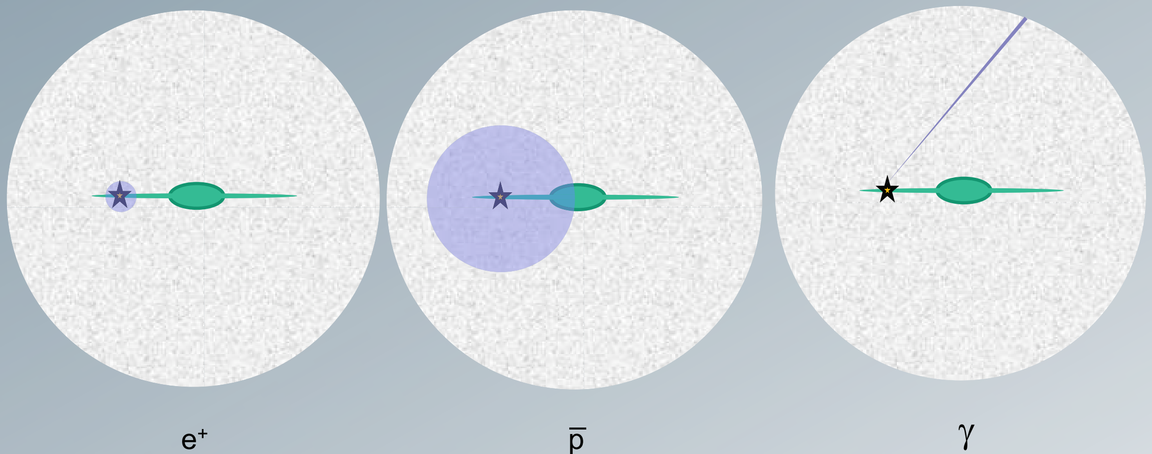

Fig.: Bergström, NJP '09

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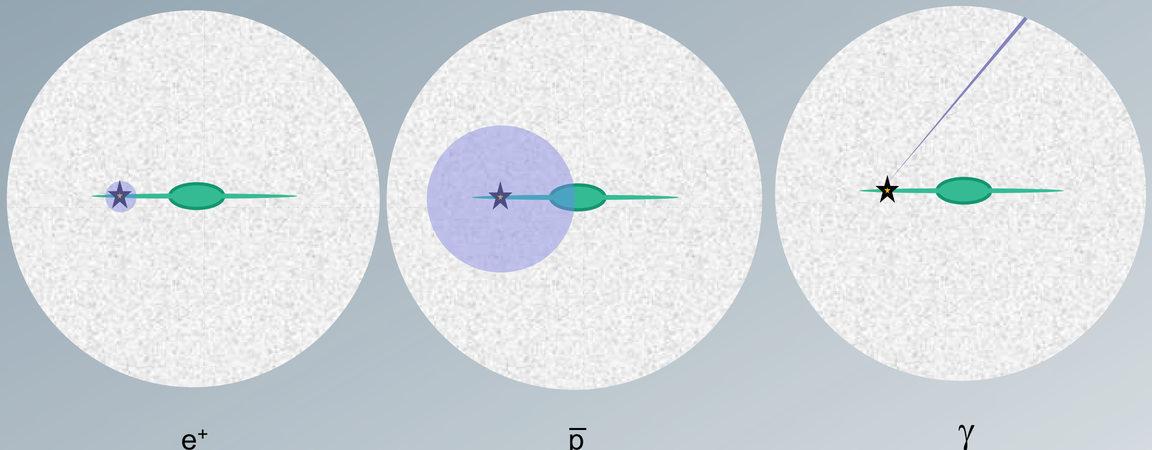


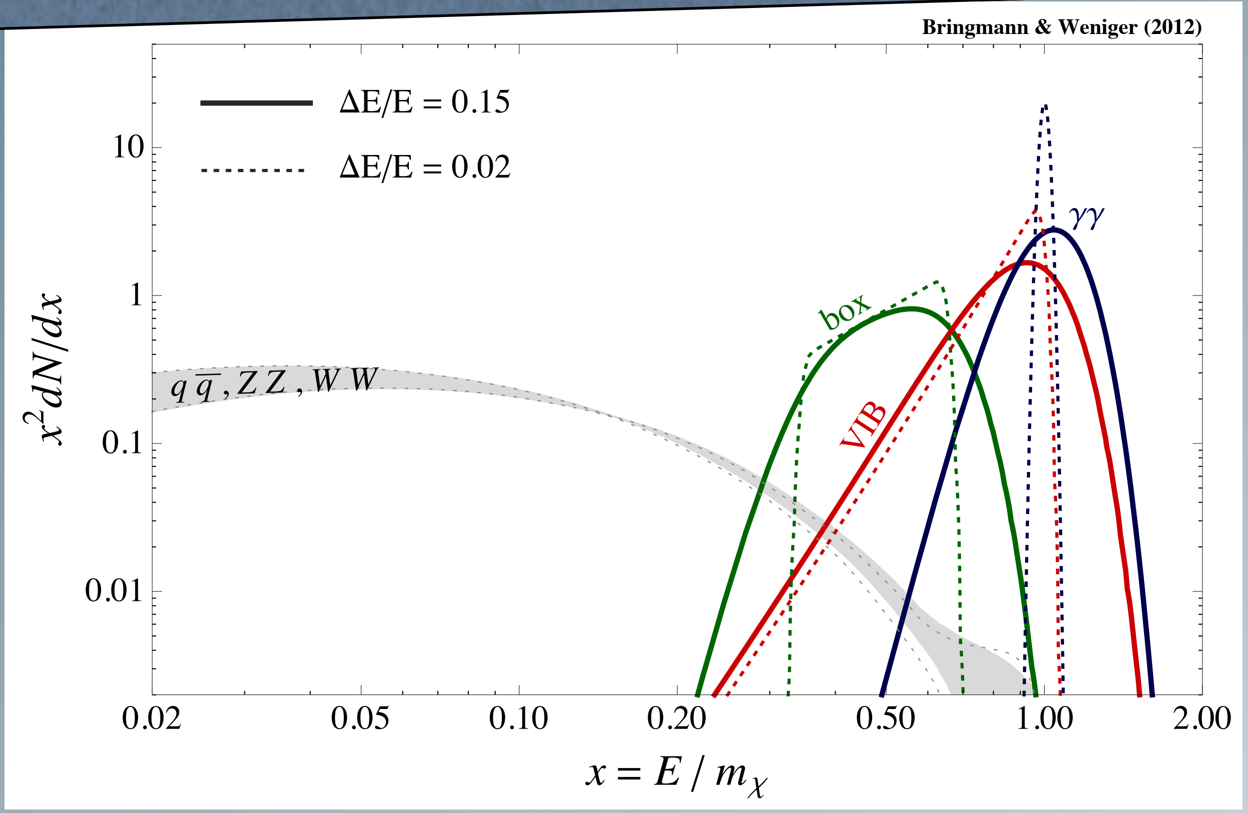
Fig.: Bergström, NJP '09

- "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!)

Annihilation spectra



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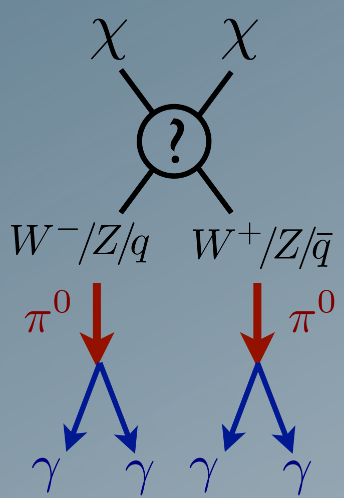

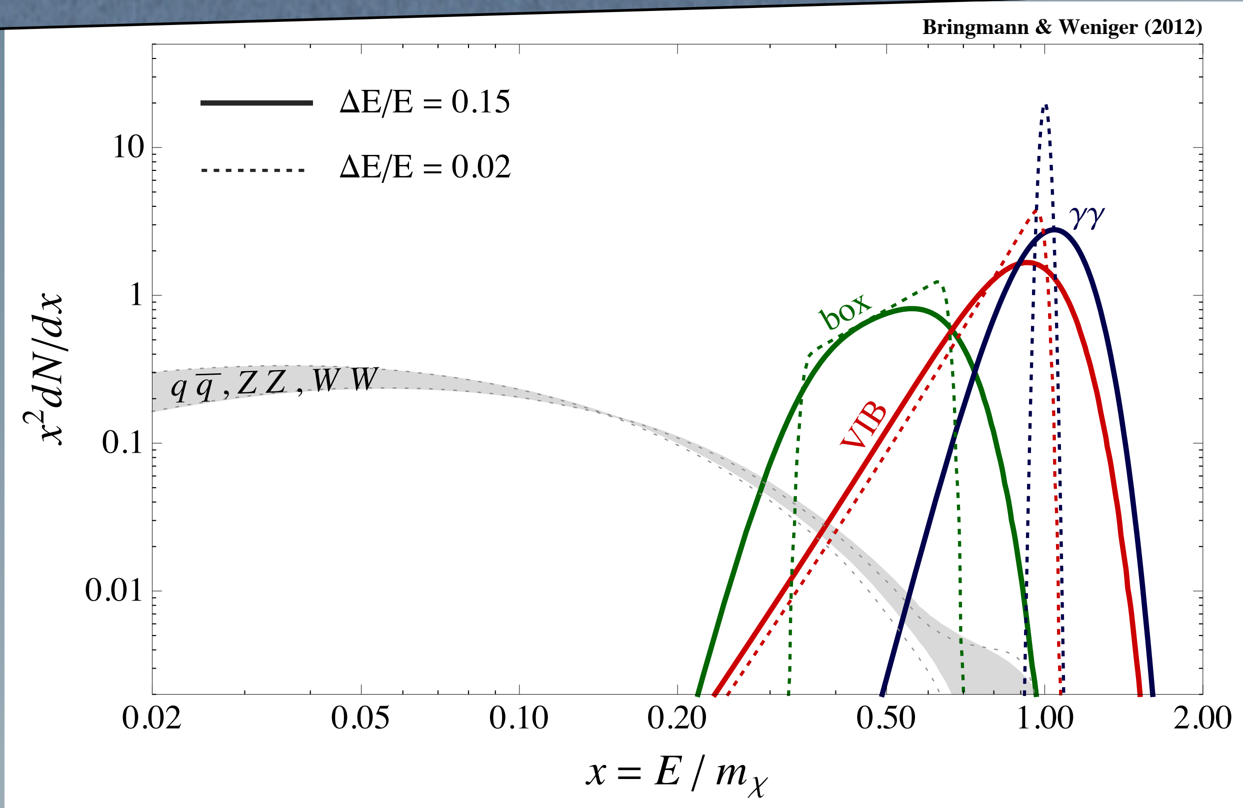

- Secondary photons
  - *many* photons but
  - featureless & model-independent
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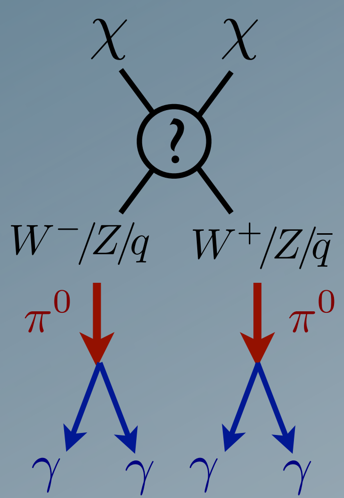

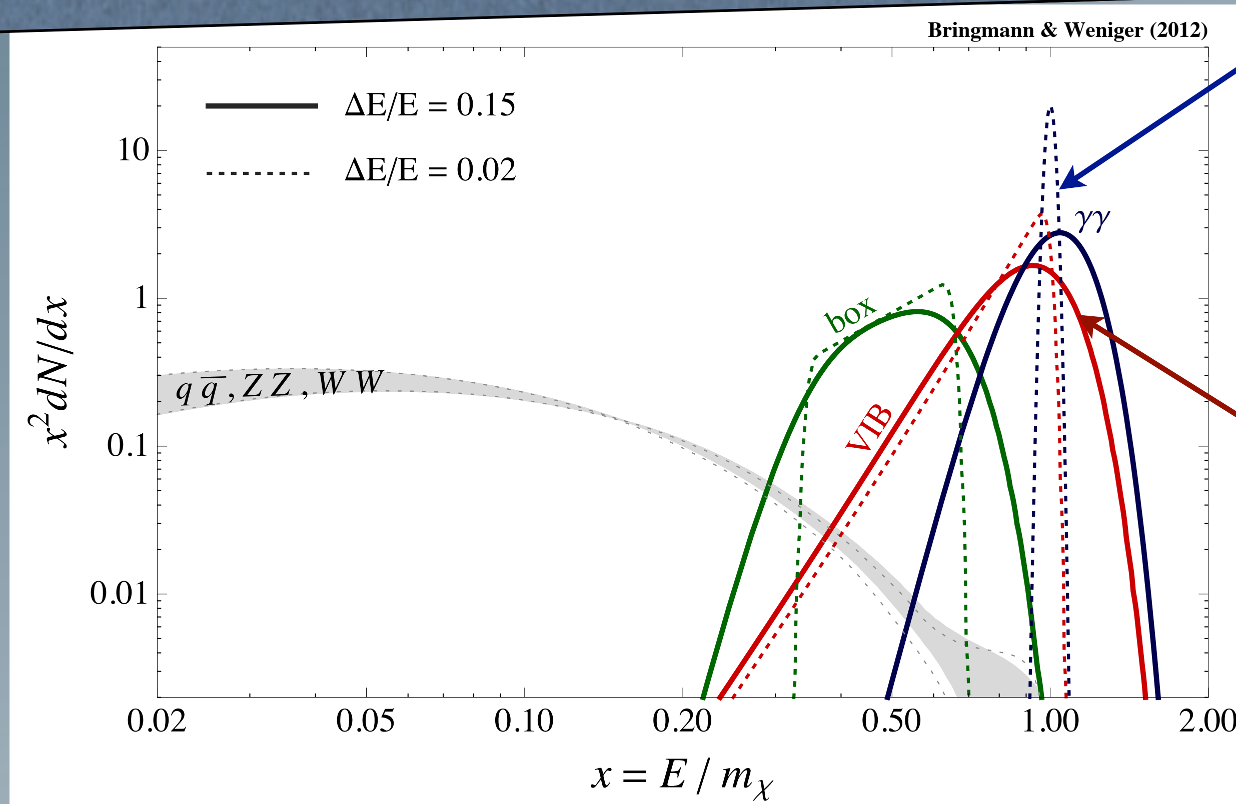

Monochromatic lines

$\chi\chi \to \gamma\gamma, \gamma Z, \gamma H$

$\mathcal{O}(\alpha_{\rm em}^2)$

(Virtual) Internal Bremsstrahlung

$\chi\chi \to \bar{f} f \gamma, W^+ W^- \gamma$

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- Primary photons
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  - model-dependent 'smoking gun' spectral features near $E_\gamma = m_\chi$

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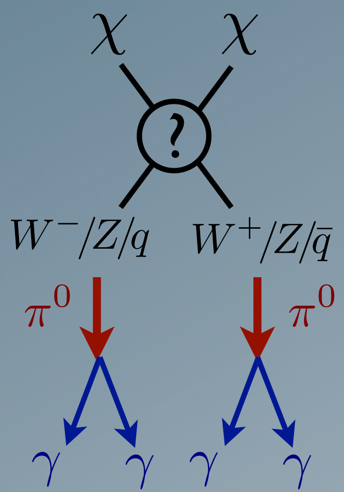

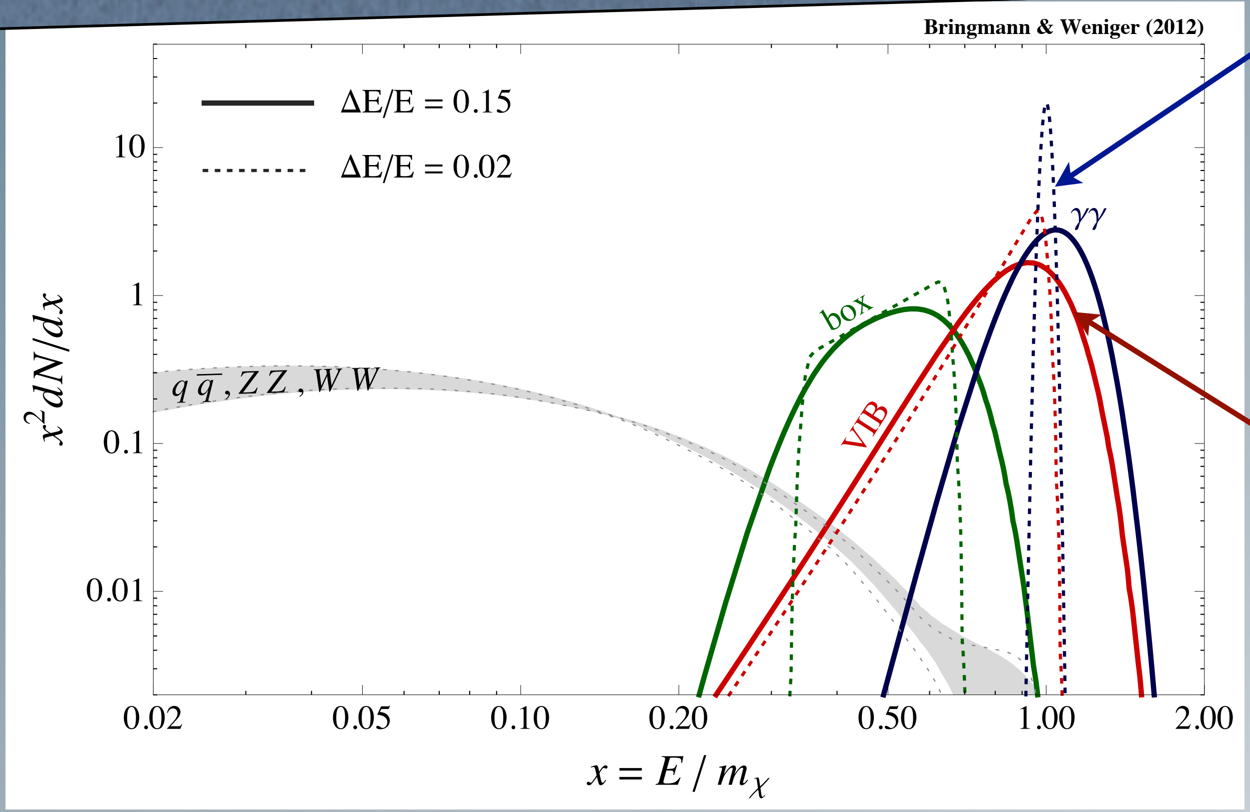

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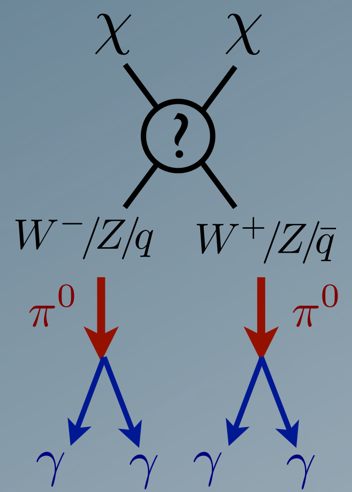

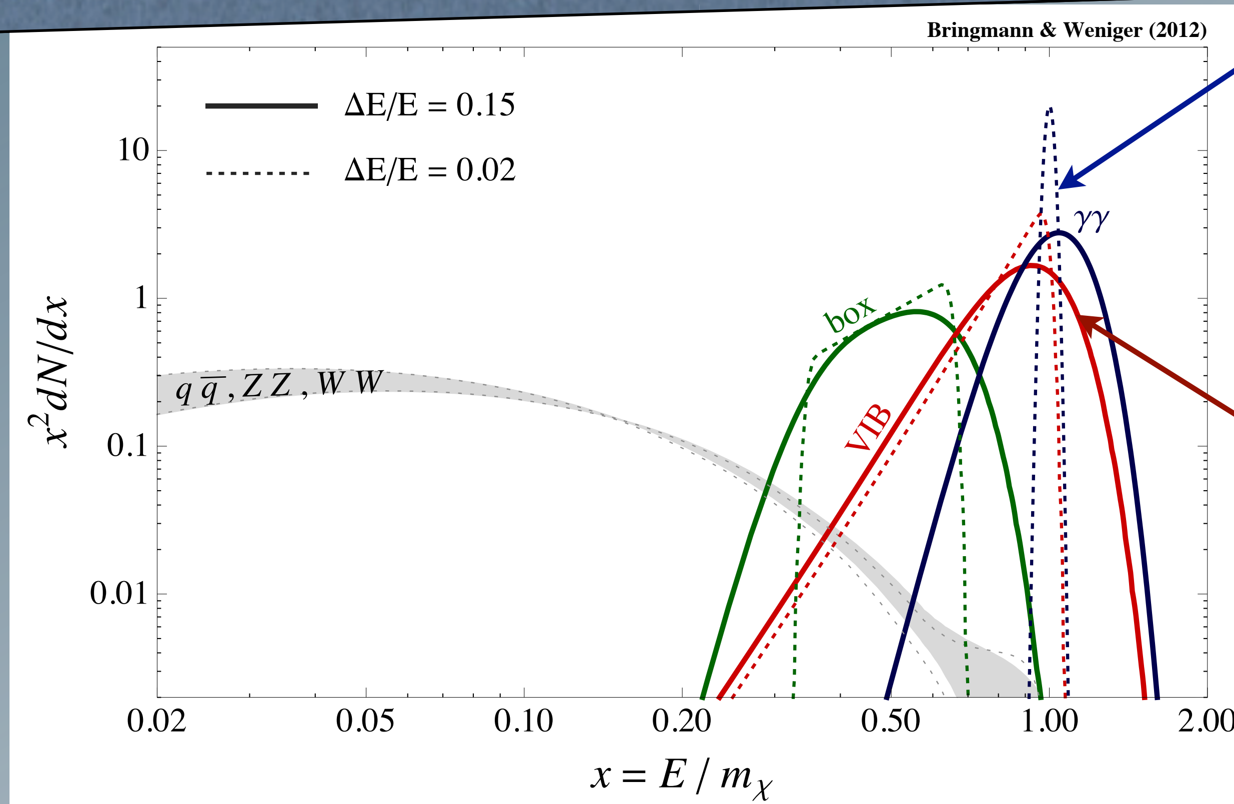

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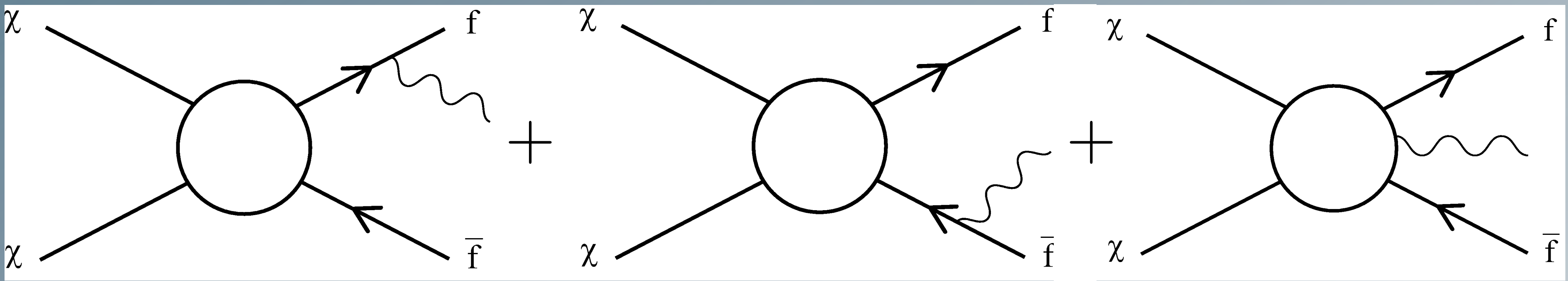
  ⇨ *discovery potential*

Internal bremsstrahlung



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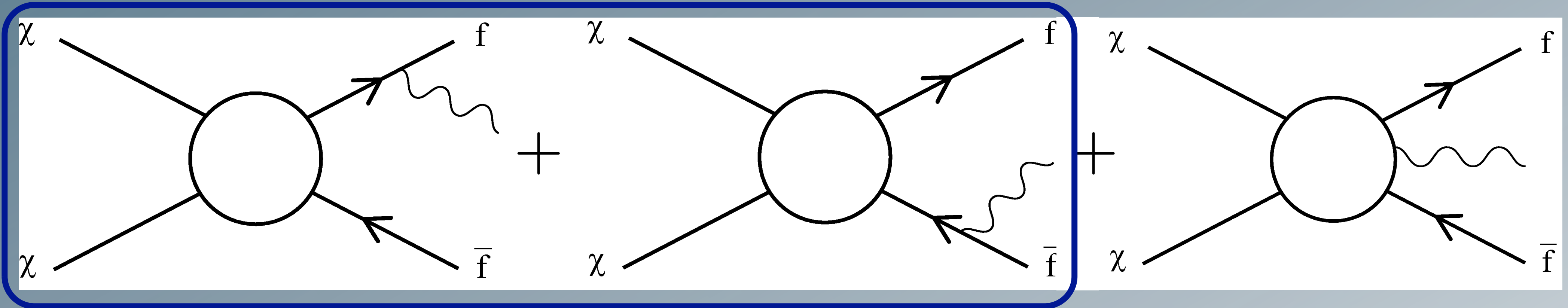
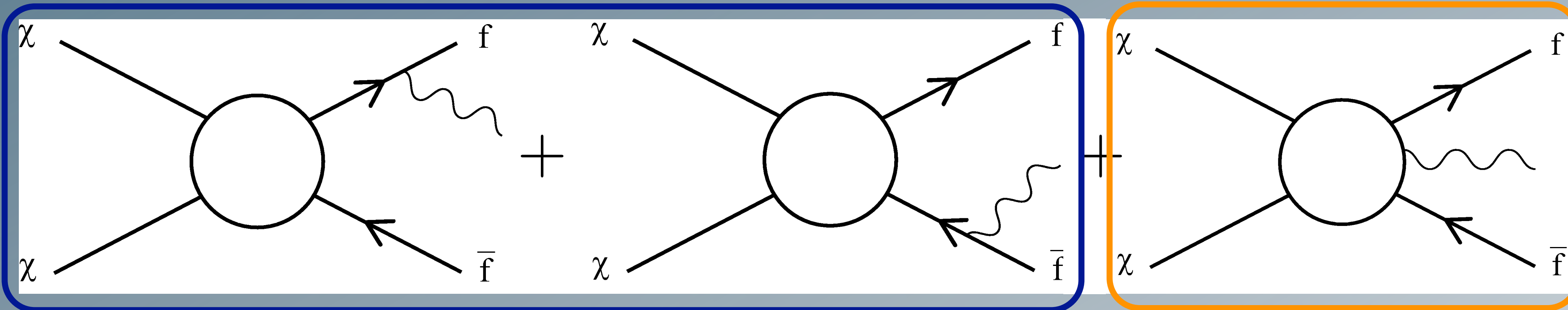


Final state radiation

- 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



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- 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 [TB, Edsjö & Bergström, JHEP '08]

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

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

Dark SUSY

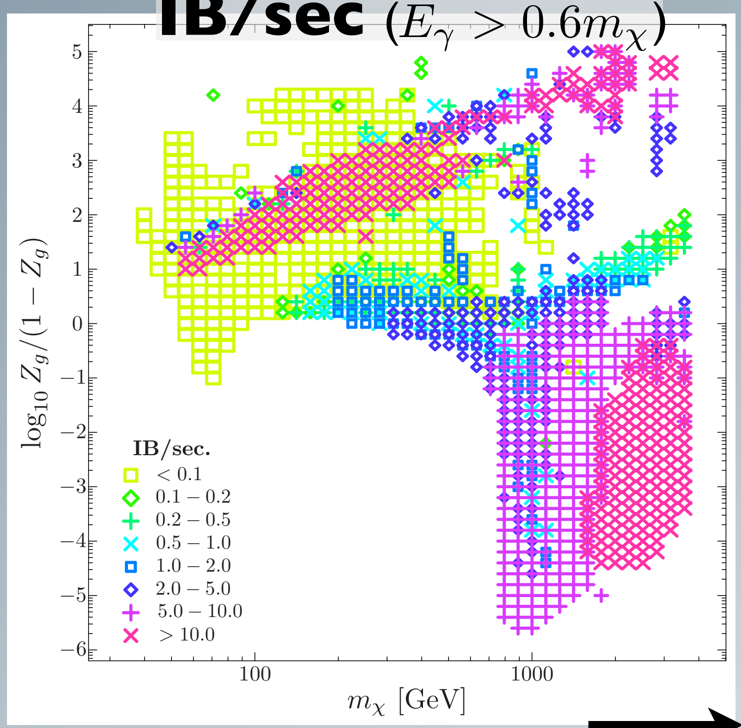
IB/sec $(E_\gamma > 0.6 m_\chi)$

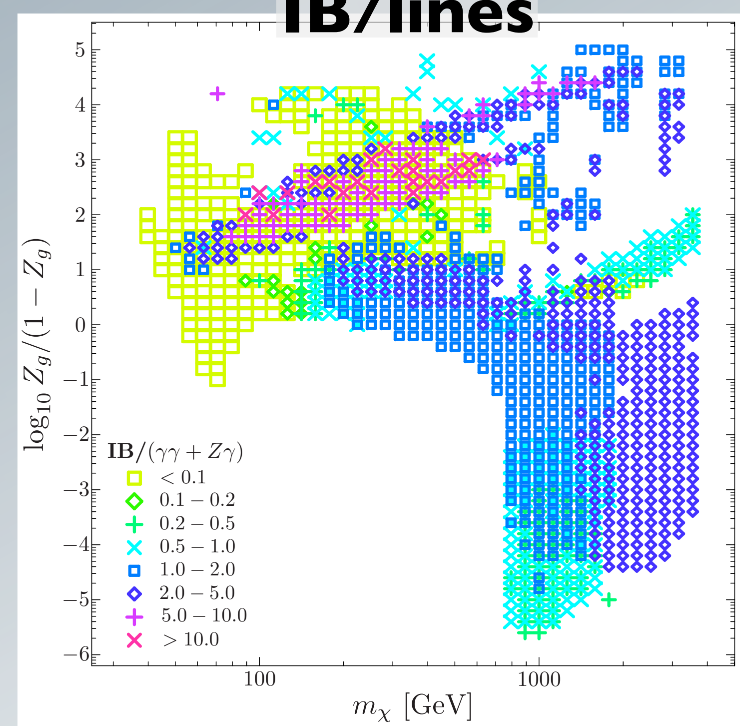
IB/lines

Gaugino →

mixed →

Higgsino →

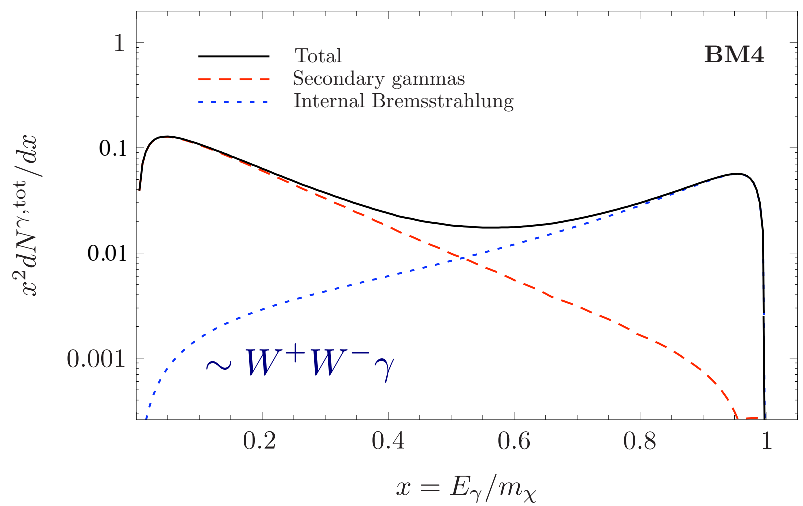




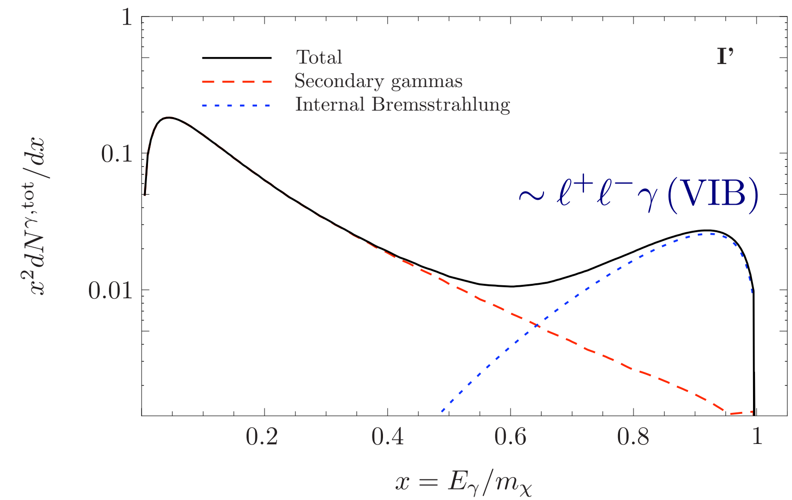
$\longrightarrow m_\chi$

mSUGRA spectra

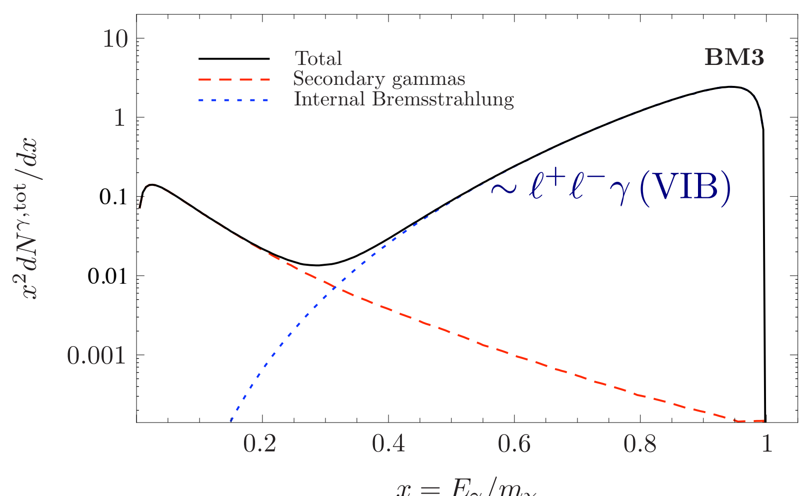
focus point region ($m_\chi = 1926$ GeV)



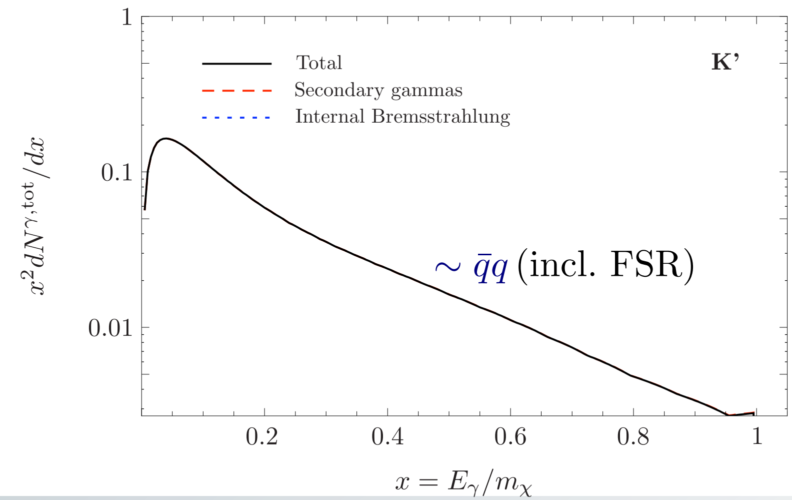
bulk region ($m_\chi = 141$ GeV)



coannihilation region ($m_\chi = 233$ GeV)



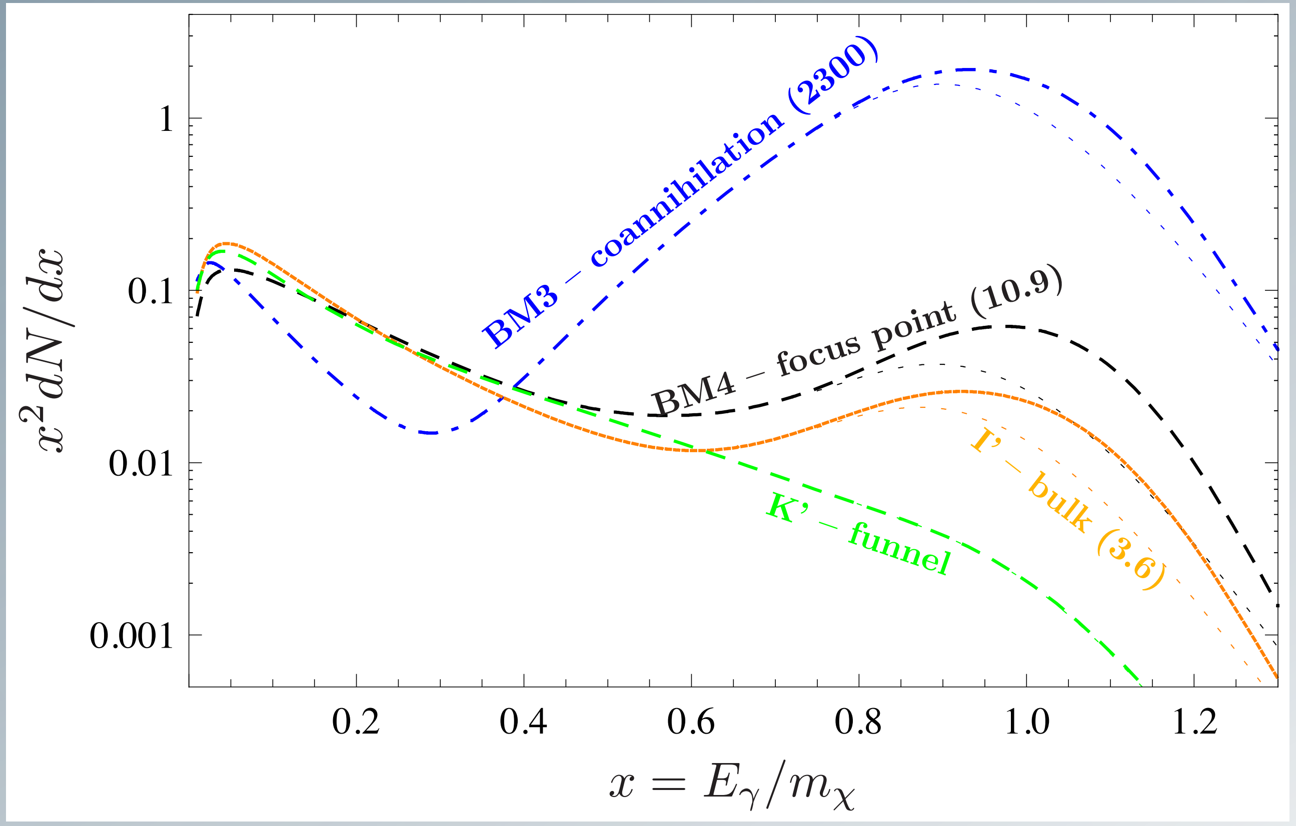
funnel region ($m_\chi = 565$ GeV)



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

Comparing DM spectra

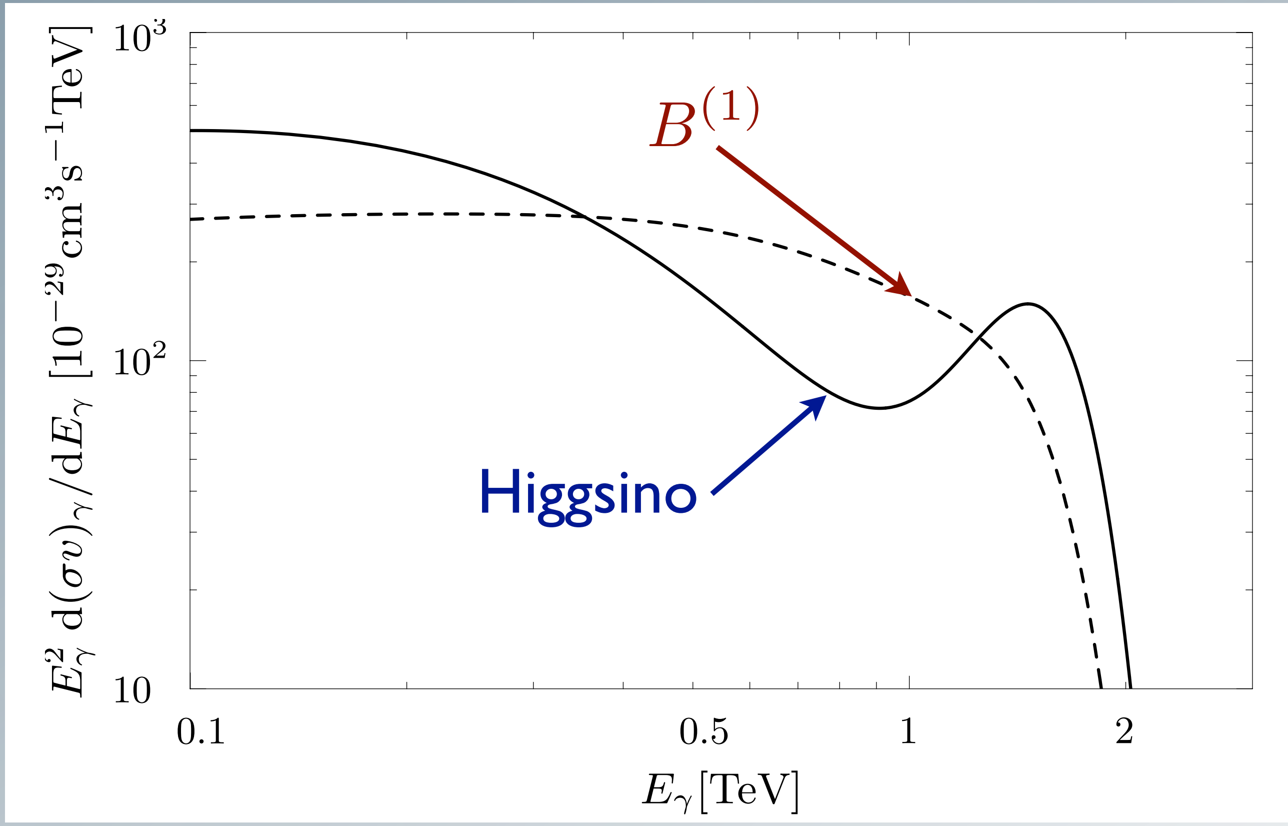
- (Very) pronounced cut-off at $E_\gamma = m_\chi$
- Further features at slightly lower energies
- Could be used to distinguish DM candidates!
  - Example: mSUGRA benchmarks (assume energy resolution of 10%)



TB, PoS '08

Comparing DM spectra

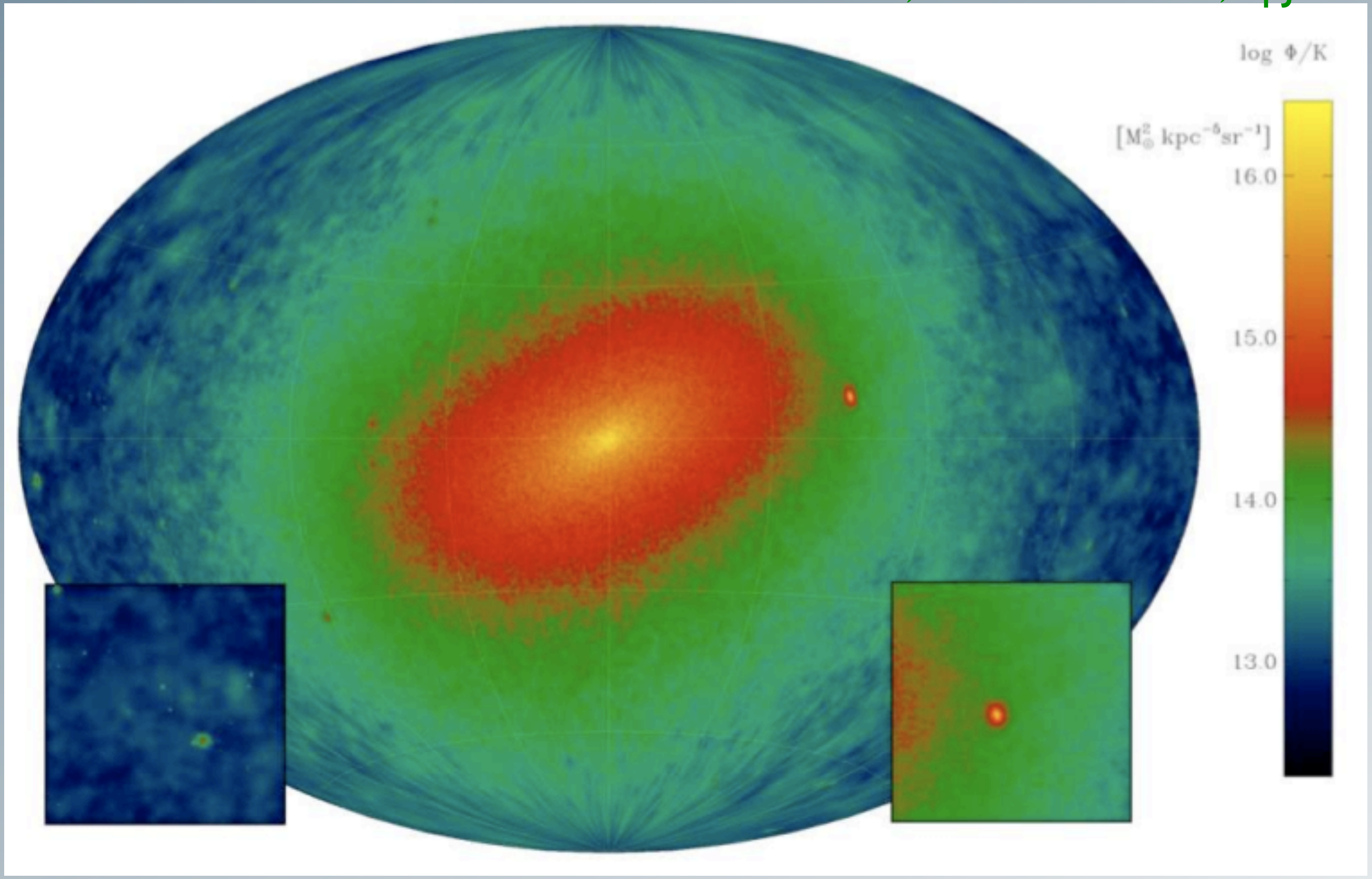
- (Very) pronounced cut-off at $E_\gamma = m_\chi$
- Further features at slightly lower energies
- Could be used to distinguish DM candidates!
  - Example: Higgsino vs KK-DM (about same mass; assume $\Delta E = 15\%$)



Bergström *et al.*, '06

Possible targets

Diemand, Kuhlen & Madau, ApJ '07



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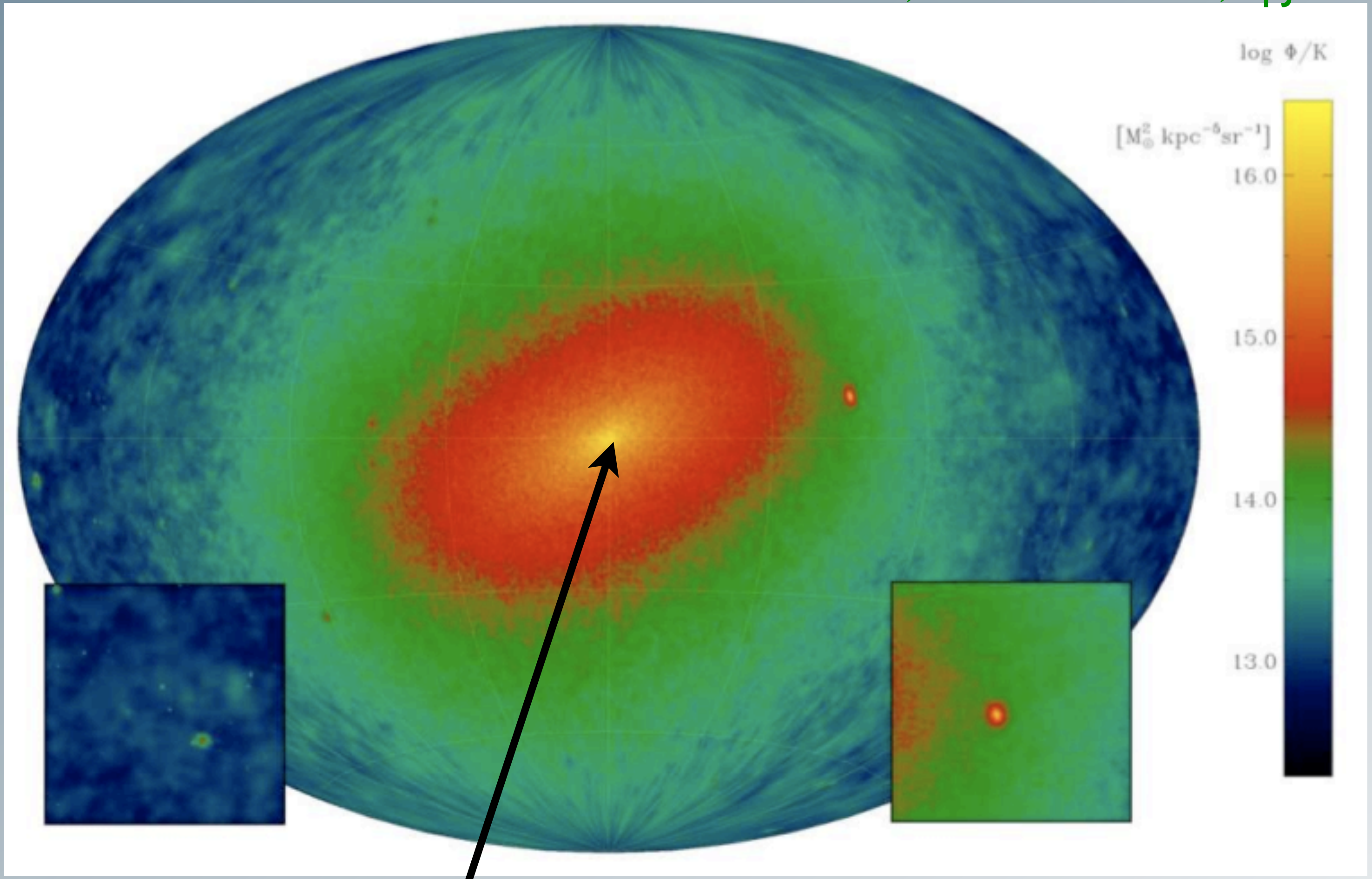

Galactic center

- brightest DM source in sky
- large background contributions

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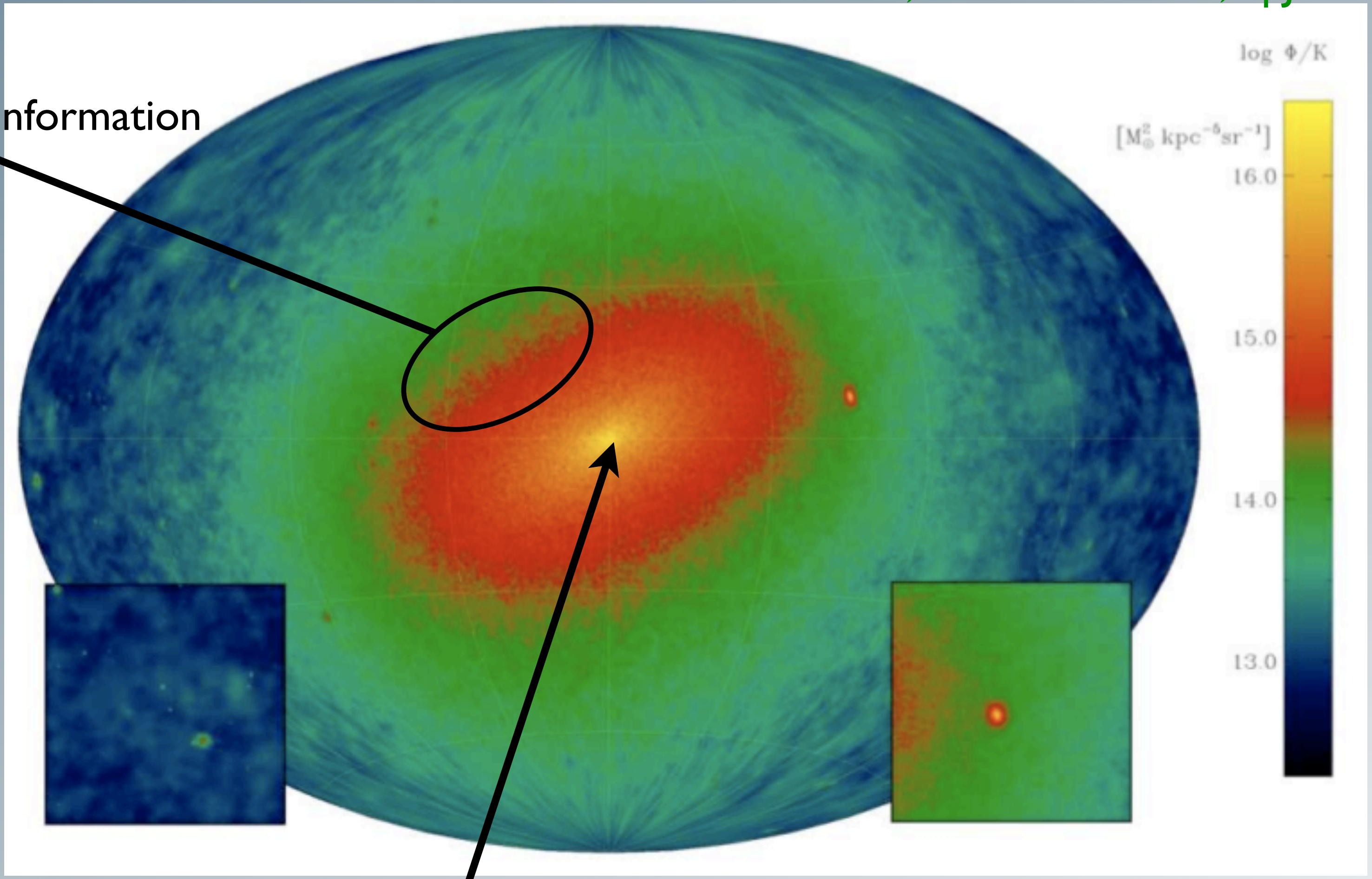

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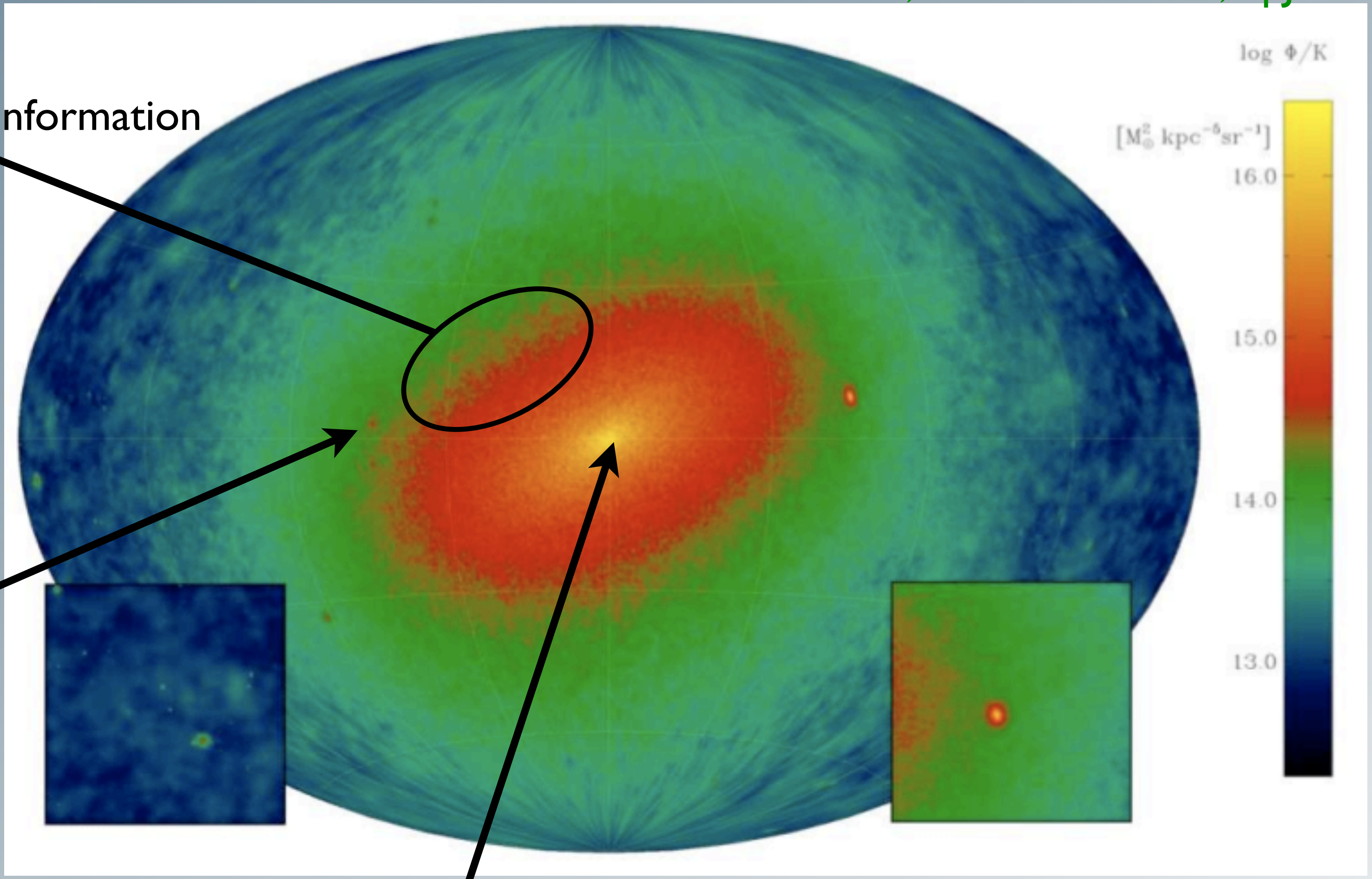

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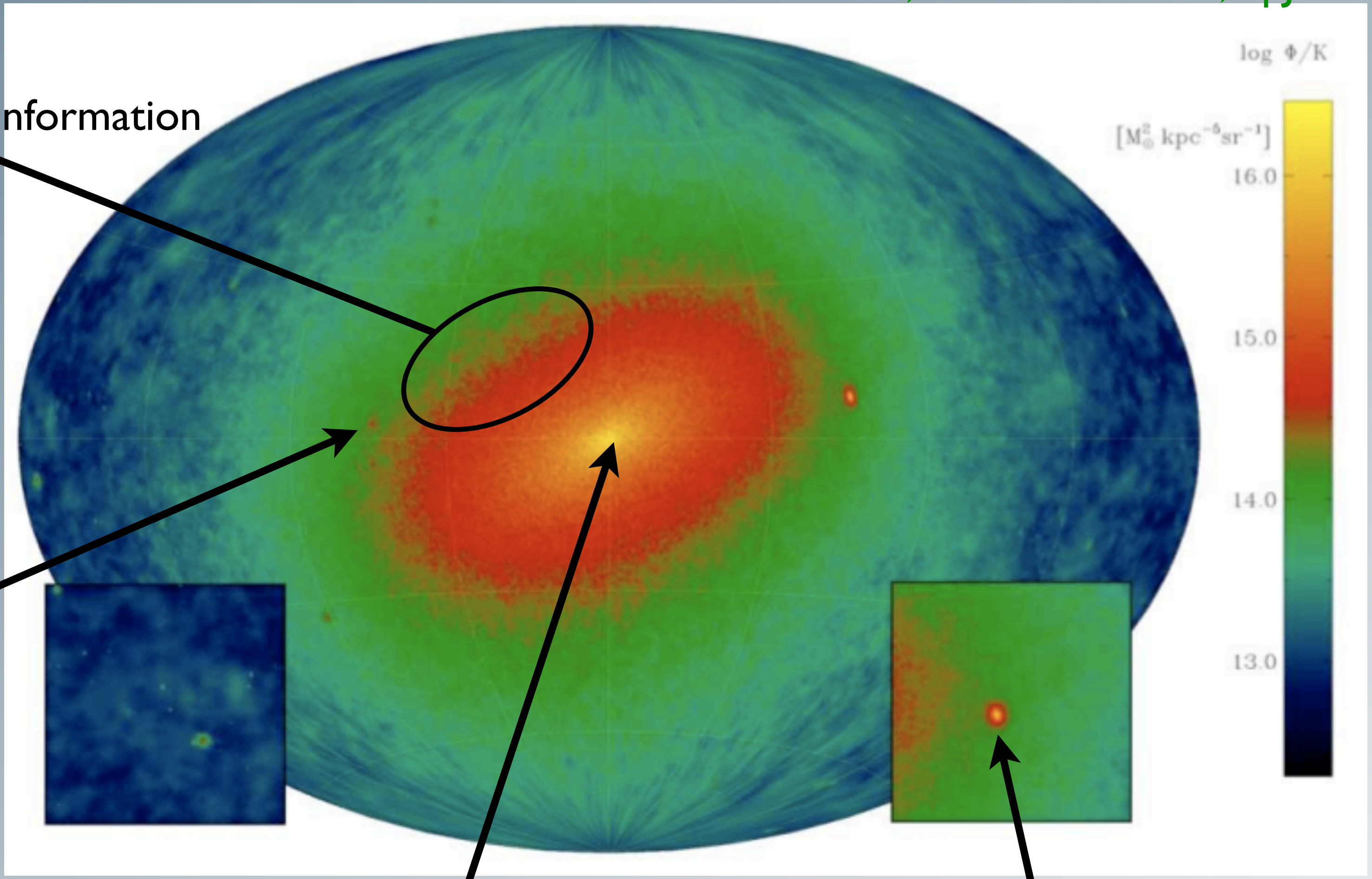

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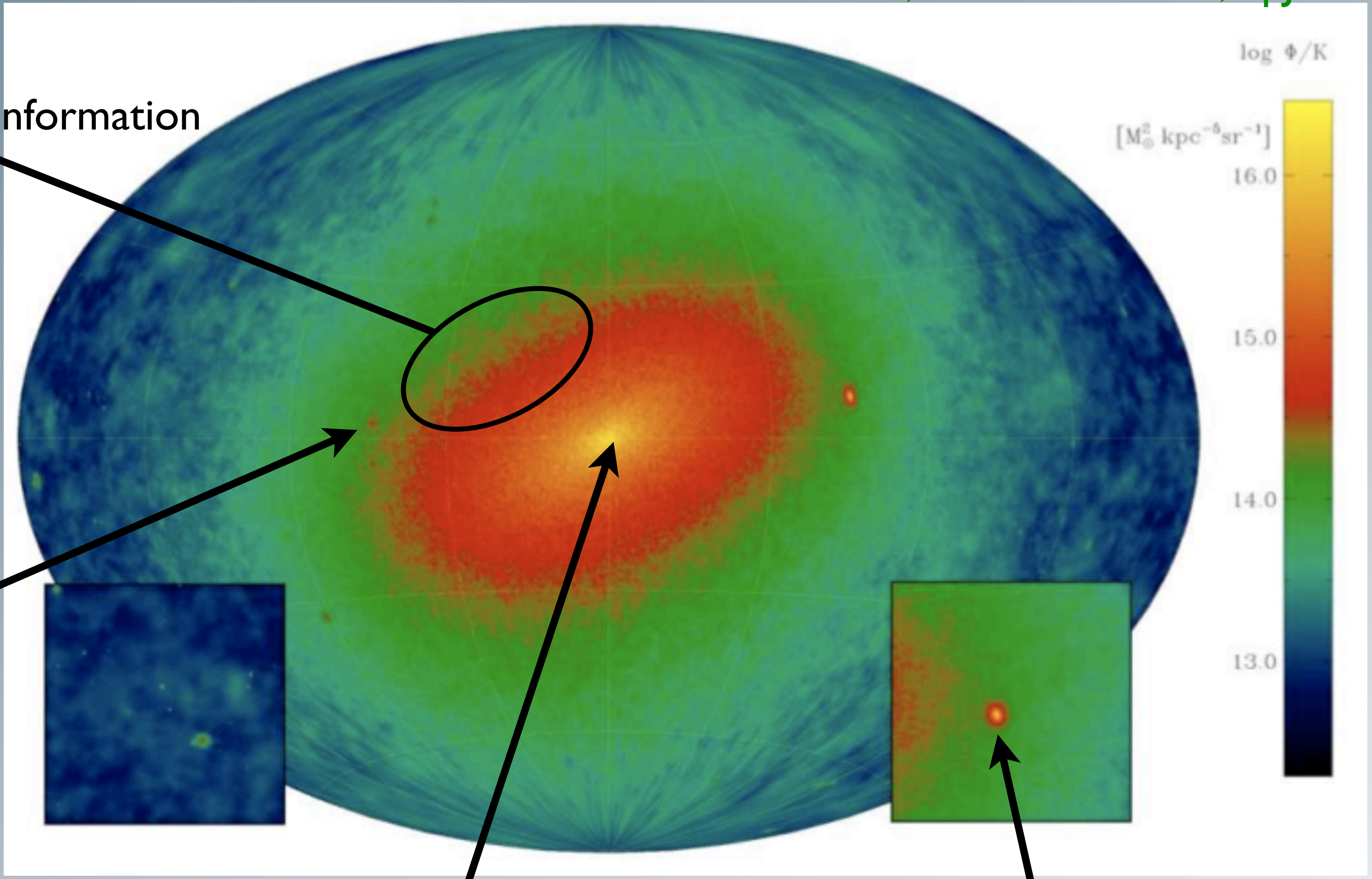

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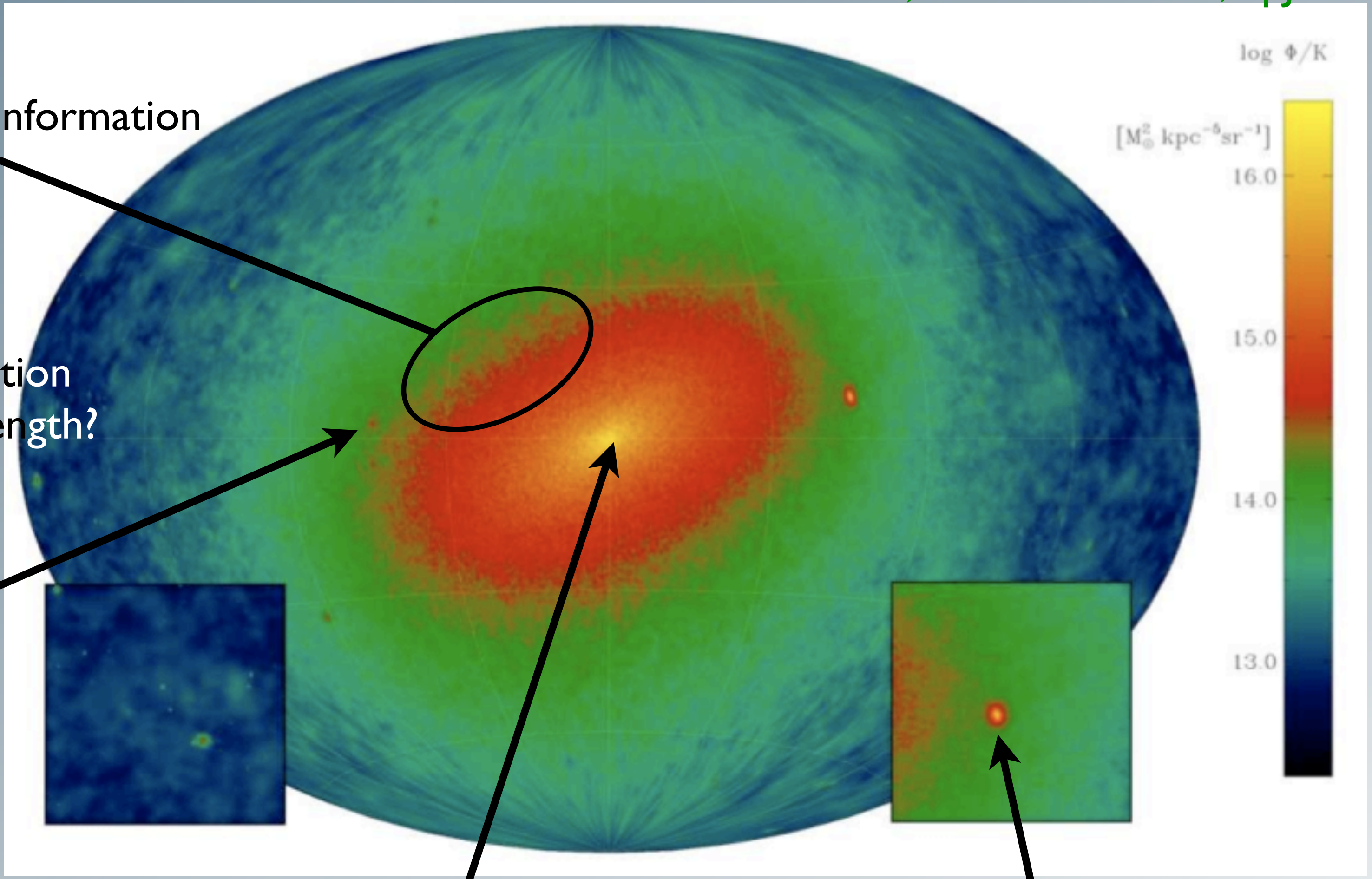

Galactic halo

- good statistics, angular information
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Galaxy clusters

- cosmic ray contamination
- better in multi-wavelength?
- substructure boost?

Dwarf Galaxies

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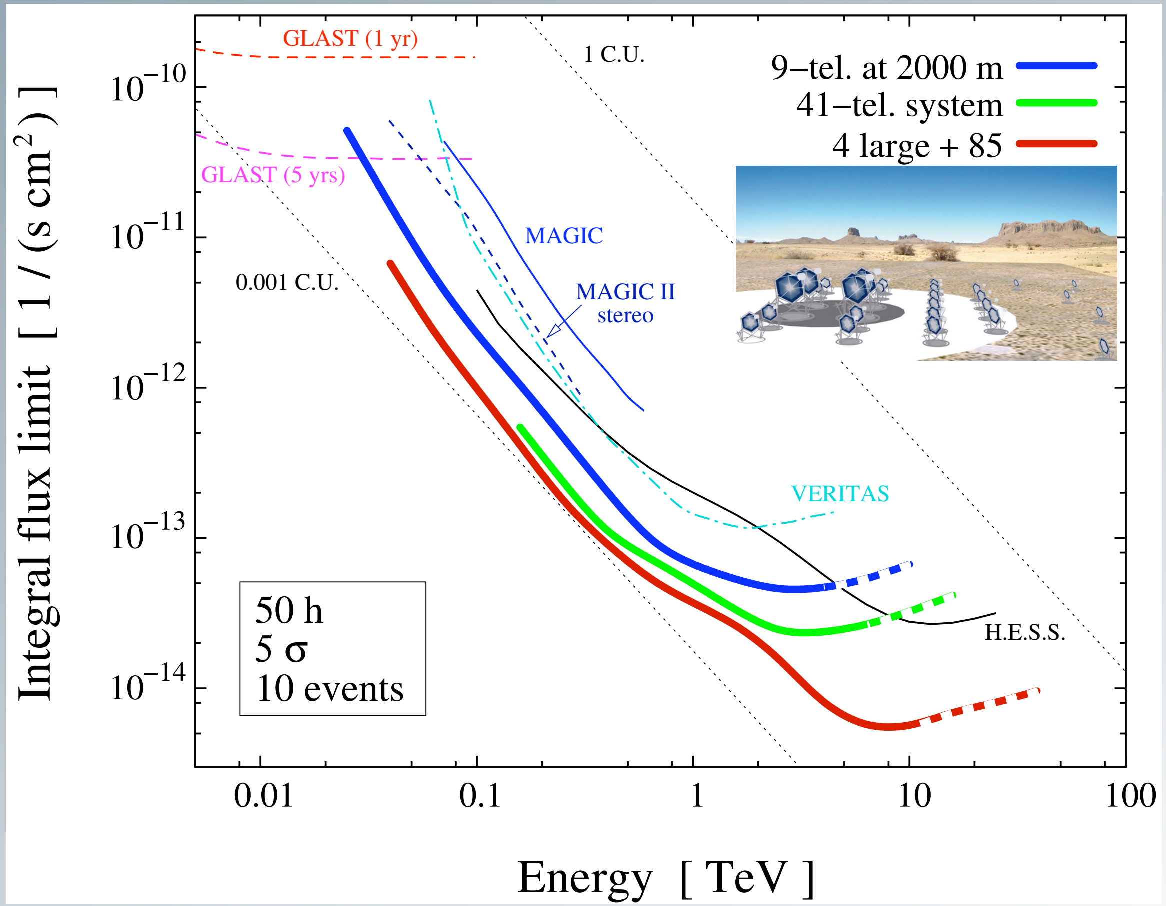
Sensitivities

Ground-based

- large eff. Area (~km^2)
- small field of view
- lower threshold $\gtrsim$ 20-50 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

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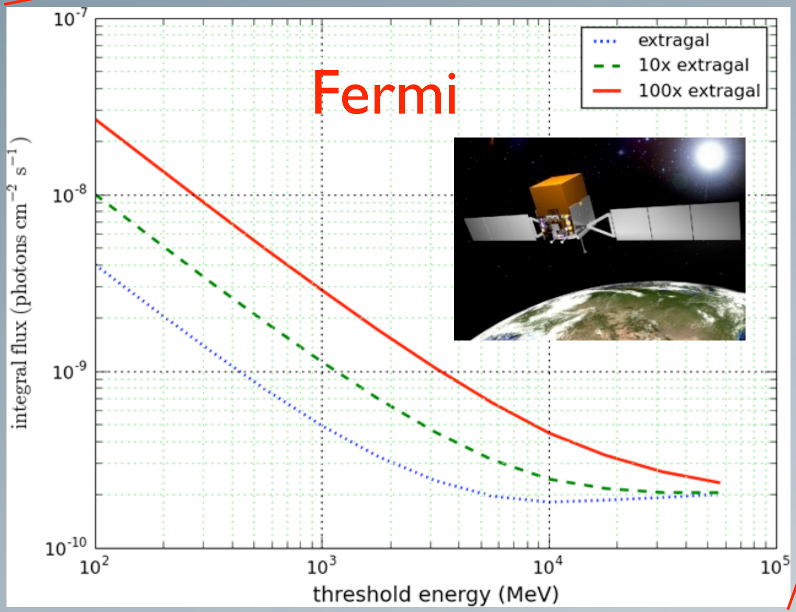
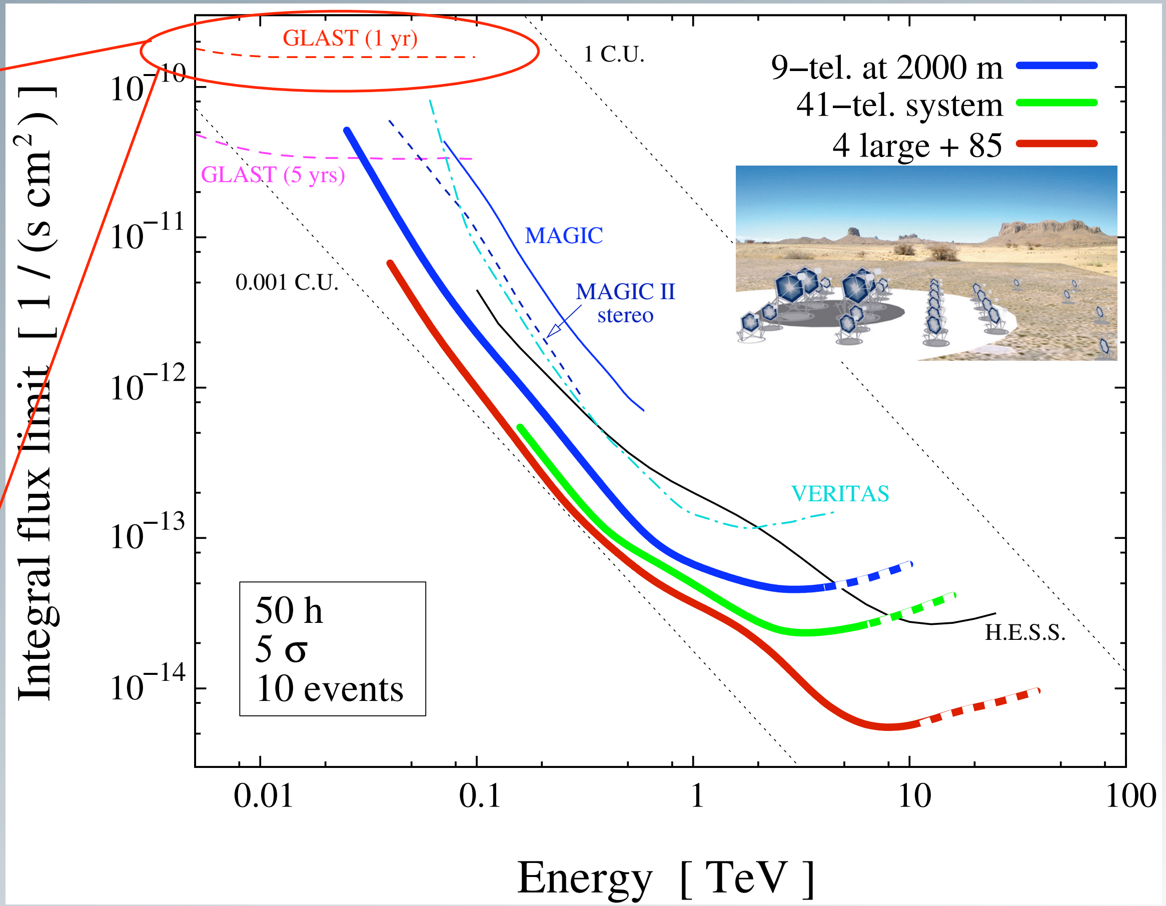


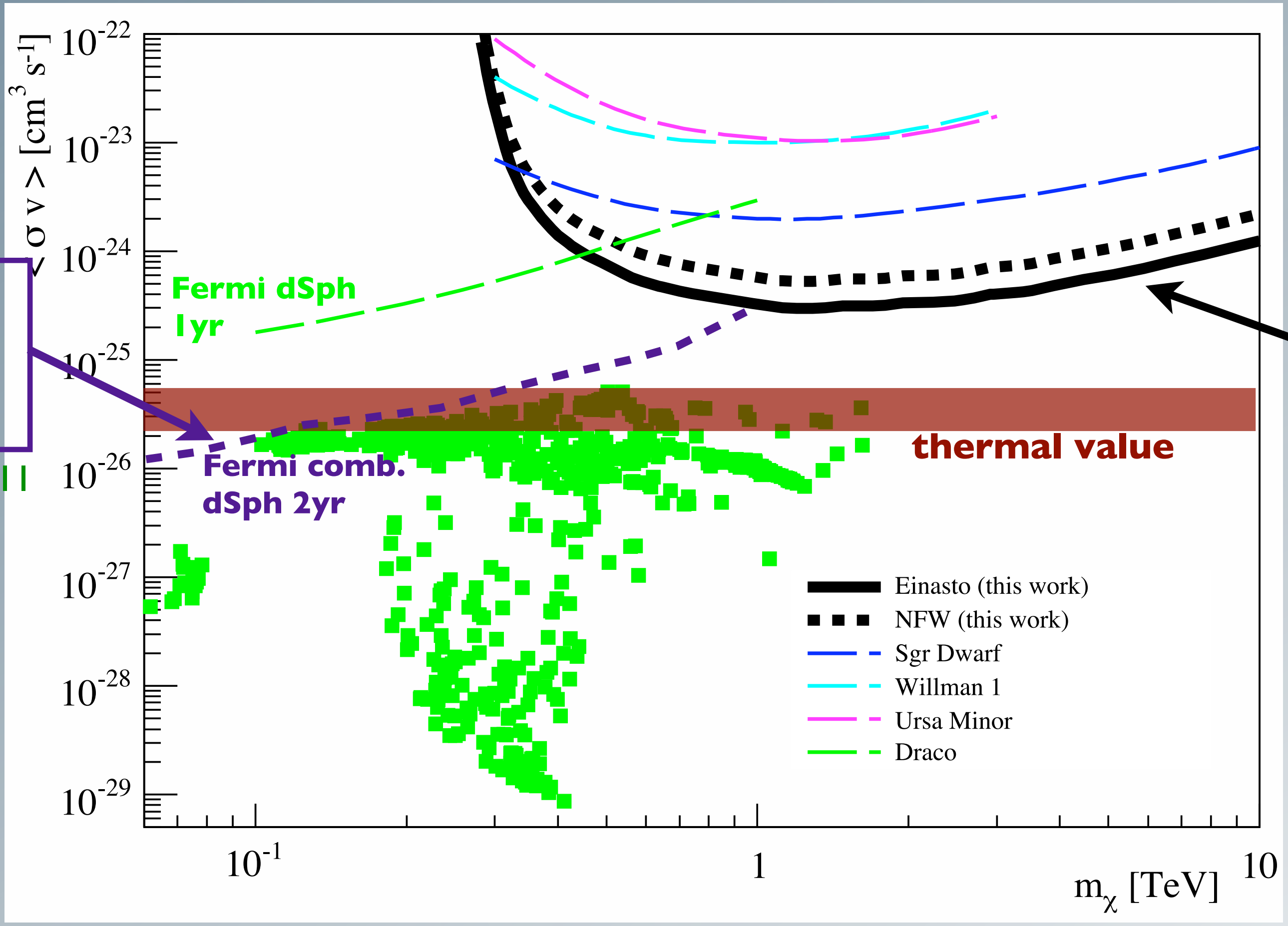
(from the LAT webpage)



Bernlöhr et al., '07

Constraints: current state

- Look for secondary photons from DM
  [typical assumption: 100% annihilation into $\bar{b}b$]



Dwarf galaxy observations by Fermi-LAT

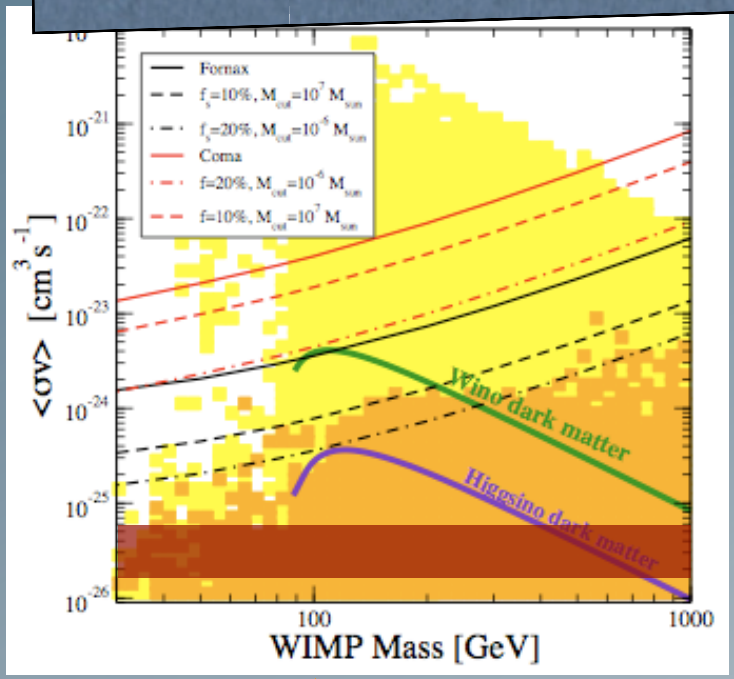
Ackermann *et al*, PRL '11

Galactic center observations with HESS

Abramowski *et al*, PRL '11

⇨ Indirect searches start to be very competitive!

Galaxy clusters & diff. BG

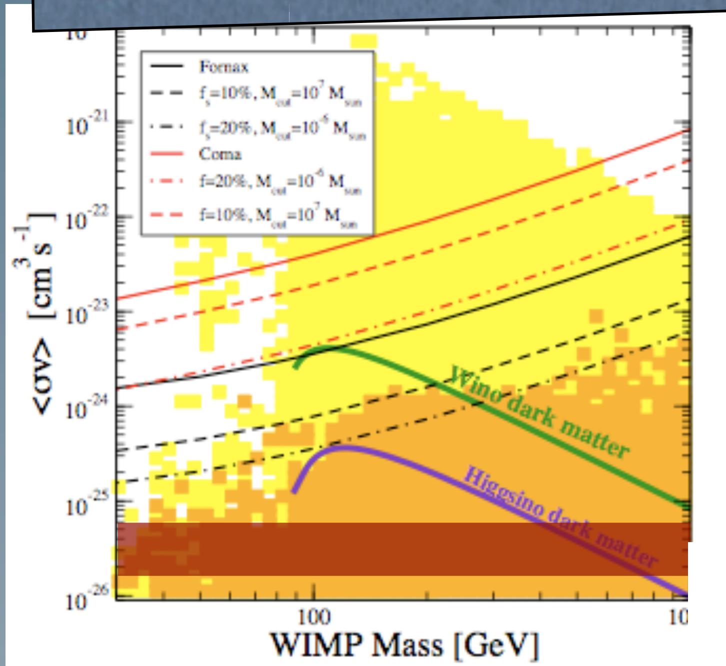


Almost as constraining:
galaxy clusters

(NB: much better **discovery potential**!)

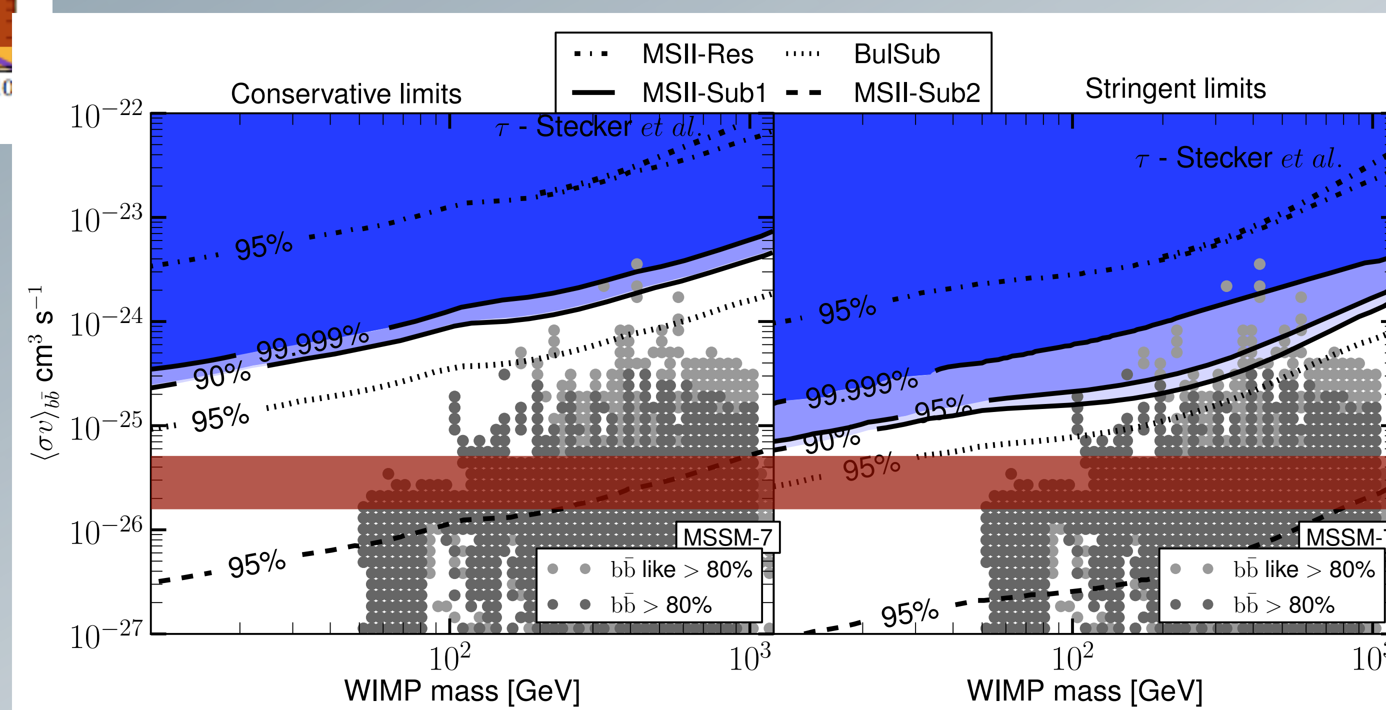
Ackermann *et al*, JCAP '10 [Fermi-LAT collaboration]

Galaxy clusters & diff. BG



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

Abdo *et al*, JCAP '10 [Fermi-LAT collaboration]



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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)

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

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

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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 $\mathcal{P}(k)$:

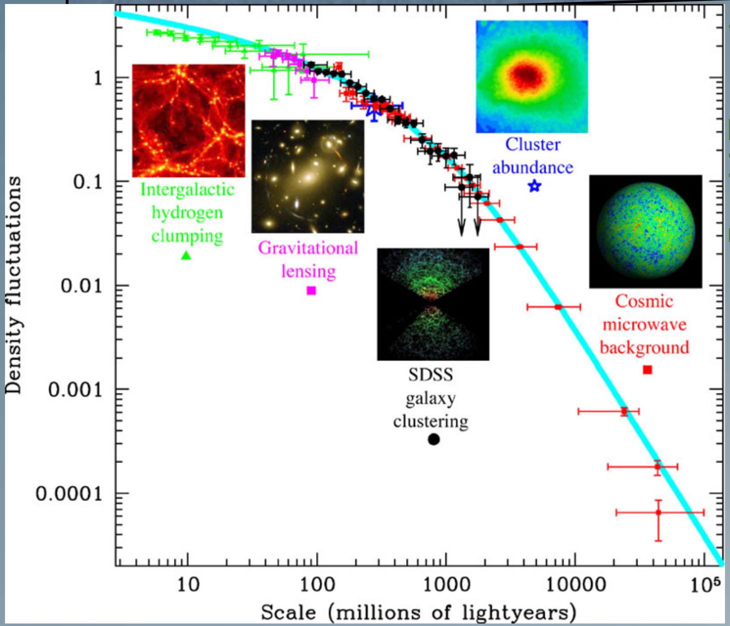

Fig.: M. Tegmark

- Primordial (linear) power spectrum well measured at ‘large‘ scales

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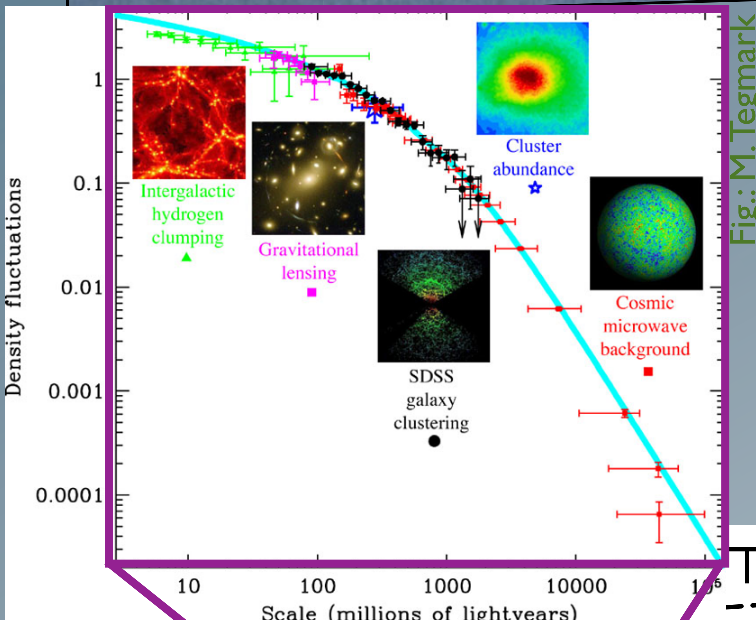
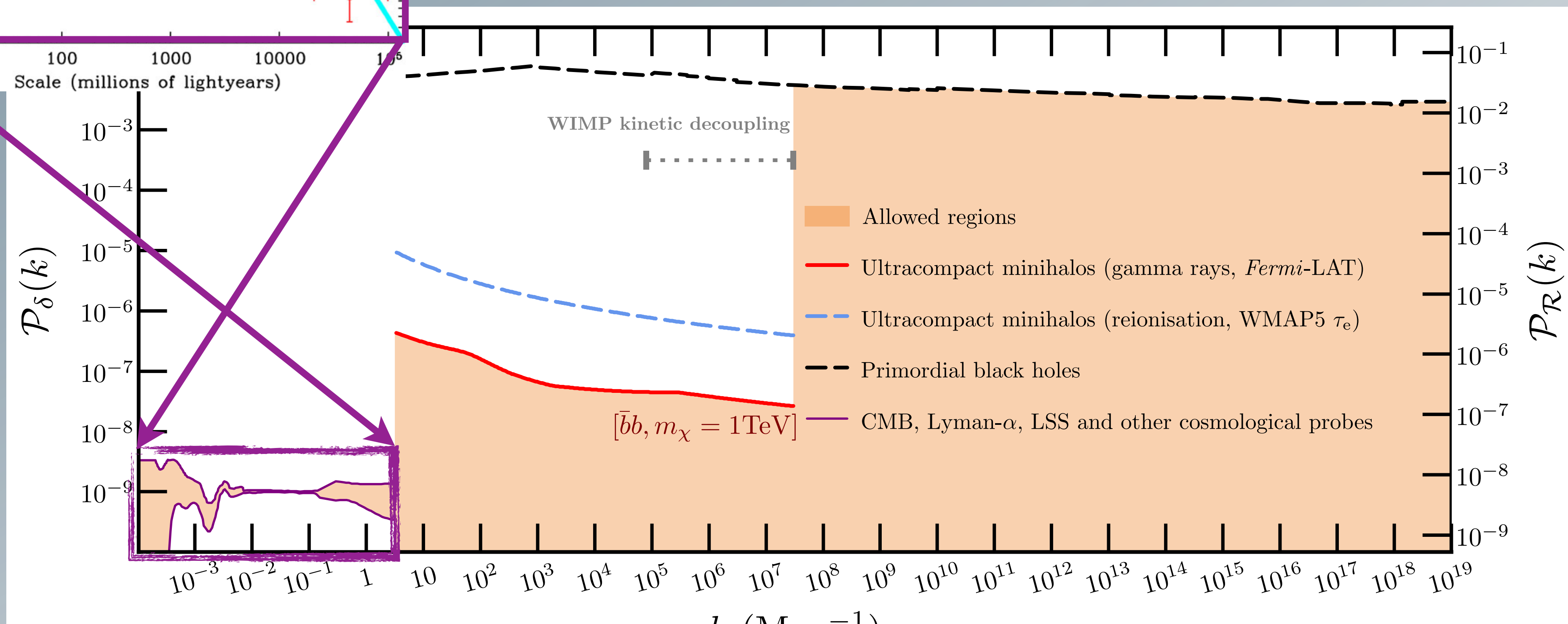


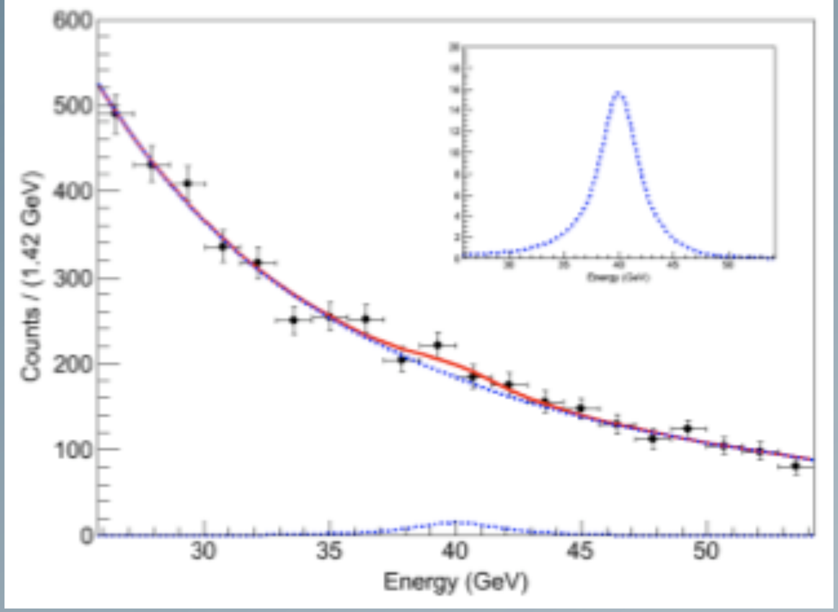
- Primordial (linear) power spectrum well measured at 'large' scales
- Below ~Mpc scales, only upper bounds available...



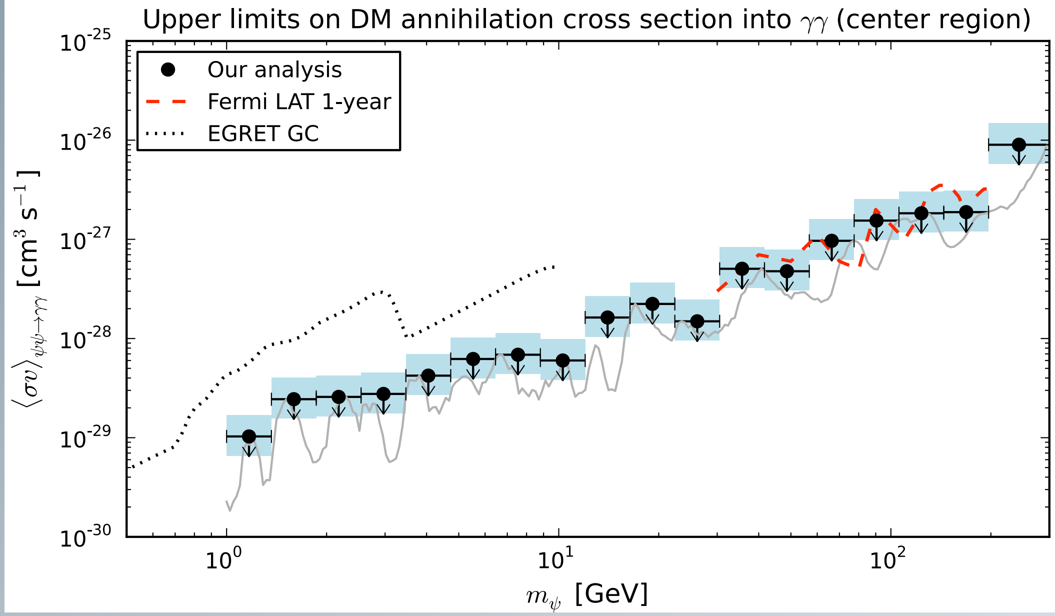
TB, Scott & Akrami, PRD '12

Line signals (before 03/2012)

- Fermi all-sky search for line signals:



Abdo *et al*, PRL '10



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*, PRD '12

IB features with Fermi?

TB, Huang, Ibarra, Vogl & Weniger, JCAP '12

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

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

~MSSM:

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

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

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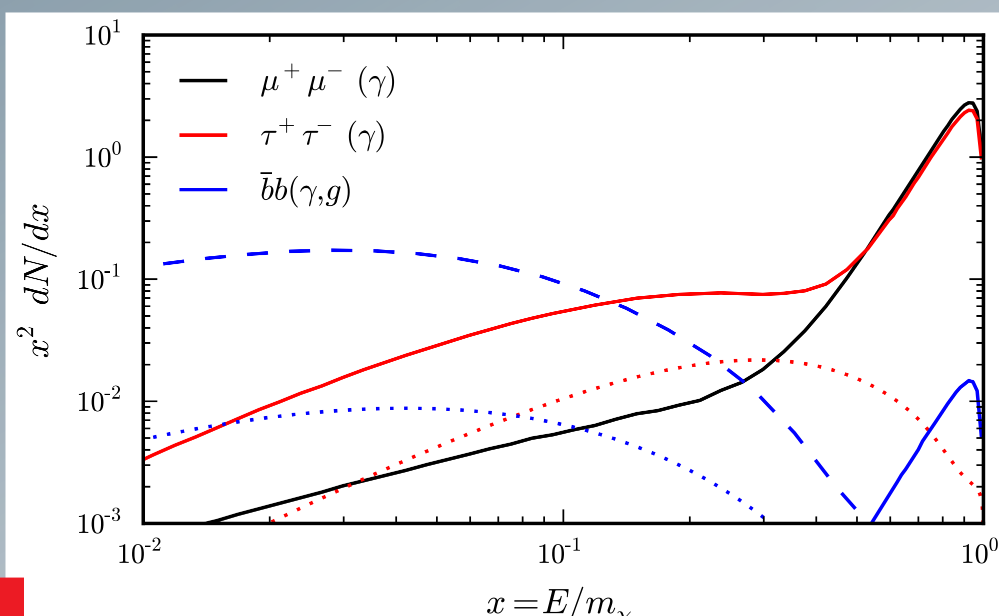

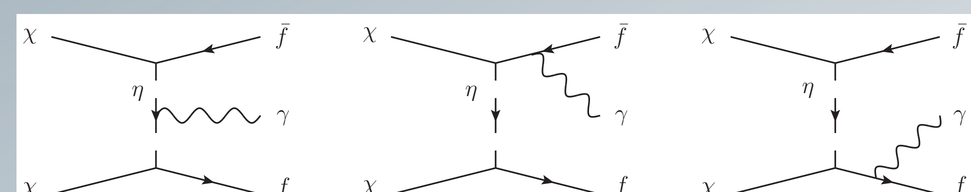

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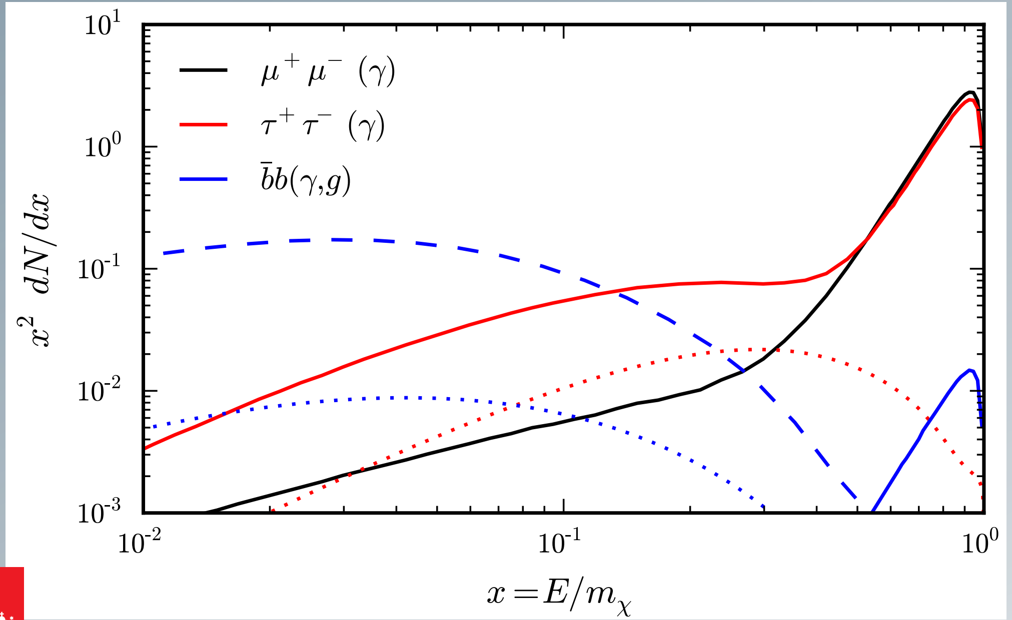

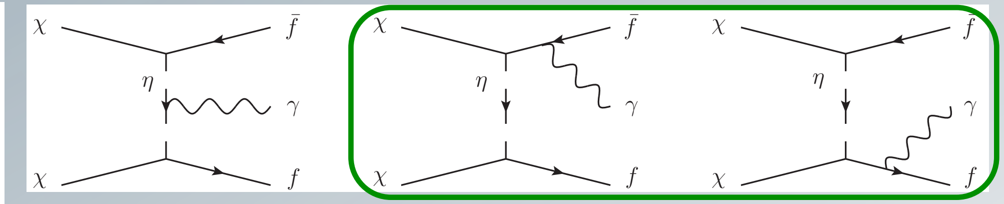

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dotted: 2-body + FSR

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

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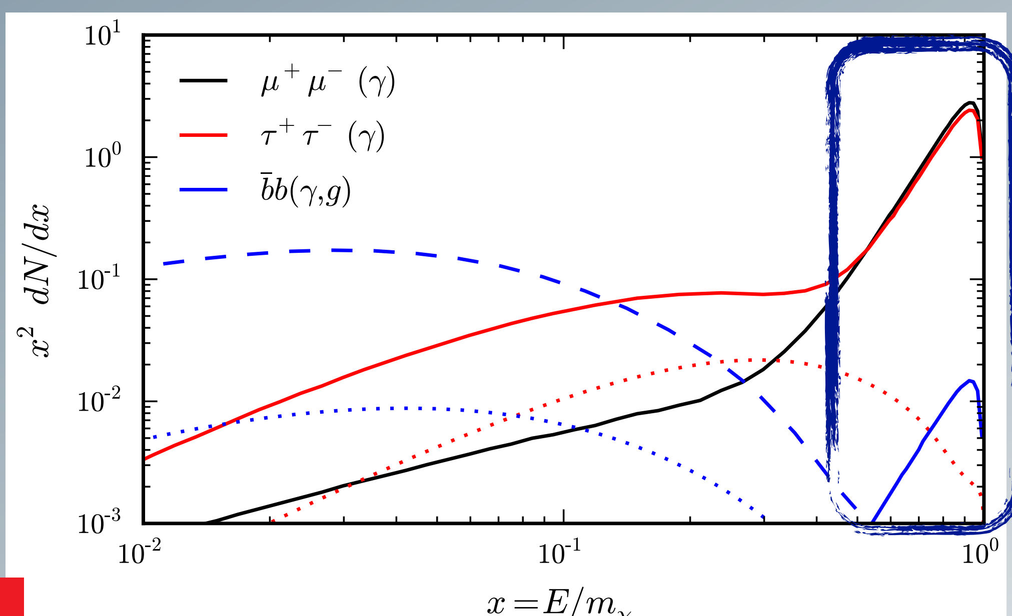

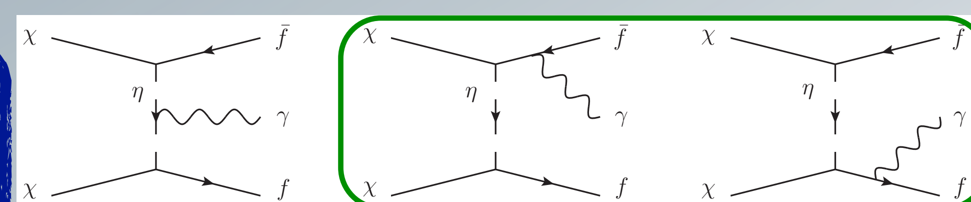

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focus on this part!

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
  - ...

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  - exclude galactic plane
  - ...
- New idea: data-driven approach to optimize ROI
  - 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:

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

signal

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

target region (ROI)

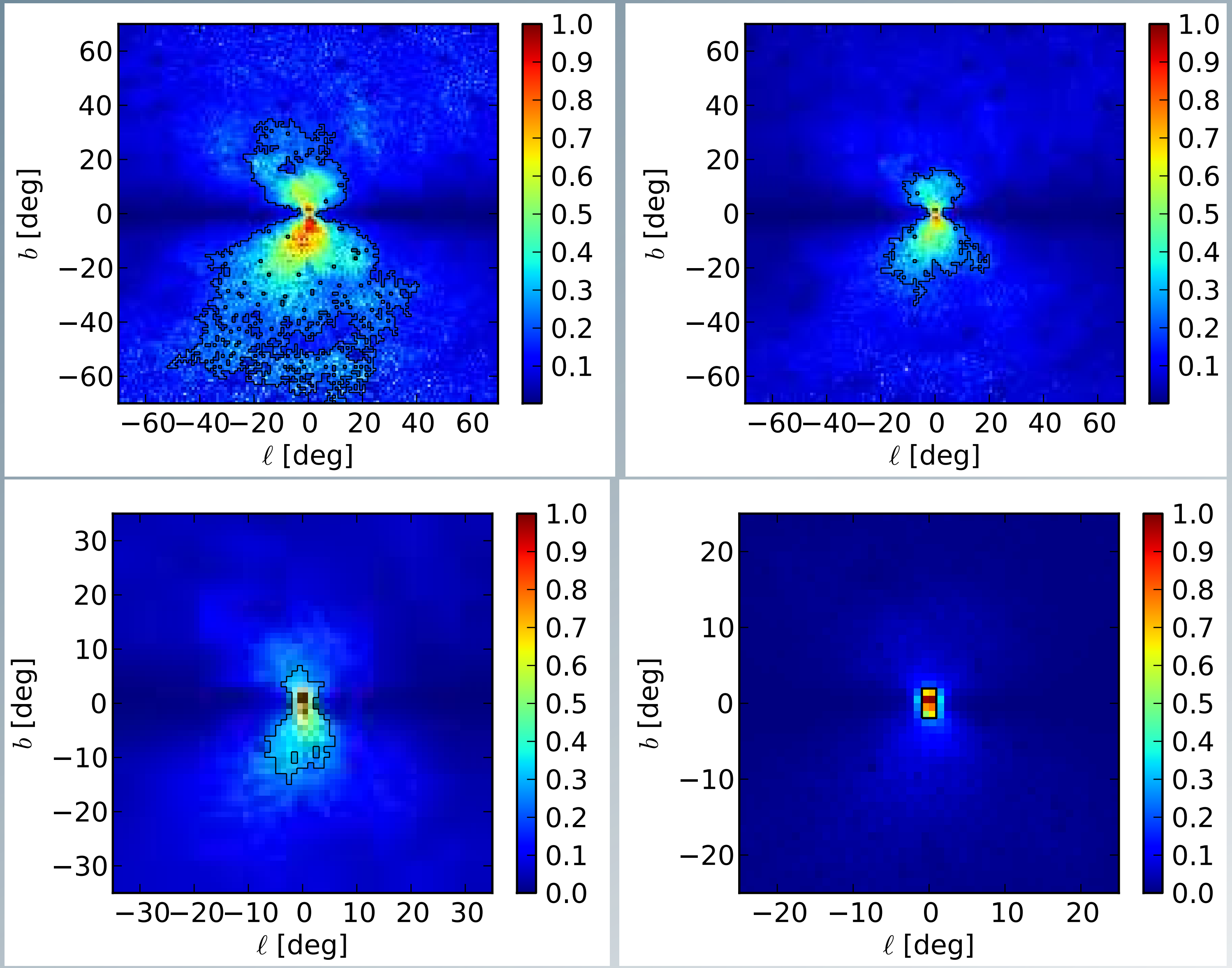
Optimal target regions

TB, Huang, Ibarra, Vogl & Weniger, JCAP '12

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

'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!

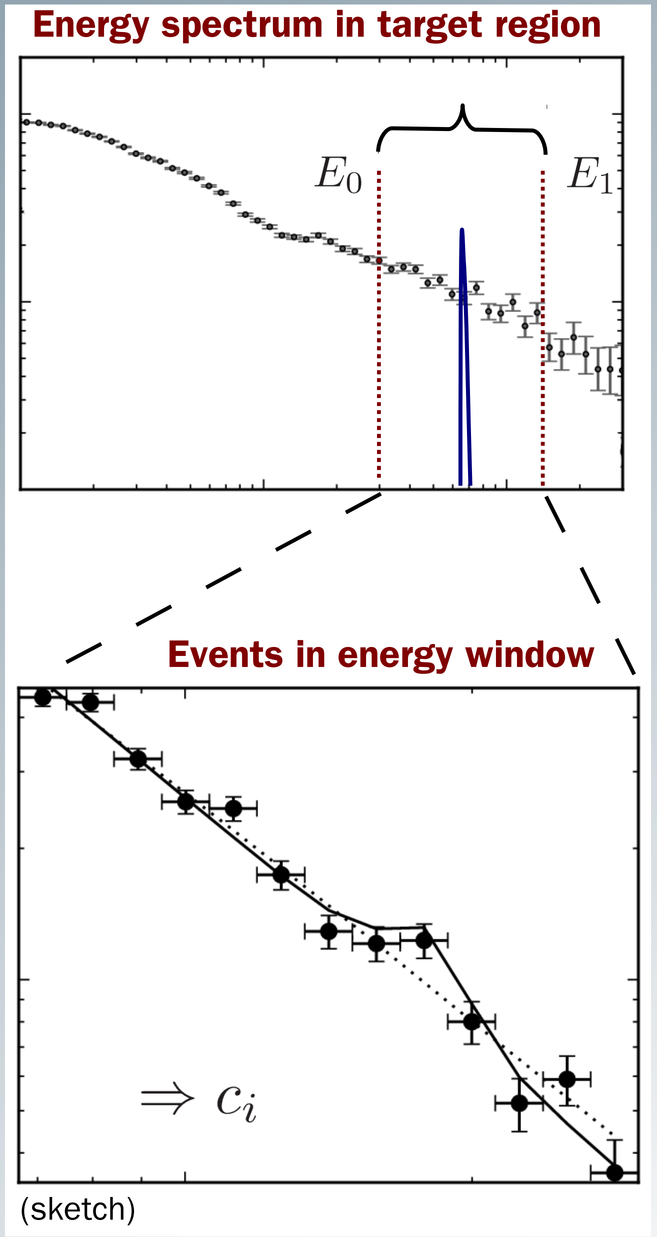


Fig.: C. Weniger

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

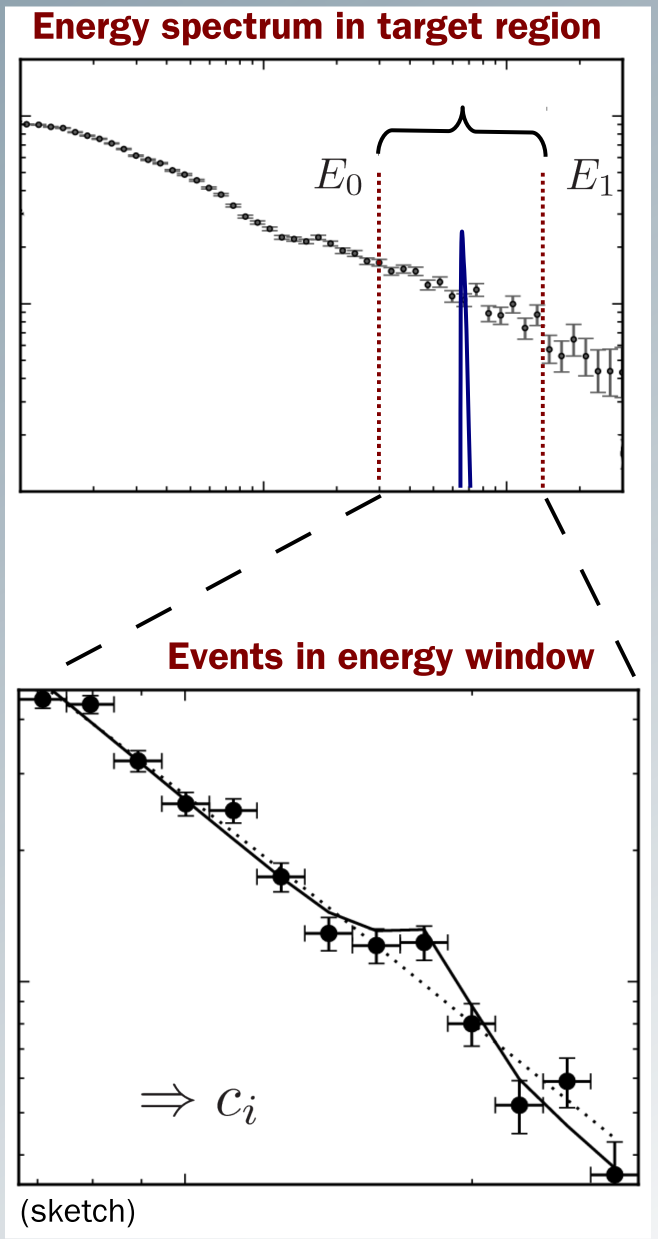

Fig.: C. Weniger

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- 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

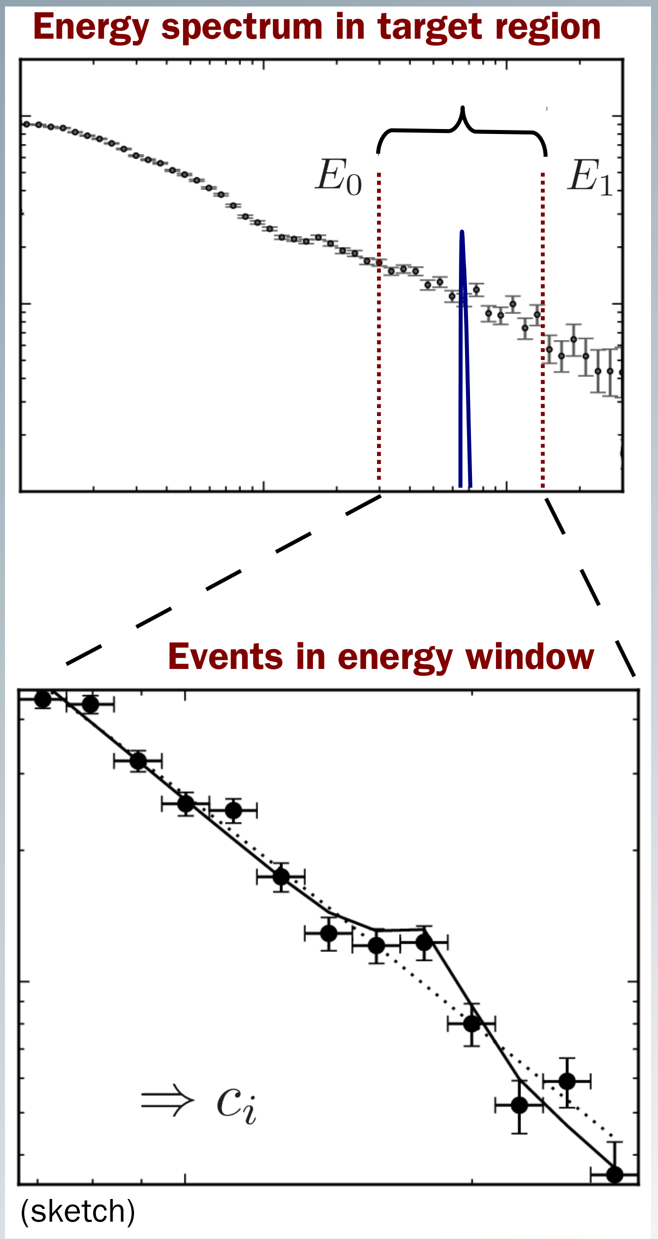


Fig.: C. Weniger

Likelihood analysis

- ‘binned’ likelihood
  - NB: bin size $\ll$ energy resolution $\rightsquigarrow$ same as un-binned analysis!

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

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 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 $S \overset{!}{=} 0$

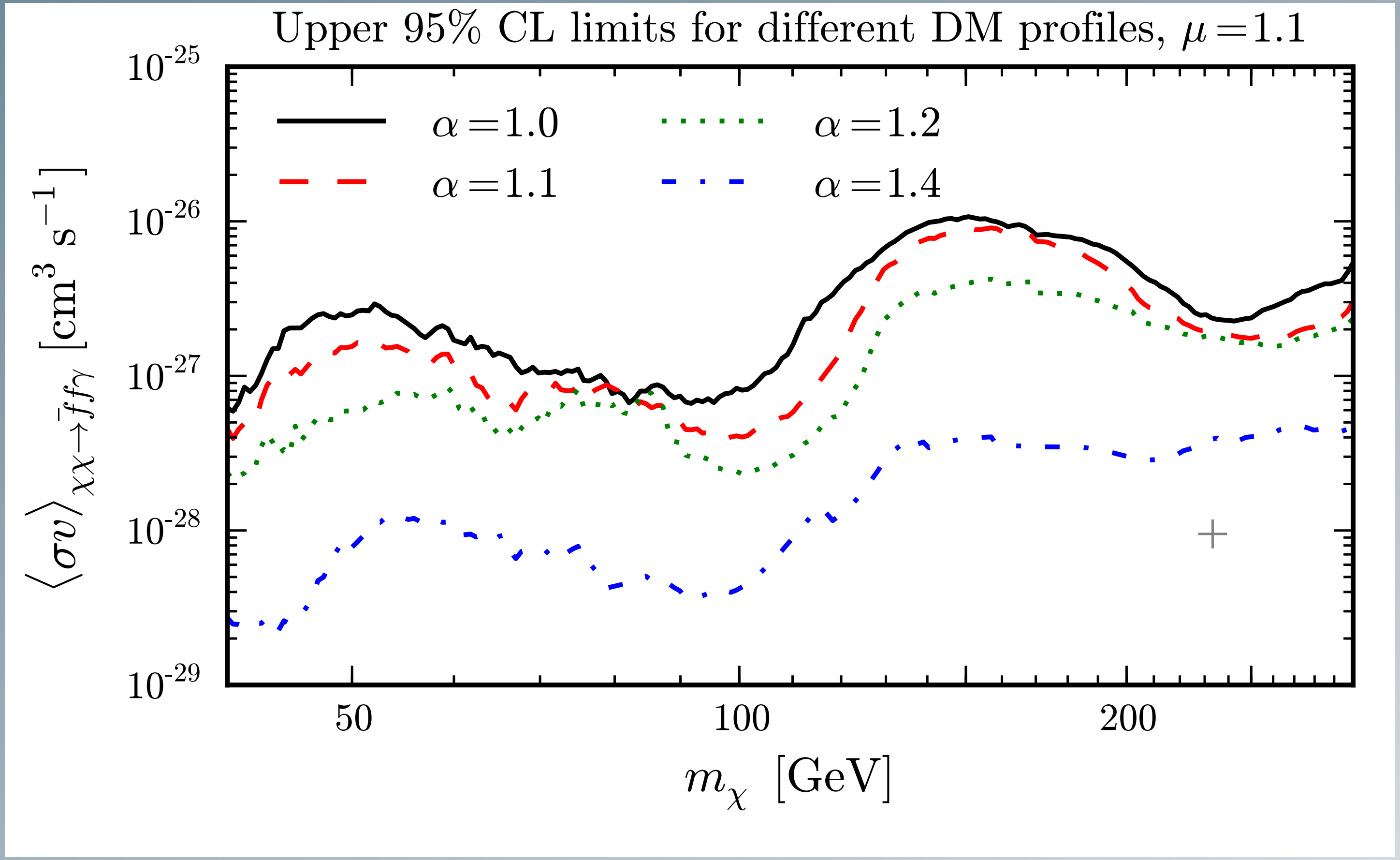
best fit with $S \geq 0$

➪ 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)

IB limits from Fermi-LAT

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!
  [NB: prospects also excellent for IACTs: (TB, Calore, Vertongen & Weniger, PRD '10)]

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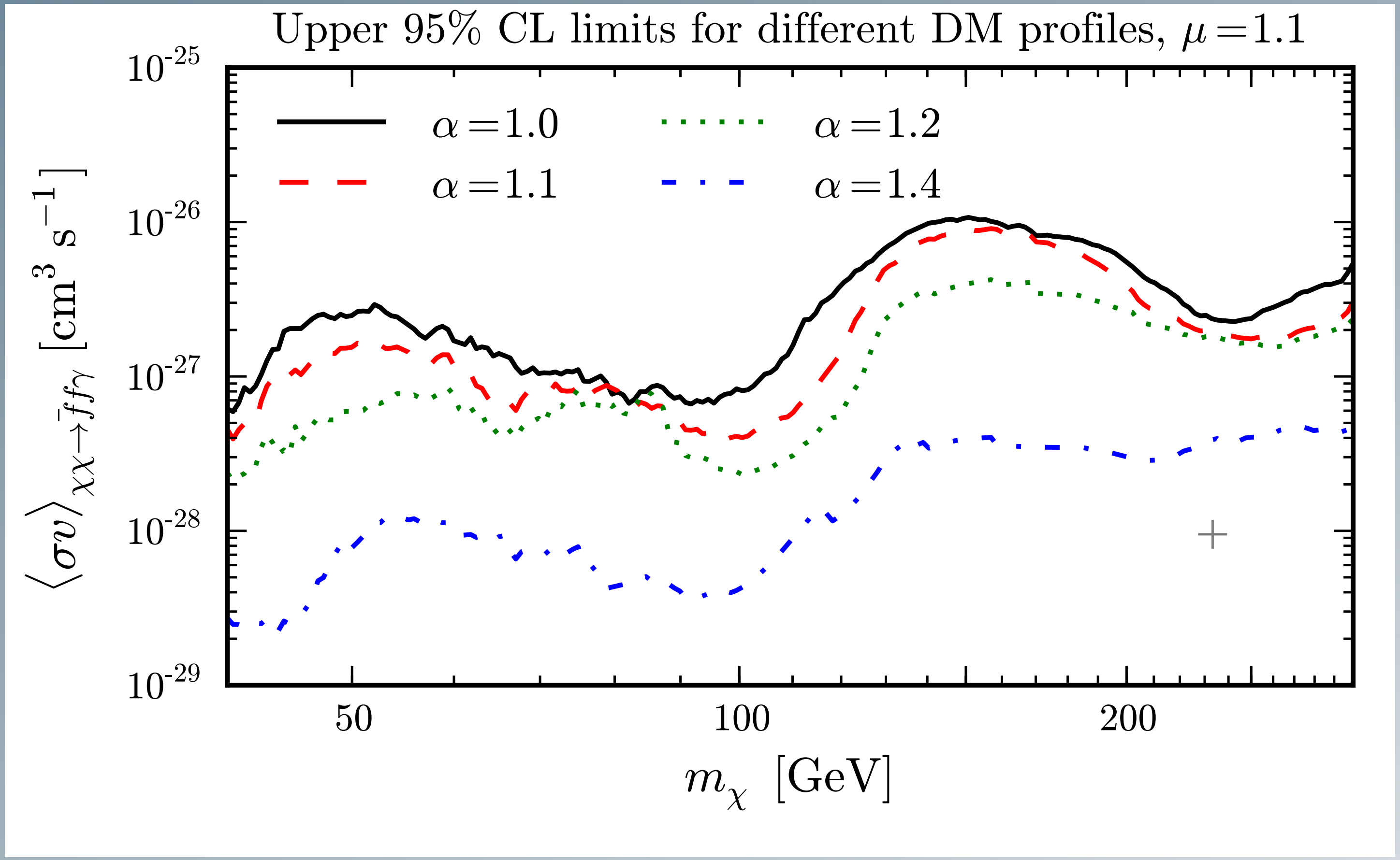

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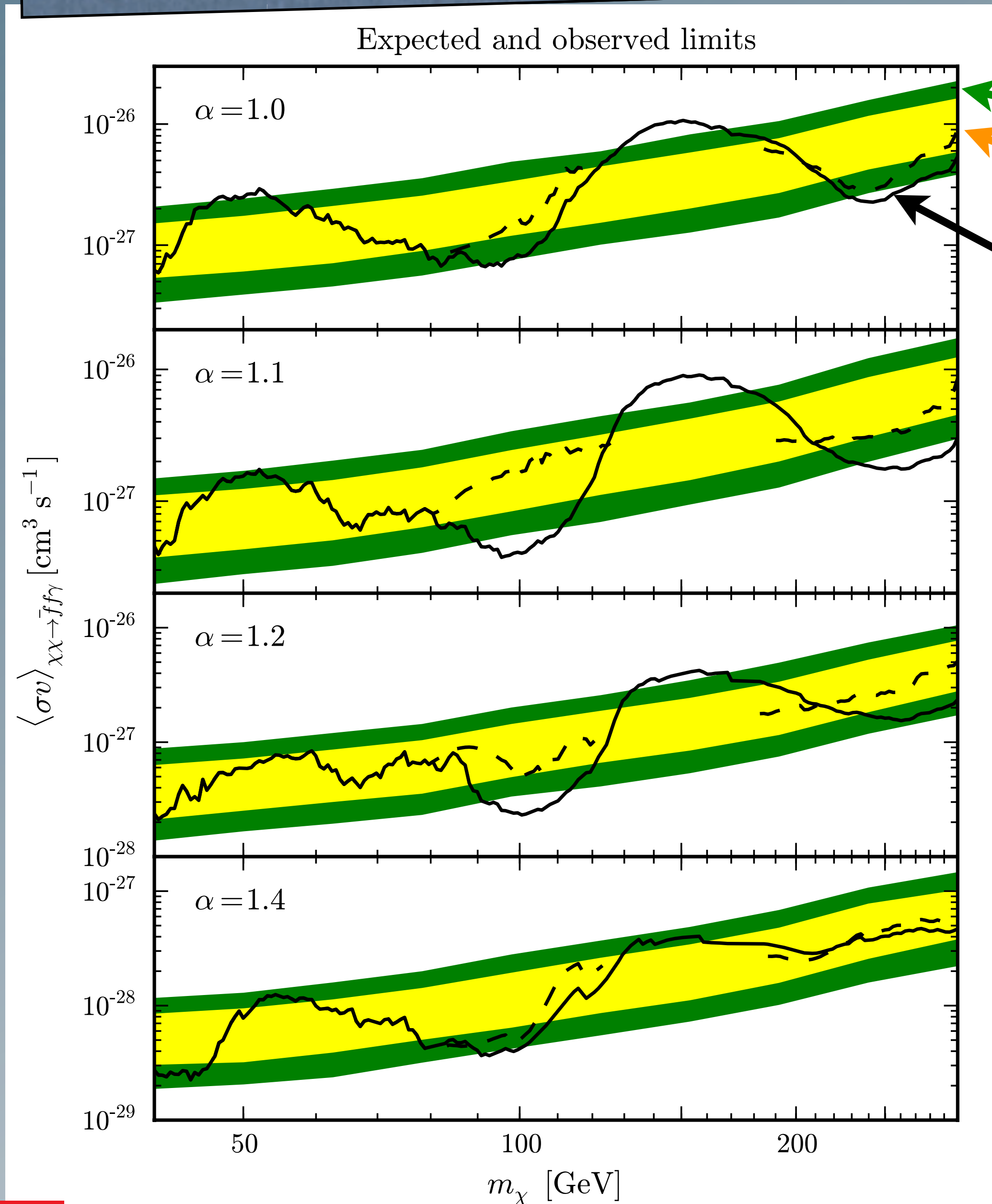
- now let's compare this to the limits one should expect...
  (to do so, generate large number of mock data sets from null model)

Expected vs observed limits

TB, Huang, Ibarra, Vogl & Weniger, JCAP ’12



expected limits (95% CL)

expected limits (68% CL)

observed limits

(dashed: excluding data from 115 to 145 GeV)

95% CL upper limits

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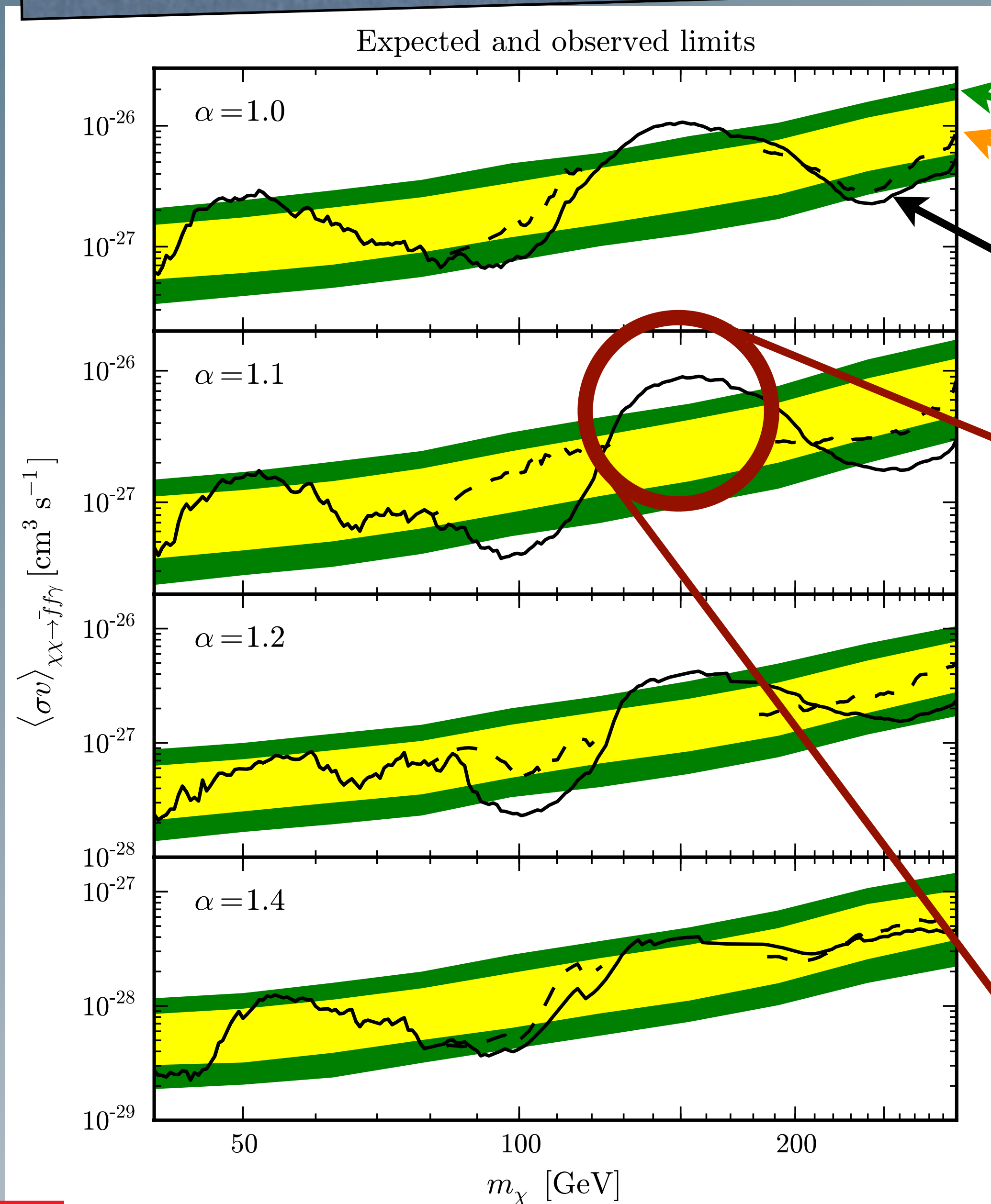

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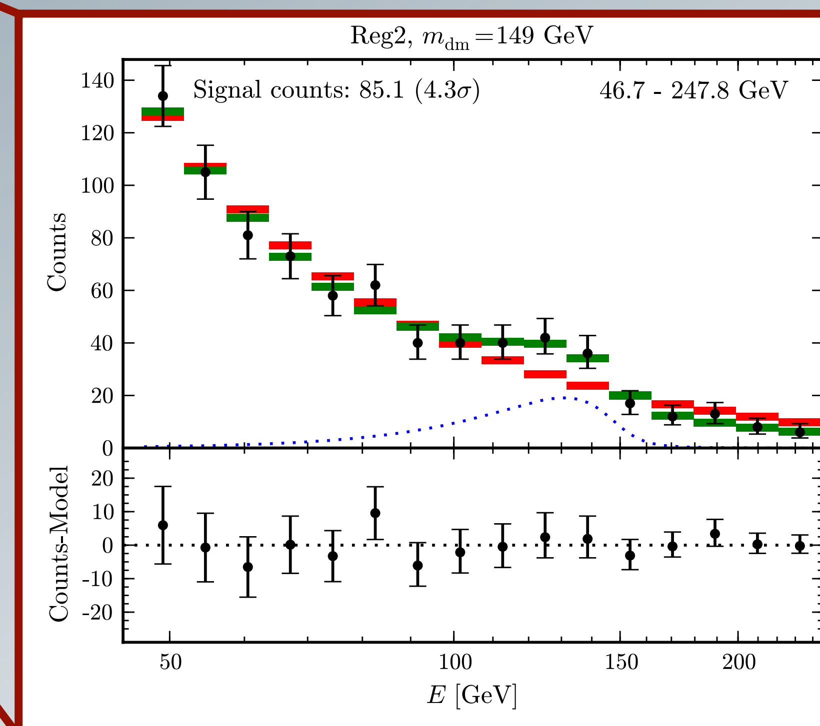
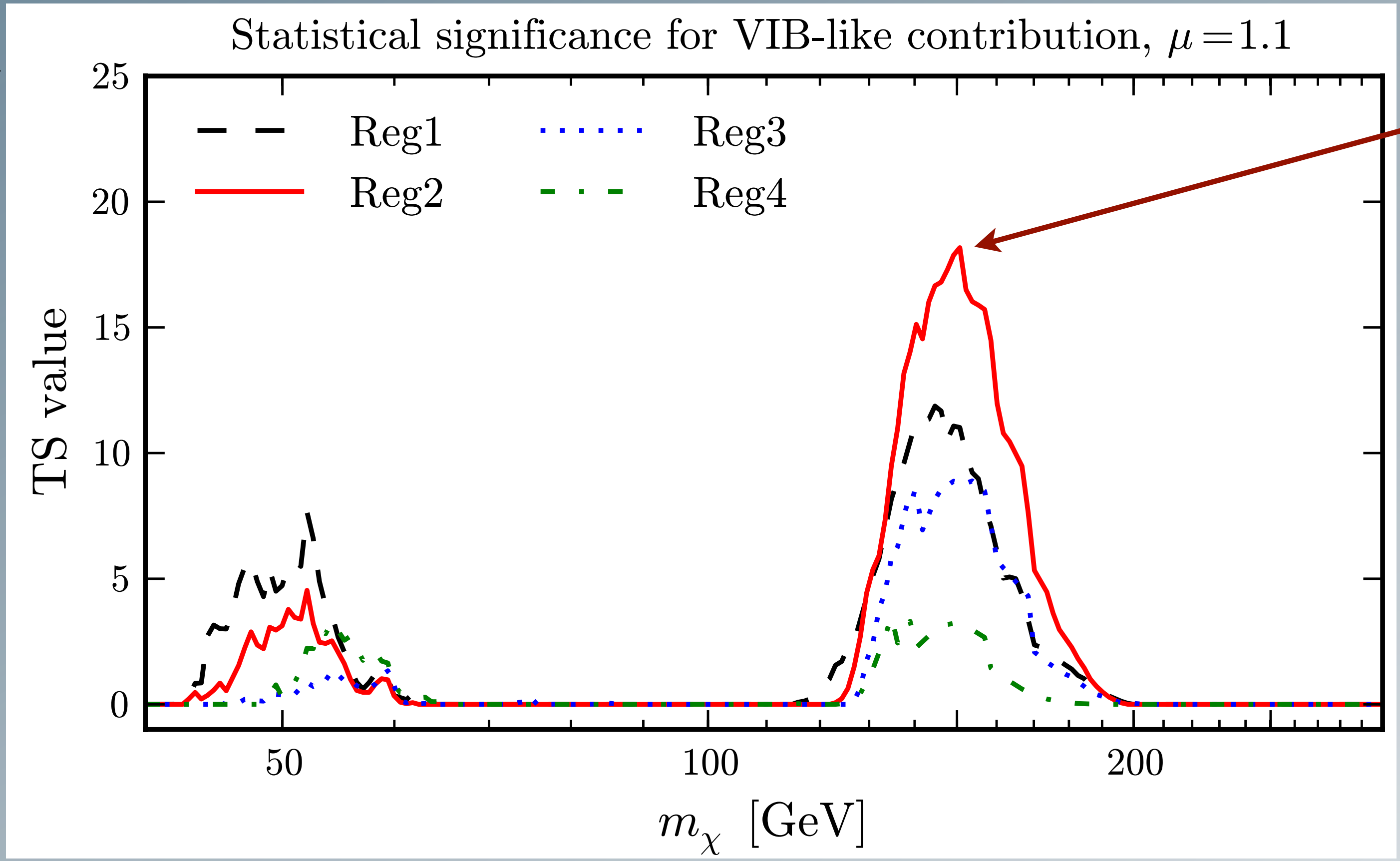


95% CL upper limits

A tentative signal!

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

Reg2: $\alpha = 1.1$



peak value nominally corresponds to signal significance of 4.3σ

- Best-fit values:

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

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

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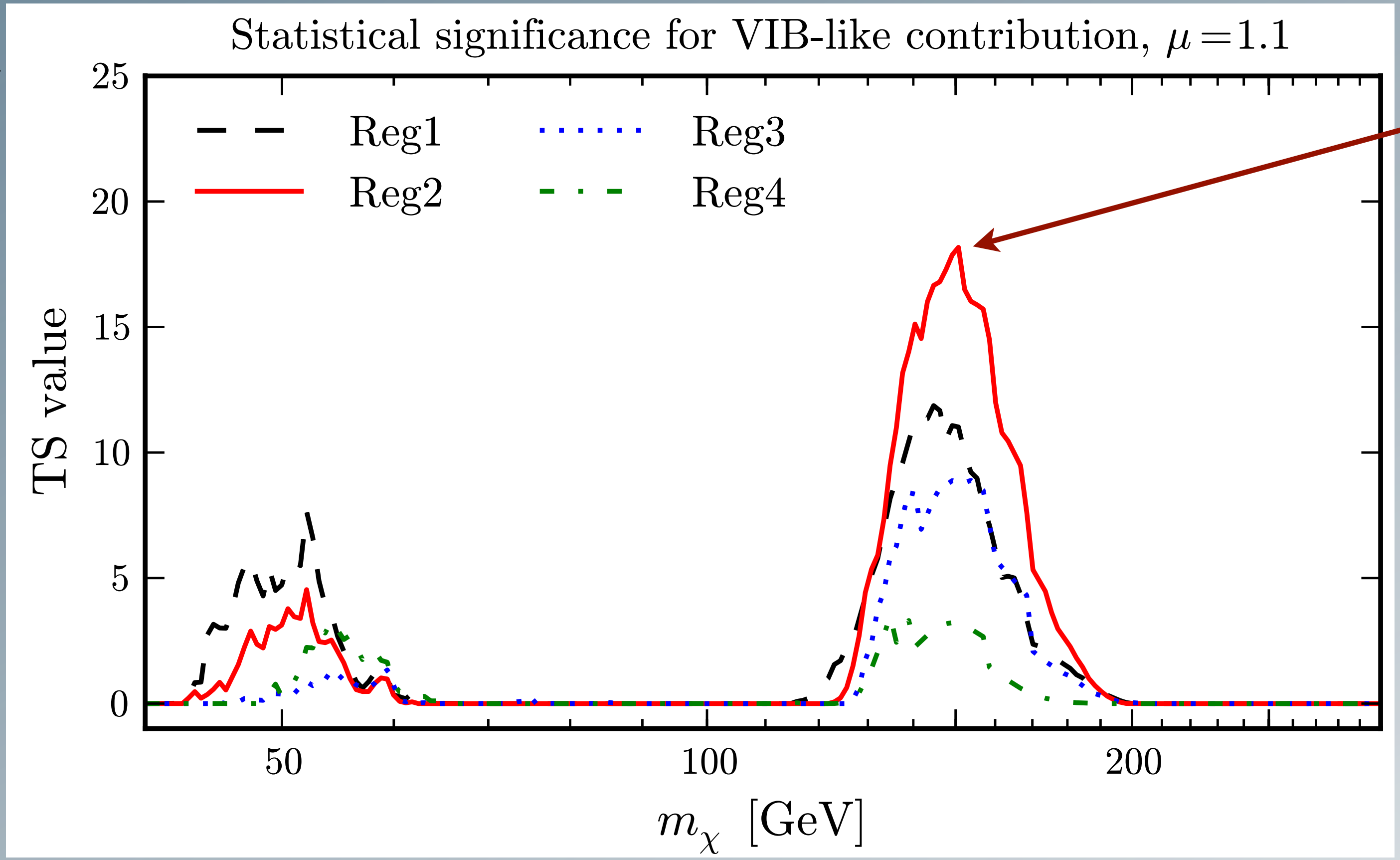

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- NB: also very well fit by line with

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

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]

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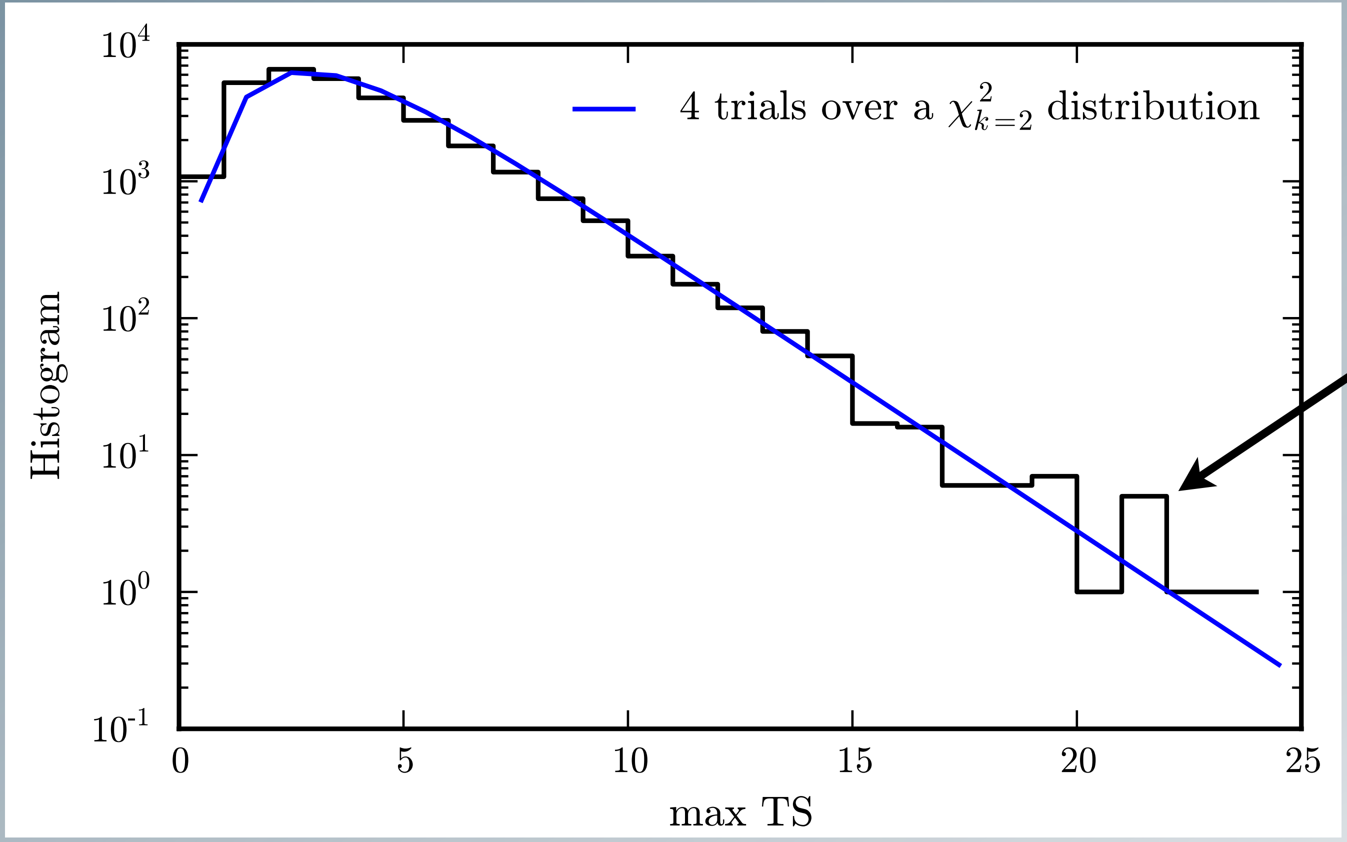

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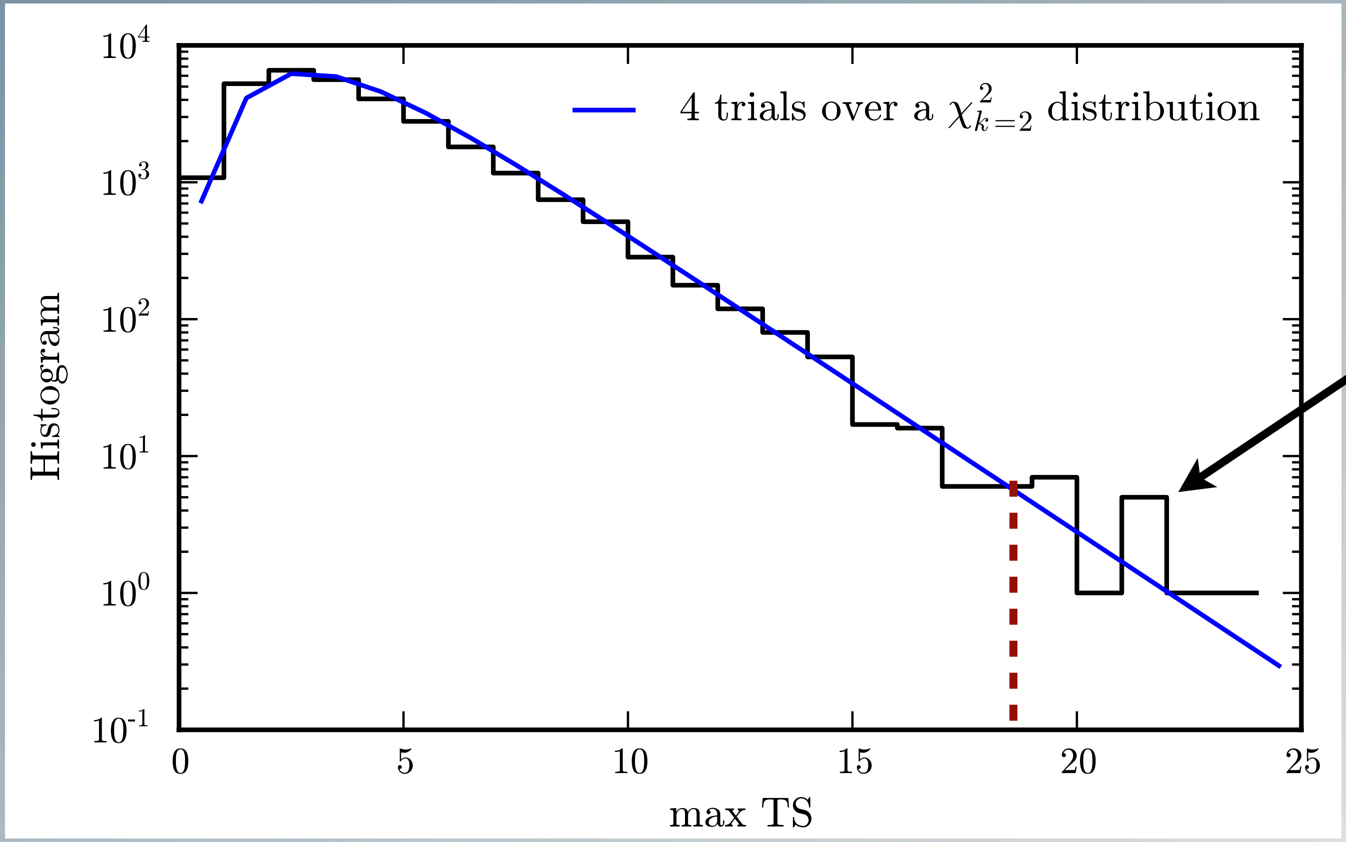


from subsampling analysis of galactic anticenter hemisphere

solve

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

$t = 4 \times 4$

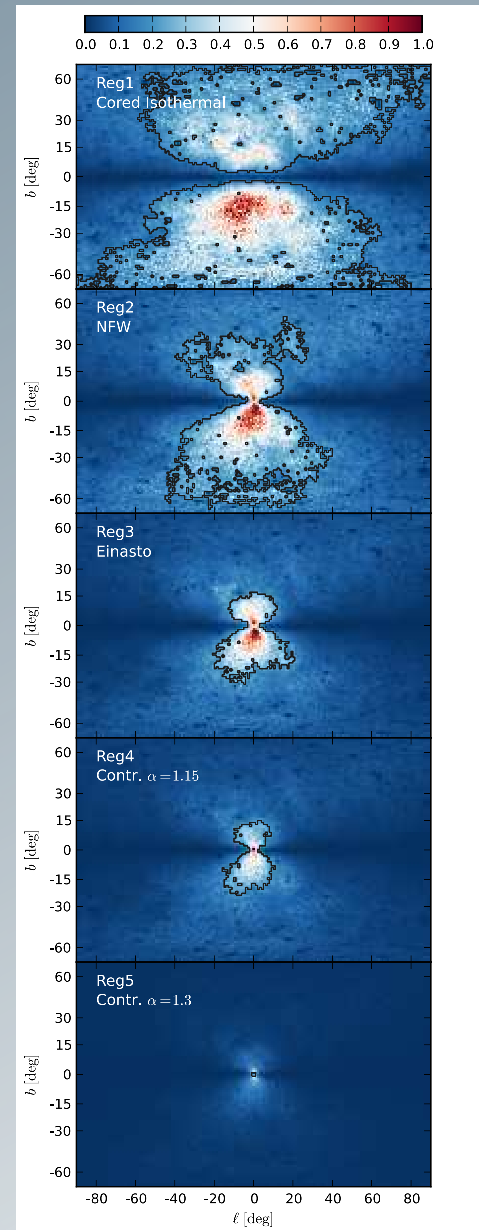
observed maximal TS value corresponds to significance of 3.1σ

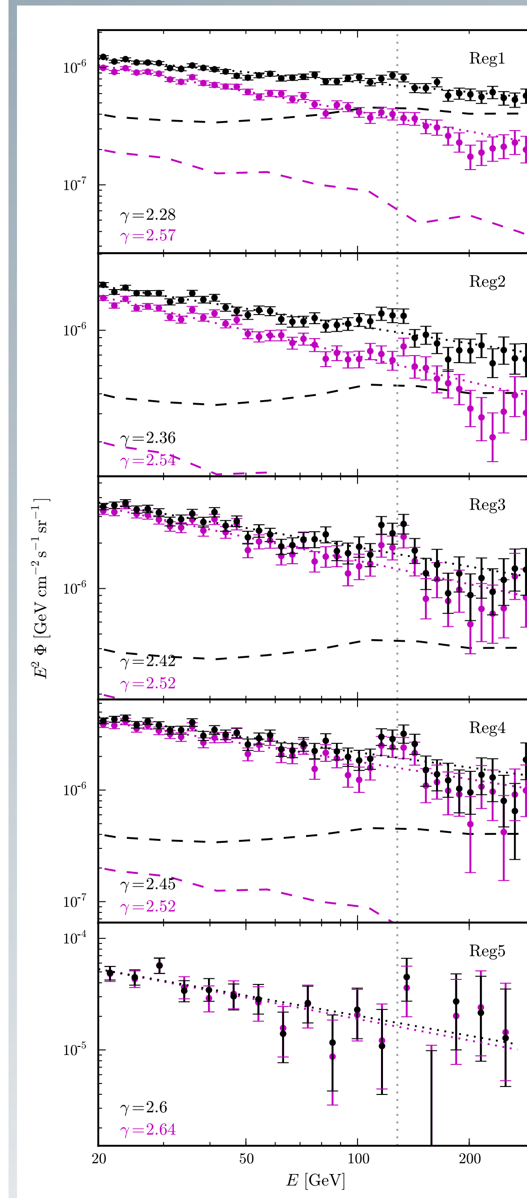
Line analysis

Weniger, JCAP '12

- "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
  - $\langle \sigma v \rangle_{\chi\chi\to\gamma\gamma} = (1.27 \pm 0.32 ^{+0.18}_{-0.28}) \times 10^{-27}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$
- Excess indep. confirmed by:

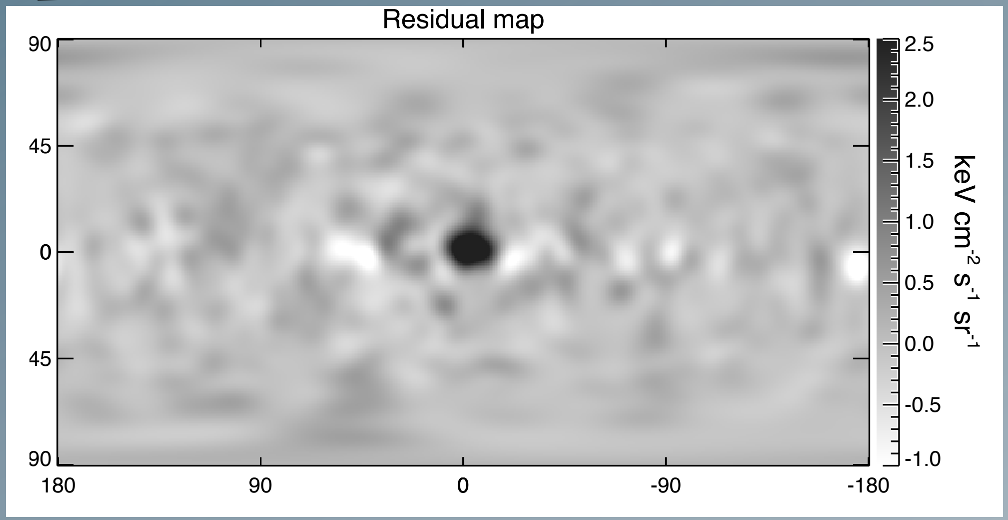
Tempel, Hektor & Raidal, JCAP '12
Rajaraman, Tait & Whiteson, JCAP '12
Su & Finkbeiner, 1206.1616





‘Strong evidence’

Su & Finkbeiner, 1206.1616



- 120-140 GeV residual map
  - created by subtracting background estimate = $E^2 dN/dE$ average of (80-100,100-120, 160-180) maps
  - all maps smoothed with FWHM=10°
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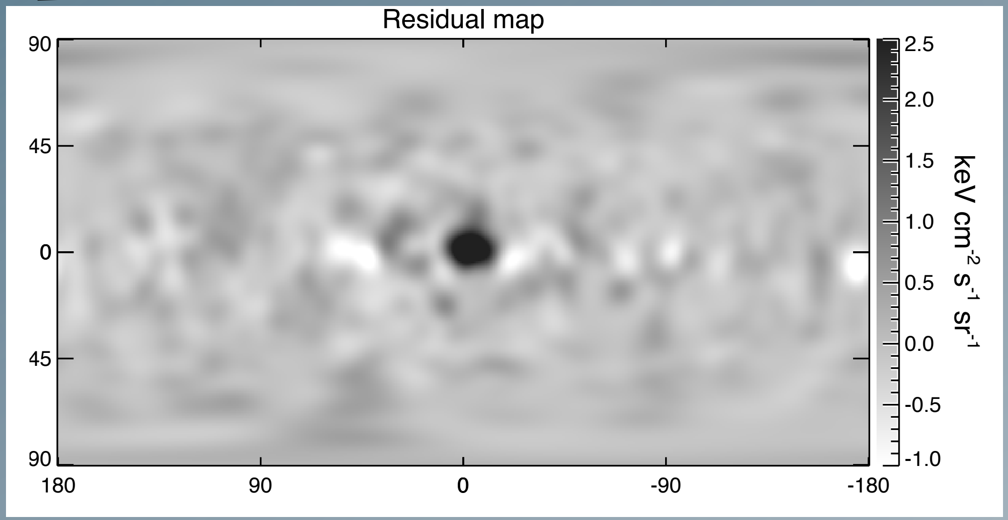

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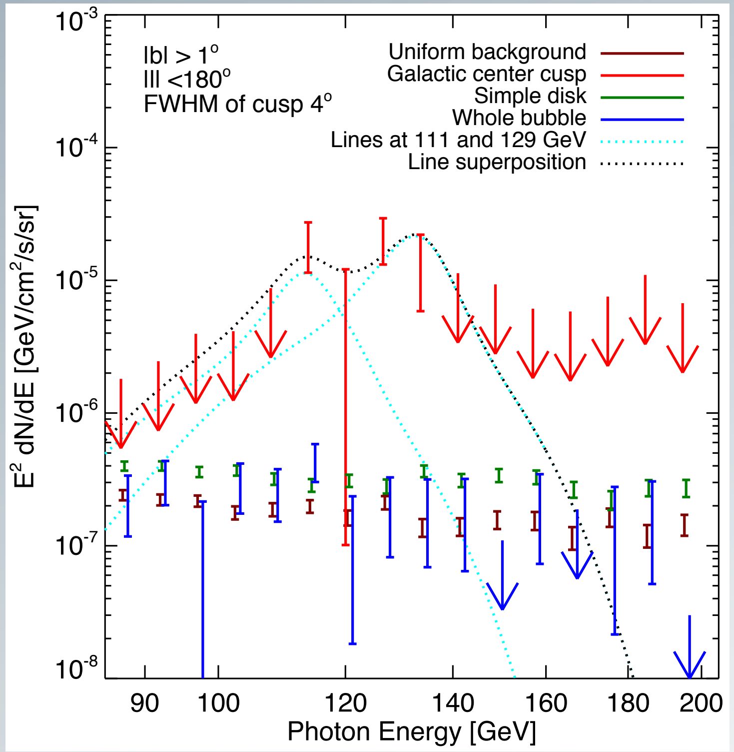
(fit linear combinations of spatial templates)



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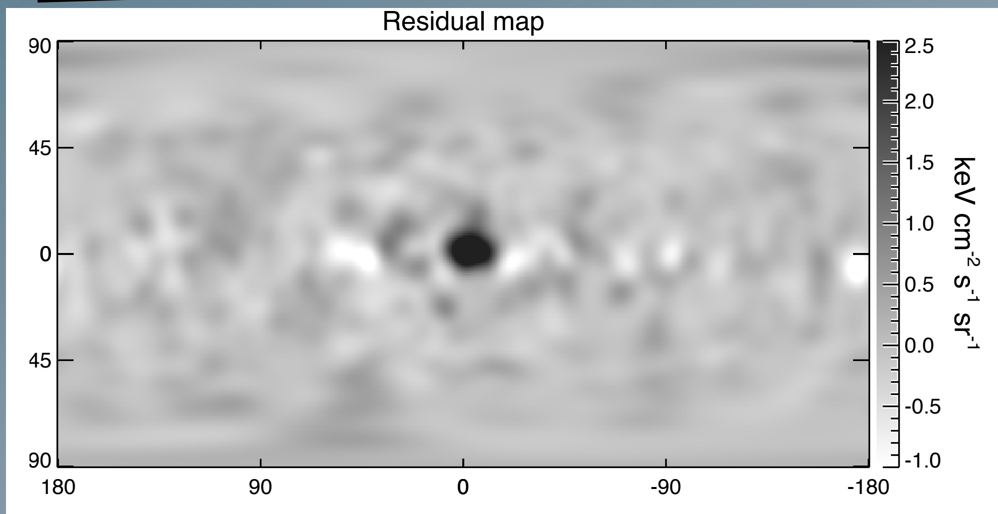

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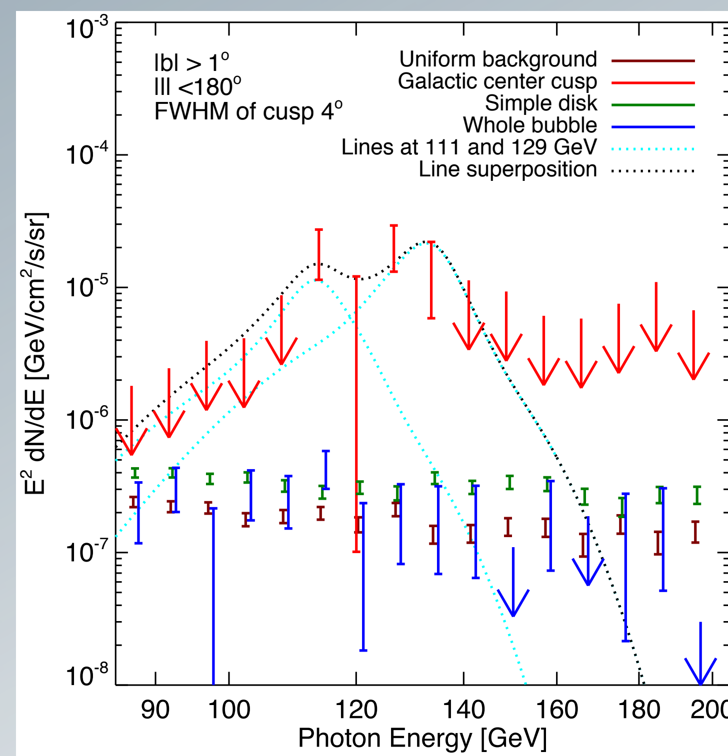


- *Global* significance in σ

	one line	two lines
Gauss	**3.7**	**4.3**
NFW	**4.5**	**4.9**
Einasto	**5.1**	**5.5**

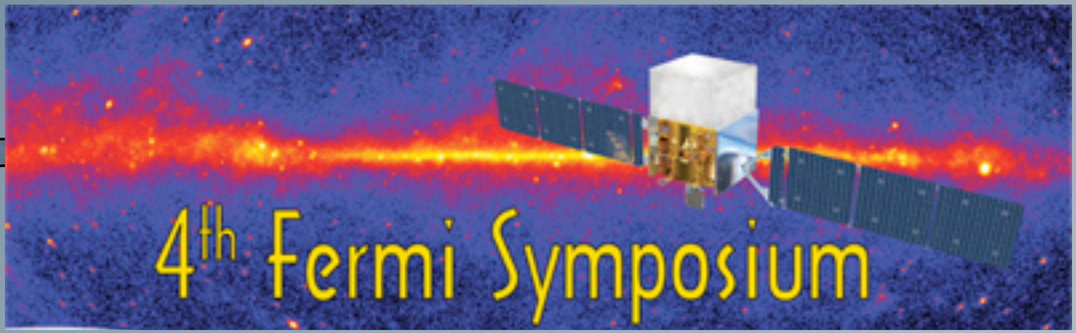
Latest news

- Analysis relies on public Fermi tools...
  - ➜ need independent confirmation by collaboration!

Latest news

4th Fermi Symposium
28 Oct - 2 Nov 2012
Monterey, CA
The fourth symposium will focus on new scientific investigations and results enabled by the Fermi Gamma-ray Space Telescope, as well as mission and instrument characteristics, coordinated multiwavelength/multimessenger studies, and future opportunities.
Topics include:
• Pulsars
• Supernova remnants & pulsar wind nebulae
• γ-ray-bright binaries & novae
• Diffuse γ-ray emission
• Cosmic rays
• Active, starburst, & normal galaxies
• GRBs & other transient sources
• Dark matter & new physics
• Unidentified γ-ray sources
fermi
Gamma-ray Space Telescope
http://fermi.gsfc.nasa.gov/science/mtgs/symposia/2012/

Latest news



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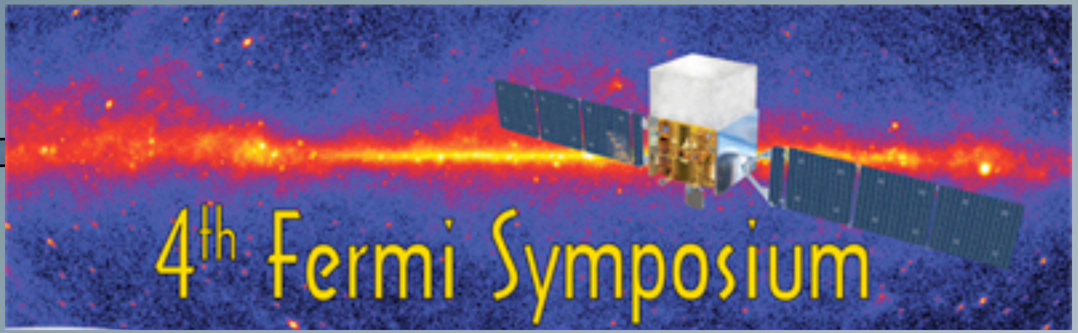

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- some more details:
  - updated calorimeter calibration: peak moves to 135 GeV
  - up to 3σ in limb data, but nothing in 'inverse ROI' (disk)
  - local significance of 3.4σ in 4°x4° box around GC
  - no globally significant excess in own optimized ROI

For more details, see talks by E. Charles, E. Bloom and A. Alberts…
[official analysis expected for spring next year]

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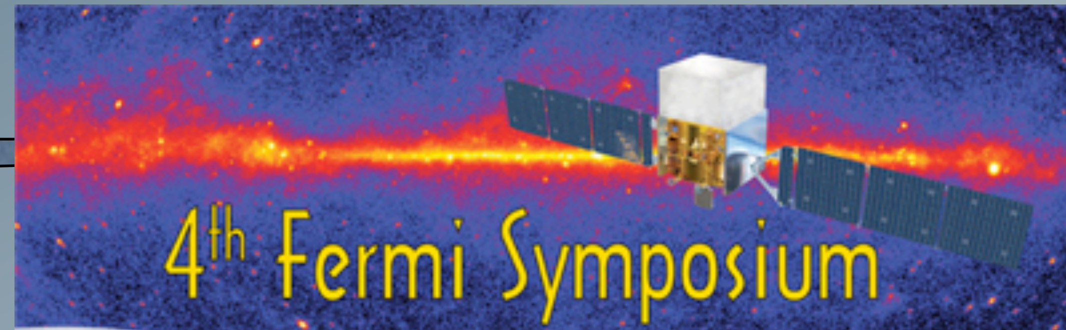

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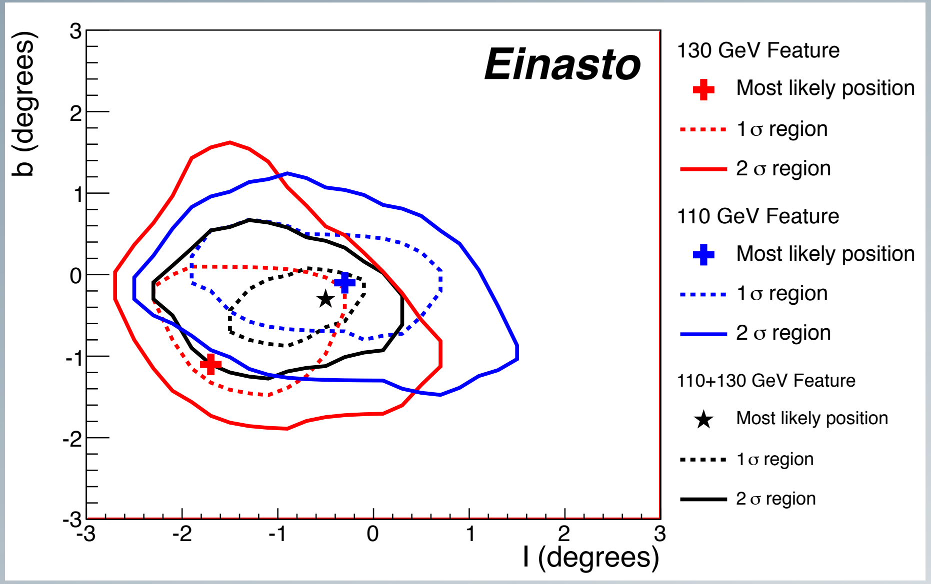
- Bottom line:
  the excess is there and could at this point be either
  - ***instrumental***
  - ***statistical***
  - ***real***

  !

Caveats for a DM interpretation?

- Signal appears offset from (dynamical) galactic center!
  Tempel, Hektor & Raidal, 1205.1045;Su & Finkbeiner, 1206.1616
  - possibility surprisingly little discussed in literature (but ~1.5° ~ 200 pc is a lot)!
  - OK for 'realistic' simulations of late-type spiral galaxy formation like ERIS ?
    Kuhlen *et al.*, 1208. 4844
  - What about SMBH?
    Gorbunov & Tinyakov, 1212.0488
  - Centered distribution also consistent?
    Rao & Whiteson, 1210.4934



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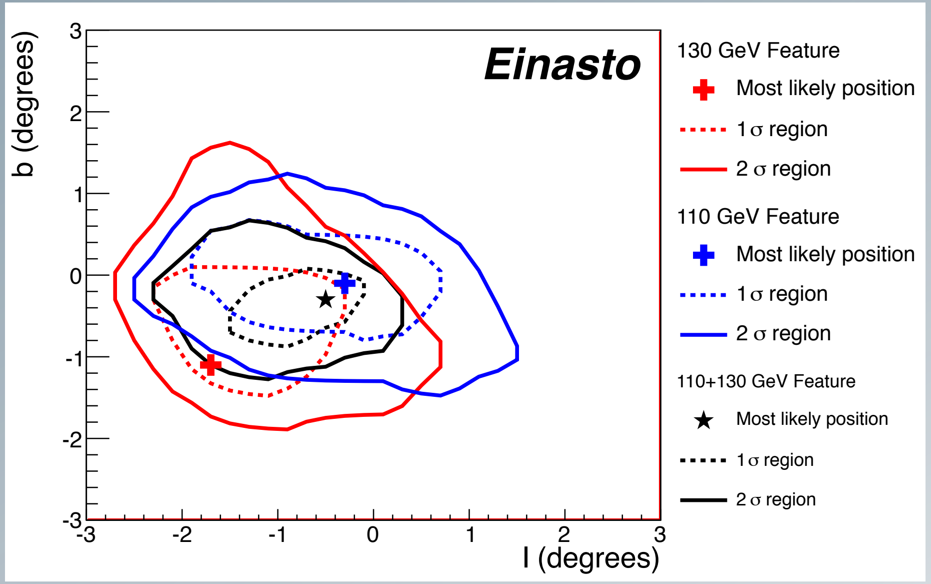

- A contamination from the earth limb?
  - (weak?) indication for line(s) at *same* energy! Su & Finkbeiner, 1206.1616
  - would be a serious challenge to the DM interpretation
  - atm completely unknown what could cause such a line...
  - several indications for *statistical fluctuation* [e.g. only for very specific incident angles; no lines in astrophysical photons at these angles]
    Finkbeiner, Su & Weniger, 1209.4562
    Hektor, Raidal & Tempel, 1209.4548

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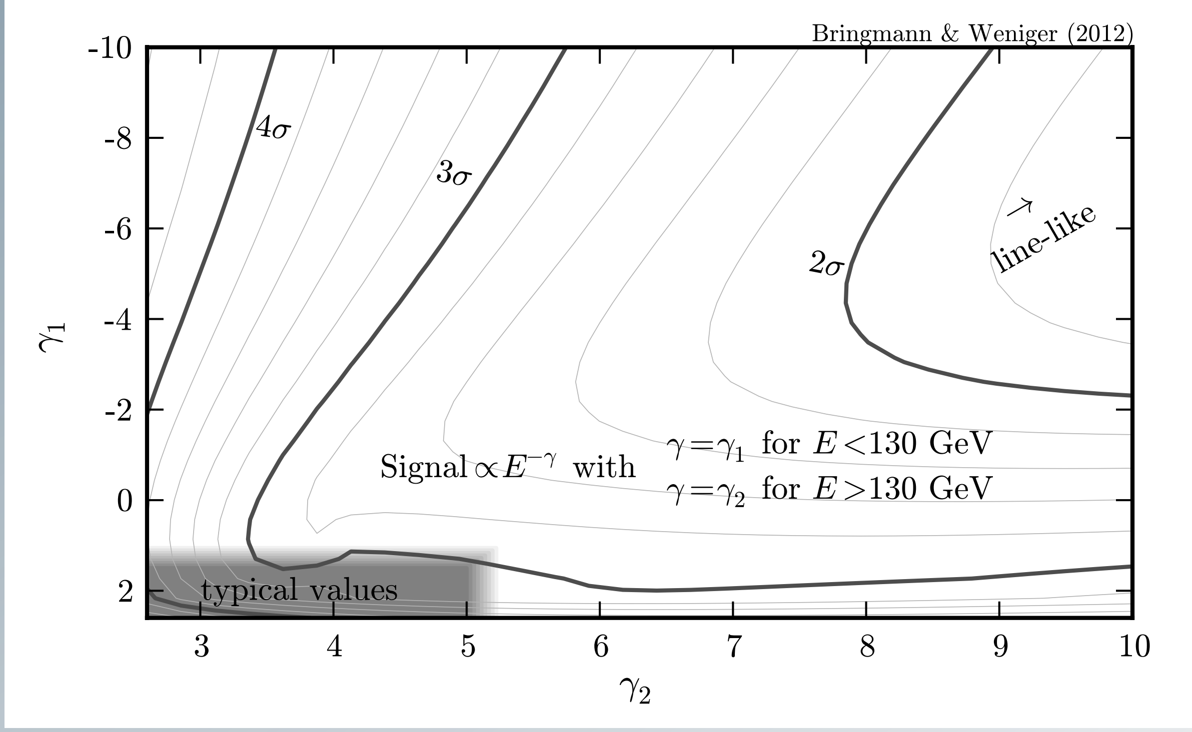

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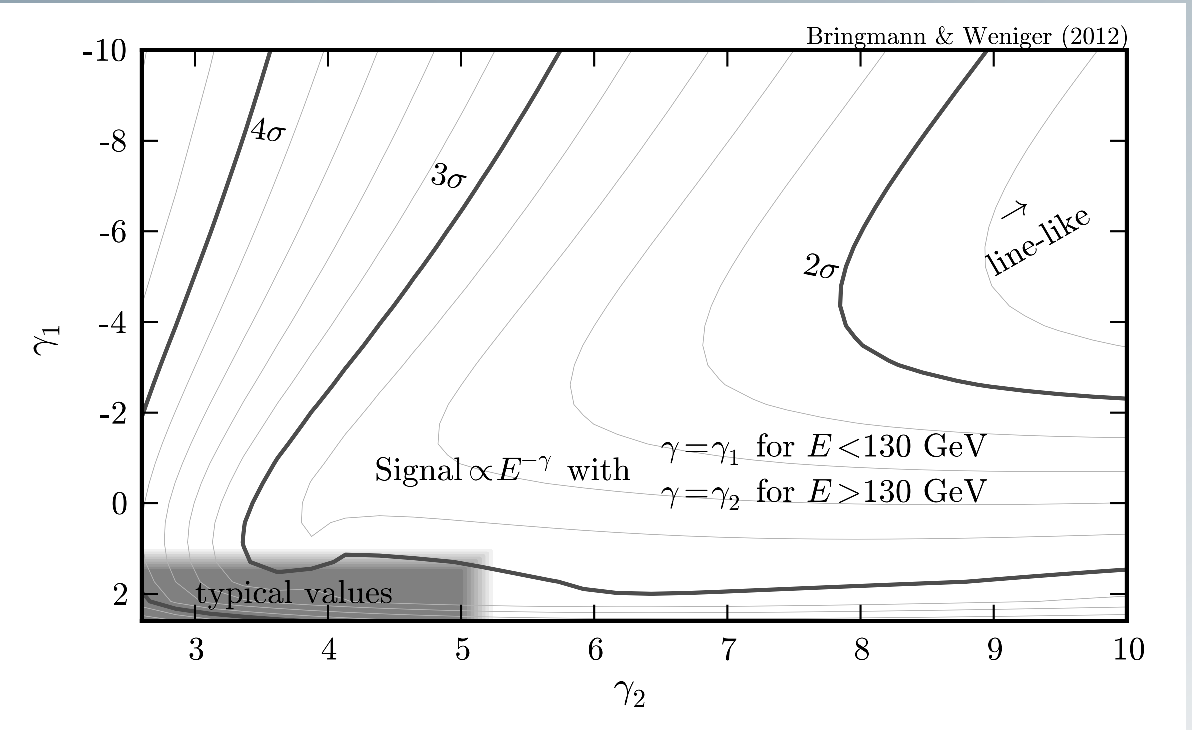
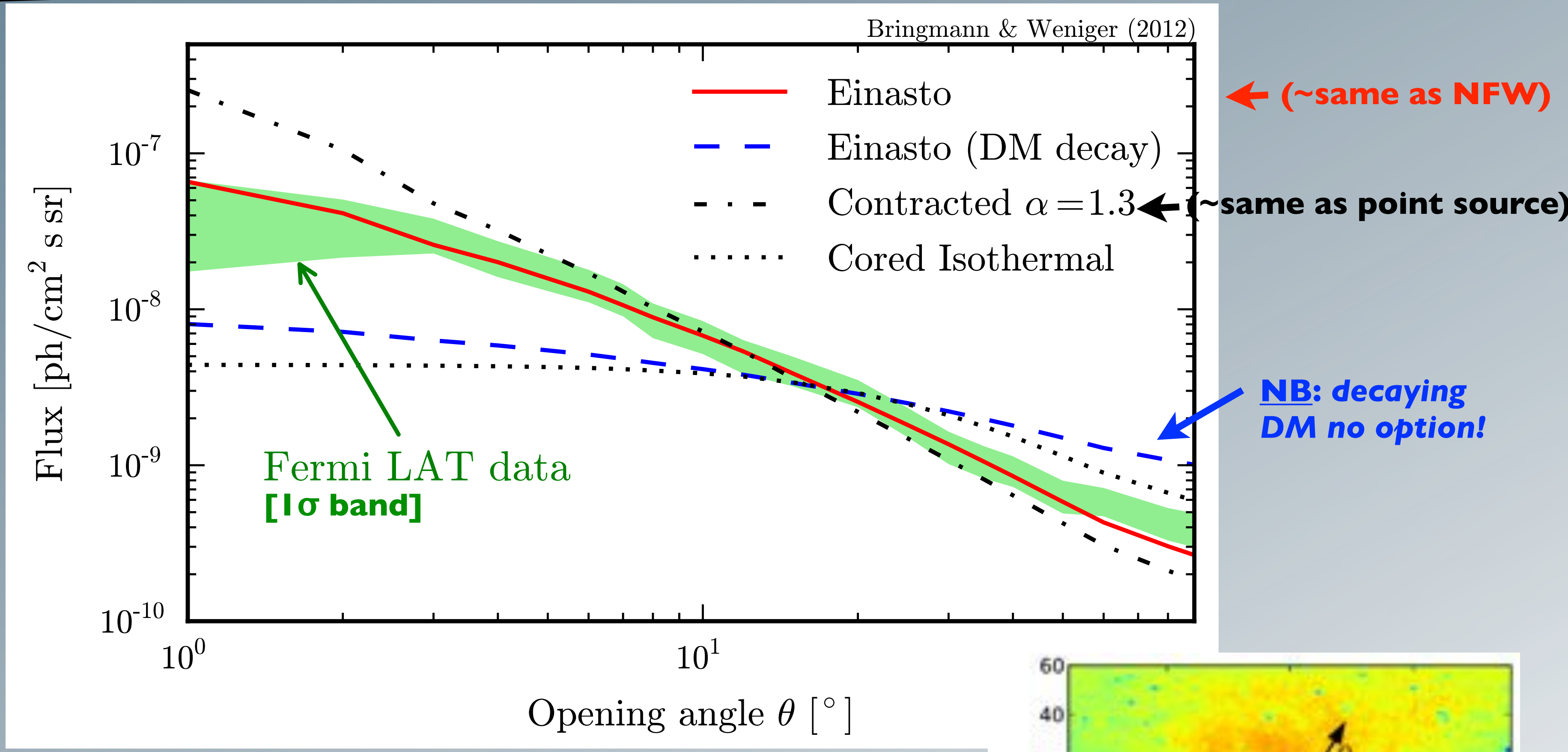


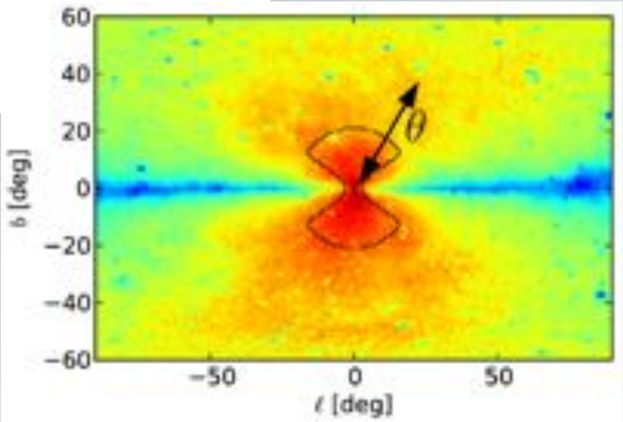
- Signal proportional to $\boxed{E^{-\gamma}\exp[-(E/E_{\rm cut})^2]}$ also disfavored wrt line by at least 3σ

  [same for astro-physical toy example: ICS from mono-energetic $e^{\pm}$]

➡ ***Extremely difficult to achieve with astrophysics!***

Signal profile





ROI [Color scale: signal to background]

➪ Signal not compatible with point source, but (almost) *only* with standard NFW or Einasto profile!

[Symmetry around GC checked by masking half ROIs]

Which line(s)?

TB & Weniger, 1208.5481

- DM mass and annihilation rate depend on channel

γX	m_χ [GeV]	$\langle \sigma v \rangle_{\gamma X}$ $[10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}]$
$\gamma\gamma$	$129.8 \pm 2.4^{+7}_{-14}$	$1.27 \pm 0.32^{+0.18}_{-0.28}$
γZ	$144.2 \pm 2.2^{+6}_{-12}$	$3.14 \pm 0.79^{+0.40}_{-0.60}$
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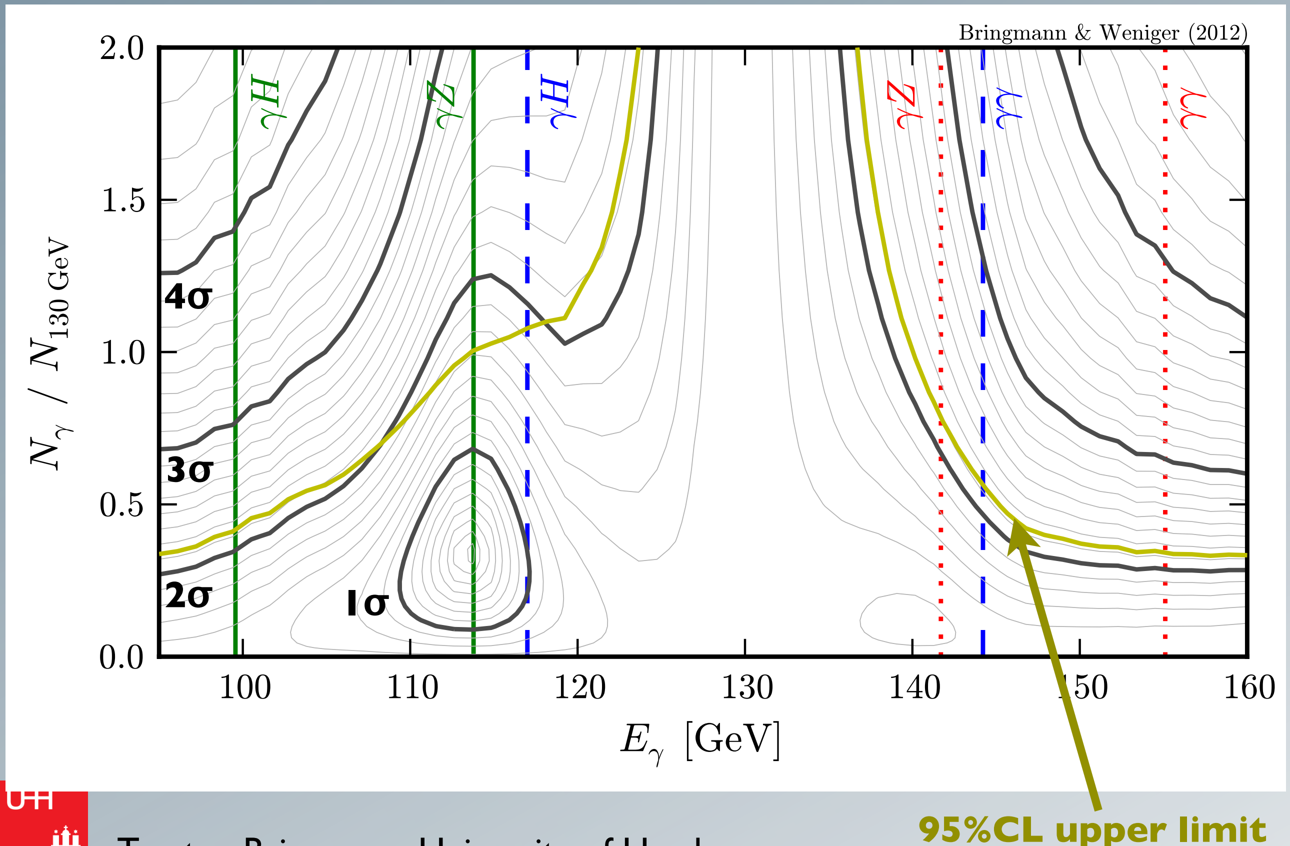
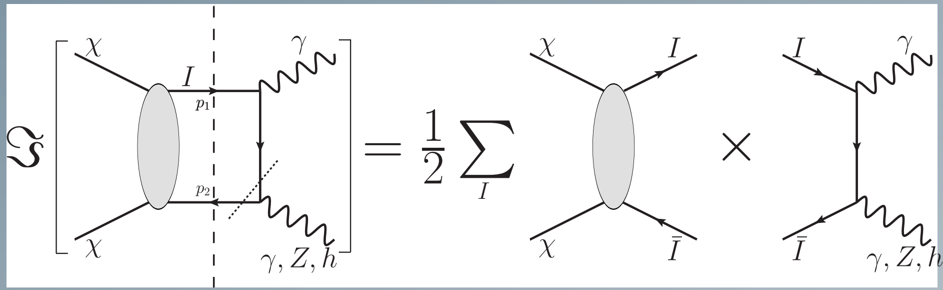


- DM **spectroscopy** !?
  - usually at least two lines (eff. operators...)
  - relative rates provide important constraints on viable models
  - currently *weak (1.4σ) indication* for 2nd line

see also:
Rajaraman, Tait & Whiteson, JCAP '12
Su & Finkbeiner, 1206.1616

More DM model implications

- Need rather large annihilation rate
  - implies resonances and/or large couplings (see e.g. Buckley & Hooper, PRD '12)
  - *difficult* to achieve for *thermally* produced DM!
  - expect large secondary rates (optical theorem!)



Asano, TB, Sigl & Vollmann, 1211.6739

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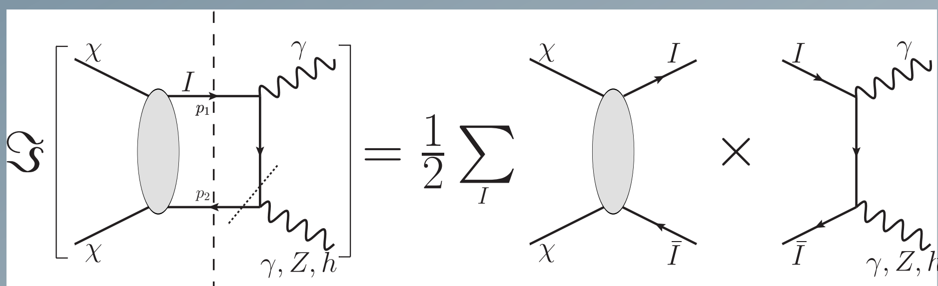

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➡ Constraints from cont. γ-rays, antiprotons and radio!

- E.g. neutralino DM already ruled out!?

Buchmüller & Garny, JCAP '12
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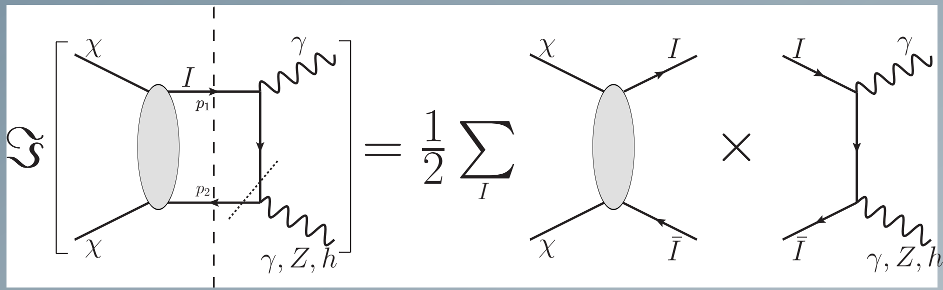

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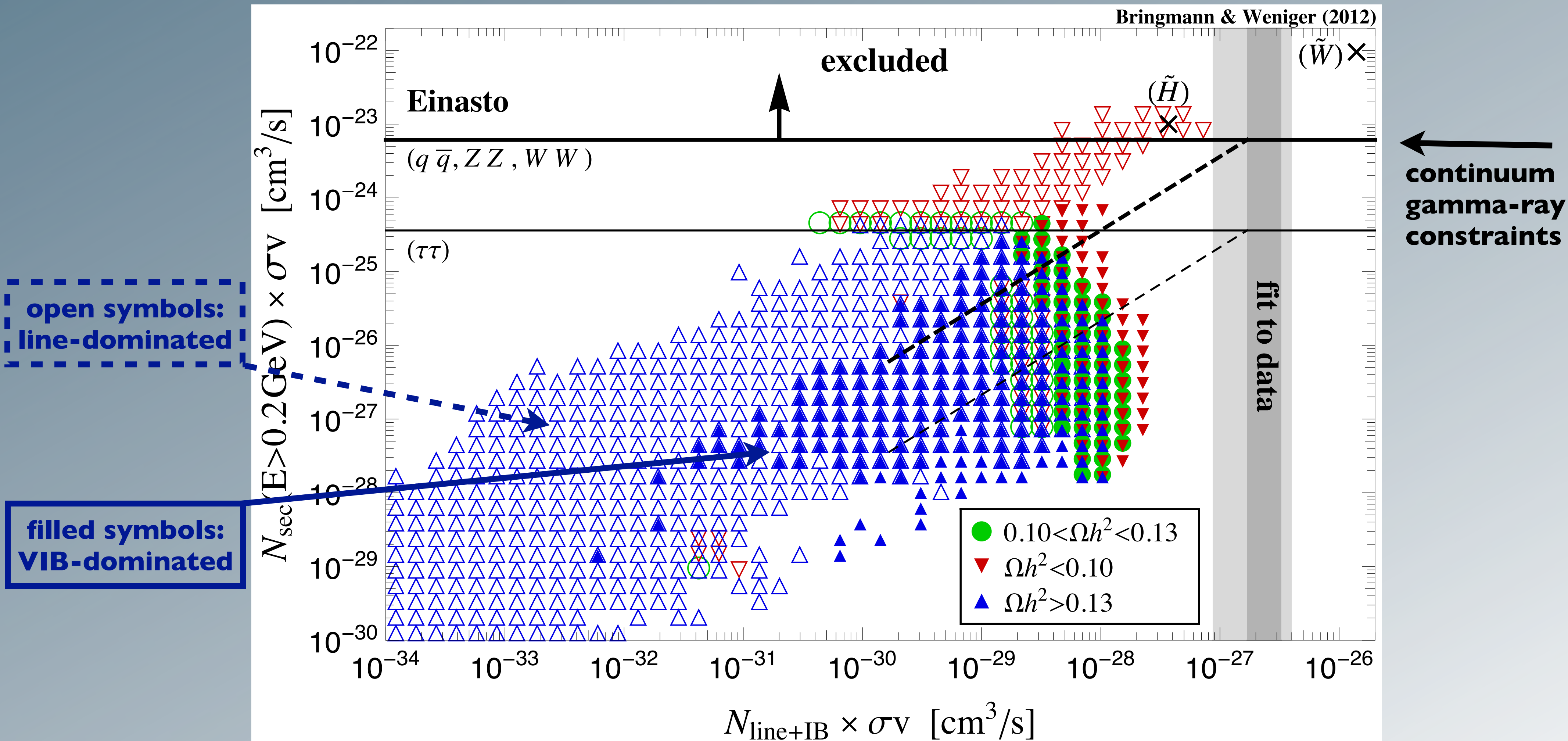
- Possible exceptions:
  - only new particles in loop (independent model-building motivation?)
  - cascade decays (fine-tuning to get narrow box!?)
  - Internal Bremsstrahlung

A SUSY scan

[cMSSM + MSSM-7; keep only models with correct mass and line-like spectra]



➪ *VIB more likely explanation than lines?*

(see also Bergström, 1208.6082, Shakya 1209.2427, ...)

A note on absolute rates

- For standard (SUSY) couplings, still a missing factor of $\lesssim 10$ to obtain necessary rate
- Not possible to enhance signal by point-like cuspy profiles, nor large substructure boosts
  [both result in wrong signal profile; latter is also highly unlikely in light of simulations]

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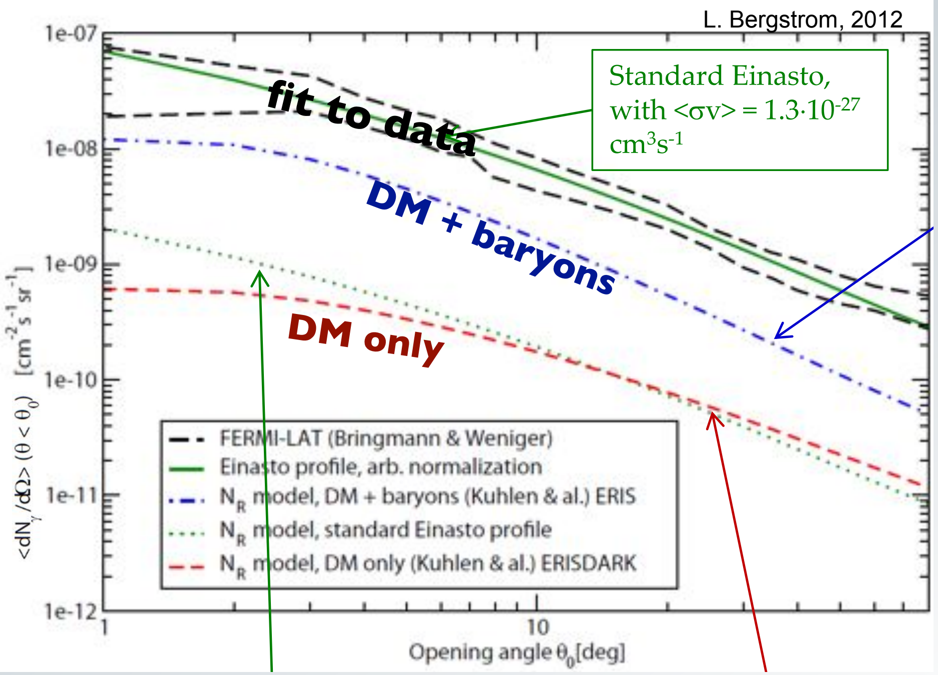
- Not possible to enhance signal by point-like cuspy profiles, nor large substructure boosts
  [both result in wrong signal profile; latter is also highly unlikely in light of simulations]
- Still maybe possible through
  - larger *local DM density* than
    $$\rho_\odot^\chi = 0.4\,\mathrm{GeV}/\mathrm{cm}^3$$
    (e.g. factor 2-3 claimed when including oblate halo and 'dark disk': Garbari *et al*, 1206.0015)
  - Enhanced DM profile due to effect of baryons as in new ERIS simulation
    Kuhlen *et al.*, 1208. 4844

L. Bergstrom, 2012



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Future confirmation?

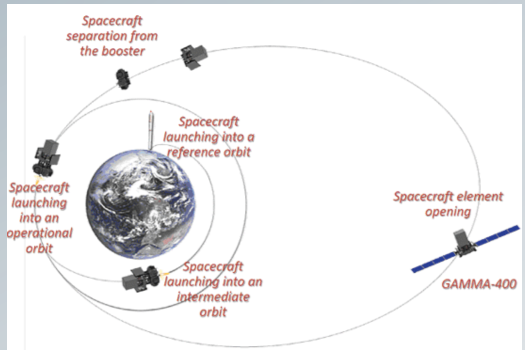
- ‘Tentative evidence’ based on ~50 photons
  ⇨ need a few years more data to confirm signal...
- … but maybe much faster if Fermi collaboration publishes PASS8 event selection before!
- HESS II will look at GC as one of the first targets
- final word possibly by GAMMA-400

  Galper *et al.*, 1210.1457
  - launch around 2018
  - greatly improved angular and energy resolution (at the expense of sensitivity)
  - $\sim 5\sigma$ signal significance after 10 months !

    Bergström *et al.*, 1207.6773

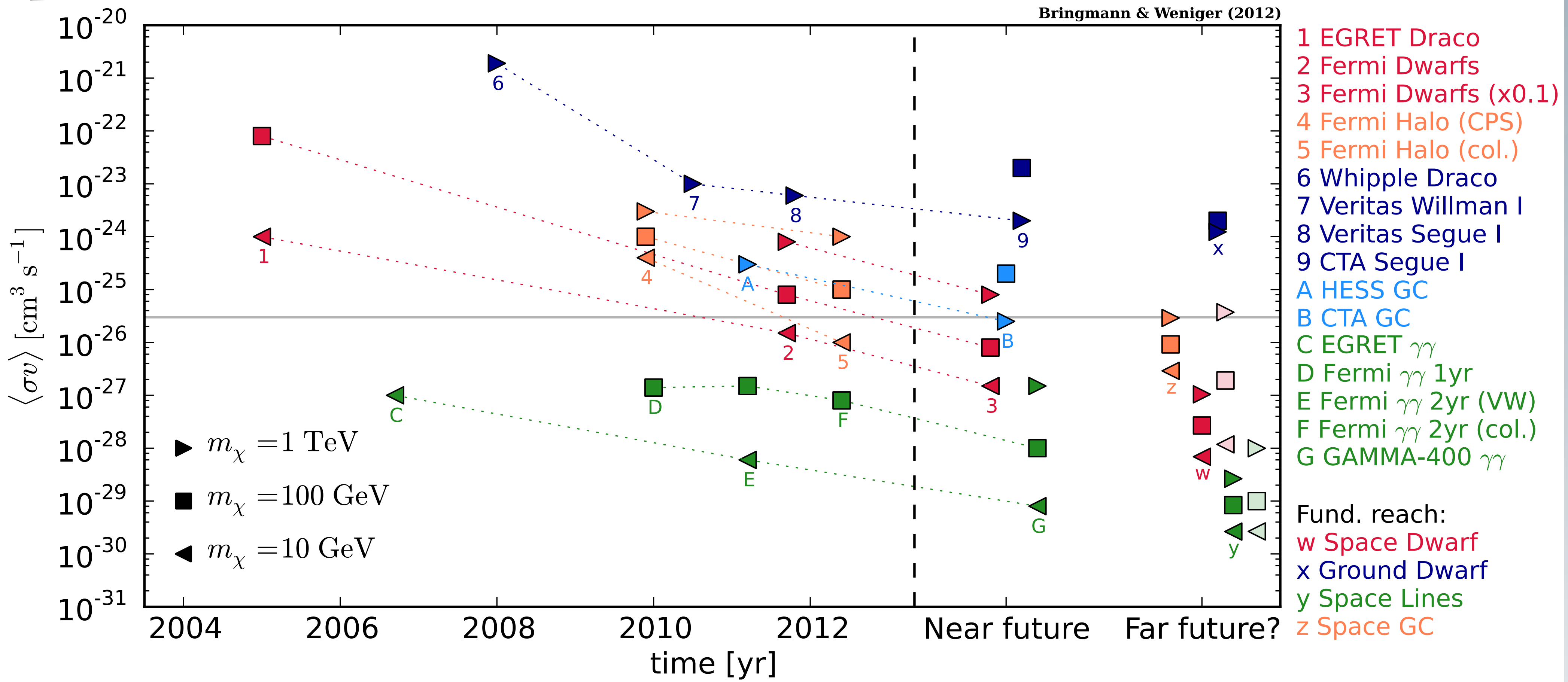
⇨ may also provide further information about the spectrum!

[NB: Similar performance expected by chinese DAMPE & HERD!]



	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

(Far) future of DM searches



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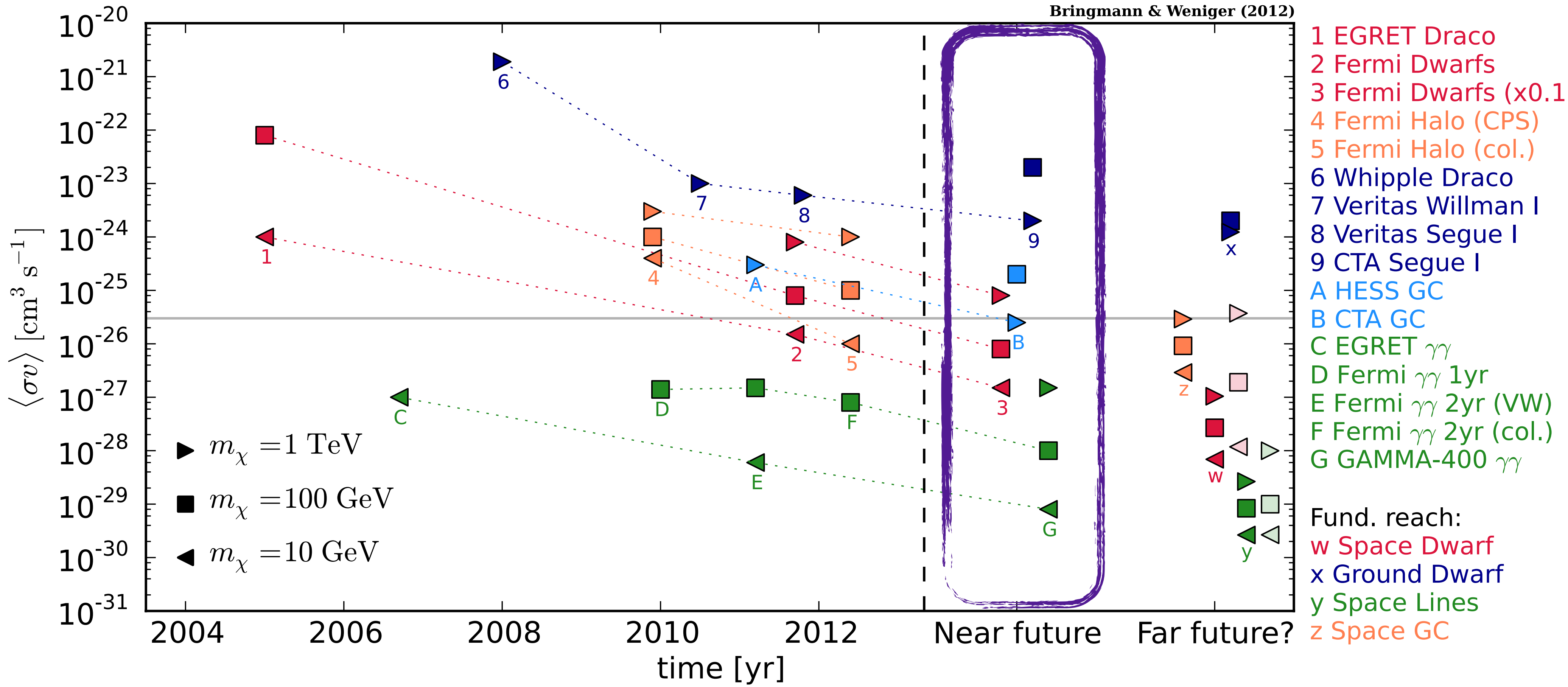
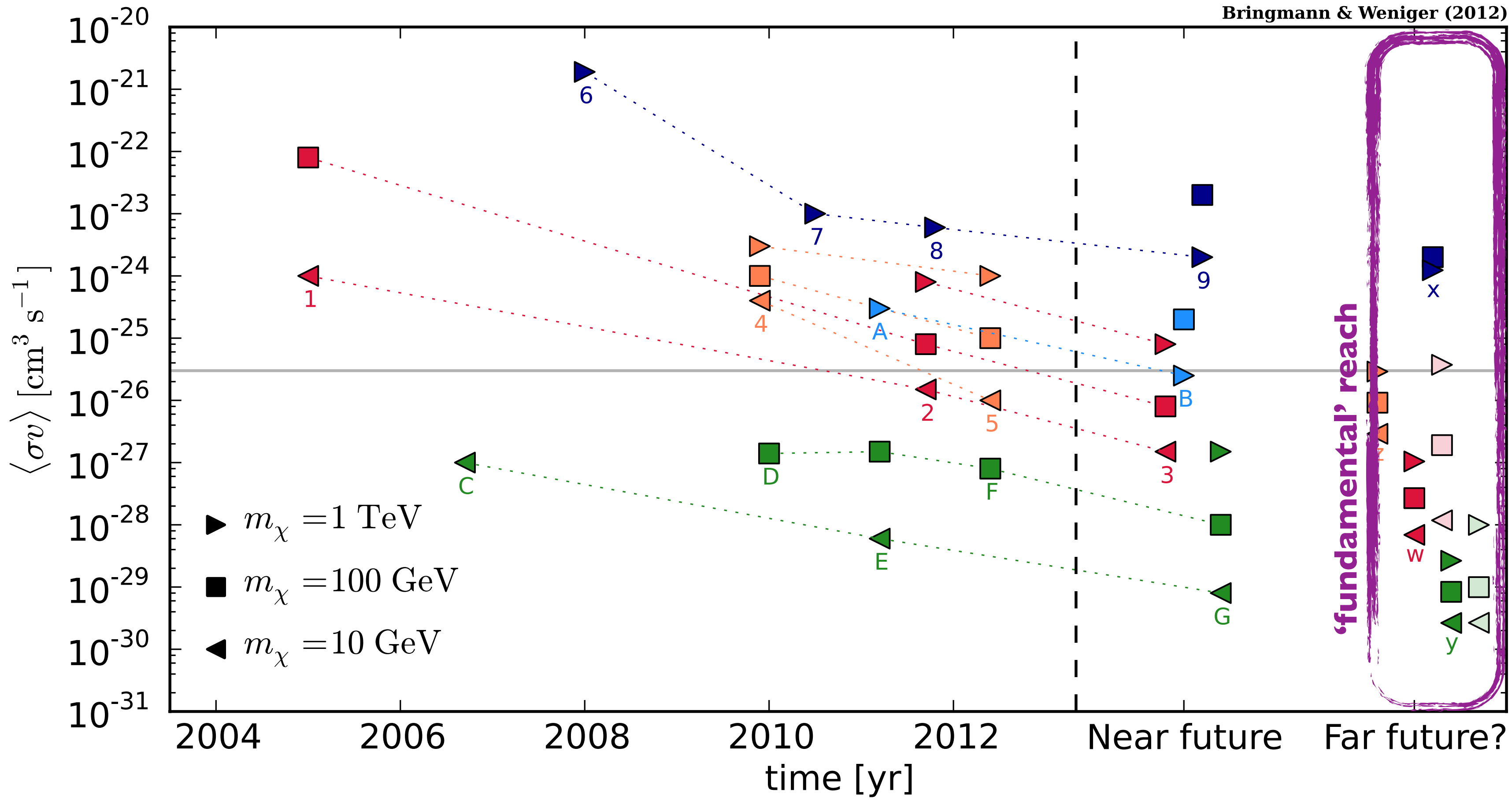


- Roughly one order of magnitude improvement during last decade, expect ~same for next decade

(Far) future of DM searches



:= systematics under control at 1% level

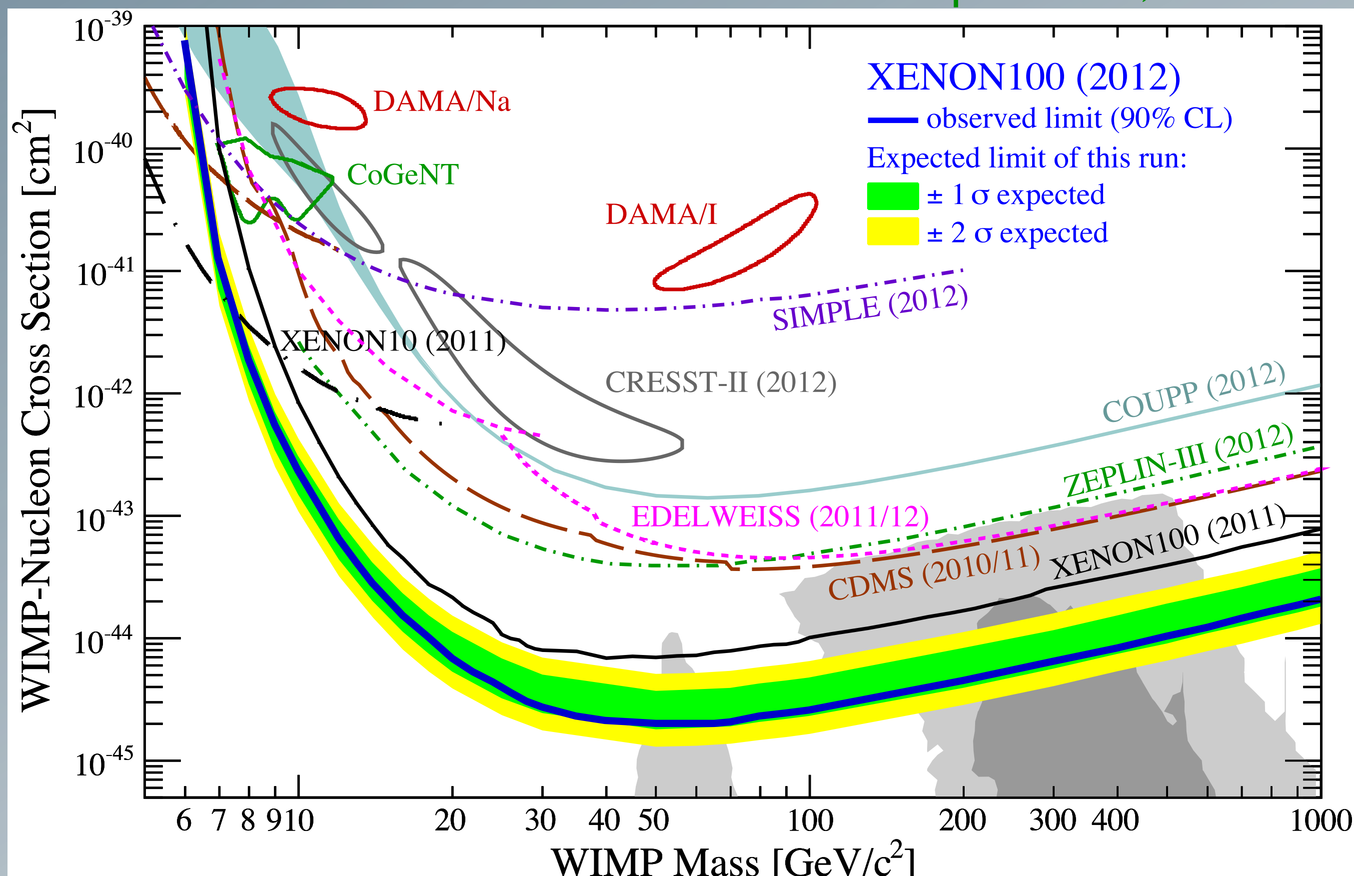
[light: 100x10yr Fermi]

- further significant improvement possible with current technology
  - in particular space-based instruments (but need very large exposures)
  - earth-based soon systematics-limited $\rightsquigarrow$ need to e.g. reject e$^-$-background!

Direct searches

- Impressive improvements of direct detection limits in recent years:

Aprile *et al.*, 1207.5988



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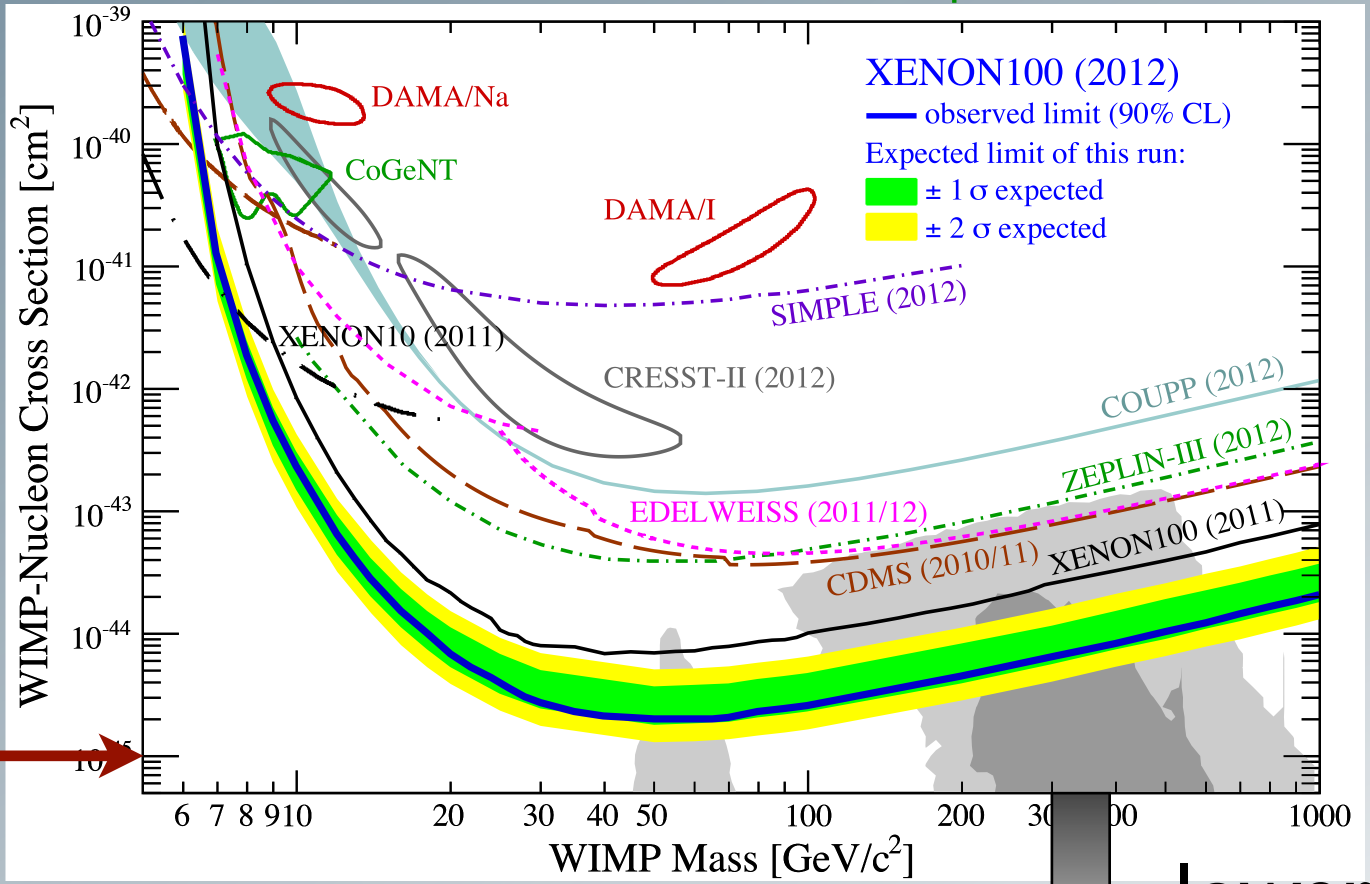


10^{-9} pb

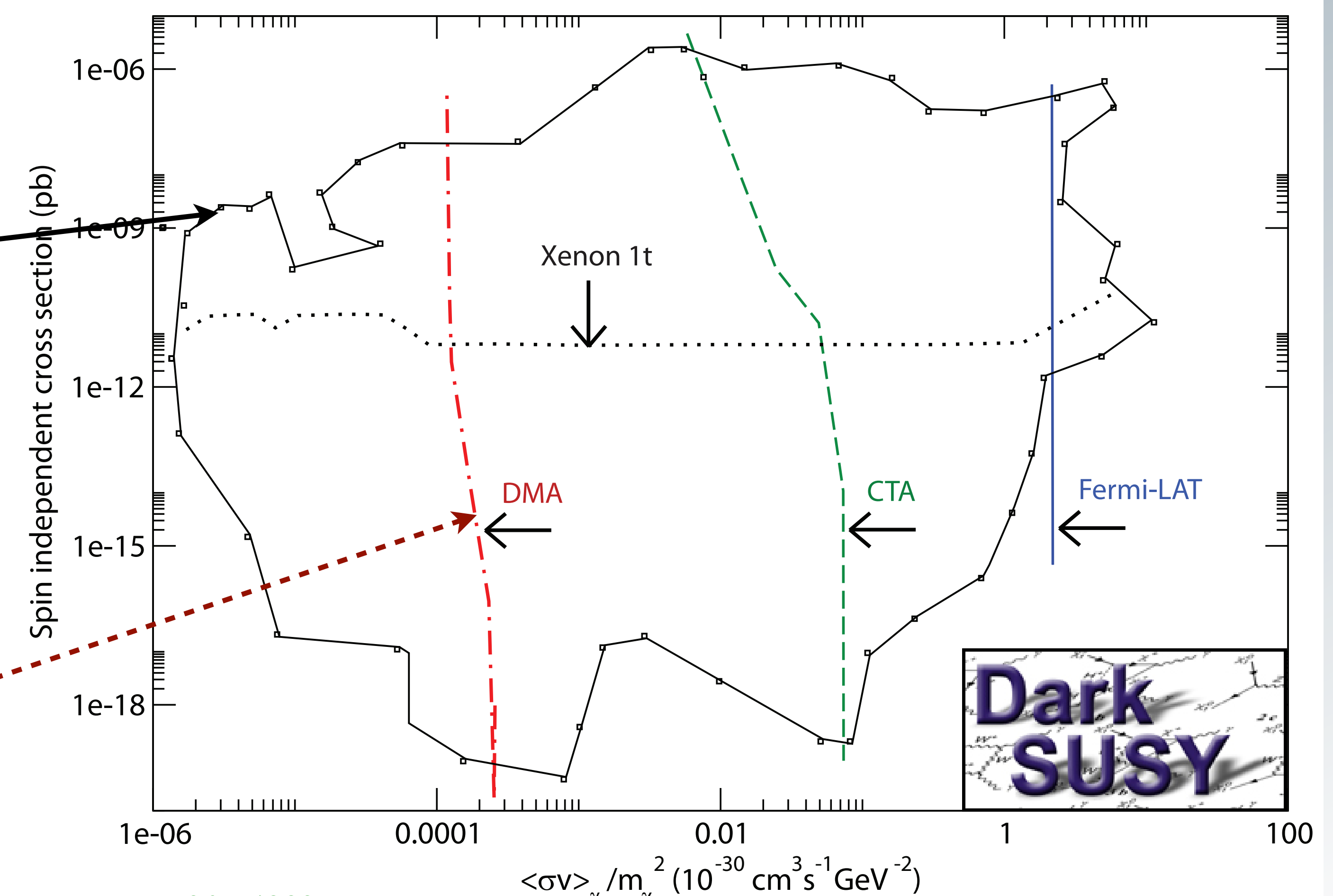
lower limit to $\sigma_{\rm SI}$?

Direct vs. indirect searches

- Direct and indirect searches probe SUSY parameter space from an 'orthogonal' direction Bergström, TB & Edsjö, PRD '11
  - remains true after most recent LHC bounds Bechtle *et al.*, JHEP '12

- MSSM scan
  - relic density, (pre-LHC) collider bounds OK
  - Galactic center (NFW, no boost)

- The "Dark Matter Array":
  - 10 x A_{eff}(CTA)
  - E > 10 GeV
  - *dedicated*: t_{obs} ~5000*h*



Bergström, 1205.4882

Conclusions and Outlook

Exciting times for dark matter searches

- Gamma-ray experiments seriously start to probe the parameter space of realistic WIMP models

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- They do so in a way that is complementary to both direct and accelerator searches
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- 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!

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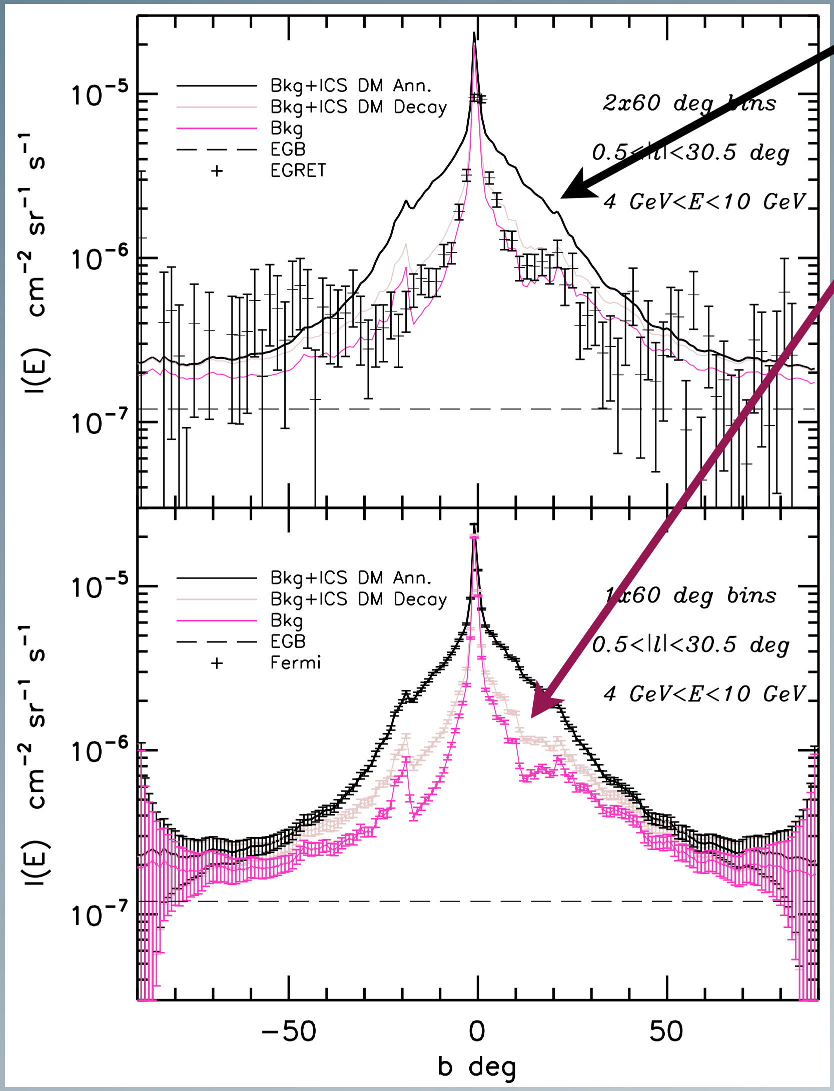
- Distinct spectral features in gamma rays
  - help to identify a DM annihilation signal
  - could reveal a lot about the nature of the DM particles
  - ⇨ discovery (rather than exclusion) channel!
- Have we already seen a signal?
  - based on O(50) photons ⇝ need more data...
  - If confirmed, *first BSM particle* maybe *detected in space* − *not* at the LHC!

Backup slides

Diffuse γ-ray constraints



Borriello, Cuoco & Miele, PRL '09

- Already EGRET data in some tension with annihilating WIMP explanation of PAMELA
- Prediction for Fermi:
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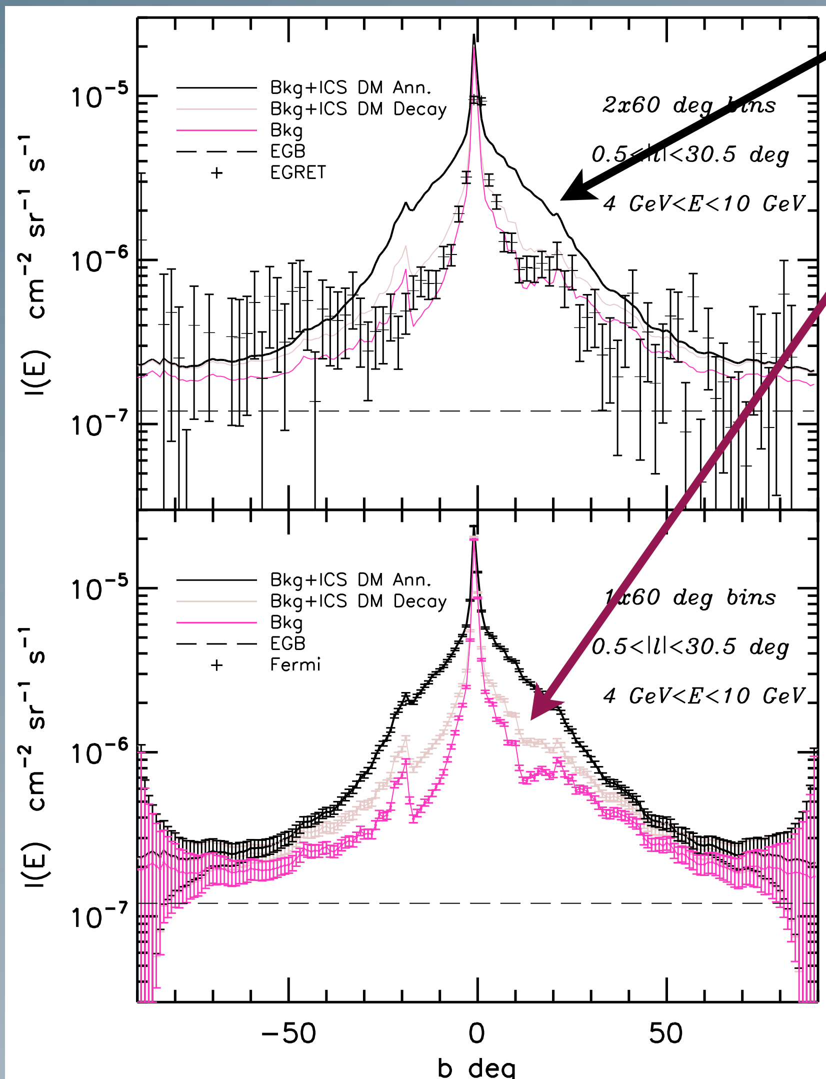
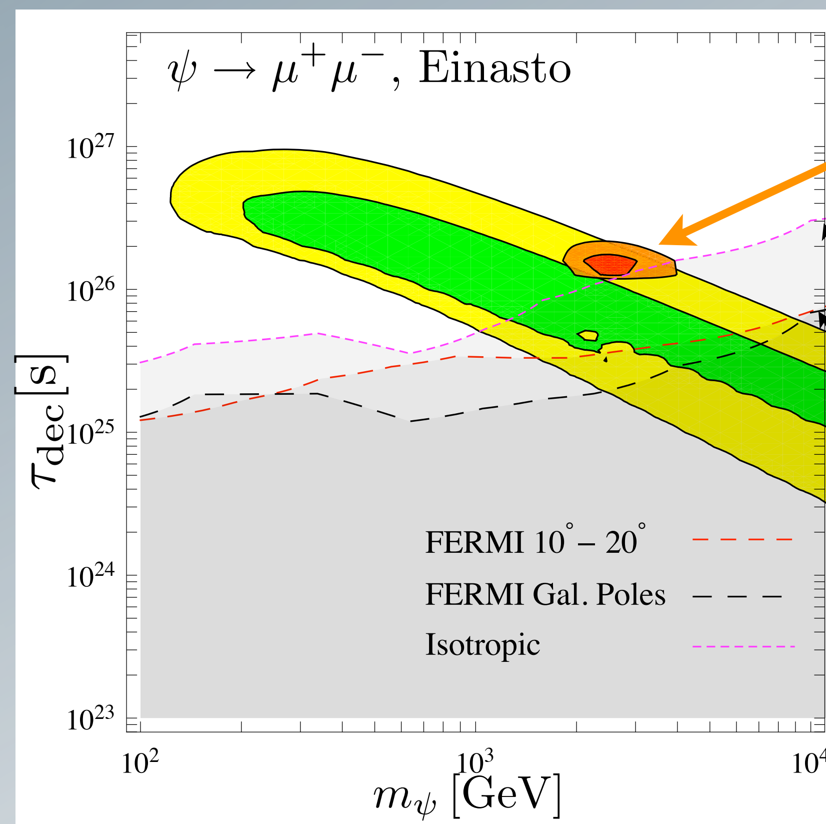


Borriello, Cuoco & Miele, PRL '09



Cirelli, Panci & Serpico, 0912.0663

CMB constraints

- DM annihilation at high z injects energy that effects the CMB photons by
  - ionizing the thermal gas
  - inducing Ly-a excitations of H
  - heating the plasma

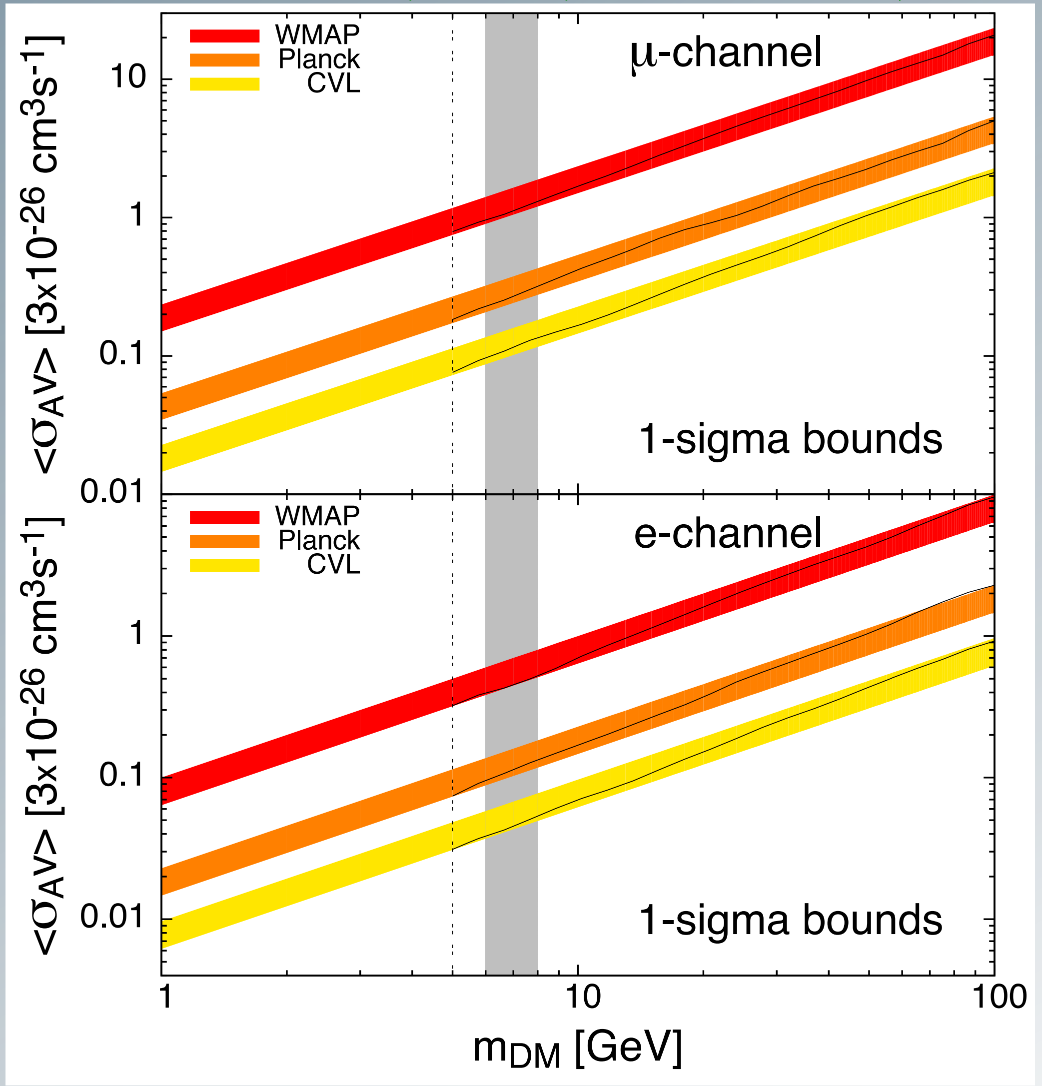
CMB constraints

Hütsi, Chluba, Hektor & Raidal, AA '11

- DM annihilation at high z injects energy that effects the CMB photons by
  - ionizing the thermal gas
  - inducing Ly-a excitations of H
  - heating the plasma

↓

- Significant constraints on light DM!
  - (other channels bracketed by the two cases shown)



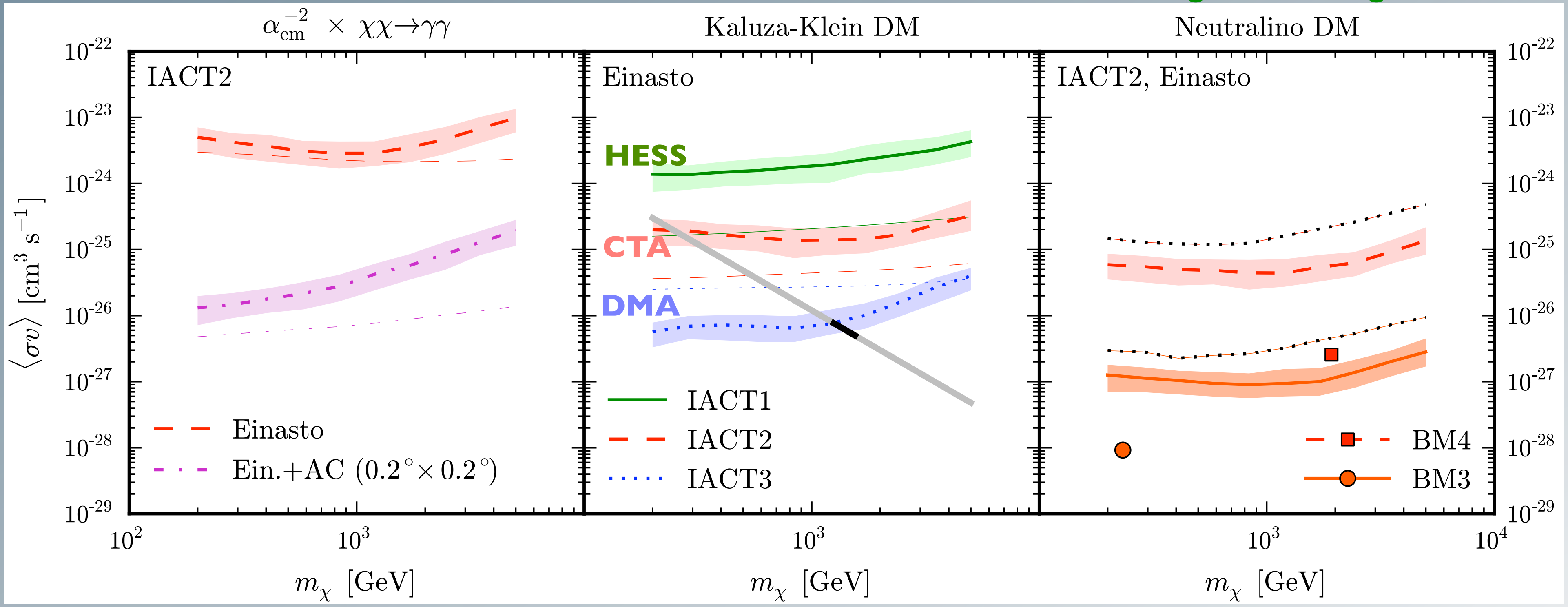
↑

~direct detection?

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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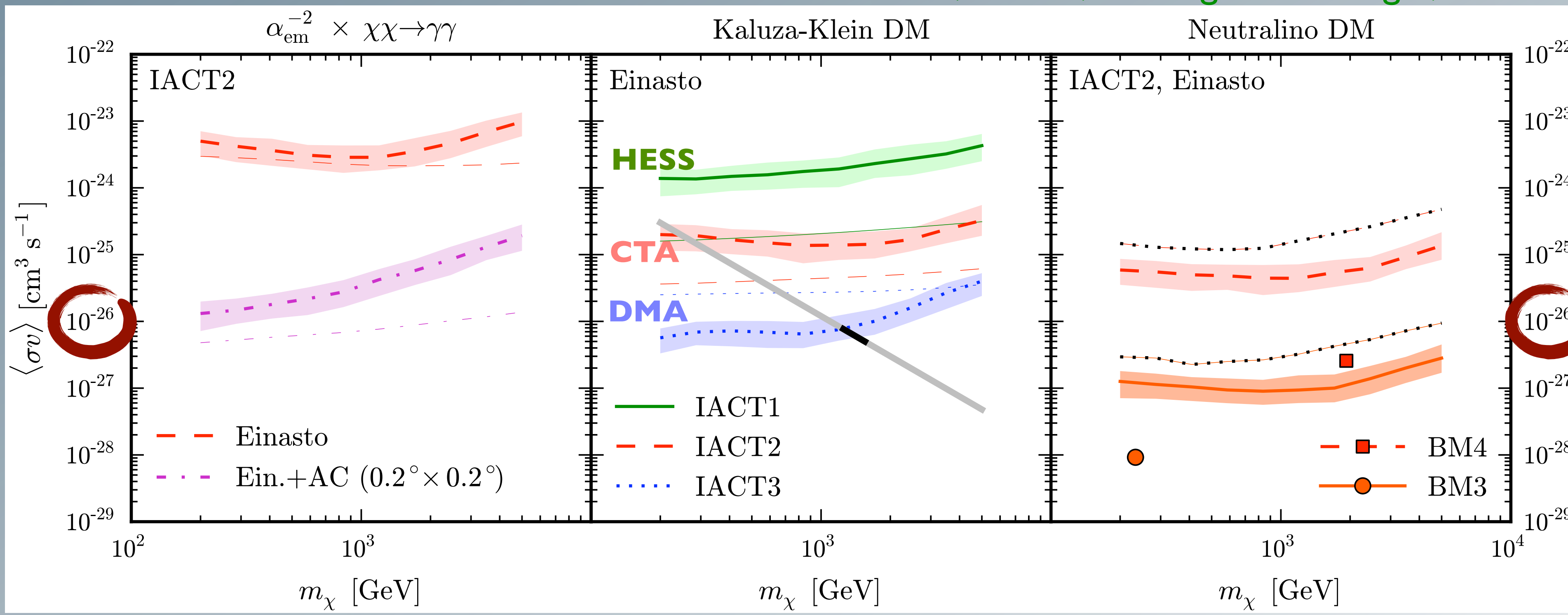
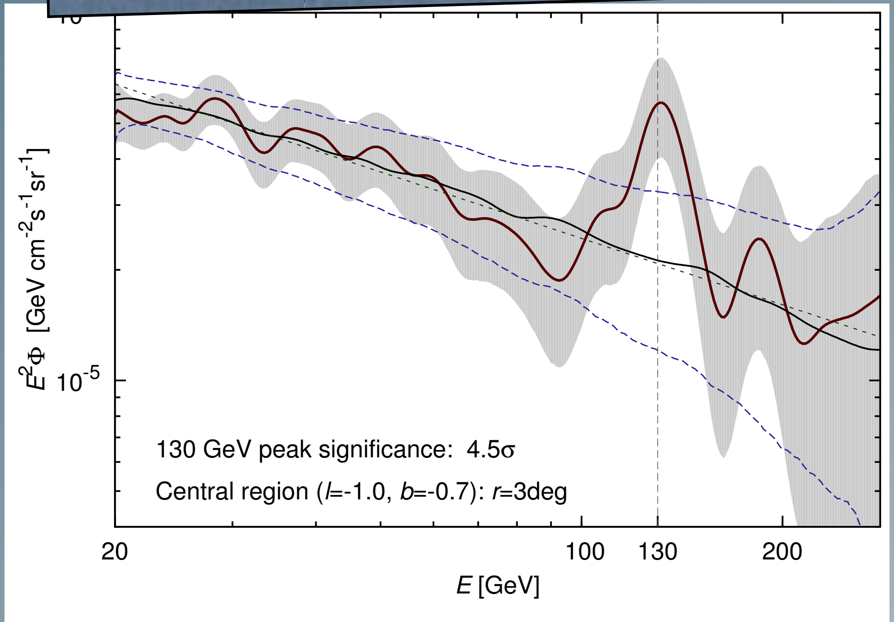


Line signals **Kaluza-Klein DM (step)** **Neutralino DM (IB bump)**

⇨ Natural cross sections well within reach for ACTs!

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

An independent confirmation

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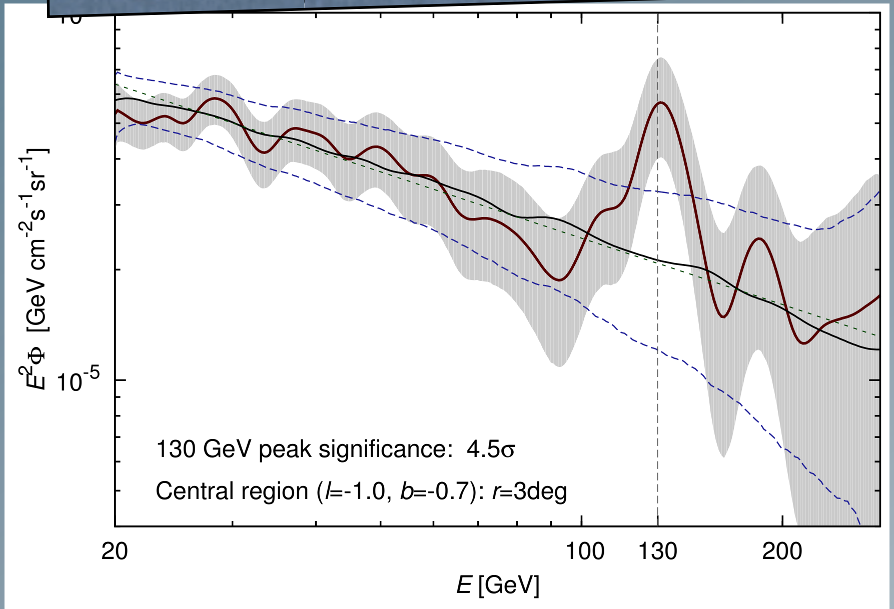

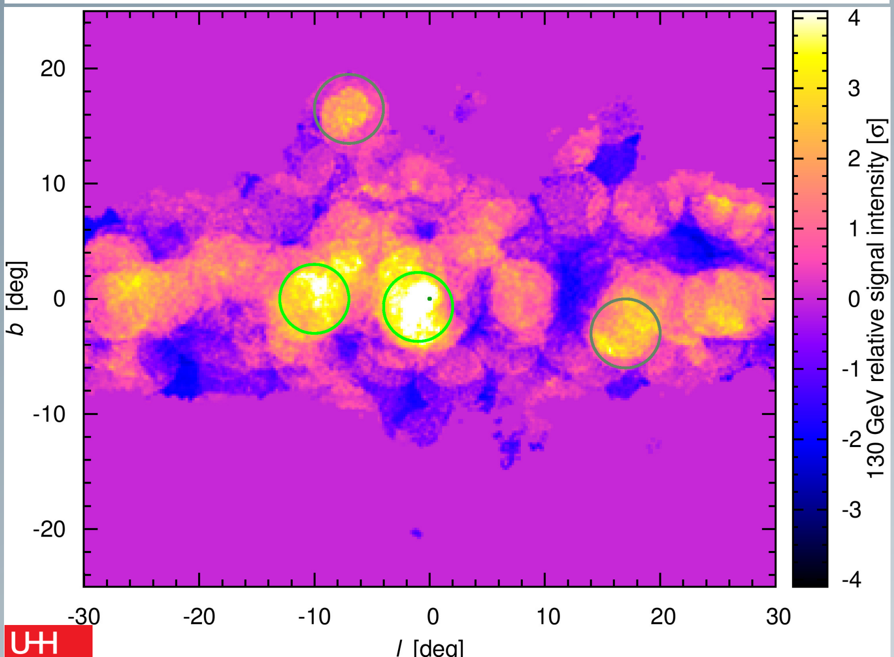

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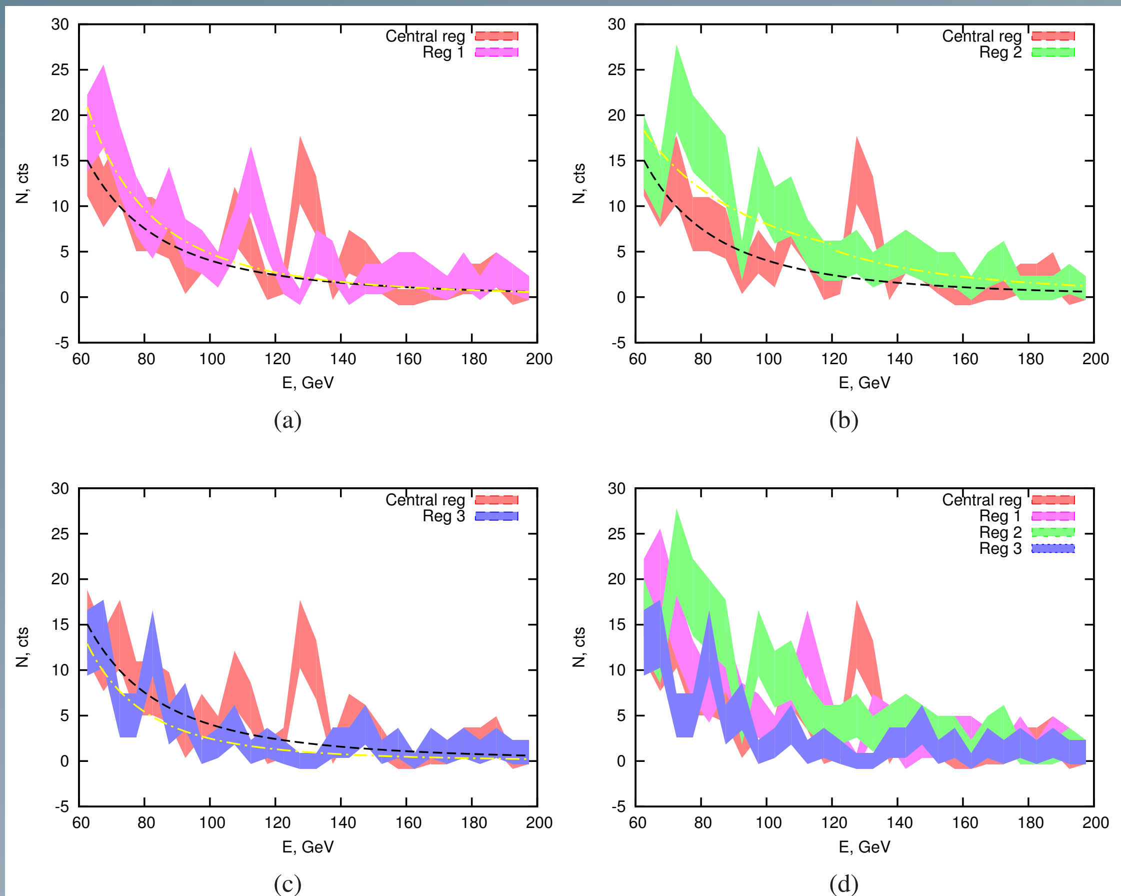
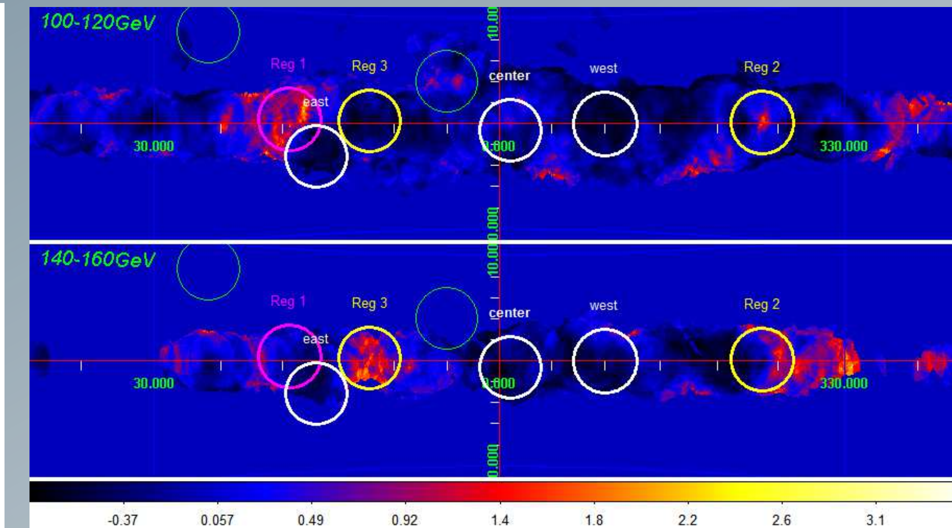
  - wide kernel for background estimate: highly consistent with -2.6 power law
  - small adaptive kernel size to look for spectral features: line-like feature found at 130GeV!
- high significance of signal
- Identify signal regions
  - several 'hot spots'
  - no correlation with Fermi bubbles!

Look-elsewhere effect (2)

Boyarsky, Malyshev & Ruchayskiy, 1205.4700





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

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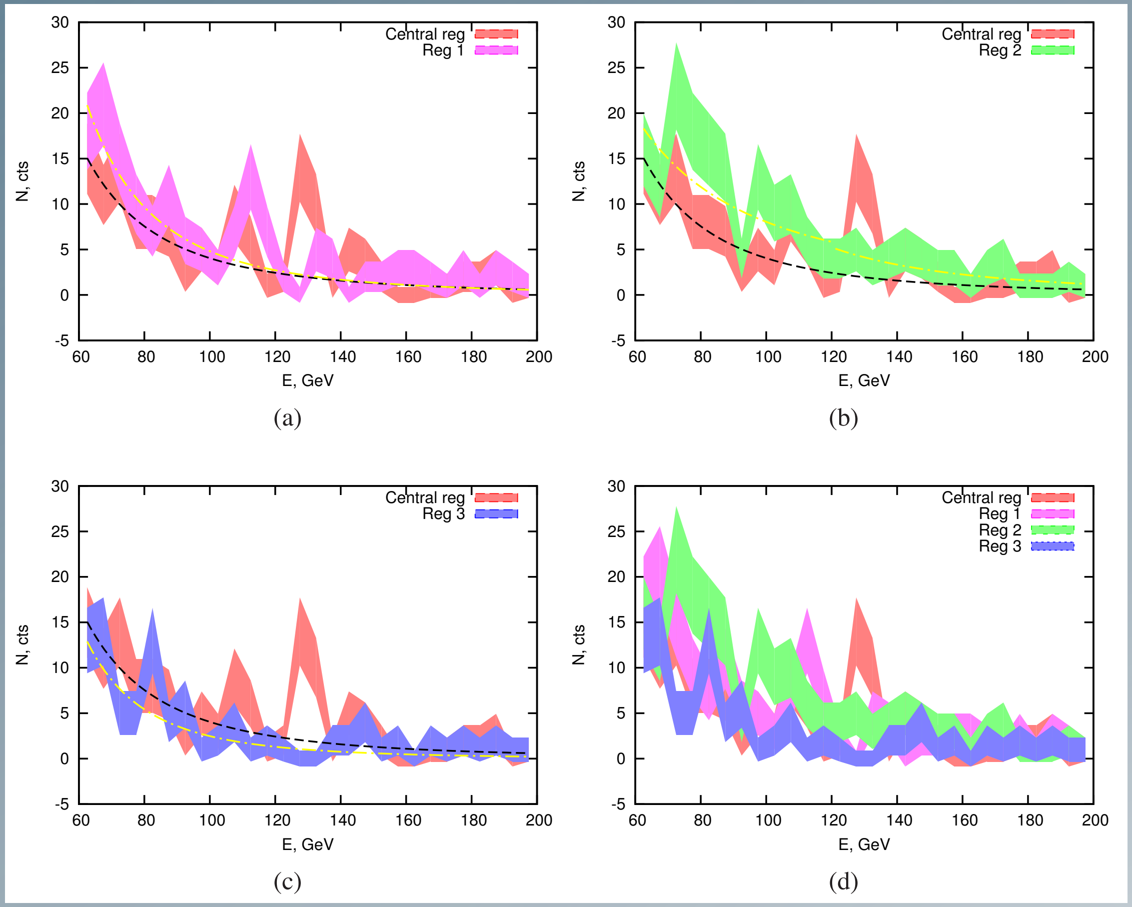
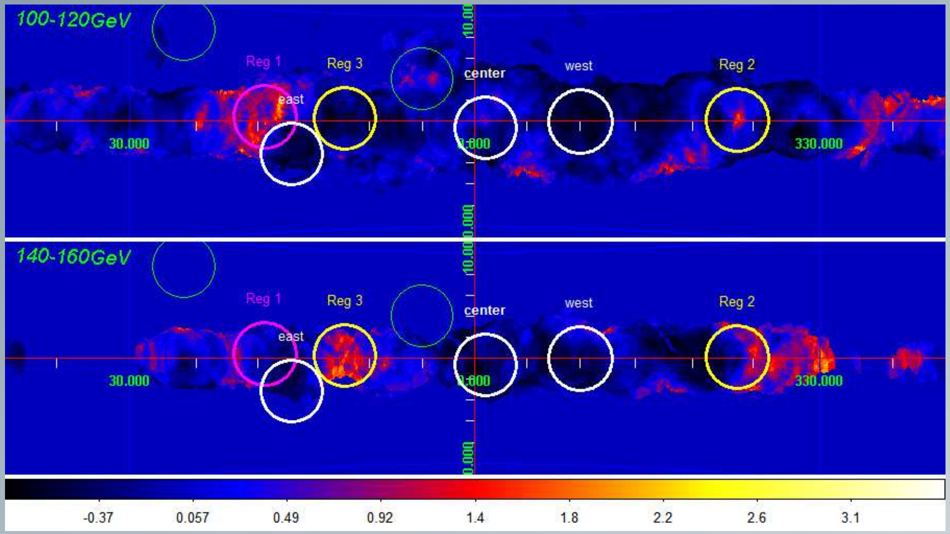


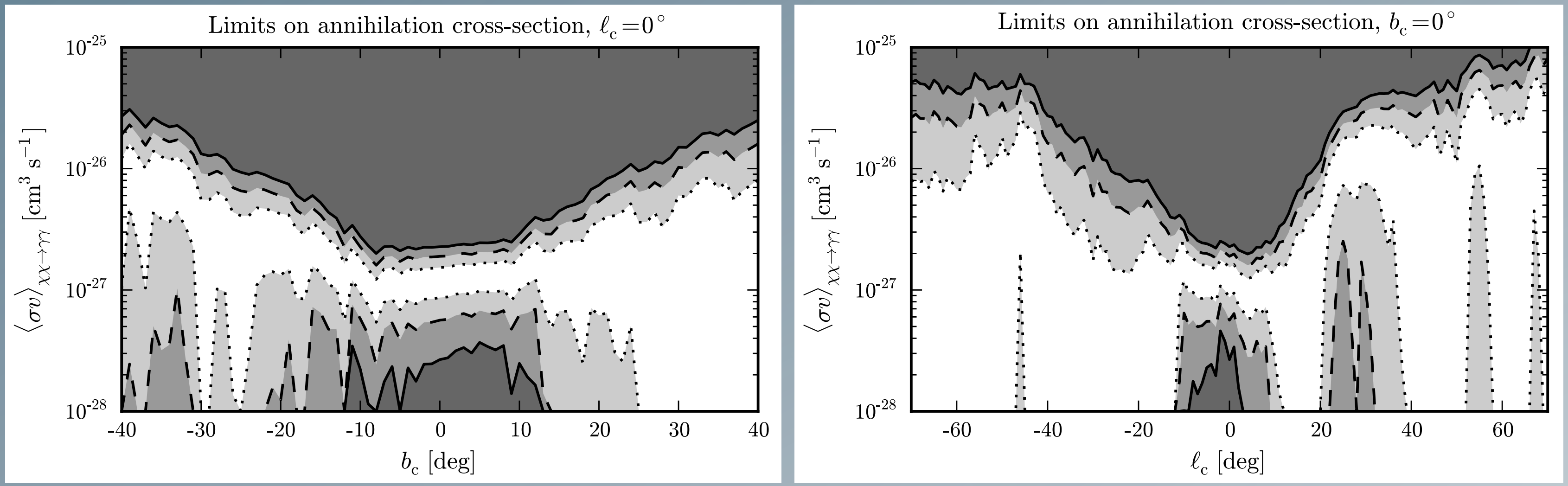


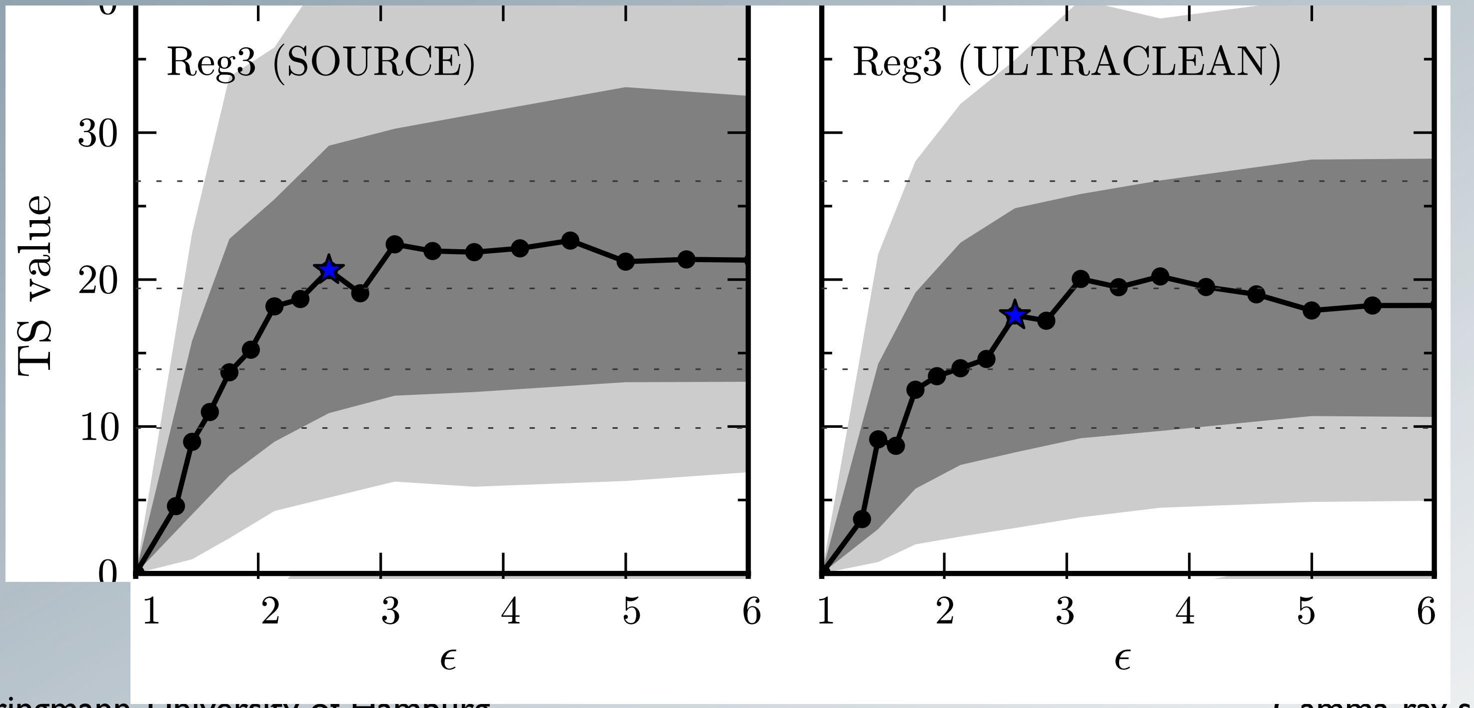
- Disk BG not a power-law/ more spectral features in other regions?

⇨ Need to carefully quantify LEE for lines!

Line analysis: more details

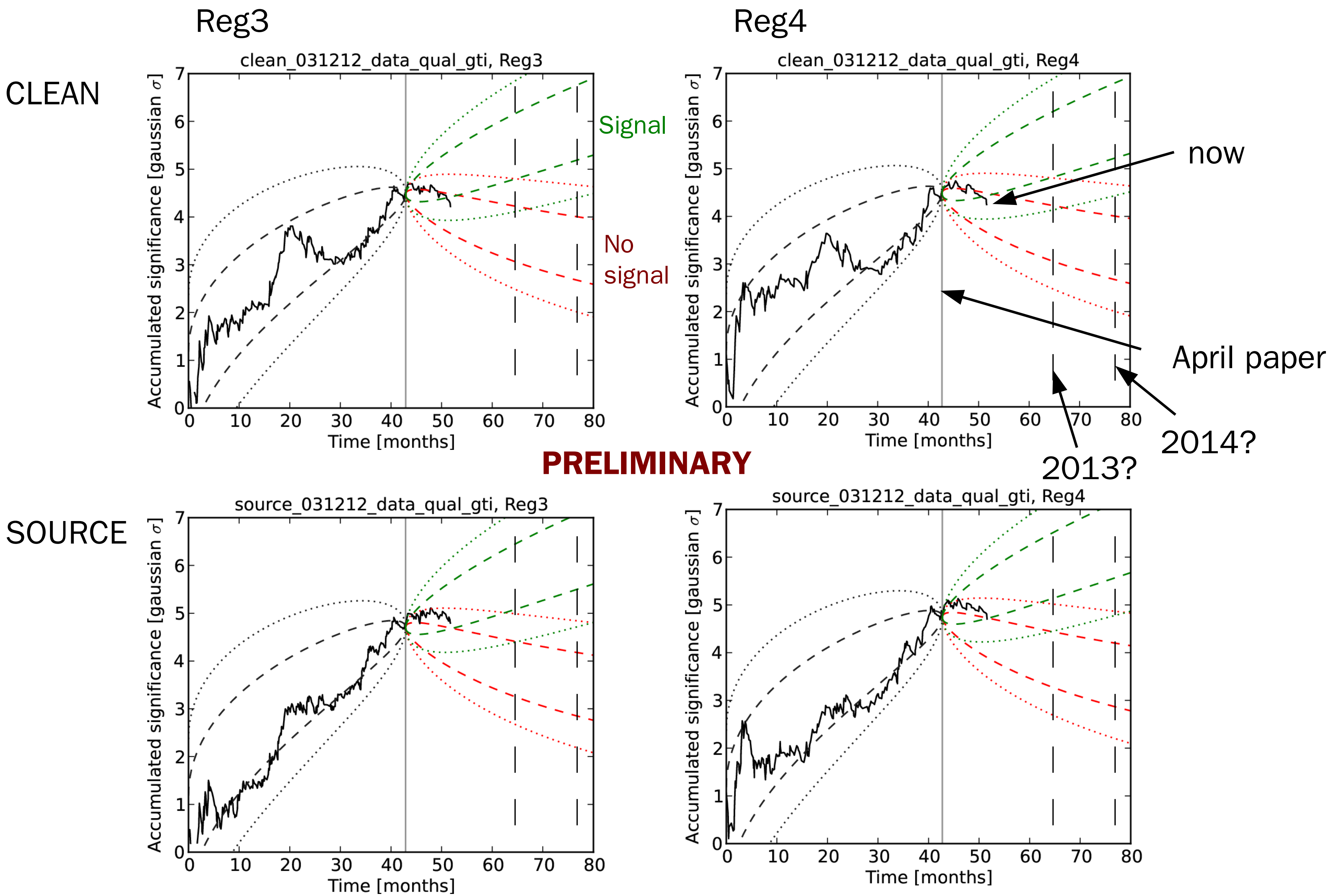
Weniger, 1204.2797





slide from C.Weniger, TeVPA '12

The fate of the 130 GeV line?



Bands: Analytical projection for ±1σ and ±2σ bands, assuming Gaussian noise with S/B~0.4 and nelgecting uncertainties in fiducial TS value; projections do not take into account expected improvements with PASS8

Fit details: 65-260 GeV energy range; 129.8 GeV line energy; 1D PDF