Bubbletrons

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A Big Picture

Higher Energies

Experimental Tests

???

~TeV

THE STANDARD MODEL

How to access higher energies? (*)

(*) before muon collider or FCC-hh

How to access higher energies? (*)

Look at the Sky!

High-Energy Cosmic Rays

Gravitational Waves

The more the merrier

(*) before muon collider or FCC-hh

How to access higher energies? (*)

Look at the Sky!

High-Energy Cosmic Rays

Gravitational Waves

Matter Power Spectrum

Sneaky preview:

Warm EeV Dark Matter from Weak Scale Phase Transition

(*) before muon collider or FCC-hh

Phase Transitions…

…as Particle Accelerators (“Bubbletrons”)

Warm EeV Dark Matter from Weak scale PT

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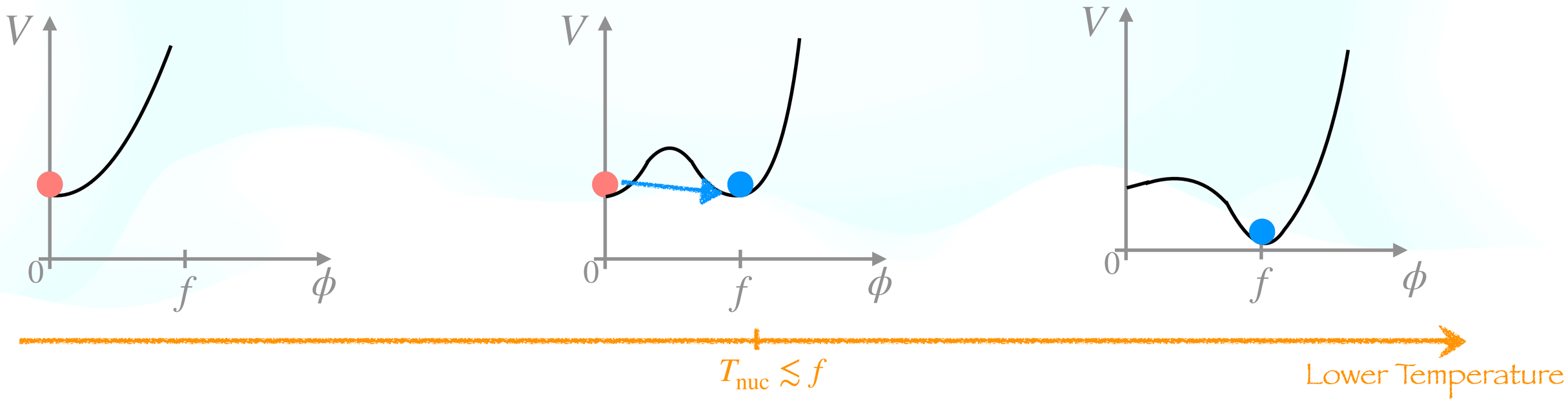
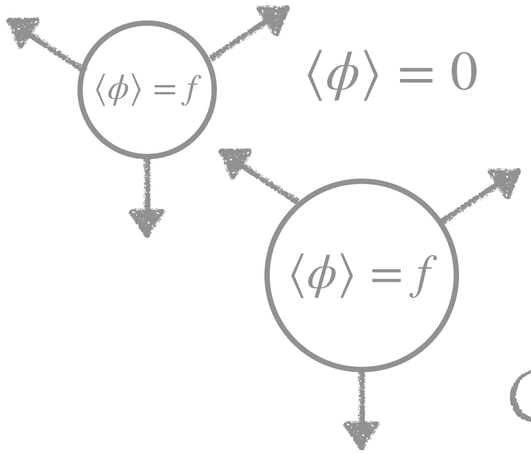
Warm EeV Dark Matter from Weak scale PT

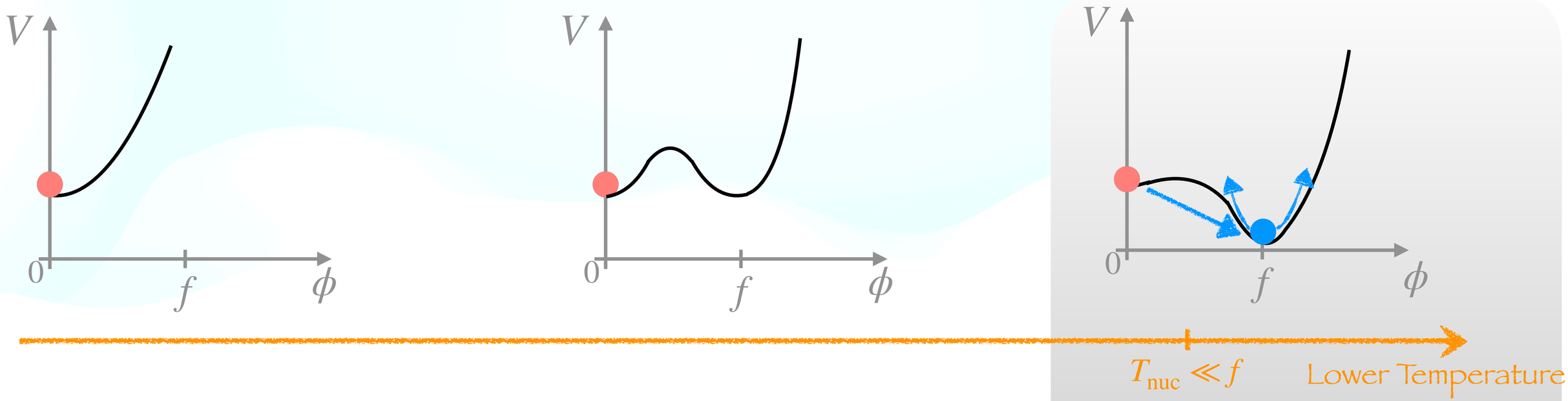
First-order Phase Transitions in Early Universe

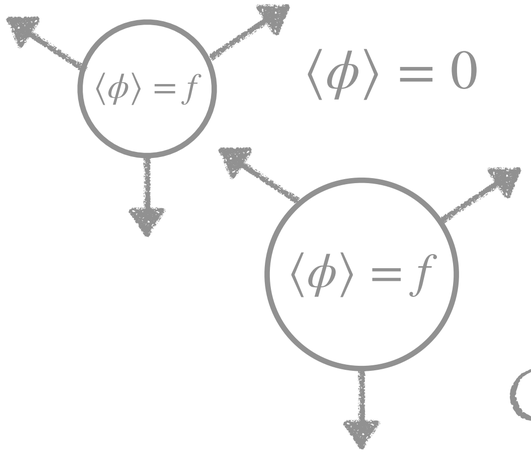




Gravity Waves!

First-order Phase Transitions in Early Universe





IF Phase Transitions here

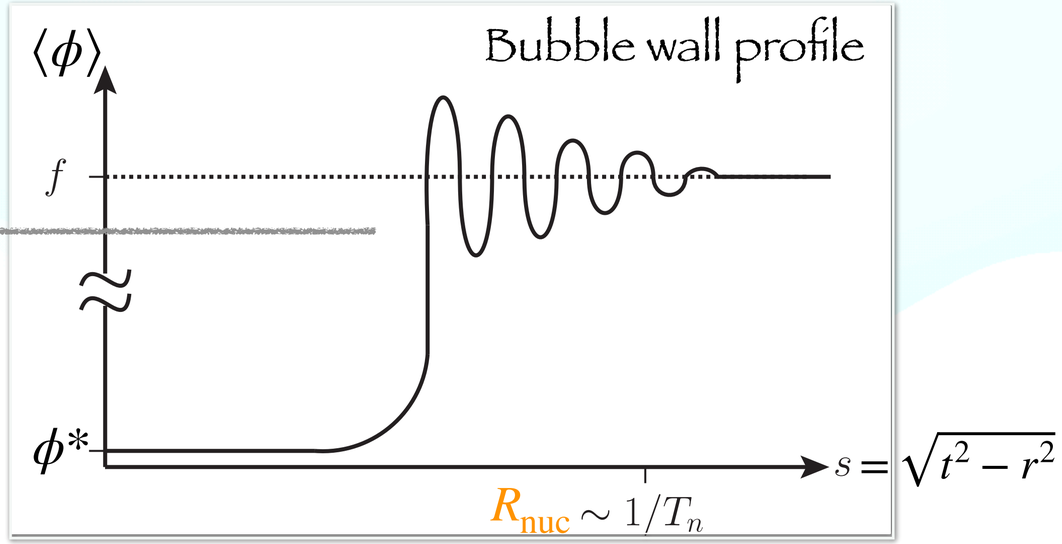
THEN Supercooling

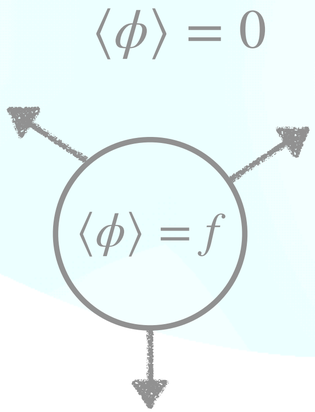
& oscillations reheat universe to

$T_{\rm RH} \lesssim f$

Bubble walls

Wall expands this way
with Lorentz boost γ





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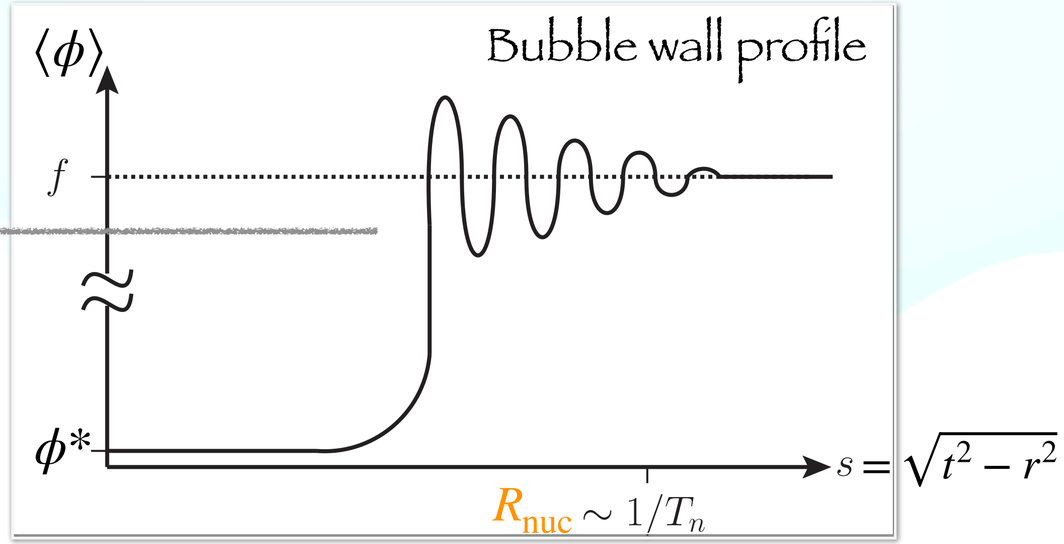
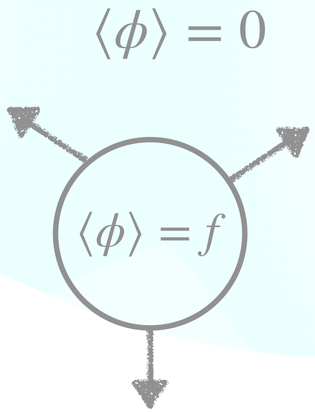


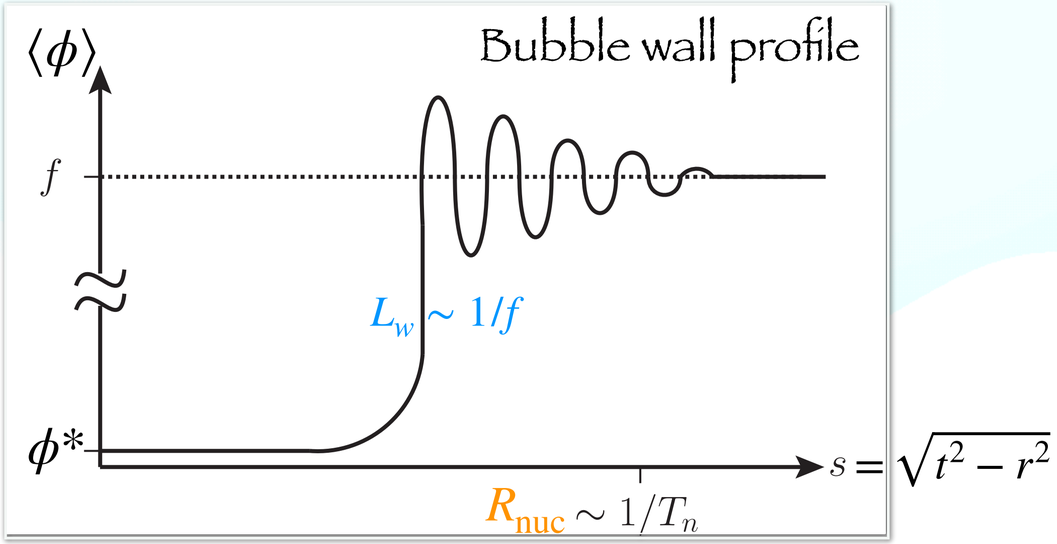


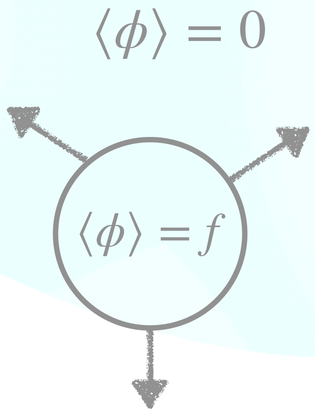
If no pressure then walls run away $\gamma(t) \sim \dfrac{R_{\rm bubble}(t)}{R_{\rm nuc}} \ggg 1$

$E_{\rm bubble} \sim R^3 f^4$

$E_{\rm wall} \sim \gamma R^2 \sigma \qquad \sigma \sim R_{\rm nuc} f^4$

Bubble walls





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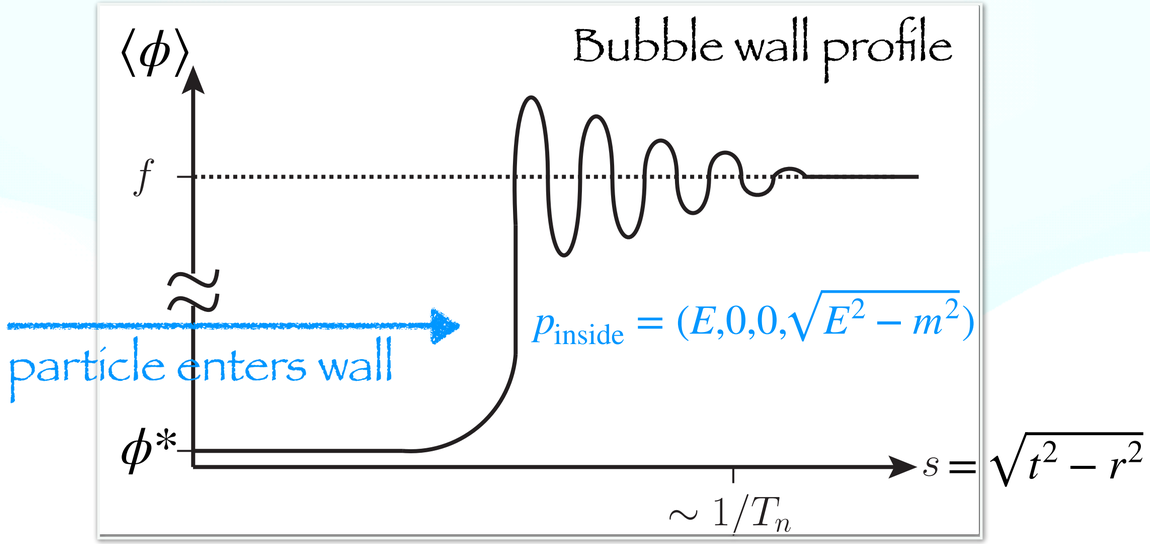
Pressure from plasma effects: Negligible if $T_{\rm nuc}/f < O(1)$

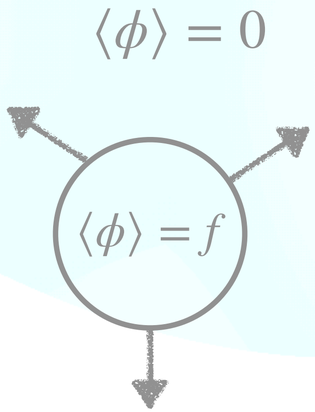
from $\gamma v/L_w \gg \Gamma_{\rm coll} \sim \alpha^2 T$

Bubble walls

$p_{\text{outside}} = (E,0,0,E)$

wall frame : $E \sim \gamma T_{\text{nuc}}$





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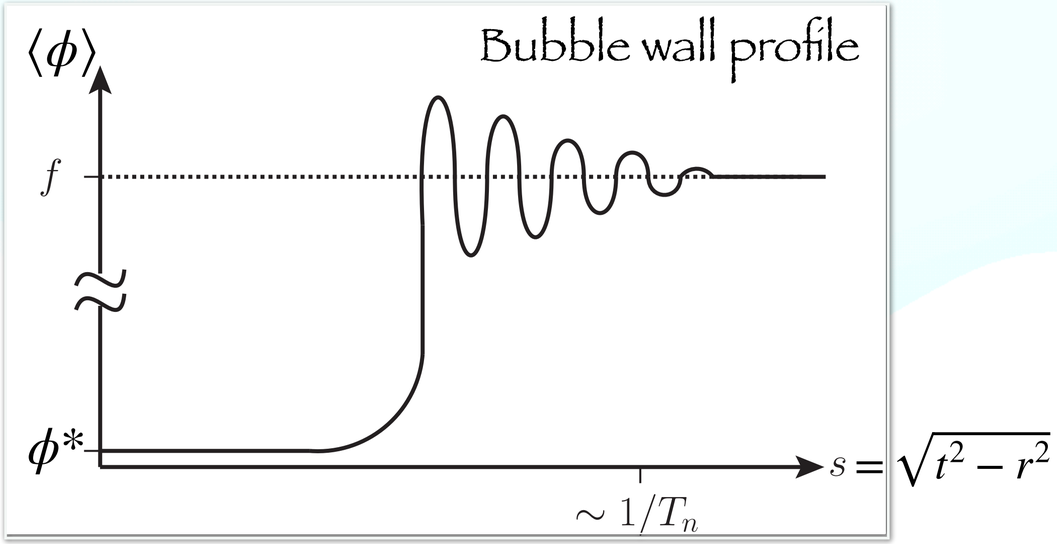
Pressure from single particles: Negligible if $T_{\text{nuc}}/f < O(1)$

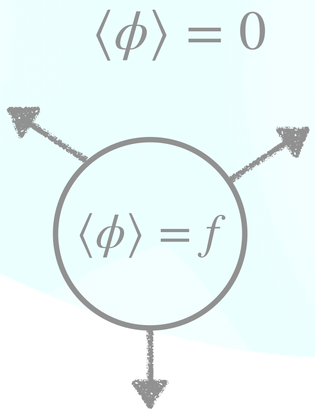
$$P_{\text{particle}} = \int \frac{d^3p}{(2\pi)^3} f(p)\, \Delta p \sim n \frac{m^2}{E} \sim g^2 f^2 T_{\text{nuc}}^2$$

$$P_{\text{bubble}} = -\left(V(\phi = f) - V(\phi = 0)\right) \sim f^4$$

Bodeker Moore 0903.4099

Bubble walls





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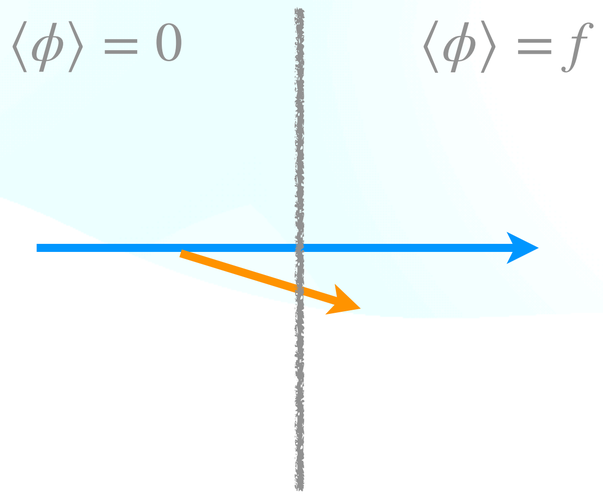
Phase Transitions with fast bubble walls

Incoming particles can emit stuff!

Vector emission IR enhanced

Bodeker Moore 1703.08215

$$P_{\rm NLO} \sim g^3 f T_{\rm nuc}^3 \gamma \xrightarrow[P_{\rm bubble} \sim f^4]{} \text{terminal velocity} \quad \gamma \sim \left(\frac{f}{T_{\rm nuc}}\right)^3$$



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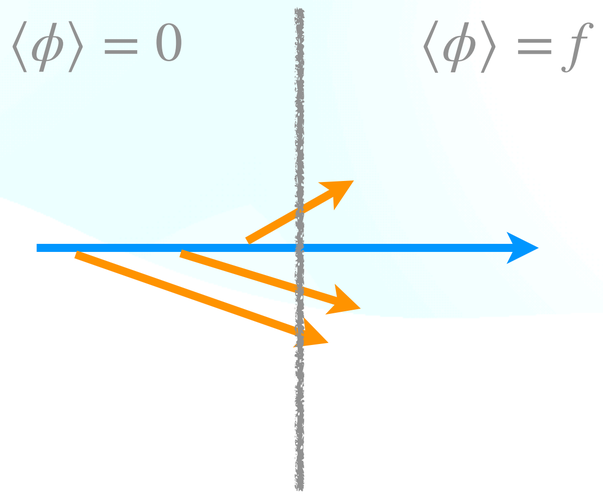
$P_{\rm LL} \simeq g^3 f T_{\rm nuc}^3 \gamma \times \log$ when resummed

Gouttenoire Jinno FS 2112.07686



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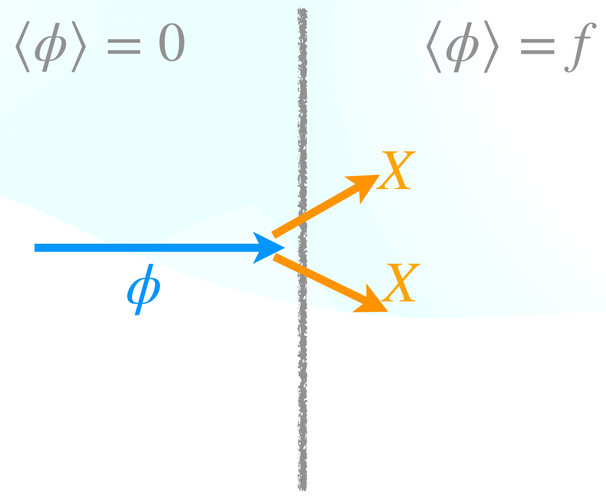

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Pressure from heavy states $M \gg f$ produced if $\gamma T_{\rm nuc} \gg M$

E.g. $\mathscr{L} \supset -\frac{M^2}{2} X^2 - \lambda \phi^2 X^2$ $\quad$ $\text{Prob}(\phi \to XX) \sim \frac{\lambda^2}{16\pi^2} \frac{f^2}{M^2}$

$P_{\rm heavy} \sim n_\phi \, \text{Prob}(\phi \to XX) \frac{M^2}{E} \sim \frac{\lambda}{16\pi^2} \frac{\lambda}{g^2} P_{\rm LO}$

Azatov Vanvlasselaer 2010.02590

Phase Transitions…

…as Particle Accelerators (“Bubbletrons”)

Warm EeV Dark Matter from Weak scale PT

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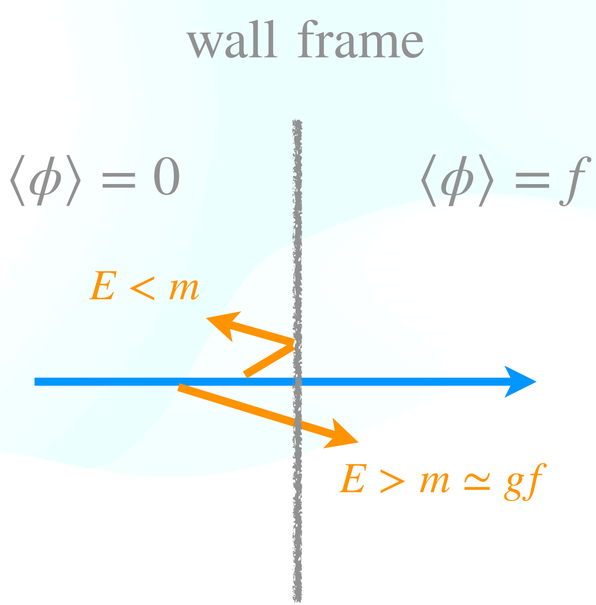
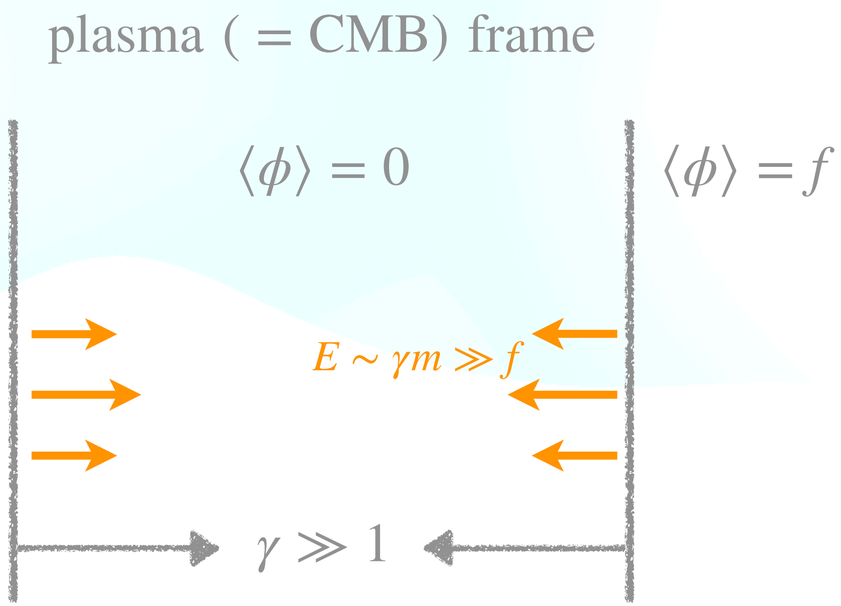
Radiation at the Bubble Walls

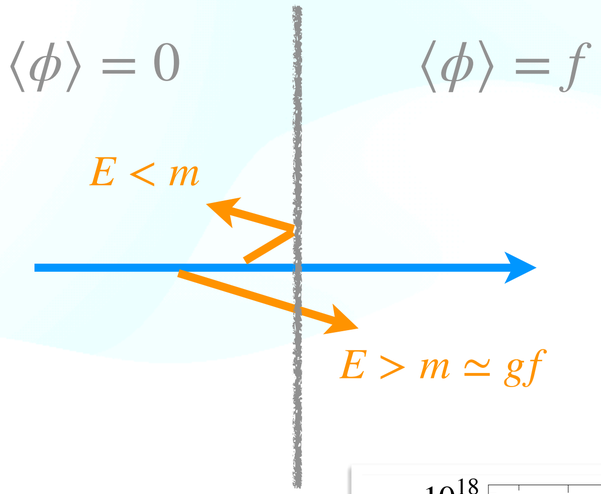


Soft radiation is reflected
fast walls are a particle accelerator!



Radiation at the Bubble Walls

wall frame



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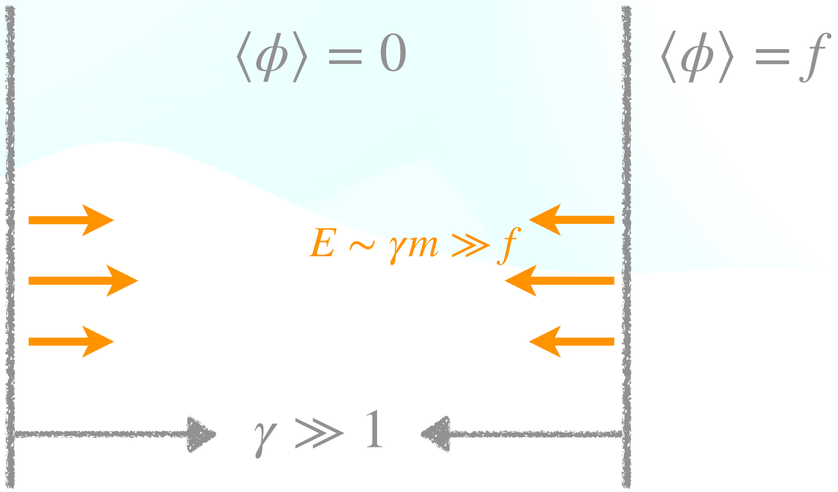
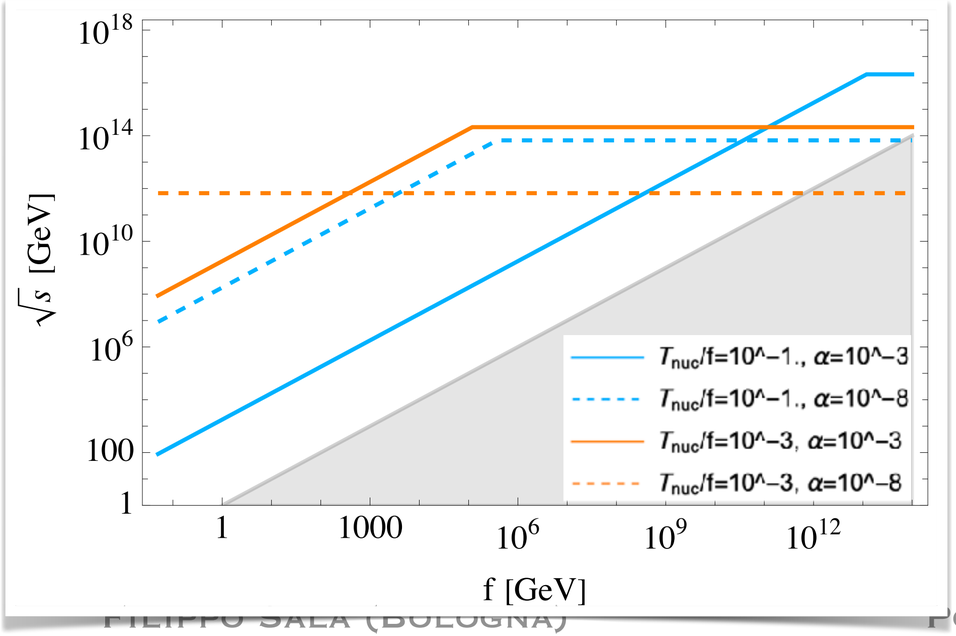
plasma (= CMB) frame



Radiation collide
before walls collide!



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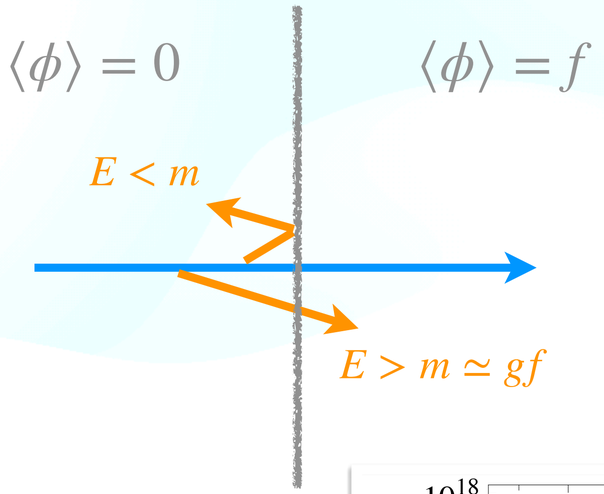

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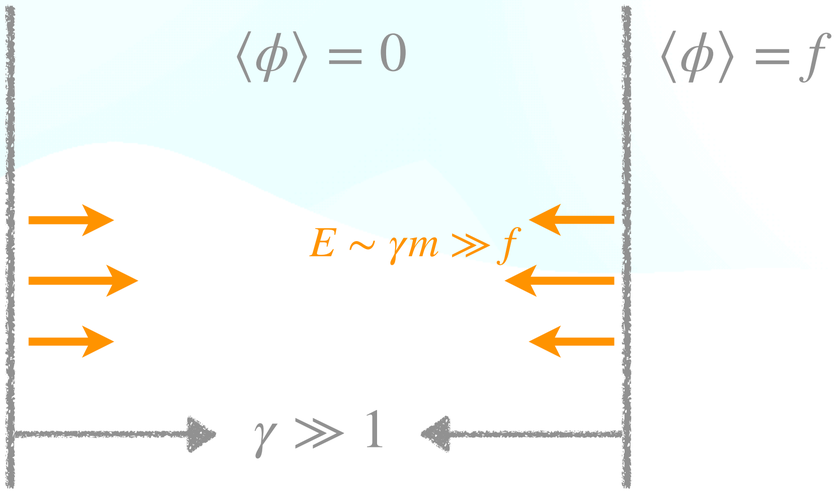

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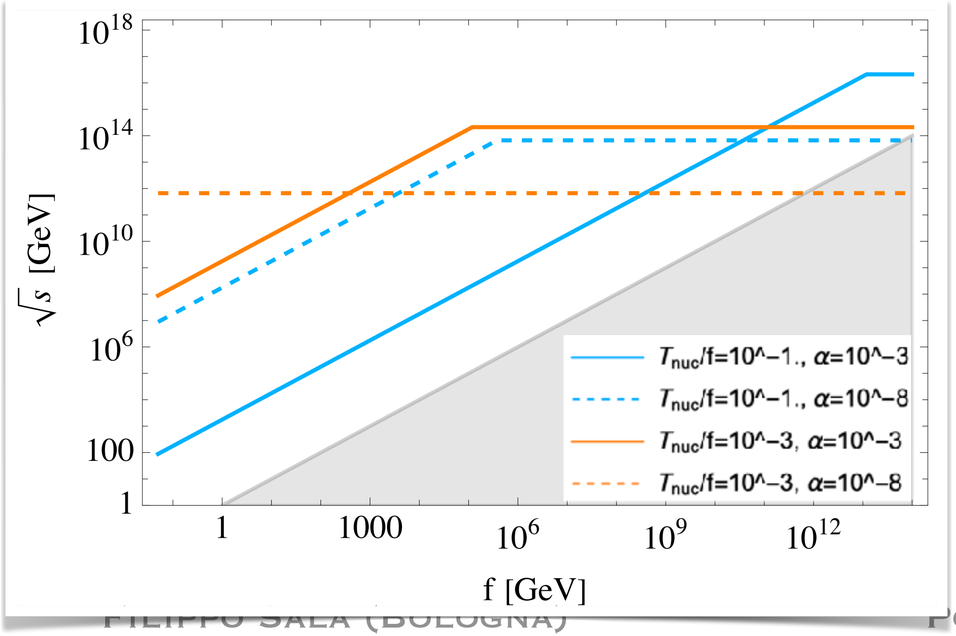
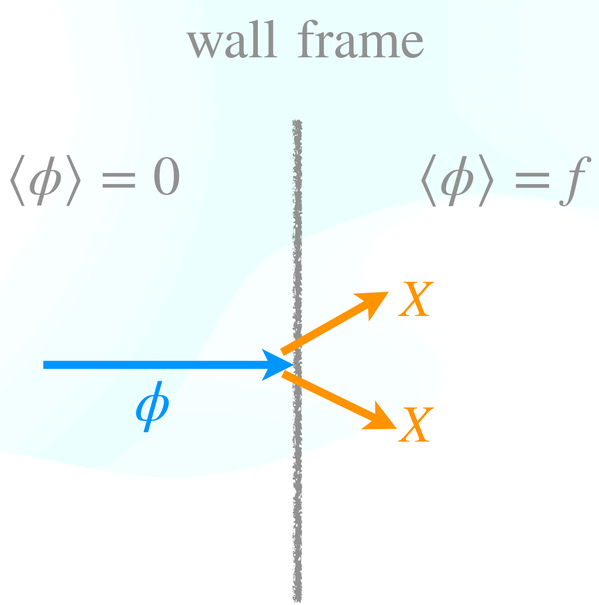


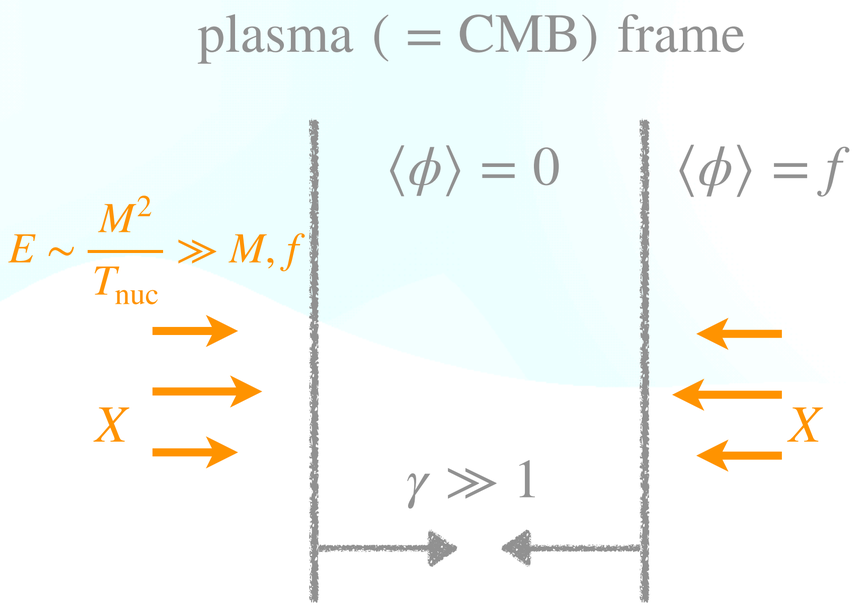
But: ? Shells scatterings with bath particles:
momentum loss: wall catches up,…
number changing: mess

? Shells thermalisation

Heavier Physics



Heavy States follow the walls
If fast, again particle accelerator!



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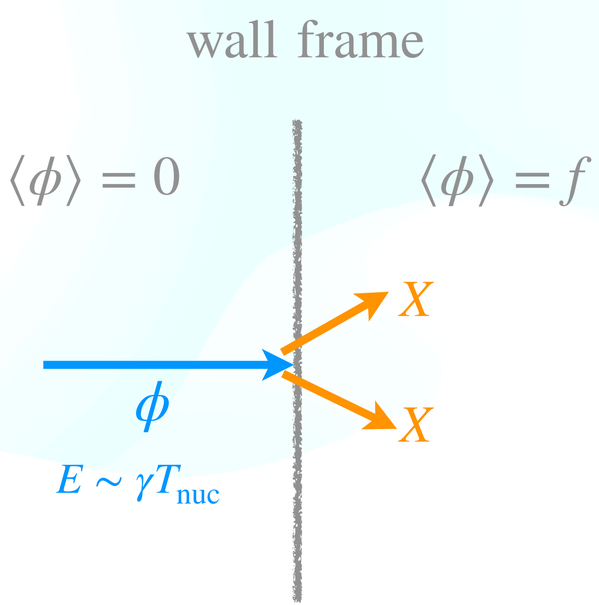

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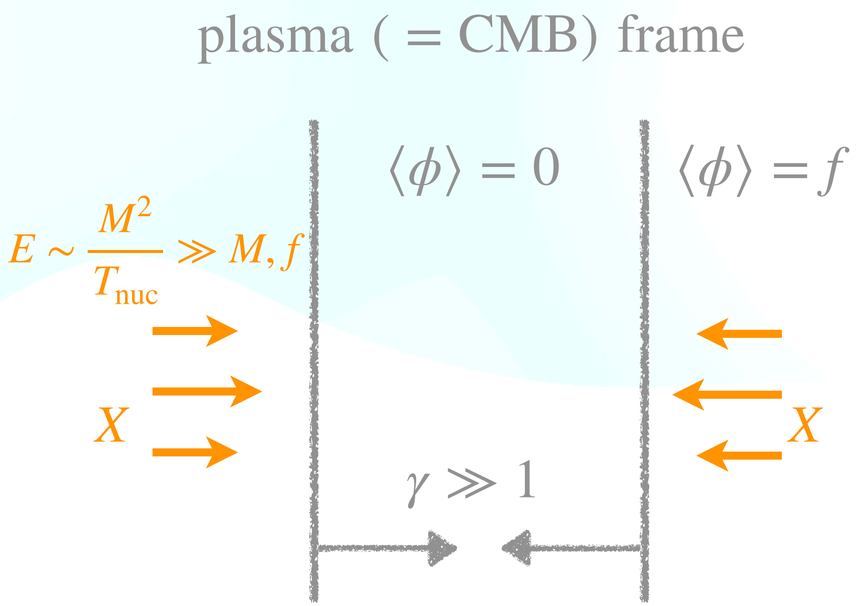


But: ? Shells scatterings with bath particles
Momentum loss: wall catches up,…
Number changing: mess

? Shells thermalisation

? Shells scattering with wall

Bubbletrons (Brand by Yann Gouttenoire)

Accelerated Particles	Gauged PT	Global PT	Shell-wall	…
Radiated vectors	✓			
Radiated scalars	✓	✓		
Heavier states	✓	✓	✓	
Dark hadrons Baldes+ 2007.08440	✓		✓	
Wall collisions Falkowski No 1211.5615	✓	✓		
Wall Decays	✓	✓	✓	

…

Phase Transitions…

…as Particle Accelerators (“Bubbletrons”)

Warm EeV Dark Matter from Weak scale PT

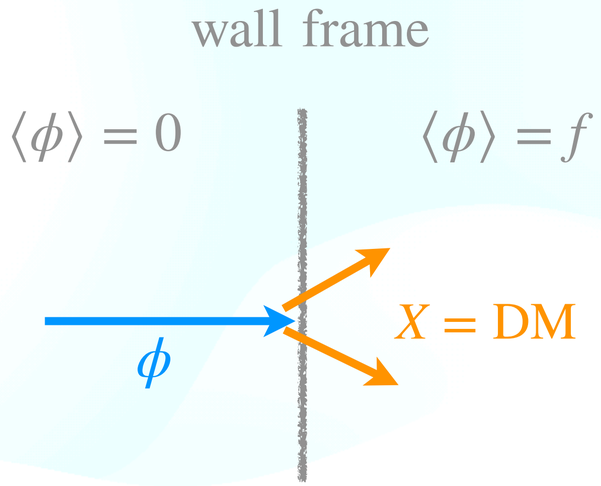
Based on Baldes Gouttenoire FS 2207.05096 (SciPost Phys.)

Phase Transit

...as Particle s ("Bu)

Warm EeV Dark Matter from Weak scale PT

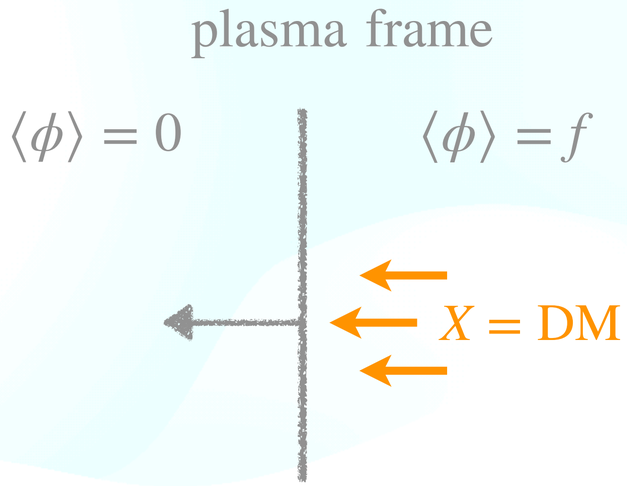
Warm EeV Dark Matter from the Weak Scale



Azatov Vanvlasselaer Yin 2101.05721

$$n_X \sim n_\phi \, \mathrm{Prob}(\phi \to XX)$$

Warm EeV Dark Matter from the Weak Scale



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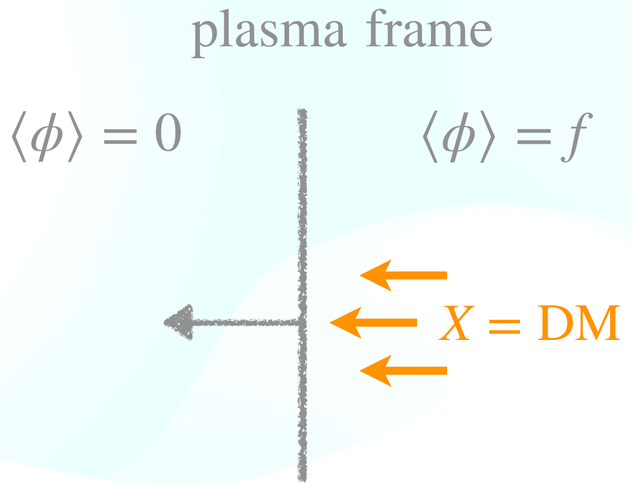
$$p_X(T \sim f) \simeq \frac{M^2}{T_{\rm nuc}} \xrightarrow{\text{redshift}} p_X(T \sim T_{\rm eq}) \simeq \frac{T_{\rm eq}}{f}\frac{M^2}{T_{\rm nuc}}$$

$$v_X(T \simeq T_{\rm eq} \simeq 0.8\mathrm{eV}) \simeq 10^{-4}\frac{f}{T_{\rm nuc}}\left(\frac{100\ \mathrm{GeV}}{f}\right)^2 \frac{M}{10^9\ \mathrm{GeV}}$$

Warm EeV Dark Matter from the Weak Scale



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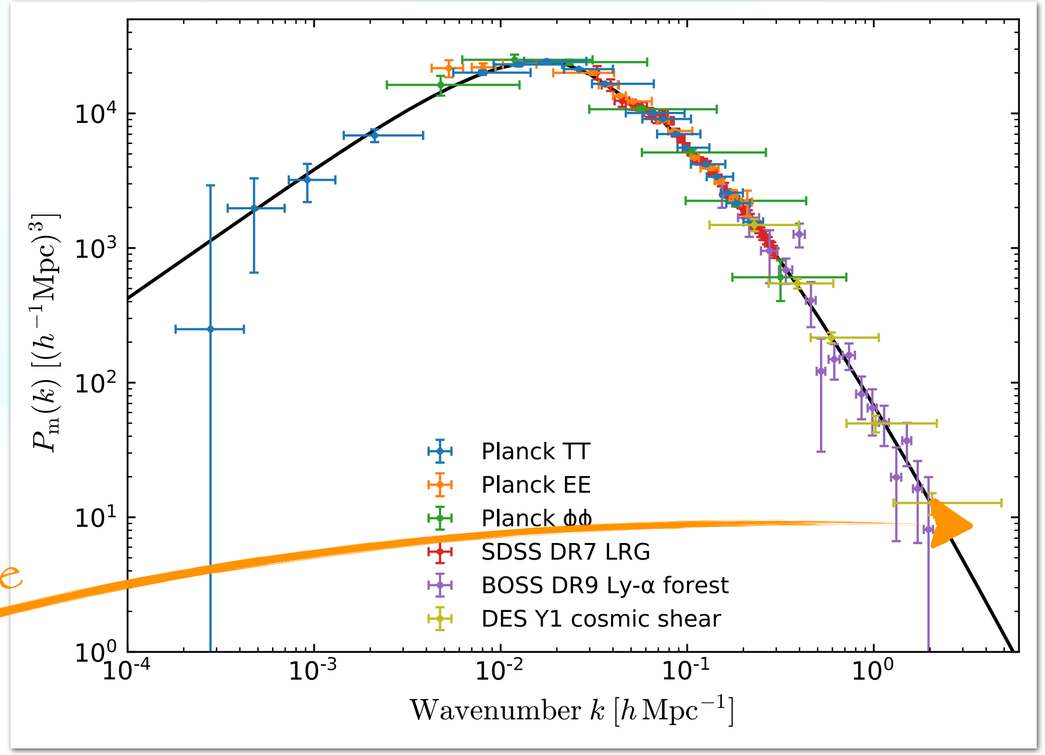

deviations here

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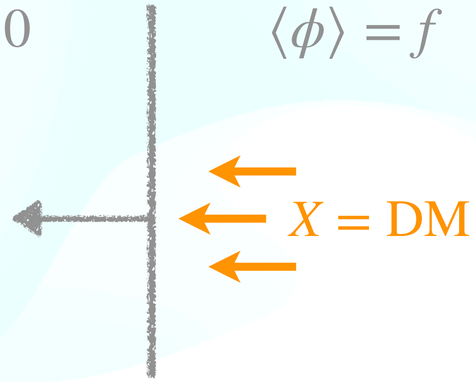
Warm EeV Dark Matter from the Weak Scale

plasma frame

$\langle\phi\rangle = 0$ $\langle\phi\rangle = f$



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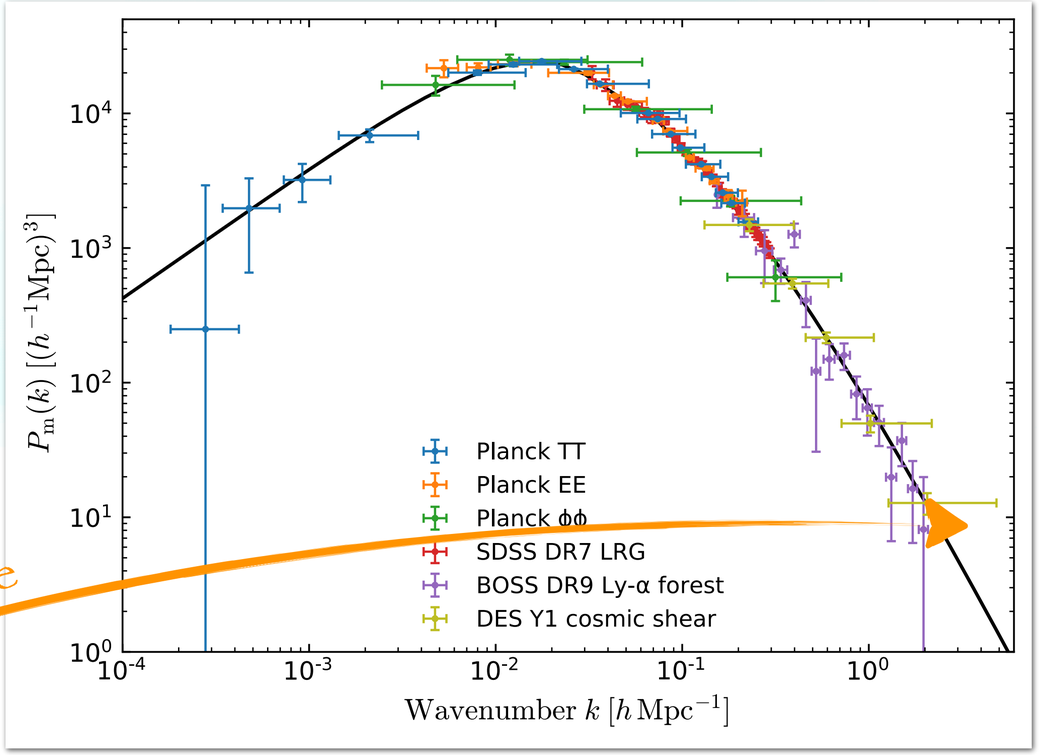

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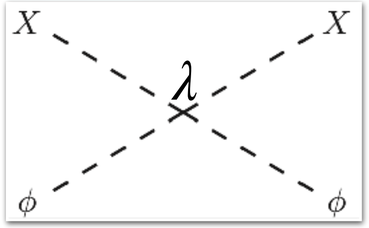
X scatterings with bath



$$\frac{1}{p_X}\frac{dp_X}{dt} < H \;\Rightarrow\; \lambda \lesssim \frac{10^9\ \mathrm{GeV}}{M}\left(\frac{f}{T_{\rm nuc}}\right)^{\frac{1}{4}}\left(\frac{\mathrm{TeV}}{f}\right)^{\frac{1}{2}}$$

Warm EeV Dark Matter from the Weak Scale

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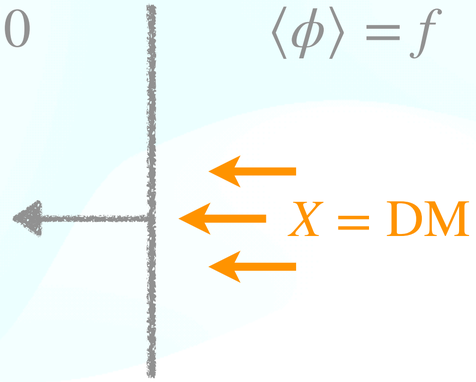

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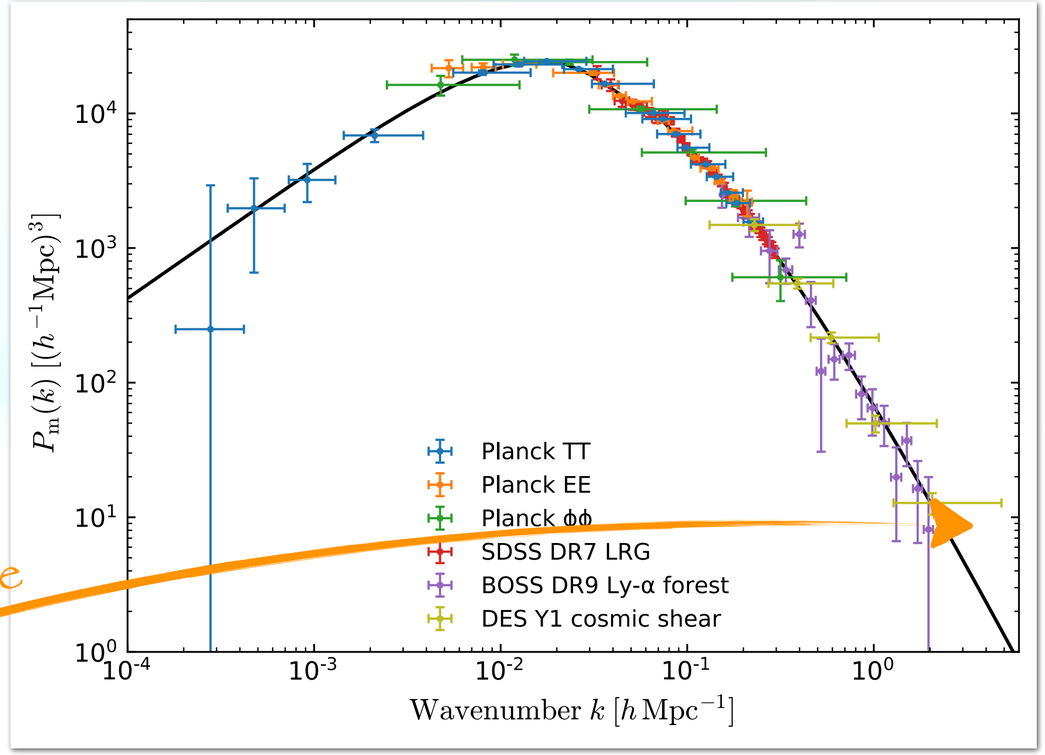

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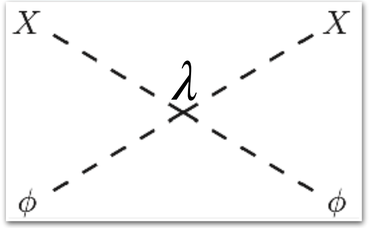

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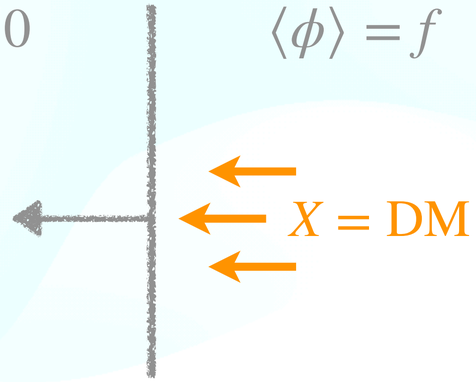

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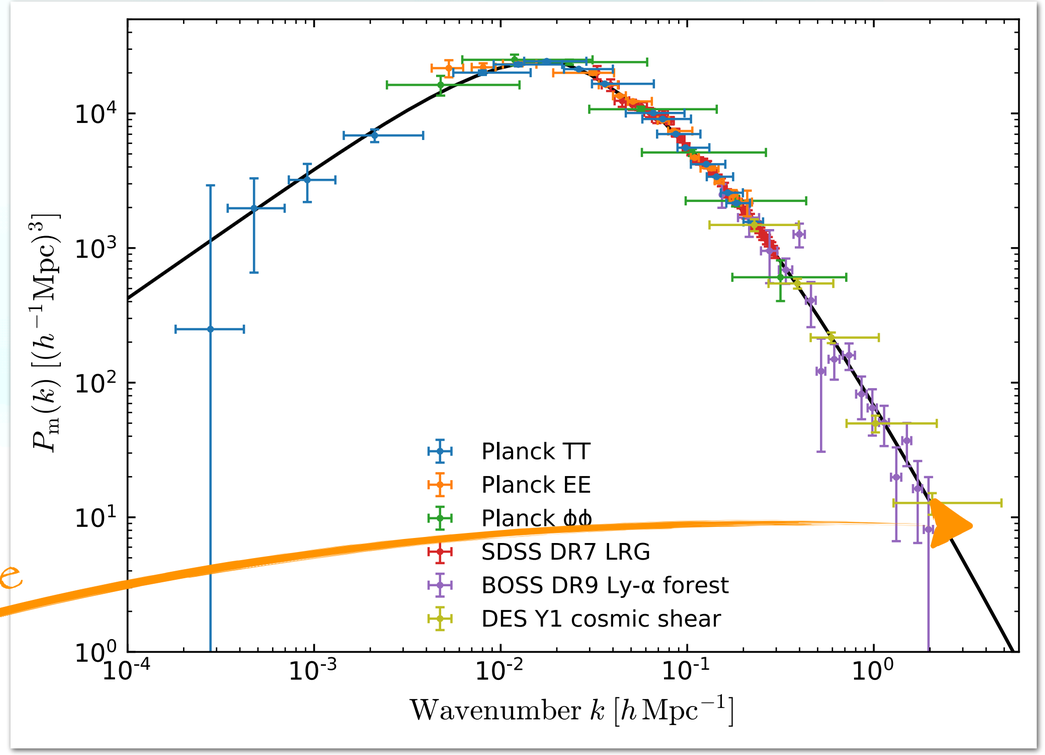
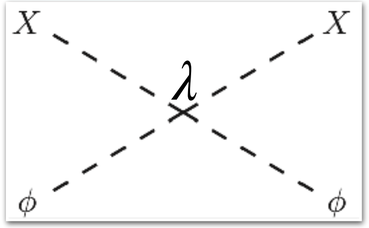


deviations here

$$p_X(T \sim f) \simeq \frac{M^2}{T_{\rm nuc}} \xrightarrow{\text{redshift}} p_X(T \sim T_{\rm eq}) \simeq \frac{T_{\rm eq}}{f}\frac{M^2}{T_{\rm nuc}}$$

$$v_X(T \simeq T_{\rm eq} \simeq 0.8\,\mathrm{eV}) \simeq 10^{-4}\,\frac{f}{T_{\rm nuc}}\left(\frac{100\ \mathrm{GeV}}{f}\right)^2 \frac{M}{10^9\ \mathrm{GeV}}$$

X scatterings with bath

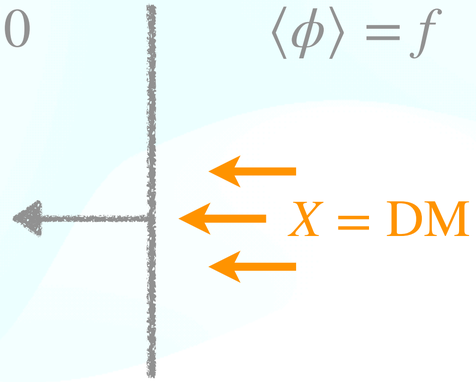


$$\frac{1}{p_X}\frac{dp_X}{dt} < H \;\Rightarrow\; \lambda \lesssim \frac{10^9\ \mathrm{GeV}}{M}\left(\frac{f}{T_{\rm nuc}}\right)^{\frac{1}{4}}\left(\frac{\mathrm{TeV}}{f}\right)^{\frac{1}{2}}$$

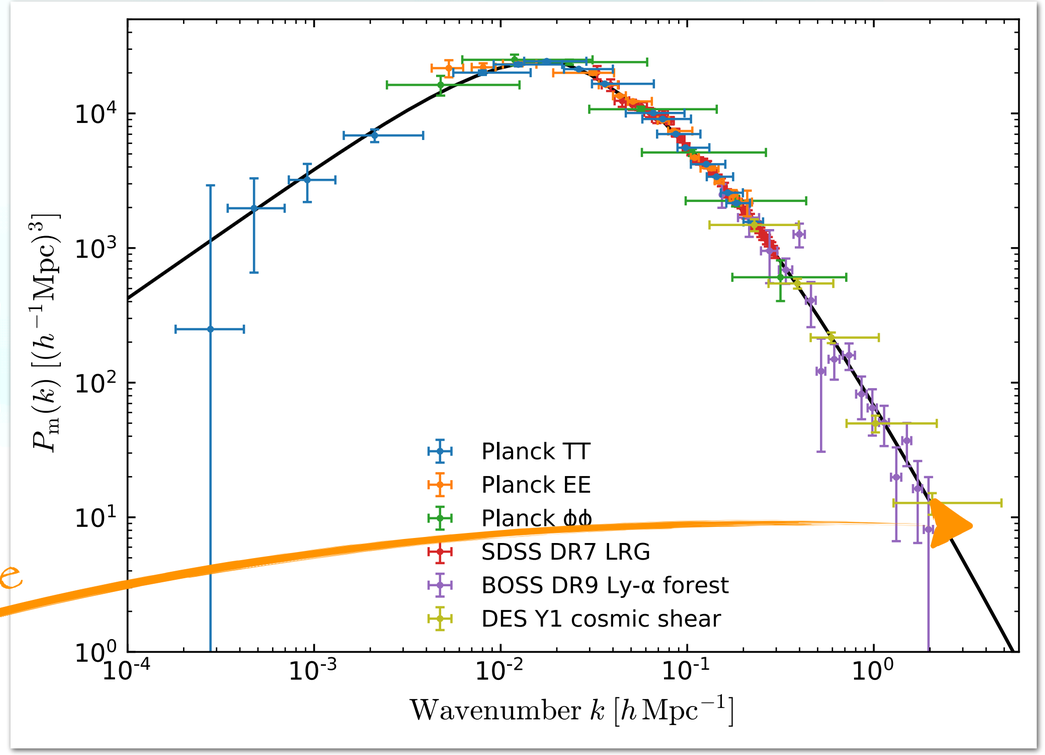
Warm EeV Dark Matter from the Weak Scale

plasma frame

$\langle\phi\rangle = 0$ $\langle\phi\rangle = f$



$$n_X \sim n_\phi \,\mathrm{Prob}(\phi \to XX) \propto \lambda^2$$



deviations here

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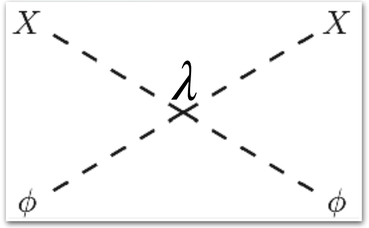
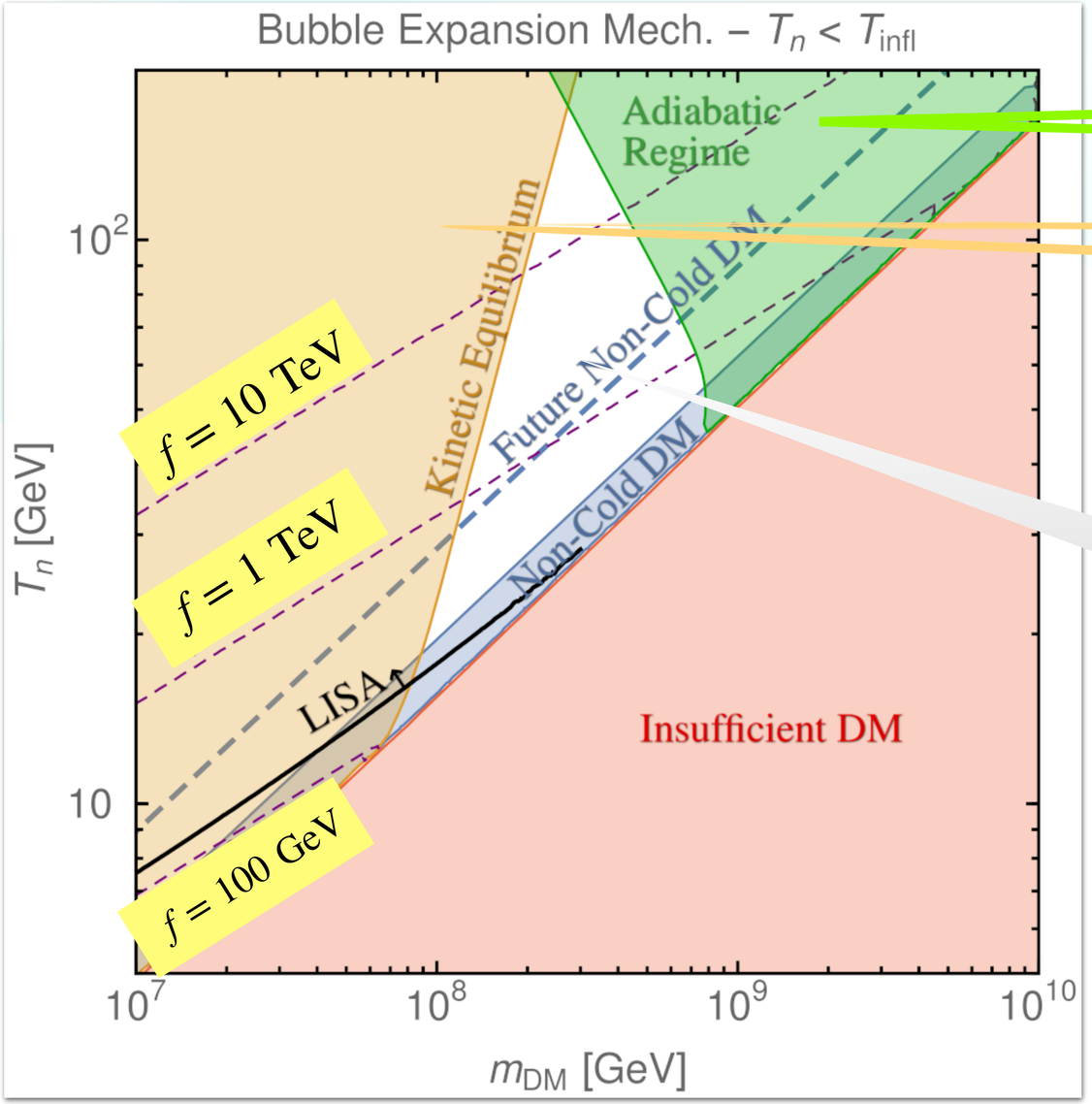
X scatterings with bath



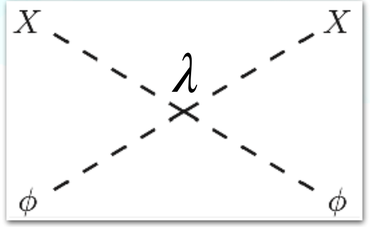
$$\frac{1}{p_X}\frac{dp_X}{dt} < H \;\Rightarrow\; \lambda \lesssim \frac{10^9\ \mathrm{GeV}}{M}\left(\frac{f}{T_{\rm nuc}}\right)^{\frac{1}{4}}\left(\frac{\mathrm{TeV}}{f}\right)^{\frac{1}{2}}$$

Warm EeV Dark Matter from the Weak Scale



Not discussed here

X's scatter with bath



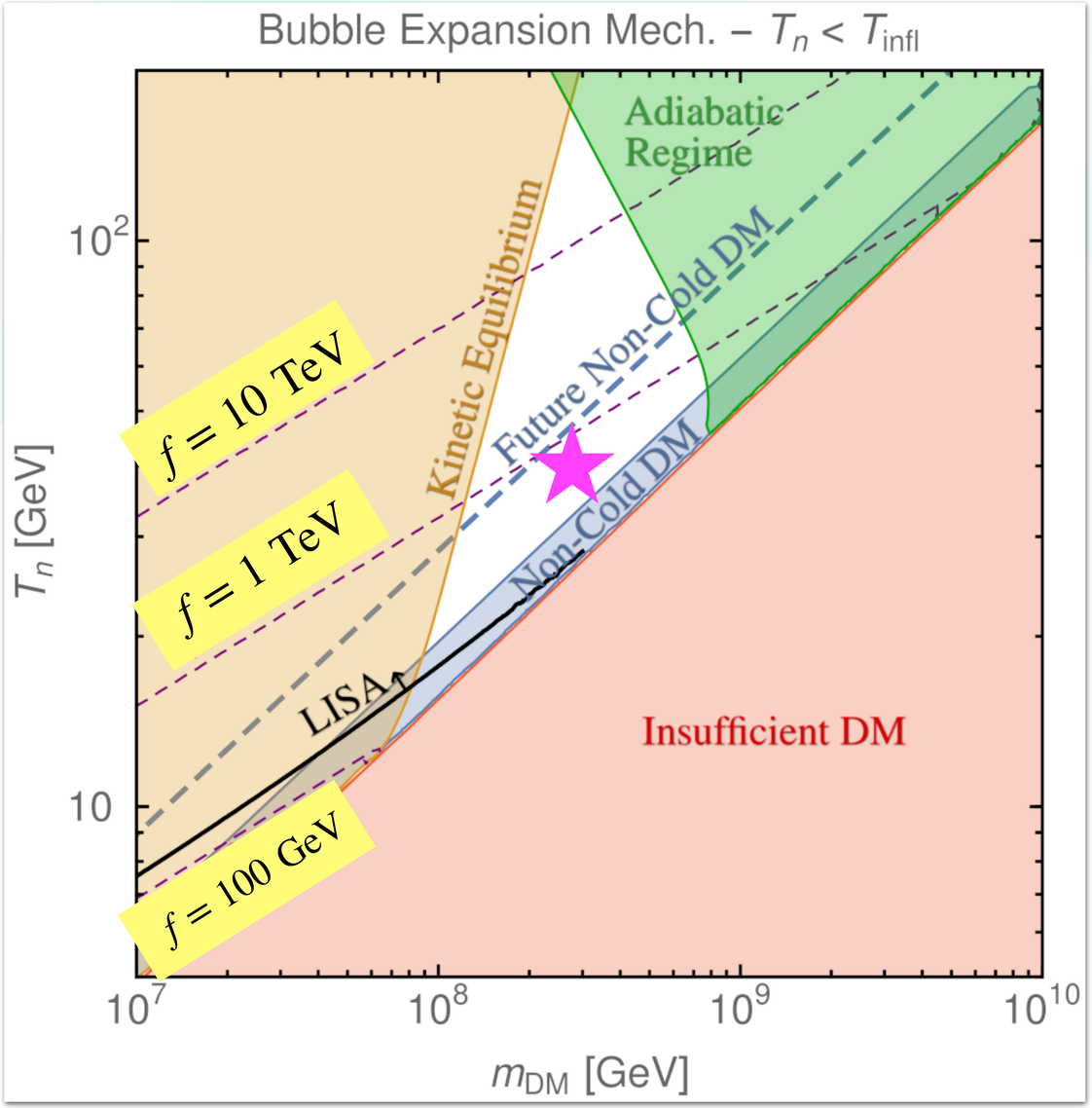
White space is viable!

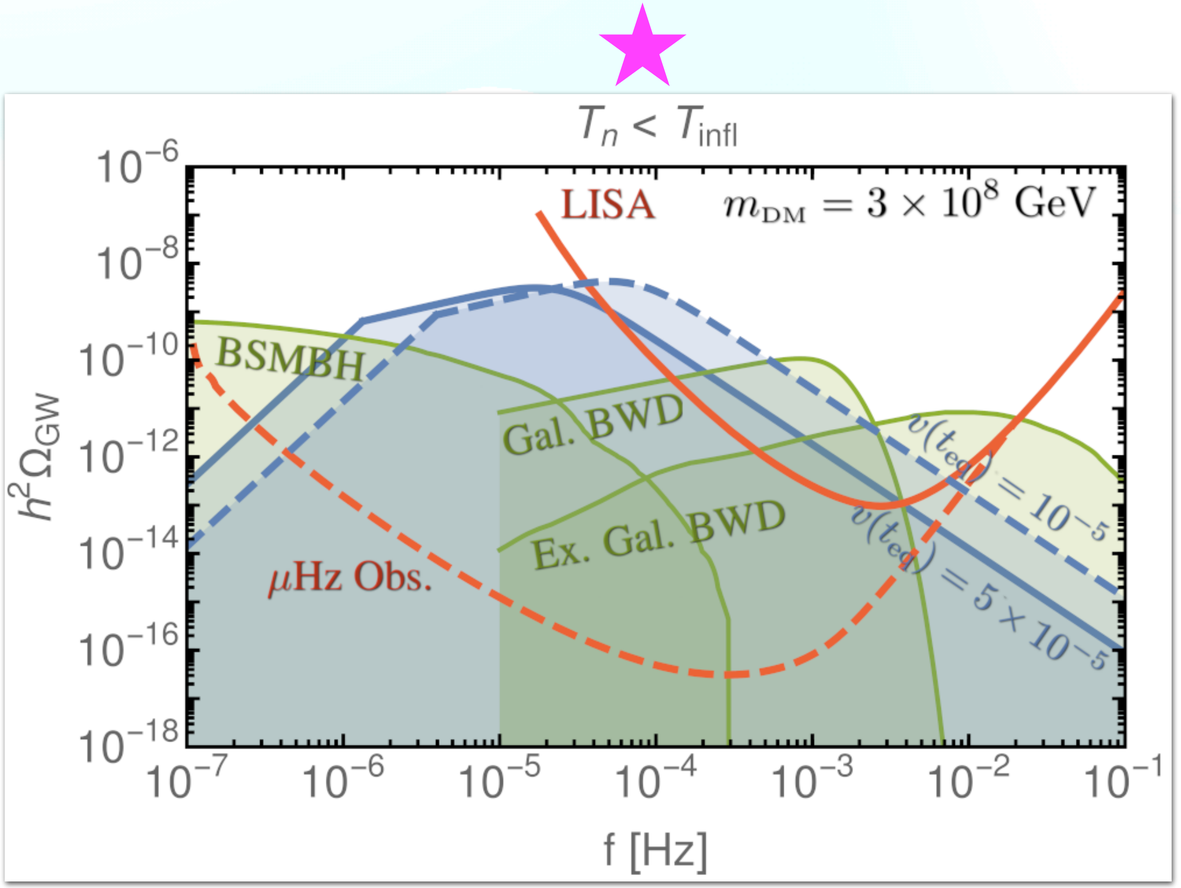
Testable with: matter power spectrum

gravity waves

cosmic rays (if DM decays)

Warm EeV Dark Matter from the Weak Scale

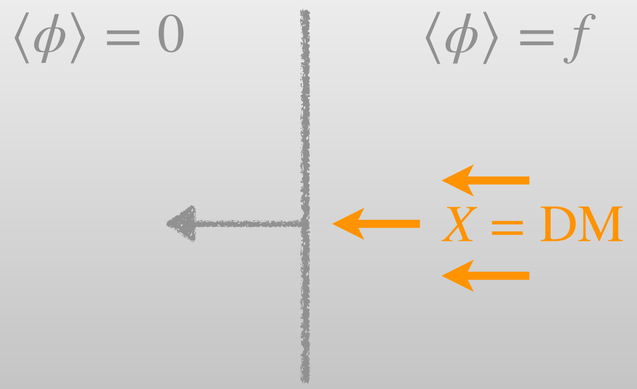


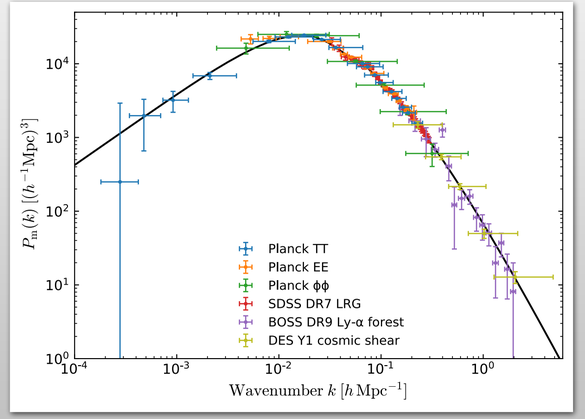


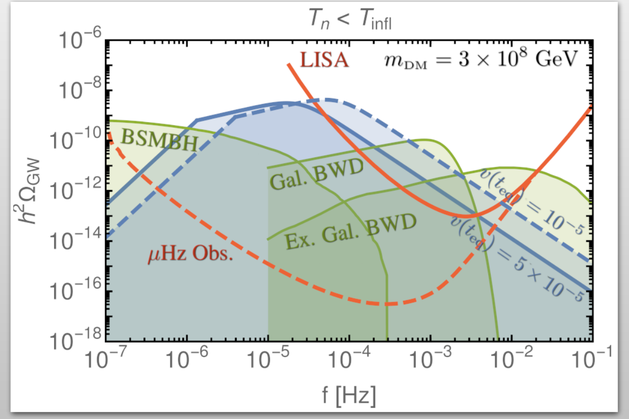
Bubbletrons: Phase transitions with fast bubble walls are particle accelerators

Application: Warm EeV Dark Matter from Weak Scale Phase Transition

Baldes Gouttenoire FS
2207.05096







Still a lot to explore!

E.g. DM beyond GUT scale from PT at much lower scale

Baldes Gouttenoire FS + M. Dichtl in progress

Back up

Gravitational Waves from Phase Transition

Randall Servant hep-ph/0607158,…

$$\Omega_{\rm GW} \propto \left(H/\beta\right)^2 \qquad \beta^{-1} \sim \text{duration of PT}$$

$$\frac{\beta}{H} \simeq T\frac{dS_4}{dT}\bigg|_{T_{\rm nuc}} \simeq 15\left(\frac{10}{N_{\rm e-fold}}\right)^2$$

Standard 1st order PT

$\beta/H \sim 100$

Supercooled PT

$\beta/H \sim 10$