Big-Bang Nucleosynthesis (BBN)
&
Wino Dark Matter
&
SUSY Model with Heavy Sfermions

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1. Introduction & Outline

Today, I discuss:

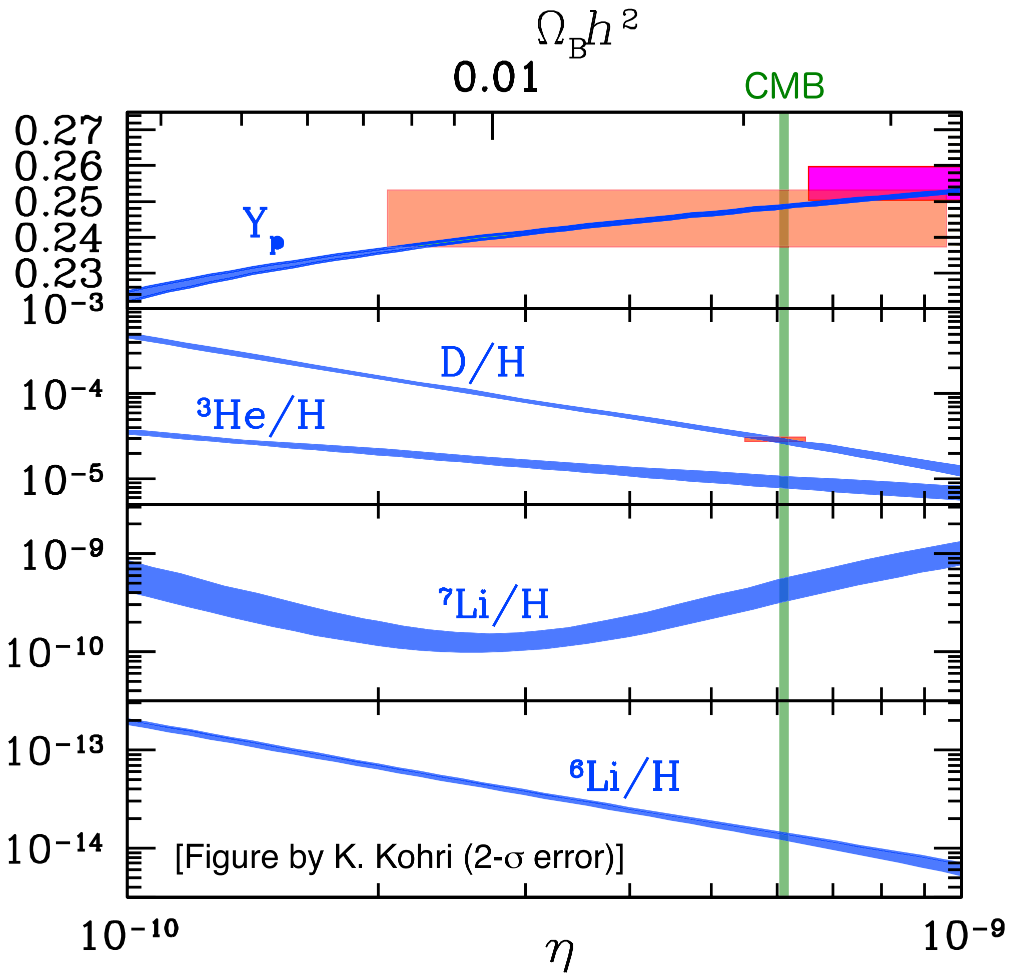
- BBN constraints on the decaying gravitino (with observational data as well as calculation being updated)
- A suggested SUSY scenario, and DM (i.e., Wino)

Outline

1. Introduction & Outline
2. BBN, Gravitino, and Reheating Temperature
3. Suggestion to SUSY Breaking
4. Wino DM
5. Summary

2. BBN, Gravitino, and Reheating Temperature

BBN is an important check point in cosmology



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

  [Cooke et al. ('14)]

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

  [Aver, Olive & Skillman, ('15)]

- Cf.: $Y_{BBN} = 0.2551 \pm 0.0022$

  [Izotov, Thuan & Guseva ('14)]

$\Rightarrow$ Prediction of the standard BBN is (more-or-less) consistent with observations

Exotic particles may affect the light element abundances

- The light element abundances may change via exotic reactions, like Photo-dissociation, Hadro-dissociation, $\cdots$
- We may acquire information / constraints on the models of BSM physics

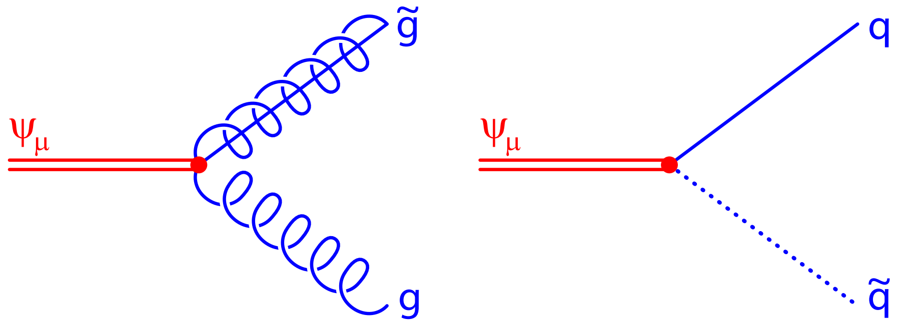
Some of the SUSY particles are cosmologically dangerous:

- Gravitino (superpartner of graviton)
- Wino, if it is dark matter
- $\cdots$

Gravitino is cosmologically dangerous

[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); ···]

- Interaction of gravitino is Planck suppressed



- Gravitinos produced after inflation may decay during the BBN epoch because its lifetime is extremely long

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

Gravitino production after inflation

- Gravitino production rate

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

- Yield variable (s: entropy density)

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

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

[with $\langle \sigma_{\rm prod} v_{\rm rel} \rangle$ by Bolz, Brandenburg & Buchmuller]

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

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

Unstable gravitino may affect the light element abundances

- Hadro-dissociation (due to hadronic shower)
- Photo-dissociation (due to electromagnetic shower)
- $p \leftrightarrow n$ conversion

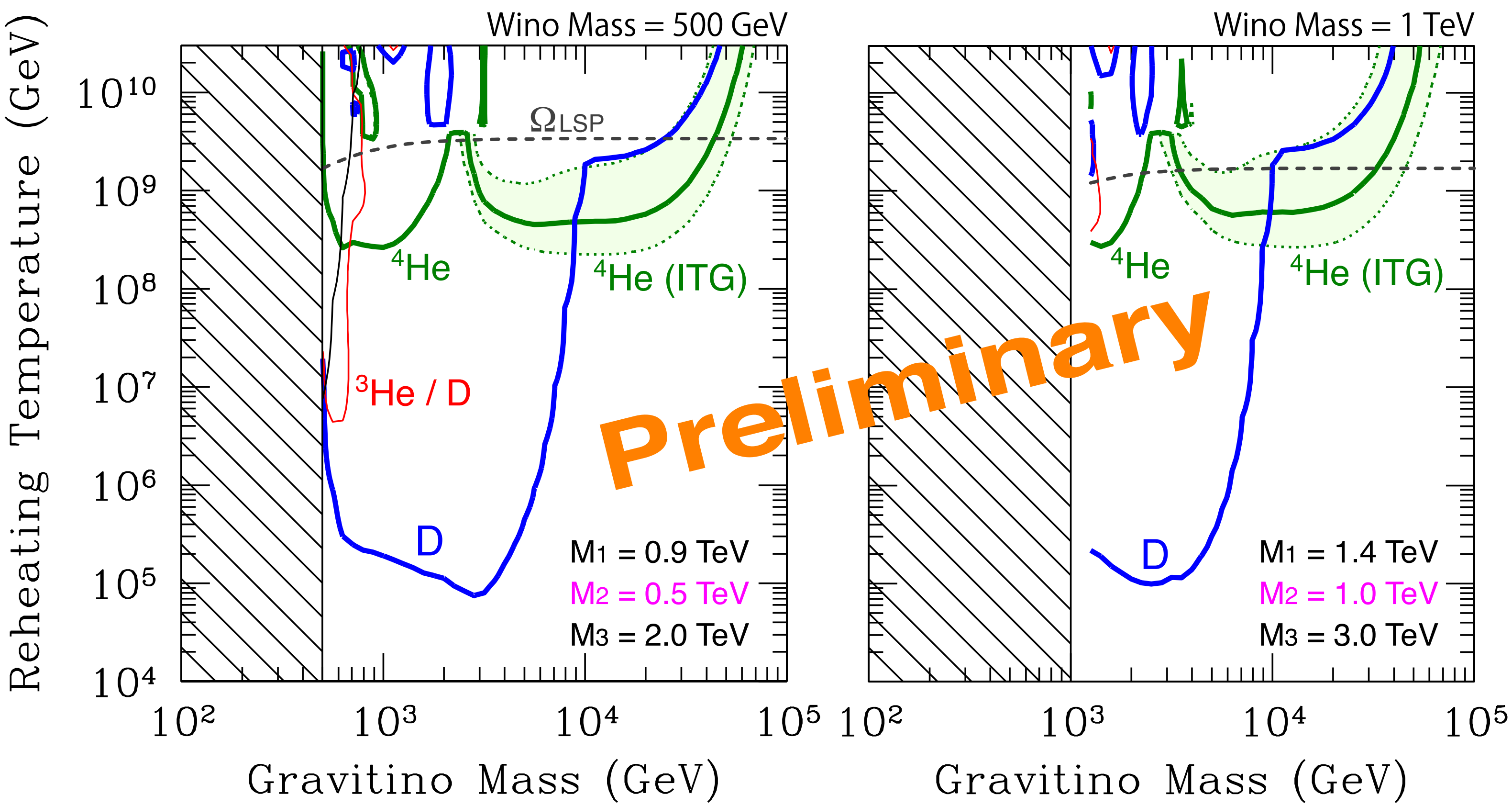
We have studied the BBN with decaying gravitino

- We adopt the most recent observational constraints on the light element abundances
- We updated the reaction rates of the standard BBN processes

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

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

Sfermions are assumed to be heavier than gravitino



[Kawasaki, Kohri, TM, Takaesu (work in progress)]

$\Rightarrow m_{3/2} \sim 10 - 100$ TeV & $T_{\mathrm{R}} \gtrsim 10^9$ GeV seems interesting

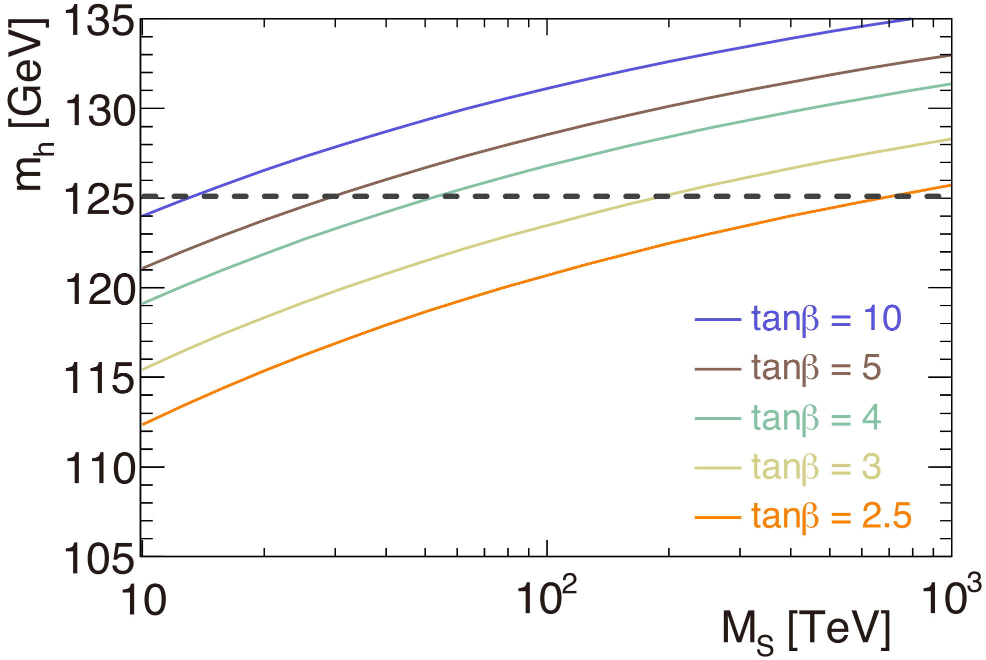
3. Suggestion to SUSY Breaking

$m_{3/2} \sim 10 - 100$ TeV & $T_{\mathrm{R}} \gtrsim 10^9$ GeV

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

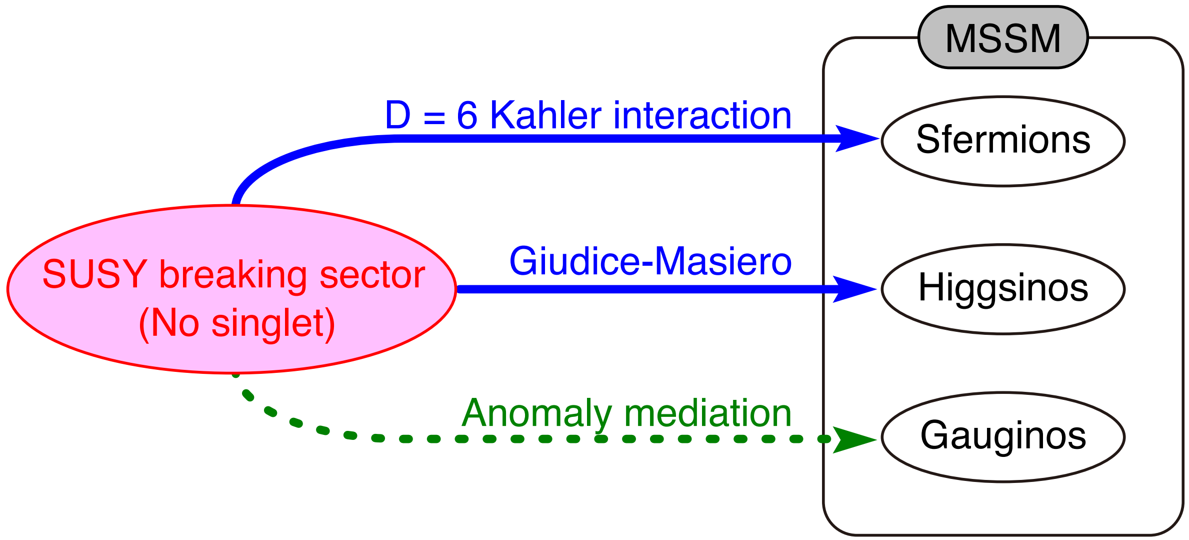
[See, for example, Buchmuller, Di Bari & Plumacher ('02); Giudice, Notari, Raidal, Riotto & Strumia ('03)]

Observed Higgs mass suggests stop masses of $O(10 - 100)$ TeV



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

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

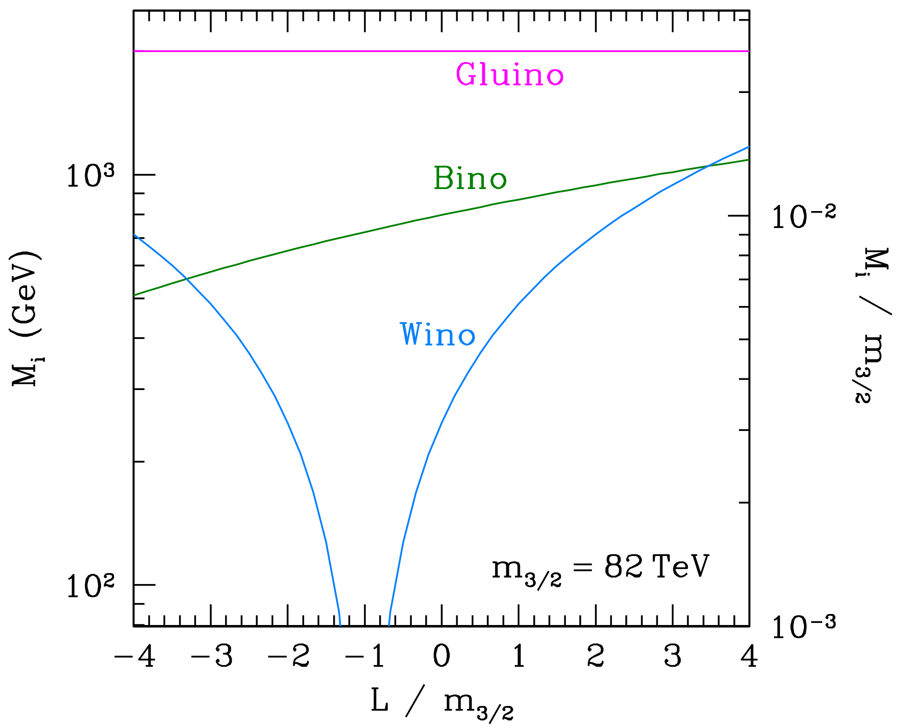


Mass spectrum

- 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



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

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

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

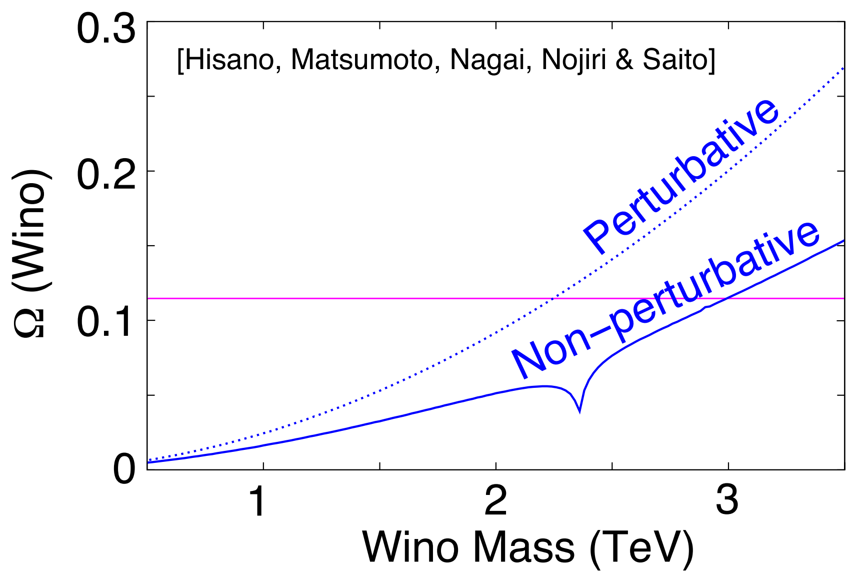
$$L \equiv \mu \sin 2\beta \frac{m_A^2}{\mu^2 - m_A^2} \ln \frac{\mu^2}{m_A^2}$$

⇒ Wino is likely to be the LSP

⇒ In some region of the parameter space, Bino becomes the LSP

4. Wino DM

Thermal relic abundance of Wino



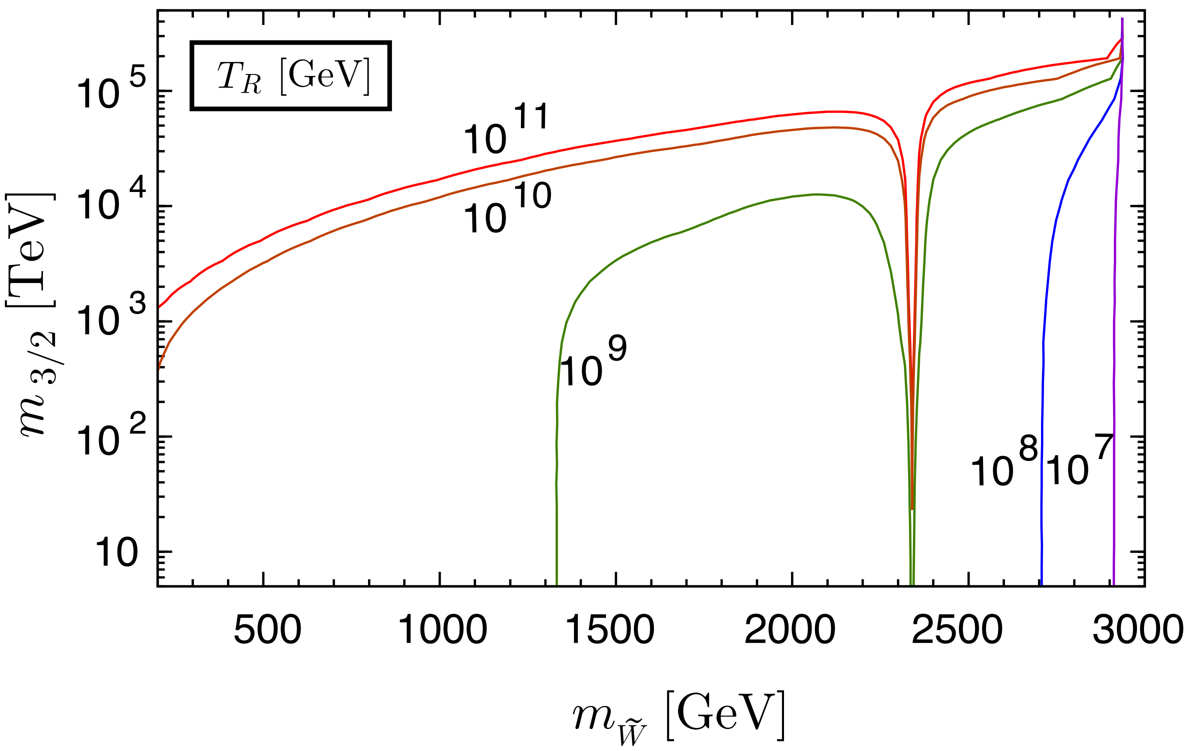
- $\Omega_{\tilde{W}}^{(\text{thermal})} \simeq \Omega_c$, if $m_{\tilde{W}} \simeq 3$ TeV
  [Hisano, Matsumoto, Nagai, Nojiri & Saito]
- Wino may be also produced non-thermally
  [Giudice, Luty, Murayama & Rattazzi; TM & Randall]

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

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



[TM, Nagai & Takimoto ('13)]

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

The Wino abundance has two contributions

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

Wino can be dark matter even if $\Omega_{\mathsf{LSP}}^{(\mathsf{thermal})} \ll \Omega_c$

$\Rightarrow T_{\mathsf{R}} \sim 10^9 - 10^{10}$ GeV is needed, if $m_{3/2} \sim 1$ TeV

Such a scenario is consistent with (simple) leptogenesis

$\Leftrightarrow$ Leptogenesis requires $T_{\mathsf{R}} \sim 10^9 - 10^{10}$ 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

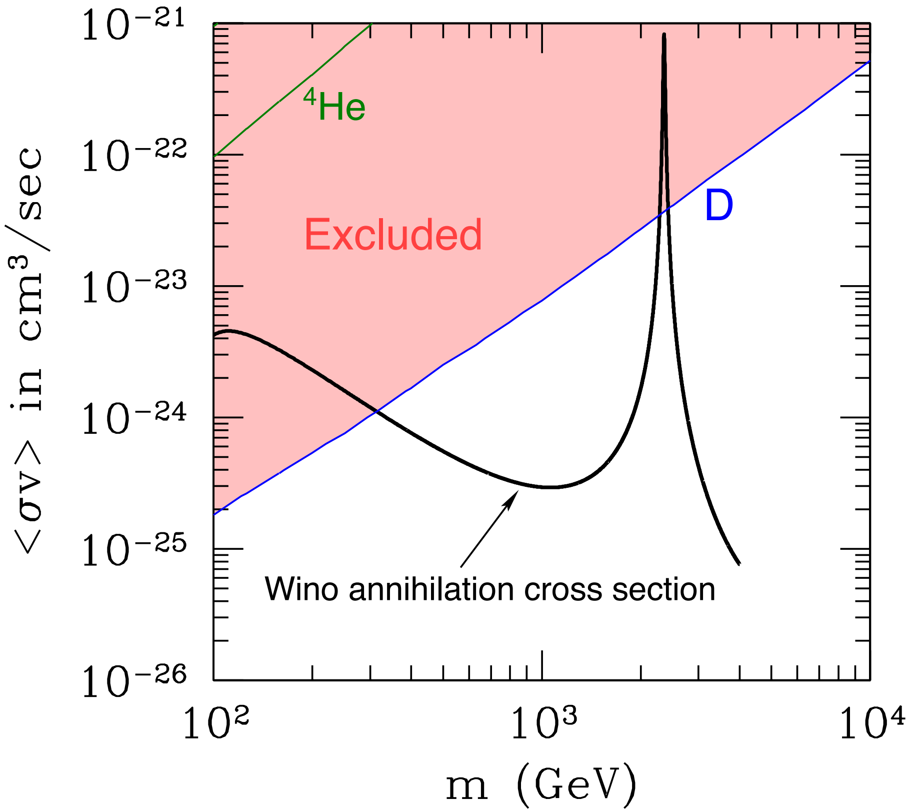
$\Rightarrow$ Energetic particles are produced

Important check points:

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

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

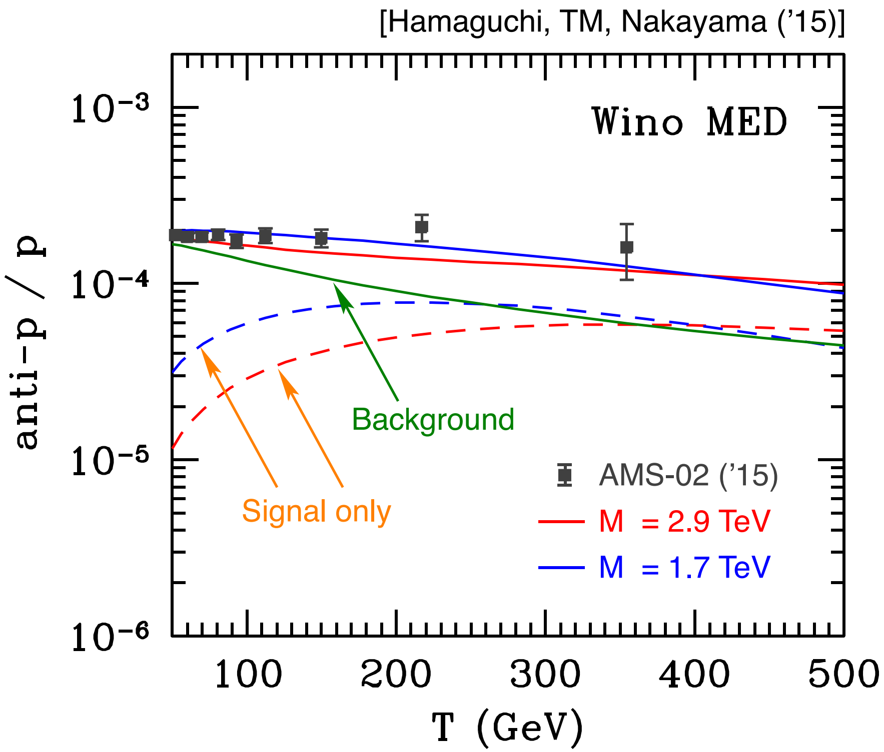
[Jedamzik ('04); Hisano, Kawasaki, Kohri & Nakayama ('09); Kawasaki, Kohri, TM, Takaesu ('15)]

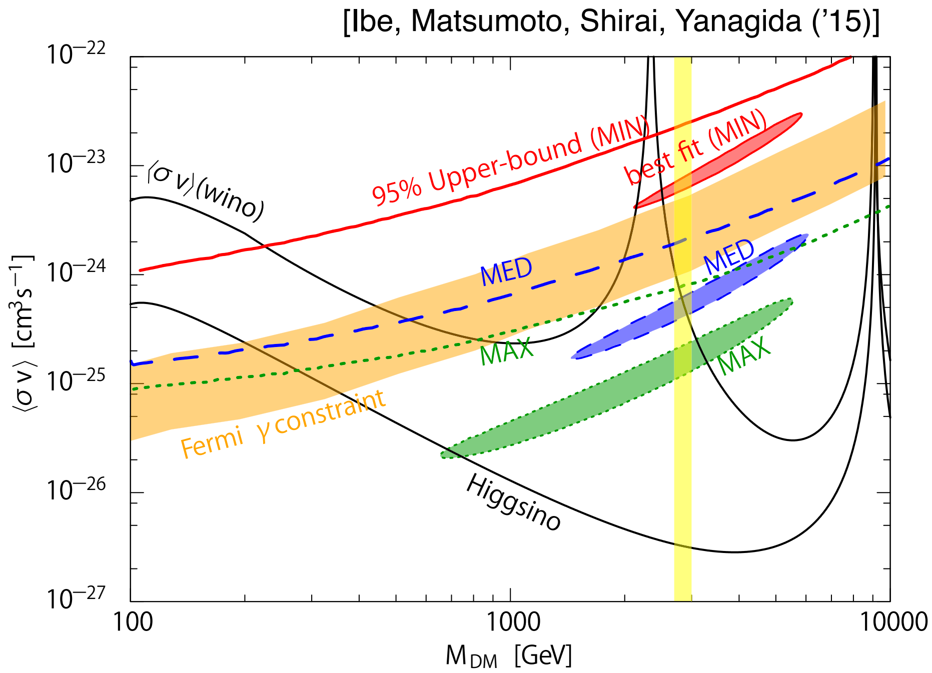


[Kawasaki, Kohri, TM, Takaesu 1509.03665]

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

Effects on the fluxes of cosmic rays





- Anti-proton from the Wino annihilation may explain the shape of the spectrum observed by AMS-02

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

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

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

LHC : $m_{\tilde{W}} \gtrsim 270\ \mathrm{GeV}$

$^{\#}$ 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. Summary

Today, I discussed:

- Updated BBN constraints on decaying gravitino
- Cosmology with Wino DM

Wino DM is interesting because:

- Wino LSP is suggested in the theoretically-motivated scenario, i.e., PGM SUSY breaking scenario
- $T_{\rm R} \sim O(10^9 - 10^{10})$ GeV is suggested (if $m_{\tilde{W}} < 3$ TeV), which is consistent with leptogenesis

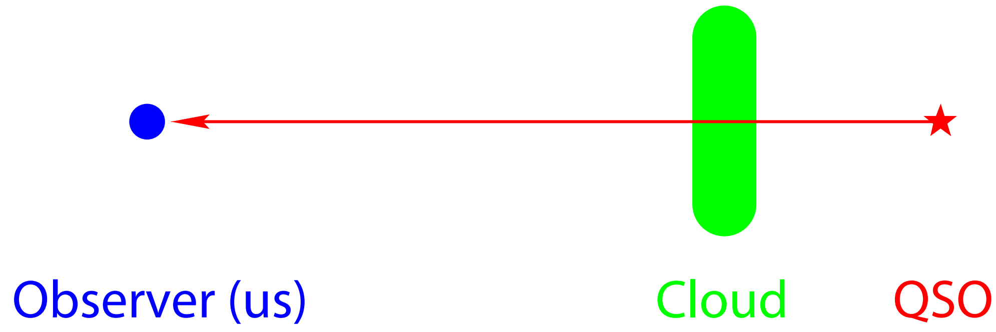
Possible tests of the Wino DM scenario in the future

- Direct discovery of the Wino LSP at the LHC
- γ-ray from dSph
- $\cdots$

Back Up

Deuterium

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

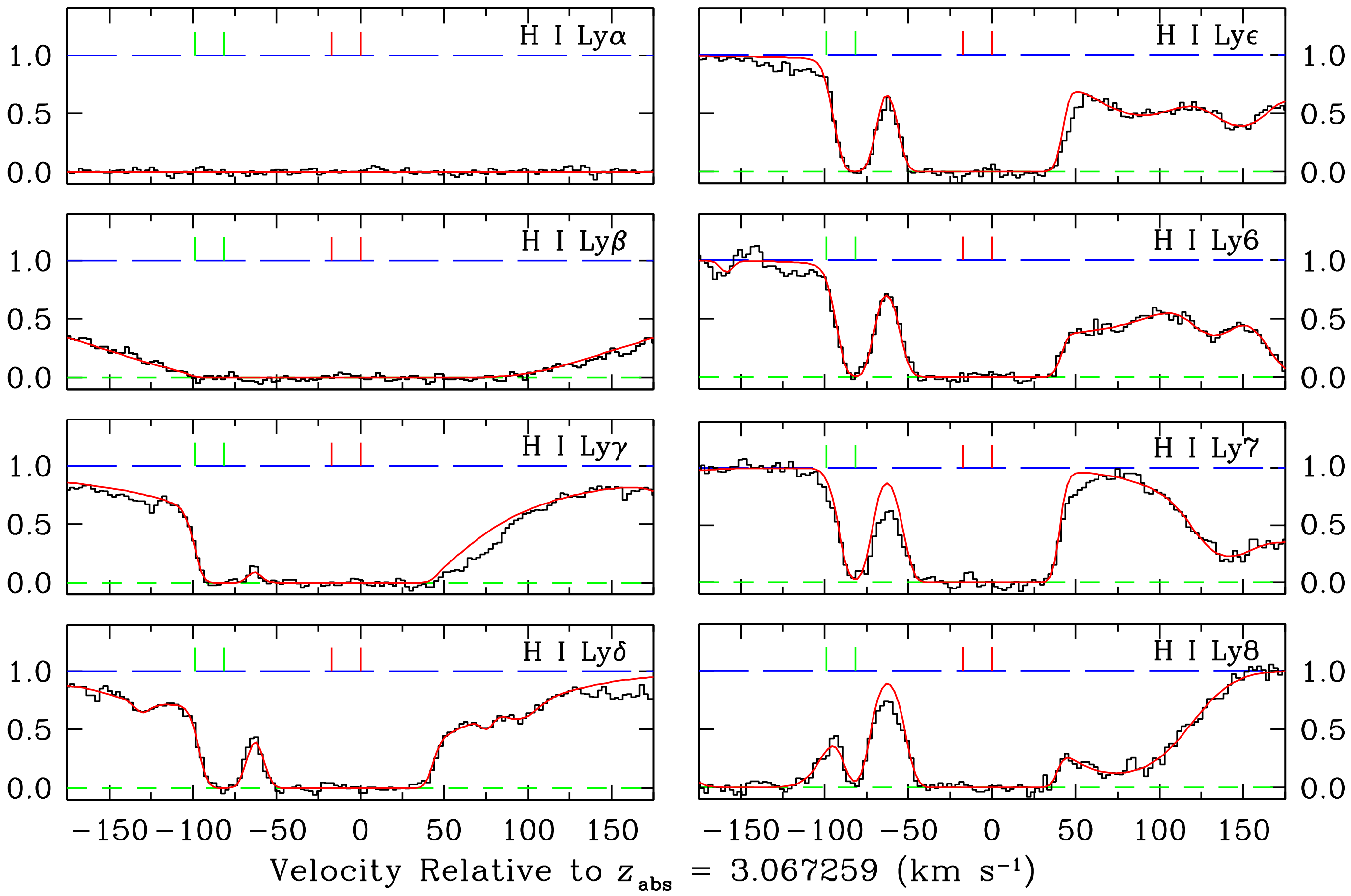


$$E_{\mathsf{H}}^{(n)} \simeq -\frac{\alpha^2}{2n^2}\left(\frac{1}{m_e}+\frac{1}{m_{\mathrm{p}}}\right)^{-1} \quad \text{vs.} \quad E_{\mathsf{D}}^{(n)} \simeq -\frac{\alpha^2}{2n^2}\left(\frac{1}{m_e}+\frac{1}{m_{\mathrm{D}}}\right)^{-1}$$

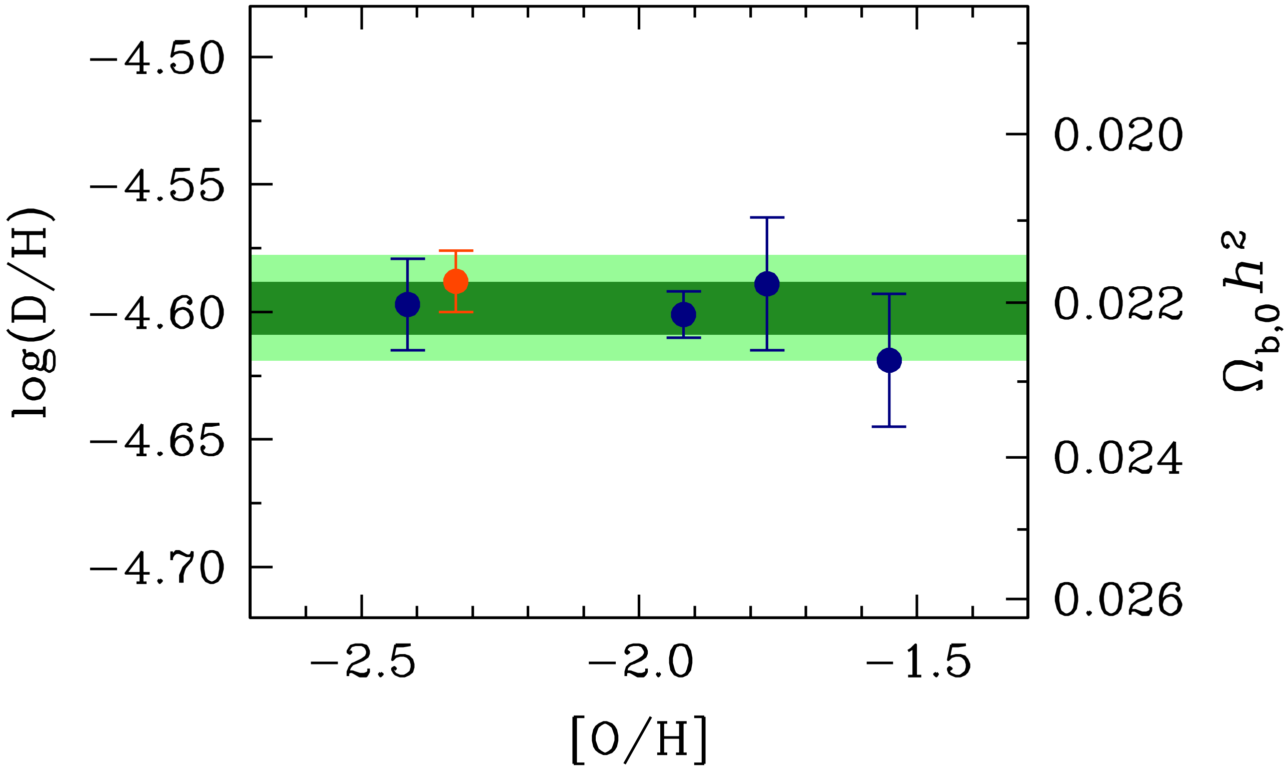
$$\Rightarrow \frac{E_{\mathsf{H}}^{(n)} - E_{\mathsf{D}}^{(n)}}{E_{\mathsf{H}}^{(n)}} \sim -2.7 \times 10^{-4} \quad \Rightarrow \quad \delta v \sim 80 \ \mathrm{km/sec}$$

Observation of DLA toward QSO SDSS J1358+6522

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



Primordial abundance of D

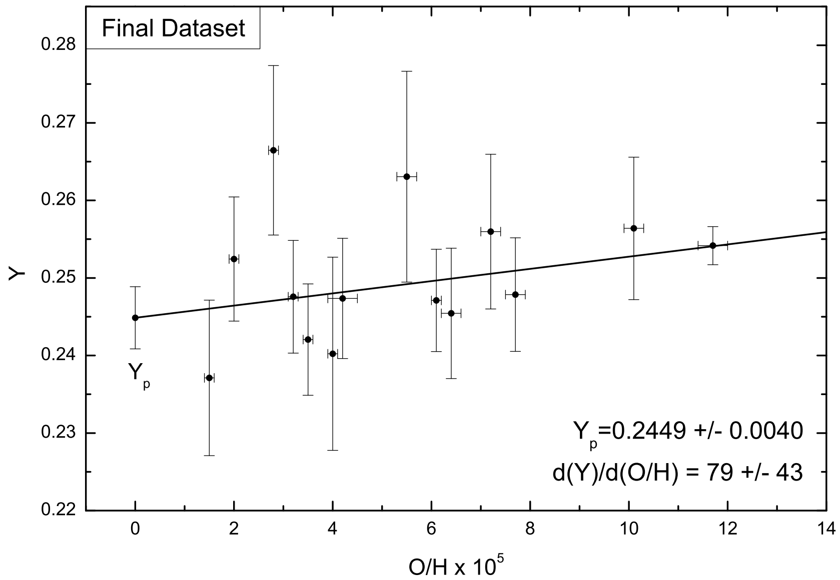


- D/H $= (2.53 \pm 0.04) \times 10^{-5}$

  [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



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

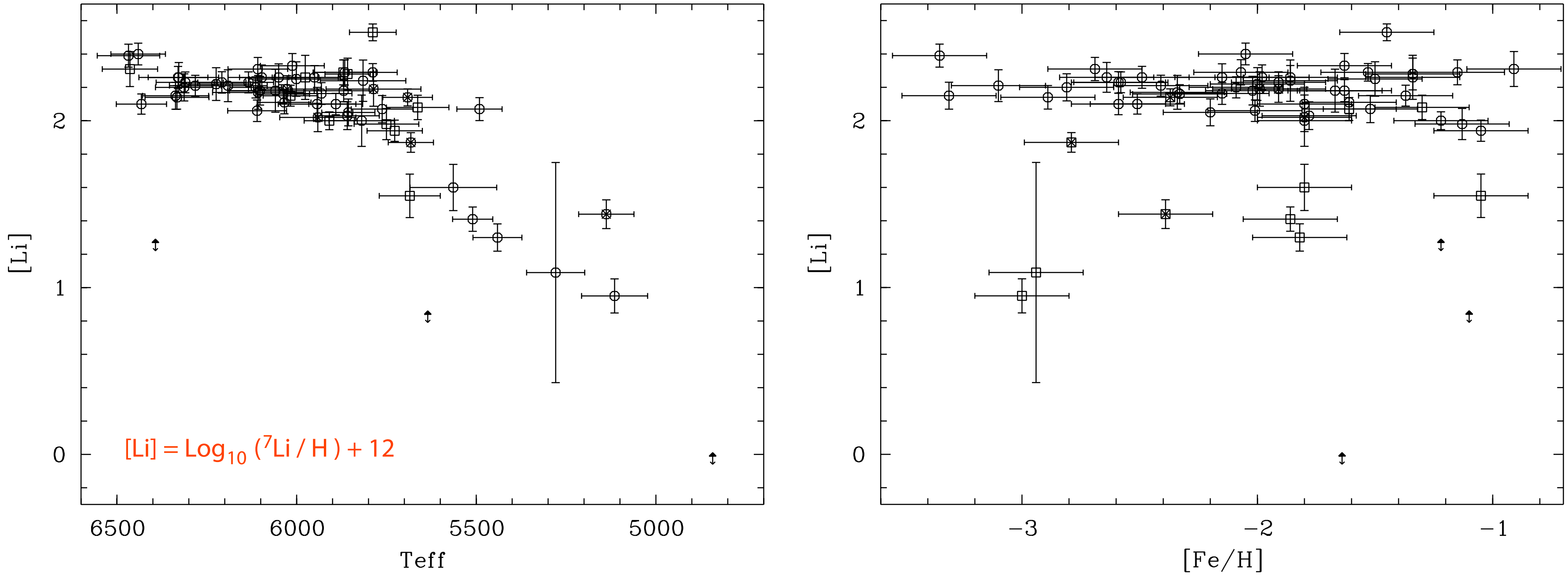
  [Aver, Olive & Skillman, JCAP 1507 (2015) 011]

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

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

Lithium-7

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

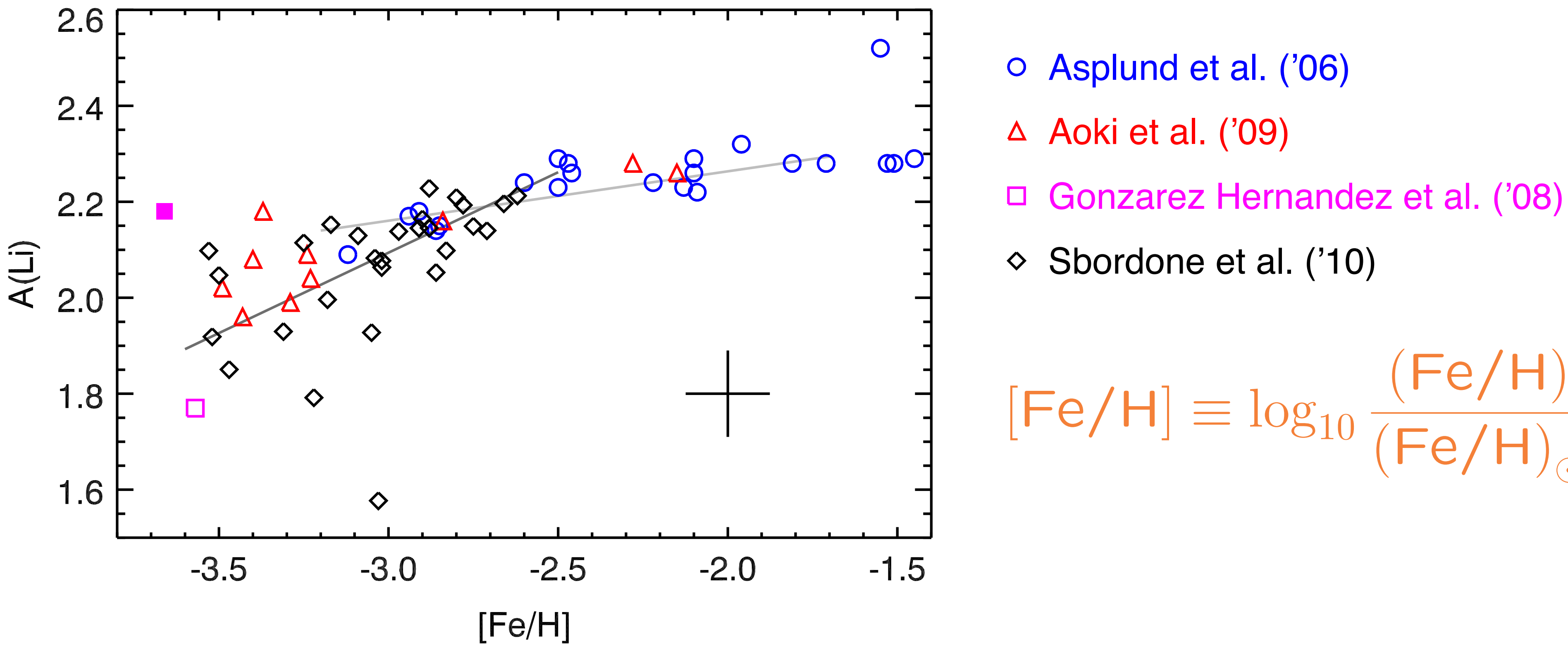


[Bonifacio and Malaro, MNRAS 285 (1997) 847]

- 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

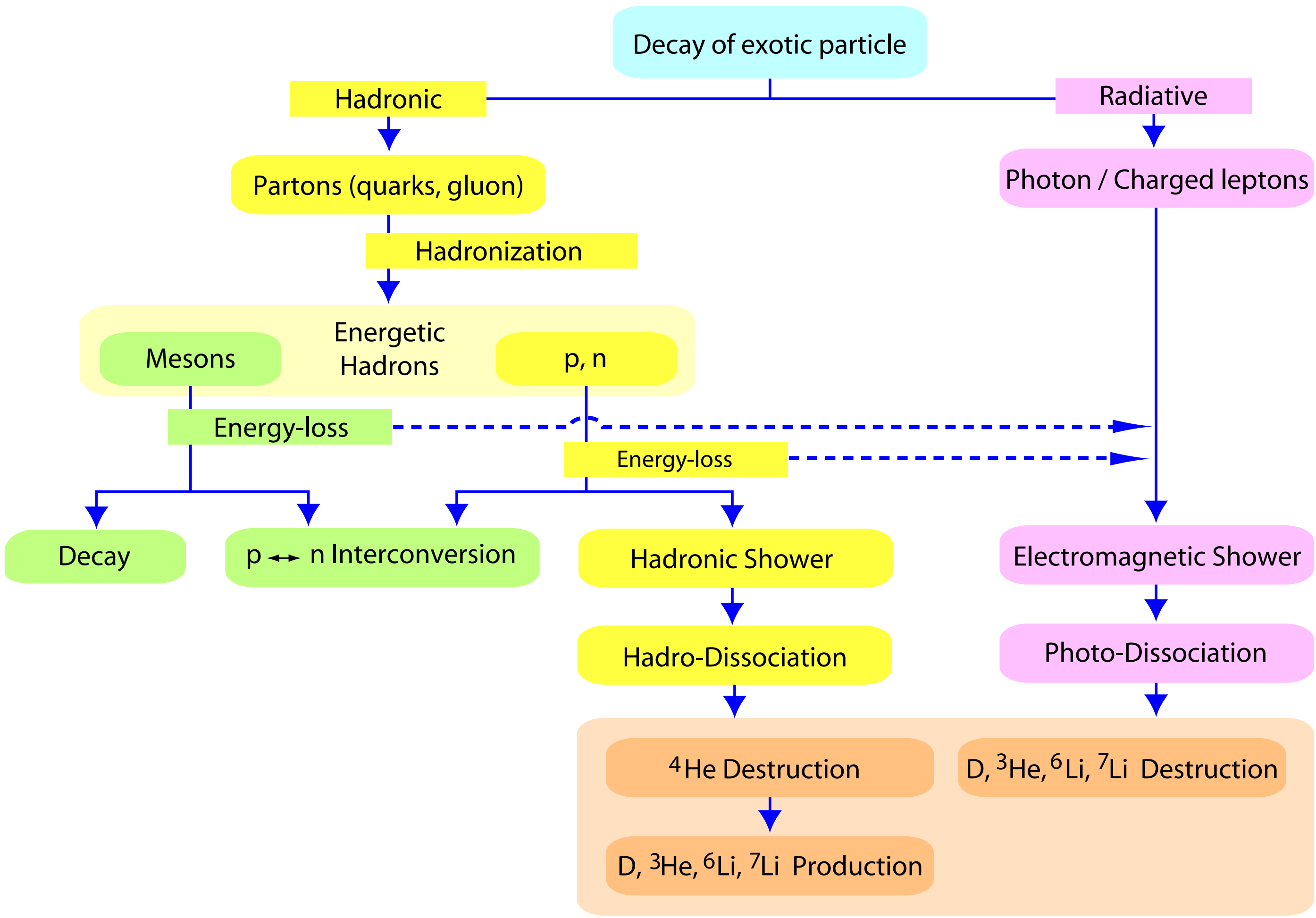


$$[\mathrm{Fe/H}] \equiv \log_{10} \frac{(\mathrm{Fe/H})}{(\mathrm{Fe/H})_\odot}$$

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

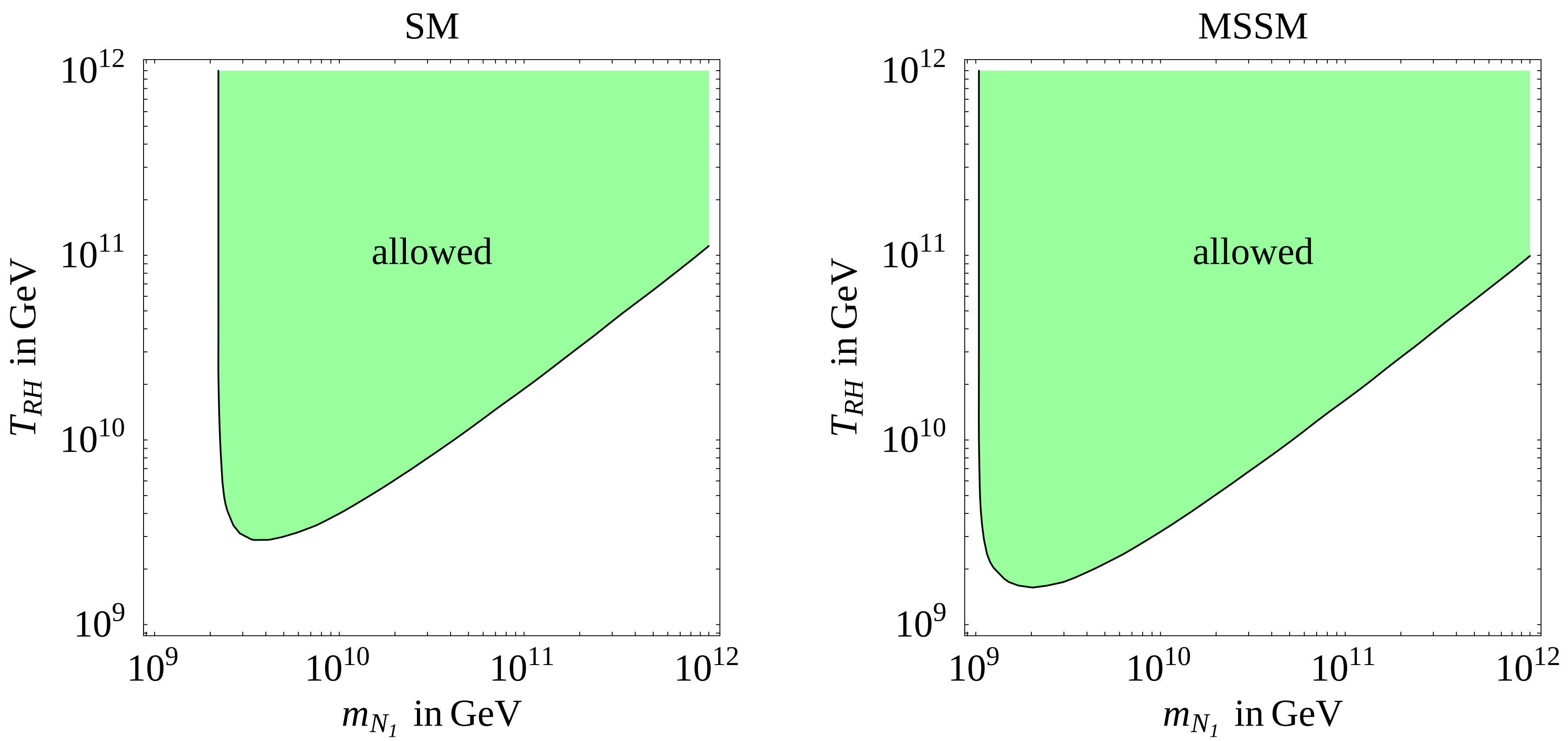
$\Rightarrow$ We do not use ^{7}Li to test BBN

Flow-chart of our analysis

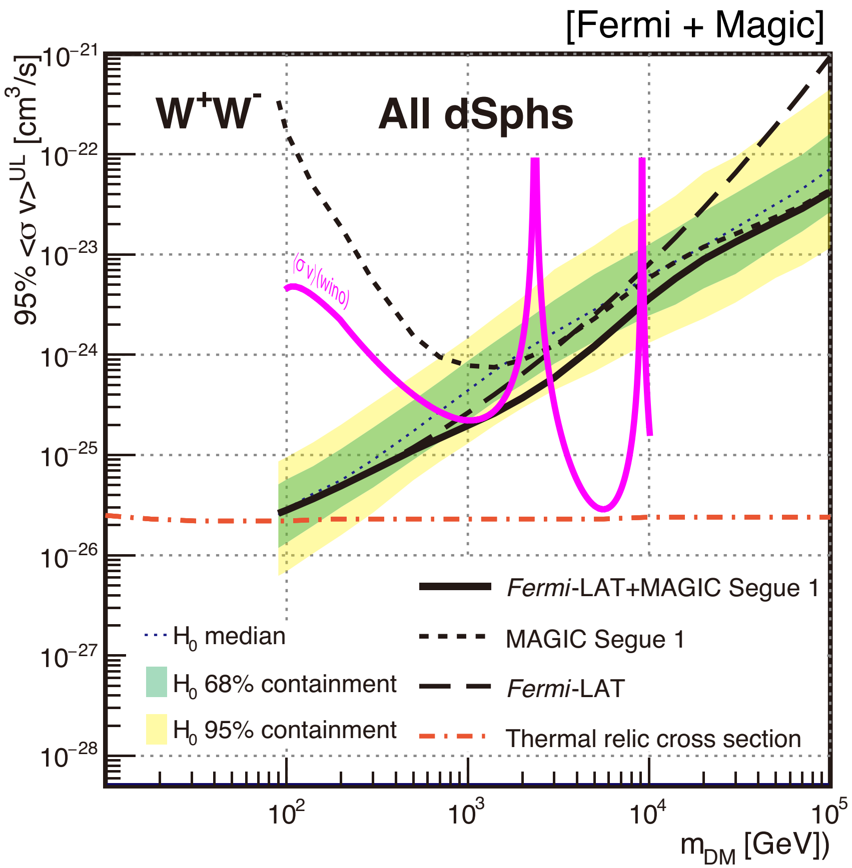


Bound on the reheating temperature for leptogenesis

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



dSph constraint on Wino DM from Magic + Fermi



[Magic + Fermi-LAT 1601.06590]

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