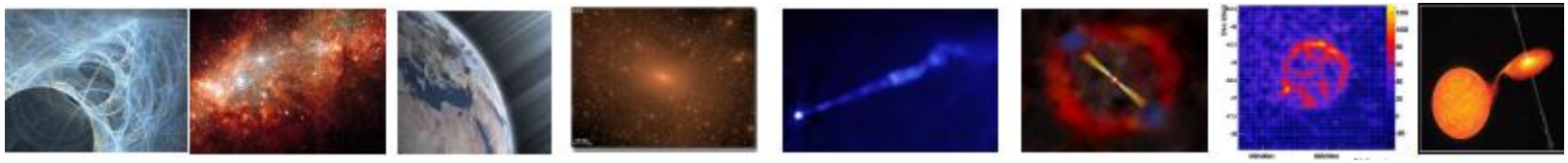
Introduction au domaine d'Astroparticules



Agnieszka Jacholkowska

Biennale, LPNHE, Tirrenia 06/10/2016

Plan

Introduction – Rayons Cosmiques (CRs)

1. Rayons Cosmiques de Très Hautes Energies – UHECRs

2. Brisure de Invariance de Lorentz (LIV) et Gravité Quantique (QG)

3. Recherches Indirectes de la Matière Noire – DM

Conclusions

Domaine d'Astroparticules

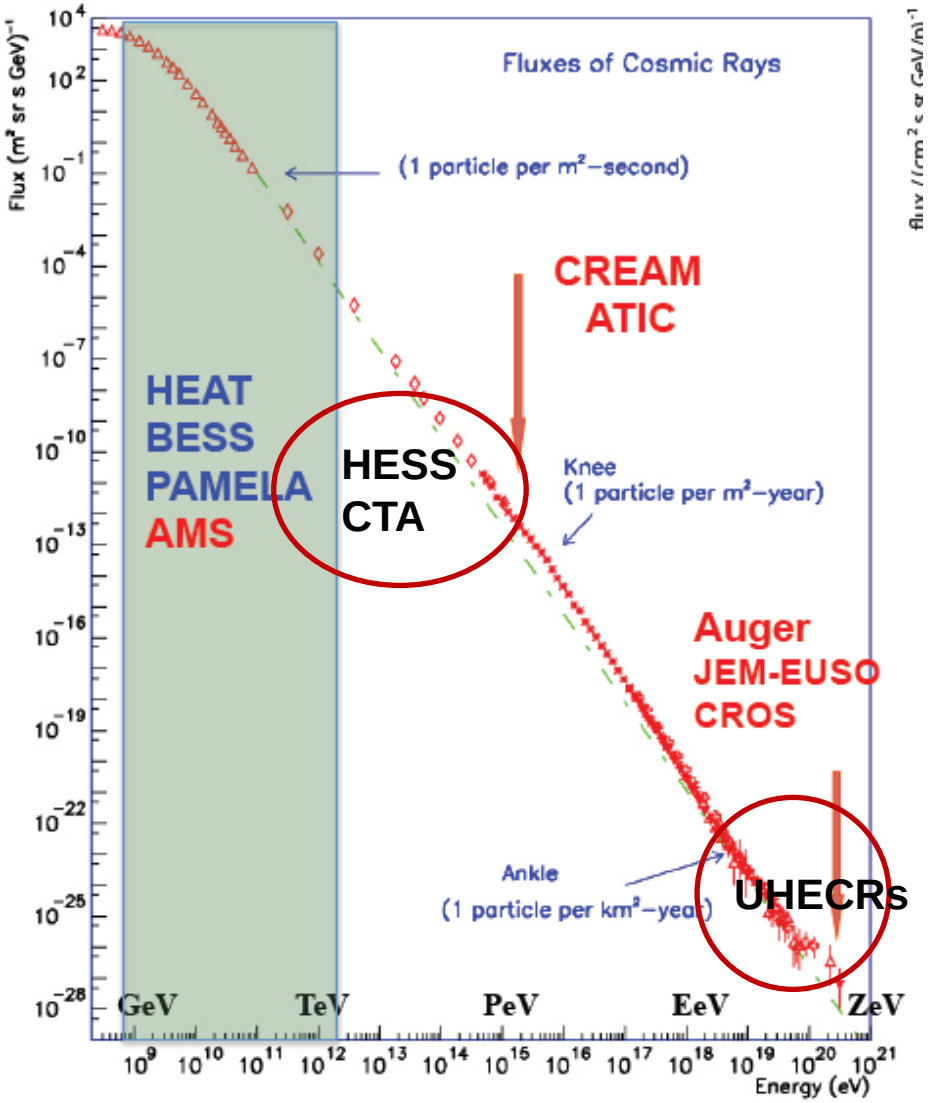
1. **Multidisciplinaire**
   Astrophysique – Physique des Particules – Cosmologie
   Astrophysique: compréhension des processus de production
   et propagation des Rayons Cosmiques (CRs)
   Physique des Particules: Modèle Standard (SM) + Extensions
   fournit candidats aux particules et interactions
   Cosmologie: paramètres cosmologiques (ΛCDM)

2. **Multi-messager:** confirmation des résultats dans différents canaux
   fort impact sur les modèles

3. **Multi-longueur d'onde**
   Synergie avec observations astrophysiques à basses fréquences
   Radio, Optique, Rayon-X

→ **Domaine Fédérateur de différentes disciplines**

Rayons Cosmiques



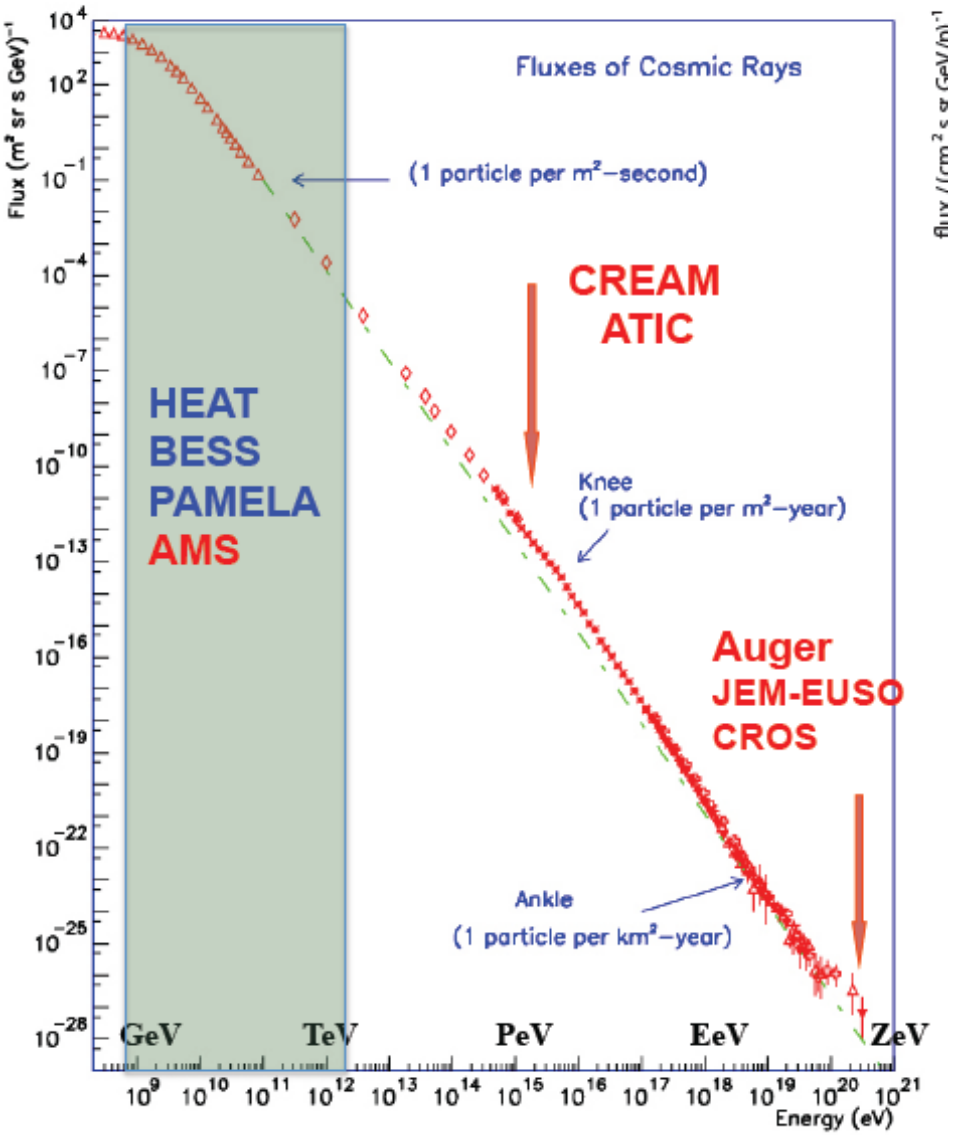
Impressionnant:

Spectre en énergie couvre 12 décades :MeV – ZeV

Question Fondamentale:
<u>Origine</u> (depuis > 50 ans)

Sources - (extra) galactiques
Processus – standards ou exotiques ?

Mesures avec CRs



Mesures primaires:

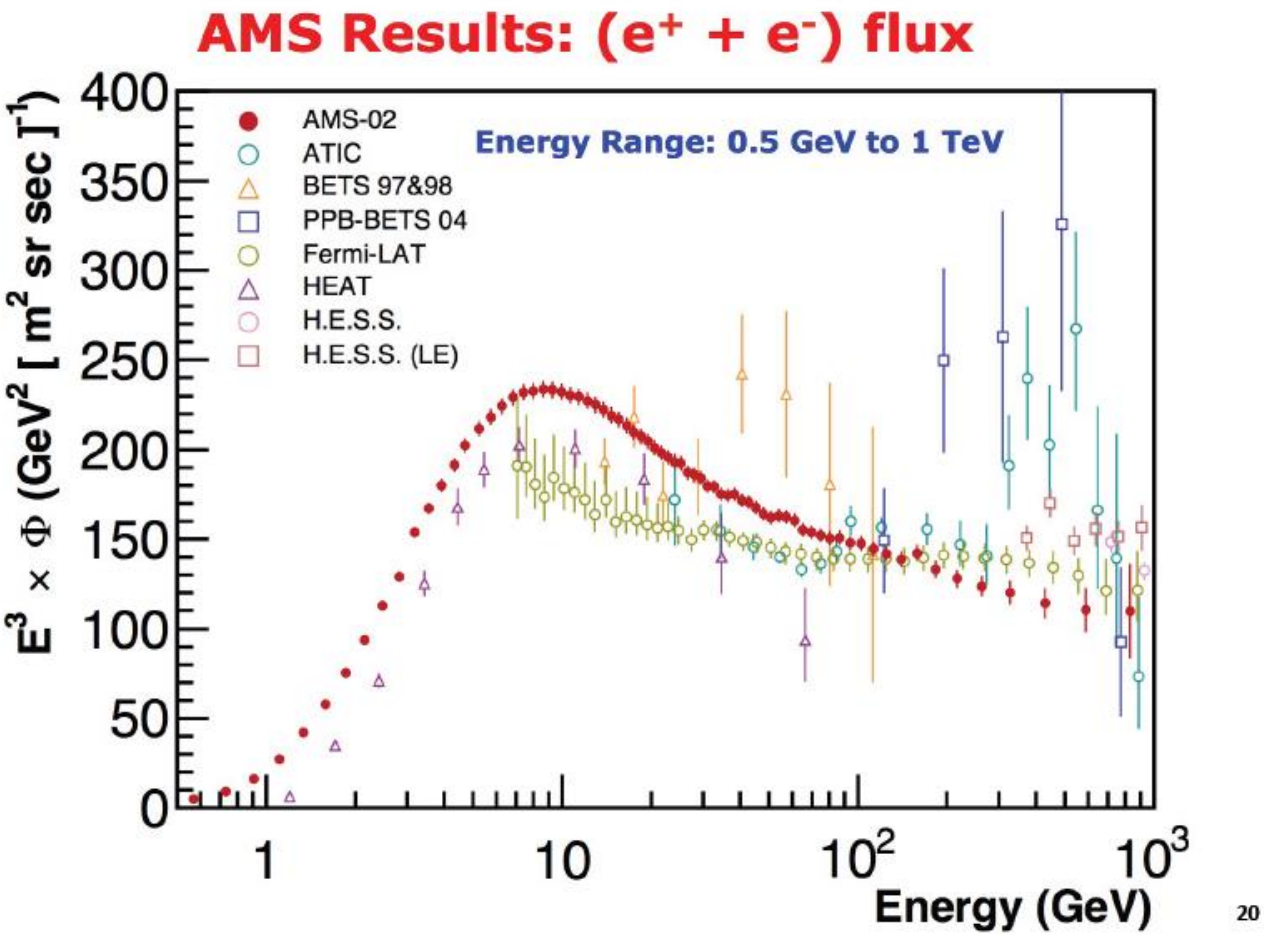
Temps d'arrivée - T
Energie - E
Direction – θ (angle d'émission)
Composition – nature
p, ions, e-, ɣ, v + antimatière

Flux & Courbes de Lumière (LC) reconstruit en variables à la source
Nécessite hypothèses et modélisation MC

→ entités physique évoluées
ex. LIV: échelle de QG
<σv>:section efficace d'annihilation de DM

Spectre en énergie des $e^+ + e^-$

PRL 113, 221102 (2014) PHYSICAL REVIEW LETTERS week ending 28 NOVEMBER 2014



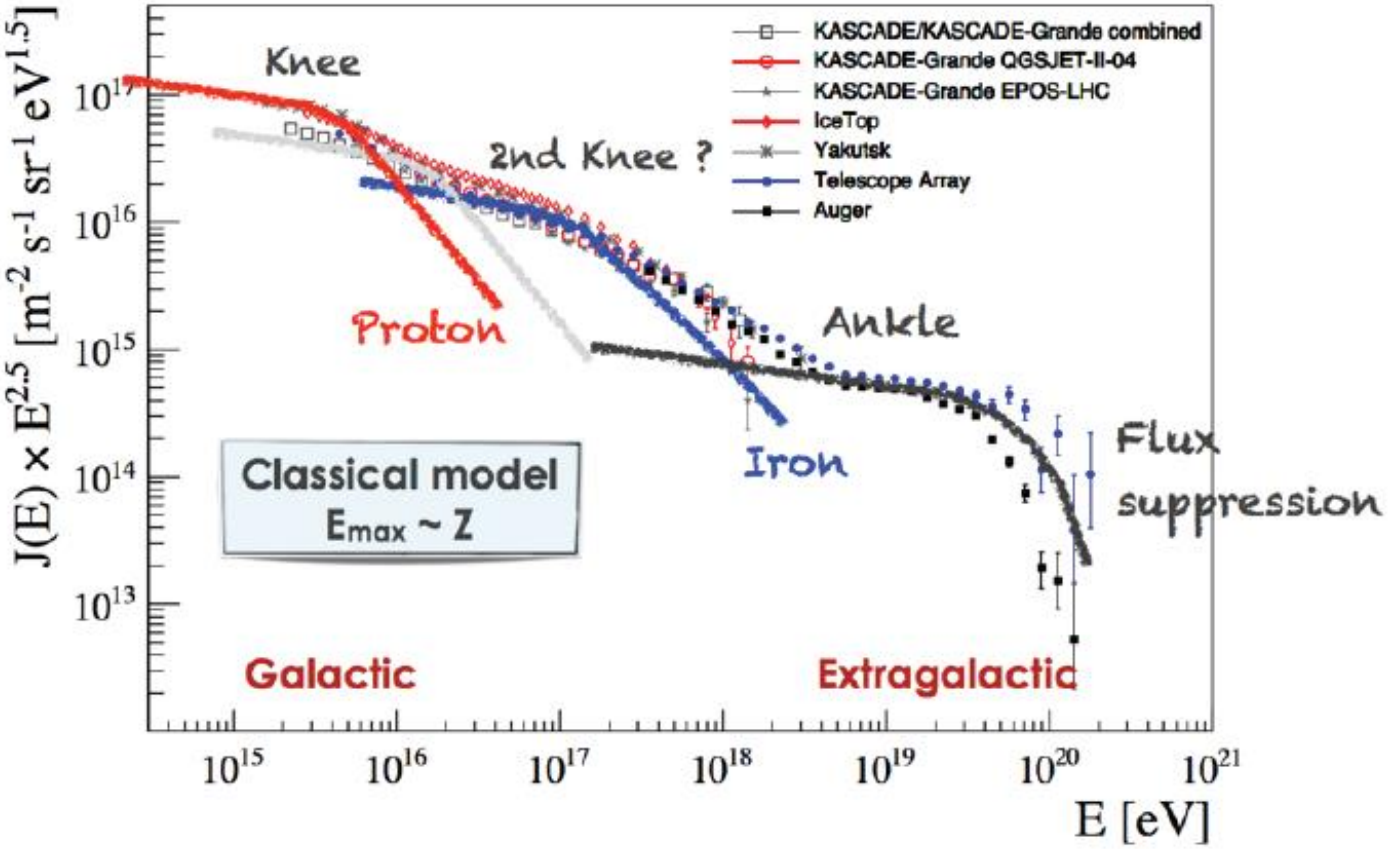
H.E.S.S. : nouveaux résultats en attente – voir thèse de D. Kerszberg

Études avec UHECRs

UHECRs: "state of art"

M. Settimo, ICHEP 2016

The classical model (not the only possible interpretation)

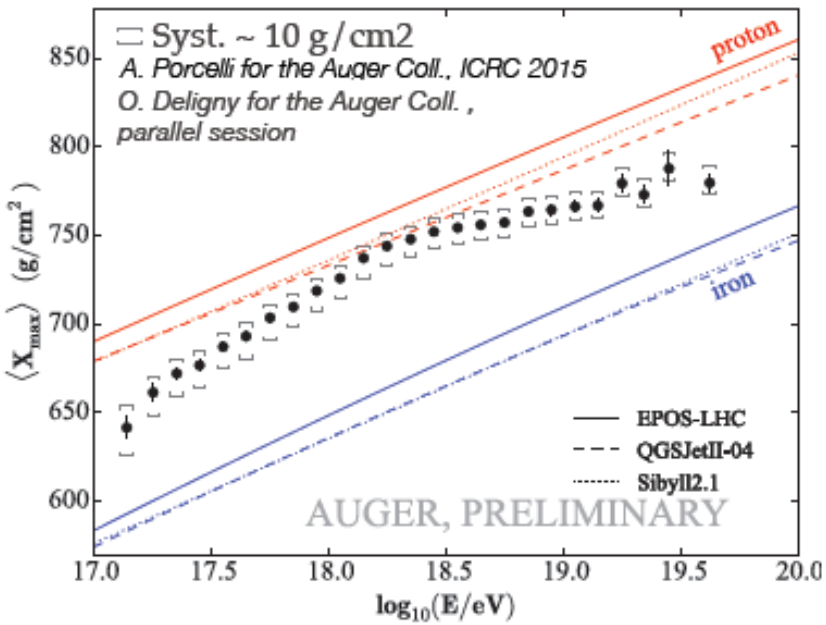


→ mesures précises permettant de interprétations complexes

UHECRs: composition en masse

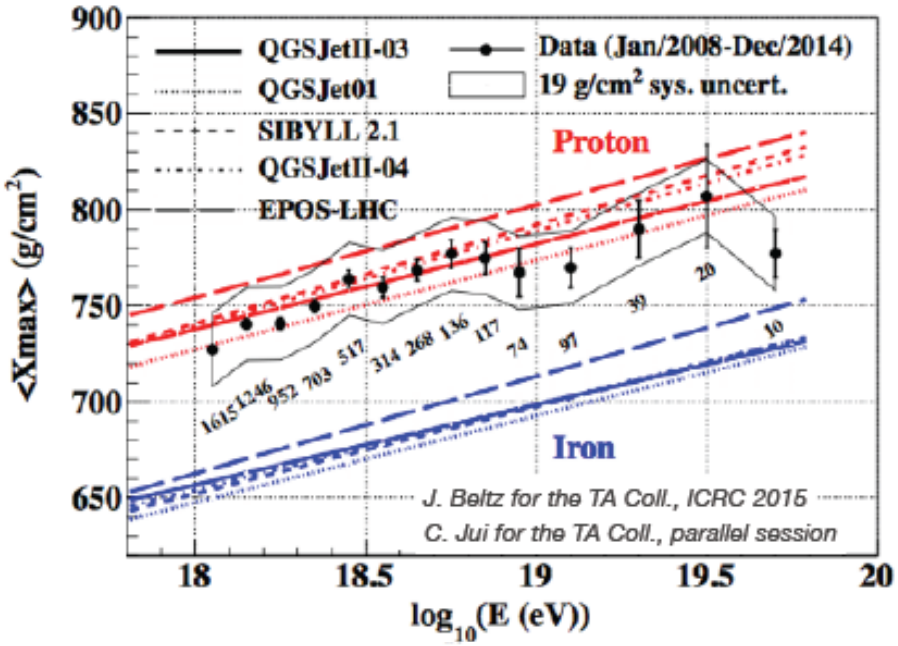
M. Settimo, ICHEP 2016

Pierre Auger Observatory



Change in composition and break point at E ~$10^{18.3}$ eV

Telescope Array



Proton dominant composition

→ future: combiner résultats AUGER et Telescope Array

UHECRs: anisotropie E > 5.5 EeV

M. Settimo, ICHEP 2016

Telescope Array

Max significance: 5.1σ (pre-trial)
post-trial: 3.4 σ
E_{thr} > 57 EeV, ψ = 20°

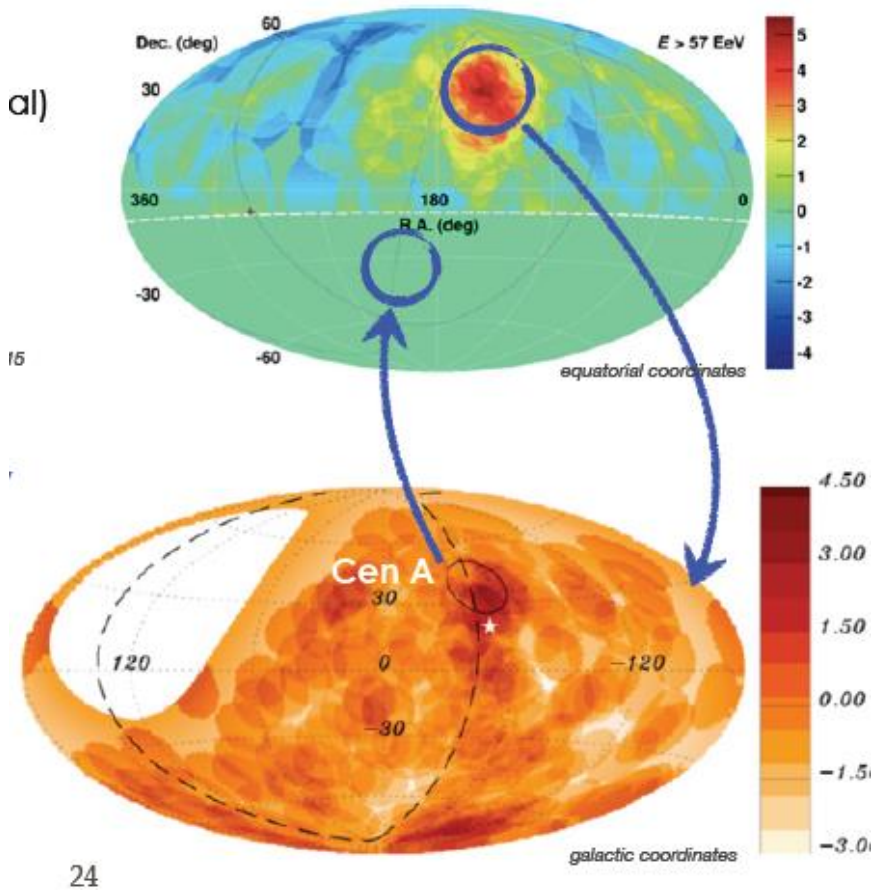
(N_{obs} = 24, N_{bg}=6.88)

K.Kawata for the Telescope Array Collab., ICRC 2015

Pierre Auger Observatory

Largest excess: pre-trial 4.3 σ,
69% post-trial probability)

E_{thr} > 54 EeV, ψ = 12°,
N_{obs} = 14 / N_{bg} = 3.23



→ discussions concernant traitement statistique

UHECRs – perspectives

UHECRs fournissent résultats aux énergies extrêmes >> E_{LHC}

Plusieurs nouveaux résultats avec précision croissante
parfois contradictoires
→ "upgrades" des expérience (ex. AUGER-muons)

Questions ouvertes:

- transition Galactique- Extra-galactique
- origine de la cheville
- composition aux énergies intermédiaires
- sources: besoin d'**études multi-messagers** – corrélations avec émission gamma
- modélisations …

Physique Fondamentale avec Rayons-γ

Gravité Quantique – Théorie globale ?

Objectif:
réunir Mécanique Quantique et Relativité Générale

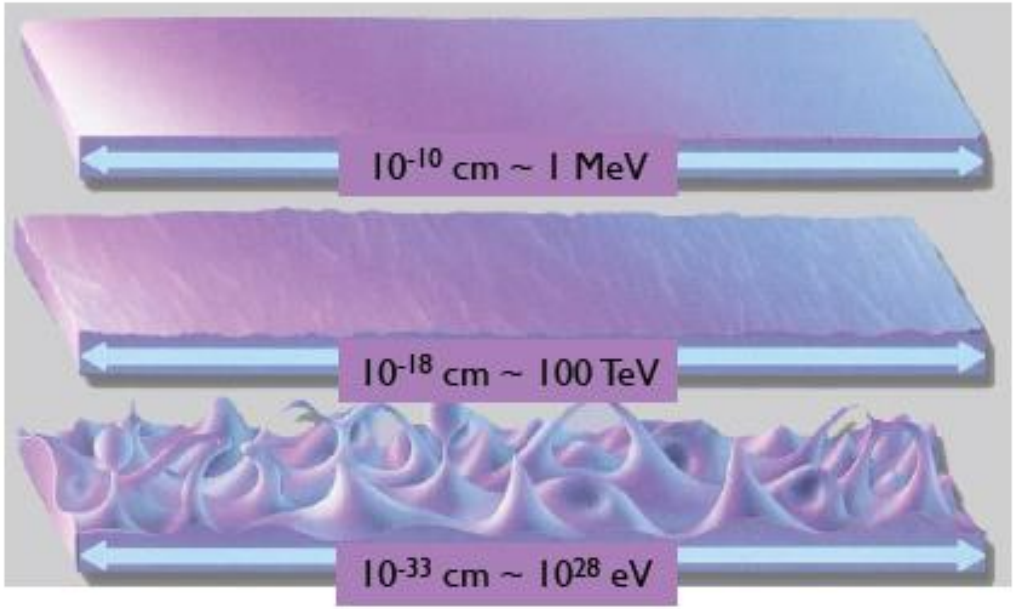
→ Three roads to Quantum Gravity
(Lee Smolin, 2000):

- In **Loop Quantum Gravity** scheme
  (e.g. Gambini, Pullin 1999, Alfaro et al., 2002)

- In extra-dimension **String Theories**
  Liouville strings, <u>space-time foam</u>, non-comutative geometry, …
  (e.g. J. Ellis, N. E. Mavromatos, D.V.Nanopoulos 1999,
  L.J. Garay 1998, G. Amelino-Camelia 2001)

- **Black Hole** thermodynamics – physics at Planck scale
  (e.g. Hawking, Penrose, 2000)

Tests de l'Invariance de Lorentz



Structure Quantique
de l'espace-temps peut produire
dépendance de la vitesse c de la lumière dans vide avec énergie du photon

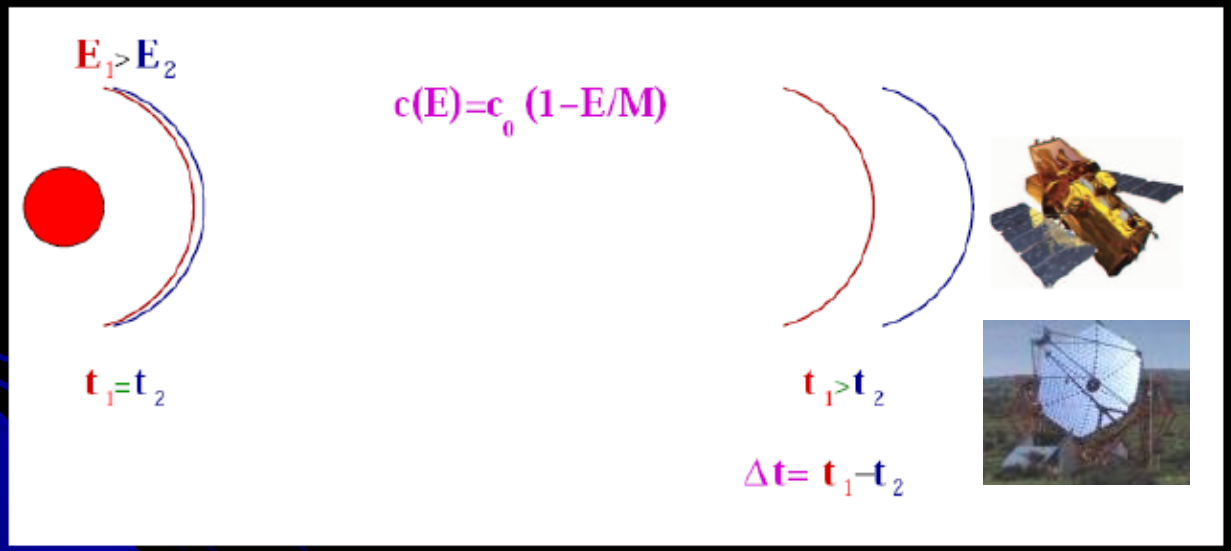
$$v = c\left(1 \pm \xi\left(\frac{E}{M_P}\right) \pm \zeta\left(\frac{E}{M_P}\right)^2 \pm \ldots\right)$$

Accès à l'énergie de Planck M_P

- avec larges distance et très hautes énergies
- via études des événements rapides : GRBs, AGNs (flare), Pulsars
- résultats dépendants du type d'événement

Tests LIV avec sources astrophysiques

The modification of the group velocity would affect the simultaneity of the arrival times of photons with different energies from remote sources (G. Amelino-Camelia et al, 1998)



Amelino-Camelia, Ellis, Mavromatos, Nanopoulos, Sarkar, Nature (1996)
G. Amelino-Camelia, Perspectives on QG (2003)

LIV & QG – résultats

Source	Experiment	Method	Results linear, quadratic (GeV)
Mrk 421	Whipple	Likelihood	$E_{QG} > 0.6 \times 10^{17}$
Mrk 501	MAGIC	ECF + Likelihood	$E_{QG} > 0.3 \times 10^{18}$, $> 0.3\ 10^{11}$
PKS 2155-304	H.E.S.S.	MCCF + Wavelets + Likelihood	**$E_{QG} > 2.1 \times 10^{18}$, $> 0.5\ 10^{11}$**
GRB 021206	RHESSI	Fit + Mean arrival time in a spike	$E_{QG} > 1.5 \times 10^{17}$
GRB 080916C	Fermi GBM + LAT	Δt = t(Photon with highest E) – t_0	$E_{QG} > 1.5 \times 10^{18}$
GRB 090510	Fermi GBM + LAT	CCF, cost function/Shannon	**$E_{QG} > 1.2 \times 10^{19}$, $> 0.5\ 10^{11}$**
9 GRBs	BATSE + OSSE	Wavelets	$E_{QG} > 0.6 \times 10^{16}$
15 GRBs	HETE-2	Wavelets	$E_{QG} > 0.4 \times 10^{16}$
17 GRBs	INTEGRAL	Likelihood	$E_{QG} > 0.4 \times 10^{11}$
35 GRBs	BATSE + HETE-2 + SWIFT	Wavelets	$E_{QG} > 1.4 \times 10^{16}$
CRAB pulsar	VERITAS	Mesure directe $\Delta\Phi/\Delta t$	$E_{QG} > 3.0 \times 10^{17}$

LIV & QG – perspectives

Etudes Futures:

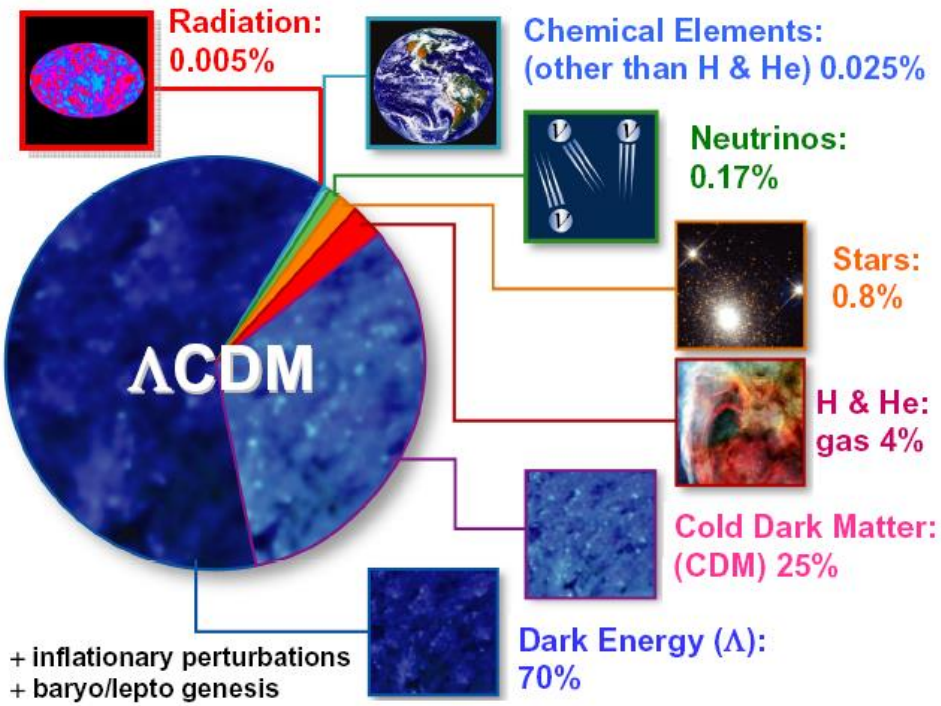
Objectif – recherche des effets LIV globale

- Une **collaboration H.E.S.S+MAGIC+VERITAS** s'est constituée;

  - améliorer la sensibilité
  - étudier dépendance en Redshift → évaluer mieux systématiques
  - inclure les 3 types des sources

- En **préparation des analyses avec CTA**
  - fournir le statut final des résultats LIV obtenue en Astronomie-γ
  - faire prédictions pour CTA:
    → avec observation de nombreux « flares » des AGNs
    détection d'émission pulsée des Pulsars
    et détection possible des GRBs

Matière Noire - Cosmologie

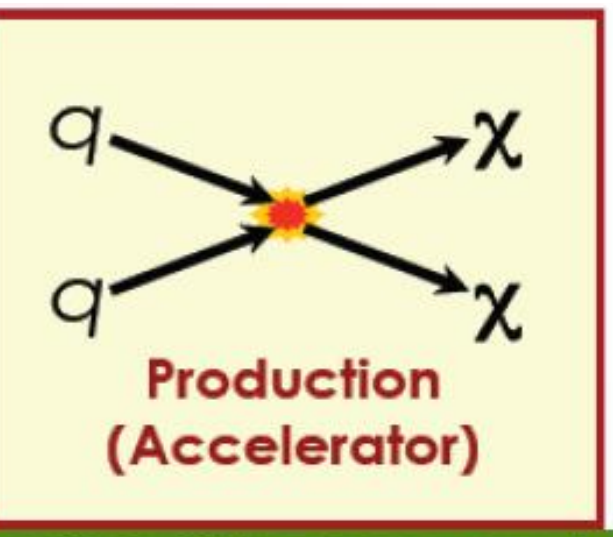


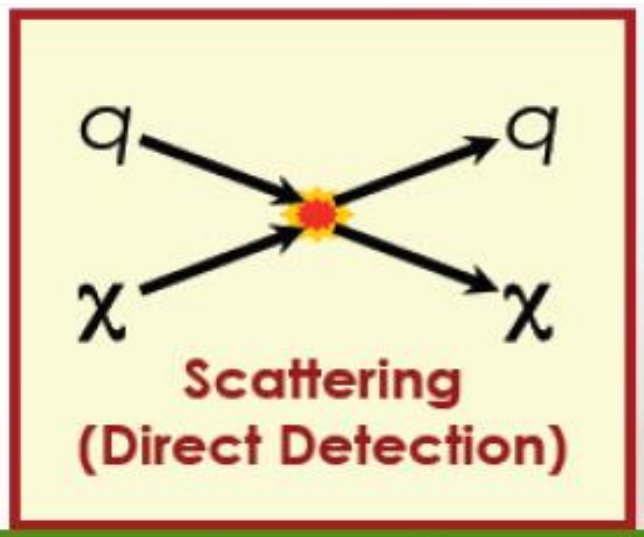
Simulations à n-corps
de formation des structures
favorisent <u>paradigme</u>
de Matière Noire Froide (CDM)
composée des particules
Massives interagissant faiblement:
WIMPs

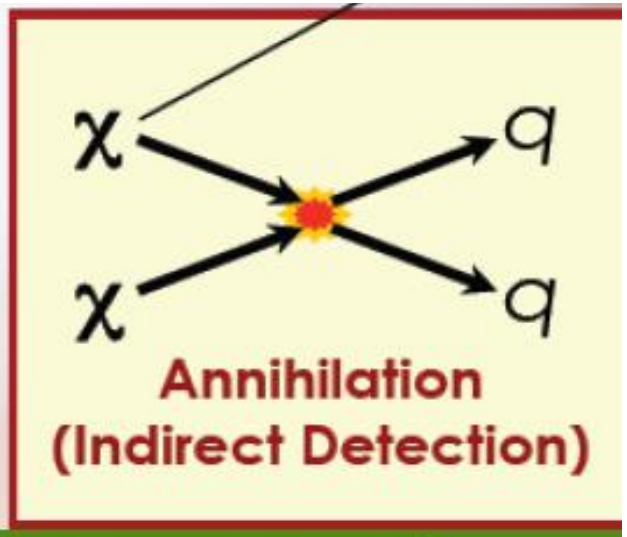
Gamme des masses:
10^{-6} eV (10^{-40}g) – 10^{-8} M_{sol} (10^{25}g)

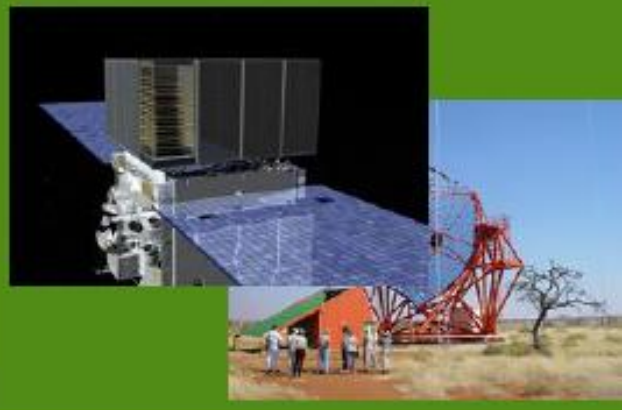
Candidats: Neutrinos - HOT
Sterile neutrinos, gravitinos - WARM
LSP (lightest SUSY particle - **neutralino**, axino, …) - COLD
LKP (lightest Kaluza-Klein particle) - COLD
Axions, axion clusters - COLD
Solitons (Q-balls, B-balls, Odd-balls, …) - COLD
Supermassive Wimpzillas - COLD

Détection de la Matière Noire







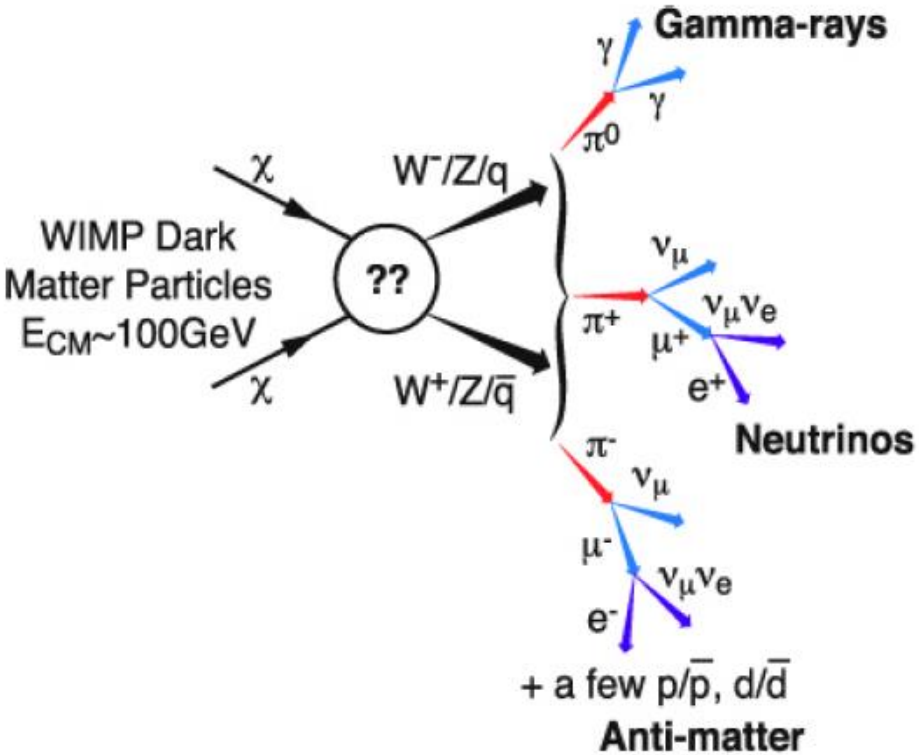


Large Hadron Collider

Deep underground detectors (e.g based on Xenon)

Gamma ray telescopes, neutrino telescopes, Charged cosmic ray detectors

Détection Indirecte: annihilations des WIMPs



Dernières 15 années:

Grandes expériences spatiales – PAMELA, *Fermi*-LAT, AMS, …
Au sol – **H.E.S.S.**, MAGIC, VERITAS, IceCube, **CTA**, km3

Annihilations des WIMPs en rayons γ

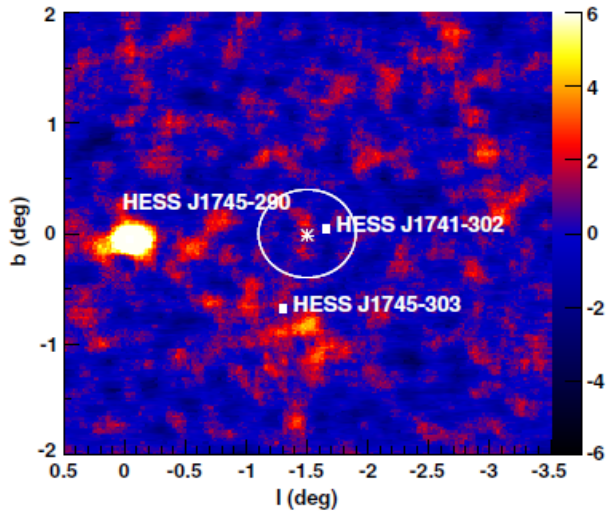
- Halo au Centre Galactique:
  Avantages – grande densité, proche
  Inconvénients - incertitude sur la forme du halo
  bruit de fond astrophysique
  → la meilleure source

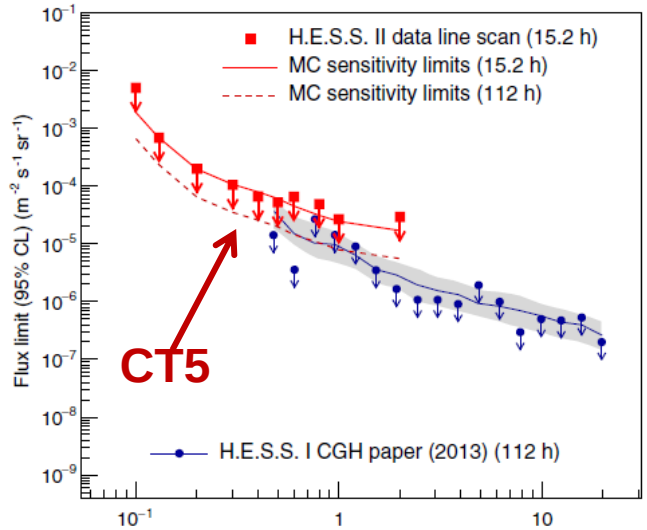
- Les Galaxies Naines Sphéroïdales:
  Avantages – pas de bruit astrophysique
  nombreuses halo DM mieux connu
  Inconvénients - densité du halo moindre (~10^{-2})
  → bonnes candidates car si signal découvert: DM !

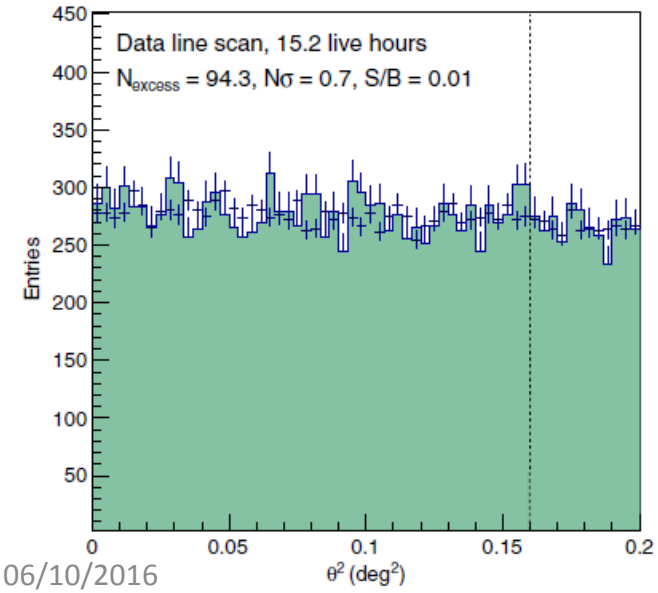
- Amas des Galaxies
  Très massifs mais lointains
  à la portée de CTA car seuil en énergie bas et
  excellente sensibilité au signal γ
  (voir présentation J. Bolmont)

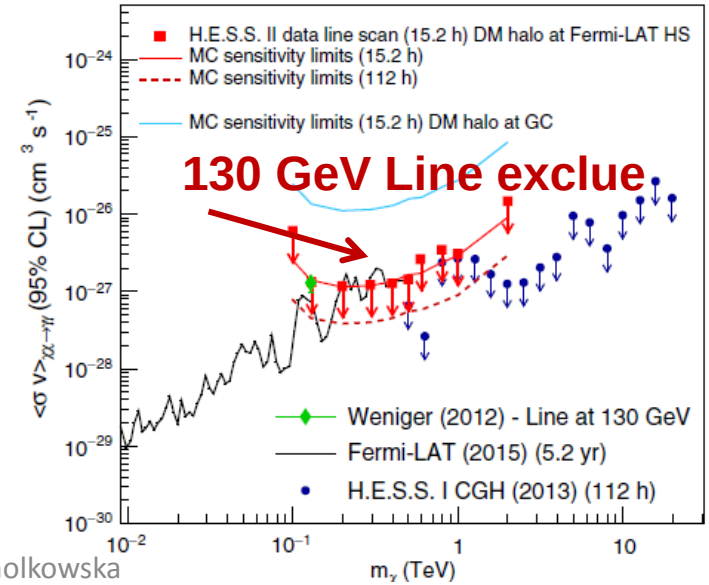
Annihilations des WIMPs en γ monochromatiques

1ère publication de H.E.S.S. avec 5e télescope: acceptée par PRL

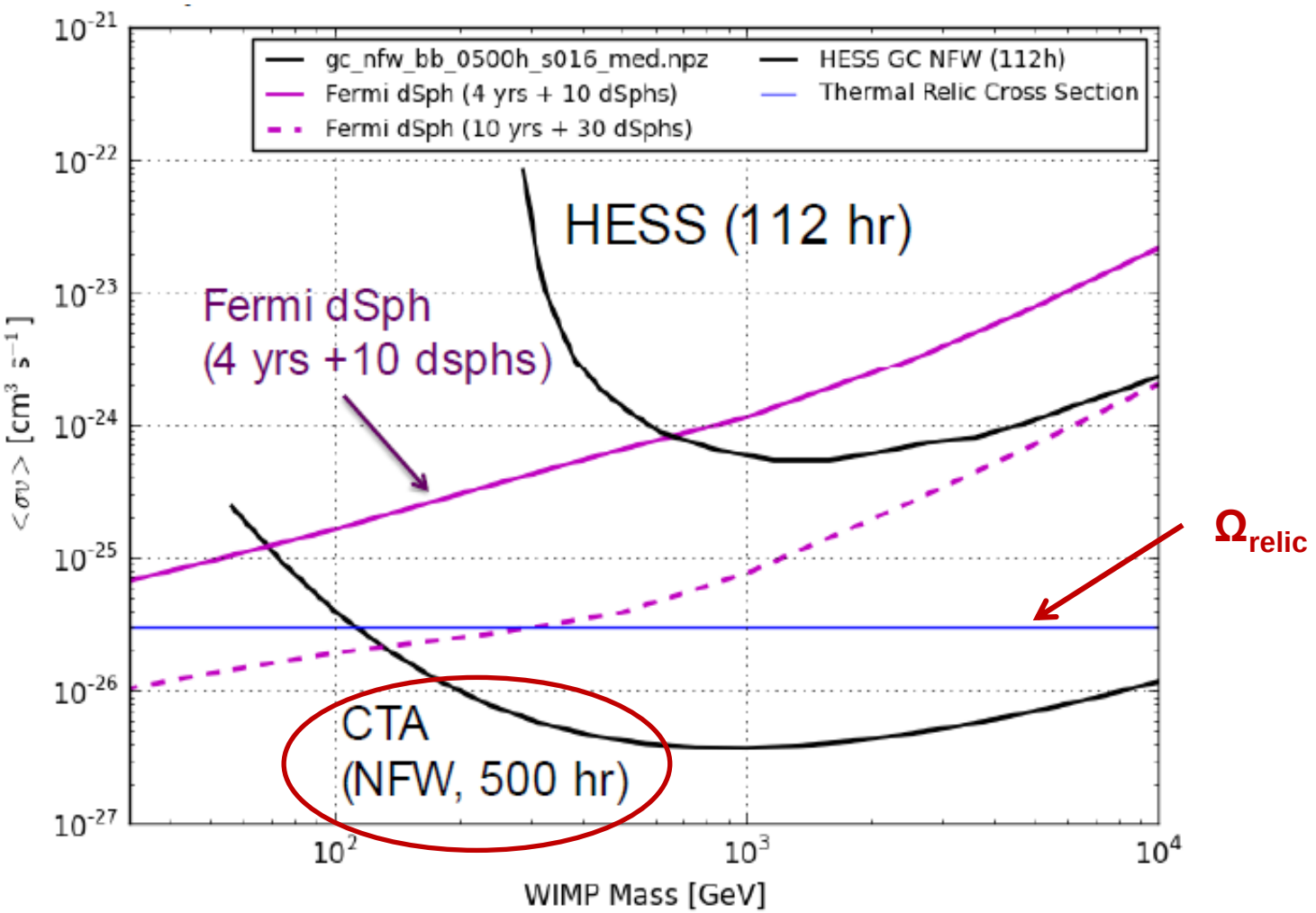








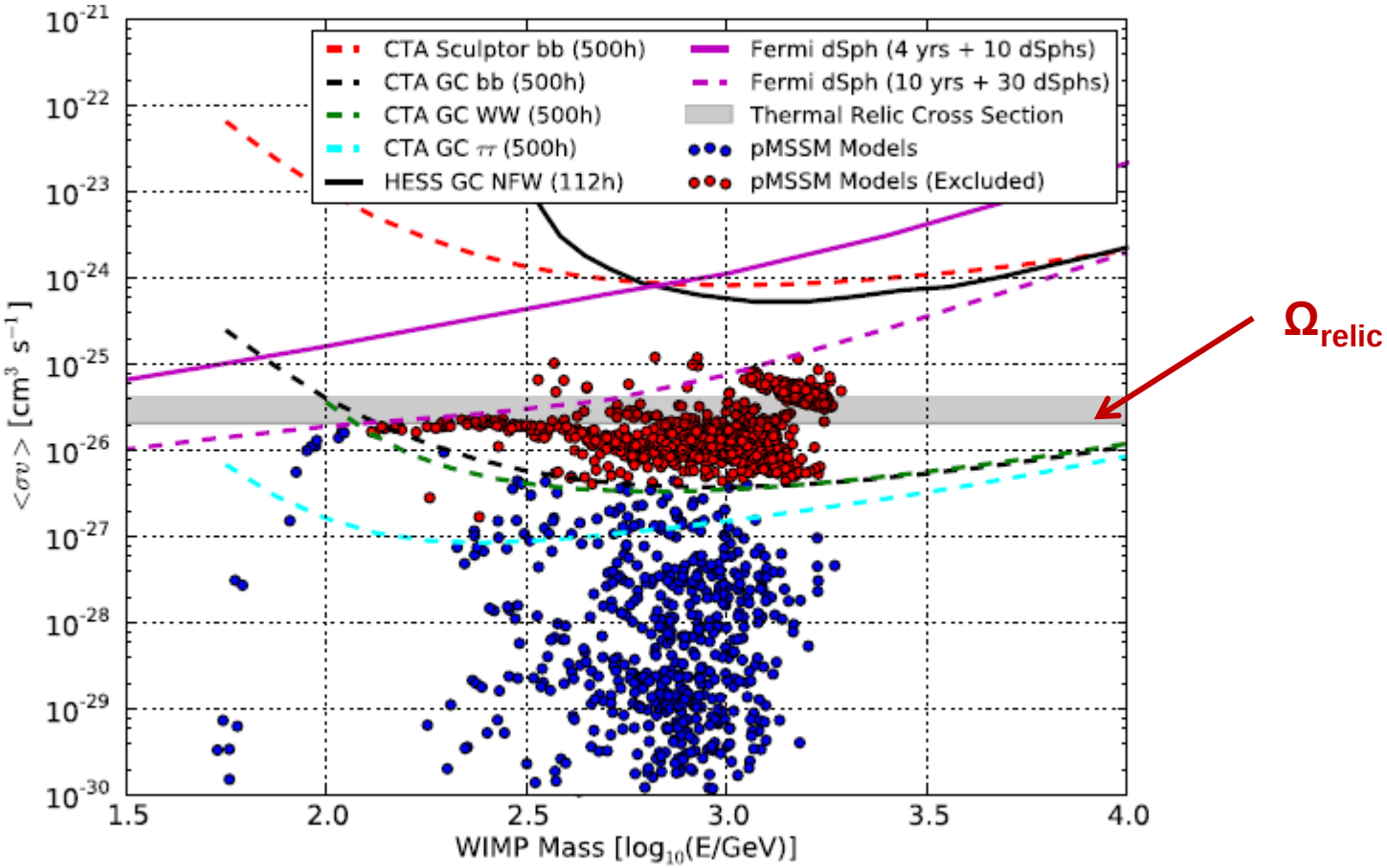
Sensitivité: annihilations des WIMPs en rayons γ



See also latest H.E.S.S. (254 hr): 1607.08142

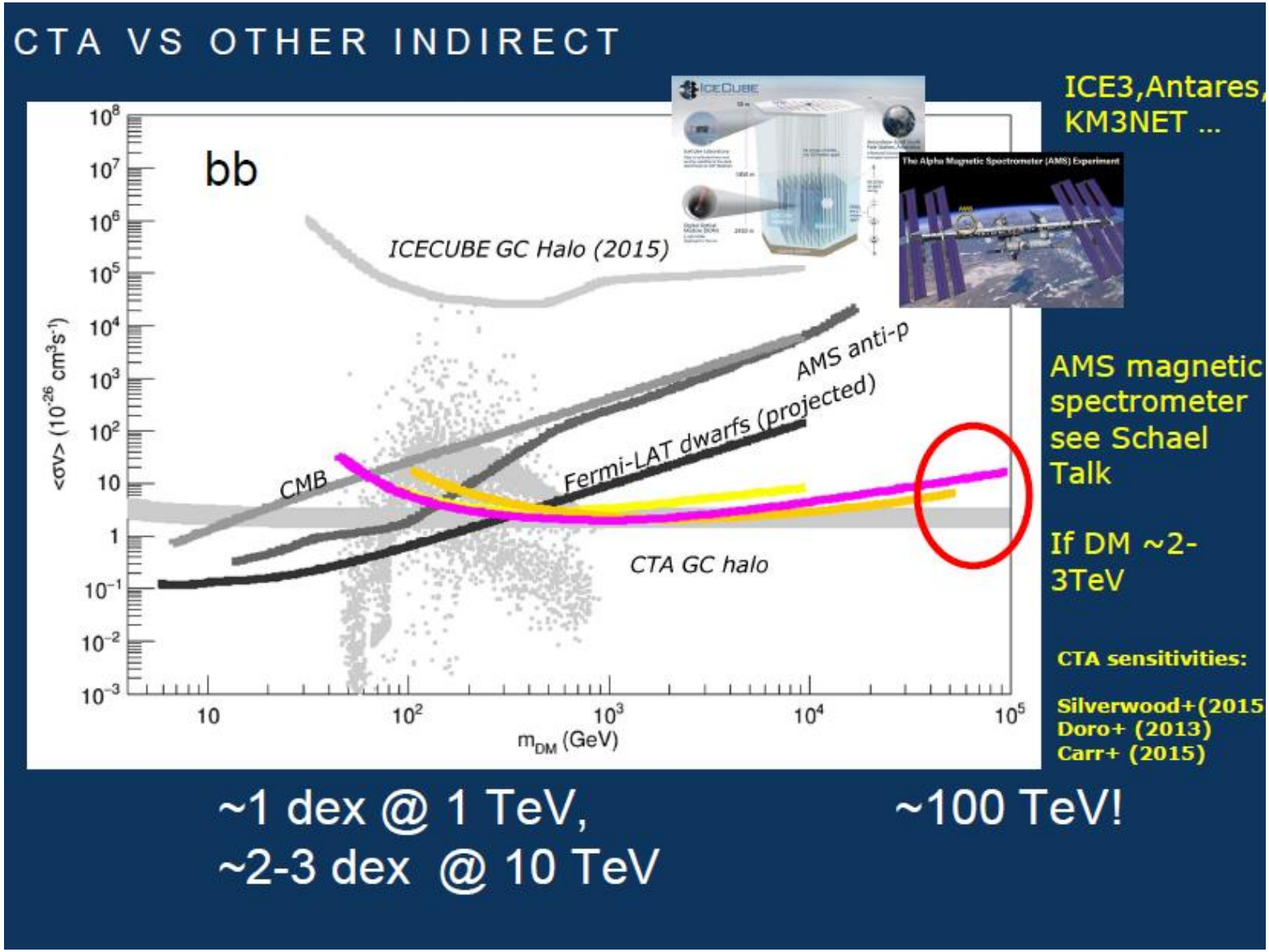
Limites sur <σv> annihilation de CTA

→ CTA testera plusieurs Modèles SUSY jusqu'à m_{WIMP} ~ multi-TeV



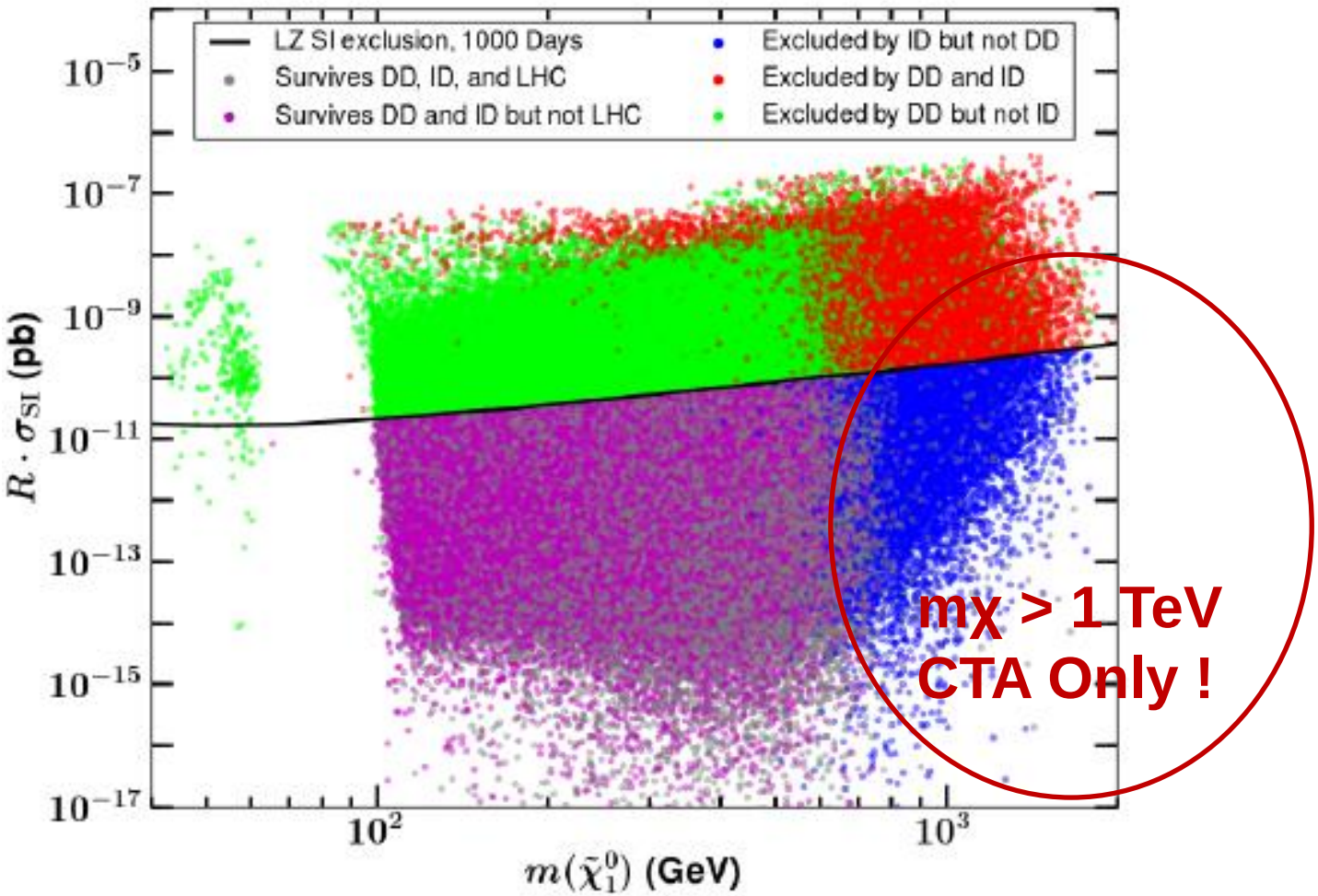
M. Wood et al. Snowmass 1305.0302

CTA limites vs autres recherches Indirectes



Complémentarité
recherches Indirectes – Directes - LHC

Cahill-Rowley et al. PRD 91, 055011 (2015)



Conclusions

Astroparticules: domaine riche et complexe

- En pleine expansion:
  nouveaux résultats et inattendus
  nouvelles expériences: HAWC, CTA, + missions spatiales
  Auger Prime (muons)

- UHECRs – bonnes perspectives pour résoudre les énigmes

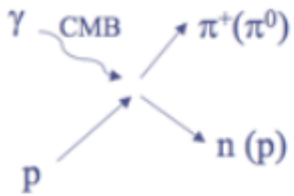
- LIV & QG – échelle de Planck avec modèles en $E\gamma^2$ (plus génériques)

- DM – toujours en quête des réponses sur sa nature
  pour avancer:
  → **besoin de développer études multi-messager – cohérence ?**
  → **faire des études de complémentarité/redondance**
  confirmation de signal DM cosmologique

Back-up

UHECRs

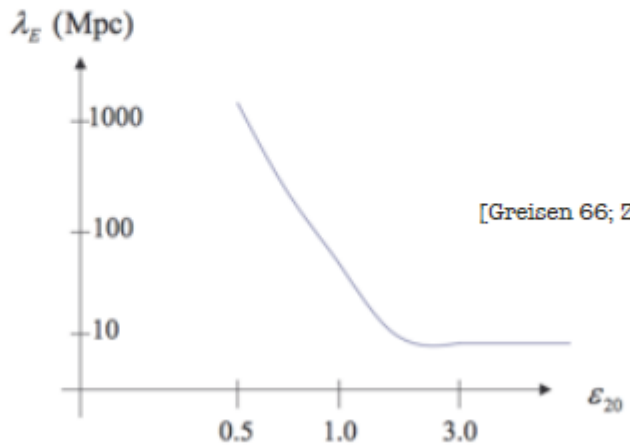
The GZK Paradigm



$$\varepsilon_\gamma > \frac{m_\pi m_p}{\varepsilon_p} \sim 10^{-3}\varepsilon_{20}^{-1}\ \text{eV} \Rightarrow \quad n_\gamma \sim \frac{400}{\text{cm}^3}\exp\left[1-\frac{3}{\varepsilon_{20}}\right]$$

$$\lambda_E \sim \frac{m_p}{m_\pi}\frac{1}{n_\gamma \sigma_{p\gamma}}$$

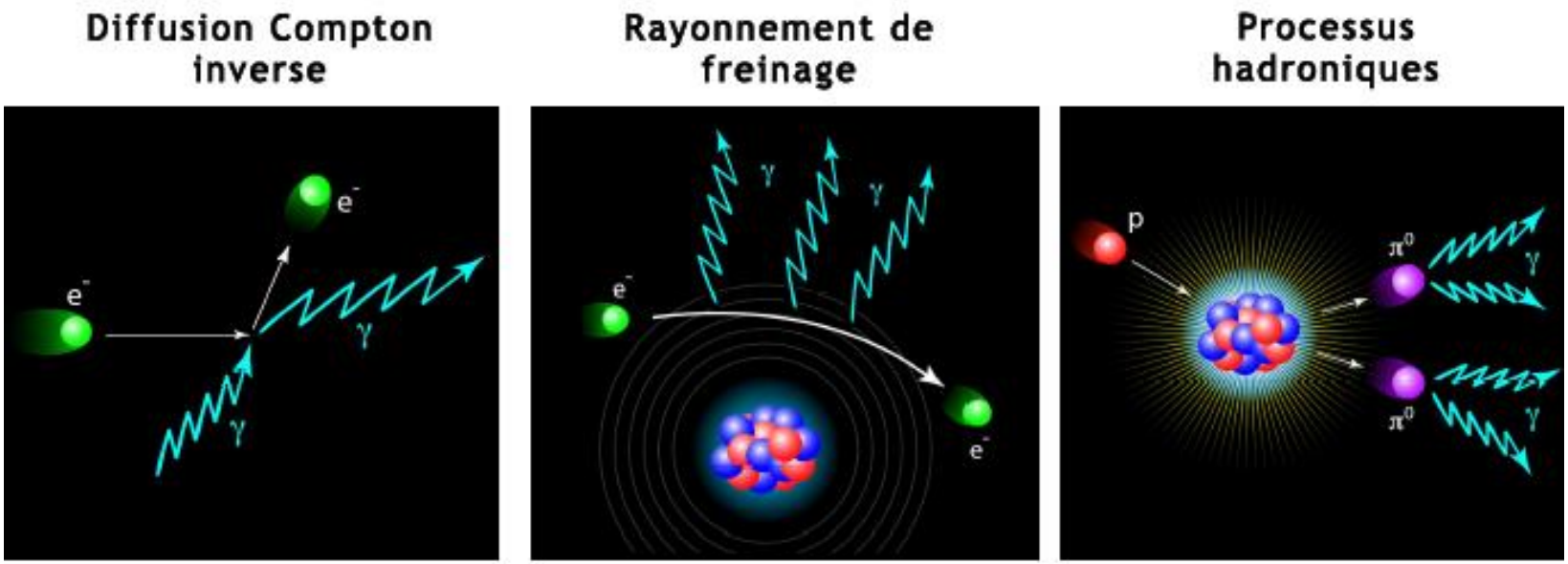
$$\sim 11\exp\left[\frac{3}{\varepsilon_{20}}-1\right] \quad \text{Mpc}$$



[Greisen 66; Zatsepin & Kuzmin 66]

- Rapid reduction of the horizon ⇒ Flux suppression at UHE
- Anisotropy of extragalactic local matter + small magnetic deflection for 10^{20} eV protons ⇒ possibility of UHECR astronomy

Production of γ-rays: basic processes

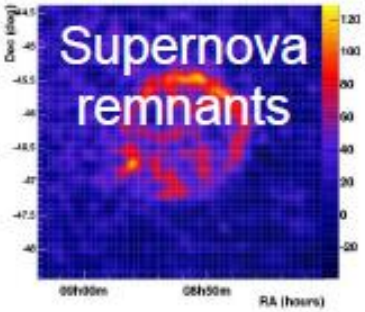


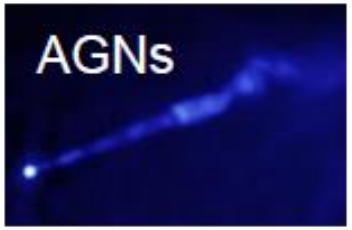
propagation en ligne « droite »

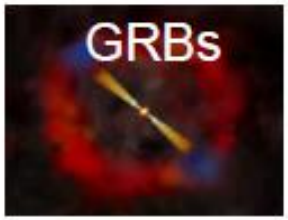
➡ exploration de l'Univers non-thermique

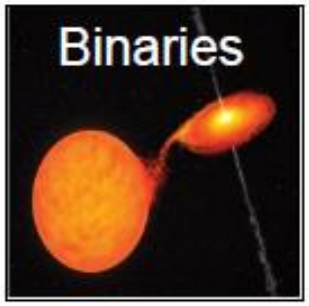
➡ origine et propagation des rayons cosmiques

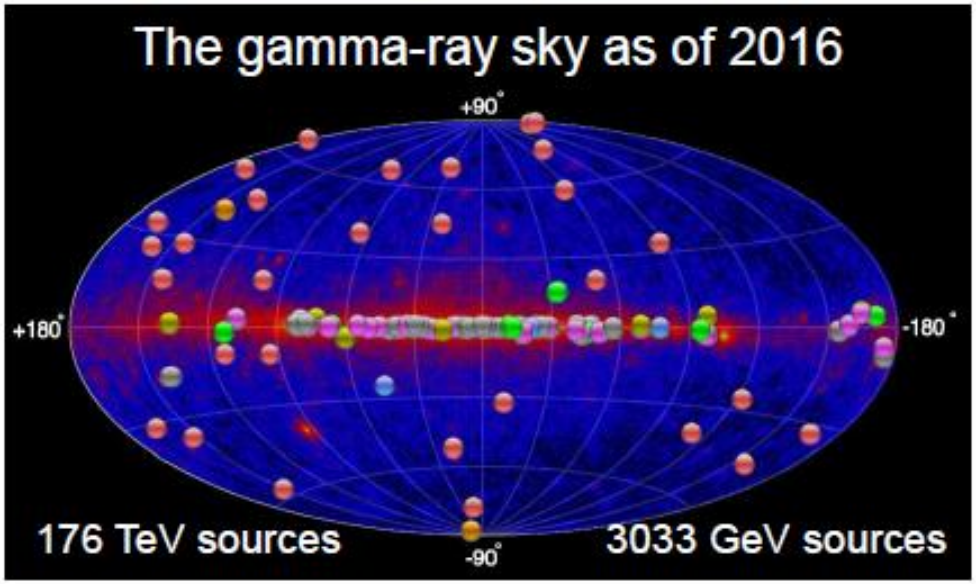
Physique avec rayons-ɣ au TeV

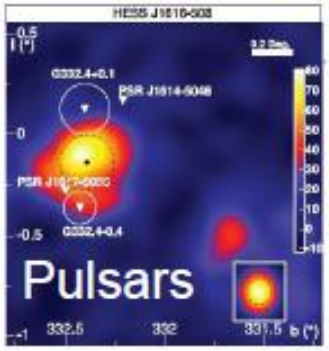


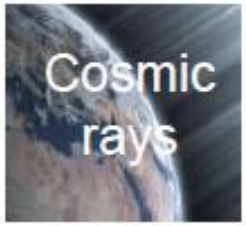




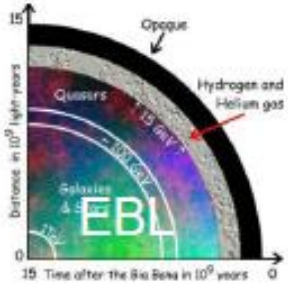




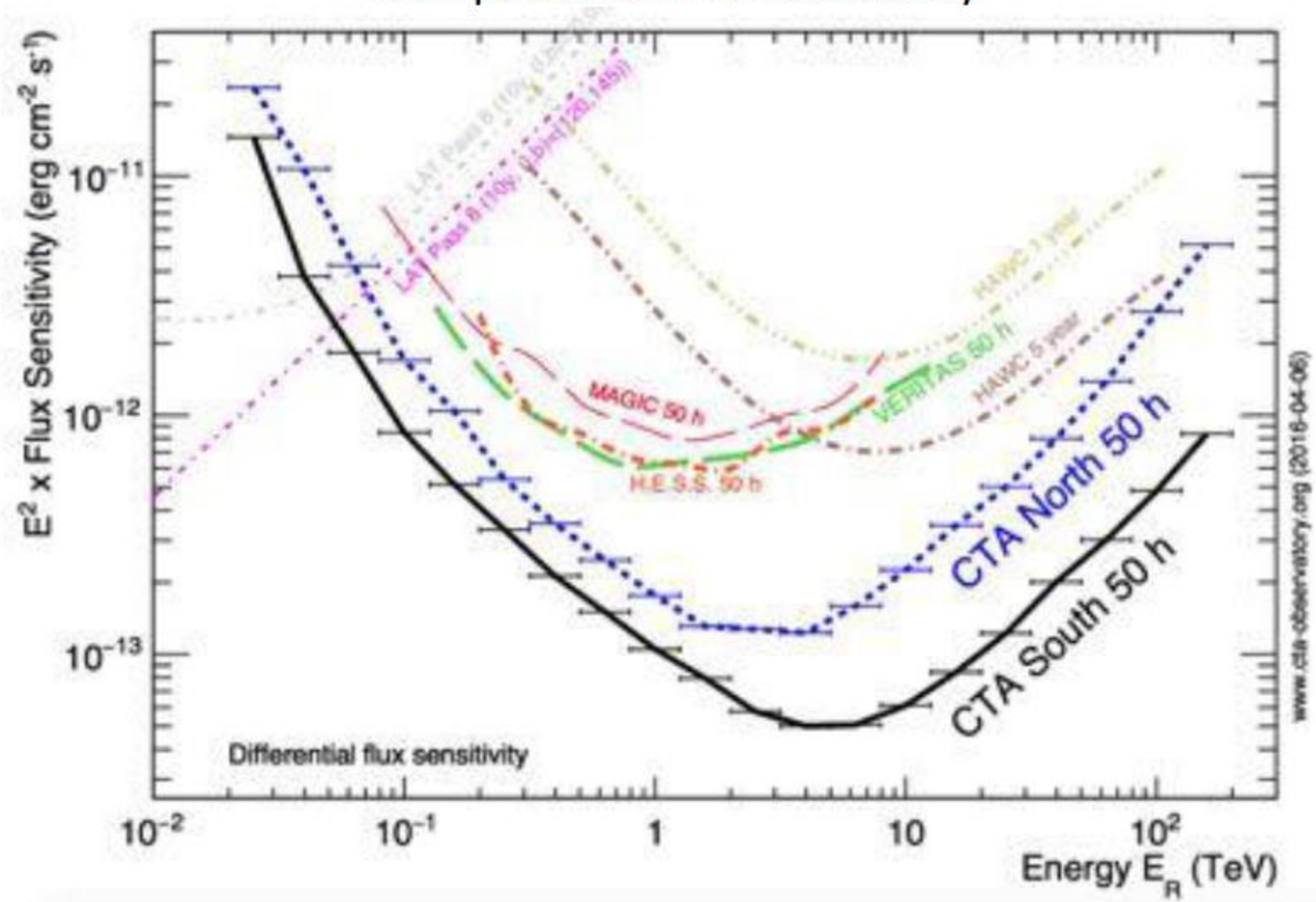




Axions, …



CTA point source sensitivity



Lorentz Symmetry and Quantum Gravity

- Strong theoretical and experimental interest in possible high energy violation of local Lorentz Invariance (LI) driven by hints from Quantum Gravity (QG)

- Possibility of LI violation or different realization than SR:
  → String Theory, Loop QG, non-commutative geometry, space-time foam, brane-world background, "emergent gravity*, …

→ local (LI) <u>may be not exact symmetry</u> of the vacuum

→ The Lorentz Symmetry breaking is not expected in all models but its detection could be <u>a signature</u> of Quantum Gravity

Tests of LIV & Astrophysics

- Astrophysical messengers

Photons: simple modeling, limited in ΔE

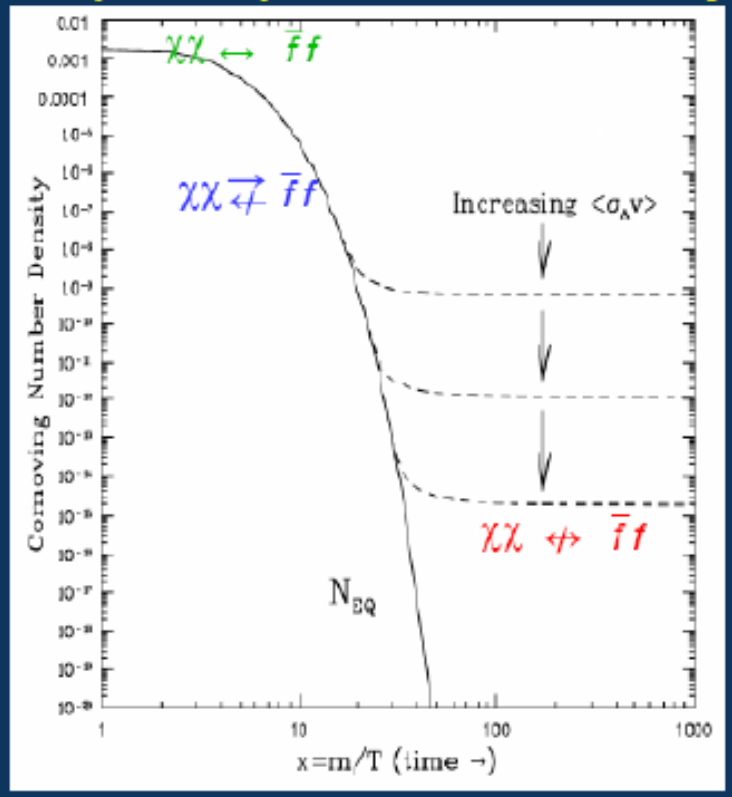
Electrons: synchrotron radiation of pulsars
UHECRs: model dependent formalism
for threshold modifications of the GZK limit
Neutrino: limited in statistics, not seen from sources
Gravitons: not seen yet

- Astrophysical experiments with Photons
  - Space missions: excellent space detectors for violent event detection Pulsars, GRBs, AGNs – past BATSE, HETE2, present SWIFT, Fermi, future SVOM, …
  - Ground based telescopes: highest ΔE, limited variability of the AGN flares - H.E.S.S., MAGIC, VERITAS, and future CTA

Paradigme des WIMPs

Thermal particle production in the Early Universe

~abundance (~ Ω)



~ time , 1/T

$$\Omega_{Wimp} \approx \frac{10^{-26} cm^{-3} s^{-1}}{\langle \sigma v \rangle} \approx 0.27$$

$$\langle \sigma v \rangle_{\sim weak} \sim \frac{\alpha_{weak}^{2}}{m_{WIMP}^{2}} \sim 10^{-25} cm^{-3} s^{-1}$$

~ 100 GeV

Jungman+, Phys. Rept. (1996)

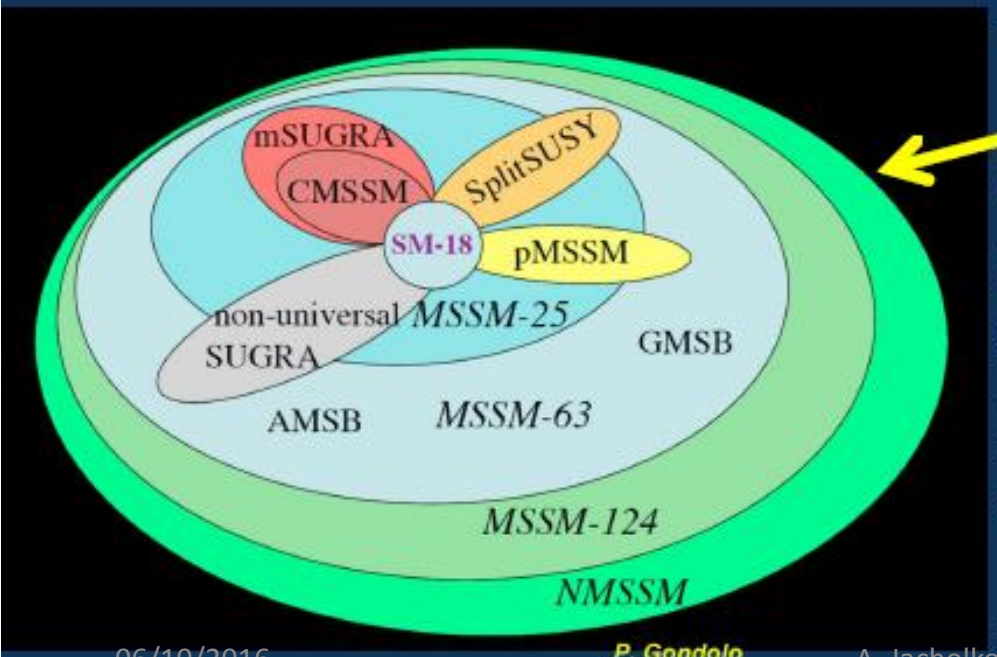
Deux quantités à priori non liées

<σv> annihilation → ΩDM cosmologique

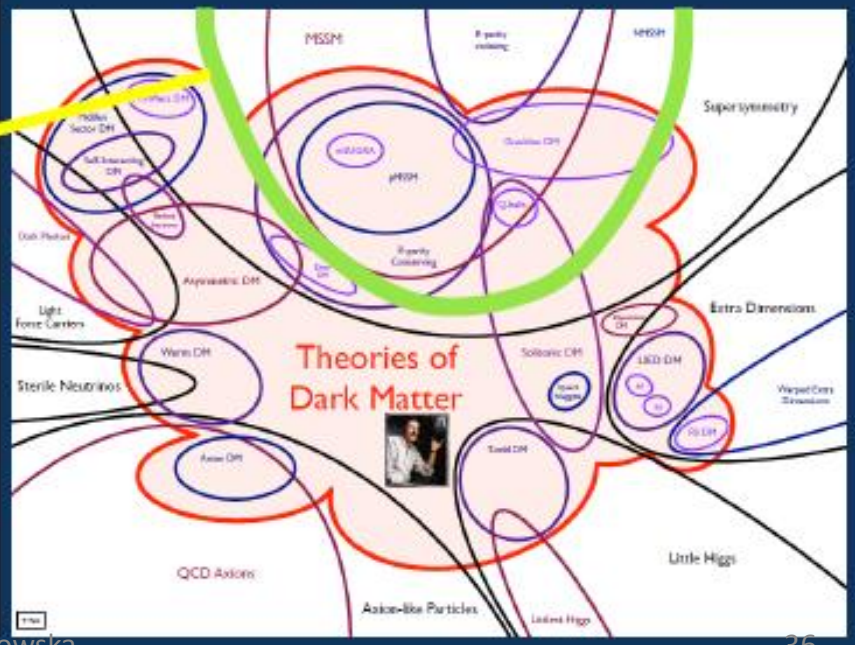
- Thermally produced WIMPs can have masses from a few GeV to upto ~100 TeV.

- The most studied WIMP candidate is realized within Supersymmetry. By naturalness arguments, WIMP masses above about ~TeV are disfavoured in Supersymmetry.

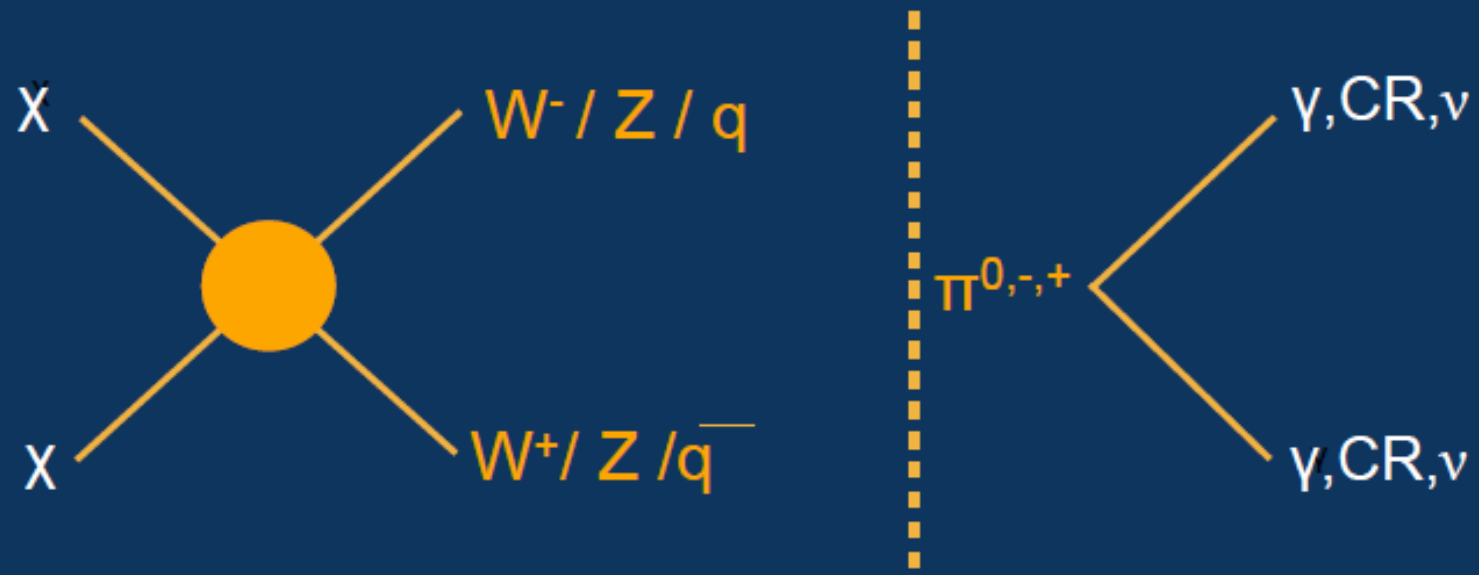
See however e.g, Dine (2015), "Naturalness under stress"



P. Gondolo



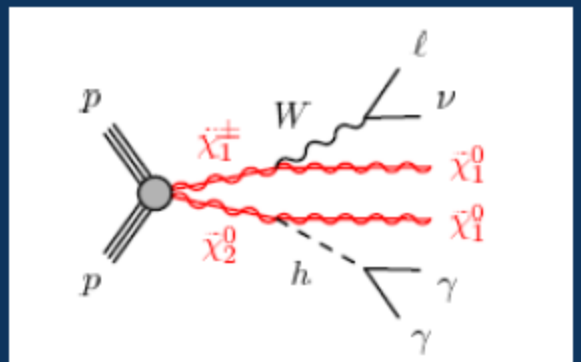
Indirect detection of WIMPS



Measured DM density provides a benchmark

$$\frac{d\Phi_\gamma}{dE_\gamma} = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_\chi^2}\sum_f \frac{dN_\gamma^f}{dE_\gamma} B_f}_{\Phi_{PP}} \times \underbrace{\int_{\Delta\Omega}\int_{l.o.s.} \rho^2(r)dl\ d\Omega'}_{\mathrm{J-factor}}$$

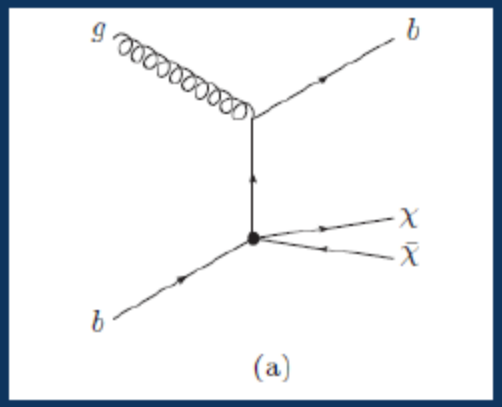
CTA VS LHC



(b) One lepton and two photons channel

e.g. Aad+ (2015a)

SUSY particles (here charginos and neutralinos)?

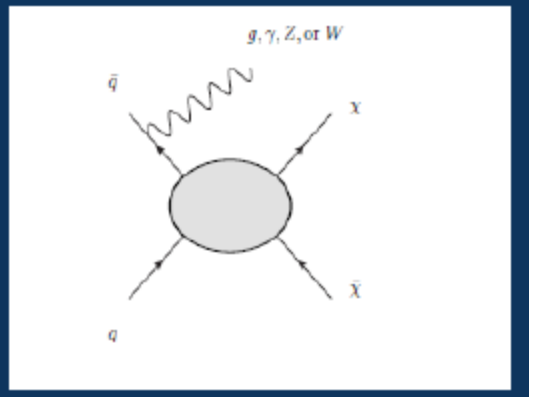


(a)

e.g. Aad+ (2015b)

DM final states with missing transverse energy.

Mono-X



e.g. Zhou+ (2013)

LHC → new particles

new particles → dark matter?

MODELS CONSIDERED

The pMSSM (19 parameters)

- Preserves Standard Model symmetries
- Lightest neutralino is the LSP.
- No assumptions wrt SUSY-breaking , simplifying assumptions on masses and couplings

→ encompasses all relevant phenomenology (at least that's the hope) for SUSY models

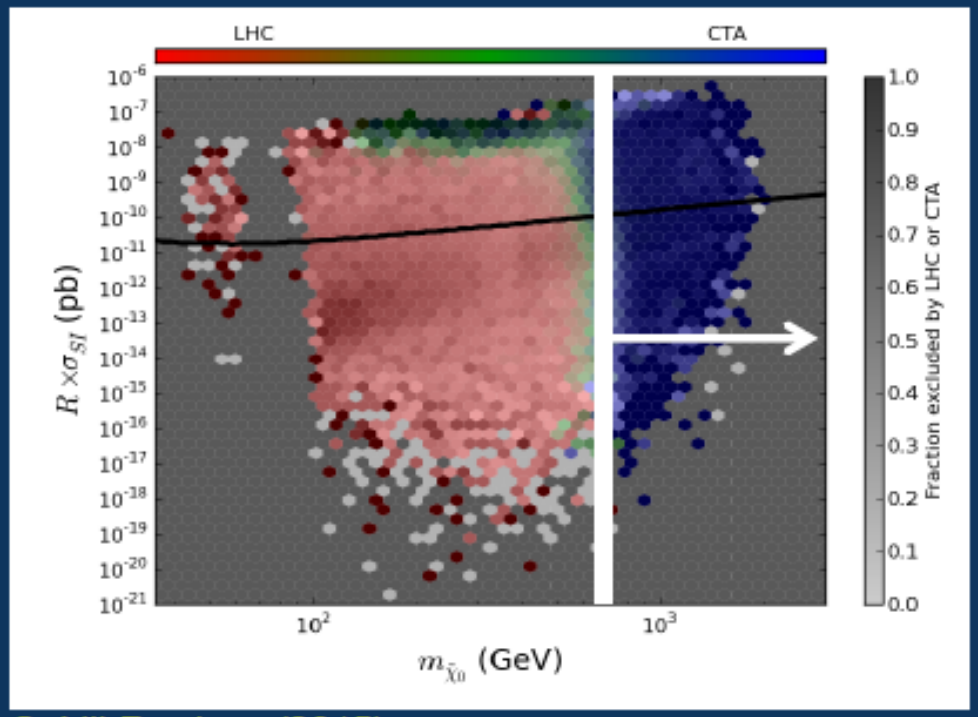
Effective Field Theory

- Mediated interactions treated as point-like (valid if momentum transfer << mediator mass)
- possible operators restricted by symmetries only.
- Three parameters: DM mass and cut-off scale, coupling

→ Allows to parametrize results in terms of mass and interaction strength but considering different interactions .

→ conclusions reasonably model-independent.

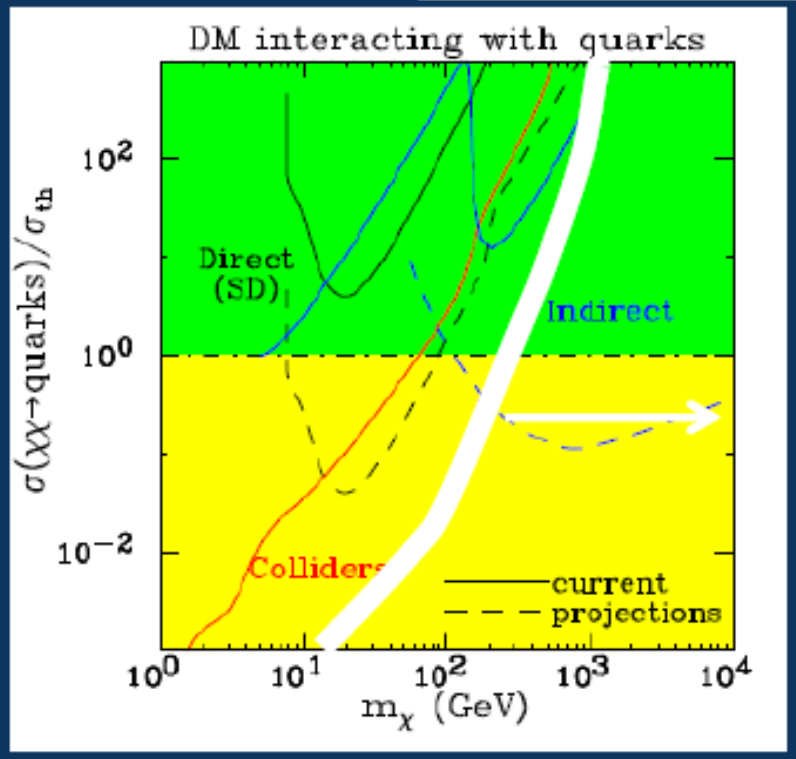
pMSSM19



Cahill-Rawley+ (2015)

EFT

$$\frac{1}{M_*^2}\,\bar{\chi}\gamma^{\mu}\gamma_5\chi\sum_q \bar{q}\gamma_\mu\gamma_5 q$$



Arrenberg+ [Snowmass] (2013)

WIMP masses > 1TeV not in reach for LHC