BSM theories with long-lived charged particles at the LHC

based on:

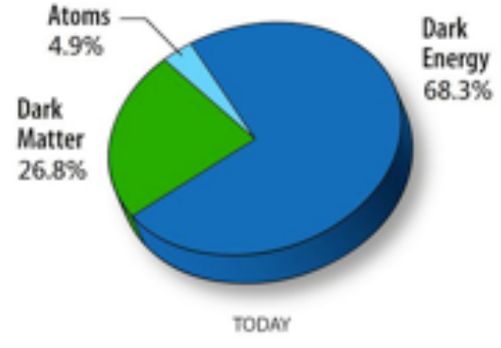
JH, Andre Lessa, Loic Quertenmont, JHEP 1512 (2015) 087 [1509.00473]
JH, Jörn Kersten, Boris Panes, Tania Robens, JHEP 1404 (2014) 053 [1310.2825]
JH, JCAP 1404 (2014) 023 [1310.6352]

Jan Heisig (RWTH Aachen University)

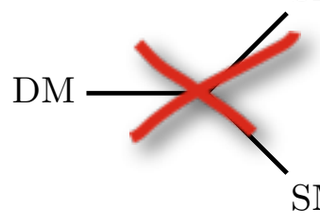
Seminar at the UC Louvain, February 17th 2016

Why looking at long-lived charged particles?

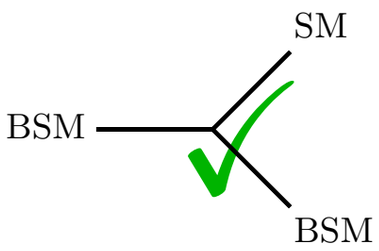
(or heavy stable charged particels - HSCPs)



- Most BSM theories motivated by Dark Matter
  Need for a stable candidate!
- Impose a Z_2-symmetry: Dark matter Z_2-odd
- Only vertices with even numbers ⇒ no decay



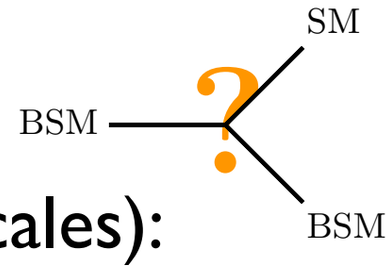
- Full theories: complete Z_2-odd sector
  (R-parity, KK-parity)
  ⇒ Cascade decays in the Z_2-odd sector



- Lightest Z_2-odd particle neutral
  For prompt decays ⇒ missing energy signature at the LHC

Why looking at long-lived charged particles?

(or heavy stable charged particels - HSCPs)



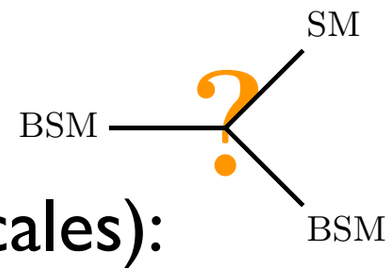
- Two situations in which not all decays are promt, charged particle can become stable (on collider time-scales):

I. Suppressed coupling of lightest Z_2-odd particle
   - SUSY: Axino/gravitino LSP → NLSP long-lived

II. Decay of a heavier Z_2-odd particle is kinematically suppressed
   - SUSY: Wino/Higgsino-LSP [e.g. Bomark, Kvellestad, Lola, Osland, Raklev, 1310.2788]
   - Extra Dimensions [Byrne, hep-ph/0311160]
   - SUSY: Stau-neutralino degeneracy (co-annihilation strip) [e.g. Jittoh, Sato, Shimomura, Yamanaka, hep-ph/0512197]

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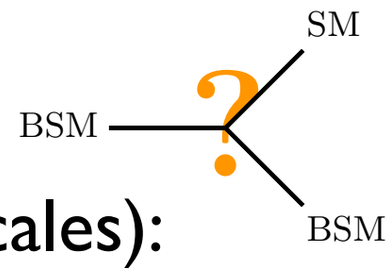
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Outline

- Introduction

  HSCPs at the LHC
  HSCPs in Cosmology

- Cosmological implications for HSCP searches

  Gravitino LSP - stau NLSP scenario

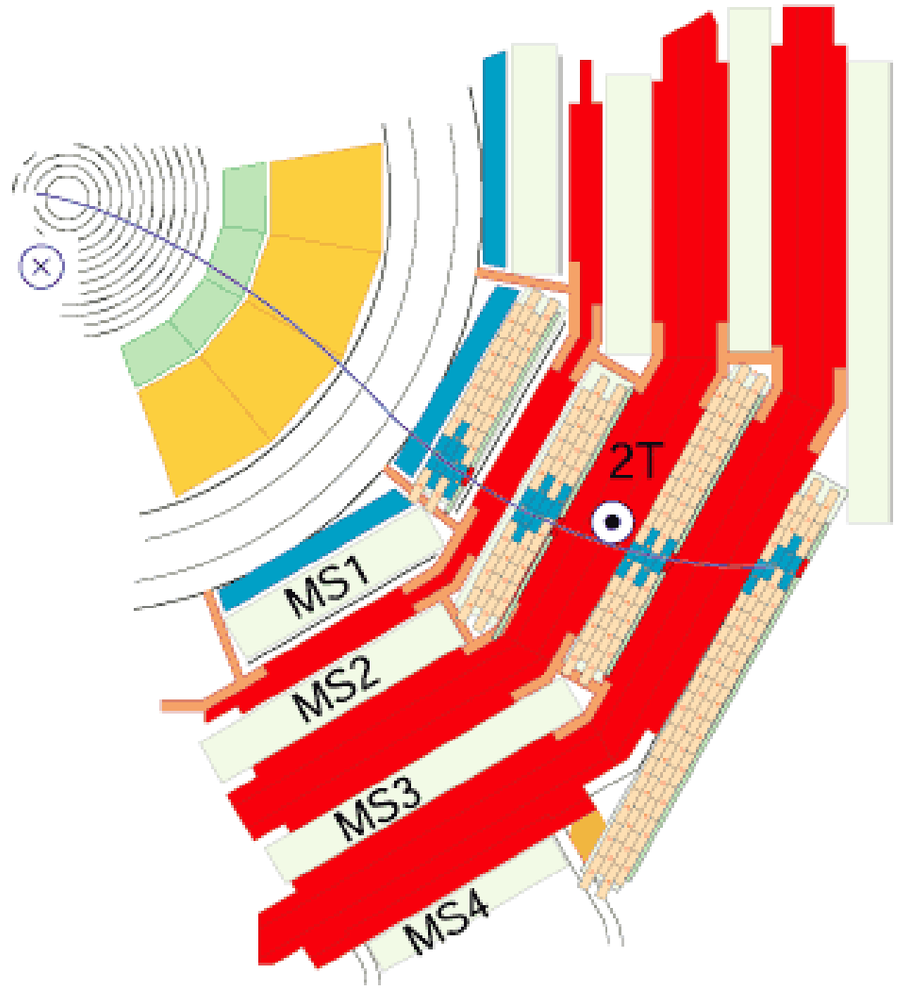
- Simplified models for HSCPs

  Why simplified models?
  Implementation into SModelS
  Application to stau co-annihilation strip

Introduction

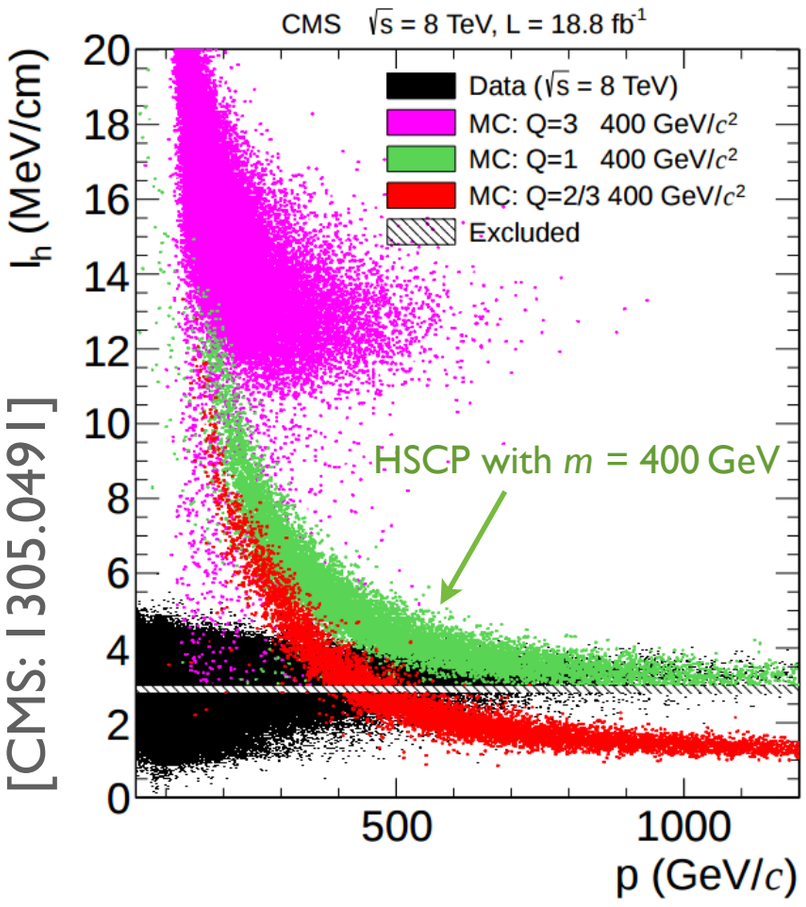
HSCP at the LHC: a prominent signature

- Pass the whole detector: muon-like signature
- Two disctinct features

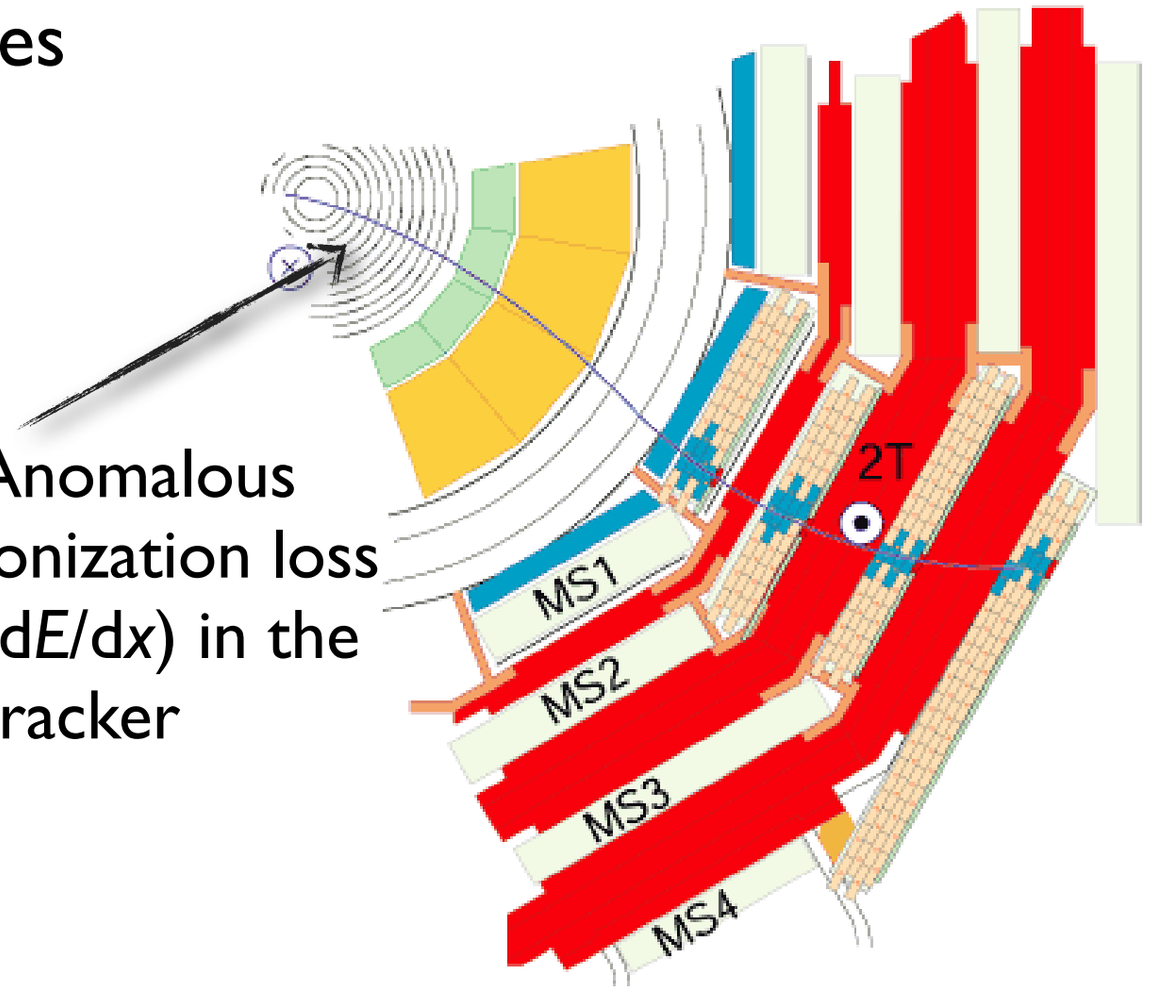


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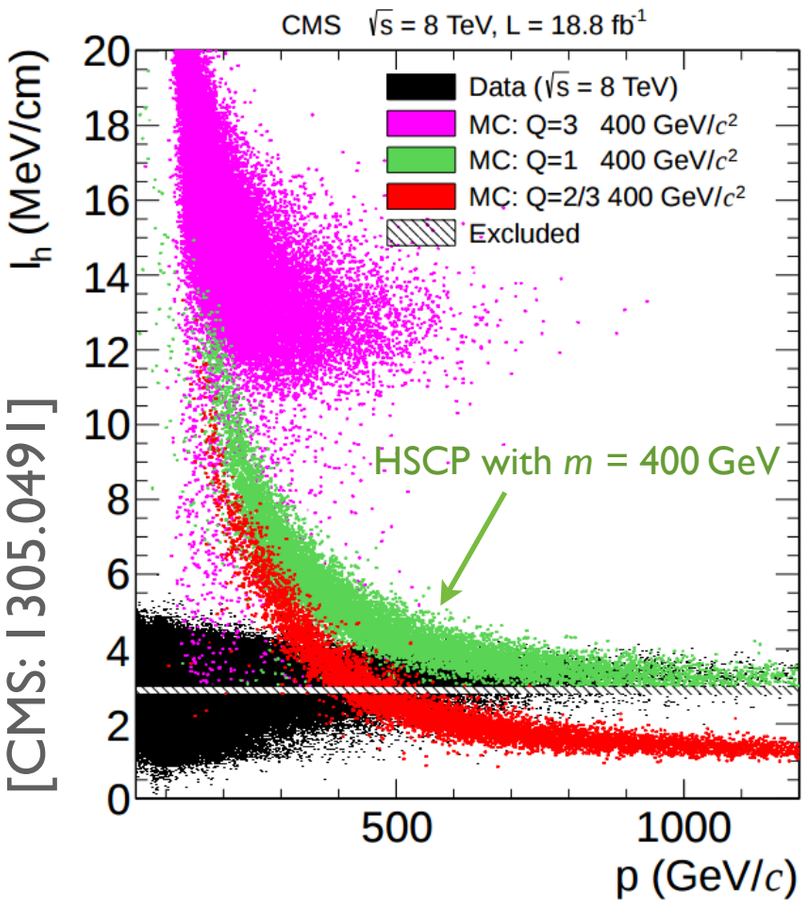


Anomalous ionization loss (d*E*/d*x*) in the tracker

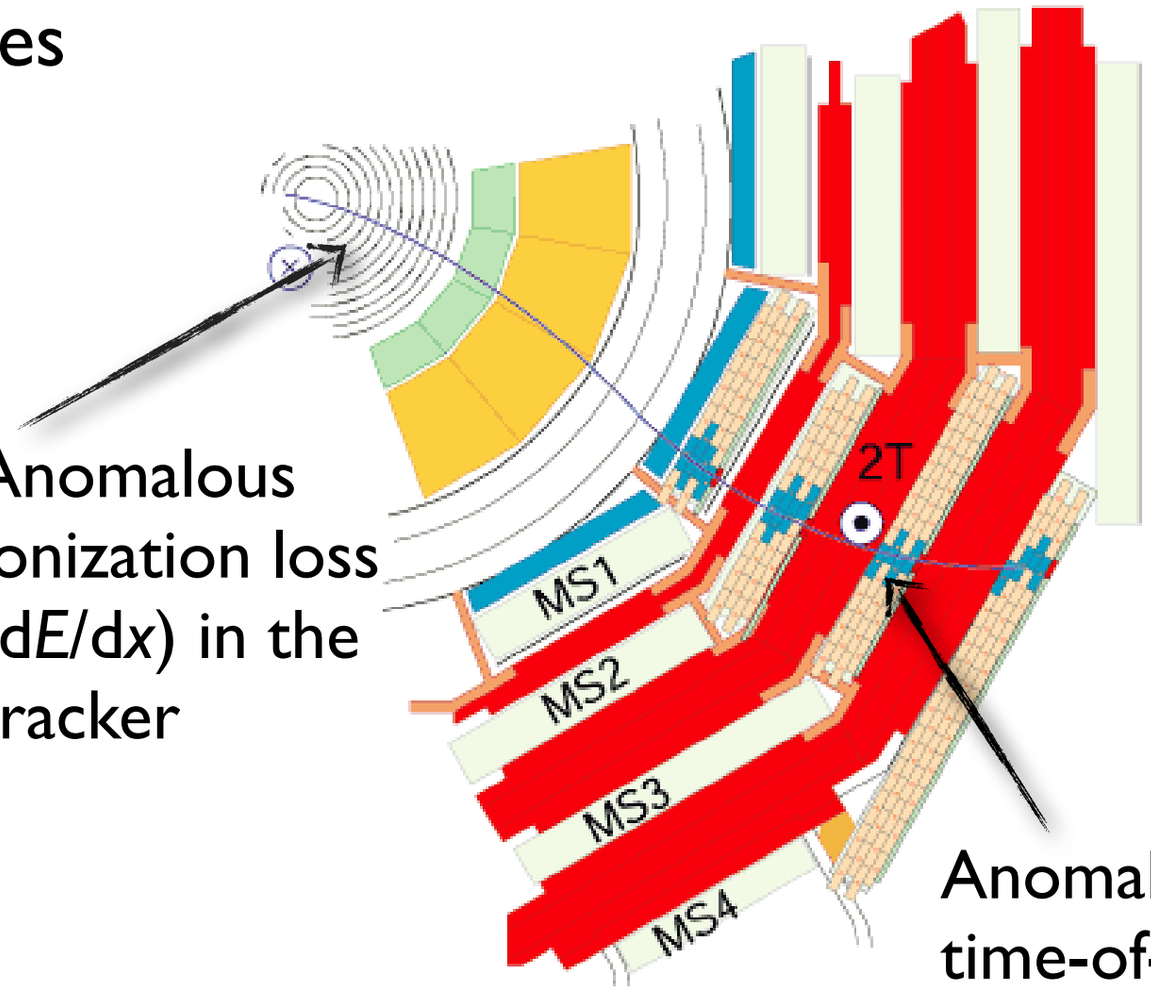


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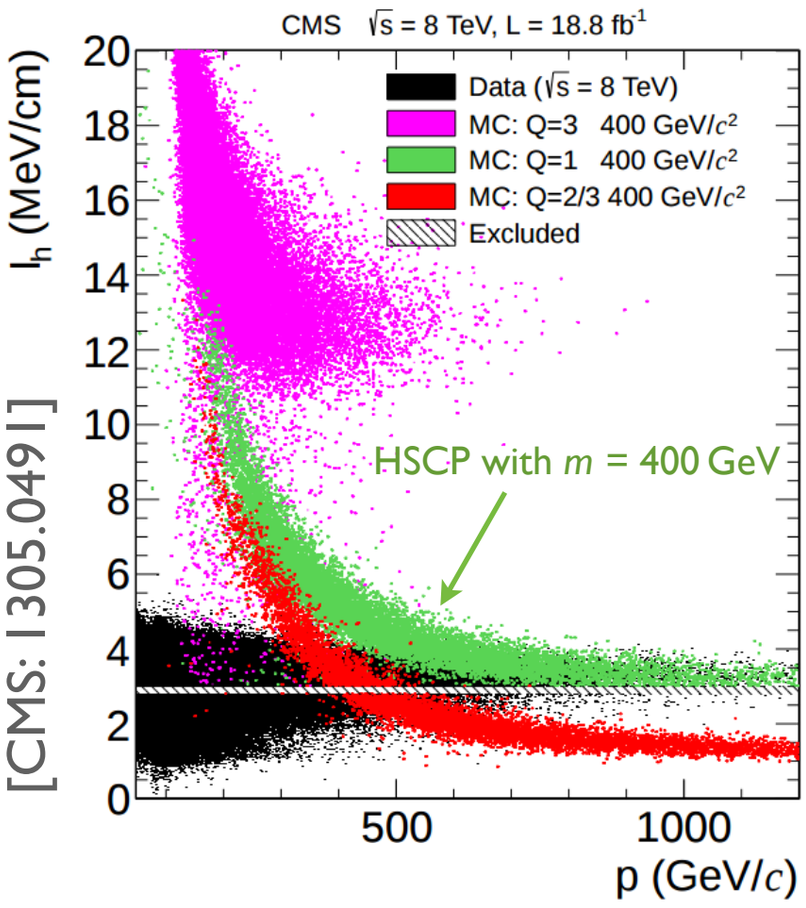
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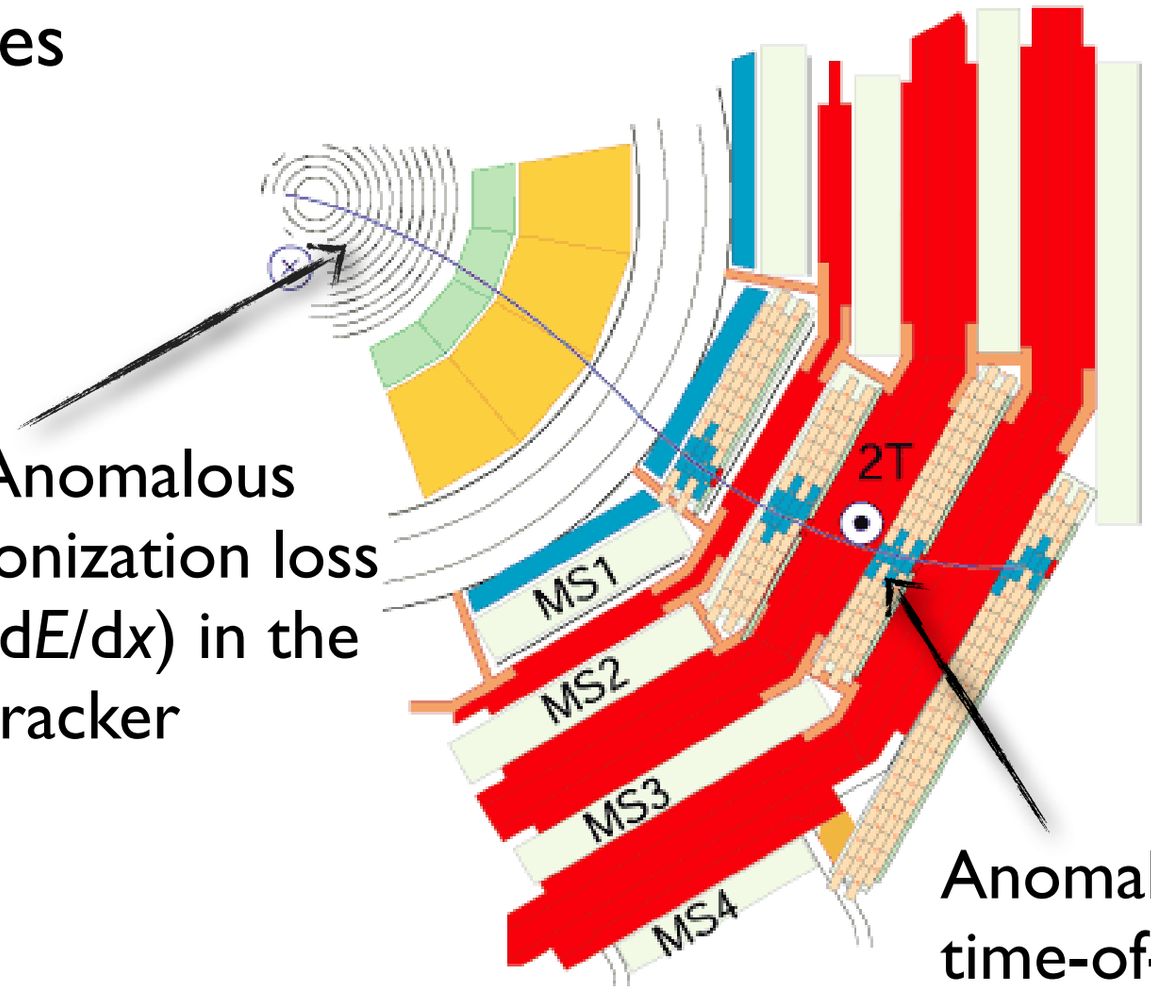
Anomalous time-of-flight in the muon-system

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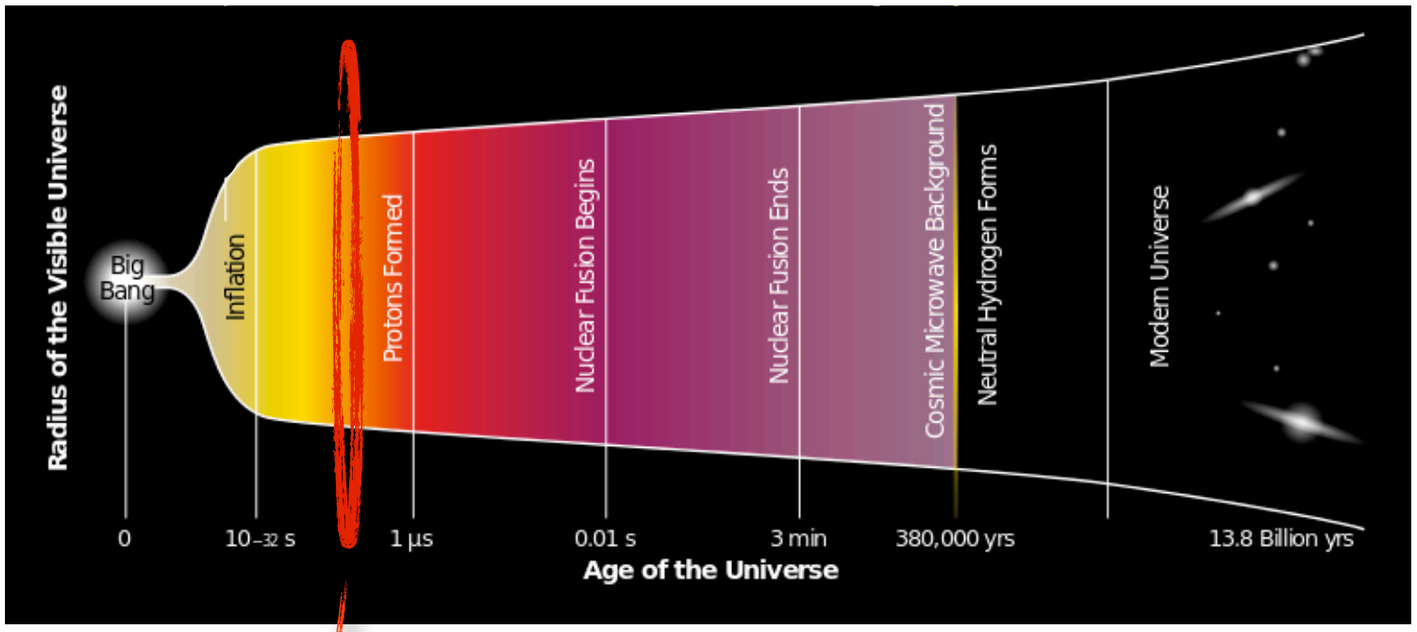
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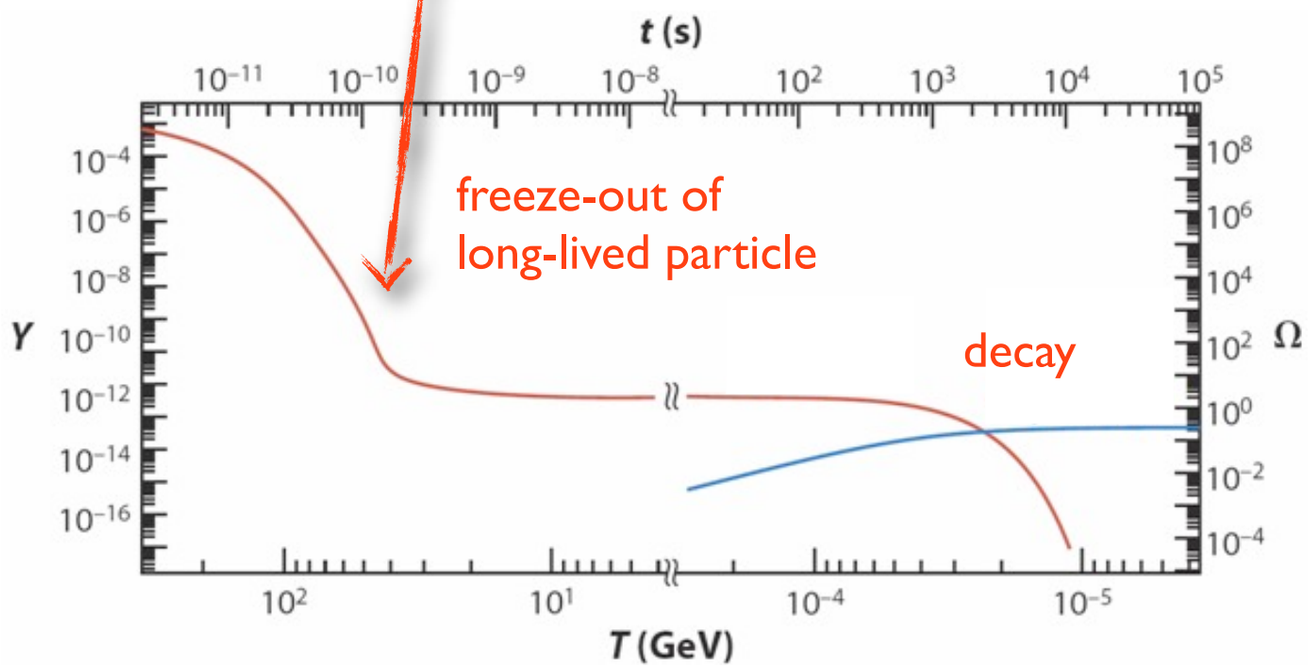


Anomalous time-of-flight in the muon-system

High sensitivity!

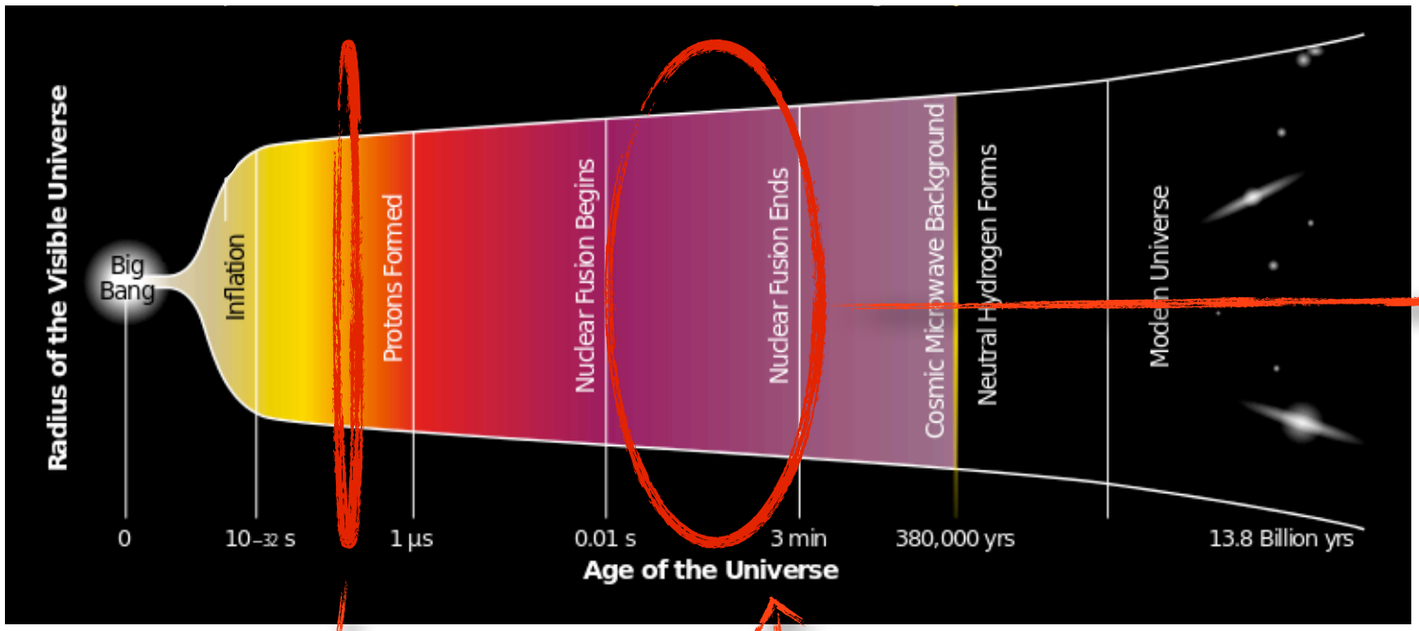
HSCPs and Cosmology

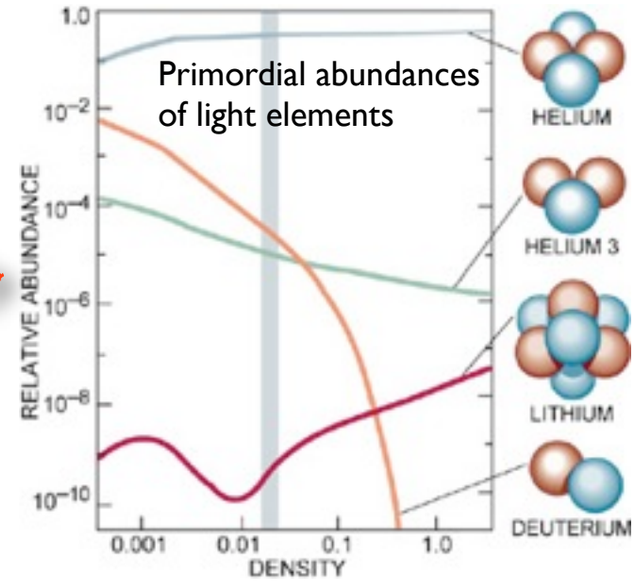




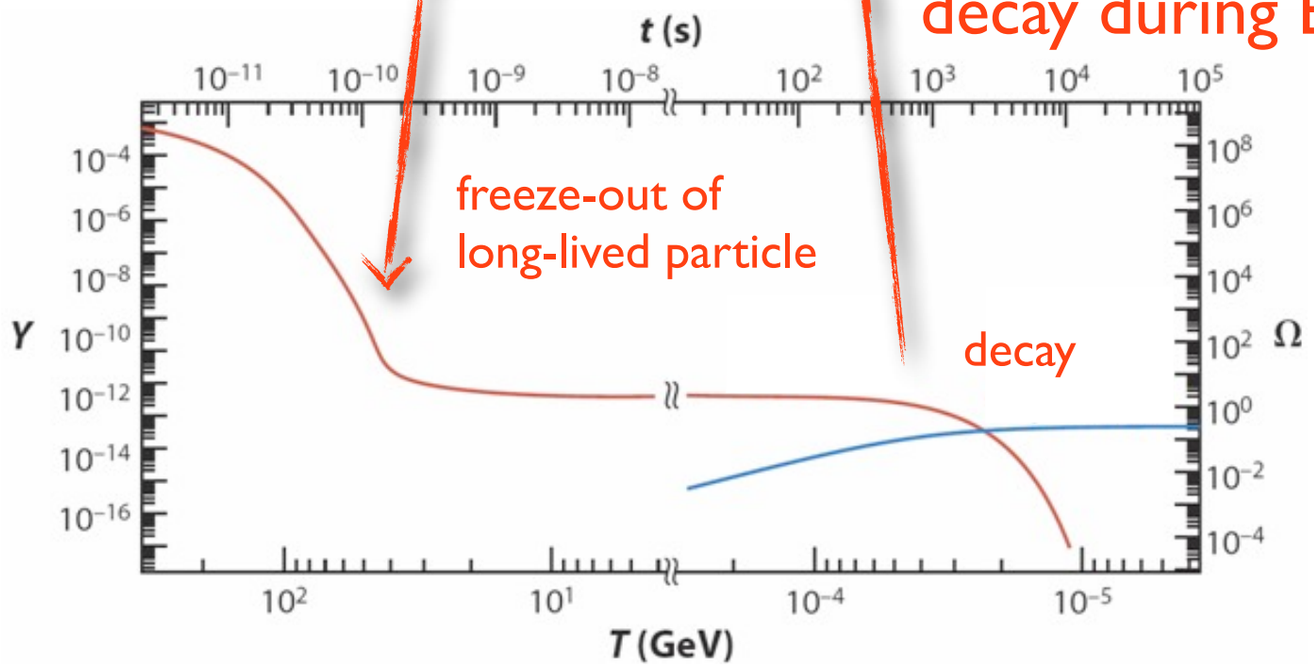
- Very early universe:
  Z_2-odd particles in thermal eq.
- $T < m_{\mathrm{HSCP}}$: Long-lived Z_2-odd particle freezes out (like DM)
- Decays out-of-equilibrium

HSCPs and Cosmology





decay during BBN?



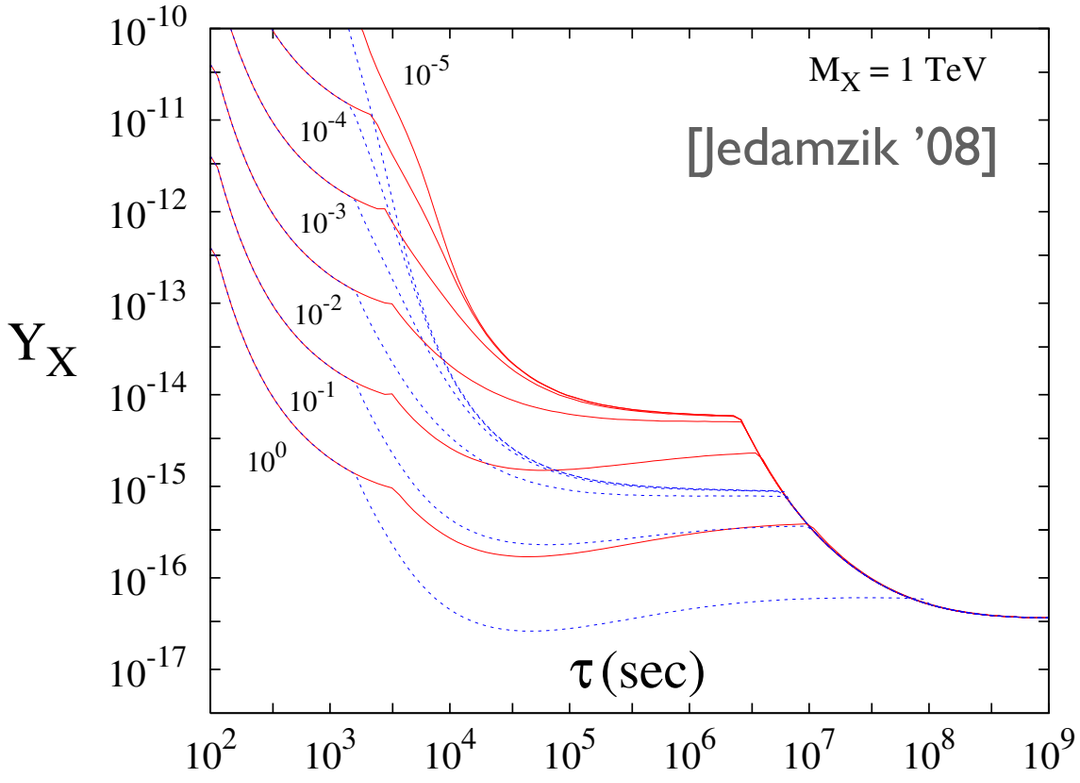
- Decay during or after Big Bang Nucleosynthesis (BBN): Predictions change
- Standard BBN explains D, ^{3}He, ^{4}He
- Some discrepancy for ^{7}Li

HSCPs and Cosmology

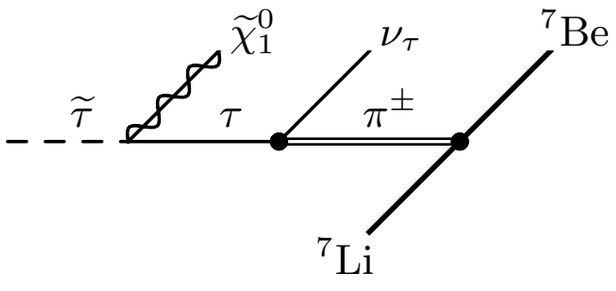
- BBN sets constraints on the <u>live-time</u> and <u>abundance</u> of long-lived particles
- ^{7}Li-Problem:

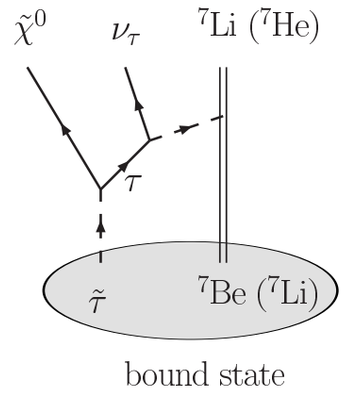
$$\left(\frac{^7\mathrm{Li}}{\mathrm{H}}\right)_{\mathrm{theo}} = (4.68 \pm 0.67) \times 10^{-10},$$

$$\left(\frac{\mathrm{Li}}{\mathrm{H}}\right)_{\mathrm{exp}} = (1.6 \pm 0.3) \times 10^{-10}\,.$$



- Proposed solution: Depletion of ^{7}Li via HSCPs



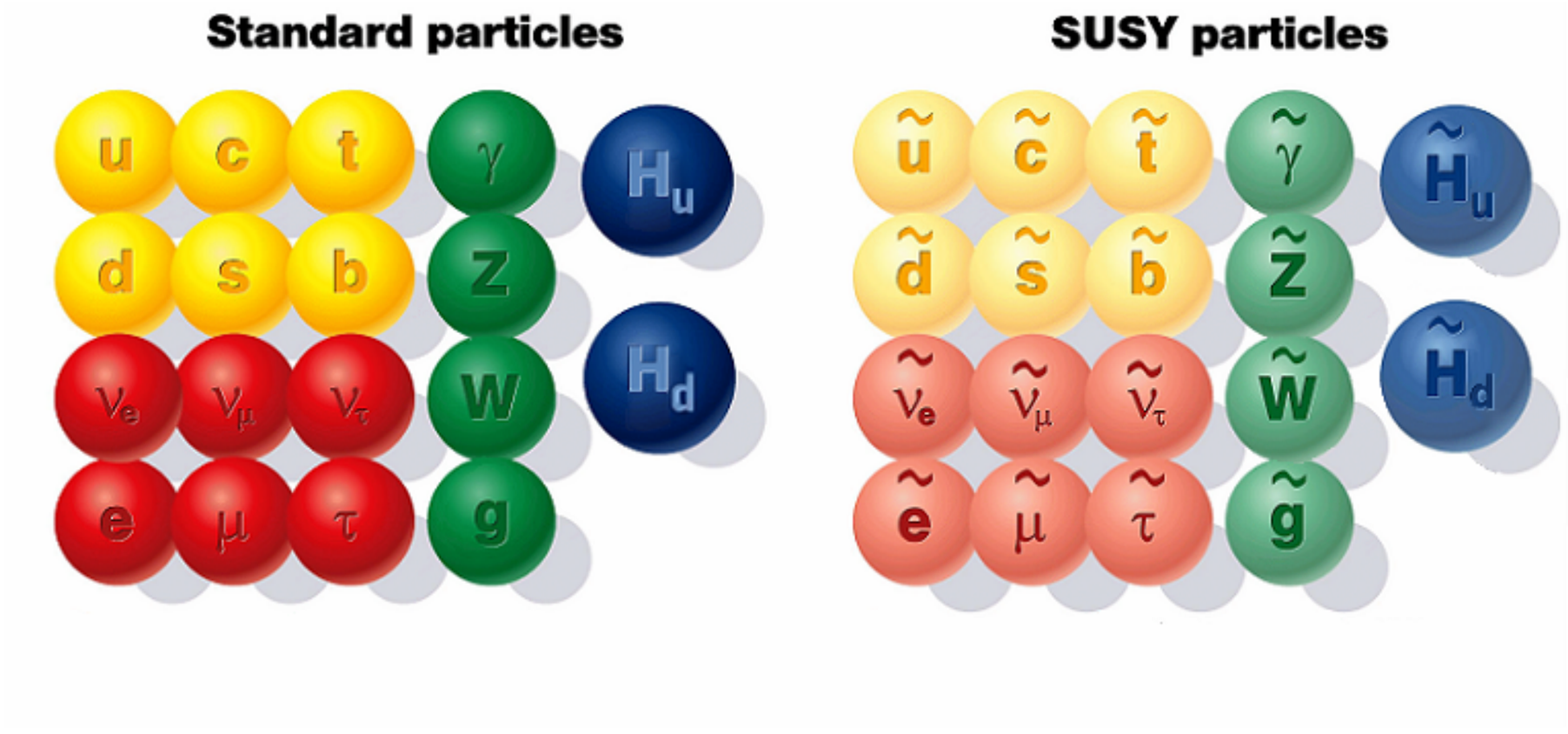


[see e.g. Jittoh, Kohri, Koike, Sato, Shimomura, Yamanaka, 0704.2914]

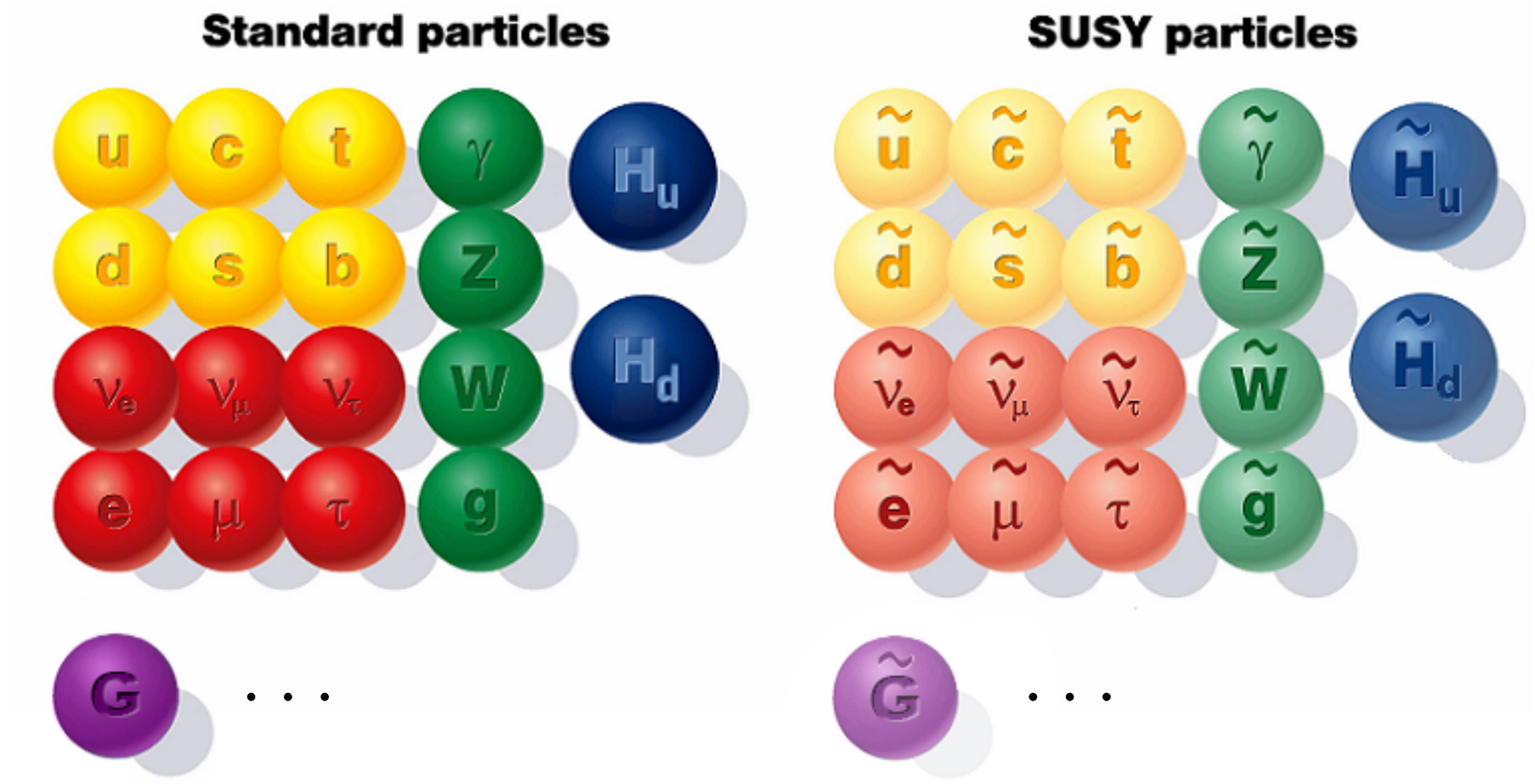
Cosmological implications for HSCP searches

Gravitino LSP - stau NLSP scenario

Gravitino LSP: Motivation

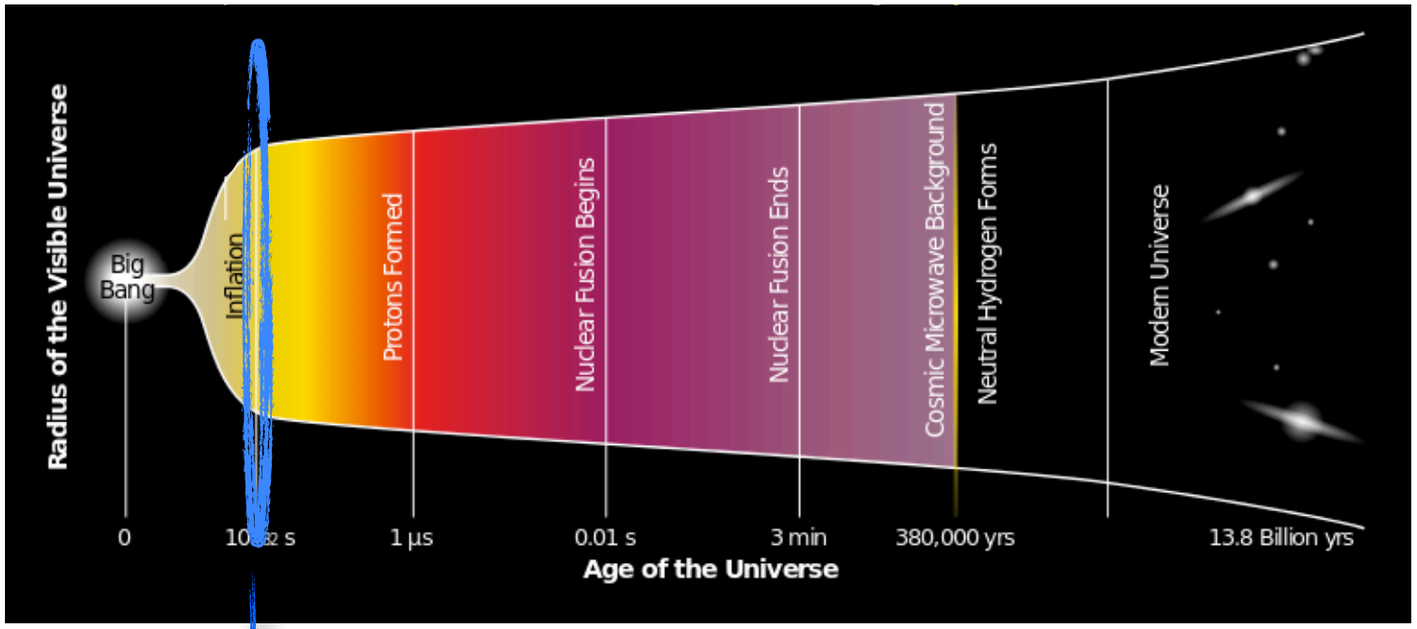


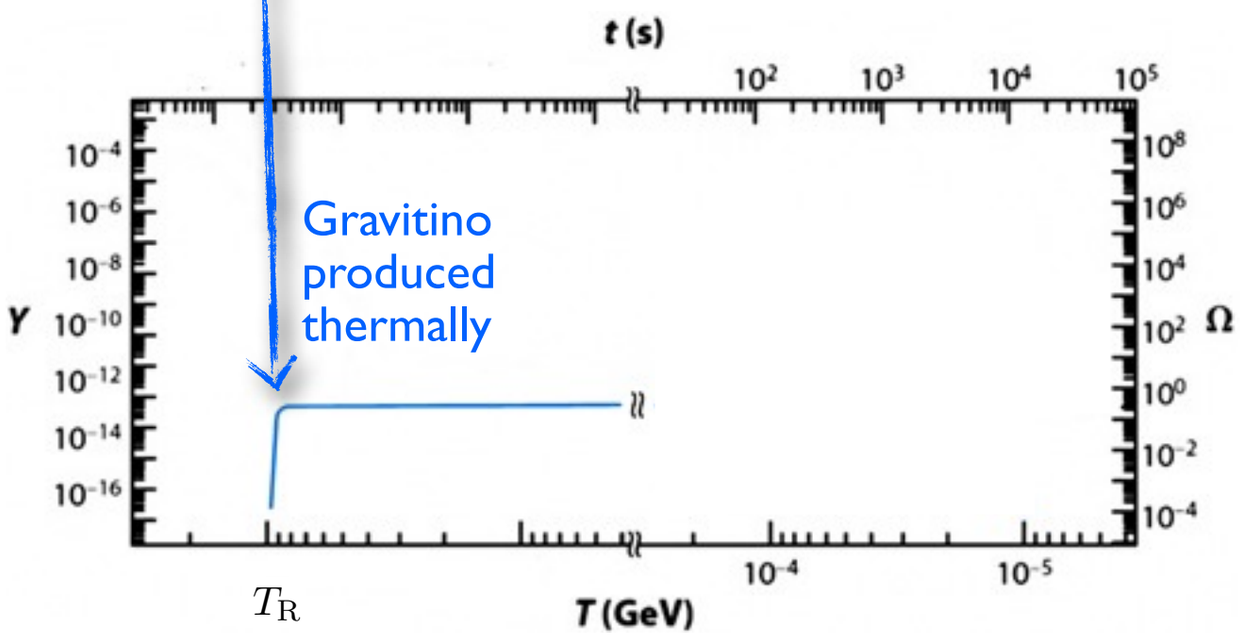
Gravitino LSP: Motivation



- If Supersymmetry is a fundamental symmetry: supergravity
  $\Rightarrow$ gravitino $\widetilde{G}$
- Gravitino couplings Planck suppressed: Not in thermal eq.

Gravitino LSP: Motivation

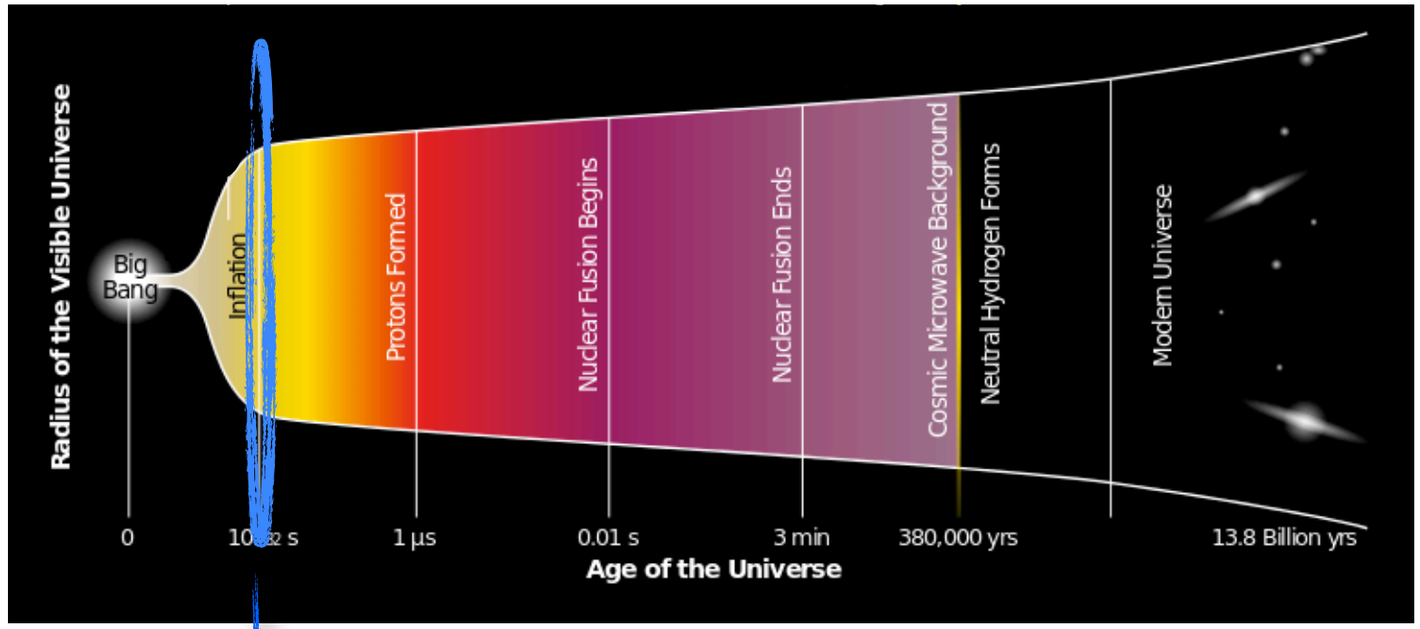


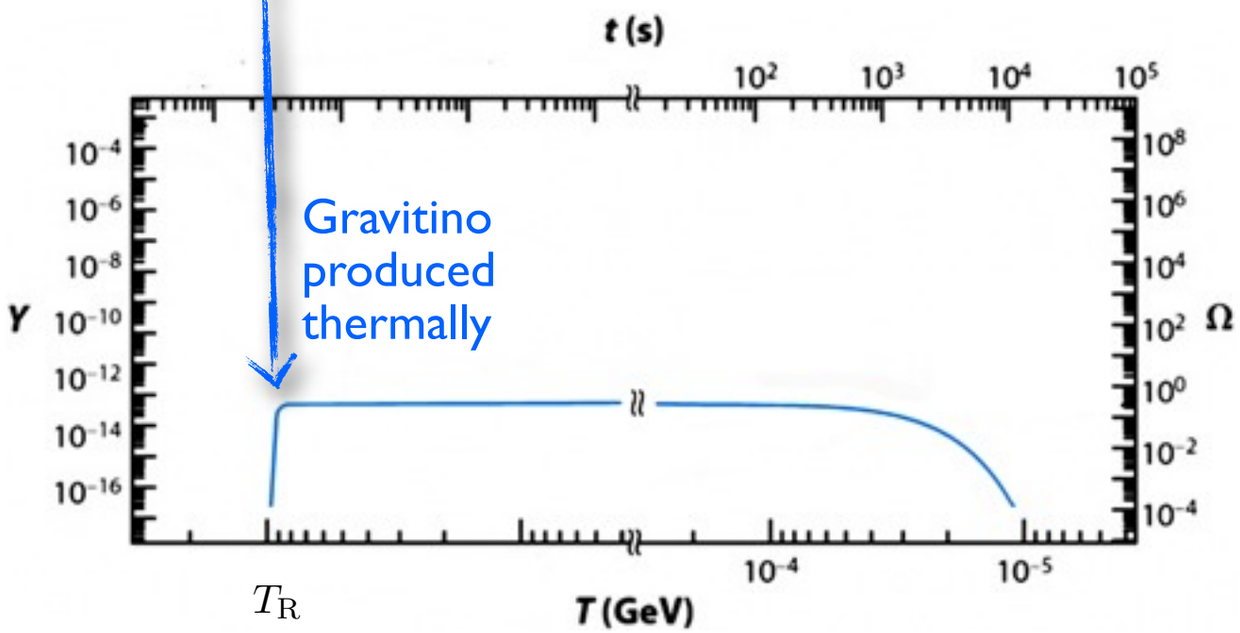


- Gravitino thermally produced during reheating: $\Omega_{\widetilde{G}} \sim \frac{T_{\rm R}}{m_{\widetilde{G}}}$

[Bolz, Buchmüller, Plümacher '98; Bolz, Brandenburger, Buchmüller '00; Pradler, Steffen '07]

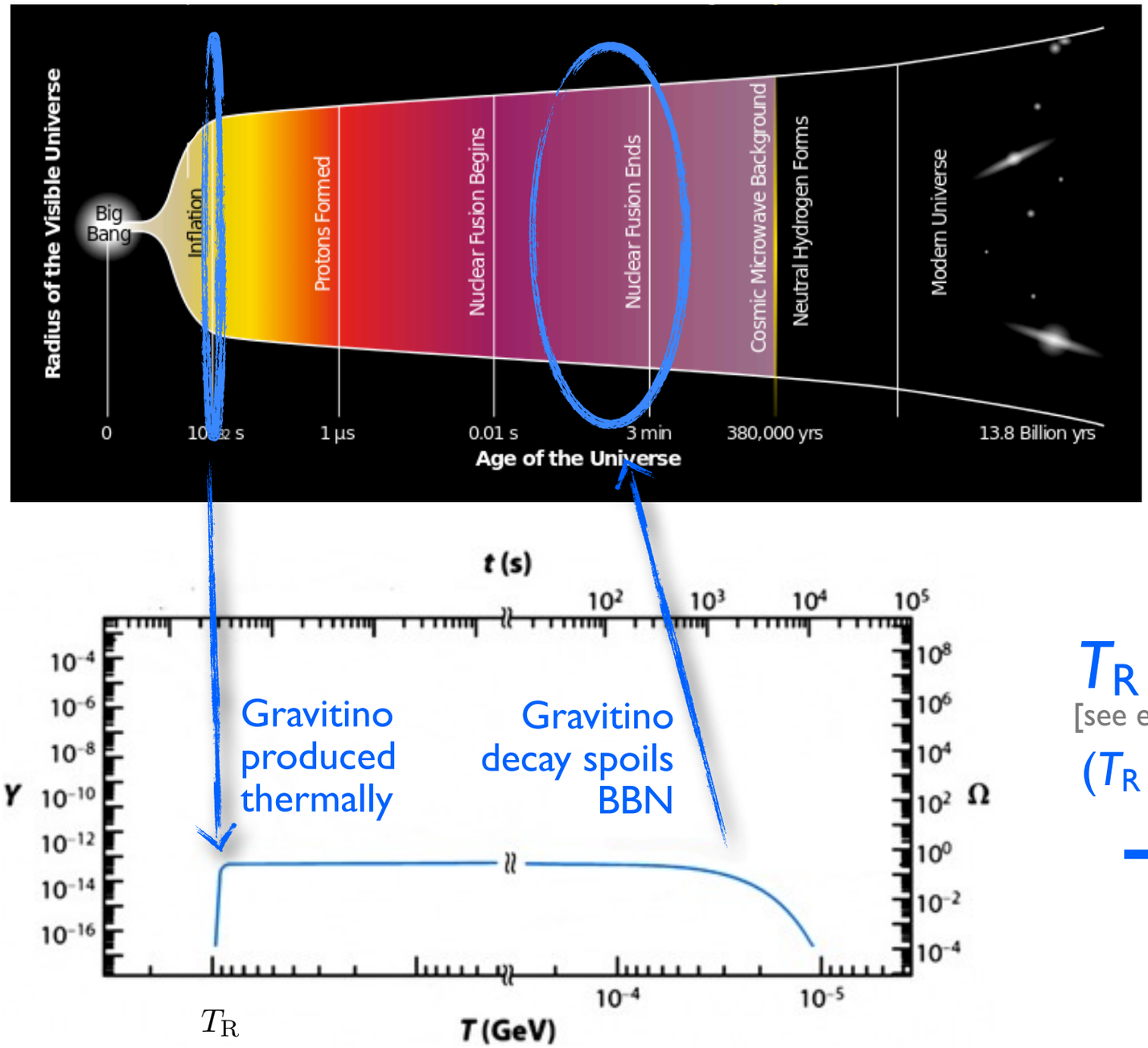
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- For $m_{\widetilde{G}} \gtrsim m_{\widetilde{\chi}_1^0}$ gravitino decays late
- Large $T_{\rm R} \Rightarrow$ large $\widetilde{G}$-abundace $\Rightarrow$ spoils BBN

$T_{\rm R}$ set by Inflation model

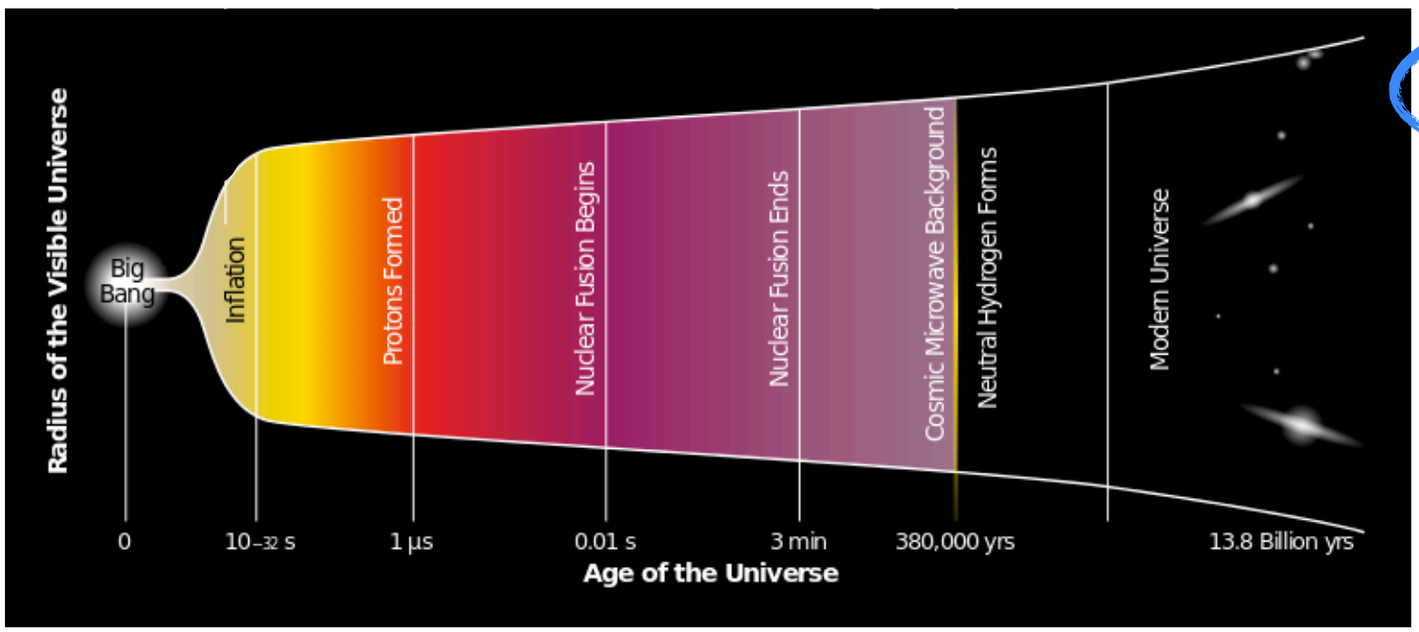
[see e.g. Martin, Ringeval, Vennin '14; Domcke, JH '15]

($T_{\rm R} \gtrsim 10^9$ GeV for th. Leptogenesis)

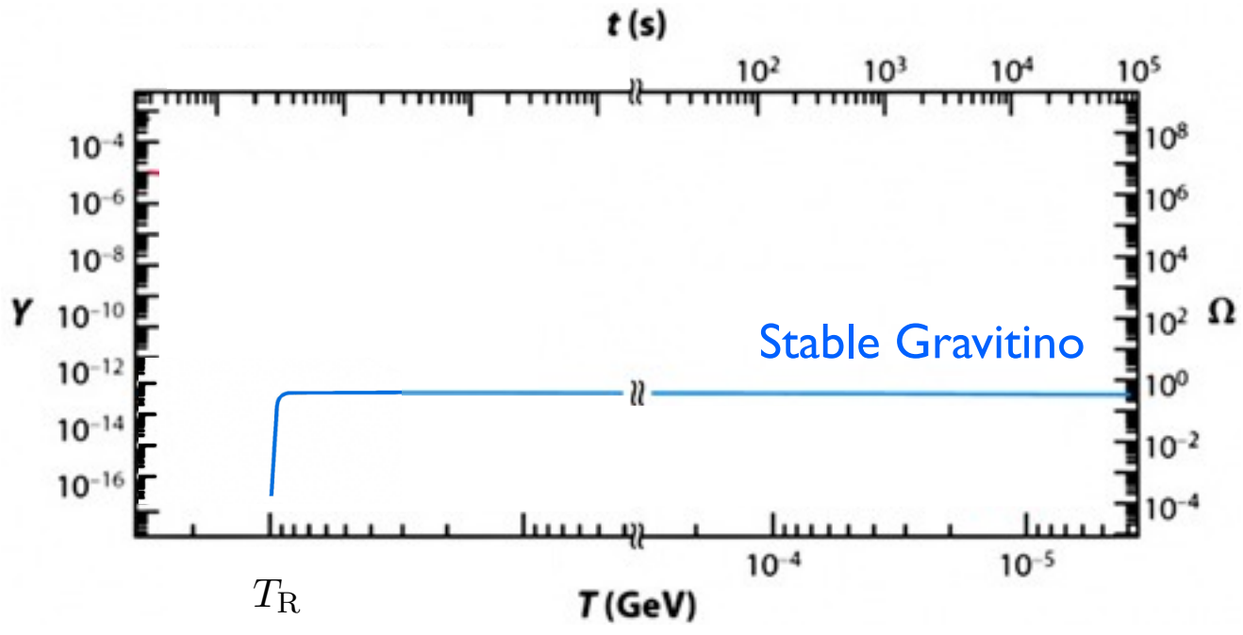
➔ Gravitino problem

[Weinberg '82; Ellis *et al.* '84]

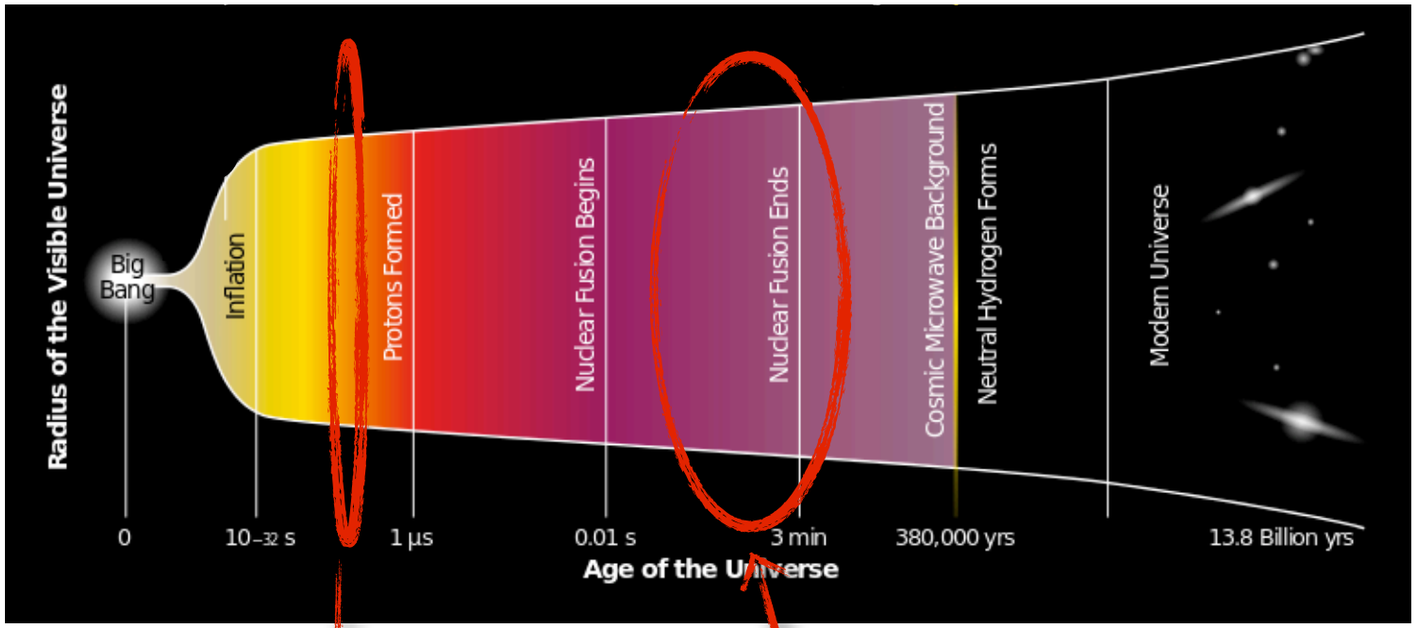
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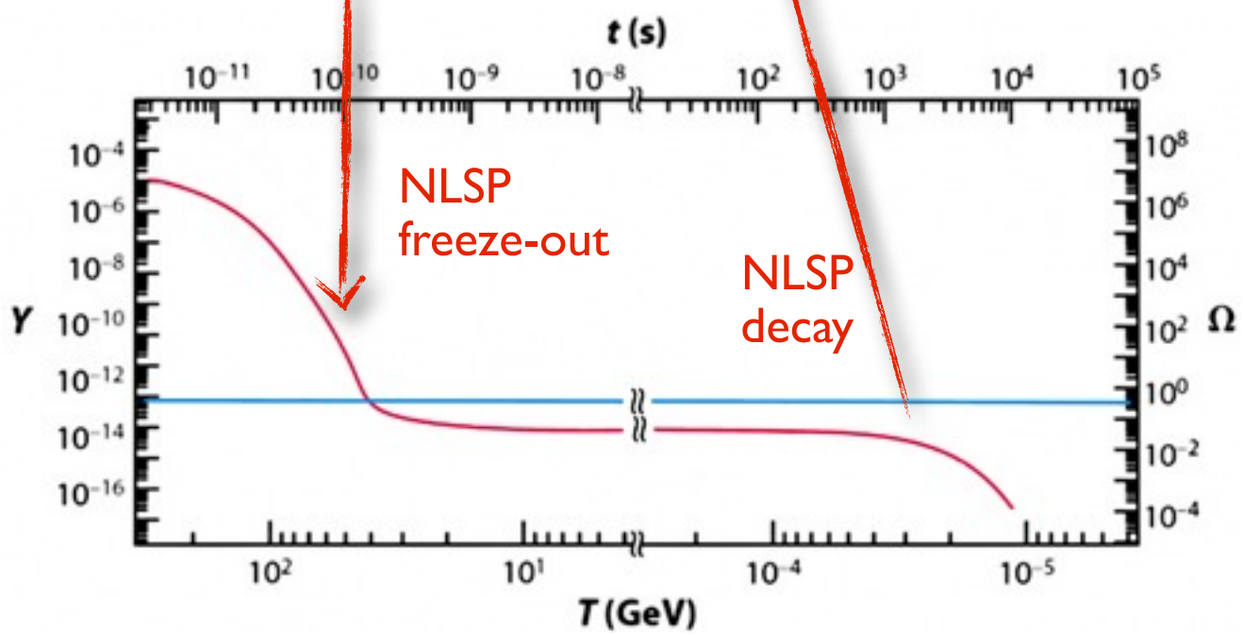


- Alleviate problem: Gravitino stable DM



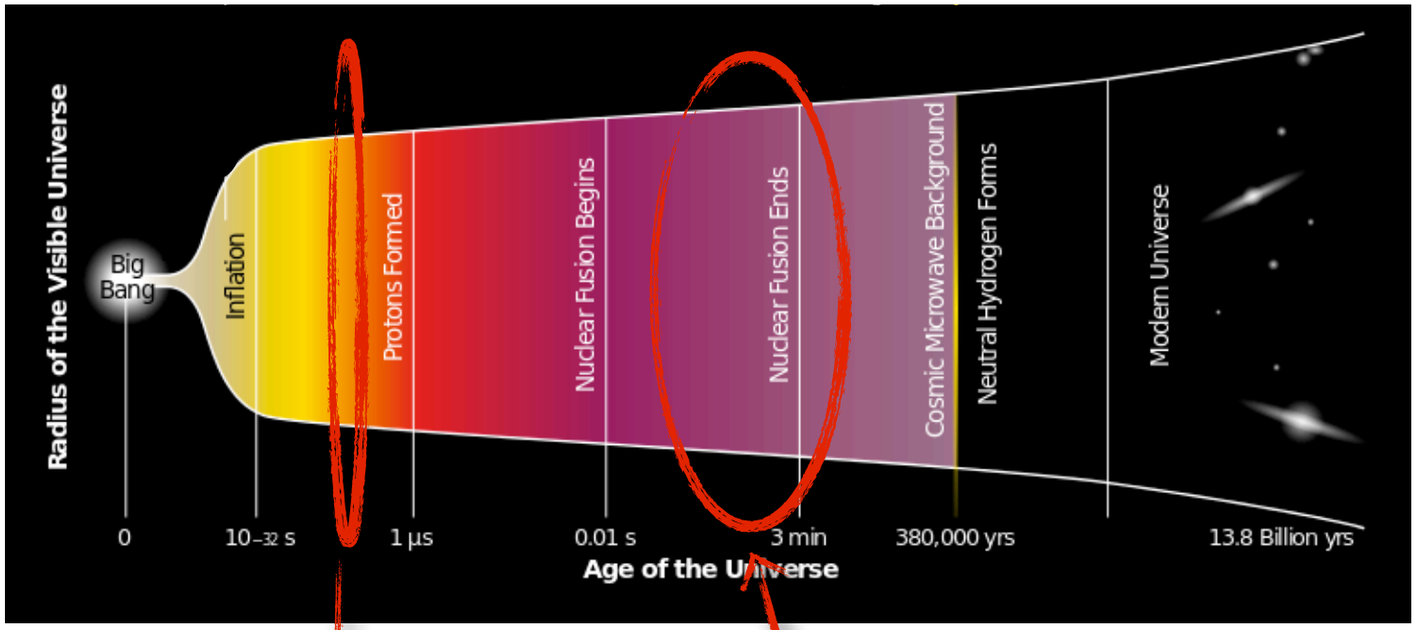
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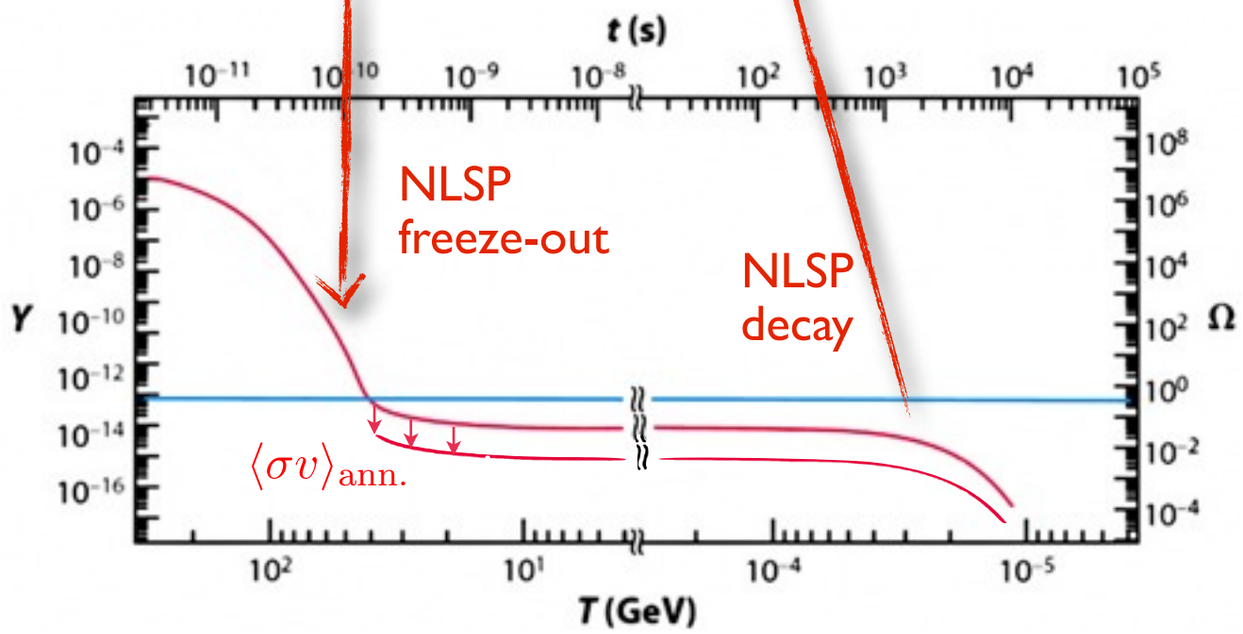




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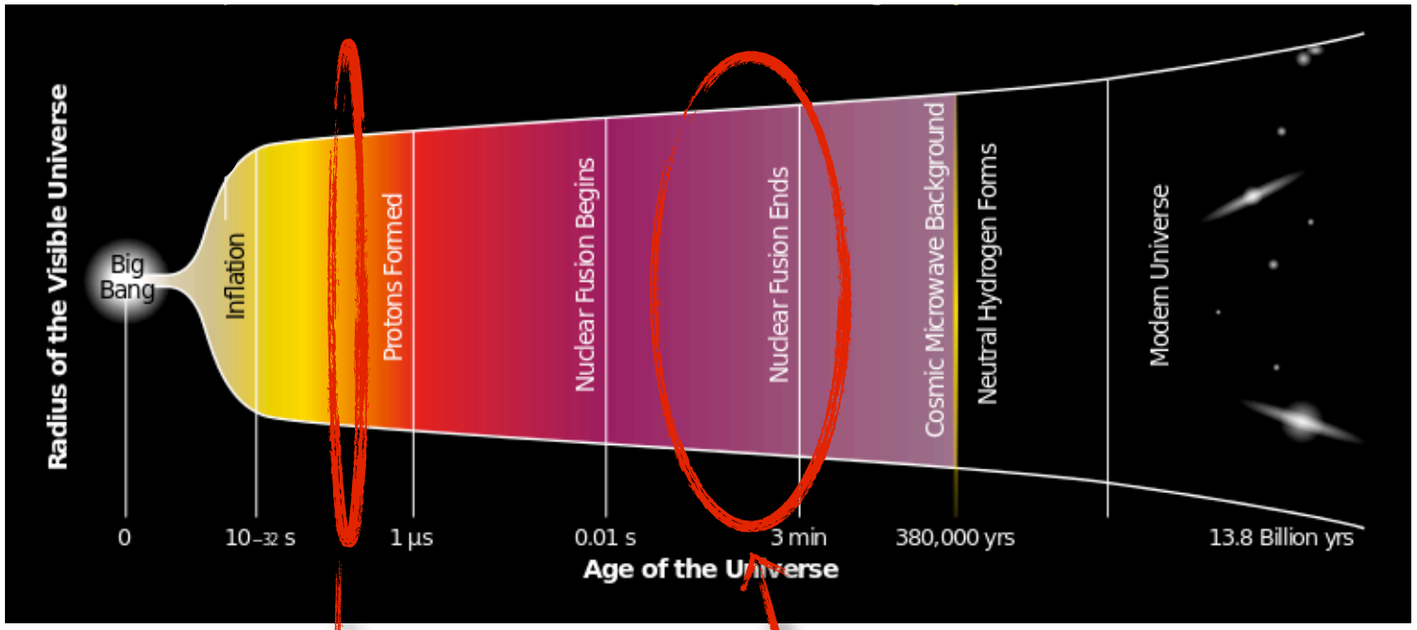
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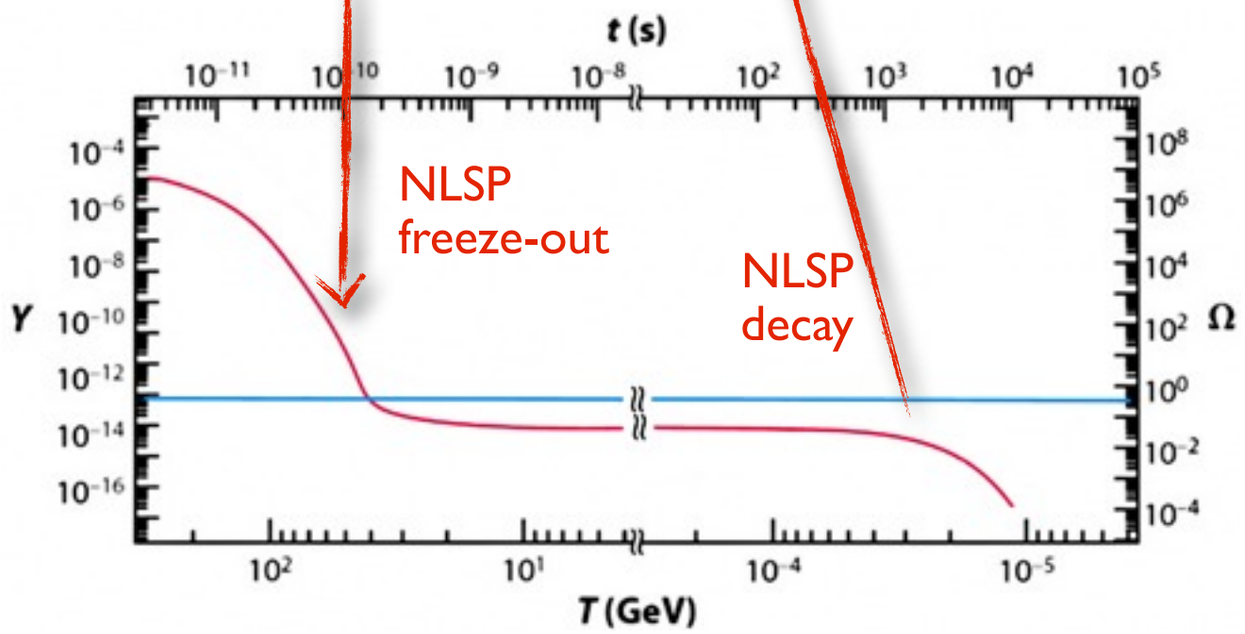




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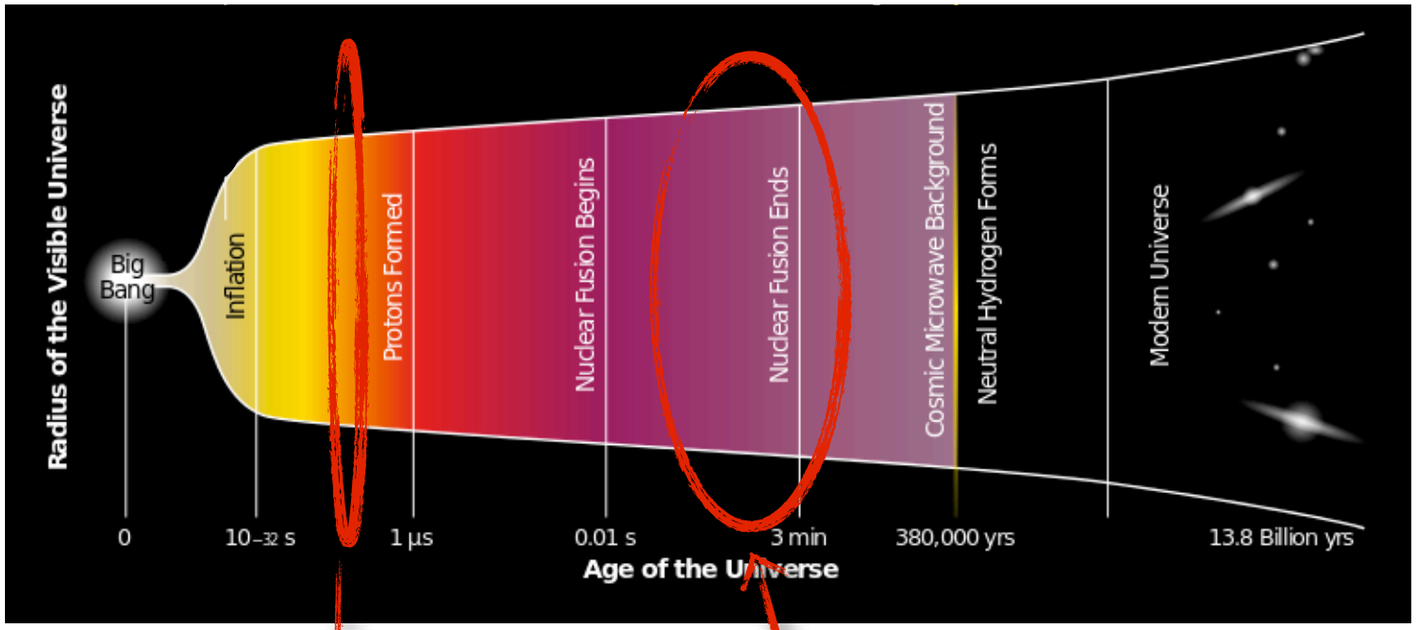
Bino NLSP disfavored
Stau viable candidate!

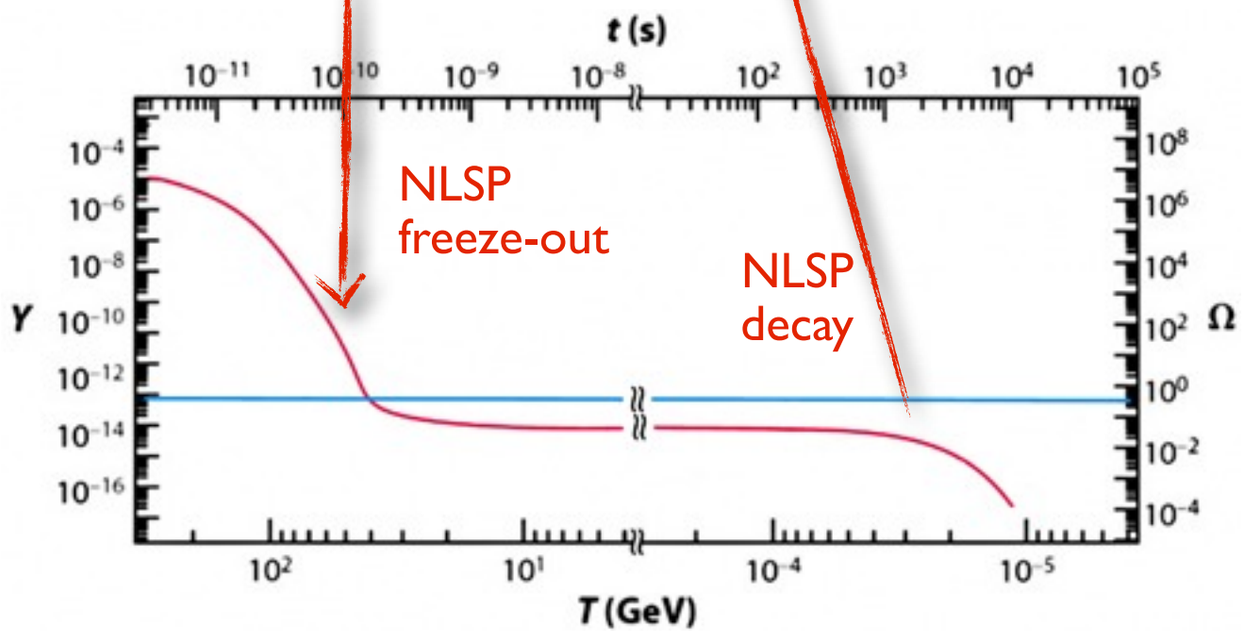
[Moroi *et al.* '93; Fujii *et al.* '03; Roszkowski *et al.* '04; Feng *et al.* '04; Pradler *et al.* '06; Steffen '08; Olechowski *et al.* '09, Endo *et al.* '10]

Stau NLSP also motivated in GMSB or GinoMSB

[JH, Kersten, Murphy, Strumke, work in progress]

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➔ Gravitino-stau scenario

Gravitino-stau scenario: pMSSM scan

[JH, Jörn Kersten, Boris Panes, Tania Robens, 1310.2825; JH, 1310.6352]

Monte Carlo scan over (17 + 1)-dim. pMSSM:

A_t, A_b, A_τ; μ, $\tan\beta$, m_A; M_1, M_2, M_3; $\theta_{\tilde{\tau}}$, $m_{\tilde{\tau}_1}$; $\theta_{\tilde{t}}$, $m_{\tilde{t}_1}$, $m_{\tilde{b}_1}$;
$m_{\tilde{L}_{1,2}}$, $m_{\tilde{e}_{1,2}}$, $m_{\tilde{Q}_{1,2}} = m_{\tilde{u}_{1,2}} = m_{\tilde{d}_{1,2}}$; $m_{\tilde{G}}$

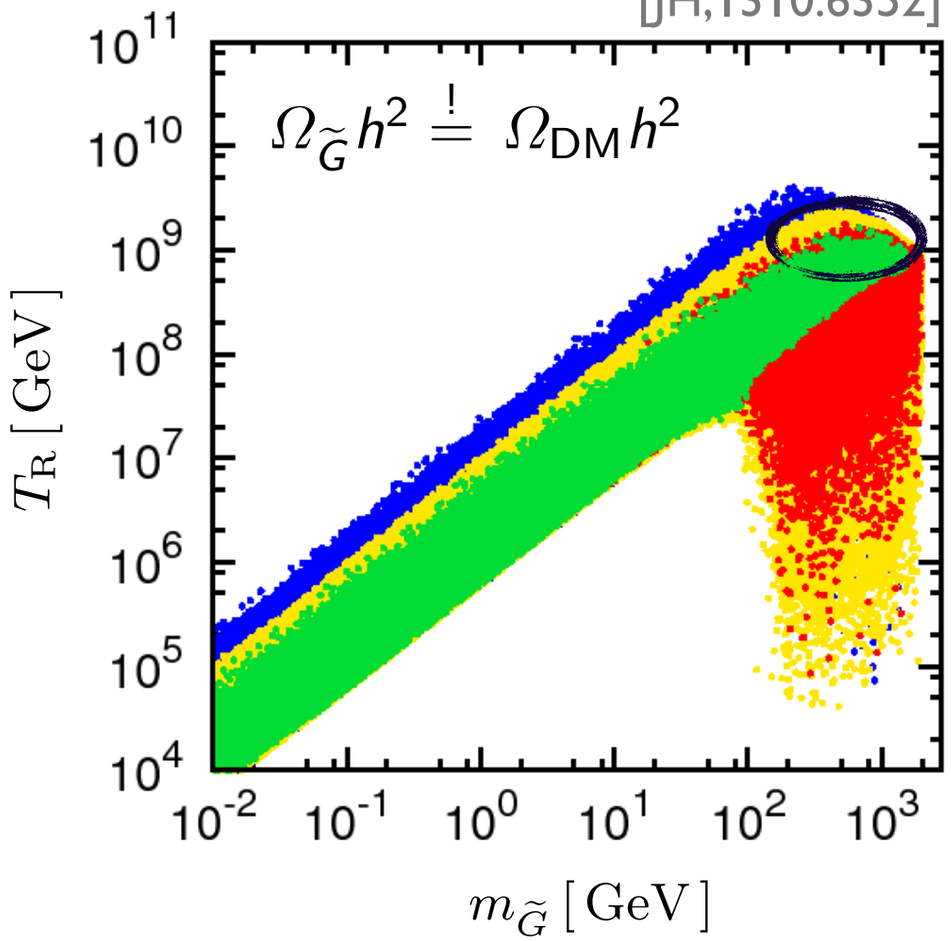
Impose constraints:

- Relic density $\Omega_{\tilde{G}} h^2 \stackrel{!}{=} \Omega_{\text{DM}} h^2$ [Planck '13]
- Higgs mass $123\,\text{GeV} < m_{h/H} < 128\,\text{GeV}$ [ATLAS, CMS '12]
- Interpretation of the HSCP search at the 7 and 8 TeV LHC [CMS '13]
- MSSM Higgs searches (HB) [HiggsBounds '13]
- Flavor and precision observables (FP) [TEW Group '12; HFA Group '12; LHCb '12]
- Constraints from vacuum (meta-)stability (CCB) [Kitahara *et al.* '13; Casas *et al.* '96]
- BBN Constraints [Jedamzik '08]

➔ Search for parameter points with high reheating temperatures

Gravitino-stau scenario: pMSSM scan

[JH,1310.6352]



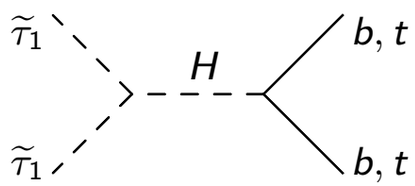
Points with largest T_{R}:

- To match DM density:
  ⇒ large gravitino mass
  ⇒ small gaugino masses

$$\Omega^{\mathrm{th}}_{\widetilde{G}} \sim \sum_{i=1}^{3} C_i \left(1 + \frac{M_i^2}{3 m^2_{\widetilde{G}}}\right) m_{\widetilde{G}}\, T_{\mathrm{R}}$$

[Pradler, Steffen; '07]

- To pass BBN bounds:
  large stau annihilation xs
  ⇒ resonant annihilation
  via *s*-channel *H*:



$m_H \simeq 2 m_{\widetilde{\tau}_1}$

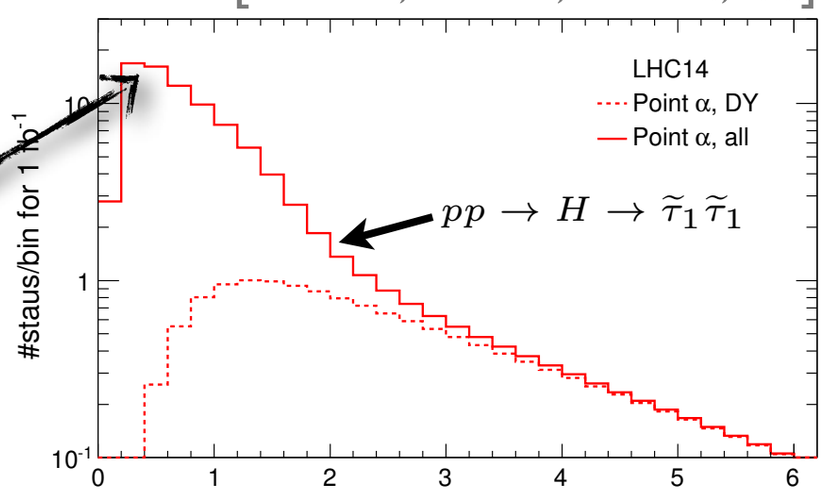
- no constraints
- passed HSCP search 7 and 8 TeV LHC [CMS Collaboration '13]
- (additionally) passed FP+HB+CCB
- (additionally) passed BBN bounds [Jedamzik '08]

Gravitino-stau scenario: pMSSM scan

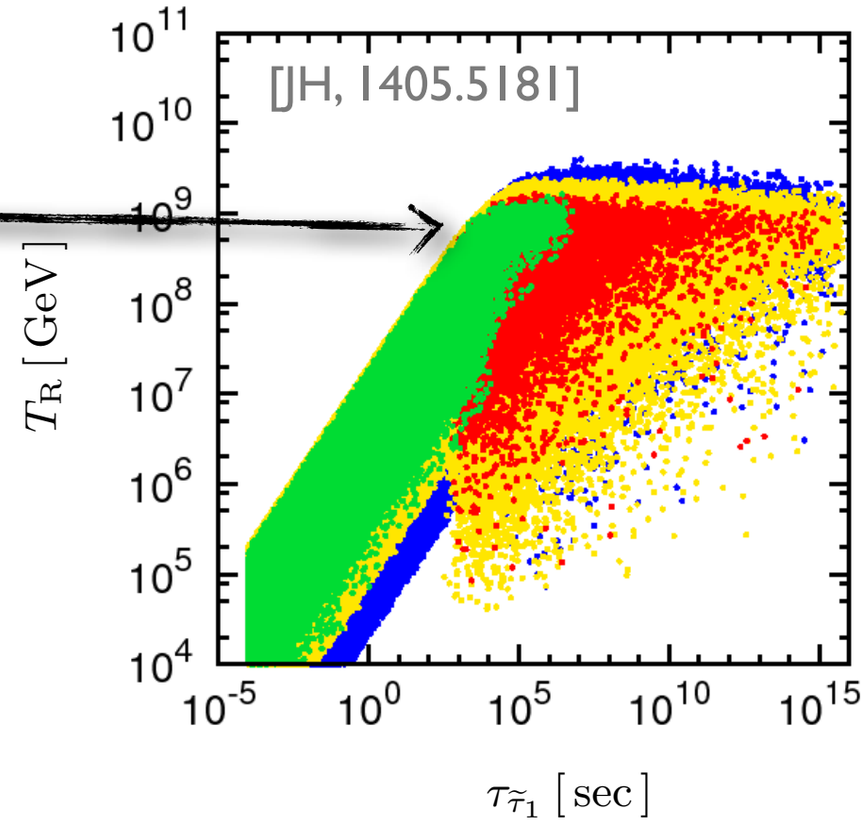
Points with largest T_R:

- Production close to threshold
- Production via heavy Higgs
  - ➔ Low velocities
  - ➔ Challenging for trigger
- HSCP stopped in the detector
- Life-times 10^3-10^7 sec

[Lindert, Steffen, Trenkel; '11]



[JH, 1405.5181]



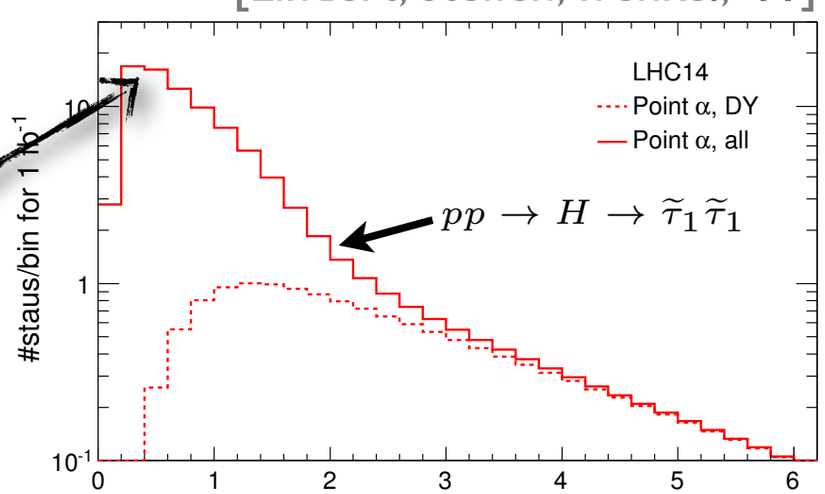
Gravitino-stau scenario: pMSSM scan

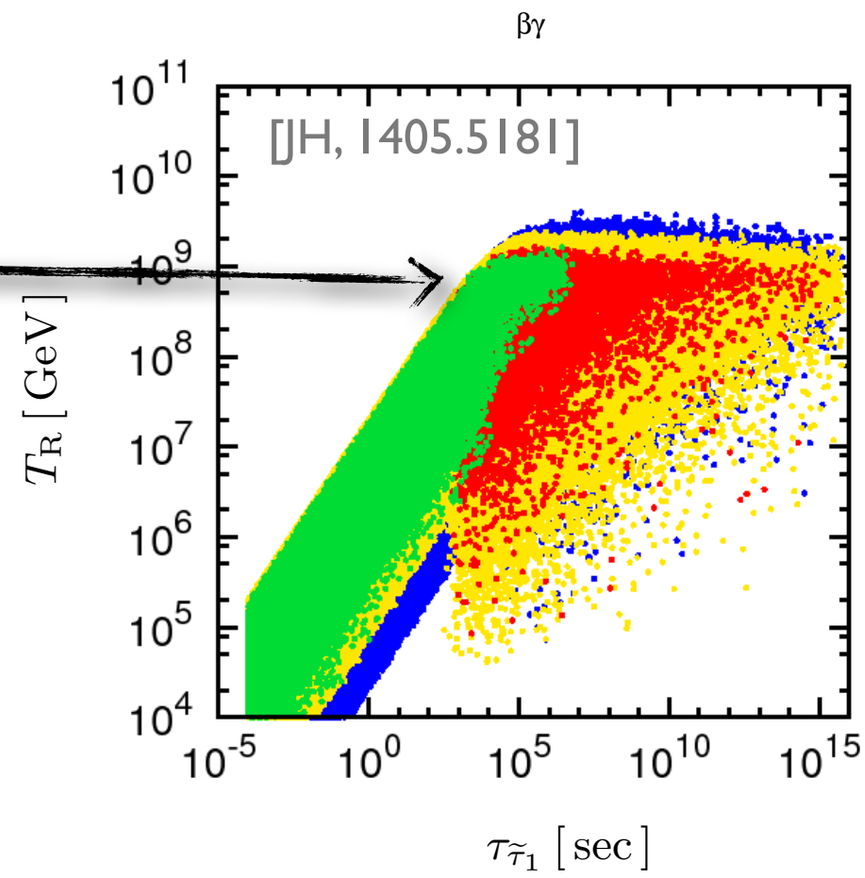
Points with largest T_R:

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  - ➔ Low velocities
  - ➔ Challenging for trigger
- HSCP stopped in the detector
- Life-times 10^3-10^7 sec

Intriguing test for supergravity!

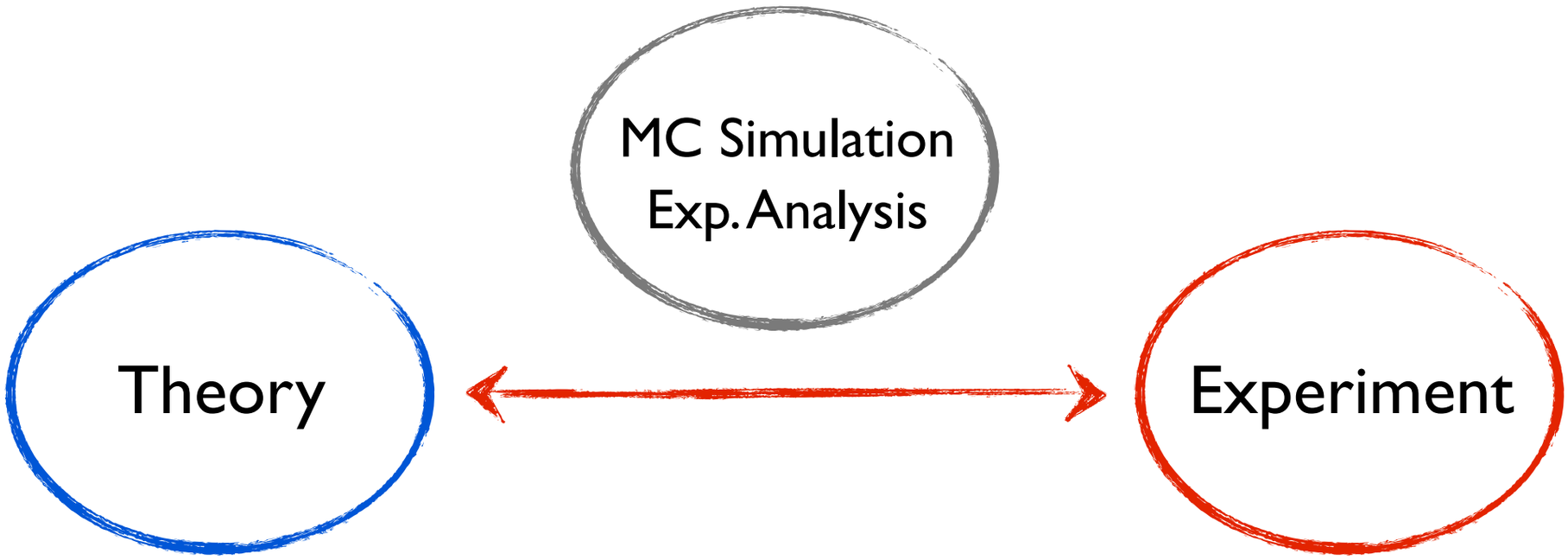
[Lindert, Steffen, Trenkel; '11]



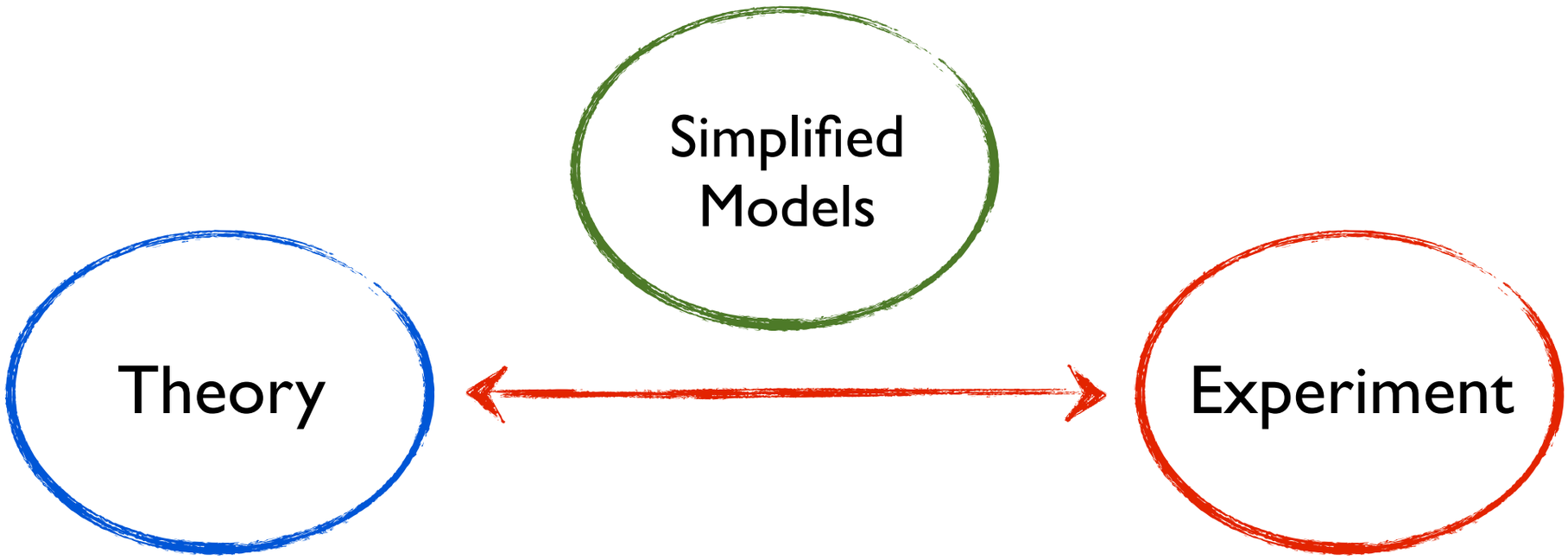


Simplified models for HSCPs

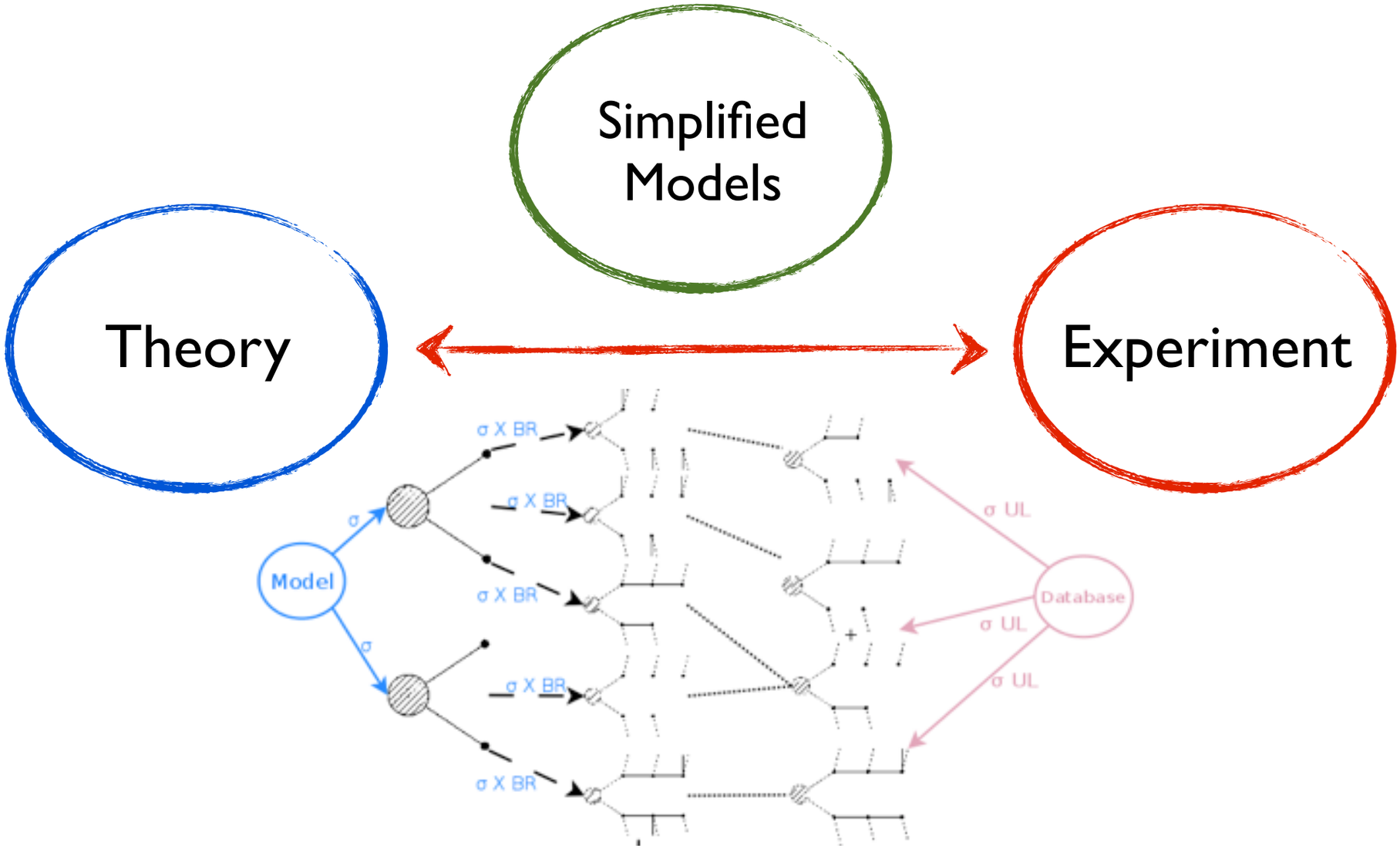
Why Simplified Models?



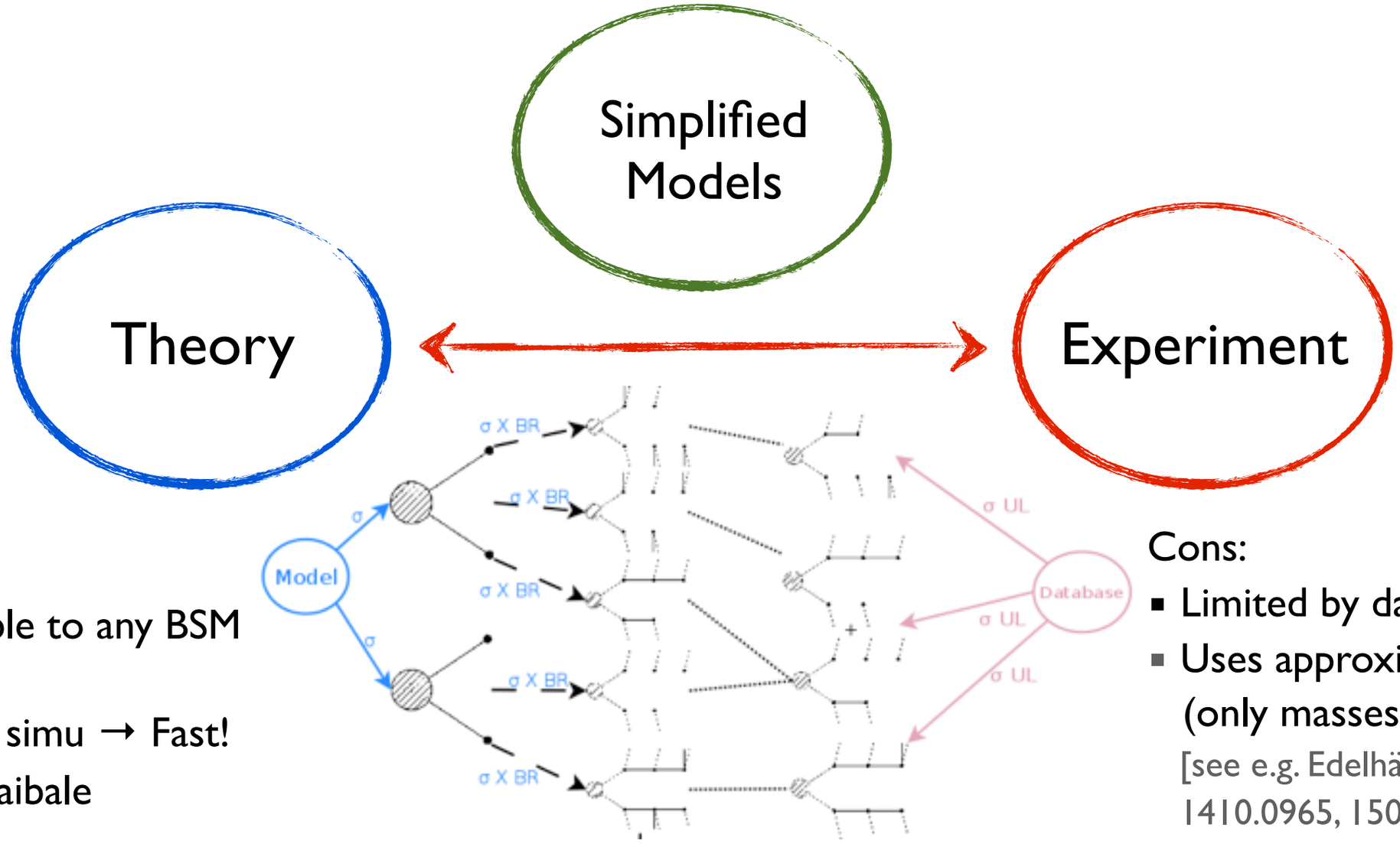
Why Simplified Models?



Why Simplified Models?



Why Simplified Models?



Pros:

- Applicable to any BSM model
- No MC simu → Fast!
- Tools avaibale

Cons:

- Limited by database
- Uses approximations (only masses, topologies)

[see e.g. Edelhäuser et al. 1410.0965, 1501.03942]

[SModelS: Kraml, Kulkarni, Laa, Lessa, Magerl, Proschofsky, Waltenberger, 1312.4175]
[Fastlim: Papucci, Sakurai, Weiler, and Zeune, 1402.0492]

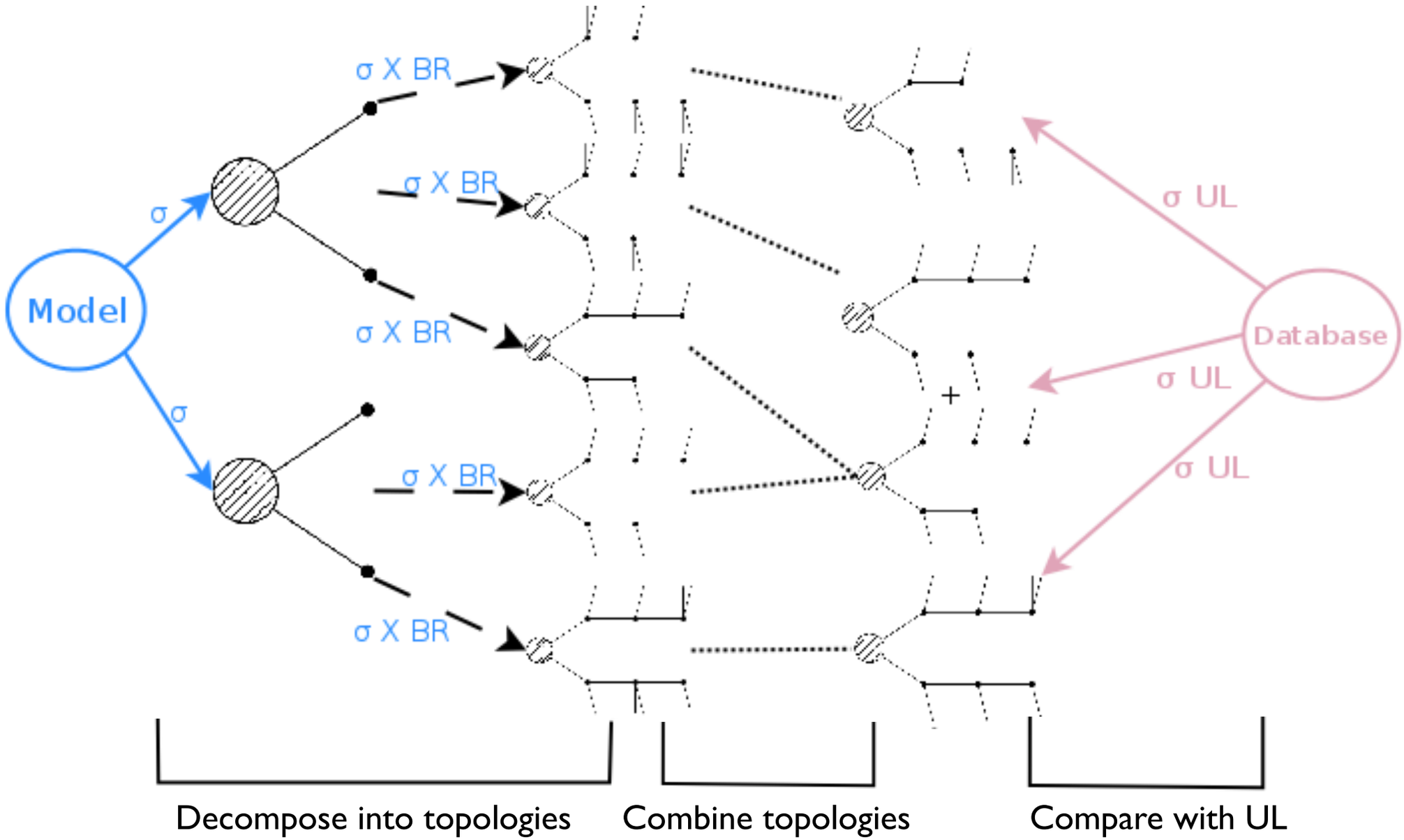
Simplified Models

- So far: Missing Transverse Energy (MET) searches only
- But: HSCP signatures can be very important!

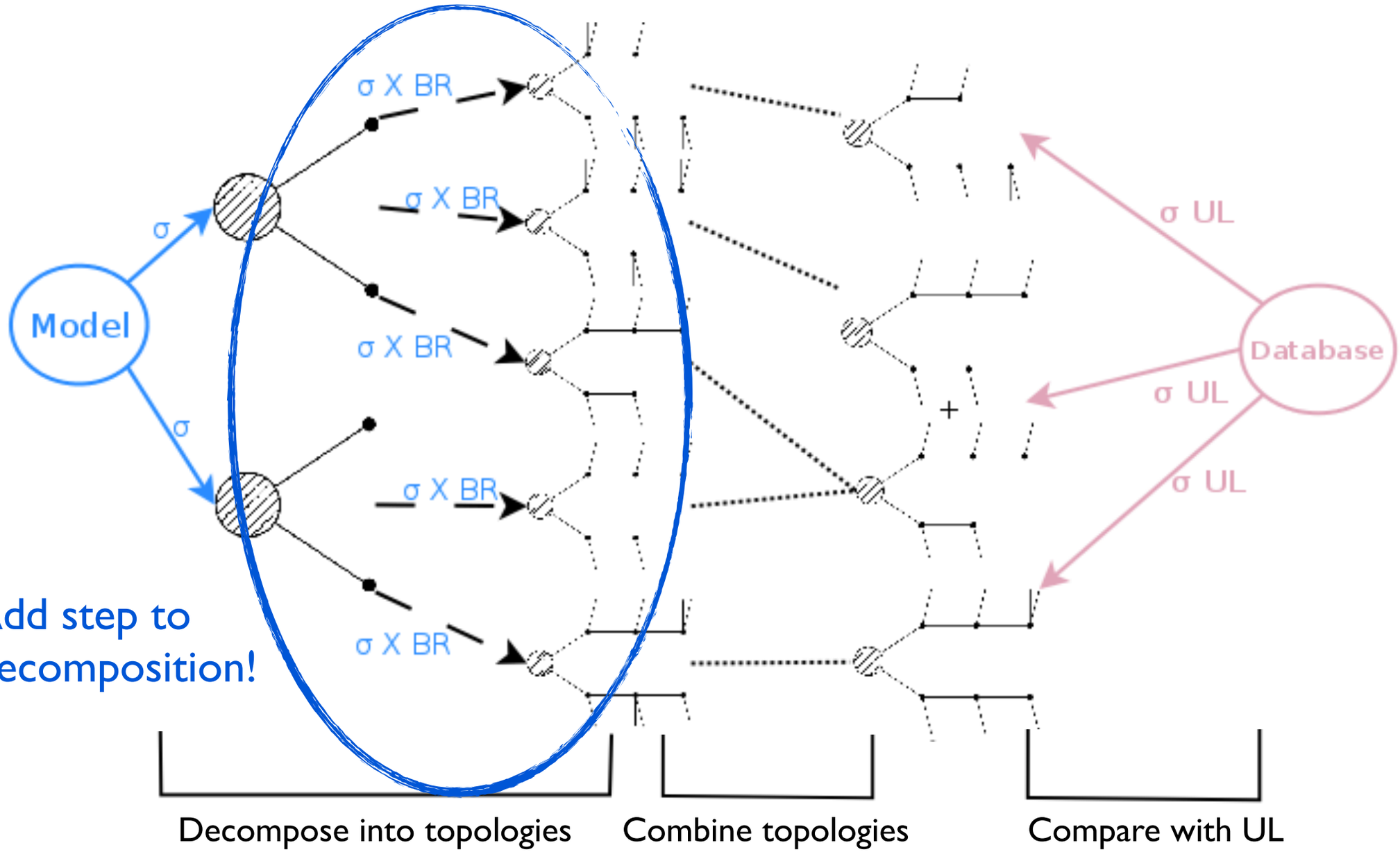
This work:
Implement HSCP searches into SModelS

Implementation into SModelS

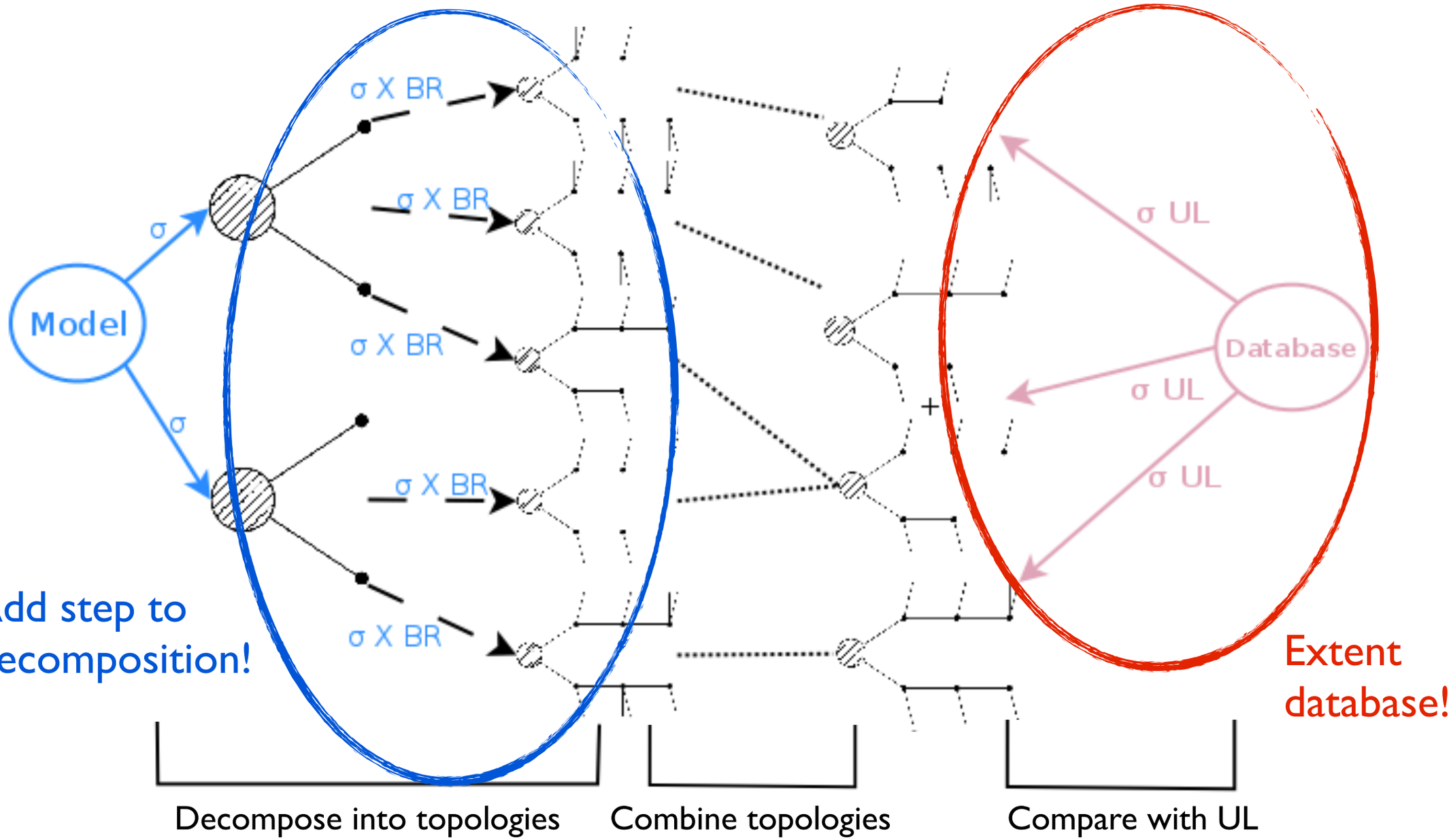
Extending SModelS



Extending SModelS



Extending SModelS

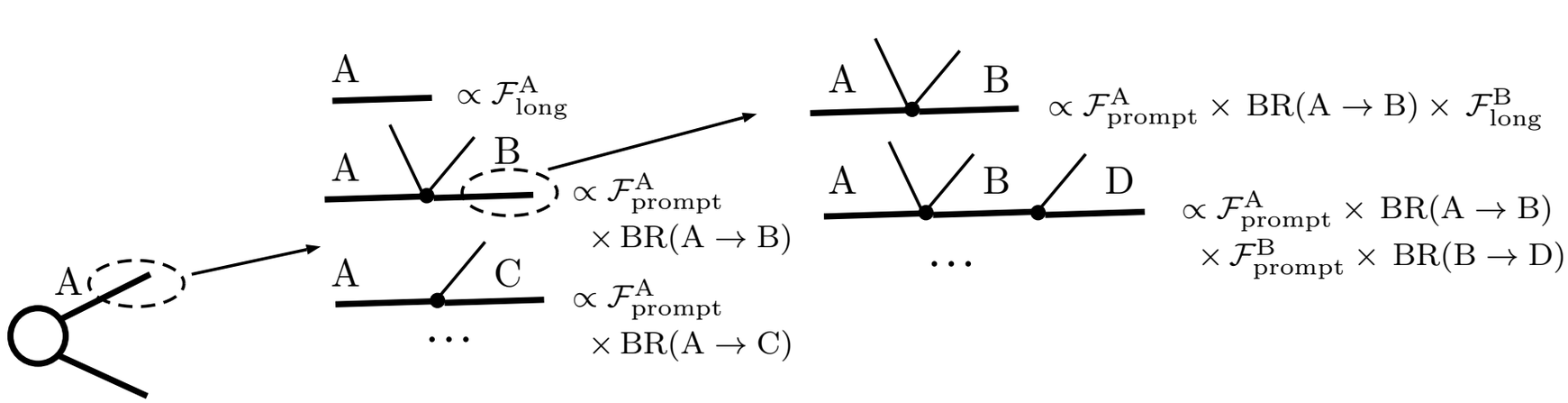


Extending SModelS

- Add step to decomposition:

  Probability to decay prompt: $\mathcal{F}_{\text{prompt}} = 1 - e^{-\Gamma l_{\text{inner}}/(\gamma\beta)}$,

  or appear metastable: $\mathcal{F}_{\text{long}} = e^{-\Gamma l_{\text{outer}}/(\gamma\beta)}$,



- End up with:

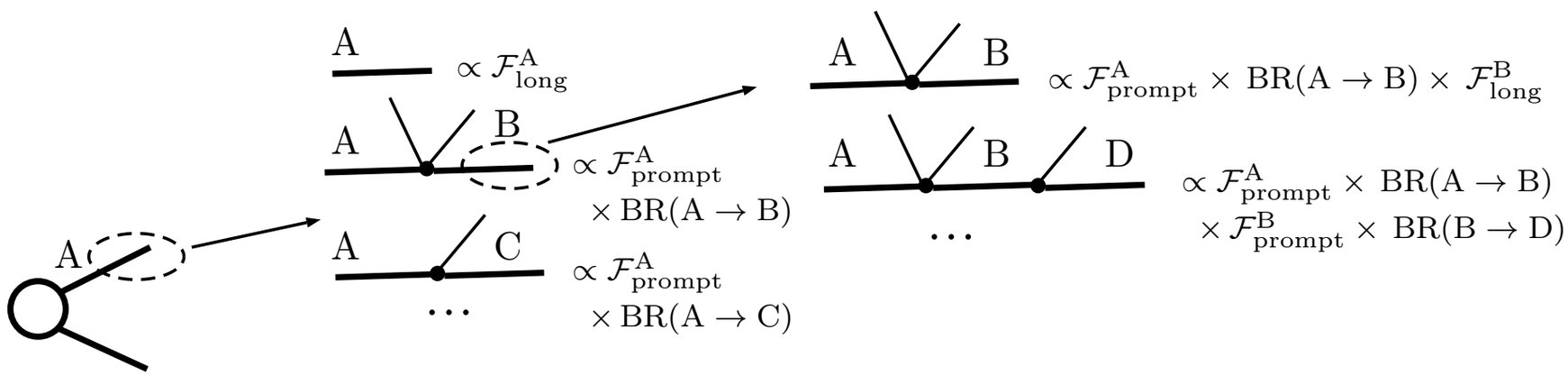
  pure MET, mixed MET/HSCP and pure HSCP

Extending SModelS

- Add step to decomposition:

  Probability to decay prompt: $\mathcal{F}_{\text{prompt}} = 1 - e^{-\Gamma l_{\text{inner}}/(\gamma\beta)}$,

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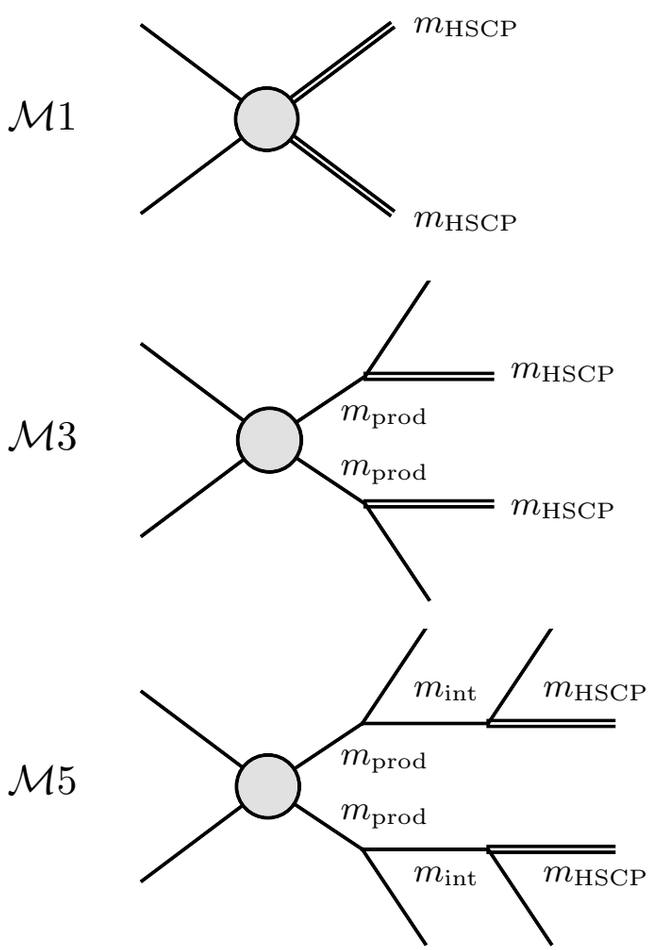
- End up with:

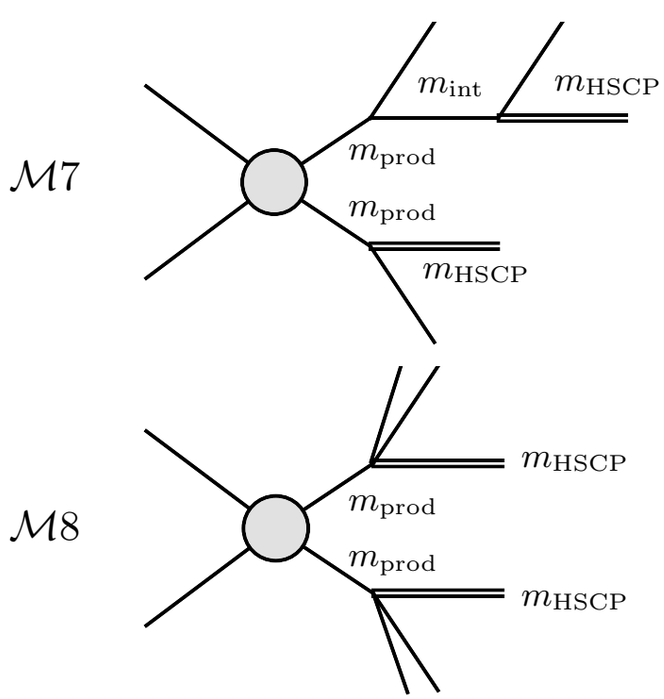
  pure MET, mixed MET/HSCP and pure HSCP

Extent database!

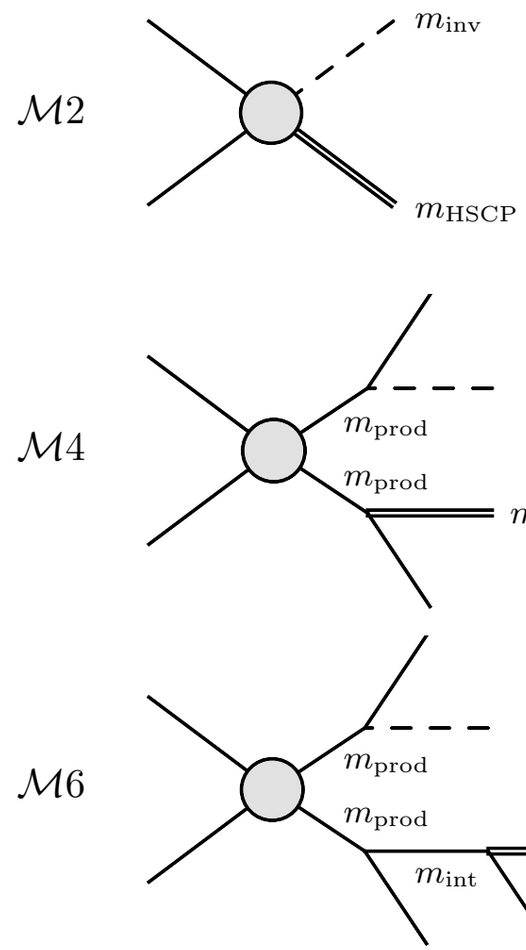
Extending SModelS: Considered Topologies

Pure HSCP:





MET/HSCP:



Extending SModelS: Efficiencies

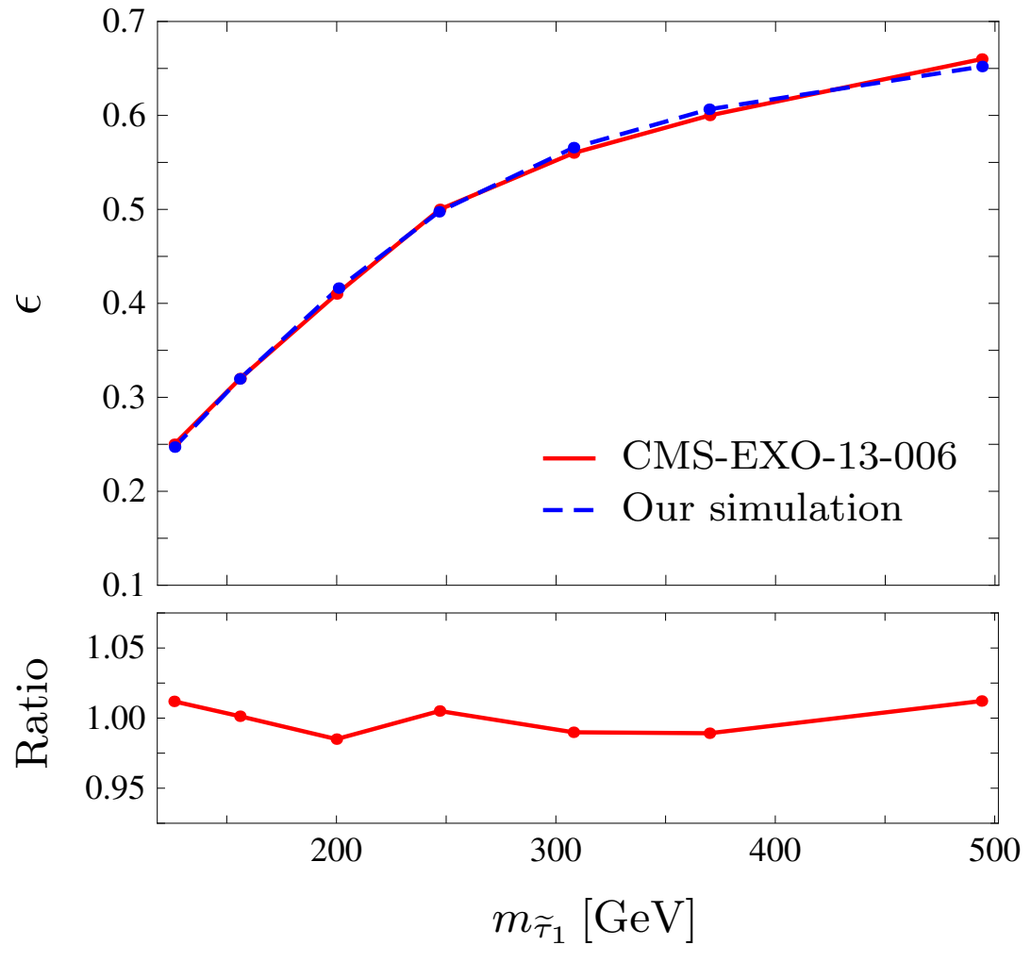
- Extent database:

  Compute efficiencies for 8 topologies

- Simulation: MadGraph/Phythia
- CMS HSCP analysis:

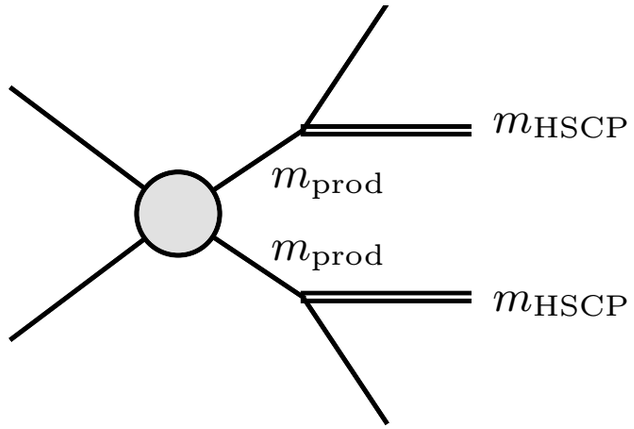
  Novel methode based on probabilities passing cuts

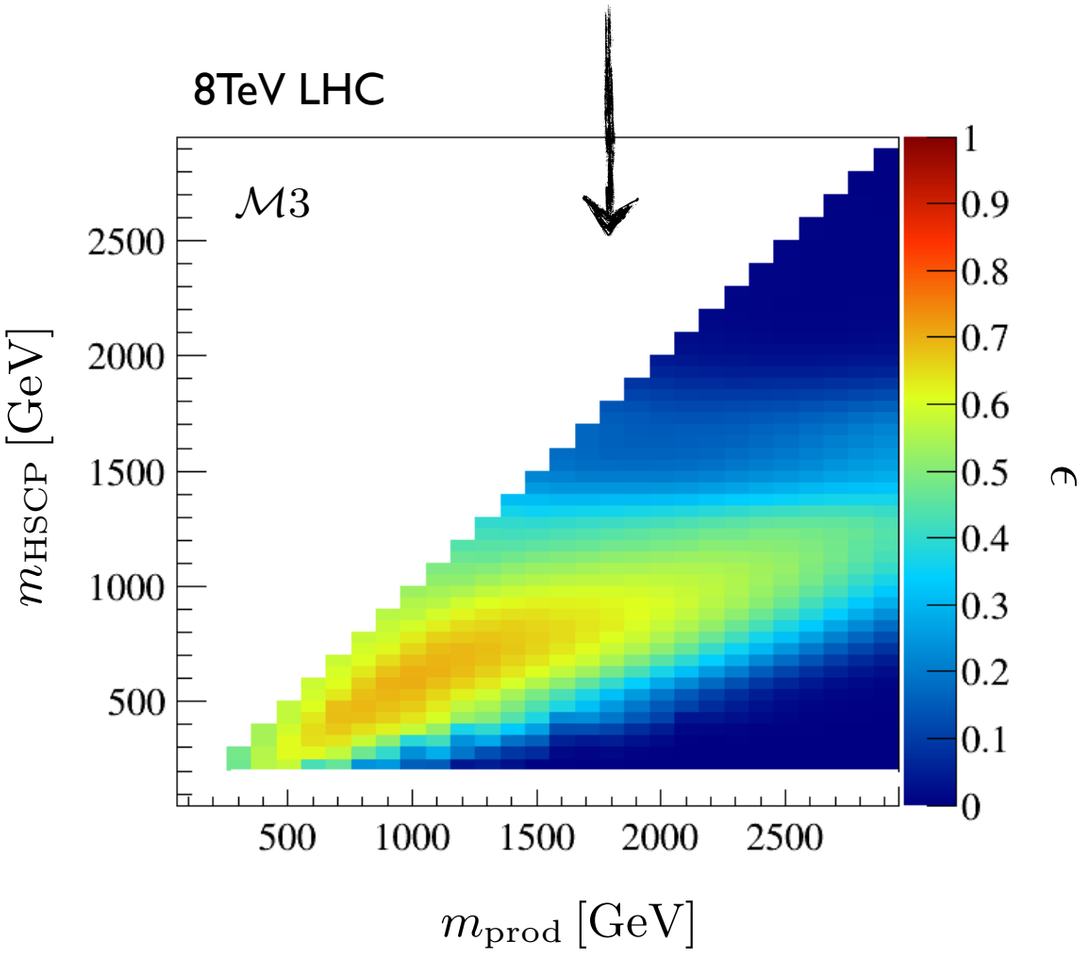
  [CMS: 1502.02522]
- Validation GMSB model
- Less than 5% deviation



Extending SModelS: Efficiencies

Exemplarily for $\mathcal{M}3$





- Signal efficiencies up to 70%
- Efficiencies drop for
  - $\beta \to 1$ (muon-background)
  - $\beta \lesssim 0.45$ (trigger)

[*cf.* JH, Kersten, 1203.1581]

→ Use efficiencies for general model

Application to stau co-annihilation strip

The Tip of the CMSSM Co-annihilation Strip

[see also: Desai, Ellis, Luo, Marrouche, 1404.5061]

- CMSSM with neutralino LSP, stau NLSP
- Require $\delta m = m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0} < 0.1 \text{ GeV}$, $\tau_{\tilde{\tau}} \gtrsim 1 - 100 s$

  → possible solution to the ^{7}Li-Problem [Konishi et al. 1309.2067]
- Monte Carlo scan over

  $$m_0, M_{1/2}, A_0$$

  for fixed $\tan\beta$ and $\mu > 0$
- Stau abundance (before its decay): $Y^0_{\tilde{\tau}} \gtrsim 10^{-13}$

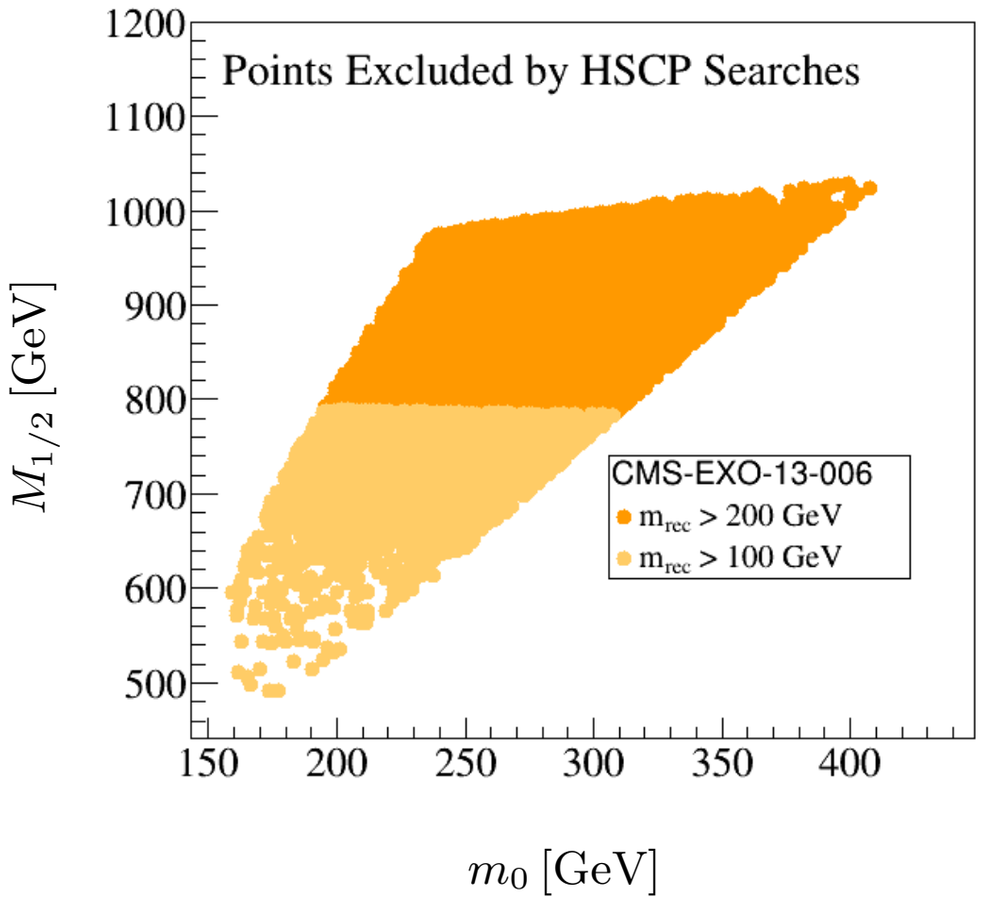
The Tip of the CMSSM Co-annihilation Strip

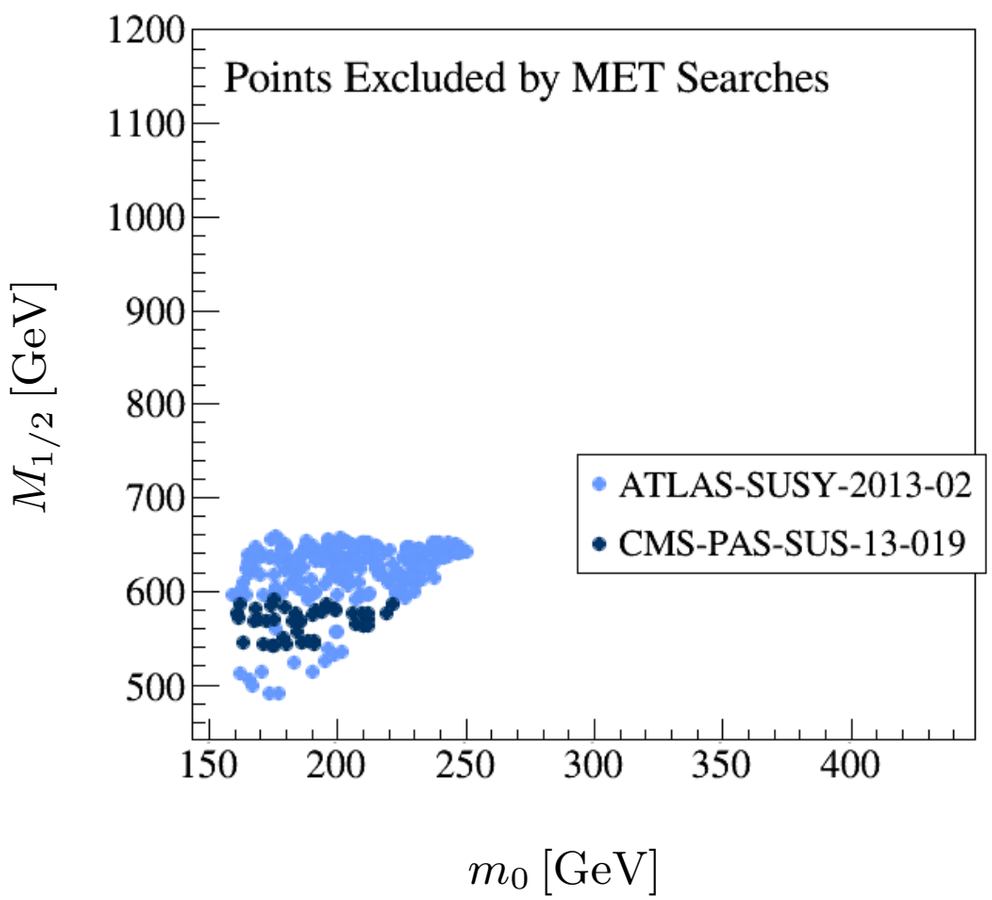
- LHC sensitivity:
  - ~70% signal: MET signatures (dominant $\widetilde{q}\widetilde{q} \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0 + 2j$)
  - ~20% signal: mixed MET/HSCP (dominant $\widetilde{\chi}_1^\pm\widetilde{\chi}_2^0 \to \widetilde{\tau}_1^\pm\widetilde{\chi}_1^0 + \nu_\tau Z$)
  - ~10% signal: pure HSCP (dominant $\widetilde{\chi}_1^\pm\widetilde{\chi}_1^\pm \to \widetilde{\tau}_1^\pm\widetilde{\tau}_1^\pm + 2\nu_\tau$)
- For HSCP and mixed: Efficiency database (8 topologies)
- For pure MET: Apply UL from most sensitive topology from SModelS MET-database

The Tip of the CMSSM Co-annihilation Strip

- LHC: HSCP versus MET sensitivity

[JH, Lessa, Quertenmont, 1509.00473]

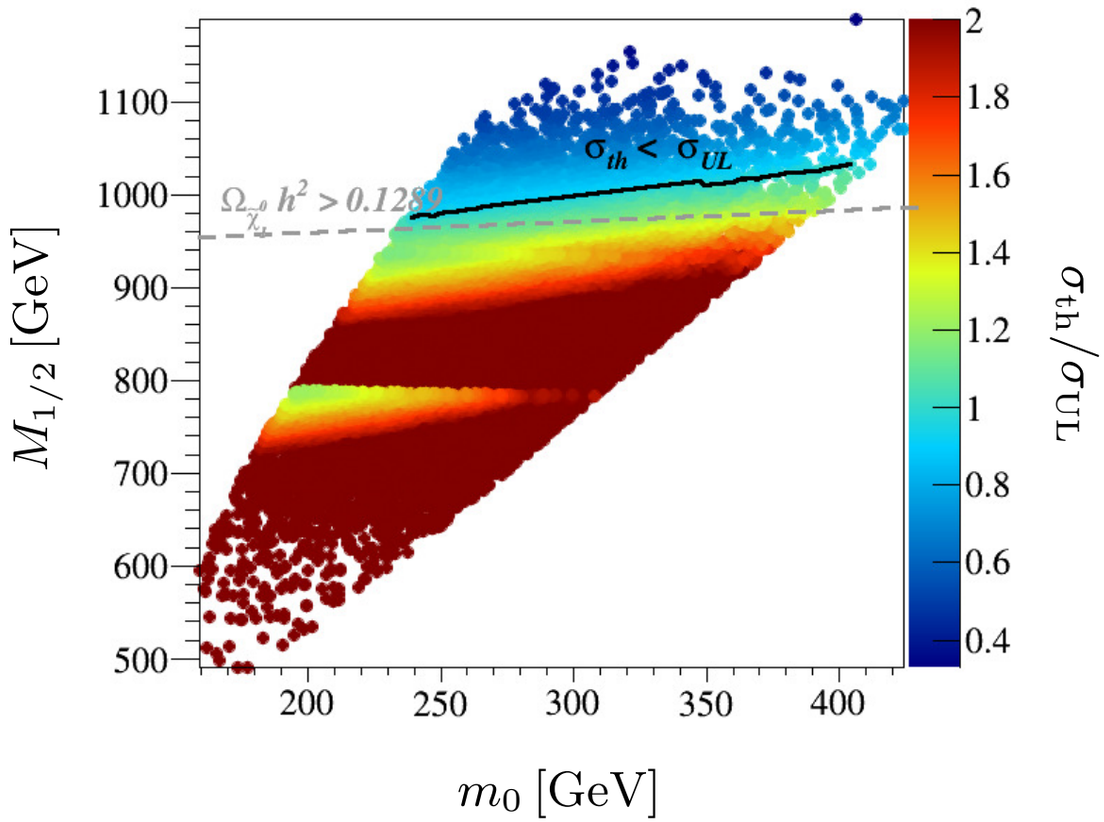


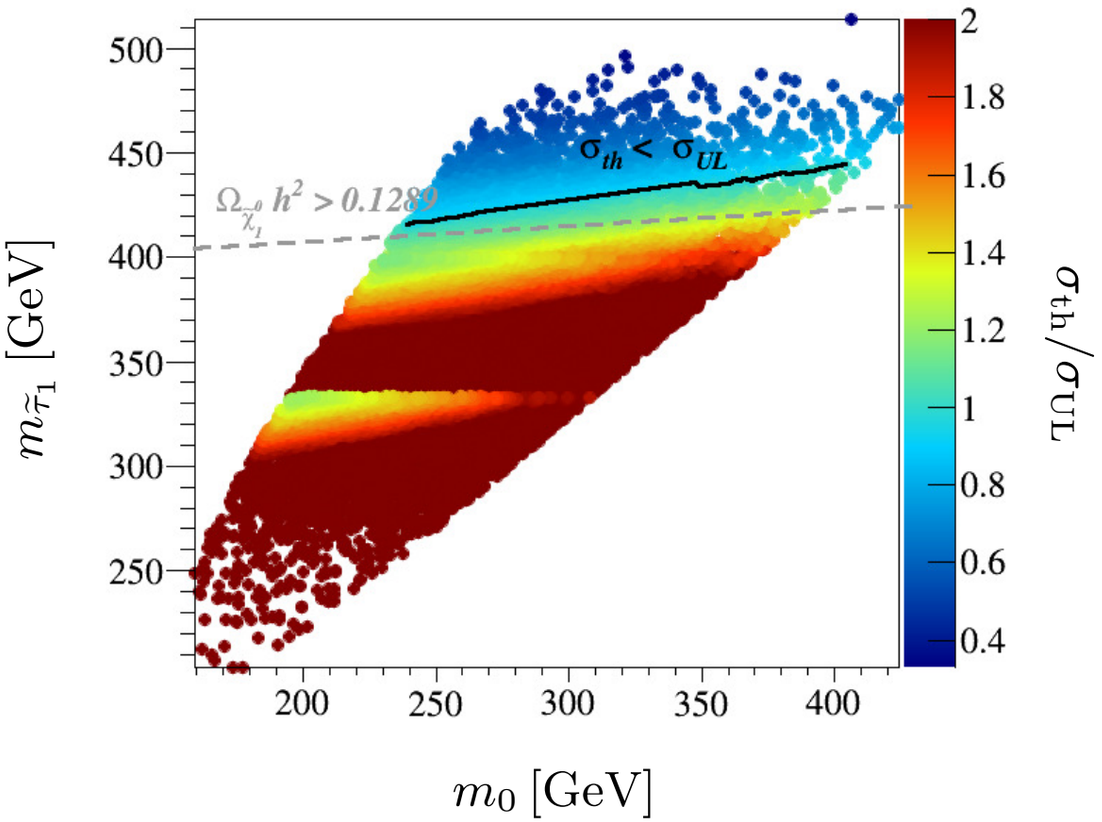


The Tip of the CMSSM Co-annihilation Strip

- LHC sensitivity (for $\tan\beta = 10$):

[JH, Lessa, Quertenmont, 1509.00473]

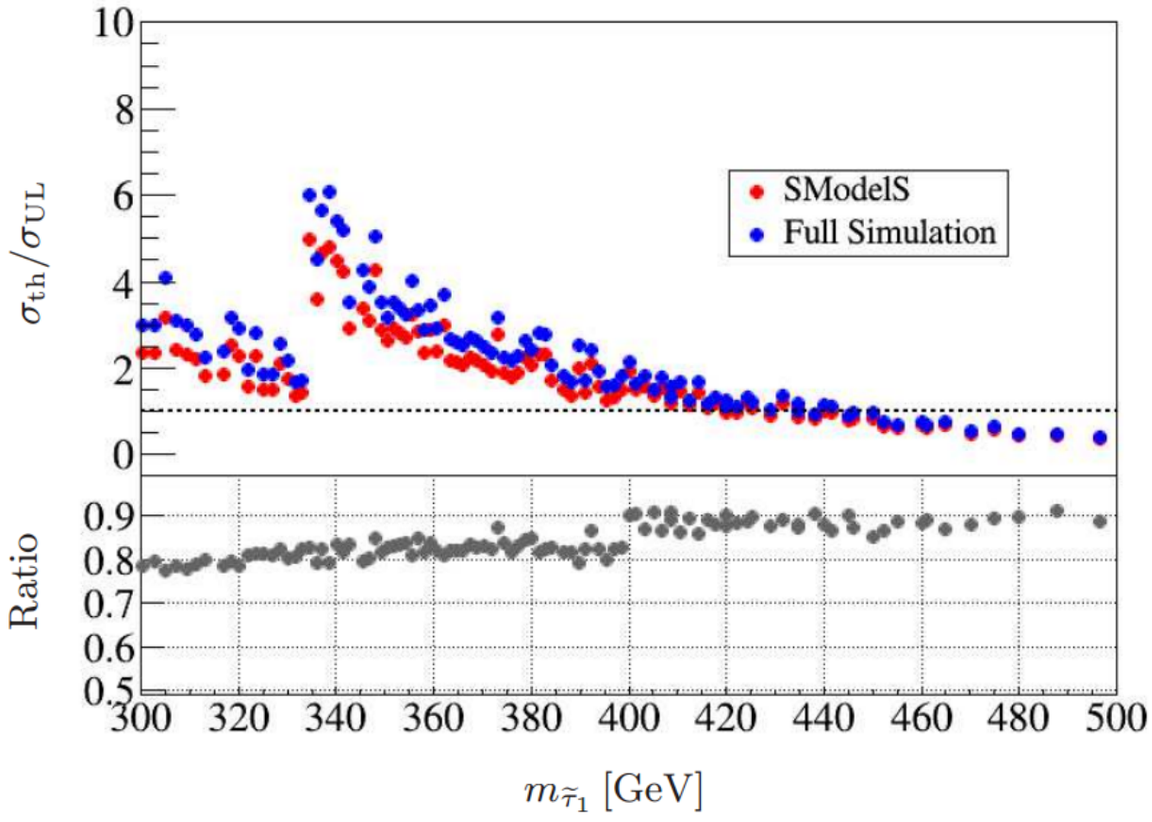




The Tip of the CMSSM Co-annihilation Strip

- Simplified models versus full simulation:

[JH, Lessa, Quertenmont, 1509.00473]



- SModelS conservative
- Signal coverage: ~90%

Summary

- Heavy stable charged particles (HSCP) occur
  - very weakly interacting DM (axinos/gravitinos)
  - mass-degeneracies (co-annihilation scenarios)
- Strong connection between cosmology and LHC
  - Gravitino-stau scenario: Large T_R in distinct corner
  - SModelS extension: automatically test HSCP signatures
  - HSCP highest sensitivity although only ~30% of signal
  - Tip of stau-coannihilation strip excluded (from LHC or Planck) for low $\tan\beta$

Outlook

- SModelS: Extension for colored HSCPs
  Gluino can become long-lived in parts of the pMSSM
- Include other exotics
  (like displaced vertices)
- SModelS website:

  smodels.hephy.at

Thank you for your attention!

The Tip of the CMSSM Co-annihilation Strip

- Scan (for $\tan\beta = 10$):

[JH, Lessa, Quertenmont, 1509.00473]

