Model Independent Constraints on Warm Hidden Dark matter

Subinoy Das
RWTH, Aachen University, Germany

Warm Dark Matter Meudon Workshop 2012

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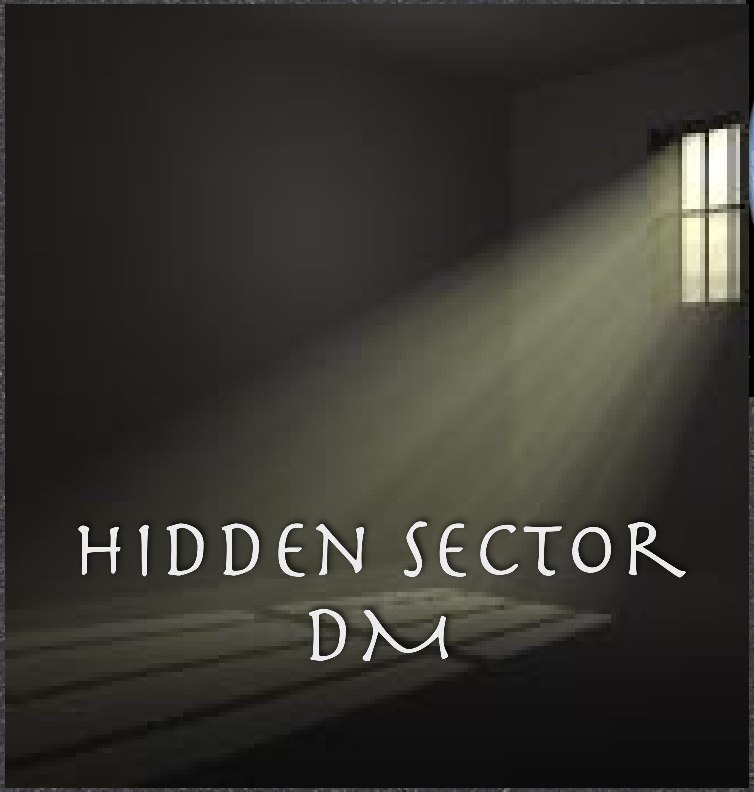

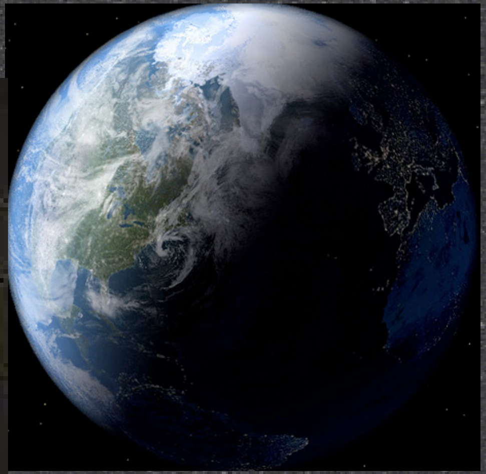

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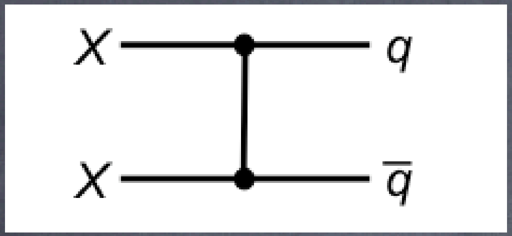
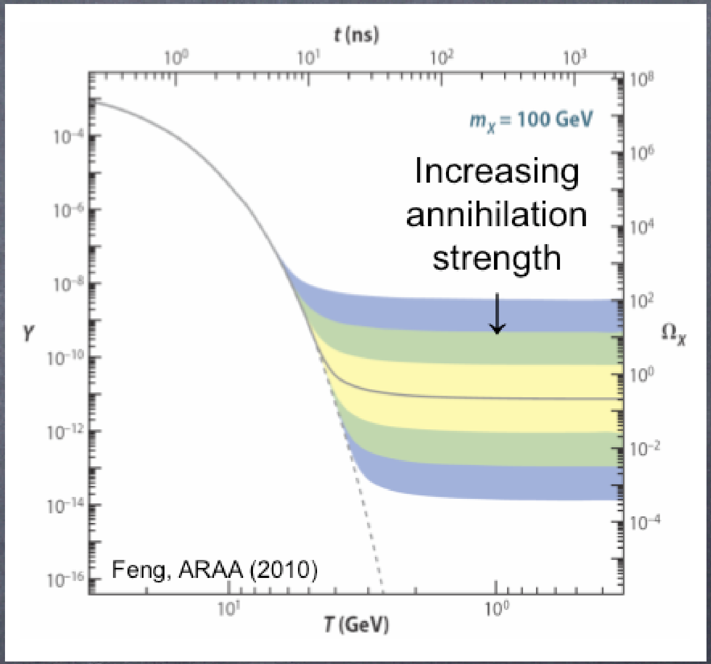
- To date, all evidence of dark matter is only from its gravitational effects. Have not directly seen DM yet!
- Cosmologically long lived (stable), produced in early Universe.
- Do we have any idea about dark matter mass .. may be some...



WIMP MIRACLE ?

- For thermal freeze-out the relation between dark matter relic density and cross-section is remarkably simple

$$\Omega_\chi \propto \frac{1}{<\sigma v>} \sim \frac{m_\chi^2}{g_\chi^4}$$



For $m_{weak} \sim 100\ GeV$ & $g_{weak} \sim 0.6$

We get $\Omega_\chi \simeq 0.1$

An amazing coincidence

- Both cosmology and particle physics independently point to weak scale

--- guide for many experimental search.

But Nature can be much more mischievous..

- In spite of extensive search for electro-weak WIMP there is no evidence yet. Stringent constraints on the parameter space from LHC search on SUSY and wimp CDM.
- May be discovery is near the corner or need to think out of the box ?
- It is highly possible that DM mass is not in the weak scale. many ideas .... one promising alternative -- WDM (either visible/ hidden)

What I am going to talk about ...

- A broader perspective to warm DM candidates and extending the realm of traditional WDM.

- Particle Model Independent constraints on WDM either in visible or in hidden sector.

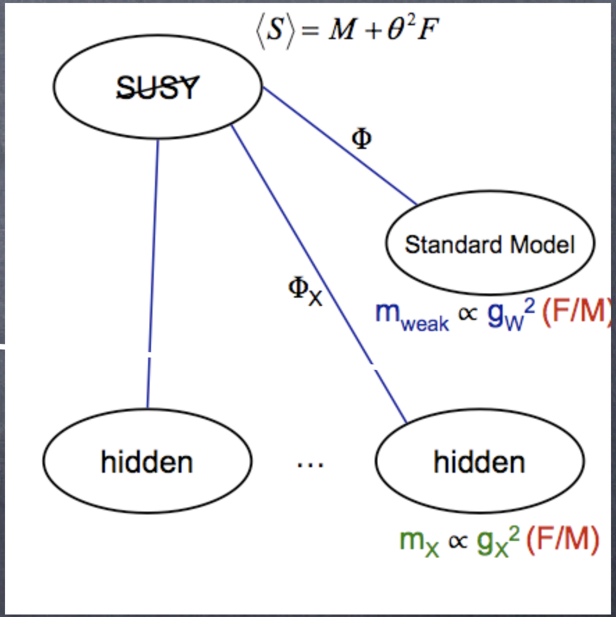
- Warm Dark Matter with cold DM pedigree

KEEPING THE WIMP MIRACLE ALIVE WITH KEV WDM?

One recent idea: Wimpless Miracle PRL (J Feng, J kumar)

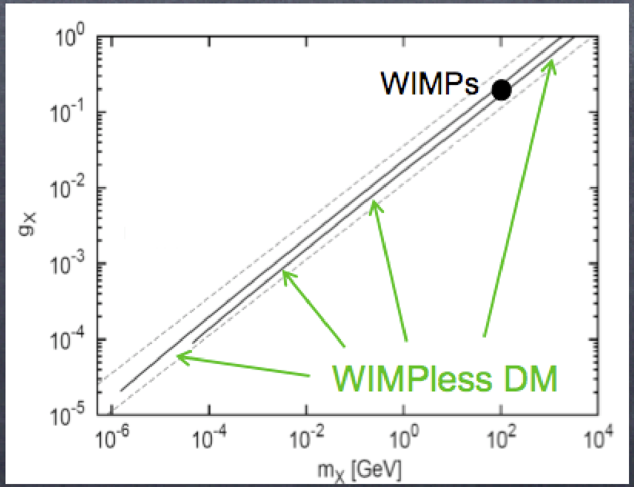
Dark matter candidate in hidden sector. Soft scale can be different but relic density is universal.

$$\frac{m_h^2}{g_h^4} = \frac{m_x^2}{g_x^4} = F/M$$



Not necessarily in thermal equilibrium with SM

Wide range of DM mass opens up encompassing wimp miracle!



BBN + CMB constraints on hidden WDM sector

It may self-interact through "dark photons," Coulomb interactions
– Light degrees of freedom can change the expansion history of the Universe.

$$g_*^h(T_{\rm CMB}^h)\left(\frac{T_{\rm CMB}^h}{T_{\rm CMB}}\right)^4 = \frac{7}{8}\cdot 2\cdot (N_{\rm eff}-3.046)\left(\frac{T_\nu}{T_\gamma}\right)^4 \leq 1.30\ (68\%\ {\rm CL})$$

- Hidden sector DM at different (lower) temp $\xi = \dfrac{T_h}{T_{vis}}$

→ Low re-heating temp. and not in thermal contact with SM.

☆ **Recent hints of dark radiation from ACT + SPT may point out to light relativistic hidden d.o.f.**

Model independent constraints from cosmology / Astrophysics on hidden WDM

What do we really know about DM mass?

- The smaller the DM mass ---larger number of particle. For fermions there exists a maximal phase space density(Degenerate fermi gas). So DM mass > m0 (Tremain - Gunn 1979)
- Objects with highest phase -space density dwarf spheroidal galaxy puts a lower bound on DM mass.

Free-streaming bound on thermal DM mass

- DM particle erases primordial density perturbation on scales up to DM particle horizon known as Free-streaming scale.

$$\lambda_{FS}^{co} = \int_0^t \frac{v(t')dt'}{a(t')}$$

All DM models falls in 3 categories

- CDM -- negligible free-streaming eg. EW wimp
- WDM--free-streaming at galaxy scale eg. keV sterile
- HDM--free-streaming at cosmological scale eg. SM (Ruled out)

CDM and WDM works equally well at large scales

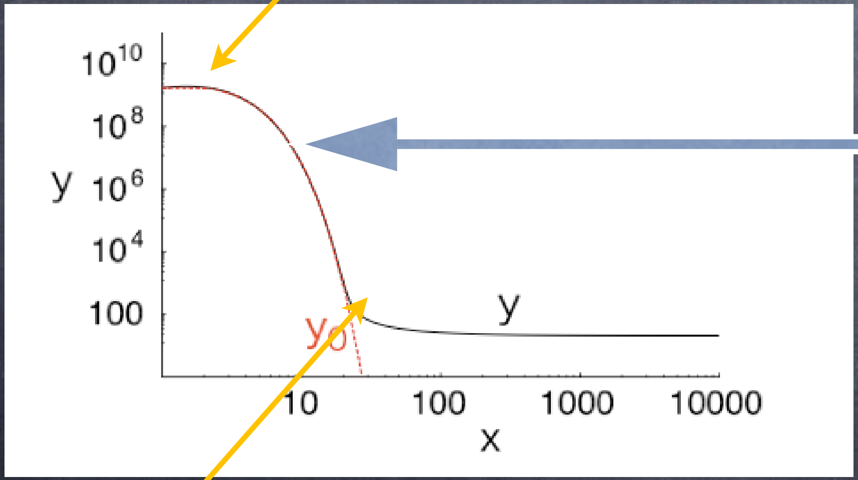
Necessary ingredients to apply the cosmological bound

More on freeze-out to understand astrophysical constraints in a model independent way.

Approximate analytical solution well known for relativistic and non-relativistic decoupling.

$x_f \equiv m_X/T_f \ll 1$

Relativistic (HDM)



Hard for Warm Dark Matter (WDM)

For intermediate semi-relativistic case thermally averaged cross-section $< \sigma v >$ can not be expanded either in DM mass or velocity.

Non-relativistic (CDM) $x_f \geq 3$

Details of the freeze-out for WDM..

The general expression for thermally averaged cross-section

$$\langle \sigma v \rangle = \sigma \frac{4}{x^6 K_2^2(x)} \int_0^\infty dt\, t^2 \,(t^2 + x^2)^2 K_1(2\sqrt{t^2 + x^2})$$

In the non-relativistic and ultra-relativistic limit it reads

$$\langle \sigma v \rangle_{NR} \equiv \lim_{x \gg 3} \langle \sigma v \rangle = \sigma$$

$$\langle \sigma v \rangle_{R} \equiv \lim_{x \ll 1} \langle \sigma v \rangle = \frac{\sigma}{4x^2}(12 + 5x^2)$$

A simple ansatz that interpolates between these

$$\langle \sigma v \rangle \equiv \sigma f(x) \equiv \sigma \left(\frac{3}{x^2} + \frac{\frac{5}{4} + x}{1 + x} \right)$$

Dress, Kakizaki, Kulkarni PRD 2009

Extending to the hidden sector

for $< \sigma v >= \sigma f(x)$

$$\frac{dy}{dx} = -\frac{1}{x^2}\left[y^2 - y_0^2(x;\xi)\right] + y\,\frac{d\ln f(x)}{dx}.$$

where $$y_0(x;\xi) \equiv [s(m_\chi)/H(m_\chi)]\langle\sigma v\rangle Y_0(x;\xi).$$

Freeze-out depends on 3 parameters

Dark matter mass m_χ

DM annihilation cross-section σ_χ

Hidden to visible temp. ratio $\xi = \frac{T^f_{hid}}{T^f_{vis}}$

We have 3- dimensional parameter space for general freeze-out (cold, warm, hot)

- Apply relic density constraint $$\Omega_\chi = m_\chi s_0 \frac{Y(x_\infty, \xi)}{\rho_c}$$
- Free-streaming bound $$\lambda^{FSH} = \int_{t_f}^{t_{eq}} \frac{\langle v \rangle}{a} dt$$ has to be consistent with structure formation
- Phase space bound on dark matter mass $$m_\chi \geq m^{TG}(x_f^h)$$

$$x_f^h = f(m_\chi, \xi, \sigma)$$

Free-streaming horizon for hidden warm DM

$$\langle v \rangle = \langle v(\bar{a}) \rangle \equiv \frac{\int_0^\infty dq\, q^2 \left(\frac{q}{\sqrt{q^2+\bar{a}^2 m^2}} \right) f(q, T_f^h)}{\int_0^\infty dq\, q^2 f(q, T_f^h)}$$

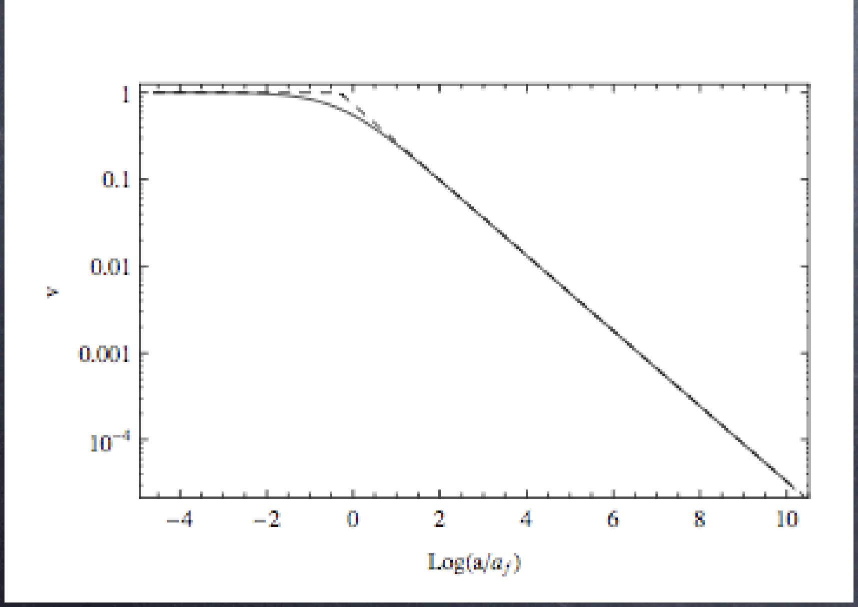
Where $\bar{a} = \frac{a}{a_f}$

$$\langle v \rangle = \langle p/\sqrt{m^2+p^2} \rangle$$

and $$f(q, T_f^h) = [1+\exp(\sqrt{m^2+q^2}/T_f^h)]^{-1}$$

At early times $\bar{a} \to 0$ $< v > \to 1$

As $\bar{a}$ increases $< v > \to (\bar{a})^{-1}$



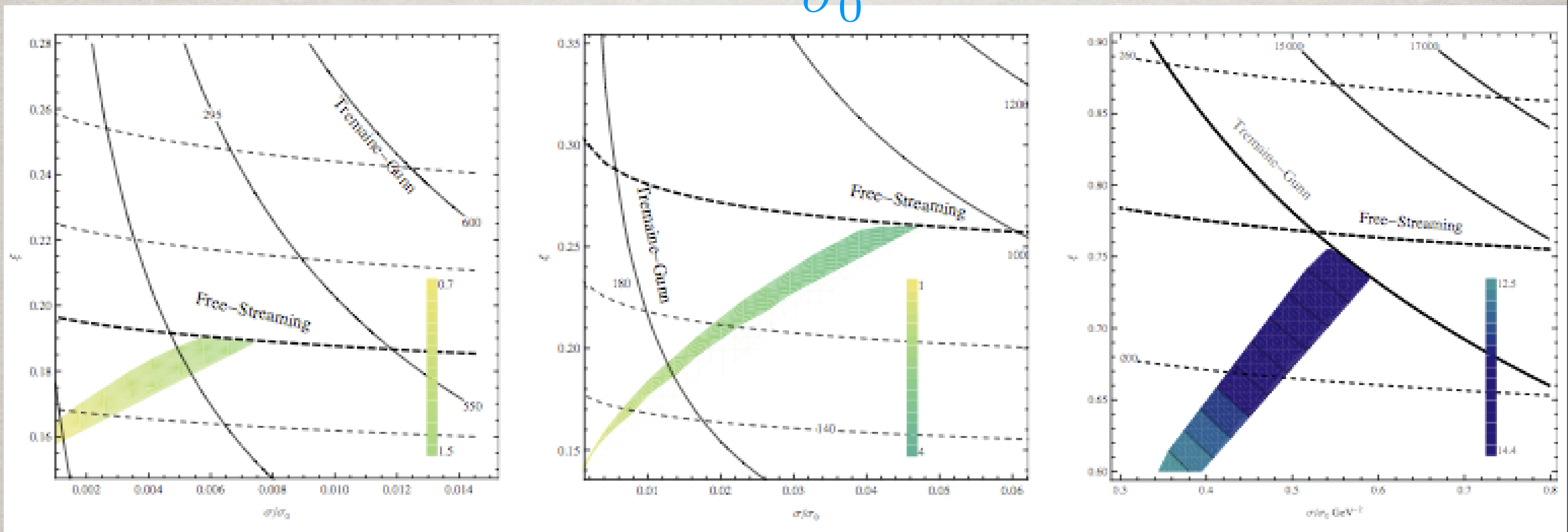
$$\lambda^{FSH} = \frac{1}{\sqrt{\Omega_r} H_0} \left[\int_{a_f}^{a_\lambda} da + \int_{a_\lambda}^{a_e} \frac{a_{nr}\, da}{\sqrt{a^2 + \frac{a^3}{a_e}}} \right]$$

Free-streaming constraint --less stringent compared to visible WDM.

Freeze-out and Constraints on Hidden DM

SD & Kris Sigurdson
PRD 2012

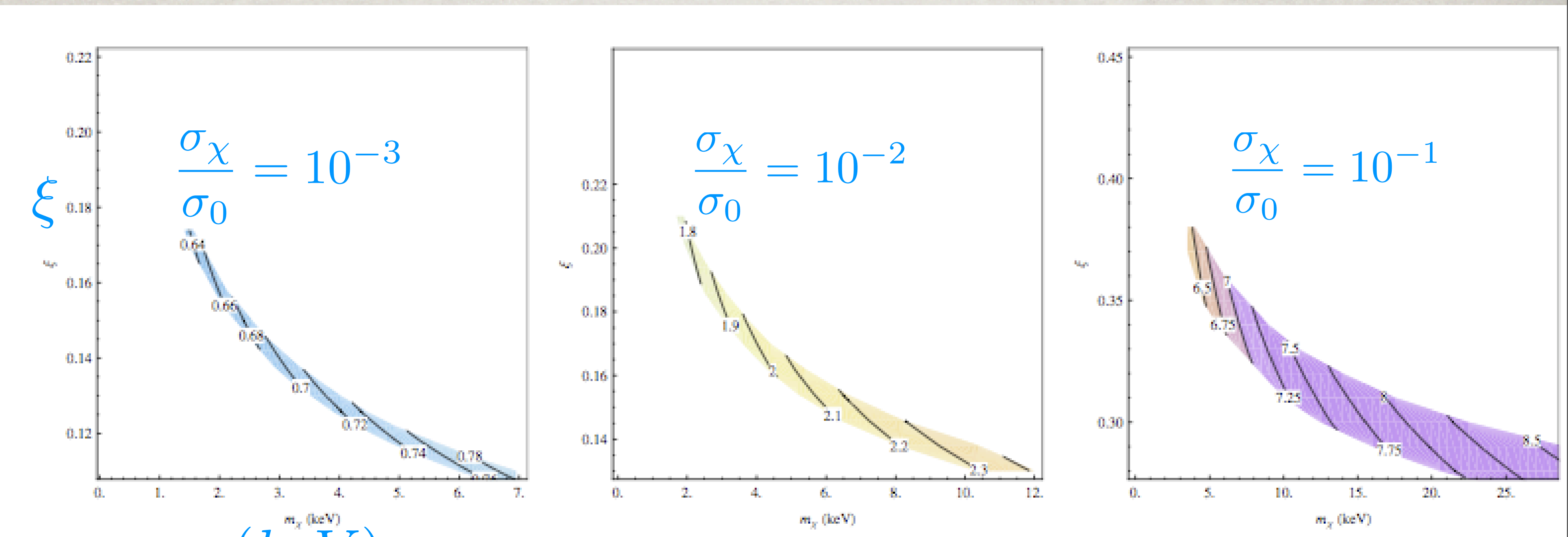
Representative constraints over $\left(\frac{\sigma}{\sigma_0}, \xi\right)$ plane for different mass



$m_\chi = 1.9\,\mathrm{keV}$ $m_\chi = 3.0\,\mathrm{keV}$ $m_\chi = 12.5\,\mathrm{keV}$

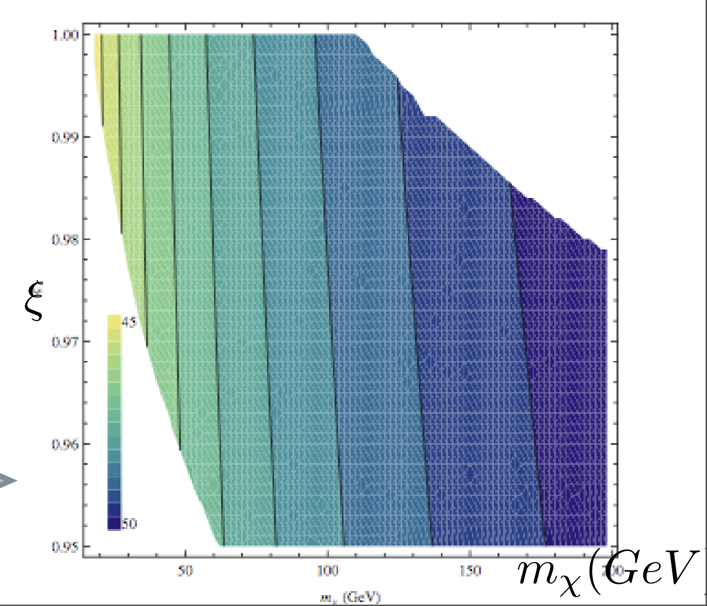
we find -- Universal lower bound $m_\chi \geq 1.5\ \ keV$ compatible with free-streaming & phase space bound.

Representative constraints over (m_χ, ξ) plane for different cross-section σ_χ



We see that most of the constraints come for the WDM case. Which points towards lower mass, cross-section and ξ

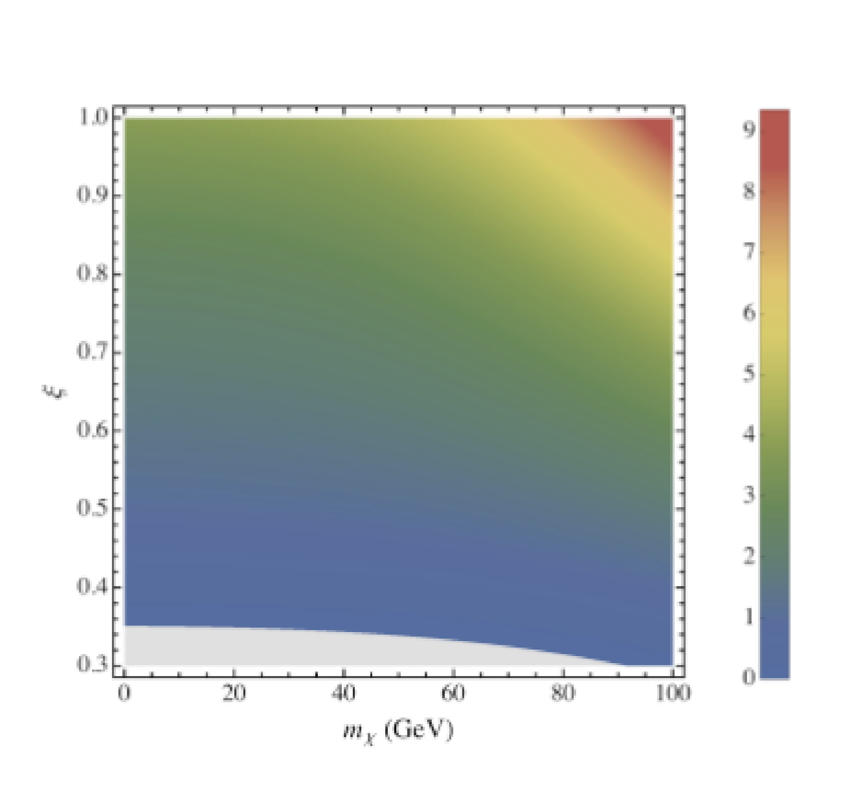
For higher mass and higher ξ we recover the electroweak cdm case.



Surface of Allowed hidden DM Abundance

$$\sigma(m_\chi, \xi) = \sigma_0 \sum_{i,j=0}^{3} C_{ij} \left(\frac{m_\chi}{\text{GeV}}\right)^i \xi^j$$

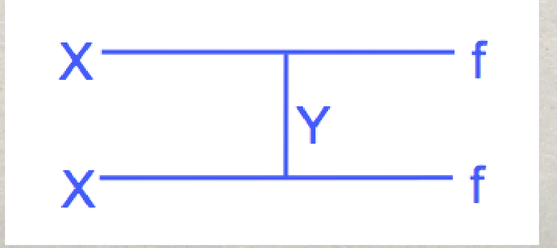
C	$i=0$	$i=1$	$i=2$	$i=3$
$j=0$	-5.2345	-0.0016	0.0001	1.028×10^{-6}
$j=1$	23.3984	0.0053	-0.0004	-4.0929×10^{-6}
$j=2$	-29.4988	0.0029	0.0005	5.4513×10^{-6}
$j=3$	15.2099	-0.0018	-0.0002	-2.6184×10^{-6}



Detection of Hidden DM?

Very hard : Interaction with SM has to be super-weak, so remains out of thermal equilibrium.

But not impossible:

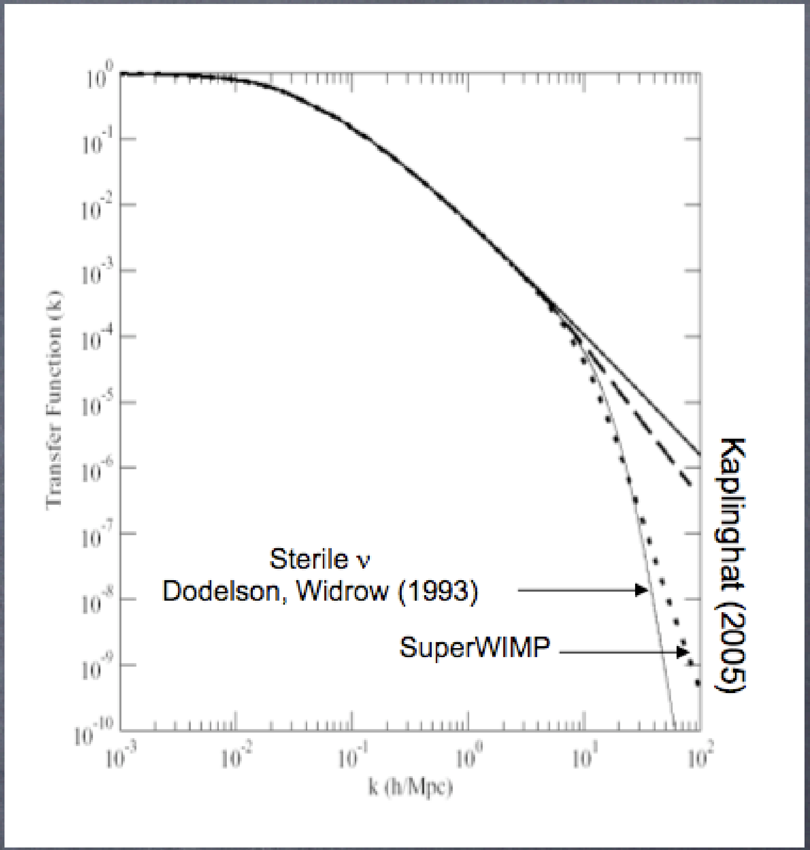


Interaction through connector particle.

Warm Dark Matter with cold DM pedigree

There are particles with different mass range which can mimic suppression in matter power spectra!

Hidden WDM with pushes the suppression at smaller scales compared to standard WDM. So lower mass ~ 1.5 keV allowed.



SIGURDSON, KAMIONKOWSKI (2004)
STRIGARI, KAPLIGHAT, BULLOCK(2006)
Cembranos, Feng, Rajaraman, Takayama (2005)

New dynamics at mili-ev scale? $m_A \sim 10^{-3} eV \gg H_0$

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New physics @ TeV ?	New physics @ meV ?
✩ Relevant parameter m_H^2 sensitive to high scale unless new TeV physics cuts of quantum correction.	✩ Relevant parameter Λ sensitive to high scale unless new meV physics cuts of quantum correction.

Rob Fardon, A.E.N., Neal Weiner; astro-ph/0309800, JCAP 0410:005,2004, hep-ph/0507235, JHEP 0603:042,2006
David B Kaplan, A.E.N., Neal Weiner; hep-ph/0401099, PRL 93:091801,2004

Warm Dark Matter like effects through phase transition in the early Universe!

- *Late Forming Dark Matter (LFDM)*

  SD, Neal Weiner PRD 2011

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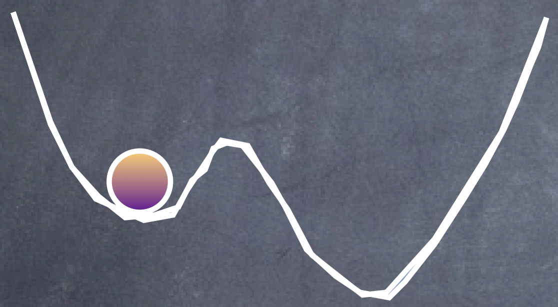

High temp.
(meta-stable minima)

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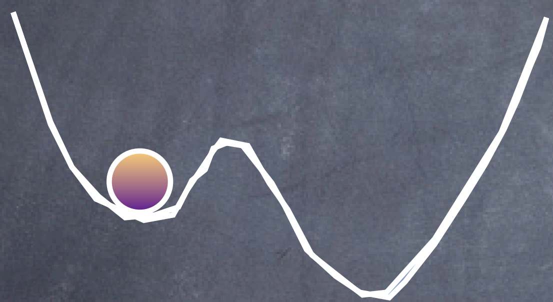

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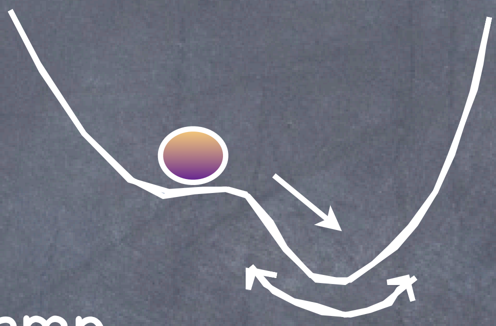

Low temp.
coherent oscillation about true minima

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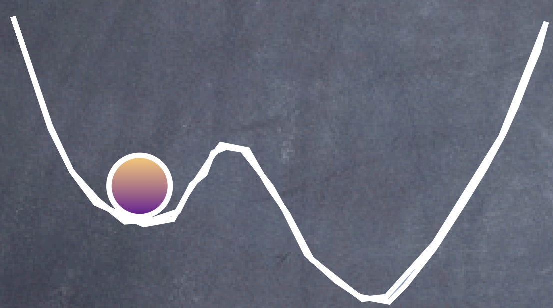

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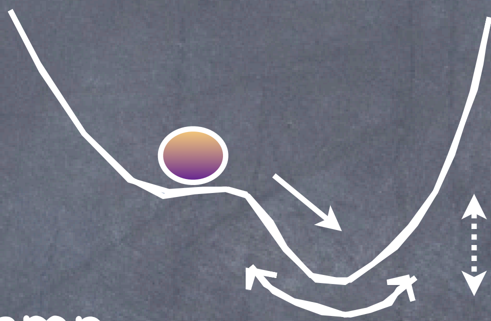

What happened to this energy ? appear as DM

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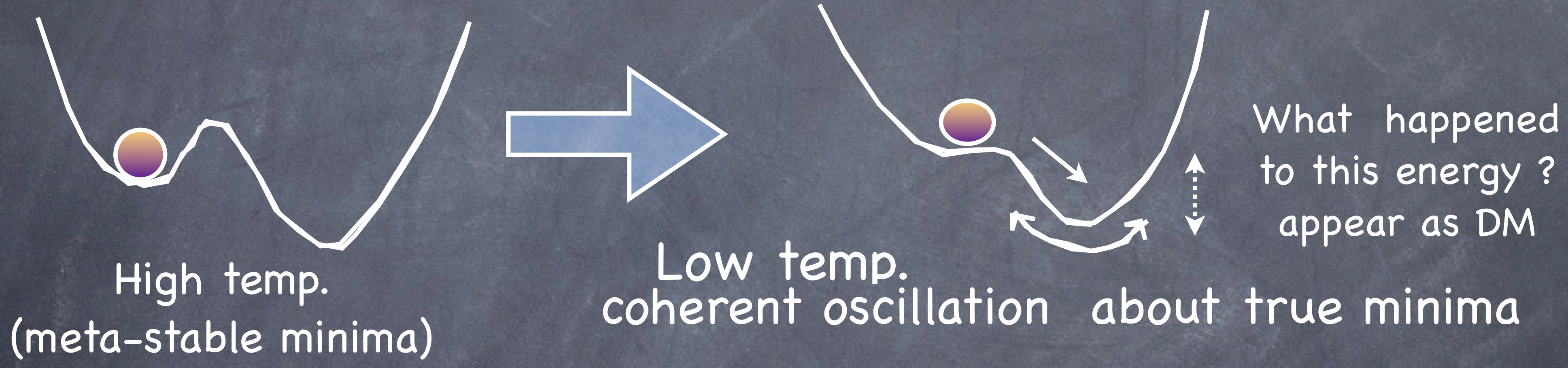

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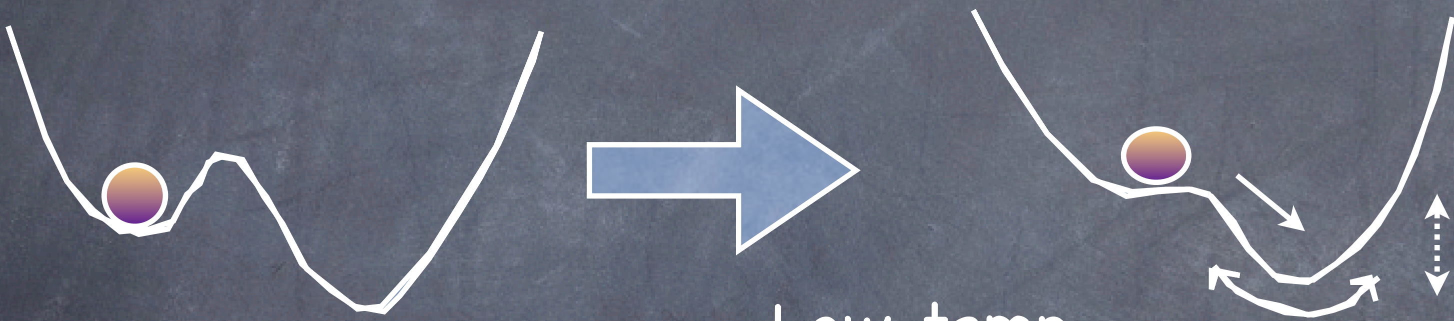

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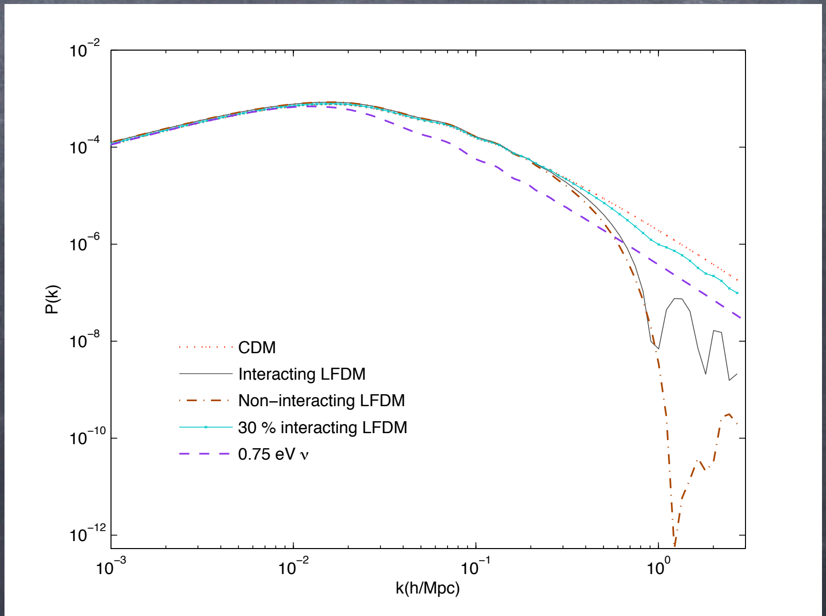

A generic WDM like signature

$$m_\phi \simeq 10^{-3} eV$$

connected to BSM neutrino physics

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- contradicts present observation $\lambda_{FS} \leq 240Kpc$ **ruled out**

Exotic Warm dark matter from hot dark matter

SD and Kris Sigurdson (2012) ...to appear

- Neutrino has extra interaction with a scalar
- It was free-streaming in RDE. But at some point in RDE, a phase transition happened. Fifth force wins over free-stream and neutrino gets trapped into *compact bubbles*.

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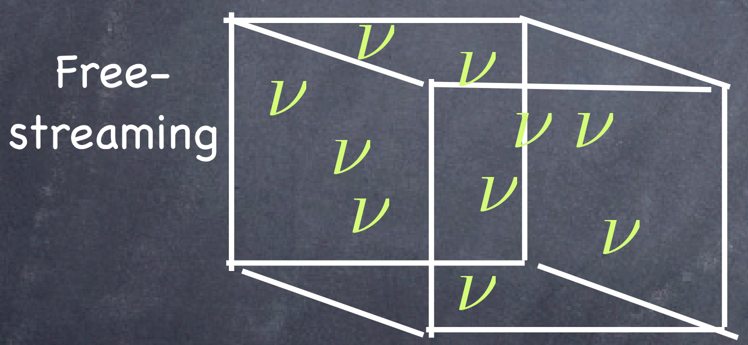

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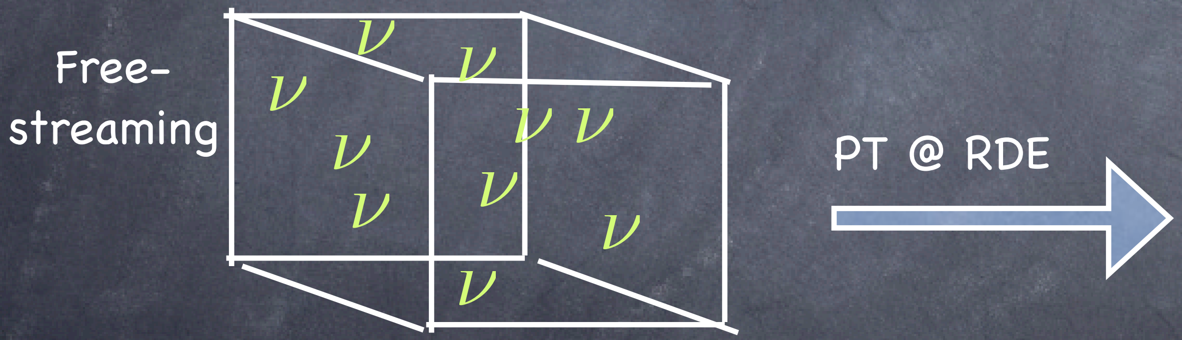

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  -> determines the RADIUS of Bubble.

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- Fifth forces is balanced by fermi pressure of neutrino.
  -> determines the RADIUS of Bubble.
- Each bubble behaves as *cold* dark matter particle.

Neutrinos outside the bubbles behaves like normal neutrino.

Solving the bubble profile

Solving the bubble profile

- Fermion mass varies with "r"

Each point in the space which is at a distance r from the center of the bubble,

there exists a Fermi-sea with local Fermi radius $k_F(r)$

Thomas-Fermi approximation

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First, is the Klein-Gordon equation for $\phi(r)$ under the potential $V(\phi)$, where neutrino acts as source term for $\phi(r)$

$$\phi'' + \frac{2}{r}\phi' = \frac{dU}{d\phi} - \frac{dln[m(\phi)]}{d\phi} T^\mu_\mu$$

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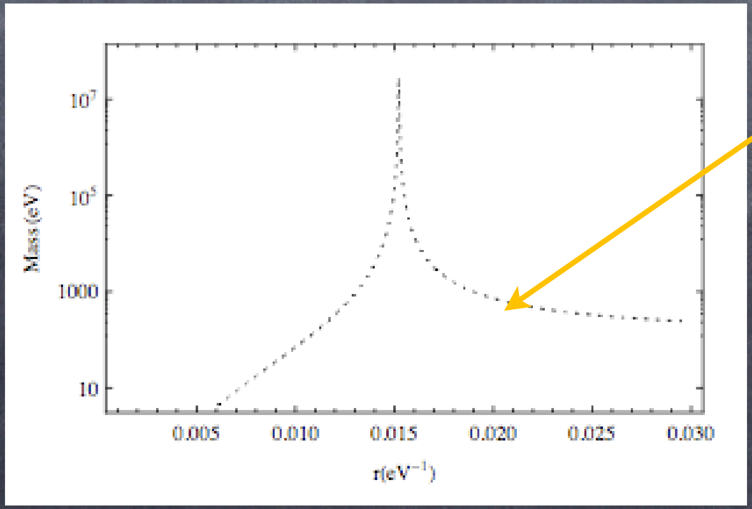
Second, balancing scalar force by Fermi pressure

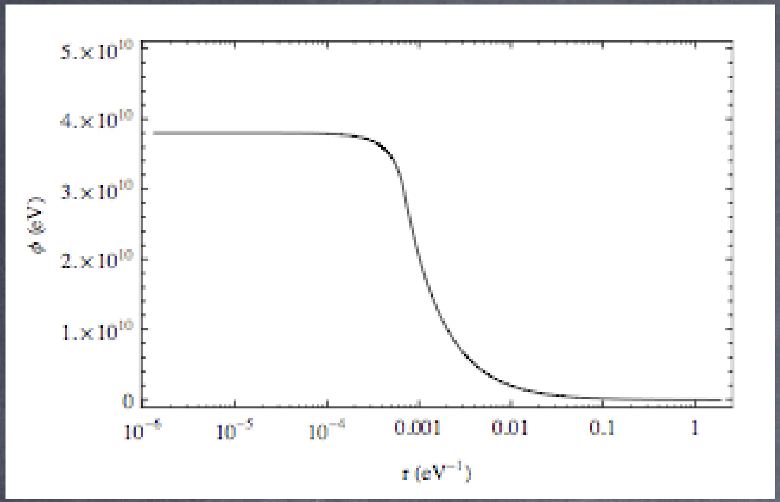
$$\frac{dp}{d\phi} = \frac{d[ln(m(\phi))]}{d\phi}(3p - \rho)$$

Trapped fermion mass
is much smaller inside
the bubble.
The bump in m(r) gives the
stability to the bubble.



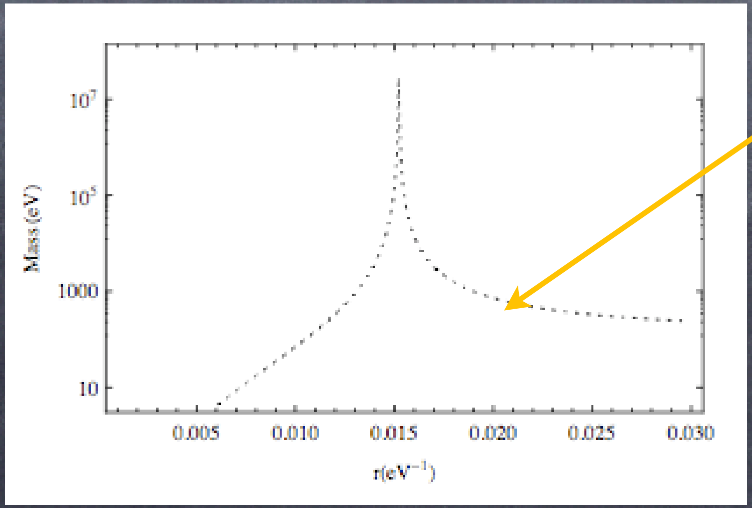
Corresponds to present
cosmological value of
fermion mass.

Numerical results



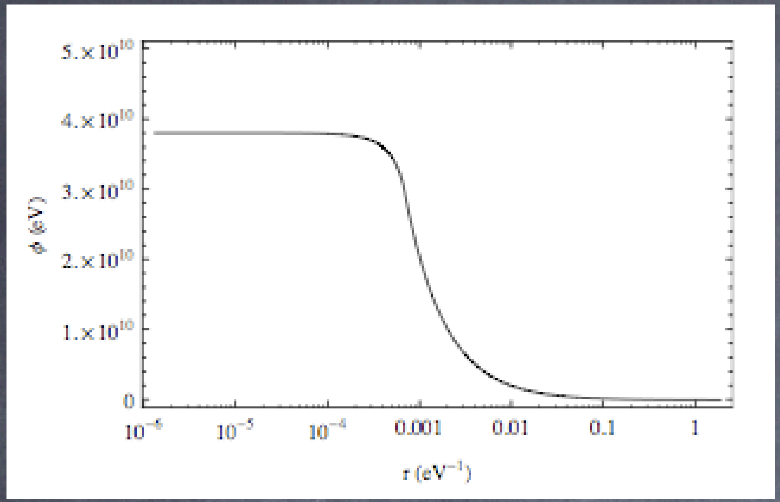
$\phi(r)$ is displaced to higher value inside and asymptotically reaches to zero.

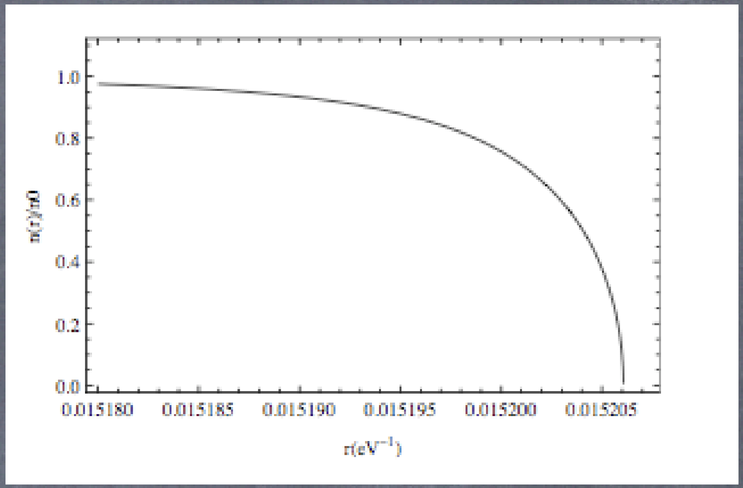
Trapped fermion mass is much smaller inside the bubble.
The bump in m(r) gives the stability to the bubble.



Corresponds to present cosmological value of fermion mass.

Numerical results

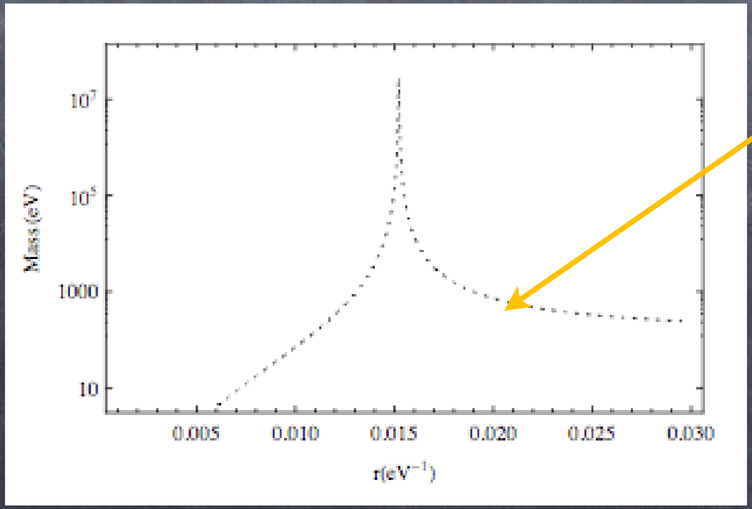




$\phi(r)$ is displaced to higher value inside and asymptotically reaches to zero.

$n(r) = \frac{p_F^3}{3\pi^2}$, choose $p_F(0)$ to match the total number of neutrinos just before the phase transition.

Trapped fermion mass is much smaller inside the bubble.
The bump in m(r) gives the stability to the bubble.



Corresponds to present cosmological value of fermion mass.

Conclusion

- DM can be warm as well as visible or hidden. Hidden DM has one more extra parameter $\xi = \frac{T^h}{T^{vis}}$ which influence the cosmological constraint. Thermalized WDM has to be hidden.

- Hidden dark matter is also subject to phase space bound and free-streaming bound. We scan 3 dimensional parameter space (m_χ, ξ, σ) : Hidden DM mass > 1.5 keV.

- While eV mass sterile neutrinos are ruled out as dark matter , it is possible to reconcile it as DM through phase transition in RDE . Recent anomaly from neutrino experiment data might prefer such eV sterile states
- WDM simulation of this kind of model may reveal new facts.

Phase space bound

$$m \geq m_{min} = \left(\frac{9\, h^3}{(2\pi)^{5/2} d_\chi\, G_N\, \sigma_{\rm v}\, r_c^2} \, \frac{1}{f(q, T_f^h)|_{max}} \right)^{1/4}$$