Dark Matter that can form Dark Stars

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Precaution

Dark Matter Annihilation Cross Section

$$\langle \sigma v \rangle_{\text{freezeout}} \neq \langle \sigma v \rangle_{\text{galaxy}}$$

In general the annihilation cross section at freeze-out can be different from the one at the galactic center.

For instance, the most popular dark matter candidates in supersymmetry (mostly bino) has a p-wave suppression.

$$\langle \sigma v \rangle \simeq b v^2$$

different for different velocity

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Dark Stars

Spolyar Freese Gondolo, PRL 100(2008)051101

The first stars in the universe might have been powered by dark matter annihilation.

It is called 'dark stars'.

* Originally dark star was the name for what is nowadays known as a 'black hole'.

The First Stars (Population III Stars)

It is made of H/He.
It happens at redshifts z=10~50 (>5).
It forms inside DM halos of $10^5 \sim 10^6 M_{\rm sol}$

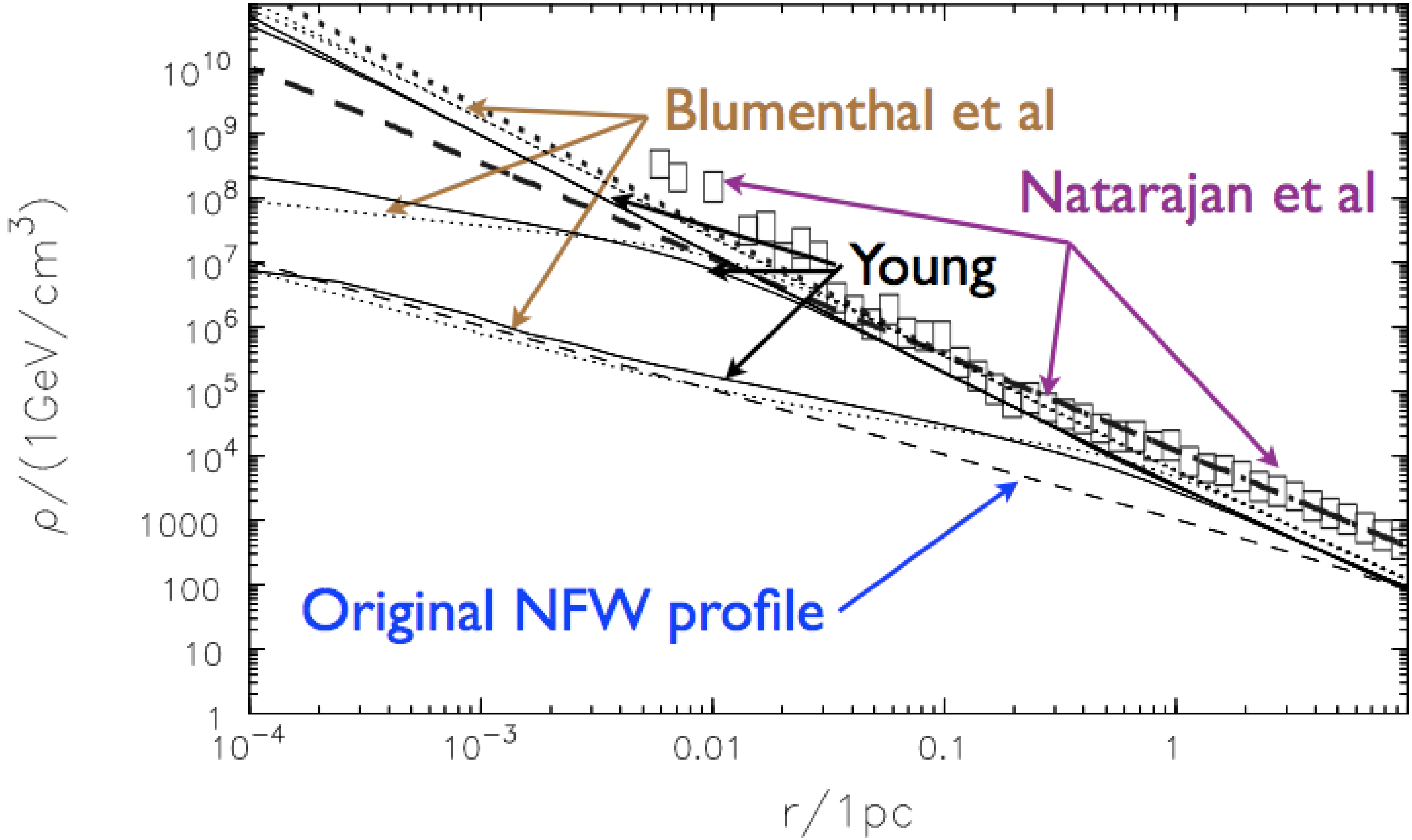
Dark ages end.
Universe is reionized.

Dark matter annihilation provides an extra heat to the collapsing gas cloud and can delay the process toward the main sequence.

New phase of star fueled by DM annihilation
=> Dark Star

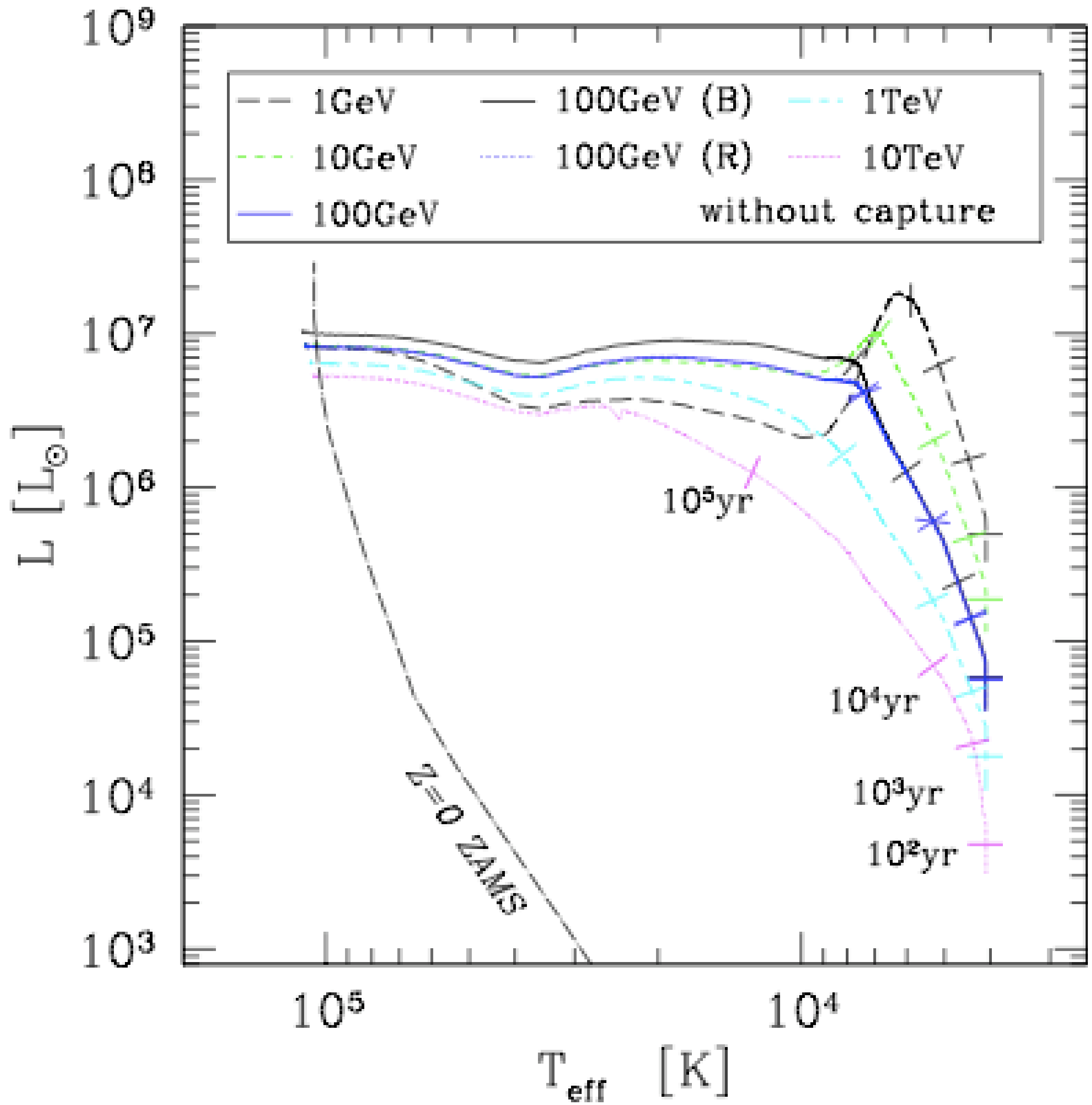
Dark matter distribution

Baryon density at the core : $10^{10}, 10^{13}, 10^{16} cm^{-3}$



Dark star phase

Spolyar Bodenheimer Freese Gondolo (2009)



WIMP miracle

A WIMP in thermal equilibrium in the early universe provides the right relic abundance to be cold dark matter.

It is called 'WIMP miracle'.

$$\Omega h^2 = \frac{3 \times 10^{-27} cm^3/s}{\langle \sigma v \rangle} \sim 0.1$$

$$\langle \sigma v \rangle = 3 \times 10^{-26} cm^3/s$$

Comment on WIMP indirect detection

Indirect detection is based on the same
annihilation cross section of dark matter.

The annihilation cross section can be very different
from the cross section at the freeze-out
due to the velocity dependence in the cross section.

Indirect detection can be extremely difficult
if the cross section is dominated by p-wave
(or even d-wave) suppressed contribution.

WIMP Cold Dark Matter

Indeed two ingredients are enough for DM.
New particles at TeV or weak scale.
Parity under which new particles is odd.

Supersymmetry with R-parity $\rightarrow$ Neutralino as LSP

Extra dimension with KK-parity $\rightarrow$ Kaluza-Klein DM as LKP

Little Higgs fields with T-parity $\rightarrow$ LTP

... ...

Conditions for dark star formation

Heating given by dark matter annihilation
should win H2 cooling.

Heating rate : $\Gamma_{\mathrm{DM\ \ heat}} = f_Q Q_{\mathrm{ann}}$

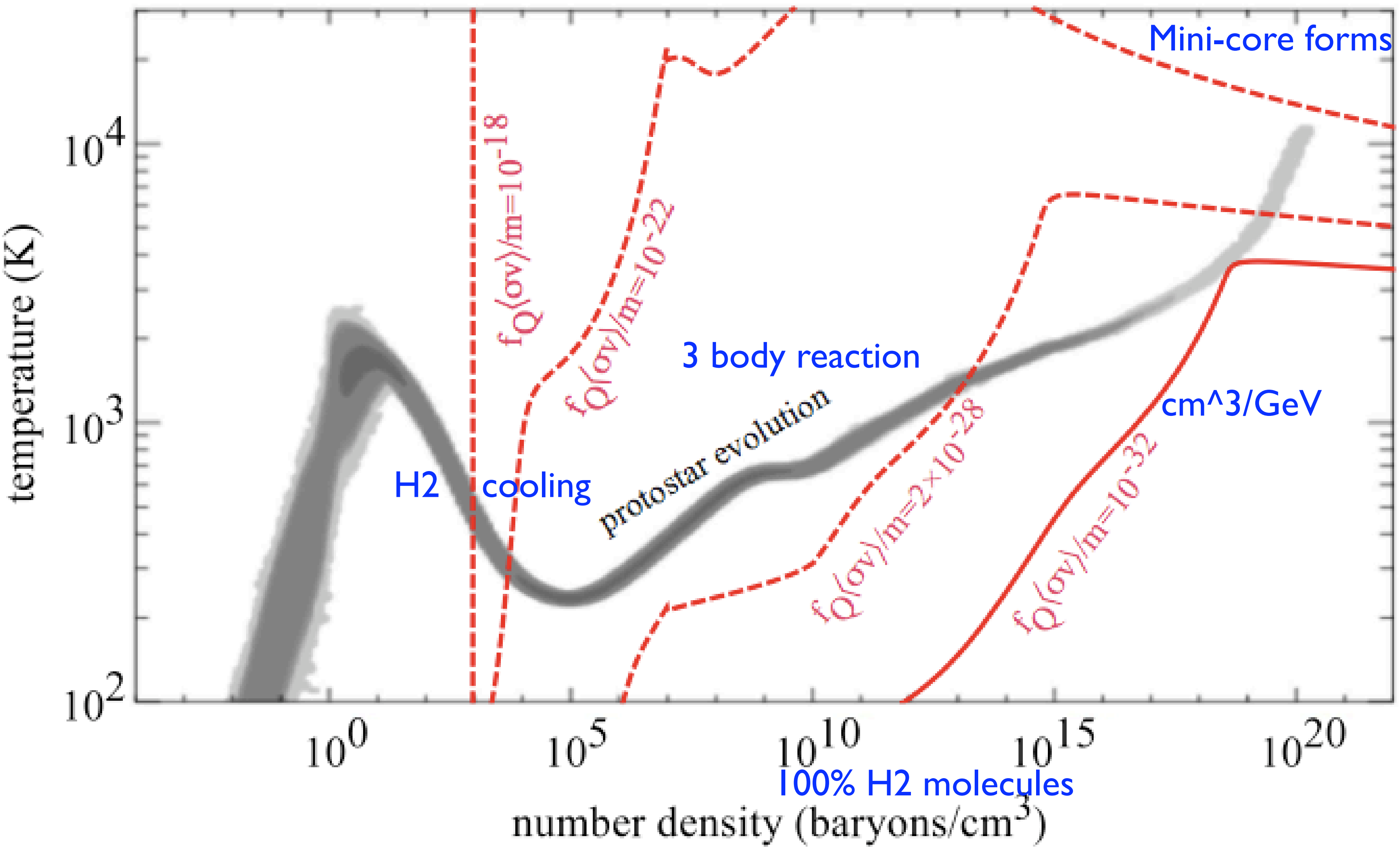
$$Q_{\mathrm{ann}} = n_\chi^2 \langle \sigma v \rangle m_\chi = \rho_\chi^2 \frac{\langle \sigma v \rangle}{m_\chi}$$

f_Q : fraction of visible energy (not neutrinos)

Annihilation products escape for $n \leq 10^4 cm^{-3}$

$f_Q = \dfrac{2}{3}$ is a representative choice.

Thermal evolution of Pop III star



Condition for dark star formation

$$f_Q \langle \sigma v \rangle / m_\chi \geq 10^{-32} cm^3 s^{-1} \mathrm{GeV}^{-1}$$

Let us compare it with the constant cross section to obtain the dark matter density.

$$\langle \sigma v \rangle = 3 \times 10^{-26} cm^3 s^{-1}$$

With $f_Q = 1/3$, the condition is satisfied as long as

$$m_\chi \leq 1000 \ \mathrm{TeV}$$

Condition for dark star formation

Indeed the cross section at freeze out and at dark star can be different

At freeze out, $$\frac{v}{c} \sim \frac{1}{3} \text{ or } \frac{1}{4}$$

At dark star, $$\frac{v}{c} \sim 10^{-5}$$

If $\langle \sigma v \rangle$ is v dependent, we have to examine whether this really works.
Also we can consider the toy model in which f_Q is close to zero.

Condition for dark star formation

$$\langle \sigma v \rangle_{\rm fo} = 3 \times 10^{-26} cm^3/s$$

Three exceptional situations other than p-wave suppression

Griest Seckel 1991

Resonance at freeze out : Breit-Wigner enhancement

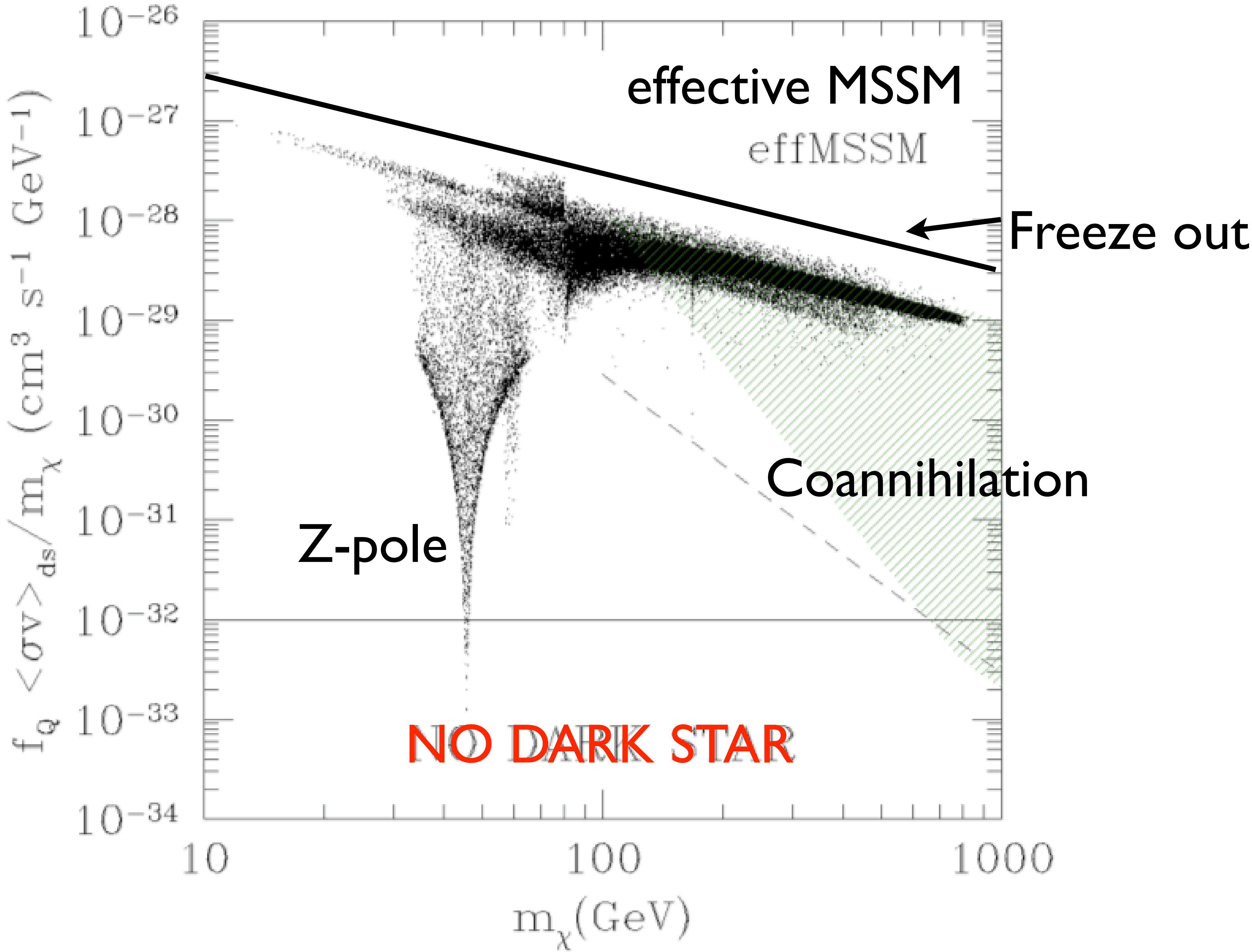
$$2m_\chi < M_Z \qquad 2m_\chi(1+\frac{1}{2}v^2) \simeq M_Z$$

Coannihilation at freeze out

$$\frac{v_{\rm ds}^2}{v_{\rm fo}^2} < \frac{m_{\tilde\tau} - m_\chi}{m_\chi} < 0.05$$

At the threshold

$$\langle \sigma v \rangle_{\rm ds} \ll \langle \sigma v \rangle_{\rm fo}$$


effective MSSM
effMSSM
Freeze out
Coannihilation
Z-pole
NO DARK STAR
$f_Q \langle \sigma v \rangle_{ds} / m_\chi$ (cm^3 s^{-1} GeV^{-1})
m_χ(GeV)
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10
100
1000

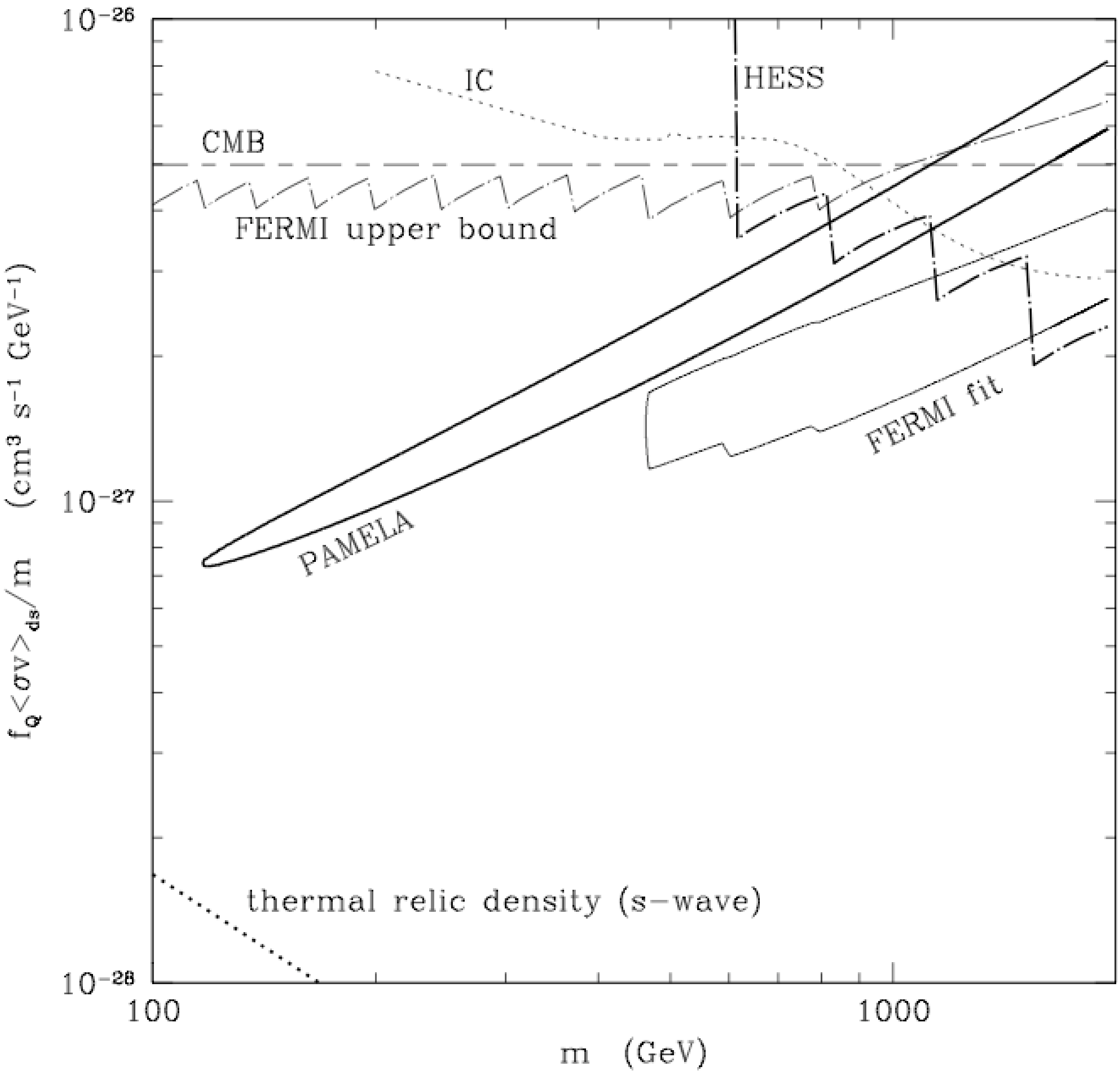
Kaluza-Klein dark matter

The variation according to the velocity is small since there is no p-wave suppression.

Coannihilation with KK gluon can be significantly change the difference between freeze out and dark star cross section.

For the mass range providing the dark matter density (around 5 TeV),
it safely satisfies the condition to form a dark star.

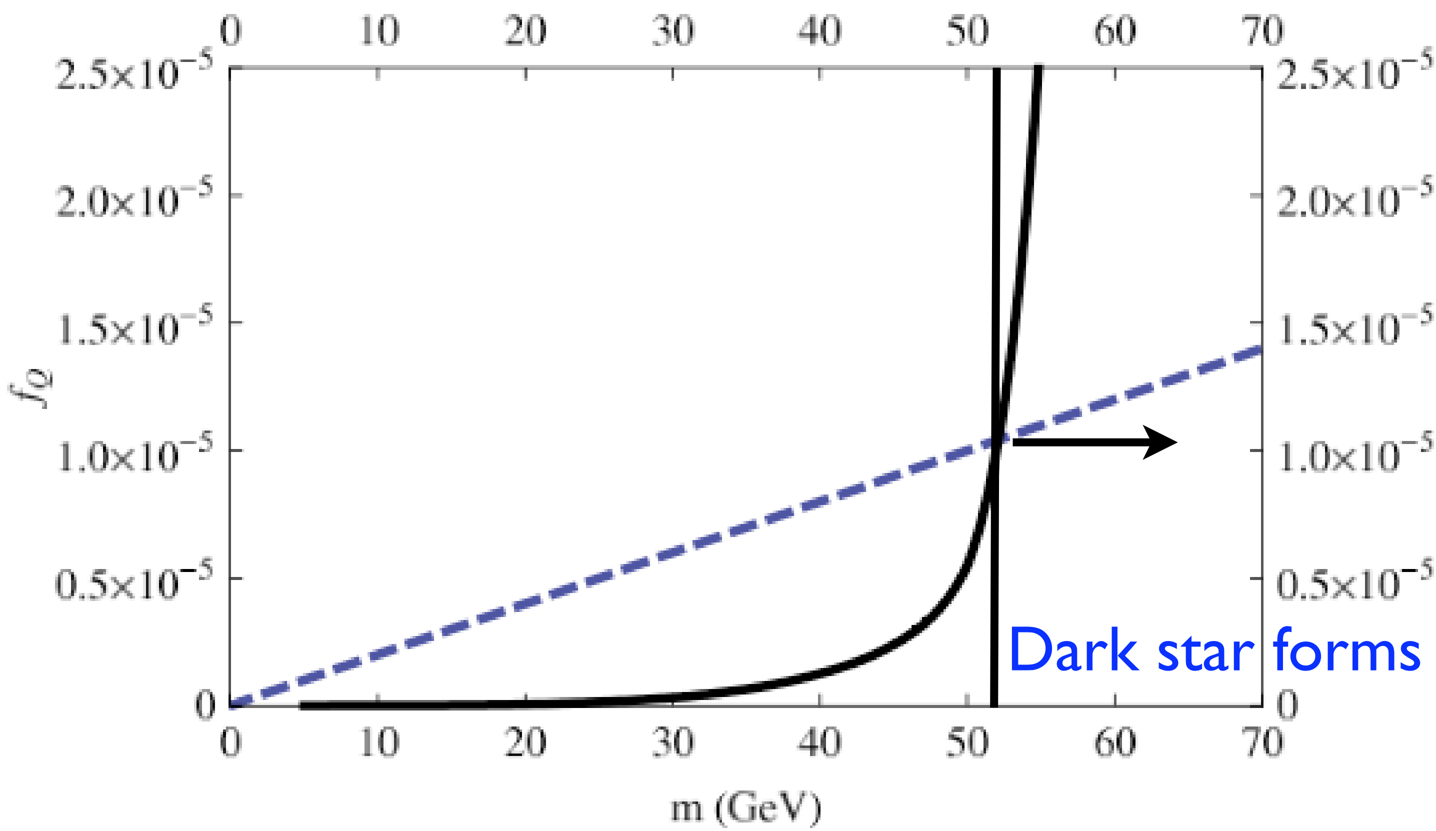
Leptophilic (Pamela) dark matter



Neutrinophilic dark matter

$\chi\chi \to \nu\nu$ $(\nu^* \to \nu Z^* \to \nu ll)$

Electroweak Breamsstrahlung



Conclusion

Dark star phase is a robust prediction of dark matter models which can explain the observed dark matter density in terms of freeze out.

For MSSM neuralino, it works for m < 1 TeV.

For KK DM, it works for m < 5 TeV.

For leptophilic DM, it works safely.

For neutrinophilc DM, it works for m > 50 GeV.

Dark matter forms dark stars.

Backup : Dark Stars

JWST might observe PopIII stars.
If luminous and red, it is a dark star.

Dark star phase can make stars more massive before explosion and can provide a bigger seed for a black hole.
Supermassive black hole can be understood from it.

Nucleosynthesis in the star formation and evolution can be changed compared to the standard scenario.
Even/odd puzzle might be understood from this scenario.