LC10, LNF. Dec. 1 - 3 , 2010

DARK MATTER, DARK ENERGY and the TEV NEW PHYSICS

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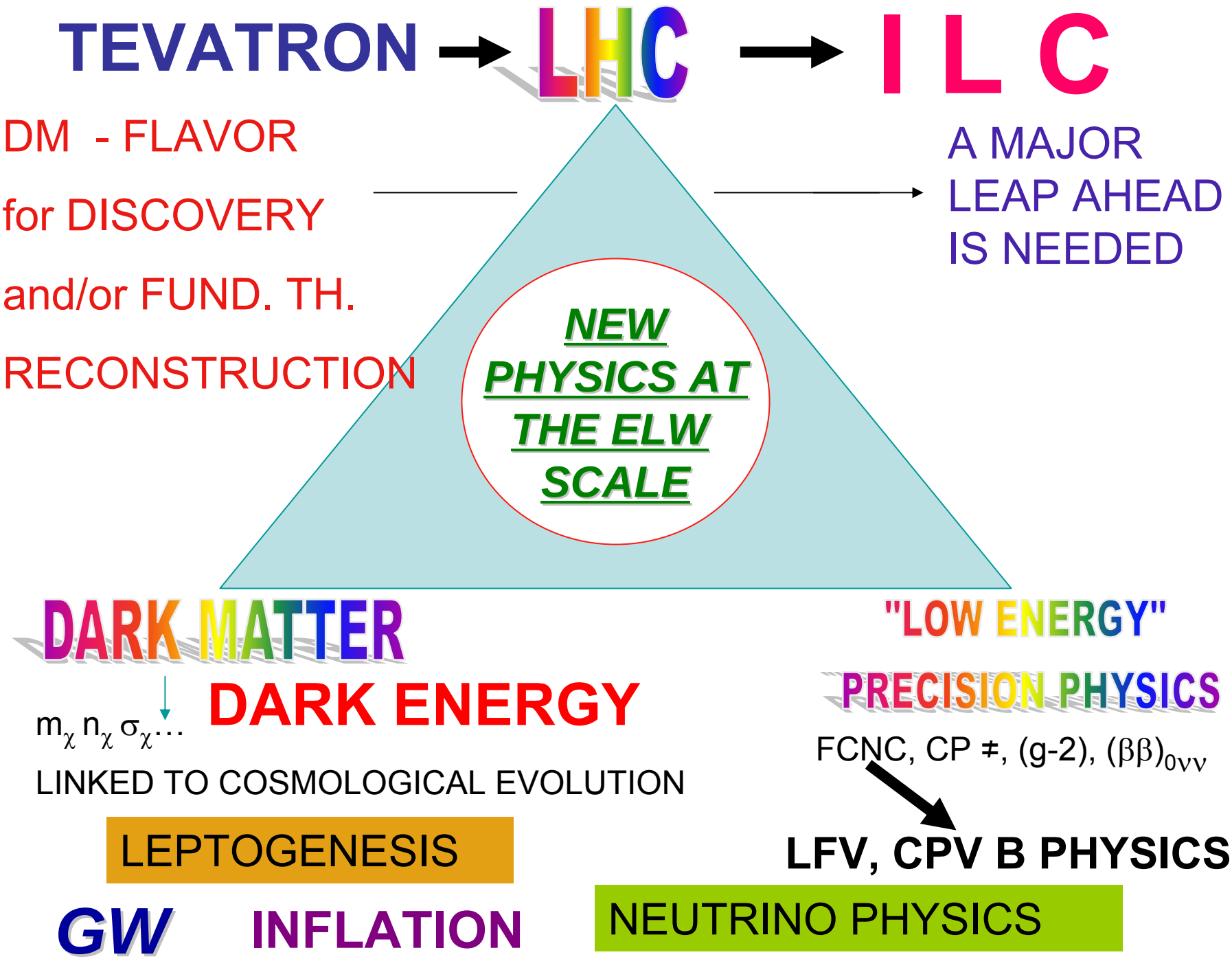

TEVATRON → LHC → I L C
DM - FLAVOR
for DISCOVERY
and/or FUND. TH.
RECONSTRUCTION
A MAJOR
LEAP AHEAD
IS NEEDED
NEW
PHYSICS AT
THE ELW
SCALE
DARK MATTER
DARK ENERGY
m_χ n_χ σ_χ…
LINKED TO COSMOLOGICAL EVOLUTION
"LOW ENERGY"
PRECISION PHYSICS
FCNC, CP ≠, (g-2), $(\beta\beta)_{0\nu\nu}$
LFV, CPV B PHYSICS
LEPTOGENESIS
NEUTRINO PHYSICS
GW
INFLATION

MICRO
PARTICLE PHYSICS

GWS STANDARD MODEL

MACRO
COSMOLOGY

HOT BIG BANG STANDARD MODEL

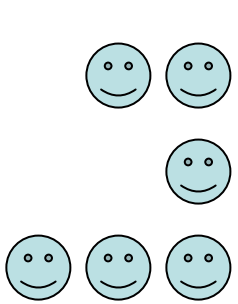
HAPPY MARRIAGE

Ex: **NUCLEOSYNTHESIS**

NUCLEAR ASTROPHYSICS

BUT ALSO

POINTS OF FRICTION



NEW SOURCE OF CP VIOLATION

- COSMIC MATTER-ANTIMATTER ASYMMETRY

- INFLATION ***NEW SCALAR POTENTIAL***

- DARK MATTER + DARK ENERGY

NEW PARTICLES AND INTERACTIONS

"OBSERVATIONAL" EVIDENCE FOR NEW PHYSICS BEYOND THE (PARTICLE PHYSICS) STANDARD MODEL

SOMETHING is needed at the TeV scale to enforce the unitarity of the electroweak theory

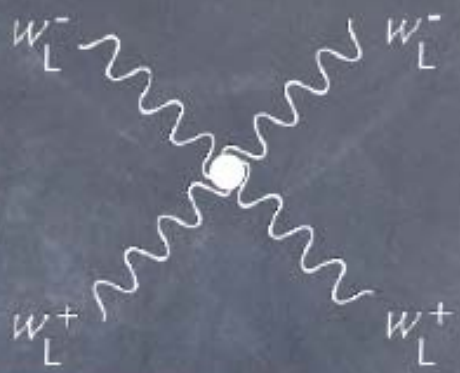
What is the mechanism of EWSB?

susy, LH... models assume that we already know the answer to

What is unitarizing the WW scattering amplitudes?

W_L & Z_L part of EWSB sector ⊃ W scattering is a probe of Higgs sector interactions

$$\epsilon_l = \left(\frac{|\vec{k}|}{M}, \frac{E}{M} \frac{\vec{k}}{|\vec{k}|} \right)$$



$$\mathcal{A} = g^2 \left(\frac{E}{M_W} \right)^2$$

loss of perturbative unitarity around 1.2 TeV

Weakly coupled models

prototype: Susy

susy partners ~ 100 GeV

Different signatures at the LHC!

Strongly coupled models

prototype: Technicolor

rho meson ~ 1 TeV

Grojean

Is it possible that there is "only" a light higgs boson and no NP?

- **This is acceptable if one argues that no ultraviolet completion of the SM is needed at the TeV scale** simply because there is **no actual fine-tuning related to the higgs mass stabilization** (**the correct value of the higgs mass is "environmentally" selected**). This explanation is similar to the one adopted for the cosmological constant

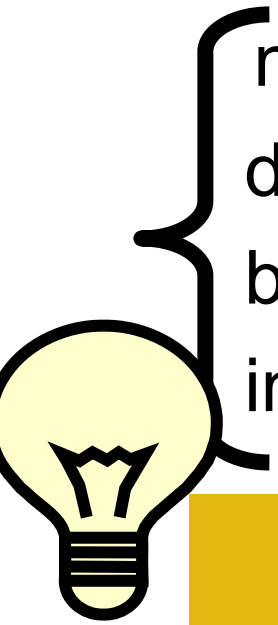
- Barring such wayout, **one is lead to have TeV NP to ensure the unitarity of the elw. theory at the TeV scale**

GENERAL FEATURES OF NEW PHYSICS AT THE ELW. SCALE

- Some amount of **fine-tuning** (typically at the % level) is required to pass unscathed the elw. precision tests, the higgs mass bound and the direct search for new particles at accelerators.
- The **higgs is typically rather light** (<200 GeV) apart from the extreme case of the “Higgsless proposal”
- All models provide **signatures which are (more or less) accessible to LHC physics** (including the higgsless case where new KK states are needed to provide the unitarity of the theory)

COULD (AT LEAST SOME OF) THE "OBSERVATIONAL" NEW PHYSICS BE LINKED TO THE ULTRAVIOLET COMPLETION OF THE SM AT THE ELW. SCALE ?

The Energy Scale from the "Observational" New Physics



neutrino masses

dark matter

baryogenesis

inflation

NO NEED FOR THE NP SCALE TO BE CLOSE TO THE ELW. SCALE

The Energy Scale from the "Theoretical" New Physics

★ ★ ★ **Stabilization of the electroweak symmetry breaking at M_W calls for an ULTRAVIOLET COMPLETION of the SM already at the TeV scale**

+

★ **CORRECT GRAND UNIFICATION "CALLS" FOR NEW PARTICLES AT THE ELW. SCALE**

DM: the most impressive evidence at the "quantitative" and "qualitative" levels of New Physics beyond SM

- QUANTITATIVE: Taking into account the latest WMAP data which in combination with LSS data provide stringent bounds on Ω_{DM} and Ω_B → **EVIDENCE FOR NON-BARYONIC DM AT MORE THAN 10 STANDARD DEVIATIONS!! THE SM DOES NOT PROVIDE ANY CANDIDATE FOR SUCH NON-BARYONIC DM**

- QUALITATIVE: it is NOT enough to provide a mass to neutrinos to obtain a valid DM candidate; LSS formation requires DM to be COLD → **NEW PARTICLES NOT INCLUDED IN THE SPECTRUM OF THE FUNDAMENTAL BUILDING BLOCKS OF THE SM !**

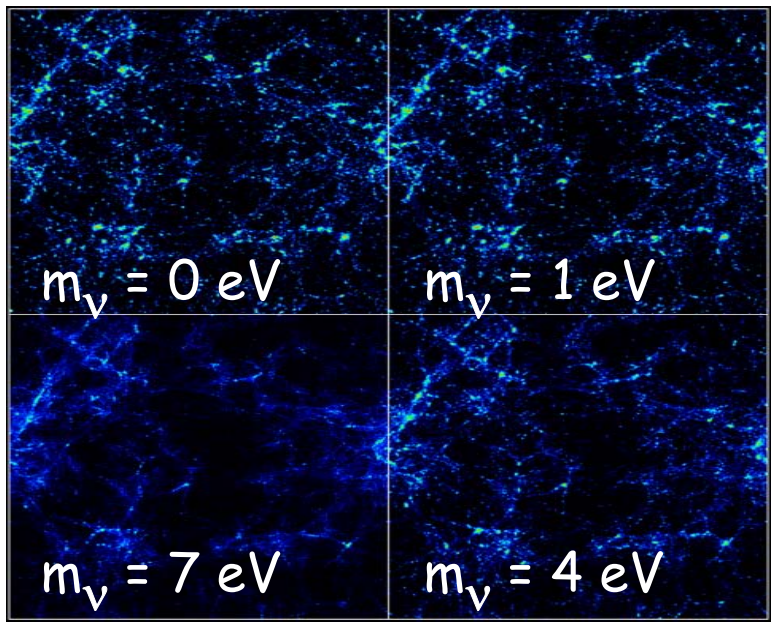
THE RISE AND FALL OF NEUTRINOS AS DARK MATTER

- Massive neutrinos: only candidates in the SM to account for DM. From here the “prejudice” of neutrinos of a few eV to correctly account for DM

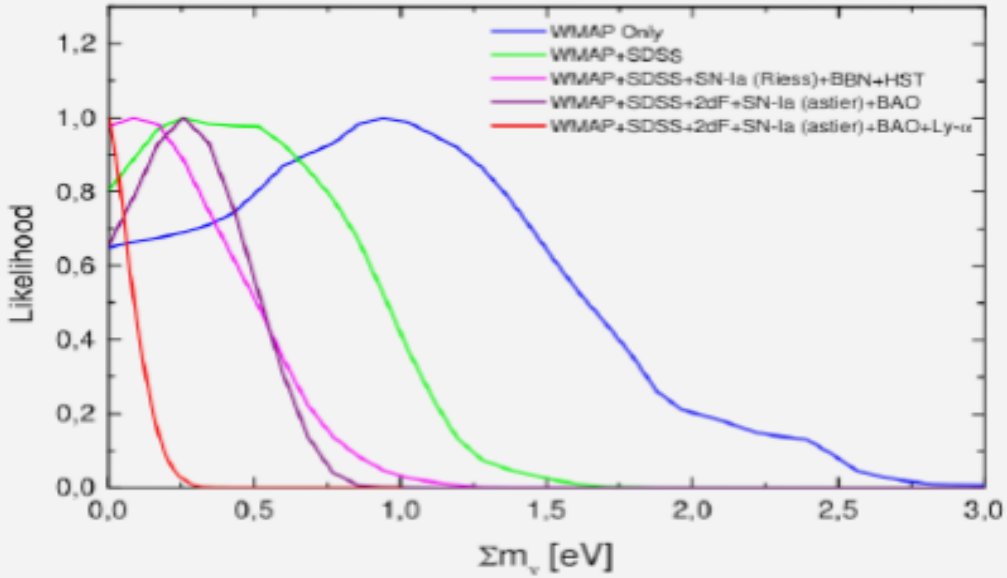
- Neutrinos decouple at ~1 MeV ; being their mass<<decoupling temperature, neutrinos remain relativistic for a long time. Being very fast, they smooth out any possible growth of density fluctuation forbidding the formation of proto-structures.

- The “weight” of neutrinos in the DM budget is severely limited by the observations disfavoring scenarios where first superlarge structures arise and then galaxies originate from their fragmentation

LSS PATTERN AND NEUTRINO MASSES



(E..g., Ma 1996)



Cosmological Bounds on the sum of the masses of the 3 neutrinos from increasingly rich samples of data sets

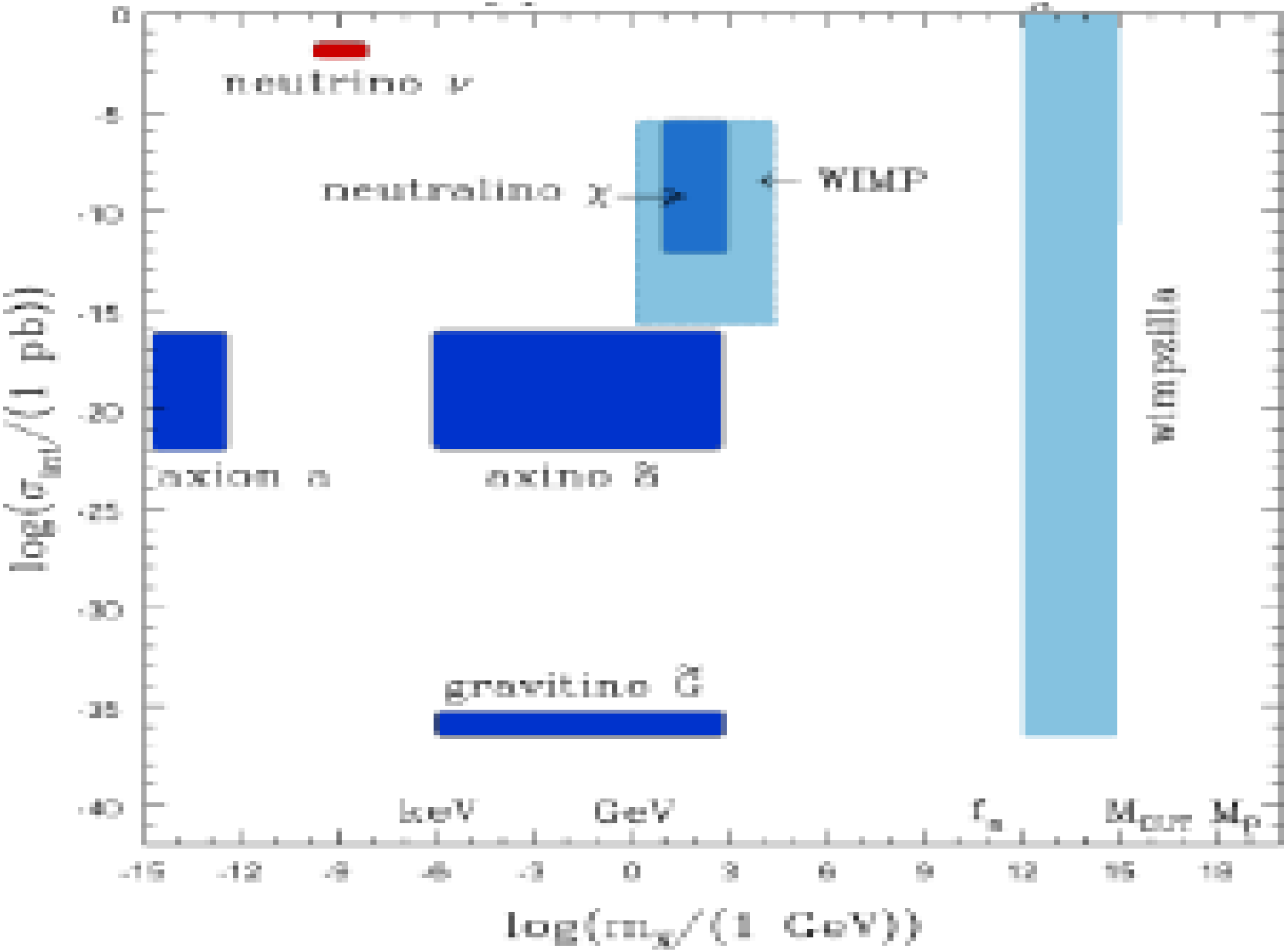
Case	Cosmological data set	Σ bound (2σ)
1	WMAP	< 2.3 eV
2	WMAP + SDSS	< 1.2 eV
3	WMAP + SDSS + SN_{Riess} + HST + BBN	< 0.78 eV
4	CMB + LSS + SN_{Astier}	< 0.75 eV
5	CMB + LSS + SN_{Astier} + BAO	< 0.58 eV
6	CMB + LSS + SN_{Astier} + Ly-α	< 0.21 eV
7	CMB + LSS + SN_{Astier} + BAO + Ly-α	< 0.17 eV

Fogli et al., Phys. Rev. D 75, 053001 (2007)

TEN COMMANDMENTS TO BE A “GOOD” DM CANDIDATE

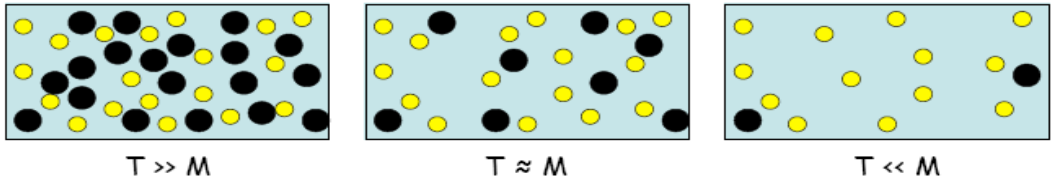
BERTONE, A.M., TAOSO

- **TO MATCH THE APPROPRIATE RELIC DENSITY**
- **TO BE COLD**
- **TO BE NEUTRAL**
- **TO BE CONSISTENT WITH BBN**
- **TO LEAVE STELLAR EVOLUTION UNCHANGED**
- **TO BE COMPATIBLE WITH CONSTRAINTS ON SELF – INTERACTIONS**
- **TO BE CONSISTENT WITH DIRECT DM SEARCHES**
- **TO BE COMPATIBLE WITH GAMMA – RAY CONSTRAINTS**
- **TO BE COMPATIBLE WITH OTHER ASTROPHYSICAL BOUNDS**
- **“TO BE PROBED EXPERIMENTALLY”**

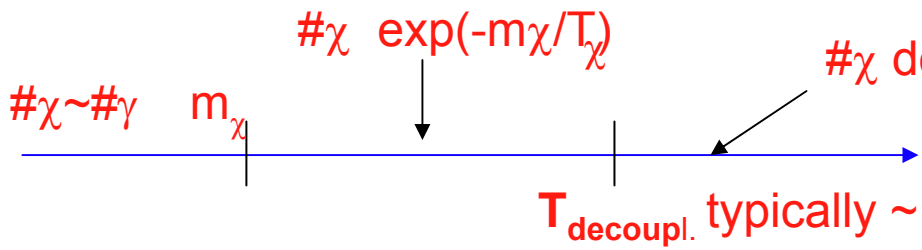

neutrino ν
neutralino χ
WIMP
wimpzilla
axion a
axino ã
gravitino G̃
keV
GeV
f_a
M_{GUT}
M_P
$\log(\sigma_{nl}/(1\ pb))$
$\log(m_\chi/(1\ GeV))$
0
-5
-10
-15
-20
-25
-30
-35
-40
-15
-12
-9
-6
-3
0
3
6
9
12
15
18

THE DM ROAD TO NEW PHYSICS BEYOND THE SM:

IS **DM** A PARTICLE OF THE *NEW PHYSICS AT THE ELECTROWEAK ENERGY SCALE* ?



WIMPS (Weakly Interacting Massive Particles)



Ω_χ depends on particle physics ($\sigma_{annih.}$) and "cosmological" quantities (H, T_0, …

$$\Omega_\chi h^2 \simeq \frac{10^{-3}}{\langle(\sigma_{annih.})\, V\, \chi\rangle \;\; TeV^2}$$

$\langle(\sigma_{annih.})\, V\, \chi\rangle \sim \alpha^2 / M^2_\chi$

From T^0 M_{Planck}

COSMO – PARTICLE CONSPIRACY

$\Omega_\chi h^2$ in the range 10^{-2} -10^{-1} to be cosmologically interesting (for DM)

$m_\chi \sim 10^2 - 10^3$ GeV (weak interaction) $\quad \Omega_\chi h^2 \sim 10^{-2}$ -10^{-1} !!!

THERMAL RELICS (WIMP in thermodyn.equilibrium with the plasma until $T_{decoupl}$)

CONNECTION DM – ELW. SCALE

THE WIMP MIRACLE :STABLE ELW. SCALE WIMPs

	SUSY	**EXTRA DIM.**	**LITTLE HIGGS.**
1) **ENLARGEMENT OF THE SM**	(x^μ, θ) Anticomm. Coord.	(x^μ, j^i) New bosonic Coord.	SM part + new part to cancel Λ^2 at 1-Loop
2) **SELECTION RULE**	***R-PARITY LSP***	***KK-PARITY LKP***	***T-PARITY LTP***
→ **DISCRETE SYMM.**	Neutralino spin 1/2	spin1	spin0
→ **STABLE NEW PART.**	↓	↓	↓
3) FIND REGION (S) PARAM. SPACE WHERE THE "L" NEW PART. IS NEUTRAL + $\Omega_L h^2$ OK	m_{LSP} ~100 - 200 GeV *	m_{LKP} ~600 - 800 GeV	m_{LTP} ~400 - 800 GeV

* But abandoning gaugino-masss unif. → Possible to have m_{LSP} down to 7 GeV

Bottino, Donato, Fornengo, Scopel

SUSY & DM : a successful marriage

- Supersymmetrizing the SM does not lead necessarily to a stable SUSY particle to be a DM candidate.
- However, the mere SUSY version of the SM is known to lead to a too fast p-decay. Hence, necessarily, the SUSY version of the SM has to be **supplemented with some additional (ad hoc?) symmetry to prevent the p-decay catastrophe.**
- Certainly the simplest and maybe also the most attractive solution is **to impose the discrete R-parity** symmetry
- MSSM + R PARITY ⟶ LIGHTEST SUSY PARTICLE (LSP) IS STABLE .
- The LSP can constitute an interesting DM candidate in several interesting realizations of the MSSM (i.e., with different SUSY breaking mechanisms including gravity, gaugino, gauge, anomaly mediations, and in various regions of the parameter space).

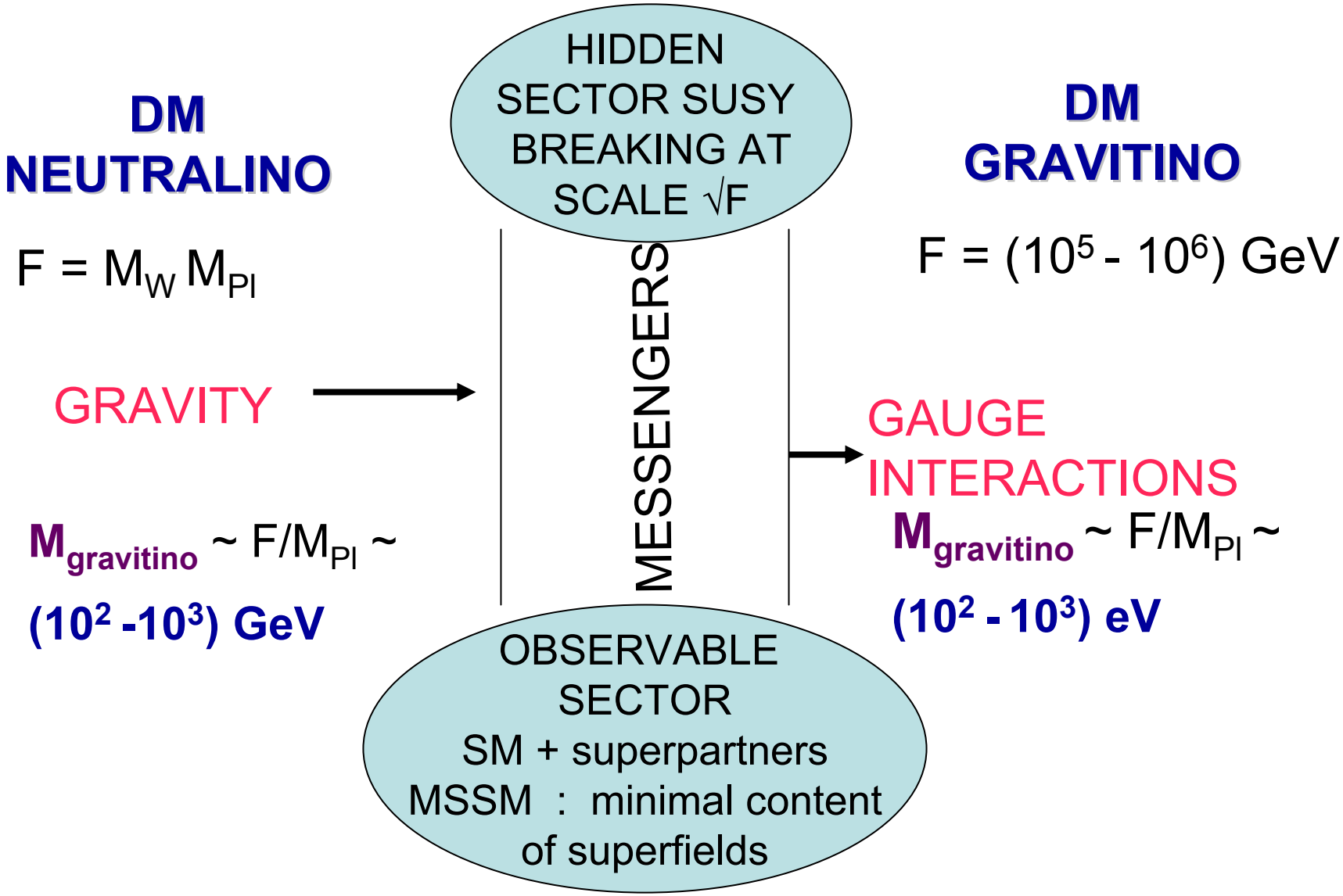
WHO IS THE LSP?

- **SUPERGRAVITY** (transmission of the SUSY breaking from the hidden to the obsevable sector occurring via gravitational interactions): best candidate to play the role of LSP:

  NEUTRALINO (i.e., the lightest of the four eigenstates of the 4x4 neutralino mass matrix)

In **CMSSM**: the LSP neutralino is almost entirely a BINO

DM ⟺ THE ORIGIN OF THE SUSY BREAKING



GRAVITINO LSP?

- **GAUGE MEDIATED SUSY BREAKING**

(GMSB) : LSP likely to be the GRAVITINO (it can be so light that it is more a warm DM than a cold DM candidate)

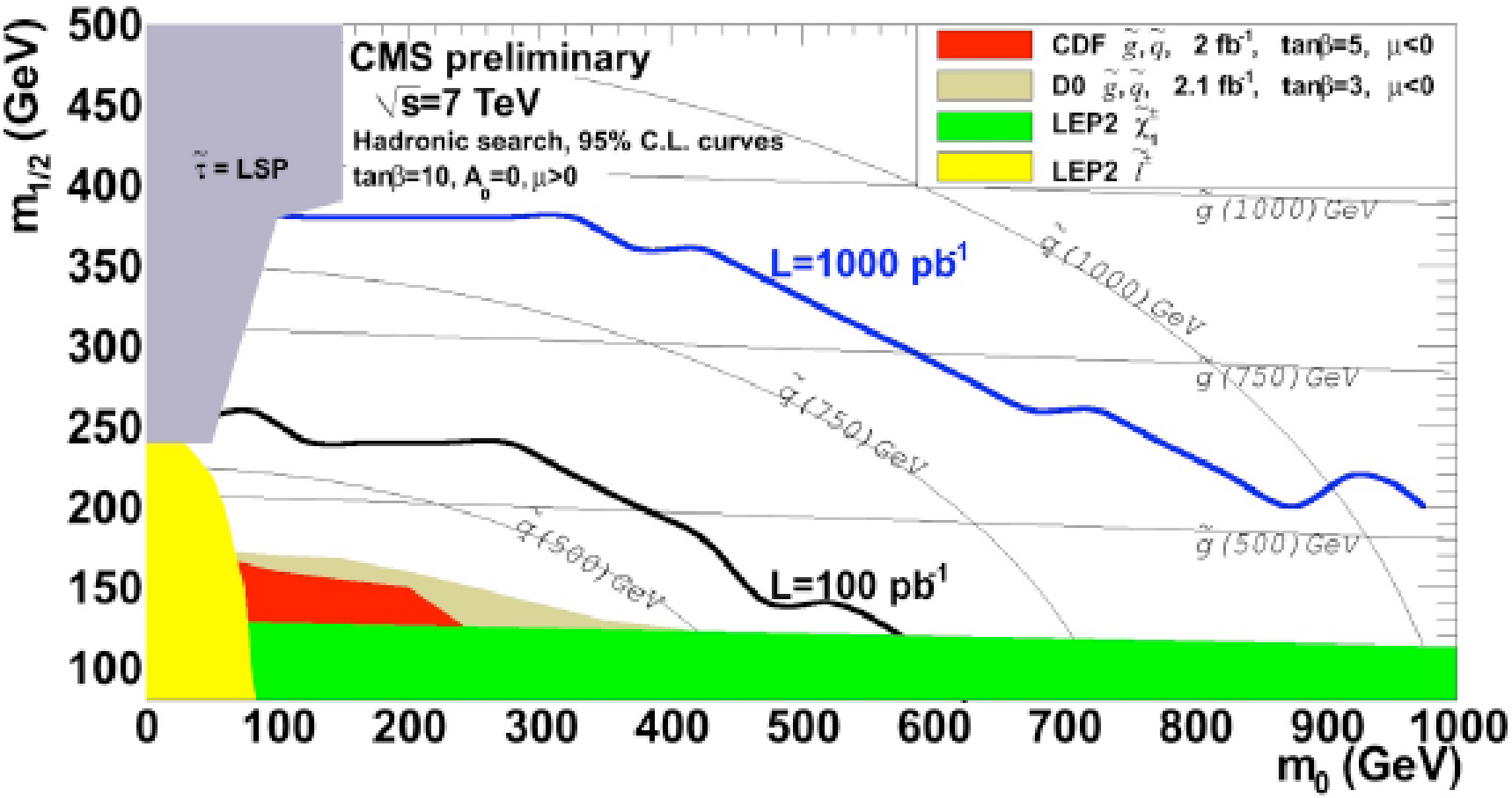
Although we cannot directly detect the gravitino, there could be interesting signatures from the **next to the LSP (NLSP)** : for instance the s-tau could decay into tau and gravitino, Possibly with a very long life time, even of the order of days or months

SUSY: jets + missing E_T

"Classic" all-jets search:

- 3 or more jets, E_T > 50 GeV
- missing E_T > 250 GeV
- no leptons

J. CONWAY
PHENO10



IS THE "*WIMP MIRACLE*" AN **ACTUAL MIRACLE?**

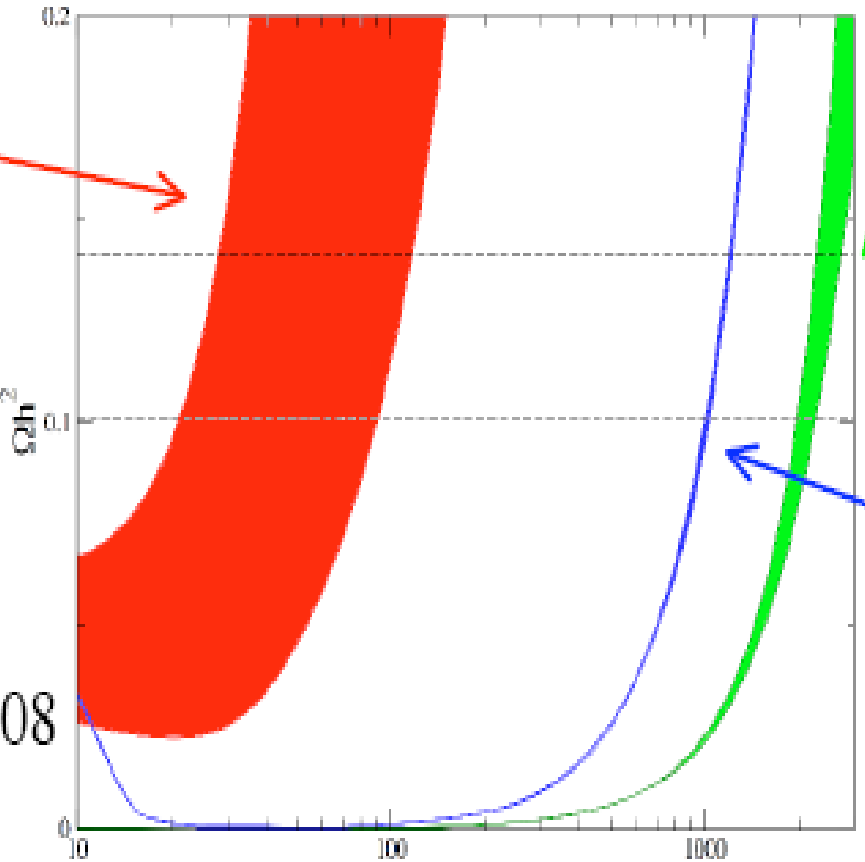
USUAL STATEMENT

Many possibilities for DM candidates, but WIMPs are really special: peculiar coincidence between particle physics and cosmology parameters to provide a VIABLE DM CANDIDATE AT THE ELW. SCALE

HOWEVER

when it comes to quantitatively reproduce the precisely determined DM density → once again the fine-tuning threat…

After LEP: tuning of the SUSY param. at the % level to correctly reproduce the DM abundance: NEED FOR A "WELL-TEMPERED" NEUTRALINO



Bino

$$1.1 < \frac{\tilde{m}_{e_R}}{M_1} < 3$$

Wino

$$1.5 < \frac{\tilde{m}_{\ell_L}}{M_2} < \infty$$

Higgsino

$$1.5 < \frac{\tilde{m}_t}{\mu} < \infty$$

$$\Omega_{DM} h^2 = 0.105 \pm 0.008$$

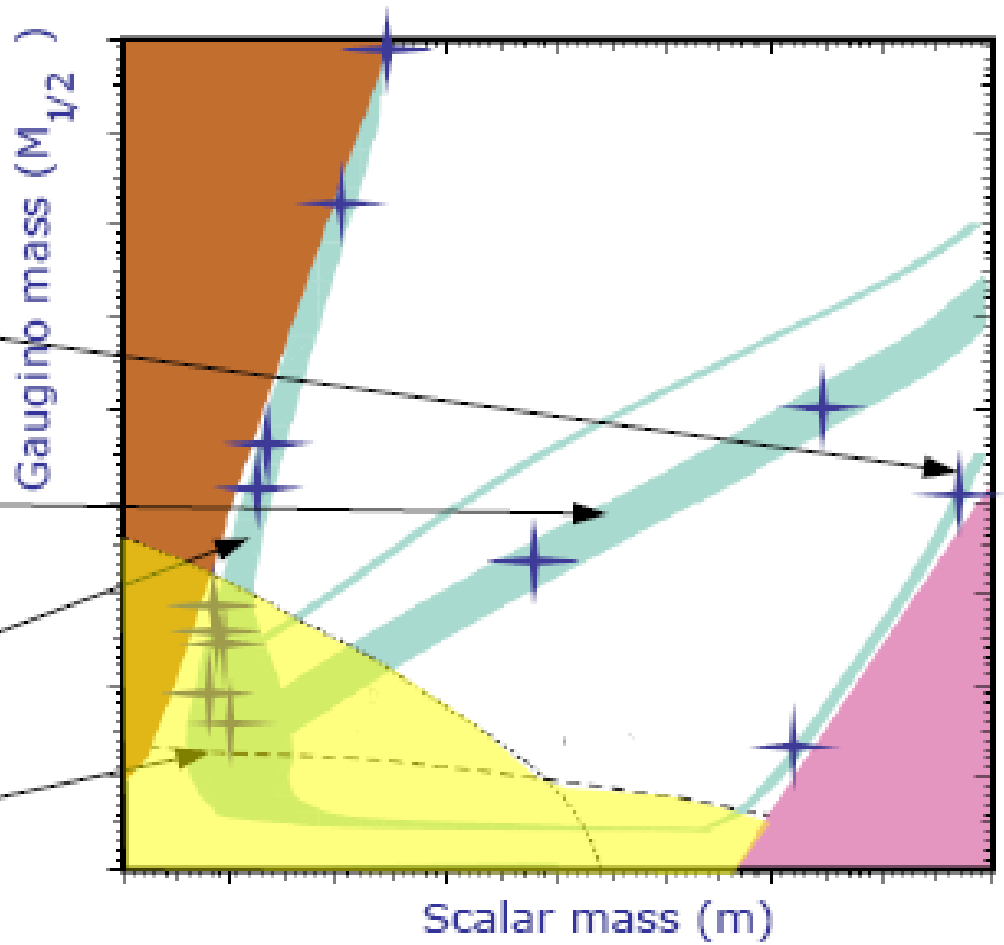
Arkani-Hamed-Delgado-Giudice

LHC reach in the SUSY parameter space (example CMSSM – A, M, m, tanβ, μ)

Regions compatible with Neutralino DM (having correct relic density)

- Focus-Point region (Higgsino-Bino neutralino)
- Resonant annihilation (with pesudoscalar Higgs
- Coannihilation region (small LSP-NLSP mass difference)
- Bulk (small SUSY masses)

  Mostly excluded by LEP constraints (still available in non-minimal models)



(see e.g., Ellis, Ferstl, Olive)

Cerdeno '09

DM and NON-STANDARD COSMOLOGIES BEFORE NUCLEOSYNTHESIS

- **NEUTRALINO RELIC DENSITY MAY DIFFER FROM ITS STANDARD VALUE**, i.e. the value it gets when the expansion rate of the Universe is what is expected in Standard Cosmology (EX.: **SCALAR-TENSOR THEORIES OF GRAVITY**, **KINATION**, **EXTRA-DIM. RANDALL-SUNDRUM TYPE II MODEL**, ETC.)

- **WIMPS MAY BE "COLDER",** i.e. they may have smaller typical velocities and, hence, they may lead to smaller masses for the first structures which form **GELMINI, GONDOLO**

WHY $H \neq H_{GR}$

$$H_{GR}^2 = \frac{1}{3M_p^2}\rho_{tot} \simeq 2.76\, g_* \frac{T^4}{M_p^2}$$

1. Change the number of relativistic d.o.f.'s, g_* ;

R. Catena

2. Consider a ρ_{tot} not dominated by relativistic d.o.f.'s;
   - Kination
     P. Salati, Phys. Lett. B 571 (2003) 121

3. Consider theories where the effective Planck mass is different from the constant M_p:
   - Scalar-Tensor theories
     R. C., N. Fornengo, A. Masiero, M. Pietroni and F. Rosati, Phys. Rev. D 70 (2004) 063519
   - Extradimensions
     L. Randall and R. Sundrum, Phys. Rev. Lett. 83 (1999) 4690

LARGER WIMP ANNIHILATION CROSS-SECTION IN NON-STANDARD COSMOLOGIES

- **Having a Universe expansion rate at the WIMP freeze-out larger than in Standard Cosmology→ possible to provide a DM adequate WIMP population even in the presence of a larger annihilation cross-section** (**Catena, Fornengo, A.M., Pietroni**)

- **Possible application to increase the present DM annihilation rate to account for the PAMELA results in the DM interpretation** (instead of other mechanisms like the Sommerfeld effect or a nearby resonance)

El Zant, Khalil, Okada

Scalar-Tensor Gravity (Jordan Frame)

$$S = S_G[\tilde{g}_{\mu\nu}, \Phi] + S_M[\psi_M, \tilde{g}_{\mu\nu}]$$

MASSES AND NON-GRAV. COUPL. ARE CONSTANT

$$S_g = \frac{1}{16\pi}\int d^4x\sqrt{-\tilde{g}}\left[\Phi^2\tilde{R} + \right.$$
$$\left. + 4\,\omega(\Phi)\tilde{g}^{\mu\nu}\partial_\mu\Phi\partial_\nu\Phi - 4\tilde{V}(\Phi)\right]$$

ENERGY-MOMENTUM TENSOR OF MATTER IS CONSERVED

S_M is just the (MS)SM lagrangian

- All fields feel the same metric :eq. princ. OK

- $m_\phi^2 \sim R \sim G\, T^\mu{}_\mu \sim \Lambda_{uv}^4/M_P^2 = O(H_0^2)$: the cc fine-tuning protects m_ϕ^2

Cosmology is easier in the Einstein Frame

$$\tilde{g}_{\mu\nu} \equiv A^2(\varphi) g_{\mu\nu}$$
$$\Phi^2 \equiv 8\pi M_*^2 A^{-2}(\varphi)$$
$$V(\varphi) \equiv \frac{A^4(\varphi)}{4\pi}\tilde{V}(\Phi)$$
$$\alpha(\varphi) \equiv \frac{d\log A(\varphi)}{d\varphi}\,.$$

Effective Planck Mass

Measures the distance from GR

$$S_g = \frac{M_*^2}{2}\int d^4x\sqrt{-g}\left[R + g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - \frac{2}{M_*^2}V(\varphi)\right] \qquad S_M = S_M[\psi_M, A^2(\varphi)g_{\mu\nu}]$$

$$\frac{\ddot{a}}{a} = -\frac{1}{6M_*^2}\left[\rho + 3p + 2M_*^2\dot{\varphi}^2 - 2V(\varphi)\right]$$
$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{1}{3M_*^2}\left[\rho + \frac{M_*^2}{2}\dot{\varphi}^2 + V(\varphi)\right]$$
$$\ddot{\varphi} + 3\frac{\dot{a}}{a}\dot{\varphi} = -\frac{1}{M_*^2}\left[\frac{\alpha(\varphi)}{\sqrt{2}}(\rho - 3p) + \frac{\partial V}{\partial\varphi}\right]\,,$$

$T^\mu{}_\mu$

Masses and non-gravitational couplings are space-time dependent

The energy-momentum tensor of matter is not conserved

Free particles do not follow geodesics of the metric $g_{\mu\nu}$

PHYSICAL OBSERVABLES ARE FRAME-INDEPENDENT (Catena, Pietroni, Scarabello 06)

EXP. BOUNDS on the DEVIATION from H in GR

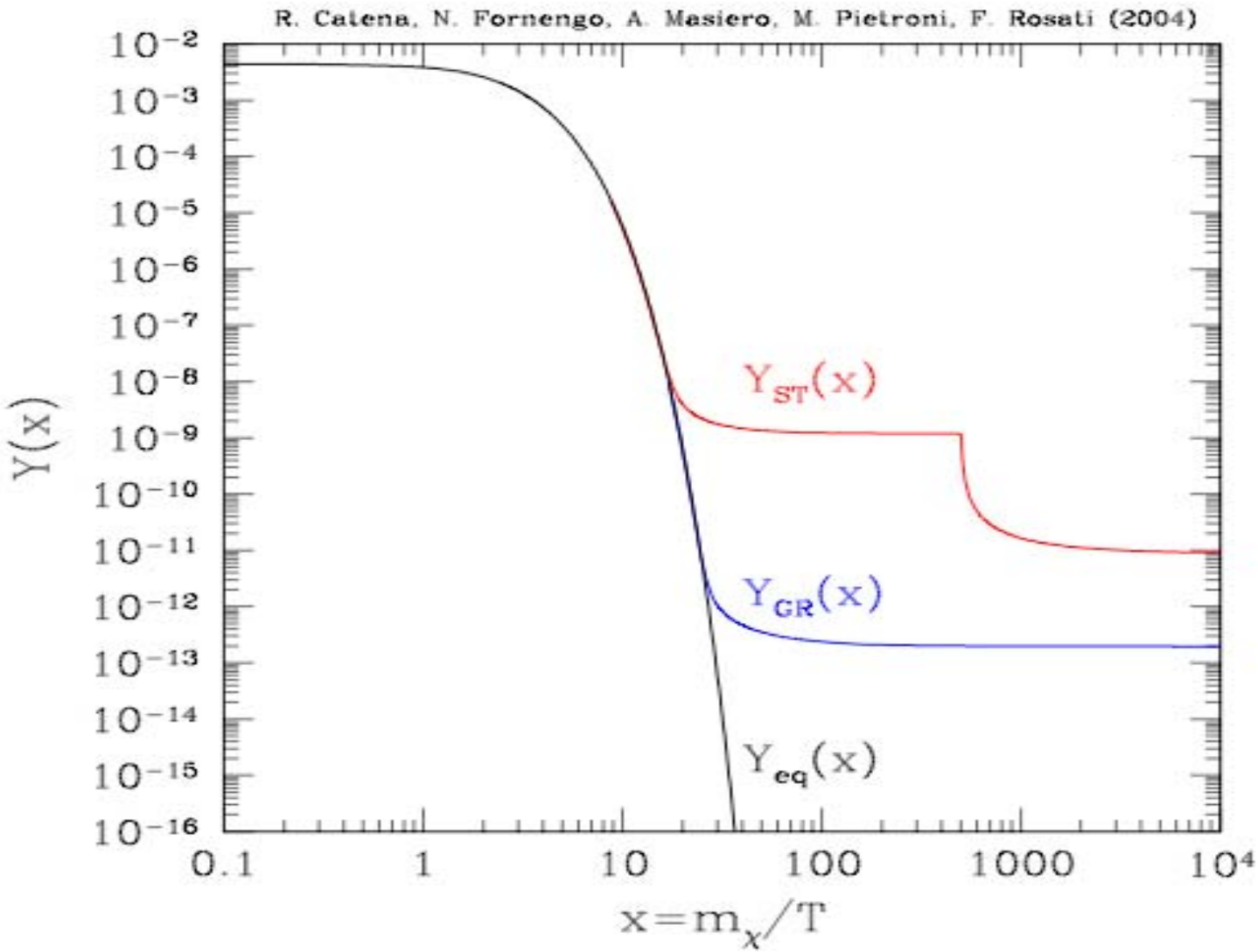
$$H_{ST}^2 \simeq A^2(\varphi) \times H_{GR}^2$$

$$\begin{cases} 0.1 \gtrsim \dfrac{\Delta H^2}{H^2} \equiv \dfrac{H_{ST}^2 - H_{GR}^2}{H_{GR}^2} = A^2(\varphi_{BBN}) - 1 & \text{at BBN}^1 \\ \gamma_{PN} - 1 = -\dfrac{2\alpha^2}{1+\alpha^2} = (2.1 \pm 2.3) \times 10^{-5} & \text{Today}^2 \end{cases}$$

CATENA, FORNENGO, A.M., PIETRONI, ROSATI

BERTOTTI, IESS, TORTORA

NEUTRALINO RELIC ABUNDANCE IN GR AND S-T THEORIES OF GRAVITY

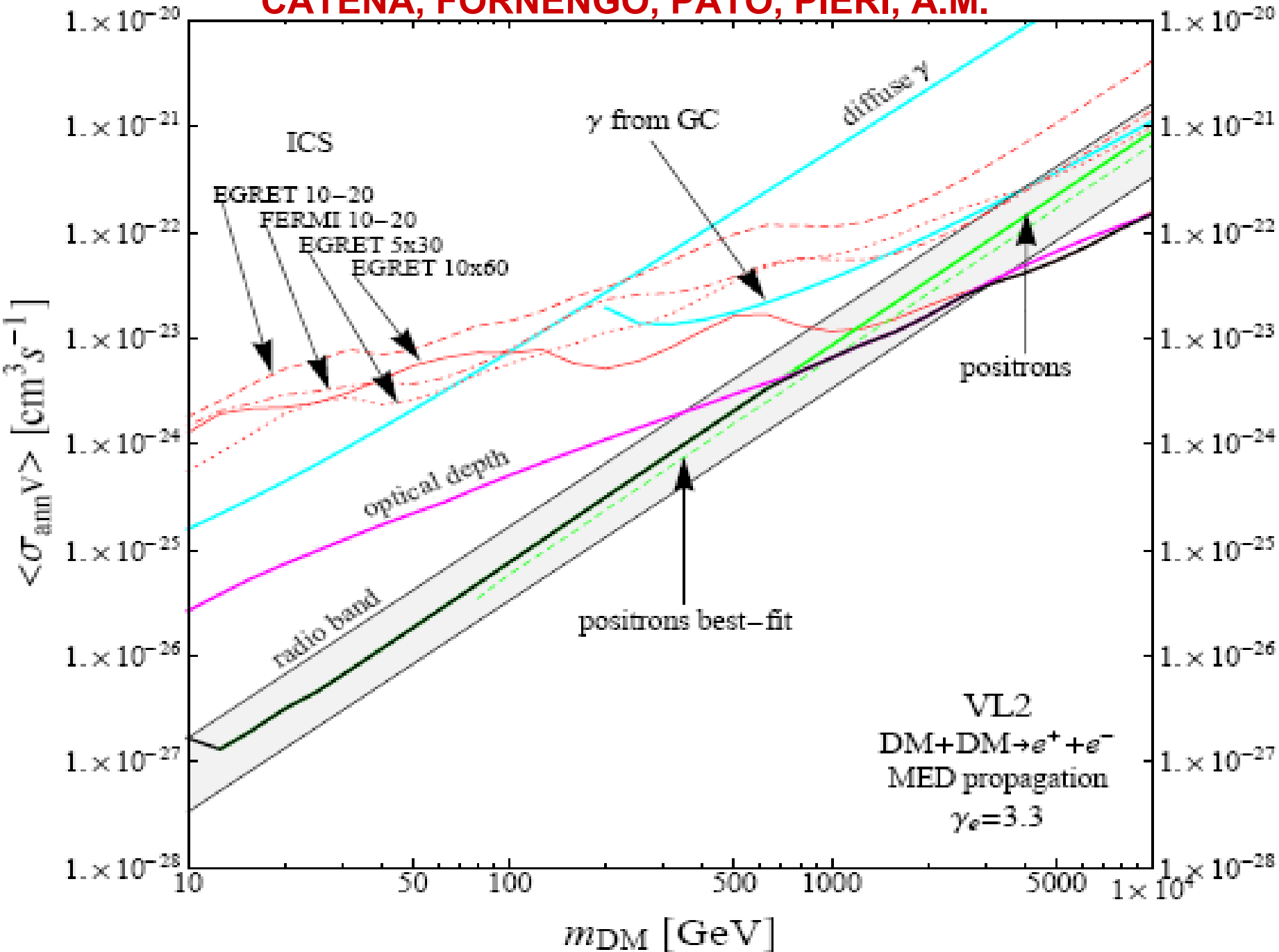


ST THEORIES AND DE

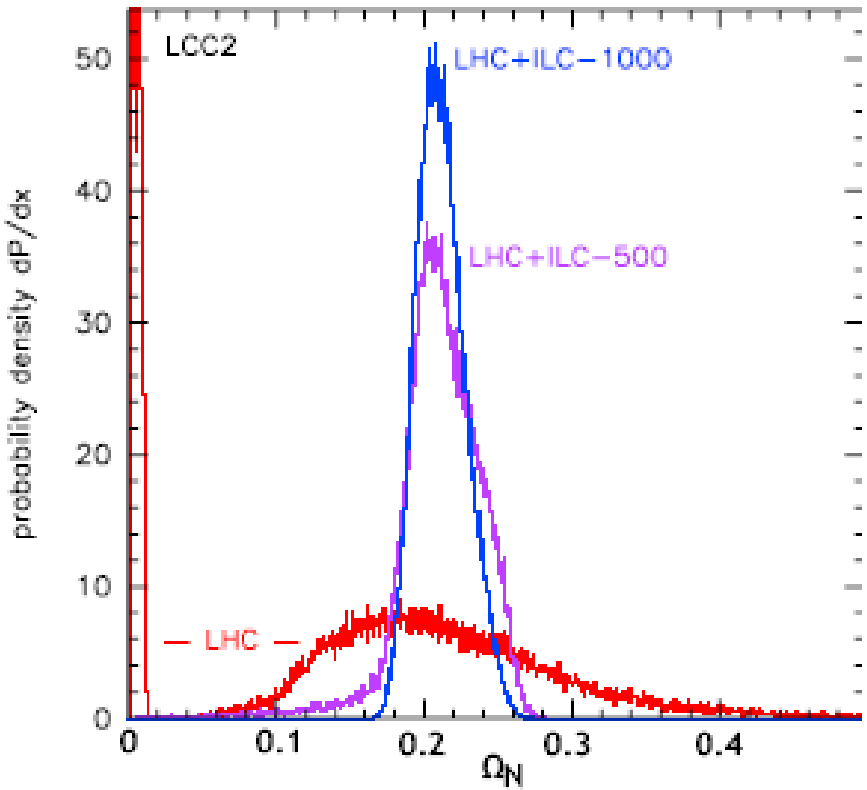
- Scalar-Tensor gravity is a nice environment to accommodate DE, and may lead to drastic revisions of standard DM studies

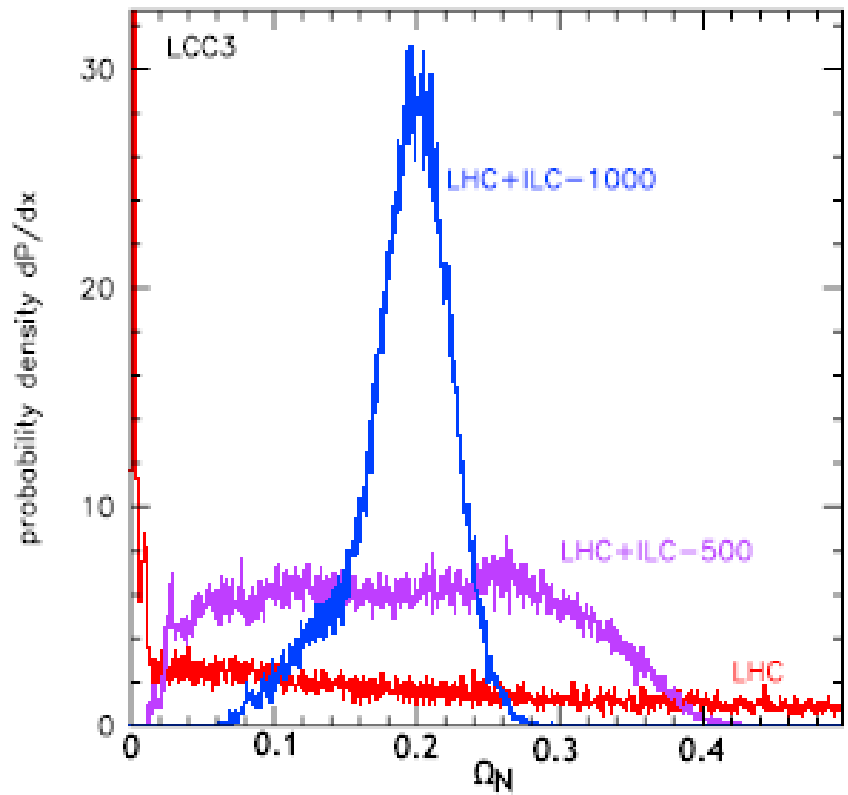
- The expansion history at $T \sim 10$ GeV $>> T_{BBN}$ may be constrained by cosmic antiprotons

CATENA, FORNENGO, PATO, PIERI, A.M.

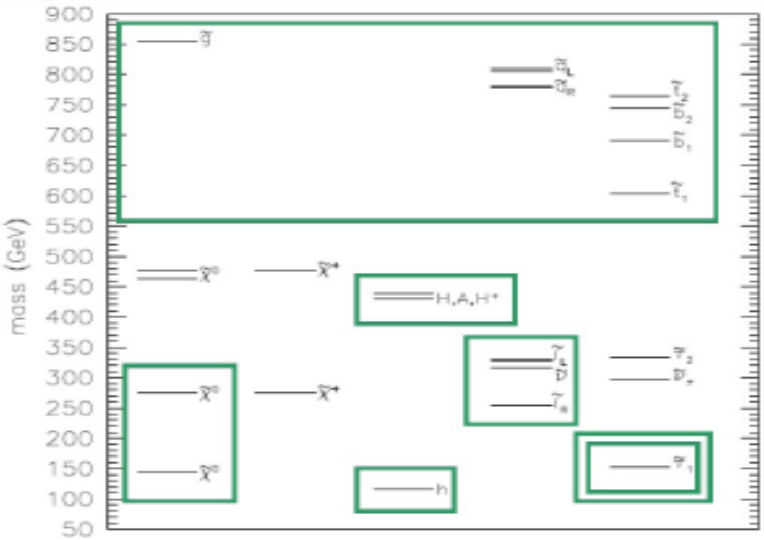


PREDICTION OF Ω DM FROM LHC AND ILC FOR TWO DIFFERENT SUSY PARAMETER SETS



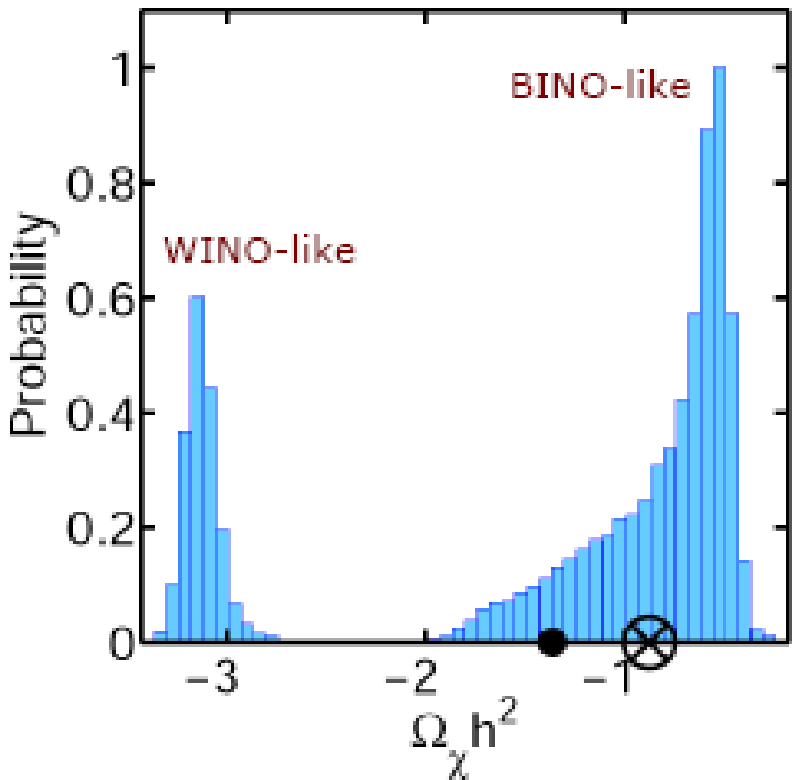


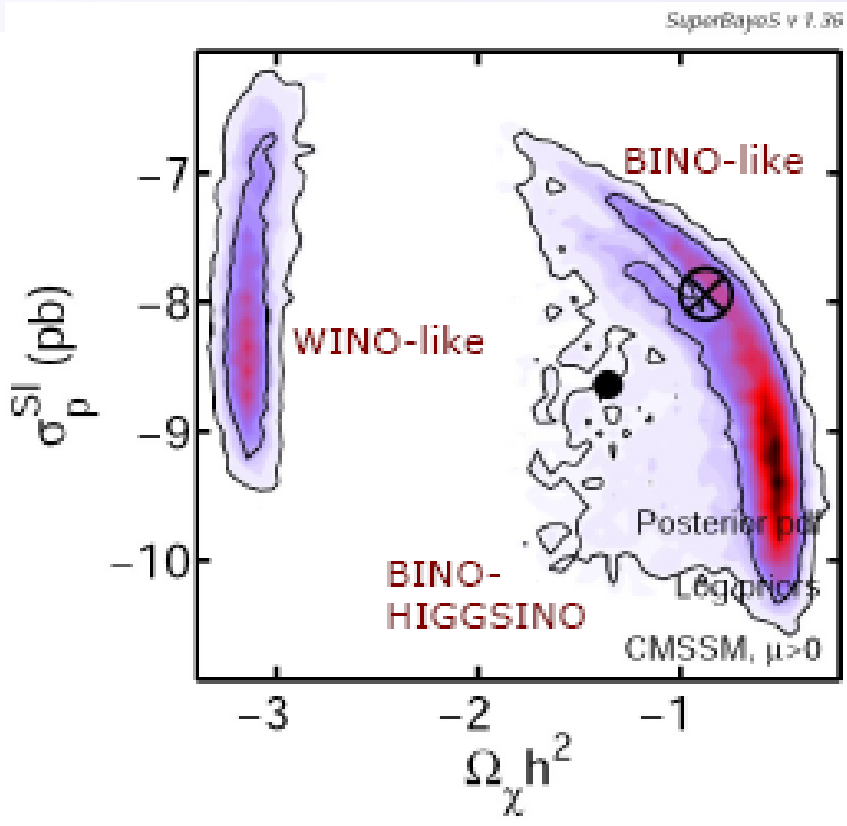
BALTZ, BATTAGLIA, PESKIN, WIZANSKY



Let's suppose to find part of the SUSY particle spectrum at LHC: will we be able to reconstruct then which s-particle is going to be the

LSP?





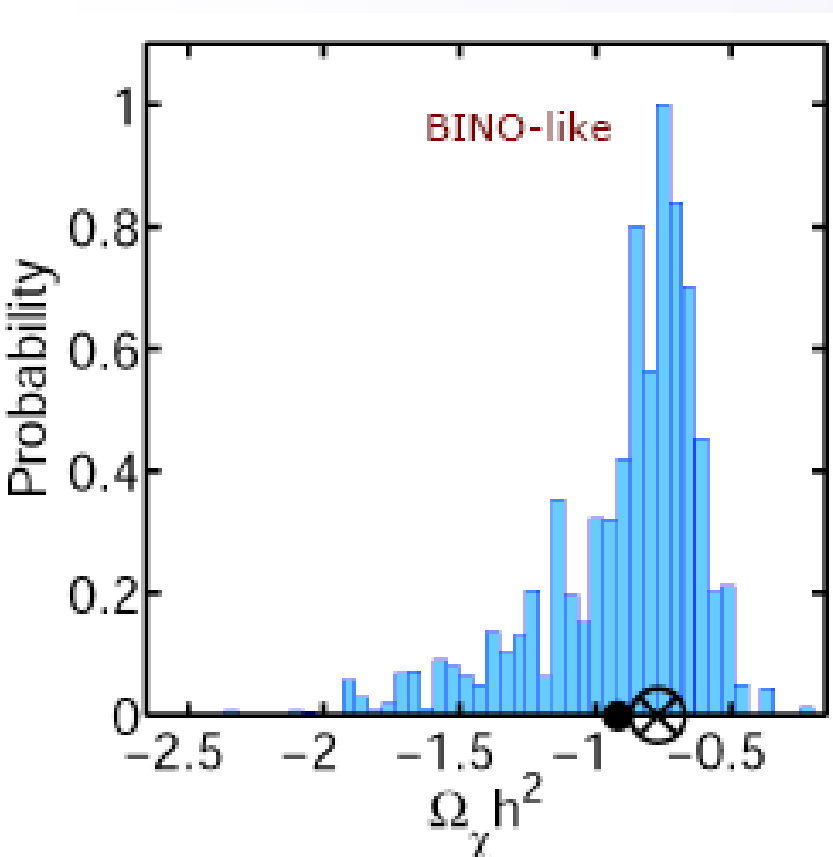
…but if we succeed to find the DM

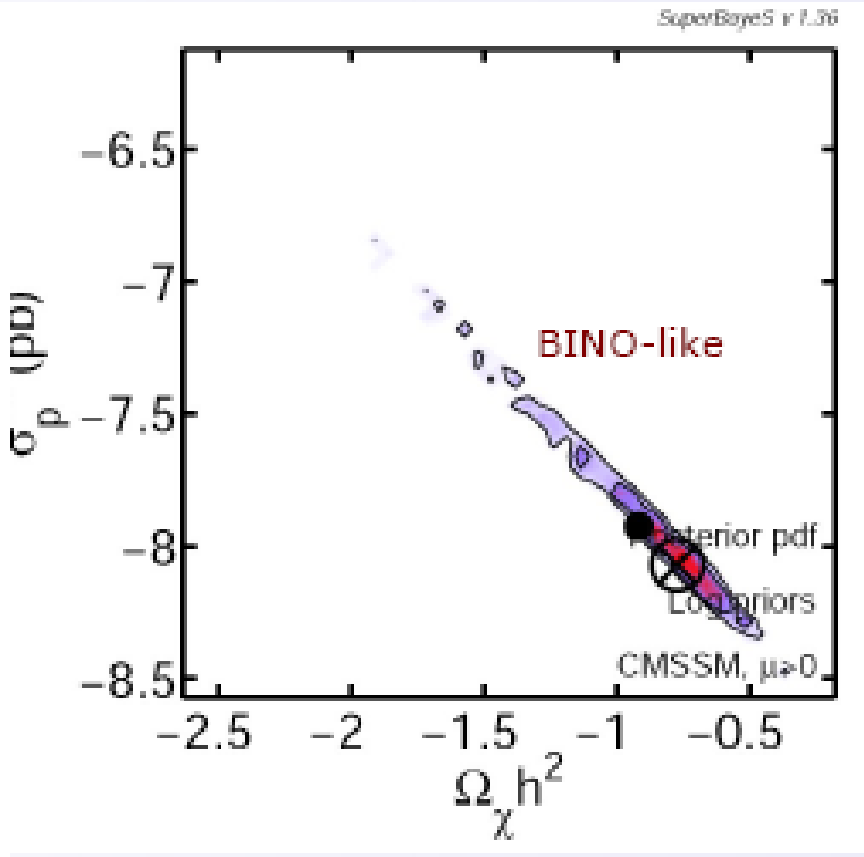
synergy LHC - DM

The combination of LHC data with Direct Detection data can resolve the degeneracy

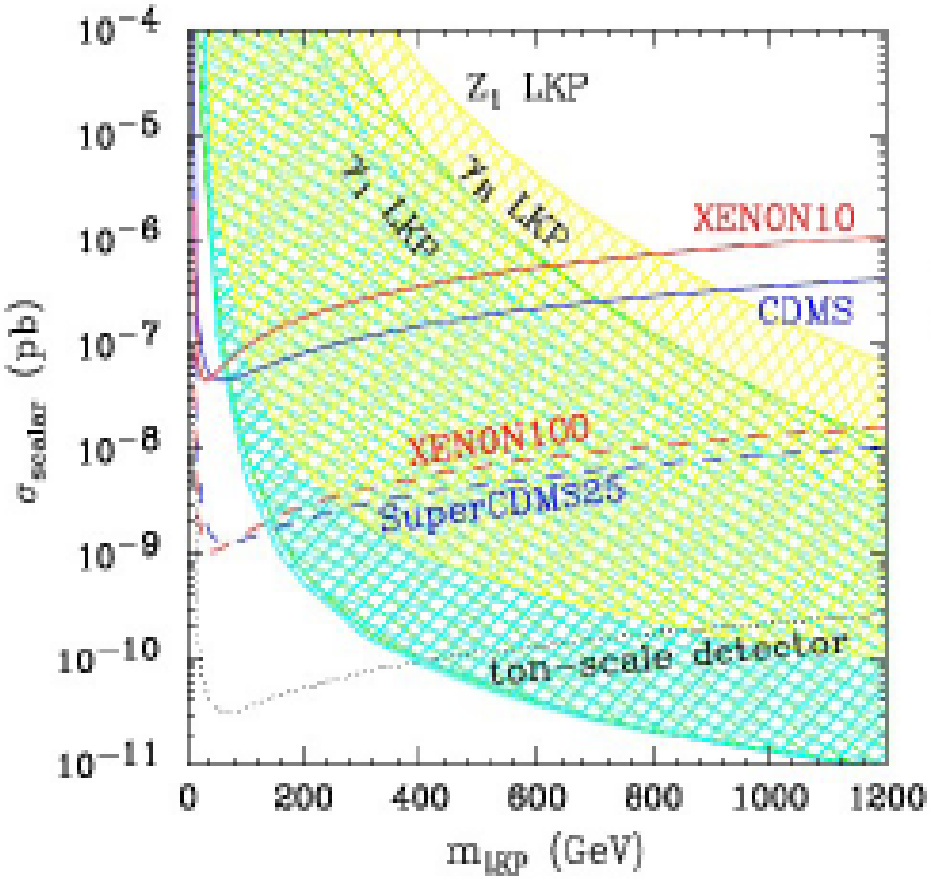
The reconstruction of the relic abundance has a similar accuracy but spurious maxima disappear

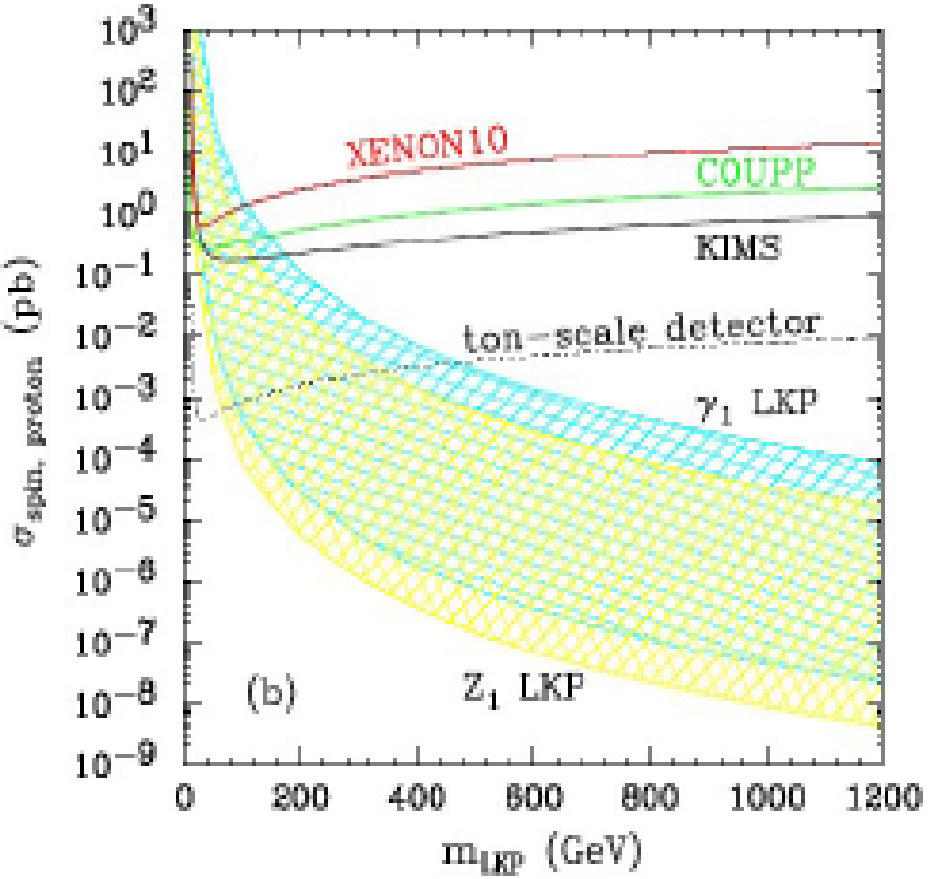
(Bertone, Cerdeño, Fornasa, Trotta, de Austri – in preparation)





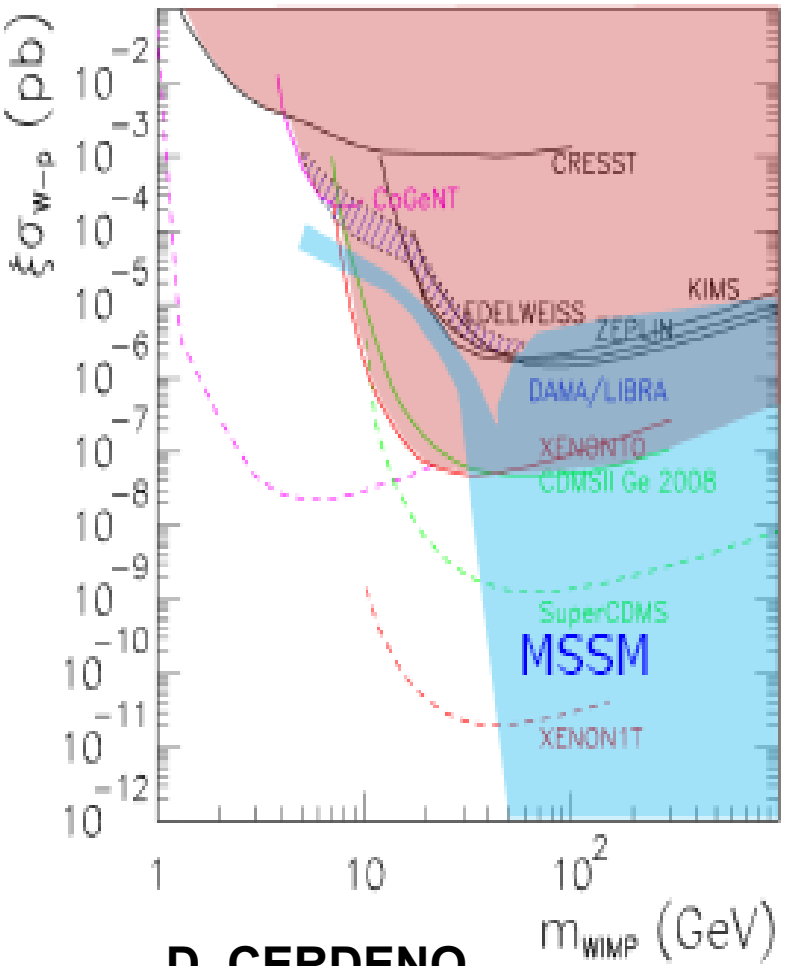
DM and Extra Dimensions



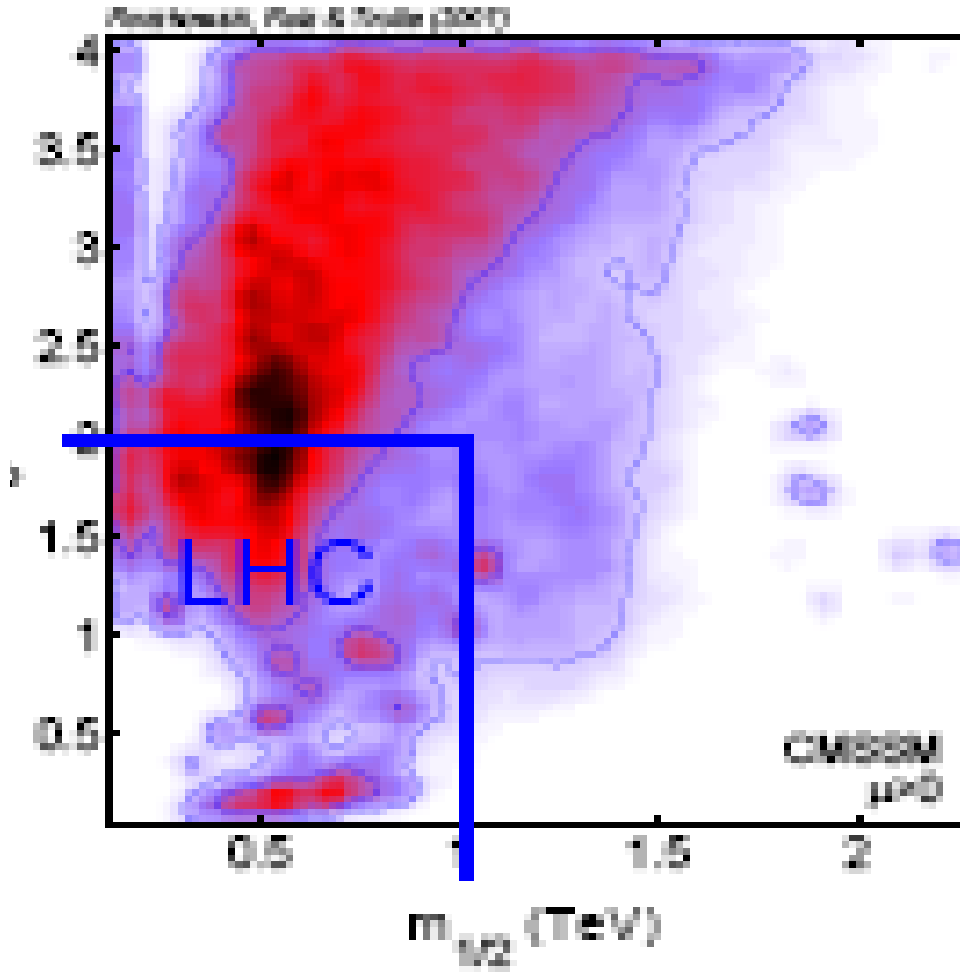


(Arrenberg et al.'08)

On the LHC – Direct DM searches coverage of the MSSM parameter space

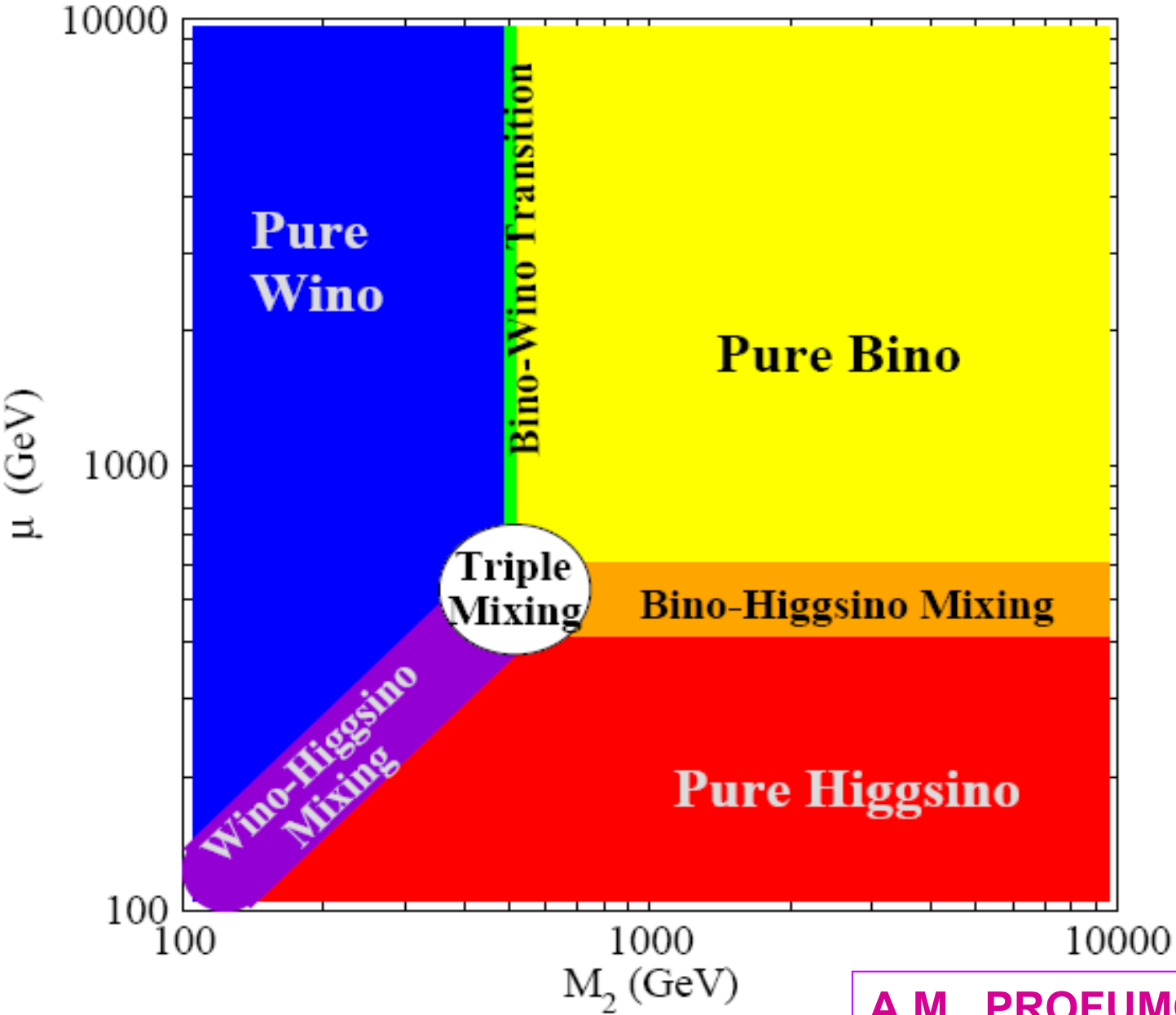


D. CERDENO
WONDER10



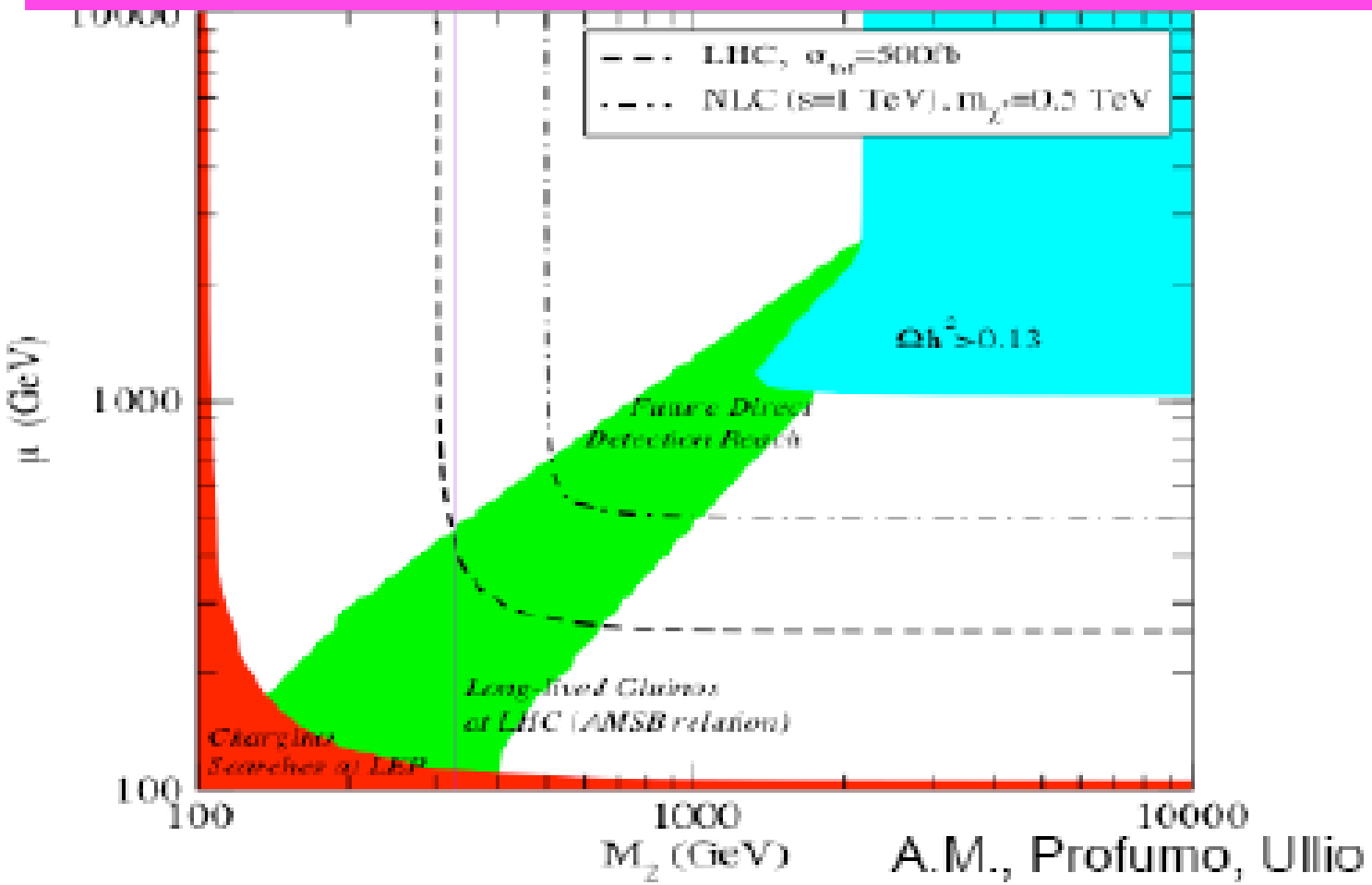
L. Roszkowsk et al.

NEUTRALINO LSP IN SUPERGRAVITY



A.M., PROFUMO, ULLIO

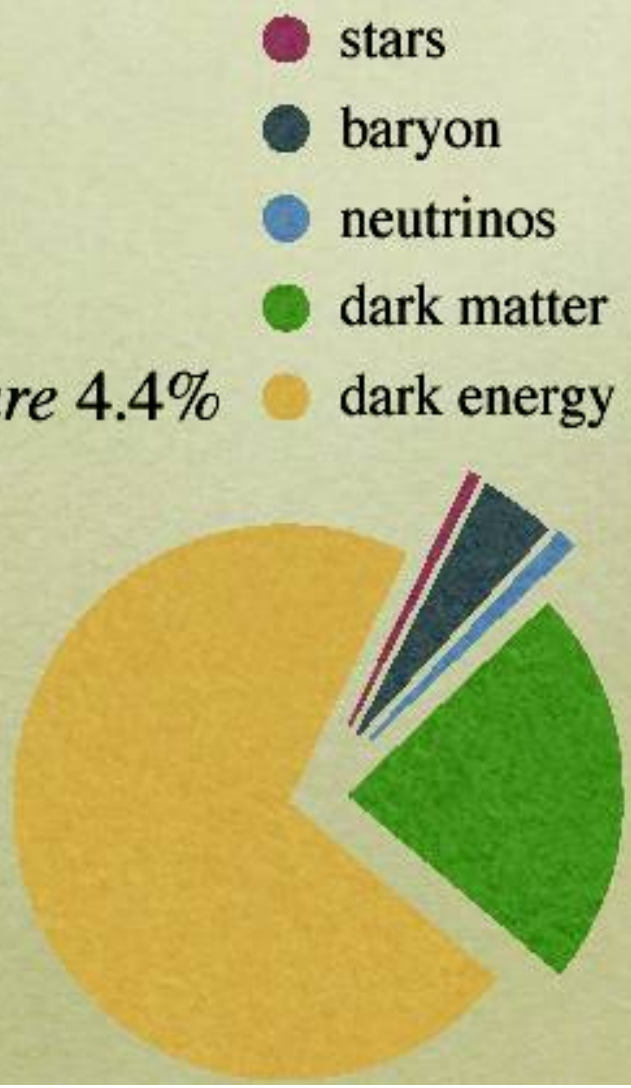
LHC, ILC, DM SEARCHES SENSITIVITIES



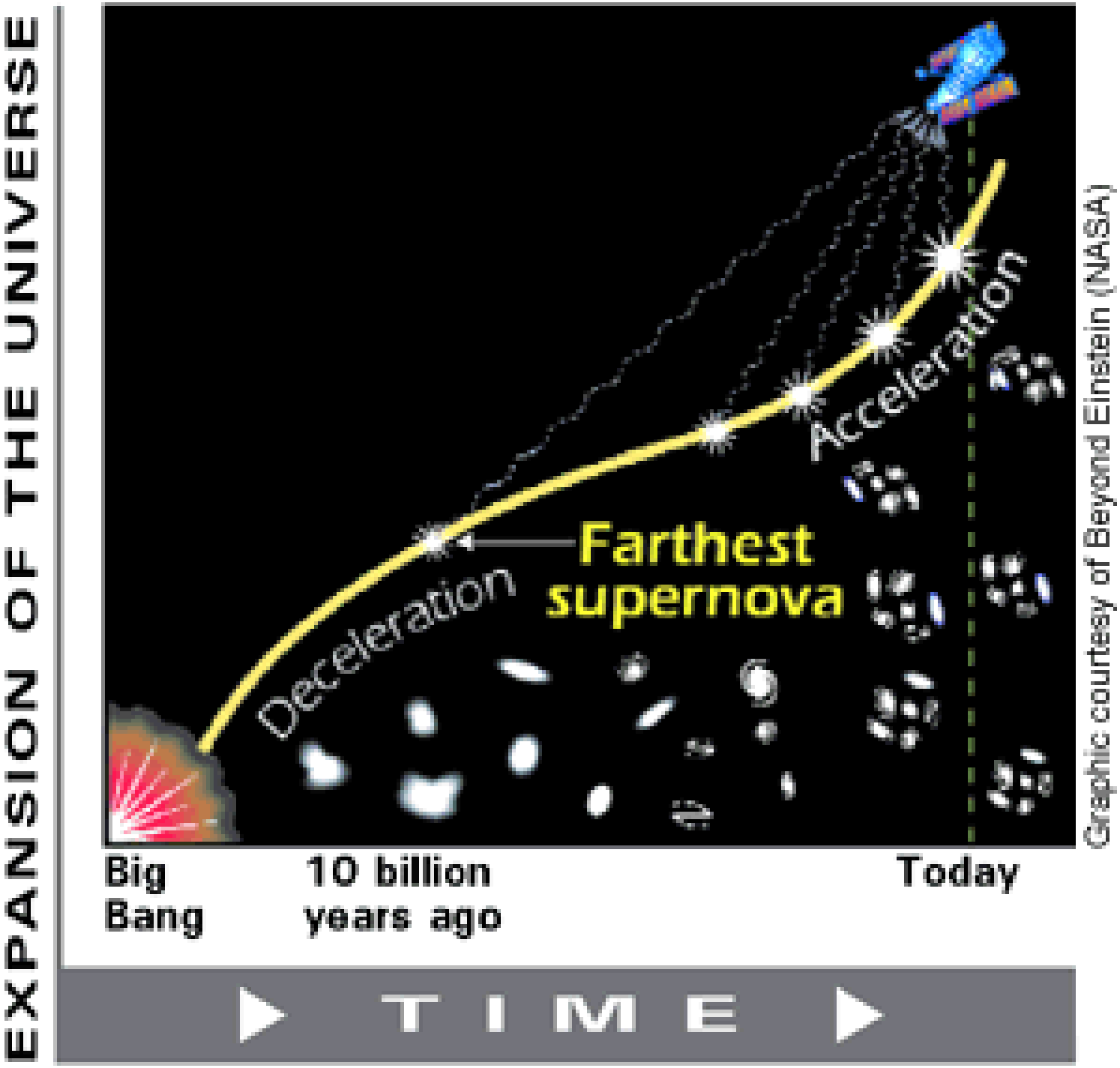
A.M., Profumo, Ullio

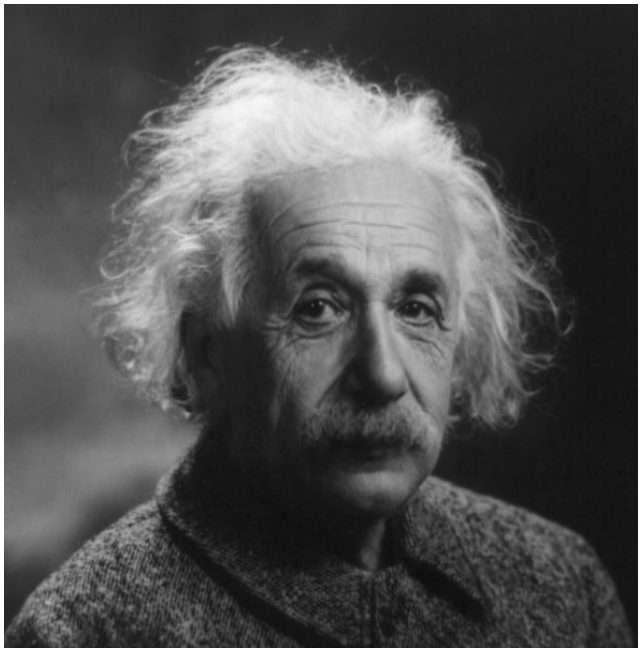
On the Energetic Budget of the Universe

- *Stars and galaxies are only* ~0.5%
- *Neutrinos are* ~0.1–1.5%
- *Rest of ordinary matter*
  (electrons, protons & neutrons) are 4.4%
- *Dark Matter* 23%
- *Dark Energy* 73%
- *Anti-Matter* 0%
- *Higgs Bose-Einstein condensate*
  ~10^{62}%??



Courtesy of H. Murayama


EXPANSION OF THE UNIVERSE
Deceleration
Farthest supernova
Acceleration
Big Bang
10 billion years ago
Today
TIME
Graphic courtesy of Beyond Einstein (NASA)



Albert Einstein (1879-1955)

1916. № 7.

ANNALEN DER PHYSIK.

VIERTE FOLGE. BAND 49.

1. ***Die Grundlage der allgemeinen Relativitätstheorie;***
von A. Einstein.

Die im nachfolgenden dargelegte Theorie bildet die denkbar weitgehendste Verallgemeinerung der heute allgemein als „Relativitätstheorie
ich im folgenden zu
Relativitätstheorie'
Verallgemeinerung
leichtert durch die
theorie durch Mir
matiker zuerst die

Equazione del Campo di Gravitazione

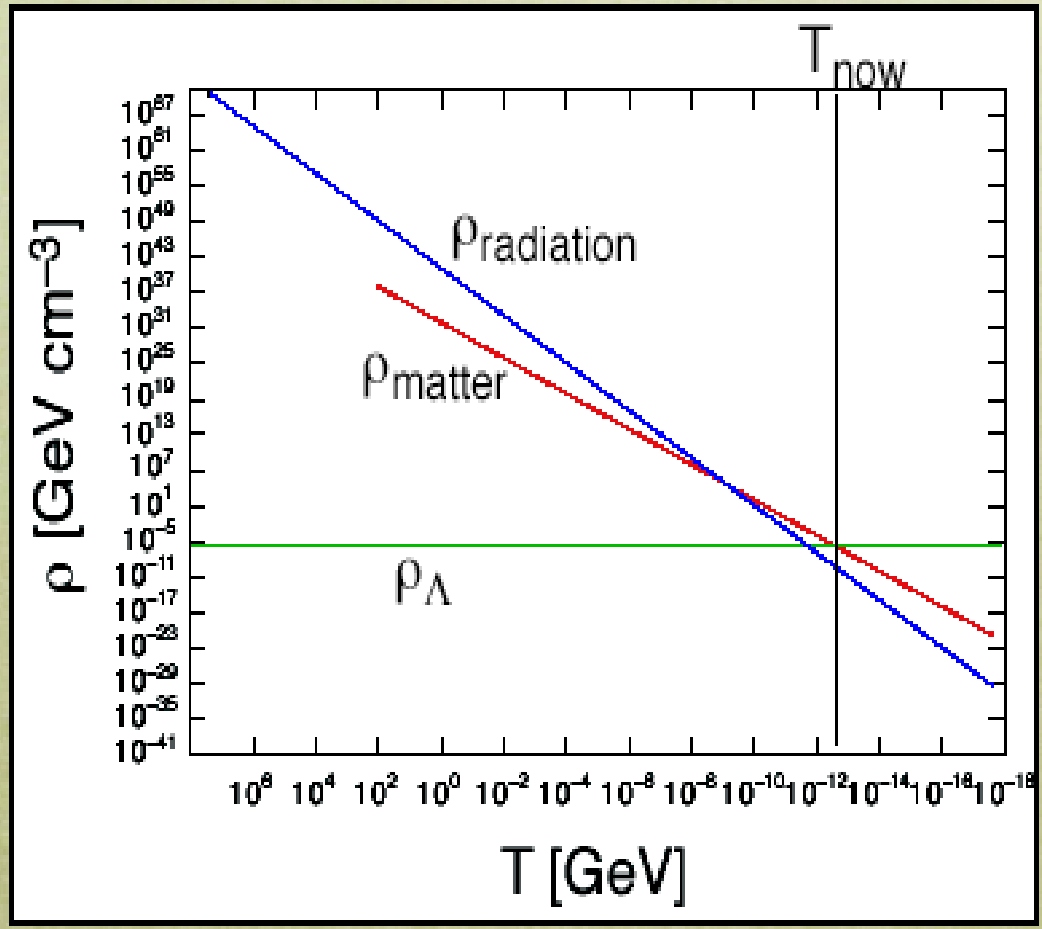
$$R_{ik} - \frac{1}{2} g_{ik} R + \Lambda g_{ik} = \frac{8\pi G}{c^4} T_{ik}$$

Costante Cosmologica

IS THE COSMOLOGICAL CONSTANT THE SOURCE OF THE DARK ENERGY OG THE UNIVERSE AND THE CAUSE OF ITS ACCELERATED EXPANSION?

THE "WHY NOW" PROBLEM

- *Why do we see matter and cosmological constant almost equal in amount?*
- *"Why Now" problem*
- *Actually a triple coincidence problem including the radiation*
- *If there is a deep reason for $\rho_\Lambda \sim ((\mathrm{TeV})^2/M_{Pl})^4$, coincidence natural*



Arkani-Hamed, Hall, Kolda, HM

DO THEY "KNOW" EACH OTHER?

- DIRECT INTERACTION ϕ (quintessence) WITH DARK MATTER

DANGER:
ϕ Very LIGHT
$m\phi \sim H_0^{-1} \sim 10^{-33}$ eV

→ Threat of violation of the equivalence principle
constancy of the fundamental "constants",…

- **INFLUENCE OF ϕ ON THE NATURE AND THE ABUNDANCE OF CDM**

Modifications of the standard picture of
WIMPs FREEZE - OUT

CDM CANDIDATES

CATENA, FORNENGO, A.M., PIETRONI, SCHELKE

ON THE LHC – DM –FCNC COOPERATION TO CORNER TeV NEW PHYSICS

- The traditional competition between direct and indirect (DM,FCNC, CPV) searches to establish who is going to see the new physics first is no longer the priority, rather

- COMPLEMENTARITY between direct and indirect searches for New Physics is the key-word

- Twofold meaning of such complementarity:

i) synergy in "reconstructing" the "fundamental theory" staying behind the signatures of NP;

ii) coverage of complementary areas of the NP parameter space (ex.: multi-TeV SUSY physics)

SLOW "DECOUPLING" of NEW PHYSICS EFFECTS in DM and FCNC SEARCHES w.r.t. the DIRECT ACCELERATOR SEARCHES.

MICRO

STANDARD MODEL of PARTICLE PHYSICS

G-W-S MODEL

MACRO

***MODELLO STANDARD* of COSMOLOGY**

HOT BIG BANG

HAPPY MARRIAGE

EX: **NUCLEOSYNTHESIS**

FRICTION POINTS

BUT ALSO

DARK MATTER AND DARK ENERGY

LHC → AN EXCEPTIONAL WINDOW TO EXPLORE THE UNIVERSE AND ITS ORIGIN, BUT…

BACK-UP SLIDES

DM → NEW PHYSICS BEYOND THE (PARTICLE PHYSICS) SM - if Newton is right at scales>size of the Solar System

- $\Omega_{DM} = 0.233 \pm 0.013$ *
- $\Omega_{baryons} = 0.0462 \pm 0.0015$ **

*from CMB (5 yrs. of WMAP) + Type I Supernovae + Baryon Acoustic Oscillations (BAO)

**CMB + Typel SN + BAO in agreement with Nucleosynthesis (BBN)

The **BULLET CLUSTER**: **two colliding clusters of galaxies**

Stars, galaxies and putative DM behave differently during collision, allowing for them to be studied separately. In **MOND** the lensing is expected to follow the baryonic matter, i.e. the X-ray gas. However the lensing is strongest in two separated regions near the visible galaxies → **most of the mass in the cluster pair is in the form of collisionless DM**