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13ème Recontres de Vietnam: “Exploring the Dark Universe”
29 July 2017, Quy Nhon, Vietnam
Outline

• Introduction
• Theme I: new data / new models / new questions
• Theme II: communication between communities
• A high level tour of science topics with various personal biases and a few random asides
• Meta Summary
THEMES: NEW DATA / NEW MODELS / NEW QUESTIONS
New Data Tests Existing Models & Methods

Data: antiprotons

Meta level: “WIMP ‘Miracle’ seems pretty compelling, lets start by going out and looking for 100 GeV WIMPs.”
New Data Push us to New Models & Methods

Meta level: “Well, none of use have found these 100 GeV WIMPs. How do we look for those XX you mentioned?”

Sterile $\nu$

Primordial Black Holes

Axions & ALPS

Spin-2 Fields

PeV DM

Asymmetric DM
New Models & Methods raises New Questions

Meta level: “Oh, XX is a rich model space, and in looking for it we are learning lots of new things”
Theme II: Communicating between Communities

• This conference brings together people for multiple communities:
  • Accelerator-based
  • Direct-detection
  • High-Energy Astronomy / Astrophysics
  • Cosmology
  • Particle Theory / phenomenology
• We all had to take a step back and focus on things that will be of interest to people outside our specific communities
• I hope this talk follows in that spirit, i.e., I’m not going to be saying a lot about nano-Bq / kg, pseudo-rapidity cuts, or γ-ray telescope instrument response functions
SCIENCE TOPICS
Topics Covered

• Intro & Keynote
• Dark matter theory
• Searches
  • Accelerator Searches
    • Light DM at $e^+e^-$ colliders & fixed target experiments
    • Searches at the LHC
  • Direct detection:
    • Direct detection of WIMPs
    • Directional Detection
    • Direct detection of WISPs, ALPs & axions
  • Indirect detection:
    • Indirect detection with neutrinos
    • Indirect detection with $\gamma$ rays
    • Indirect detection with charged particles
• Cosmology & Astrophysical Dark Matter
INTRO & KEYNOTE

• Some quotes:
  • “Space has become time, and time has become space”
  • “This is a pure state only if you combine universe 1 with universe 2”
  • “A time Mobius strip ... this rescues unitarity & causality.”
Will EDU2017 bring new lights on Dark Matter?

- Dark Matter has not yet been identified
- Here and now is EDU2017
- 75 participants
- 60 presentations on
  - Theories, models
  - Indirect detection of Dark Matter
  - Direct Detection of Dark Matter
  - Dark Matter production at accelerators (LHC, e+e-, fixed target…)
  - …

- We are going to learn …
Direct, Indirect, Accelerator-based Searches

"Direct detection" of Dark Matter: playing billiard with Dark Matter particles and nuclei

Very tiny and rare expected signals

SM → DM

DM → SM

Wimp « indirect » detection: detect products of annihilation of DM particles

Annihilation in clumpy halo

Annihilation in galactic center of dense regions

Gerbier
THEORY
Massive efforts underway to explore the massive SUSY parameter space

Identify DM candidates (i.e., the lightest SUSY particle) for different scenarios

Explore representative simplified models to probe SUSY space

Combine LHC / direct detection / indirect detection / cosmological constraints (e.g., codes such as GAMBIT)
Full Theories -> Simplified Models -> Effective Theories

DM “models”

FULL THEORIES
- SUSY, KK, ...
- many particles and parameters

SIMPLIFIED MODELS
- 2 new particle (DM + mediator)
- few parameters ($M, m_{DM}$, couplings)

EFFECTIVE THEORIES
- 1 new particle (DM)
- 2 parameters ($\Lambda, m_{DM}$)
**Simplified Models**

**LHC results on simplified models**

- **Quietsch-Maitland**
  - mono-jet
  - di-jet + MET
  - di-top/bottom + MET

- **Bhattacharya**
  - mono-\(\gamma/Z\)

- **Benitez**
  - resonant searches: di-jet, di-leptons...

- **Dodd**
  - mono-higgs
For an optimistic, the low mass of the Higgs means that the favored SUSY mass scale is high, which helps to explain why we haven’t seen it at LHC, and could be great news for Cerenkov Telescope Array (CTA)
Specific Theoretical Developments

- Parts of parameters space for which DM interactions at LHC would be “long-range”, implying bound states have important effect on phenomenology, boosting the LHC mass reach.
- Self consistent solutions where spin 2 fields behave as DM. Available parameters space could be closed with factor of 100 improvement in limits on DM decay.
- PeV DM is feasible in rich dark sector theories and should be explored in more detail.

Graphs and data are used to illustrate these points, showing exclusion limits and decay constraints.
SEARCHES
DIRECT DETECTION
**Direct Detection Techniques**

Discrimination is crucial!
- Use technology detecting two signals
- Or if one single signal, it should provide significant discrimination

- **CUORE, COUPP, PICASSO, PICO**
  - TeO$_2$, Al$_2$O$_3$, LiF, C$_3$F$_8$

**Phonons/Heat**
- 10 meV/ph
- 100% energy

Representative experiments, not meant to be completed

**Scintillation**
- Xe, Ar, Ne, NaI
- DEAP-3600
- CLEAN
- XMASS
- DAMA, KIMS
- DM-Ice
- SABRE
- LUX
- LZ
- XENON
- PandaX
- ArDM
- DarkSide
- Darwin

**Ionization**
- Xe, Ar
- Ge, Si
- SuperCDMS
- EDELWEISS
- Ge, CS$_2$, CF$_4$
- CoGeNT
- CDEX
- Malbek
- DAMIC
- DMTPC
- DRIFT

Julien Masbou, EDU 2017, Quy Nhon, 25th July 2017
How is evolving the field of Direct Detection?

\[ R \sim 0.13 \frac{\text{events}}{\text{kg \cdot year}} \left[ \frac{A}{100} \times \frac{\sigma_{\chi N}}{10^{-38} \text{cm}^2} \times \frac{\langle v \rangle}{220 \text{ km/s}} \times \frac{\rho_{\odot}}{0.3 \text{ GeV/cm}^3} \right] \]

Threshold & atomic mass

Detector size \times time matter
• Common themes: reducing background radiation, thermal noise, increasing fiducial volume, mixing new and tested technologies
Some Developments that Stood Out (for me)

- $\nu$-floor is much lower for $\text{C}_3\text{F}_8$ than for Xe
- Using resonance effect to go beyond diffractive limit in emulsion resolution
- Adding minority carriers to measure drift time start time (z-position)
• Flagship liquid noble detectors continue to bravely push down to the neutrino floor
• Given the background level required, this is a truly impressive achievement
For low-mass WIMP searches the main goal is to lower the threshold and push down to lower masses.

Technically, this means lowering the threshold for measuring ionization or heat deposition.

We expect orders of magnitude improvement in cross-section sensitivity in the 1-10 GeV mass range.
Direct Detection: DAMA / LIBRA

SABRE Performance – Expected modulation signals
Independent modelling of the expected modulation signals.
Each based on the respective background modelling and a standard galactic halo.
Both based on 50 kg of NaI(Tl) in the PoP vessel

- Good agreement.
- 3 year measurement should give either a 6σ refutation or a 4σ verification.
- SABRE North and South can be combined if the signal is DM related and not a seasonal background.

• Several experiments are reproducing DAMA / LIBRA scenario with increasing fidelity
• Expect to probe DAMA / LIBRA signal region with almost identical setup in next few year
• This will test explanations offered for tension between DAMA / LIBRA signal region and exclusion regions of other experiments

Expected sensitivity for COSINE-200 (Phase-II)
200 kg x 3 year (Assumed 1 dru flat backgrounds)

Chang Hyon Ha, Center for Underground Physics, IBS
Exploring the Dark Universe, Quy Nhon, July 2017
• Low-mass Axions (~μeV) more “field-like” that “particle-like”
• Haloscopes: couple to local axions or axion-like particles in Galactic halo using tunable microwave resonating cavities and magnetic fields
• ADMX-2 will probe coupling-mass plane in region that would produce DM at the relic density between 2 – 41 μeV
Direct Detection: Light Shining through a Wall

- **Light Shining through a Wall**: use powerful magnetic fields to convert photons to axions and back so that they can pass an optical barrier.
- **Current sensitivity** not as good as Helioscopes (e.g., CAST), but ALPS-II upgrade would read CAST sensitivity as well as parts of cosmologically significant region.

![Image of LSW Experiment](image)

**LSW Experiment**

- Use of two standard spare magnets for LHC at the CERN SM18 magnet testing hall, where cryogenics for magnet cooling (1.9 K) and vacuum facilities are available and are provided. The 2 dipoles are aligned at warm conditions cooled down, cold tested and finally powered.
  - $B = 9 \text{T}$ over effective $L = 14.3 \text{ m}$

**Photon Source**: COHERENT Verdi V18 CW Laser
  - $\lambda = 532 \text{ nm (2.3 eV)}$ - Optical power: $18.5 \text{ W}$

**Photon beam is linearly polarized with $E_z \parallel B$**
- Search for pseudoscalar ALPs
- Use of a $\lambda/2$ wave plate for polarization $E_z \perp B$
- Search for scalar ALPs
- Use of beam expander telescope to reduce the Laser beam divergence.

![Image of ALPS-II upgrade](image)

**Scientific impact of the expected sensitivity reach of the final stage of ALPS-II**

- ALPS-II will surpass CAST in the lower mass region.
- ALPS-II will reach bounds set from astrophysical considerations (1987a super-nova gamma burst, TeV transparency of the universe, WD cooling, ...)
- ALPS-II will tackle the uncolored and gray (DM) parameter region of ALPs predicted in string theory motivated SM extensions.
• Directional detection: measure direction of recoiling electron or neutron
• Fundament challenge: extracting enough information to estimate direction before recoil particle direction is randomized by multiple scattering
  • This gets harder as the recoil energy goes down
• Gas approach: decrease the density of the target
  • Works, but reduces the target mass tremendously
• Other approaches: increasing the tracking resolution
  • This is hard, we are already very good at tracking
ACCELERATOR SEARCHES
• Very nice summary talk describing numerous accelerator-based low mass DM searches probing “Heavy Photon” at 1-1000 MeV scale
• Complementary approaches: missing mass, energy, momentum, direct search for dark photons
Light Dark Matter at e+e- Colliders

Search for dark matter in A’ invisible decay

- A’ invisible decay (search for bump in recoil mass spectrum)
- A’ decay to leptons (spectrum of $\gamma e^+e^-, \gamma \mu^+\mu^-$ doesn’t match QED)
- Also sensitive to axions / axion like particles
Several talks about searches for different topological signatures at the LHC

As an outsider, biggest questions are: how they all tie together, and what are the implications for WIMPs as DM
Simplified Models

LHC results on simplified models

- Quietsch-Maitland
- Bhattacharya
- Benitez
- Dodd

 mono-jet

 mono-\gamma/Z

 resonant searches: di-jet, di-leptons...

 di-jet + MET

 mono-higgs

 di-top/bottom + MET
Making Sense of all the LHC SUSY Searches

Complementary talks walking us through the implications of the numbers SUSY searches performed at the LHC:

- From experimental perspective, in the simplified model space, looking for particular topological signatures
- From the theoretical perspective, in SUSY parameters space, asking which particle is the LSP and hence the DM candidate
Aside: Spectral Features in Limit Curves

- Structured features in limit curves can indicate systematic limitations in the background modeling.
- E.g., the background spectral model isn’t quite right, or the empirically fit background model parameters are under-constrained & correlated with the signal.
Aside: Spectral Features in Limit Curves

Search for low-mass spectral lines with Fermi-LAT (in systematics dominated region)

Use negative control, i.e., fits for signal in region where there should be no signal, to establish level at which model uncertainties can fake (or mask) a signal

Apply this to constrain a nuisance “template” in the fitting procedure, reducing the significance of any signal at or below the systematic level

arXiv:1406.3430v1 (also: 1704.05458v1)


Outlook

- Supersymmetry is too rich a theory to be easily excluded... Very different DM candidates are possible with various signatures!

- Nevertheless the simplest models of supersymmetric Dark Matter like Bino in the CMSSM are under siege and survive only in corners of the parameter space.

- On the other side Wino Dark Matter is also challenged by indirect detection thanks to the Sommerfeld enhancement.

- For gravitino Dark Matter a lot of parameter space is still viable, but the window for thermal leptogenesis may be closed soon by the LHC, if the gluino is not seen below ~2 TeV.

- Cosmologically though there are advantages to heavy SUSY, like scenarios for baryogenesis in RPV with gravitino DM!
DM Implications of LHC Searches

- Mono-jet search (red) looks for missing transverse energy from DM particle but is limited high missing energy cut need to reduce background
- Di-jet search (blue) looks for DM mediator particle producing pairs of SM particles and can reach higher energies
• Study covered 4 different $e^+e^-$ collider scenarios, 2 storage rings and 2 linear colliders
• Test coupling to leptons
  • complementary to LHC and direct detection searches
• In event of SUSY discovery we can expect to determine relic density with few percent precision (similar to Planck)
INDIRECT DETECTION
Indirect Detection with Charged Particles

Two spectral features that have generated excitement as potential dark matter signals:

- Increase of positron fraction / spectral bump in total $e^+ + e^-$ spectrum above 10 GeV up to $\sim$TeV
- Flatness of anti-proton to proton ratio above the geomagnetic cutoff
Interpretations of Positron Fraction

- Increase in the positron to electron ratio from 10 GeV up to > 100 GeV
- Caveat: both spectra are steeply falling (note factor of $E^3$ in left-hand plot), the positron spectrum is just falling less steeply than the electron spectrum
- This implies some source of large number of electron / positron pairs at high energy
- Favored interpretations: dark matter or pulsar wind nebulae (PWNe)
• At least five PWNe are close enough and young enough (high spin-down power) to produce the positron spectrum assuming reasonable efficiency for $e^+e^-$ pairs
Flatness of anti-proton to proton ratio was unexpected in 2015

“If anti-p are secondaries, their rigidity dependence should be different from p”

Boron/Carbon ratio measure by AMS-02 suggest propagation parameters should be updated, leading to flatter expected anti-p spectrum

Updated measurements of cross-sections also lead to flatter expected anti-p spectrum
• We expect secondaries (such as anti-p) to have softer spectra than primaries (p) because of their spectra steepens after they are produced, as the highest energies ones are more likely to escape the Galaxy
• We expect electron spectra to soften because of radiative energy losses
Antideuterons are potentially good channel to look for DM signals, but must address geomagnetic deflection and uncertainties in production cross sections.
Comparison of features, approximations, philosophy of existing Galactic particle propagation codes: GALPROP, PICARD, DRAGON, USINE
Indirect Detection with Neutrinos

Galactic Center limits

- Limits on thermally averaged annihilation cross section
- Recent DeepCore analysis improves limits for $m_\chi < 100$ GeV
- Antares best limits from Neutrino Telescopes for $m_\chi > 100$ GeV

- Searches for high-energy $\nu$ from Galactic Center sensitive to annihilation cross section
  - Strongest limits in some channels above $\sim 30$ TeV
- Searches for high-energy $\nu$ from Sun sensitive to scattering cross section (in conjunction with annihilation cross section)
Since asymmetric DM suppresses annihilation rate, the DM density of the sun can be much larger than it would be if the annihilation and capture rates were in equilibrium.

In this case the DM can affect the stellar heat transport, which can be probed, e.g., by helio-siesmology.
Many targets for indirect searches with $\gamma$ rays, but here we focused on the Galactic center (where there is an excess w.r.t. diffuse emission models) and the dwarf spheroidal galaxies (which set the strongest constraints).
• Galactic center is a very complicated astrophysical region
• Many phenomena that have been interpreted as potential DM signals
• For example, the 511 keV line seen at the Galactic center:
  • However, the GC 511 keV line seems to come from bound-state positronium, implying the positrons are produced at low energies (i.e., not from DM or pulsars)
Measuring J-factors in Dwarf Galaxies

- Moving from flux measurement to discuss of DM annihilation cross section depends on J-factors
- Many uncertainties in estimating the astrophysical J-factors of Dwarf Spheroidal (dSph) galaxies: velocity anisotropy, galaxy membership, light profile, region of integration
**GeV Galactic Center Excess is Probably Pulsars**

- **Strong support for MSP hypothesis**
  - Results:
    - Can explain ~100% of the GeV excess with MSP population with reasonable cutoff luminosity
    - "Resolved" component of modeled emission accounts for ~10% of the GeV excess, 90% are extrapolated based on reasonable luminosity function
  - 10 sigma detection in 1-4 GeV
  - Maximum MSP luminosity [erg/s]
  - More bulge MSPs
  - Inner Galaxy wavelet analysis
  - Expected for bulge MSPs

- **“Best candidates [to explain the Galactic center GeV excess] are arguably millisecond pulsars in the Galactic bulge”**
- **Highly significant (7-10σ with three complementary methods)**
  - Observation that data favor a population of point sources with pulsar-like spectra
- **Population for ~10,000 millisecond pulsars in the bulge would give the flux needed to make the excess**
Aside: Pulsar Populations

**Pulsar Zoo with over 2530 subjects**

- **Young Pulsars** ($\tau \sim 10$ My)
- **Pulsars in Binary Systems** ($\tau > 1$ Gy)


Peter L. Gonthier (Hope College)  Millisecond Pulsars and the Galactic Center E  July 27, 2017  5 / 27
Aside: Two Pulsar populations

Position in Galactic Coordinates of All Known Pulsars (LAT-detected pulsars highlighted)

- Young pulsars are found closer to Galactic plane
- Millisecond pulsar are more isotropically distributed

Abdo+ [LAT CIB]
2013ApJS..208...17A
Observational Horizon for Pulsars

- Most γ-ray detected pulsars are within 2 kpc
  - Even less for ms pulsars
  - GC at 8.5 kpc
Detecting Pulsars

Pulsars are detected primarily in radio and γ-ray searches.

Radio searches: point radio array at pulsar, look for pulses
- Weak towards galactic center where free electrons disperse pulse profile

γ-ray searches:
- Weak for binary searches where orbital motion modulates timing solution
Constraints on the DM continuum signal

For the Einasto profile, strongest limits so far in the TeV mass range:

- in the $W^+W^-$ channel: $6 \times 10^{-26}$ cm$^3$ s$^{-1}$ at 1.5 TeV

- They well complement the Fermi-LAT limits down to about 300 GeV

- Full H.E.S.S.-II array observations within the inner Galaxy Survey programme with pointings up to 3° in Galactic latitudes started in 2015
New Eyes on the $\gamma$-ray Skies

Significant bands (~1MeV, ~few TeV, > PeV) where upcoming instruments will improve sensitivity by over an order of magnitude

This will result in over 30 times more detected sources in those bands
COSMOLOGY & ASTROPHYSICAL DARK MATTER
Both Cold and Warm DM are compatible with CMB & galaxy clustering.

Kinetic energy (temperature) of DM can suppress structure formation at small scales.

If we could see the dark matter directly, it would be very easy to distinguish Cold DM from Warm DM.
Distinguishing Cold v. Warm DM

- **EAGLE (?)** Simulations tell us that the fraction of sub-halos that are “dark” goes from ~1 at $10^9 \, M_\odot$ to ~0 at $10^{10} \, M_\odot$.
- This reduces the statistics in counting satellites, leaving ambiguity between WDM and CDM.

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**Fraction of dark subhalos**

$$V_c = \sqrt{\frac{GM}{r}} \quad V_{\text{max}} = \max V_c$$

- All halos of mass $< 5 \times 10^8 M_\odot$ or $V_{\text{max}} < 7 \, \text{km/s}$ are dark ($m.<10^4 M_\odot$).
Fermat’s principle as a variational principle: paths near the path of least time to add constructively.
Gravitational time dilation means that light from lensed galaxy (behind) reaches us more quickly by travelling around the lensing galaxy (in front).
Aside: Strong Lensing

Light will appear for lines of sight where the gradient of the travel time is small: This includes minima, maxima and saddle points.
Aside: Strong Lensing

Key point for us: a strong lens creates a number of directions where the light travel time surface is flat: our sensitivity to lensing from sub-halos along these lines of sight is vastly improved.

Light will appear for lines of sight where the gradient of the travel time is small: This includes minima, maxima and saddle points.

Einstein Ring  Einstein Cross  Weak Lensing
Measuring Strong Lensing Substructure Will Resolve CDM v. WDM

Detecting substructures with strong lensing

Vegetti & Koopmans ‘09

\[ m_{\text{sub}} = 10^8 M_\odot \]

If WDM is right, should find NO $10^7 M_\odot$ halos

If CDM is right, should find MANY $10^7 M_\odot$ halos

Can detect subhalos as small as $10^7 M_\odot$
Simulations including realistic feedback from baryonic processes (e.g., star formation, supernovae) used to explore case for self-interacting DM (SIDM).

With SIDM, Dwarf Galaxies are much less sensitive to feedback.
Primordial Black Holes

• Unexpected large rate & mass of black holes in LIGO gravity wave detections lead to question: what fraction of DM is attributable to high-mass primodial black holes
  • < 10⁻¹⁵ M☉: evaporation emits γ rays and puts energy back into CMB
  • 10⁻¹⁵ – 10² M☉: various lensing studies
  • > 2M☉: emission from accretion
• The CMB sees the neutrino background
• Future large surveys should be able to detect the neutrino mass and strongly constrain WDM properties / see CDM velocity dispersion
• For MeV WDM cross section for annihilation to $\nu\nu$ sets relic abundance
Euclid is Sensitive to Warm Dark Matter

- Euclid will greatly extend galaxy surveys for redshifts 1-2 (7-10 Gyr ago)
- This will improve constraints on structure growth rate and cosmic expansion
  - Could constrain $m_{WDM} < 2$ keV

(e.g. VIPERS: Scodeggio+, 2017)
META SUMMARY
The Good News

- No convincing (or even particularly compelling) DM signals in any searches: be they direct, indirect or accelerator-based
  - Some things that have been interpreted as signals are now strongly disfavored by other measurements (e.g., DAMA/LIBRA) or face strong competing hypotheses (e.g., positron fraction, Galactic center GeV excess)
  - Some interesting observations that merit careful follow up: (Helioseismology anomaly, particle rigidities)
- This is a great application of the scientific method: we are finding ways of testing (and falsifying) hypotheses & developing new hypotheses
- Dark matter is more interesting that a simple ~100 GeV thermal relic WIMP
The Even Better News

Many impressive efforts are underway:

- to understand what the astrophysical data are telling us about the nature of dark matter
- to continue to test the dominant WIMP paradigm by building more sensitive experiments and better understanding backgrounds
- to develop ways to test other types of DM candidates

This is a great application of the scientific method: we are finding ways of testing (and falsifying) hypotheses & developing new hypotheses.

We know that dark matter exists, perhaps we might be very lucky the discover that its particle nature is more interesting than, say, a ~100 GeV thermal relic WIMP from one of the simpler SUSY models.
THANK YOU