Exciting Dark Matter

Doug Finkbeiner
Harvard Center for Astrophysics

with Neal Weiner, NYU Physics

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Outline:

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

Ways of detecting WIMP dark matter:

(in increasing degree of speculation)

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

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

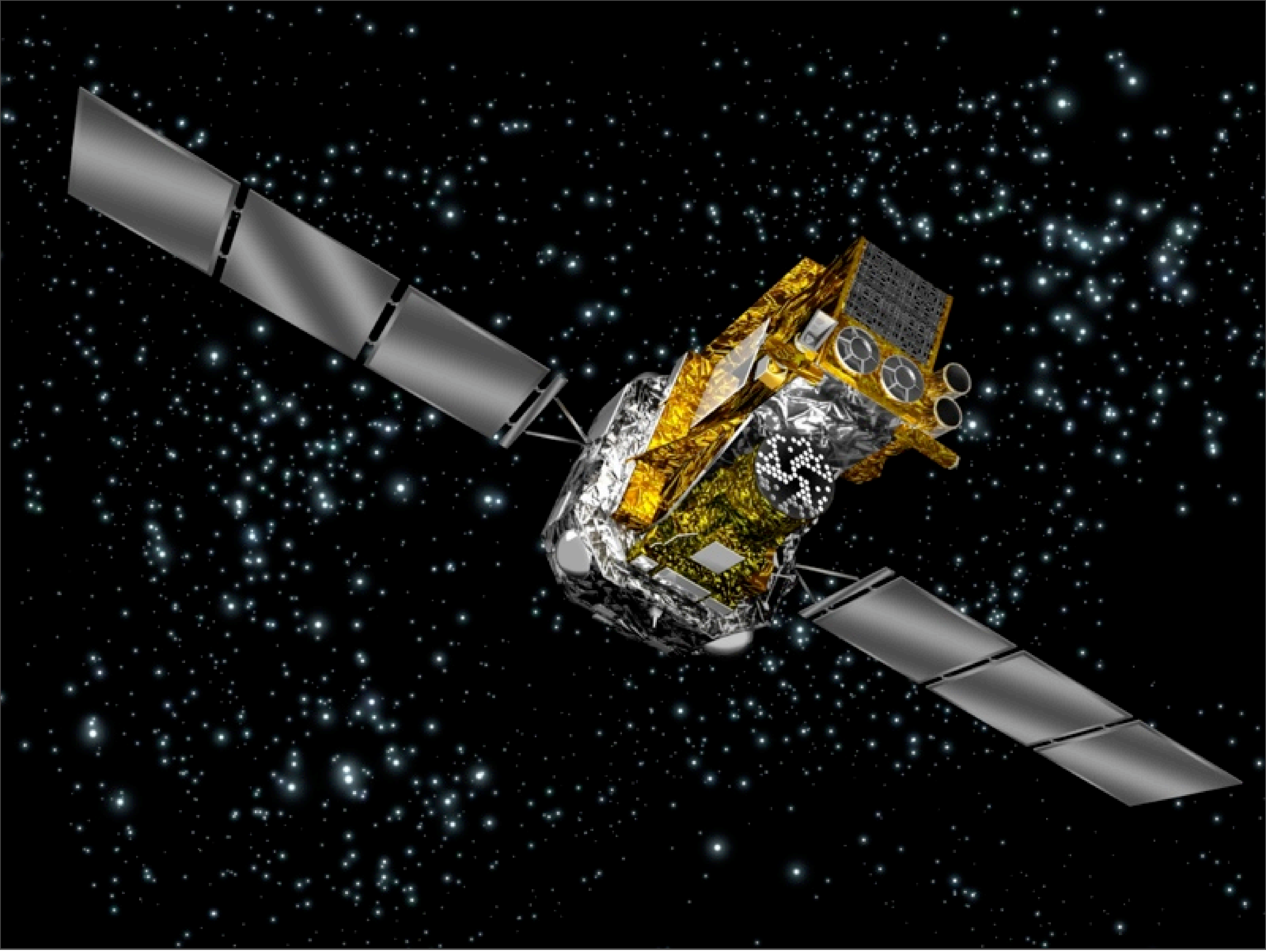
Consider the 511 keV line / continuum from positron annihilation, observed by many balloon and satellite experiments, most recently CGRO/OSSE and INTEGRAL / SPI (Weidenspointner et al., Knoedlseder et al. ...)

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?

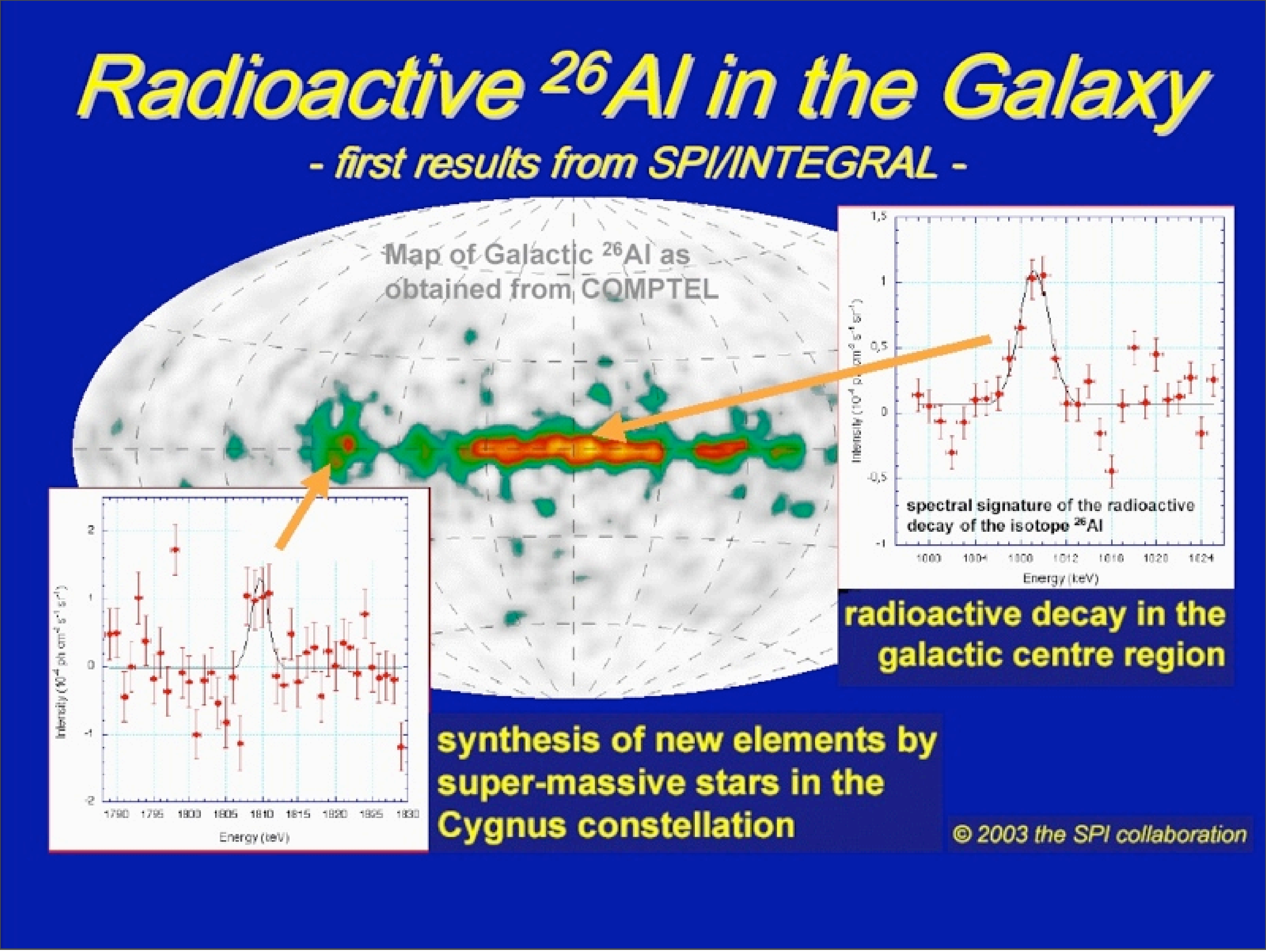
Integral / SPI: (spectrometer)

- 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...



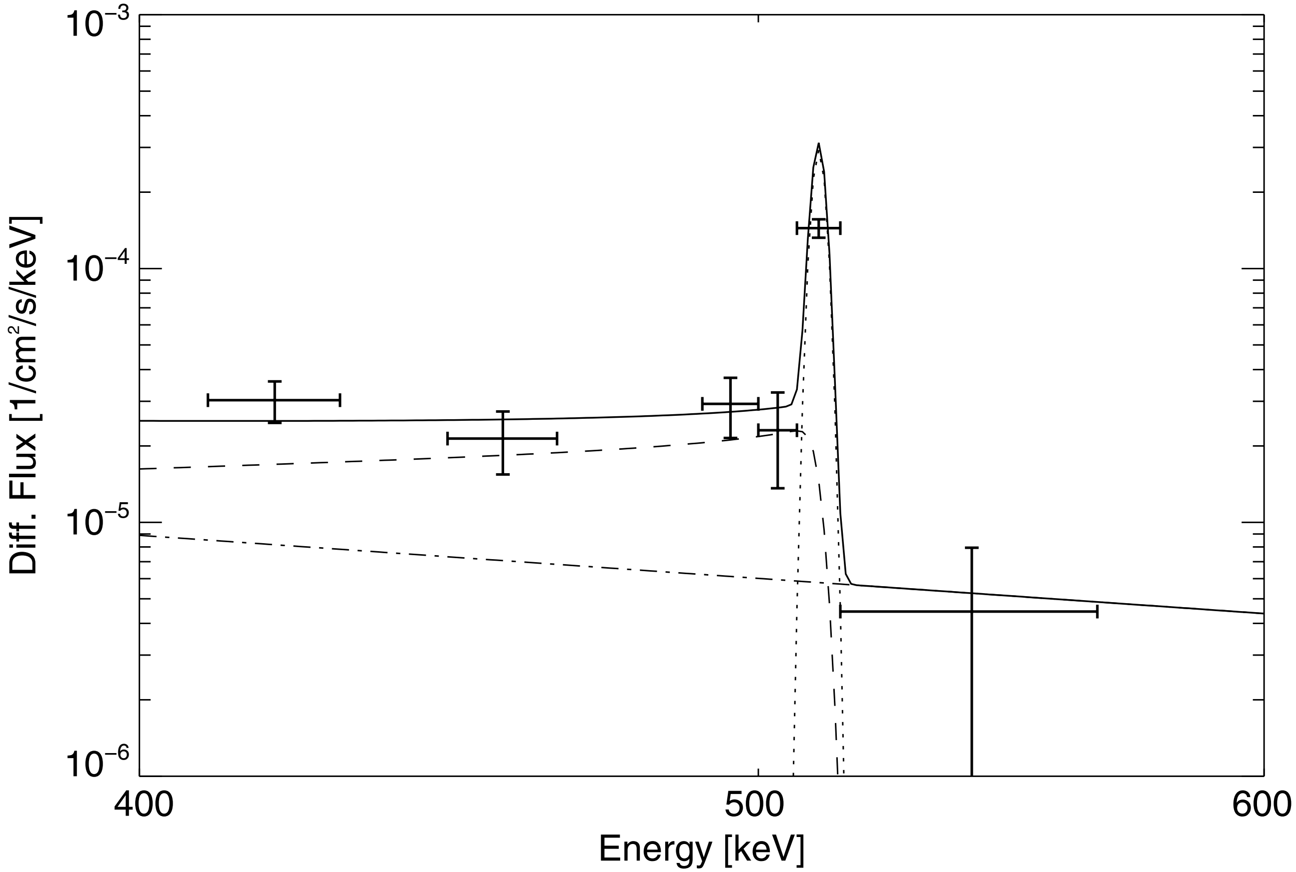
With this spectrograph, one can look at the 1.8 MeV ^{26}Al line, the 511 keV e^+e^- line, etc.

^{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 -
Map of Galactic ^{26}Al as obtained from COMPTEL
spectral signature of the radioactive decay of the isotope ^{26}Al
Energy (keV)
radioactive decay in the galactic centre region
synthesis of new elements by super-massive stars in the Cygnus constellation
Energy (keV)
© 2003 the SPI collaboration

- 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)



A fit of the SPI result for the diffuse emission from the GC region ($|l|, |b| \leq 16°$) 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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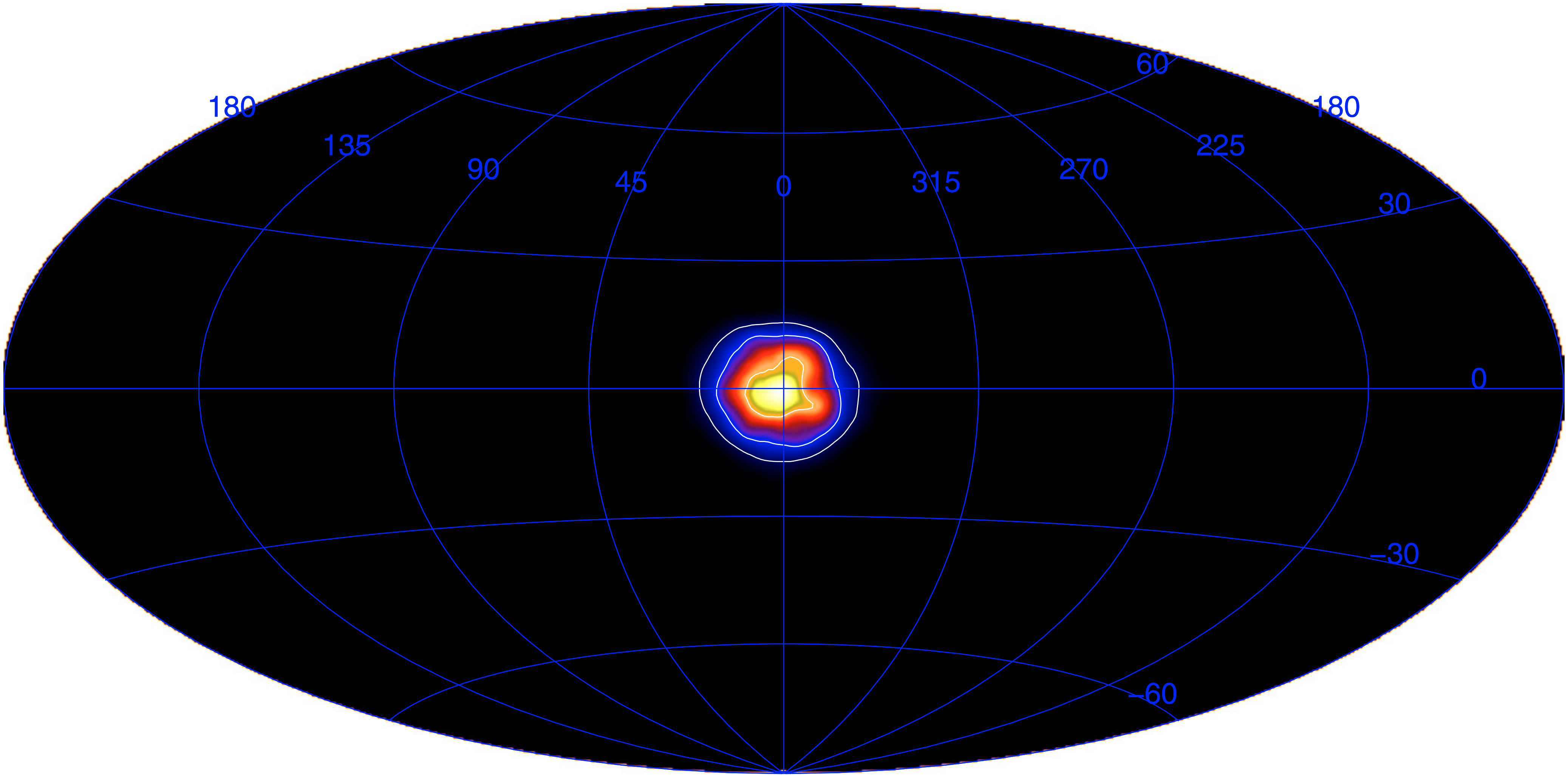
- Does the Ps emission trace star formation also?

(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.

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

Let's try something more... *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

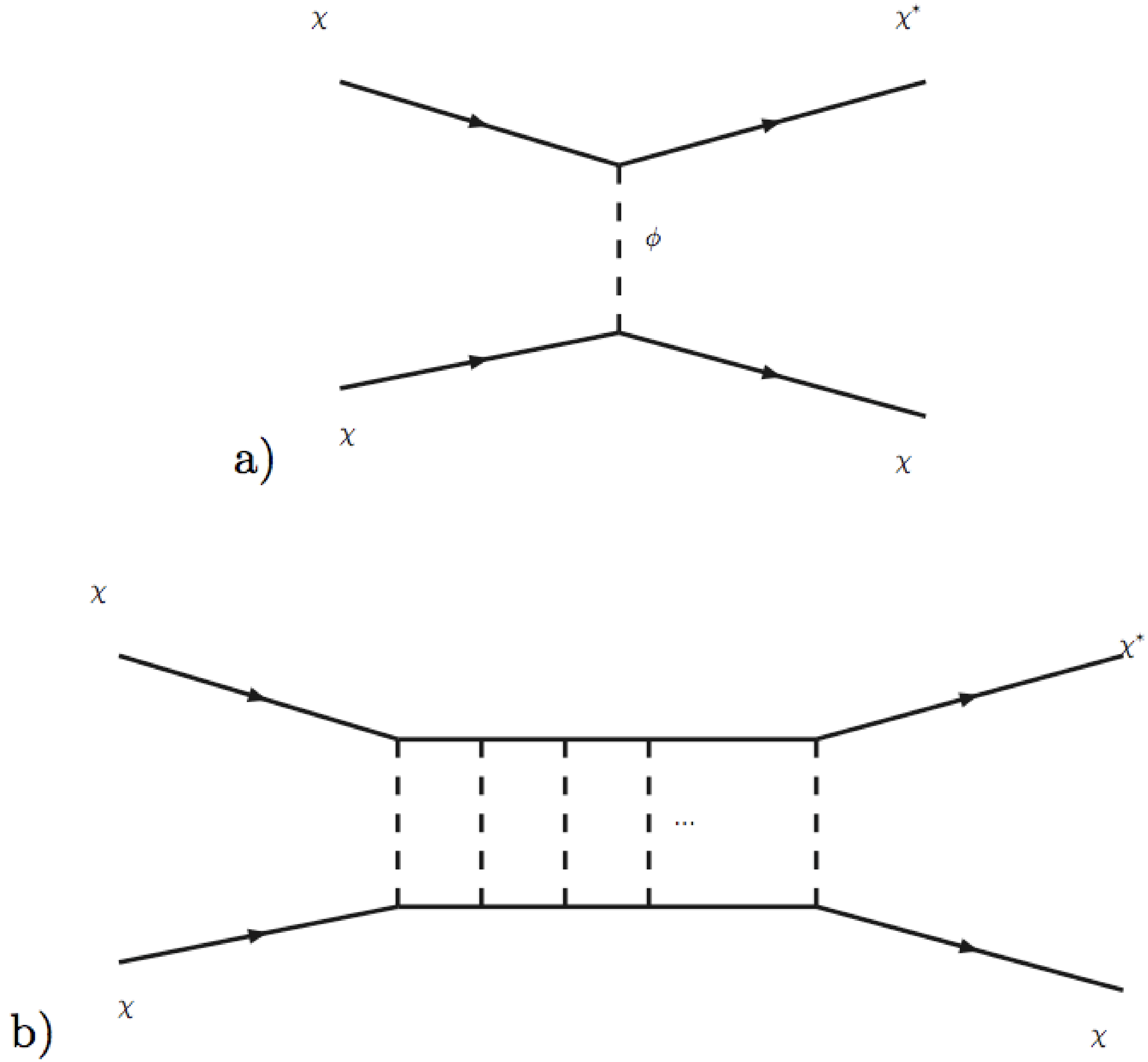


FIG. 4: Excitation diagrams for $\chi\chi \to \chi^*\chi$.

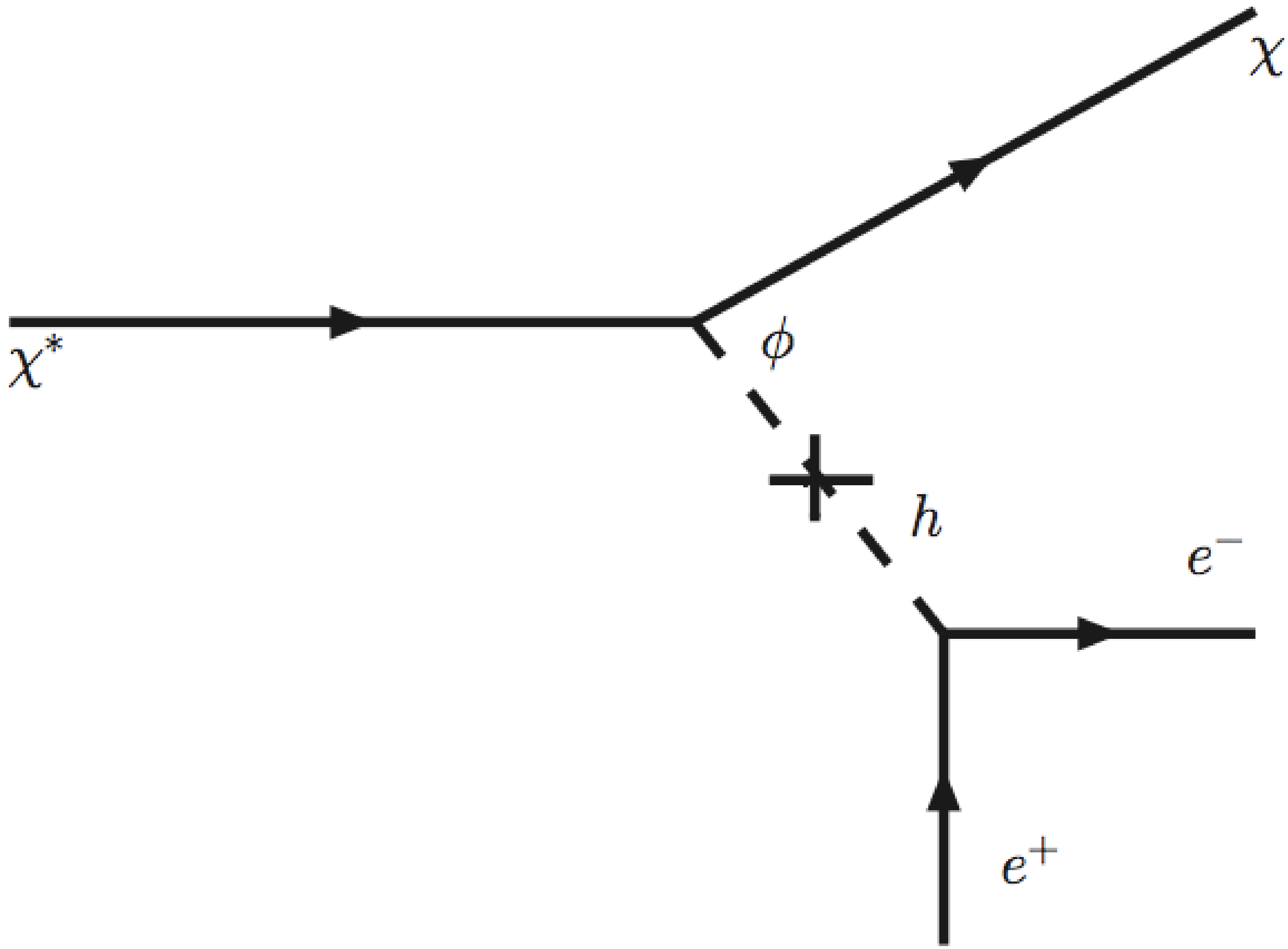


FIG. 5: Decay of the excited state into the ground state.

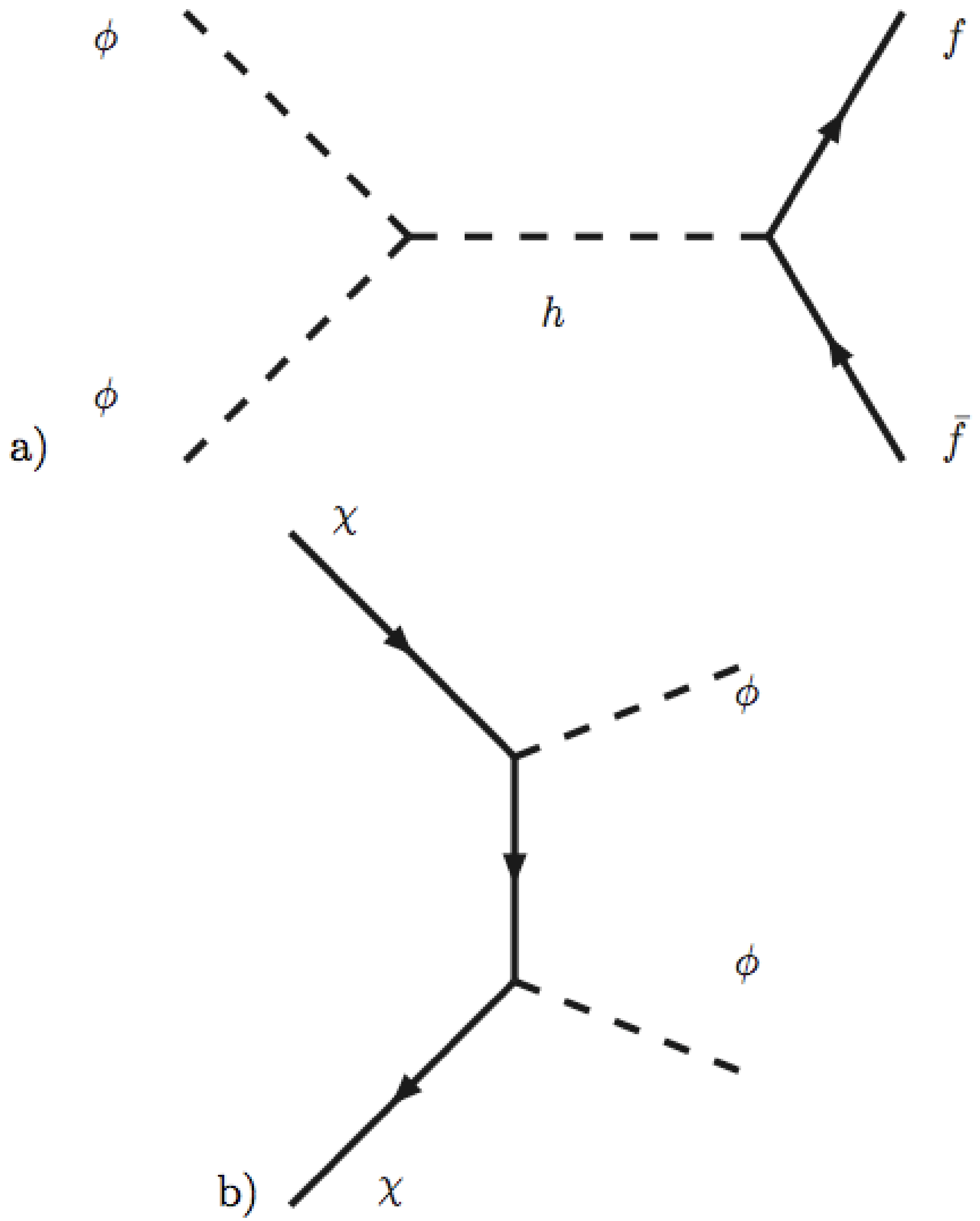


FIG. 6: Diagrams contributing to thermal equilibrium in the dark sector and between the dark sector and the visible sector.

Other details:

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

BBN results are unchanged.

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)

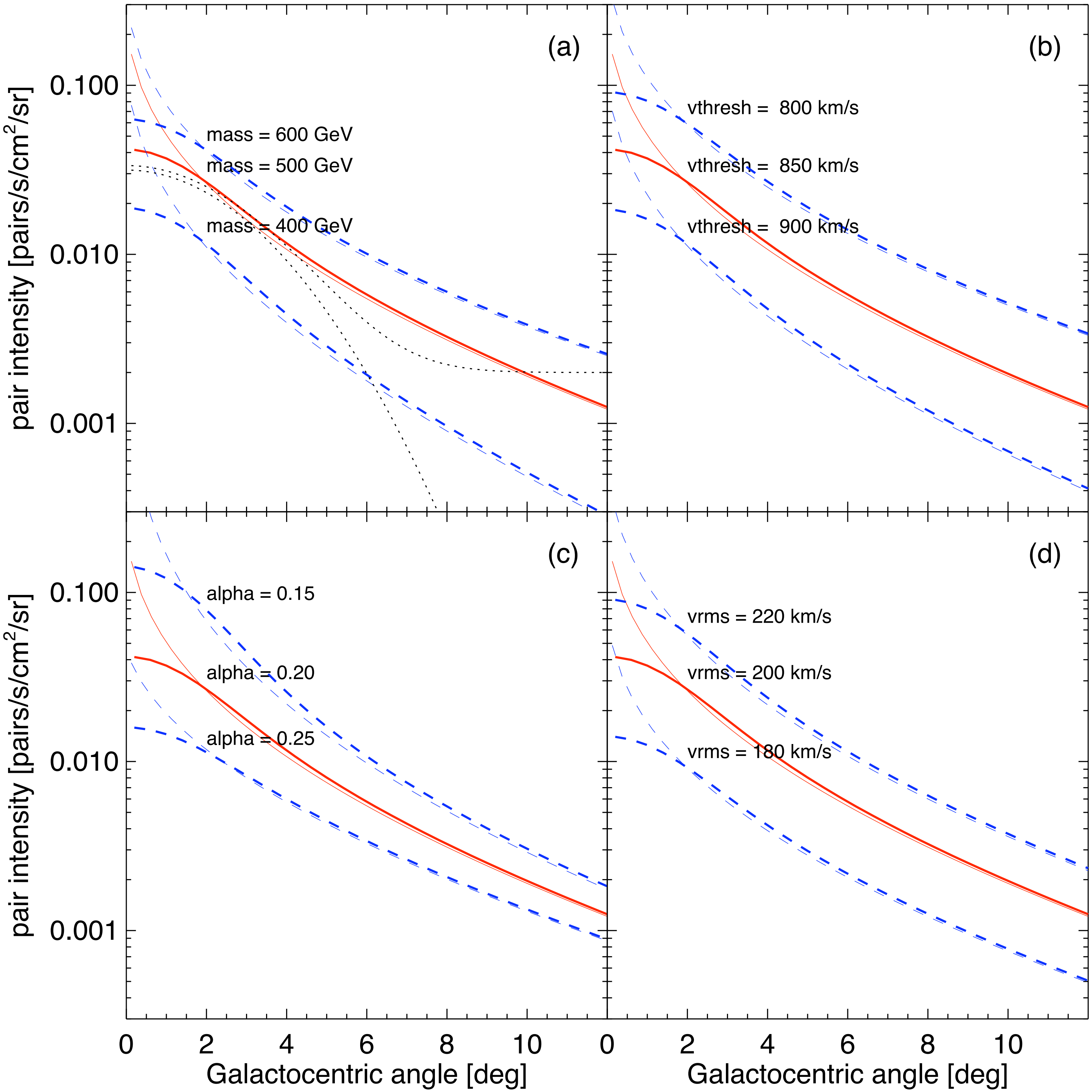
Important point:

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

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

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.

Rather astonishing point:

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%.

Everyone said "no can do!"

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 electrons!

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

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)

Potential observable consequences:

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

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

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.

arXiv.org > astro-ph > arXiv:astro-ph/0702587

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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)

Cite as: arXiv:astro-ph/0702587v3

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References & Citations

- SLAC-SPIRES HEP (refers to, cited by, arXiv reformatted)
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