Connecting Particles with the Cosmos

3. - 4. November 2009
DESY Hamburg, Auditorium

Landesexzellenzinitiative Hamburg

Supergravity in the sky

Laura Covi

LEXI LANDESEXZELLENZINITIATIVE HAMBURG

DESY

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Outline

- Introduction:
  Cosmology & the present Universe
- SUGRA Part I:
  de Sitter/inflation in String-inspired SUGRA
- SUGRA Part II:
  Gravitino Dark Matter
- Outlook

Introduction

Einstein's legacy: Energy is Geometry

$$\mathcal{R}^{\nu}_{\mu} - \frac{1}{2}\delta^{\nu}_{\mu}\mathcal{R} \;=\; 8\pi G_N \, T^{\nu}_{\mu} + \Lambda\delta^{\nu}_{\mu}$$

Einstein's Tensor:
Geometry of Space-time

Energy-momentum Tensor:
ALL the Physics content

The birth of Cosmology as a science:
the Universe's dynamics and fate is determined
by its Energy (Particle) content,
both the known and the unknown....!

FRIEDMANN EQUATION:

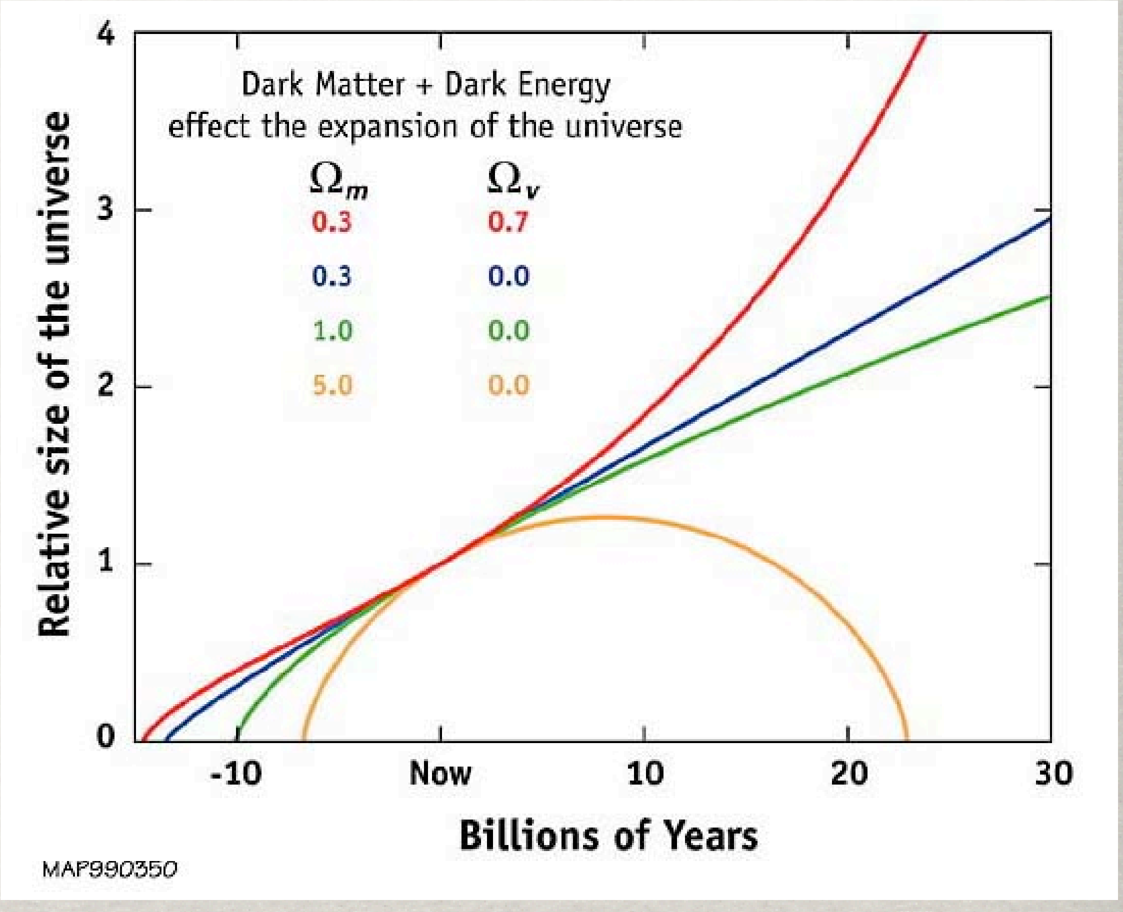
$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N}{3}\rho + \Lambda - \frac{\kappa}{a^2}$$

- The energy density & curvature decree the time evolution of the scale factor
- Key parameter is the critical density:

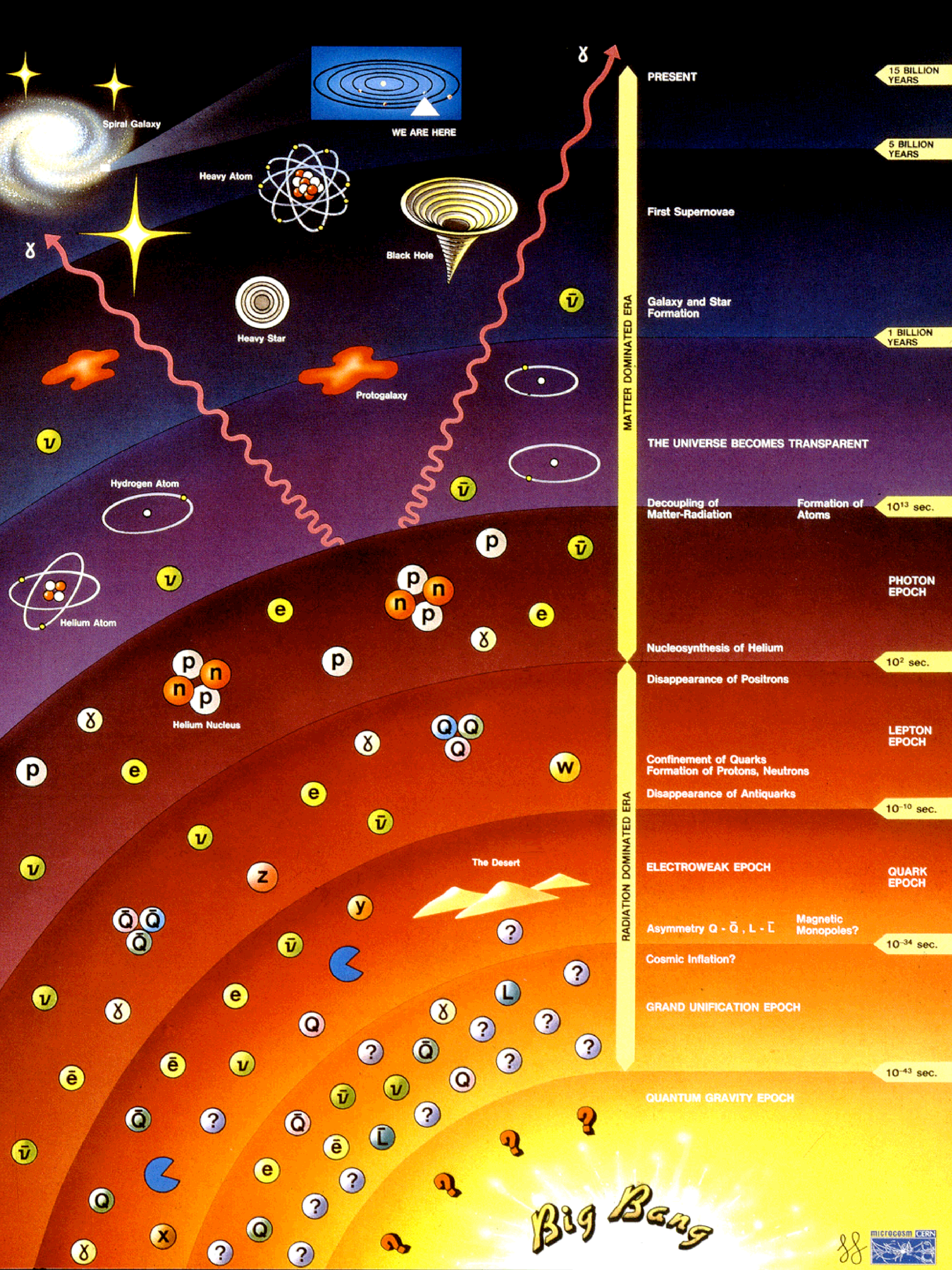
$$\rho_c = \frac{3H^2}{8\pi G_N} \qquad \Omega_i = \frac{\rho_i}{\rho_c}$$

Ω_i :density in $\sim 10^4 \mathrm{eV/cm}^3$

(~10 protons/m3)

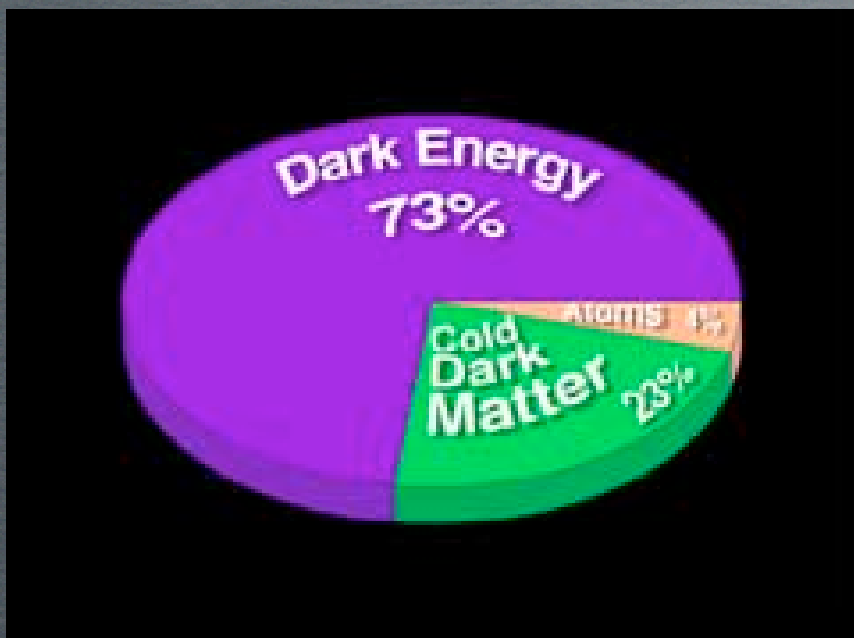


http:/www.wmap.gsfc.nasa.gov



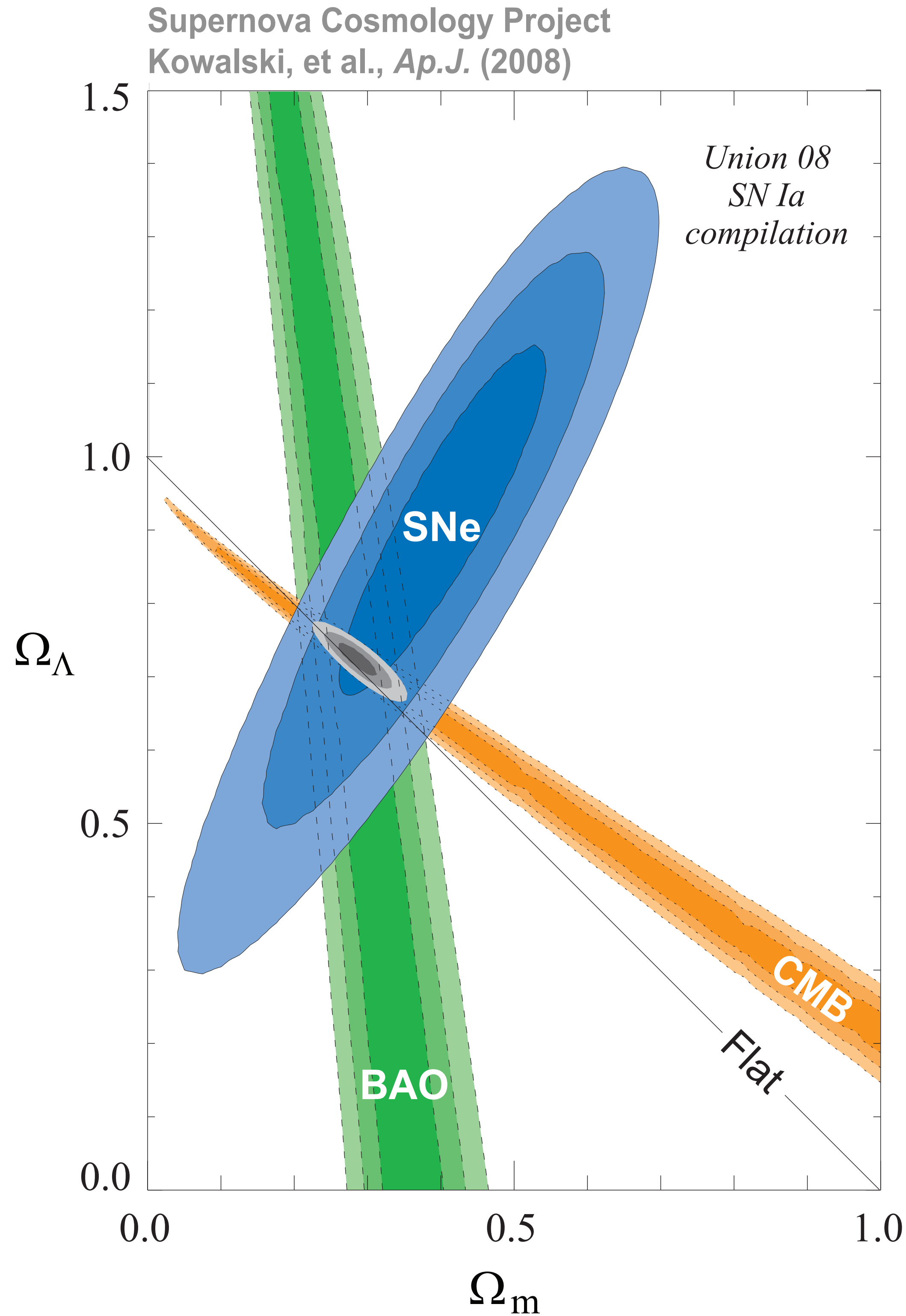
Spiral Galaxy
WE ARE HERE
Heavy Atom
Black Hole
Heavy Star
Protogalaxy
Hydrogen Atom
Helium Atom
Helium Nucleus
The Desert
MATTER DOMINATED ERA
RADIATION DOMINATED ERA
PRESENT
First Supernovae
Galaxy and Star Formation
THE UNIVERSE BECOMES TRANSPARENT
Decoupling of Matter-Radiation
Formation of Atoms
PHOTON EPOCH
Nucleosynthesis of Helium
Disappearance of Positrons
LEPTON EPOCH
Confinement of Quarks Formation of Protons, Neutrons
Disappearance of Antiquarks
ELECTROWEAK EPOCH
QUARK EPOCH
Asymmetry Q - Q̄ , L - L̄
Magnetic Monopoles?
Cosmic Inflation?
GRAND UNIFICATION EPOCH
QUANTUM GRAVITY EPOCH
15 BILLION YEARS
5 BILLION YEARS
1 BILLION YEARS
10^{13} sec.
10^{2} sec.
10^{-10} sec.
10^{-34} sec.
10^{-43} sec.
Big Bang
microcosm CERN

PRESENT ENERGY CONTENT

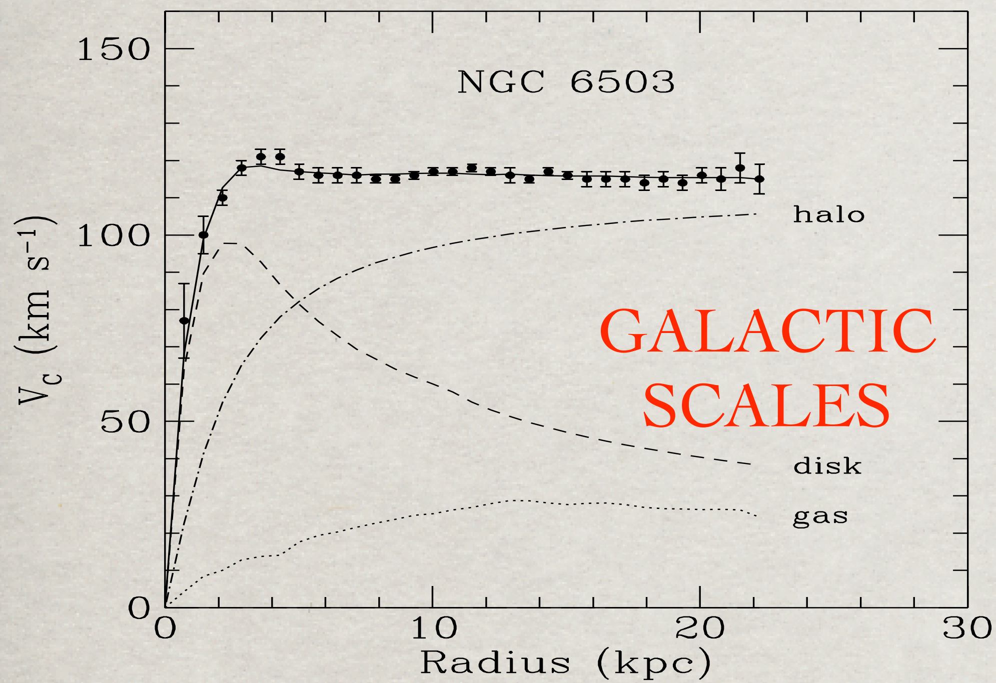


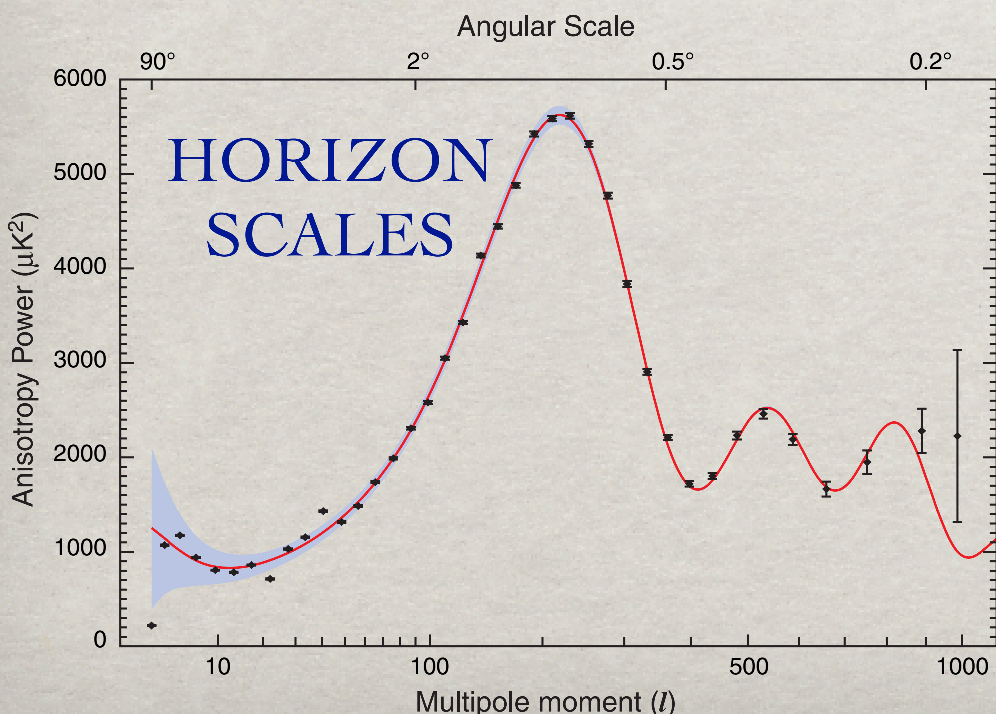
with traces of photons, neutrinos & ... ?

What are DE and DM ???



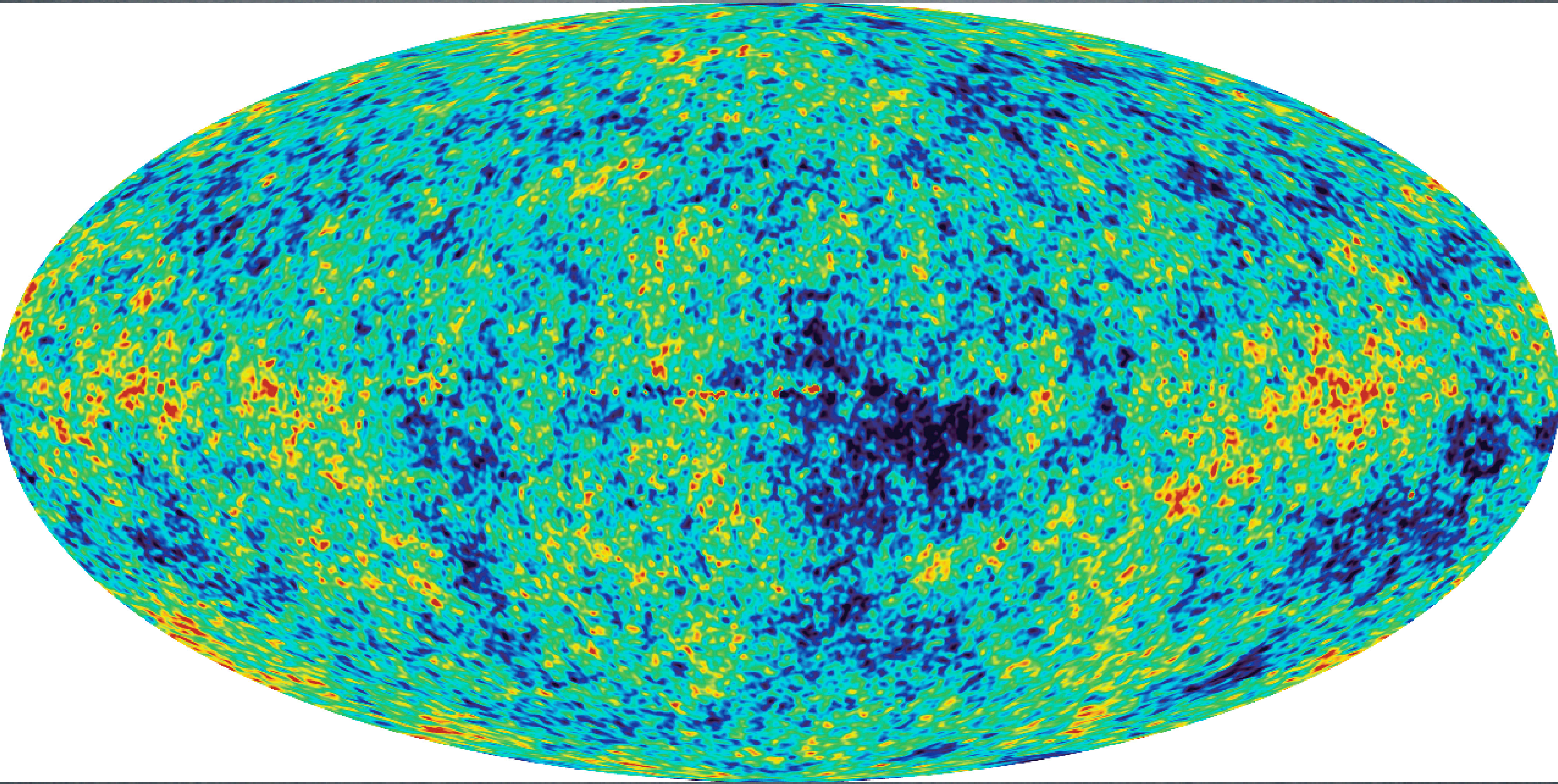
DARK MATTER EVIDENCE





Particles	Ωh^2	Type
Baryons	0.0224	Cold
Neutrinos	< 0.01	Hot
Dark Matter	0.1-0.13	Cold

The Universe is NOT perfectly homogeneous !



[WMAP 06]

Tiny ripples on the black body spectrum at level of 0.01%...

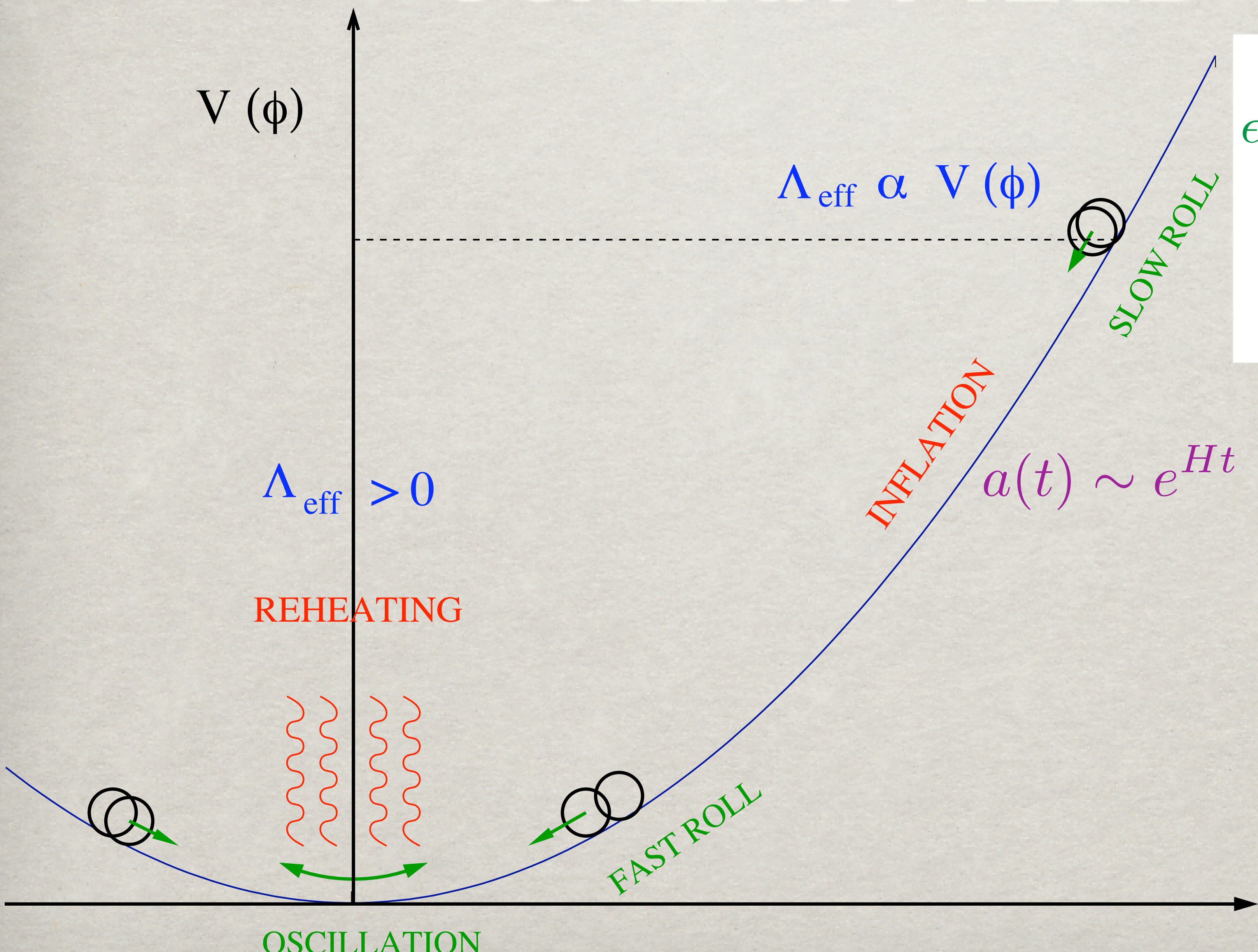
WHY IS THE UNIVERSE FLAT, HOMOGENEOUS & ISOTROPIC ?

WHAT CAUSED THE TINY RIPPLES, WHICH ARE ORIGIN OF STRUCTURE?

INFLATION

EARLY PHASE OF EXPONENTIAL EXPANSION

Inflation: driven by a scalar field ϕ



$$\epsilon = \frac{1}{2}\left(\frac{V'}{V}\right)^2 \ll 1$$

$$|\eta| = \left|\frac{V''}{V}\right| \ll 1$$

$a(t) \sim e^{Ht}$ Quasi - de Sitter

de Sitter ???

INFLATON: A QUANTUM FIELD !

Apart for the classical motion, there are fluctuations:

$$\phi = \varphi_c + \delta\varphi$$

In an inflationary (~ de Sitter) phase these are given by

$$\delta\varphi = \frac{H}{2\pi}$$

THEY REMAIN IMPRINTED IN THE METRIC AND ARE STRETCHED TO COSMOLOGICAL SCALES !!!

LOOK FOR A SIGNAL THERE !

HH Cosmo activities

The present cosmological model leaves many open questions:

- What is Dark Energy ?
  - Is it really there ? Study SN — SW
  - Cosmological constant ? Vacuum — DESY, UniHH
  - Dynamical field ? Constants ?? — SW,DESY
- What is the Dark Matter ?
  - WIMP: @TH, ID, LHC ... — DESY, UniHH
  - or not WIMP @TH, ID, LHC... — DESY, UniHH
- Where does the baryon number come from ?
  - baryogenesis via leptogenesis — DESY
  - thermal FT in the Early universe — DESY
- Weakly coupled light fields ?
  - WISPs: @TH, ALPS — DESY, SW
- How did inflation happen ? — DESY, UniHH

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WHY SUPERGRAVITY ?

- Provides a coherent framework to study different signals in high energy physics, astrophysics and cosmology.
- Theoretically attractive: supersymmetry gives gauge unification, solves hierarchy problem,etc...
- It is surely necessary to extend supersymmetry to supergravity to discuss cosmology !
- Allows extension to string theory...:
  the low energy 4D limit of some string theories is a N=1 supergravity (of the no-scale type).

What is supergravity ?

- Largest and unique extension of the Poincare` symmetry, includes general coordinate transformations and hence gravity !!!

local SUPERSYMMETRY: boson <-> fermion

Standard Model			
Matter			Forces
e	μ	τ	γ
ν_e	ν_μ	ν_τ	$W^\pm, Z$
u	c	t	g
d	s	b	G

SUSY SM				
SMatter			SForces	
$\tilde{e}$	$\tilde{\mu}$	$\tilde{\tau}$	$\tilde{\gamma}$	$\tilde{\chi}$
$\tilde{\nu}_e$	$\tilde{\nu}_\mu$	$\tilde{\nu}_\tau$	$\tilde{W}^\pm, \tilde{Z}$	
$\tilde{u}$	$\tilde{c}$	$\tilde{t}$	$\tilde{g}$	
$\tilde{d}$	$\tilde{s}$	$\tilde{b}$	$\tilde{G}$	$\psi_{3/2}$

Gravity multiplet

Part I:
de Sitter in
no-scale SUGRA

(QUASI)DE SITTER IN SUGRA

- A de Sitter or quasi-de Sitter phase is needed to account for the present cosmological constant and for inflation

- But in SUGRA the absolute minima are either anti-de Sitter or Minkowski... and do not break SUSY !

$$V = e^K (K^{i\bar{j}}(W_i + K_i W)(\bar{W}_{\bar{j}} + K_{\bar{j}}\bar{W}) - 3|W|^2)$$

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- Also inflation is difficult → η problem
  the SUGRA potential is usually steep with $V'' \sim V$
  as long as one does not resort to some tuning...
  ... SLOW ROLL inflation not easy to realise !

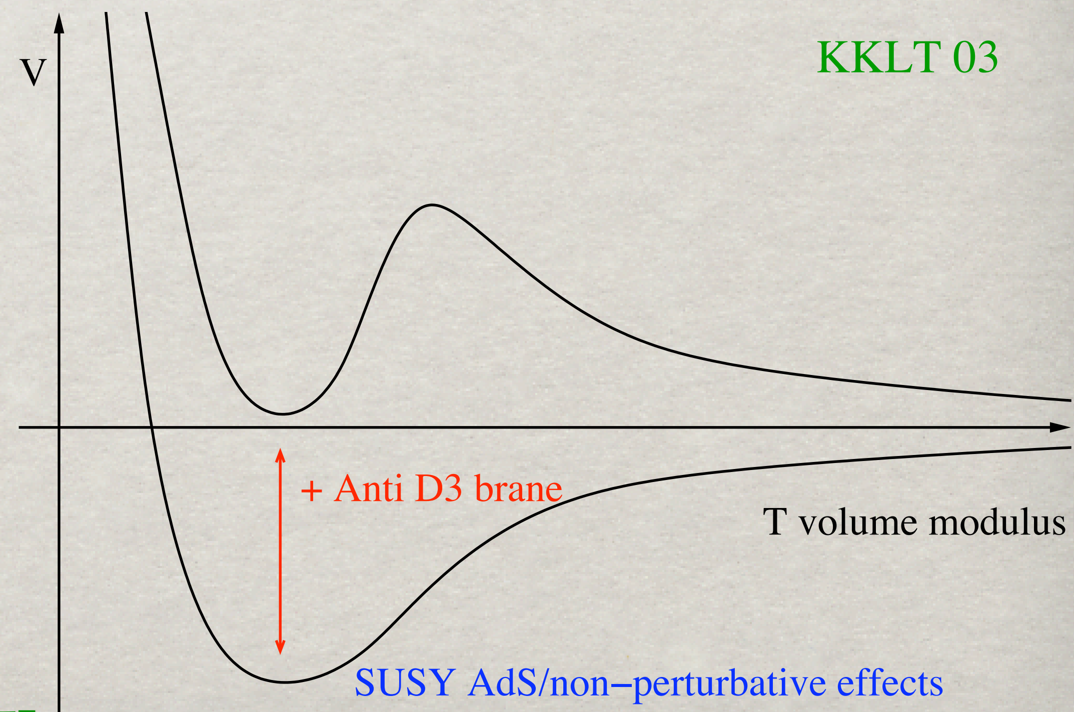
[Copeland et al 94; Guth, Randall & Thomas 94, ...]

de Sitter vacua and moduli stabilisation

- One of the historical problems of string theory is to stabilise all the moduli fields.

- Progress in the last years: possible to stabilise most moduli using flux compactifications !

- But in these models one has to rely to explicit SUSY breaking terms to stabilise all the moduli and up-lift the vacuum (e.g. KKLT...)



[Kachru, Kallosh, Linde & Trivedi 03]

No-Scale Kaehler

[Cremmer, Ferrara, Kounas & Nanoupoulos 83, ...]

- The no-scale property requires $K_i K^i = 3$ so that the cosmological constant is zero at tree level since the potential vanishes if $W_i = 0$

$$V = e^{K(\Phi,\bar{\Phi})}\left[|W_i + K_i W|^2 - 3|W|^2\right]$$
$$= e^{K(\Phi,\bar{\Phi})}\left[|W_i|^2 + 2Re[K_i W \bar{W}^i]\right]$$

- For a single field the no-scale Kaehler is simply

$$K = -3\ln[T + \bar{T}]$$

The trouble of no-scale

- The problem is the logarithmic Kaehler potential...

$$K = -3\ln(T+\bar{T}) \qquad G = K + \ln(|W|^2)$$

- For a single modulus in de Sitter one mass is always negative for any superpotential W [Brustein & de Alwis 04]
- In general Minkowski metastable vacua with broken SUSY need the holomorphic sectional curvature for the metric $K_{i\bar{j}}$ to be bounded: $R_{i\bar{j}n\bar{m}}G^i G^{\bar{j}} G^n G^{\bar{m}} < 6$

[Gomez Reino & Scrucca 04]

- This result can be generalised to de Sitter into:

$$\sigma = \frac{2}{3}(g_{i\bar{j}}G^i G^{\bar{j}})^2 - R_{i\bar{j}n\bar{m}}G^i G^{\bar{j}} G^n G^{\bar{m}} > 0$$

- $\sigma = 0$ for $G_i \propto K_i$: NO GO for a single field !

[LC, Gomez Reino, Gross, Luis, Palma & Scrucca I 08]

Scalar mass matrix

- Project the scalar mass matrix along the Goldstino direction for any V and obtain

$$\lambda = e^{-G} V_{i\bar{j}} G^i G^{\bar{j}} = -\frac{2}{3} e^{-G} V (e^{-G} V + 3) + \sigma$$

where $$\sigma = \frac{2}{3}(g_{i\bar{j}} G^i G^{\bar{j}})^2 - R_{i\bar{j}n\bar{m}} G^i G^{\bar{j}} G^n G^{\bar{m}}$$

- A necessary condition for metastability is that λ is positive, then if $V > 0$ we need $\sigma > 0$

- Note: the curvature tensor depends only on the Kaehler potential, while the Goldstino direction on the whole G, including W

Two moduli in strings

[LC, Gomez Reino, Gross, Luis, Palma & Scrucca I 08]

Heterotic Calabi-Yau

$$K = -\log(\mathcal{V})$$

$$\mathcal{V} = \frac{4}{3} d_{ijk} v^i v^j v^k$$

$$\Re(T^i) = v^i$$

Type II b orientifolds

$$K = -2\log(\mathcal{V})$$

$$\mathcal{V} = \frac{1}{48} d^{ijk} v_i v_j v_k$$

$$\Re(T^i) = \frac{1}{16} d^{ijk} v_j v_k$$

Then we have simply

$$\sigma \sim -\frac{3}{8} e^{4K} \frac{\Delta}{detg} |C|^4$$

$$\sigma \sim \frac{3}{8} e^{4K} \Delta \, detg \, |C|^4$$

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Where Δ is the discriminant of the cubic polynomial

What about inflation ?

A New η problem !

[LC, Gomez Reino, Gross, Luis, Palma & Scrucca II 08]

- In modular inflation η is constrained:

$$\eta \leq -\frac{2}{3} + \frac{\sigma}{9\gamma\,(1+\gamma)} + \mathcal{O}(\sqrt{\epsilon})$$

where $\gamma = \frac{H_I^2}{m_{3/2}^2}$ for $m_{3/2}^2 = e^G = e^K |W|^2$

- To realise slow roll inflation, i.e. $\epsilon, |\eta| \sim 0$, we need

$$\sigma \geq 6\gamma(1+\gamma)$$

For $\gamma \ll 1$ this reduces to $\sigma > 0$ as for pure de Sitter, while for $\gamma \geq 1$ it is more stringent !

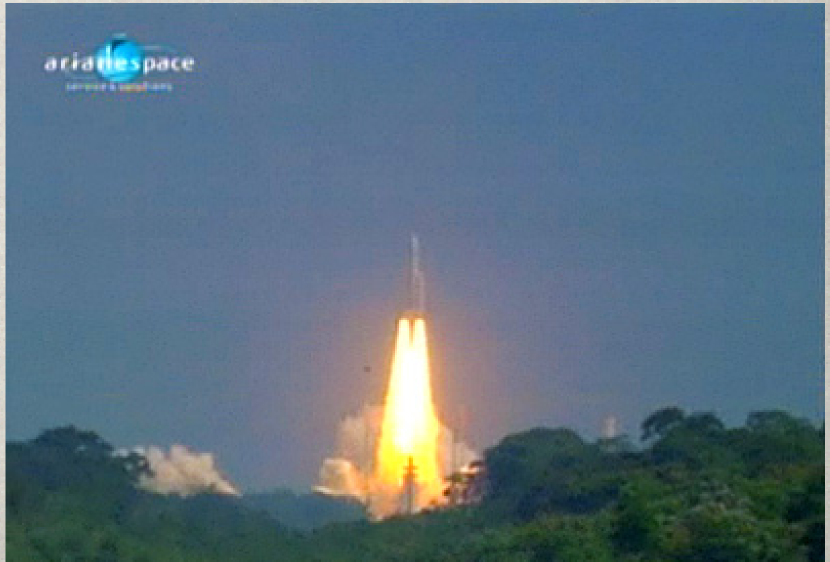
INFLATION at HIGH SCALE is more difficult !

General predictions:

- We need more than one modular field to allow for inflation: we may expect deviation from the single field predictions, i.e. isocurvature perturbations and non-gaussianities

- Low scale inflation is preferred ! Probably no detectable gravity waves for modular inflation... apart if the gravitino mass was very large during inflation.

Planck satellite was launched on the 14th May this year and will measure the CMB with better precision !



Part II: gravitino Dark Matter

GRAVITINO properties: completely fixed by SUGRA !

Gravitino mass: set by the condition of "vanishing" cosmological constant

$$m_{3/2} = \langle W e^{K/2} \rangle = \frac{\langle F_X \rangle}{M_P}$$

~~SUSY~~ scale

It is proportional to the SUSY breaking scale and varies depending on the mediation mechanism, e.g. gauge mediation can accomodate very small $\langle F_X \rangle$ giving $m_{3/2} \sim$ keV, while in anomaly mediation we can even have $m_{3/2} \sim$ TeV (but then it is not the LSP...).

Gravitino couplings: determined by masses, especially for a light gravitino since the dominant piece becomes the Goldstino spin 1/2 component: $\psi_\mu \simeq i\sqrt{\frac{2}{3}}\frac{\partial_\mu \psi}{m_{3/2}}$. Then we have:

$$-\frac{1}{4M_P}\bar{\psi}_\mu \sigma^{\nu\rho}\gamma^\mu \lambda^a F^a_{\nu\rho} - \frac{1}{\sqrt{2}M_P}\mathcal{D}_\nu \phi^* \bar{\psi}_\mu \gamma^\nu \gamma^\mu \chi_R - \frac{1}{\sqrt{2}M_P}\mathcal{D}_\nu \phi \bar{\chi}_L \gamma^\mu \gamma^\nu \psi_\mu + h.c.$$

$$\Rightarrow \quad \frac{-m_\lambda}{4\sqrt{6}M_P m_{3/2}}\bar{\psi}\sigma^{\nu\rho}\gamma^\mu \partial_\mu \lambda^a F^a_{\nu\rho} + \frac{i(m_\phi^2 - m_\chi^2)}{\sqrt{3}M_P m_{3/2}}\bar{\psi}\chi_R \phi^* + h.c.$$

Couplings proportional to SUSY breaking masses and inversely proportional to $m_{3/2}$.

SUSY breaking mechanism determines which particle is the LSP and the gravitino couplings !

The gravitino gives us direct information on SUSY breaking

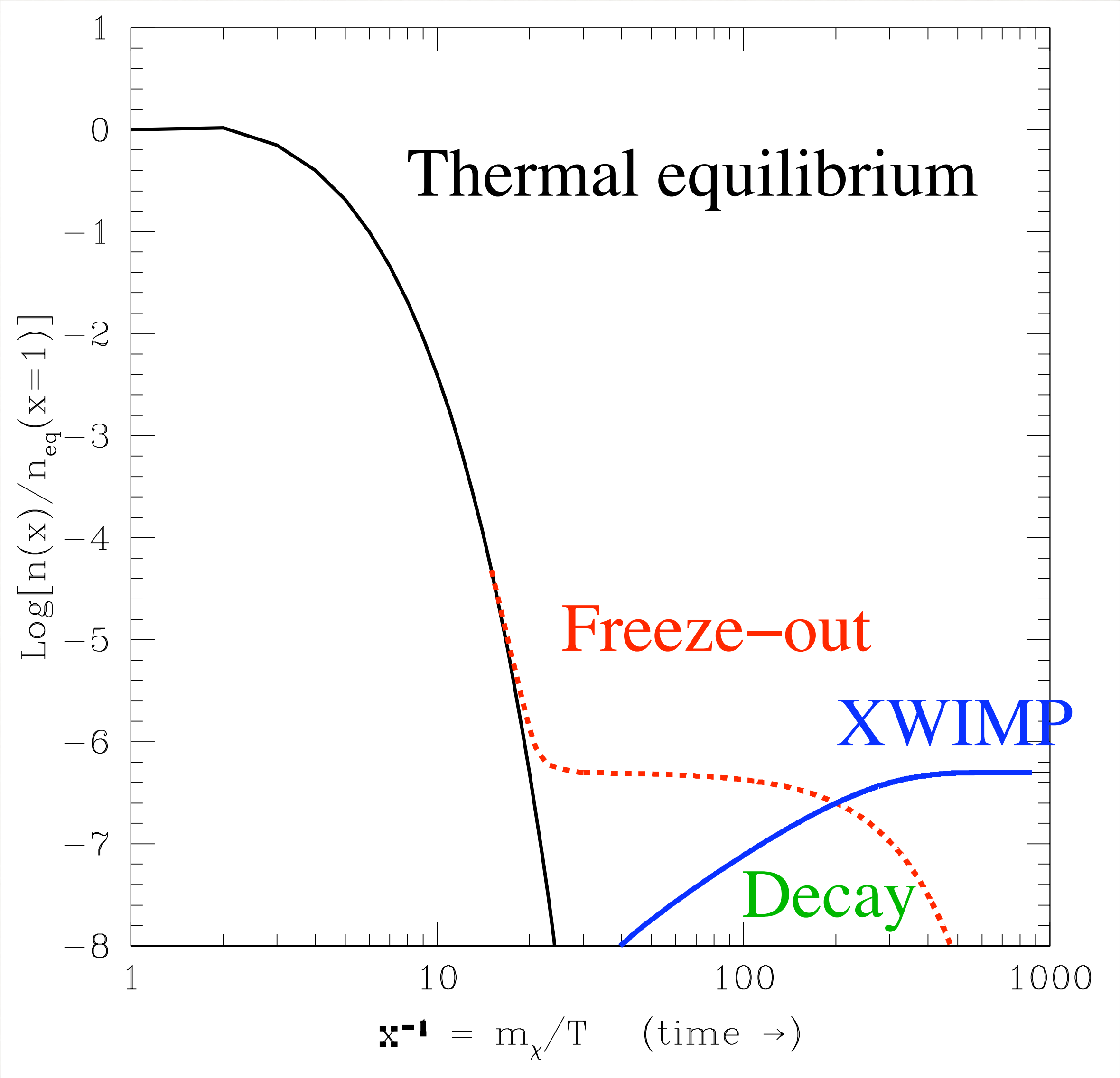
NLSP DECAY

[JE Kim, Masiero, Nanopoulos '84]
[LC, JE Kim, Roszkowski '99], [Feng et al '04]

- If R-parity is conserved and for GeV gravitino masses, the NLSP decays after freeze-out

$$\Omega_X^{NT} = \frac{m_X}{m_{NLSP}} \Omega_{NLSP}$$

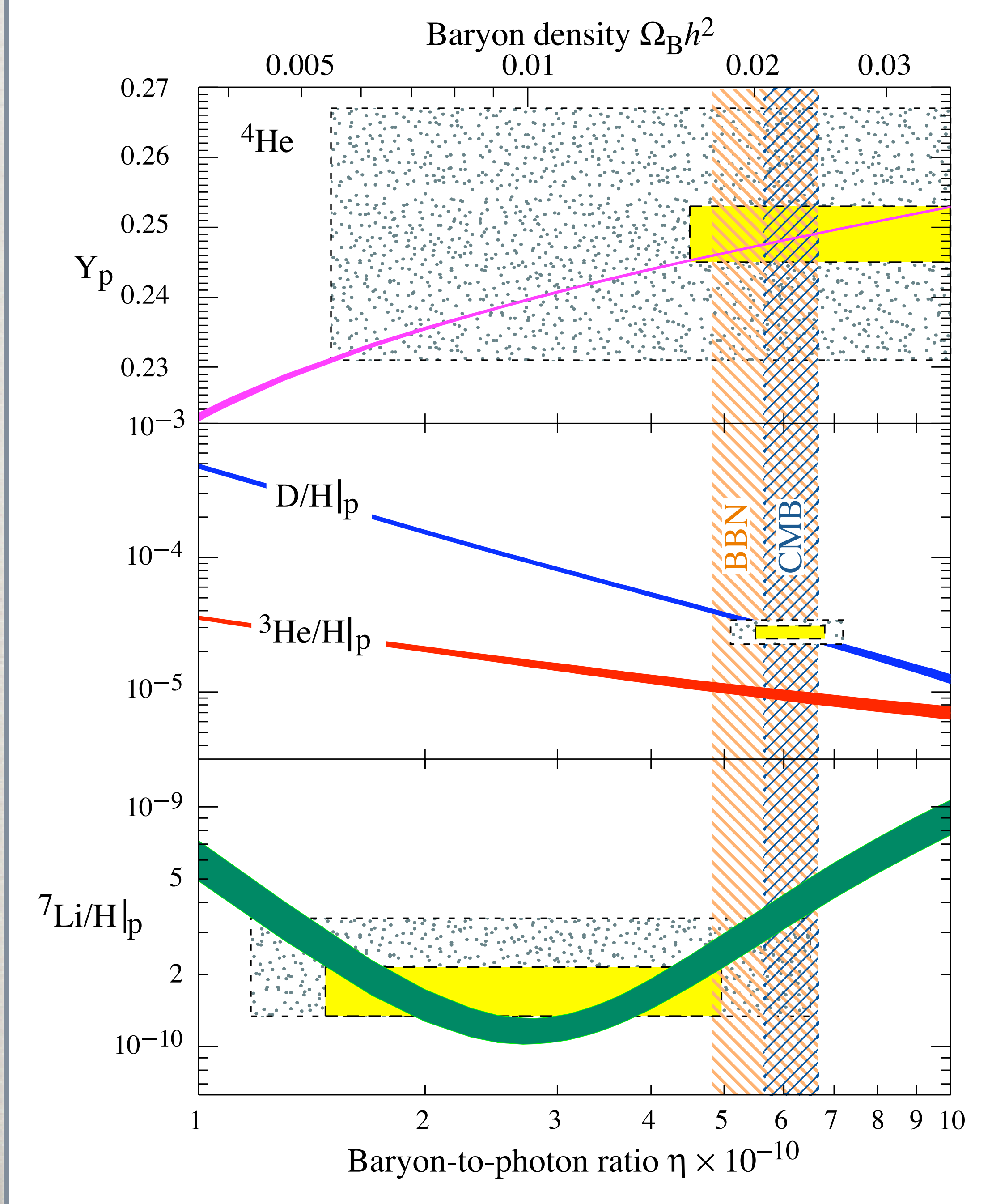
- The LSP is not thermal
- Other energetic particles are produced in the decay: beware of BBN...



Big Bang Nucleosynthesis

[Fields & Sarkar PDG 07]

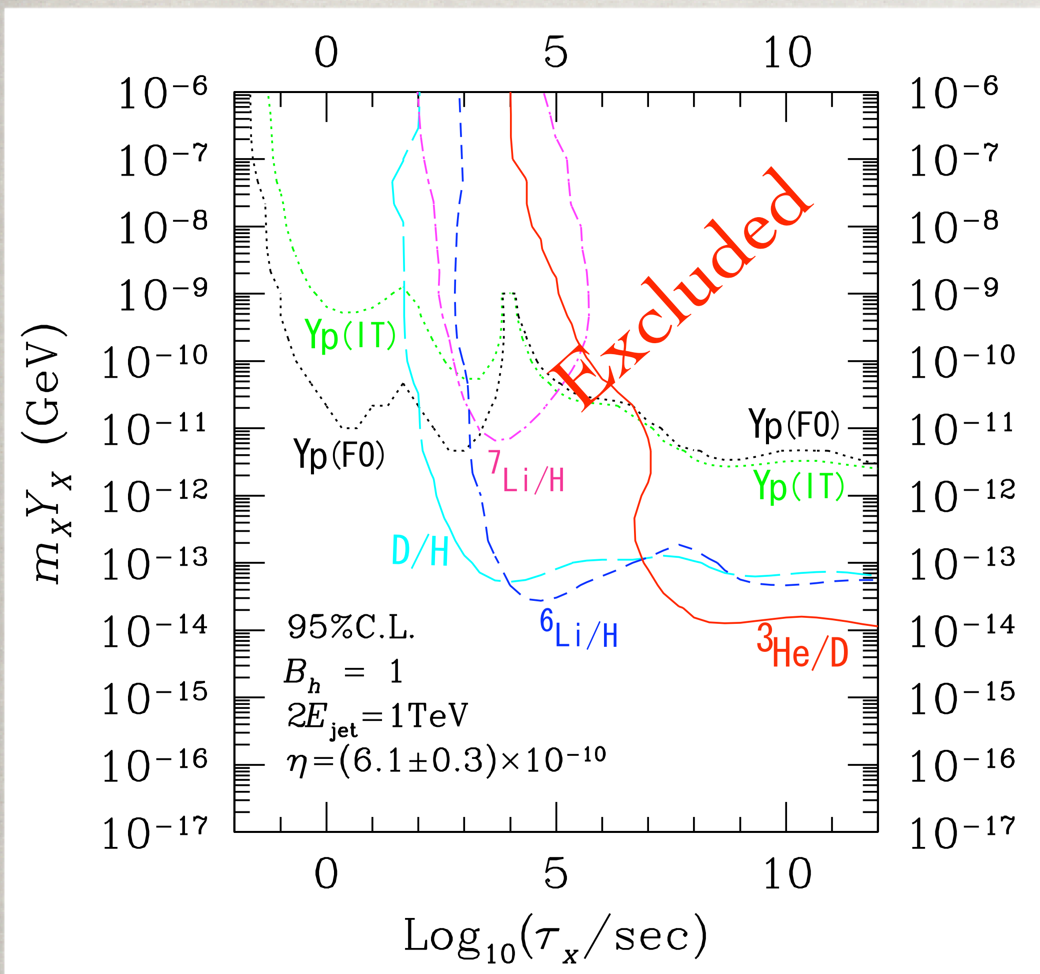
- Light elements abundances obtained as a function of a single parameter $\Omega_B h^2$
- Perfect agreement with WMAP determination
- Some trouble with Lithium 6/7



BBN bounds on NLSP decay

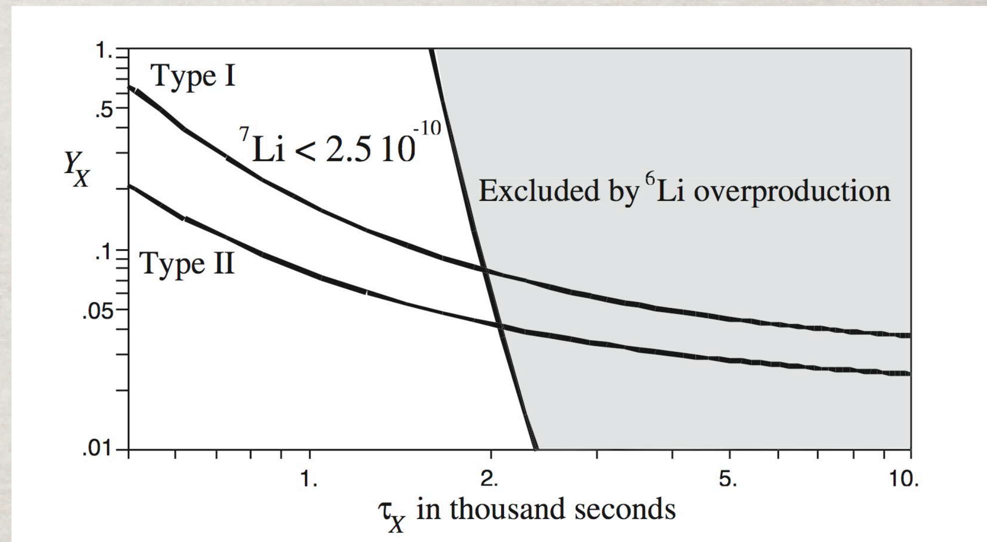
Neutral relics

[...,Kohri, Kawasaki & Moroi 04]



Charged relics

[Pospelov 05, Kohri & Takayama 06, Cyburt at al 06, Jedamzik 07,...]

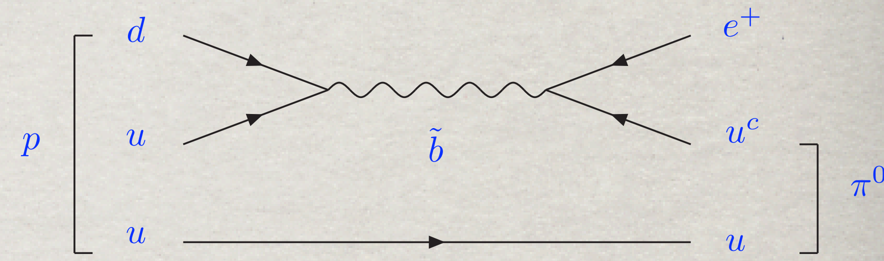


Need short lifetime & low abundance for NLSP

Big problem for gravitino LSP with 10-100 GeV mass...

R-parity or not R-parity ?

R-parity is imposed by hand in the MSSM in order to avoid fast proton decay due to renormalizable couplings explicitly violating B and L:



$$W = \lambda L L E^c + \lambda' L Q D^c + \lambda'' U^c D^c D^c + \mu_i L_i H_2$$

$\Rightarrow$ Dimension 4 proton decay operators $\propto \frac{\lambda' \lambda''}{m_{\tilde{q}}^2}$

R-parity = $(-1)^{3B+L+2s}$ forbids these terms $\Rightarrow$ No dimension 4 proton decay (and LSP is stable)!

Proton decay can be avoided also if only B violating couplings λ'' are forbidden. So do we really need R-parity to have gravitino DM ? NO: the decay rate of the gravitino is doubly suppressed by M_P and the R-parity breaking couplings:

$$\tau_{3/2} \simeq 10^{26} s \left(\frac{\lambda^{(\prime)}}{10^{-7}} \right)^2 \left(\frac{m_{3/2}}{10\text{GeV}} \right)^{-3}$$

It is sufficient to have $\lambda, \lambda' < 10^{-7}$ for the gravitinos to live long enough. Such small value also gives sufficient suppression to L violating wash out processes and allows for leptogenesis. On the other hand, requiring the NLSP to decay before BBN just gives $\lambda, \lambda' > 10^{-14}$.

ANY NLSP is allowed if R-parity is broken and still we can have supersymmetric DM !

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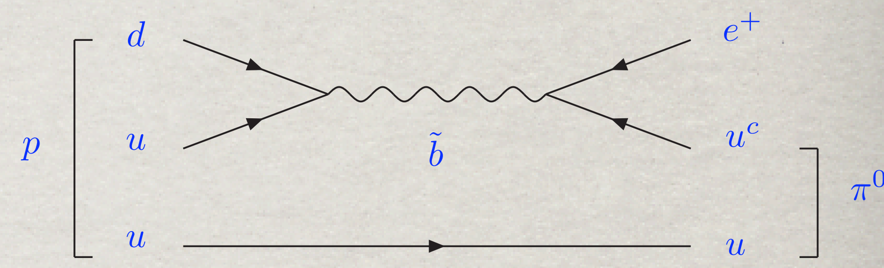

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$$\tau_{3/2} \simeq 10^{26} s \left(\frac{\lambda^{(')}}{10^{-7}} \right)^2 \left(\frac{m_{3/2}}{10\text{GeV}} \right)^{-3} \gg H_0^{-1} \sim 10^{17}\text{s}$$

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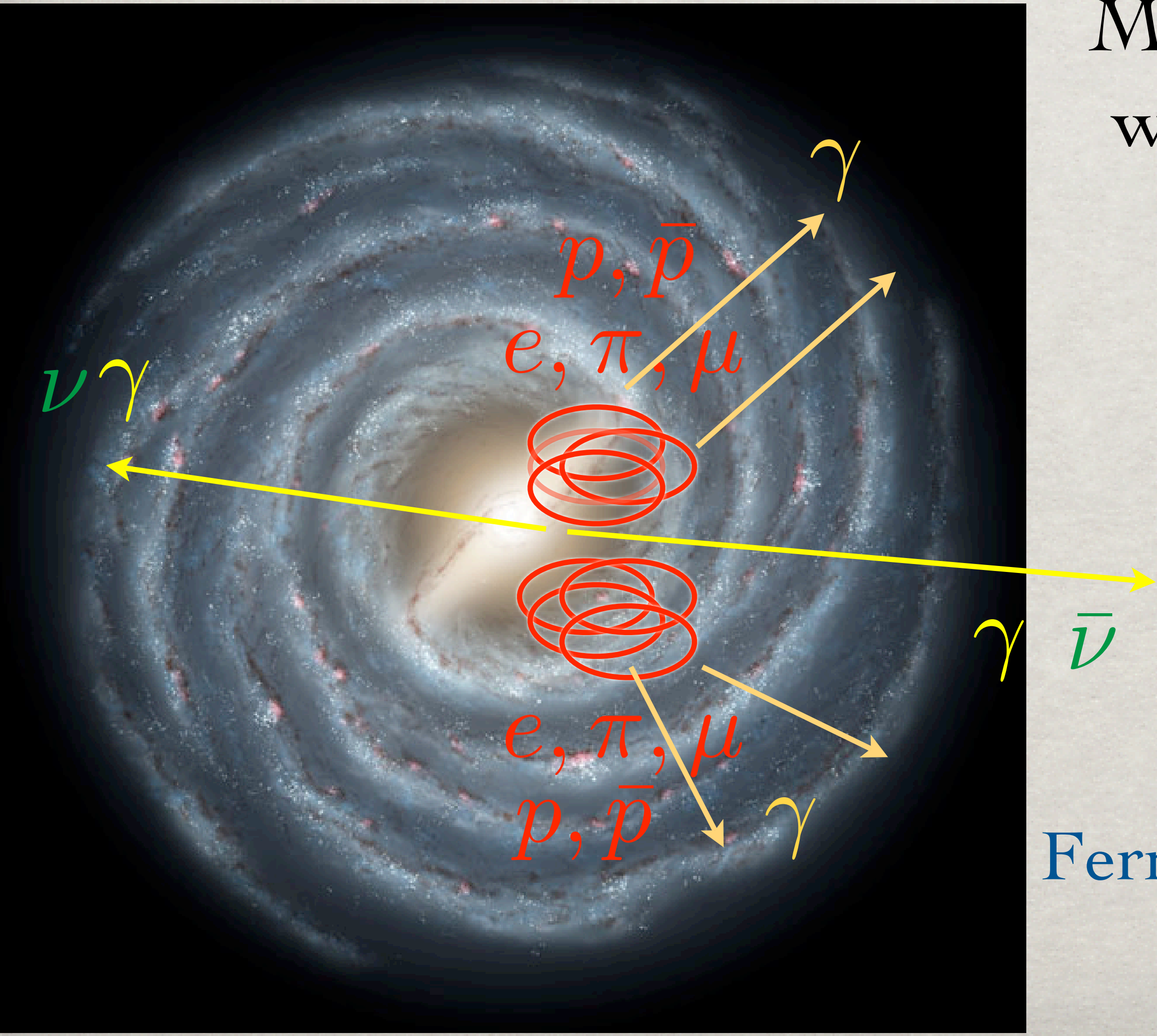
ANY NLSP is allowed if R-parity is broken and still we can have supersymmetric DM !

DECAYING GRAVITINO CDM

THE HOPE: DETECT DM !

- Look for gravitino decay signal from the Milky Way, other galaxies, clumps of DM, etc...



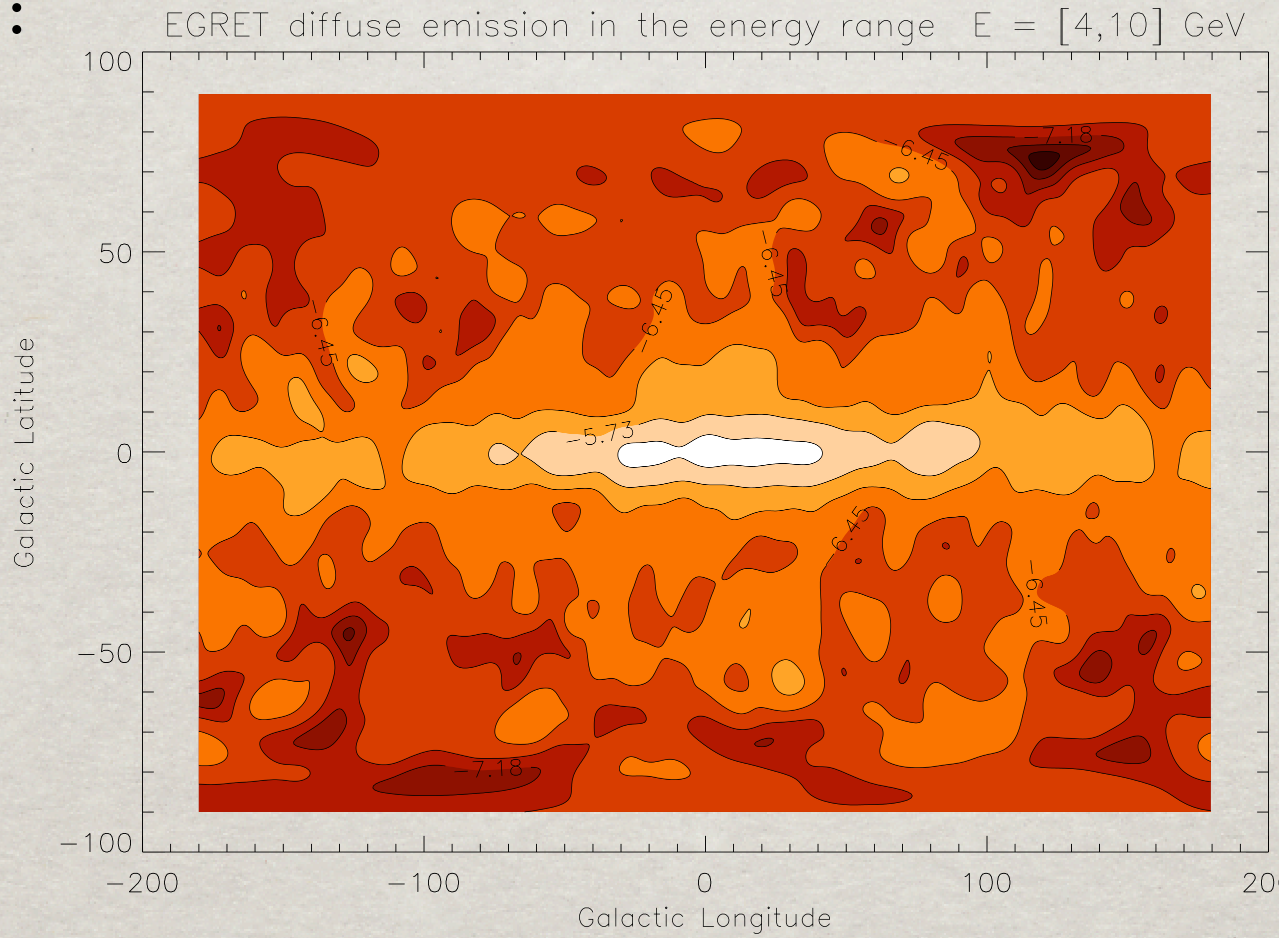
Measure the decay products with balloons or satellites !

Fermi Gamma-Ray Space Telescope

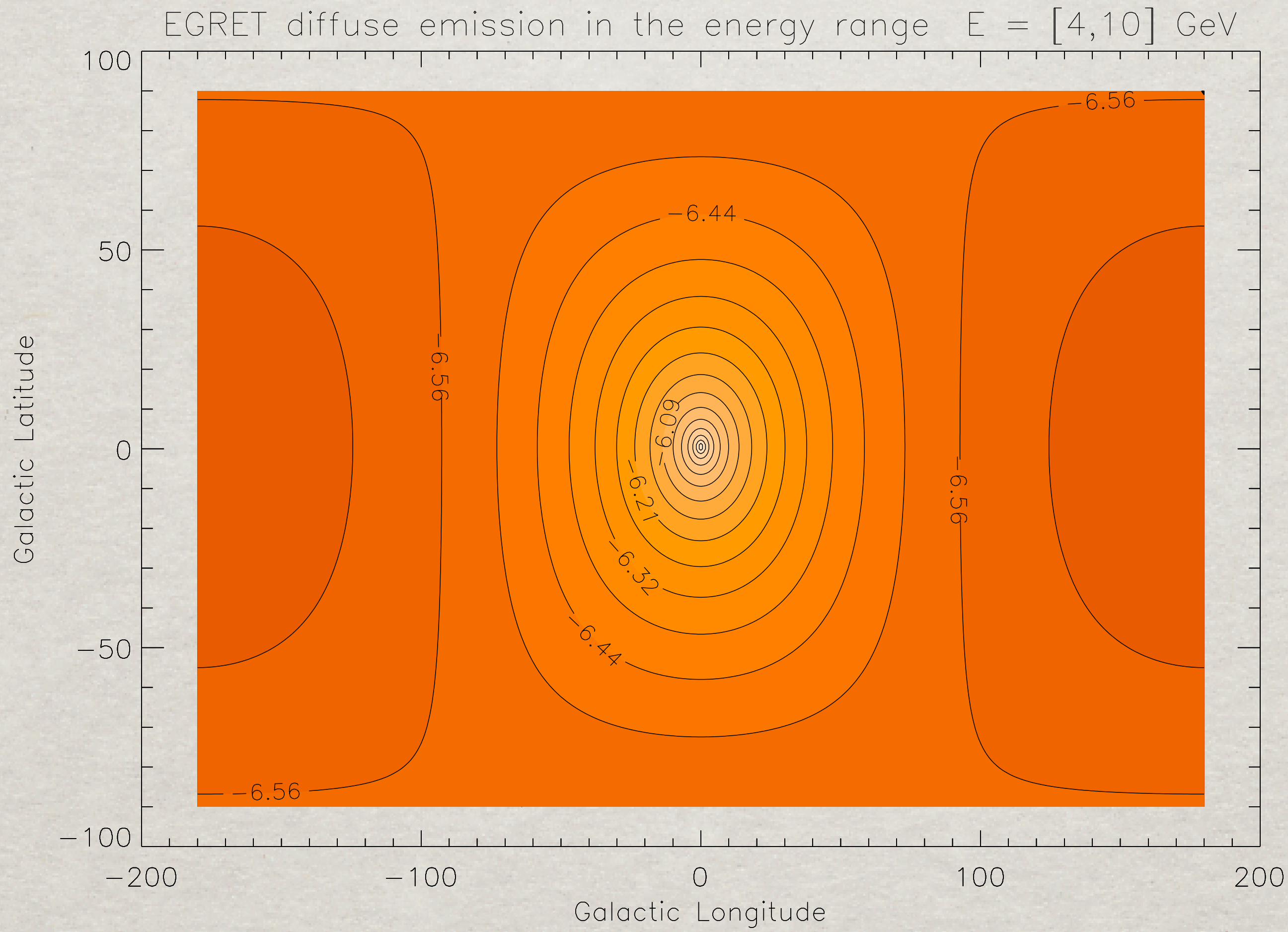
PAMELA

The Milky Way signal in gamma-ray

EGRET:



The Milky Way signal in gamma-ray



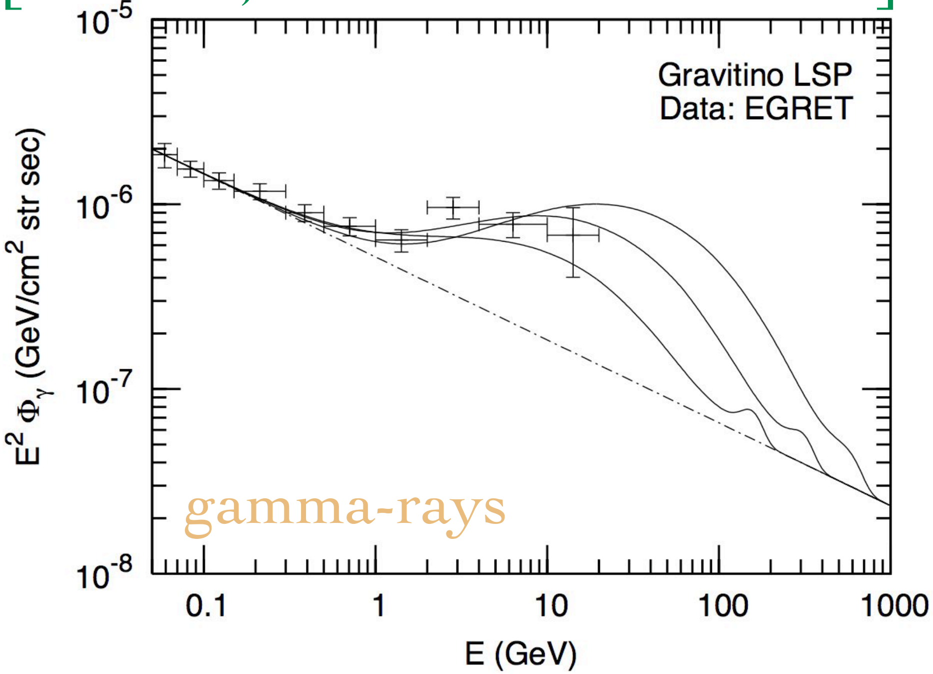
[Bertone, Buchmuller, LC & Ibarra 07]

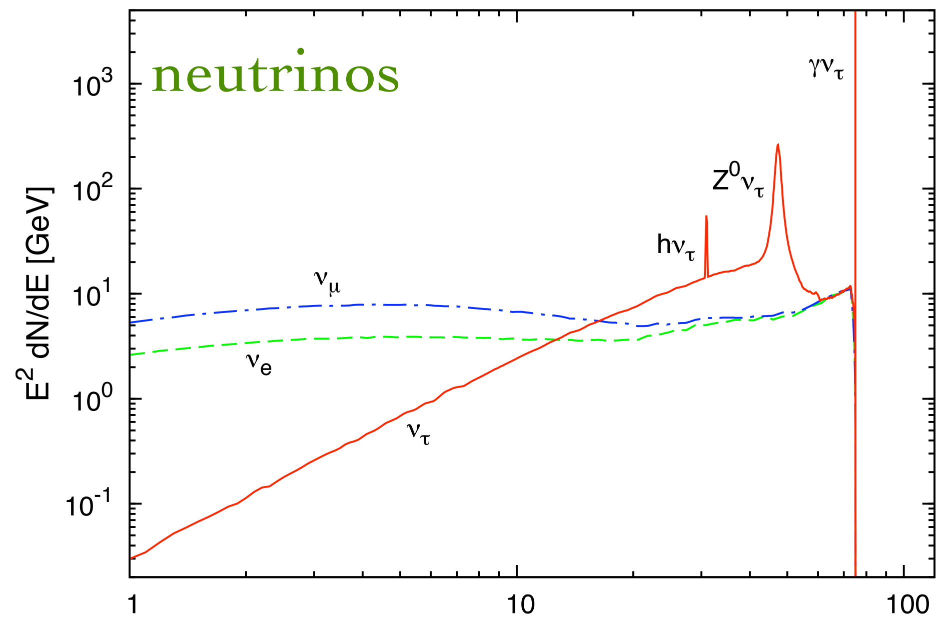
Hopefully the FERMI telescope will be able to see it !

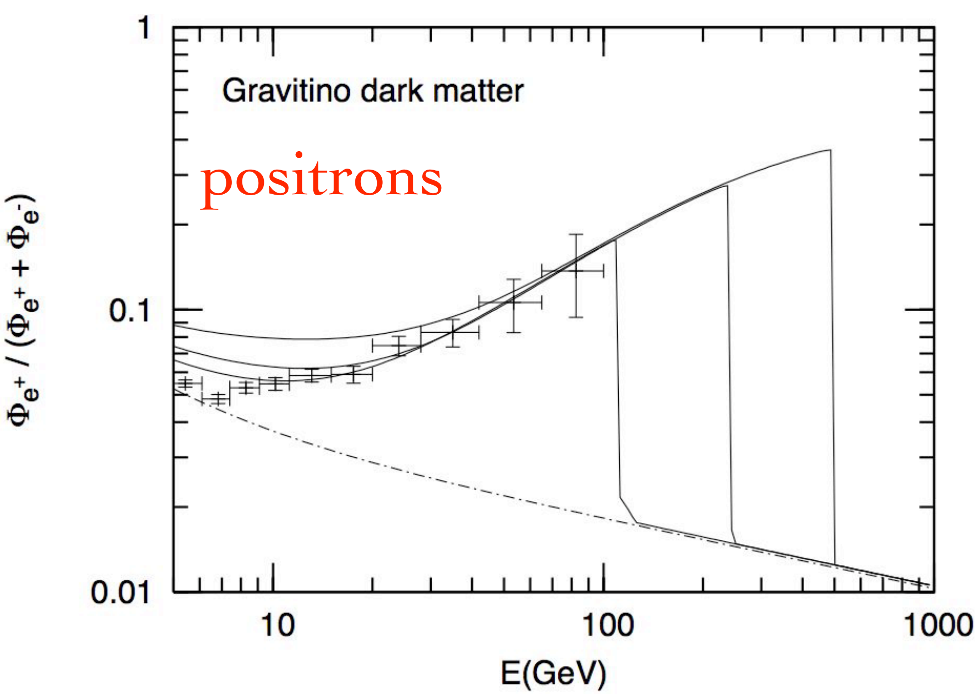
GRAVITINO DM WITHOUT R_P

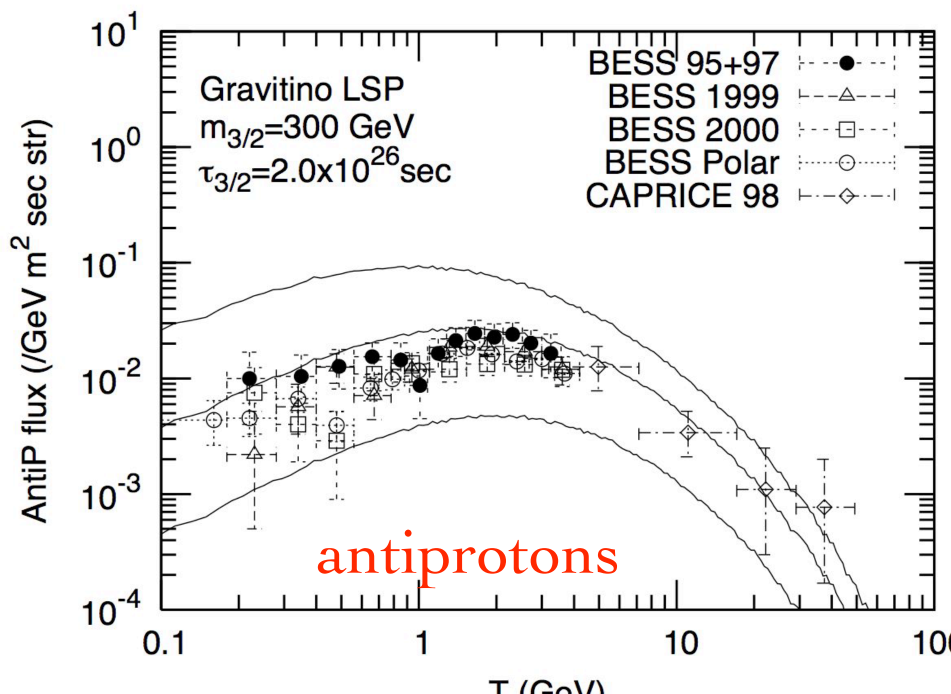
[Ishiwata, Matsumoto & Moroi 09]

[LC, Grefe, Ibarra & Tran 08]



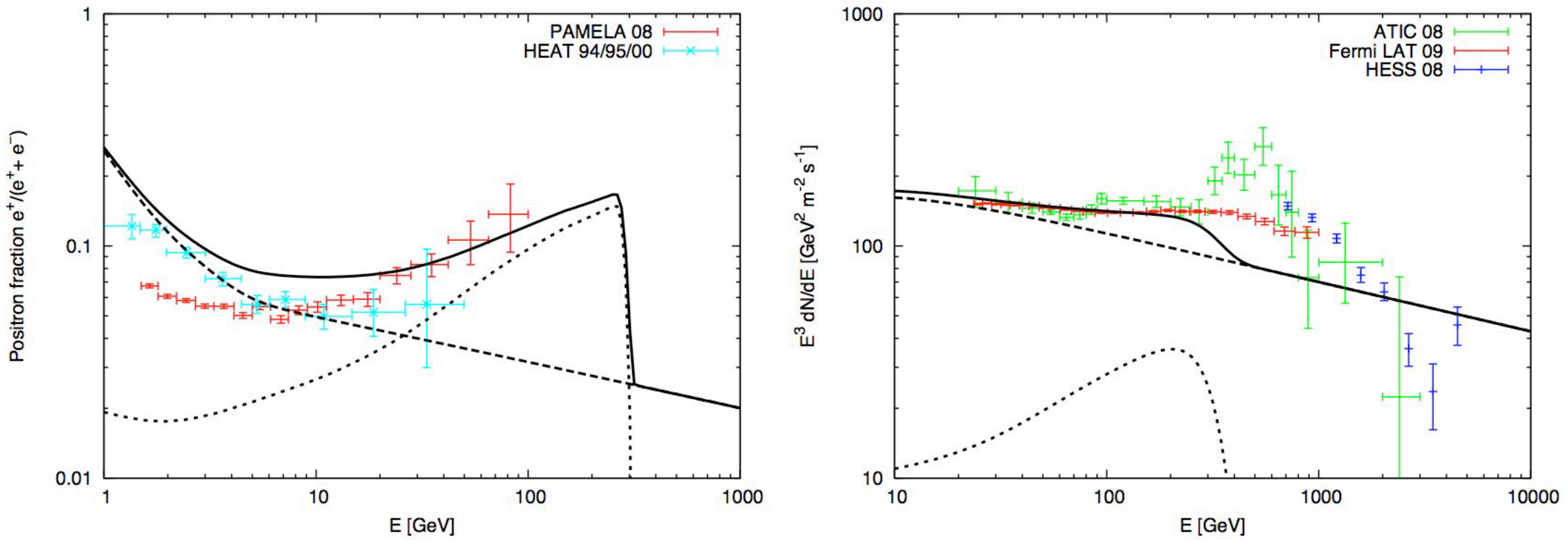






Decaying Gravitino vs ID

[Buchmueller, Ibarra, Shindou, Takayama & Tran 09]



Difficult to explain both spectra purely by gravitino decay with bilinear R-parity violation (also without overproducing antiprotons) for reasonable gravitino masses < 600 GeV...

Still gravitino could be part of the signal !

Different signals @ LHC depending on the NLSP...

- NLSP decaying within the detector... Need

$$\tau_{NLSP} \leq 10^{-7} \text{ s} \quad \Rightarrow \quad m_{3/2} \leq 10 \text{ keV}$$

or R-parity breaking at the level larger than 10^{-7}

- Charged meta-stable NLSP: $\tilde{\tau}_R$

- Colored meta-stable NLSP: $\tilde{t}_R$

- Neutral meta-stable NLSP: χ_1^0 vs $\tilde{\nu}_L$

Outlook

Outlook

The next decade will bring us some answers:

- Cosmic Microwave Background & Large Scale Structure measurements will be able to tell us more about dark matter, dark energy and inflation...

- The LHC & DM experiments & astrophysical observations could soon find out if the world is supersymmetric and if gravitinos are Dark Matter.

- Perhaps we will know soon one key parameter: the gravitino mass ! Give a unique access to SUSY breaking and improve model building.

Exciting time ahead of us for LEXI and beyond...