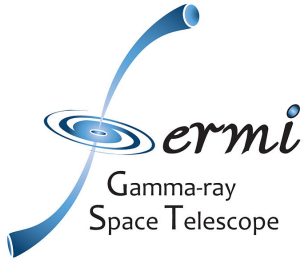
SCIPP

SANTA CRUZ INSTITUTE FOR PARTICLE PHYSICS

UC SANTA CRUZ



Stefano Profumo

UC Santa Cruz

Santa Cruz Institute for Particle Physics

Affiliated Member, Fermi Collaboration

Terascale: key to the origin of baryonic and dark matter?

UCSC - Physics 205

Monday February 11, 2013

- ✓ PhD **Theoretical Particle Physics** (2004)
  International School for Advanced Studies (SISSA-ISAS), Trieste, Italy

- ✓ Postdoc, FSU and California Institute of Technology (2005-2007)
  Theoretical Astrophysics and Particle Physics

- ✓ Joined **UCSC Physics** Faculty (Assistant Professor, 2007-2011, Associate Professor, July 2011-)

- ✓ Research funded by Department of Energy (Outstanding Junior Investigator Award), National Science Foundation, NASA

- ✓ **Fermi**-LAT affiliated scientist; collaborate with **ATLAS** group

- ✓ **SCIPP Deputy Director** for **Theory** (July 2011-)

Profumo's Research Group

Particle Theory Group
Banks, Dine, Haber

Fermi Telescope Group
Atwood, Johnson, Ritz

ATLAS Group
Nielsen, Schumm, Seiden

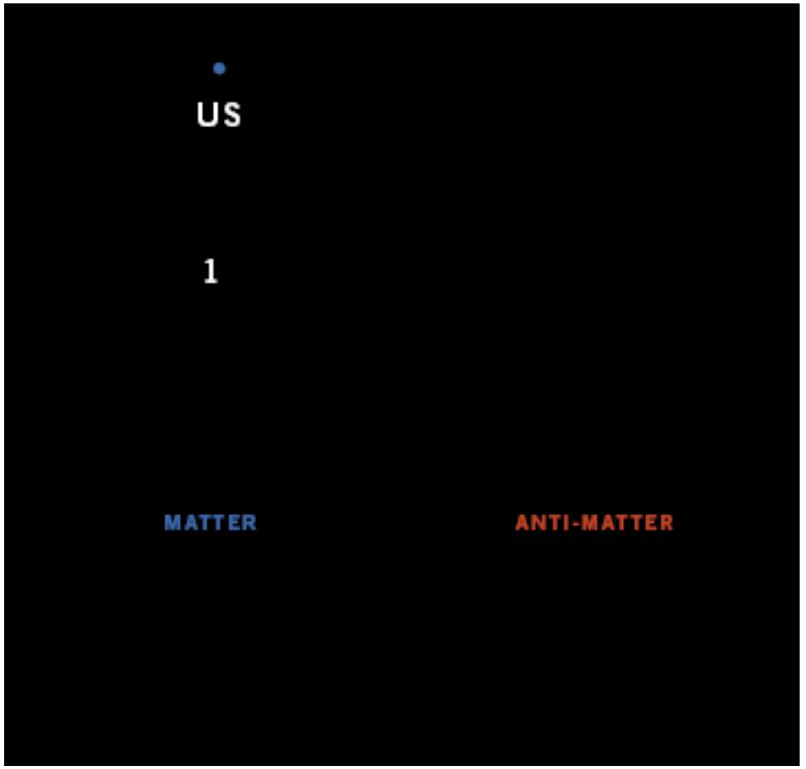
Postdocs
- Draper
- Shepherd

Graduate Students

Kehyias*	Cornell
Ubaldi**	Carlson
	Coogan
Linden***	
Wainwright***	Storm (with Jeltema)
Kozaczuk***	Manning (with Seiden)

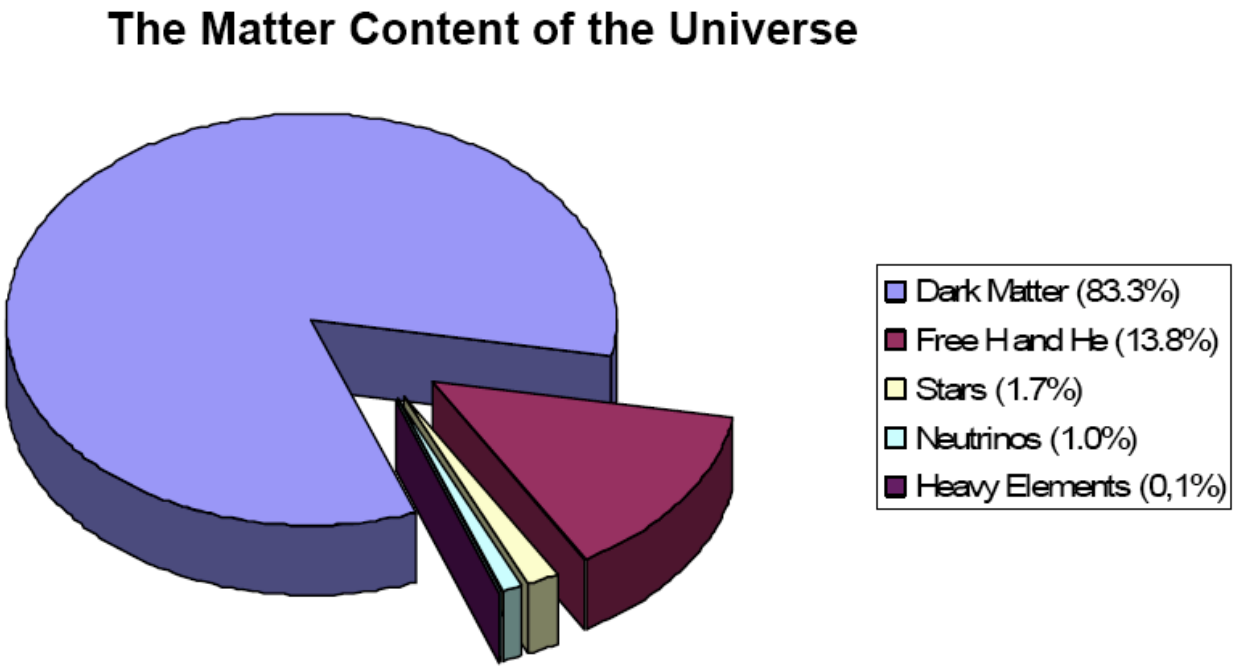
Undergraduate Students
- Bergeron, Gray, Gruzdas

* *graduated in 2011, postdoc at University of Tokyo, IPMU*
** *graduated in 2011, postdoc position at Bonn University*
*** *will graduate in 2013*

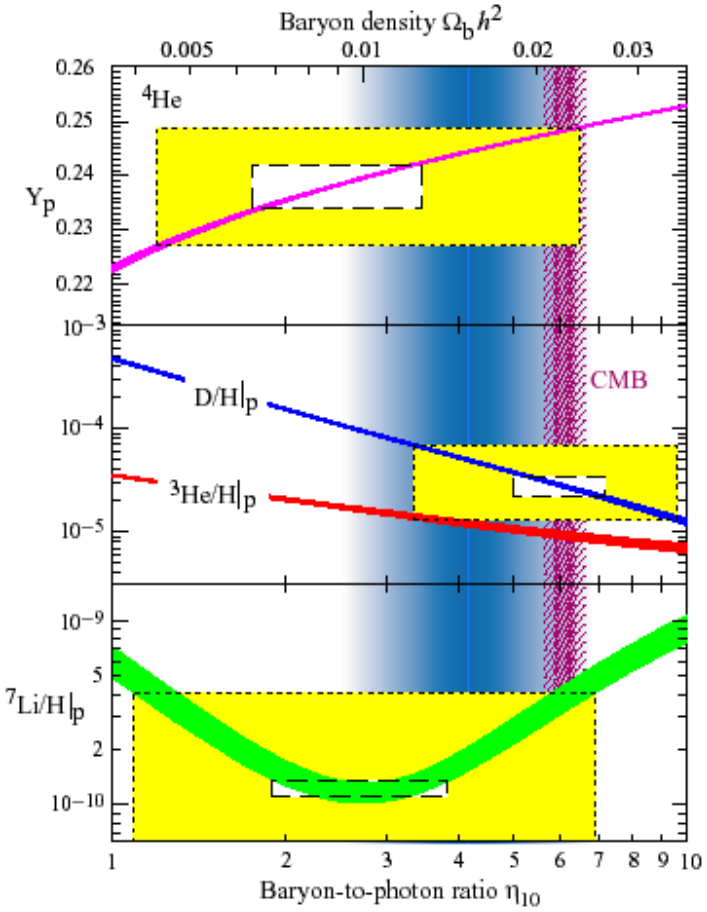


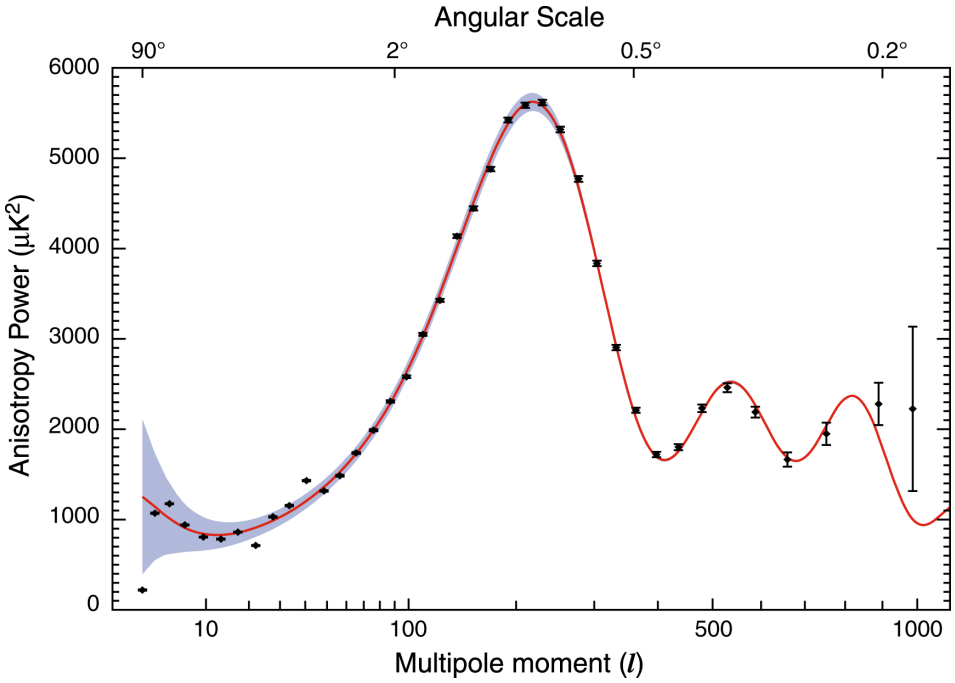
1. What is the origin of the tiny excess of matter over anti-matter?

2. What is the fundamental particle physics nature of Dark Matter?



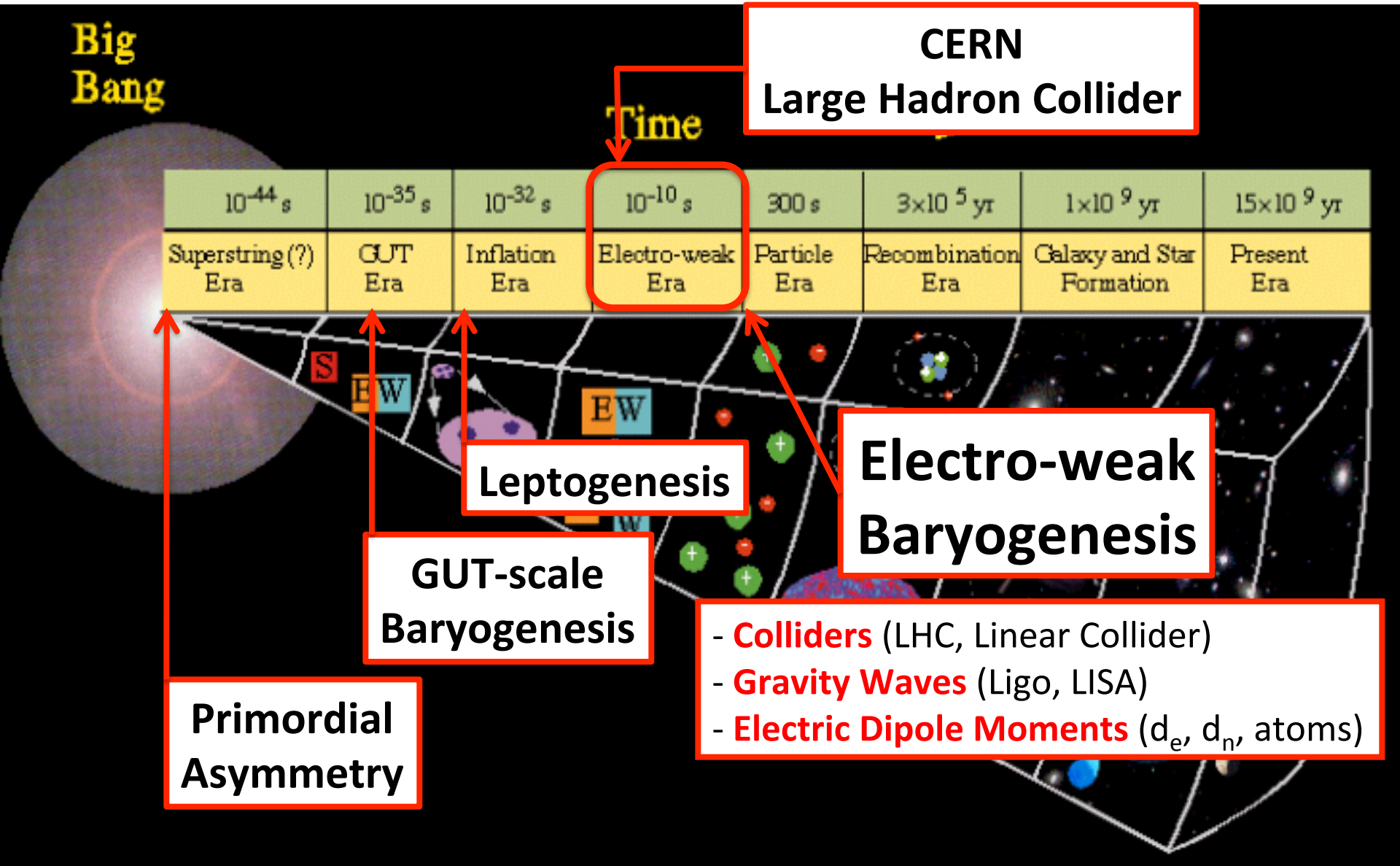
The Matter-Antimatter (Baryon) Asymmetry



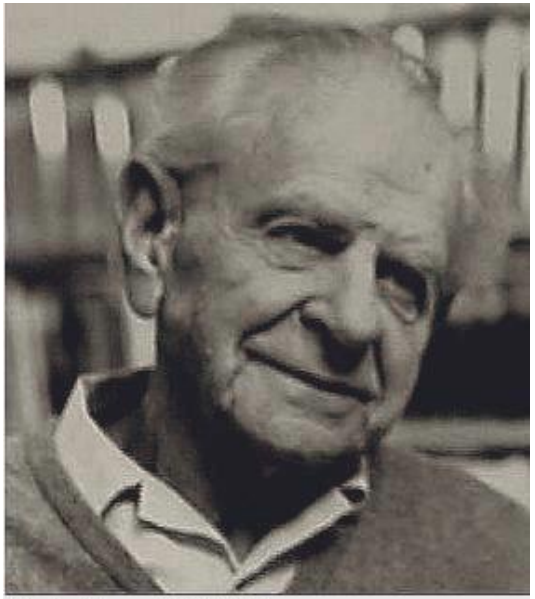


$$\frac{n_{Baryons} - n_{Antibaryons}}{n_\gamma} \approx 10^{-10}$$

No "Standard Model" of Baryogenesis!



"In so far as a scientific statement
speaks about reality,
it must be falsifiable:
And in so far as it is not falsifiable
it does not speak about reality"


Sir Karl Popper (1902-1994)

Karl Popper, "*Logik der Forschung*" (1934)
"*The Logic of Scientific Discovery*"

(Supersymmetric) Electro-Weak Baryogenesis:
a falsifiable theory

Ingredients of Baryogenesis

(1) ***B***aryon Number violation

If B is conserved, the present BAU can only reflect asymmetric initial conditions

(2) ***C*** and ***CP*** violation

In the absence of a "preference" for matter or antimatter, B-noncoserving interactions will produce baryon and antibaryon excesses at the same rate: no net baryogenesis

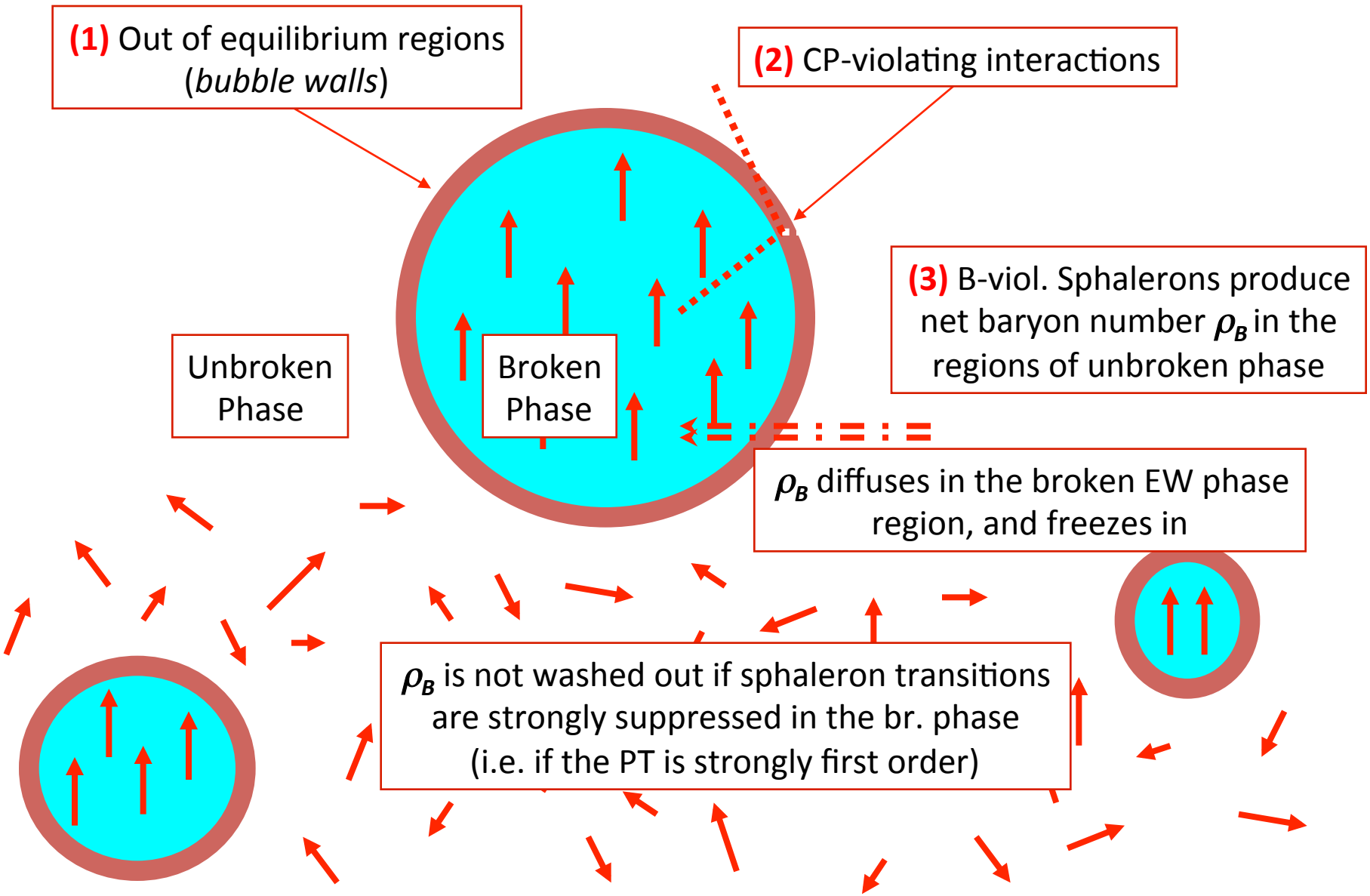
(3) **Out of Equilibrium** conditions

In chemical equilibrium the entropy is maximal when the chemical potential associated with all nonconserved quantum numbers vanishes

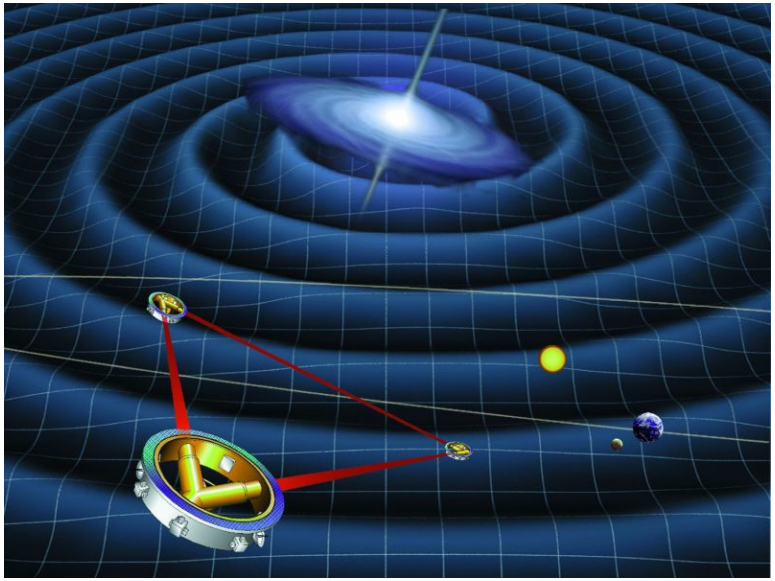
"Sakharov conditions"(*)

(*)A.D.Sakharov, JETP Letters **5**, 24 (1967)

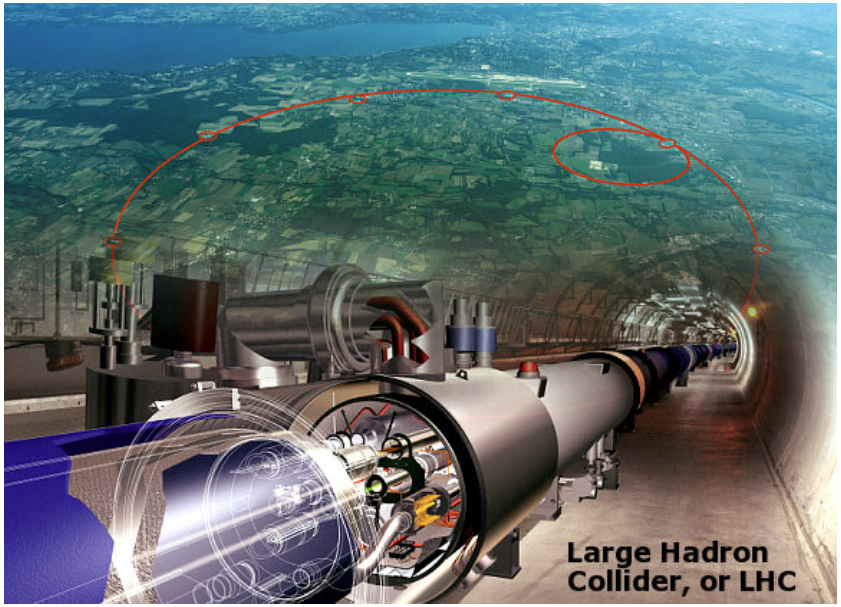
Electro-Weak Baryogenesis



Experimental Tests of Electro-Weak Baryogenesis

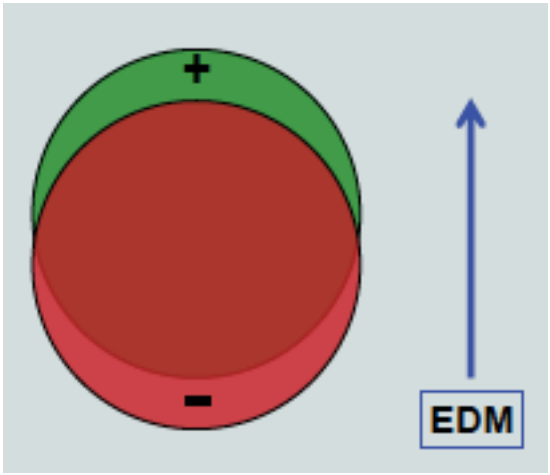


Gravity Waves from Bubble Collisions

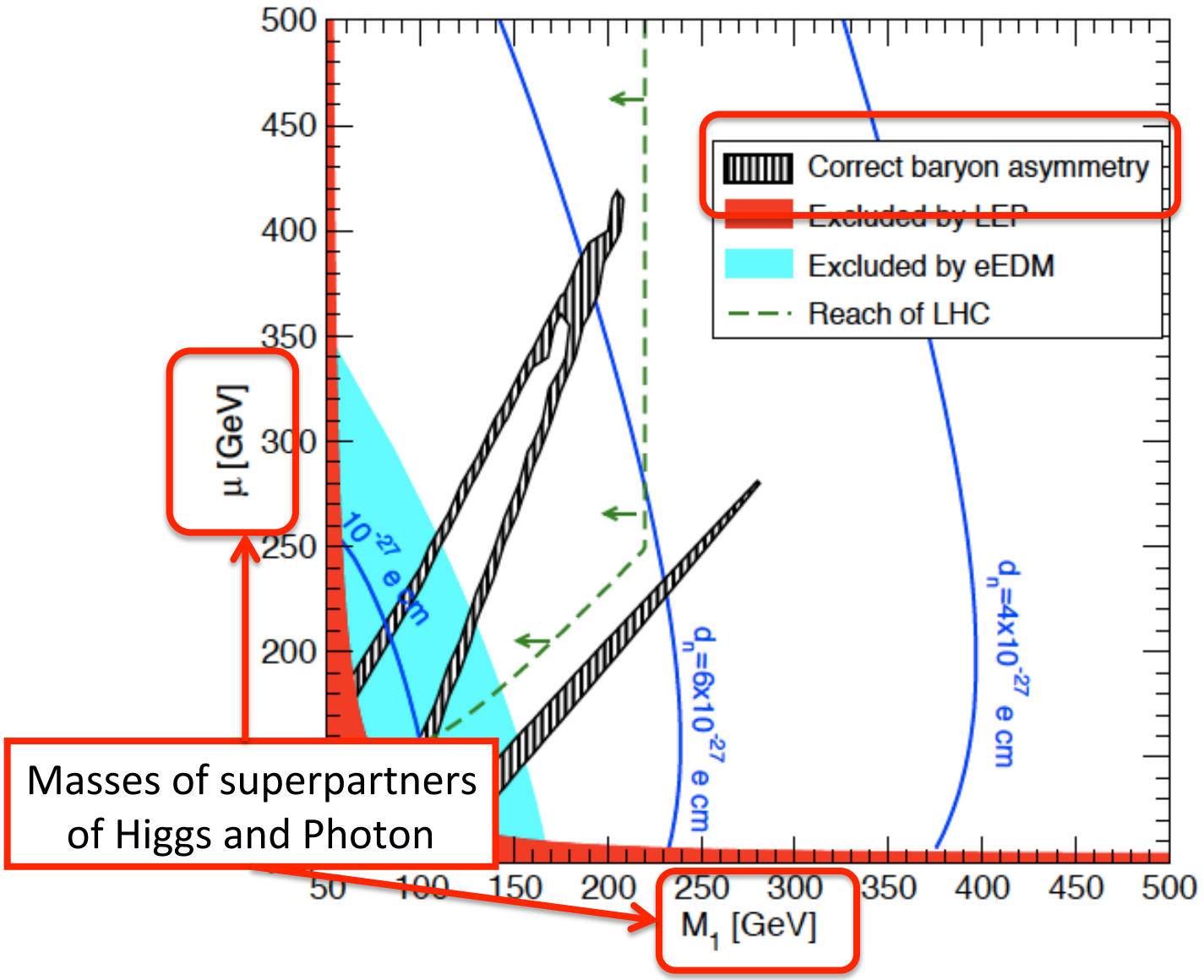


Light superpartners, distinctive phenomenology at LHC

Large Electric Dipole Moments from CP violation

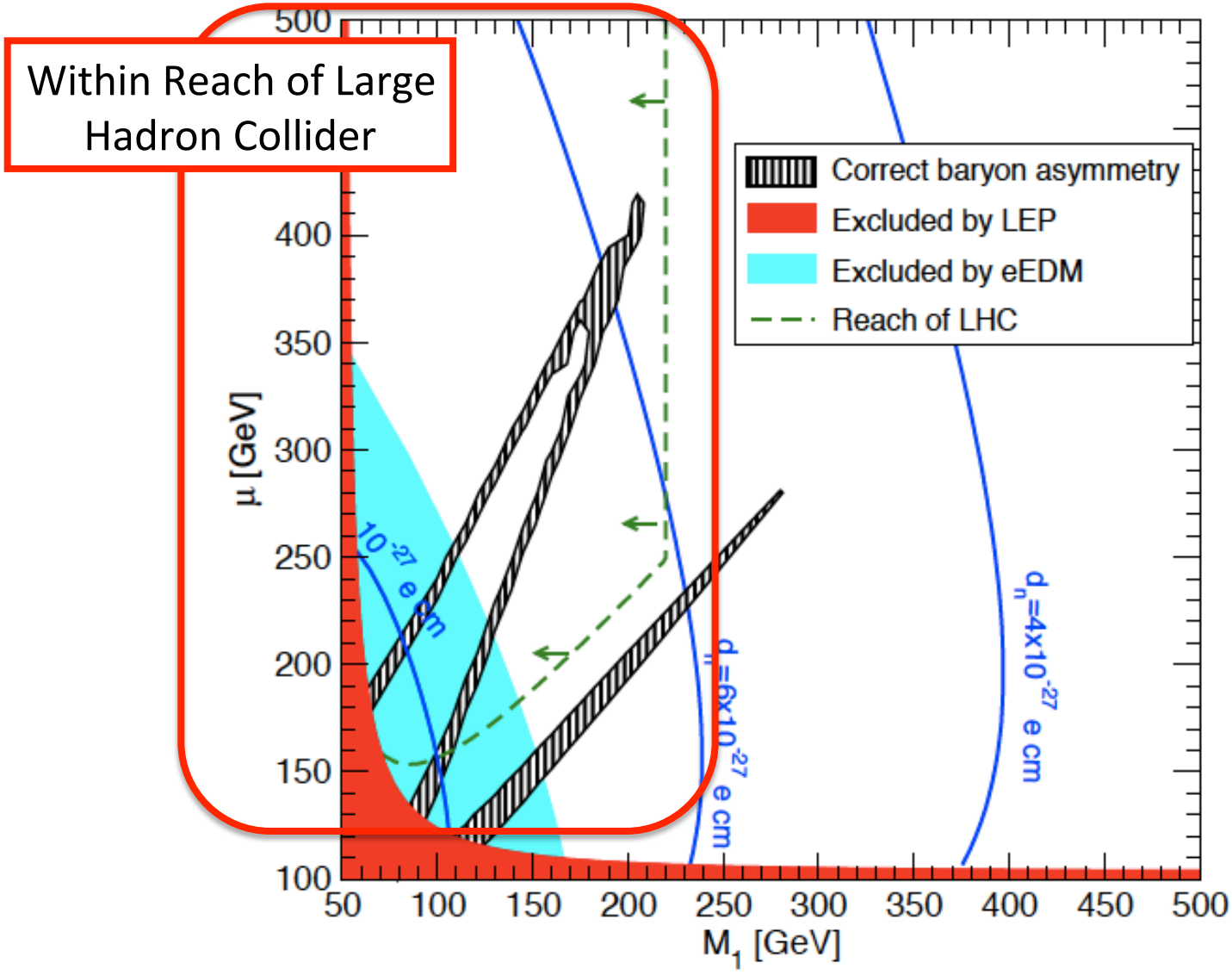


Electro-Weak Baryogenesis



Cirigliano, Profumo and Ramsey-Musolf, JHEP 2009; DoE NP Long Range Plan

Electro-Weak Baryogenesis



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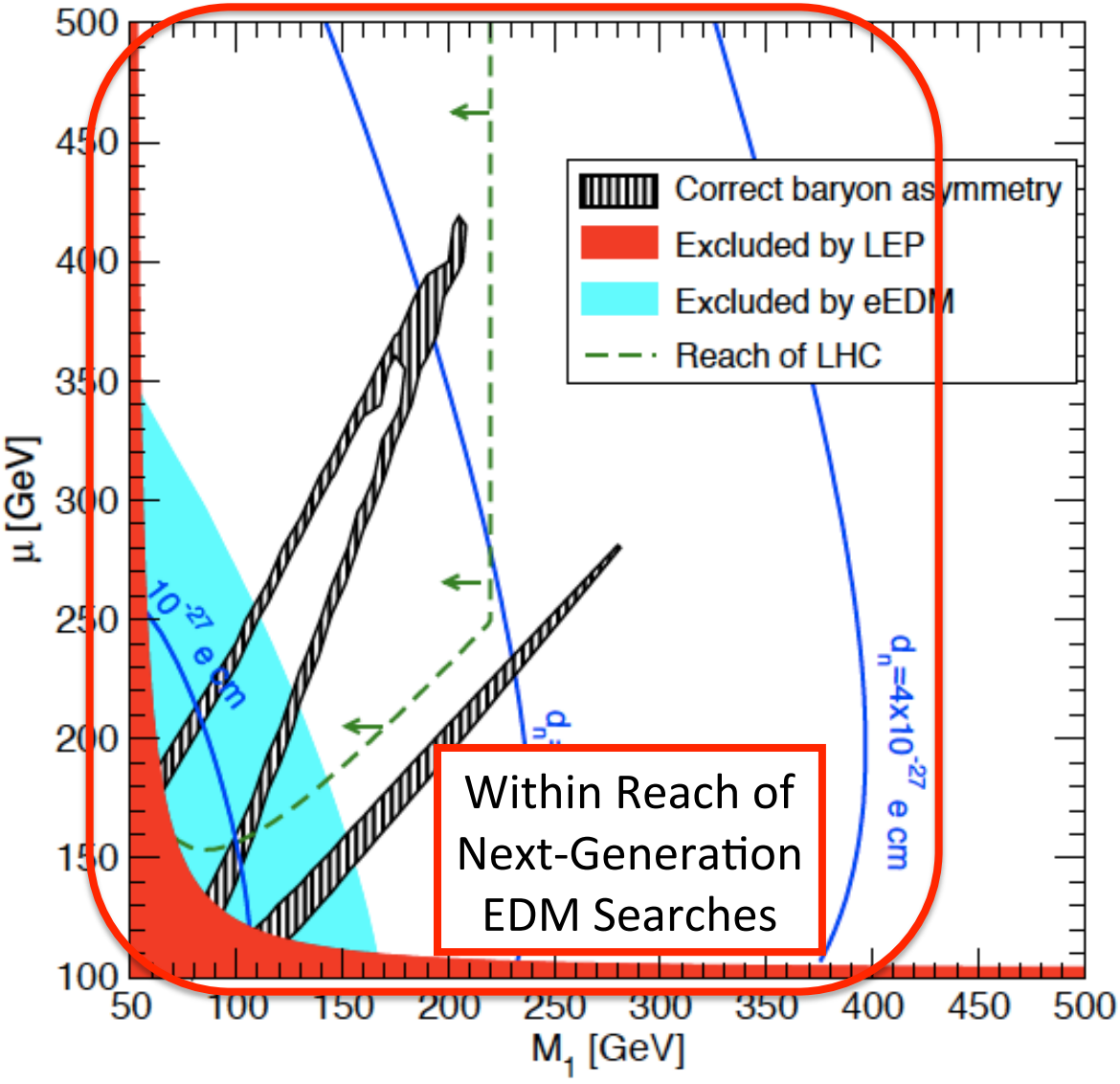
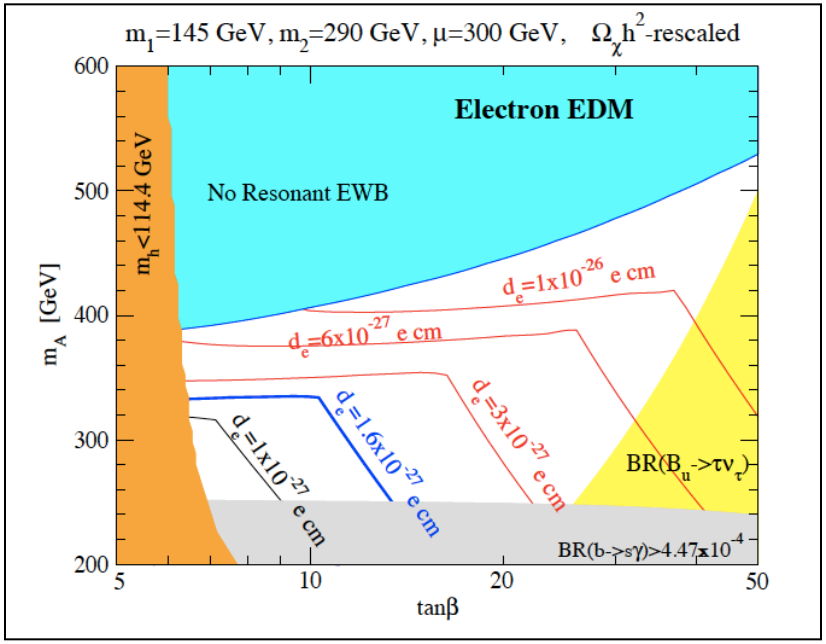


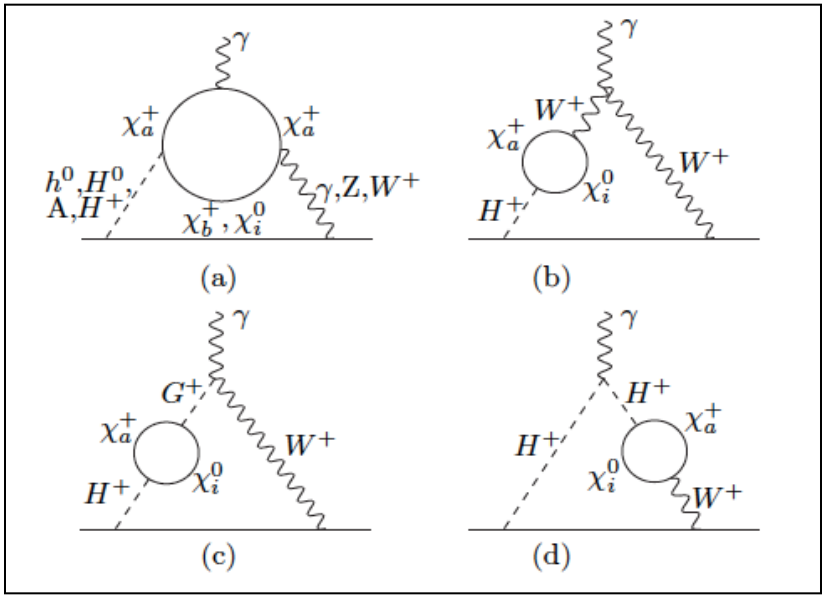
Cirigliano, Profumo and Ramsey-Musolf, JHEP 2009; DoE NP Long Range Plan

Electro-Weak Baryogenesis: Recent Progress

- Comprehensive Phenomenological Analysis of MSSM Electro-weak Baryogenesis (1)



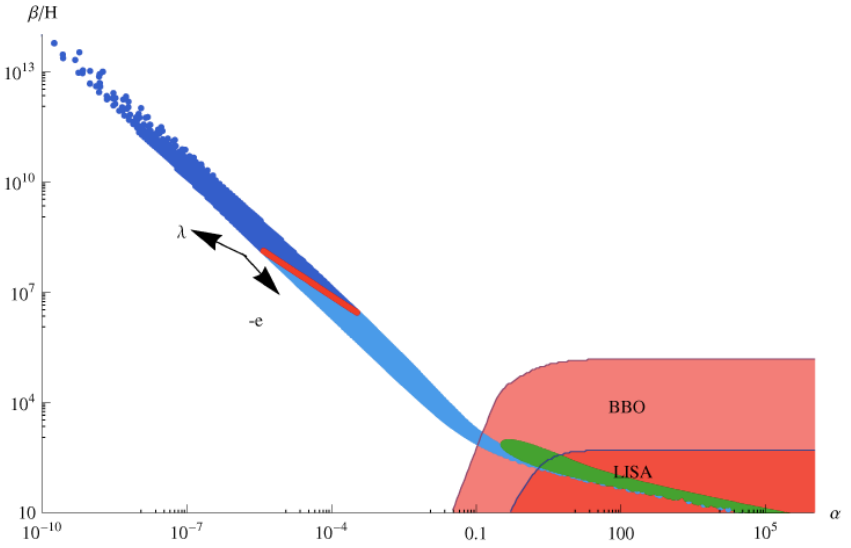
- Complete calculation of electro-weak 2-loop EDM amplitudes (2)
  + publicly available interface to numerical codes (2LEDM, 3)



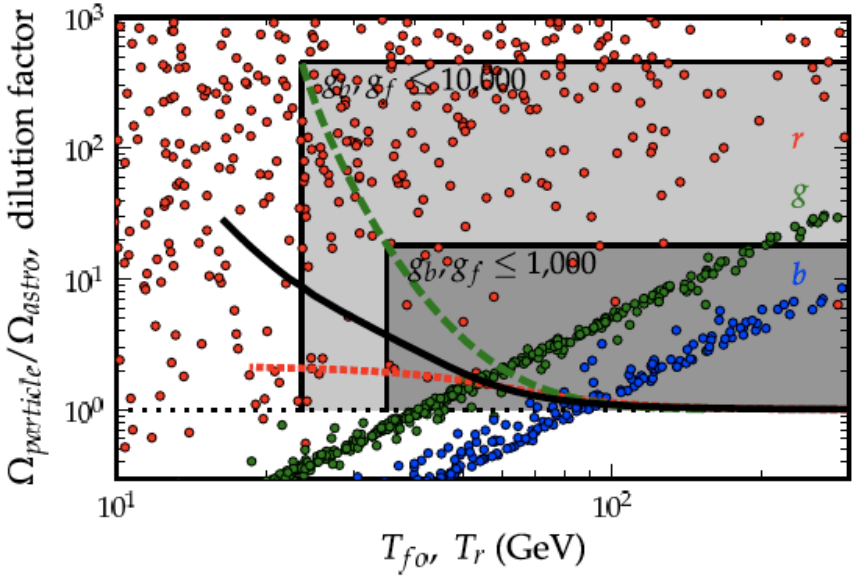
(1) Cirigliano, Li, Profumo, Ramsey Musolf, JHEP 2010
(2) Li, Profumo, Ramsey-Musolf, PRD 2008, PLB 2009
(3) Li, Profumo, Ramsey-Musolf, JHEP 2010

Electro-Weak Baryogenesis: Recent Progress

- Gravity Waves as potential probes of EWB semi-analytic study (4)

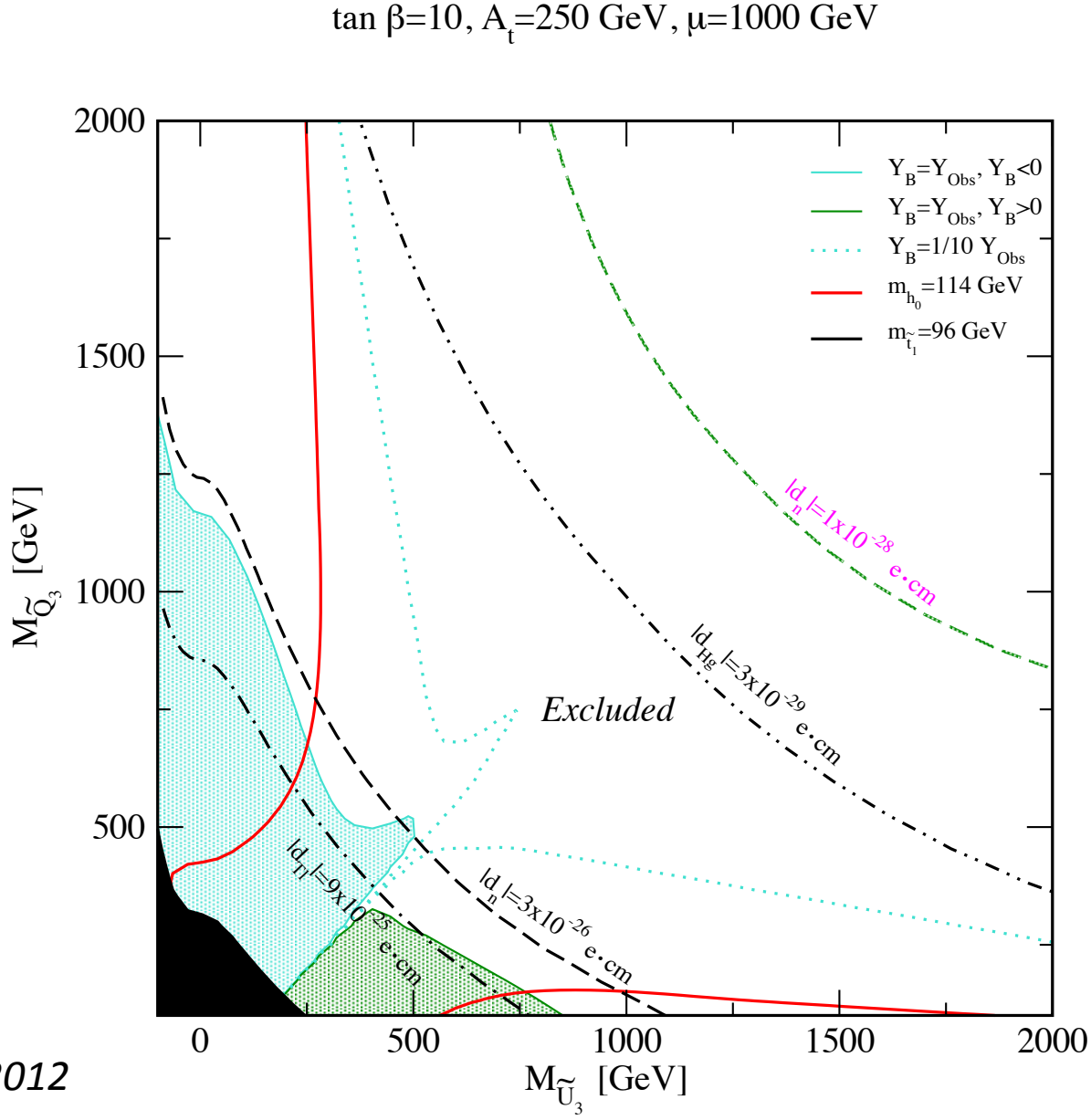


- Impact of strongly first-order EW phase transition on thermal relics (5)



(4) Kehayias and Profumo, JCAP 2010
(5) Wainwright and Profumo, PRD 2009

Baryogenesis: Ongoing Work



Kozaczuk, Wainwright and Profumo, 2012

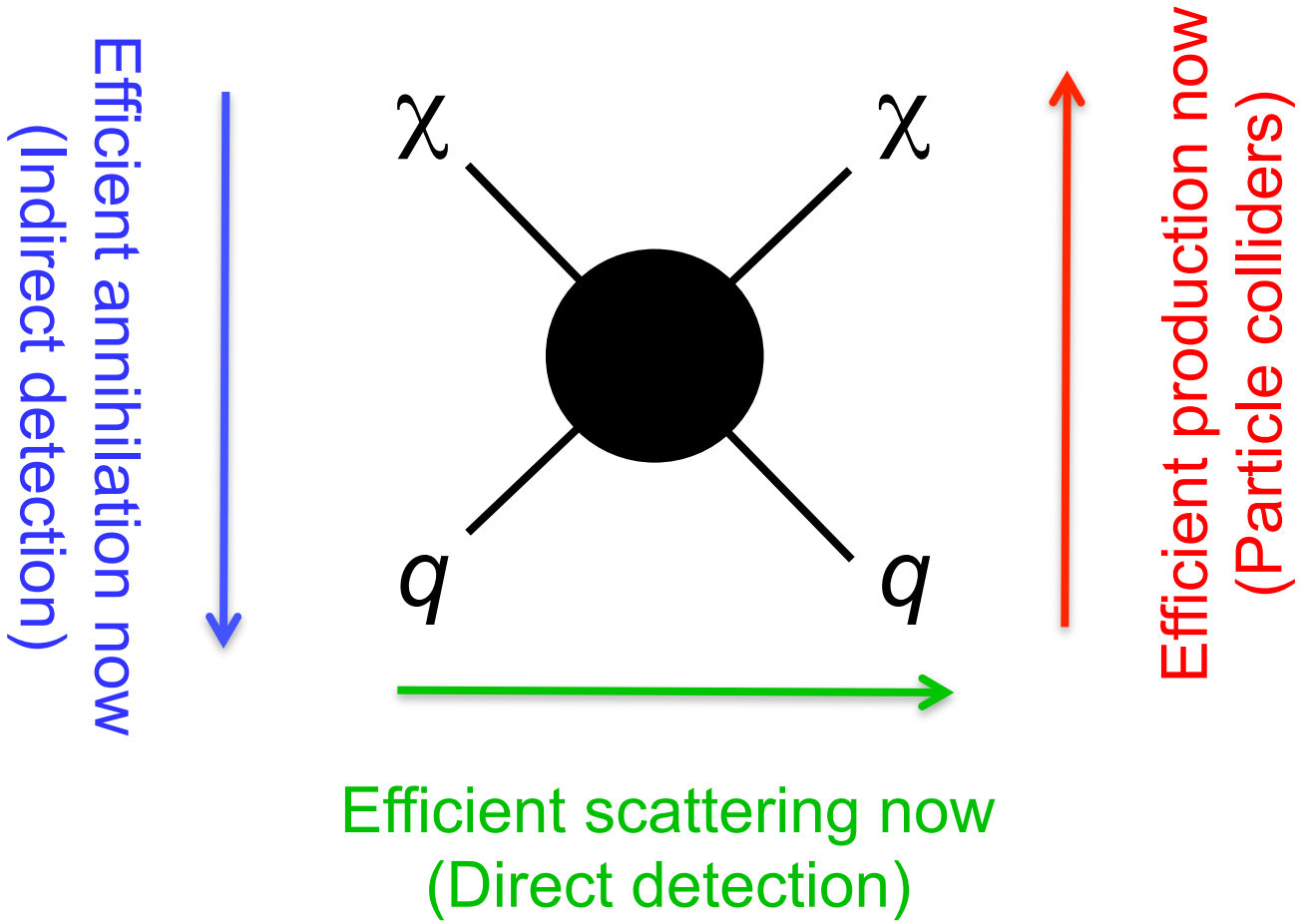
Baryogenesis: Ongoing Work

- New sources for electroweak baryogenesis (staus, sbottoms) *(with **Wainwright** and **Kozaczuk,** 2012)*

- Analysis of issues of gauge invariance in finite-T effective potential *(with **Wainwright** and Ramsey-Musolf, 2012)*

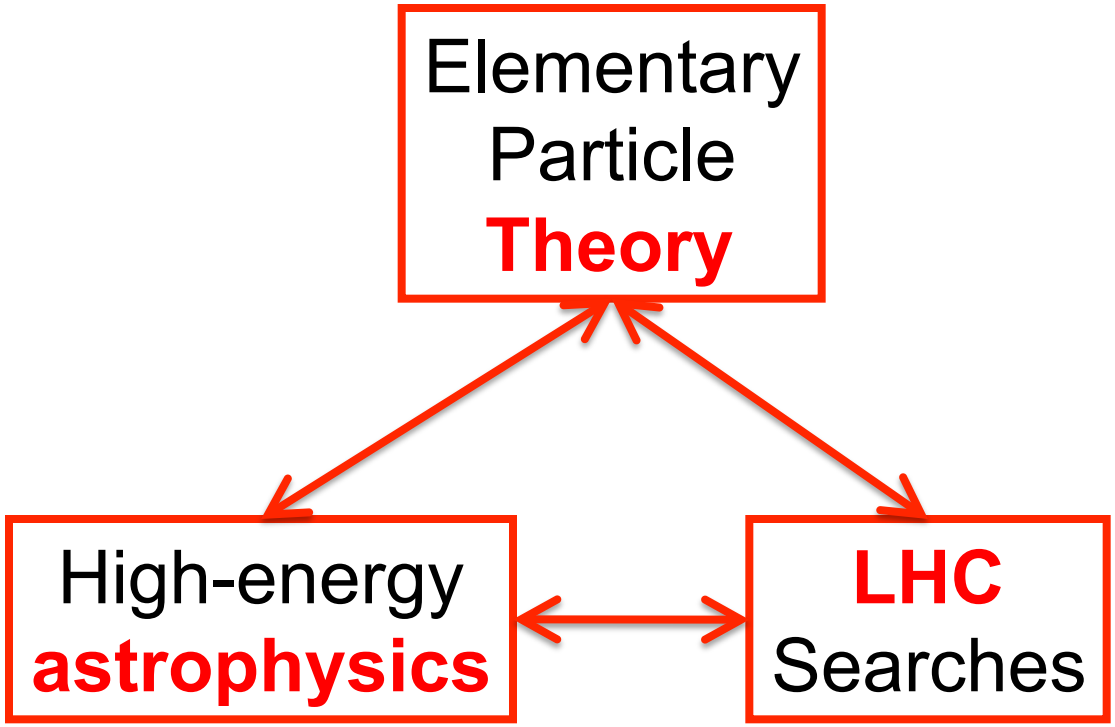
- Self-consistent models for Higgs, 130 GeV line, thermal DM in MSSM+singlet *(with **Wainwright** and **Kozaczuk**, 2013)*

Particle Dark Matter: a multi-pronged approach in a Time of Discovery



Slide Concept: J. Feng

Particle Dark Matter: a comprehensive approach for a cross-disciplinary science

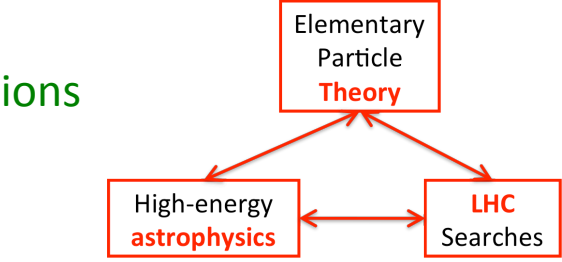


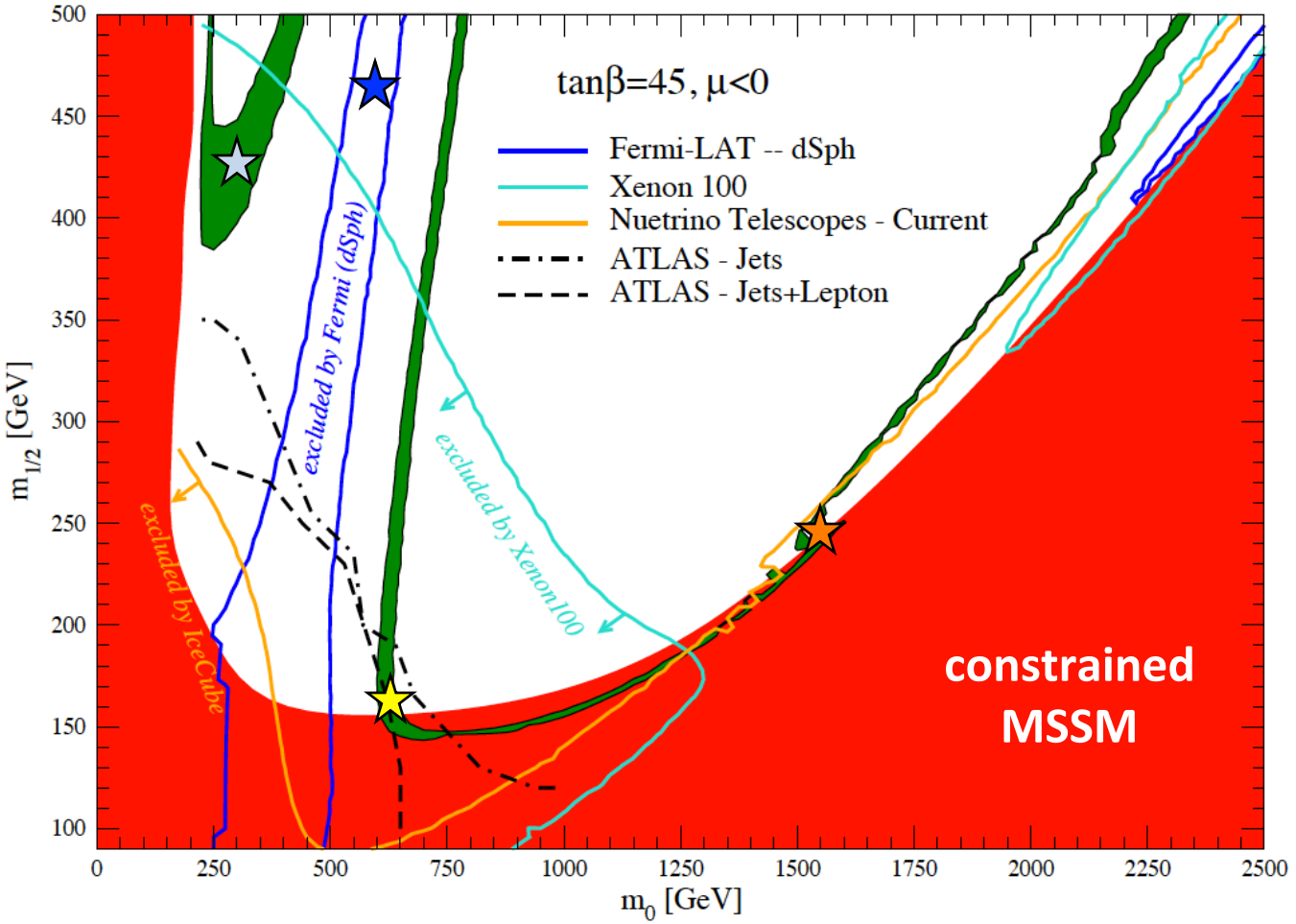
LHC is probing cosmologically interesting regions

Only probed by Direct Detection

Only probed by Neutrino Telescopes

Only probed by Gamma-Ray Telescopes

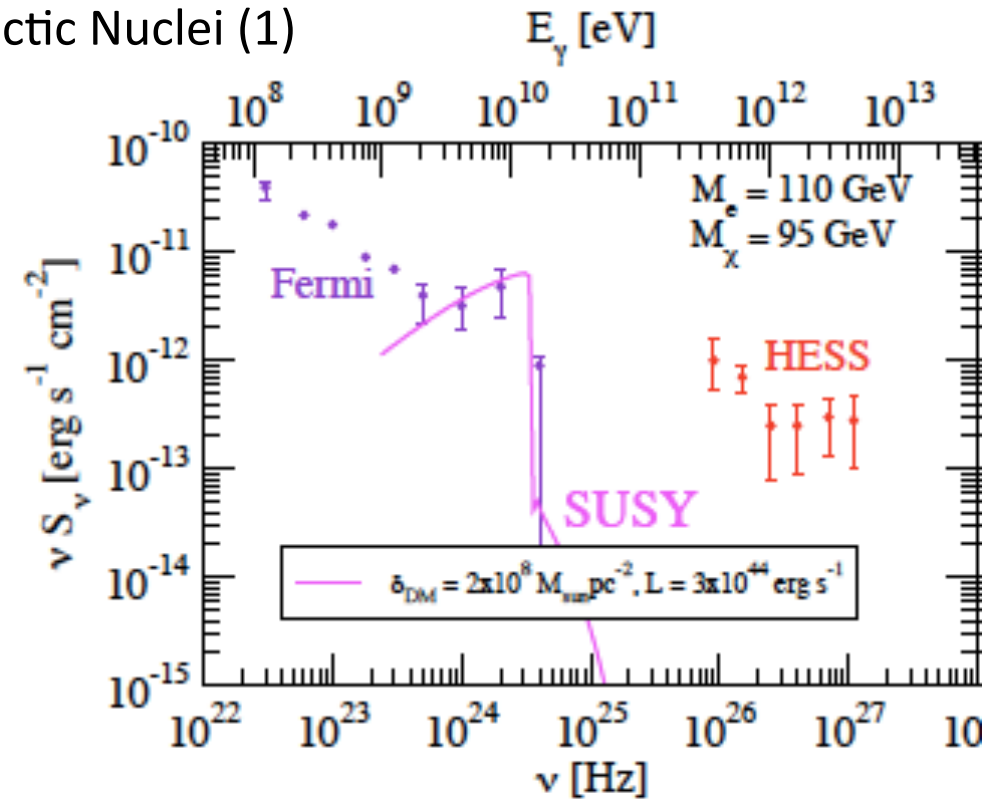




*Profumo, arXiv 1105.5162, Phys. Rev. D **84**, 015008 (2011)

Particle Dark Matter: Theory

- **Electron-DM scattering** in Active Galactic Nuclei (1)



- Singlet dark matter models – **2-photon decay** amplitude, role of meta-stable vacua (2)

- Cosmology of **Saxions** in gauge mediation (3)

- Direct detection in lepton-specific **2 Higgs Doublet models** (4)

(1) Ubaldi, Gorchteyn and Profumo, PRD
(2) Ubaldi, Waiwright and Profumo, PRD
(3) Dine, Profumo and Ubaldi, in preparation
(4) Boucenna, Cornell and Profumo

Particle Dark Matter: LHC Physics

- Searches for **2UED** with LHC; ATLAS code development (**FeynRules -> Madgraph**) (1)

- Vertex $\{WH11i,1\}, \{WH11i,2\}, \{Wmu11i,3\}, \{W$

$$-\frac{3}{4}ig_w^2\delta_{k_1,k_4}\delta_{k_2,k_3}\eta_{\mu_3,\mu_4} - \frac{3}{4}ig_w^2\delta_{k_1,k_3}\delta_{k_2,k_4}\eta_{\mu_3,\mu_4}$$

- Vertex $\{Wmu11i,1\}, \{Wmu11i,2\}, \{Wmu11i,3\}, \{$

$$-\frac{9}{2}ig_w^2\delta_{k_1,k_4}\delta_{k_2,k_3}\eta_{\mu_1,\mu_4}\eta_{\mu_2,\mu_3}+\frac{9}{4}ig_w^2\delta_{k_1,k_3}\delta_{k_2,k_4}\eta$$
$$\frac{9}{4}ig_w^2\delta_{k_1,k_4}\delta_{k_2,k_3}\eta_{\mu_1,\mu_3}\eta_{\mu_2,\mu_4} - \frac{9}{2}ig_w^2\delta_{k_1,k_3}\delta_{k_2,k_4}\eta_{\mu_1,\mu_3}\eta$$
$$\frac{9}{4}ig_w^2\delta_{k_1,k_4}\delta_{k_2,k_3}\eta_{\mu_1,\mu_2}\eta_{\mu_3,\mu_4} + \frac{9}{4}ig_w^2\delta_{k_1,k_3}\delta_{k_2,k_4}\eta_{\mu_1,\mu_2}\eta$$

- **Multi-top** (4x, 6x, 8x) LHC searches (2)

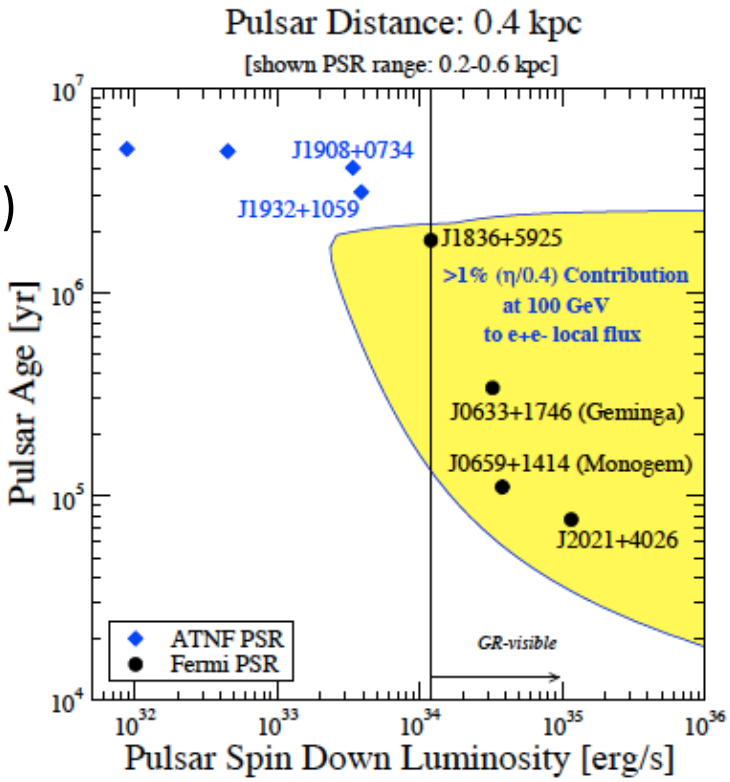
- Discriminating **axinos** and **gravitinos** at LHC (3)

(1) Manning and Profumo, in progress
(2) Manning, Profumo and Seiden, in progress
(3) Lee, Profumo and Ubaldi, in progress

Particle Dark Matter: Astrophysical Backgrounds

The field does not seem to need theory model building as much as **reliable assessment of signals**, and hence of the relevant **astrophysical backgrounds**

- **Pulsars** as sources of high-energy positrons – connection to Fermi gamma-ray pulsars (1)
- **Milli-second pulsars** and diffuse gamma rays (2)
- Systematic effects in signals from diffuse emissions ("**Fermi Haze**")(3)
- Hadronic models for **cluster radio halos** (4) – relevant for **Cosmology** !!!

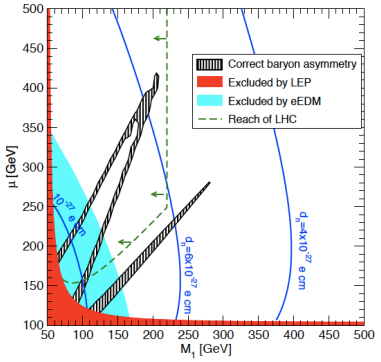


(1) Gendelev, Profumo and Dormody, JCAP 2010
(2) Siegal-Gaskins, Profumo et al, MNRAS 2011
(3) Linden and Profumo, APJL 2011
(4) Jeltema and Profumo, Astroph. J. 2010

Summary

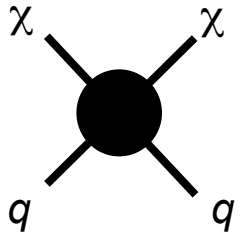
Testable theories for

the **origin of matter**

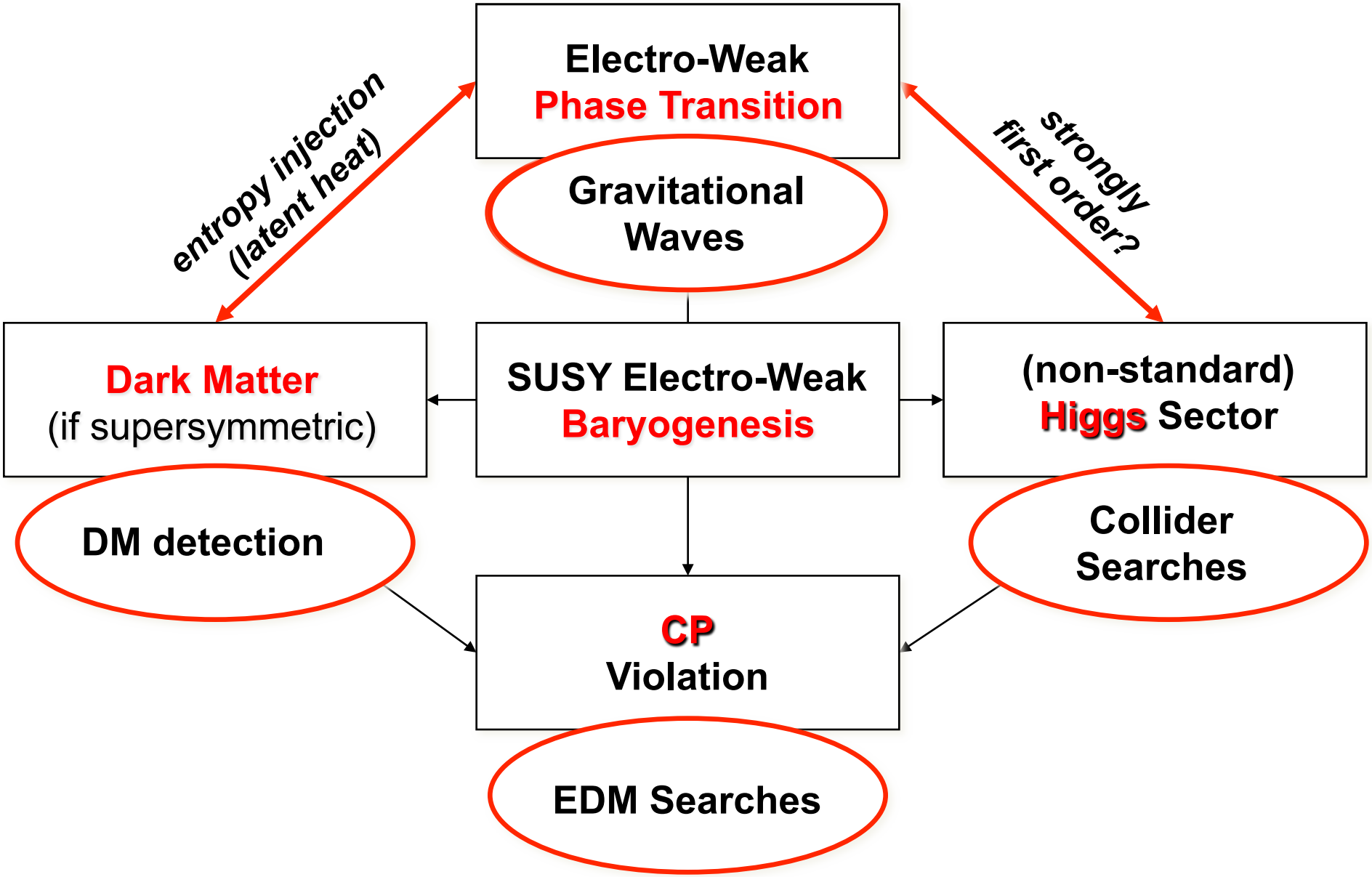


A **cross-disciplinary approach**

in the hunt for **dark matter**



Electro-Weak Baryogenesis: Probes



Ingredients of Baryogenesis

- ***B***aryon Number violation

  If B is conserved, the present BAU can only reflect asymmetric initial conditions

- ***C*** and ***CP*** violation

  In the absence of a "preference" for matter or antimatter, B-noncoserving interactions will produce baryon and antibaryon excesses at the same rate: no net baryogenesis

- **Out of Equilibrium** conditions

  In chemical equilibrium the entropy is maximal when the chemical potential associated with all nonconserved quantum numbers vanishes

"Sakharov conditions"(*)

(*)A.D.Sakharov, JETP Letters **5**, 24 (1967)

Electro-Weak Baryogenesis

The Electro-Weak Phase Transition fulfills all

3 Sakharov requirements[(*)] (**Electro-weak Baryogenesis**)

[(*)]V.A.Kuzmin, V.A.Rubakov and M.E.Shaposhnikov, Phys.Lett. **B197**, 49 (1989)

Electro-Weak Baryogenesis

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✓ ***B*** violation: Weak **Sphaleron** Transitions

(*)V.A.Kuzmin, V.A.Rubakov and M.E.Shaposhnikov, Phys.Lett. **B197**, 49 (1989)

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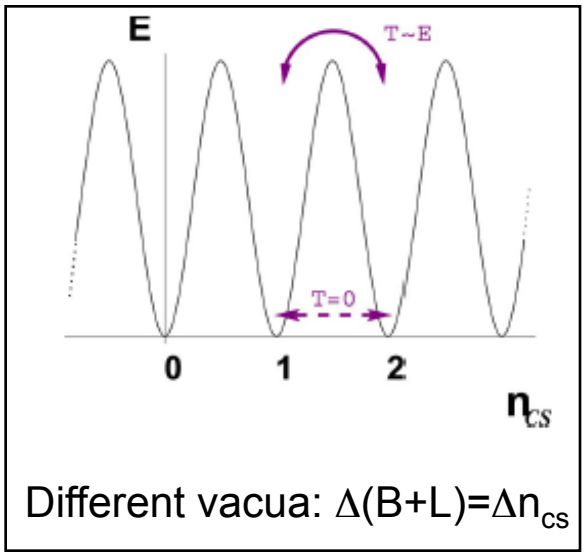

Different vacua: $\Delta(B+L)=\Delta n_{cs}$

- *Classically, baryonic and leptonic currents are **conserved** in the EW theory*
- *Quantum corrections produce **anomalous transitions** between non-degenerate SU(2) field configurations vacua that **violate B+L** (but preserve B-L)*
- ***B-violation** rate is **unsuppressed** at $T>T_c$, and is **exp**onentially suppressed at $T<T_c$*

$$\Gamma_{sph} \propto \alpha_W T^4$$

$$\Gamma_{sph} \propto \exp[-E_{sph}(T)/T]$$

$$E_{sph}(T) \propto \langle\phi\rangle(T)$$

(*)V.A.Kuzmin, V.A.Rubakov and M.E.Shaposhnikov, Phys.Lett. **B197**, 49 (1989)

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- ✓ ***B*** violation: Weak **Sphaleron** Transitions
- ✓ ***CP*** violation: **CKM** (*or new CP-phases)*

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- ✓ ***B*** violation: Weak **Sphaleron** Transitions
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- ✓ ***Out of Equilibrium***: **Bubble Walls** of broken EW phase

(*)V.A.Kuzmin, V.A.Rubakov and M.E.Shaposhnikov, Phys.Lett. **B197**, 49 (1989)

Electro-Weak Baryogenesis

The Electro-Weak Phase Transition fulfills all

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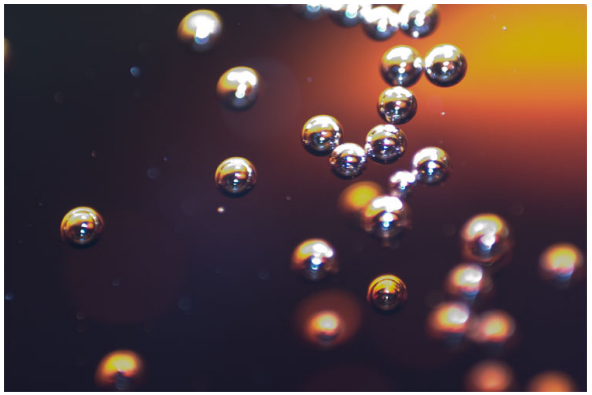
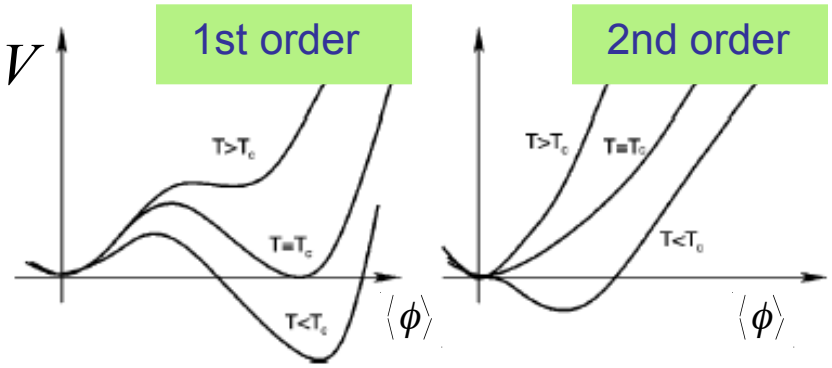


✓ ***B*** violation: Weak **Sphaleron** Transitions

✓ ***CP*** violation: **CKM** (*or new CP-phases)*

✓ ***Out of Equilibrium***: **Bubble Walls** of broken EW phase



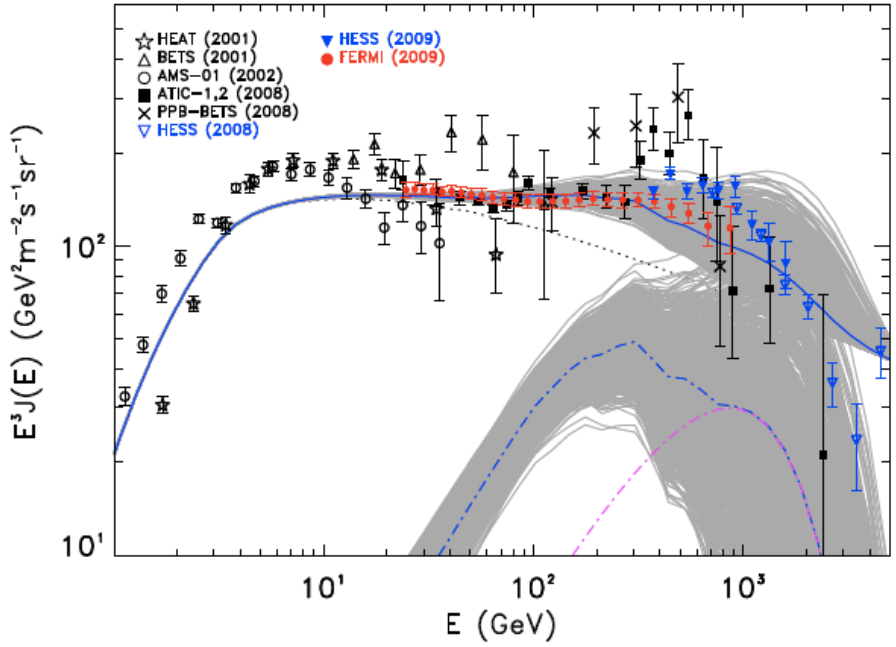
- *If the EWPT is first order (cubic term!), it proceeds through Bubble nucleation*
- *The (expanding) Bubble Walls are out of thermal equilibrium*

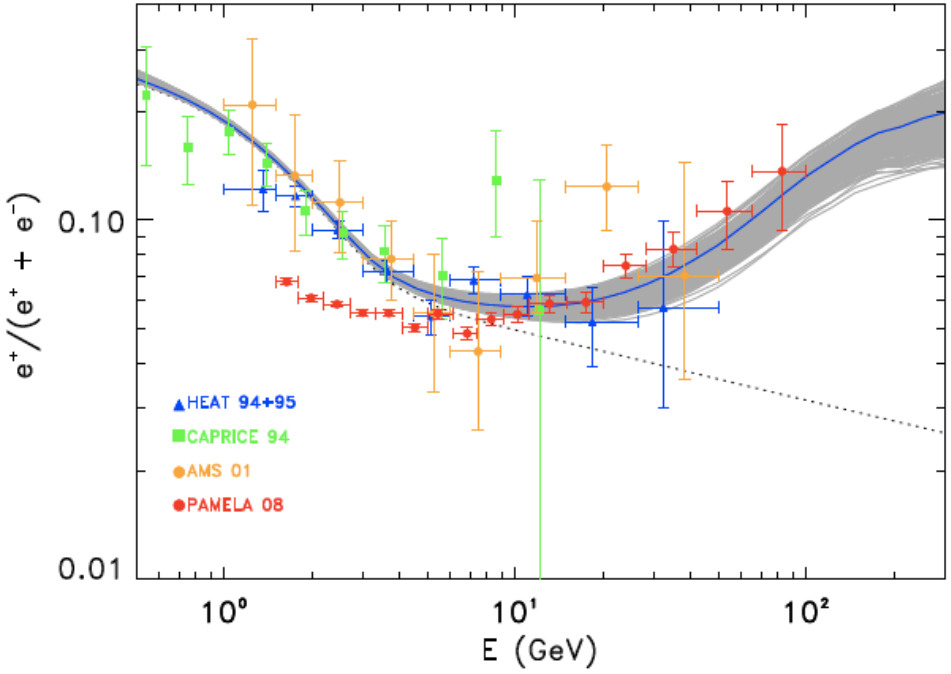
(*)V.A.Kuzmin, V.A.Rubakov and M.E.Shaposhnikov, Phys.Lett. **B197**, 49 (1989)

Particle Dark Matter: Indirect Detection and Theory

- **Cosmic Rays**

- Interpretation of Fermi electron/positron data (1)
- Fermi pulsars vs excess positrons (2)
- Dark Matter vs excess positrons (3,4,5)





(1) Grasso, Profumo, Strong et al, Astropart.Phys. 2009
(2) Gendelev, Profumo and Dormody, JCAP 2010
(3) Jeltema and Profumo, JCAP 2009
(4) Brun, Delahayie, Diemand, Profumo, PRD 2009
(5) Cyr-Racine, Profumo and Sigurdson, PRD 2009

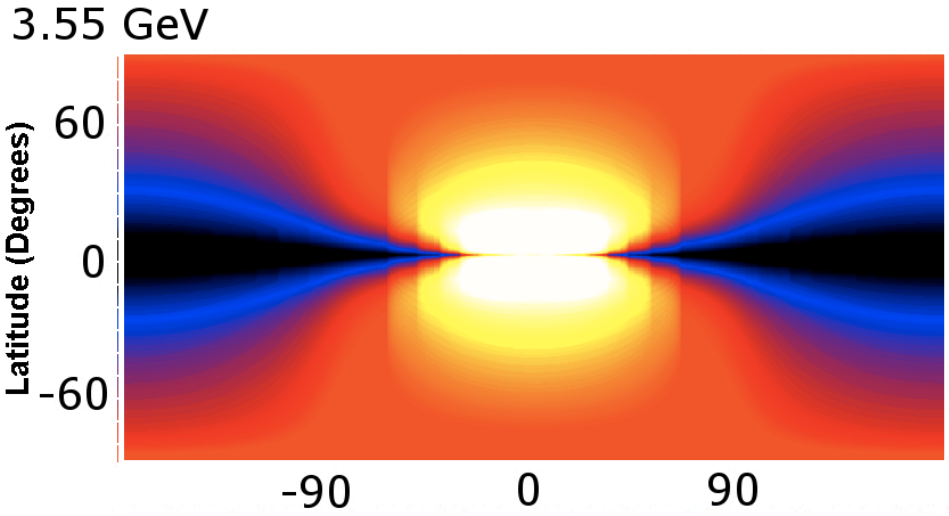
Particle Dark Matter: Indirect Detection and Theory

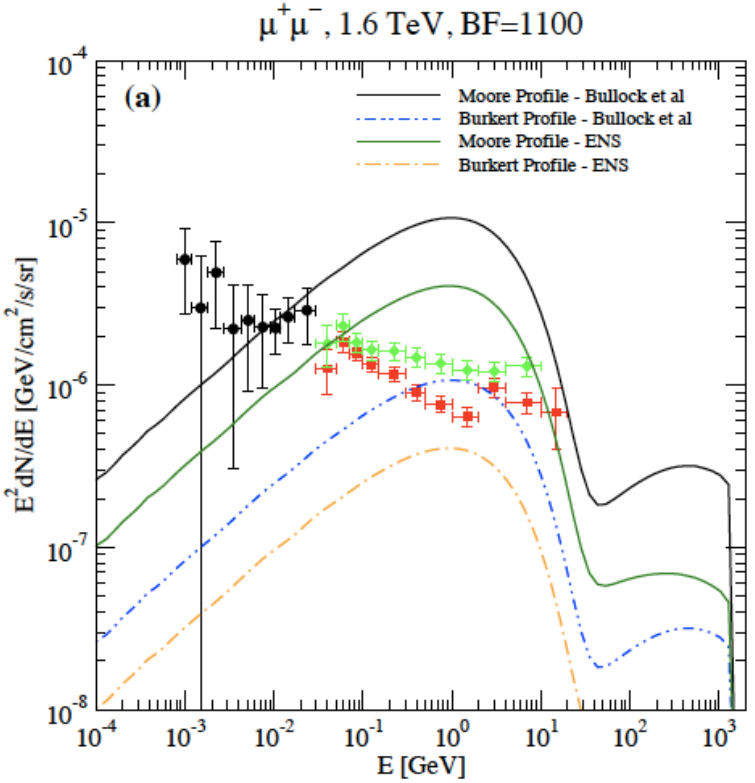
- **Diffuse Emissions**

  - WMAP Haze with consistent CR models (1)
  - A Fermi haze? Systematic effects (2)
  - Extragalactic Inverse Compton (3)

- **Theory/Multi-disciplinary**

  - Multi-component Dark Matter models: direct, indirect and collider searches (4)





(1) Linden, Profumo and Anderson, PRD 2010 sub.
(2) Linden and Profumo, Astroph. J. Lett. 2010
(3) Jeltema and Profumo, JCAP 2009
(4) Profumo, Sigurdson and Ubaldi, PRD 2009