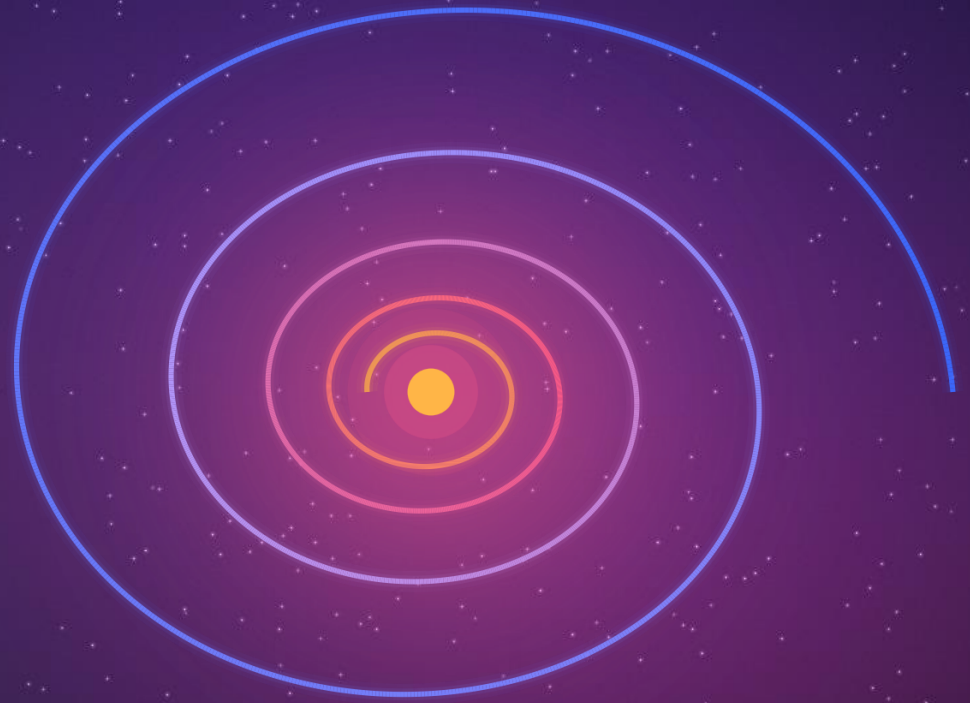
PARIS-SACLAY ASTROPARTICLE SYMPOSIUM 2026

Thermal Damping of Scalar Fields

How a thermal bath tames overclosure, and erases isocurvature



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Dark matter: we know how much, not what



● 27% dark matter ● 5% baryons ● 68% dark energy

≈ 5× more than ordinary matter

$\Omega_c h^2 \approx 0.12$ (Planck 2018): only interacts gravitationally

Cold and collisionless

Slow enough to cluster on small scales

Adiabatic

Its fluctuations track the photons: **isocurvature ≲ a few %**

THIS TALK: a displaced light scalar

CANDIDATE MASSES SPAN ~50 ORDERS OF MAGNITUDE

ultralight bosons: wave-like | **particles: sterile ν, WIMPs…** | **heavy and super-heavy relics**

10^{-22} eV · 10^{-12} eV · μeV · eV · keV · GeV · TeV · 10^{10} GeV · M_{Pl}

Light scalars and the CMB: it’s complicated

Planck

online · staring at the CMB since 2009

Hi Planck! Can I be all of the dark matter?

Sure, as long as your perturbations are adiabatic.

Hmm. I was a light spectator during inflation…

Then $\delta\chi \approx H_{inf}/2\pi$. That’s isocurvature. $\beta_{iso} < 0.04$.

Fine, I’ll start hugely displaced: $X_i \gg H_{inf}$!

…and overclose the Universe? Next.

What if I had friends in the thermal bath?

SCORECARD

ISOCURVATURE

$\delta\chi \sim H_{inf}/2\pi$, uncorrelated with the curvature perturbation ζ

OVERCLOSURE

Huge $X_i \Rightarrow$ far too much dark matter

PLOT TWIST?

Talking to the plasma changes the story

Light spectators fluctuate. Planck notices.

Light scalars face the same problem

ROAD A

Sit at the minimum



$$\langle \chi^2 \rangle \simeq \frac{3H_{\rm inf}^4}{8\pi^2 m_\chi^2}$$

Stochastic equilibrium: χ is pure fluctuation, so δχ/χ ~ 1 and isocurvature is O(1).

Only safe if heavy: $m_\chi \gtrsim H_{inf}$

ROAD B

THIS TALK

Start displaced

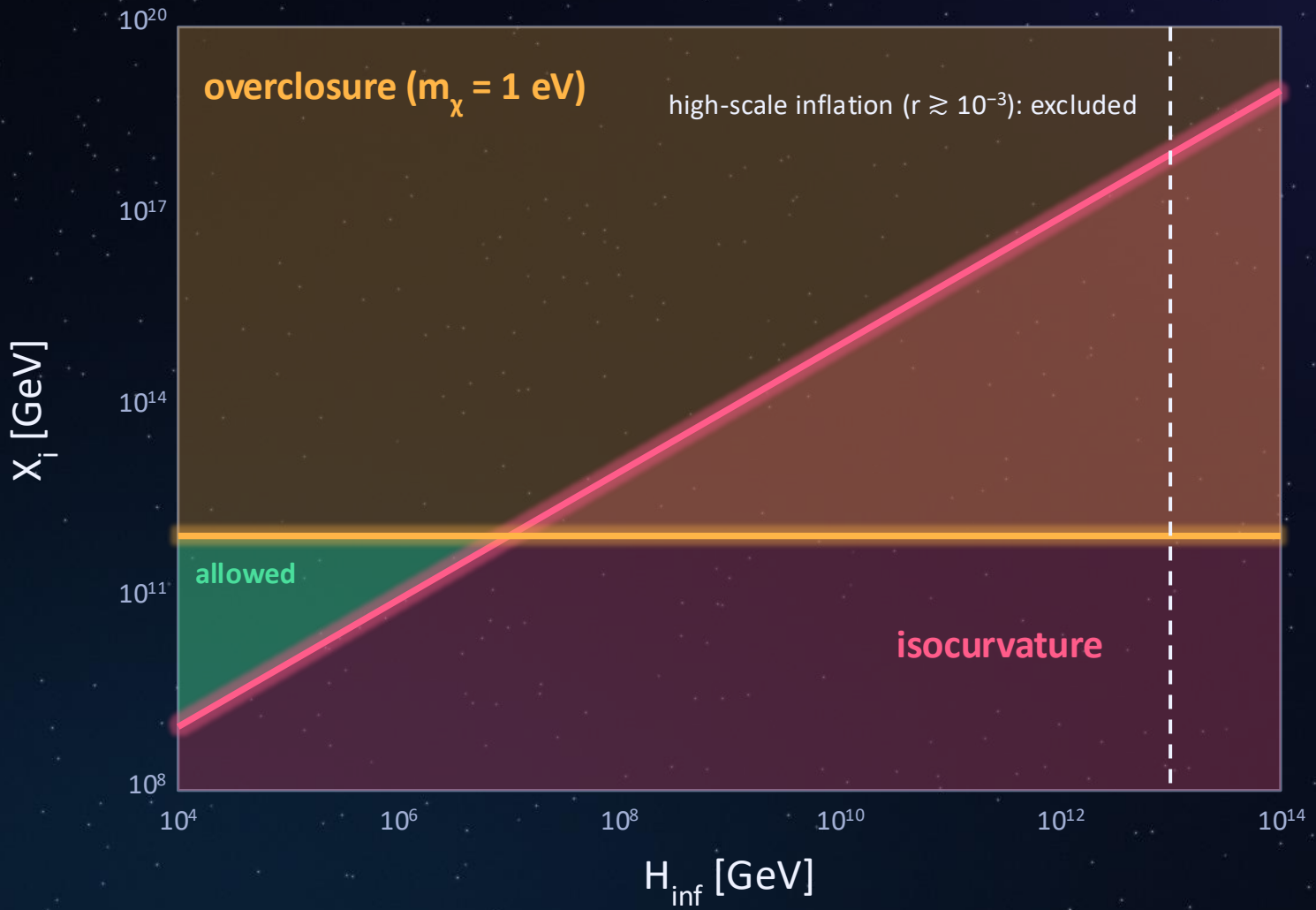


$$S_\chi \simeq \frac{\partial \ln \Omega_\chi}{\partial \ln X_i} \frac{H_{\rm inf}}{2\pi X_i}$$

Isocurvature is suppressed by H_{inf}/X_i: just make X_i huge…

…but huge X_i ⇒ overclosure

The squeeze: isocurvature vs. overclosure



ISOCURVATURE (PLANCK)

$$X_i \gtrsim 10^{12}\,\mathrm{GeV}\left(\frac{H_{\rm inf}}{10^7\,\mathrm{GeV}}\right)$$

OVERCLOSURE (NO DAMPING)

$$X_i \lesssim 10^{12}\,\mathrm{GeV}\left(\frac{m_\chi}{\mathrm{eV}}\right)^{-1/4}$$

No room at all if

$$H_{\rm inf} \gtrsim 10^7\,\mathrm{GeV}\,(m_\chi/\mathrm{eV})^{-1/4}$$

Same ~10^7 GeV ceiling as the axion.

Both bounds assume χ evolves in isolation. What if it talks to the plasma?

Plot twist: let the scalar talk to the plasma

$$\mathcal{L} \supset -V_{\text{vac}}(\chi) - (m_\psi - g\chi)\,\bar{\psi}\psi + \mathcal{L}_{\psi\leftrightarrow\text{SM}}$$



χ condensate
displaced, then oscillating: X cos θ

ψ: thermal fermion
its mass is modulated: $M_\psi = |m_\psi - g\chi|$

SM plasma
temperature T, keeps ψ in equilibrium

Thermal mass
equilibrium · $c_m = 1/\sqrt{6}$ (Dirac ψ)

$$m_{\chi,\text{th}} = c_m\, g\, T$$

Shifted minimum
equilibrium · $M_\chi^2 = m_\chi^2 + m_{\chi,\text{th}}^2$

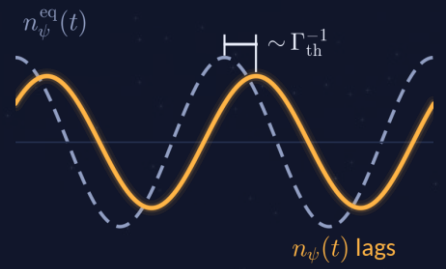
$$\chi_{\text{th}} = \frac{m_{\chi,\text{th}}^2}{M_\chi^2}\,\frac{m_\psi}{g}$$

Thermal damping
out of equilibrium (next slide)

$$-\,\Upsilon\,\dot{\chi}$$ ← the bath lags behind χ

A lagging bath is a frictional bath

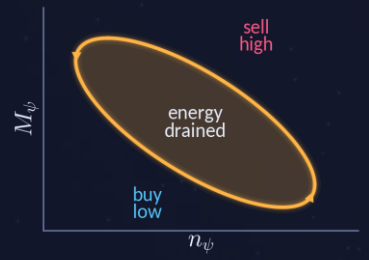
1 · The bath lags



ψ chases a moving equilibrium, ~1/Γ_{th} behind

χ drags M_ψ, and with it n_ψ^{eq}, up and down. ψ relaxes only at rate Γ_{th}, so n_ψ always trails behind.

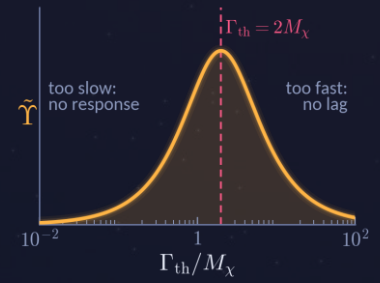
2 · Buy low, sell high



ψ is made when light, destroyed when heavy

The bath pays M_ψ per ψ made and regains M_ψ per ψ destroyed. Profit = loop area, paid by χ.

3 · Goldilocks response



strongest when the bath relaxes at $\Gamma_{th} \approx 2M_\chi$

Friction needs a response and a lag. Peak at $2M_\chi$ since $M_\psi^2 \propto \chi^2$ oscillates twice per period.

THE LAG DEFINES Υ

$$g\langle\bar{\psi}\psi\rangle = \underbrace{m_{\chi,\rm th}^2\left(\frac{m_\psi}{g} - \chi\right)}_{\text{equilibrium}} \underbrace{-\,\Upsilon\,\dot{\chi}}_{\text{lag} \;\Rightarrow\; \text{friction}}$$

The equilibrium part gives the thermal mass and the shifted minimum. The part $\propto \dot{\chi}$ is the friction Υ.

AVERAGED OVER ONE OSCILLATION ($X \gg m_\psi/g$)

$$\tilde{\Upsilon} \equiv \frac{\langle \bar{\Upsilon}\,\dot{\bar{\chi}}^2\rangle}{\langle \dot{\bar{\chi}}^2\rangle}$$

$\propto X^2$: the bigger the swing, the harder the brake

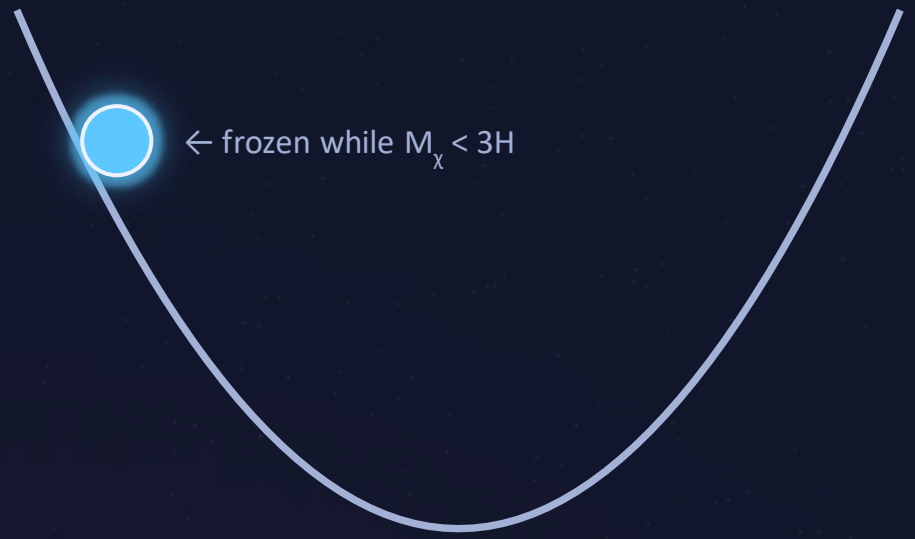
$$\tilde{\Upsilon} = c_\Upsilon \frac{g^4 X^2}{\Gamma_{\rm th}} \frac{\Gamma_{\rm th}^2}{4M_\chi^2 + \Gamma_{\rm th}^2}$$

$\bar{\chi} = X\cos\theta$: the oscillating background · $\langle\ldots\rangle$: average over a period · $c_\Upsilon = 3c_m^{\,2}/2\pi^2$

Watch the displacement evolve

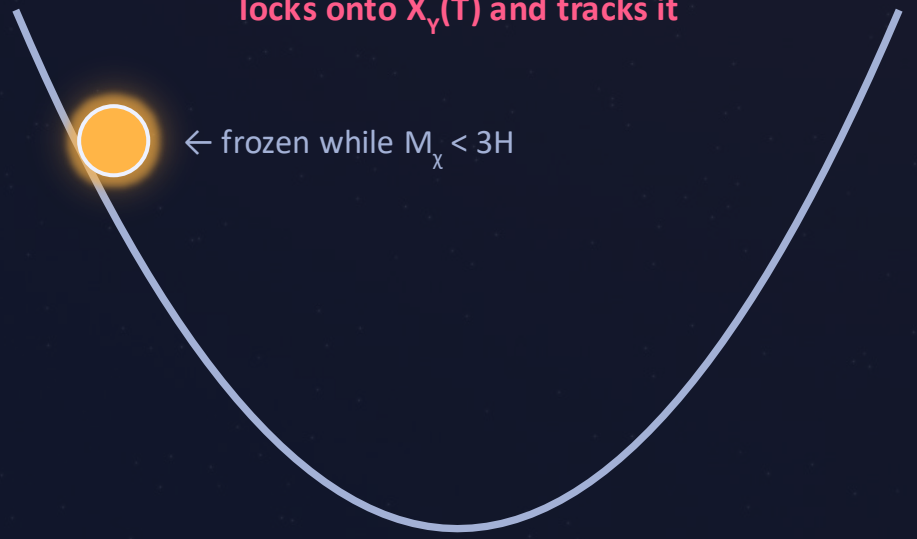
Isolated scalar

Hubble friction only: $X \propto a^{-1}$



Coupled to the bath

Hubble + thermal friction $\propto X^2$



$$\frac{\dot{X}}{X} = -\frac{1}{2}\left(3H + \tilde{\Upsilon} + \frac{\dot{M}_\chi}{M_\chi}\right)$$

Friction $\propto X^2$: the bigger the swing, the harder the brake.

Self-limiting friction locks X onto $X_\Upsilon(T)$

$X_\Upsilon(T)$: WHERE FRICTION MATCHES HUBBLE

$$\tilde{\Upsilon}(X_\Upsilon, T) = c_{\rm track}\, H$$

$\tilde{\Upsilon} \propto X^2$ picks out one amplitude at each T

$$c_{\rm track} \equiv -\left.\frac{\partial \ln \tilde{\Upsilon}}{\partial \ln T}\right|_X \qquad (= 1 \text{ for } n = 1)$$

ABOVE X_Υ

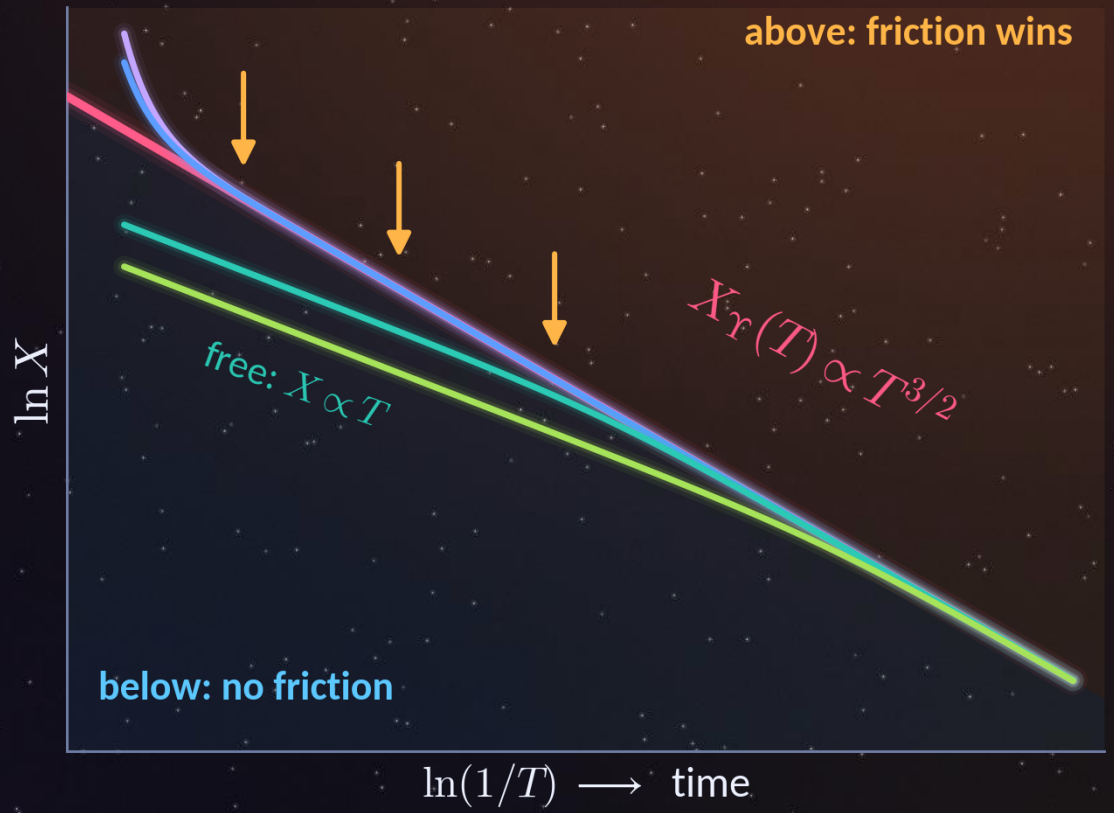
Friction beats Hubble: X is crushed onto X_Υ within a fraction of a Hubble time.

BELOW X_Υ

Friction is negligible: $X \propto T$ falls more slowly than $X_\Upsilon \propto T^{3/2}$, so X_Υ comes down to meet it.

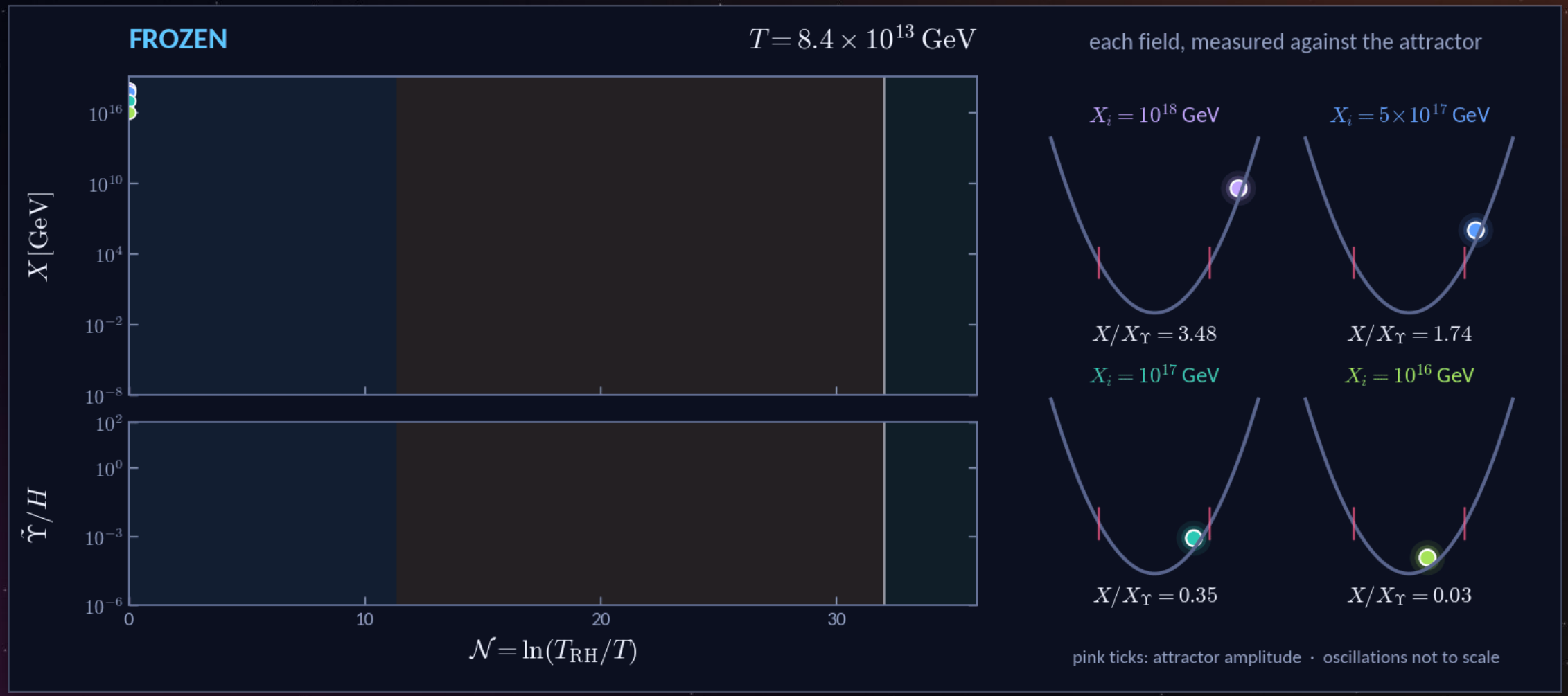
ON X_Υ

Friction keeps pace with the expansion: X follows $X_\Upsilon(T)$ and forgets X_i.



$$X_\Upsilon \propto T^{1+c_{\rm track}/2} \qquad \text{attractor} \iff c_{\rm track} > 0$$

Four initial conditions, one destiny



Envelope equation solved numerically · $g = 10^{-8}$, $\kappa = 8\times10^{-9}$, $n = 1$, $m_\chi = 10^{-7}$ eV, $m_\psi = 1$ GeV, $T_{RH} = 8.4\times10^{13}$ GeV

The thermal system in six equations

1 **Background equation of motion**

$$\ddot{\bar{\chi}} + (3H + \Upsilon)\,\dot{\bar{\chi}} + M_\chi^2\,(\bar{\chi} - \chi_{\rm th}) = 0$$

2 **Envelope: Hubble + friction + varying mass**

$$\frac{\dot{X}}{X} = -\frac{1}{2}\left(3H + \tilde{\Upsilon} + \frac{\dot{M}_\chi}{M_\chi}\right)$$

3 **Damping rate**

$$\tilde{\Upsilon} = c_\Upsilon\,\frac{g^4 X^2}{\Gamma_{\rm th}}\,\frac{\Gamma_{\rm th}^2}{4M_\chi^2 + \Gamma_{\rm th}^2}$$

4 **Attractor: friction = $c_{\rm track}$ × Hubble**

$$X_\Upsilon(T) = \frac{\sqrt{c_{\rm track}\,H\,\Gamma_{\rm th}}}{g^2\sqrt{c_\Upsilon}}\sqrt{\frac{\Gamma_{\rm th}^2 + 4M_\chi^2}{\Gamma_{\rm th}^2}}$$

5 **Attractor if $c_{\rm track} > 0$**

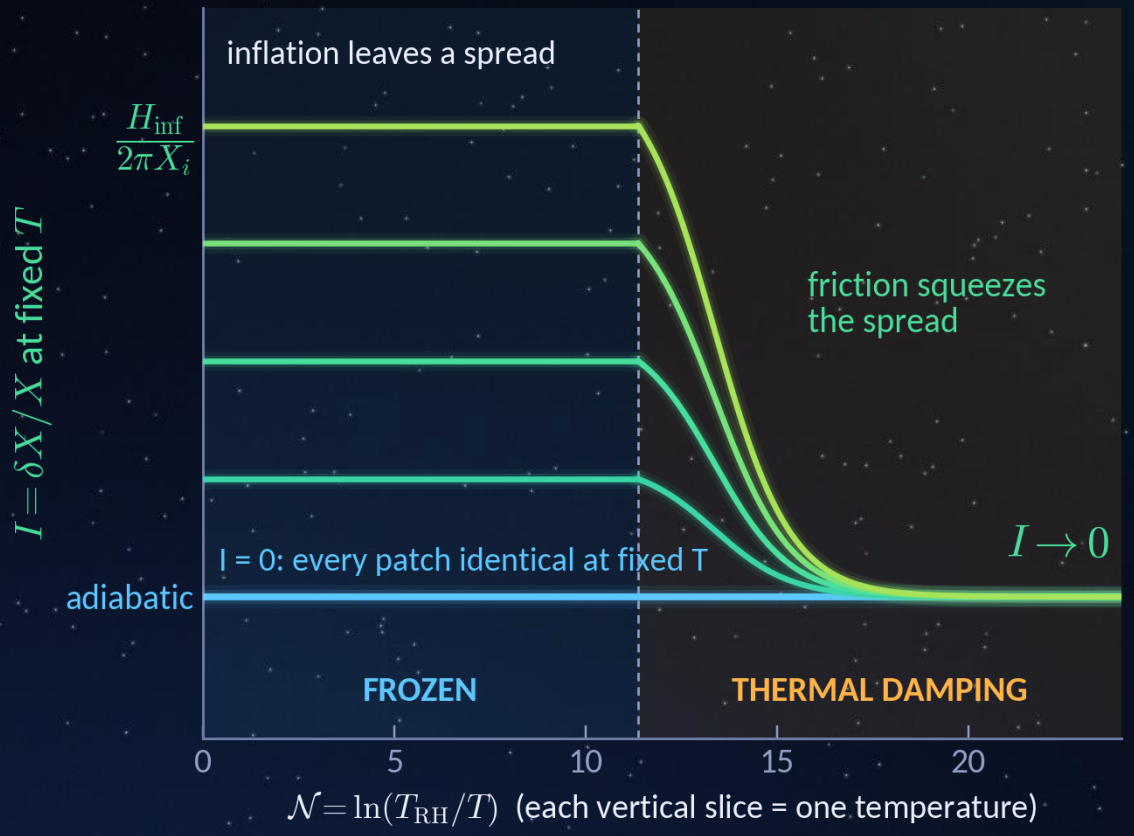
$$c_{\rm track} = -\left.\frac{\partial \ln \tilde{\Upsilon}}{\partial \ln T}\right|_X = n - \frac{8(n-1)M_\chi^2}{\Gamma_{\rm th}^2 + 4M_\chi^2}$$

6 **One factor depletes ρ_χ and erases I**

$$\frac{\rho_\chi}{\rho_\chi^{\rm free}} = \frac{I}{I_i} = \left(\frac{X}{X_{\rm free}}\right)^2$$

$X_{\rm free}$: amplitude without damping

Isocurvature: same temperature, different amplitude



ADIABATIC: IDENTICAL AT FIXED T

Adiabatic perturbations are only time shifts: read at the same temperature, every patch has the same X.

ISOCURVATURE: A SPREAD AT FIXED T

$$I \equiv \left.\frac{\delta X}{X}\right|_T$$

inflation sets its size, ~$H_{inf}/2\pi X_i$

in any slicing: $I = \delta X/X - \xi\, \delta T/T$, with $\xi \equiv d\ln \bar{X}/d\ln T$

FRICTION SQUEEZES THE SPREAD

$\tilde{Y} \propto X^2$: patches with more χ are damped harder, so every patch converges onto the background and **I** → 0.

$$S_{\chi r} = \frac{3\,I}{1+\xi}$$

what the CMB constrains: it vanishes with **I**

The same friction erases isocurvature

SUPERHORIZON PERTURBATION (NEWTONIAN GAUGE)

$$\delta\ddot{\chi} + (3H + \bar{\Upsilon})\,\delta\dot{\chi} + \left(M_\chi^2 + \frac{d\bar{\Upsilon}}{d\bar{\chi}}\dot{\bar{\chi}}\right)\delta\chi = S_\Phi + S_{\rm eq} + S_\Upsilon$$

$$S_{\rm eq} = -2\,\frac{\delta T}{T}\,m_{\chi,\rm th}^2\,\bar{\chi} \qquad S_\Upsilon = -\frac{\delta T}{T}\,\frac{\partial\bar{\Upsilon}}{\partial \ln T}\bigg|_{\bar{\chi}}\dot{\bar{\chi}}$$

Φ: metric potential (S_Φ: backup F) · $\xi_\gamma = d\ln X_\gamma/d\ln T = 1 + c_{\rm track}/2$ · $X_{\rm free}$: amplitude without damping

ISOCURVATURE OBEYS

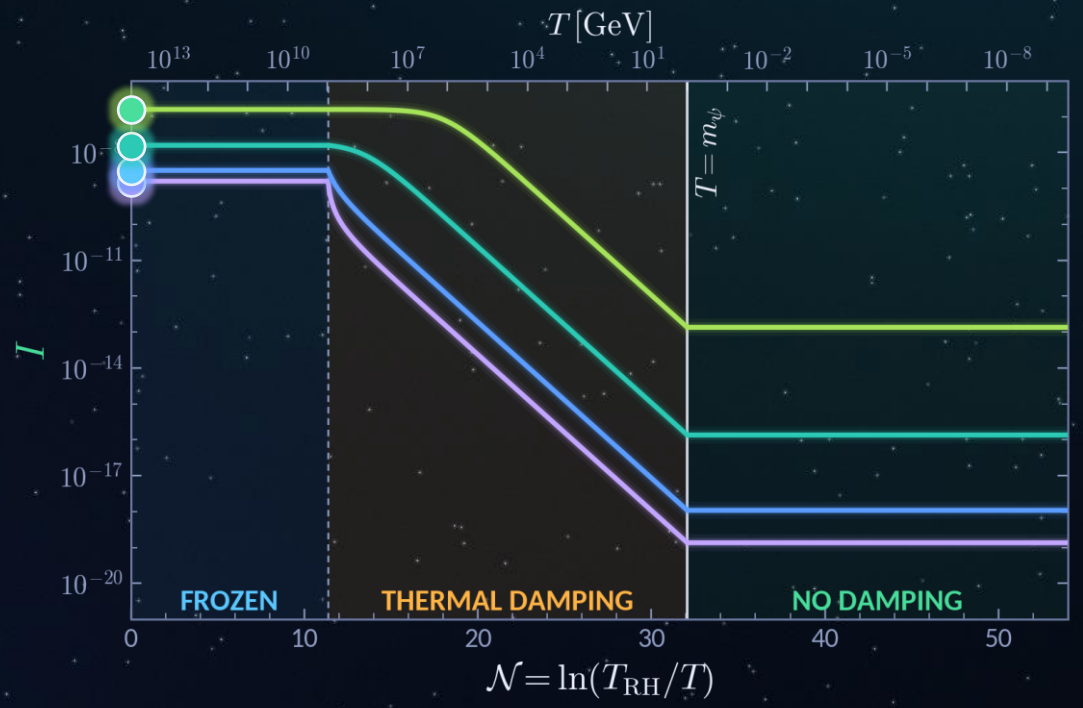
$$\dot{I} + \tilde{\Upsilon}\,I = -\left[\dot{\xi} + \tilde{\Upsilon}\,(\xi - \xi_\Upsilon)\right]\frac{\delta T}{T}$$

SOURCE VANISHES ON ANY THERMAL-MASS BACKGROUND

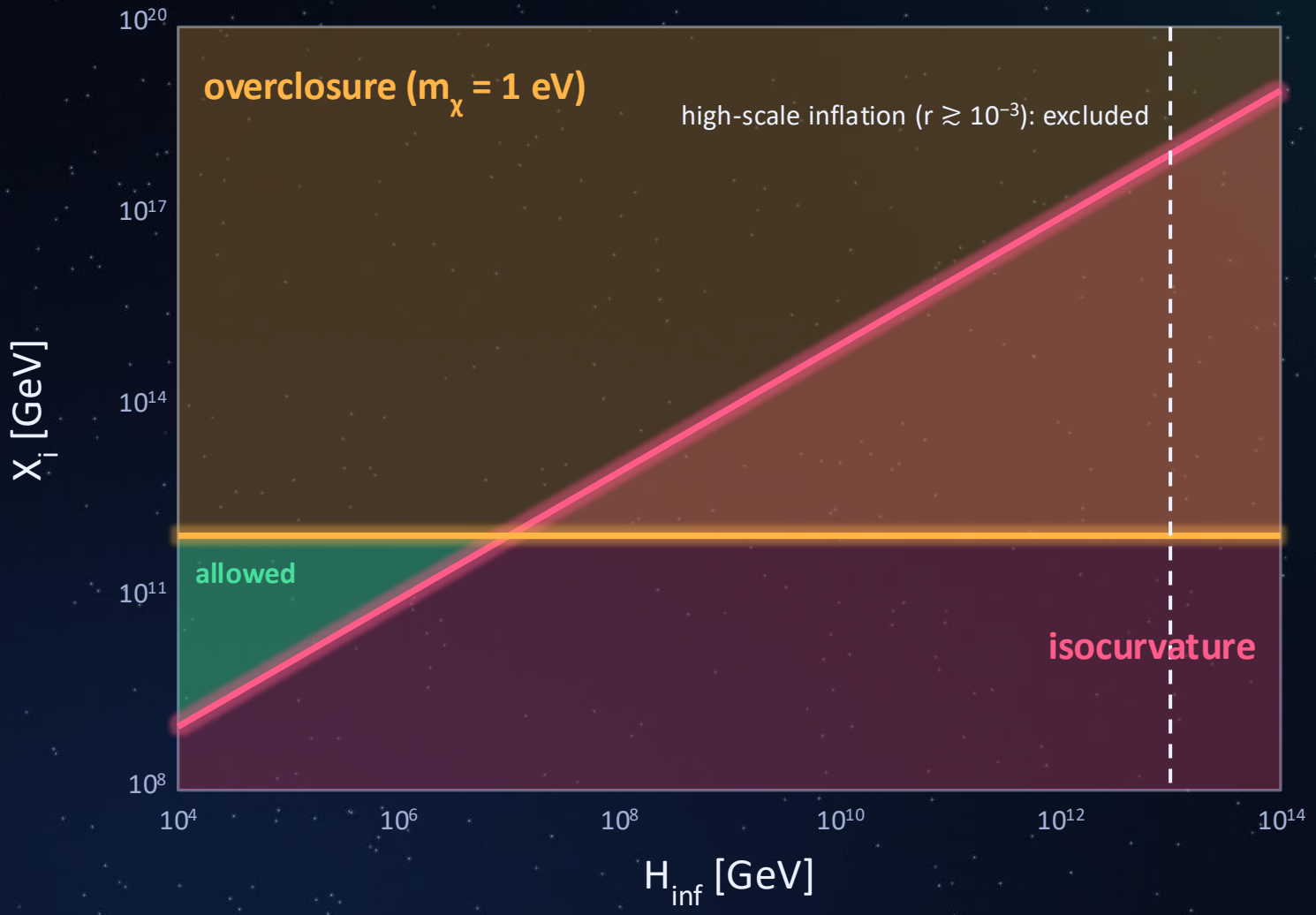
$$\dot{\xi} + \tilde{\Upsilon}(\xi - \xi_\Upsilon) = 0 \quad\Rightarrow\quad I(t) = I(t_i)\,e^{-\int_{t_i}^{t}\tilde{\Upsilon}\,dt'}$$

…SO I TRACKS THE DEPLETION OF X EXACTLY

$$\frac{I(t)}{I(t_i)} = \left(\frac{X(t)}{X_{\rm free}(t)}\right)^2$$



Back to the squeeze…



ISOCURVATURE (PLANCK)

$$X_i \gtrsim 10^{12}\,\mathrm{GeV}\left(\frac{H_{\rm inf}}{10^7\,\mathrm{GeV}}\right)$$

OVERCLOSURE (NO DAMPING)

$$X_i \lesssim 10^{12}\,\mathrm{GeV}\left(\frac{m_\chi}{\mathrm{eV}}\right)^{-1/4}$$

No room at all if

$$H_{\rm inf} \gtrsim 10^7\,\mathrm{GeV}\,(m_\chi/\mathrm{eV})^{-1/4}$$

Same ~10^7 GeV ceiling as the axion.

…thermal damping opens the window



ISOCURVATURE, AFTER TRACKING

$$X_i \gtrsim \epsilon \times 10^{12}\,\mathrm{GeV}\left(\frac{H_{\mathrm{inf}}}{10^7\,\mathrm{GeV}}\right)$$

OVERCLOSURE: THE SAME FACTOR

$$\frac{\rho_\chi}{\rho_\chi^{\mathrm{free}}} = \frac{I}{I_i} = \epsilon$$

One factor ε depletes the scalar and erases its isocurvature: the tension is gone.

Schematic: n = 1 benchmark, ε ≈ 10^{-10} for $X_i = 10^{18}$ GeV; abundance set by where tracking ends.

Take-home messages

1

The squeeze

Displaced light spectators face overclosure vs. isocurvature: the same ~10^7 GeV ceiling that haunts axions.

2

Thermal friction

A bath of ψ gives χ a thermal mass and a lagging, amplitude-dependent friction ∝ X^2.

3

The attractor

Self-limiting friction locks X onto $X_\gamma(T)$ while $c_{track} > 0$: the abundance is set by where tracking ends, not by X_i.

4

Isocurvature erased

I is damped by exactly the factor that depletes the scalar:

$$\frac{\rho_\chi}{\rho_\chi^{\rm free}} = \frac{I}{I_i} = \left(\frac{X}{X_{\rm free}}\right)^2$$

Thank you

Questions?

