Constraints on late-decaying dark-matter models

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Dark-matter decay

- Information about the particle nature of dark matter.

- DM interactions may explain cosmological observations

  e.g dark-matter decay responsible for the observed structure of the universe

Dark matter with nearly degenerate states

$$\chi \to \chi' + l, \quad \text{with} \quad \varepsilon \equiv \frac{m_\chi - m_{\chi'}}{m_\chi} \ll 1$$

- DM energy density approximately conserved
- very little energy dissipated into relativistic particles: limits from CMB anisotropies relaxed
- recoil velocities of DM particles affect galactic structure, if decays occur at appropriate time: solve some of the CDM problems
- Inelastic DM-type scenarios invoke similar decay mode (motivation and parameter space unrelated to structure formation).

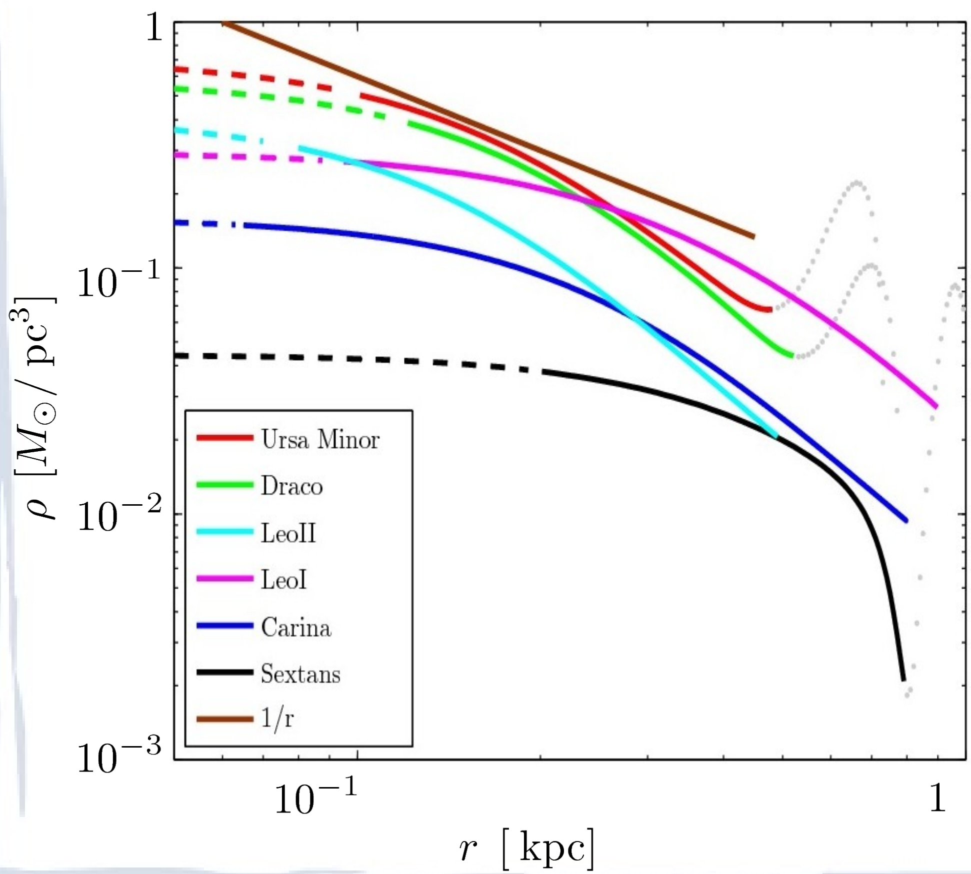
Cold Dark Matter and structure formation

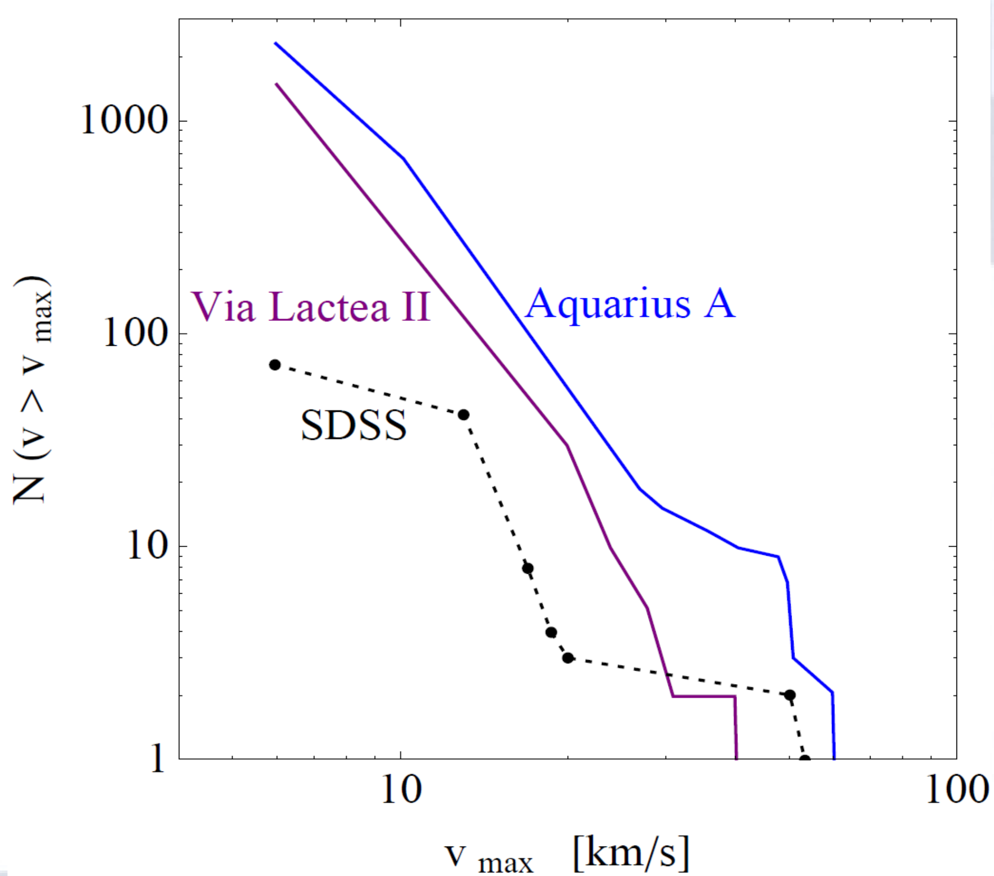
"Bottom-up" hierarchical structure formation, rich structure at small scales.

- At large scales, ΛCDM simulations reproduce observations
- At small scales, some CDM predictions do not match observations

CDM problems

- Cuspy central galactic density profiles; observations favour cores [Gilmore, Wyse; Strigari et al.]
- Overprediction of satellite galaxies [Klypin; Moore]





Possible solutions

- Astrophysical solutions: effect of baryonic matter; specific to individual problems.
- Warm Dark Matter: free-streaming suppresses structure at small scales.
- Cold Dark Matter: modification of the standard structure-formation picture → DM decay

Dark matter gets its kicks

- Early decays, before recombination: WDM; constraints from free-streaming and phase-packing [Cembranos et al.; Kaplinghat (2005)]
- Late Decays: affect the evolution of structure inside haloes. Semi-analytical methods and simulations needed [Sanchez-Salcedo (2003); Abdelqader and Melia (2008); Peter et al. (2010)]

Dark-Matter Kicks vs WDM

Warm Dark Matter

- suppresses small-scale power in the linear regime:

  fewer satellite galaxies

- primordial velocities smooth substructure inside non-linear systems:

  cored galactic profiles

Dark-Matter Kicks

- recoil velocities disrupt small haloes [Abdelqader and Melia (2008)]

- heating causes central cusps to expand, and form cores [Sanchez-Salcedo (2003)]

Dark-matter decay and structure formation

Effect depends on:

- energy imparted to daughter DM particles (recoil velocity)

$$v_k = \frac{\Delta m}{m_\chi} \equiv \varepsilon$$

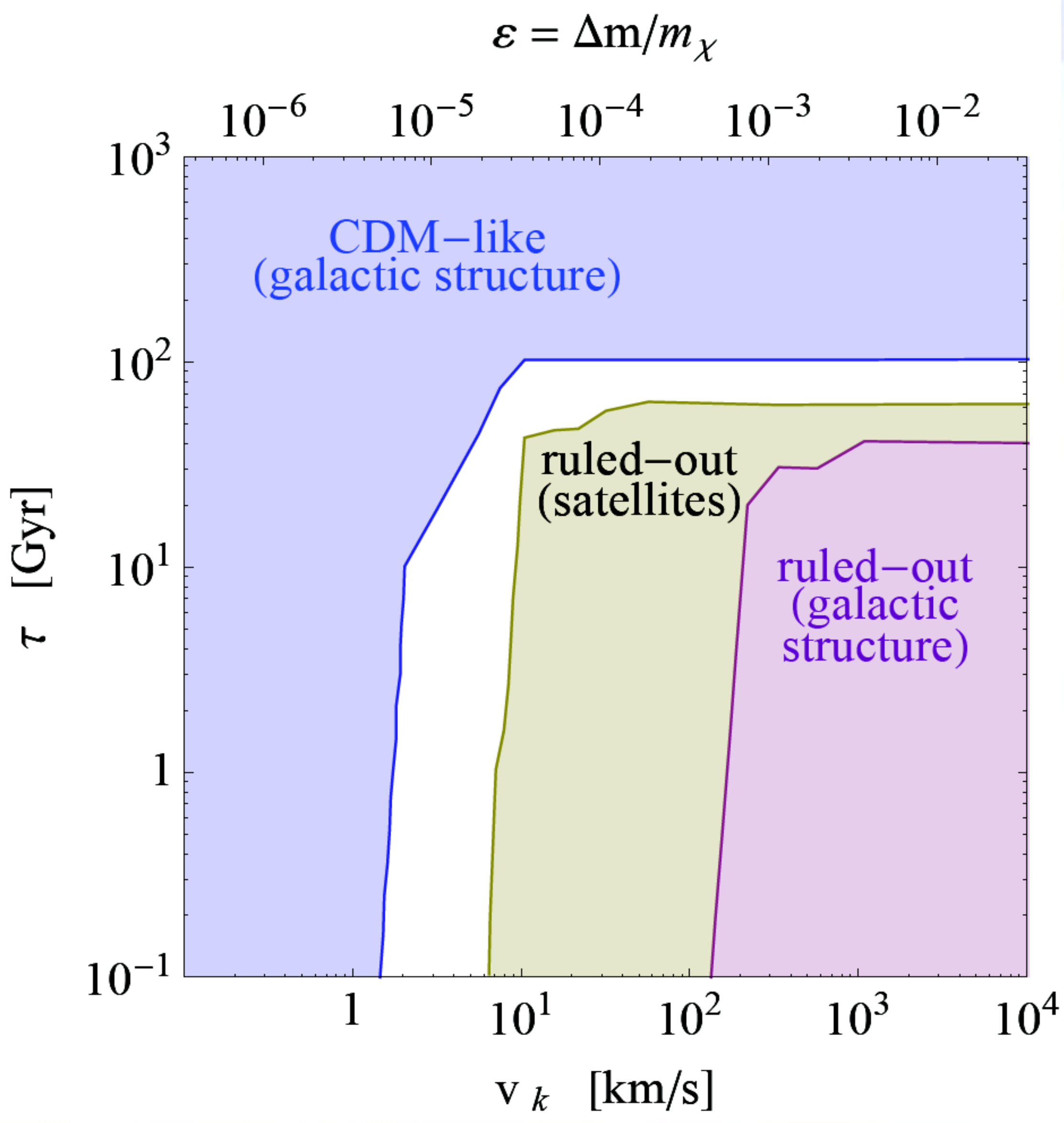
- time-scale of decay τ

Interesting region: $v_k \sim v_{\rm vir}$ & $\tau \sim \tau_{\rm dyn}$

Dark-matter decay and structure formation

- Mass-concentration relation in galaxies.
- Galaxy-cluster mass function.
- Satellite galaxy population.

[Peter et al. (2010)]



Dark-matter decay and radiation backgrounds

$$\chi \to \chi' + l$$

Constraints on DM decay using radiation backgrounds, if l belongs to the SM.

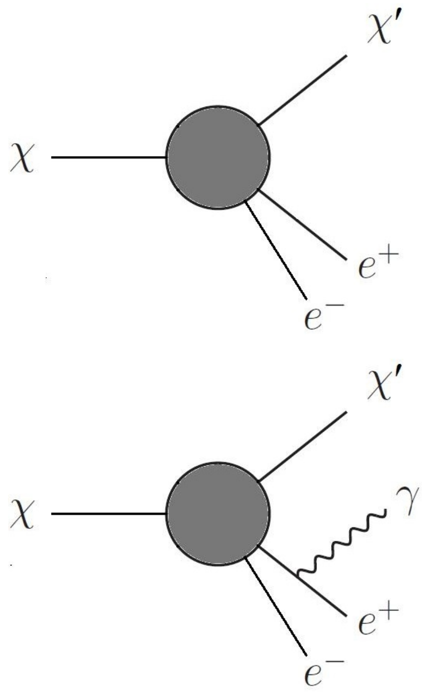
- $\chi \to \chi' + \gamma$ (*most stringent*) [Yuksel, Kistler (2007)]
- $\chi \to \chi' + e^- e^+$ [Bell, Galea, KP (2010)]
- $\chi \to \chi' + \nu\bar{\nu}$ (*least stringent*) [Bell, Galea, KP (2010)]

Dark-matter decay and radiation backgrounds

- $\chi \to \chi' + \nu\bar{\nu}$ atmospheric neutrino flux.
- $\chi \to \chi' + e^{\pm}$ positron flux; photon bgnds.

Photoproduction by $e^{\pm}$ in the galaxy occurs via:

- internal bremsstrahlung
- positron annihilations
- inverse Compton
- bremsstrahlung
- synchrotron



Dark-matter decay and radiation backgrounds

- Energy of relativistic decay products is Δm
- The flux is bounded by the observed bgnds:

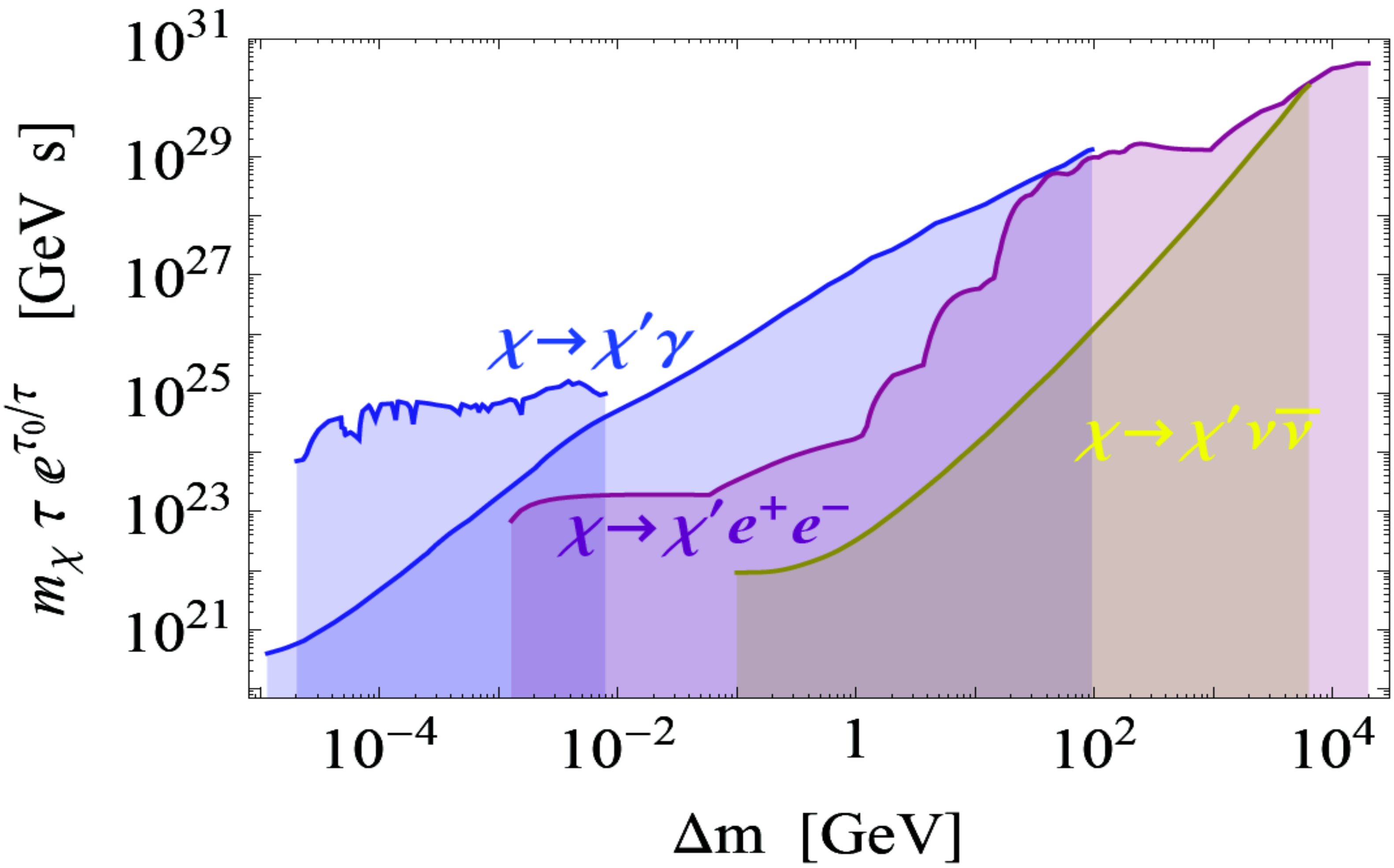
$$\Phi_{\rm d}(\Delta m) \leq \Phi_{\rm obs}$$

$$\Phi_{\rm d} \propto n_{\rm DM}\Gamma \propto \frac{e^{-\tau_0/\tau}}{m_\chi \tau}$$ (τ_0 : age of the universe)

Radiation backgrounds yield lower bounds on:

$$m_\chi \tau e^{\tau_0/\tau} \quad \text{vs} \quad \Delta m$$

Dark-matter decay and radiation backgrounds



[Yuksel, Kistler (2007); Bell, Galea, KP (2010)]

Dark-matter decay, galactic structure & radiation bgnds

Do the constraints allow for dark-matter decay to occur, such that:

- enough energy is released into the galaxies to affect the formation of structure?
- the energy release takes place at time scales that can affect the evolution of the galaxy?

Dark-matter decay, galactic structure & radiation bgnds

Constraints from radiation bgnds satisfied if:

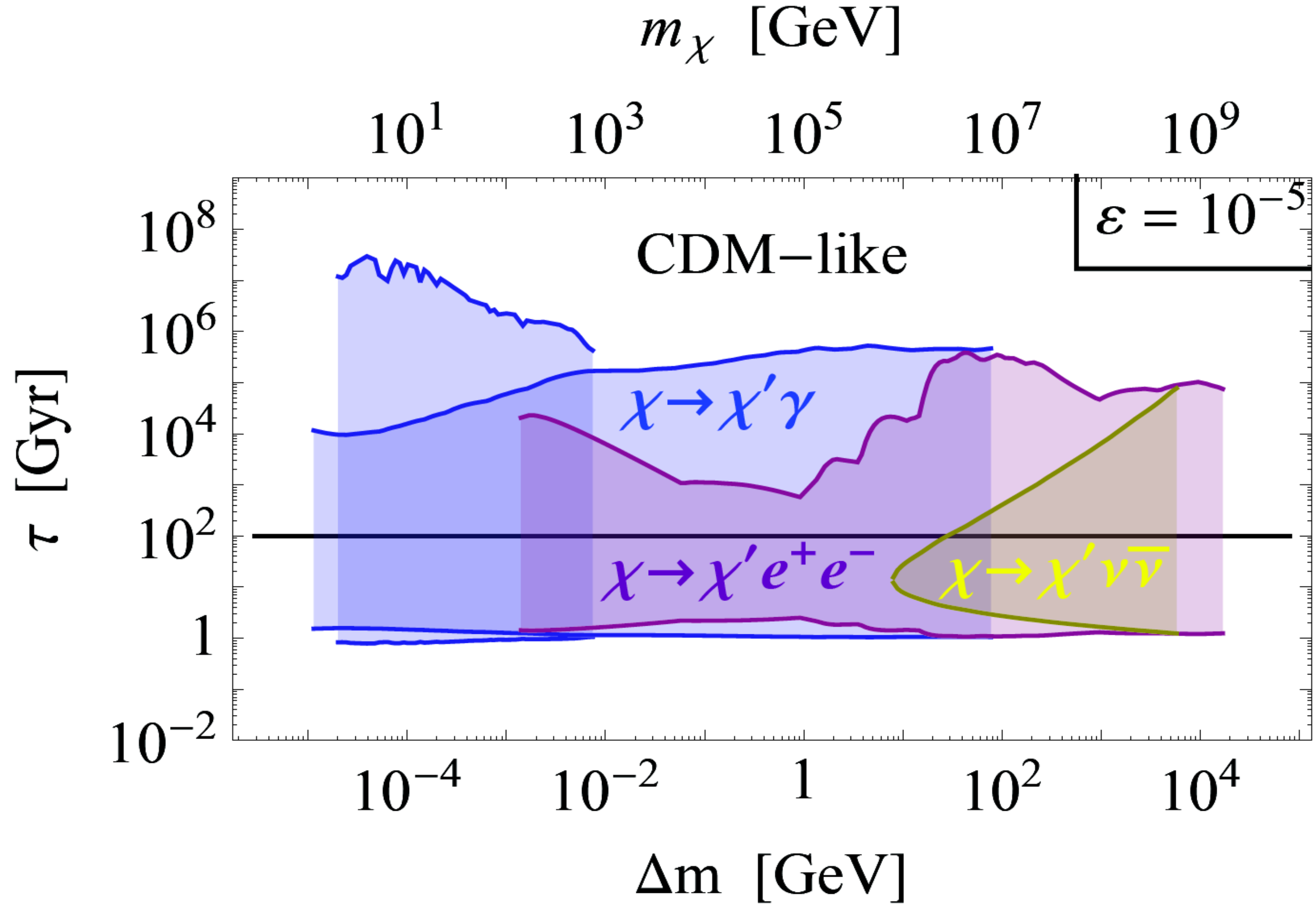
- decay rate is sufficiently small: lower bound on τ

or

- decay fast enough, abundance of parent DM particles is suppressed today: upper bound on τ

→ excluded band of lifetimes.

Dark-matter decay, galactic structure & radiation bgnds



[Yuksel, Kistler (2007); Bell, Galea, KP (2010)]

Dark-matter decay, galactic structure & radiation bgnds

- Parameter space for DM decay to affect galactic structure is quite constrained, if SM particles are produced in the decay.

- Interesting regions remain open:
  - decay into $\nu\bar{\nu}$, for a large range of m_χ, τ
  - decay into $\gamma, e^\pm, \nu\bar{\nu}$, for $\tau \lesssim 1\ \mathrm{Gyr}$

- Upper limit of the excluded band may be improved with more sensitive observations. Lower limit will remain approximately unmoved.

Conclusions

- Dark-matter decay between nearly degenerate states may be responsible for the observed small-scale structure of the universe.

  Radiation bgnds and the galactic structure can constrain such scenarios.

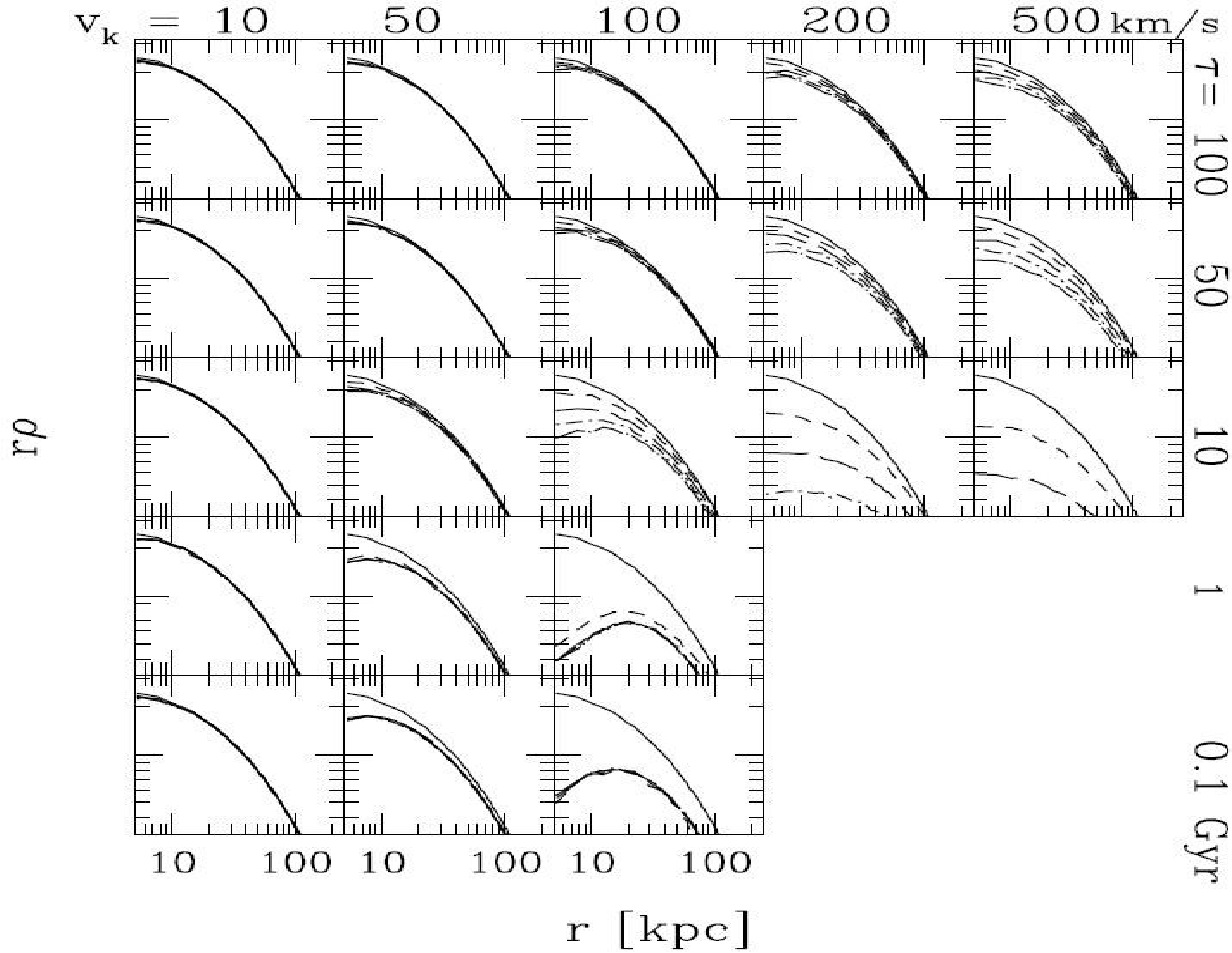
- Models with nearly degenerate DM states which cannot affect the galactic structure, may still be constrained by radiation backgrounds.

extra slides...

CDM problems

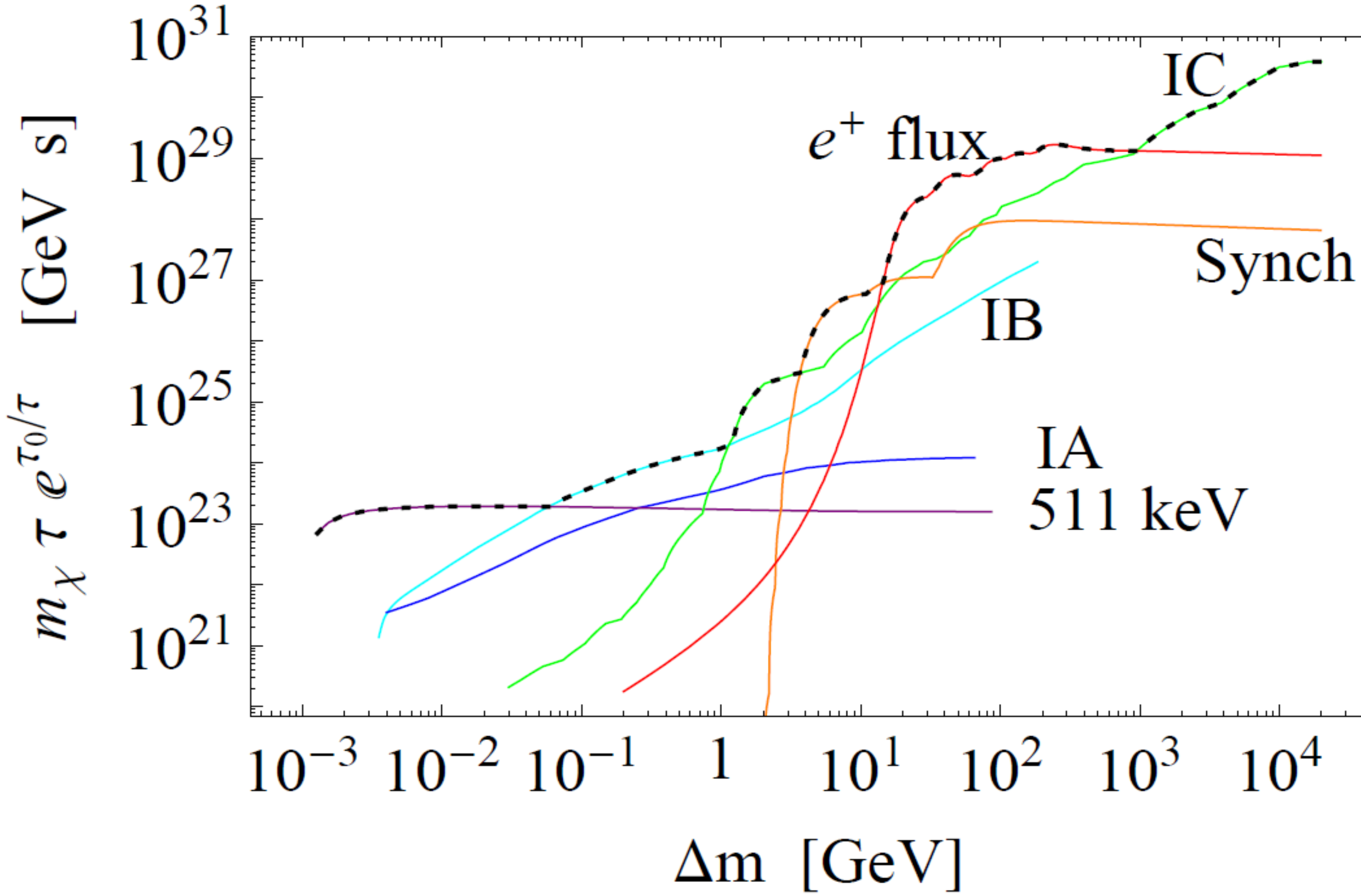
- Cuspy central galactic density profiles; observations favour cores [Gilmore, Wyse; Strigari et al.]
- Overprediction of satellite galaxies [Klypin; Moore]
- No pure-disk galaxies predicted [Governato et al; Kormendy et al.]
- Overprediction of halos in low density voids [Peebles]
- Gas condenses early and loses too much angular momentum [Dolgov]

Dark-matter decay & structure formation: simulations



[Peter, Moody, Kamionkowski (2010)]

Constraints on $\chi \to \chi' + e^+e^-$



[Bell, Galea, KP (2010)]

Limits on models with late dark-matter decay

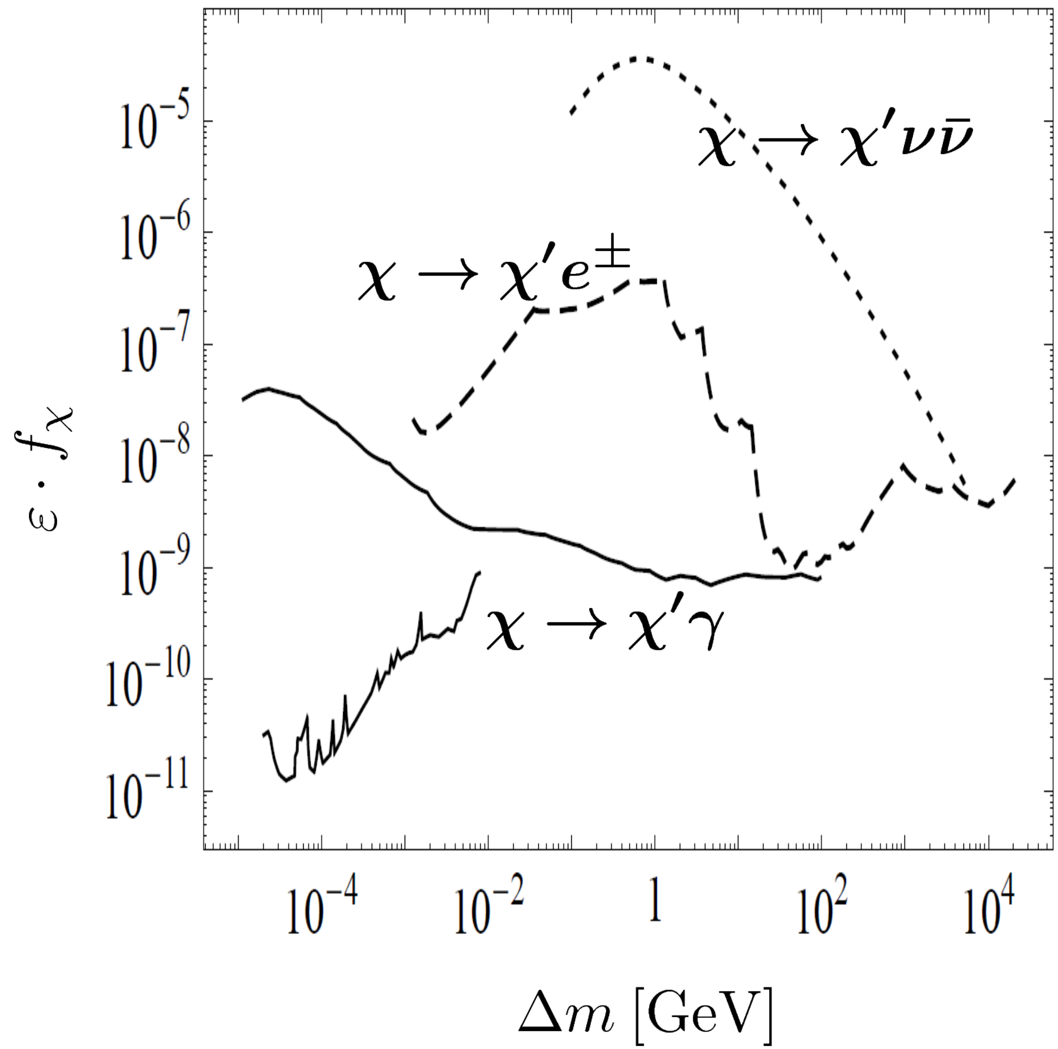
- Even if the heavy state is not abundant enough (after equality) to affect the galactic structure, radiation bgnds may still constrain τ

e.g. exciting DM - type models [Finkbeiner et al.].

$\varepsilon = \Delta m/m_\chi$, $f_\chi = Y_\chi/Y_{CDM}$

above lines: models *constrained*

below lines: models *unconstrained*



Limits on models with late dark-matter decay

- If the abundance of the heavy state is not known, but the lifetime τ is in the band

  $$1\ \mathbf{Gyr} \lesssim \tau \lesssim (10^6 - 10^{12})\ \mathbf{Gyr}$$

  radiation backgrounds can constrain the fraction of dark matter in the heavy state

  e.g. “degenerate gravitino” scenario [Boubekeur et al. (2010)]