Big-Bang Nucleosynthesis (BBN)
&
Supersymmetric Model with Heavy Sfermions

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1. Introduction & Outline

Today, I discuss:

- BBN constraints on the decaying gravitino (with observational data as well as calculation being updated)
- A suggested SUSY scenario, and DM (i.e., Wino)

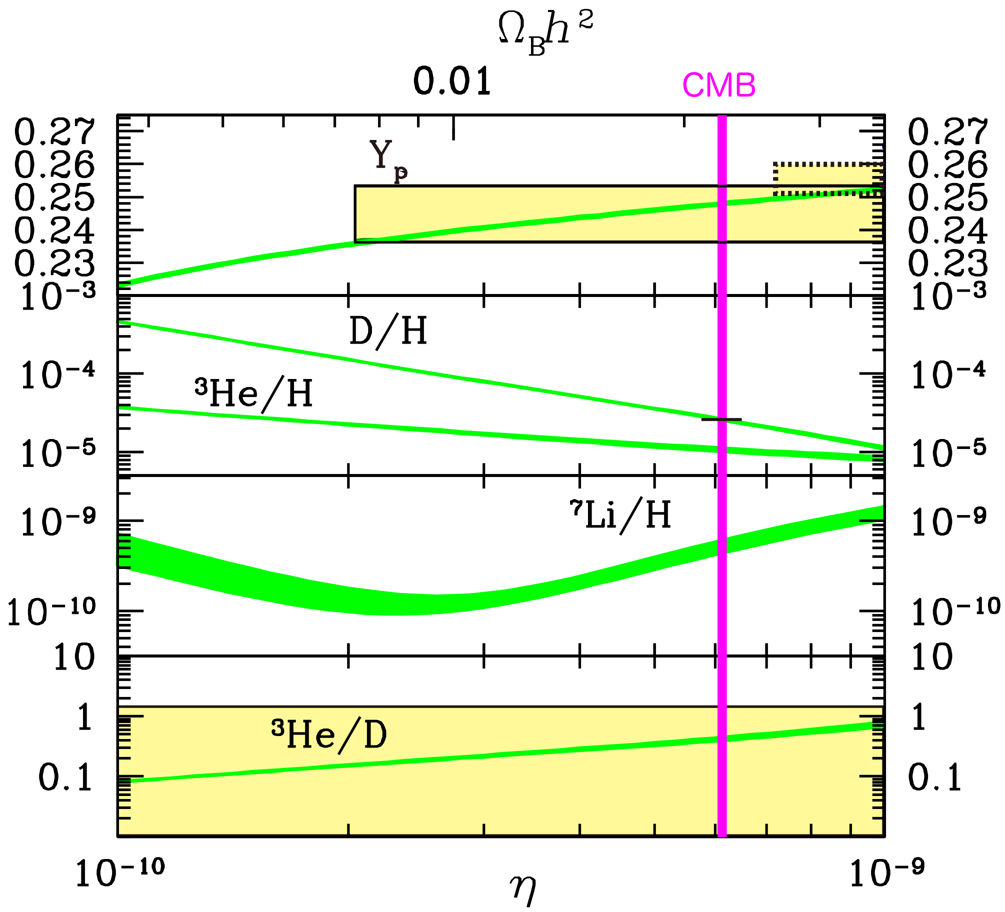
Outline

1. Introduction & Outline
2. BBN and Gravitino
3. Suggestion to SUSY Breaking
4. Wino DM
5. A New LHC Signal
6. Summary

2. BBN and Gravitino

[Kawasaki, Kohri, TM & Takaesu, arXiv:1709.01211]

BBN is an important check point in cosmology

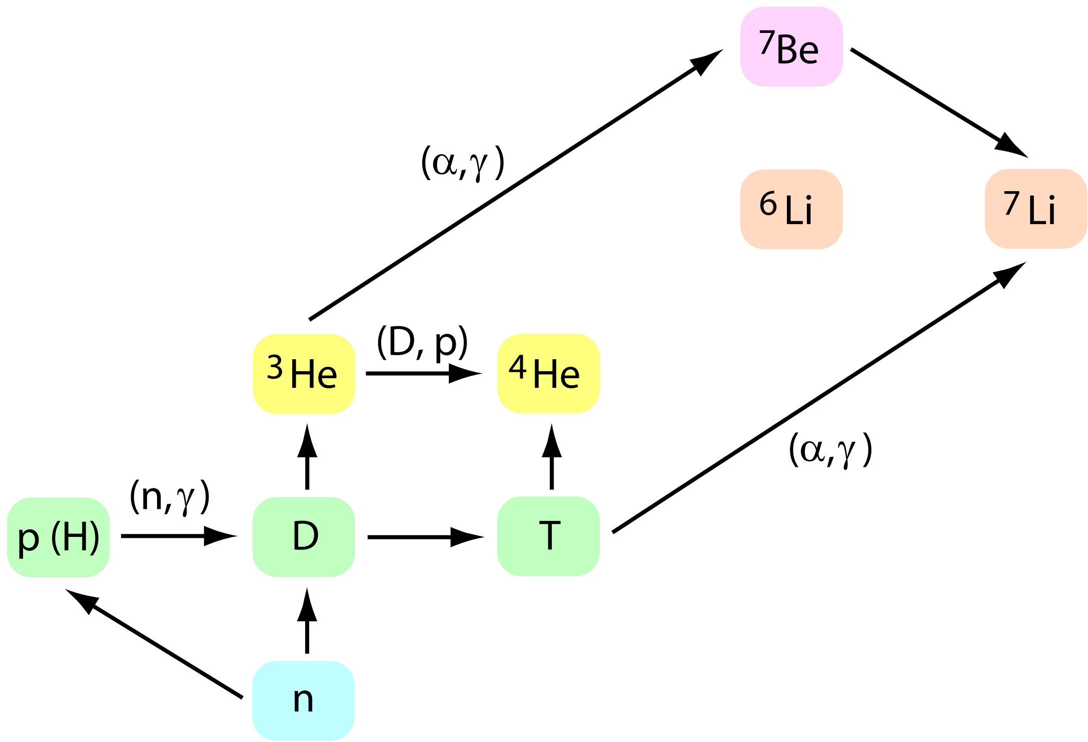


- D/H $= (2.53 \pm 0.04) \times 10^{-5}$
  [Cooke et al. ('14)]
- ^{3}He/D $< 0.83 + 0.27$
  [Geiss & Gloeckler ('03)]
- $Y_{\rm BBN} = 0.2449 \pm 0.0040$
  [Aver, Olive & Skillman, ('15)]
- Cf.: $Y_{\rm BBN} = 0.2551 \pm 0.0022$
  [Izotov, Thuan & Guseva ('14)]

In our old study in '05:

- D/H $= (2.78^{+0.44}_{-0.38}) \times 10^{-5}$
- $Y_{\rm BBN} = 0.238 \pm 0.0054$

Standard BBN occurs at $t \sim 1 - 1000$ sec



- If the n/p ratio is changed after the neutron freeze-out, ^{4}He abundance is affected
- With the dissociations of ^{4}He, D and ^{3}He are produced
- Dissociations of D and ^{3}He may be also important

We consider long-lived particle X

$$X \to \cdots$$

Important quantities

1. Lifetime

$$\tau_X$$

2. Primordial abundance (yield)

$$Y_X \equiv \left[\frac{n_X}{s}\right]_{t \ll \tau_X}$$

3. Spectra of decay products

$$\frac{dN_i}{dE_i} \text{ with } i = \text{SM particles (gluon, photon, quarks, } \cdots\text{)}$$

We have studied the BBN with long-lived particle X

1. We adopt the most recent observational constraints on the light element abundances

2. We updated the reaction rates of the standard BBN processes

   [Serpico et al. ('04); NACRE Collaboration ('13); $\cdots$]

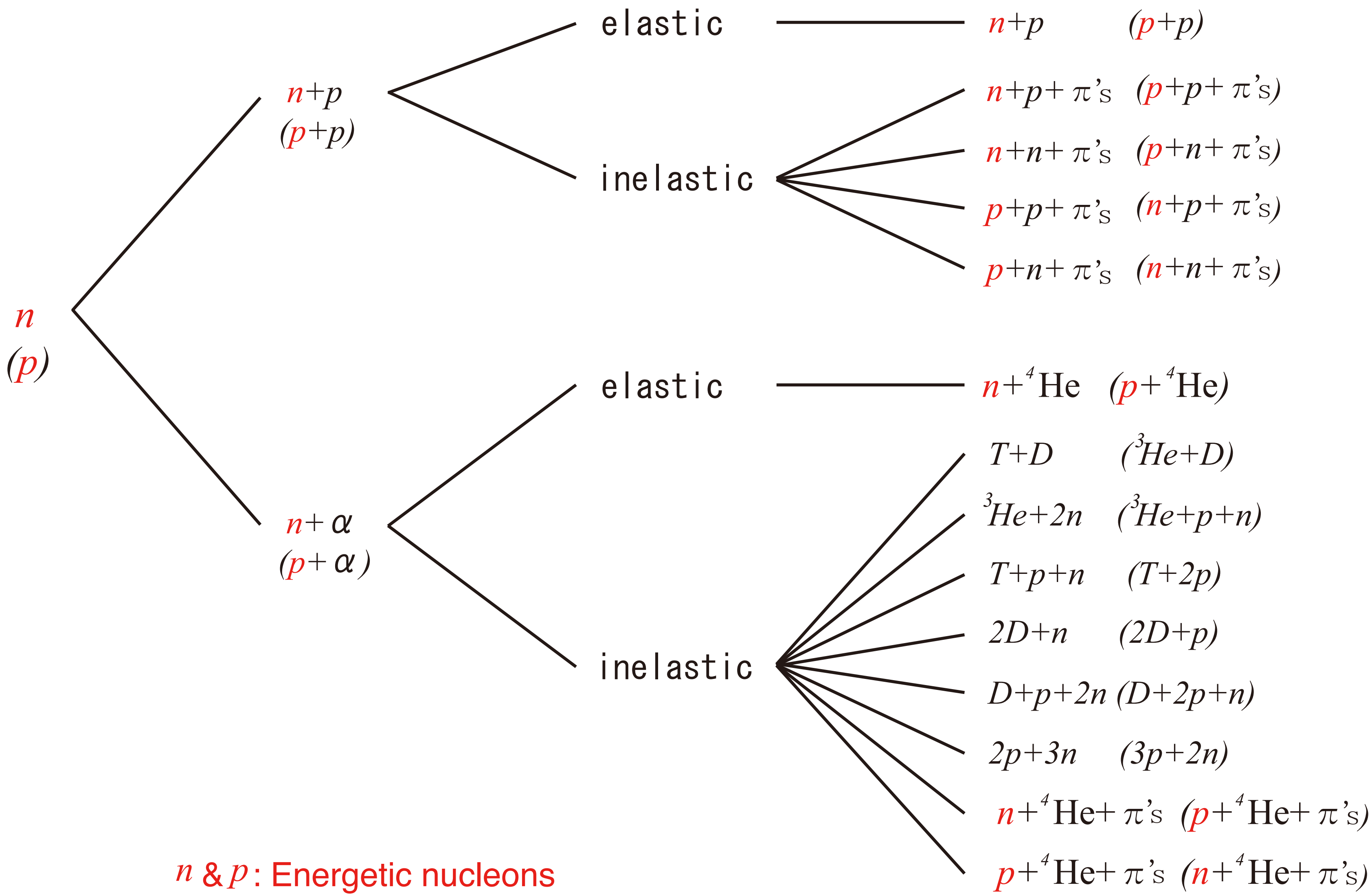
3. Evolution of hadronic shower is studied in more detail

   – $p \leftrightarrow n$ interconversion via inelastic scatterings

   – Hadronic shower induced by anti-nucleons

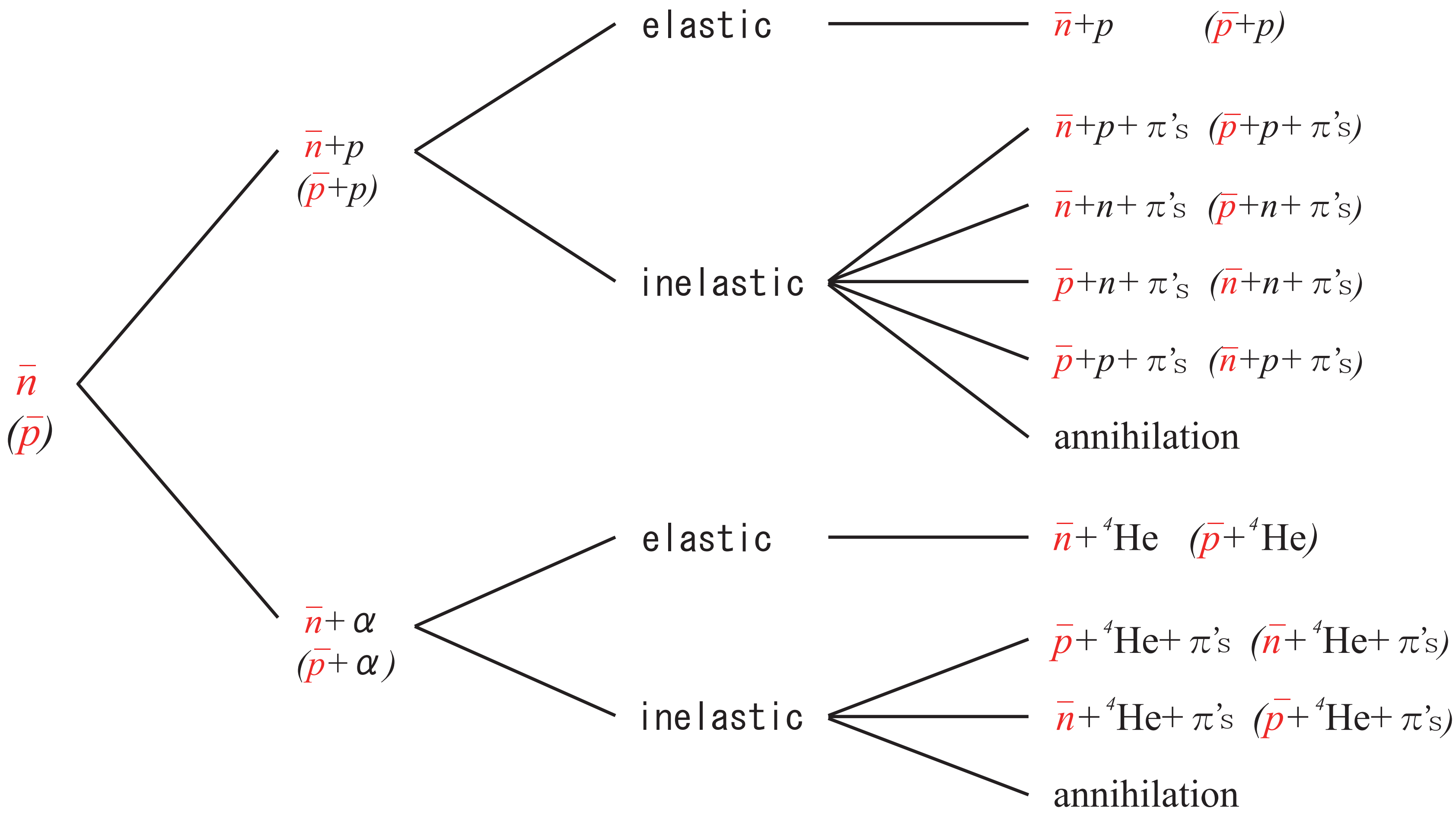
4. Energy spectra of hadrons from the hadronization are calculated with PYTHIA 8.2 package

Hadronic processes in our analysis (1)



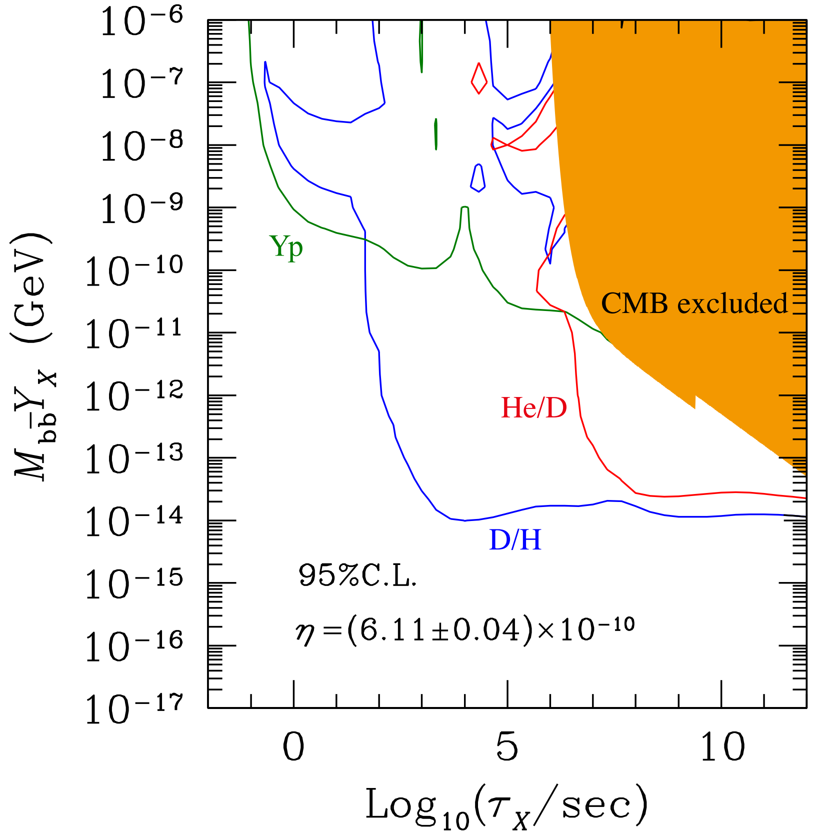
n & *p*: Energetic nucleons

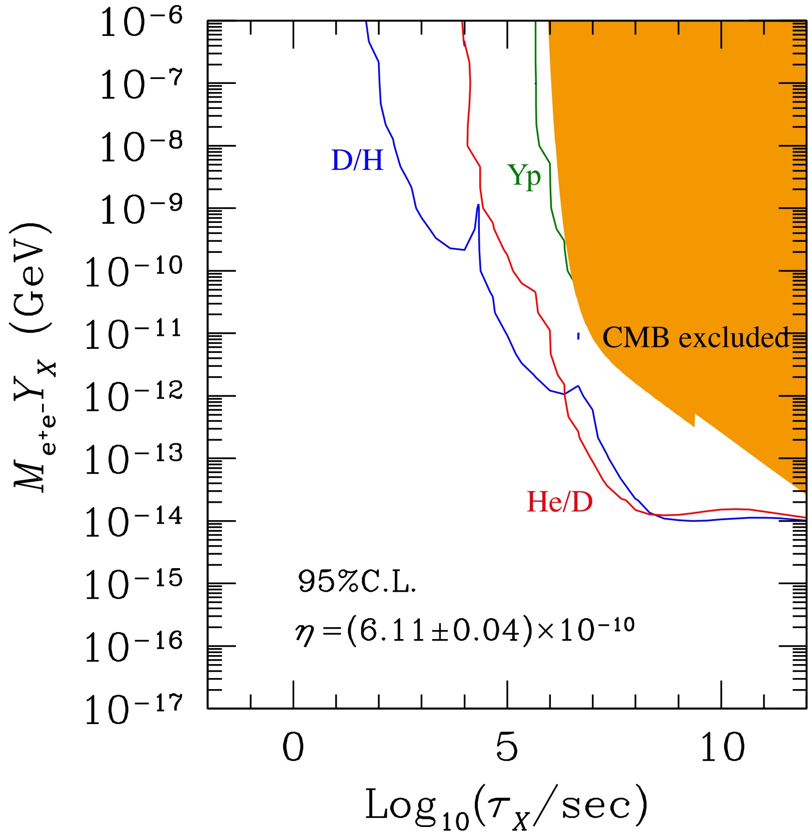
Hadronic processes in our analysis (2)



Upper bound on the yield variable (for $m_X = 1$ TeV)

$$Y_X \equiv [n_X/s]_{t \ll \tau_X}$$

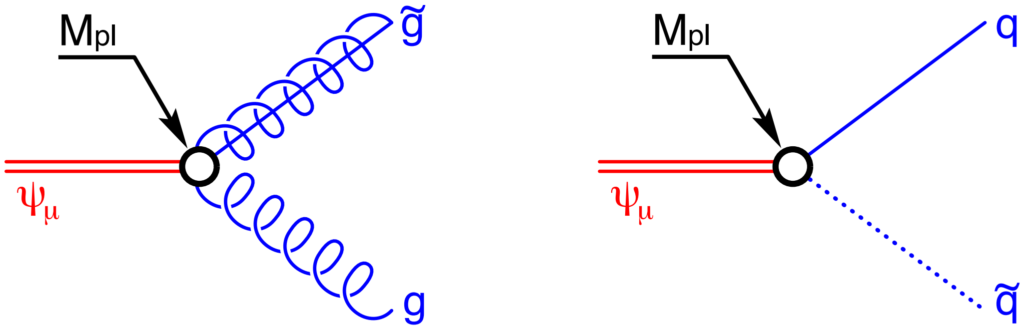




Unstable gravitino may affect the light-element abundances

[Weinberg ('82); Ellis, Kim & Nanopoulos ('84); Khlopov & Linde ('84); Lindley ('85); Ellis, Nanopoulos & Sarkar ('85); Ellis, Gelmini, Lopez, Nanopoulos & Sarkar ('90); Kawasaki & TM ('95); Jedamzik ('00); Cyburt, Ellis, Fields & Olive ('03); Kawasaki, Kohri & TM ('05); $\cdots$]

- Interaction of gravitino is Planck suppressed



- Gravitinos produced after inflation may decay during or after the BBN epoch

$$\tau_{3/2}(\psi_\mu \to g + \tilde{g}) \simeq 50 \text{ sec} \times \left(\frac{m_{3/2}}{10 \text{ TeV}} \right)^{-3}$$

Gravitino production after inflation

- Gravitino production rate

$$\langle \sigma_{\text{prod}} v_{\text{rel}} \rangle \sim \frac{\alpha_{\text{gauge}}}{M_{\text{Pl}}^2} \quad \Rightarrow \quad \Gamma_{\text{prod}} \sim \langle \sigma_{\text{prod}} v_{\text{rel}} \rangle T^3$$

- Yield variable (s: entropy density)

$$Y_{3/2} \equiv \frac{n_{3/2}}{s} \sim \Gamma_{\text{prod}} H^{-1} \to \frac{\alpha_{\text{gauge}} T_{\text{R}}}{M_{\text{Pl}}}$$

Result of the detailed calculation (for $M_i \ll m_{3/2}$)

[with $\langle \sigma_{\text{prod}} v_{\text{rel}} \rangle$ by Bolz, Brandenburg & Buchmuller; Pradler & Steffen]

$$\frac{n_{3/2}}{s} \simeq 1.9 \times 10^{-12} \times \left(\frac{T_{\text{R}}}{10^{10}\ \text{GeV}} \right) \quad \text{with} \quad T_{\text{R}} \equiv \left(\frac{10}{g_* \pi^2} M_{\text{Pl}}^2 \Gamma_\Phi^2 \right)^{1/4}$$

$\Rightarrow$ The gravitino abundance is proportional to the reheating temperature T_{R}

Gravitino decay produces lots of hadrons (p, $\bar{p}$, n, $\bar{n}$, π, $\cdots$)

1. Produced hadrons affects the n/p ratio

   $\Rightarrow$ ^{4}He may be overproduced

2. Emitted hadrons induce hadronic shower

   $\Rightarrow$ Energetic nucleons in the shower cause hadrodissociation of ^{4}He, resulting in overproduction of D

   $\Rightarrow$ At high enough temperature, nucleons are stopped by scattering off CMB

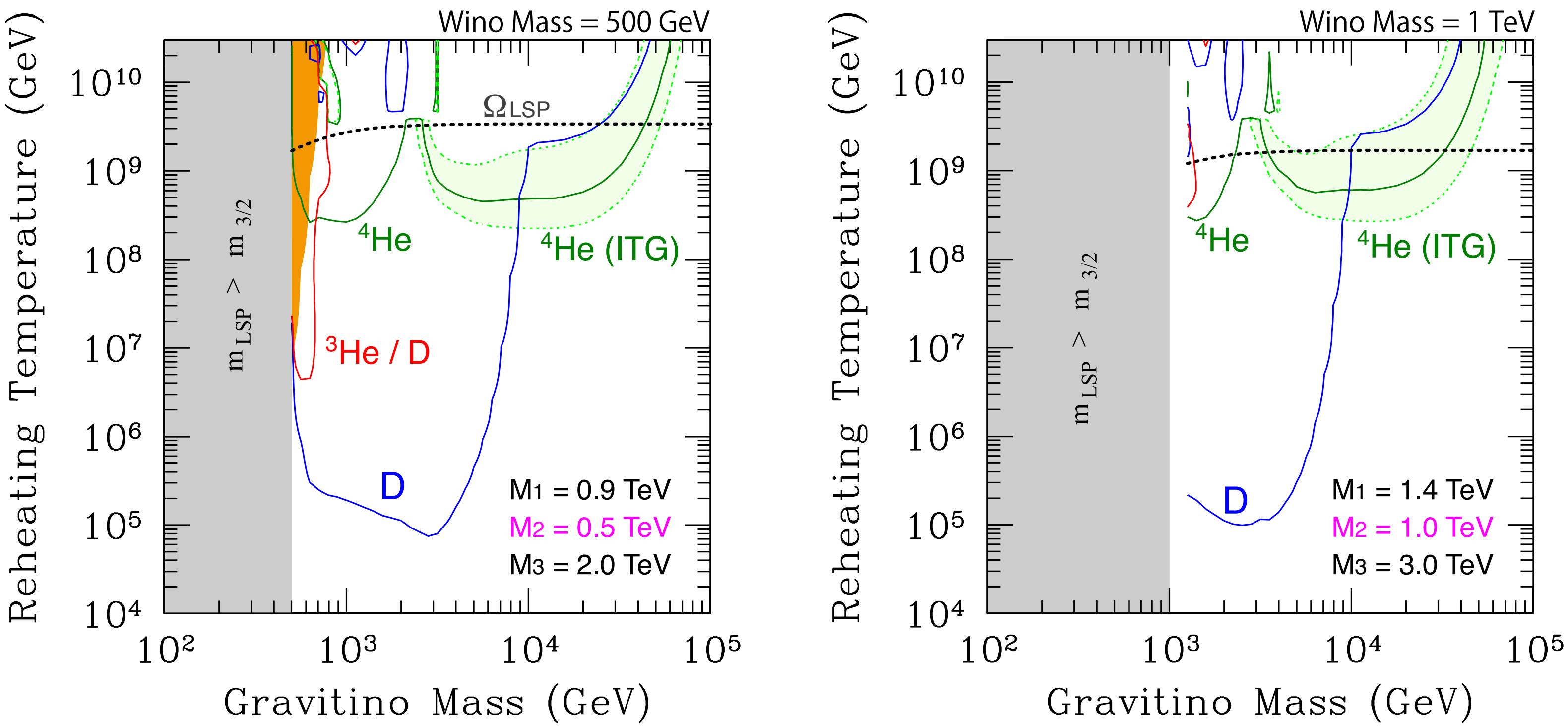
3. Energetic photons induce photodissociation processes

Gravitino decay is studied with viable MSSM mass spectrum

- MadGraph5_aMC@NLO v2.1
- PYTHIA 8.2

95 % C.L. upper bound on $T_{\rm R}$ with decaying gravitino

Sfermions are assumed to be heavier than gravitino



[Kawasaki, Kohri, TM, Takaesu]

$\Rightarrow m_{3/2} \gtrsim 10$ TeV & $T_{\rm R} \gtrsim 10^9$ GeV seems interesting

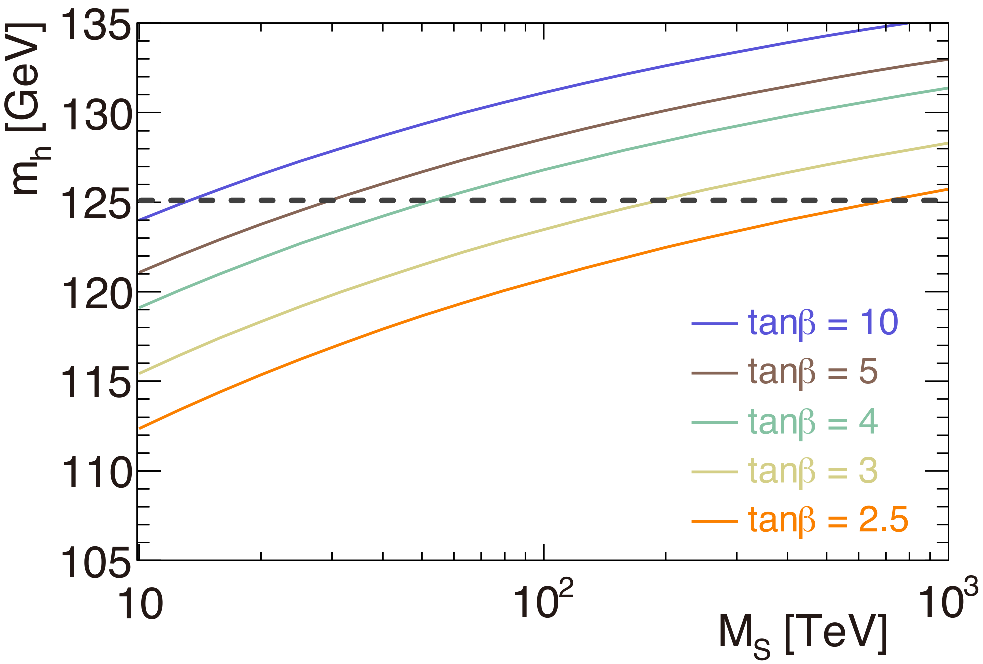
3. Suggestion to SUSY Breaking

$m_{3/2} \gtrsim 10$ TeV & $T_\mathrm{R} \gtrsim 10^9$ GeV

⇔ The Leptogenesis scenario requires $T_\mathrm{R} \gtrsim 10^9$ GeV

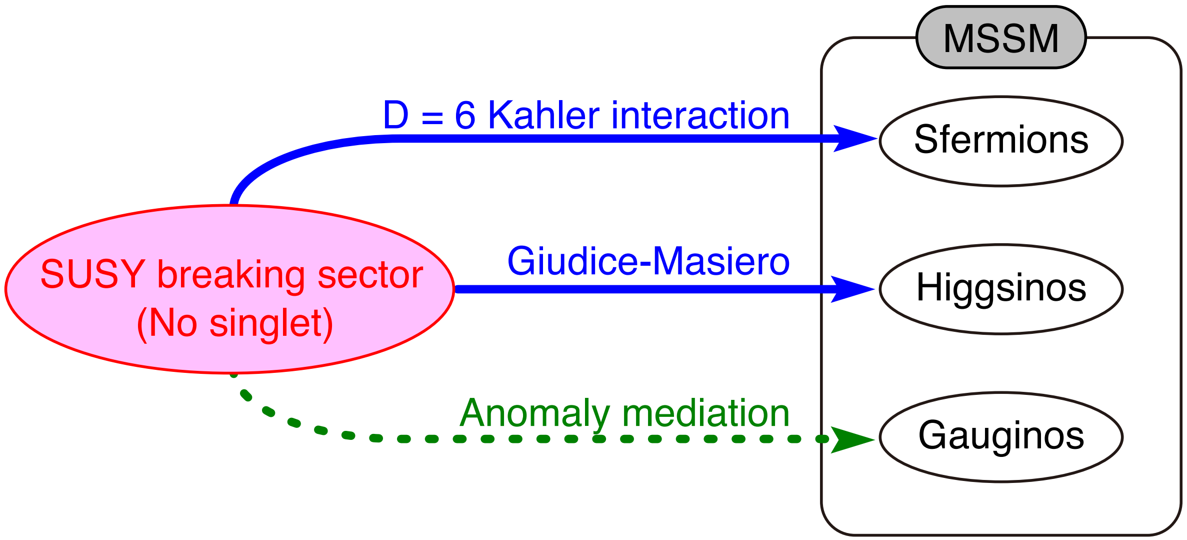
[See, for example, Buchmuller, Di Bari & Plumacher ('02); Giudice, Notari, Raidal, Riotto & Strumia ('03)]

Observed Higgs mass suggests stop masses of $O(10-1000)$ TeV



A natural scenario: "Pure gravity mediation (PGM)"

[Ibe, TM & Yanagida; Ibe & Yanagida; Arkani-Hamed et al.]

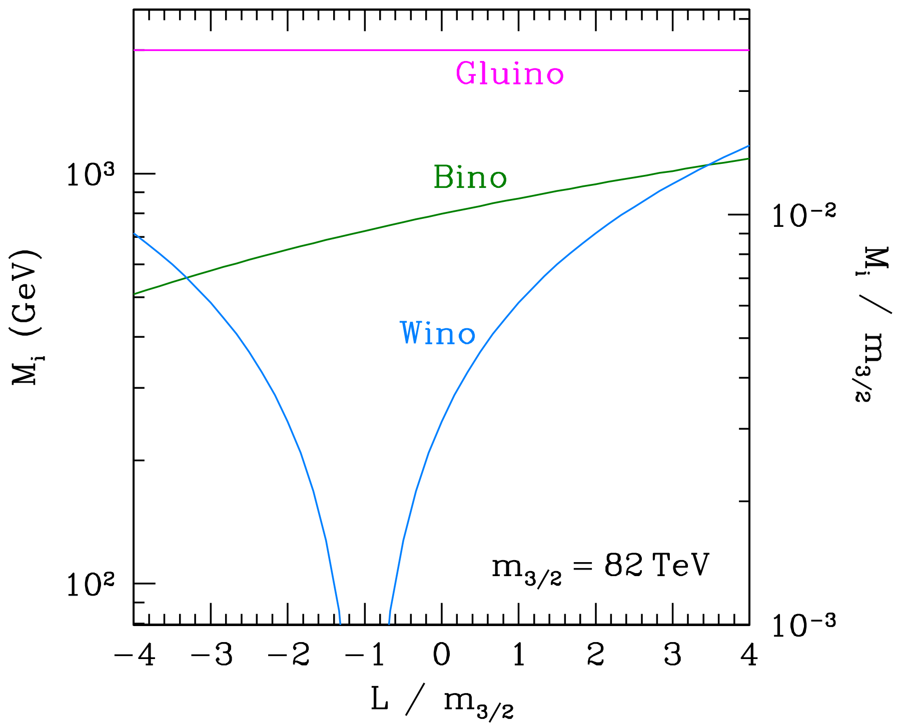


Mass spectrum

- Masses of gravitino, sfermions, and Higgsinos are of $\sim O(10)$ TeV
- Gaugino masses are from anomaly-mediation, and are $O(100\text{ GeV} - 1\text{ TeV})$

  [Giudice, Luty, Murayama & Rattazzi; Randall & Sundrum]

Gaugino masses in the PGM model



$$M_1 \simeq \frac{g_1^2}{16\pi^2}\left(11 m_{3/2} + L\right)$$

$$M_2 \simeq \frac{g_2^2}{16\pi^2}\left(m_{3/2} + L\right)$$

$$M_3 \simeq \frac{g_3^2}{16\pi^2}\left(-3 m_{3/2}\right)$$

$$L \equiv \mu \sin 2\beta \frac{m_A^2}{\mu^2 - m_A^2} \ln \frac{\mu^2}{m_A^2}$$

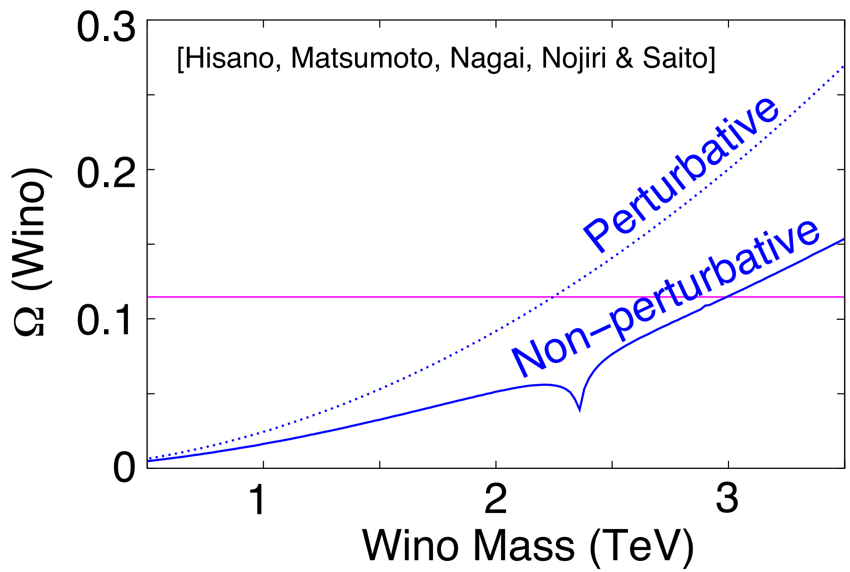
⇒ Wino (gaugino for $SU(2)_L$) is likely to be the LSP

⇒ Sfermions and Higgsinos are extremely heavy (so we give up naturalness)

4. Wino DM

Thermal relic abundance of Wino

$\Leftrightarrow$ Annihilation cross section of Wino is sizable



$\Leftrightarrow$ $\Omega_{\tilde{W}}^{\text{(thermal)}} \simeq \Omega_c$, if $m_{\tilde{W}} \simeq 3$ TeV
[Hisano, Matsumoto, Nagai, Nojiri & Saito]

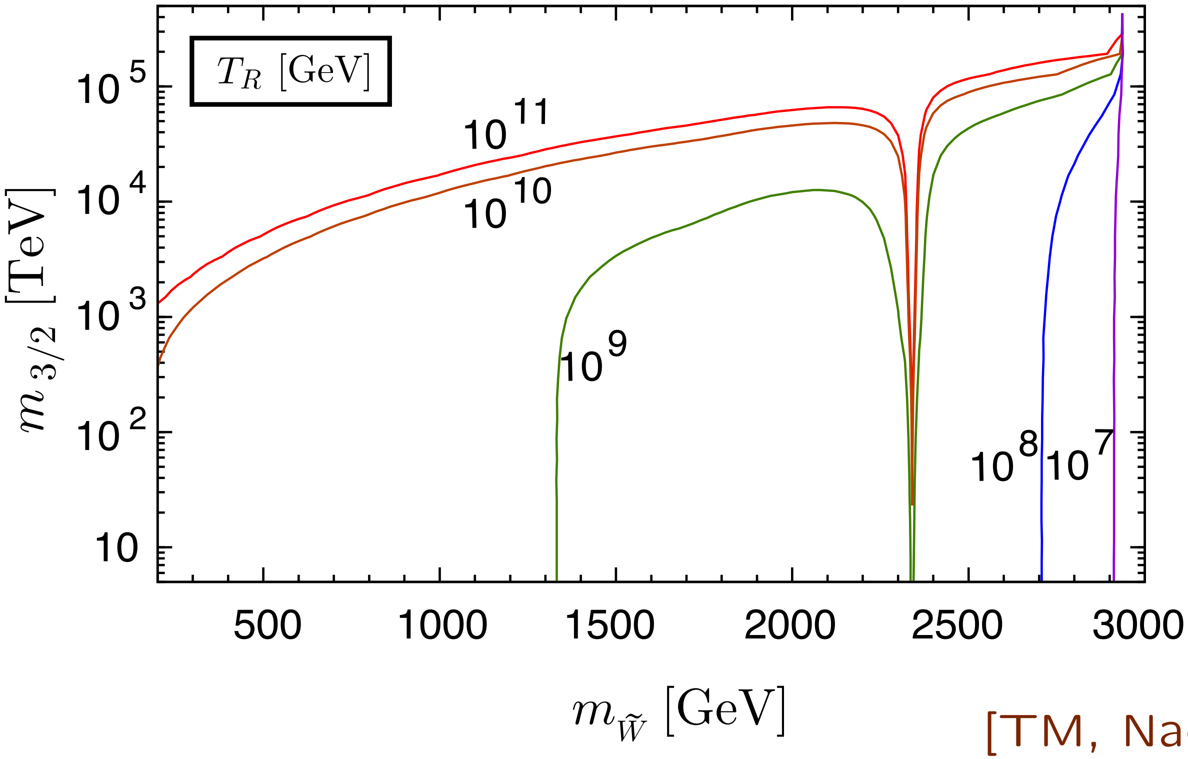
If Bino is the LSP, $\Omega_{\tilde{B}}^{\text{(thermal)}} \gg \Omega_c$ in PGM (as far as $\mu \gg M_1$)

$\Rightarrow$ Bino DM is unlikely

The Wino is also produced by the gravitino decay

[Giudice, Luty, Murayama & Rattazzi]

$\Rightarrow$ $\Omega_{\tilde{W}} = \Omega_c$ is realized with a relevant value of $T_{\rm R}$



[TM, Nagai & Takimoto]

$\Rightarrow$ If $m_{3/2} \sim O(10-100)$ TeV, the gravitino decays after the Wino freezes out

Approximated formula for $\Omega_{\tilde{W}}$ (for small enough $m_{3/2}$)

[TM, Nagai & Takimoto]

$$\Omega_{\tilde{W}} \simeq \Omega_{\tilde{W}}^{(\text{thermal})} + 0.6\,\Omega_c \times \left(\frac{m_{\text{LSP}}}{1\ \text{TeV}} \right) \left(\frac{T_{\text{R}}}{10^9\ \text{GeV}} \right)$$

Wino can be dark matter even if $\Omega_{\tilde{W}}^{(\text{thermal})} \ll \Omega_c$

$\Rightarrow T_{\text{R}} \sim O(10^9)$ GeV is needed, if $m_{\tilde{W}} \sim 1$ TeV

Such a scenario is consistent with (simple) leptogenesis

$\Leftrightarrow$ Leptogenesis requires $T_{\text{R}} \gtrsim 10^9$ GeV to make enough amount of baryon number

[See, for example, Buchmuller, Di Bari & Plumacher]

Wino annihilates via s-wave process

$\Rightarrow \tilde{W}^0 \tilde{W}^0 \rightarrow W^+ W^-$

Winos annihilate even after the “freeze-out”

$\Rightarrow$ Sizable amount of energetic particles are produced

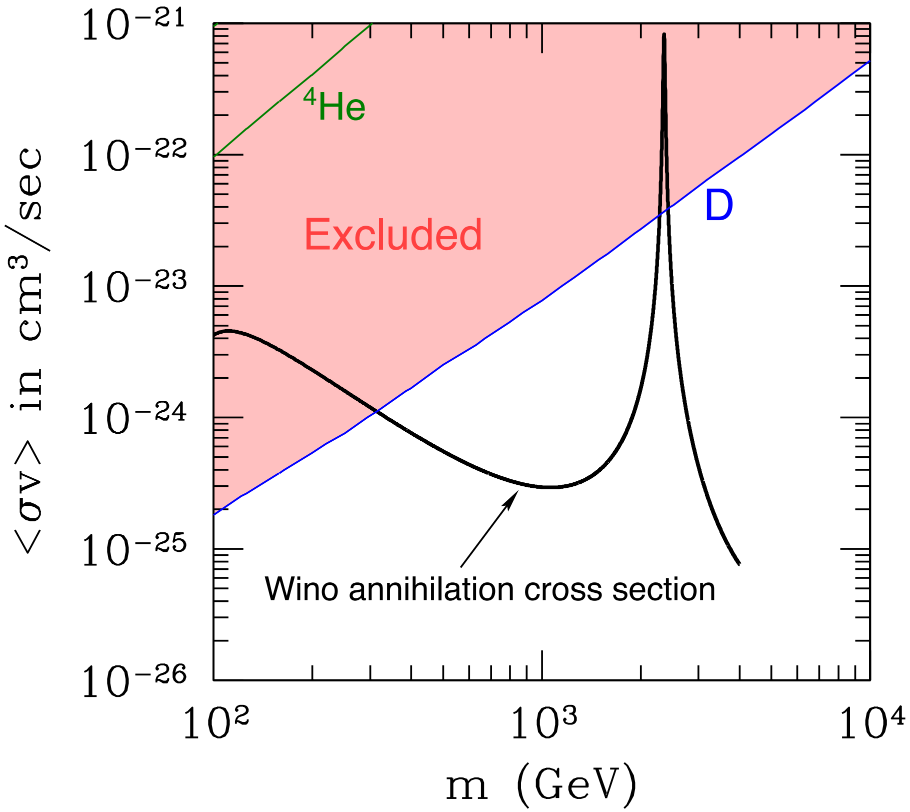
$\Rightarrow$ Energetic particles are produced

Check points:

- BBN
- $\bar{p}$ in the cosmic ray
- γ-ray from dwarf spheroidal galaxies (dSphs)

Effects on BBN: upper bound on $\langle \sigma v \rangle_{\mathrm{DM+DM} \to W^+ + W^-}$

[Jedamzik ('04); Hisano, Kawasaki, Kohri & Nakayama ('09); Kawasaki, Kohri, TM, Takaesu ('15)]

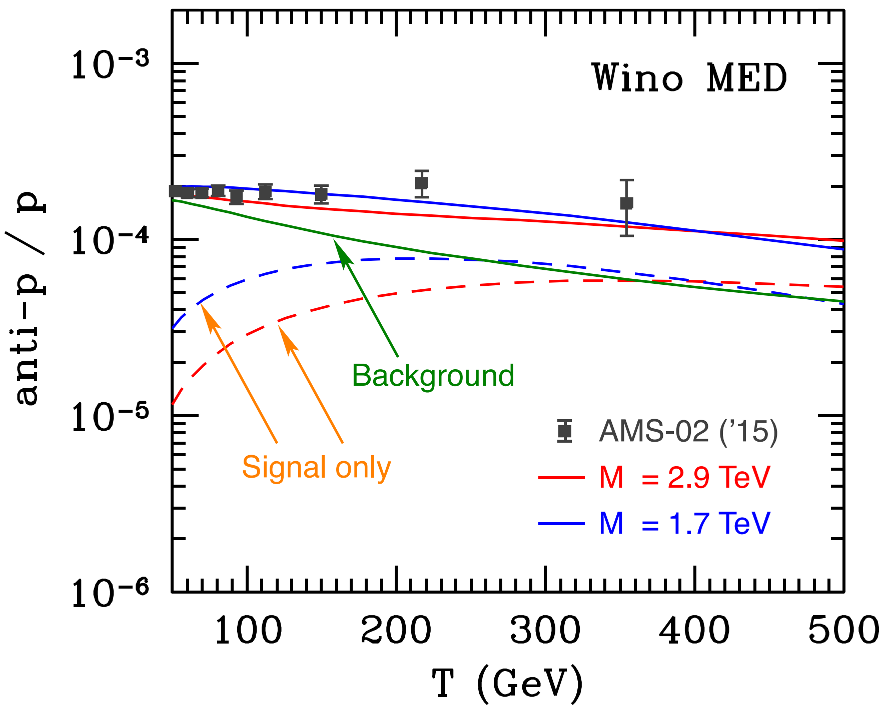


[Kawasaki, Kohri, TM, Takaesu 1509.03665]

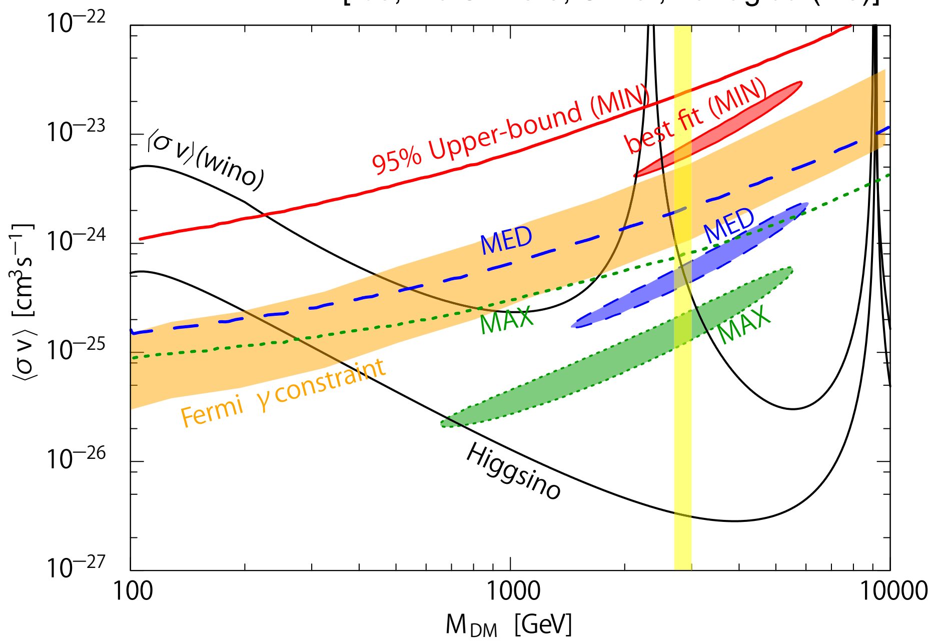
$\Rightarrow 320$ GeV $\lesssim m_{\tilde{W}} \lesssim 2.3$ TeV or $m_{\tilde{W}} \gtrsim 2.5$ TeV

Effects on the fluxes of cosmic rays

[Hamaguchi, TM, Nakayama ('15)]



[Ibe, Matsumoto, Shirai, Yanagida ('15)]



- Anti-proton flux from the Wino annihilation is consistent with the AMS-02 result

  [Hamaguchi, TM & Nakayama ('15); Ibe, Matsumoto, Shirai & Yanagida ('15)]

- γ-ray flux from dSph is an important check point

Bounds on the Wino mass (assuming Wino DM)

BBN : $320\ \text{GeV} \lesssim m_{\tilde{W}} \lesssim 2.3\ \text{TeV}$ or $m_{\tilde{W}} \gtrsim 2.5\ \text{TeV}$

Anti-proton : $230\ \text{GeV} \lesssim m_{\tilde{W}} \lesssim 2.2\ \text{TeV}$ or $m_{\tilde{W}} \gtrsim 2.5\ \text{TeV}$

γ from dSph : $440\ \text{GeV} \lesssim m_{\tilde{W}} \lesssim 2.1\ \text{TeV}$ or $m_{\tilde{W}} \gtrsim 2.6\ \text{TeV}^{\#}$

[Bhattacherjee et al. ('15)]

LHC : $m_{\tilde{W}} \gtrsim 430\ \text{GeV}$

[ATLAS-CONF-2017-017]

A more stringent bound is claimed by Magic+Fermi

[Magic + Fermi-LAT 1601.06590]

$\Leftrightarrow$ They assume NFW DM distribution in dSphs

$\Rightarrow$ Wino DM based on PGM seems an attractive possibility

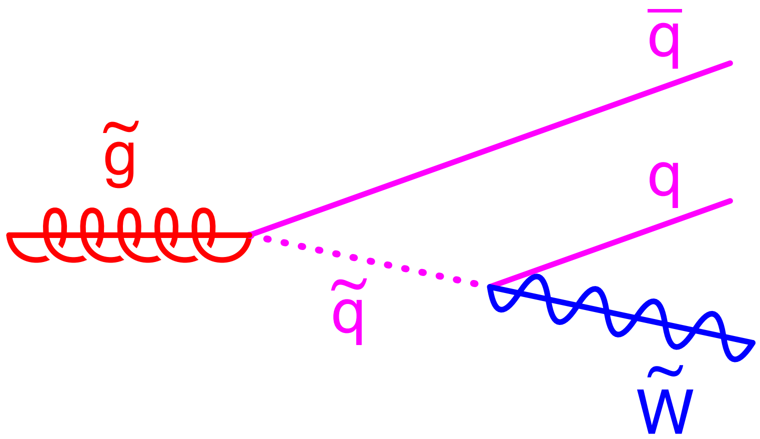
5. A New LHC Signal

[Ito, Jinnouchi, TM, Nagata & Otono, arXiv:1702.08613]

Hereafter, we consider SUSY models with:

- Gluino mass is a few TeV
- Sfermion masses are $O(100)$ TeV or higher

Decay length of the gluino may become relatively long



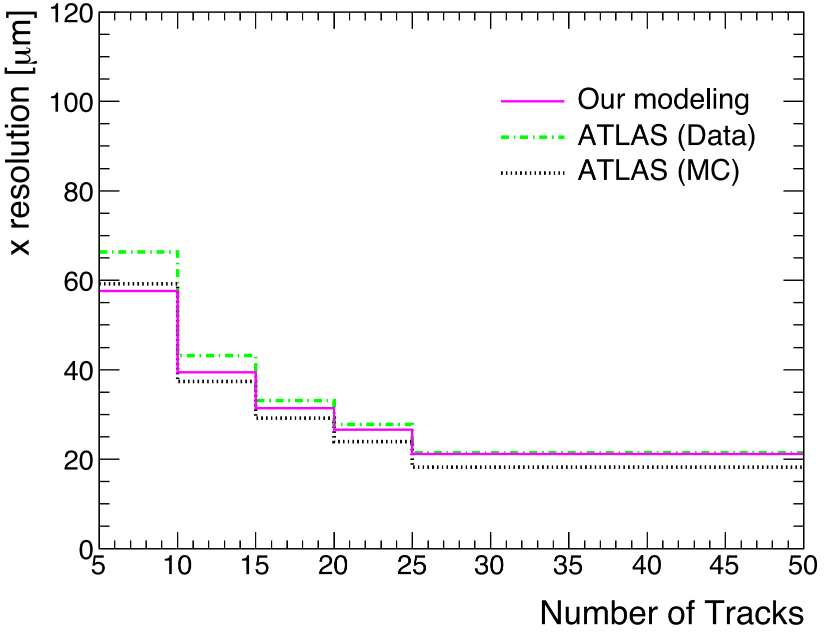
$$c\tau_{\tilde{g}} \simeq 200\ \mu\text{m} \times \left(\frac{m_{\tilde{q}}}{10^3\ \text{TeV}}\right)^4 \left(\frac{2\ \text{TeV}}{m_{\tilde{g}}}\right)^5$$

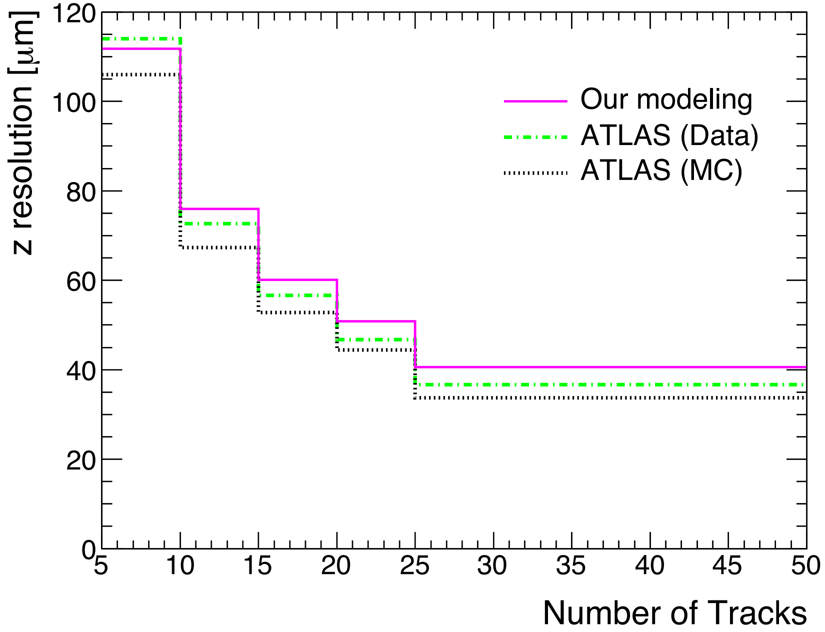
$\Rightarrow$ Displaced vertices (DVs) in gluino events

Vertex resolution of the ATLAS detector

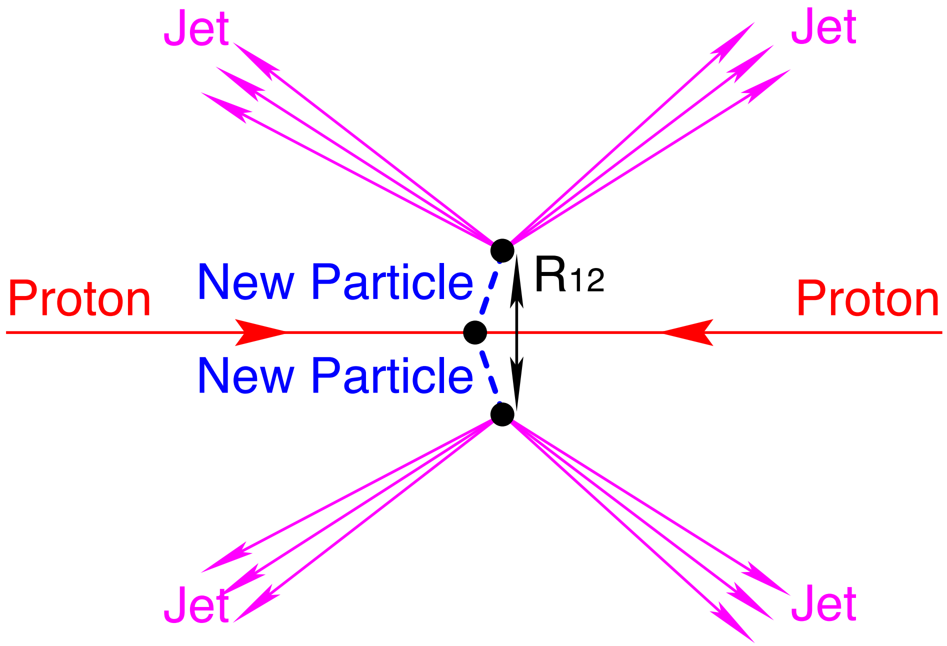
- Each jet contains many charged tracks
- The primary vertex is estimated as a point “nearest” to all the tracks

Resolution



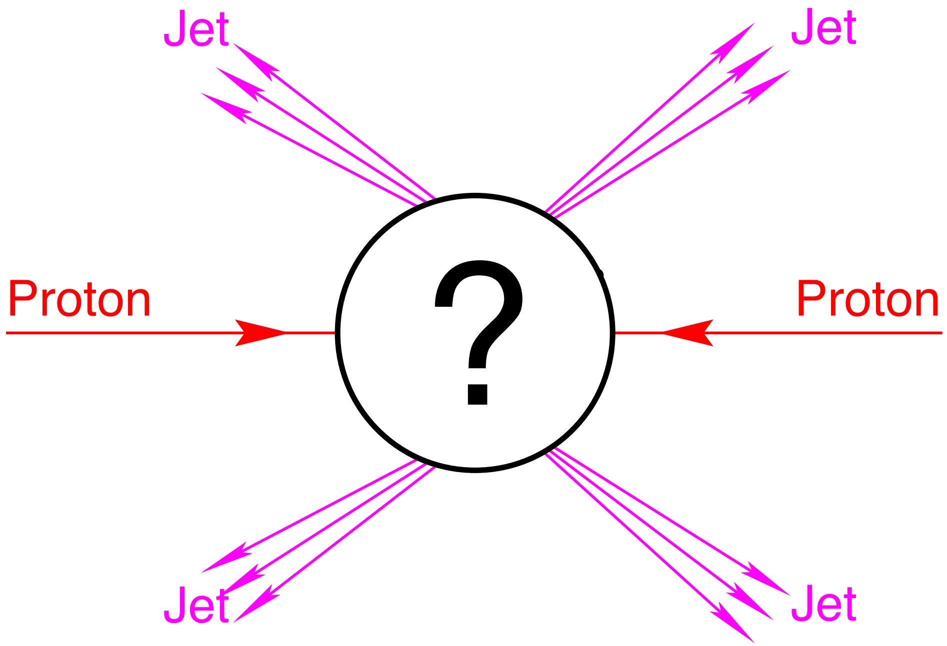


DV information can be used for gluino search



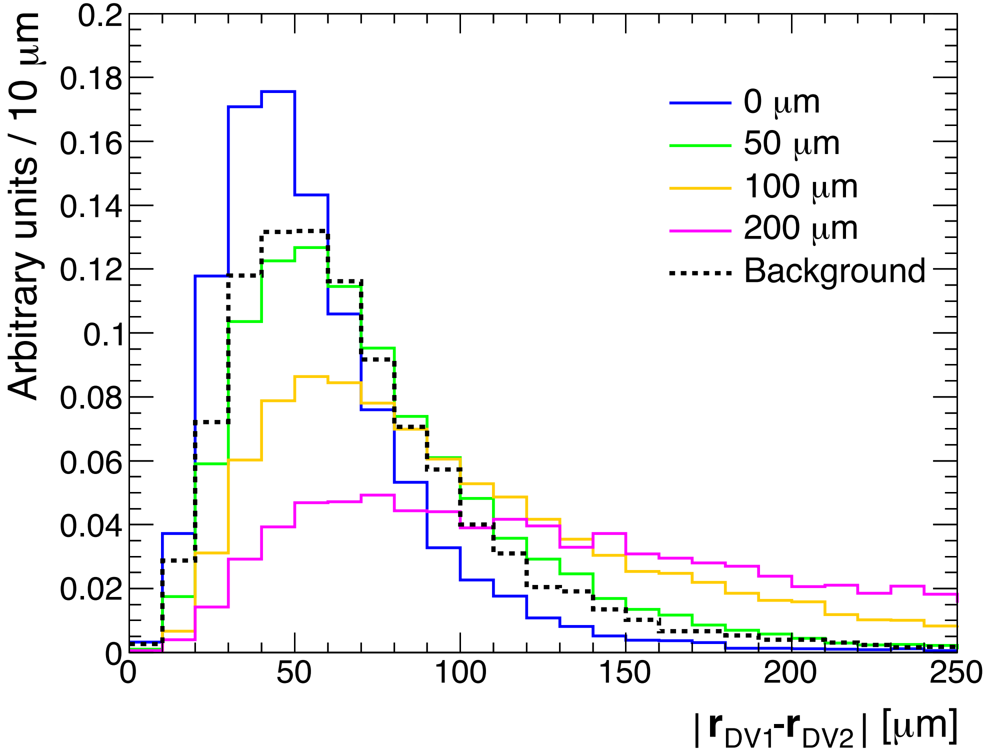
- Each signal events should have two DVs
- We can use the distance of the DVs R_{12} as a discrimination parameter

Our proposal: Use DV information on top of standard cuts



- Use leading 4 jets
- Assume two of the jets originate from a vertex V_1, while other two are from a vertex V_2
- Find the best pairings of the jets and the best-fit points of vertices (to minimize χ^2)

Reconstructed $R_{12} \equiv |\mathbf{r}_1 - \mathbf{r}_2|$ distribution for various $c\tau_{\tilde{g}}$



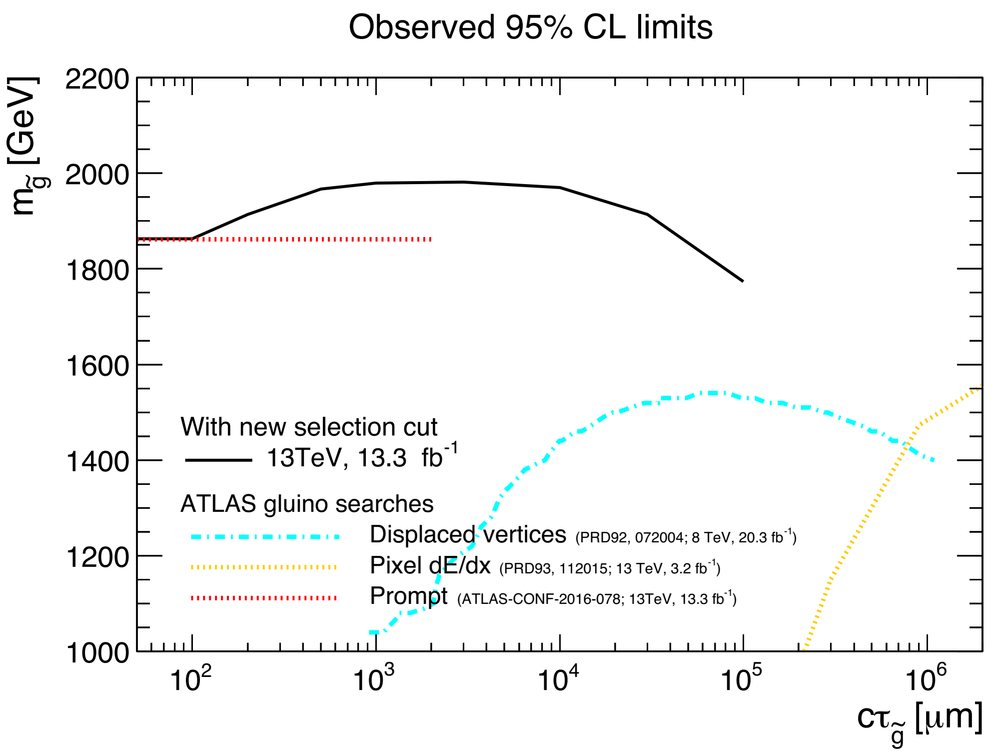
- Results of MC simulation
- ATLAS DV search algorithm is adopted

We performed MC with the cuts [`Meff-4j-2600`]

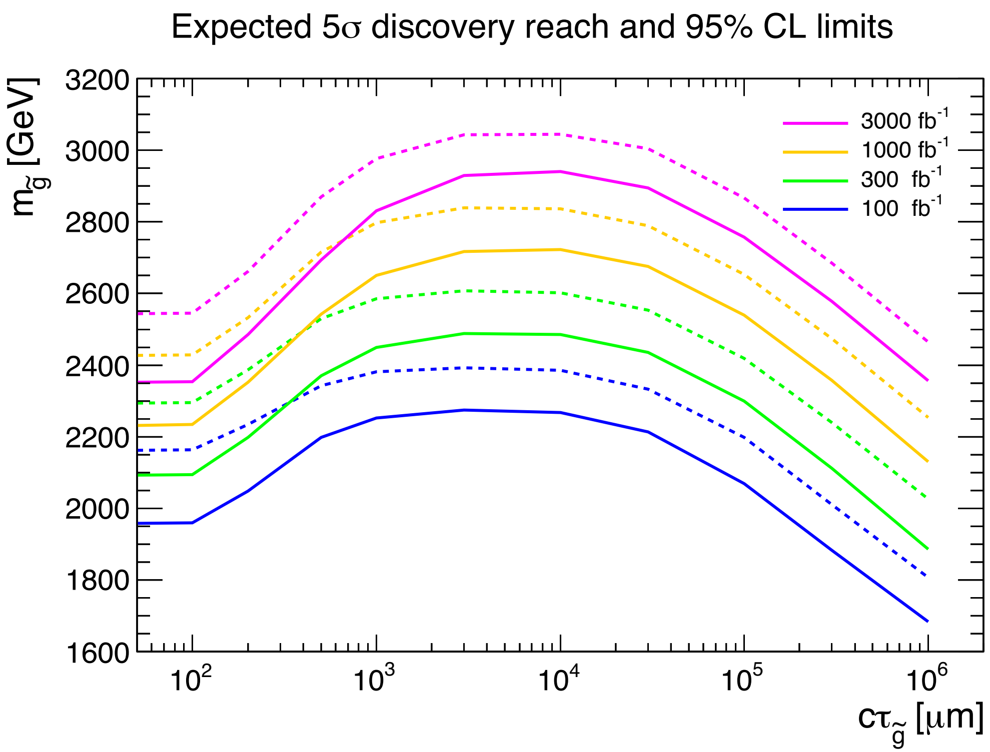
- $E_{\mathrm{T}}^{(\mathrm{miss})} > 250$ GeV, $p_{\mathrm{T}}(j_1) > 200$ GeV and $p_{\mathrm{T}}(j_4) > 150$ GeV
- $\Delta\phi(j_{1,2,3,4}, E_{\mathrm{T}}^{(\mathrm{miss})})_{\mathrm{min}} > 0.4$
- Aplanarity larger than 0.04
- $E_{\mathrm{T}}^{(\mathrm{miss})}/m_{\mathrm{eff}}(4) > 0.2$
  $m_{\mathrm{eff}}(4)$: scalar sum of $E_{\mathrm{T}}^{(\mathrm{miss})}$ and the transverse momenta of leading 4-jets
- $m_{\mathrm{eff}}(\mathrm{incl.}) > 2600$ GeV
  $m_{\mathrm{eff}}(\mathrm{incl.})$: scalar sum of $E_{\mathrm{T}}^{(\mathrm{miss})}$ and the transverse momenta of jets with $p_{\mathrm{T}} > 50$ GeV
- Using ATLAS DV search algorithm to identify the decay vertices of gluinos, we calculate R_{12}

Discovery reach with the current data

- We concentrate on the signal region `Meff-4j-2600`
- For each $c\tau_{\tilde{g}}$, we optimize r_{cut} to maximize the significance of discovery



Discovery reach (future prospects)



⇒ The reach may improve a few hundred GeV, if we use the DV information

6. Summary

Today, I discussed:

- Updated BBN constraints on decaying gravitino
- Cosmology with Wino DM
- A new LHC signal (sub-millimeter DVs)

Wino DM is interesting because:

- Wino LSP is suggested in PGM SUSY breaking scenario
- $T_{\rm R} \sim O(10^9)$ GeV is suggested (if $m_{\tilde{W}} < 3$ TeV), which is consistent with leptogenesis
- New LHC signals (based on DVs) may exist

Back Up

Deuterium

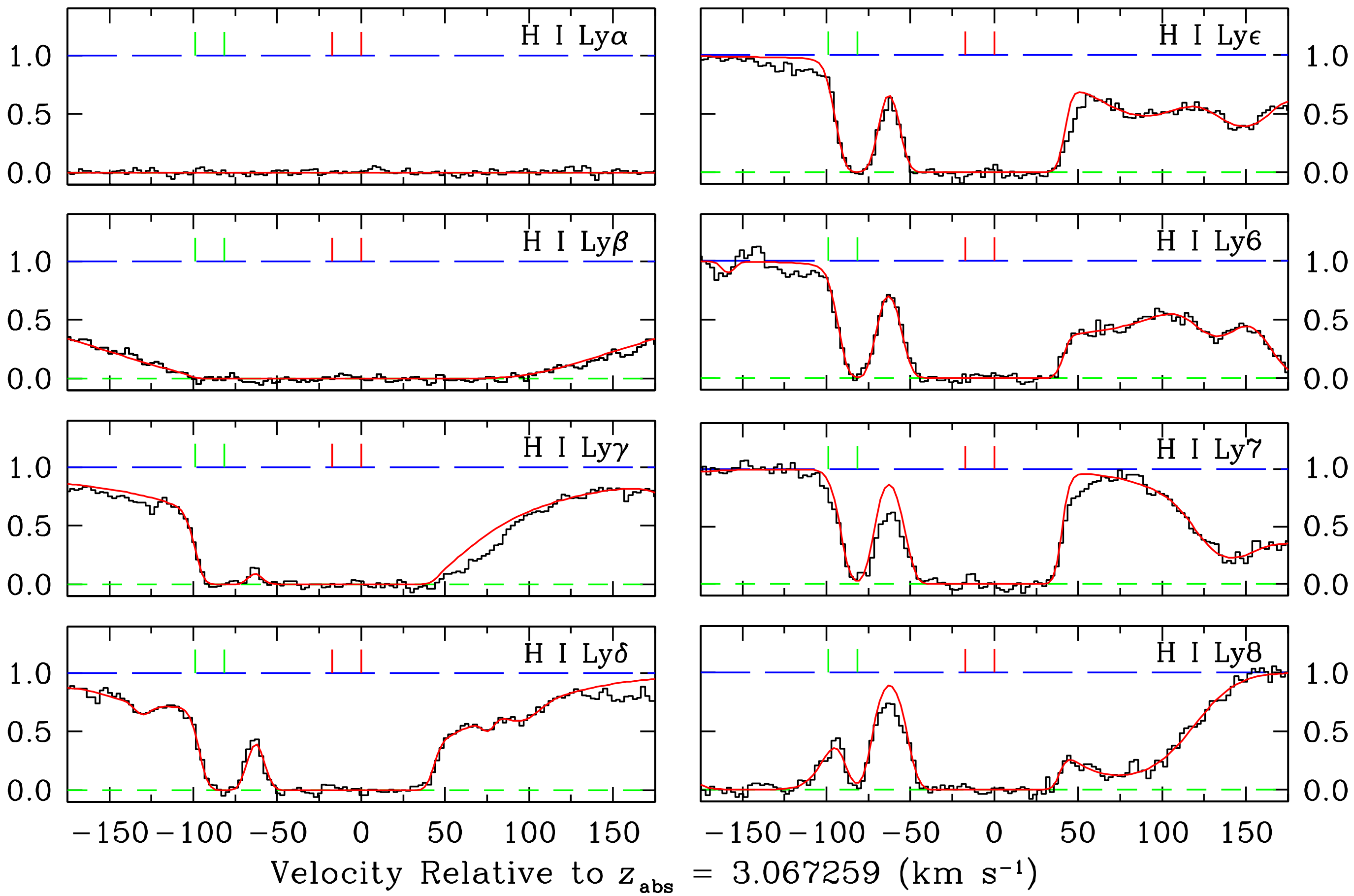
- D/H is inferred from D absorption in damped Lyα systems (DLAs)

$$E_{\mathsf{H}}^{(n)} \simeq -\frac{\alpha^2}{2n^2}\left(\frac{1}{m_e}+\frac{1}{m_{\mathsf{p}}}\right)^{-1} \quad \text{vs.} \quad E_{\mathsf{D}}^{(n)} \simeq -\frac{\alpha^2}{2n^2}\left(\frac{1}{m_e}+\frac{1}{m_{\mathsf{D}}}\right)^{-1}$$

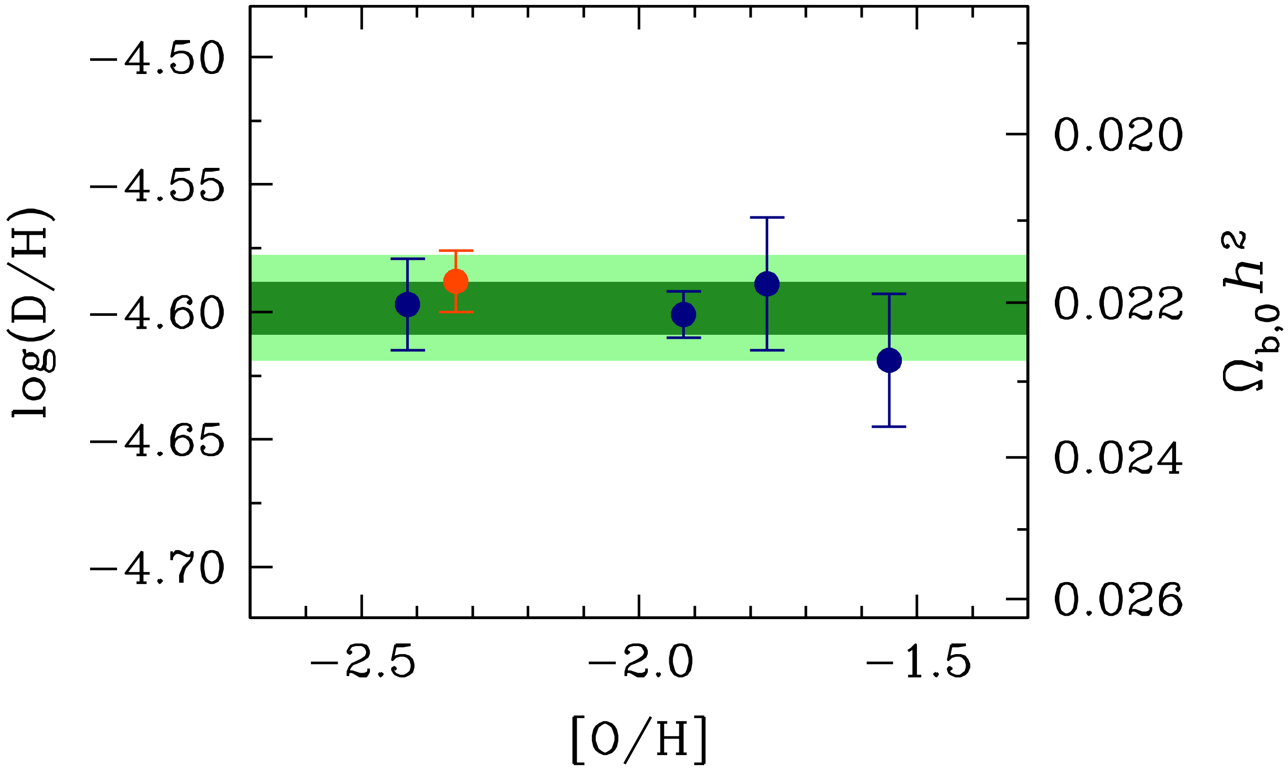
$$\Rightarrow \frac{E_{\mathsf{H}}^{(n)} - E_{\mathsf{D}}^{(n)}}{E_{\mathsf{H}}^{(n)}} \sim -2.7 \times 10^{-4} \quad \Rightarrow \quad \delta v \sim 80 \text{ km/sec}$$

Observation of DLA toward QSO SDSS J1358+6522

[Cooke et al., Astrophys.J. 781 (2014) 31]



Primordial abundance of D

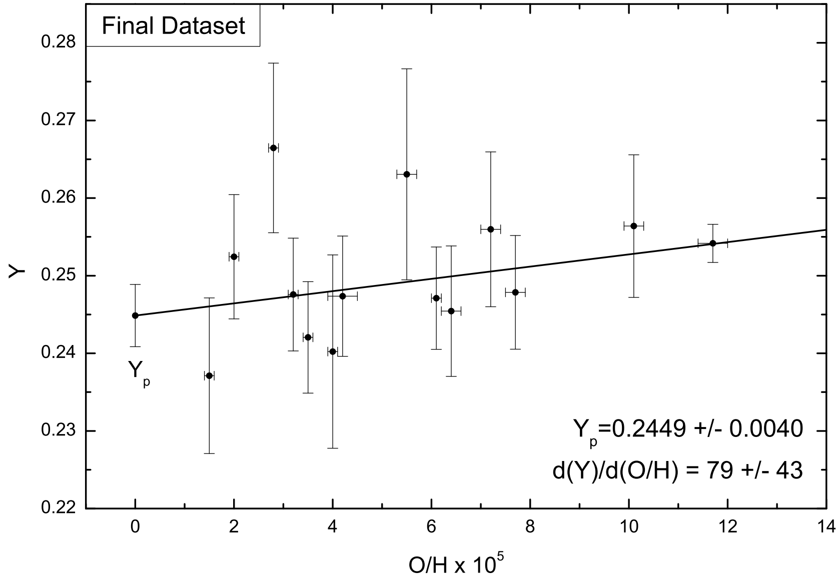


- D/H $= (2.53 \pm 0.04) \times 10^{-5}$

  [Cooke et al., Astrophys.J. 781 (2014) 31]

Helium-4

- ^{4}He abundance is inferred from observation of emission lines from extra galactic HII regions



- $Y_{\text{BBN}} = 0.2449 \pm 0.0040$

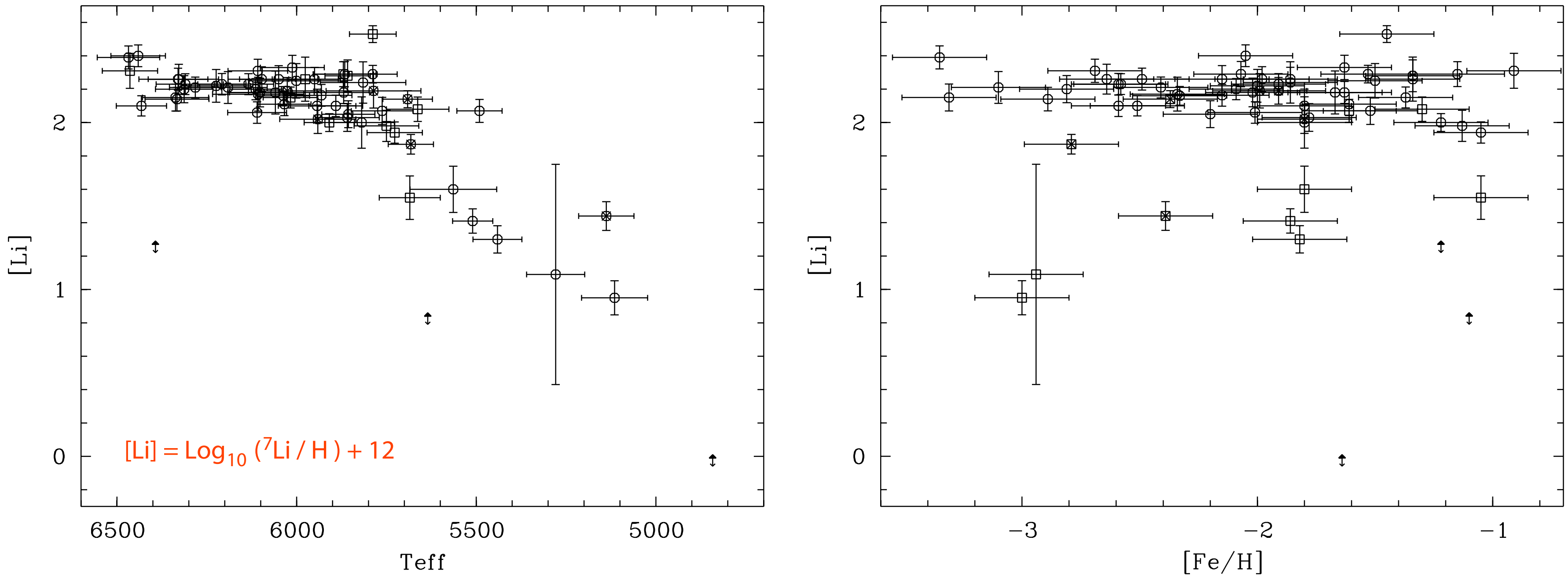
  [Aver, Olive & Skillman, JCAP 1507 (2015) 011]

- $Y_{\text{BBN}} = 0.2551 \pm 0.0022$

  [Izotov, Thuan & Guseva, MNRAS 445 ('14) 778]

Lithium-7

- ^{7}Li has been observed in Pop-II old halo stars

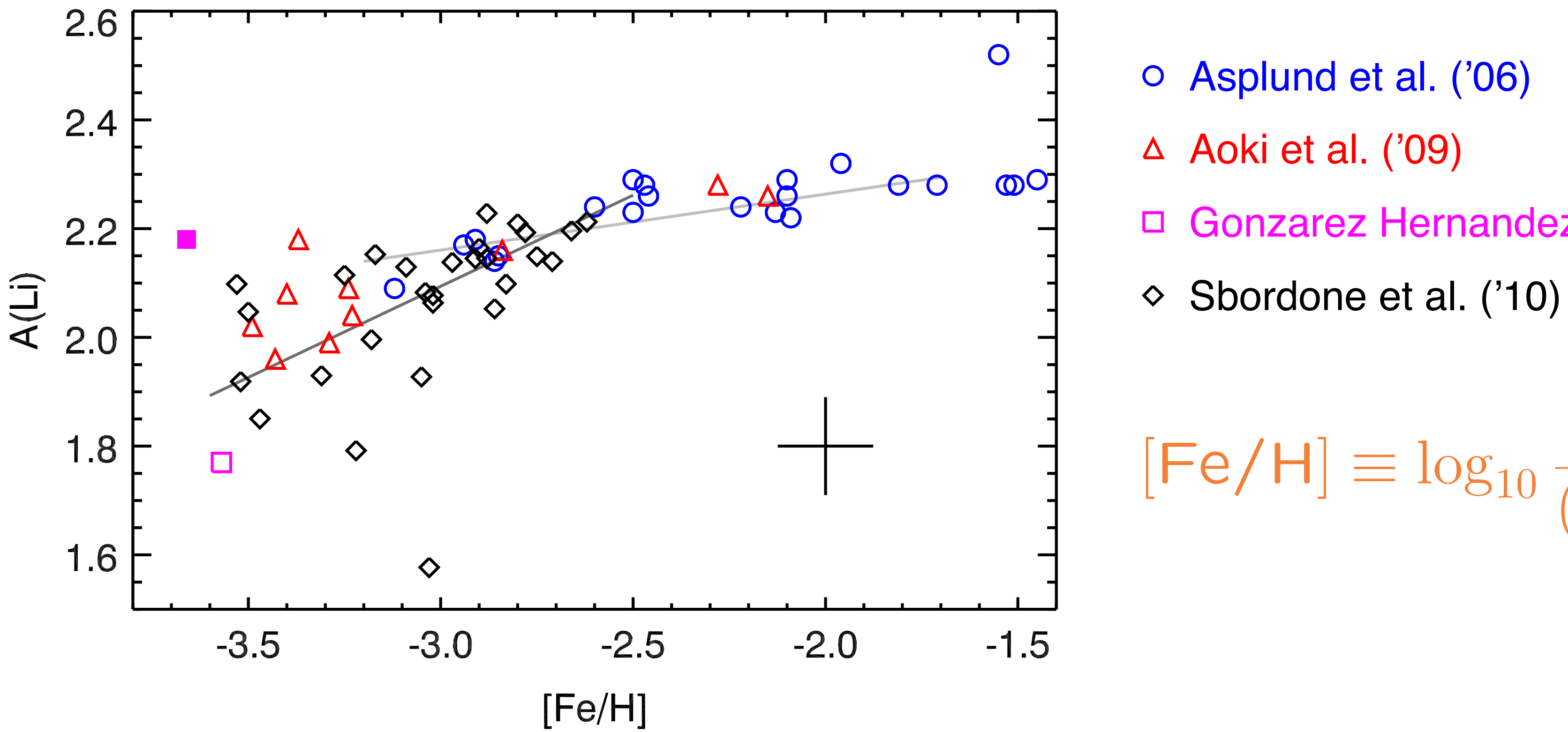


[Bonifacio and Malaro, MNRAS 285 (1997) 847]

- In stars with high surface temperature, ^{7}Li abundance was though to be almost constant (Spike plateau)

Currently, the situation is more controversial about ^{7}Li

- (^{7}Li/H) is not constant in stars with very low metallicity

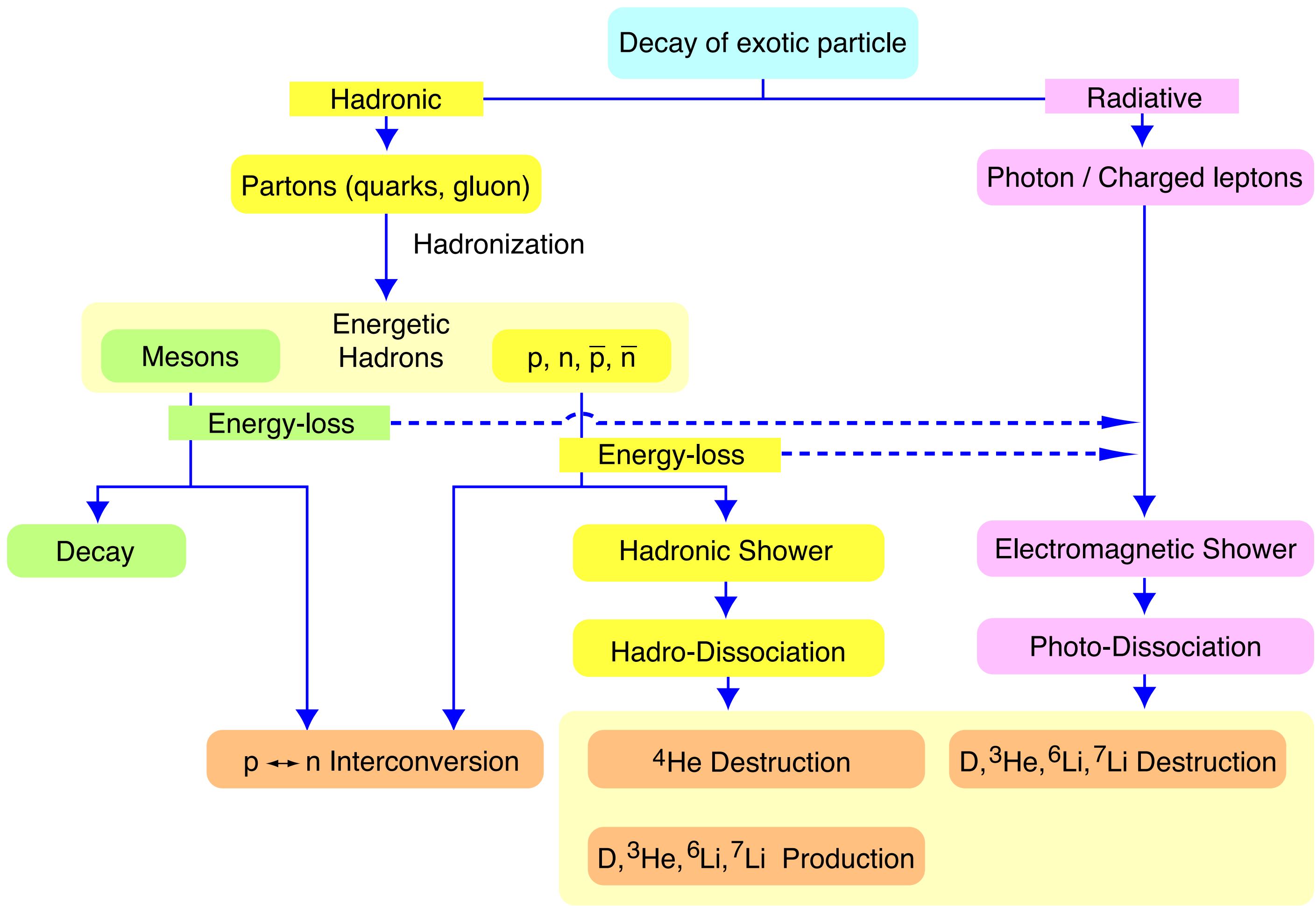


$$[\mathsf{Fe/H}] \equiv \log_{10} \frac{(\mathsf{Fe/H})}{(\mathsf{Fe/H})_\odot}$$

[Sbordone et al., Astron.Astrophys. 522 (2010) A26]

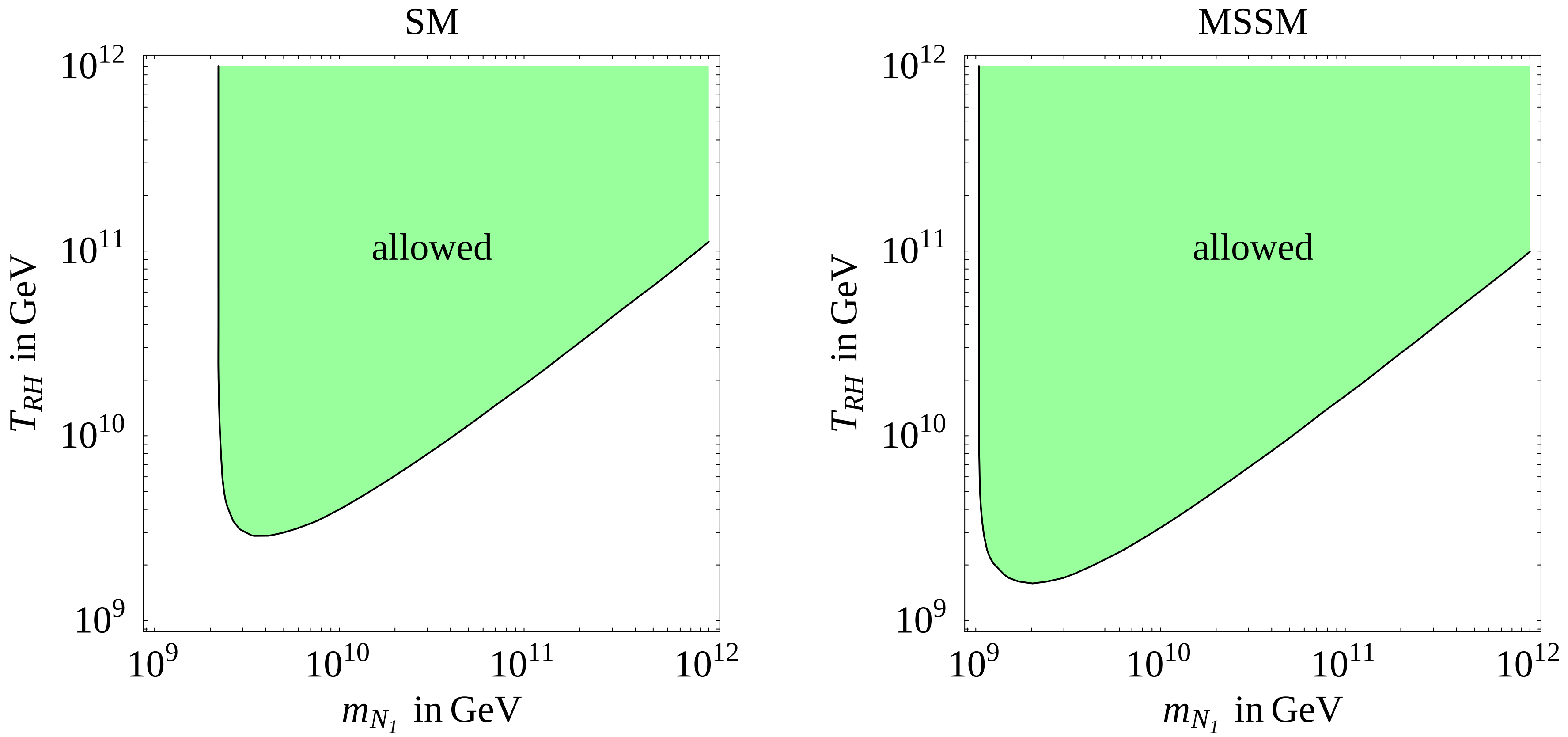
$\Rightarrow$ We do not use ^{7}Li to test BBN

Flow-chart of our analysis

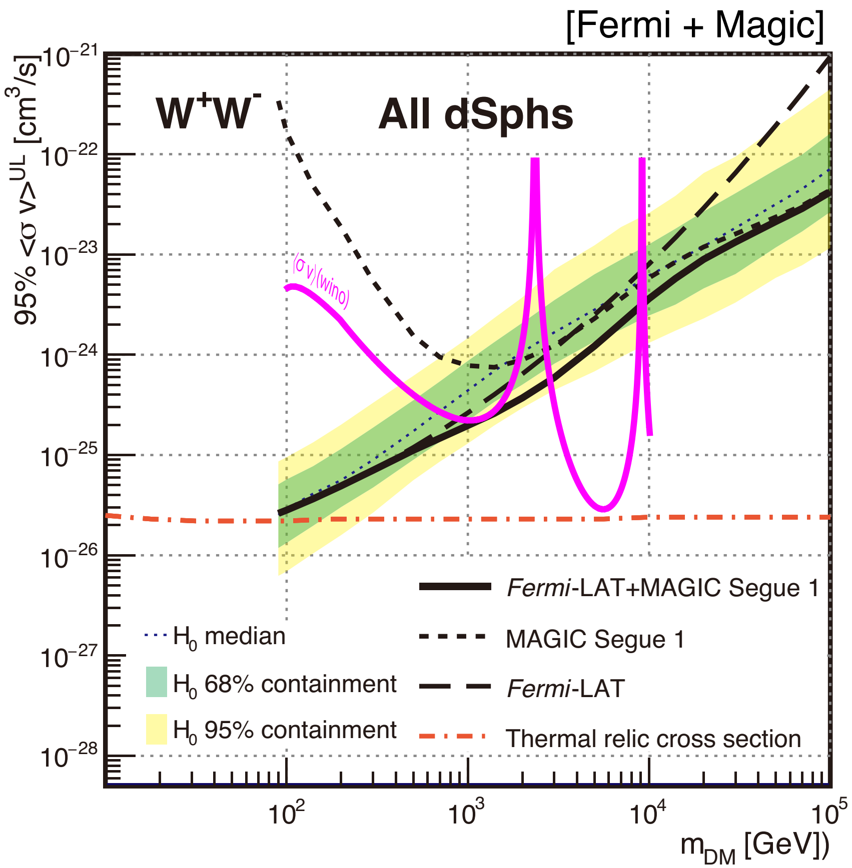


Bound on the reheating temperature for leptogenesis

[Giudice, Notari, Raidal, Riotto & Strumia 0310123]



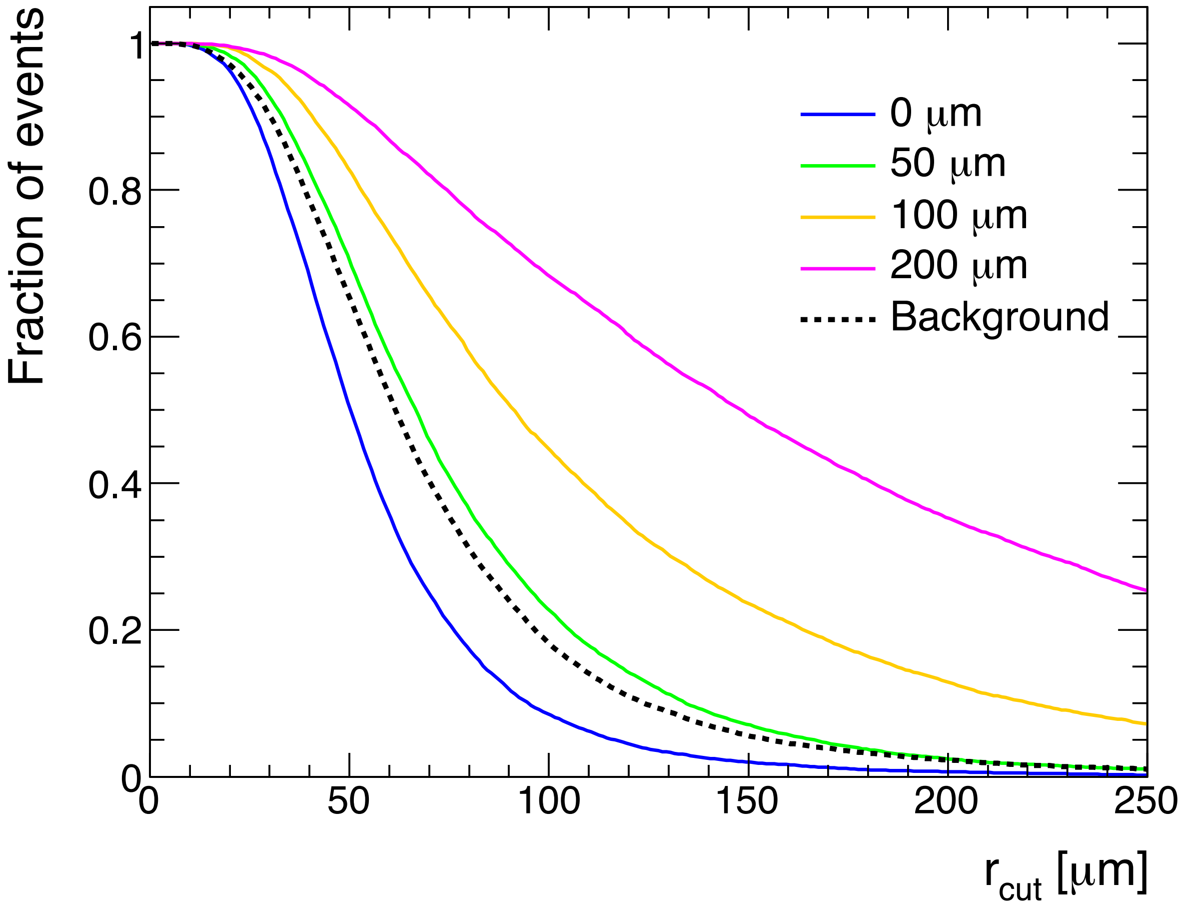
dSph constraint on Wino DM from Magic + Fermi



[Magic + Fermi-LAT 1601.06590]

- They combine the constraints from $(15+1)$ dSph samples
- They assume NFW DM distribution in dSphs

The fraction of events with $R_{12} > r_{\text{cut}}$



$\Rightarrow$ The signal may be distinguished from the background, if $c\tau_{\tilde{g}} \gtrsim 100\ \mu$m