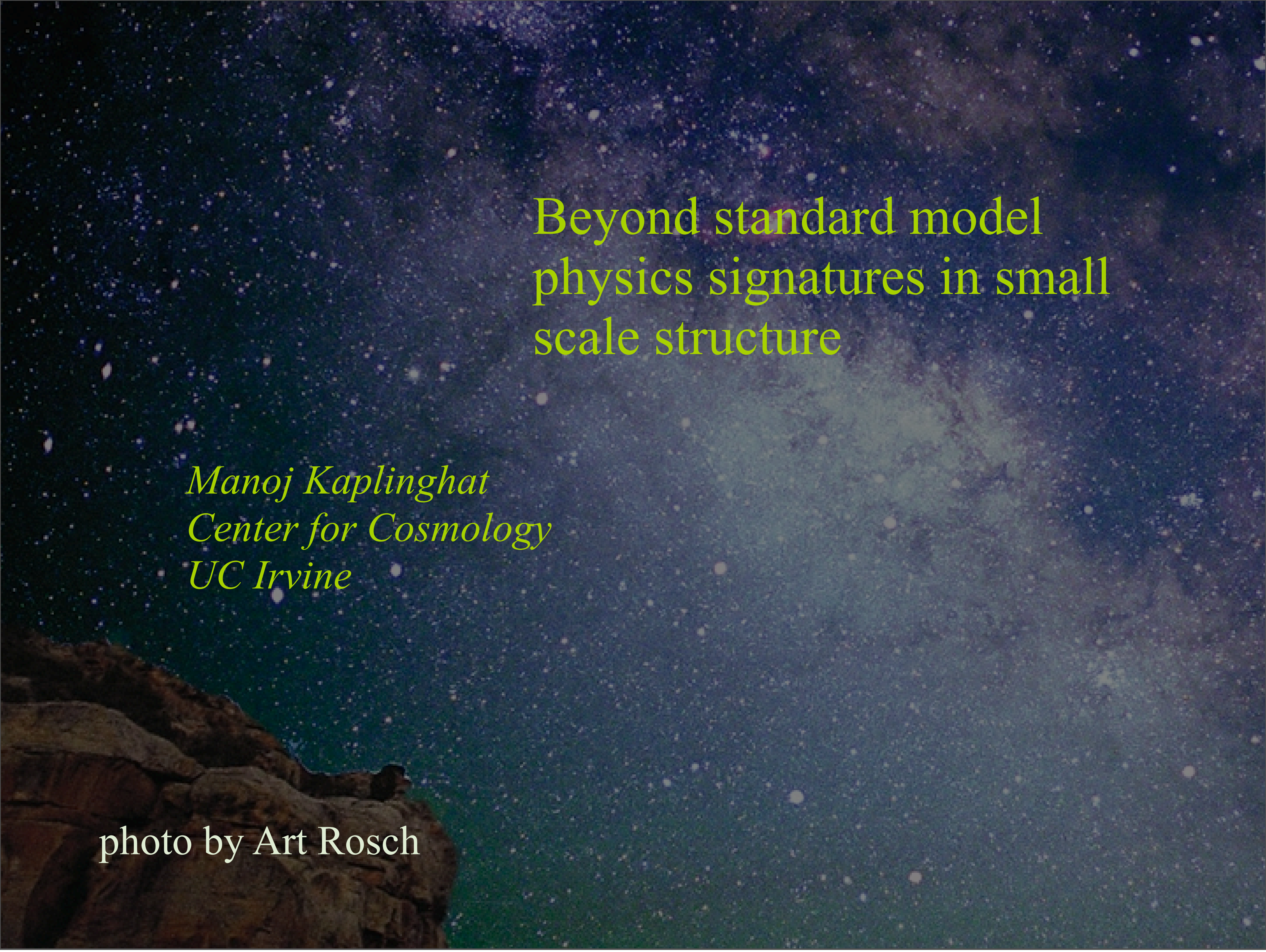

Beyond standard model physics signatures in small scale structure

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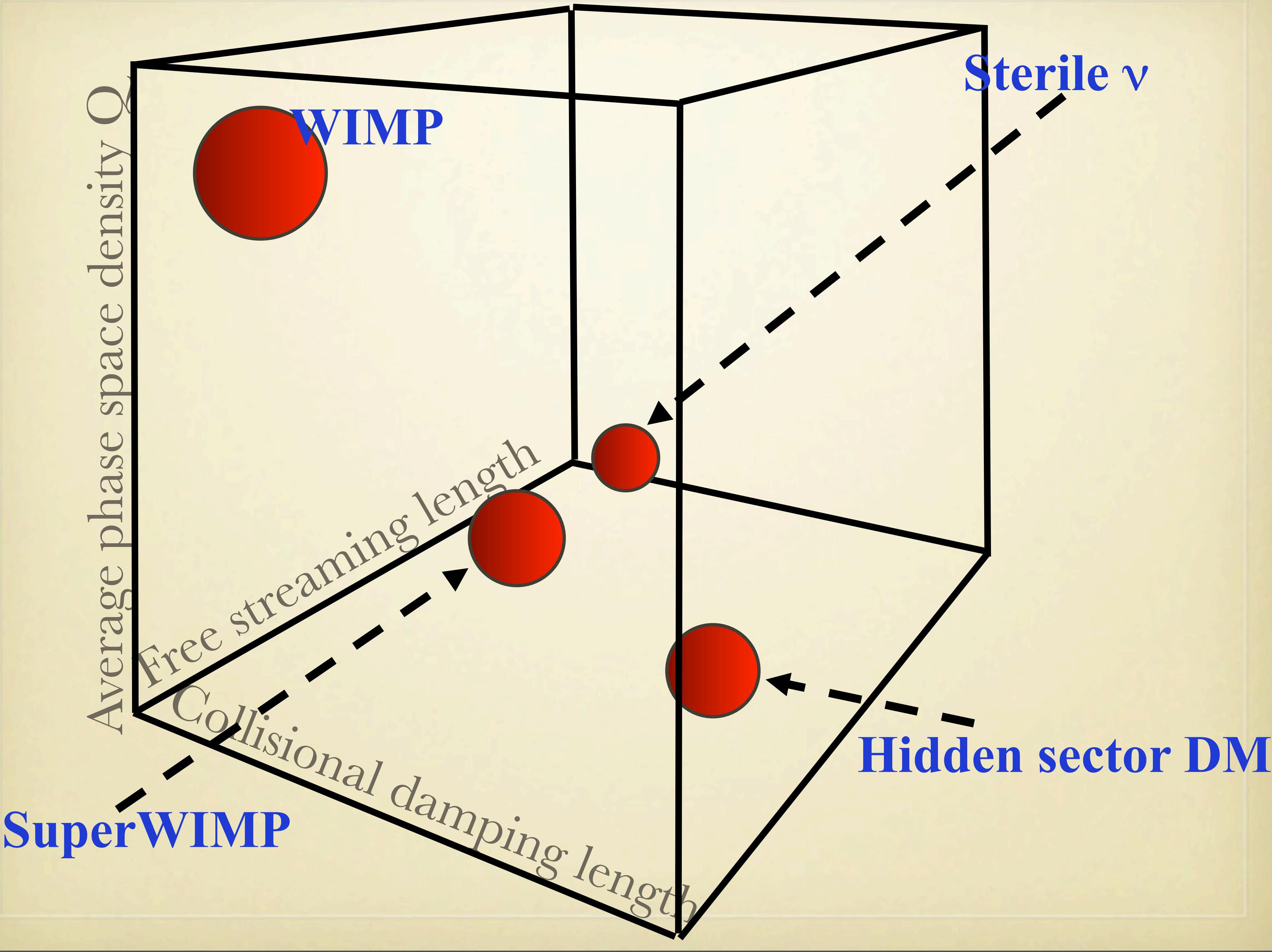
photo by Art Rosch

Outline

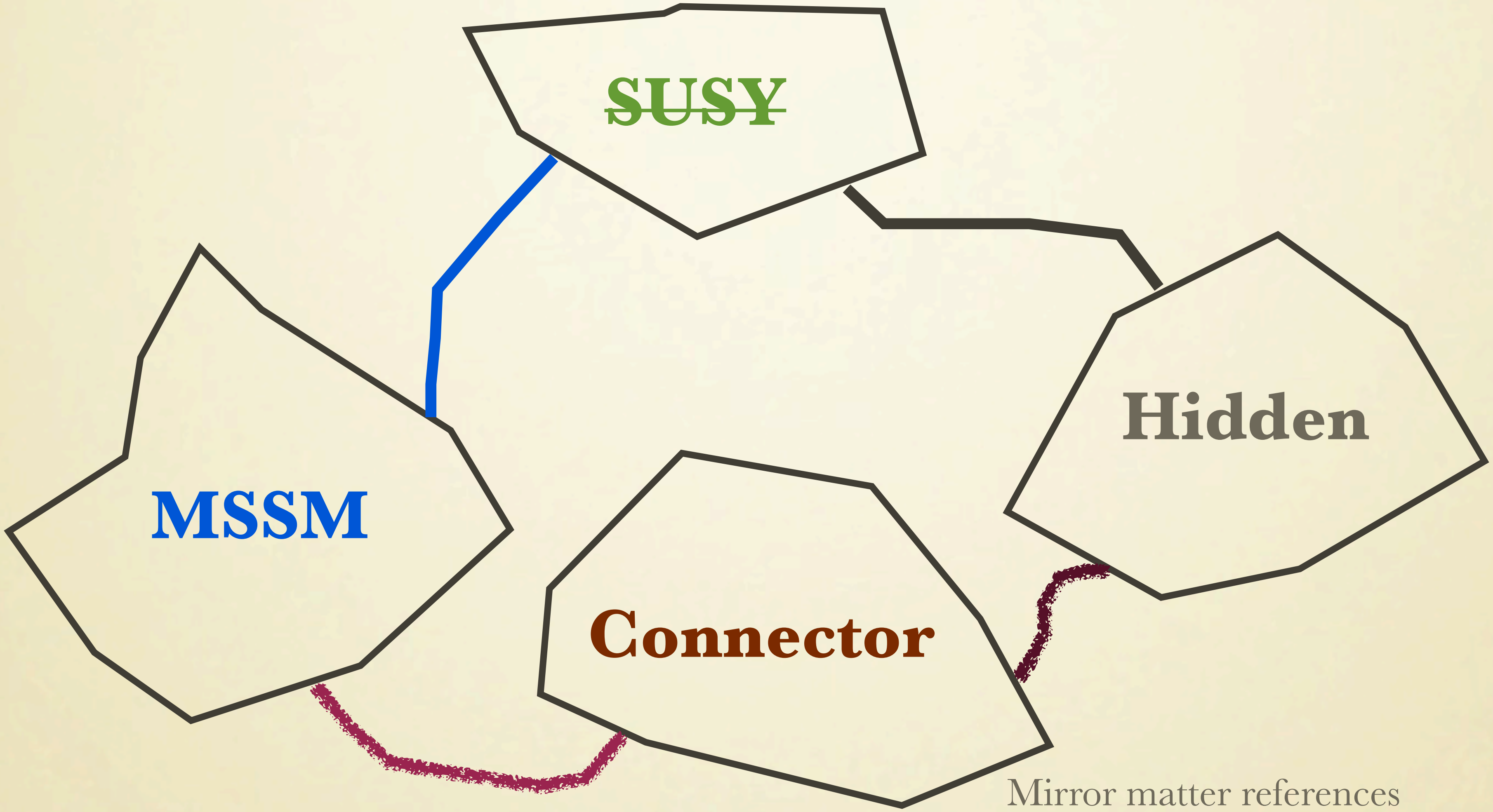
- Dark matter model space and link to Beyond Standard Model physics
- Mapping early universe momentum distribution to small-scale power spectrum and halo structure

Properties of Dark Matter

- *Damping length* λ_d : Mean-free path before kinetic decoupling.
  - Depends on DM-lepton scattering and early universe cosmology.
- *Free-streaming length* λ_{fs}: Average distance traveled by a dark matter particle before it falls into a potential well.
  - Depends on DM mass, decoupling temperature, lifetime and early universe cosmology
- *"Average" phase-space density Q*: Mass density per unit volume in velocity space.
  - Depends on DM mass, decoupling temperature, lifetime and early universe cosmology
  - After freeze-out Q ~ mass density / v_{RMS}^3 is constant


WIMP
Sterile ν
Average phase space density Q
Free streaming length
Collisional damping length
Hidden sector DM
SuperWIMP

Hidden sectors

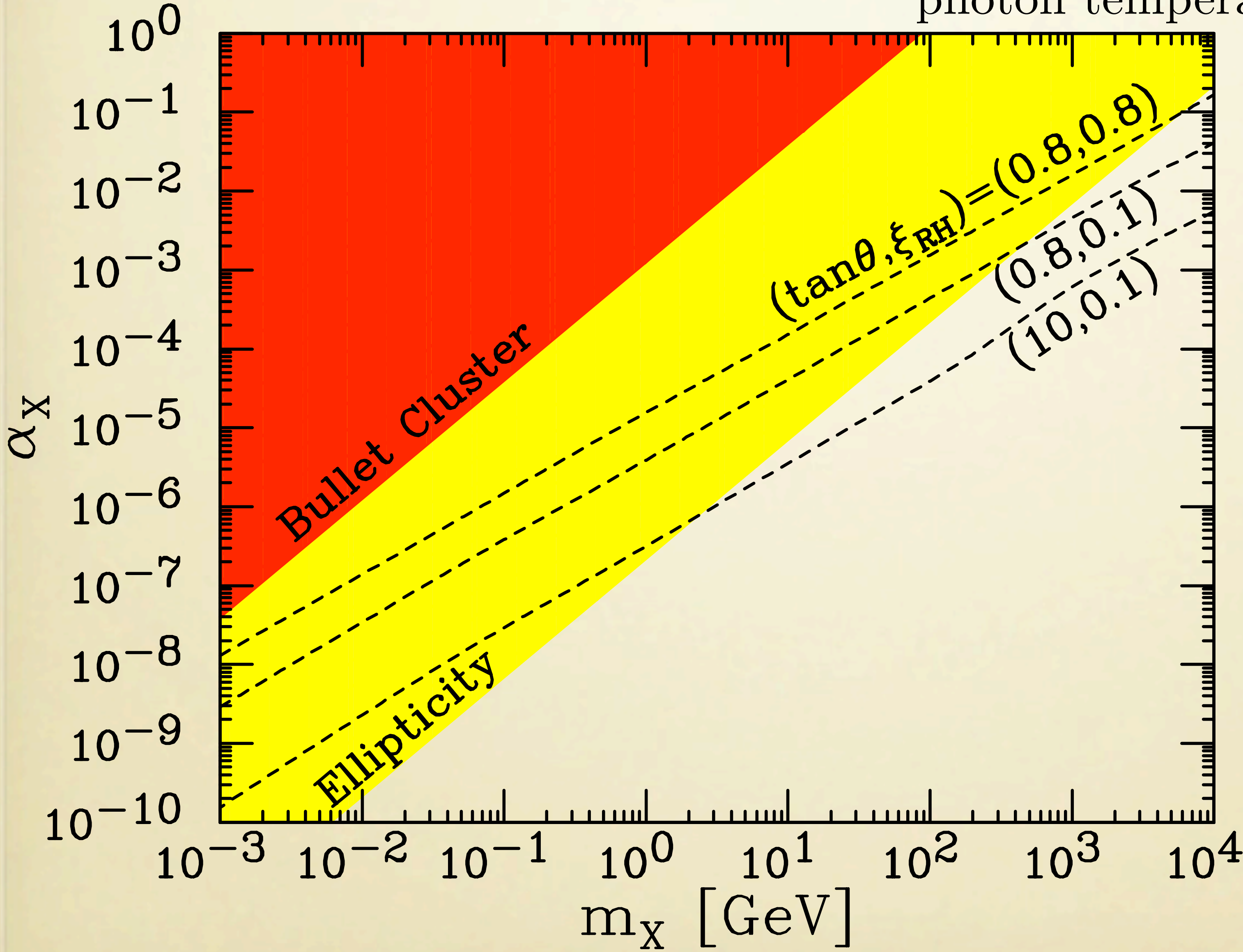


Mirror matter references
Schabinger+Wells
Patt+Wilczek
Strassler+Zurek
Georgi
Kang+Luty
+many more discussing dark matter in hidden sector

Hidden sector U(1)

θ is the weak mixing angle
in the hidden electroweak sector

ξ_{RH} is hidden to visible sector
photon temperature at reheating



$$\frac{\alpha_X}{m_X} \sim \frac{g^2_{\text{weak}}}{m_{\text{weak}}}$$

to get the right relic abundance

Feng, Kumar 08

Feng, Tu, Yu, Kaplinghat 09
See also Buckley, Ackerman, Carroll, Kamionkowski 08

No hidden sector -- Weak scale theories -- Cold Dark Matter

- Neutralino is the LSP
  - Kinetic decoupling 10-100 MeV
  - Cold Dark Matter with large primordial phase space density

$$Q_{\rm CDM} = 10^{14} \frac{\rm M_\odot}{\rm pc^3} \left(\frac{\rm km}{\rm s}\right)^{-3} \left(\frac{\rm M}{\rm 100GeV}\right)^{3/2}$$

  - Minimum halo mass ~ earth mass (big spread)

Profumo, Sigurdson, Kamionkowski 2006

  - Weak scale sets the relic abundance

No hidden sector -- Weak scale theories -- Cold to Warm Dark Matter

- Gravitino or axino LSP
  - Example: NLSP stau decays to LSP gravitino with lifetime ~ $1/(8\pi G M_{weak}^3)$ ~ month. [Feng, Rajaraman and Takayama, 2003]
  - Example: axino LSP [Covi, Kim and Roszkowski 1999]
  - Example: Charged WIMP [Sigurdson and Kamionkowski 2003]
- These particles could be warm (sliding scale) or a mix of warm and cold [Kaplinghat 2005, Cembranos et al 2005, Jedamzik, Lemoine, Moultaka 2005]
- Minimum halos mass could be large enough to be ruled out by current observations. Many models have minimum mass around dwarf galaxy scale.
- Small phase space density, Q ~ 1 (with huge spread) in the same units as last slide
- Weak scale sets the relic abundance for Gravitino LSP if mass of Gravitino ~ mass of other superpartners (as in SUGRA).

The Case for Dark matter from Decays

- Strong theoretical hints that new physics (particles) may be lurking at the 100 GeV scale.
- Weak cross-section and G_N naturally leads to the right dark matter abundance.
- Successful cosmological predictions on large (greater than about a Mpc) scales.
- Differences on small scales. May alleviate some "problems" with CDM.

Distinguishing DM from decays and CDM

- Accelerator searches
  - Look for signatures of long-lived charged particles at LHC [Hamaguchi et al 2004, Feng and Smith 2004]
- Early Universe
  - Big Bang Nucleosynthesis
  - Cosmic Microwave Background black body
- Late Universe
  - Small scale structure formation

Cosmological consequences: Early Universe

- Late entropy injection distorts CMB blackbody spectrum.

  [Feng, Su and Takayama, 2004; Austri and Roszkowski, 2004; Lamon and Durrer, 2005]

- Bound states of Helium-4 with charged NLSP

  [Pospelov 2006, Kohri and Takayama 2006, Kaplinghat and Rajaraman, 2006]

- Light element abundances affected. Can the Li7 and Li6 problems be solved?

  [Dimopoulos et al 1989; Kawasaki and Moroi 1995; Holtmann et al 1999; Jedamzik 2000; Feng, Rajaraman and Takayama, 2003; Jedamzik 2004; Ellis et al 2004; Jedamzik et al 2005; Cyburt et al 2006, Pradler and Steffen 2007]

Charged particle BBN

- Long history [Dimopoulos, Esmailzadeh, Hall, Starkman 89; Khlopov, Levitan, Sedelnikov, Sobol 94; Kawasaki, Moroi 95; ...]
- Bound states of charged particles and nuclei not considered until recently [Cahn, Glashow 91; Pospelov 07; Kohri, Takayama 07; Kaplinghat, Rajaraman 07]
- "Atoms" of negatively charged heavy (mass >> GeV) particles (X) and Helium-4 (to be concrete)
- He4 is the "electron"
- Binding energy ~ 0.3 MeV
- "Bohr radius" ~ 3.6 fm
- Expect HeX to form in earnest around 300 keV/40 ~ 8 keV

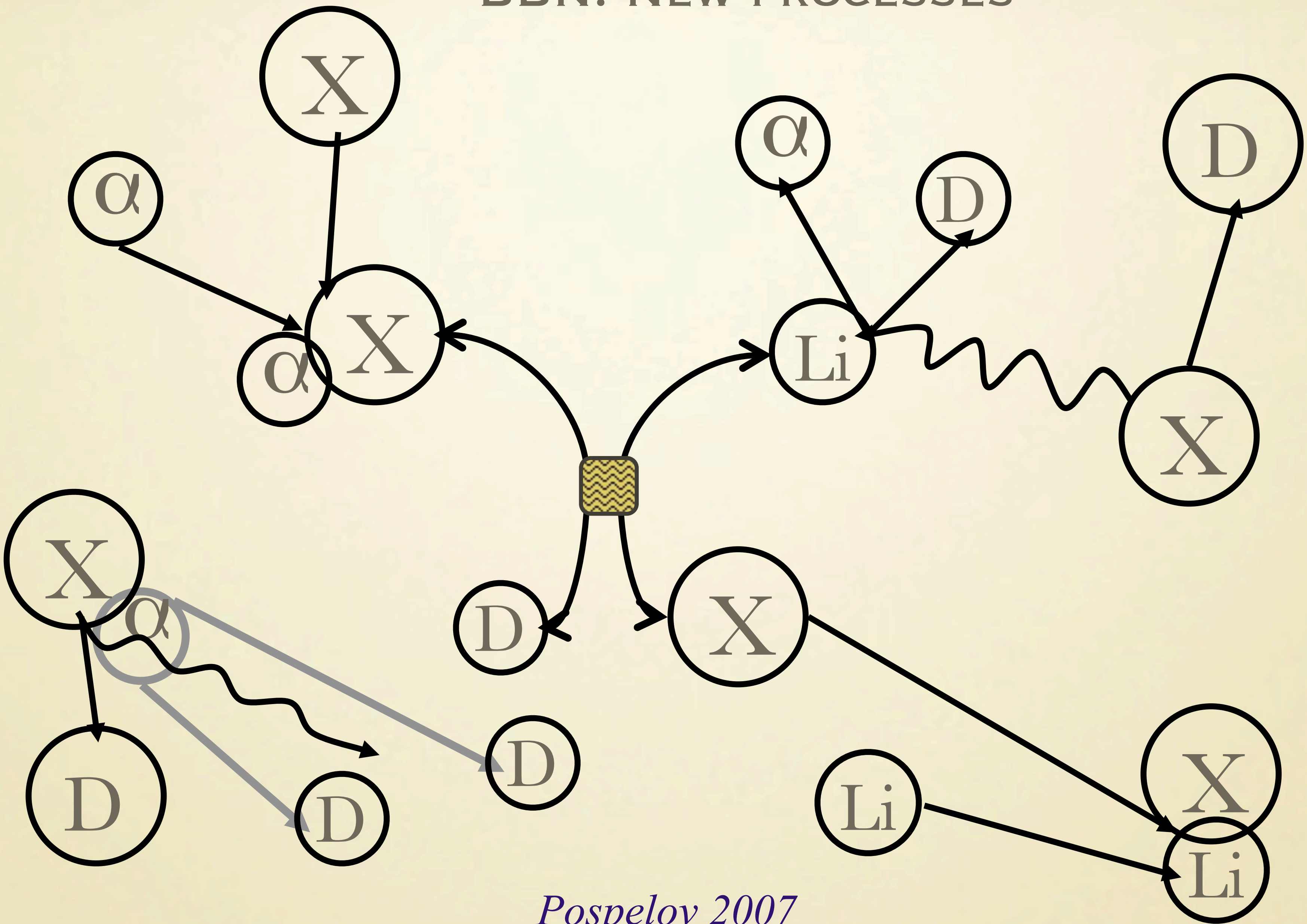
Lithium abundances

- Lithium-7 problem: Standard BBN prediction of Li^7/H ($3\text{-}5\times 10^{-10}$) is a factor of three larger than measured "primordial" abundance ($1\text{-}1.5\times 10^{-10}$) [Asplund et al 06]

- Lithium-6 problem: Measured abundance plateau at low metallicities indicative of primordial abundance of $3\text{-}5\times 10^{-12}$. [Asplund et al 06]

- Solve both these problems in the context of decaying particles? [e.g., Jedamzik 07]

BBN: New processes



Pospelov 2007
Kohri and Takayama 2007
Kaplinghat and Rajaraman 2007

Charged BBN summary

- New charged BBN processes lead to Li^6 over-production
  - Lifetimes > about 3 hours ruled out if all of dark matter populated by decays
- He^4XX is important as it is neutral and forms around the same time as He^4X

Perturbations in early universe

$$\frac{d\delta f_X}{dt} + \frac{\vec{p}}{E} \cdot \nabla \delta f_X + \frac{df_X^{(0)}}{dq}\frac{dq}{dt} = \frac{\delta f_h}{t_d} + \left(\frac{df_X}{dt}\right)_{\mathrm{coll}}$$

metric

Particle physics

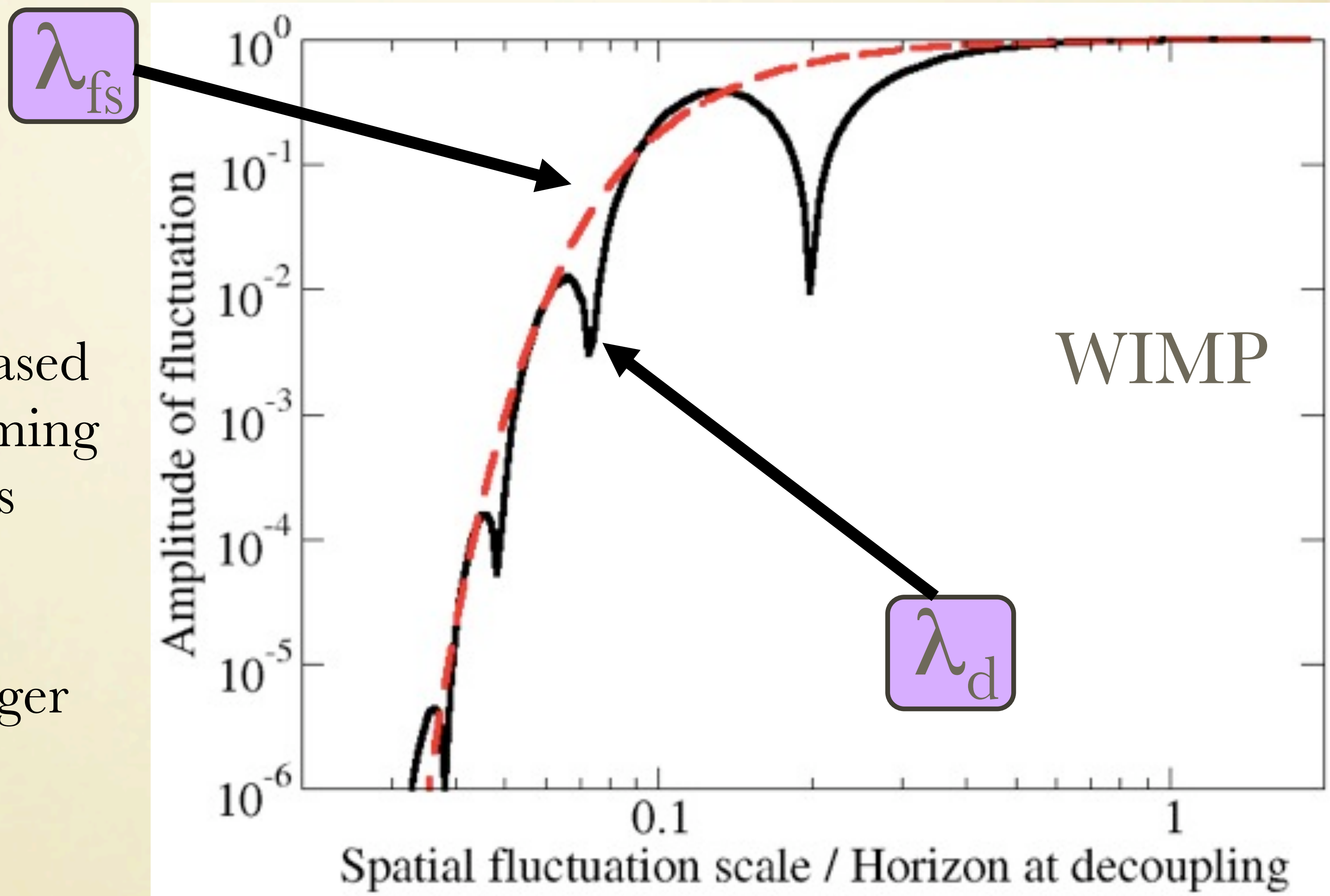
$$\dot{\delta}_X + \theta_X = -3\dot{\Phi}$$

$$\dot{\theta}_X + \frac{\dot{a}}{a}\theta_X = -k^2\Phi + k^2 c_s^2 \delta_X - k^2\sigma_X + \frac{3\dot{\tau}}{R}\left(k\Theta_1^h - \frac{\theta_X}{3}\right)$$

$$\frac{3\dot{\tau}}{R} = \frac{32\pi^3\alpha_X^2}{45}\frac{T^{h\,4}}{m_X^3}a$$

hidden sector
photon dipole

Free-streaming and Damping: Power spectrum of fluctuations (Linear theory)



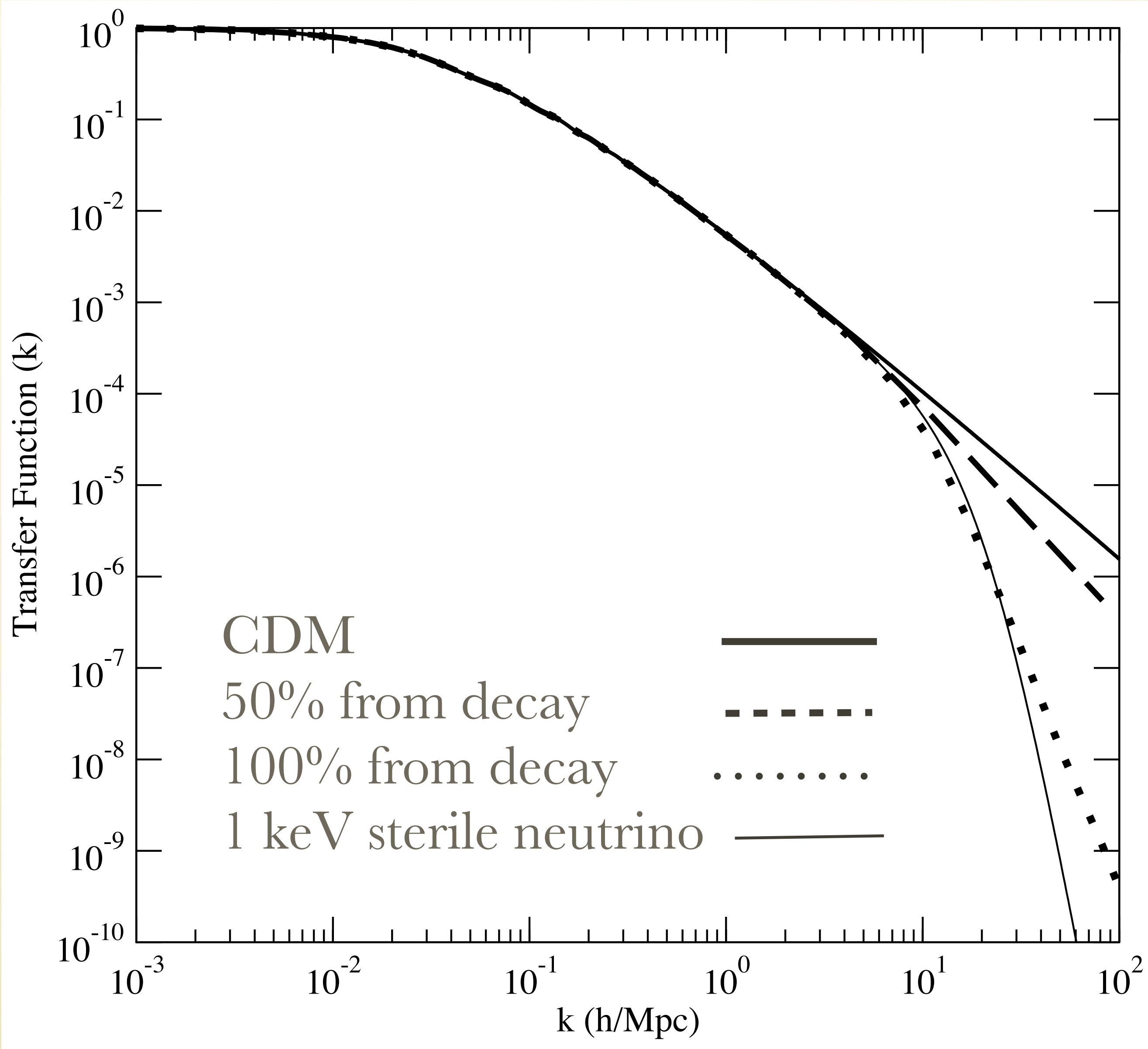
Perturbations are erased below the free-streaming and damping lengths

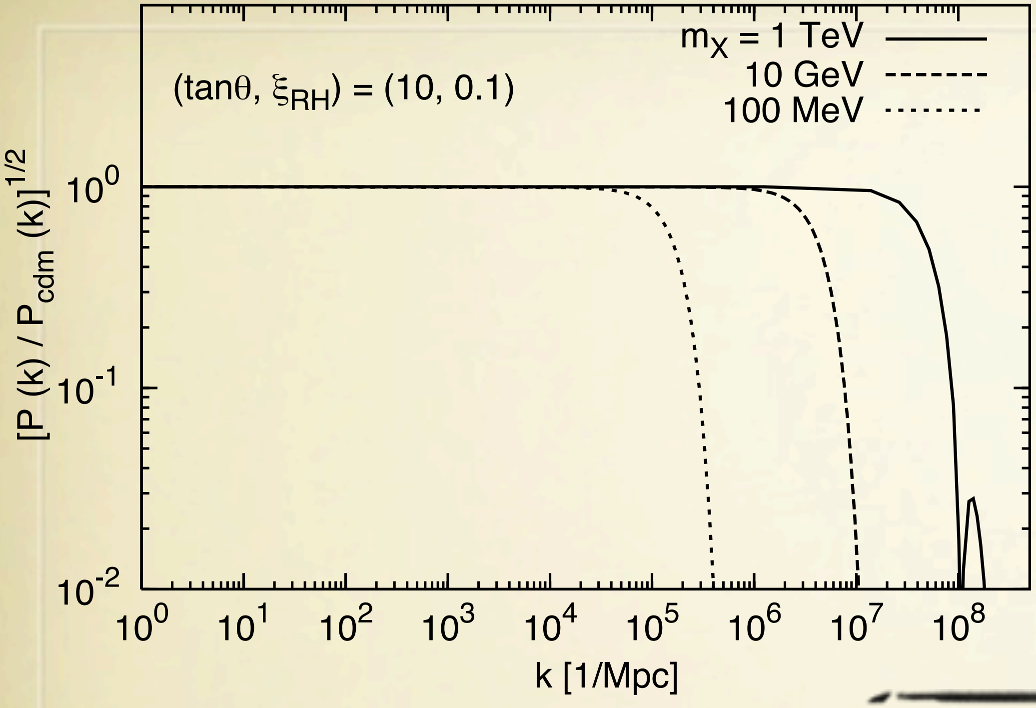
MCUT given by larger of the two length scales

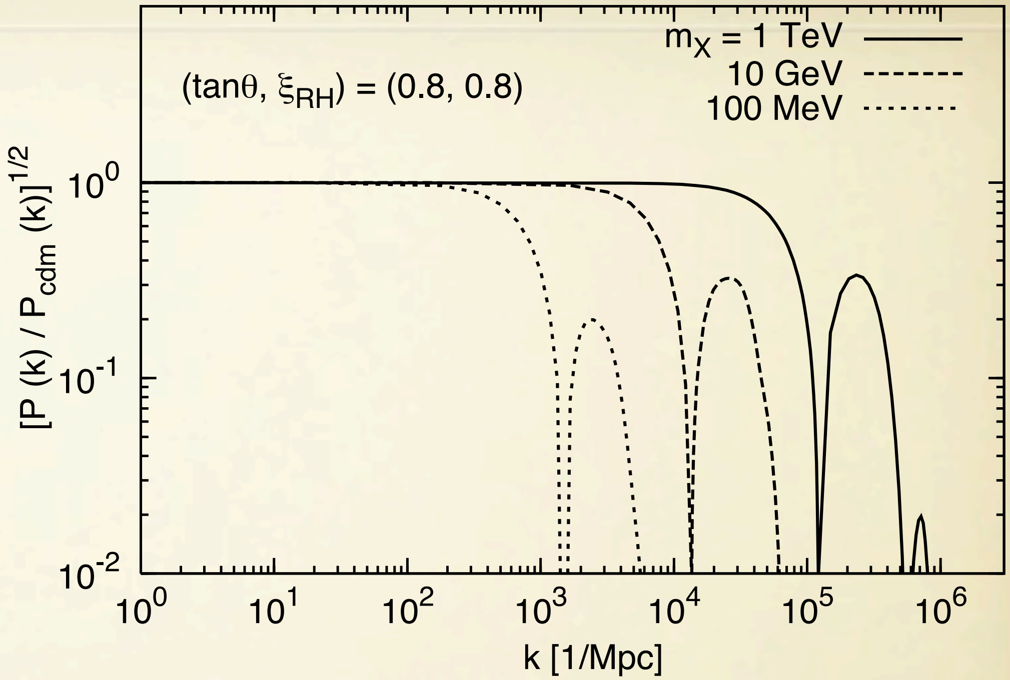
Hofmann, Schwarz and Stoecker 2001
Green, Hofmann and Schwarz 2004
Loeb and Zaldarriaga 2005
Bertschinger 2006

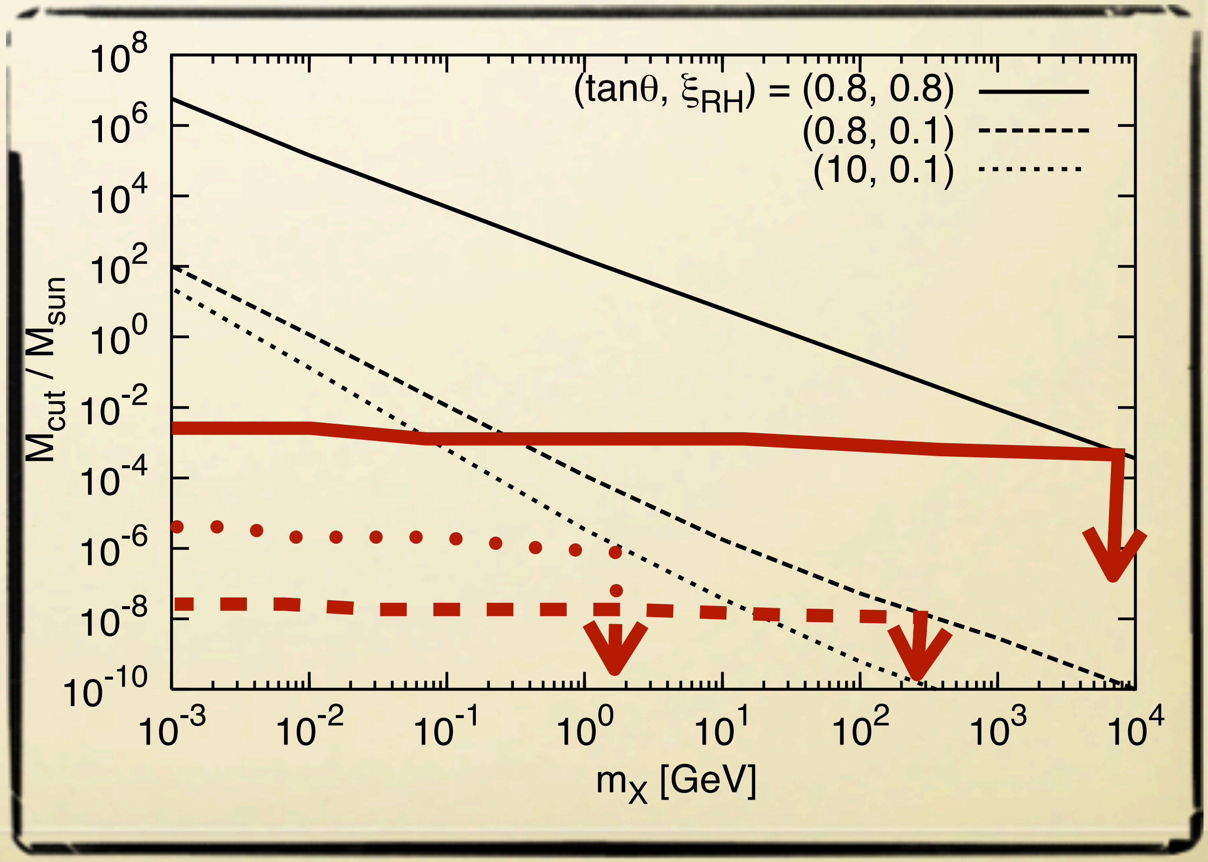
Free-streaming and Damping: Power spectrum of fluctuations (Linear theory)

Perturbations are erased below the free-streaming length









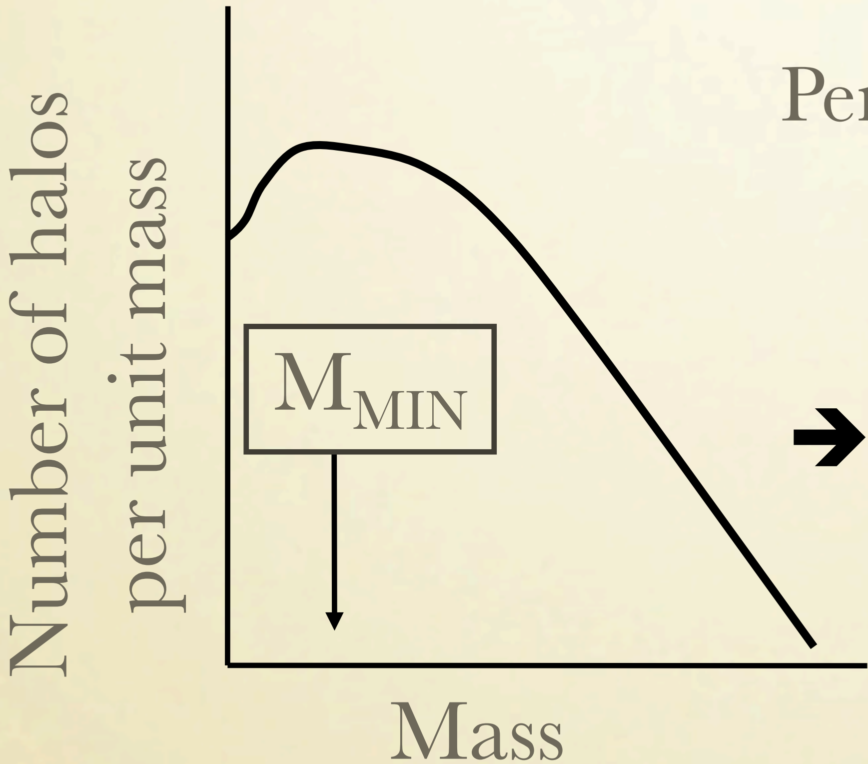
θ is the weak mixing angle in the hidden electroweak sector

ξ_{RH} is the hidden to visible sector photon temperature ratio at reheating

Larger cut off scales

- Thermal examples include MeV dark matter -- dominant scattering in the early universe with neutrinos [Mangano, Melchiori, Serra, Cooray and Kamionkowski 2006; Hooper, Kaplinghat, Strigari and Zurek 2007]
  - Mcut of million solar mass or smaller
- Non-thermal examples include WIMP decay suppressed by phase-space (almost degenerate masses for the LSP and NLSP) [Profumo, Sigurdson, Ullio and Kamionkowski 2004]
  - Mcut up to those constrained by Ly-alpha forest data

Free-streaming and Damping: Halos (non-linear effect)



Perturbations erased below λ_d and λ_{fs}

➔ Sets the mass of the smallest halos, M_{CUT}

Is $M_{CUT} = M_{MIN}$?

Phase Space of Collisionless Systems

- Fine-grained phase space density $F(x,y)$ conserved along the trajectory given by $\partial_t x = v$ and $\partial_t v = -\nabla\Phi$.
  - F_{max} conserved.
  - $M(f) = \int d^3x\, d^3v\, F(x,v)\, \Theta(F(x,v)-f)$ is conserved $\forall$ f. [Lynden-Bell, MNRAS 1967]

- Coarse-grained $F_c(x,v)$ *is not conserved*.
  - Cannot make statements about average Q.
  - However, maximum of F_c cannot exceed F_{max}
  - For Warm Dark Matter with Fermi-Dirac distribution $h^3F_{max} = 1/2$ [Gunn and Tremaine, 1979]

Phase Space : DM from Decays

- For dark matter from decay –

$$f(v) \propto \frac{1}{v} \exp\left(-\frac{v^2}{v_0^2}\right)$$

Smaller the velocity earlier the decay

- Phase space density can be large for particles from very early decay. However, number of such particles is small. To quantify this effect I will use the "Excess mass function"

Excess Mass Function

Green indicates $F_c(x,v) > f$ and orange indicates $F_c(x,v) < f$. When calculating D(f) only the green cells are counted.

- Excess Mass function:
- $\mathbf{D(f) \equiv \int_{F_C(x,v) > f} d^3x\, d^3v\, (F_C(x,v) - f)}$
- Mass in phase space cells with phase space density larger than **f**.
- Mixing decreases D(f). Conserved otherwise.

Negative contribution from the orange part is included in new D(f)

Orange part not included in old D(f)

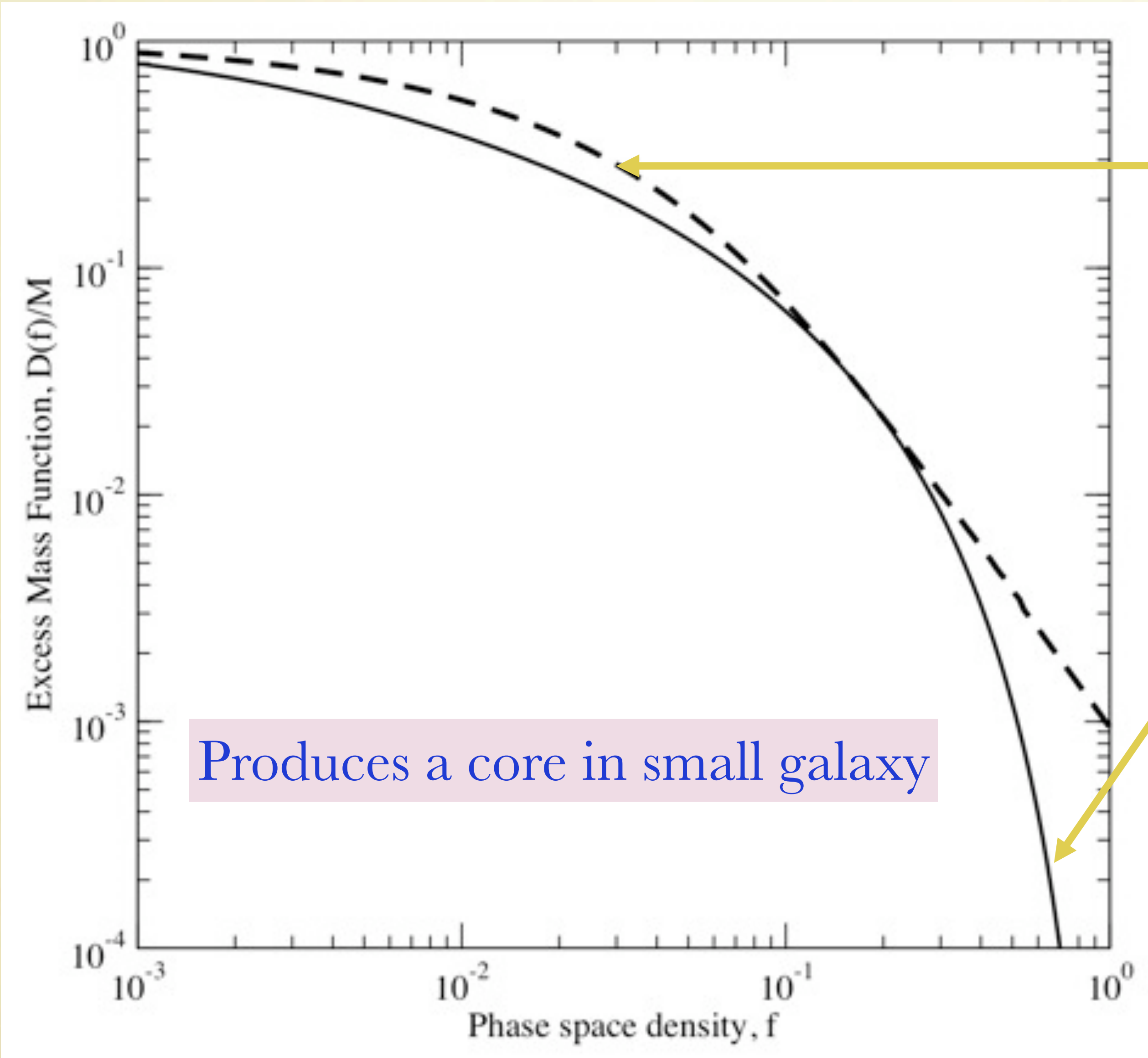
D(f) decreases

Dehnen 2005, Mathur 1988, Tremaine, Henon, Lynden-Bell 1986

Entropy and Excess Mass Function

- Change in $D(f)$ is related to change in entropy.
  - $\Delta S = -\,k_B \int_0^\infty \Delta D(f)\, df/f \quad \geq 0$ for closed systems.
- The decrease of $D(f)$ is a much stronger constraint.
- Gunn-Tremaine bound a special case

Constraints from the Excess Mass Function



For a distribution resulting from decays in the radiation dominated era.

For a halo with a constant density core at the center

[Kaplinghat 2005]

Extended Gunn-Tremaine

- The arguments outlined provide not only a minimum measure of the core, but also the form of the density profile near the core.

- For thermal warm dark matter, the core must have an isotropic velocity dispersion and

$$\rho \sim 1 - (r/r_{\rm core})^2$$

- For dark matter from early decays

$$\rho \sim 1 - r/r_{\rm core}$$

- These arguments only provide *minimum* core size -- need to factor in mergers.

Preliminary
Martinez and Kaplinghat 09

Phase space density Q
Example: dark matter from decays

$$Q = m_{\rm DM}^3 \rho_{\rm DM} \frac{\int d^3q\, f(q)}{\left[\int d^3q\, f(q) q^2\right]^{3/2}}$$

$$= 10^{-24} \left(\frac{m}{p_{\rm cm} a_{\rm dec}}\right)^3 \frac{M_\odot/{\rm pc}^3}{({\rm km/s})^3}$$

$$\lambda_{\rm fs} = \int dt\, v(t)/a(t)$$ for decays in radiation dominated regime

$$\sim \frac{\tau}{a_{\rm dec}} \frac{p_{\rm cm}}{m} \sim \frac{a_{\rm dec} p_{\rm cm}}{m} \sim \frac{1}{Q^{1/3}}$$

Relation between Q and free-streaming

- The free-streaming scale and Q are related in many models of dark matter. For example,
  - Both are fixed by specifying the mass of a warm dark matter particle like the sterile neutrino.
  - Given the cut-off in the power spectrum, the size of cores in halos can be computed using numerical simulations.
- This one-to-one relation can be broken strongly in models where dark matter results from late decays [meta-CDM: Strigari, Kaplinghat and Bullock 2007]
- Size of core probably depends on the shape of the primordial momentum distribution function and not just on the average Q.

META-CDM

Late decays will give rise to large phase space cores in dark matter halos while the power spectrum "looks like CDM"

Strigari, Kaplinghat and Bullock 2007

$$\begin{aligned} \mathrm{Free-streaming} \quad \mathrm{scale} \quad &\propto \quad 1/Q^{1/3} \qquad\qquad (RD) \\ &\propto \quad 1/(Q\tau)^{1/3} \quad (MD) \end{aligned}$$

τ is the decay half $-$ life

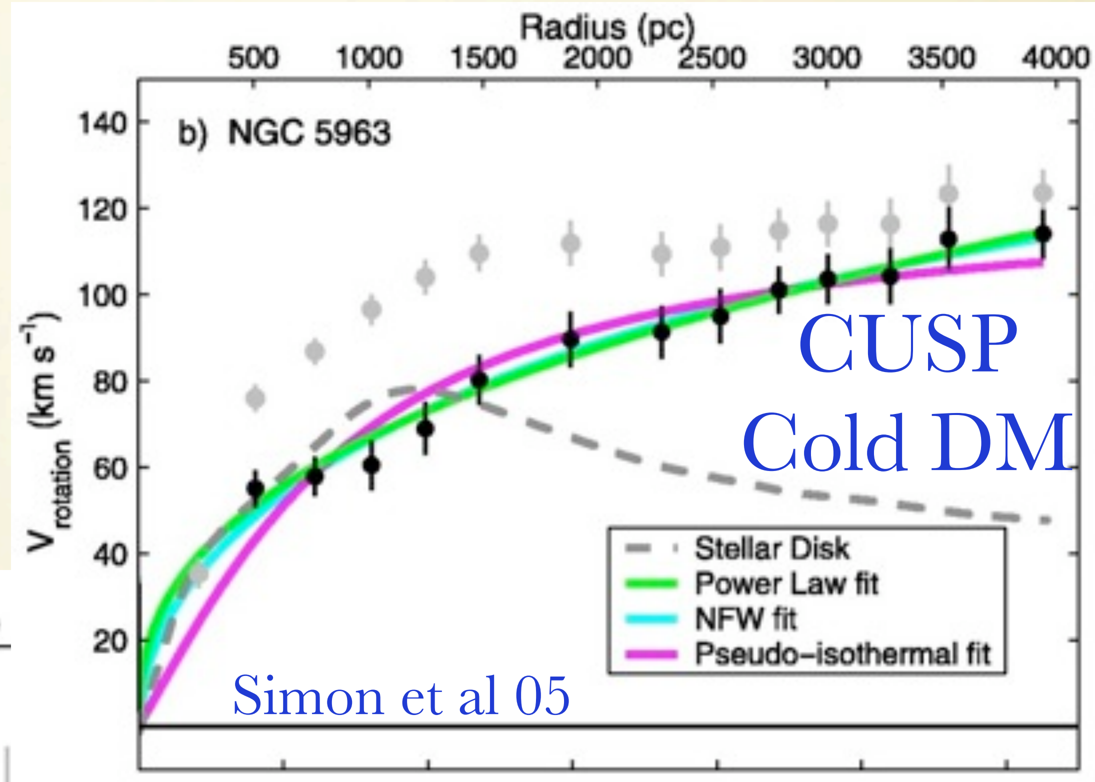
No free lunch though! Core size doesn't just depend on Q, but also on the primordial momentum distribution function.

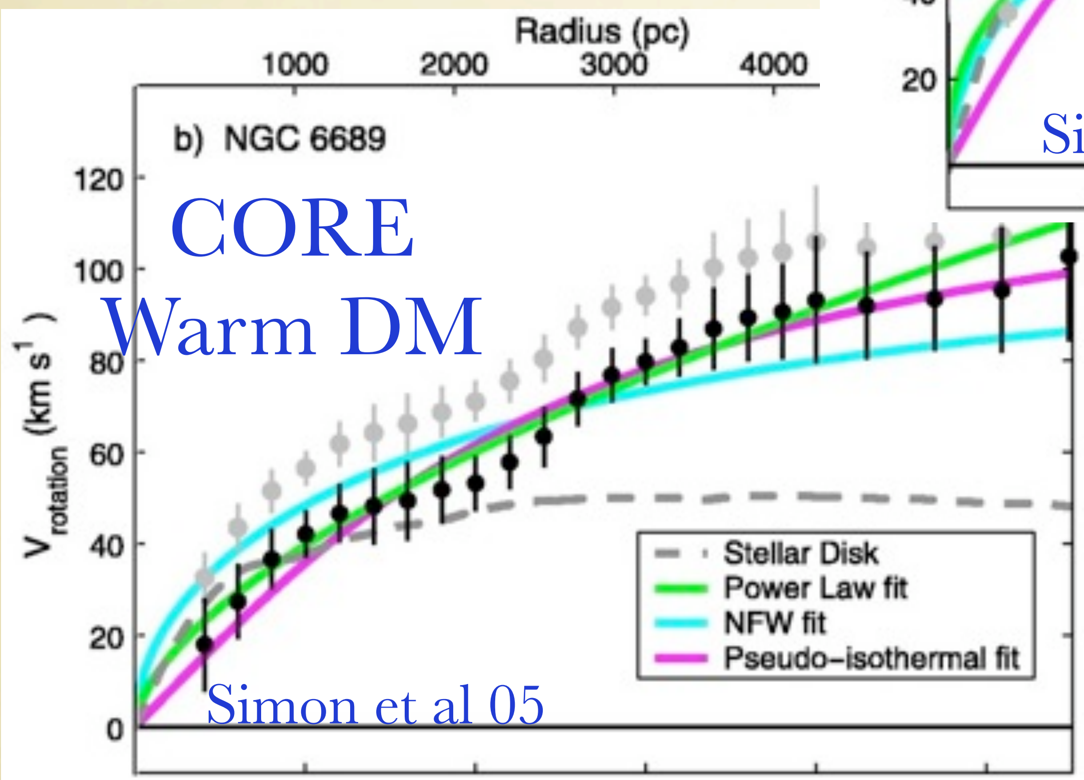
Deviations from CDM?

- Missing satellite problem? Observed numbers can be matched to theory by accounting for observational incompleteness and including a low mass threshold for galaxy formation.
- Core or cusp? Can't gauge this in dwarf galaxies but some LSB spiral galaxies prefer cores.

Cusp or Core?

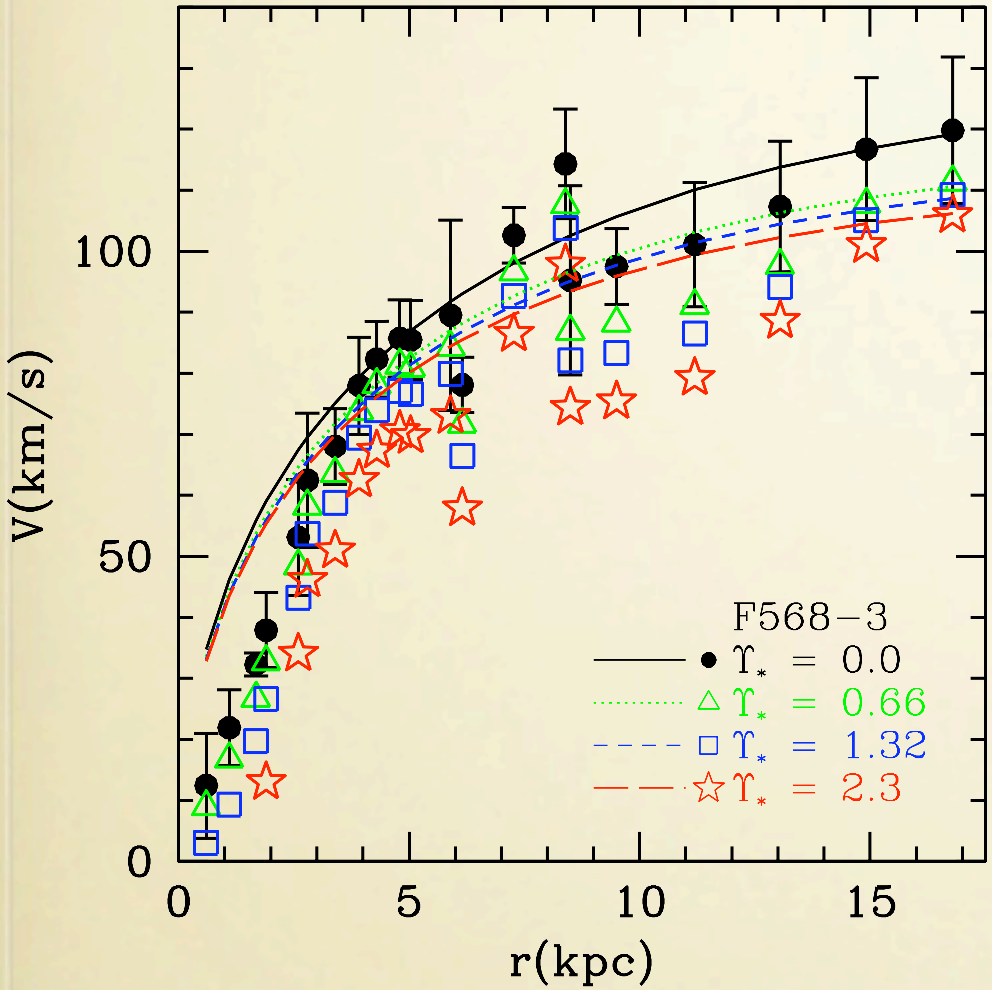
Not as bad as old HI data suggested, but problem seems to persist for some galaxies with new high quality data.



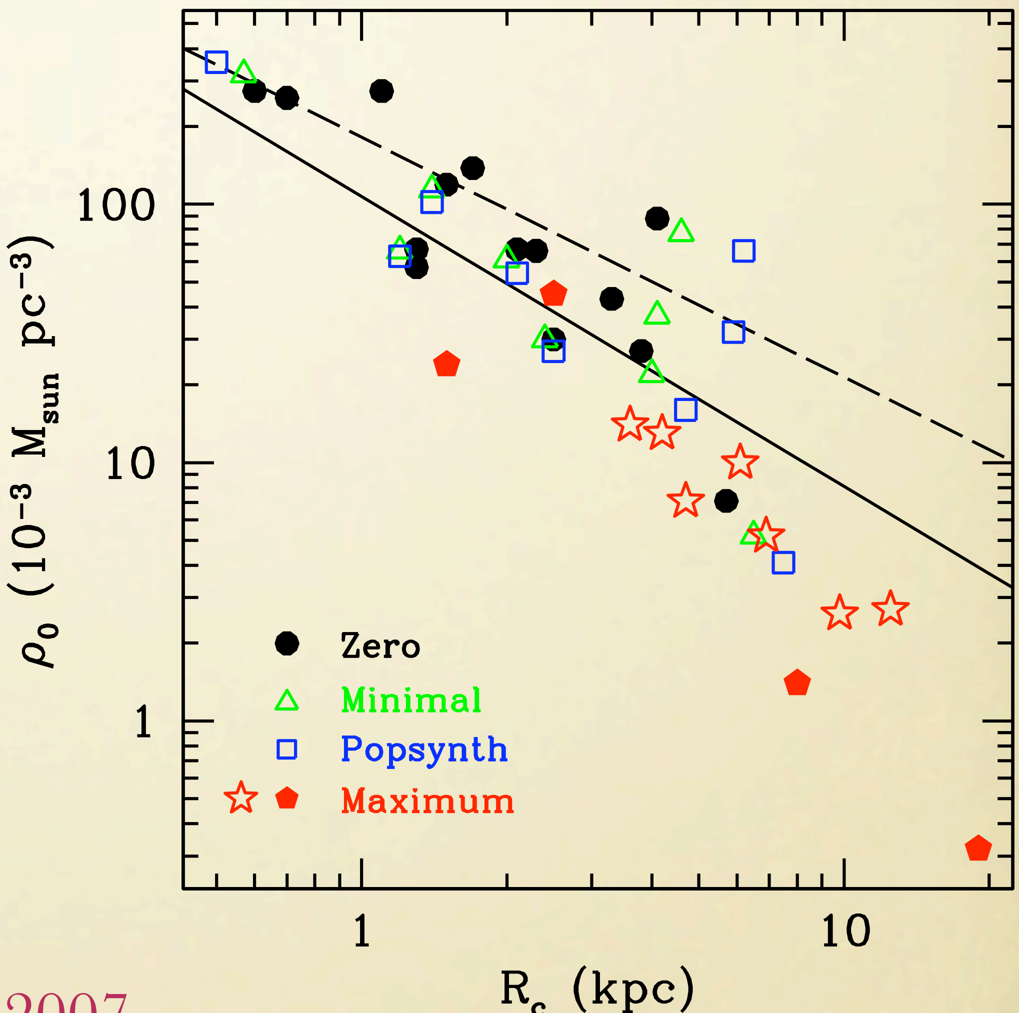


Modeling the gas and stars and including non-circular motion very important.

Cusp or Core: More data



Note density ~ 0.1 Msun/pc^3



Some of the other LSBs can be fit by NFW

Kuzio de Naray, McGaugh, de Blok 2007