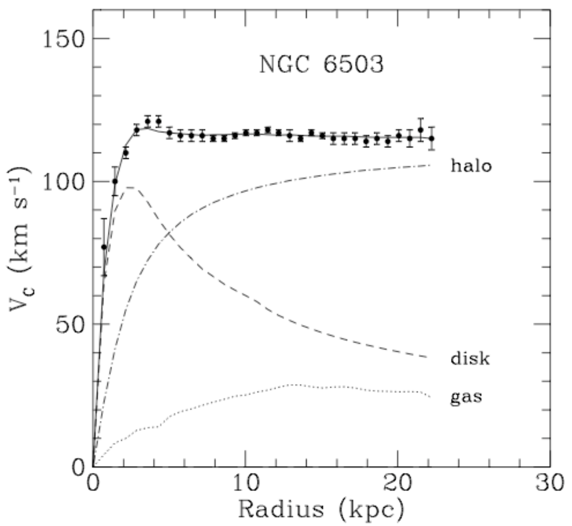
Cosmological Dark Matter and LHC: How Robust is the Connection?

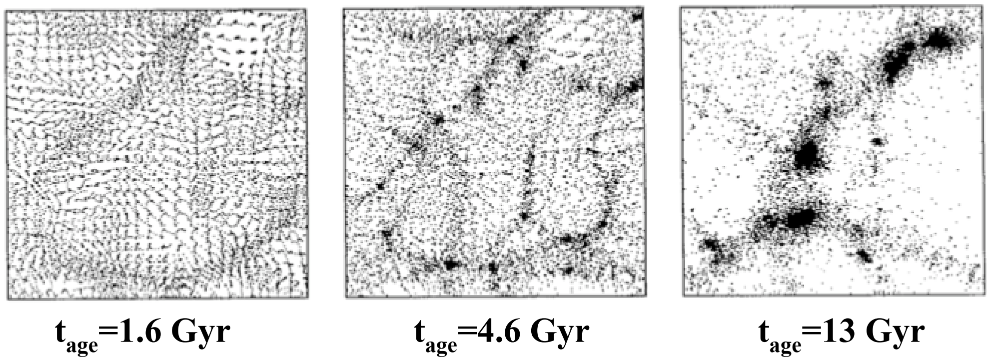
Scott Watson
University of Michigan

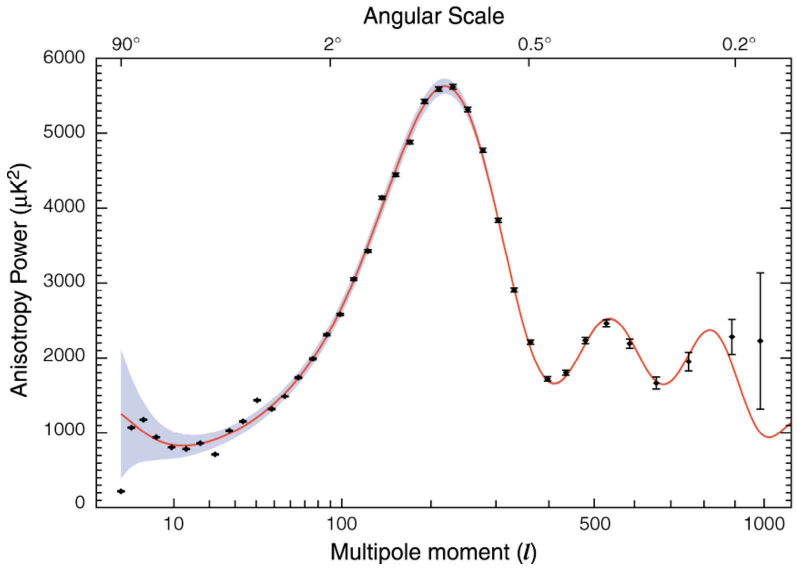
In collaboration w/ Michigan group
and L-T Wang (Princeton)

Cosmological Dark Matter

- Rotation curves
- CMB / LSS / Supernovae
- Evolution of LSS
- Gravitational Lensing







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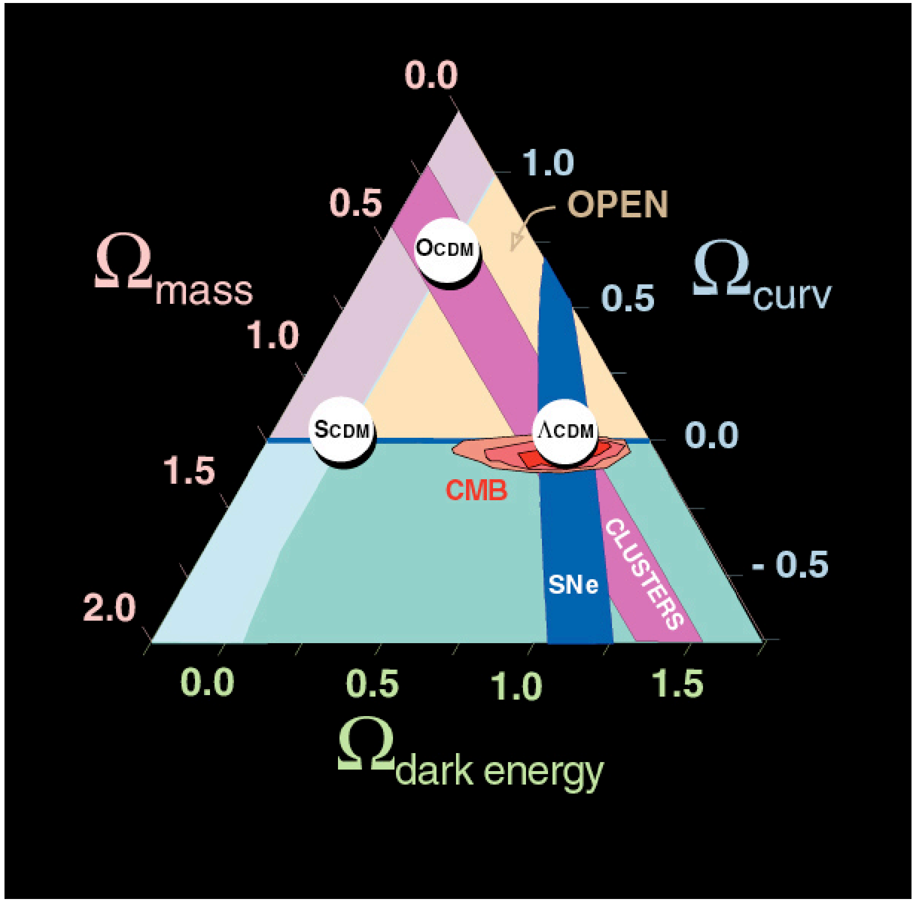
Non-Baryonic

↓

Physics beyond SM



$$\Omega_b = 0.040 \pm 0.005 \quad \text{BBN}$$

$$\Omega_b = 0.047 \pm 0.006 \quad \text{WMAP}$$

Cosmological Dark Matter

WMAP

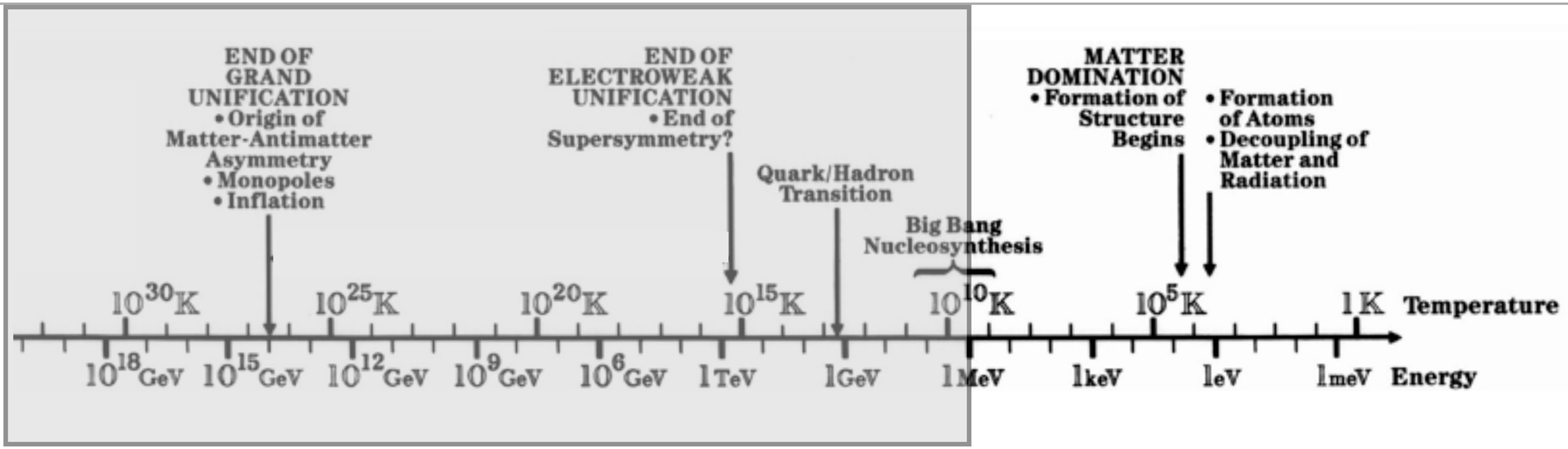
$\Omega_{cdm}\, h^2 = 0.111 \pm 0.006$ 6% Accuracy (Planck < 0.4%)

Other (in)direct observations (e.g. LSS / Lensing):

(1) Stable (or very long-lived)
(2) Neutral -- BBN / No exotic isotopes
(3) Weakly interacting
(4) “Cold” -- Non-relativistic (otherwise lack small scale structure)

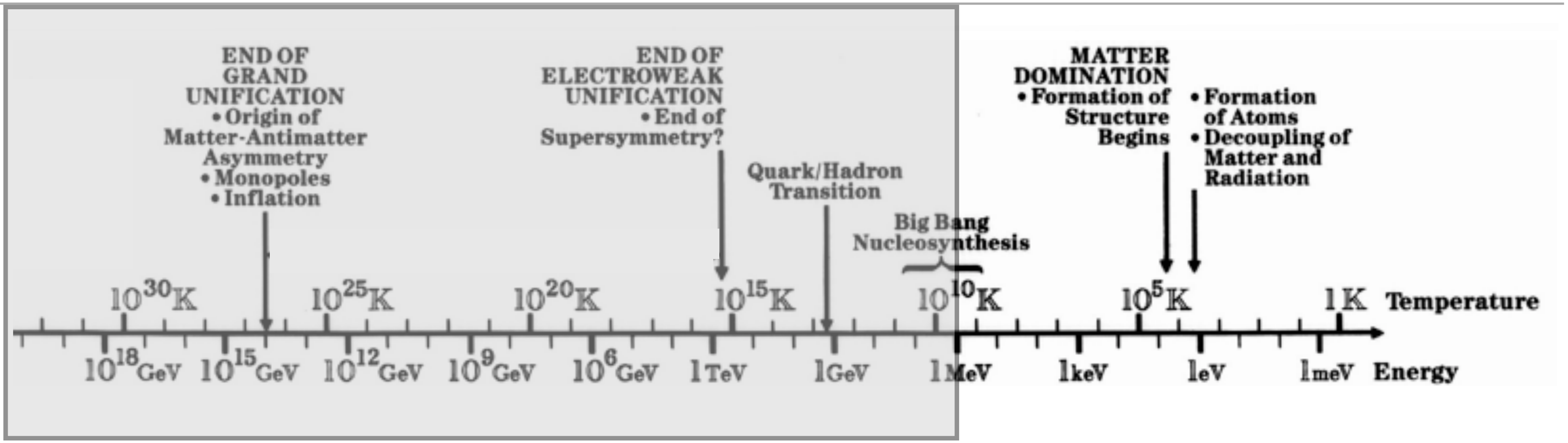
“WIMPs”

Particle Dark Matter?



Connection with Particle Theory?

Particle Dark Matter?



Thermal Relic Density

$$\Omega_X h^2 = \frac{10^{-10}\ GeV^{-2}}{\langle \sigma v \rangle} \qquad \Omega_{cdm} h^2 = 0.111 \pm 0.006$$

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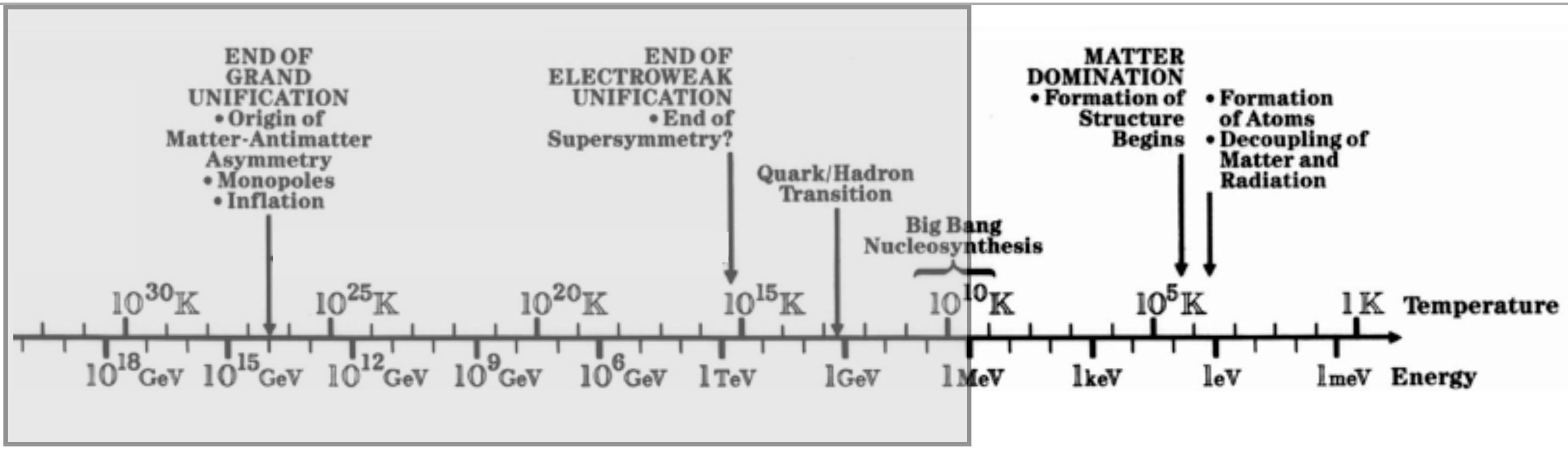

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New Physics at Weak Scale

$$\langle \sigma v \rangle \sim \frac{\alpha^2}{M_{weak}^2} \sim 10^{-9}\, GeV^{-2}$$

EW Breaking and Dark Matter

Electroweak breaking + discrete symmetry = *Stable* WIMPs

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Example: SUSY

- Explain Weak Scale
- Stabilize higgs (radiative corrections)
- Gauge Coupling Unification
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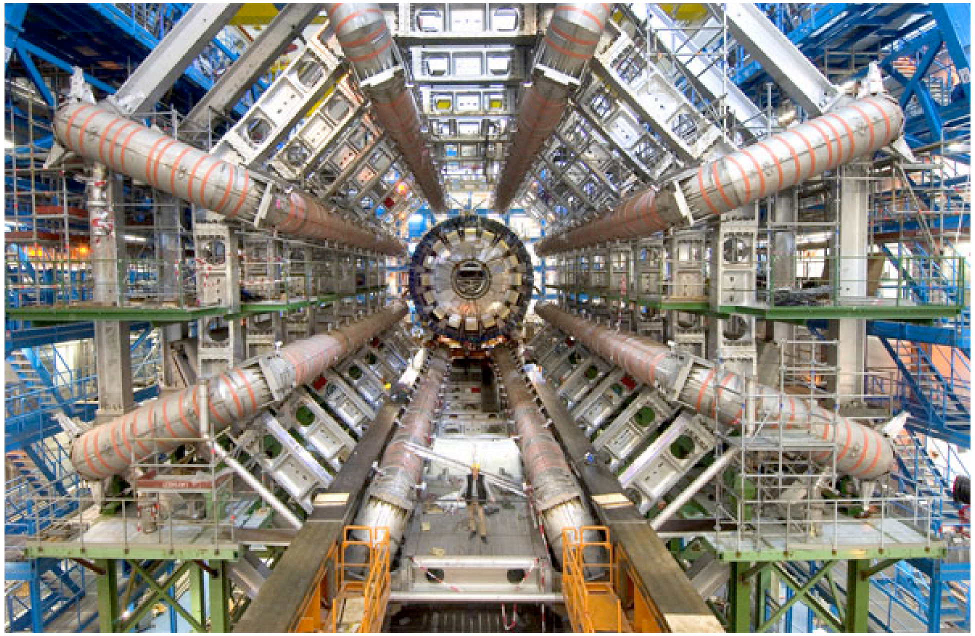
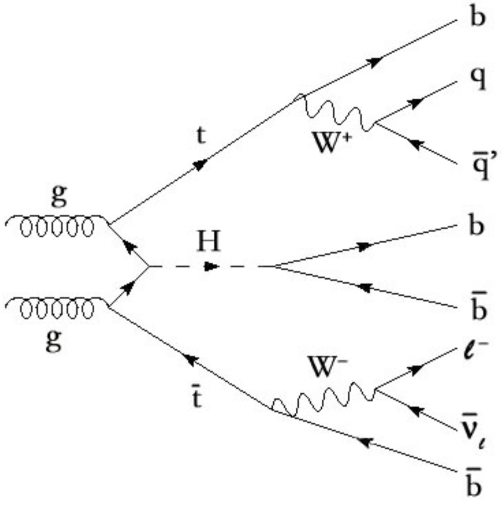
= Lightest SUSY Particle (LSP) is:

(1) Stable
(2) Weak Scale / Weakly interacting
(3) Massive (100 GeV)
(3) Correct relic density

LHC and Dark Matter

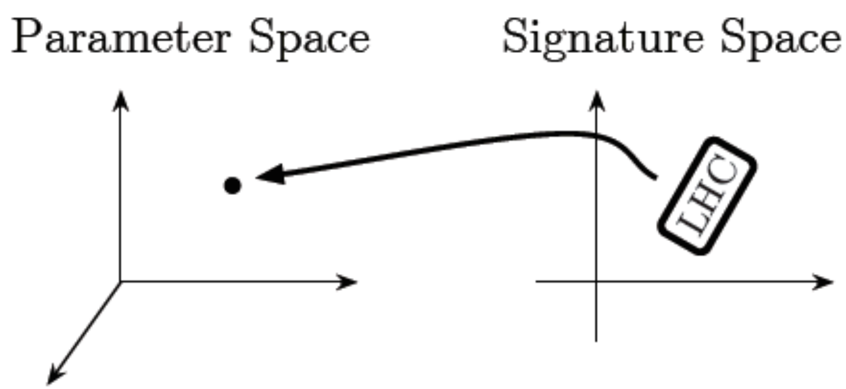
- Will Probe Higgs and EWSB
- New physics at TeV appears as missing energy
- Degeneracies make probing new physics challenging -- LHC inverse problem



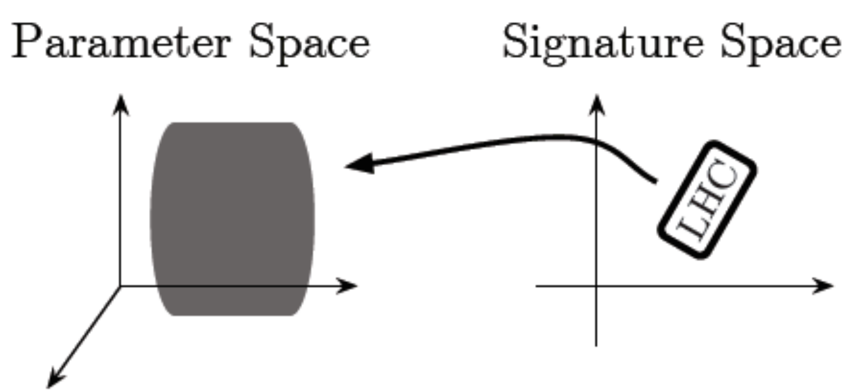


LHC Inverse Problem

Best of all Possible Worlds



Worst of all Possible Worlds



LHC and the Dark Matter Inverse Problem

Work in progress w/ K. Freese, G. Kane, (Michigan) and L.T. Wang (Princeton)

LHC →

χ m_χ

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LHC

$\chi \quad m_X$

?

CDM

Ω_{cdm}

?

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Can we reconstruct the relic density using LHC data?

CDM Inverse Problem

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  Methods can be improved (model independent methods)

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- Coannihilations can lower relic density
- Many additional dark matter particles - (e.g. neutrinos / axions)
- Many assumptions go into thermal calculation - *Today's talk*

Outline for rest of talk

- Standard Dark Matter Paradigm
- Light Scalars in the Early Universe
- Light Scalars and the CDM Inverse Problem
- Lifting constraints on WIMP candidates
- Conclusions and Outlook

Thermal Dark Matter

Thermal Abundance

Boltzmann Equation

$$\dot{n}_x = -3Hn_x - \langle \sigma v \rangle \left[n_x^2 - (n_x^{eq})^2 \right]$$

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Comoving Abundance

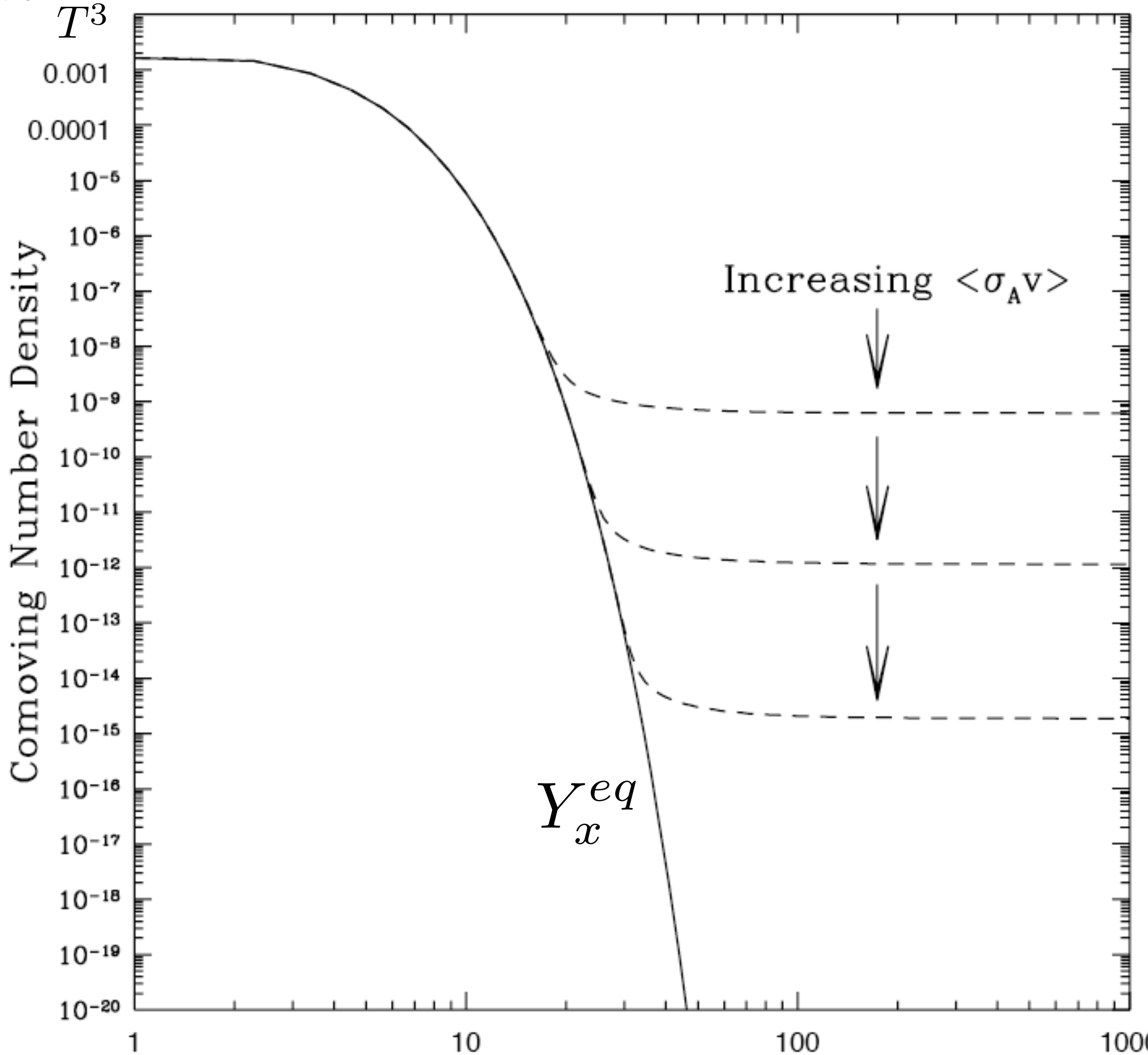
$$Y_x \sim \frac{n_x}{T^3}$$

Thermal Relic Density

Assume Chemical Equilibrium (initially)

$$XX \leftrightarrow \gamma\gamma$$

$$Y \sim \frac{n}{T^3}$$



$$x = \frac{m}{T}$$

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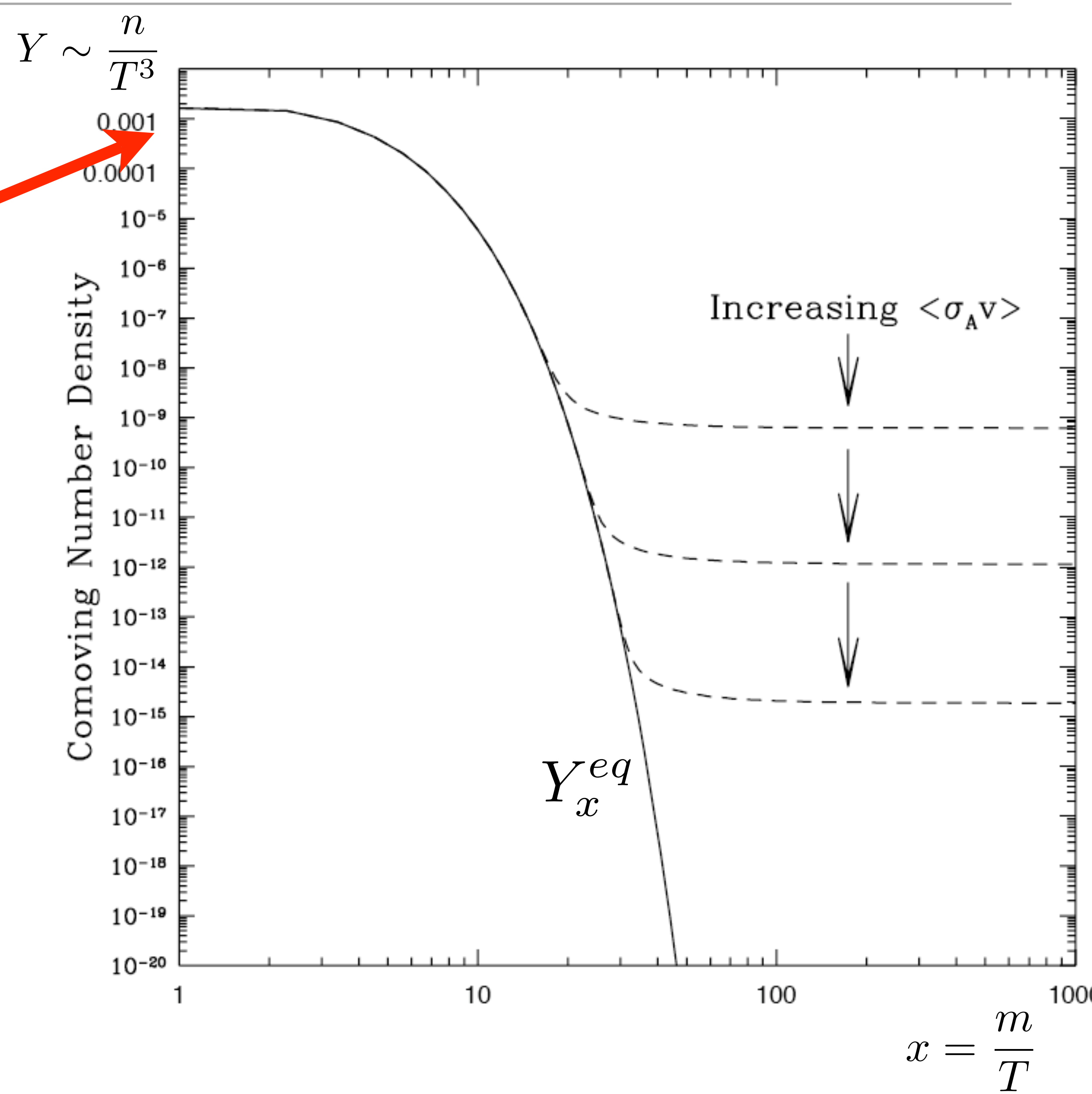
Relativistic

$$m < T$$

$$n \sim n_{eq} \sim T^3$$



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Non-relativistic

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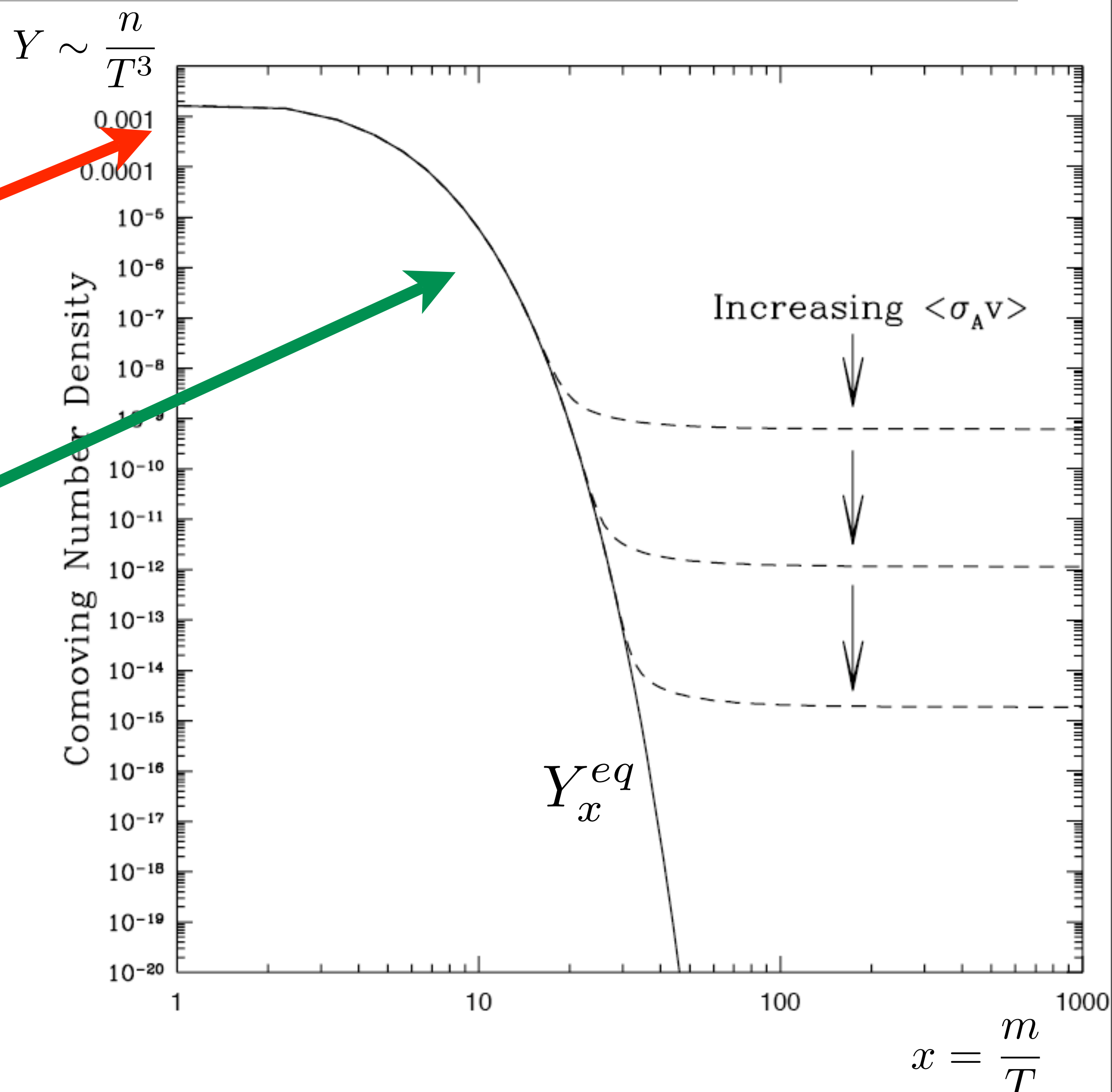
$$n \sim n_{eq} \sim (mT)^{3/2}\, e^{-m/T}$$



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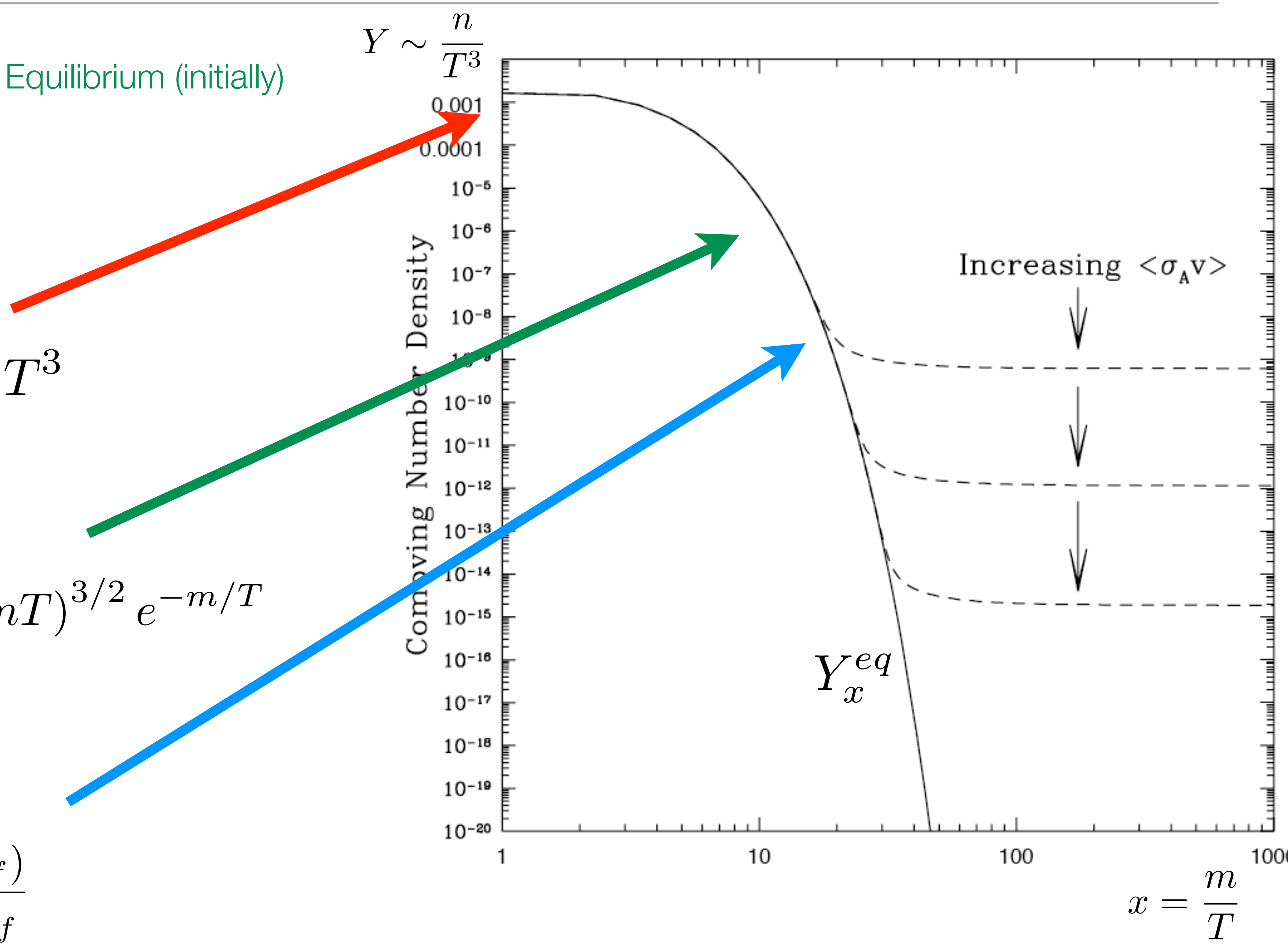
"Freeze-out"

$$H > n\langle\sigma v\rangle$$

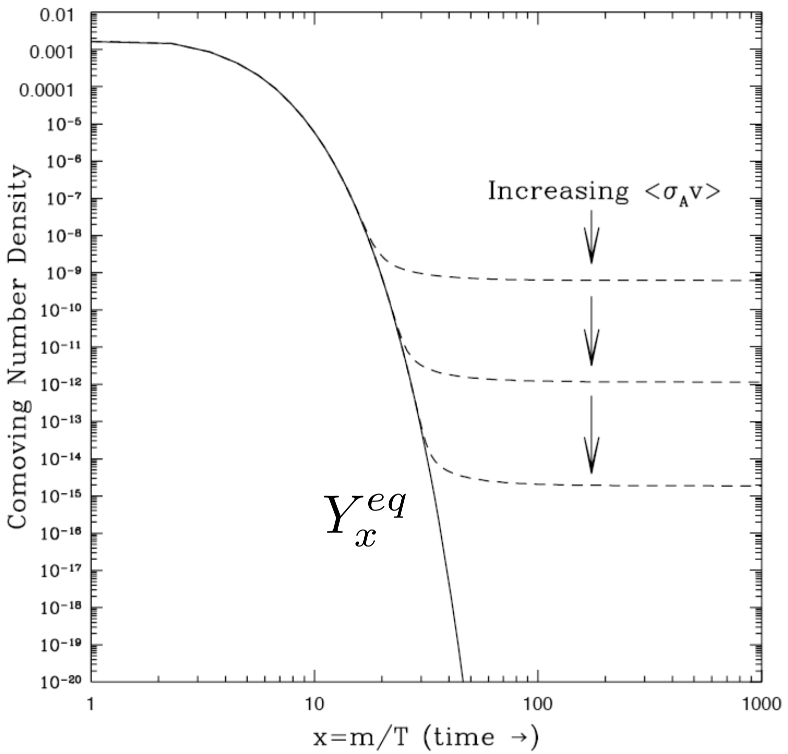
$$n(T_f) \sim \frac{H(T_f)}{\langle\sigma v\rangle_f}$$



Thermal Relic Density

Relic Abundance

$$Y \sim \frac{H_f}{\langle \sigma v \rangle_f T_f^3} \sim \frac{1}{\langle \sigma v \rangle T_f}$$



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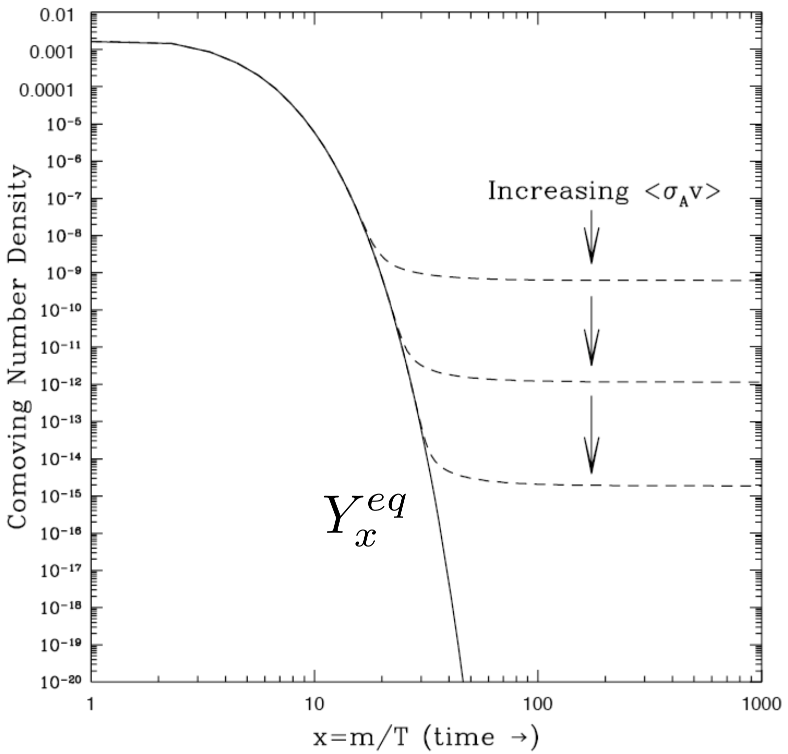
Adiabatic expansion
--> Relic abundance preserved



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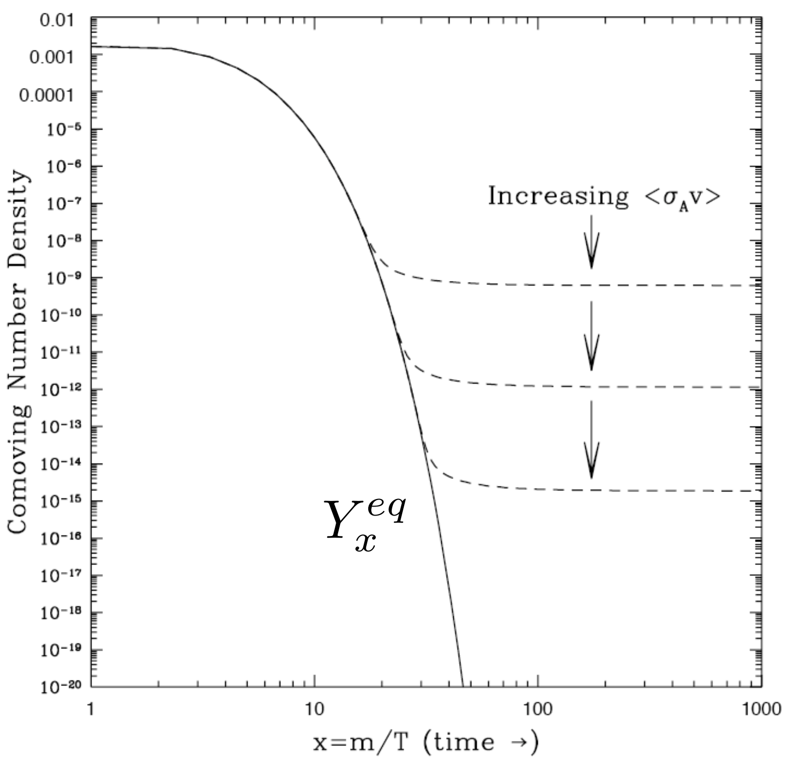
CDM Relic Density Today

$$\Omega_{dm} \sim \frac{m_x}{\langle \sigma v \rangle_f T_f} \sim \frac{10^{-10}\, GeV^{-2}}{\langle \sigma v \rangle}$$

$$T_f \approx \frac{m_x}{30}$$

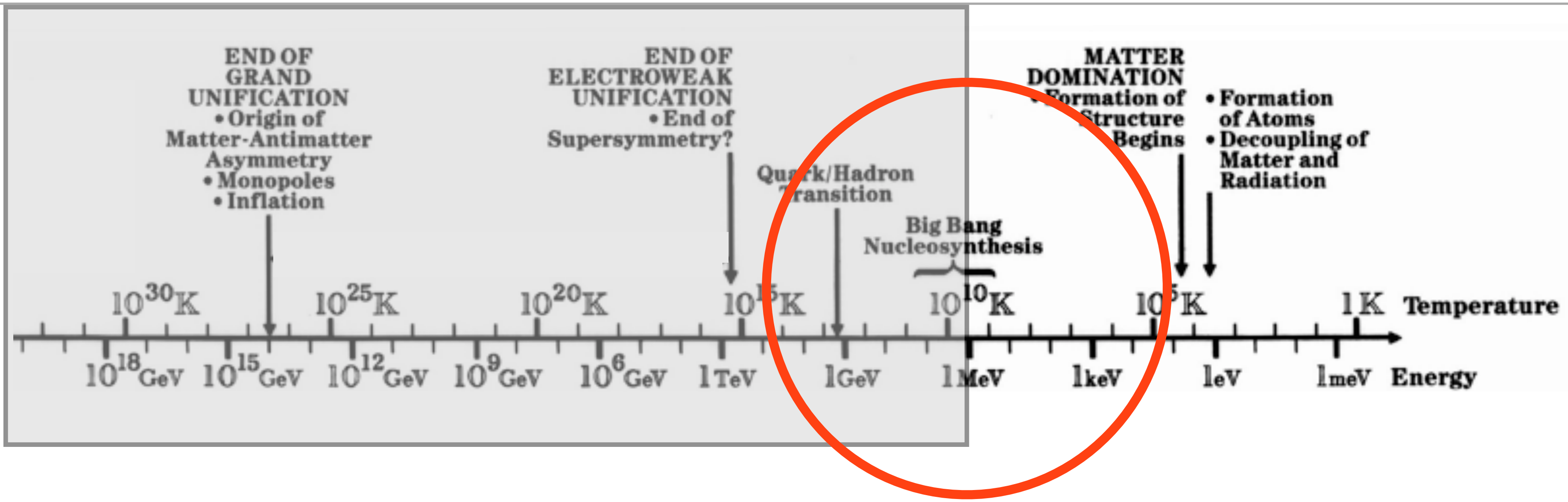
Log dependence (robust)



At freeze out:

$$n_f \sim \frac{H_f}{\langle \sigma v \rangle_f} \sim n_{eq} \sim e^{-m/T}$$

Assumptions



Thermal Relic Density

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$$\Omega_X h^2 = \frac{10^{-10}\ GeV^{-2}}{\langle\sigma v\rangle}$$

- Radiation dominated universe (RDU) at freeze-out
  BBN --> RDU
- No entropy production after freeze-out
- Particles reach chemical equilibrium
- One dark matter species

How Robust is this Scenario?

Physics beyond SM - Light Scalars

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- Inflation (and particle physics) requires physics beyond SM:
  - Inflation
  - Dark Matter
  - Dark Energy
  - Baryon Asymmetry
  - Neutrino Masses
  - Strong CP, Naturalness, etc...

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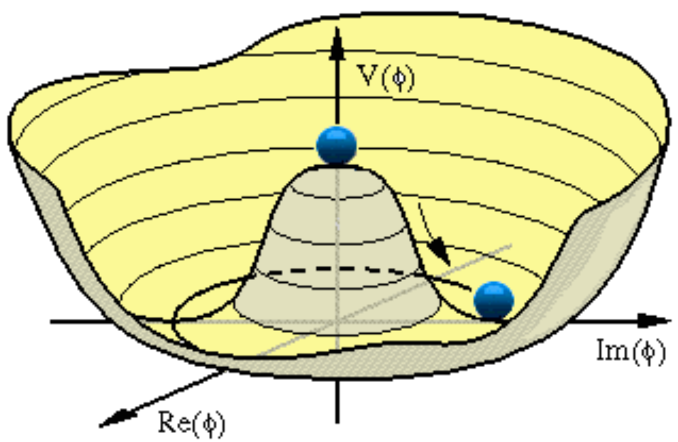
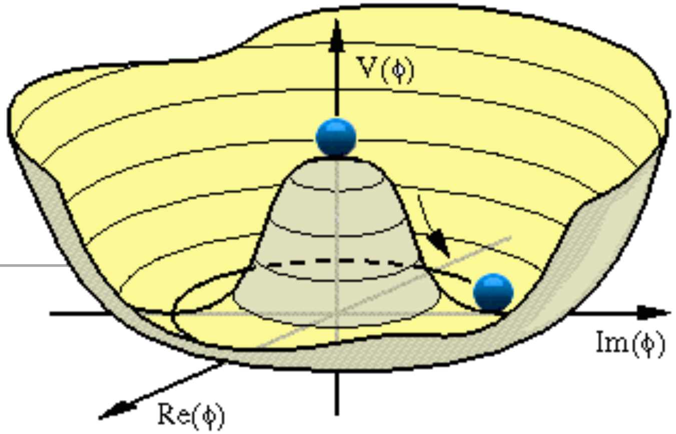
- Symmetry is not realized at low energies
  --> Spontaneous Symmetry "Breaking"
- Scalar VEVs <--> undetermined parameters



Light Scalars in the Early Universe



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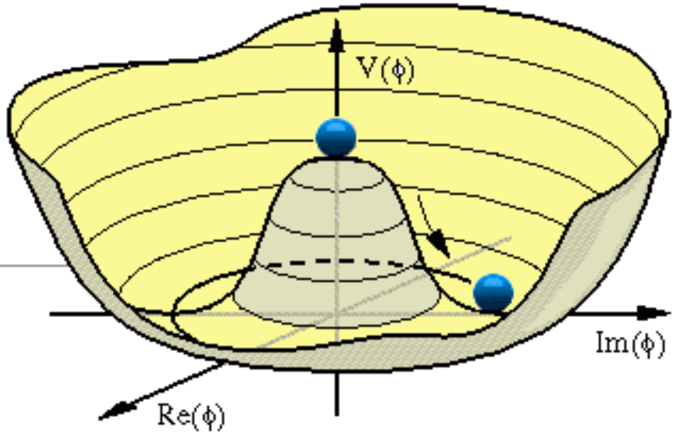

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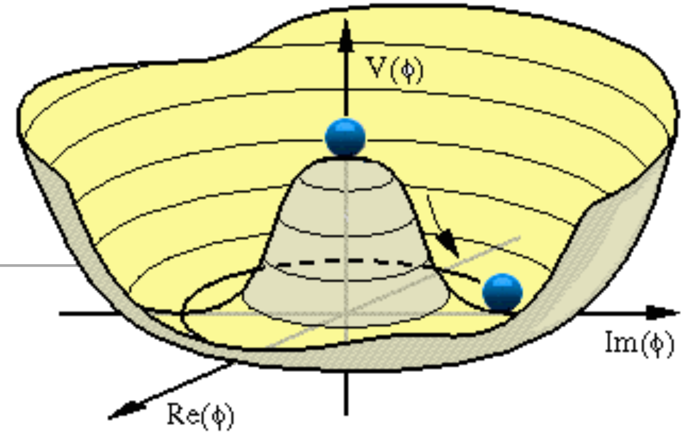

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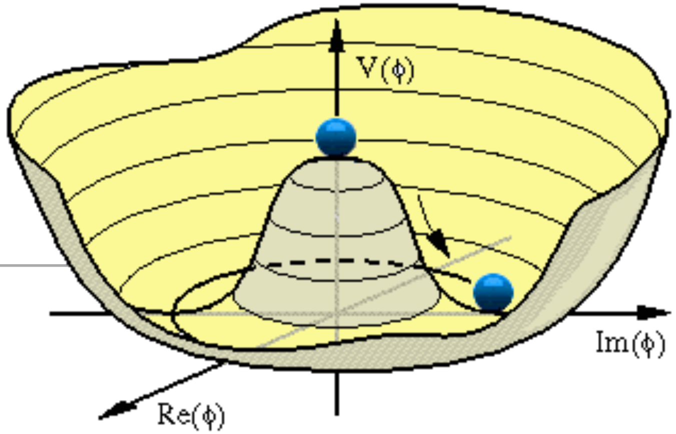

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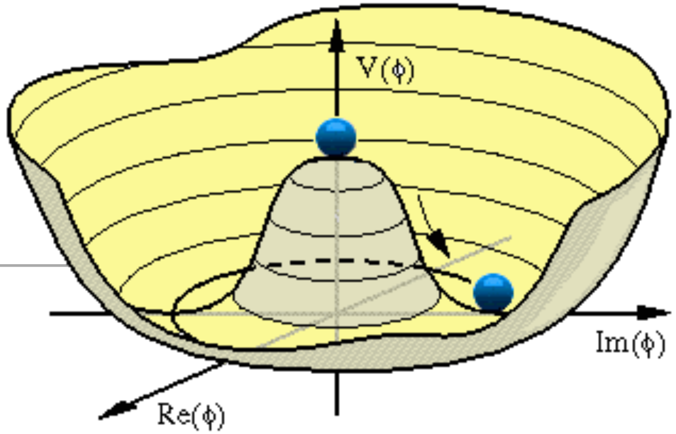

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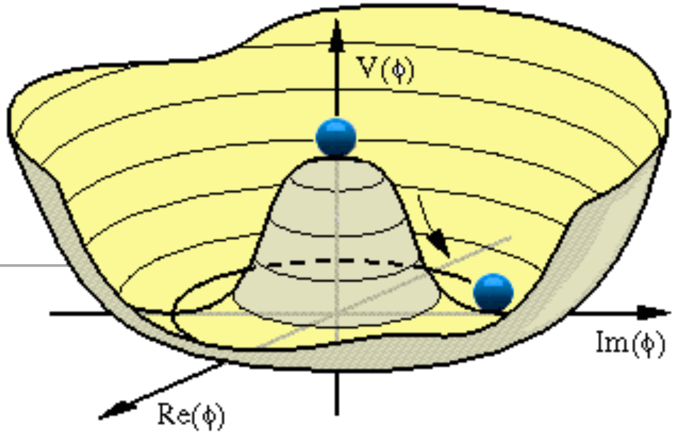

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Approximate Moduli -- Flat directions

$$V_\Phi(T, H, \Phi) = 0$$

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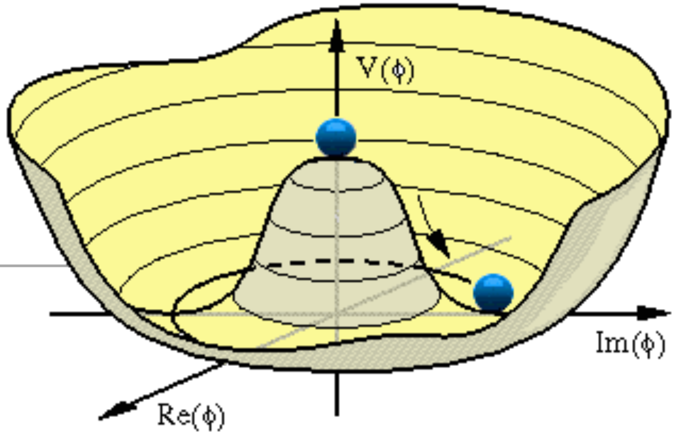

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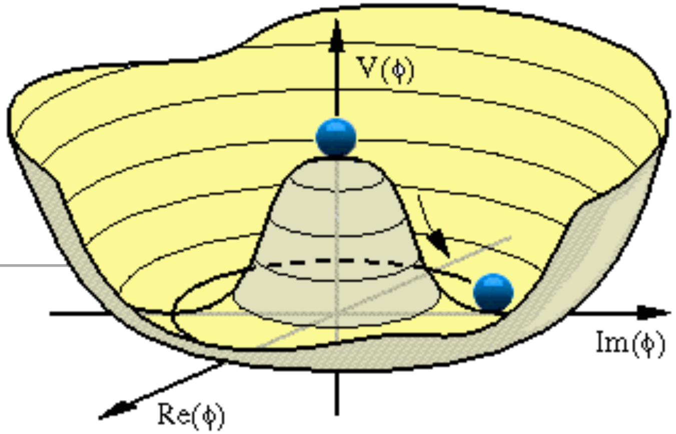

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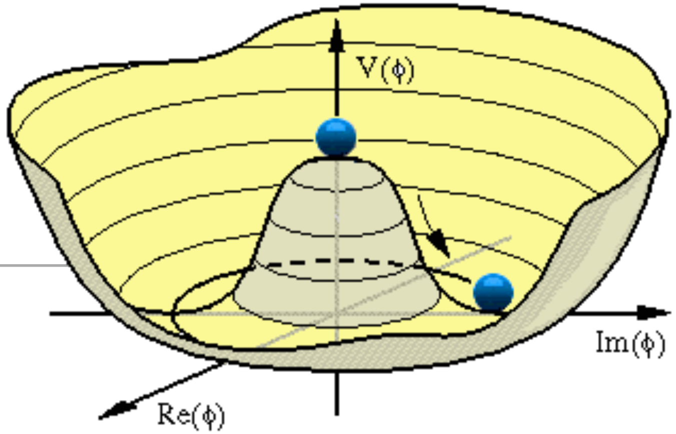

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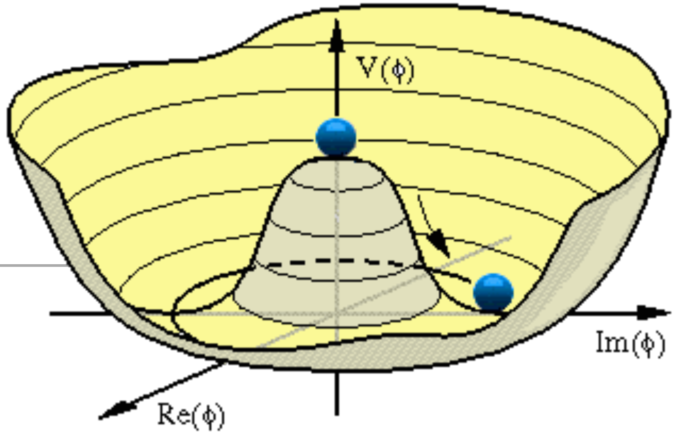

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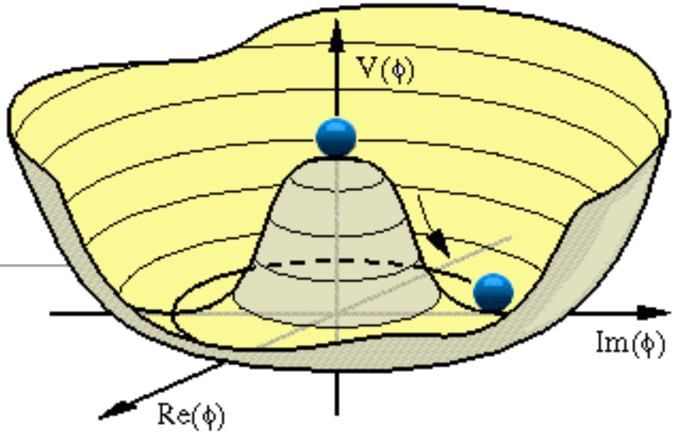

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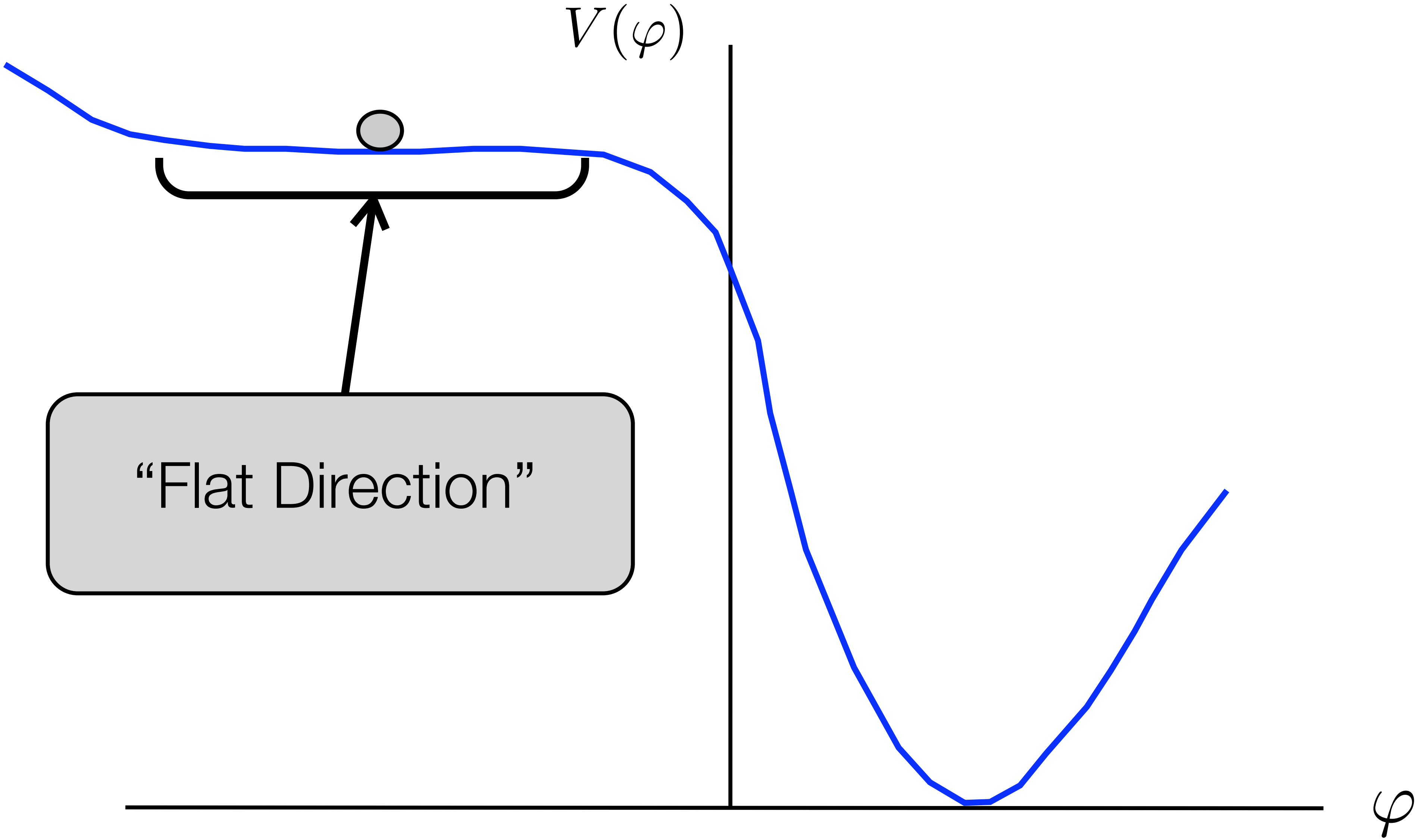
Approximate Moduli



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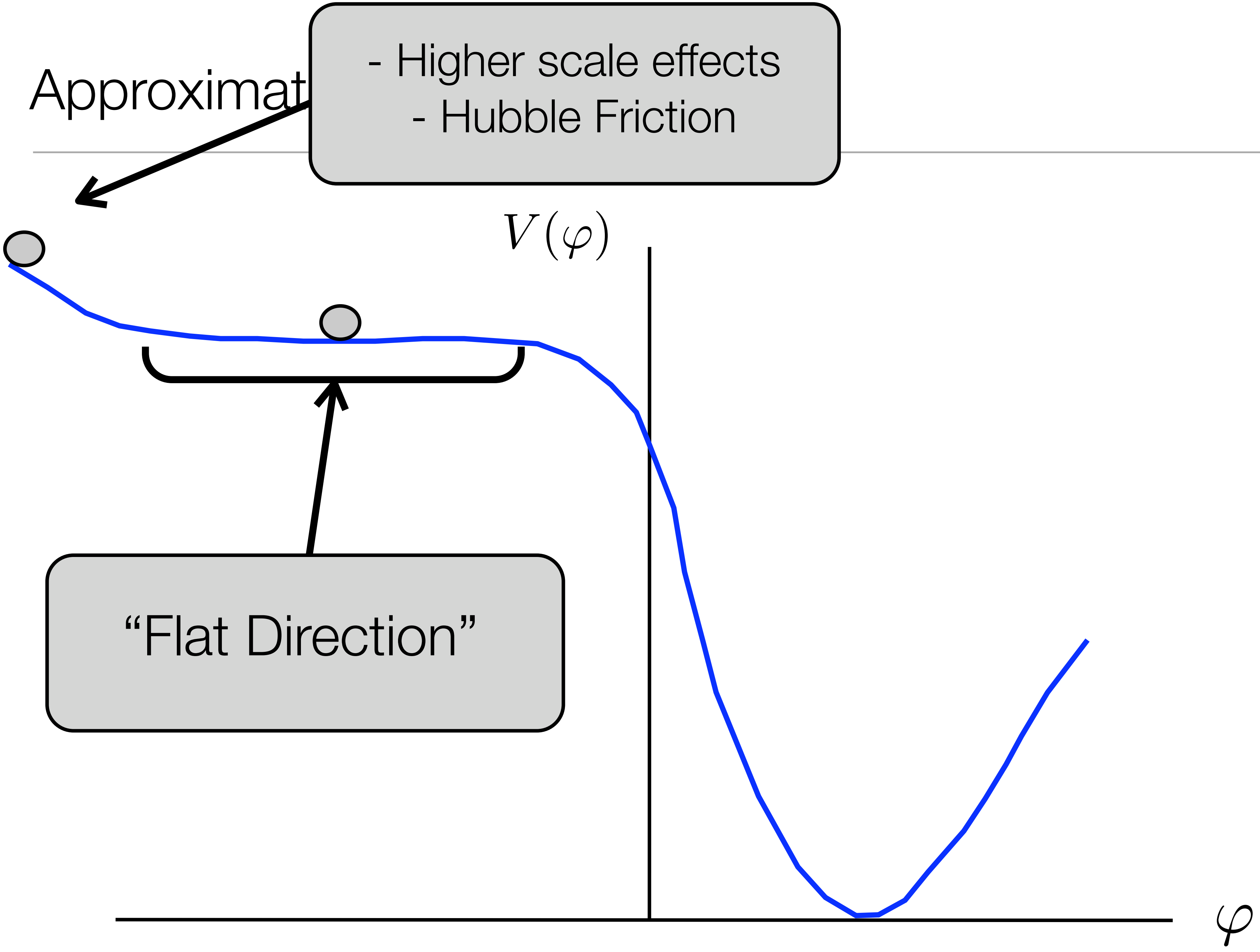
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- Hubble Friction
$V(\varphi)$
"Flat Direction"
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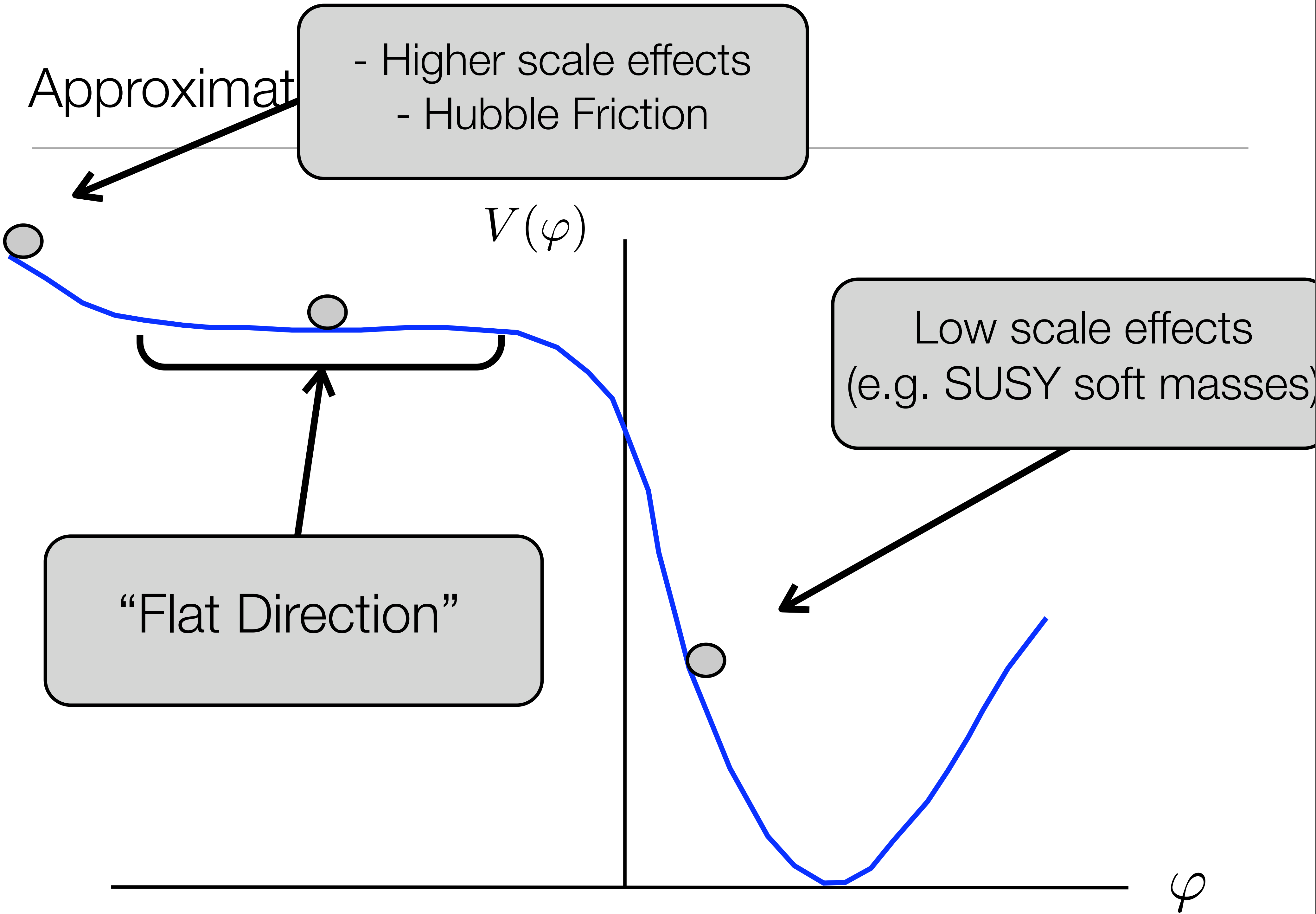

- Higher scale effects
- Hubble Friction
$V(\varphi)$
Low scale effects
(e.g. SUSY soft masses)
"Flat Direction"
φ

Moduli Stabilization

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- If moduli are not stabilized many observational consequences:
    - Spoil inflation
    - Spoil BBN (exotic isotopes, dilute primordial abundances)
    - 5th force violation
    - Changing couplings and masses

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  - Spoil inflation
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  - Changing couplings and masses

- Two generic problems for moduli:
  - Generate potential -- a lot of work has been done (e.g. Fluxes, gaugino condensation, instantons etc...)
  - Fix at the minimum and stay there! -- (not so much progress)
    " Moduli Trapping "
    -- Light scalars couple to other stuff, naturally driven and fixed at points of enhanced symmetry

    - Kofman, et. al. hep-th/0403001

    - S. W. hep-th/0404177

Cosmological Moduli

Example:

$$V_\Phi(T,H,\Phi) = 0 + m_{soft}^2\Phi^2 - H^2\Phi^2 + \frac{1}{M^{2n}}\Phi^{4+2n}$$

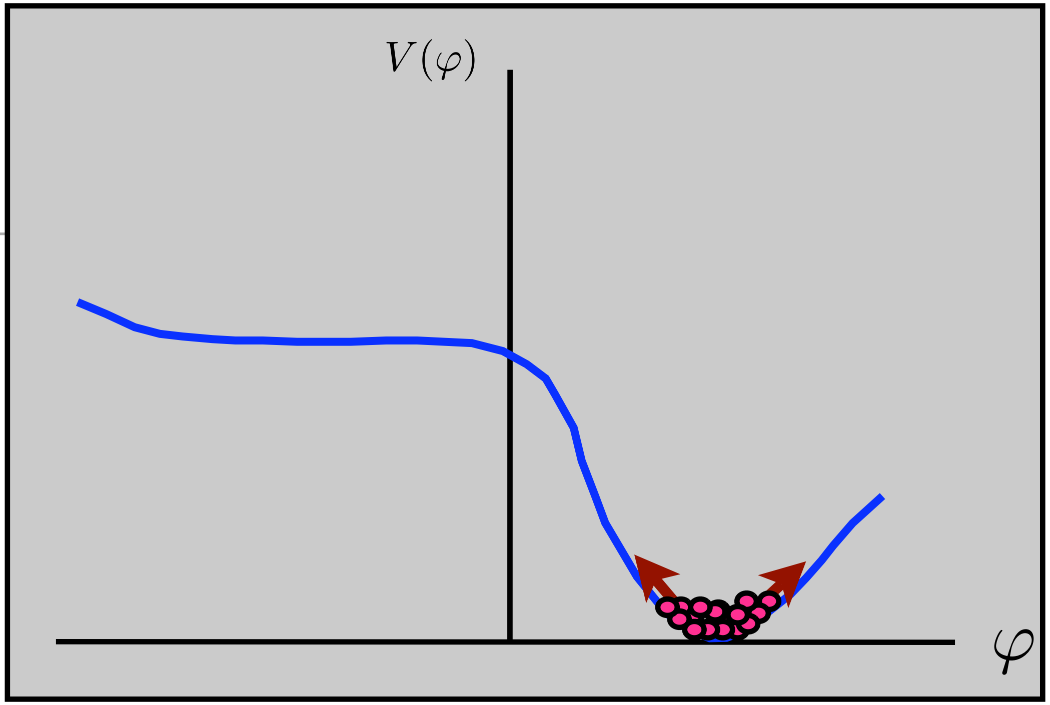
$$\langle\Phi\rangle \sim M\left(\frac{H}{M}\right)^{\frac{1}{n+1}} \qquad H \gg m_{3/2} \sim \ TeV$$

$$\langle\Phi\rangle \approx 0 \qquad H \ll M$$

Field “stuck” by Hubble friction

$\Delta\Phi \rightarrow \Delta E$ ⟶ Scalar Condensate

Approximate Moduli



Scalar Condensate forms

$$\Delta\Phi \rightarrow \Delta E$$

Typically evolve like pressure-less matter

$$\rho_m \sim \frac{1}{a^3} \qquad p = 0$$

Density grows relative to radiation
--> Danger for BBN!

Fate of Moduli

Decay Gravitationally

$$\Gamma_\varphi \sim \frac{m_\varphi^3}{M_p^2}$$

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Two possibilities:

Stable

$$m_\varphi < TeV \longrightarrow \rho_{mod} < \rho_c \longrightarrow \boxed{m_\varphi < 10^{-26}\ eV}$$

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Decay

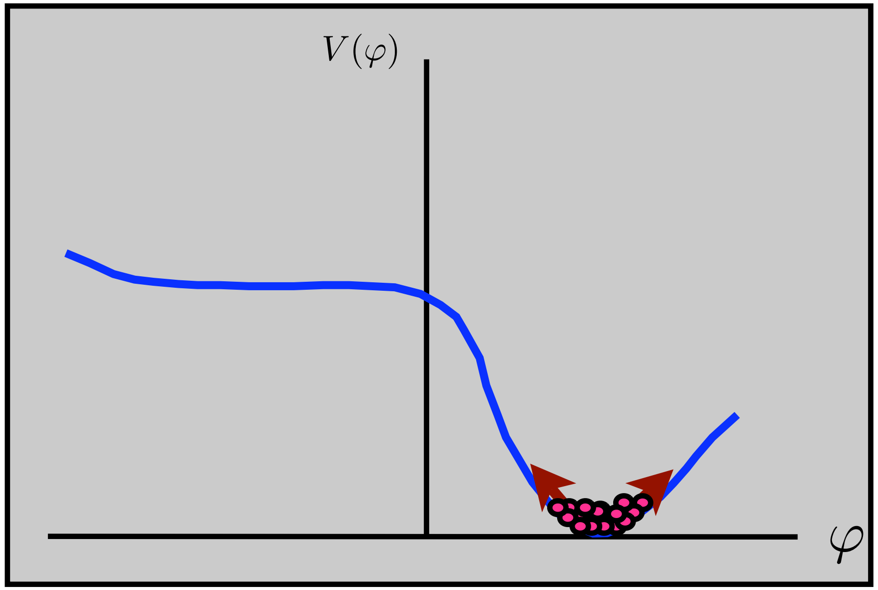
$$m_\varphi > TeV \qquad \tau_\varphi < 1s\ (BBN) \longrightarrow \boxed{m_\varphi > 10\ TeV}$$

Scalars and the CDM inverse problem

Scalar Condensates and Modified Expansion History

Coherent Oscillations

$$V(\Phi) \sim \Phi^{\gamma}, \qquad p = \left(\frac{2\gamma}{2+\gamma} - 1 \right) \rho.$$



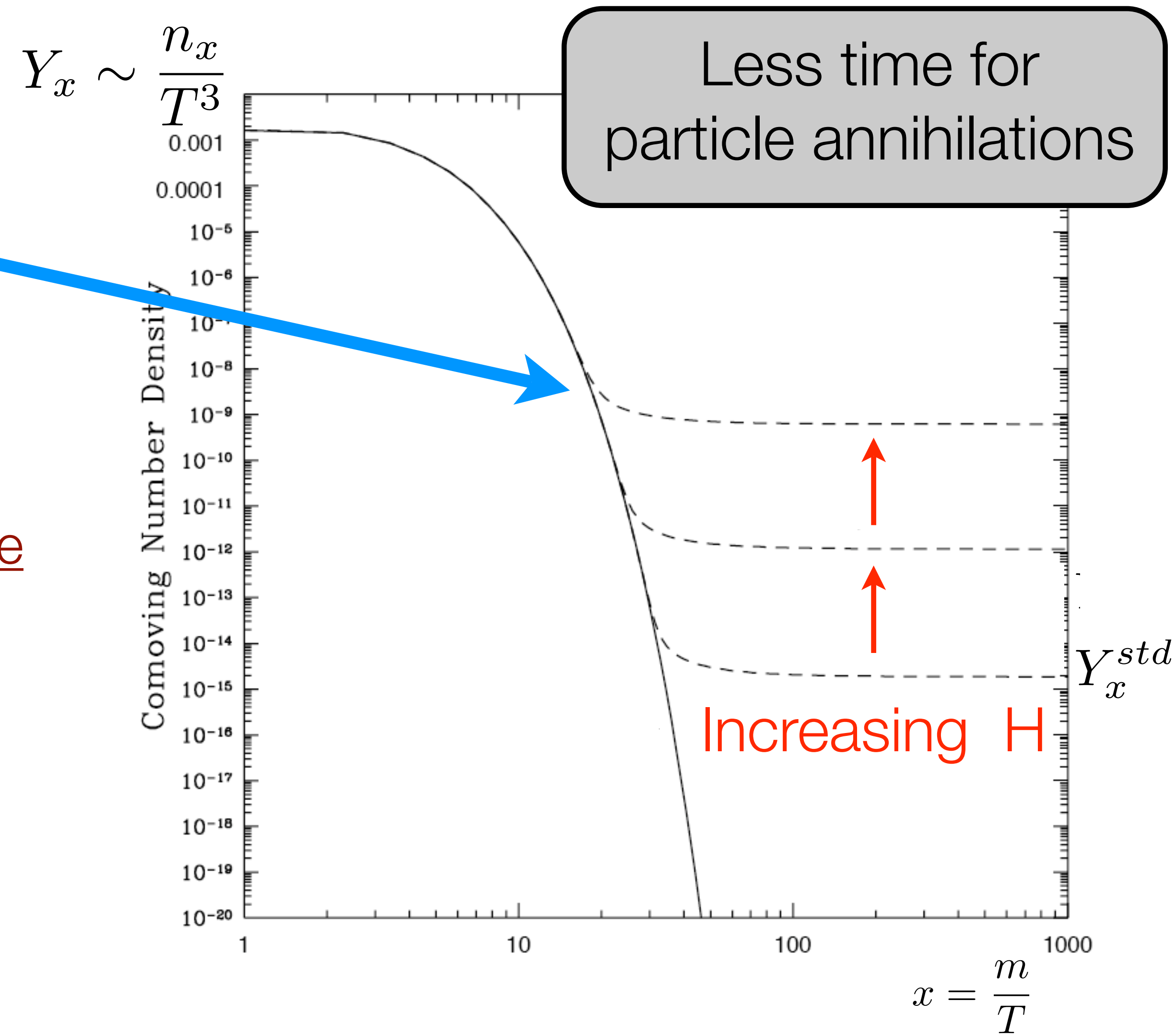
$\gamma = 0$	$p = -\rho,$	Λ
$\gamma = 1$	$p = -\frac{1}{3}\rho,$	tadpole
$\gamma = 2$	$p = 0,$	matter
$\gamma = 4$	$p = \frac{1}{3}\rho,$	radiation
$\gamma = \pm\infty$	$p = \rho,$	stiff fluid

Nonrenormalizable Operators

(1) Modified Expansion History

“Freeze-out” $H > n_X \langle \sigma v \rangle$

$$Y \sim \frac{H_f}{\langle \sigma v \rangle_f T_f^3}$$



Moduli can increase expansion rate

Increase: H

Increase: $\langle \sigma v \rangle$

Scalar Decay to Dark Matter

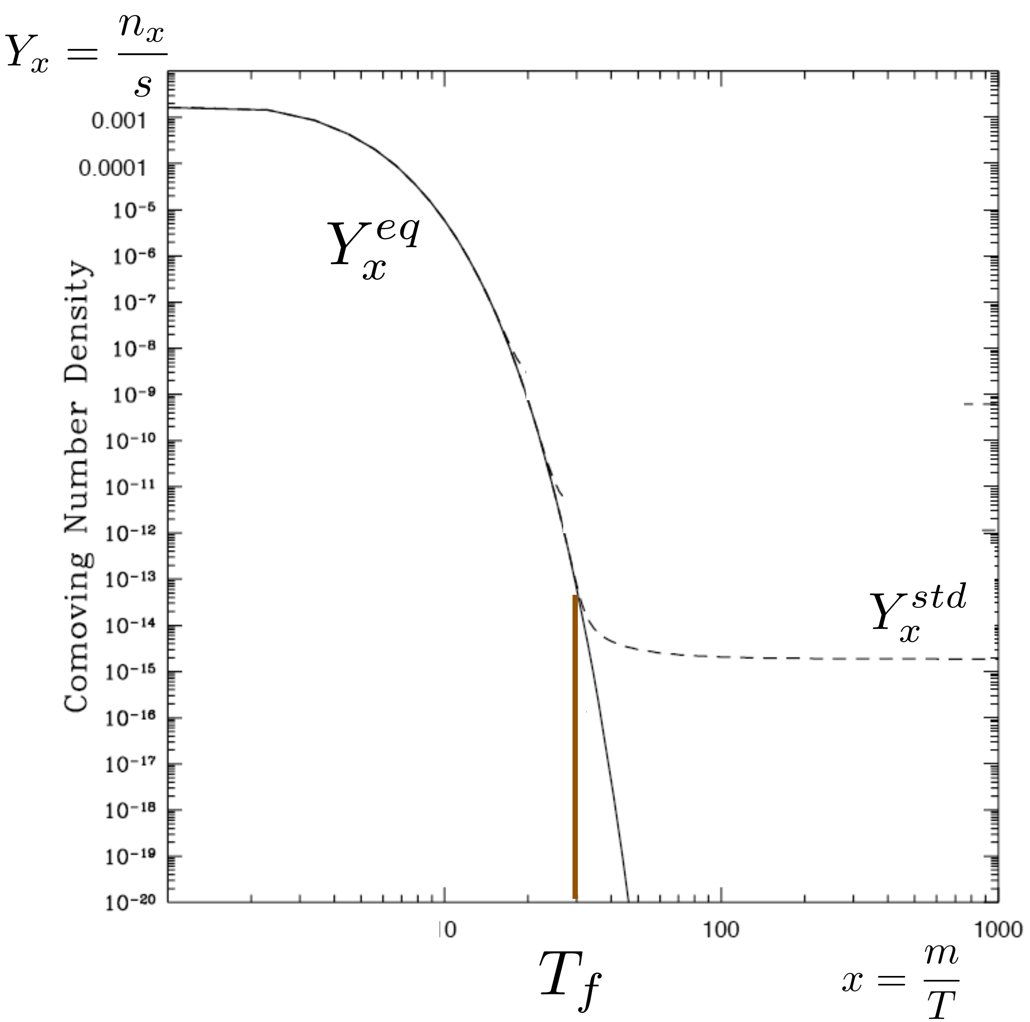
Moduli Decay

(2) Entropy production

(dilute existing dark matter)

$$\varphi \rightarrow \gamma\gamma$$

$$T_r \approx \left(\frac{m_\varphi}{10\,TeV}\right)^{3/2} \; MeV$$



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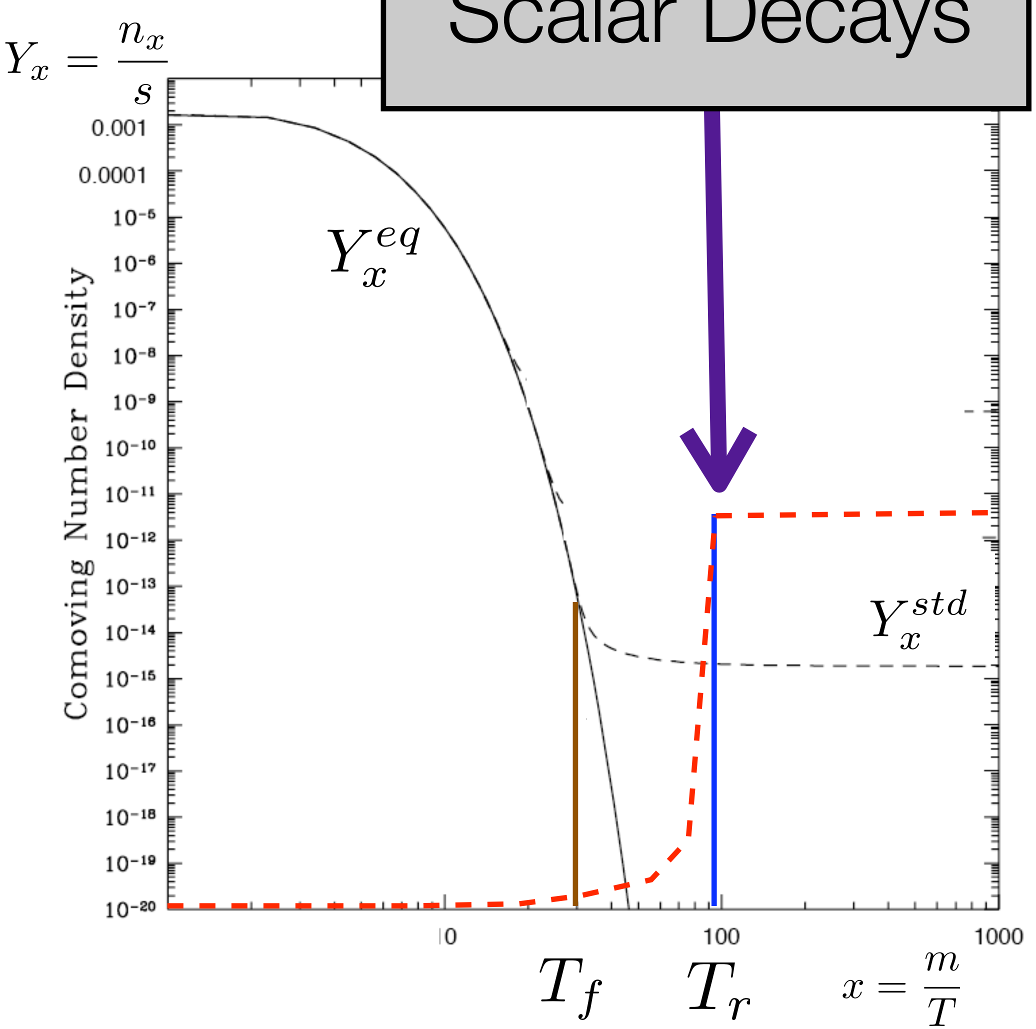
Non-thermal Production

(3) Dark matter from decay

$$\varphi \to XX$$

$$T_f \approx \left(\frac{m_X}{100\,GeV}\right) GeV$$



$$T_r < T_f \longrightarrow$$ **No Annihilation !!!**

Scalars and CDM Inverse Problem

- Modified Expansion History -- larger cross-sections allowed
- Non-thermal Production -- larger cross-sections allowed
- Entropy Production can dilute existing CDM

Modified expansion

$$\Omega_X = \Omega_X^{std}\sqrt{1+r}$$

$$\Omega_X = \frac{10^{-10}\ GeV^{-2}}{\langle\sigma v\rangle}\sqrt{1+r}$$

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$$\Omega_X \sim \frac{m_X}{\langle\sigma v\rangle T_r} \sim \Omega_X^{std}\left(\frac{T_f}{T_r}\right)$$

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All have parametric dependence on fundamental theory !!!!

Example: Dark matter in the MSSM

Neutralino WIMPs (light, stable, neutral)

$$\tilde{\chi} = N_{i1}\tilde{B} + N_{i2}\tilde{W}^3 + N_{i3}\tilde{H}_1^0 + N_{i4}\tilde{H}_2^0$$

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Bino-like cross-section (P-wave suppression)

$$\langle \sigma v \rangle \sim 10^{-9}\, GeV^{-2} \qquad \Omega_{lsp}\, h^2 \sim 0.1$$

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"Anomaly" Mediated SUSY Breaking (AMSB) (e.g. Moroi / Randall)

- Gaugino masses loop suppressed (arise via anomaly)
- Gravitino naturally 10-100 TeV
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"Cosmology of the G2 MSSM" -- (to appear soon)
B. Acharya, K. Bobkov, G. Kane, P. Kumar, J. Shao and S.W.

- M-theory compactification all moduli are geometric
- 50 TeV gravitino -- no gravitino problem(s)

$$m_{3/2} = 50\, TeV$$

- Many light moduli

$$m_{X_N} = 600\, m_{3/2} \qquad m_{\varphi} = 2\, m_{3/2}$$

$$m_{X_i} = 2\, m_{3/2} \quad i = 1 \ldots N-1$$

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In both examples:

Scalars decay to wino-like neutralino and radiation

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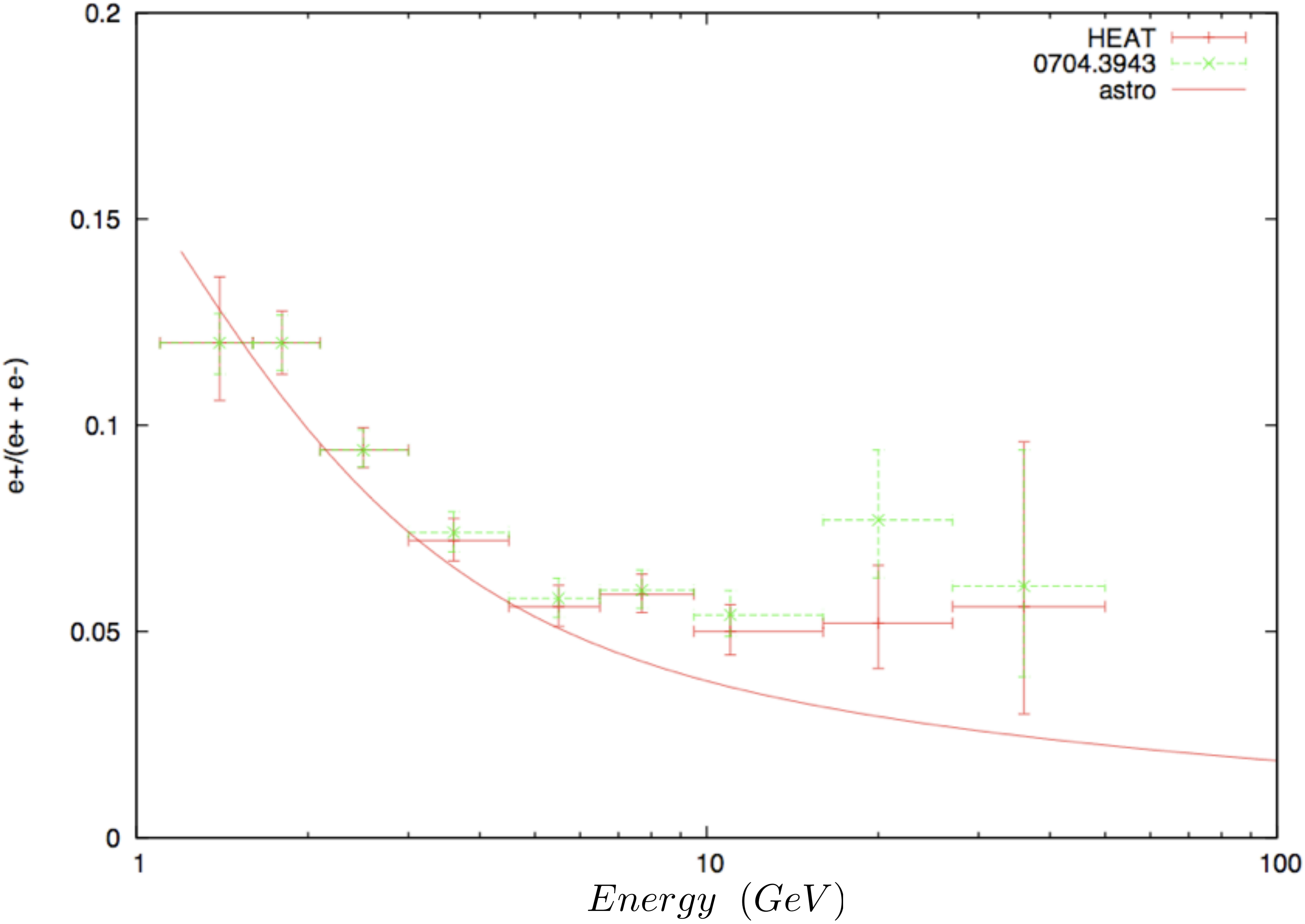
~ 0.1

Positron Excess -- Annihilating Dark Matter?



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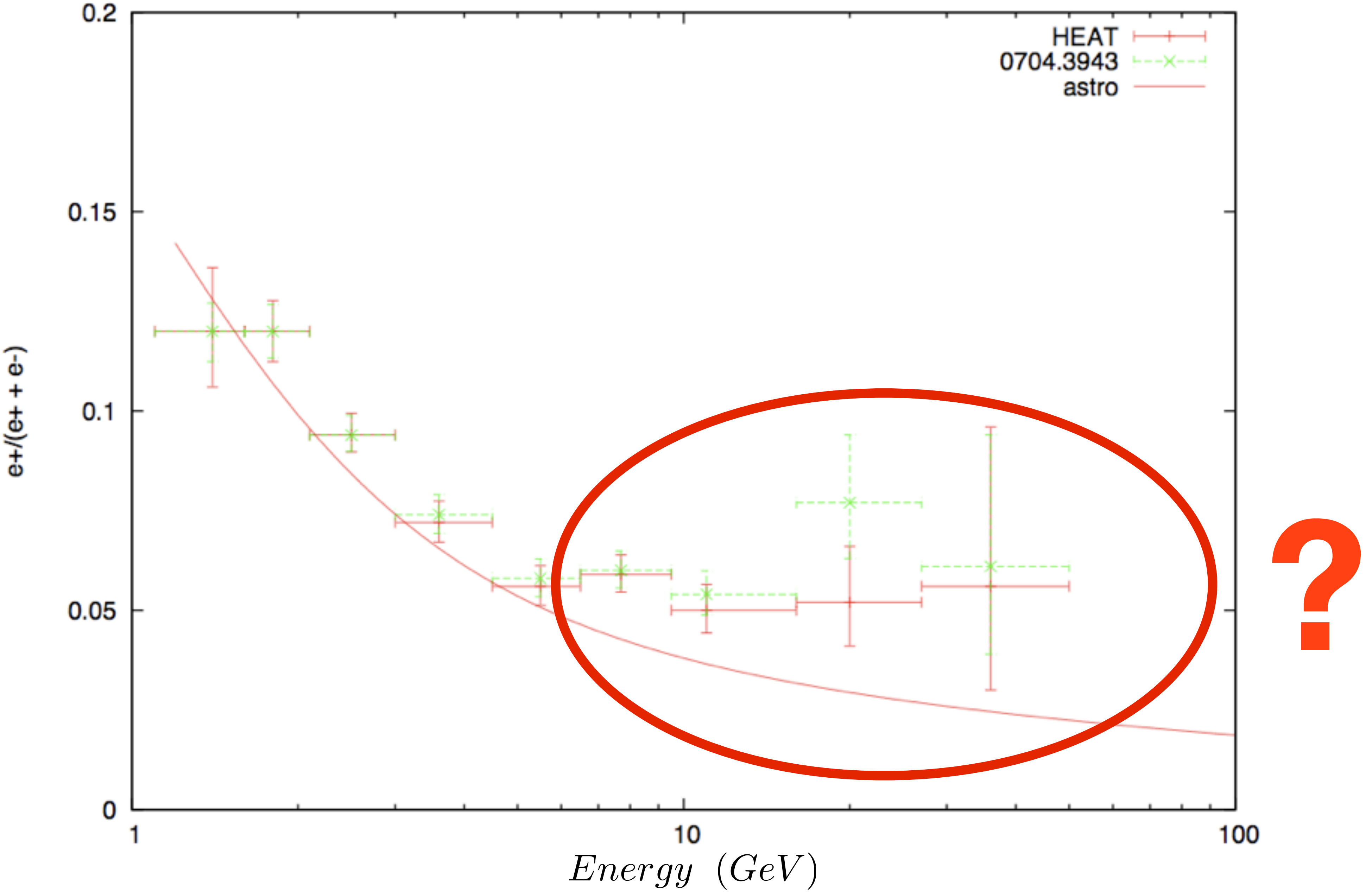

Wino-like Neutralinos - Positron Excess

Could excess be due to annihilating dark matter?

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Wino leading decay channel:

$$\chi + \chi \rightarrow W + W \rightarrow e^+ + X$$

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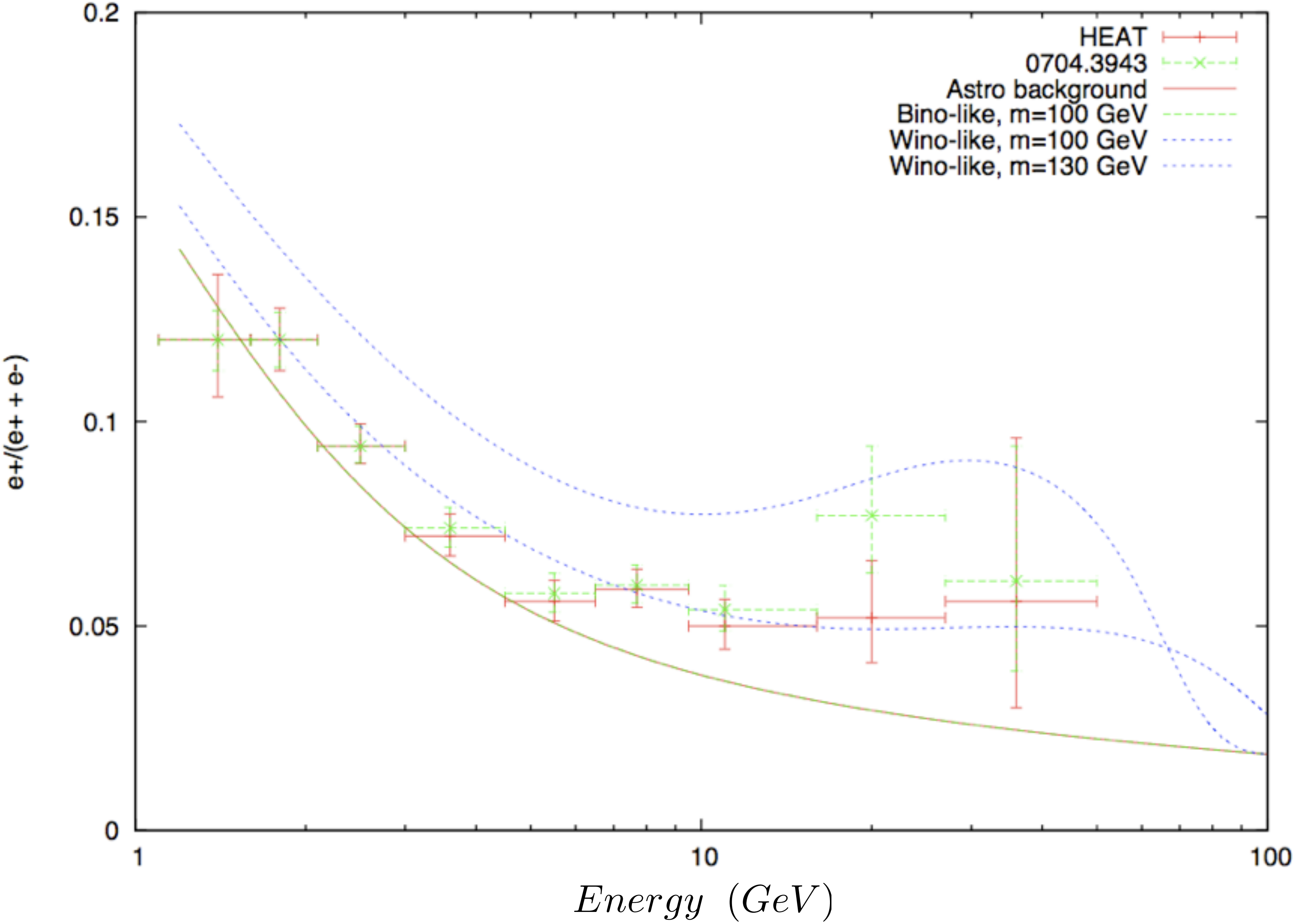

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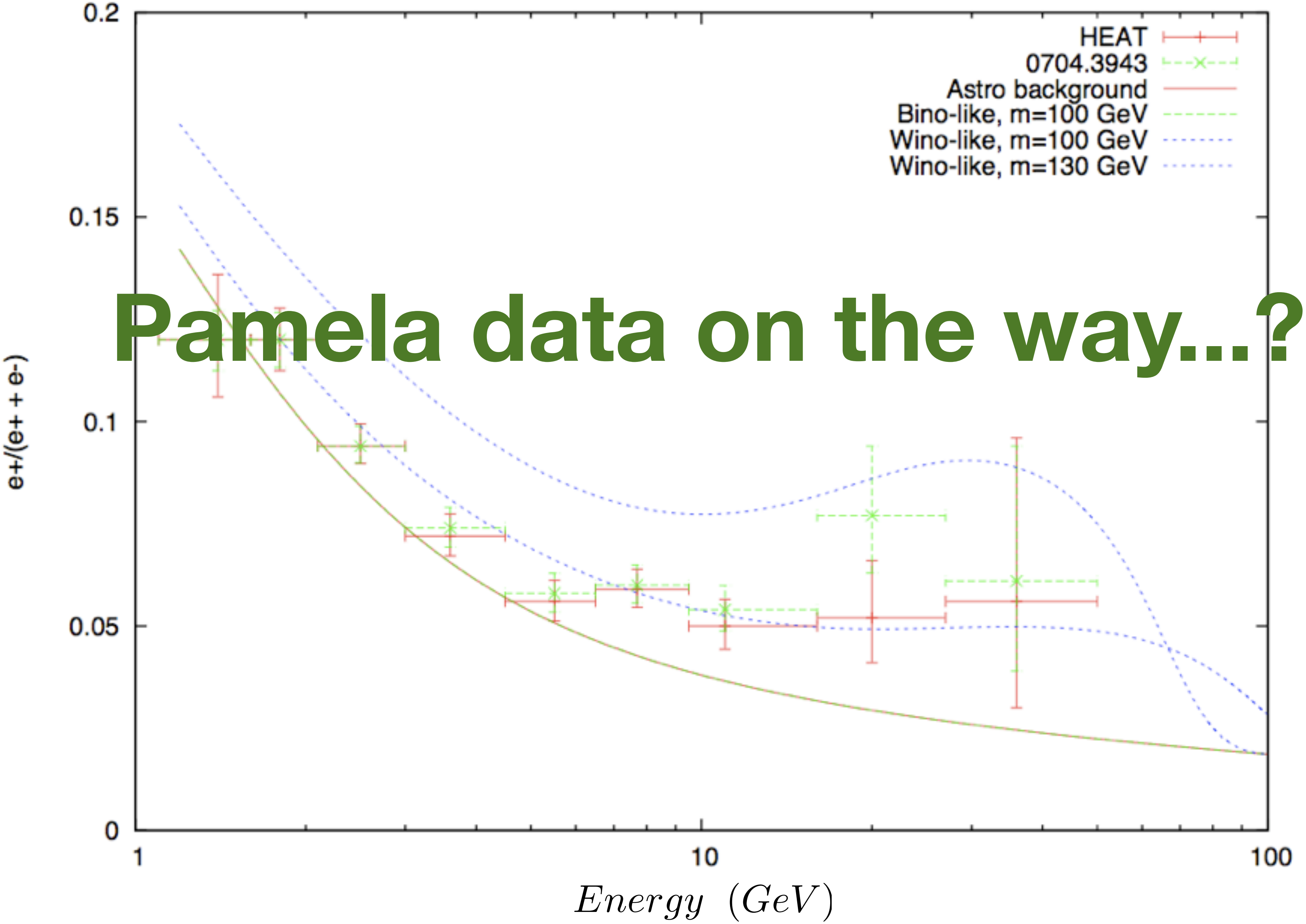
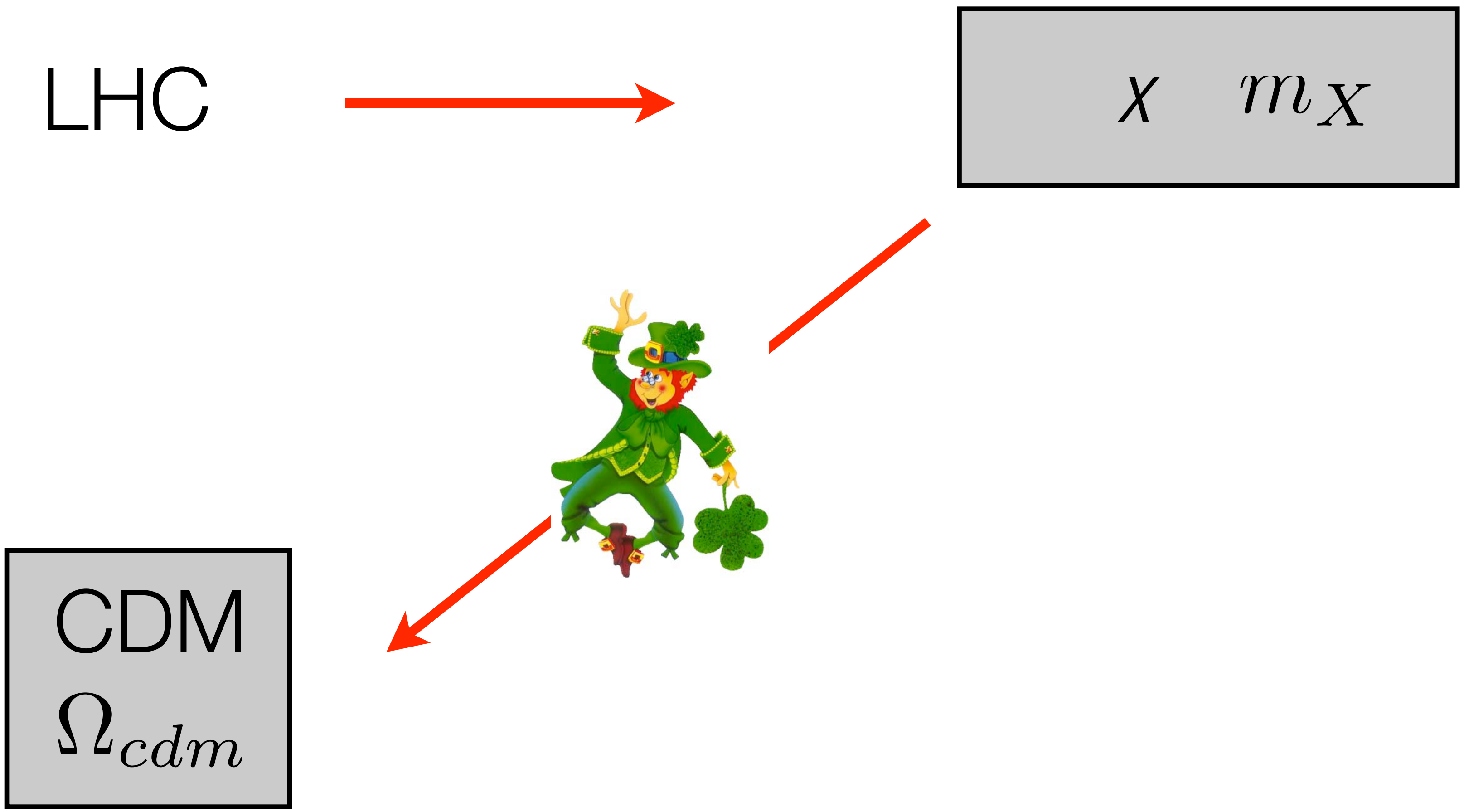


SUMMARY:
LHC and the Dark Matter Inverse Problem



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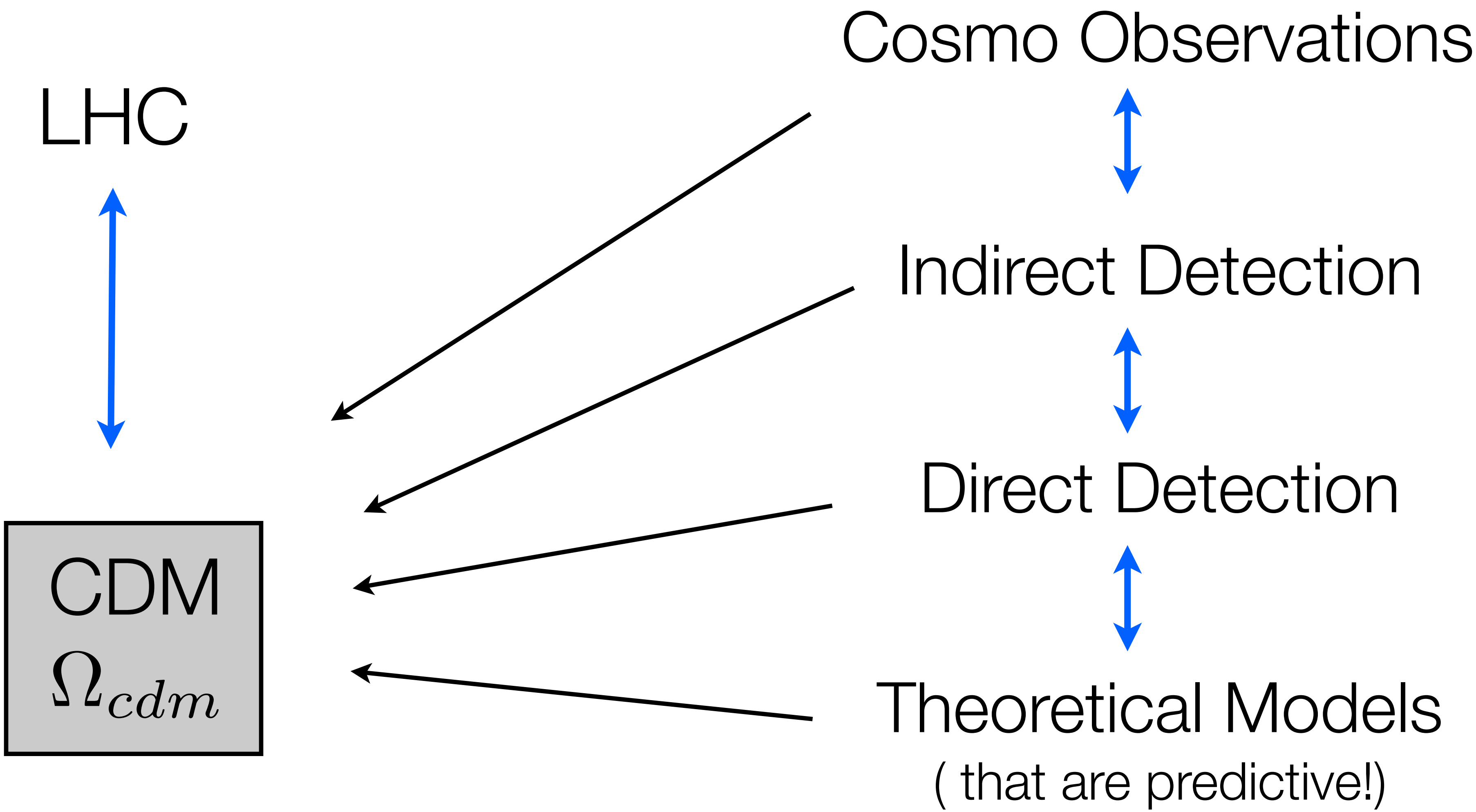

Conclusions and Outlook

- If we are CLEVER (model independent methods) and **LUCKY** (1 candidate, thermal equil): LHC may tell us the completely story
- Most likely we will not be so lucky (or clever):
    - Many CDM candidates (axions, neutrinos)
    - Many degeneracies
    - Many ways thermal abundance picture can fail

- Condensates could lead to non-thermal production
- Non-thermal production --> Probe on early universe
- Constraints on interaction cross-sections lifted (e.g. Wino-like Neutralino becomes good candidate)
- Larger cross-sections --> Detection more possible (e.g. gamma ray bursts / positrons / etc.)
- Baryon asymmetry (AD)? Coincidence problems (baryons/cdm)?
- Robust approach:
  LHC + other colliders + direct / indirect detection + cosmology probes