IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

東京大学 THE UNIVERSITY OF TOKYO

Reconciling Supersymmetry and Leptogenesis

Hitoshi Murayama (IPMU Tokyo & Berkeley)

COSMO 08, Madison, August 28, 2008

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

- New intl research institute in Japan
  - astrophysics
  - particle theory
  - particle expt
  - mathematics
- official language: English
- >30% non-Japanese
- $13M/yr for 10 years
- launched Oct 1, 2007




INSTITUTE FO
MATHEMATIC



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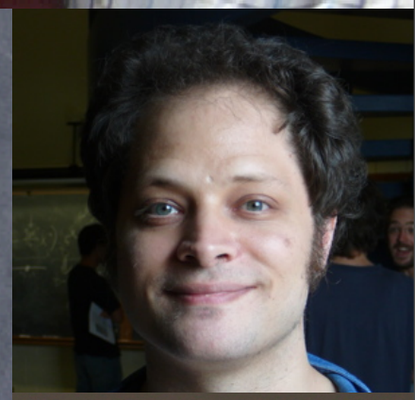
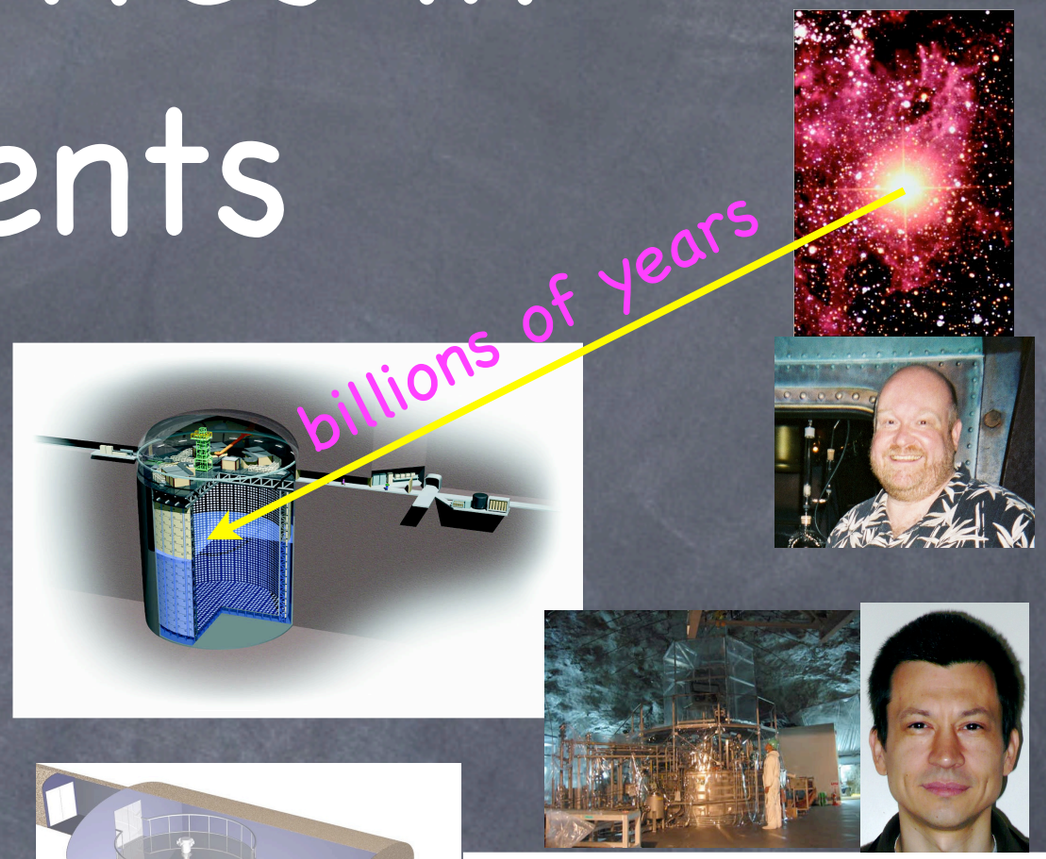
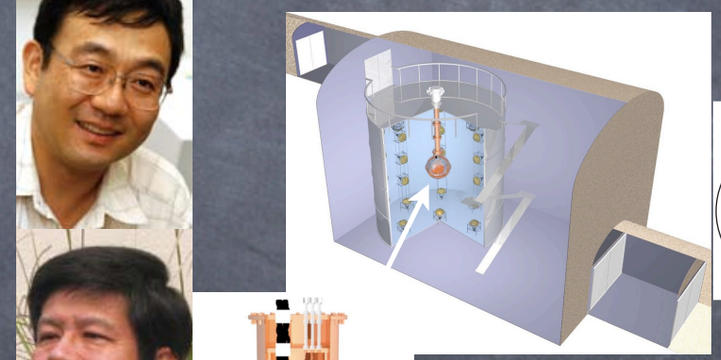
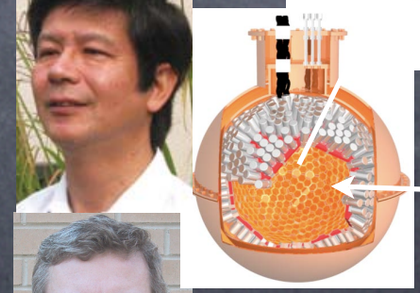


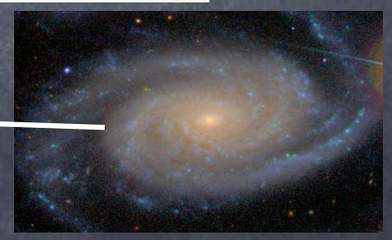

IPMU initiatives in experiments

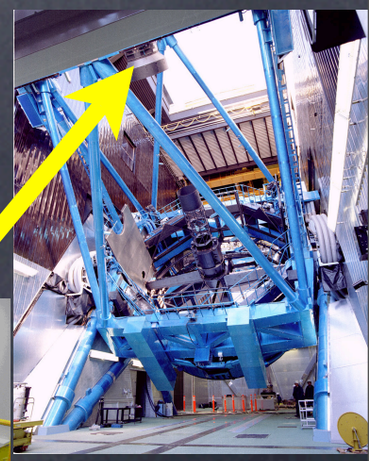
- SuperK with Gd to detect relic supernova neutrinos
- use KamLAND to look for 0νββ
- XMASS Xenon 800kg direct dark matter detection
- new HyperSuprimeCam camera at Subaru for weak lensing survey to measure dark energy w
- will join SDSS-III











Winter 2009 occupancy
~5900m^2

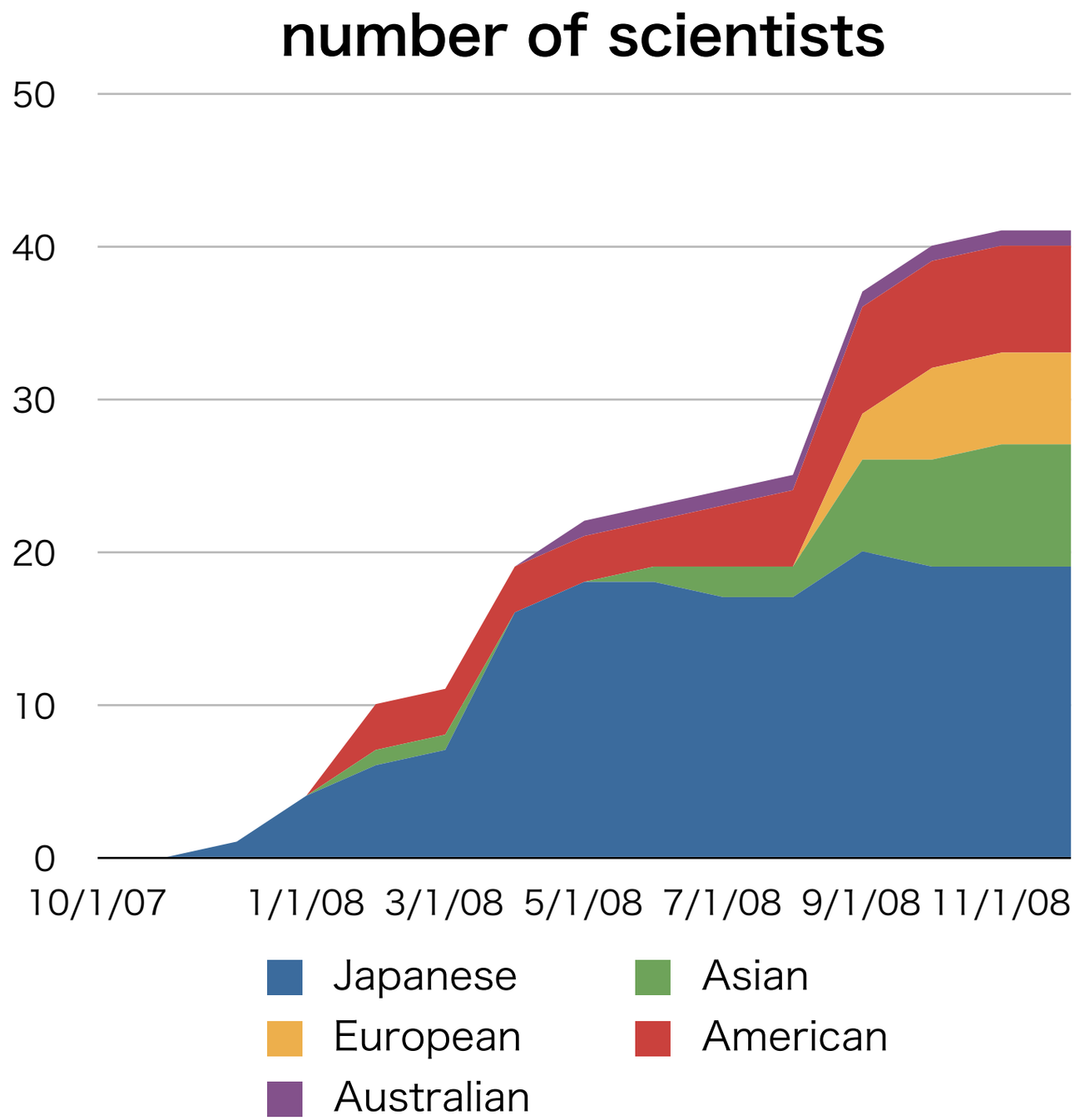
emphasis on large interaction area

"like a European town square" ~400 m^2

On Site Scientists

Expect ~15 positions this year

Check out www.ipmu.jp



non-Japanese > 50%

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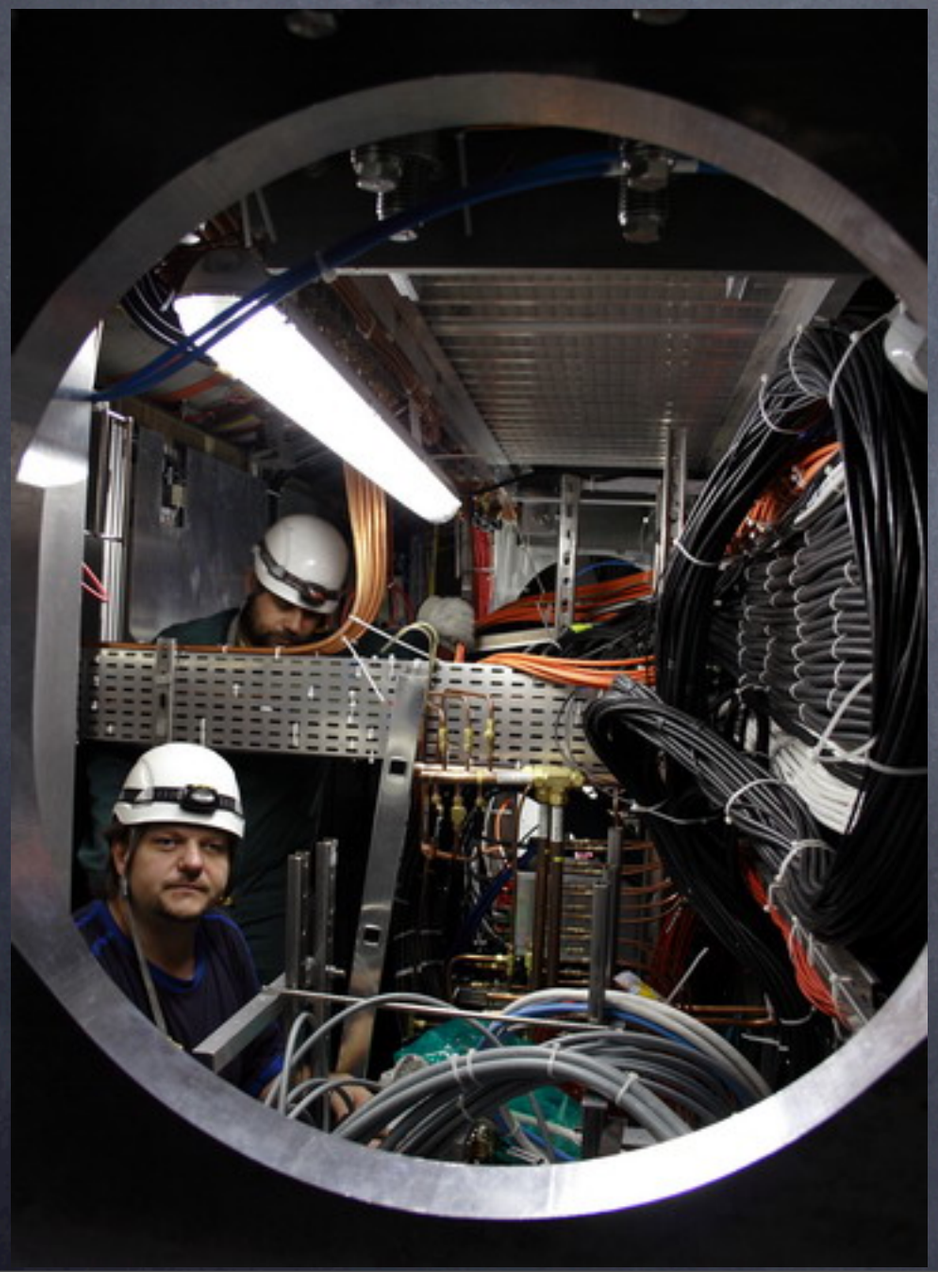
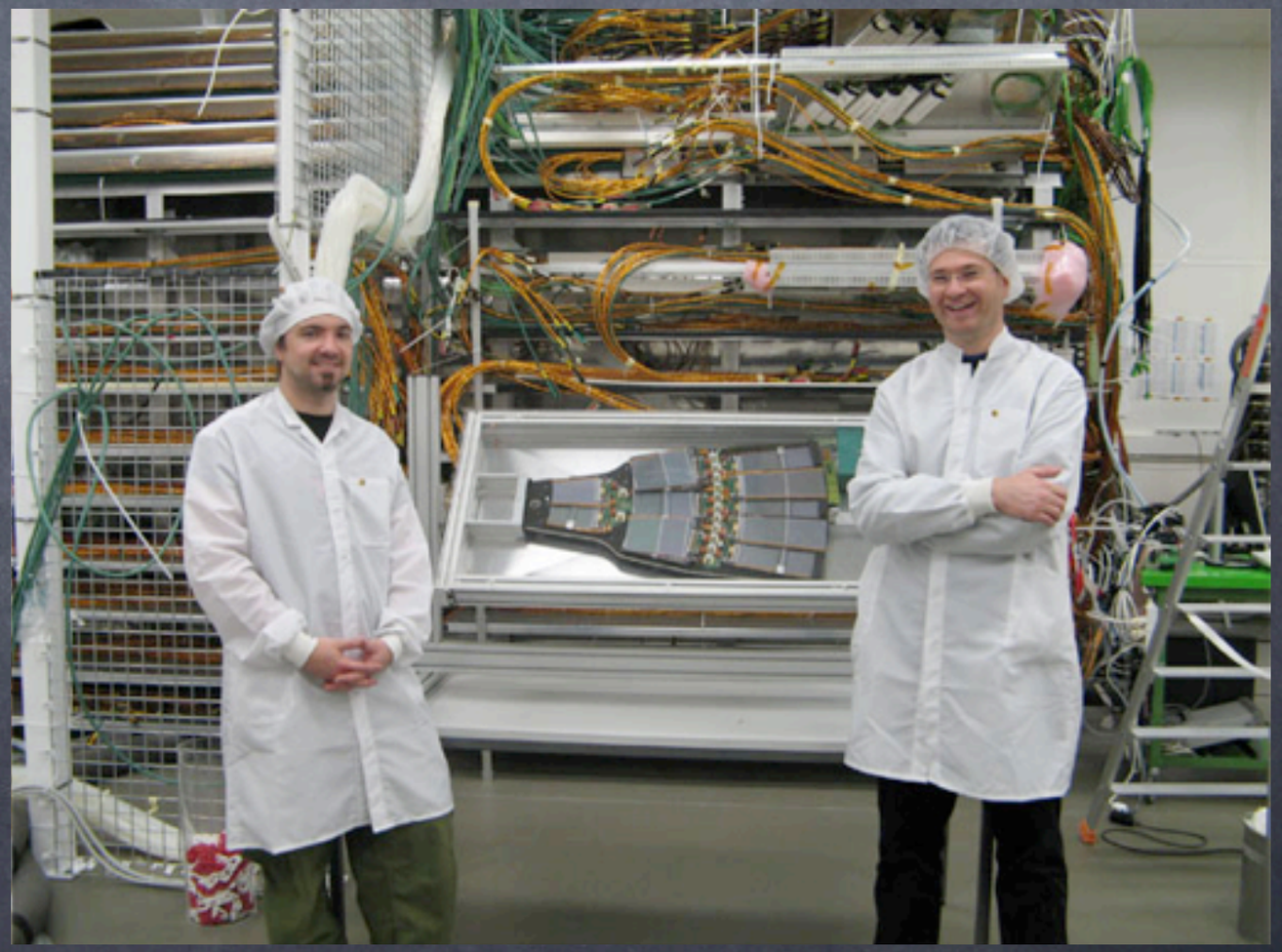
Experimentalists

working very hard to make things happen





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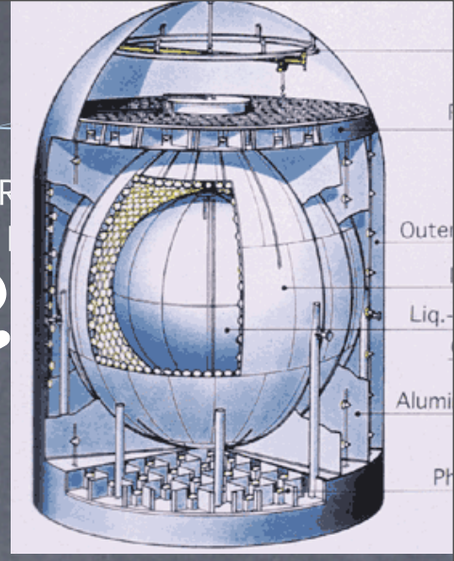
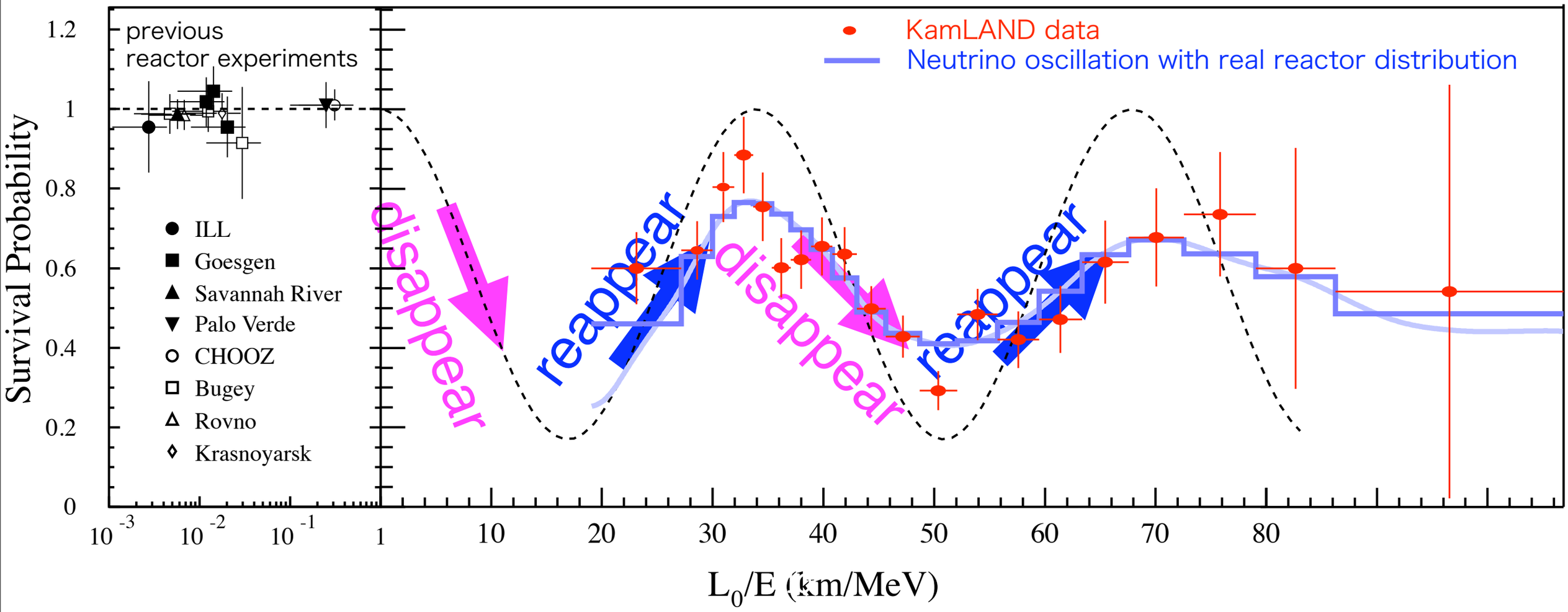
Theorists

reading tea leaves.....

Neutrinos do oscillate



- KamLAND 2008 data
- beautiful oscillation demonstrate neutrino mass ⇒ heavy right-handed neutrinos?

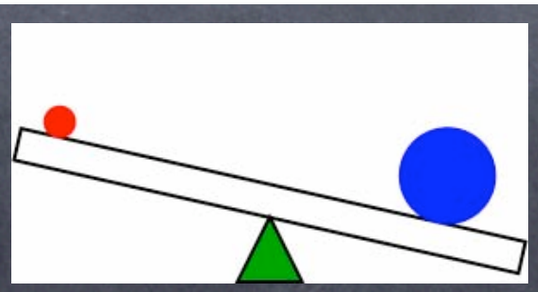


Seesaw Mechanism

- Why is neutrino mass so small?
- Need right-handed neutrinos to generate neutrino mass, but ν_R SM neutral

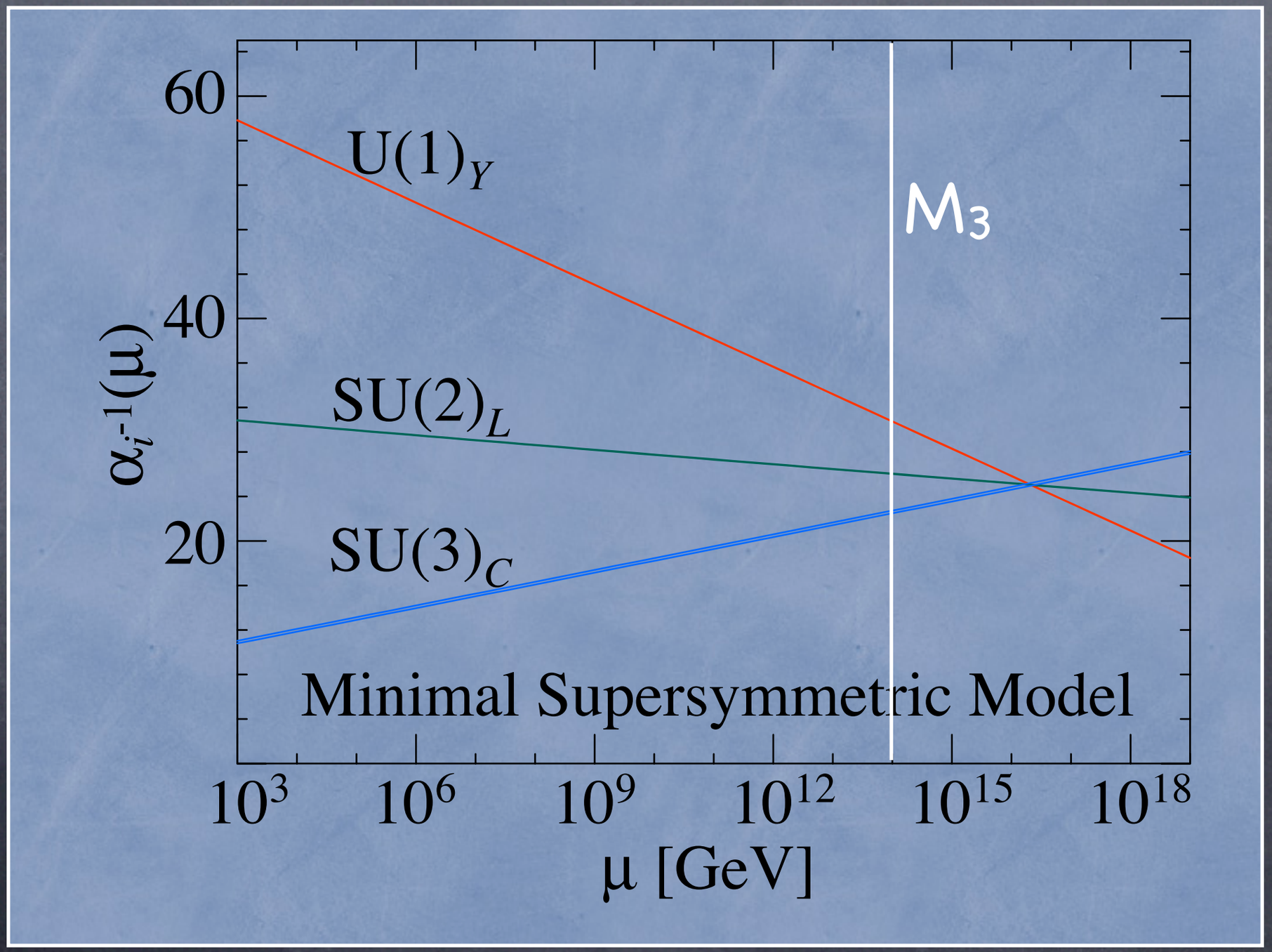
$$\begin{pmatrix} \nu_L & \nu_R \end{pmatrix} \begin{pmatrix} & m_D \\ m_D & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

$$m_\nu = \frac{m_D^2}{M} << m_D$$



To obtain $m_3 \sim (\Delta m^2_{\text{atm}})^{1/2}$, $m_D \sim m_t$, $M_3 \sim 10^{14}$GeV (GUT!)

seesaw scale



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Tea leaves 2008

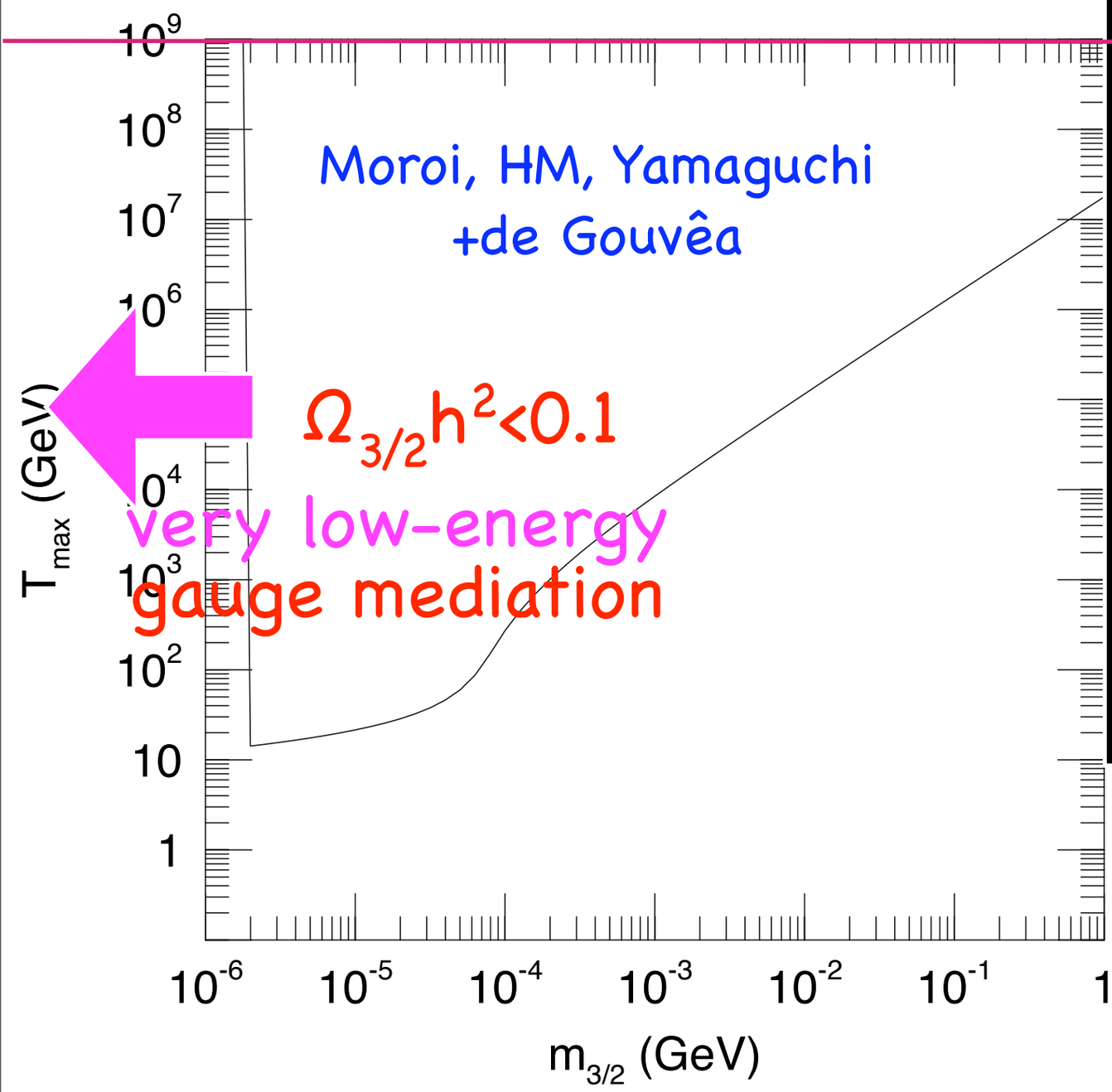
- hierarchy problem ⇒supersymmetry
- Neutrino Mass ⇒seesaw + leptogenesis
- Non-baryonic Dark Matter ⇒thermal relics with mass < 100 TeV
- Dark Energy ⇒Λ or scalar field
- Density Fluctuation ⇒inflation

Can we put them together?

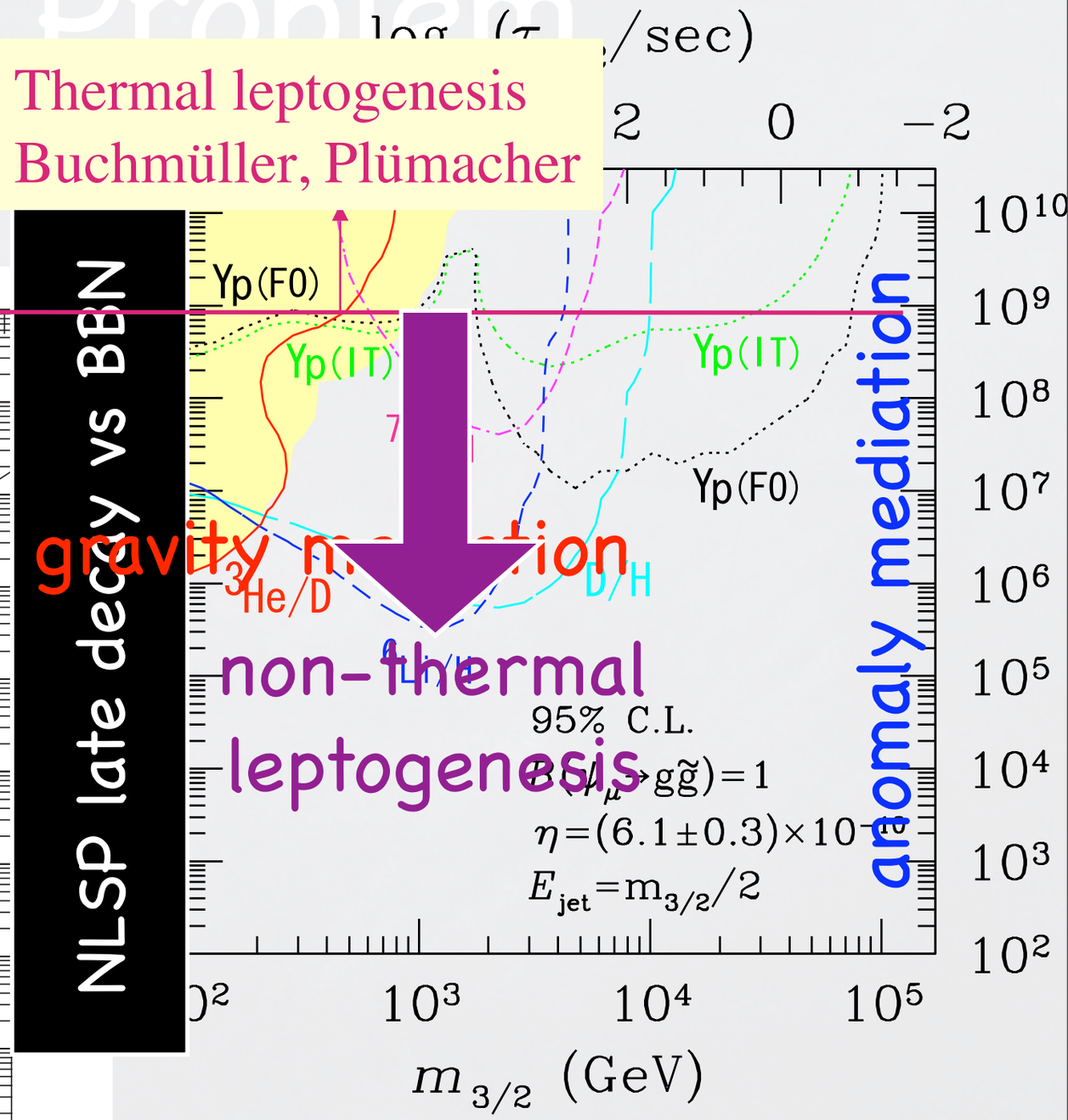
Gravitino Problem

$$\frac{n_{3/2}}{s} \approx 1.5 \times 10^{-12} \frac{T_{RH}}{10^{10}\mathrm{GeV}}$$

Thermal leptogenesis
Buchmüller, Plümacher



NLSP late decay vs BBN



gravity mediation

non-thermal leptogenesis

anomaly mediation

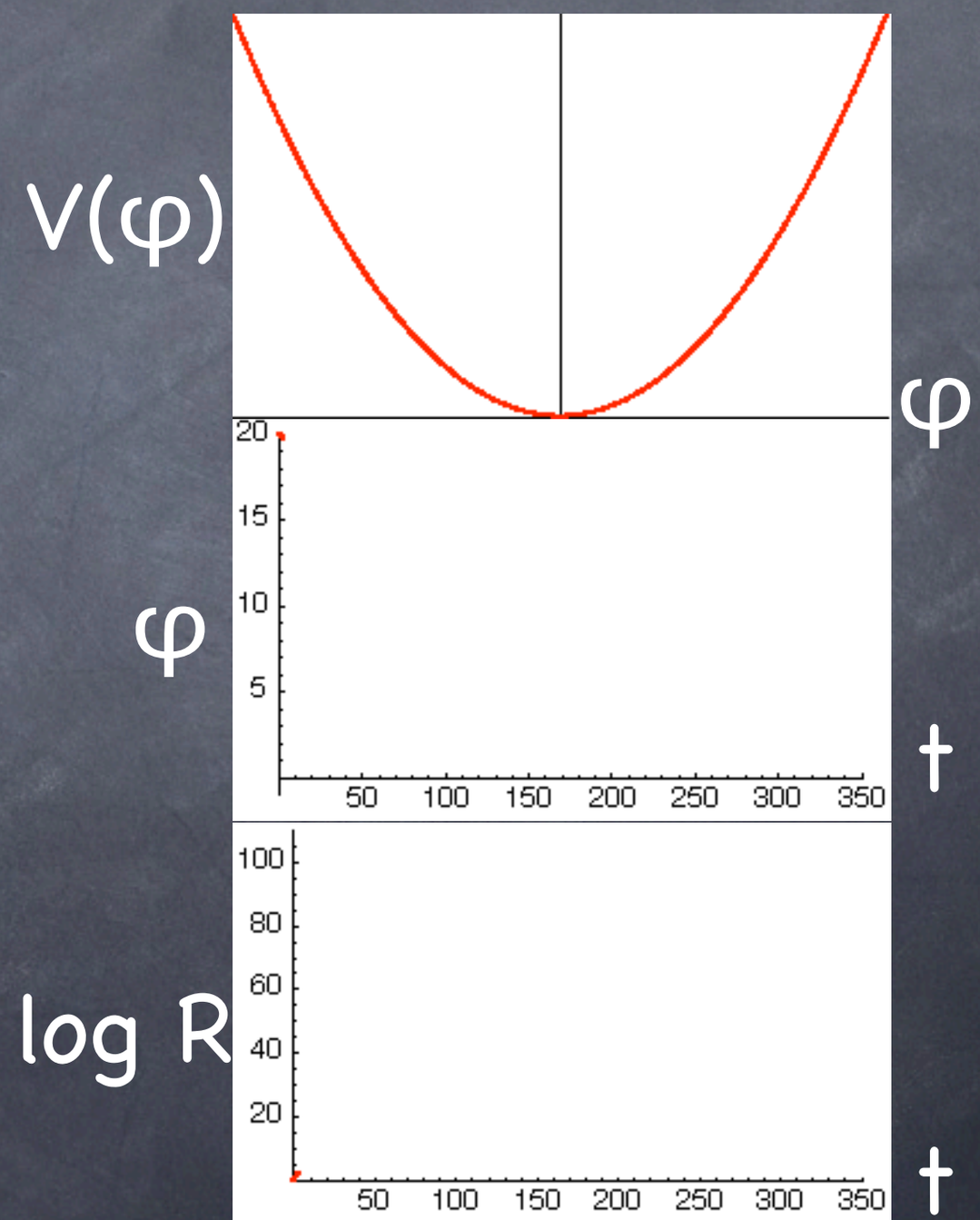
Kawasaki, Kohri, Moroi

$$m_{3/2} = \frac{\Lambda_{SUSY}^2}{M_{Pl}}$$

Non-thermal Leptogenesis

Sneutrino Inflation

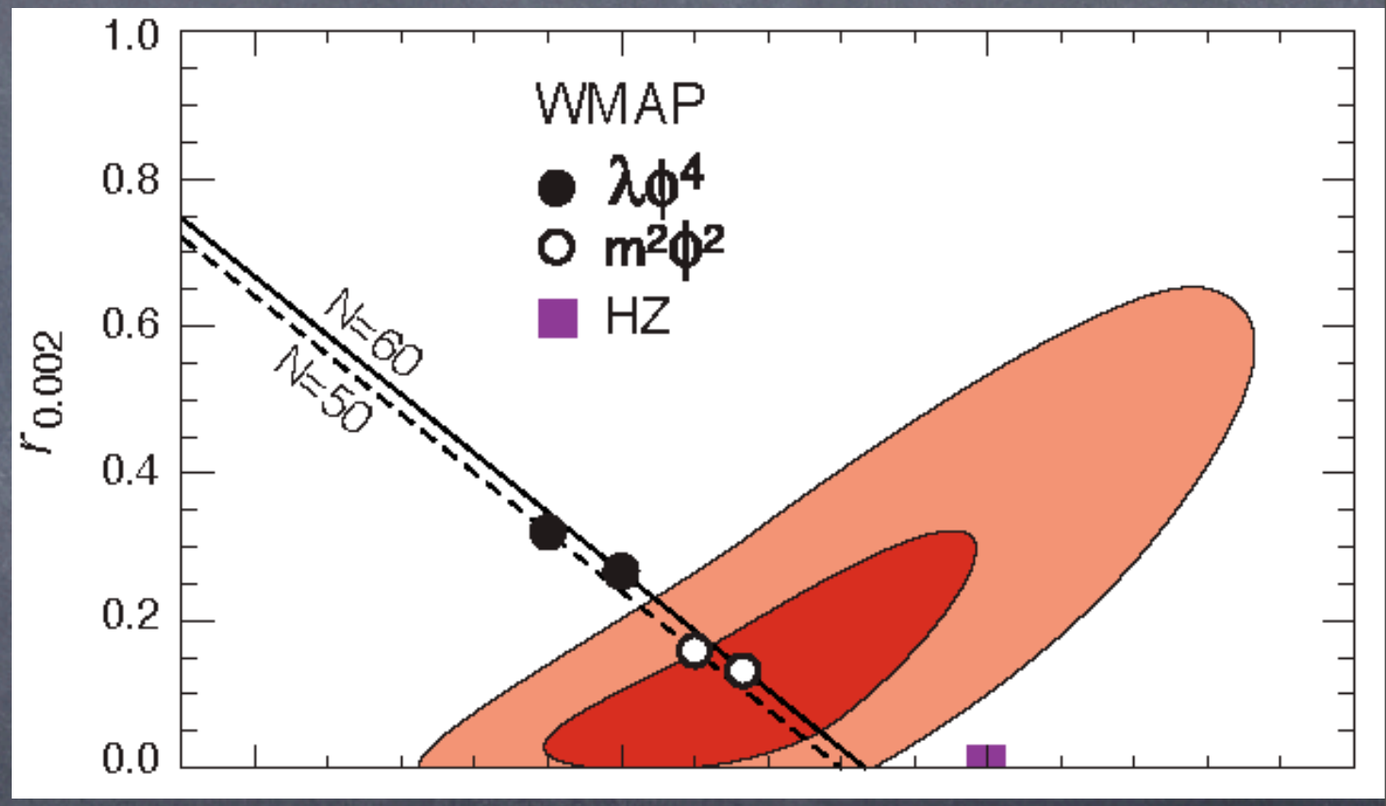
- Superpartner of ν_R: $V=m^2\varphi^2$
- displaced from the minimum at the beginning
- rolls down slowly: chaotic inflation
- now possible in string (Silverstein)
- quantum fluctuation source of later structure
- reheating = leptogenesis
- decay products contain supersymmetry and hence usual SUSY Dark Matter



HM, Suzuki, Yanagida, Yokoyama

Consistency

- n_s~0.96, r~0.16
- Need m~10^{13}GeV, seesaw scale!
- Still consistent with latest WMAP, but $V=\lambda\phi^4$ excluded
- Verification possible in the near future
- enough lepton asymmetry consistent with gravitino problem!



$$\frac{n_B}{s} \approx 10^{-10} \frac{T_{RH}}{10^6 \mathrm{GeV}}$$

Murayama, Yanagida + Hamagchi

Variants

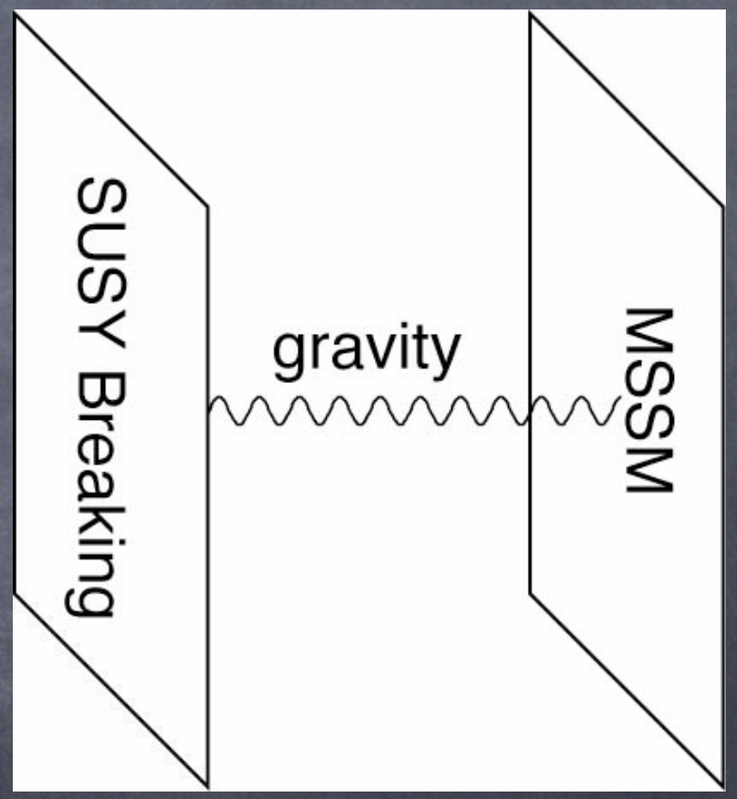
- For the leptogenesis to succeed, it is not required that sneutrino is the inflaton
- just need ν_R to dominate the universe at one point
- large coherent oscillation of ν_R from the end of inflation (HM, Yanagida)
- inflaton decay into neutrinos (Lazarides, Schaefer, Shafi) but hybrid inflation tight
- dark matter: usual WIMPs in gravity mediation

Anomaly Mediation

Anomaly Mediation

(Randall Sundrum; Giudice, Luty, HM, Rattazzi)

- used to rely on physical separation between MSSM and hidden sector
- stabilization of moduli?
- conformal sequestering replaces extra D (Luty, Sundrum)
- ISS + gauged flavor naturally realizes conformal sequestering (Schmaltz, Sundrum)
- gotten easier and more generic



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Anomaly Mediation

$$M_i = -\frac{\beta_i(g^2)}{2g_i^2} m_{3/2}, \quad m_i^2 = -\frac{\dot{\gamma}_i}{4} m_{3/2}^2, \quad A_{ijk} = -\frac{1}{2}(\gamma_i + \gamma_j + \gamma_k) m_{3/2}$$

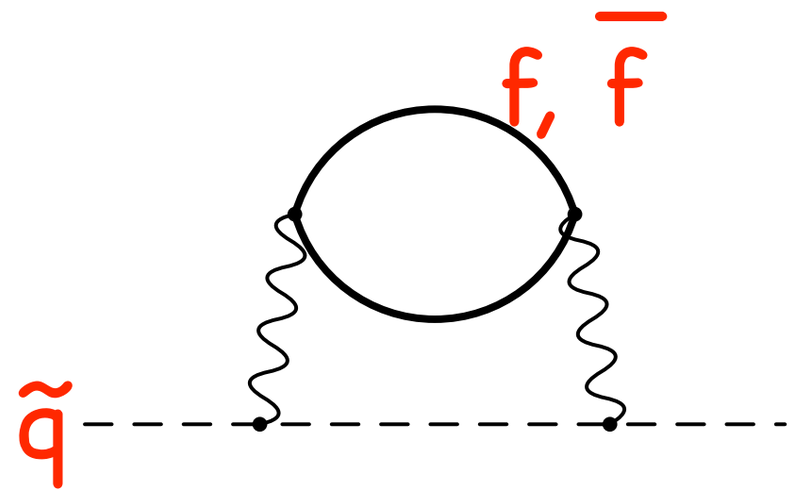
- SUSY masses due to anomaly = loops
- $m_{SUSY} \approx m_{3/2}/(16\pi^2)$
- $m_{3/2} \approx 100$ TeV, decays before BBN, safe!
- solves also the flavor problem
- tachyonic sleptons may be solved with D-terms (Arkani-Hamed, Kaplan, HM, Nomura)
- integrating out ν_R violates flavor, but lepton flavor violation still adequately suppressed (Ibe, Kitano, HM, Yanagida)

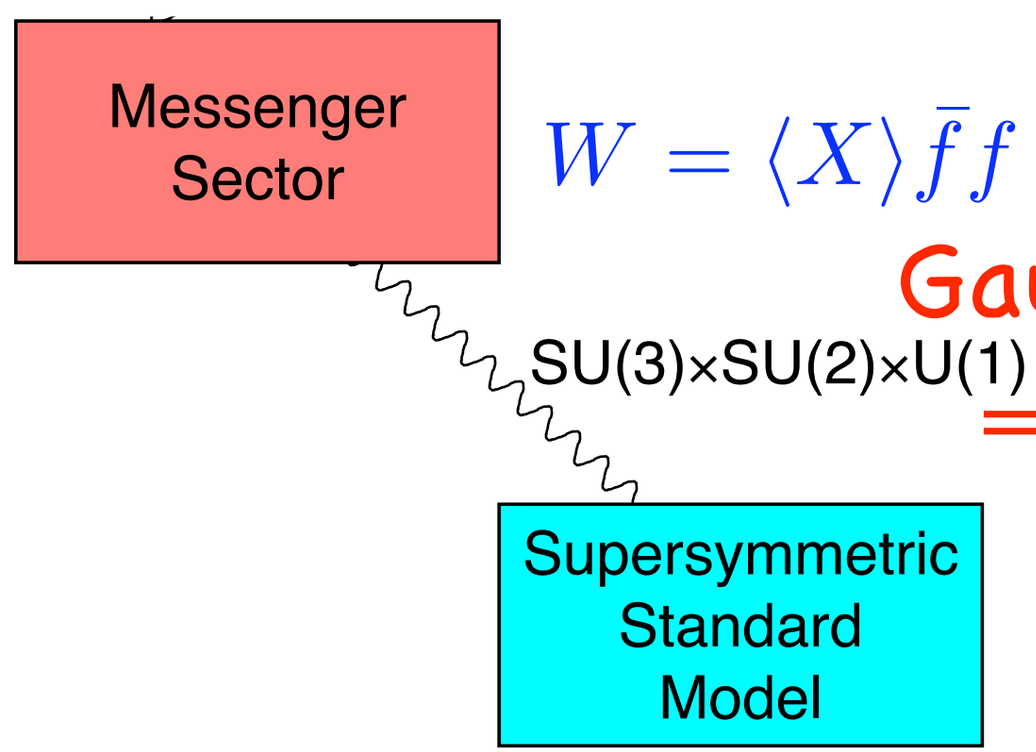
Randall, Sundrum

Giudice, Luty, HM, Rattazzi

Gauge Mediation

gauge mediation





$$W = \langle X \rangle \bar{f} f$$

Gauge Mediation

⇒flavor blind

complete models are complicated

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$\mu \sim 10^7$ GeV

Dynamical Supersymmetry Breaking

$$W = A\bar{F}^+\bar{F}^- + \bar{F}^0(F^+S^- + F^-S^+) + FF^0S^0$$

messenger U(1)

	$SU(6)$	$U(1)$	$U(1)_m$	$U(1)_R$
A	15	$+2$	0	$-\frac{18}{7}$
F	6	-5	0	$-\frac{18}{7}$
$\bar{F}^\pm$	$\bar{6}$	-1	± 1	$\frac{16}{7}$
$\bar{F}^0$	$\bar{6}$	-1	0	$\frac{16}{7}$
$S^\pm$	1	$+6$	± 1	$\frac{16}{7}$
S^0	1	$+6$	0	$\frac{16}{7}$

$\mu \sim 10^5$ GeV

Messenger Sector

$$W = \phi^+\phi^-X + X^3 + X\bar{f}f$$

Gauge Mediation

SU(3)×SU(2)×U(1)

⇒flavor blind

$\mu \sim 10^2$–10^3 GeV

Supersymmetric Standard Model

$m_{3/2} \approx 100$keV!

Dine-Nelson-Nir-Shirman

Gravitino Problem

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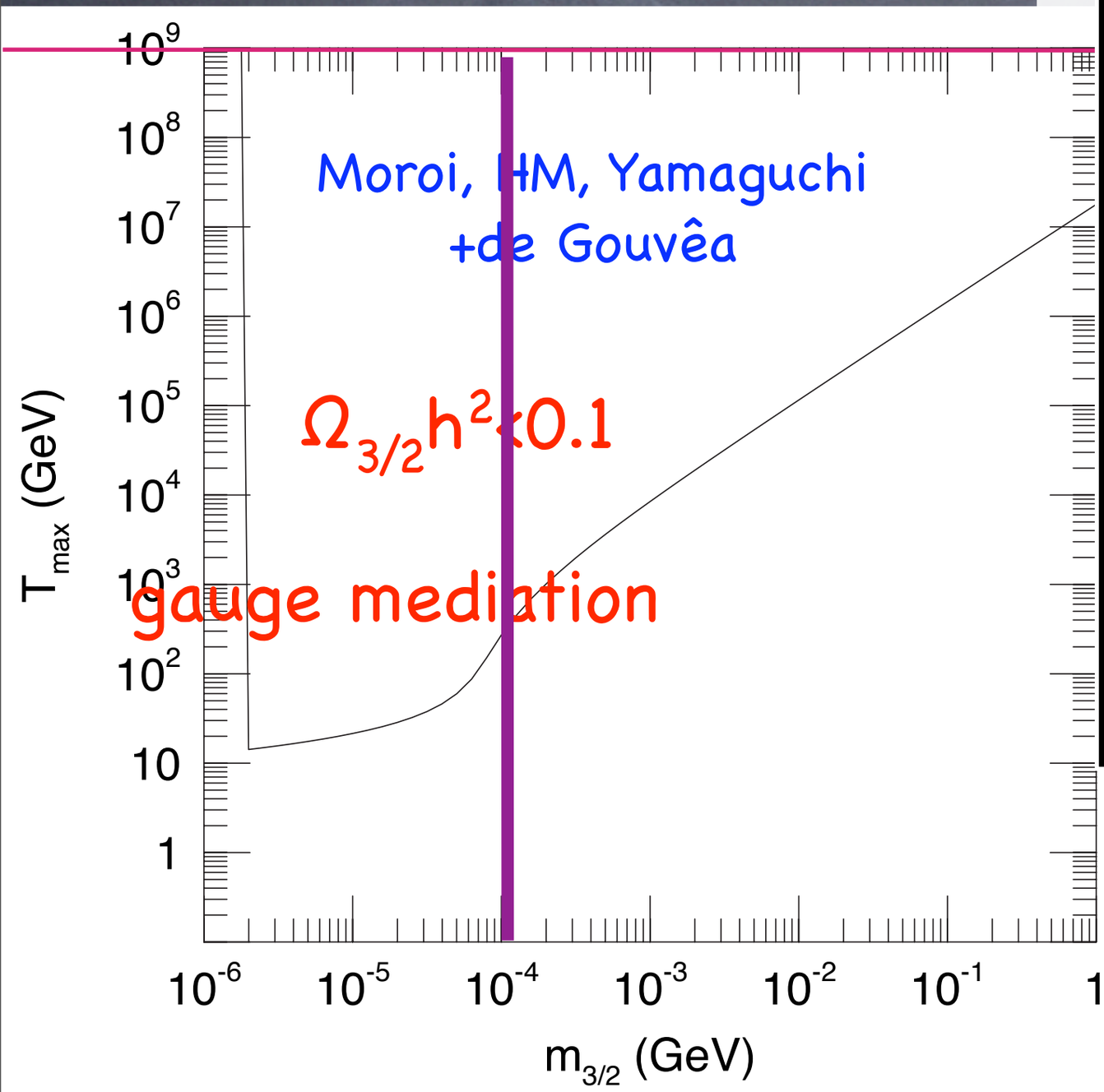

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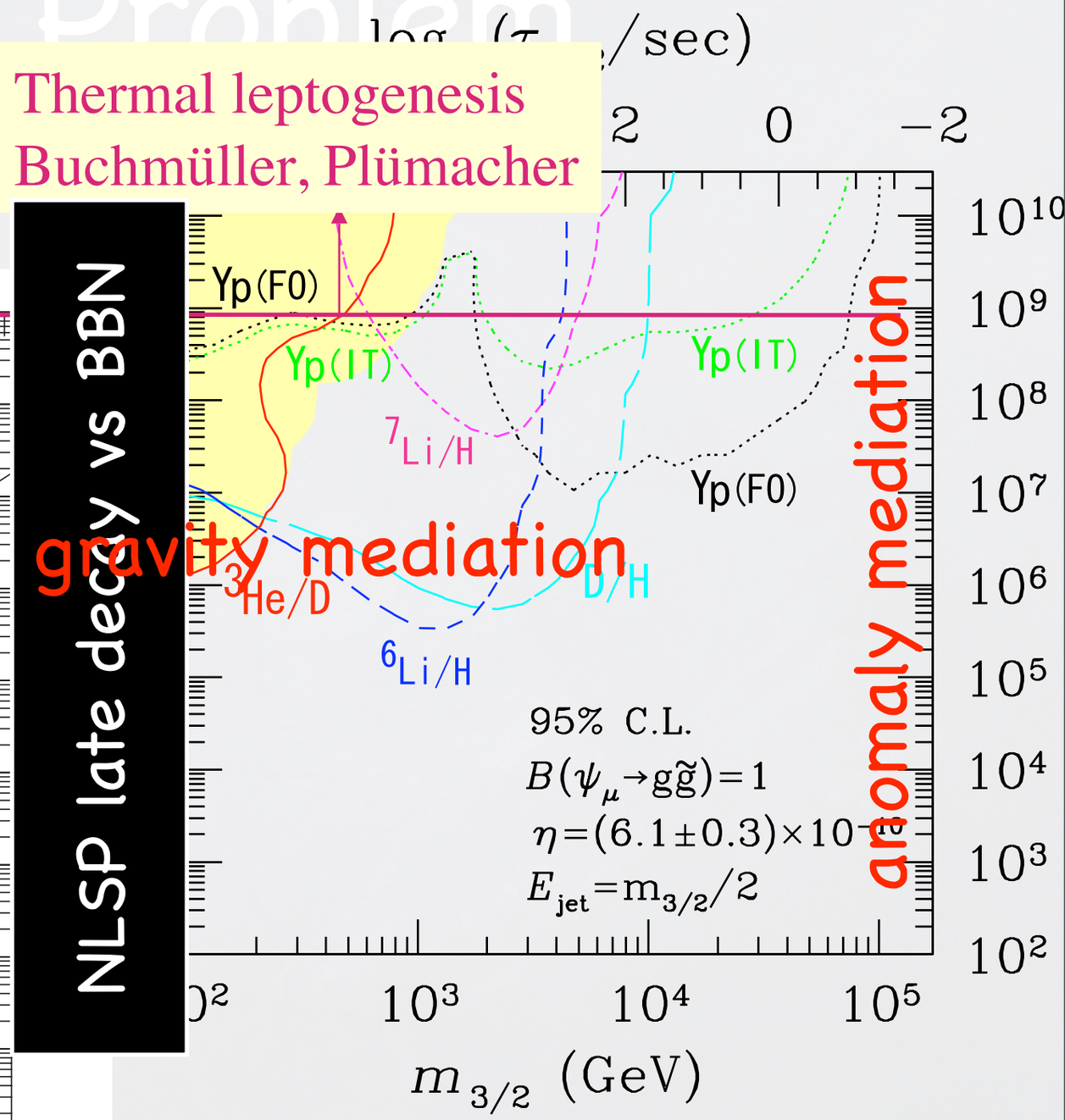
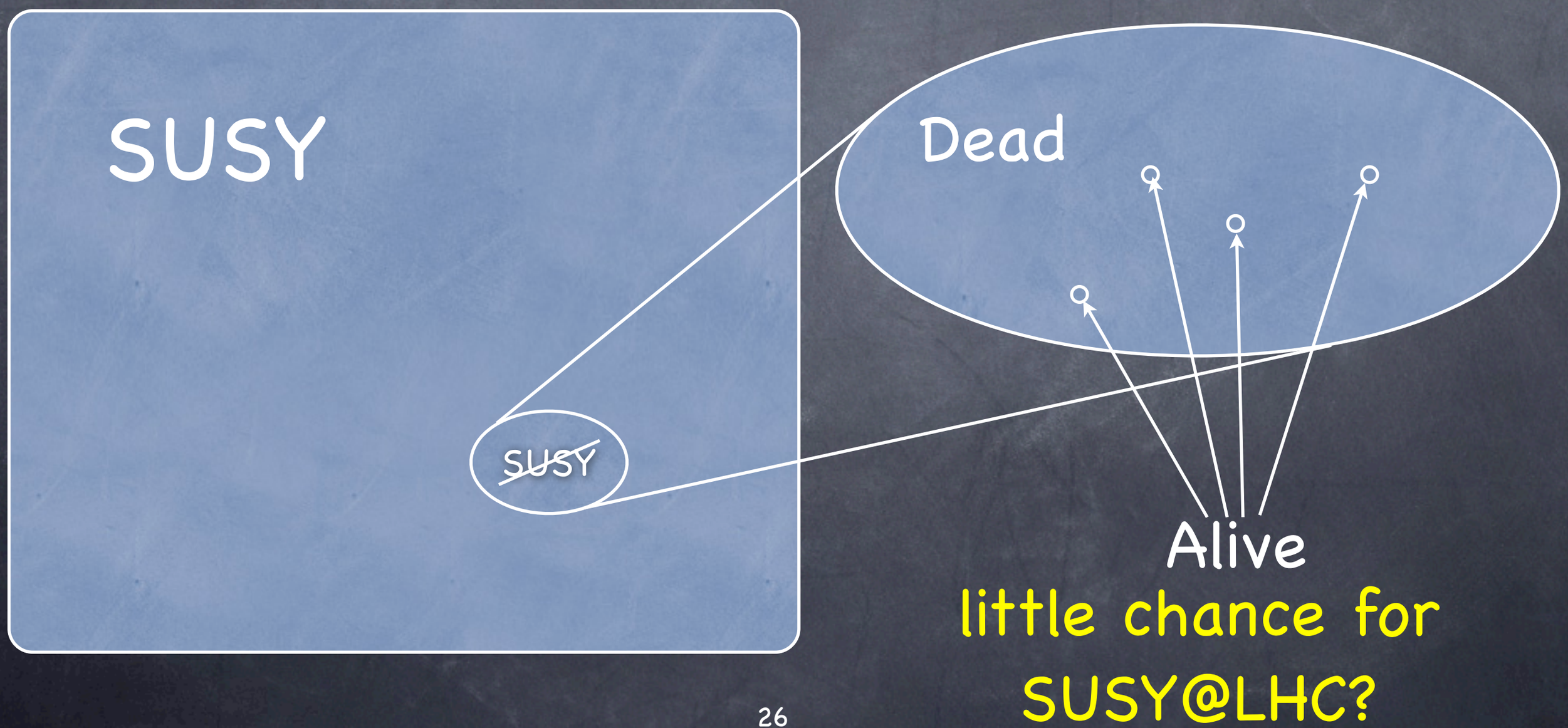


Kawasaki, Kohri, Moroi

Likelihood of viable SUSY

Landscape of theories



Generic Scheme

HM, Nomura

$$\frac{1}{M_{Pl}}\bar{Q}Q\bar{f}f$$

SUSY QCD
SU(Nc), SO(Nc), Sp(Nc)

$m_Q\bar{Q}Q$

$M\bar{f}f$

SUSY SM

no $U(1)_R$ symmetry imposed

most general superpotential

wide choice of gauge groups, matter content

$$N_c < N_f < \cancel{\frac{3}{2}N_c}$$

How it works

- SUSY SU(N_c) QCD $N_c<N_f<3N_c/2$ $\quad W = m_Q^{ij}\bar{Q}_i Q_j$
- low-energy free magnetic theory ($m_Q<\Lambda$)

  $W = m_Q^{ij}\Lambda M_{ij} + M_{ij}\bar{q}^i q^j$

  Intriligator Seiberg
- SUSY breaking @ $M_{ij} = 0, \quad \frac{\partial W}{\partial M_{ij}} = m_Q^{ij} \neq 0$ Shih
- Local minimum with long lifetime

  $W = \frac{1}{M_{Pl}}\bar{Q}Q\bar{f}f$

- Generates SUSY breaking in f, fbar
- their loops⇒gauge mediation

  HM, Nomura
- doesn't have to be ISS, many others possible

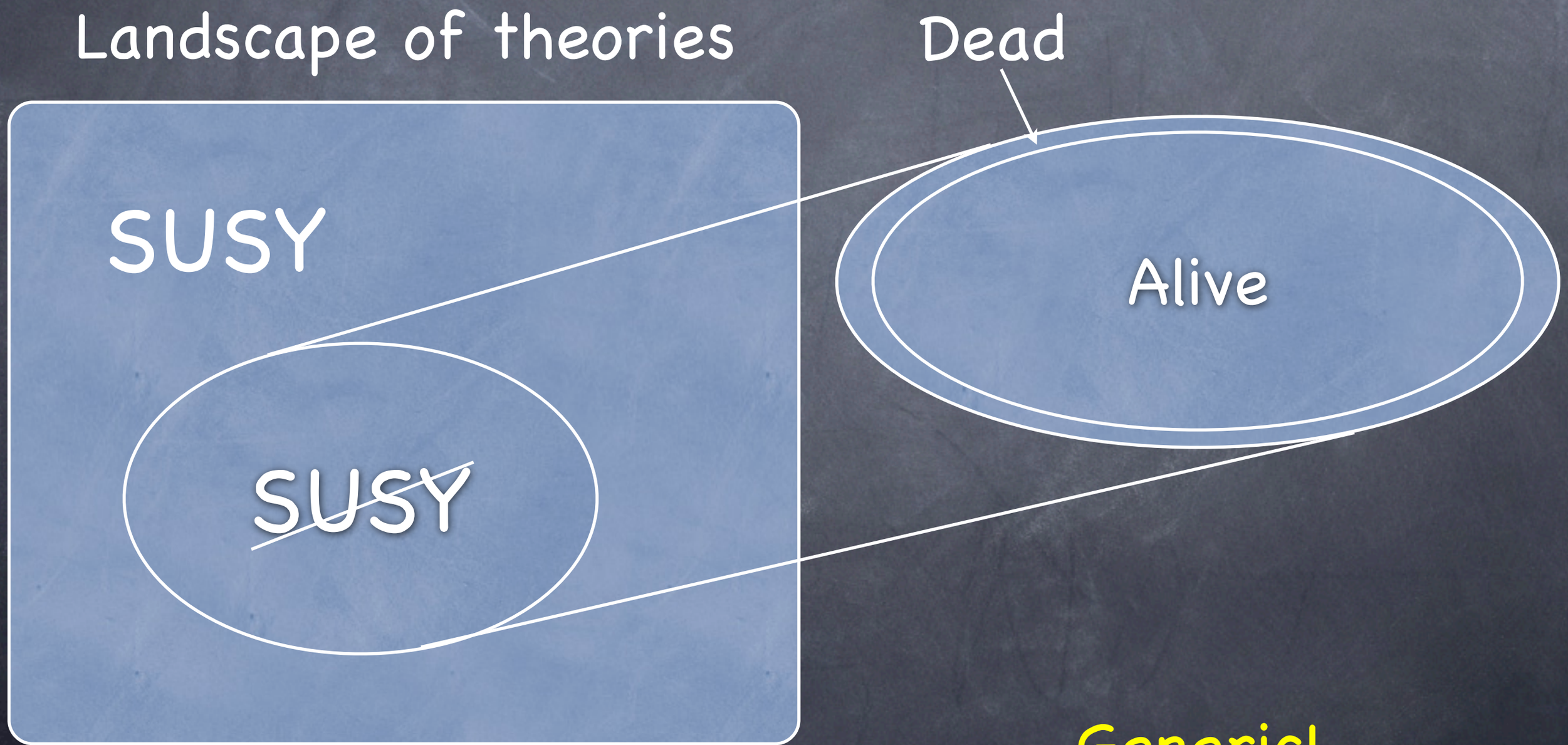
Good news for string theory

- String theory does not predict unique solution
- "Landscape" of possibilities for gauge groups, matter content, number of SUSY
- We at least need SM
- We tend to get extra "junks", i.e. extra gauge groups, extra vector-like matter
- the "junks" are precisely what we need to break SUSY via gauge mediation

Easy, Viable, Generic!

e.g., Kawano, Ooguri, Ookouchi

Likelihood of viable SUSY



Generic!

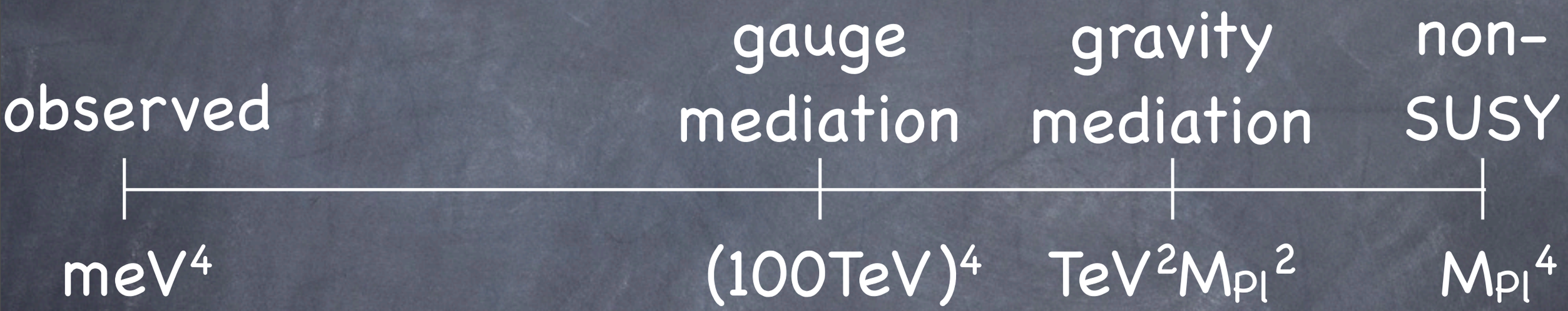
Consequences

- gravitino mass very flexible, can be ≈10eV, consistent with leptogenesis
- local minimum with low $m_{3/2}$ sufficiently long-lived (Hisano, Nagai, Sugiyama, Yanagida)
- dark matter: hidden "baryon" ≈ 100 TeV (Hamaguchi, Shirai, Yanagida)
- SUSY breaking sector may be conformal (Roy, Schmaltz), (HM, Nomura, Poland), helps to explain why $M_f \approx \Lambda$ to obtain low $m_{3/2}$

Consequences

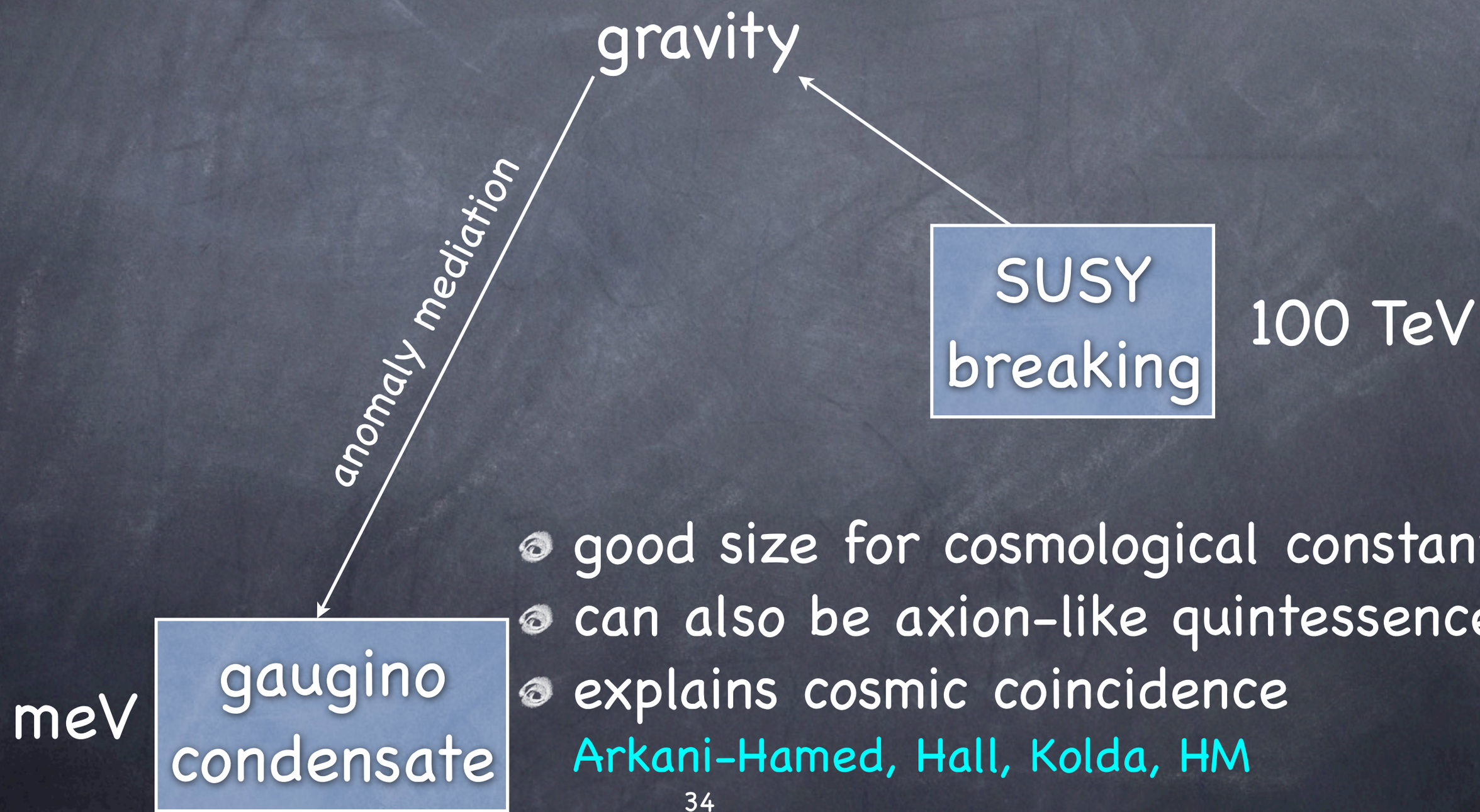
- sleptons promptly decay into lepton+gravitino with picosec lifetime → measure $m_{3/2}$!
- specific mass spectrum of SUSY particles
  - in principle depends on "hidden" sector
  - but testable sum rules if GUT (Cohen, Roy, Schmaltz), (HM, Nomura, Poland)
- superlight gravitino may be detectable in LSS, Lyman α forest
- current most aggressive analysis requires $m_{3/2}$<16eV (Viel, Lesgourgues, Haehnelt, Matarrese, Riotto), but probably weakened by systematics & WMAP5, $m_{3/2}$<100eV or so

Cosmological Constant



a half way done!

natural cosmological constant

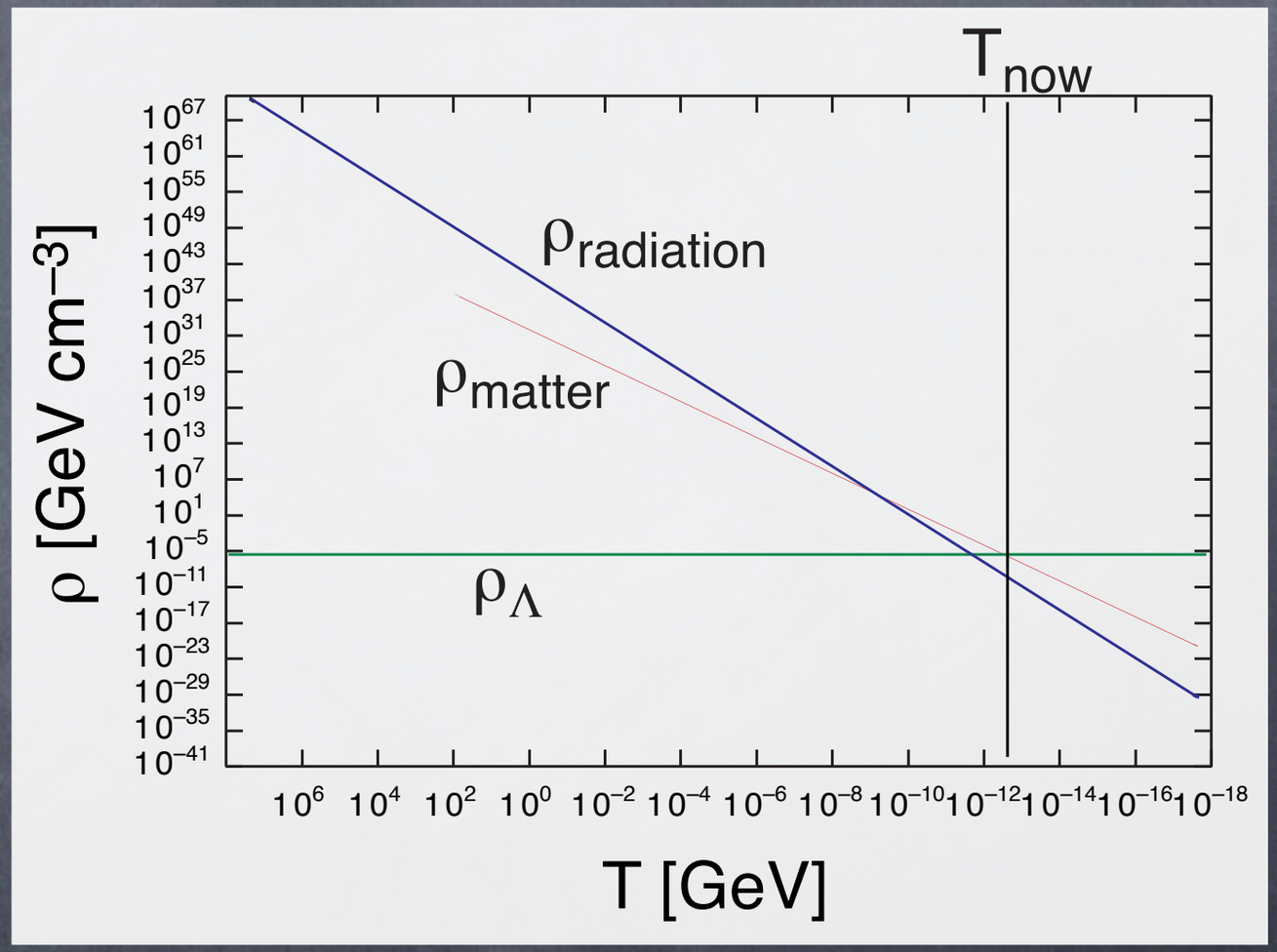


- good size for cosmological constant
- can also be axion-like quintessence
- explains cosmic coincidence

Arkani-Hamed, Hall, Kolda, HM

Cosmic Coincidence Problem

- Why do we see matter and cosmological constant almost equal in amount?
- "Why Now" problem
- Actually a triple coincidence problem including the radiation
- There must be a reason behind it



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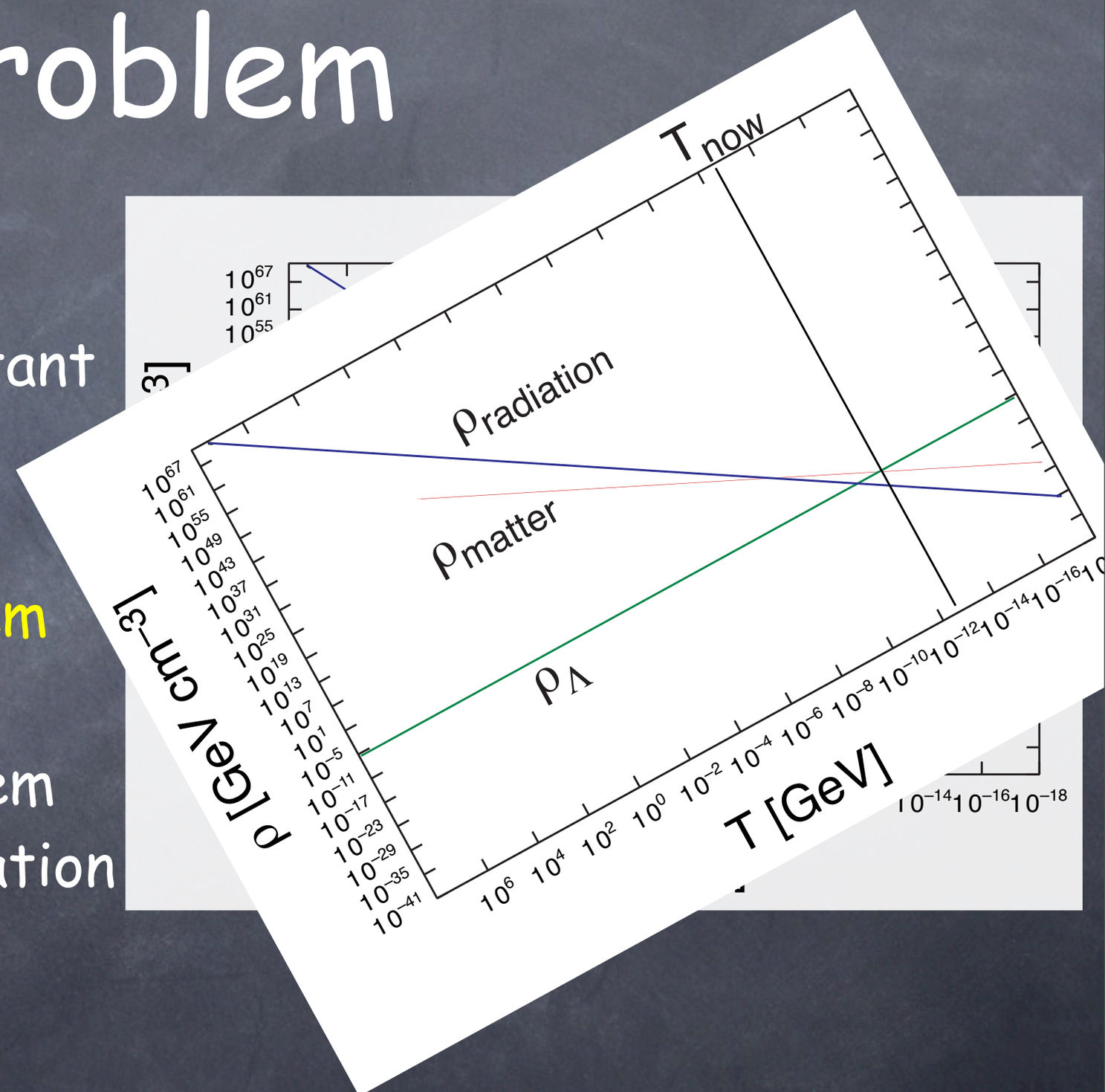
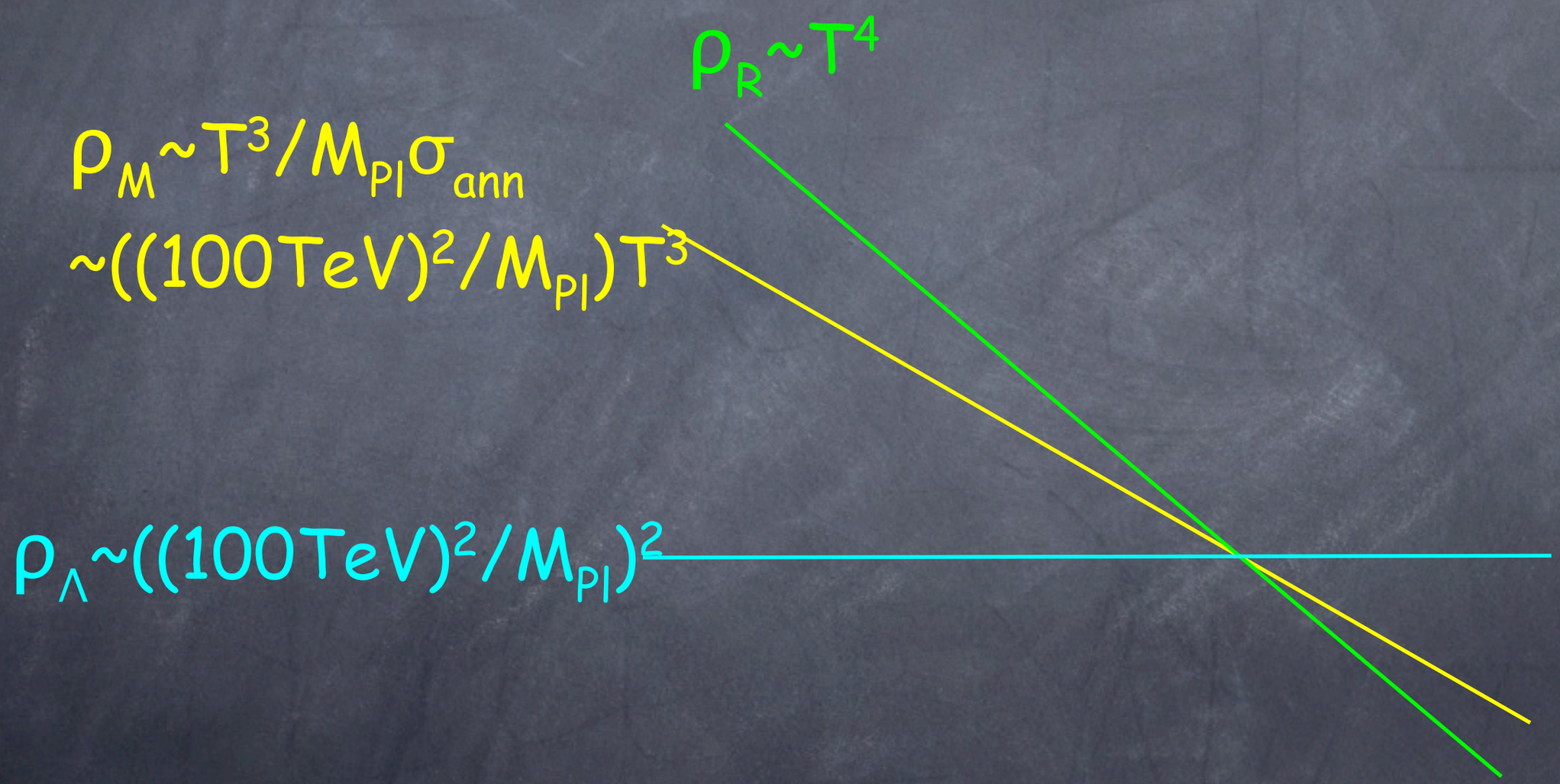


Triple Coincidence

- Radiation energy density $\rho_R \sim T^4$
- Matter energy density $\rho_M \sim (TeV^2/M_{Pl})T^3$
- They inevitably meet at $T_0 \sim (TeV^2/M_{Pl}) \sim 10K$
- If there is a reason for $\rho_\Lambda \sim ((TeV)^2/M_{Pl})^4$, all of them meet inevitably at $T \sim T_0$
- Indeed, $\rho_\Lambda \sim (2meV)^4$ while $(TeV)^2/M_{Pl} \sim 1meV$

Unique Window for Structure Growth



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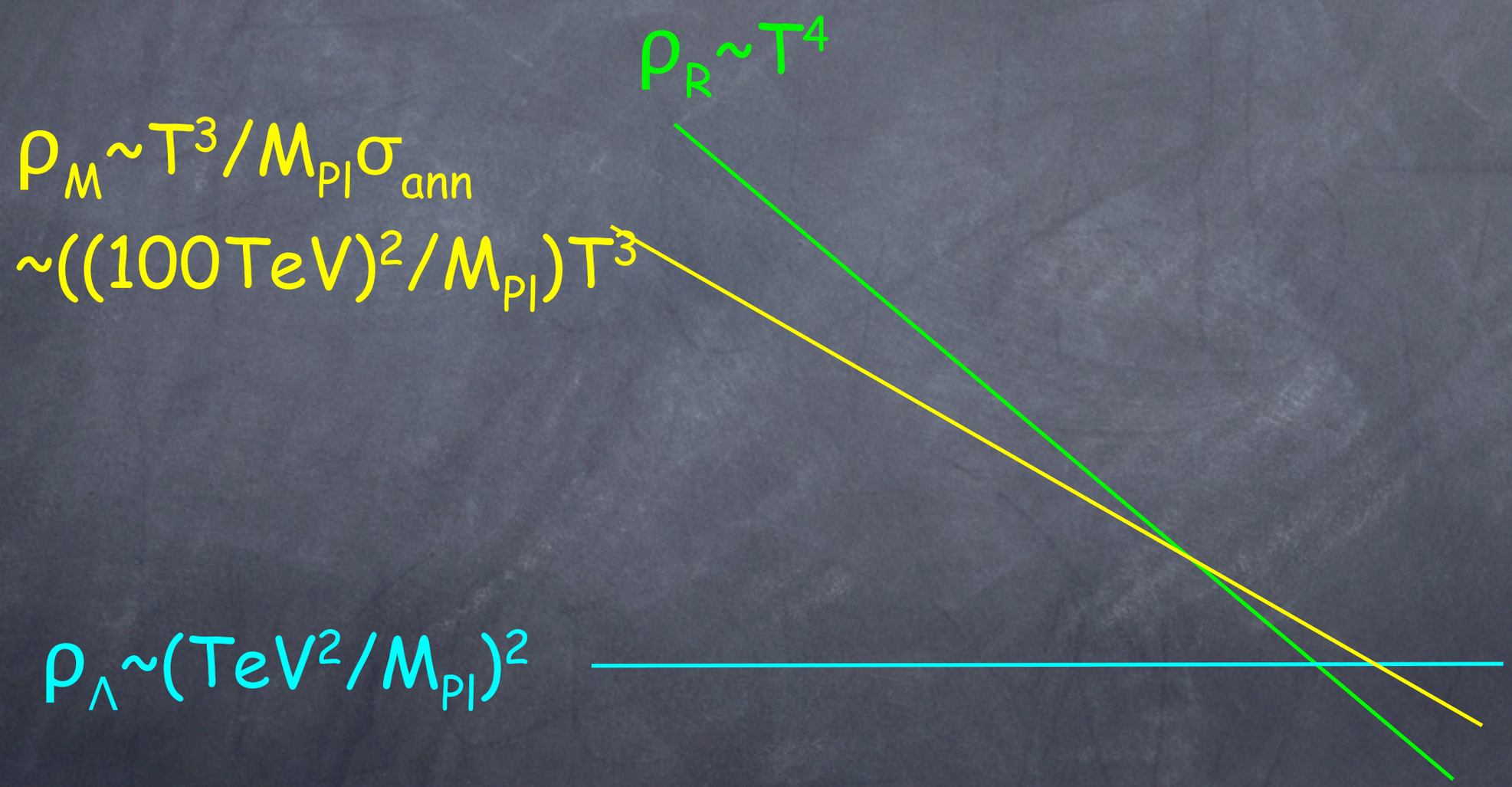
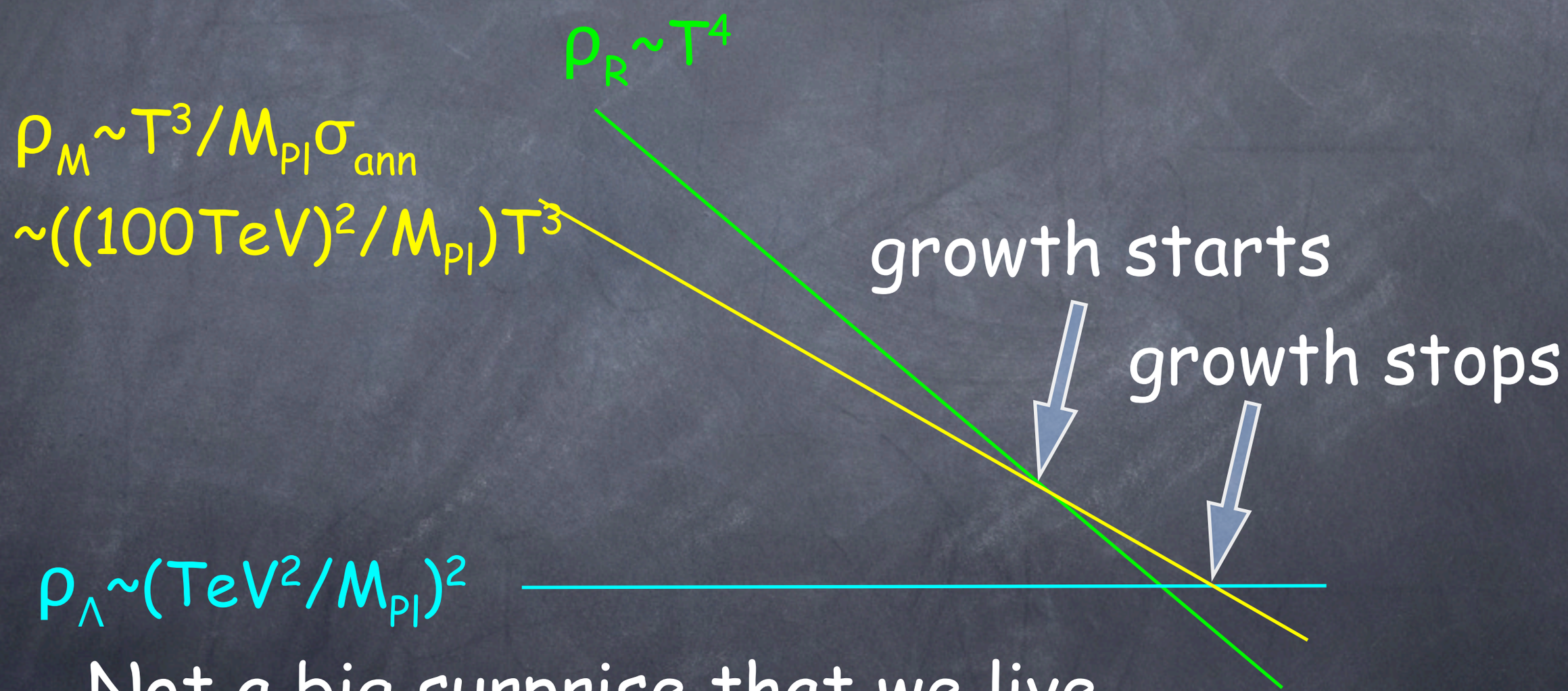


Unique Window for Structure Growth



Not a big surprise that we live in the "coincidence era".

100TeV dark matter

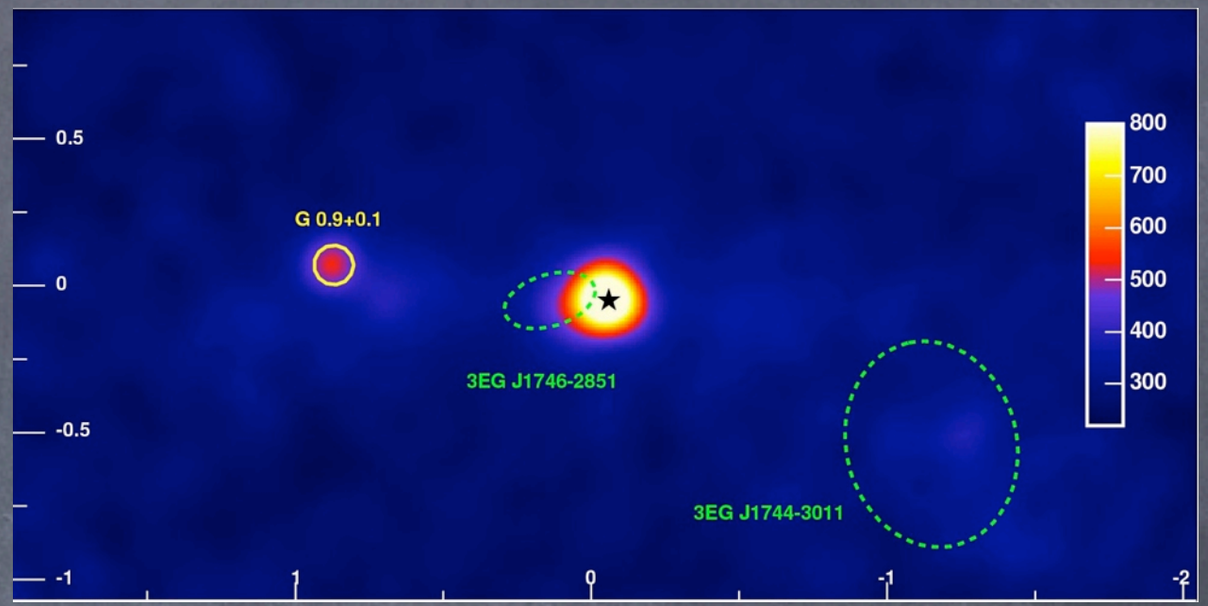
- thermal relic abundance

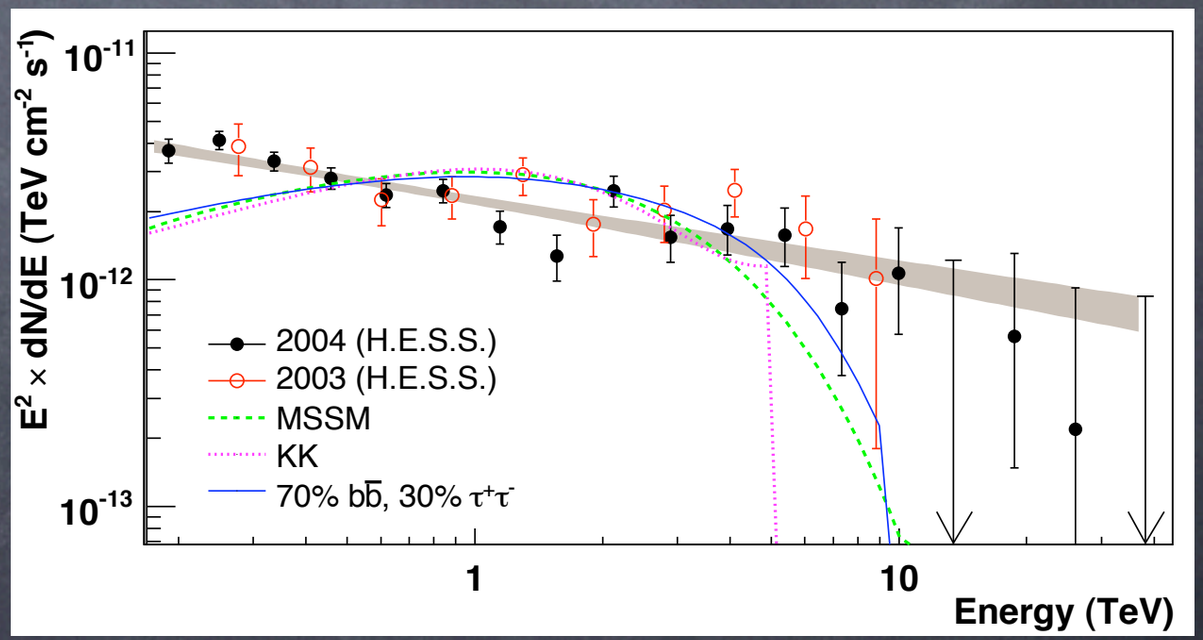
$$\Omega_M = \frac{0.756(n+1)x_f^{n+1}}{g^{1/2}\sigma_{ann}M_{Pl}{}^3}\frac{3s_0}{8\pi H_0^2} \approx \frac{\alpha^2/(TeV)^2}{\sigma_{ann}}$$

- unitarity limit $\langle\sigma\, v_{rel}\rangle \leq 4\pi(2J+1)/(m^2 v_{rel})$
- $\Omega_M \geq m^2/(100TeV)^2$
- saturates the limit with m=100TeV
- just the right scale for SUSY breaking!
- Actually m<100TeV requires light SUSY, typically m(gluino)<2TeV

DM annihilations

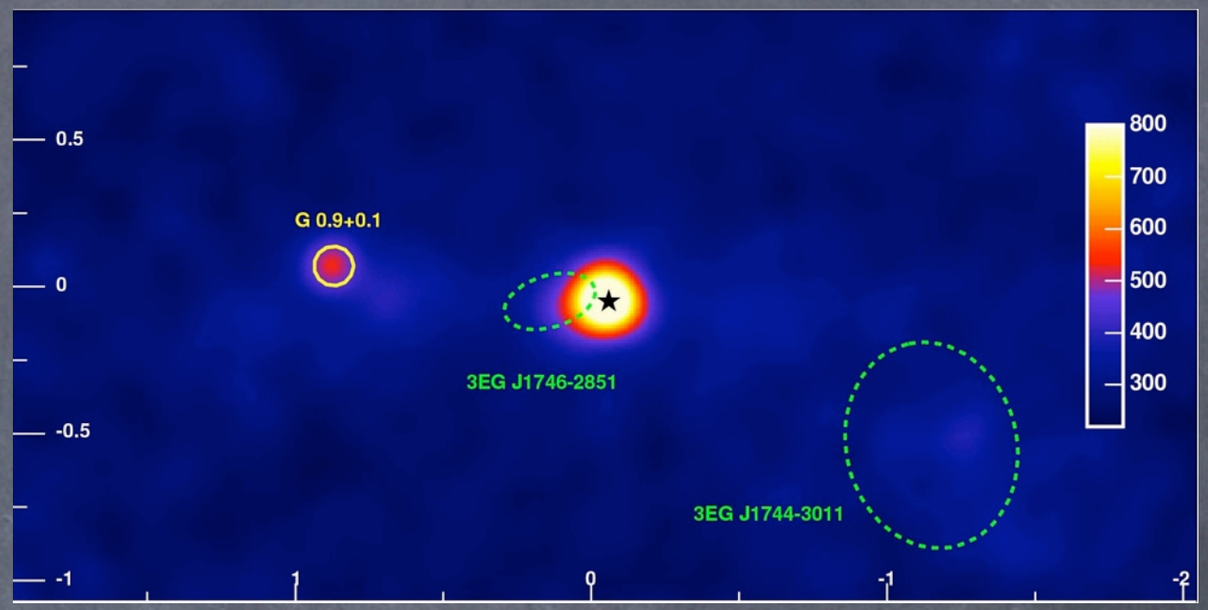
- Dark matter may annihilate in the galactic center
- very high-energy gammas (i.e. HESS)
- data consistent with power law so far

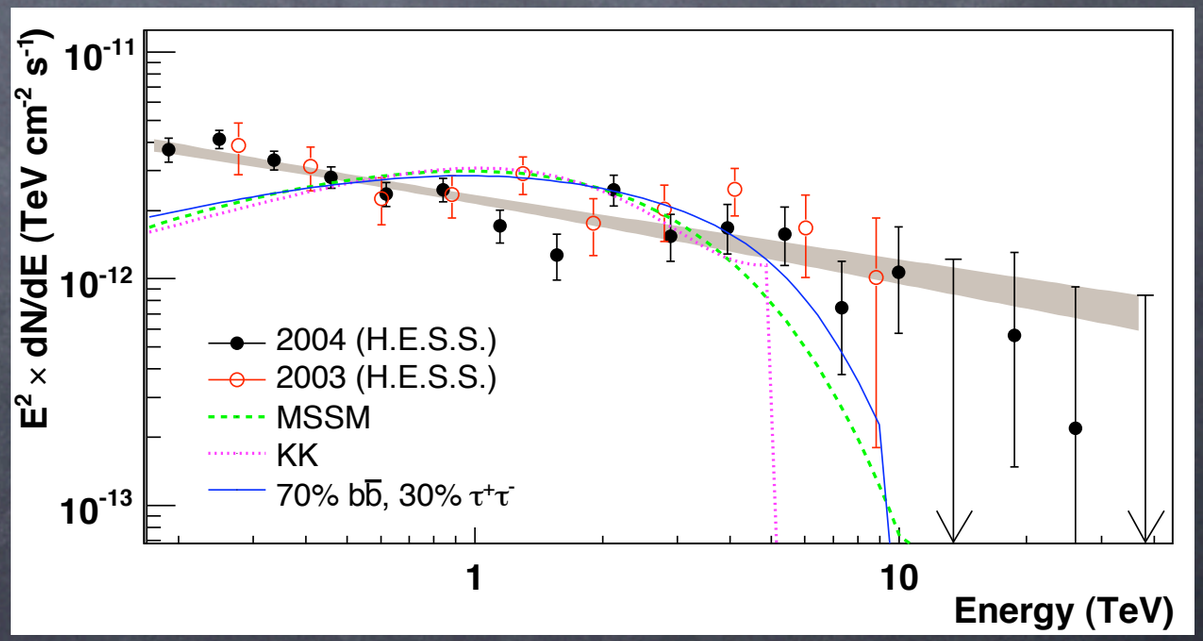




DM annihilations

- DM DM → visible
- background: $dN/dE = 2.5\ 10^{-12}\ E_{TeV}^{-2.22}$ $TeV^{-1}\ cm^{-2}\ s^{-1}$
- signal: $N \sim 3.0\ 10^{-13}\ cm^{-2}\ s^{-1}$
- could show up at higher energies (Mandal, HM)
- can demonstrate by extrapolating weakly coupled calculable models (Ibe, HM, Nakayama, Yanagida)





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Conclusion

- neutrino oscillation provides a strong motivation for leptogenesis
- conflict with SUSY: gravitino problem
- non-thermal leptogenesis
  - sneutrino inflation=φ^2 chaotic inflation
- anomaly mediation
  - much nicer w/ conformal sequestering
- gauge mediation
  - easy, generic
  - prompt decays into gravitino @ collider
  - very high energy gammas signal?

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Theorists

looking for more data to read!