Exploring (what is left from) the (thermal) DM parameter space

Céline Boehm

credit arXiv:1404.7012

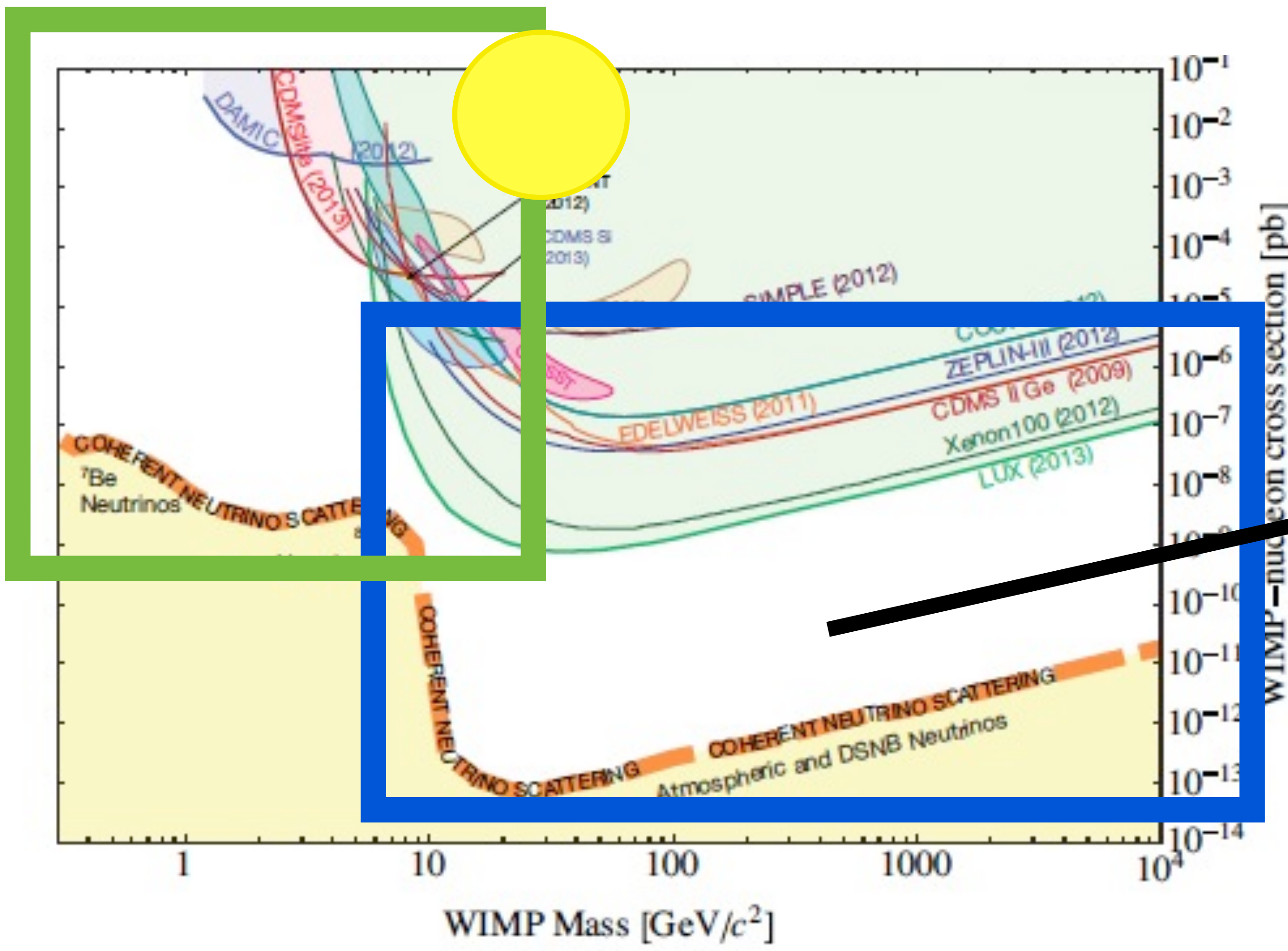
IPPP, Durham   Durham University   LAPTH, Annecy   cnrs

Paris (INVISIBLES), 17 July 2014

Tremendous achievements

The old DAMA region

The future?



coannihilation
focus point
Higgs pole

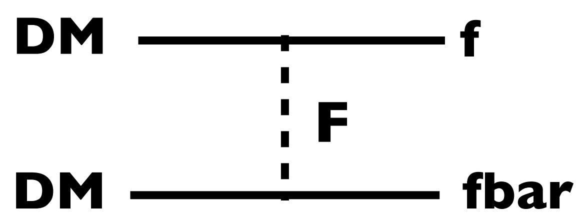
Where everybody is focusing

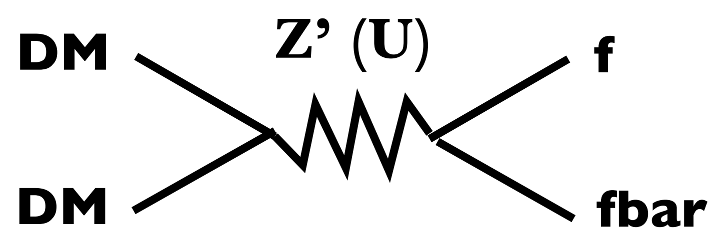
Outline of the talk: the light mass range and in particular 10-30 GeV

Gamma rays & GC excess

astro-ph/0208458 & hep-ph/030526

Relic density





Majorana DM

$$\sigma v \propto \frac{\left(2c_l c_r\ \mathrm{m_{DM}} + (\mathrm{c_l^2} + \mathrm{c_r^2})\ \mathrm{m_f}\right)^2}{\left(m_F^2 - \mathrm{m_{DM}^2} - \mathrm{m_f}^2\right)^2}$$

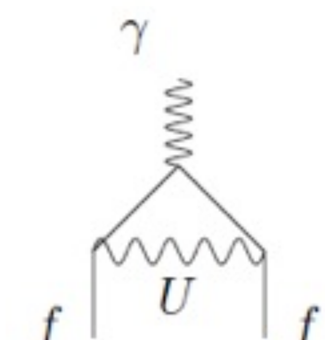
scalar DM

$$\sigma v \propto \frac{\left(2c_l c_r m_F + \left(c_l^2 + c_r^2\right) m_f\right)^2}{\left(m_F^2 - \mathrm{m_{DM}^2} - \mathrm{m_f}^2\right)^2}$$

A too heavy mediator means DM will overclose the Universe!

LIGHT (sub 10 GeV) DM = LIGHT MEDIATORS!

so likely to be a neutral mediator...



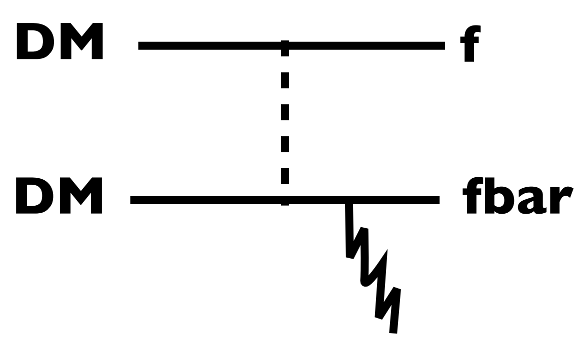
U=Z'

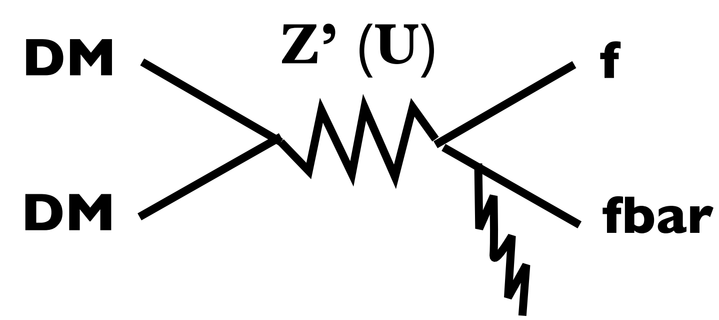
hep-ph/030526

Gamma rays & GC excess

astro-ph/0208458 & hep-ph/030526

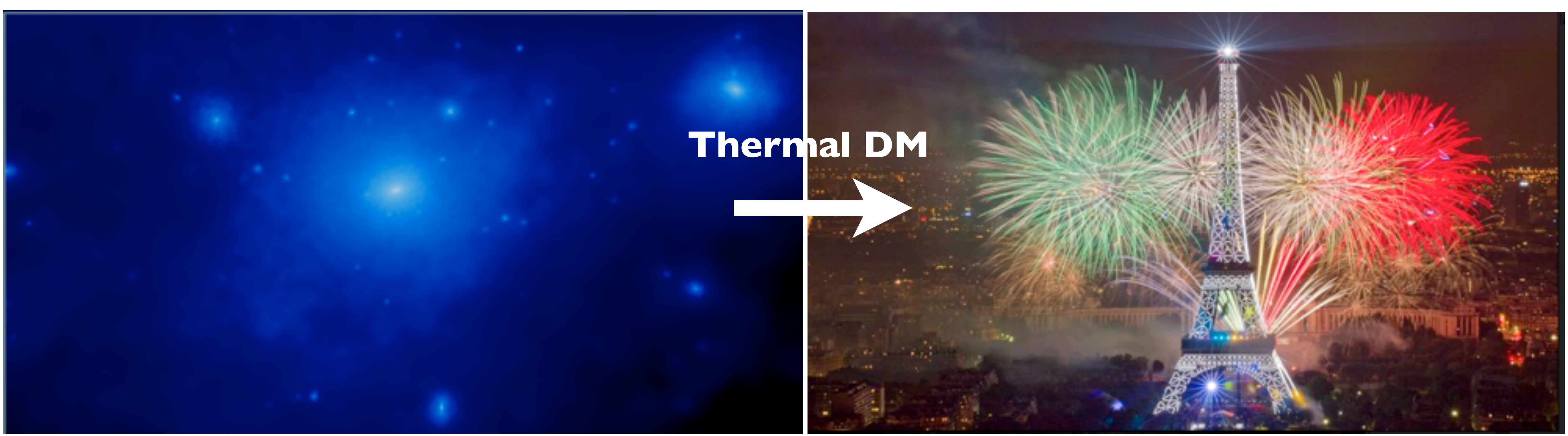
DM should not shine at energies that we already scrutinised!





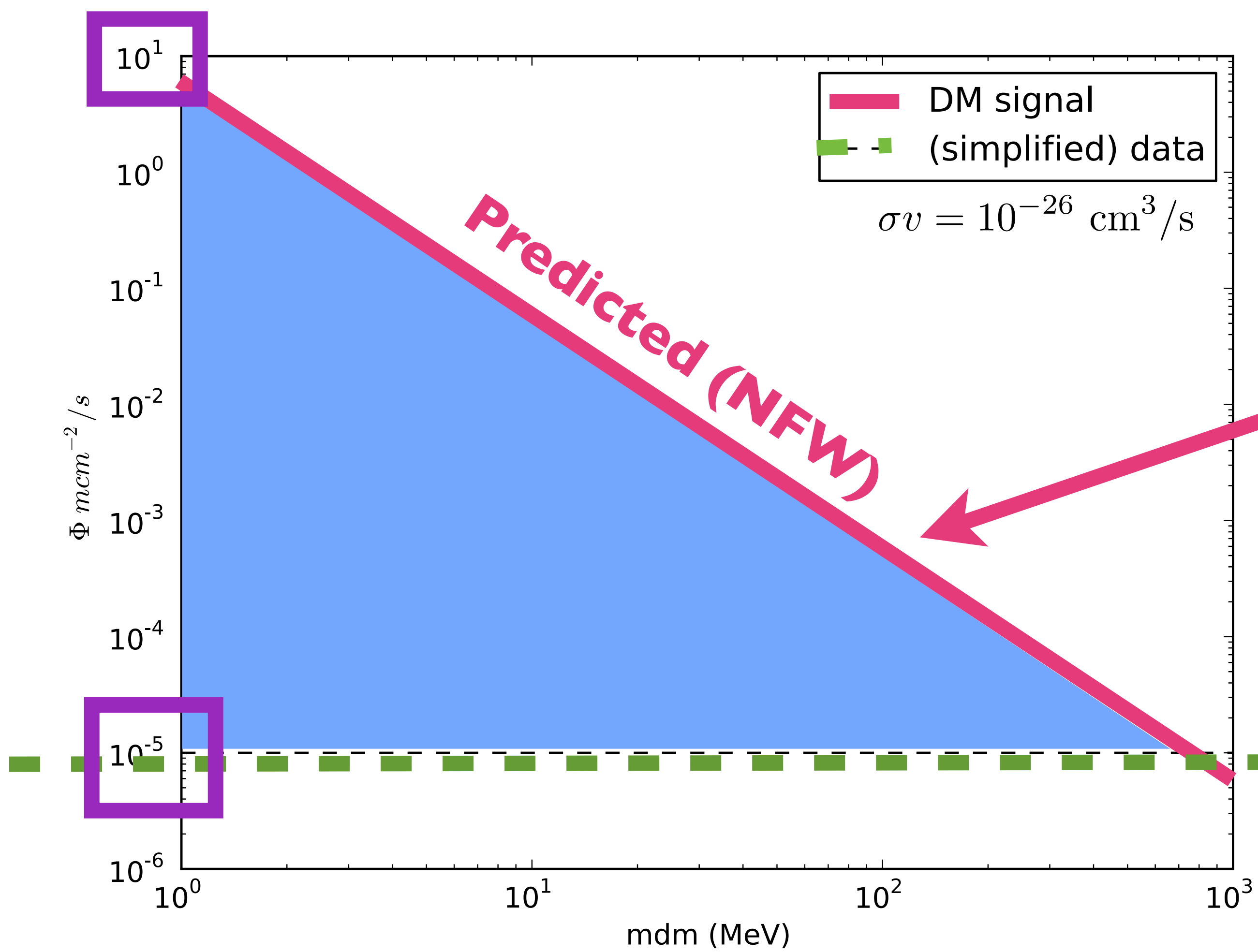
Only depends on the DM profile

$$\frac{d\phi}{dE} = \frac{1}{8\ \pi}\left(\frac{\sigma v}{m_\chi{}^2}\right) \overset{=1}{\boxed{\sum_i \mathrm{BR_i}\frac{\mathrm{dN_i}}{\mathrm{dE}}}}\ \xi^2 \boxed{\int \mathrm{dl}\ \rho_\chi^2(\mathrm{l})} \quad \Rightarrow \Phi_{\mathrm{prompt}} \propto \frac{\sigma v}{\mathrm{m_{DM}}^2}\int dl\ \rho^2(l)$$



Gamma rays & GC excess

astro-ph/0208458 & hep-ph/030526



MeV GeV

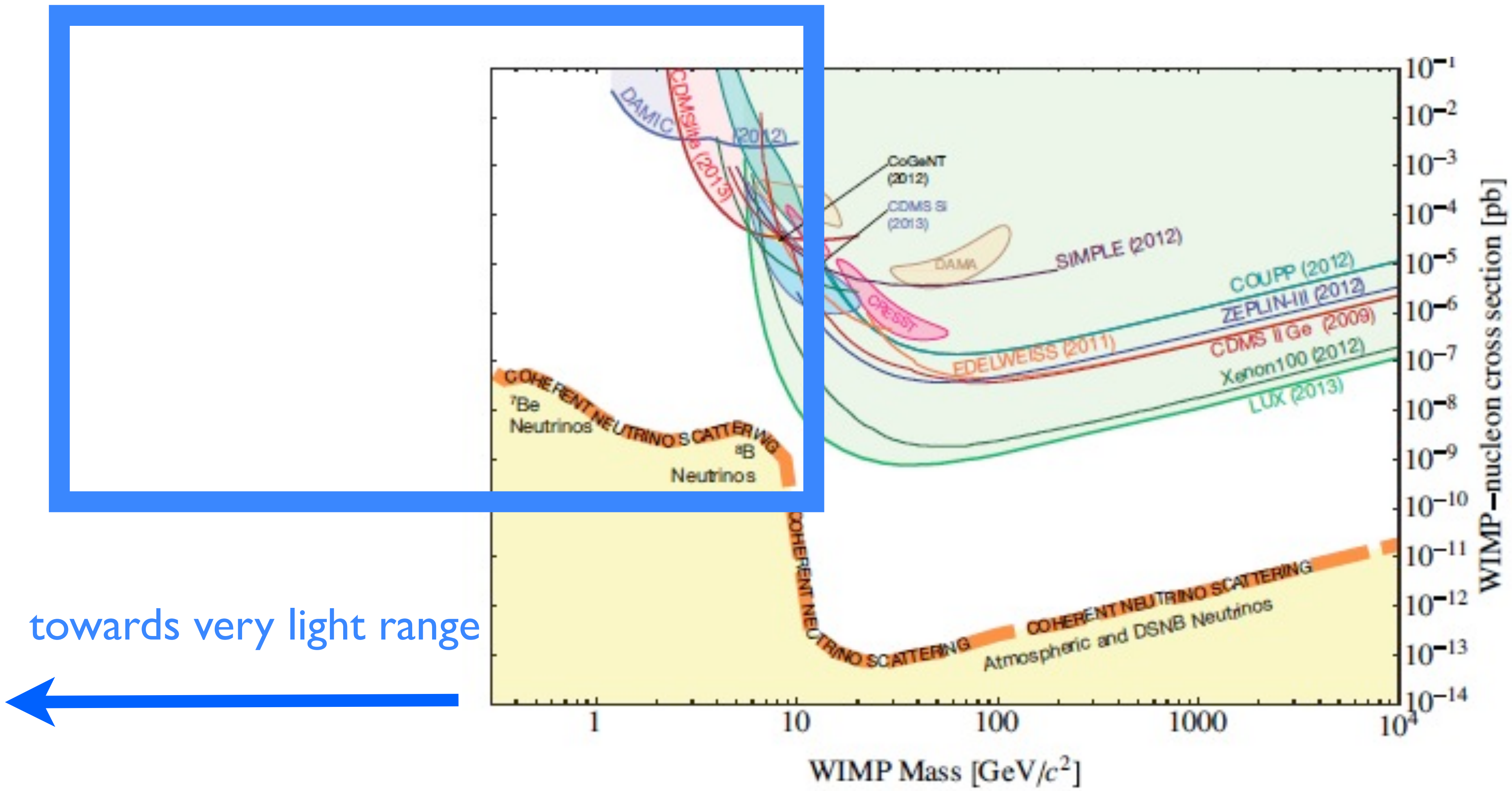
$$\Phi_{\mathrm{prompt}} \propto \frac{\sigma v}{\mathrm{m_{DM}}^2} \int dl\ \rho^2(l)$$

$$\boxed{\Phi^{GC}_{\mathrm{obs}}(< 1.5^\circ) \sim\ 5.9\ \left(\frac{m_{\mathrm{DM}}}{\mathrm{MeV}}\right)^{-2} \left(\frac{\sigma v}{10^{-26}\ \mathrm{cm}^3/\mathrm{s}}\right)\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}}$$

observations (rough guide!)

LIGHT (thermal) DM means p-wave annihilations or neutral final

Light DM



LIGHT (sub 10 GeV) DM = LIGHT MEDIATORS!

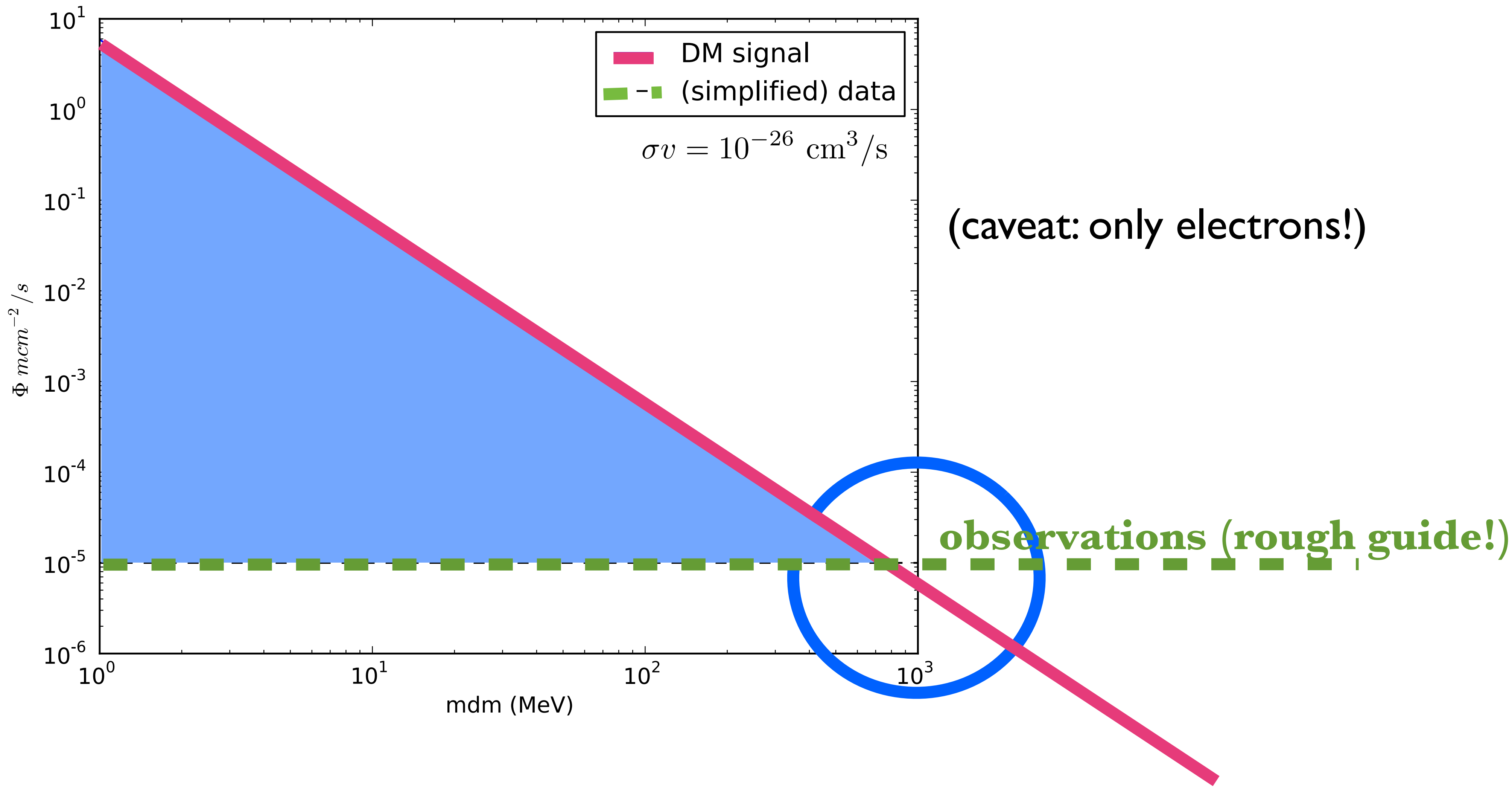
P-wave interactions or large fraction of neutral states

DD searches are crucial: they will provide complementary information (on the types of allowed e.s. cross sections)

Gamma rays & GC excess

astro-ph/0208458 & hep-ph/030526

$$\boxed{\Phi^{GC}_{\rm obs}(<1.5^\circ) \sim \; 5.9 \; \left(\frac{m_{\rm DM}}{\rm MeV}\right)^{-2} \; \left(\frac{\sigma v}{10^{-26}\ {\rm cm^3/s}}\right) \; {\rm cm^{-2}\ s^{-1}}}$$



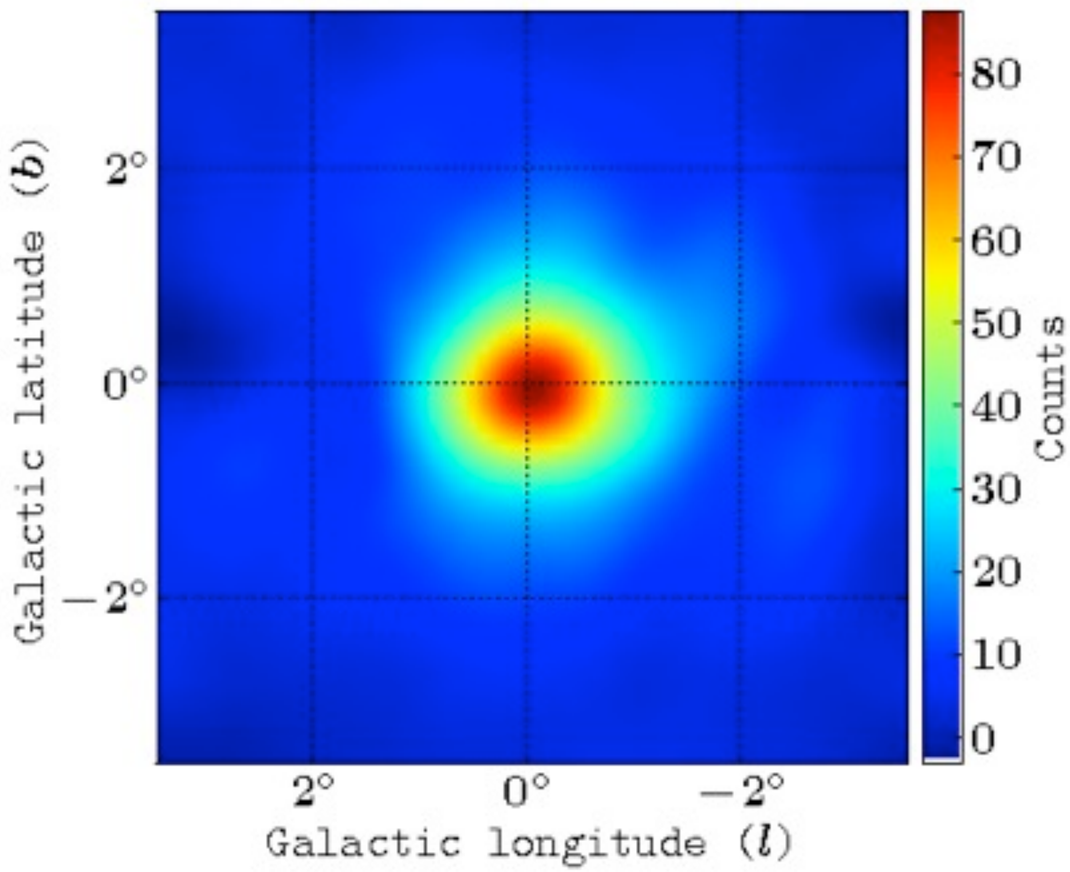
(caveat: only electrons!)

Thermal DM is only compatible with the data when mdm ~ O(10) GeV [s-wave annihilations]

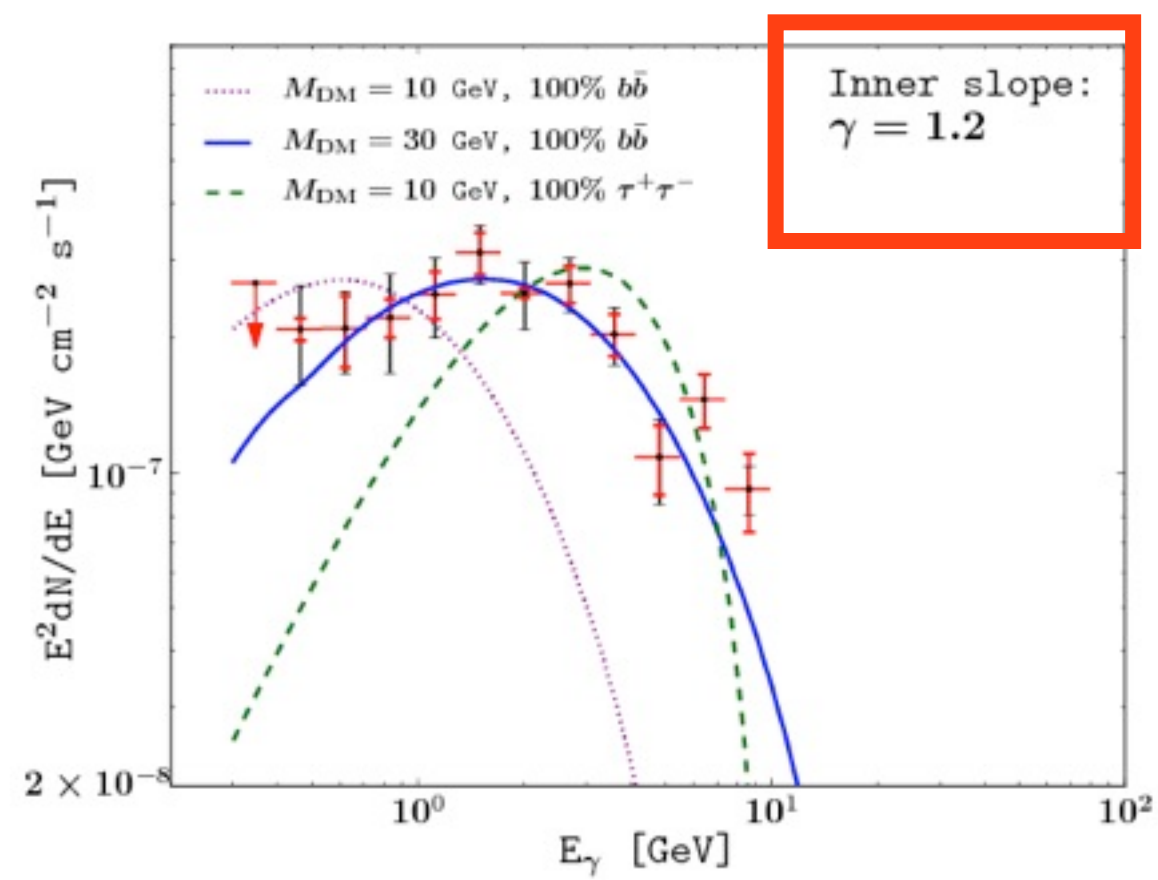
Excess in the Milky Way

arXiv:1306.5725, Gordon et al

Hooper&Goodenough 2009
FERMI-LAT 2009

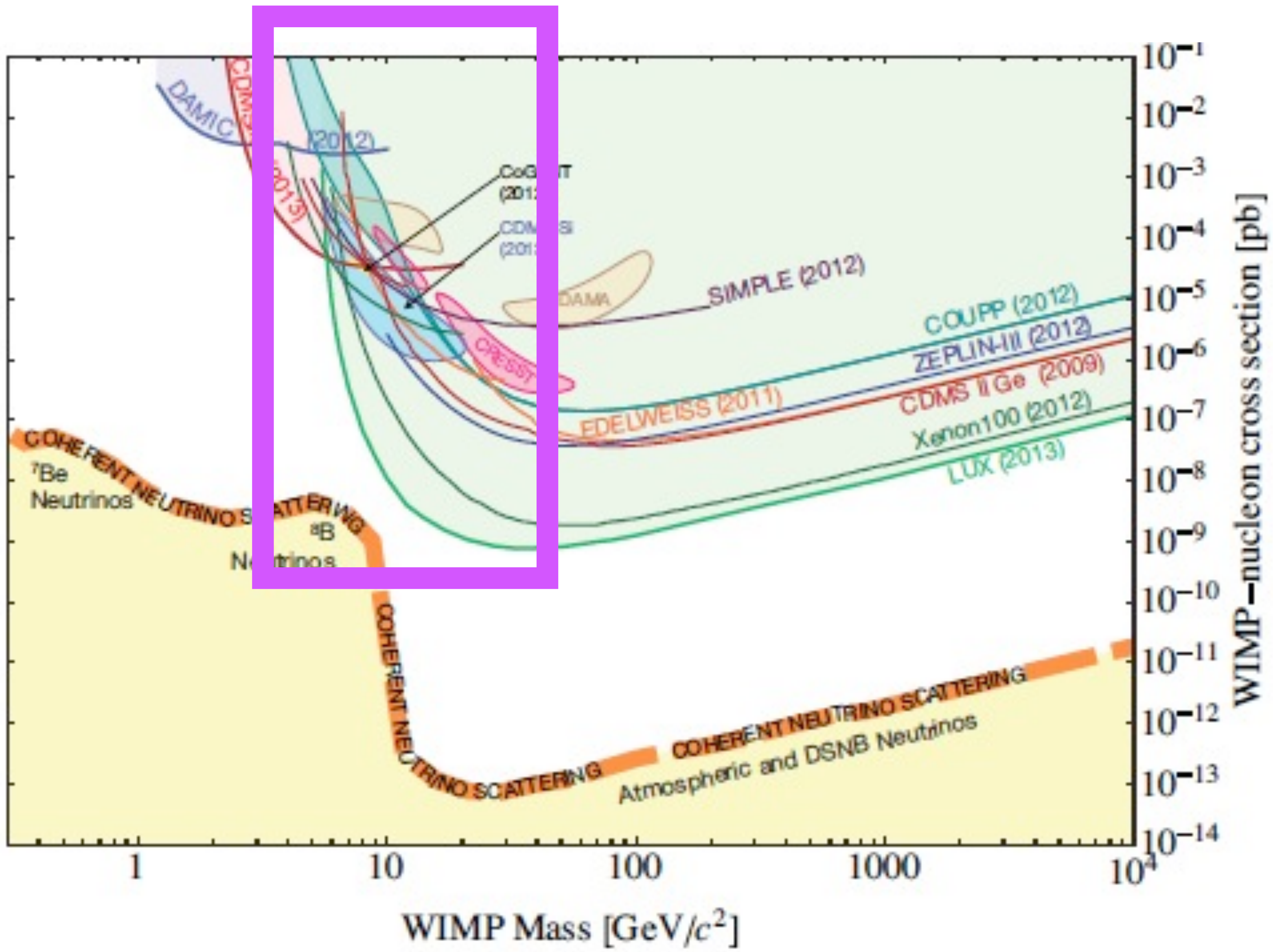


10-30 GeV DM annihilating mostly into b-quarks or muons can fit the FERMI-LAT data...



(see Aaron Vincent's talk)

Direct Detection

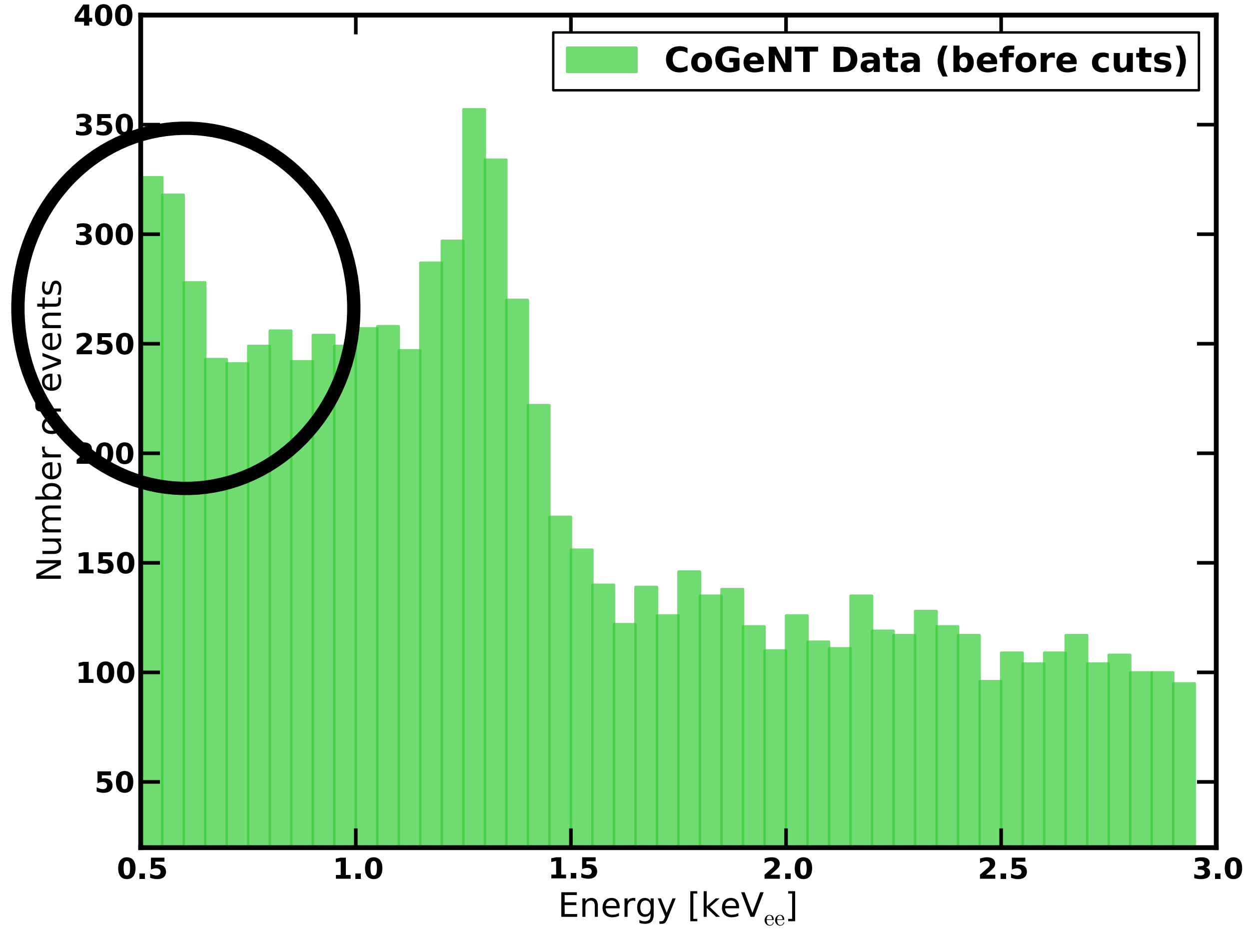


Claims from DAMA (and DAMA/LIBRA), CoGeNT

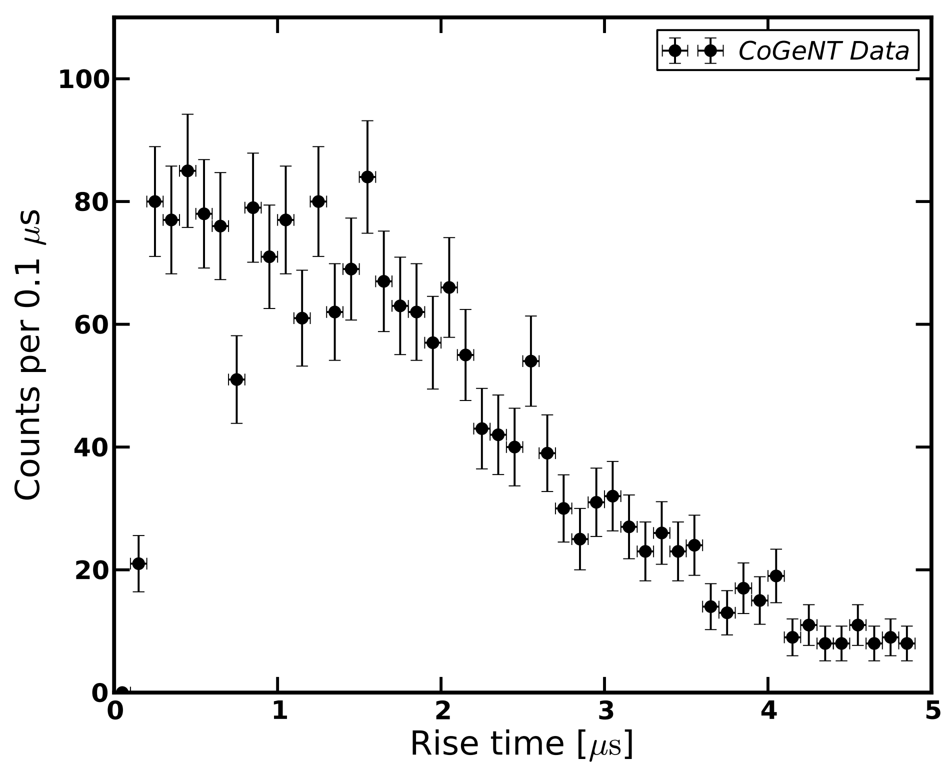
CoGeNT

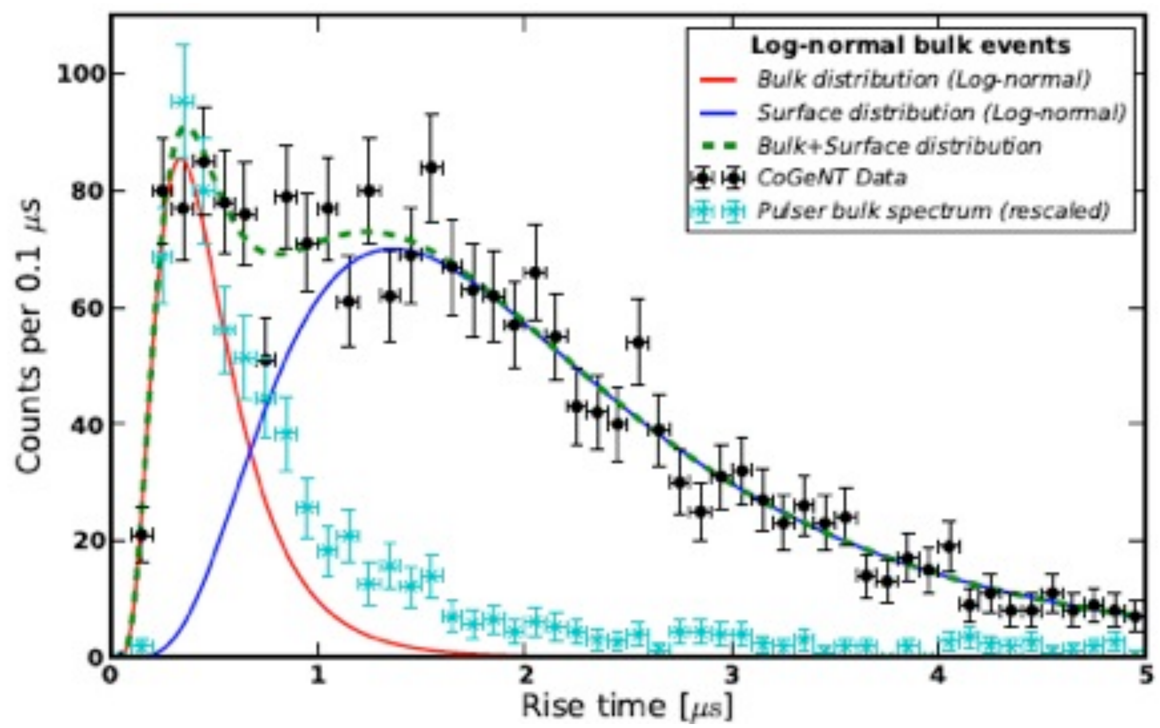
arXiv:1405.0495

Where DM lies



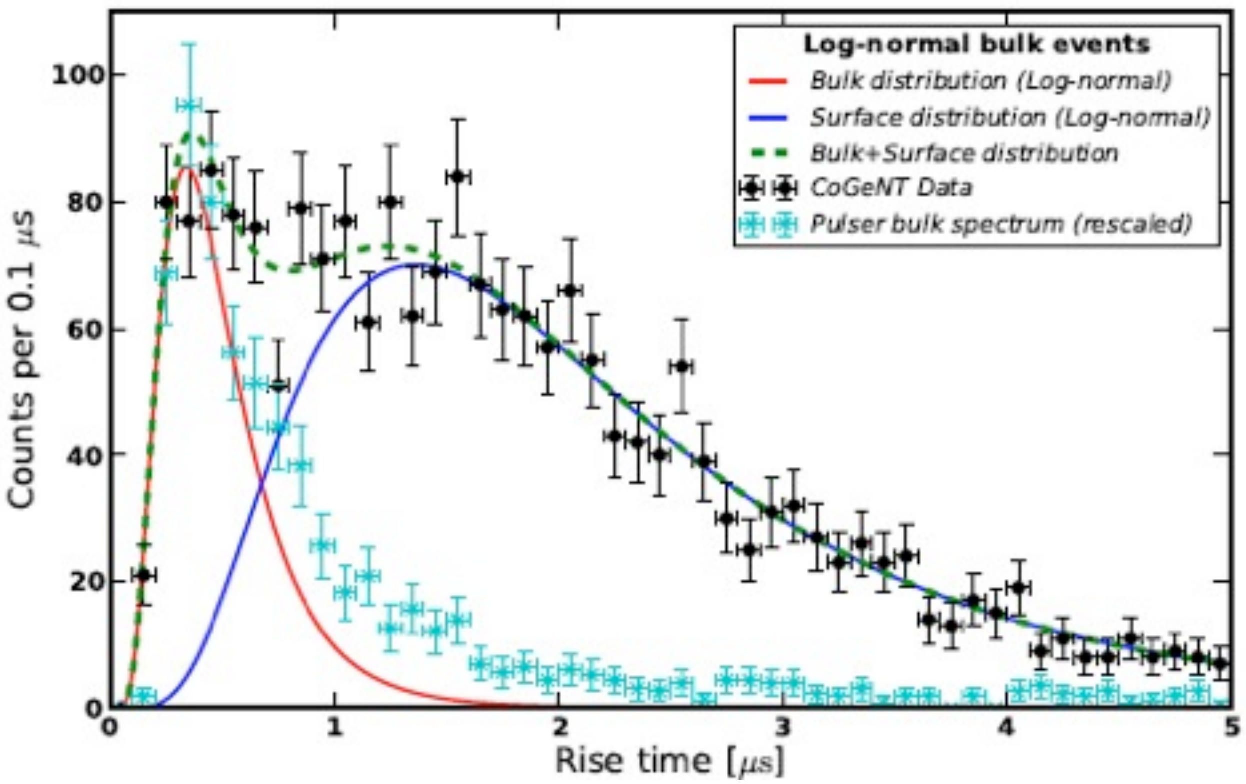
But CoGeNT cannot discriminate between DM and background unless..





CoGeNT

arXiv:1405.0495



bulk

background+DM

surface

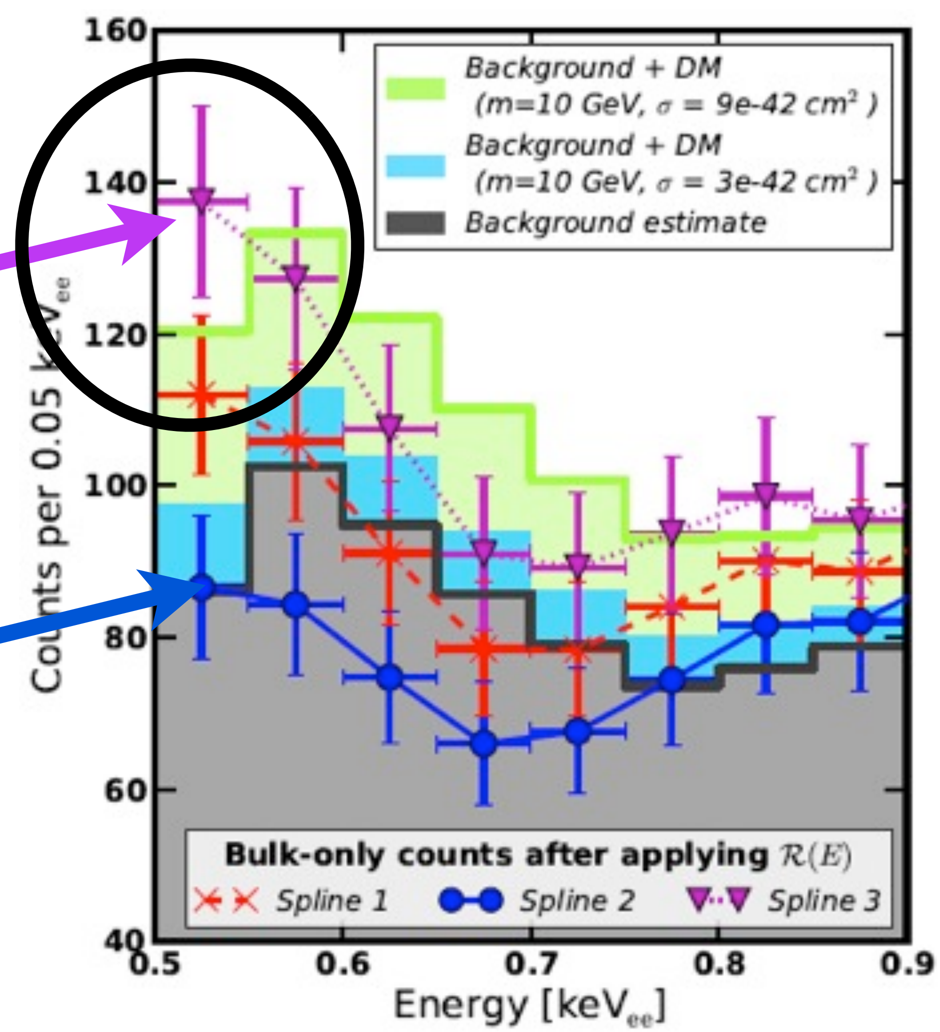
background only

surface events take more time to rise because they are happening in the part of the detector where charge collection is good

2 log normals = 6 parameters

Possible evidence for DM

No evidence for DM



After marginalising: 1 sigma evidence

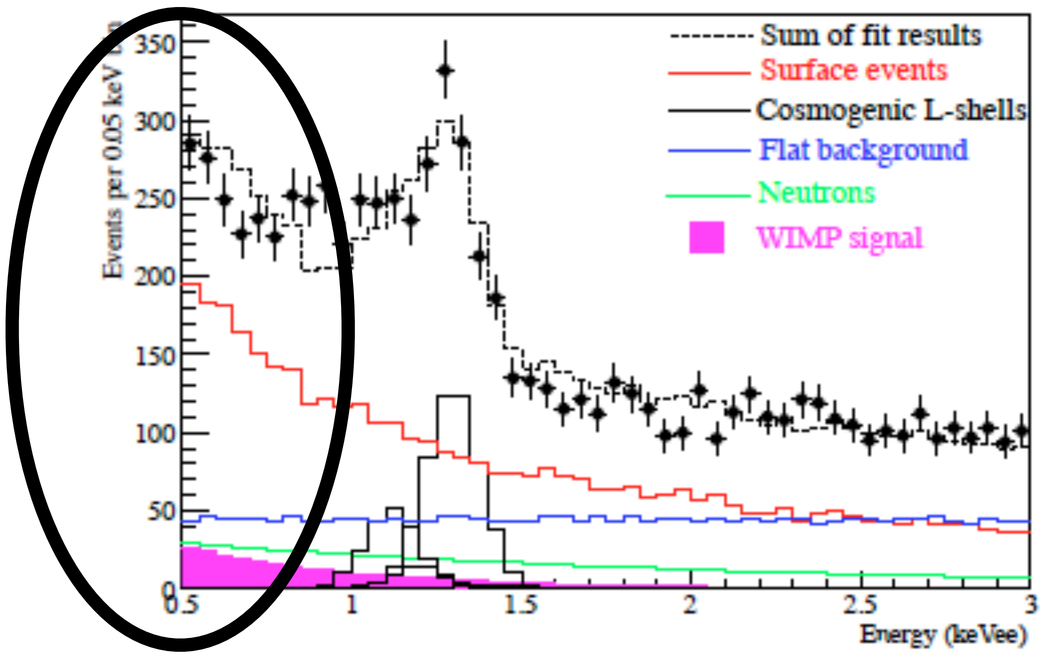
Other CoGeNT analysis

C. Kelso with M. Bellis, J. Collar, N. Fields

TeVPA

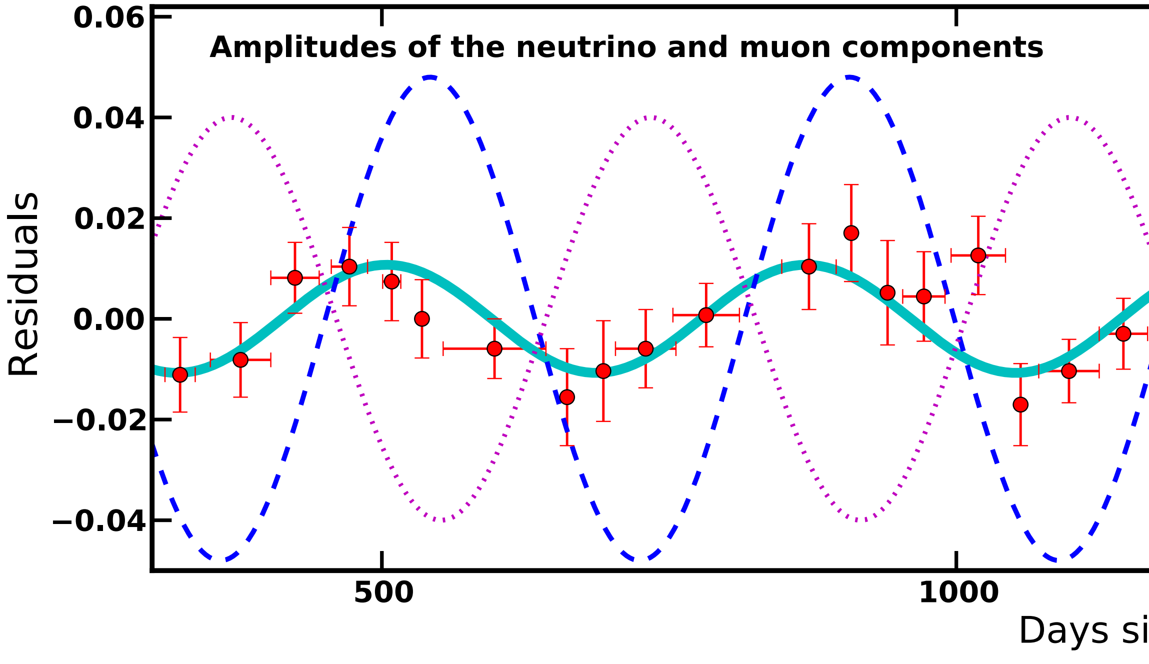
Conclusions

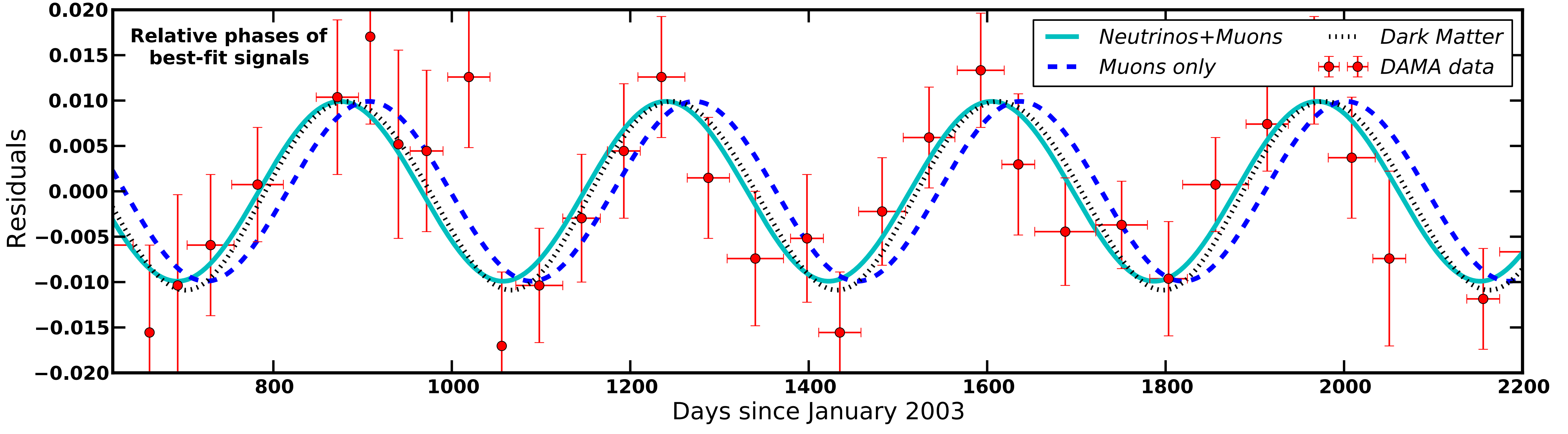
- We perform an unbinned, maximum likelihood fit to the public CoGeNT data using extensive studies to separate bulk and surface events
- We find a good fit to the data with our background model
  - The likelihood gets worse when including a WIMP component either as a standard halo or Sagittarius like stream
- Still to come
  - Try to understand the different conclusions with the likelihood analysis performed by Collaboration – (Collar and Fields)
  - Look at more exotic signals (such as axion-like particles scattering from electrons)
  - Set upper limits on the cross section



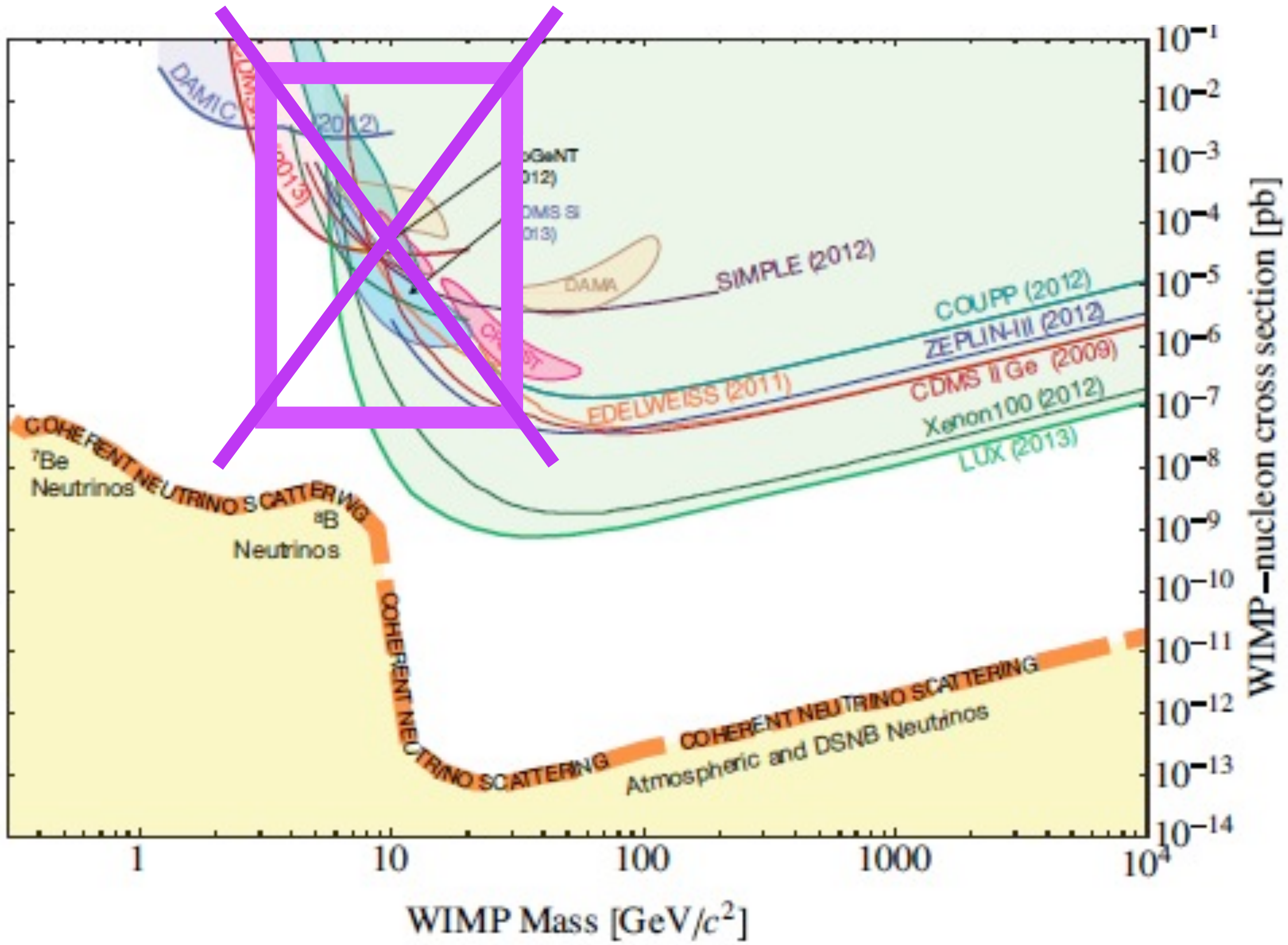
DAMA/LIBRA

arXiv:1407.1052





Direct Detection



Perhaps a signal in indirect detection but no signal in Direct Detection…!

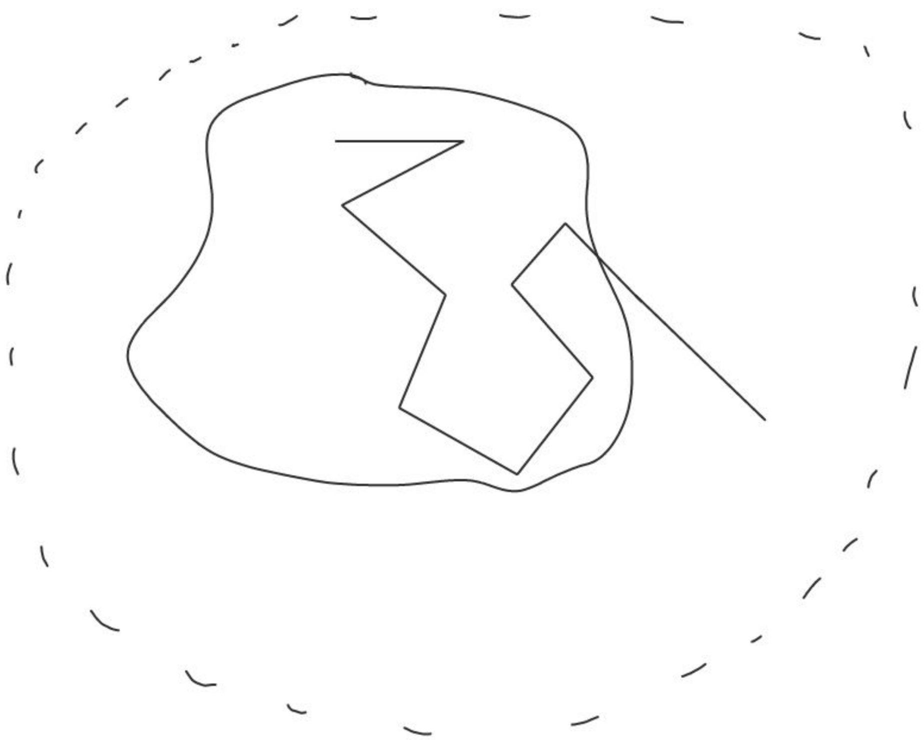
If DM is around 10-30 GeV, you need a specific type of mediator to get a signal in ID and no signal in DD!

"COY" DM : arXiv:1401.6458

semi-annihilation :arXiv:1404.4977

New way to probe the light sector?

DM interactions with neutrinos and photons.

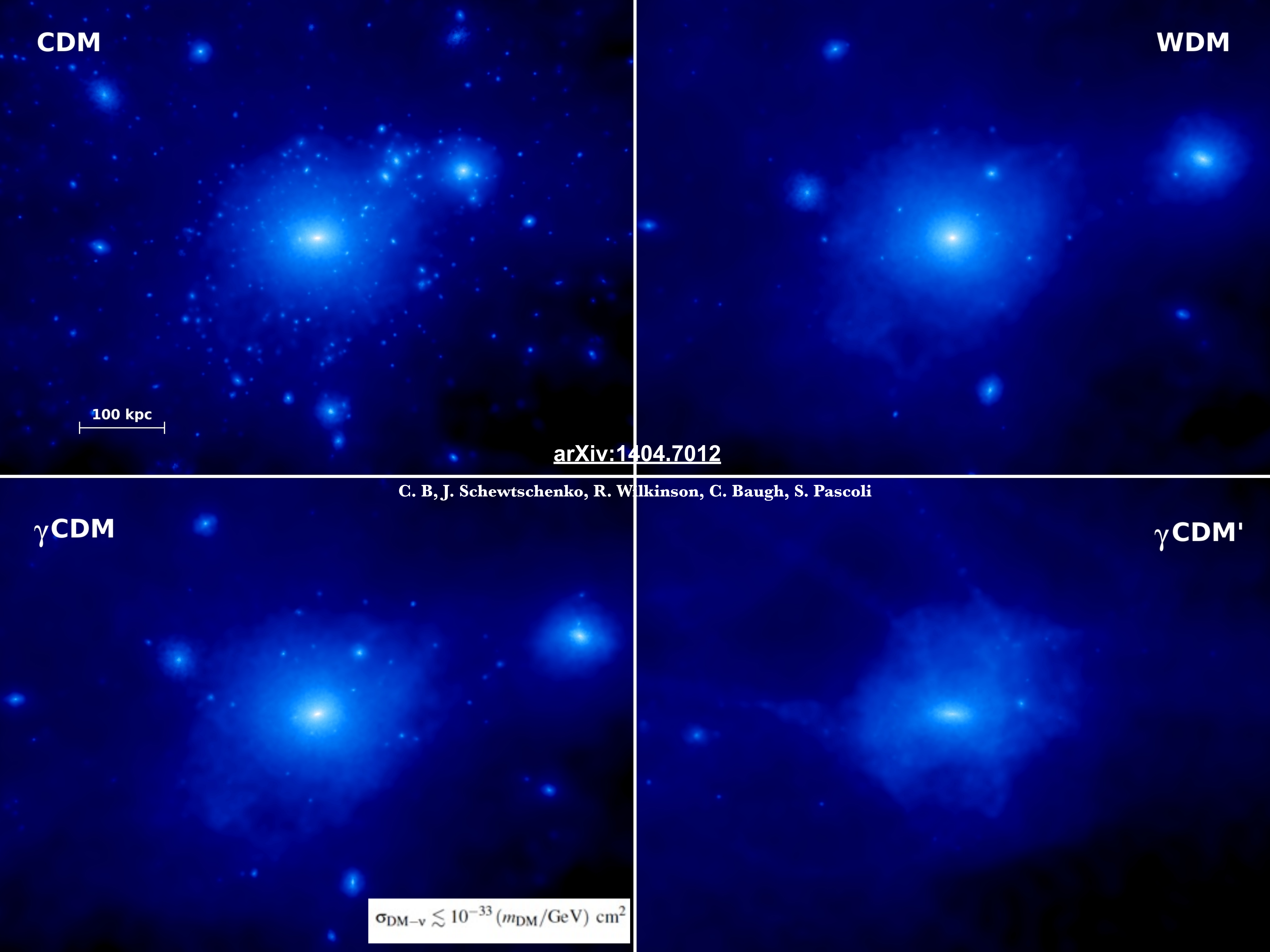


$$l_{id}^2 = \frac{2\pi^2}{3} \int_0^{t_{dec(dm-i)}} \frac{\rho_i v_i^2 t}{\rho a^2 \Gamma_i} (1 + \Theta_i) \; \frac{dt}{t}$$

astro-ph/0012504 astro-ph/0112522 astro-ph/0410591

arXiv:1401.7597

arXiv:1309.7588


CDM
WDM
100 kpc
arXiv:1404.7012
C. B, J. Schewtschenko, R. Wilkinson, C. Baugh, S. Pascoli
γCDM
γCDM'
$\sigma_{DM-\nu} \lesssim 10^{-33} \, (m_{DM}/\mathrm{GeV}) \ \mathrm{cm}^2$

Conclusion

★ Probably no DM signal at 10 GeV **in Direct Detection**

But **10-30 GeV** is the mass range where **thermal DM** is compatible with indirect detection and **may explain the GC excess**.

This could mean:

- ★ "COY" DM (no DM in direct detection experiments)
- ★ semi-annihilation (higher DM masses)

or if no signal, the end of thermal DM as we know it !!!

Do you fancy exploring the very light range???

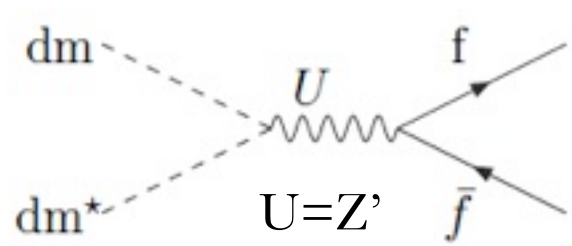
If so investigations of DM interactions on small-scale structures is the way to go!

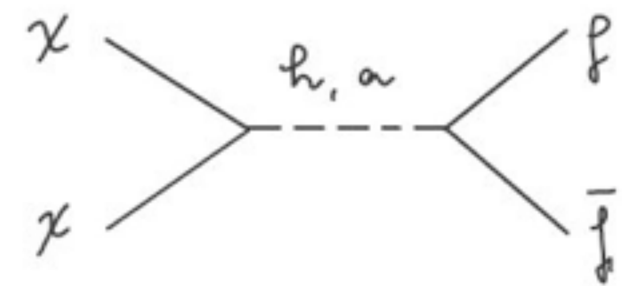
We can probe the invisible!

Light mass range & constraints

LIGHT (sub 10 GeV) DM = Light mediators

- **velocity dependent cross section**
- **or neutral final state**

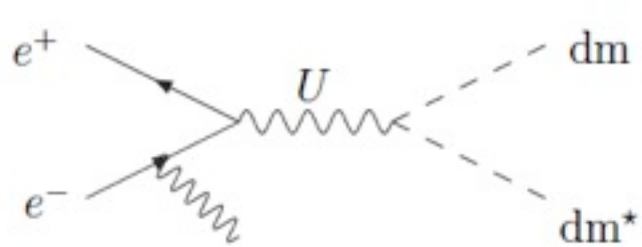


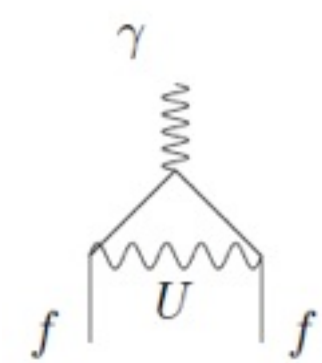


astro-ph/0208458

[hep-ph/030526](hep-ph/030526)

Z' must be light and very weakly interacting.
Same conclusion with a Higgs boson (+singlet, thus NMSSM interesting)



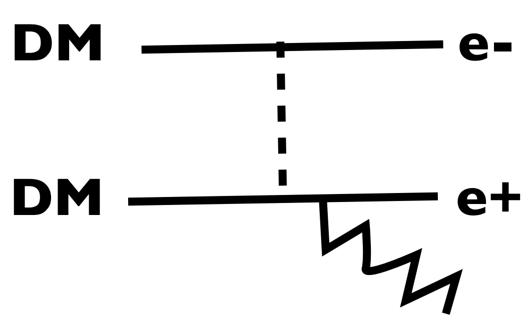


[Boehm&Fayet, hep-ph/030526](hep-ph/030526)

Light mass range: prompt gamma-rays

astro-ph/0208458 & hep-ph/030526

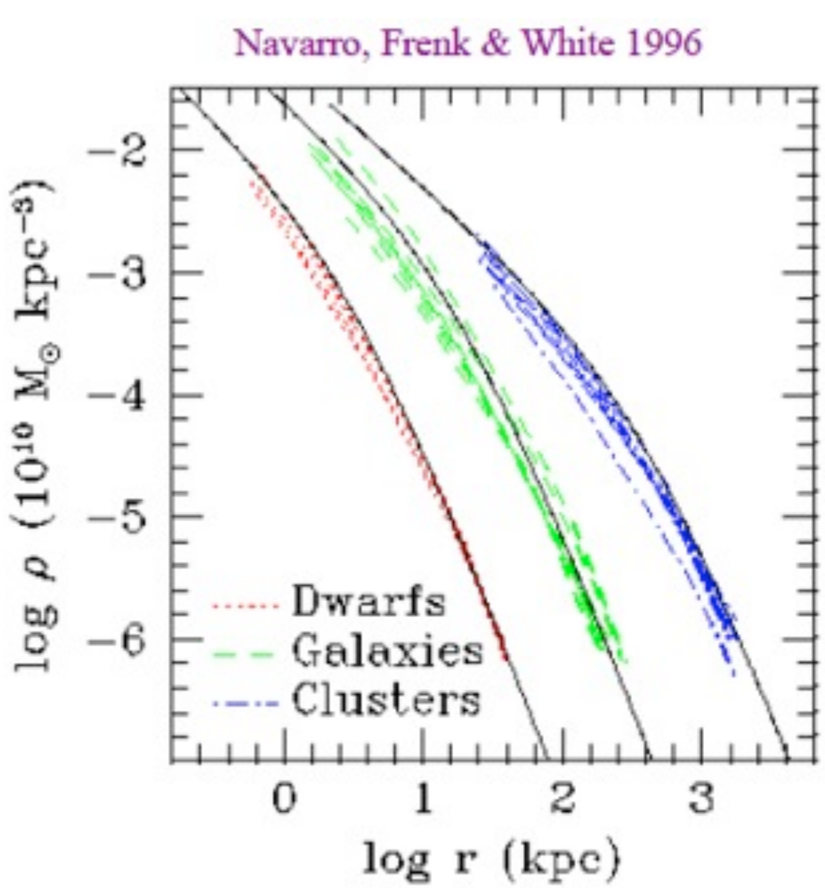
The (prompt) light DM prediction



$$\frac{d\phi}{dE} = \frac{1}{8\,\pi}\left(\frac{\sigma v}{m_\chi{}^2}\right) \underbrace{\boxed{\sum_i \mathrm{BR_i}\,\frac{\mathrm{dN_i}}{\mathrm{dE}}}}^{=1}\,\xi^2\,\boxed{\int \mathrm{dl}\;\rho_\chi^2(\mathrm{l})}$$

Only depends on the DM profile

Only electrons (**astro-ph/0208458**): dN/dE = delta(E-mdm); BR=1

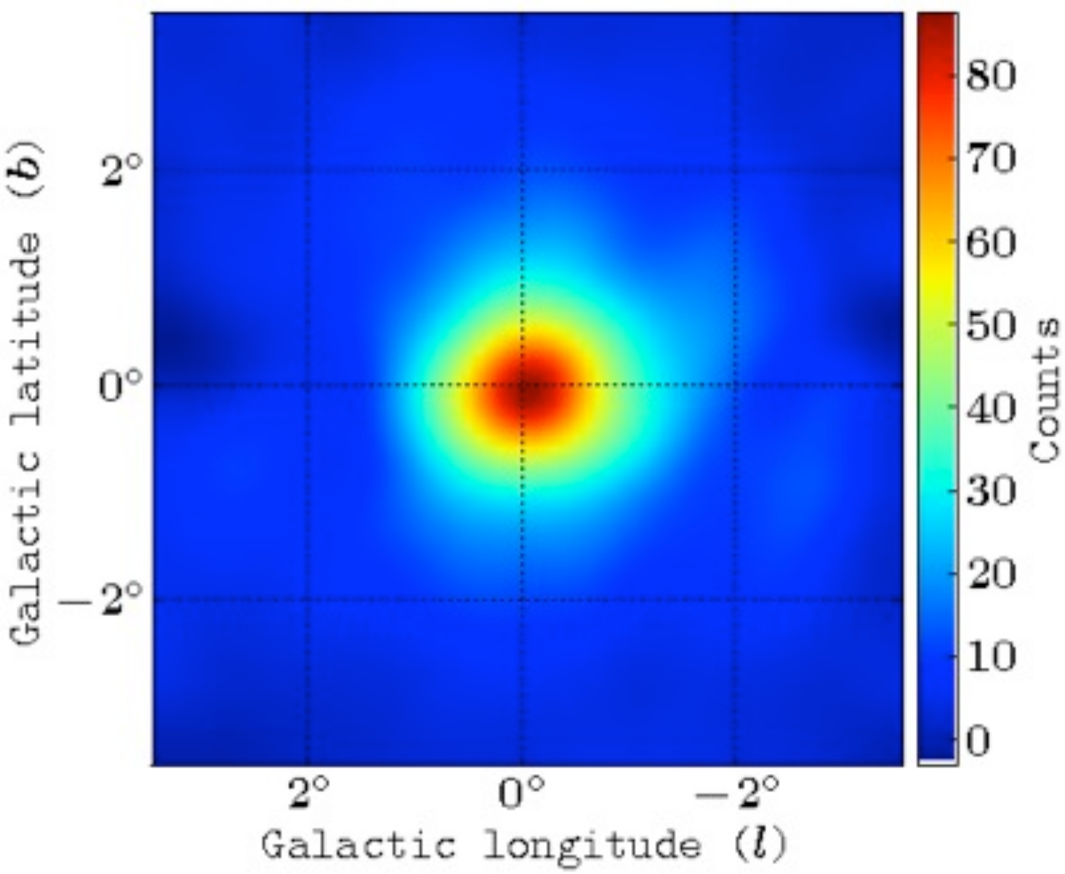


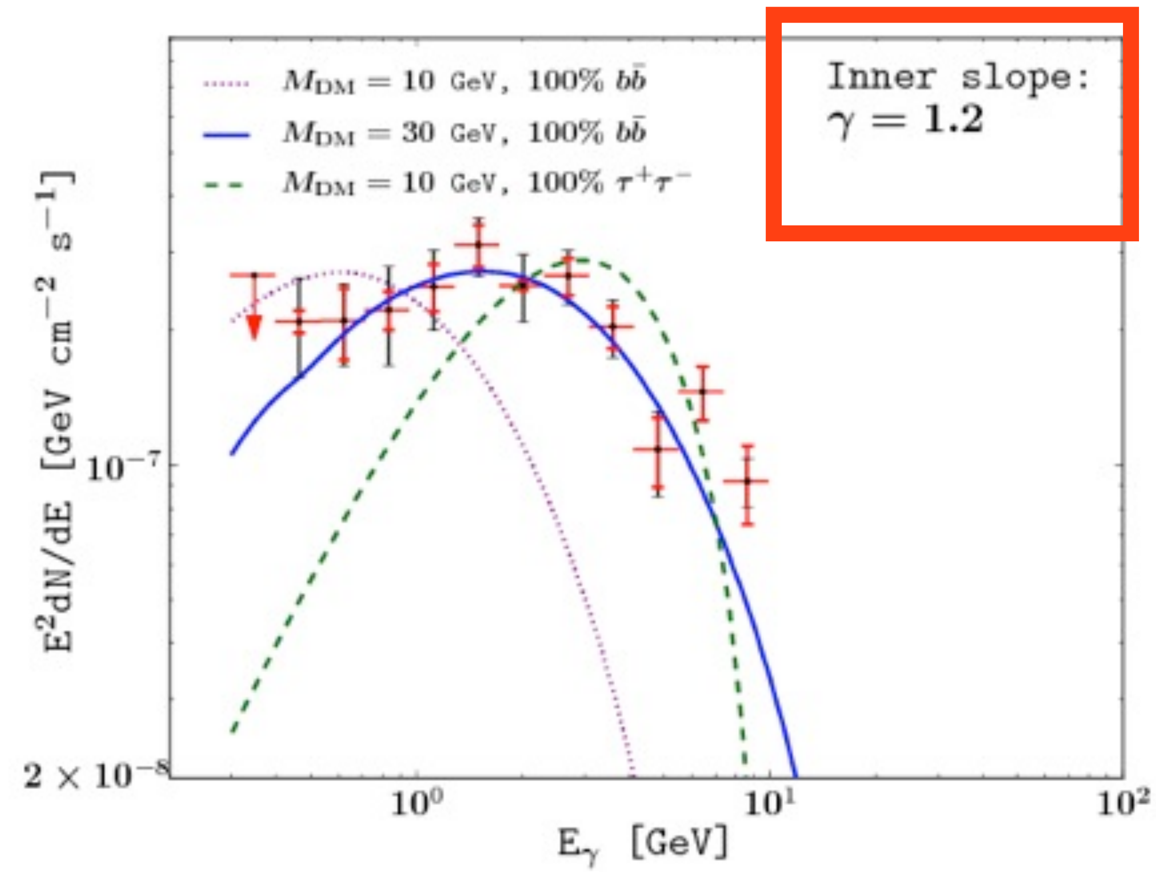
$$\Phi_{\mathrm{prompt}} \propto \frac{\sigma v}{\mathrm{m_{DM}}^2}\int\; dl\;\rho^2(l)$$

Excess in the Milky Way

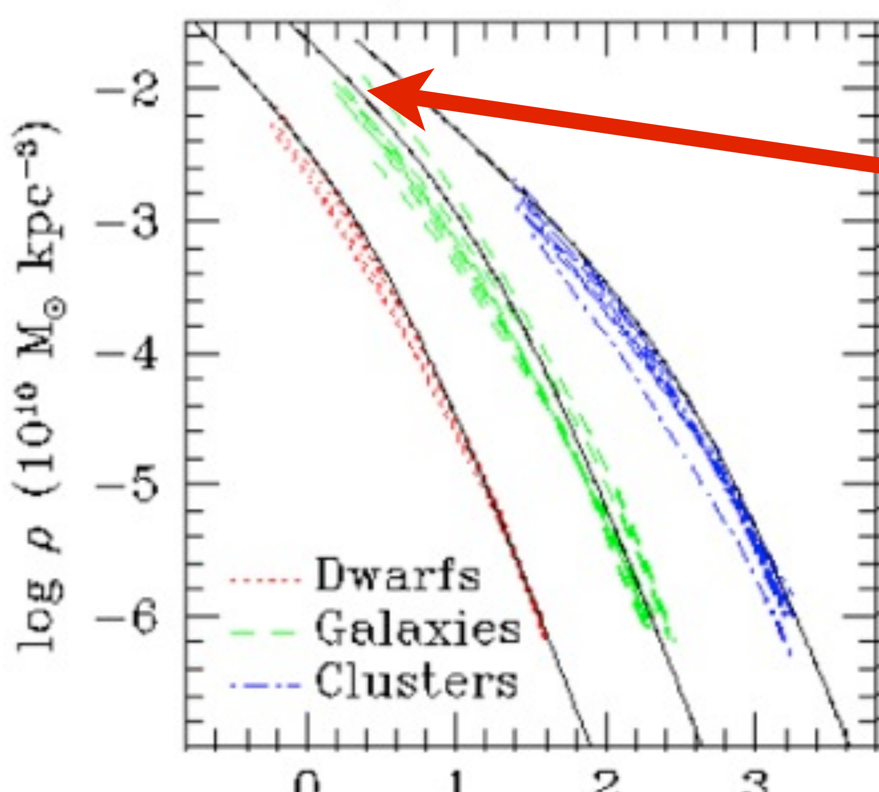
arXiv:1306.5725, Gordon et al

Hooper&Goodenough 2009
FERMI-LAT 2009

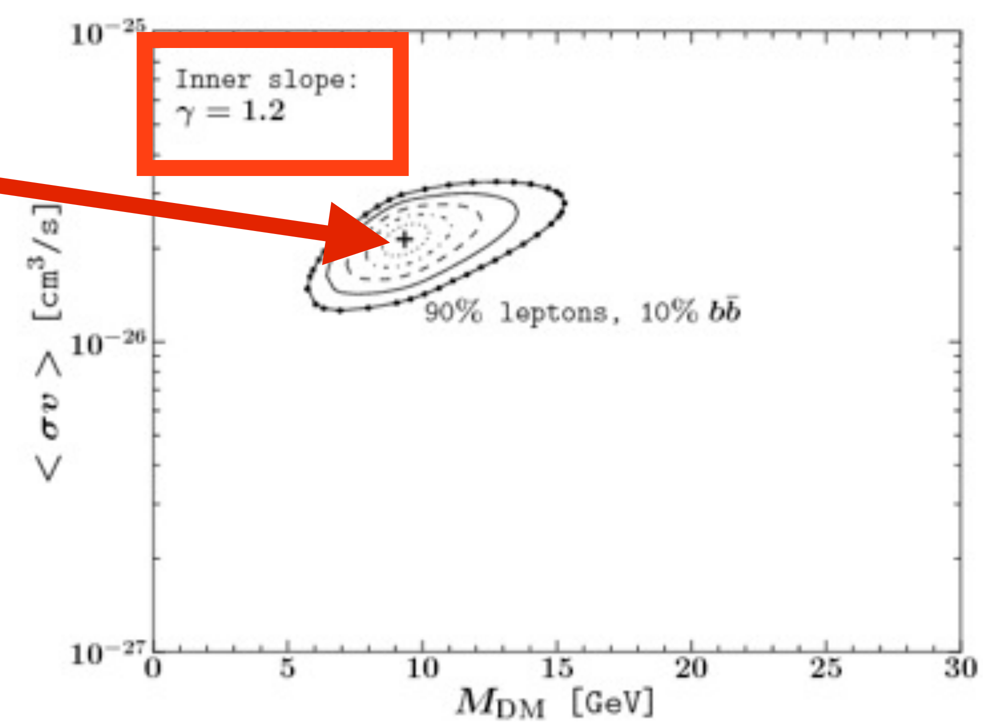




Navarro, Frenk & White 1996

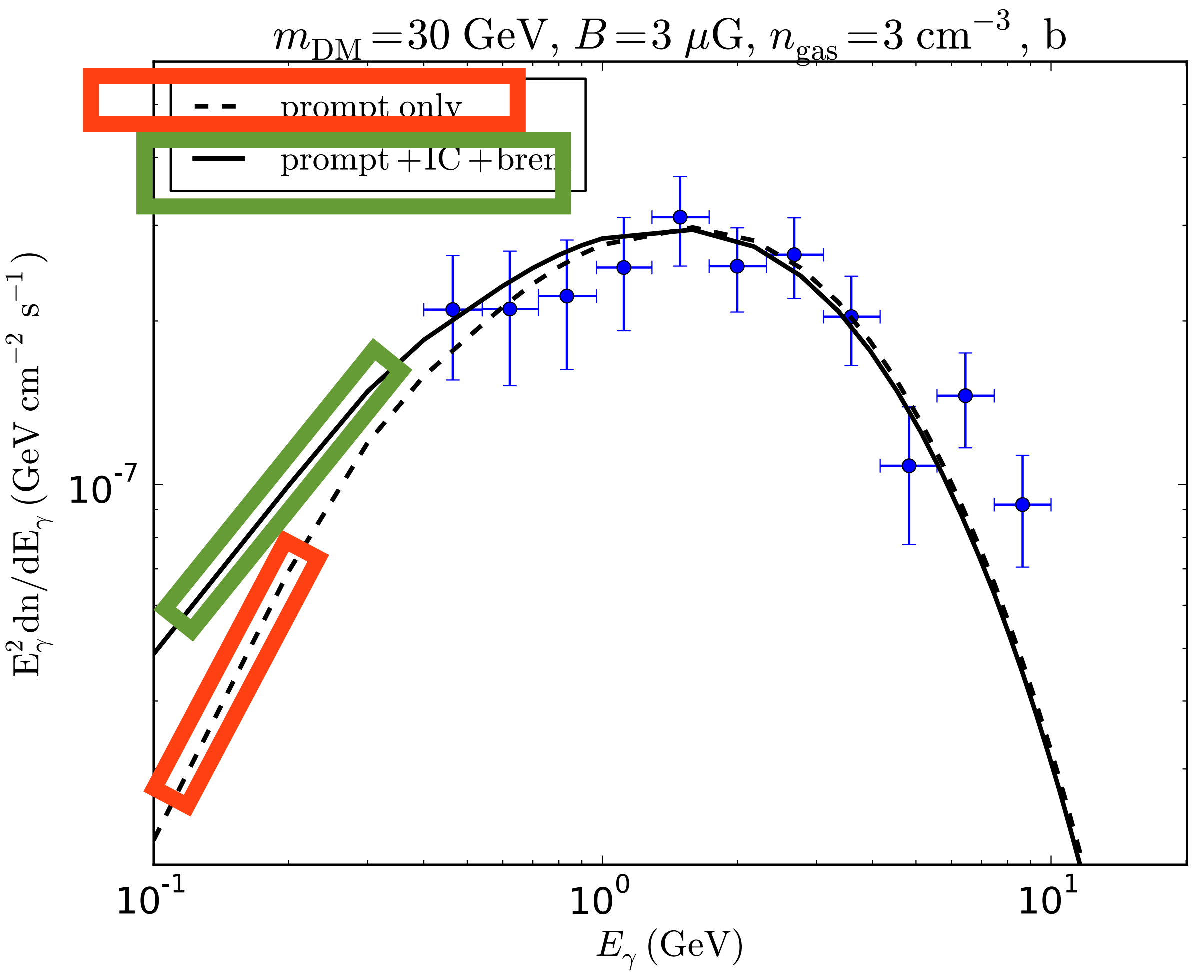


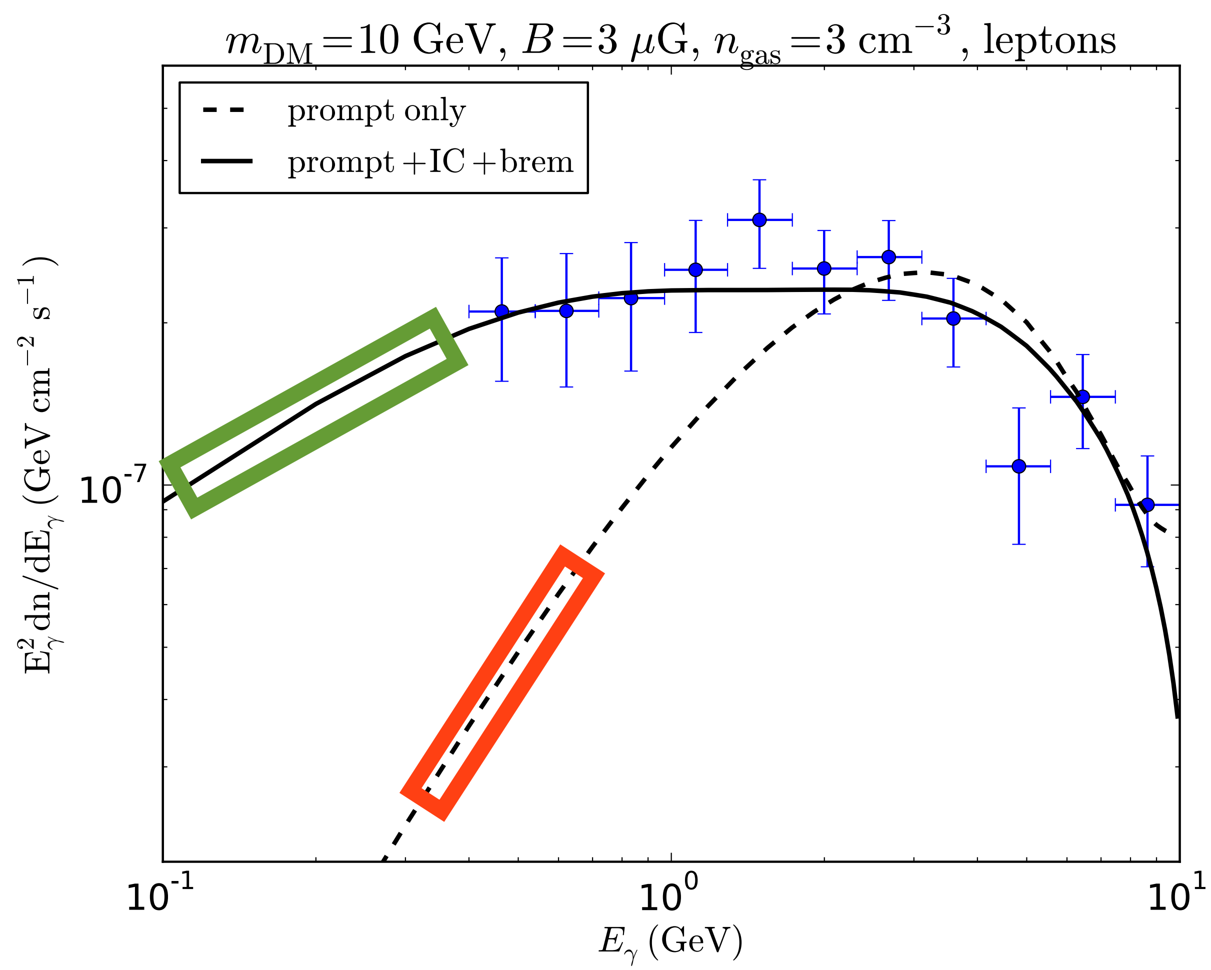
higher slope



Prompt vs diffuse gamma ray emission

arXiv:1403.1987, Lacroix et al





- diffusion changes the interpretation of the excess
- diffusion predicts low energy gamma-rays and cosmic rays...

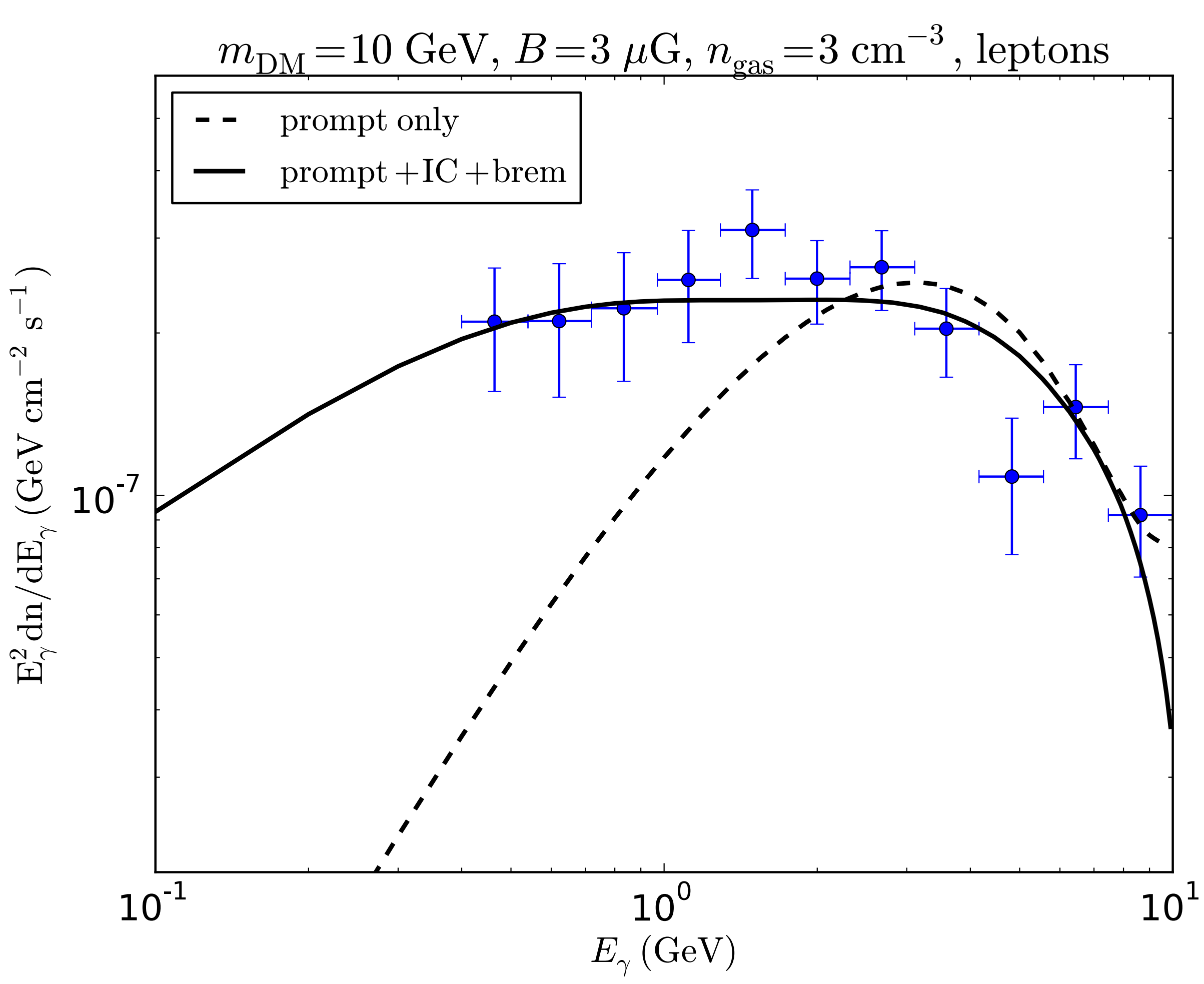
Can we discriminate between final states?

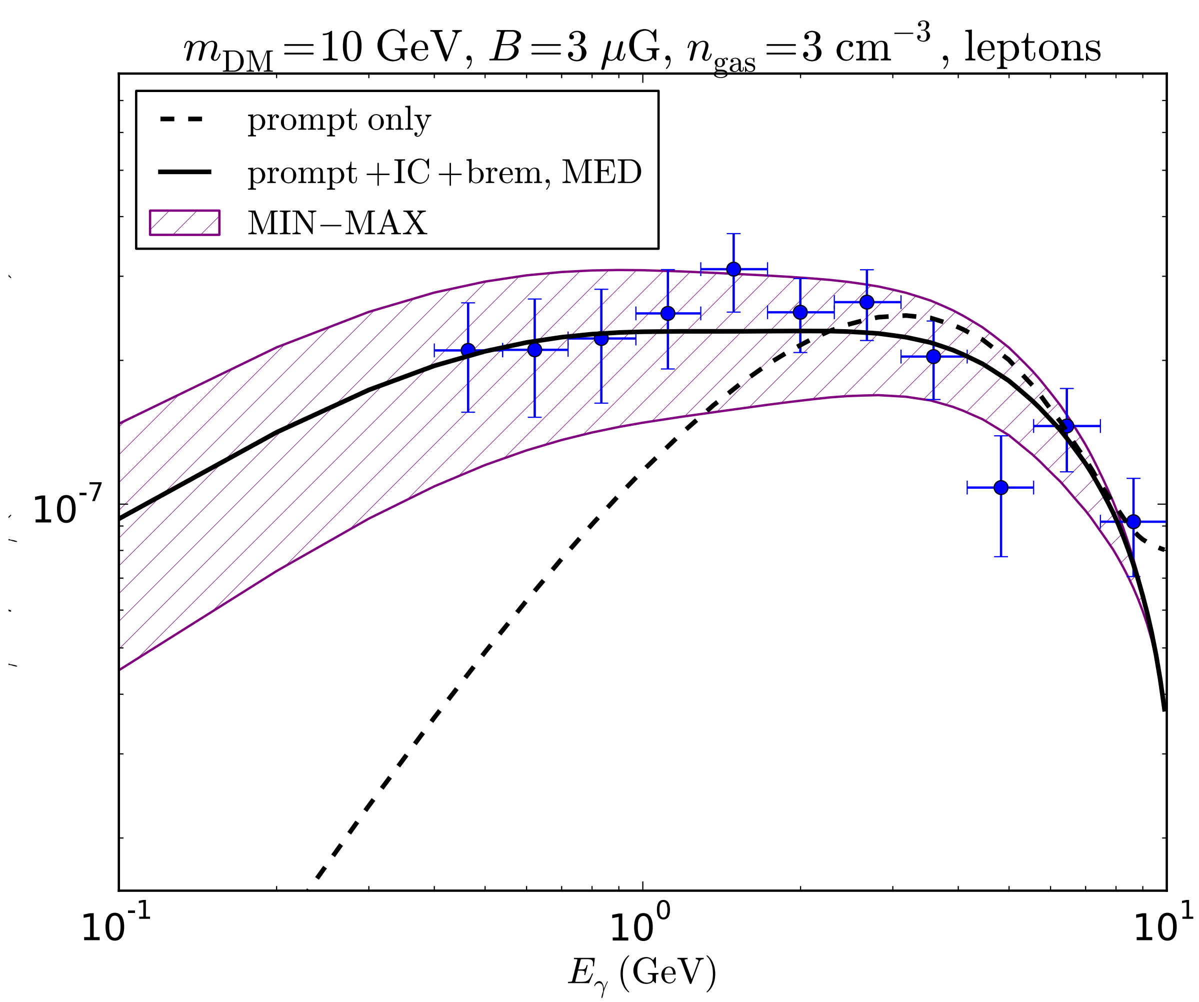
arXiv:1404.4977

arXiv:1401.6458

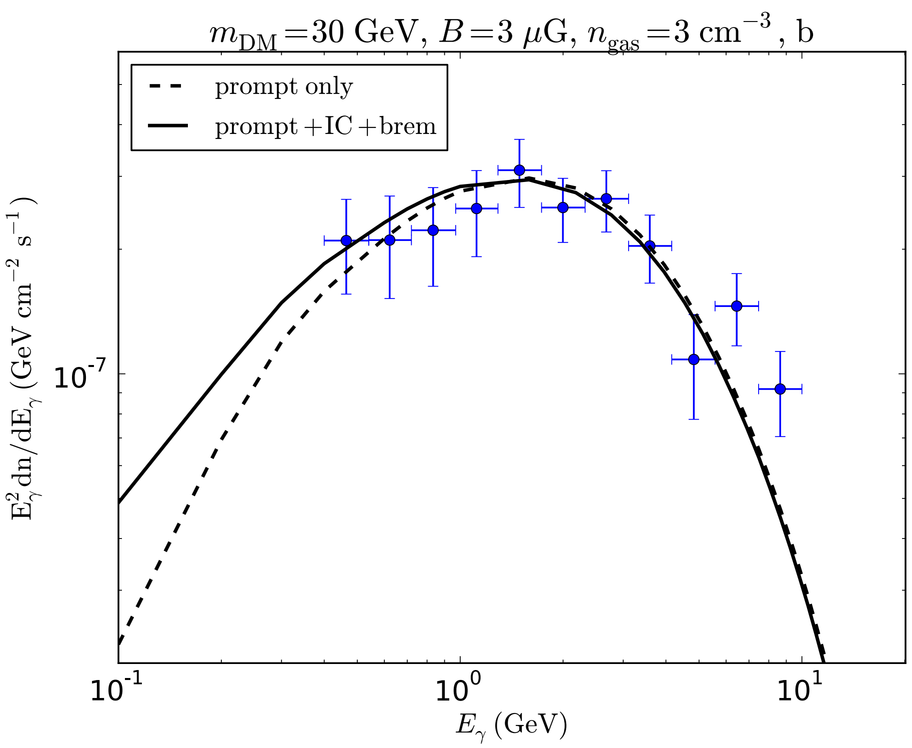
Impact of diffusion uncertainties

T. Lacroix, CB, J. Silk, 2014





Spin-off: an explanation to the 511 keV line?

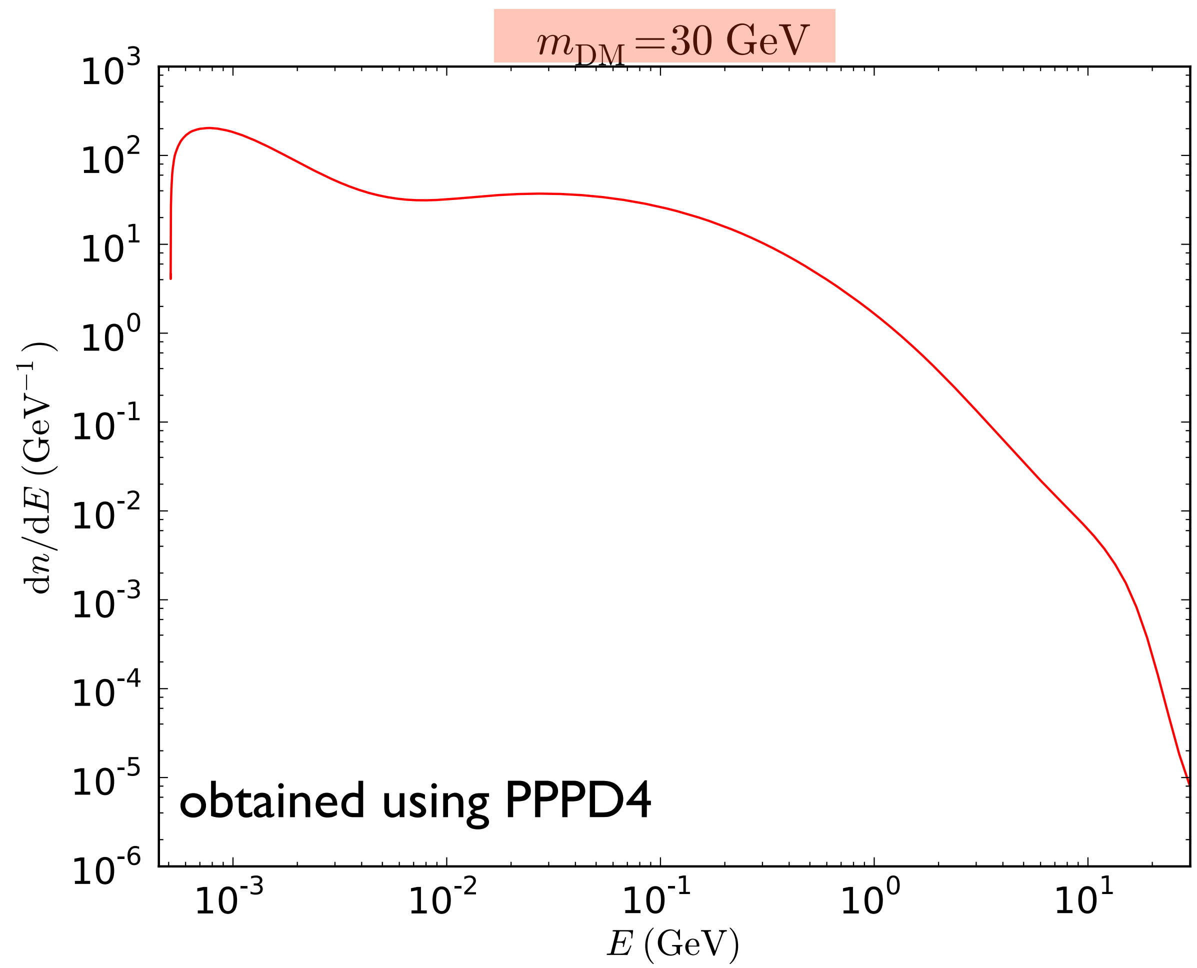


$$\mathrm{DM\ DM} \rightarrow \mathrm{b\ \bar{b}}$$

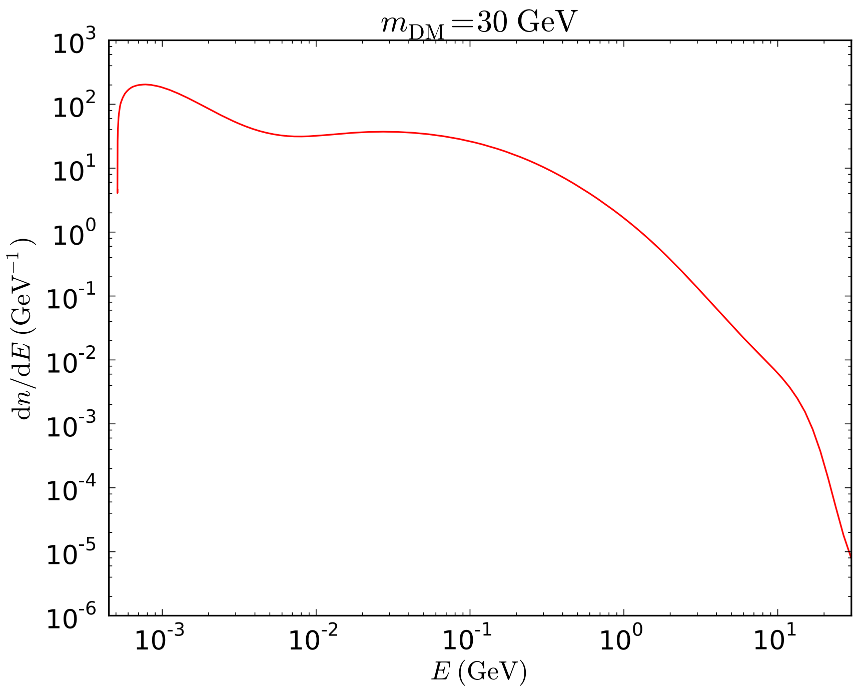
Injection spectrum for the b quarks

★ b quarks decay and/or hadronise (D & K mesons),
★ D & K mesons decay into Pions and muons
★ all eventually lead to electrons & positrons

$$\boxed{e^+ \text{ from b quarks}}$$

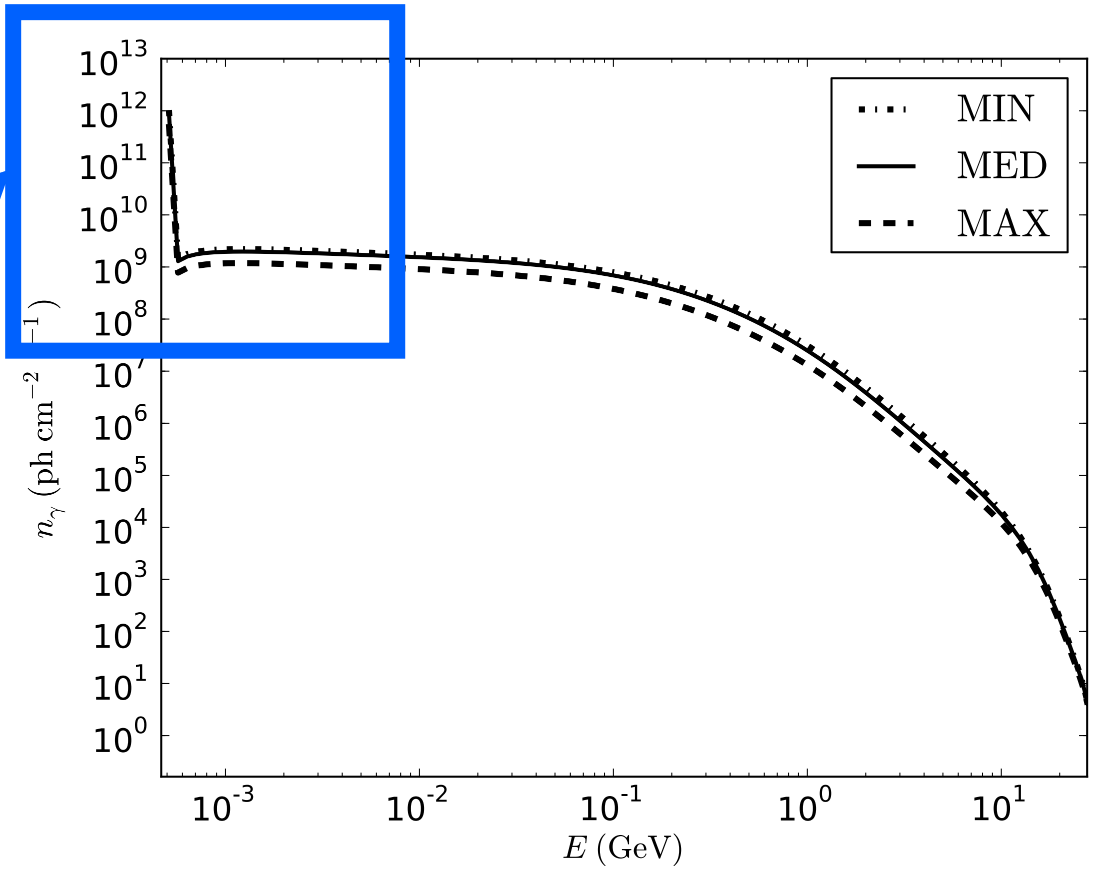


Positronium formation



start with this injection spectrum

Then e+ diffuse out
and accumulate down to a few eV



Losses fall below 13.6 eV so positrons stop there.

[Coulomb losses and Bremsstrahlung ~ 0]

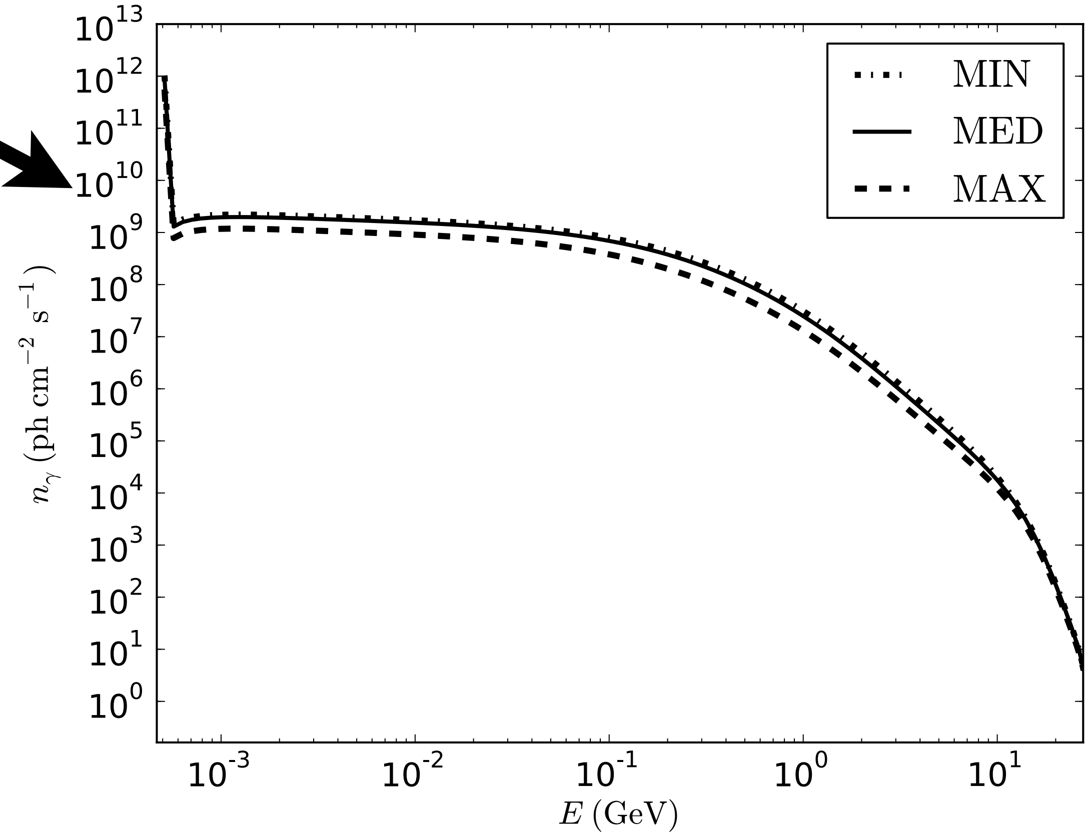
Positronium formation

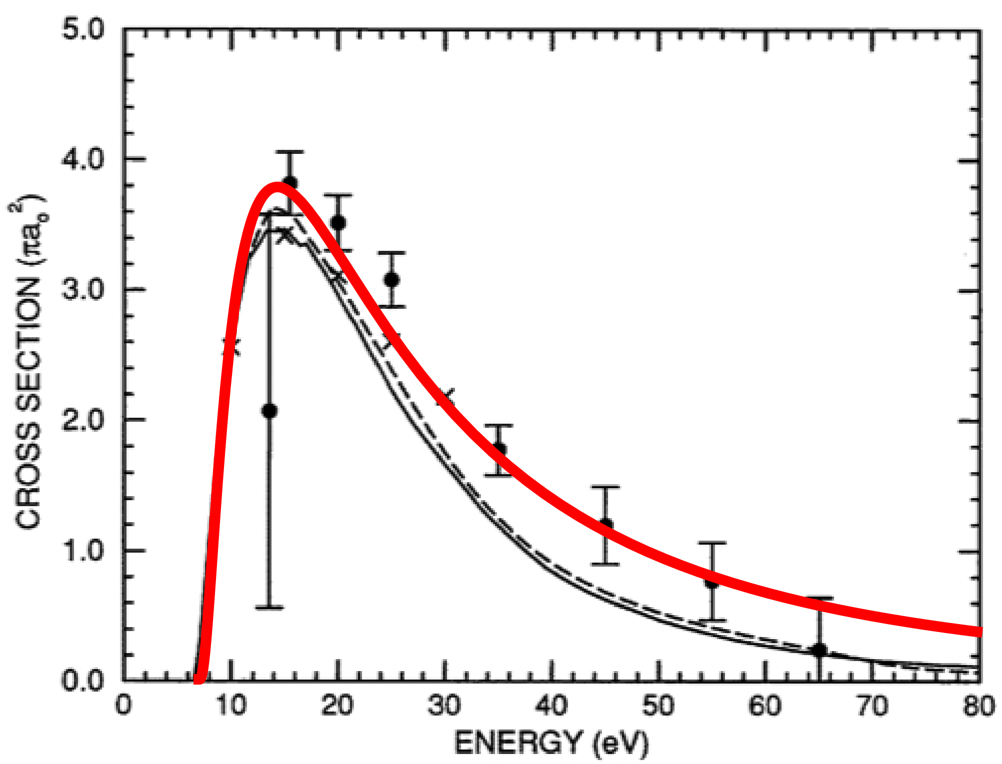
$$\frac{d\phi(E_\gamma)}{d\Omega} = \eta \int ds \int_{6.8}^{100} dE_{e^+}\ \Gamma_{Ps}(E_{e^+}) \boxed{\frac{dN_{e^+}}{dE_{e^+}}}$$

$$\boxed{\Gamma_{Ps}(E_{e^+}) = \sigma_{e^+\ H \to P_s\ H^+}(E_{e^+})\ v(E_{e^+})\ n_H}$$

$$e^+ e^- \to P_s \gamma$$

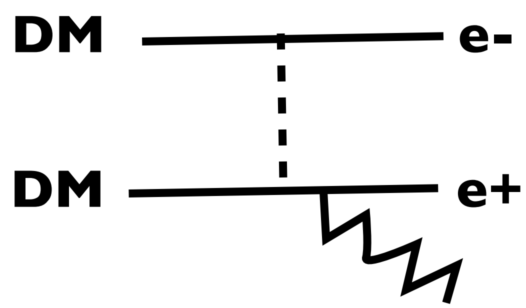
$$e^+\ H \to P_s\ H^+$$





$$\boxed{\sigma_{e^+\ H \to P_s\ H^+} = 3.6\,\pi\,a_o^2\,e^{-\left(\frac{\ln(E/\mathrm{eV}-6.8)-2}{1.5}\right)^2}}$$

Light mass range & constraints



$$\frac{d\phi}{dE} = \frac{1}{8\,\pi}\left(\frac{\sigma v}{m_\chi}\right)^2 \sum_i \mathrm{BR_i}\,\frac{\mathrm{dN_i}}{\mathrm{dE}}\,\xi^2 \int \mathrm{dl}\;\rho_\chi^2(\mathrm{l})$$

C. Boehm[1], T. A. Enßlin[2], J. Silk **astro-ph/0208458**

	α	β	γ	r_s kpc	$F(\theta)$ 1°	10°	45°	$\Phi/(\langle\sigma v_r\rangle_{26}\, m_{\rm GeV}^{-2})$ cm^{-2} s^{-1}
NFW	1	3	1	25	0.077	0.62	1.7	$5.9\ 10^{-6}$
KRA	2	3	0.2	11	$1.7\cdot10^{-4}$	0.014	0.15	$7.5\ 10^{-8}$
ISO	2	2	0	4	$1.2\cdot10^{-4}$	0.011	0.08	$1.8\ 10^{-7}$
BE	1	3	0.3	4	$1.2\cdot10^{-4}$	0.004	0.01	$4.1\ 10^{-6}$

Predicted (NFW)

$$\Phi^{GC}_{\rm obs}(<1.5^\circ) \sim\ 5.9\,\left(\frac{m_{\rm DM}}{\rm MeV}\right)^{-2}\left(\frac{\sigma v}{10^{-26}\ {\rm cm^3/s}}\right)\ {\rm cm^{-2}\ s^{-1}}$$

Observed

$$\Phi^{GC}_{\rm obs}(<1.5^\circ) \sim\ 10^{-5}\ {\rm cm^{-2}\ s^{-1}}$$
for $\mathrm{E}_\gamma > \mathrm{MeV}$

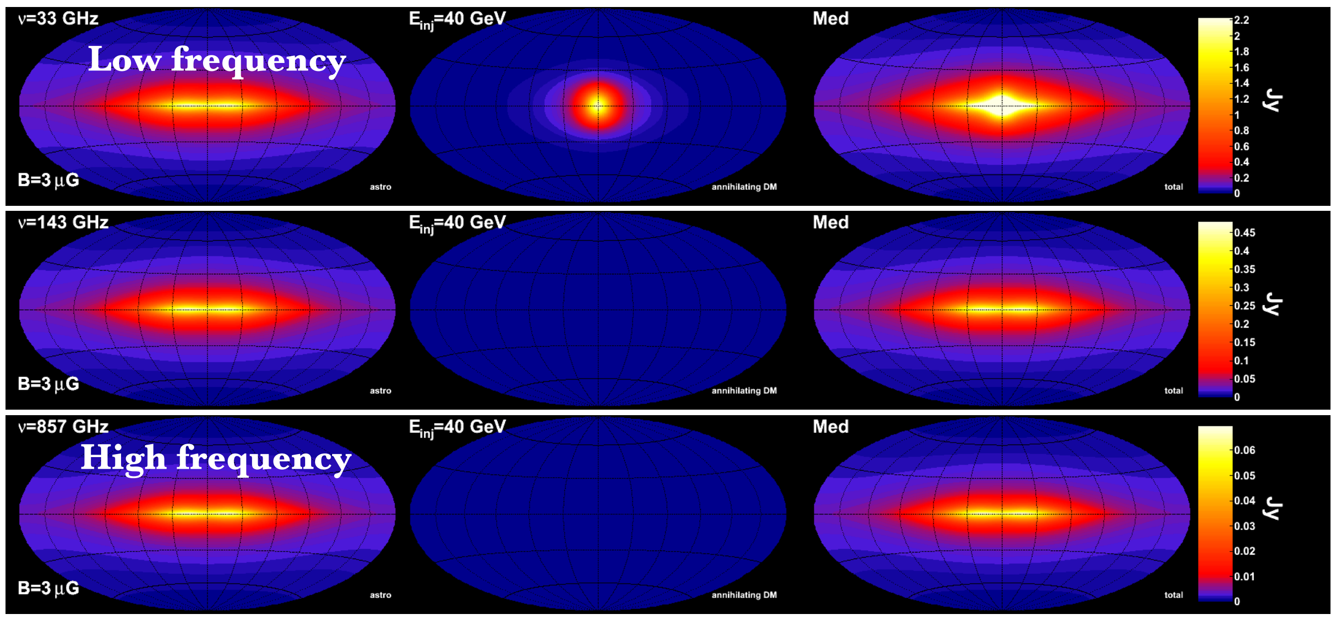
At least 5 orders of magnitude larger than observations!!

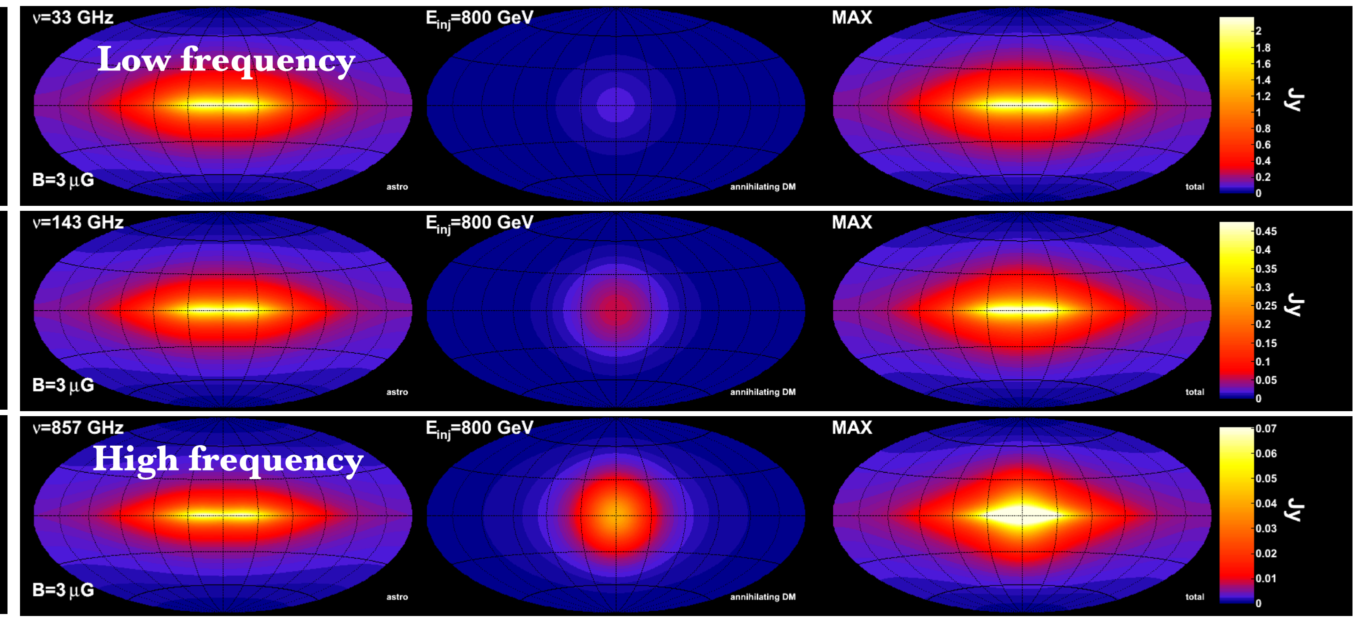
LIGHT (sub 10 GeV) DM : Annihilation cross seciton must be suppressed!

velocity dependence or neutral final state!

astro-ph/0208458

Astrophysical sources **DM** **Sum** **Astrophysical sources** **DM** **Sum**





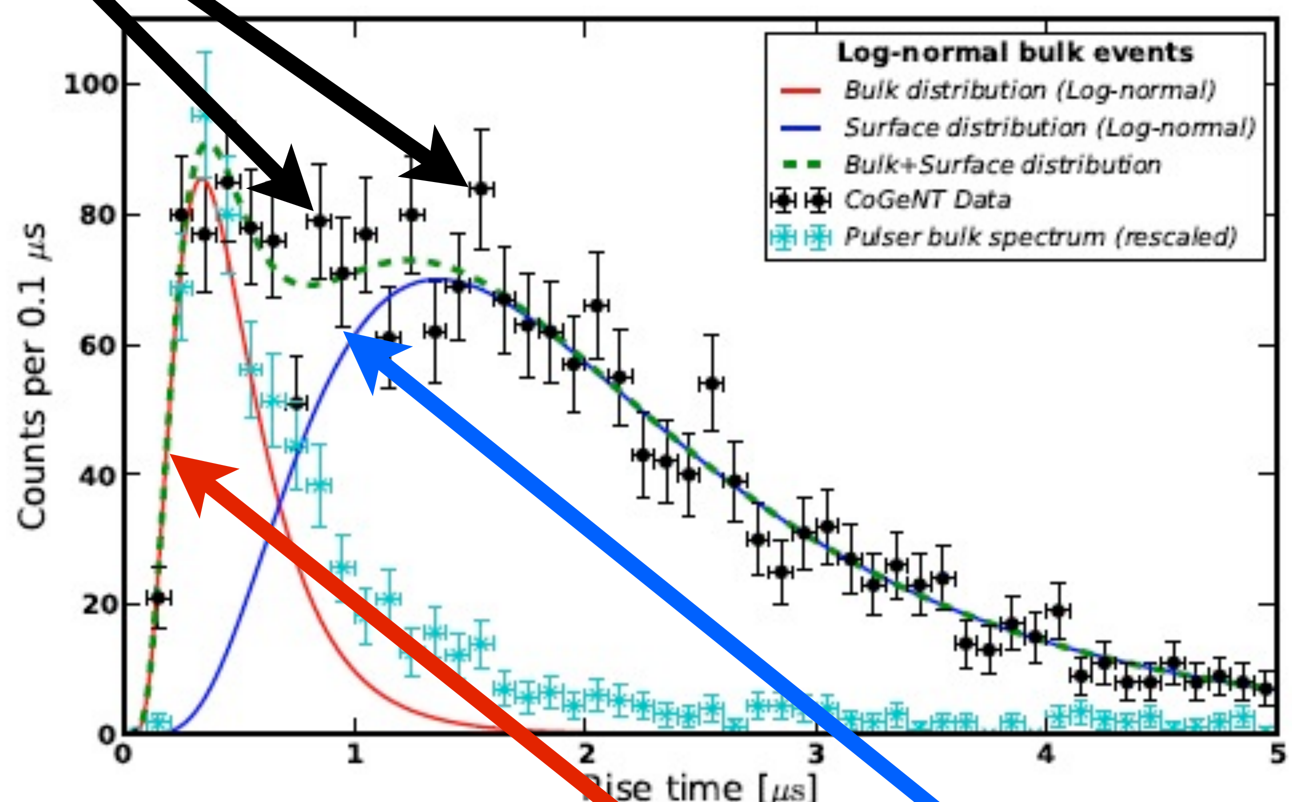
800 GeV DM

High mass DM gives a signal in HFI but not at low frequencies

CoGeNT

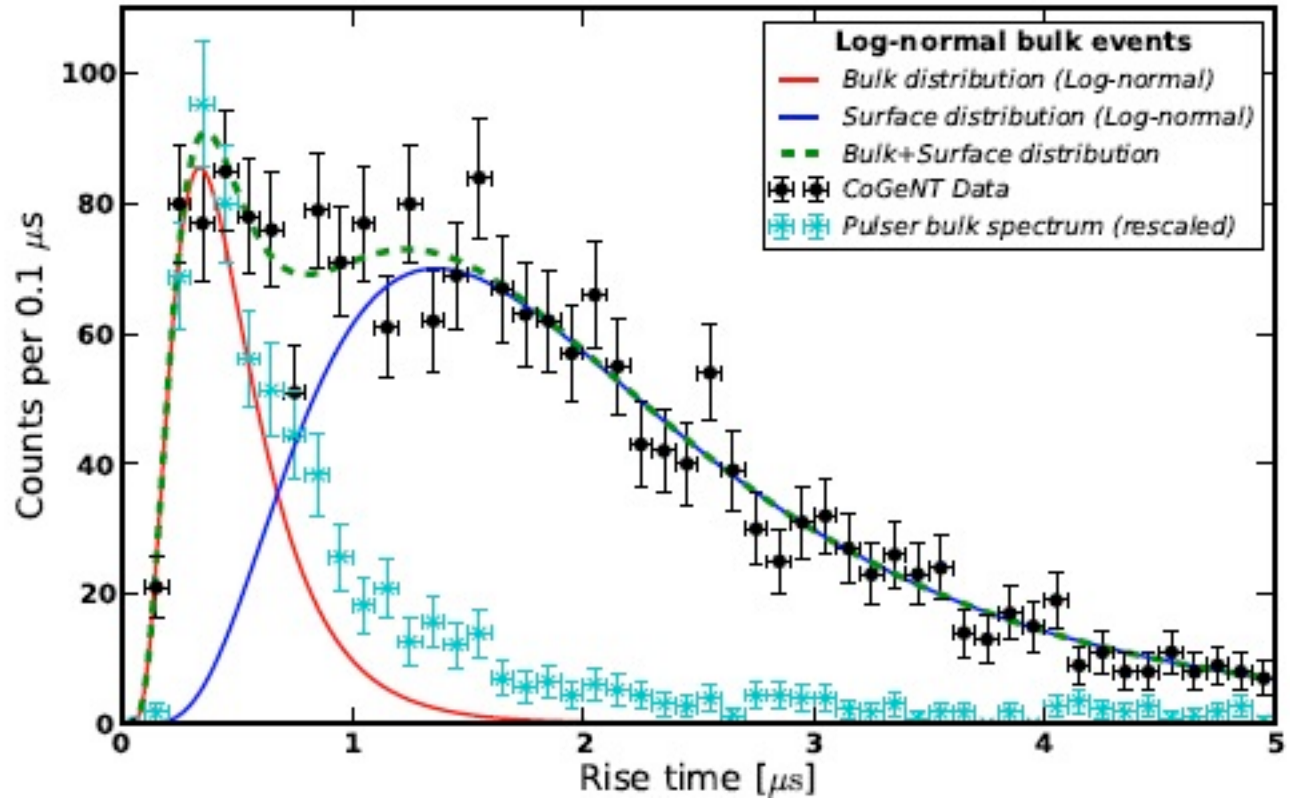
What CoGeNT reports

just a set of data points corresponding to the # of pulses
as a function of time



But those can be split into 2 populations: DM and background

The question is how to discriminate? CoGeNT's answer: lognormal



bulk

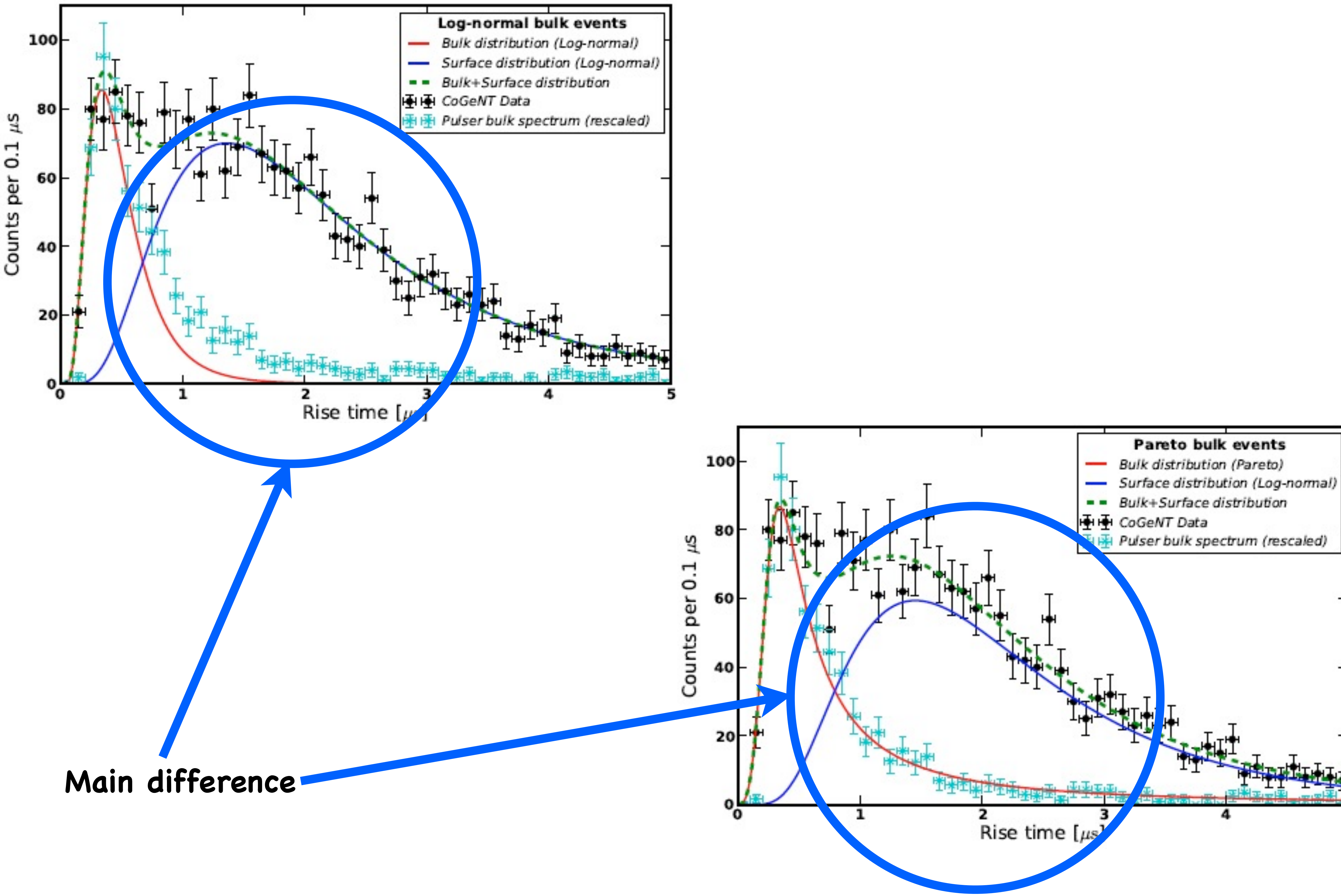
background+DM

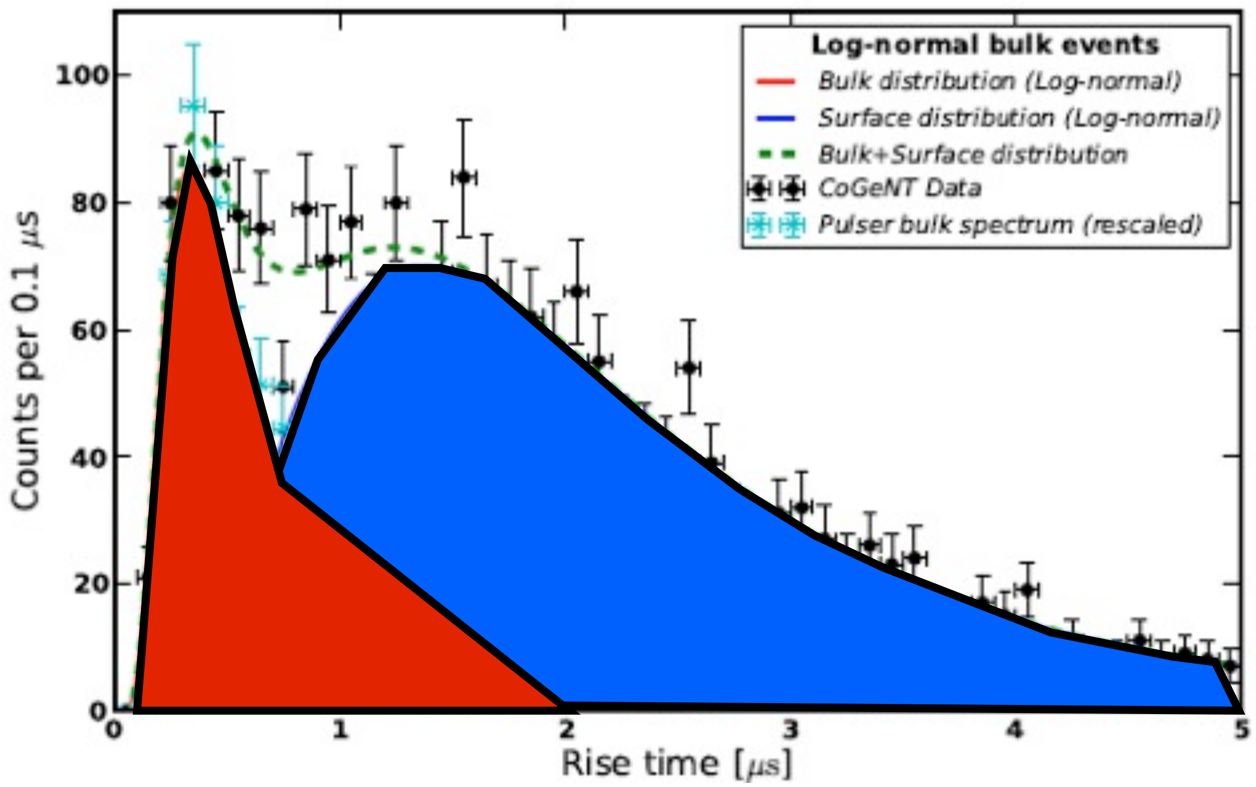
surface

background only

take more time to rise because they are happening in the part of the detector where charge collection is good

How to remove background? First determine the fraction Bulk to Surface!


Log-normal bulk events
Bulk distribution (Log-normal)
Surface distribution (Log-normal)
Bulk+Surface distribution
CoGeNT Data
Pulser bulk spectrum (rescaled)
Counts per 0.1 μs
Rise time [μs]
Pareto bulk events
Bulk distribution (Pareto)
Surface distribution (Log-normal)
Bulk+Surface distribution
CoGeNT Data
Pulser bulk spectrum (rescaled)
Counts per 0.1 μs
Rise time [μs]
Main difference



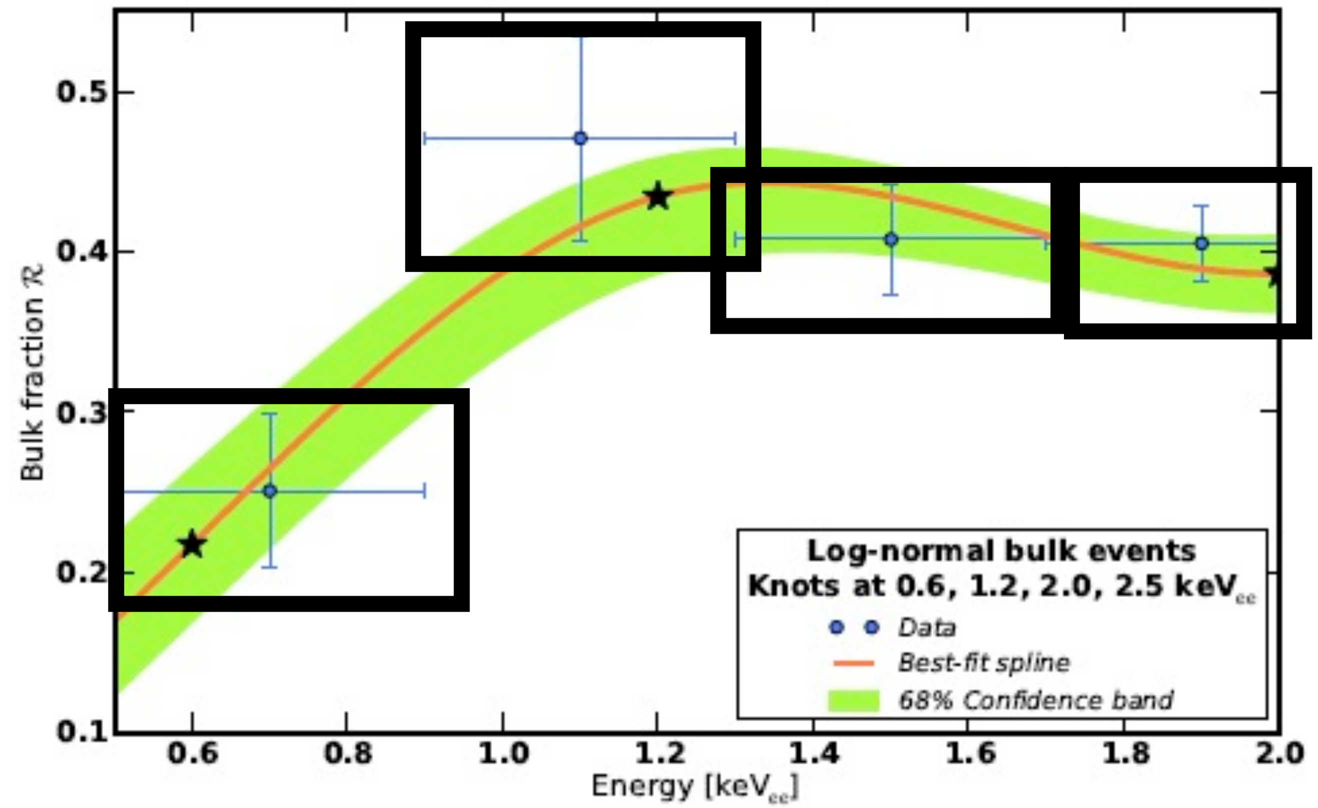
Ratio for 1 energy bin

Integrate the blue distribution = total # surface events

Integrate the red distribution = total # DM events

Ratio gives the value bulk/surface for that energy bin!

Repeat for all energy bins!



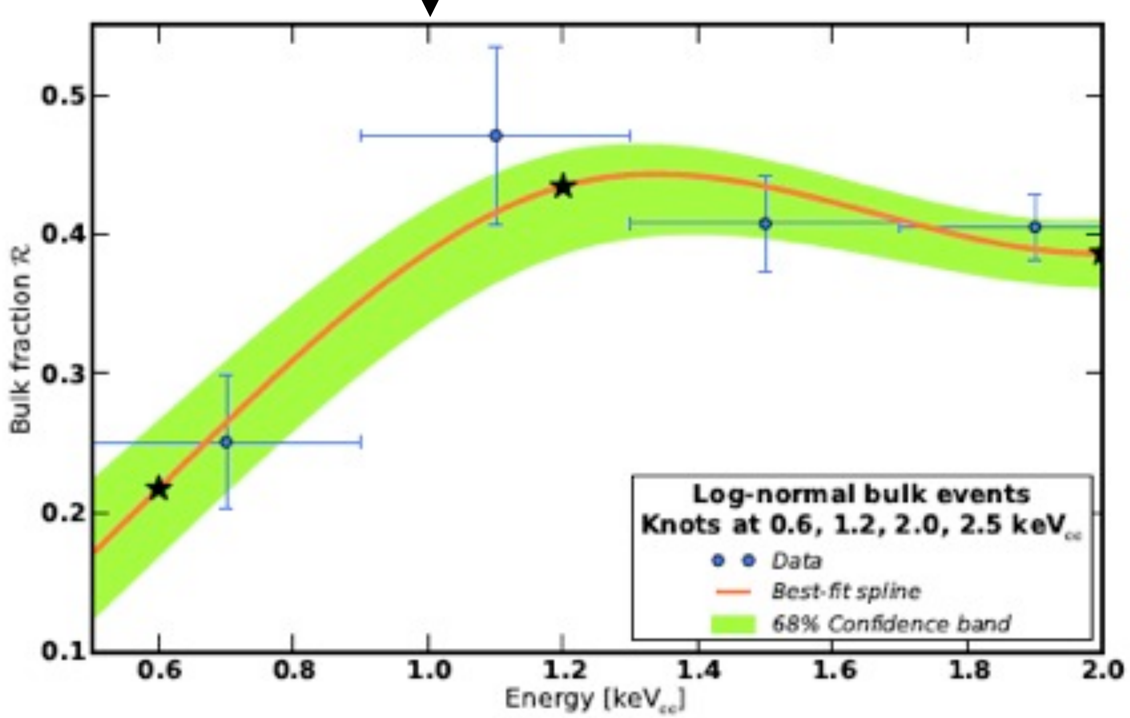
Find the functional form!

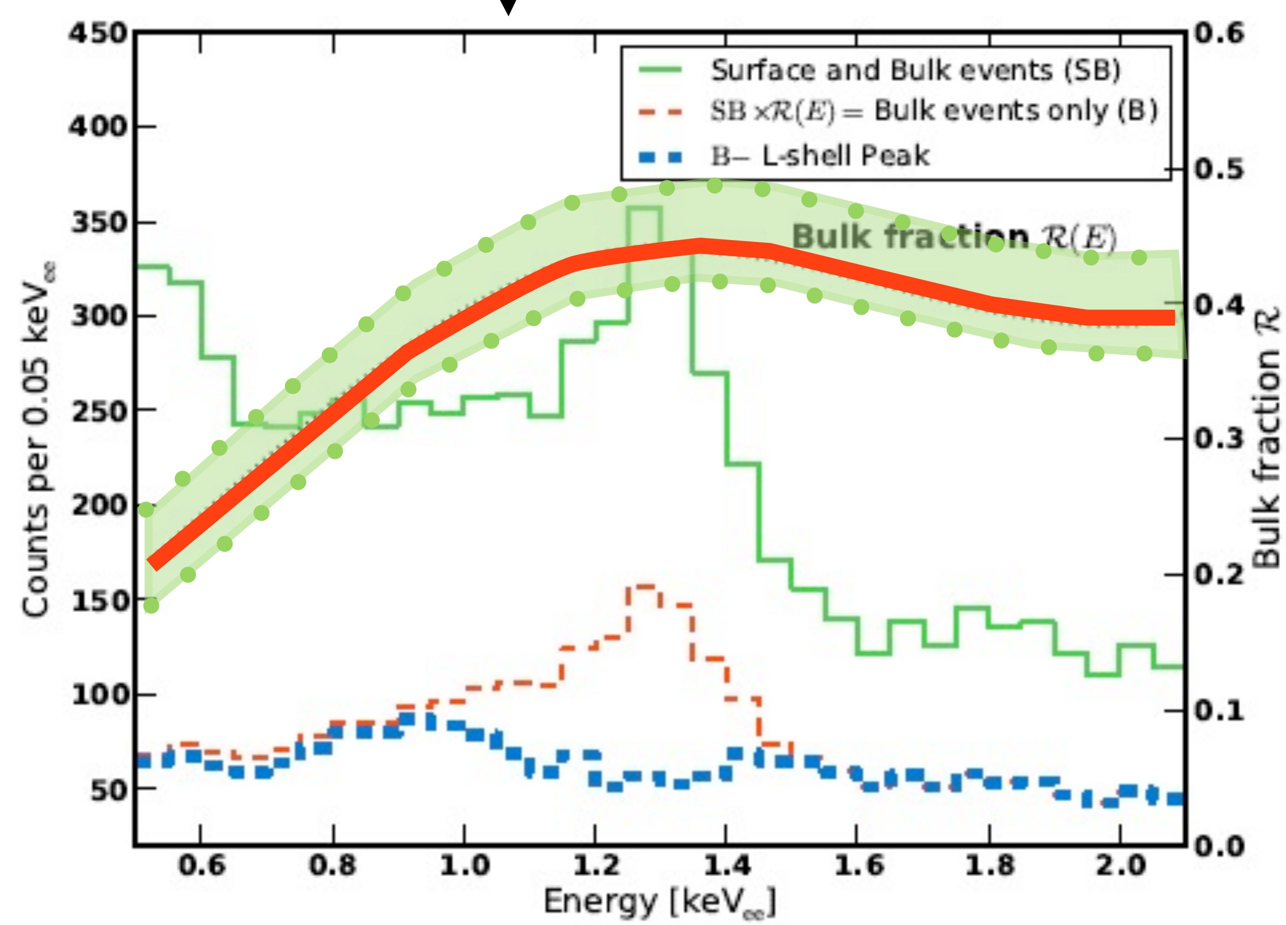
see the red curve and green band

Procedure

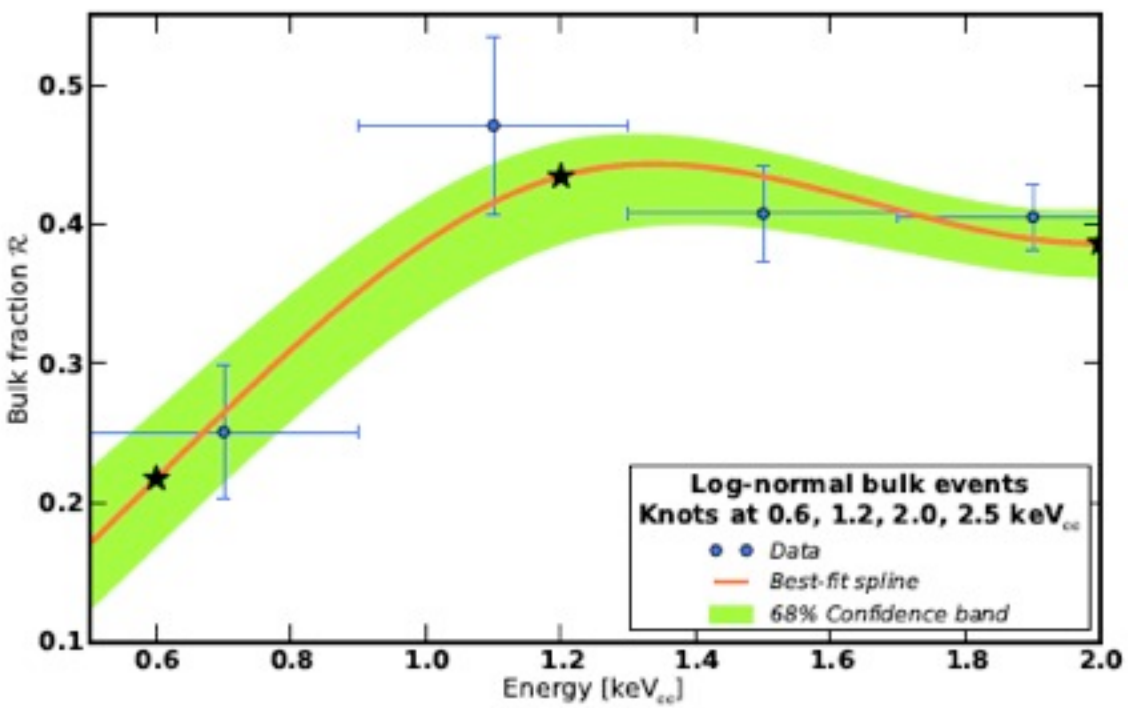
take the bulk fraction

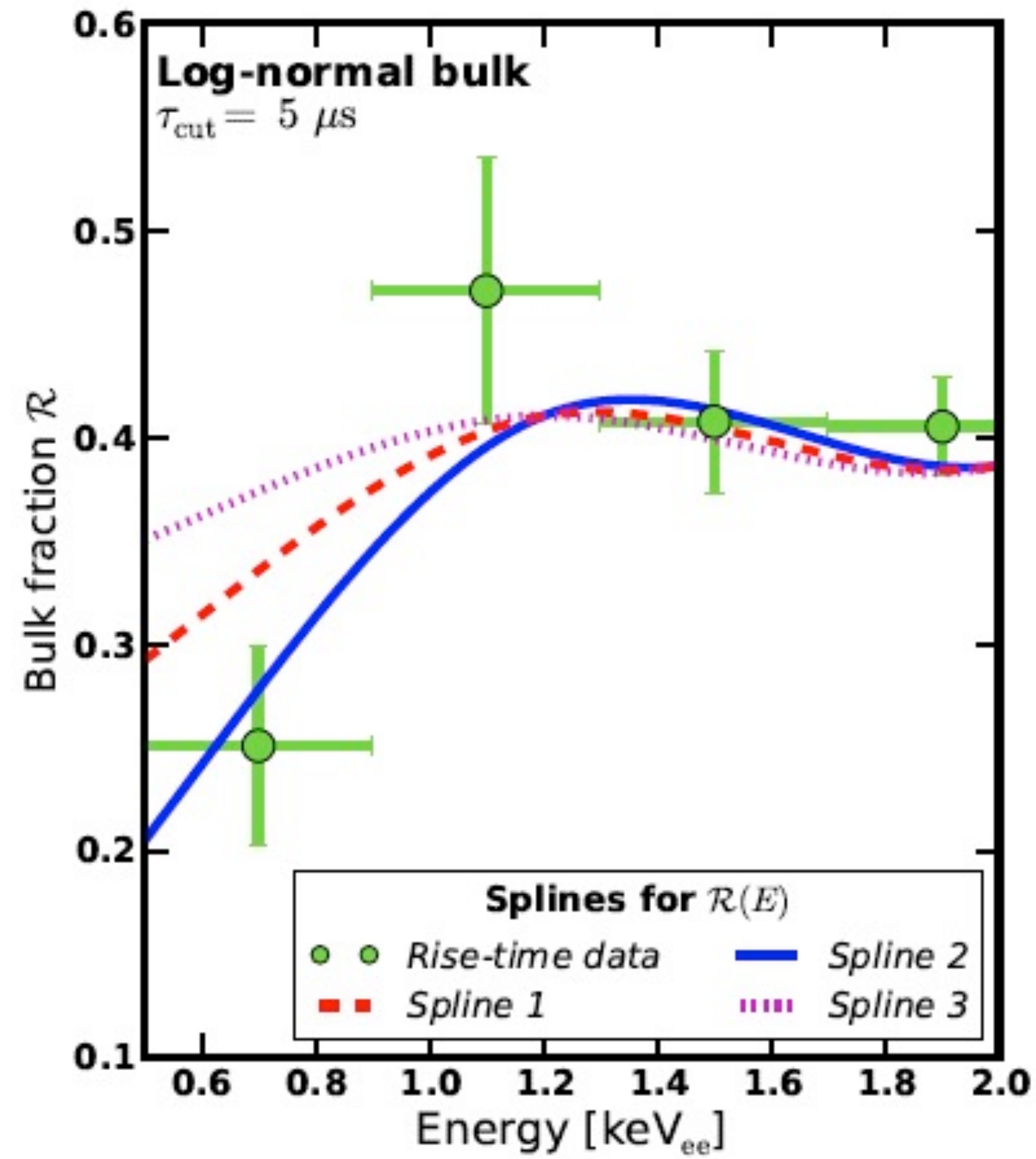
multiply it with the total number of events (great histograms)





The spectrum you get does not contain surface events anymore

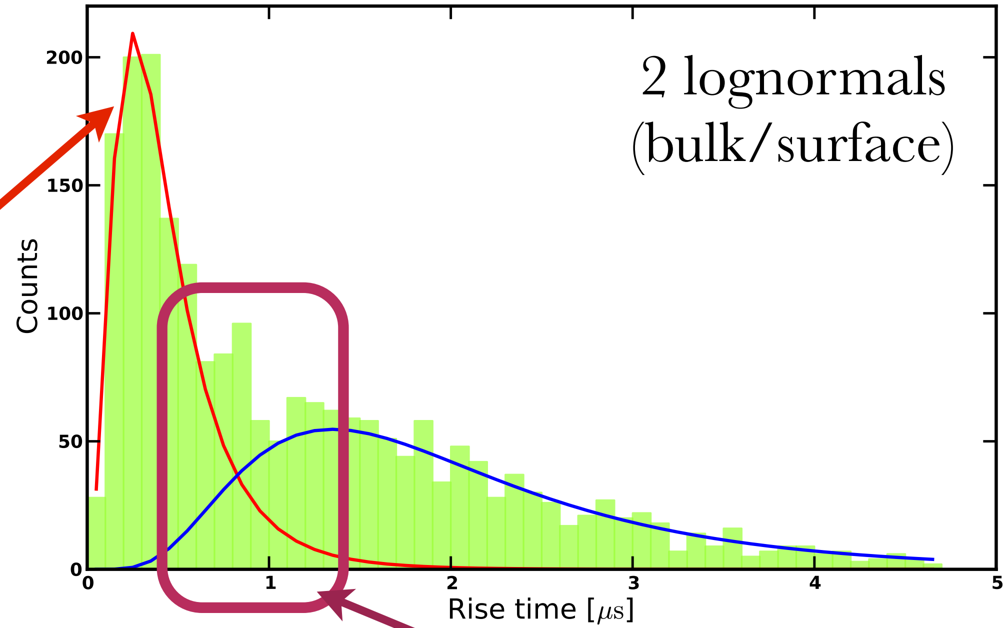

Log-normal bulk events
Knots at 0.6, 1.2, 2.0, 2.5 keV$_{ee}$
Data
Best-fit spline
68% Confidence band
Bulk fraction $\mathcal{R}$
Energy [keV$_{ee}$]
0.1
0.2
0.3
0.4
0.5
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

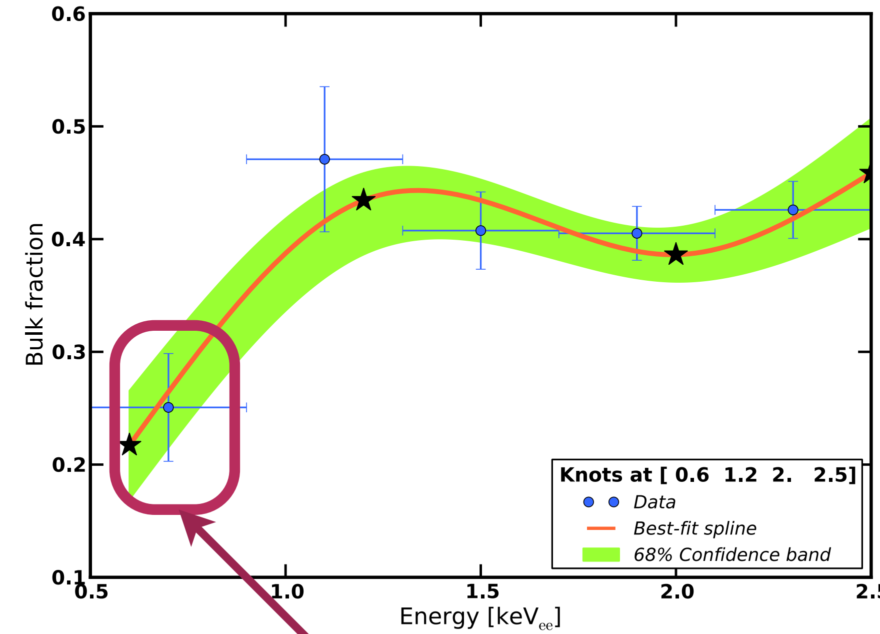

Log-normal bulk
$\tau_{\rm cut} = 5\ \mu$s
Splines for $\mathcal{R}(E)$
Rise-time data
Spline 1
Spline 2
Spline 3
Bulk fraction $\mathcal{R}$
Energy [keV$_{ee}$]
0.1
0.2
0.3
0.4
0.5
0.6
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

Only 1 sigma evidence

J. Davis, C. McCabe, C. Boehm in preparation

signal: rise time for 1 energy bin





DM rises

cross between surface and bulk rise time for each energy channel