Dark Matter Annihilation in the Late Universe

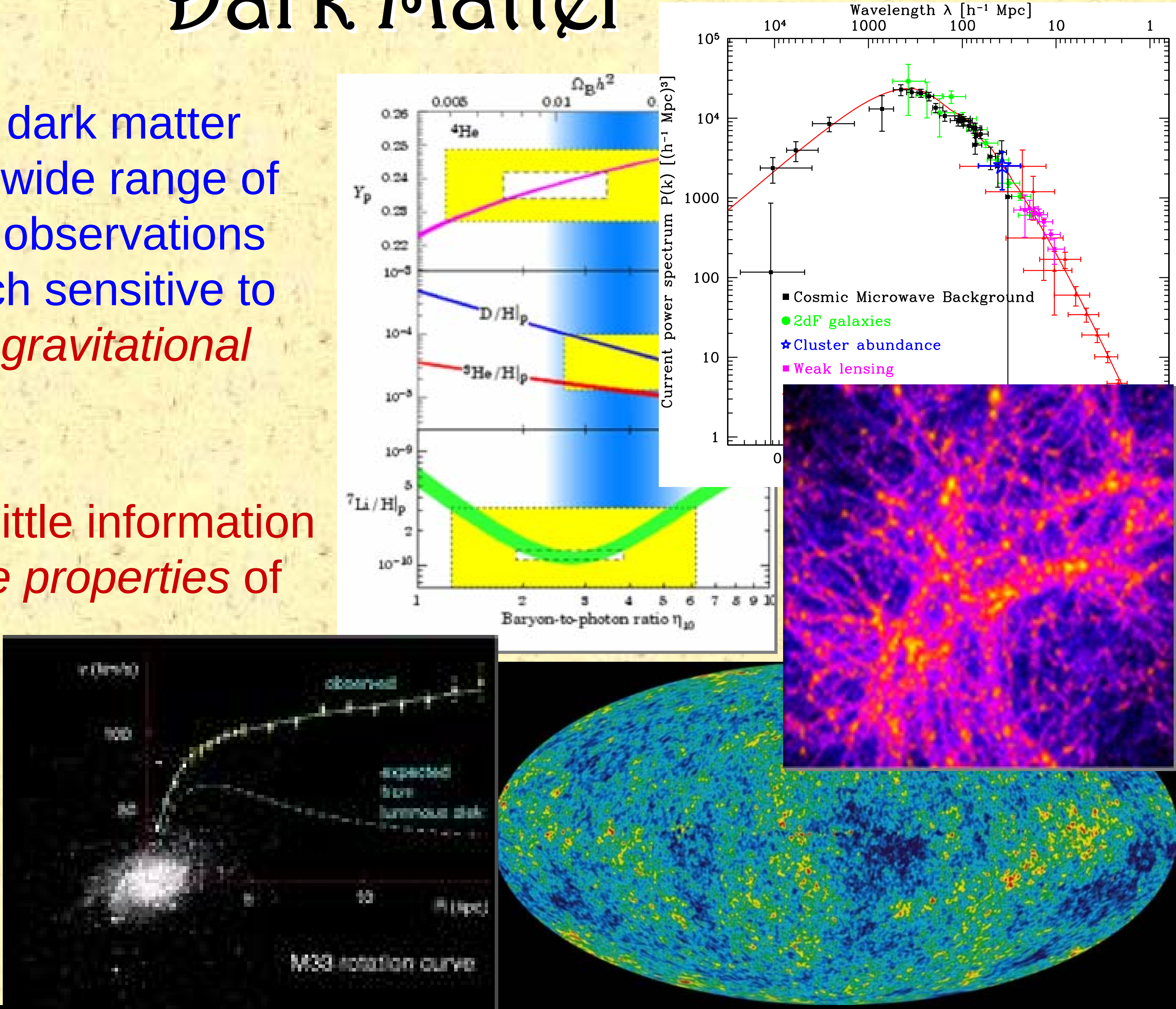
Nicole Bell
The University of Melbourne

Collaborators:
John Beacom (Ohio State), Gregory Mack (Ohio State), Hasan Yuksel (Ohio State),
Thomas Jacques (Melbourne), Gianfranco Bertone (Paris), James Dent (Vanderbilt)
and Tom Weiler (Vanderbilt).

Dark Matter

- Evidence for dark matter arises from a wide range of astrophysical observations which are each sensitive to dark matter's *gravitational influence*.

- As yet, very little information on the *particle properties* of dark matter.



Dark Matter Candidate Zoo

Axions, Neutralinos, Gravitinos, Axinos, Sneutrinos, Kaluza-Klein particles, Heavy Fourth Generation Neutrinos, Mirror particles, superWIMPs, WIMPzillas, Sterile Neutrinos, Light Scalars, Q-Balls, Brane World Dark Matter, Primordial Black Holes, …. things we haven’t thought of ….

It’s clear that any model-dependent approach to searching for dark matter has shortcomings.

Dark Matter Annihilation

- Self-annihilation cross-section is a fundamental property of dark matter

- For thermal relics it is specified by the DM relic density:

e.g. $\Omega_{DM} \sim 0.3$ implies $\langle \sigma_A v \rangle \sim 3 \times 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$

- More generally, it controls the DM annihilation rate in galaxies today → can affect galaxy halo density profiles

There exist two general constraints on the rate of dark matter annihilation/*disappearance*:

Constraint 1. - Unitarity Bound

- Unitarity sets a general upper bound on the cross-section:

$$\langle \sigma_A v \rangle \le 4\pi / m_\chi^2 v$$

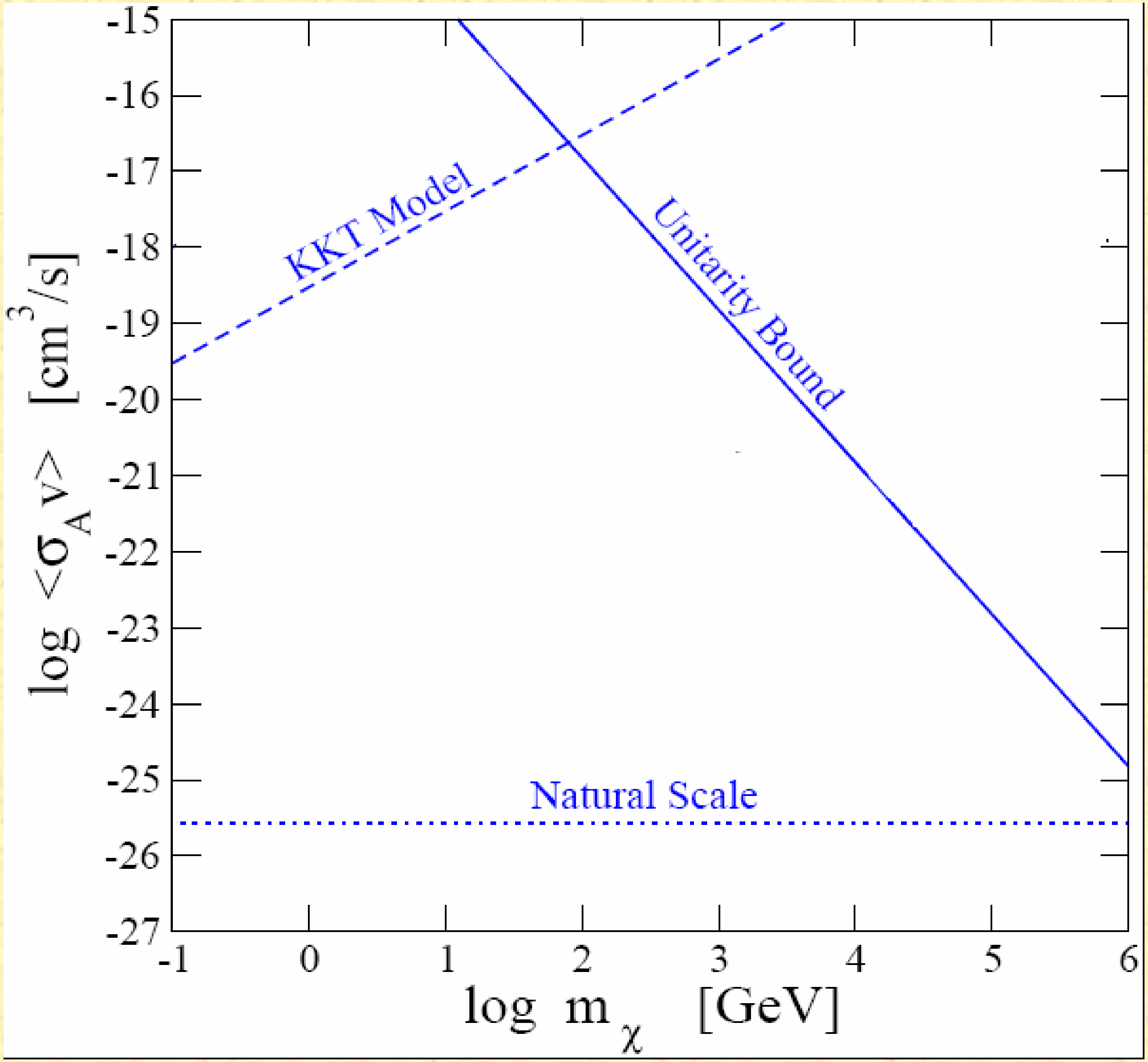
(in the low-velocity limit, where the cross-section is s-wave dominated)

→In galaxies today:

$$\langle \sigma_A v \rangle \le 1.5 \times 10^{-13} \frac{\mathrm{cm}^3}{\mathrm{s}} \left[\frac{\mathrm{GeV}}{m_\chi}\right]^2 \left[\frac{300\ \mathrm{km/s}}{v_{rms}}\right] .$$

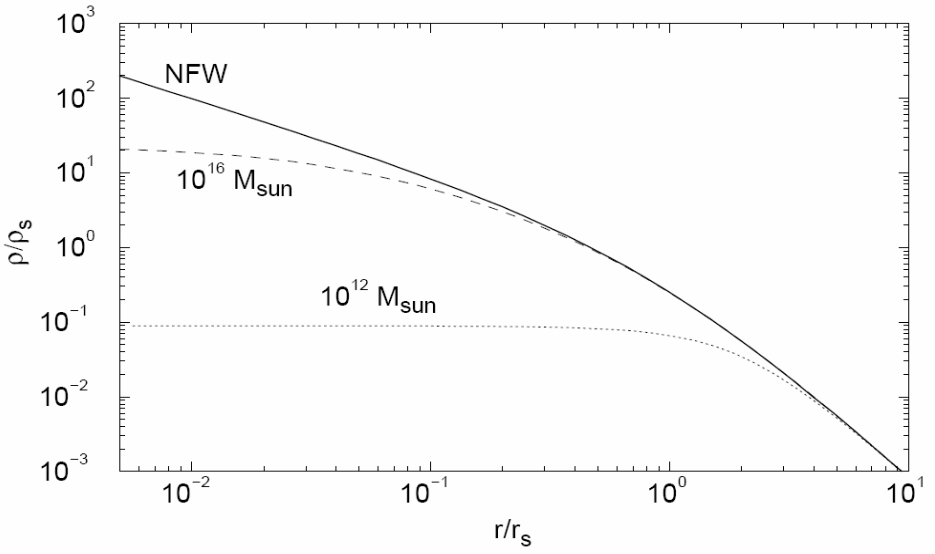
L. Hui

- Most restrictive for high masses.


KKT Model
Unitarity Bound
Natural Scale
log <σ_A v> [cm^3/s]
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
-26
-27
-1
0
1
2
3
4
5
6
log m_χ [GeV]

Constraint 2. – Kaplinghat-Knox-Turner Model

Phys. Rev. Lett. 85. 3335 (2000)



- Large dark matter annihilation rate flattens galaxy cores → invoked to resolve conflict between predicted (sharp cusps) and observed (flat cores) halo density profiles.

- KKT model requires cross-sections ~10^7 times larger than the natural scale for a thermal relic: $\langle \sigma_A v \rangle_{\rm KKT} \simeq 3 \times 10^{-19} \frac{\rm cm^3}{\rm s} \left[\frac{m_\chi}{\rm GeV} \right]$

- Reinterpret this type of model as upper bound on $\langle \sigma_A v \rangle$

Dark Matter Annihilation & Neutrinos → Indirect Detection

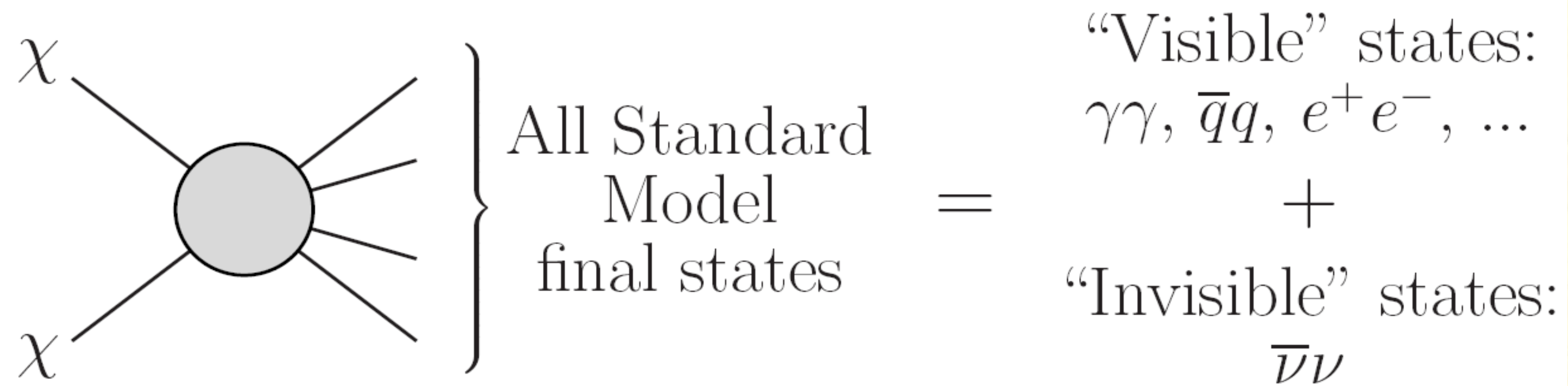
Search for fluxes of DM annihilation or decay products:

❖ Annihilation in our Galaxy
→ look for flux coming from Galactic center

❖ Annihilations in galaxies throughout the universe
→ cosmic diffuse flux

❖ Despite being harder to detect than gamma rays, neutrinos provide important information and ***strong, model independent bounds.***

If the dark matter is the lightest new particle:



$$\left.\right\}\ \begin{array}{c}\text{All Standard}\\ \text{Model}\\ \text{final states}\end{array} = \begin{array}{c}\text{“Visible” states:}\\ \gamma\gamma,\ \overline{q}q,\ e^+e^-,\ \ldots\\ +\\ \text{“Invisible” states:}\\ \overline{\nu}\nu\end{array}$$

❖All final states except neutrinos produce gamma rays,

→Bound the *total* cross-section with the neutrino signal limit
i.e. Assume Br(“invisible”) = 100%

Diffuse Neutrino Signal

❖Annihilation to neutrinos: $\chi\chi \rightarrow \bar{\nu}\nu$

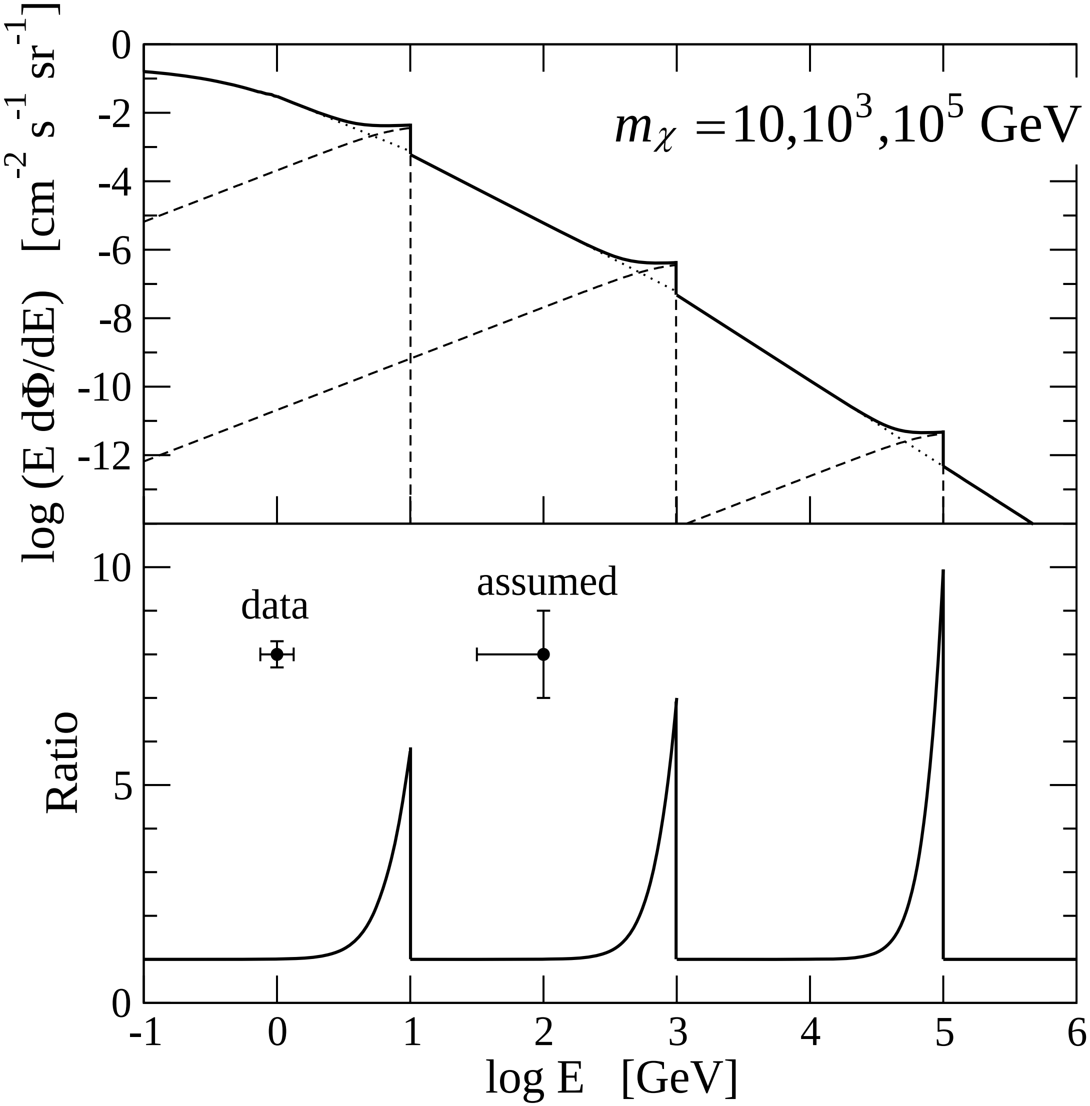
❖Diffuse flux (Ullio, et al.):

$$\frac{d\Phi_\nu}{dE} = \frac{\langle\sigma_A v\rangle}{2}\frac{c}{4\pi H_0}\frac{\Omega^2_{DM}\rho^2_{\rm crit}}{m^2_\chi}\int_0^{z_{\rm up}} dz \frac{\Delta^2(z)}{h(z)}\frac{dN_\nu(E')}{dE'}$$

The factor Δ accounts for the increase in density due to the clustering of dark matter in halos. (Δ=1 corresponds to all matter being at the average density in the Universe today)

❖Atmospheric neutrinos are the background

❖Conservative detection criteria: Signal 100% as large as angle averaged atmospheric neutrino background.



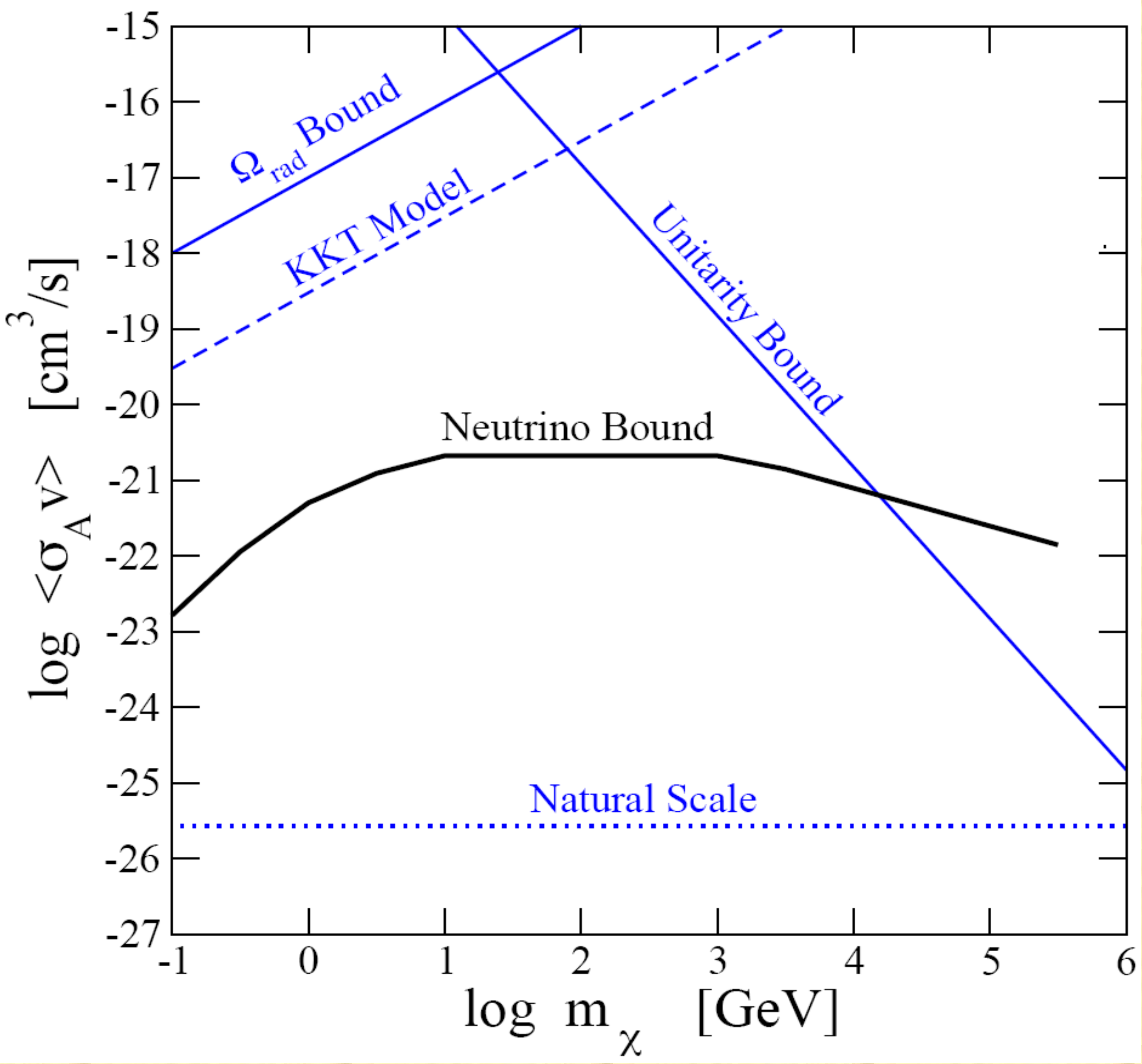
Upper panel: –

Annihilation flux superimposed on atmospheric neutrino background

Lower panel:

(Signal+Background)/ Background

Upper bounds on the dark matter total annihilation cross-section



Beacom, Bell, & Mack,
PRL99, 231301, 2007.

Also:

Yuksel, Horiuchi,
Beacom, & Ando,
PRD 76, 123506, 2007.

Kachelriess and Serpico,
PRD 76, 063516 (2007).

Bell, Dent, Jacques, &
Weiler, arXiv:0805.3423

Annihilation effect in Galaxy Halos?

- Annihilation flattens halo cusps to a core density of:

$$\rho_A \sim m_\chi/(\langle\sigma_A v\rangle H_0^{-1})$$

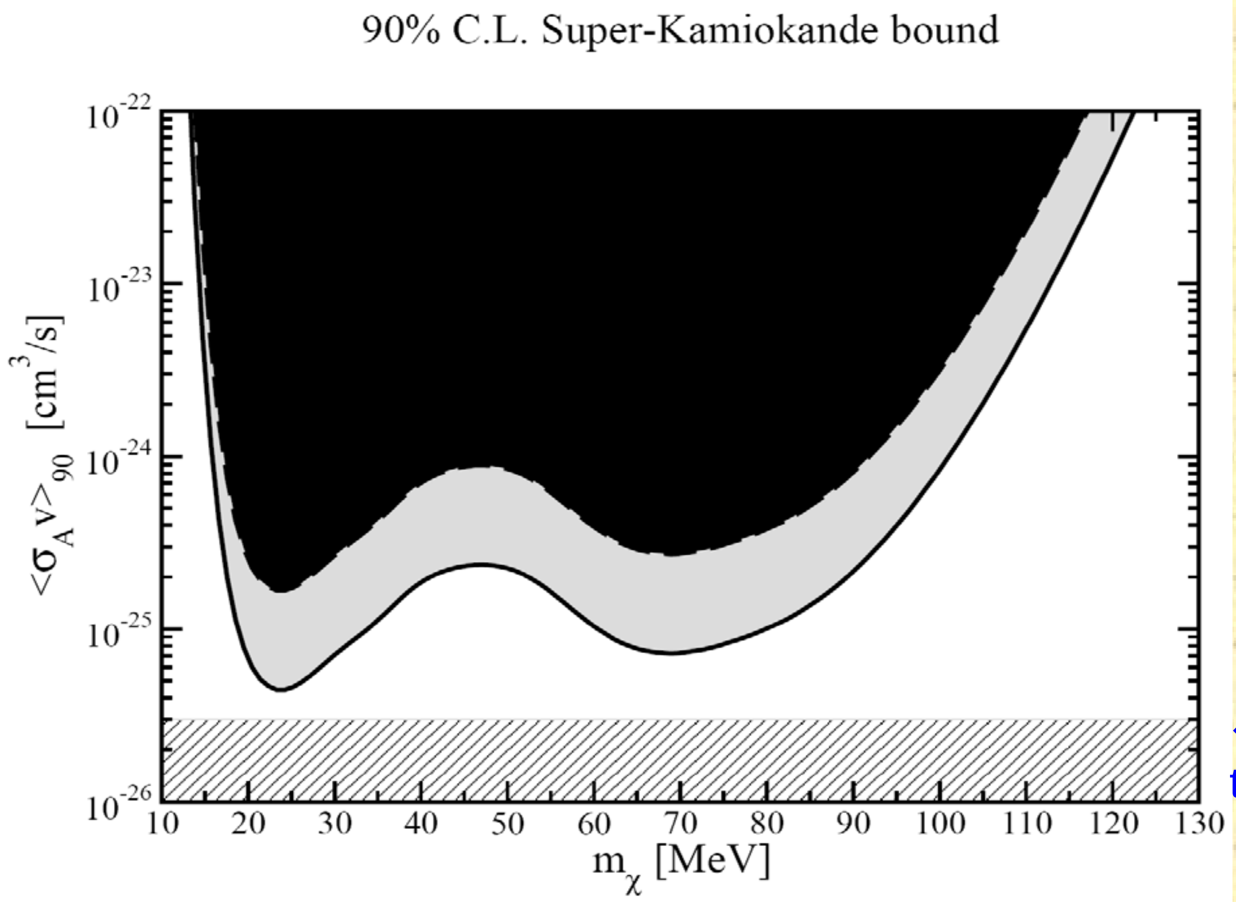
- Our bound implies that for all m > 0.1 GeV:

$$\rho_A \gtrsim 5 \times 10^3 \ \mathrm{GeV/cm^3}$$

→Only affects the very inner region of typical galaxies.
e.g. In the Milky Way, this density occurs only at radii < 1 pc for an NFW profile (and maybe not at all for less steep profiles).

Dark matter annihilation cannot have a macroscopic effect on galactic halos.

Dark matter annihilation – MeV mass



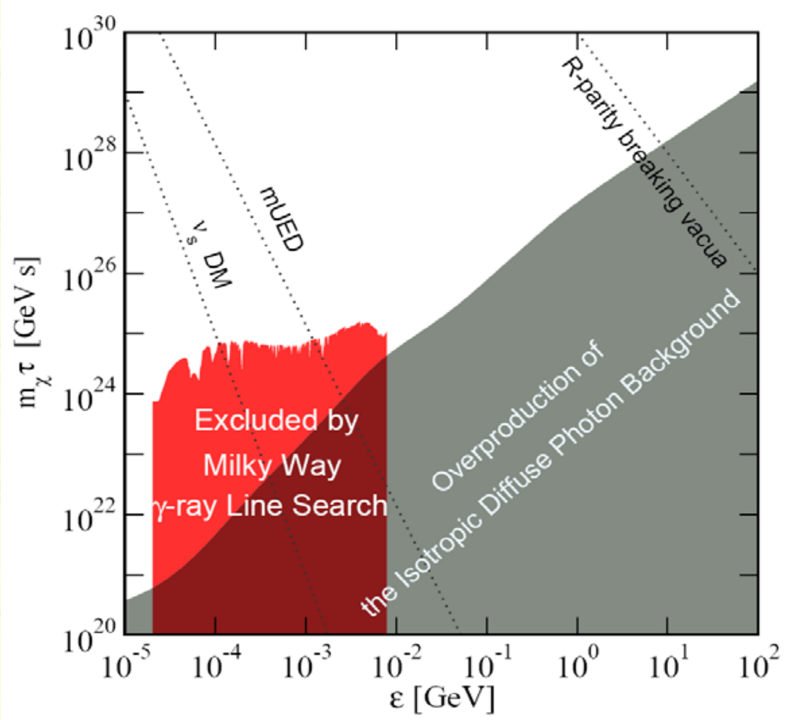
← cross-section for thermal relic DM

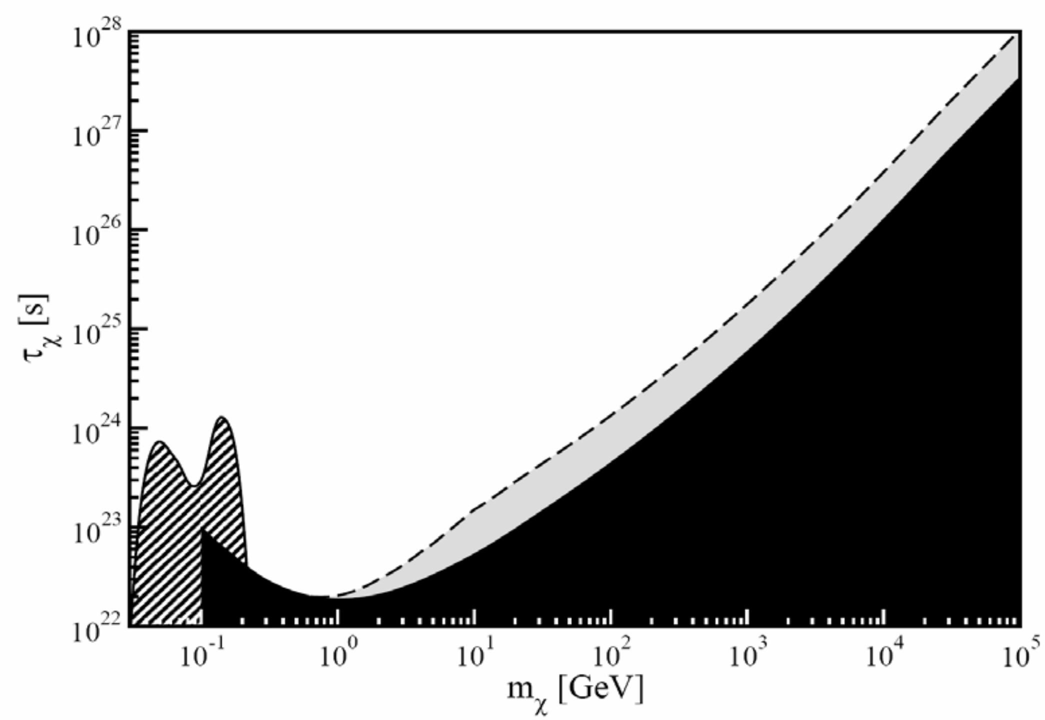
Palomares-Ruiz & Pascoli, PRD 77, 025025 (2008)

Dark Matter Lifetime

Photons X→X'γ
... strong limit

Neutrinos X→νν
... *model-independent* limit



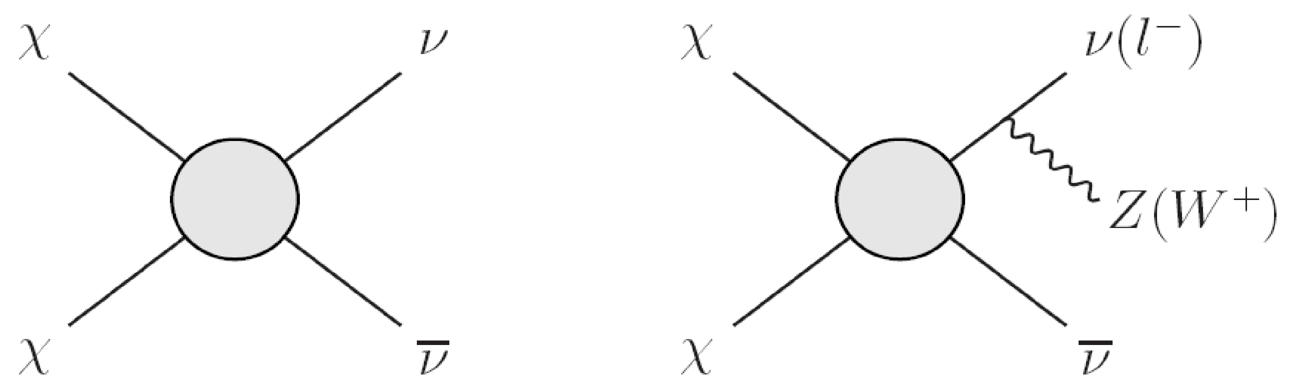


Yuksel & Kistler

Palomares-Ruiz

Radiative corrections → photons

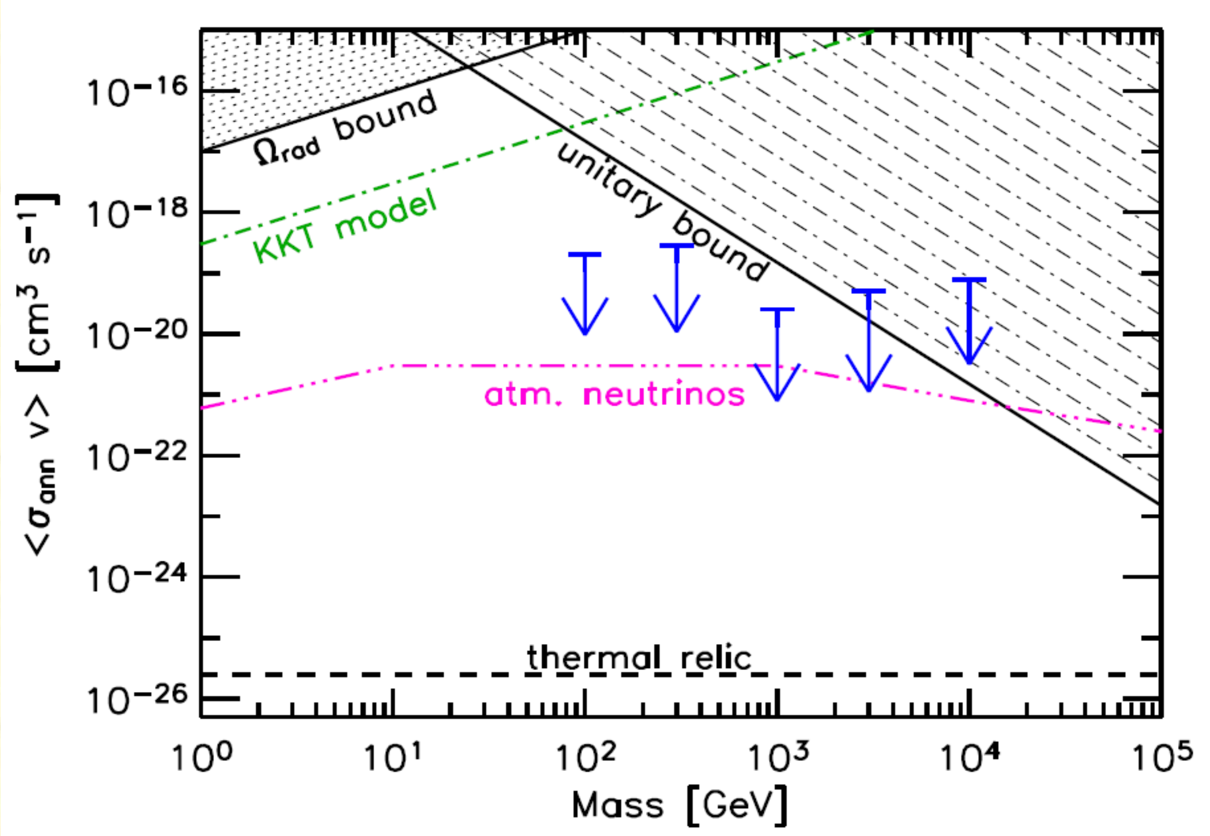
$\chi\chi \rightarrow \nu\bar{\nu}$ is accompanied by: $\chi\chi \rightarrow \nu\bar{\nu}Z \rightarrow$ gamma rays



- Z decays to hadrons ~ 70% of the time.
- On average, 20 neutral pions per Z decay, which in turn decay as $\pi \rightarrow \gamma\gamma$

- For E>>M_Z: ratio of the cross-sections ~ α

Radiative corrections to neutrino processes give photons



But direct neutrino limits are comparable/ stronger!

Kachelriess and Serpico, PRD 76, 063516 (2007).

Bell, Dent, Jacques, & Weiler, arXiv:0805.3423

Direct Annihilation to gamma rays

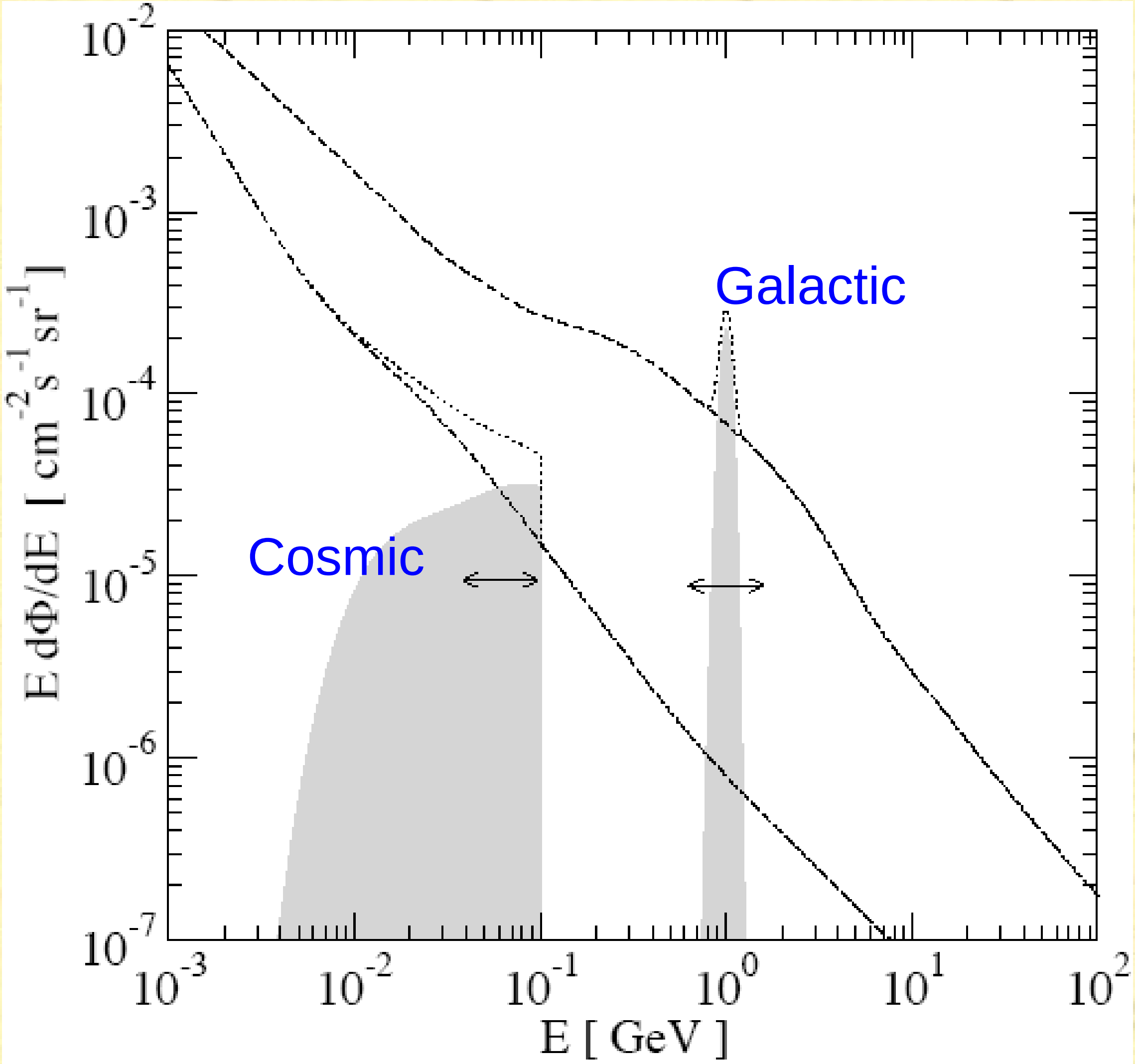
$\chi\chi\rightarrow\gamma\gamma$

- The process $\chi\chi\rightarrow\gamma\gamma$ is present in most dark matter models, though with a model-dependent rate. (Usually occurs at loop order.)

- It's detection would be a "smoking gun" signature of dark matter.

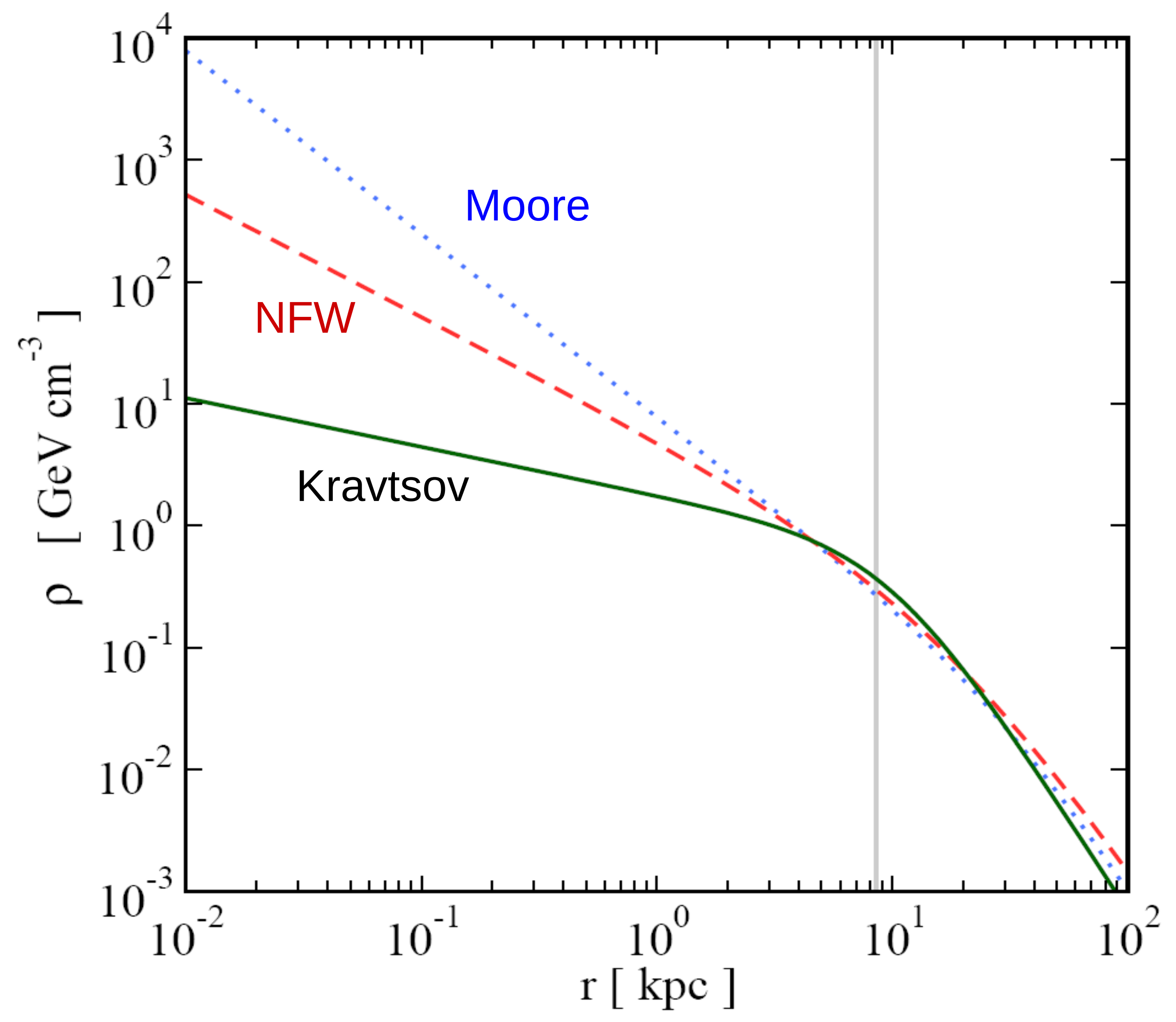
- Monocromatic line at $E_\gamma=M_\chi$ would measure DM mass.

Annihilation signals & γ-ray background



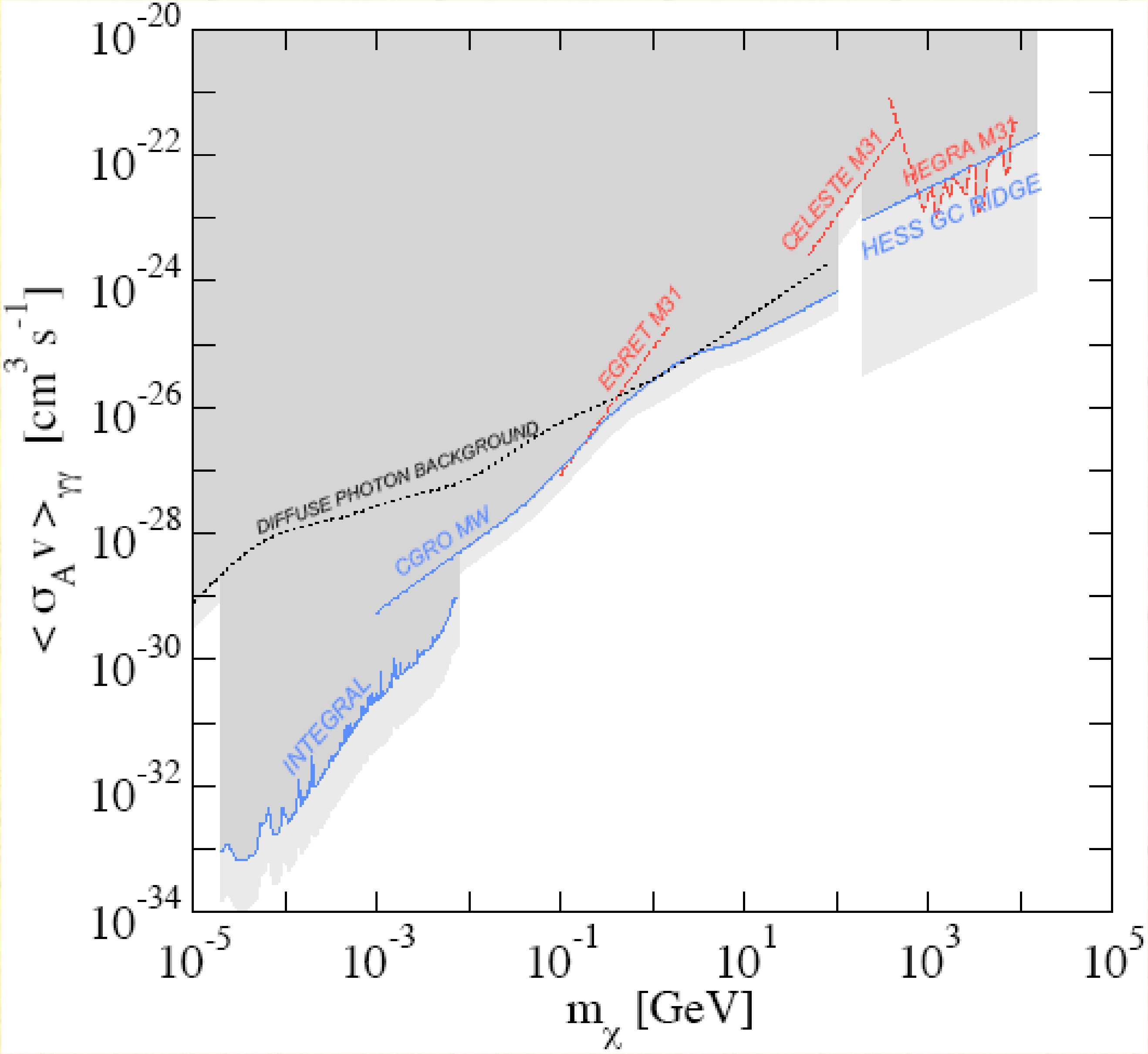
Mack, Jacques,
Beacom, Bell,
Yuksel
arXiv:0803.0157

DM halo density vs radius



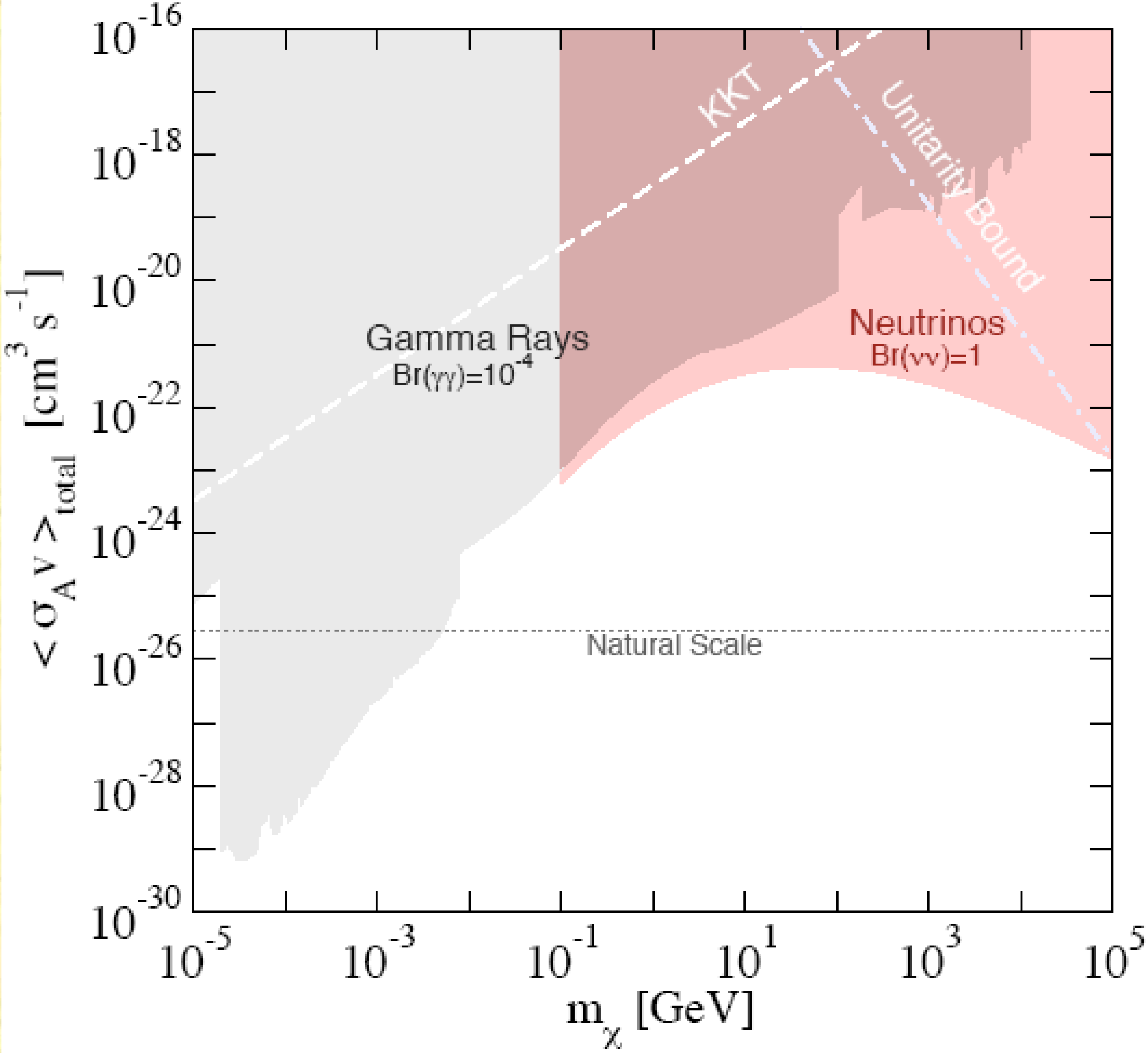
Yuksel, Horiuchi, Beacom, & Ando, PRD 76, 123506, 2007.

Cross-section limits for $XX \rightarrow \gamma\gamma$



Mack, Jacques, Beacom, Bell, Yuksel arXiv:0803.0157

Comparison of neutrino and photon limits on dark matter annihilation



Mack, Jacques, Beacom, Bell, Yuksel
arXiv:0803.0157

Summary – DM Annihilation

- Dark matter total annihilation cross-section can be bounded using the least detectable annihilation products (i.e. neutrino appearance rate.)

- Neutrino bound much stronger than Unitarity for m < 10 TeV.

- For large mass, neutrinos bounds are comparable to those for $\gamma\gamma$

- Dark Matter halos cannot be significantly modified by annihilation.