Exciting Dark Matter

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Outline:

- Review current observations
- INTEGRAL 511 keV line
- Inelastic scattering WIMP (XDM) model
- Consequences of the model

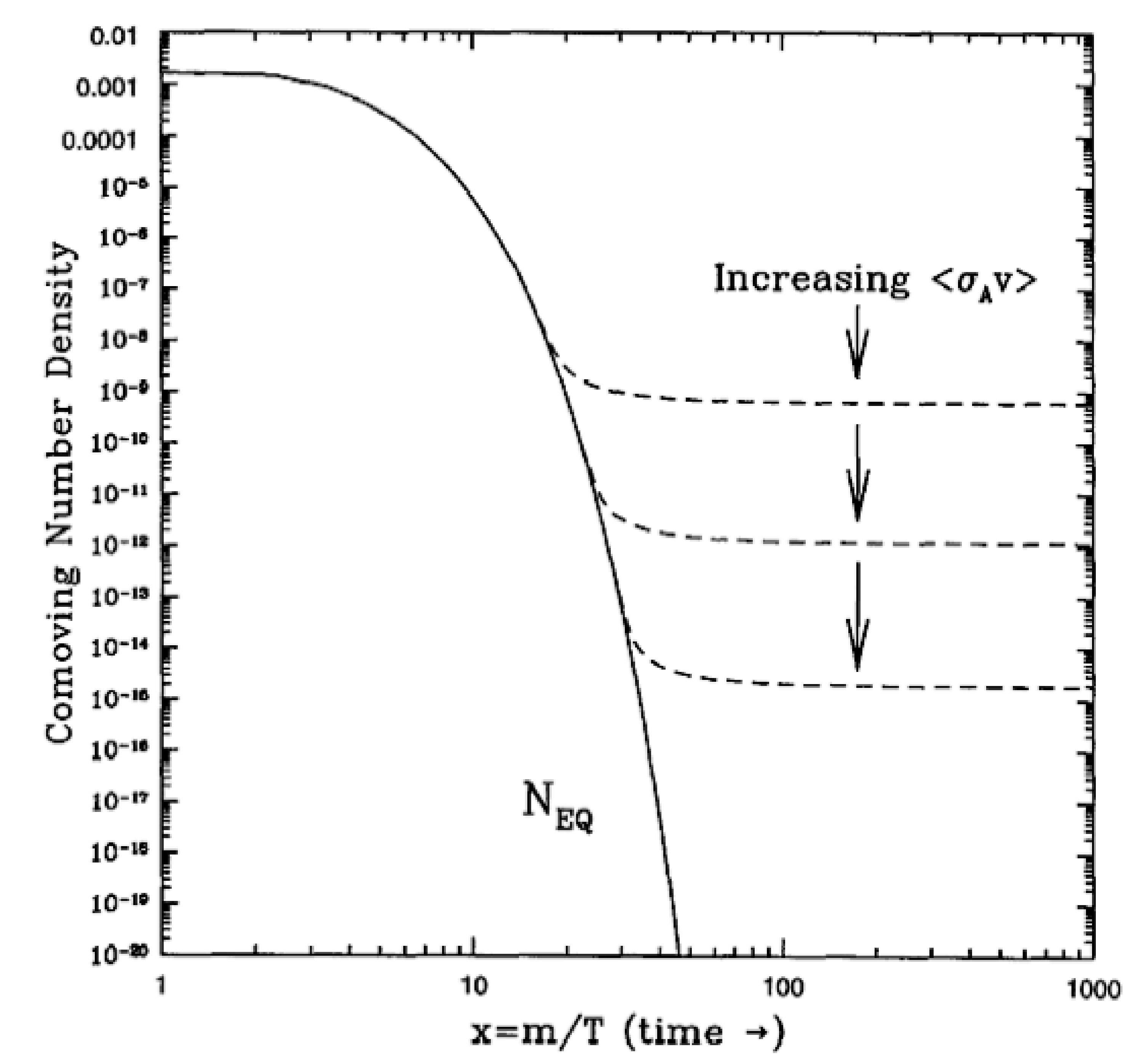
Ways of detecting WIMP dark matter:

(in order of increasing speculation)

- Gravitational force (rot. curves, lensing, CMB)
- Direct detection (e.g. nuclear scattering)
- Annihilation (gamma-rays, particles, microwaves)
- Inelastic scattering (pairs, cluster heating, BHs)

We will focus on the last two.

Dark Matter may be more than an inert substance that is gravitationally "along for the ride."



For a thermal relic of the Big Bang, relic density depends on annihilation cross section at freeze-out.

Jungmann, Kamionkowski, & Greist (1996)

After freeze out, annihilation is negligible until galaxies form and densities are relatively high again.

In the inner Milky Way, annihilation rates are high enough that the gamma-rays and synchrotron emission from annihilation products may be visible.

“Indirect detection.”

Signals have already been observed that are consistent with WIMP annihilation, though there may be (exotic) astrophysical explanations as well.

EGRET excess	(few GeV gammas, Galactic center)
HEAT excess	(10-50 GeV positrons near Earth)
WMAP excess	(microwaves from Galactic center)
OSSE excess	(511 keV gammas from GC)

This is an exciting time in high energy astrophysics.
Each of these is being replaced by a new project:

EGRET -- GLAST (5th or 6th quarter, 2007)
HEAT -- PAMELA (in orbit, announce any day now?)
WMAP -- Planck (launch in 2008?)
OSSE -- Integral (results are in)

Some of these signals are tentative, but fit in nicely with WIMP annihilation scenarios. If future projects confirm these excesses, then WIMP annihilation must be taken seriously as a possible explanation.

The 511 keV line is the exception. Until recently, no weak-scale WIMP has been able to explain it.

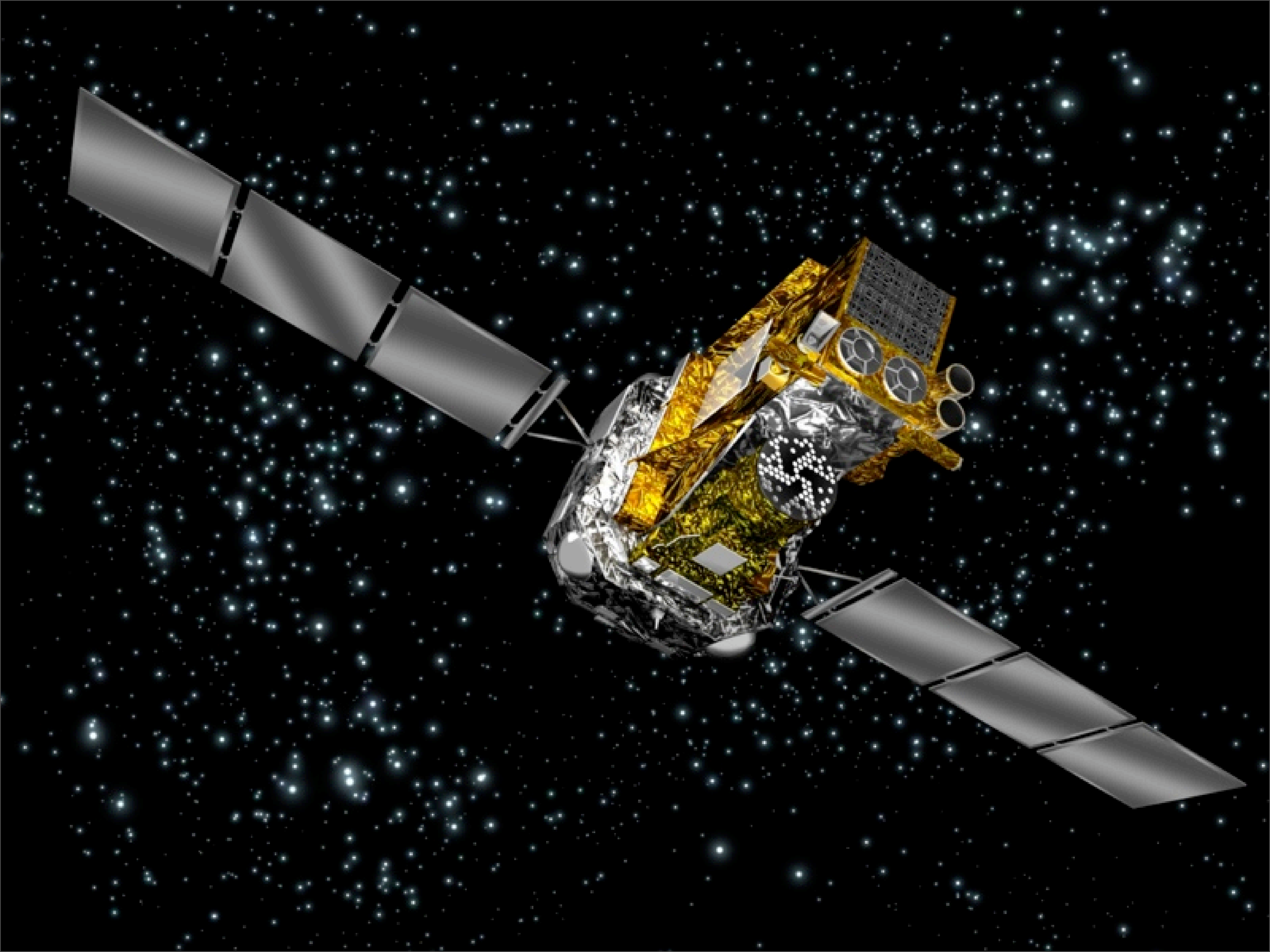
Let's consider the 511 keV line / continuum from positron annihilation, observed by many balloon and satellite experiments, most recently CGRO/OSSE and INTEGRAL / SPI (Weidenspointner et al., Knoedlseder et al. ...)

The unexplained excess is roughly a 6 deg FWHM Gaussian with a total of
3×10^{42} pairs/s = 3×10^{39} GeV/s = 5×10^{36} erg/s

This is very roughly the power from the bulge region dissipated by the haze electrons, EGRET excess, etc. Is this a coincidence?

Integral / SPI: (spectrometer)

- Energy range: 20 keV - 8 MeV
- Detector area: 500 cm^2
- Field of view: 16 deg (fully coded)
- Angular resolution: 2.5 deg FWHM
- Launched: 2002 Oct 17
- Still operating...

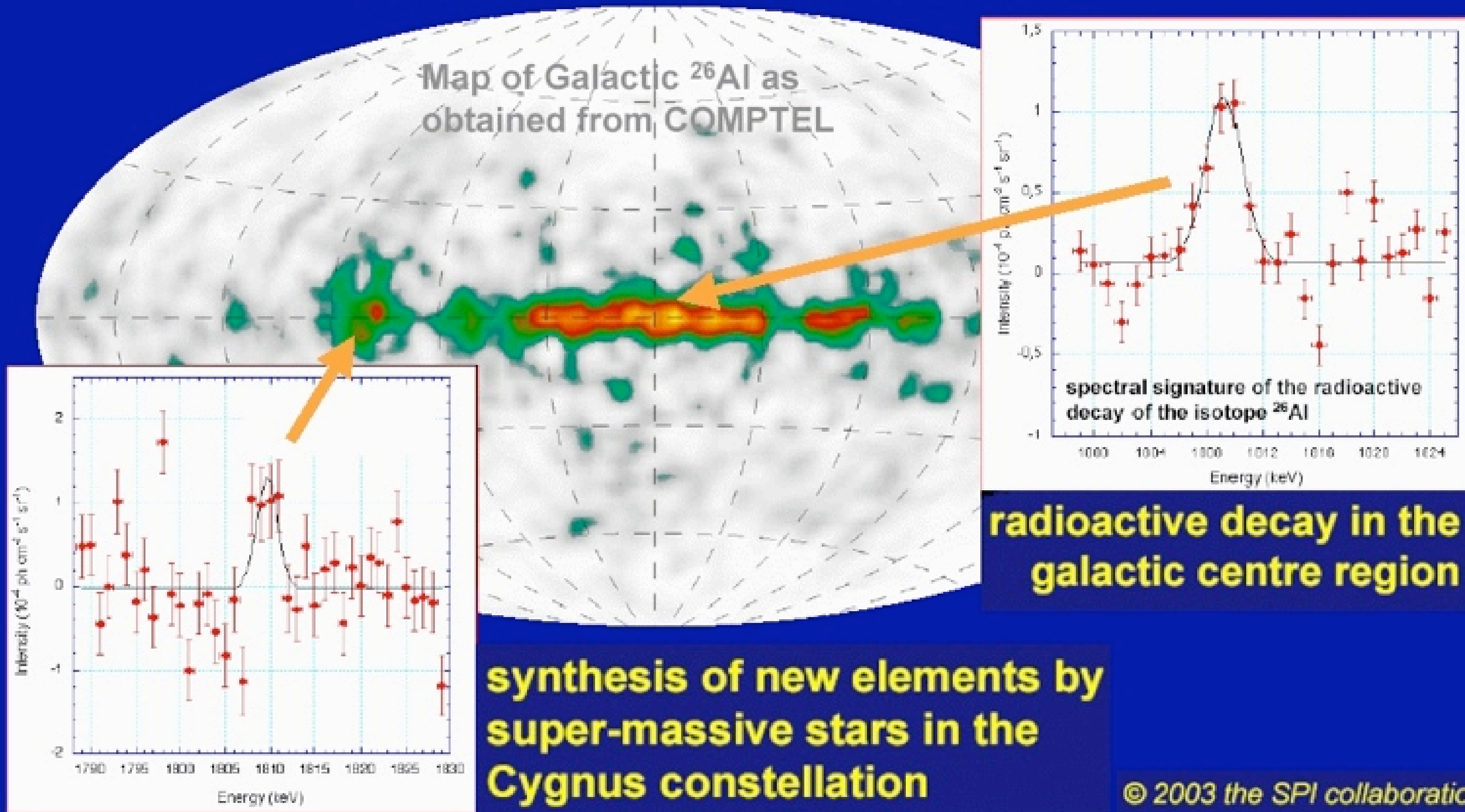


With this spectrograph, one can look at the 1.8 MeV ^{26}Al line, the 511 keV e^+e^- line, etc.

^{26}Al traces massive star formation (i.e. SNe) half life is ~ 10^6 years.

Radioactive ^{26}Al in the Galaxy

- first results from SPI/INTEGRAL -



- Most (92+-8%) of the positrons form positronium (Ps, an e^+e^- atom) before annihilating. (Weidenspointner 2006,2007)

- 3/4 are ortho-Ps and annihilate to 3 photons
- 1/4 annihilate to 2 photons (511 keV line)

Weidenspointner (2006)

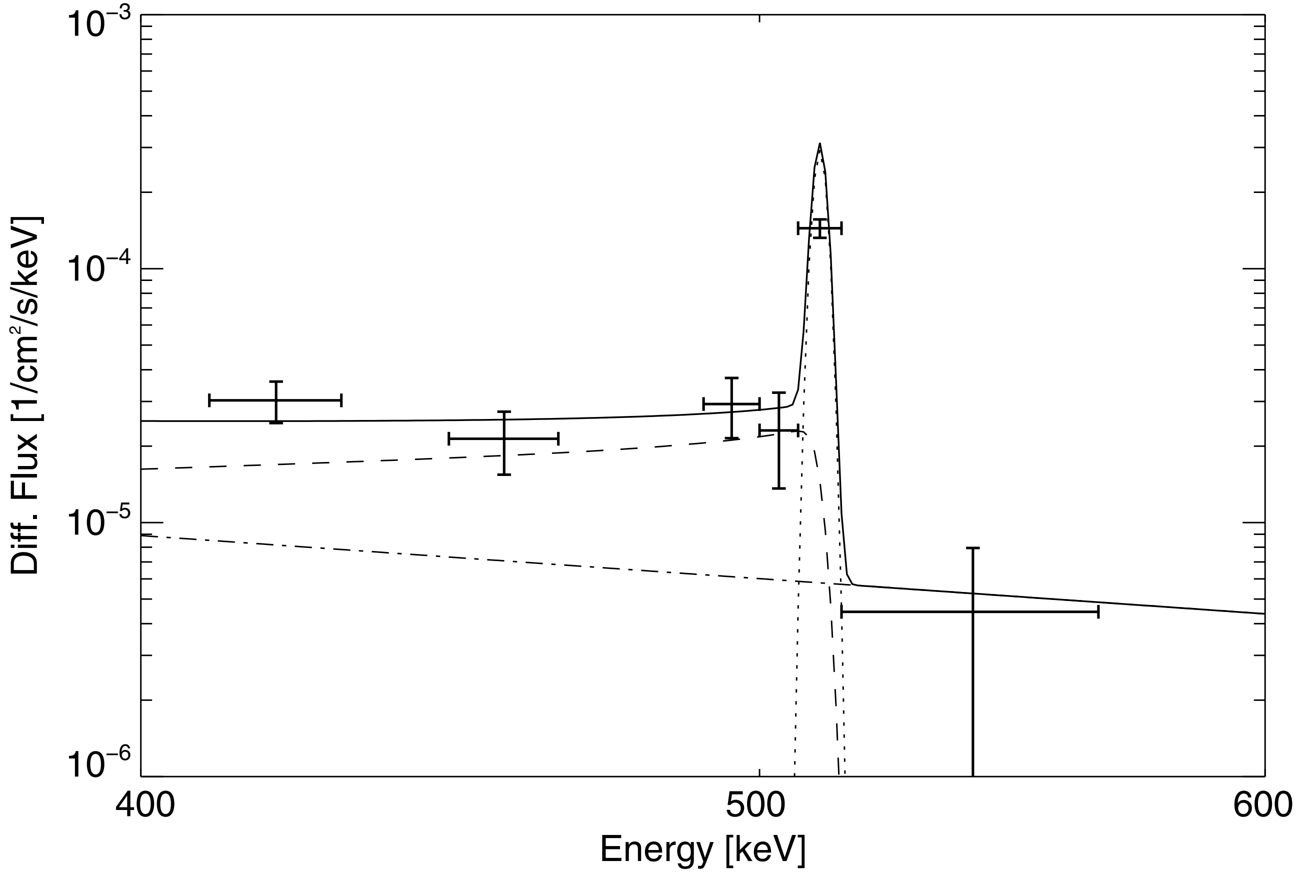


Fig. 2. A fit of the SPI result for the diffuse emission from the GC region ($|l|, |b| \leq 16^{\circ}$) obtained with a spatial model consisting of an 8° *FWHM* Gaussian bulge and a CO disk. In the fit a diagonal response was assumed. The spectral components are: 511 keV line (dotted), Ps continuum (dashes), and power-law continuum (dash-dots). The summed models are indicated by the solid line. Details of the fitting procedure are given in the text.

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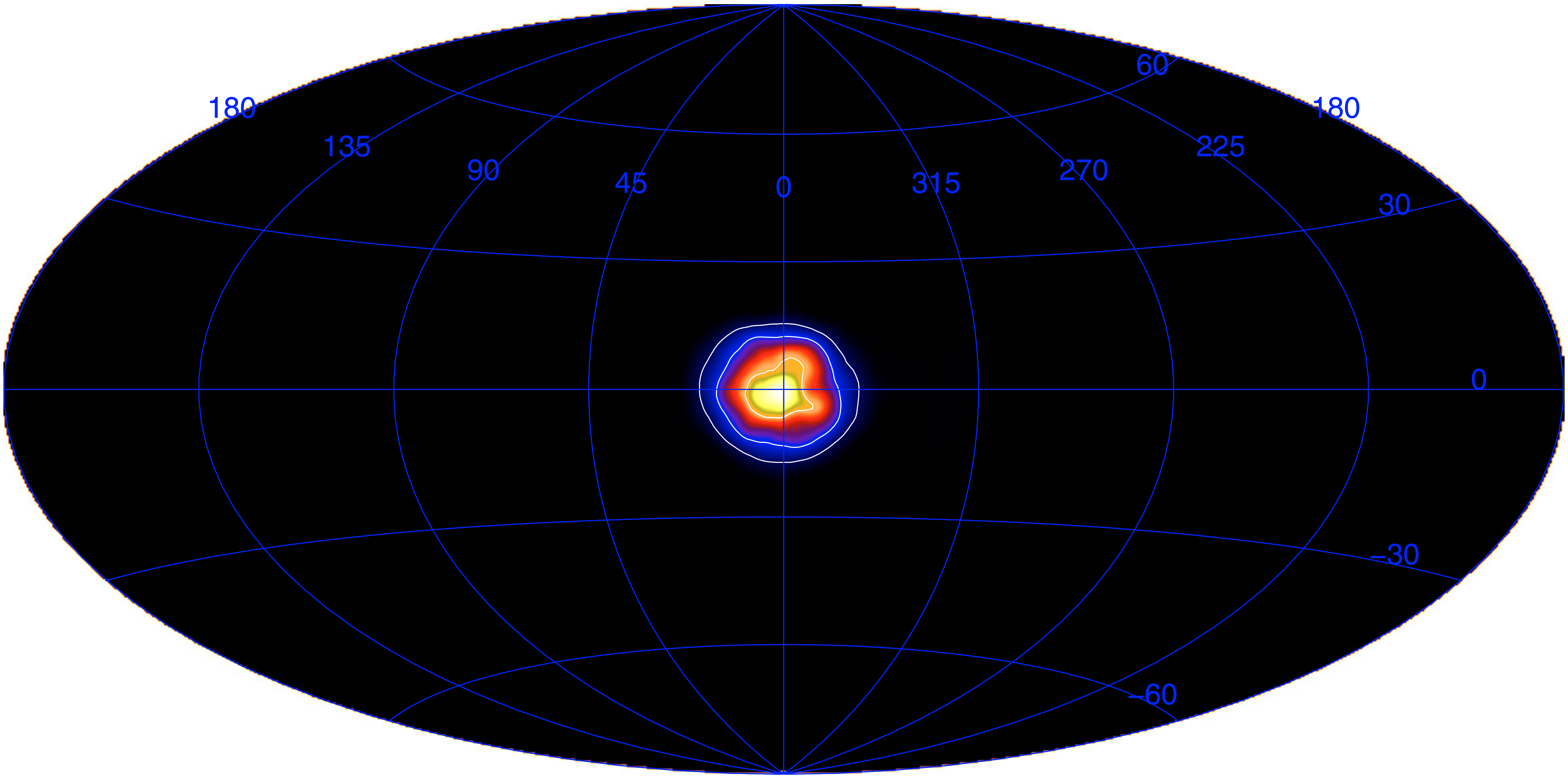
- Does the Ps emission trace star formation also?

(2006)

G. Weidenspointner et al.: The sky distribution of positronium continuum emission



No.

- The positronium signal is centrally concentrated.
- There is a disk component, but much fainter.
- The disk component is roughly what we expect from SNe Ia; the bulge component is 10 times brighter than expected.

- Kalemci et al (2006) find positron escape fraction is too low anyway.
- After 37 years of work, we don't know where the positrons come from.

- LDM (light dark matter, mass ~ 3 MeV) annihilation has been proposed (Boehm et al. 2004) but DM at this mass scale is not well-motivated.

- Weak-scale DM (mass ~ 100 GeV - 1 TeV) is better motivated, "naturally" has the right cross section to give the correct thermal relic density. Annihilation in MW even gives enough power to make the SPI signal!

- But... must cascade each e^+e^- pair to produce ~ 10^4 low-energy pairs.

- Cascade requires column densities of ~ 10^{27} cm^{-2}

Weak-scale DM annihilation doesn't work.
LDM annihilation does work, but seems a bit contrived.

Ideally, we would stick to models with "deep roots" in physics - but can't find any that explain the data.

If we are going to *engineer* a particle to solve the problem, maybe we can do better.

Let's try something... *exciting!*

IDEA: eXciting Dark Matter (XDM)
K.E. of pair of 500 GeV WIMPs moving
at relative speed of 850km/s = 1 MeV

If WIMPs have a ground state & excited state,
with ~ MeV mass splitting, they could collisionally
excite and decay to ground-state WIMP plus e^+e^-.

e.g. neutron-protron mass difference, split by a weakly
broken isospin symmetry. Mass splitting << mass;
protected against radiative corrections by the
approximate symmetry.

Let's try the same thing... arXiv:astro-ph/0702587

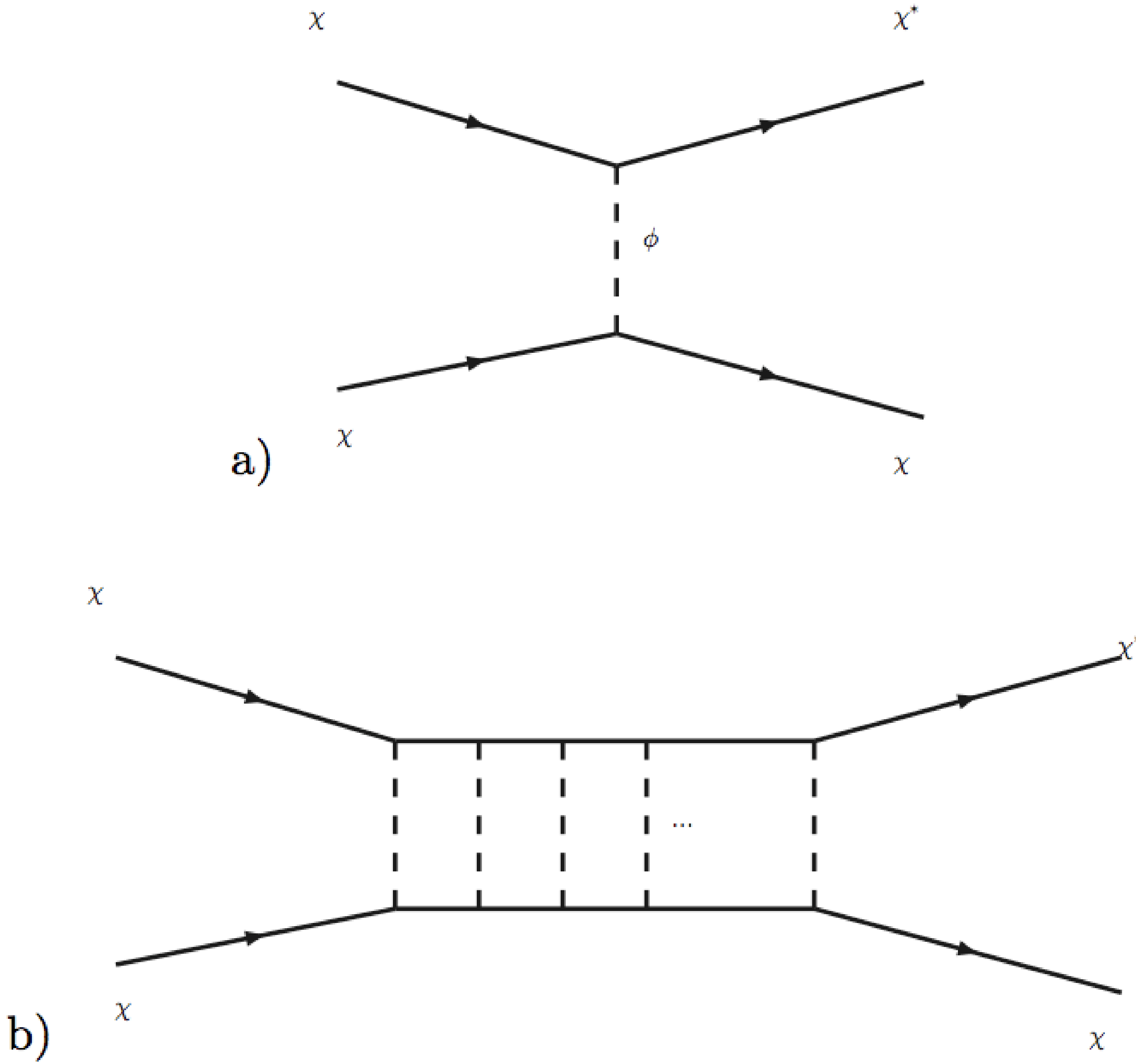


FIG. 4: Excitation diagrams for $\chi\chi \to \chi^*\chi$.

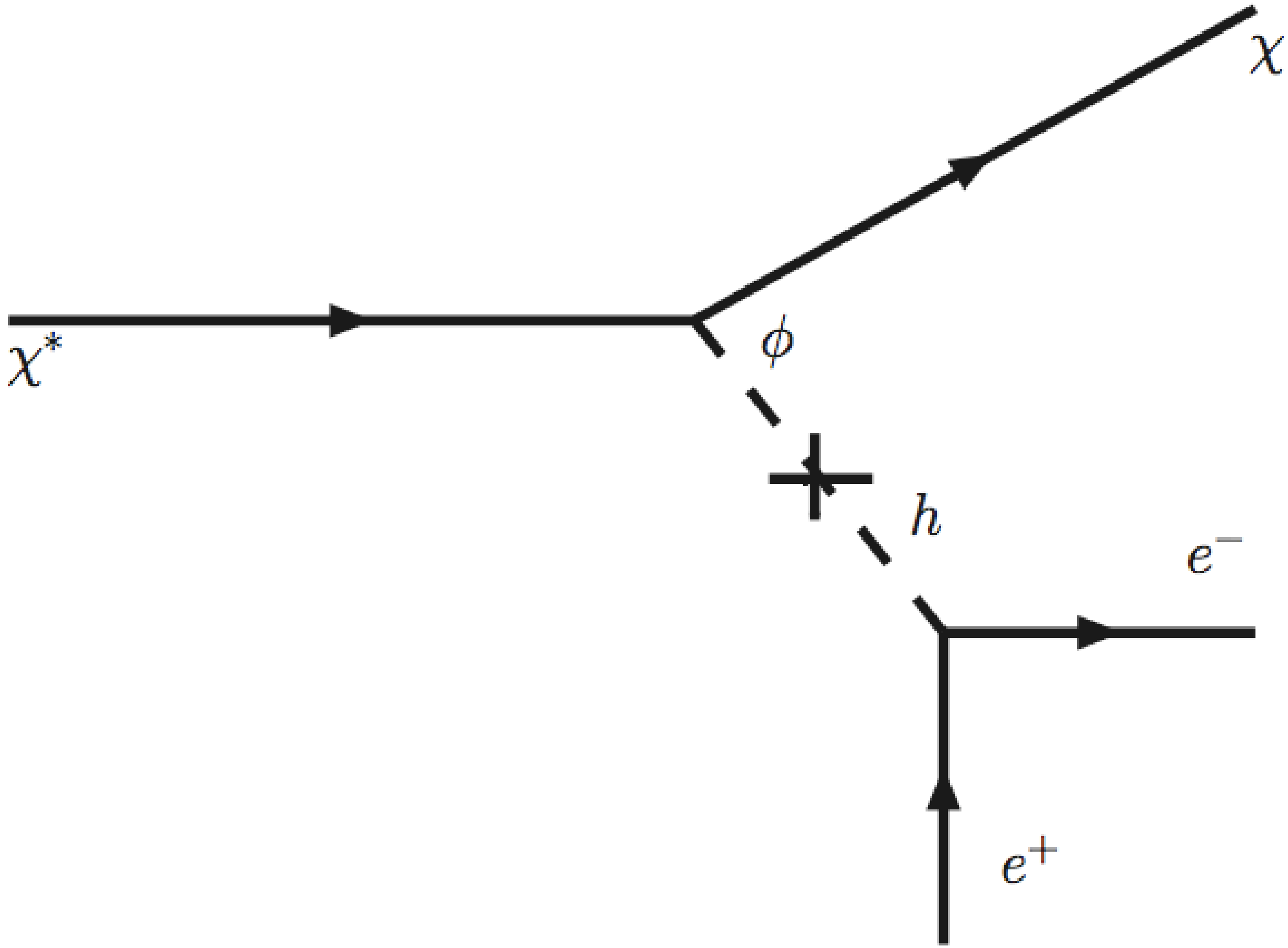


FIG. 5: Decay of the excited state into the ground state.

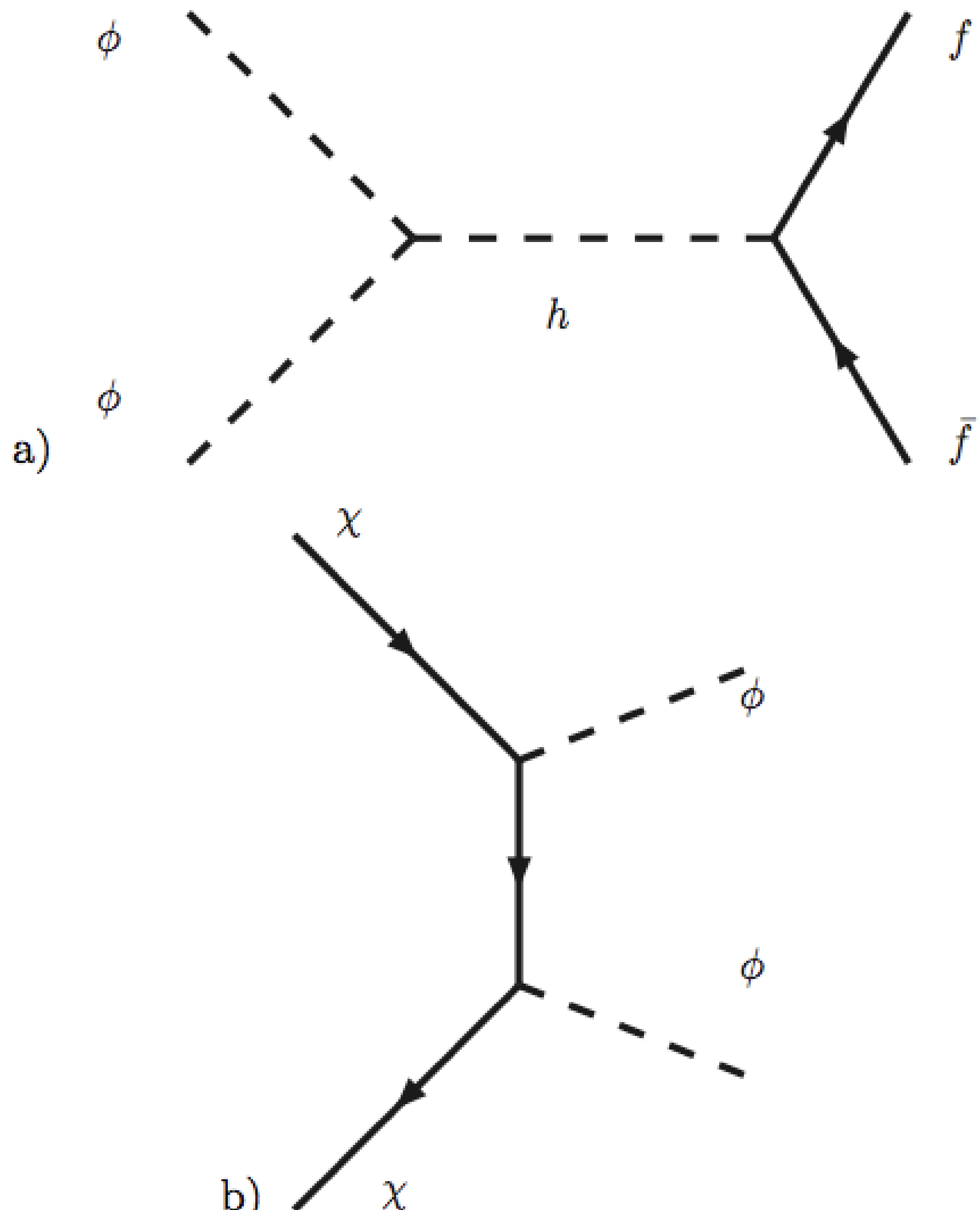


FIG. 6: Diagrams contributing to thermal equilibrium in the dark sector and between the dark sector and the visible sector.

Other details:

ϕ boson has mass of ~ 10-100 MeV, correct cross-section for scattering (~ 10^{-26} cm^2)

BBN results are unchanged. (mostly!)

Interactions between χ, ϕ keep χ in thermal equilibrium until freeze-out; no change to thermal relic calculation (other than we have 2 species!)

Weak-scale annihilation cross section gives correct density to be the DM (determined by gauge coupling)

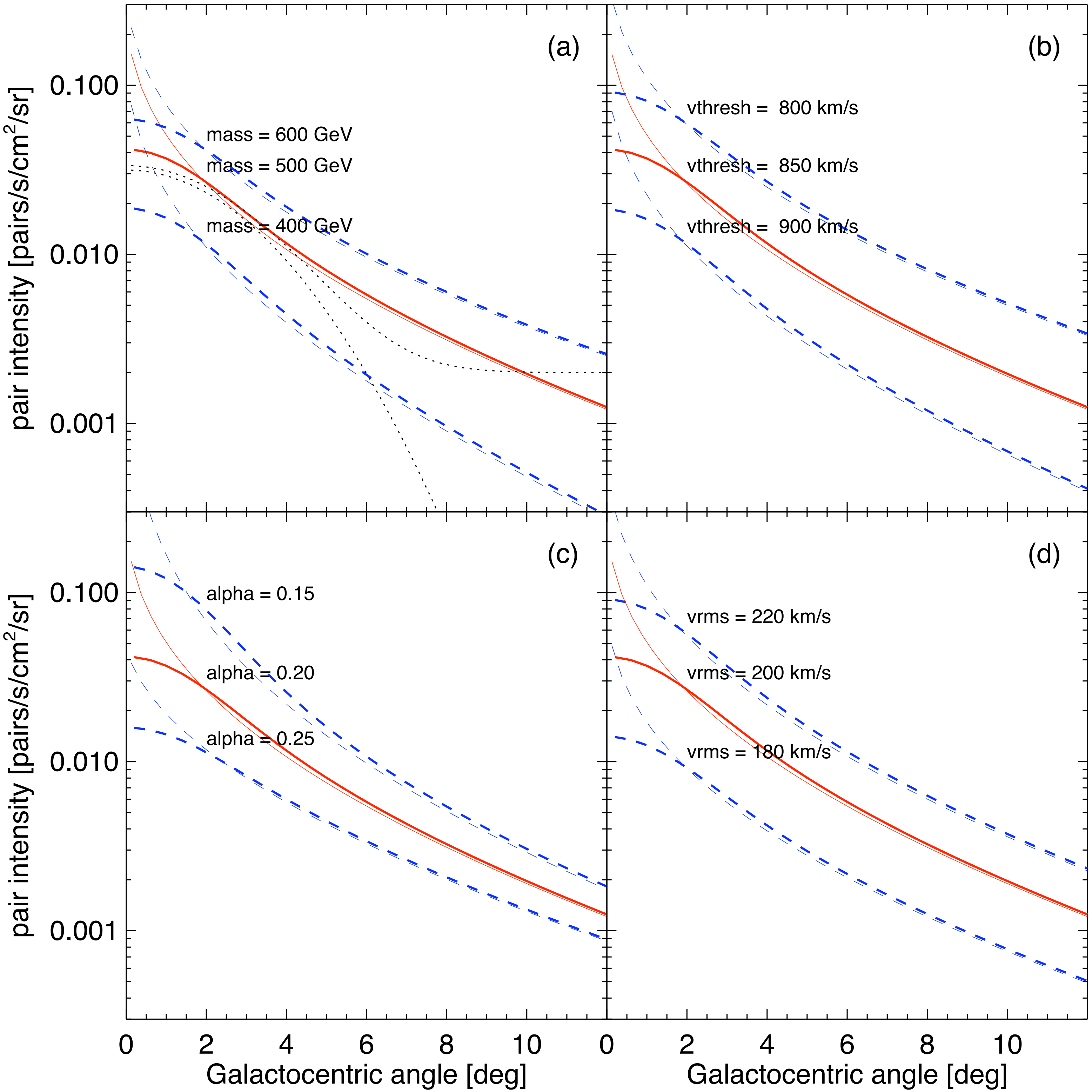
Important point:

Excitation arises from exchange of relatively light boson, so naturally has larger cross section than annihilation
(which is suppressed by the WIMP mass)

$\sigma_{\mathrm{ann}} / \sigma_{\mathrm{scatter}} \sim 10^{-5}$
$\delta / M \sim 10^{-5}$

This feature is essential to the success of XDM.

So, how does the model compare to INTEGRAL?



(a)
(b)
(c)
(d)
mass = 600 GeV
mass = 500 GeV
mass = 400 GeV
vthresh = 800 km/s
vthresh = 850 km/s
vthresh = 900 km/s
alpha = 0.15
alpha = 0.20
alpha = 0.25
vrms = 220 km/s
vrms = 200 km/s
vrms = 180 km/s
pair intensity [pairs/s/cm²/sr]
0.100
0.010
0.001
0
2
4
6
8
10
Galactocentric angle [deg]

Why is there only ~ one parameter to tune?

The mass of the ϕ determines both the scattering cross section AND the χ mass splitting.

This is a very appealing feature of the model.

We use a fairly large coupling constant (0.18) which requires resumming the ladder diagrams, but gives a nice cross section without violating the unitarity bound.

What else would such a model be able to do?

Because WIMP annihilation goes via two highly boosted ϕ particles, we get mainly e^+e^- because the ϕ is light.

We should produce enough electrons to produce the WMAP "microwave haze." (see previous talk by G. Dobler)

The original naive "model" of mine to explain the microwave haze with WIMP annihilation assumed that WIMPs annihilate directly to e^+e^- with efficiency of order 10-100%.

You can't do this in the MSSM. But XDM does.

The ϕ mixing to h gives branching ratio of ~100% to e^+e^- (if ϕ lighter than 2 muons)

i.e. our χ particle has a weak-scale annihilation cross section to e^+e^- !

We find exactly what we need, without having contrived anything -- or even expecting it to work!

This would be less interesting if the model had been designed to solve the *haze* problem, but it was designed to solve the *Integral 511 keV* problem, and inadvertently explained the haze also.

Does this imply some deeper connection between these two problems? Maybe.

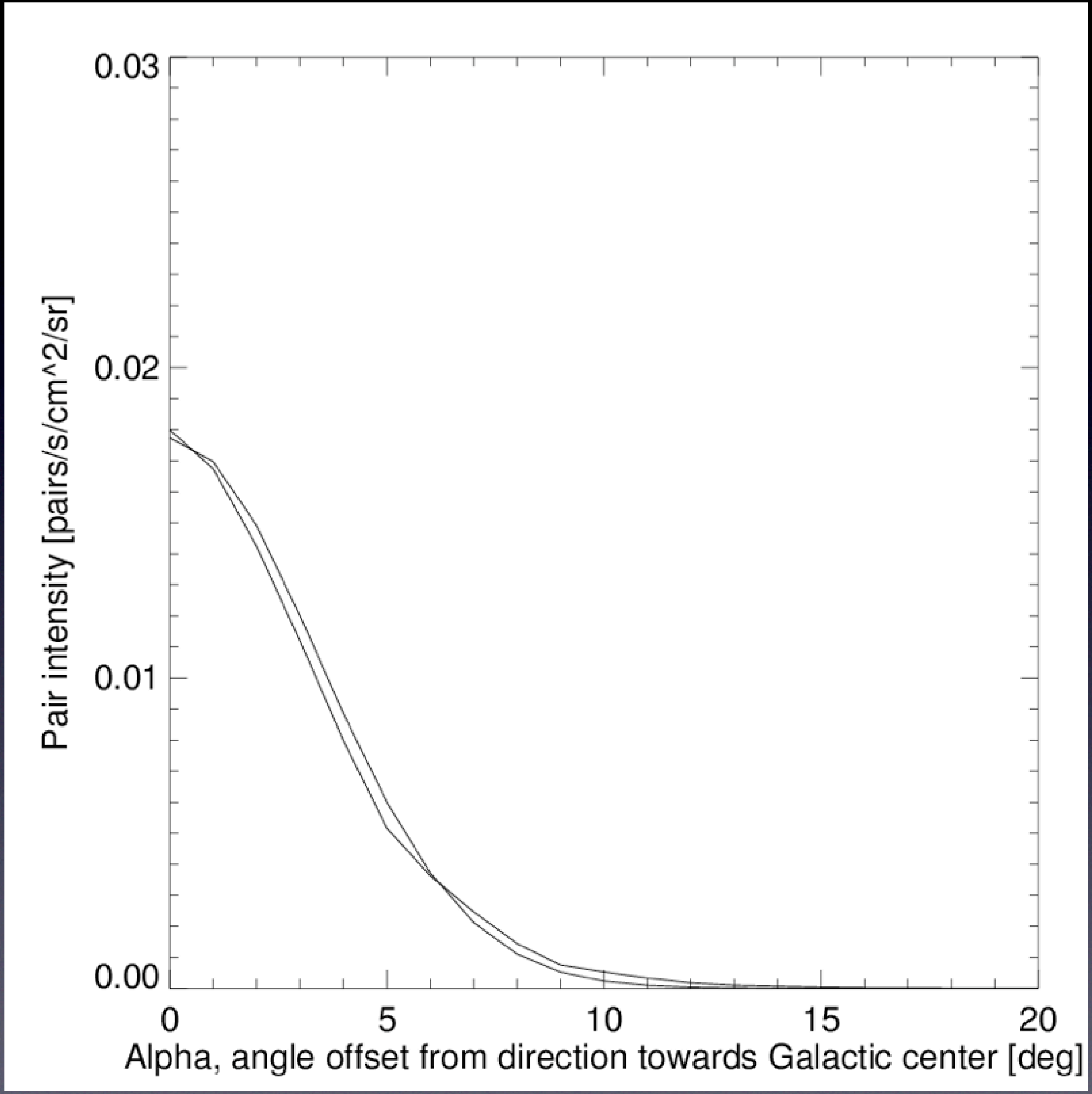
So far, we have tried the simplest (NFW) model with essentially no parameters, then a -1.2 index, a Merritt profile...

Are there just too many choices being made here? There are many free parameters, and we must insist on (at least!) a self-consistent solution.

One way is to tie to a simulation, such as the Milky Way simulation of Governato et al. (2007)

Which is the real galaxy?

Chris Brook, SUNRISE radiative transfer code



Finkbeiner, Dobler, & Satinover (2007)

Potential observable consequences:

- Cluster heating
- BH formation / super-Eddington accretion
- high-z 21 cm
- Make ϕ in accelerators?

- Also, GLAST, PAMELA, LHC, etc...

Cluster heating:

Because of velocity dependence, might get much more excitation in massive clusters (but not more than 1-2 orders of magnitude more).
This would then provide a source of significant heating. (via scattering, Alfven wave excitation, etc.)

In extreme cases, the non-thermal tail of the electron energies would distort the SZ effect.

BH formation:

Need seed BH of 200 Msun at z=30 or 10^4 Msun at z=15 (Li, Hernquist, etal) in order to make z=6.4 SDSS quasar.

DM should collapse inside of radius where
$t_H n\sigma v > 1$
yielding BH in the *very largest halos* even at early times (i.e. as soon as they collapse).

(Greg Dobler, Nikhil Padmanabhan)

High-z 21cm observations (MWA, LOFAR, etc.)

The possible formation of BHs at early times should ionize bubbles in the HI.

Later, the heating from the pairs in large halos may also cause some additional ionization.

(Matt McQuinn)

Make ϕ in Accelerators?

Hard to do, since coupling can be *very* weak.
But... 10-100 MeV has not been "cutting edge"
for decades. Would anyone have seen the signal?

(Greg Dobler)

Conclusions:

We have proposed a WIMP with two nearly degenerate mass states, resulting from a weakly broken symmetry. Collisions cause transitions to the "excited" state; decay emits e^+e^- pair.

I have described one model, a Majorana fermion, that does this.

The XDM idea is more general than this,
i.e. there are other realizations of this basic scenario.

Conclusions:

Any XDM model has the potential to explain:

- 511 keV line
- WMAP microwave excess
- EGRET gamma-ray (~10 GeV) excess
- HEAT positron (50 GeV) excess

... and possibly other astrophysical mysteries

There is a rich phenomenology from both particle physics and astrophysical perspectives.
This class of models is worth exploring in detail.

Astrophysics

Exciting Dark Matter and the INTEGRAL/SPI 511 keV signal

Douglas P. Finkbeiner (CfA), Neal Weiner (CCPP, NYU)

(Submitted on 21 Feb 2007 (v1), last revised 10 May 2007 (this version, v3))

We propose a WIMP candidate with an ``excited state'' 1-2 MeV above the ground state, which may be collisionally excited and de-excites by e+e- pair emission. By converting its kinetic energy into pairs, such a particle could produce a substantial fraction of the 511 keV line observed by INTEGRAL/SPI in the inner Milky Way. Only a small fraction of the WIMPs have sufficient energy to excite, and that fraction drops sharply with galactocentric radius, naturally yielding a radial cutoff, as observed. Even if the scattering probability in the inner kpc is << 1% per Hubble time, enough power is available to produce the ~3x10^42 pairs per second observed in the Galactic bulge. We specify the parameters of a pseudo-Dirac fermion designed to explain the positron signal, and find that it annihilates chiefly to e+e- and freezes out with the correct relic density. We discuss possible observational consequences of this model.

Comments: 11 pages; v2 references added; v3 updated model to allow for single excitations and calculation of single excitation cross section; updated halo profiles; references added; conclusions unchanged
Subjects: Astrophysics (astro-ph); High Energy Physics - Phenomenology (hep-ph)
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