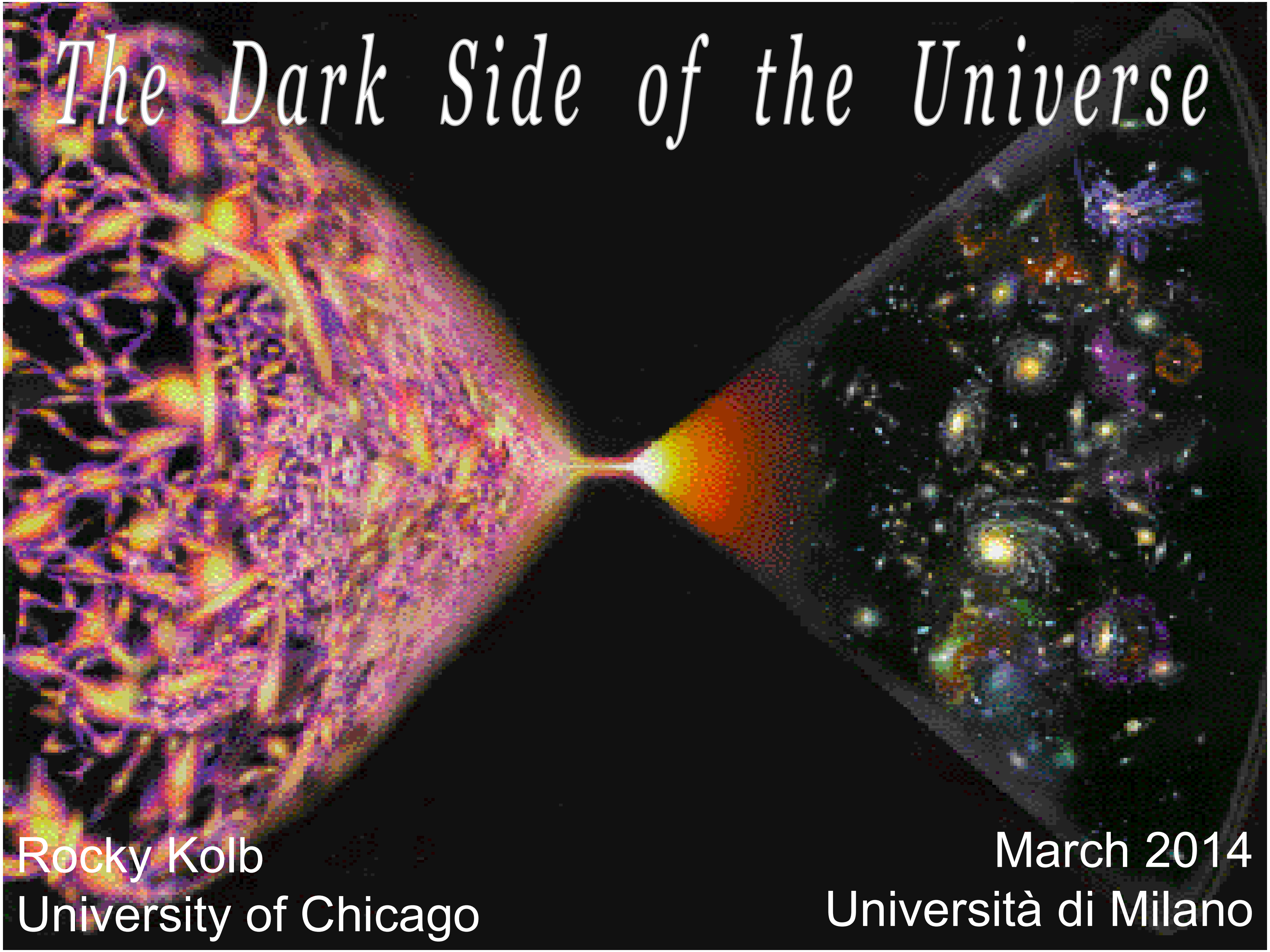
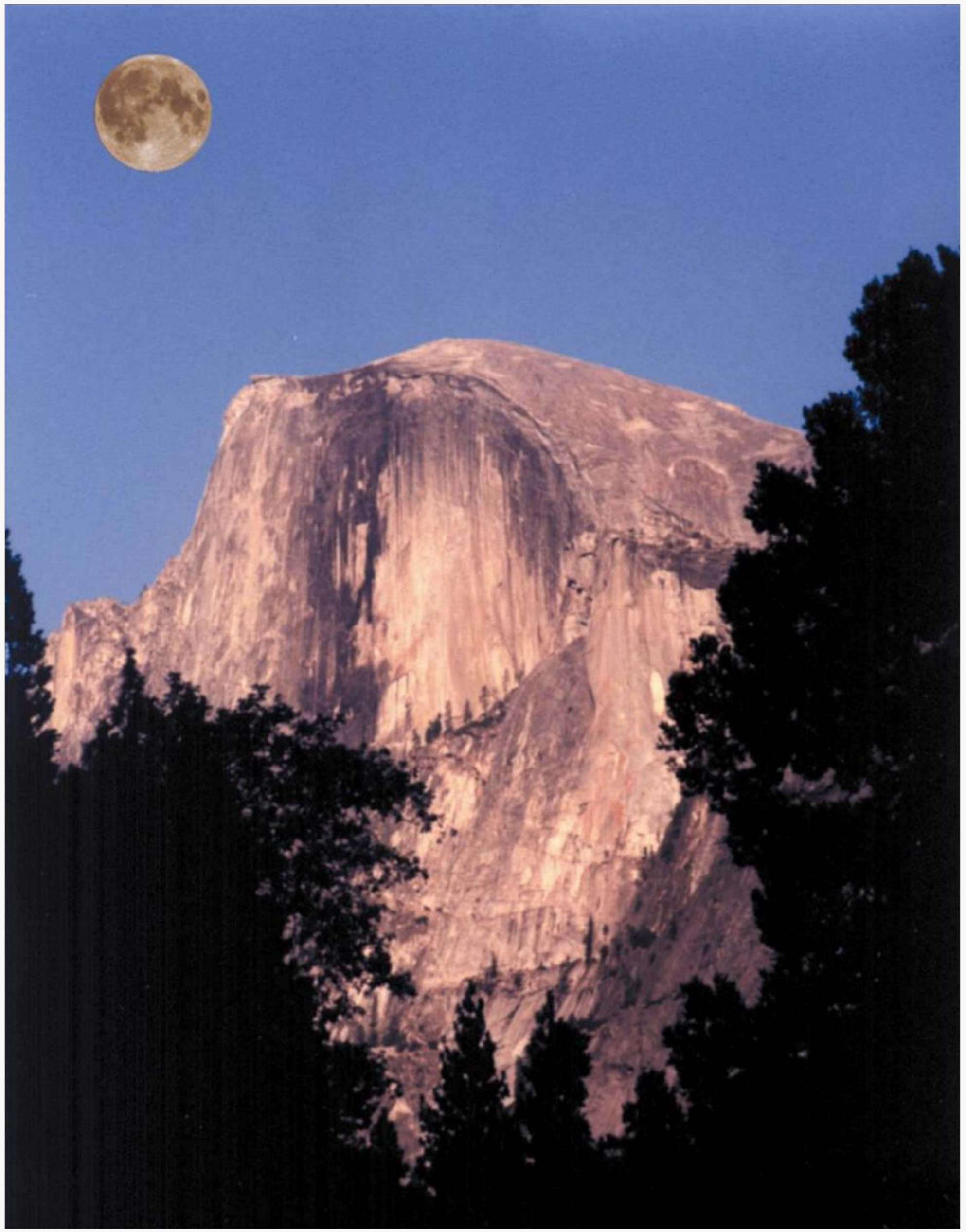
The Dark Side of the Universe



Rocky Kolb
University of Chicago

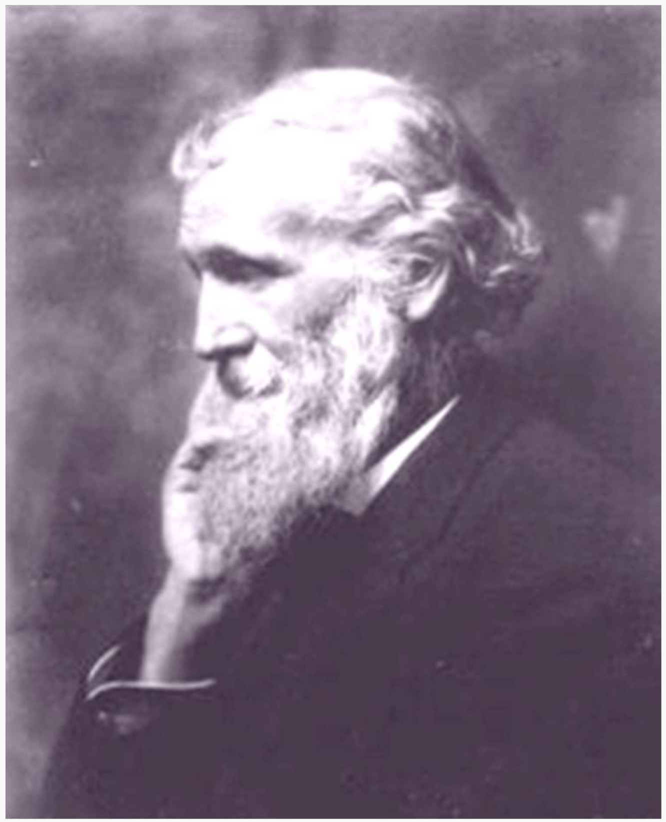
March 2014
Università di Milano

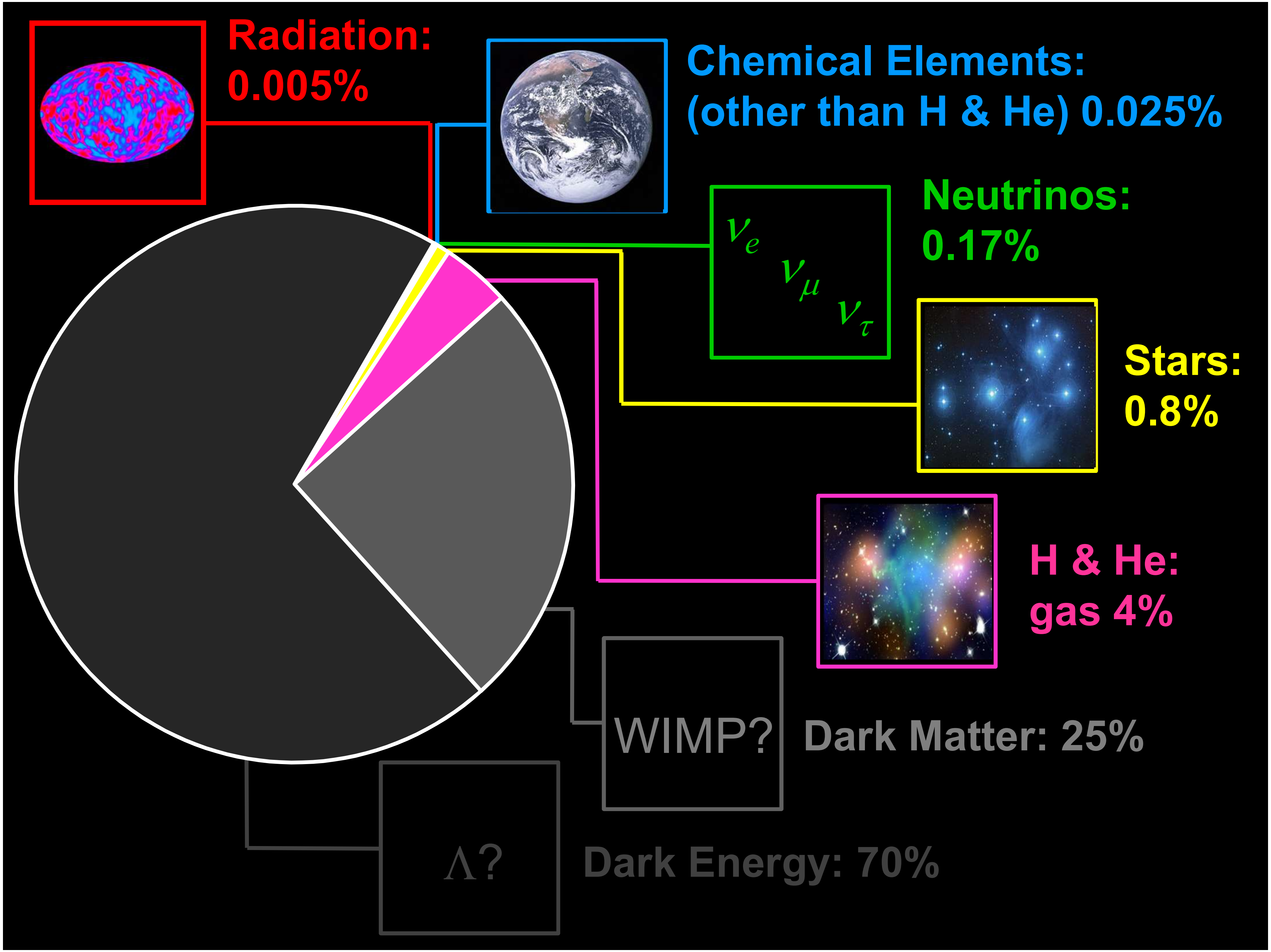
The Quantum & the Cosmos



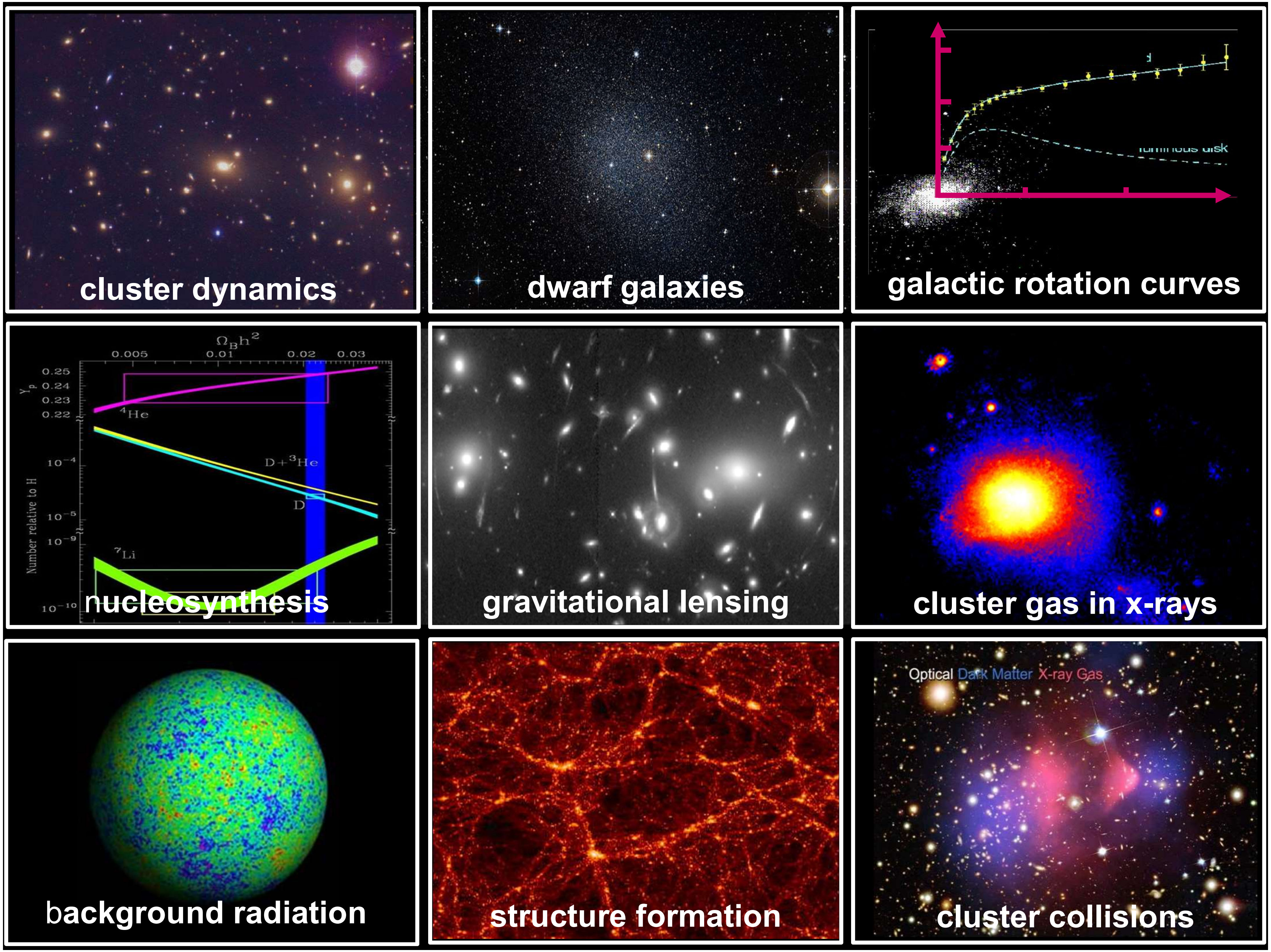
When we try to pick out anything by itself, we find it bound fast, by a thousand invisible cords that cannot be broken, to everything else in the universe.

– John Muir





Radiation:
0.005%
Chemical Elements:
(other than H & He) 0.025%
Neutrinos:
0.17%
ν_e ν_μ ν_τ
Stars:
0.8%
H & He:
gas 4%
WIMP?
Dark Matter: 25%
Λ?
Dark Energy: 70%


cluster dynamics
dwarf galaxies
galactic rotation curves
$\Omega_B h^2$
0.005
0.01
0.02
0.03
Y_p
0.25
0.24
0.23
0.22
^4He
10^{-4}
$D+^3He$
D
Number relative to H
10^{-5}
10^{-9}
^7Li
10^{-10}
nucleosynthesis
gravitational lensing
cluster gas in x-rays
background radiation
structure formation
Optical Dark Matter X-ray Gas
cluster collisions

Dark Matter

- Newton or Einstein didn't have the last word
  - Modified Newtonian Dynamics, *i.e.*, $F \neq m\, a$
  - Modified Gravity
- Rocky Rogue Planets
- Mass Challenged Stars
- Black Holes

(Rocky Rogue Planets, Mass Challenged Stars, Black Holes) → Massive Compact Halo Objects (MACHOs)

- New Particle Species

Don’t look now, but …

… invisible things are passing through you!

A mysterious, invisible particle species is all around us,

a relic of the first fraction of a second of the Universe,

about 10^7 are in this room at any instant

flying around at about 10^6 kilometers per hour,

about 10^{12} of them will pass through you during this talk,

but you can’t see them, feel them, or smell them, and yet …

… they shape the large-scale structure of the Universe.

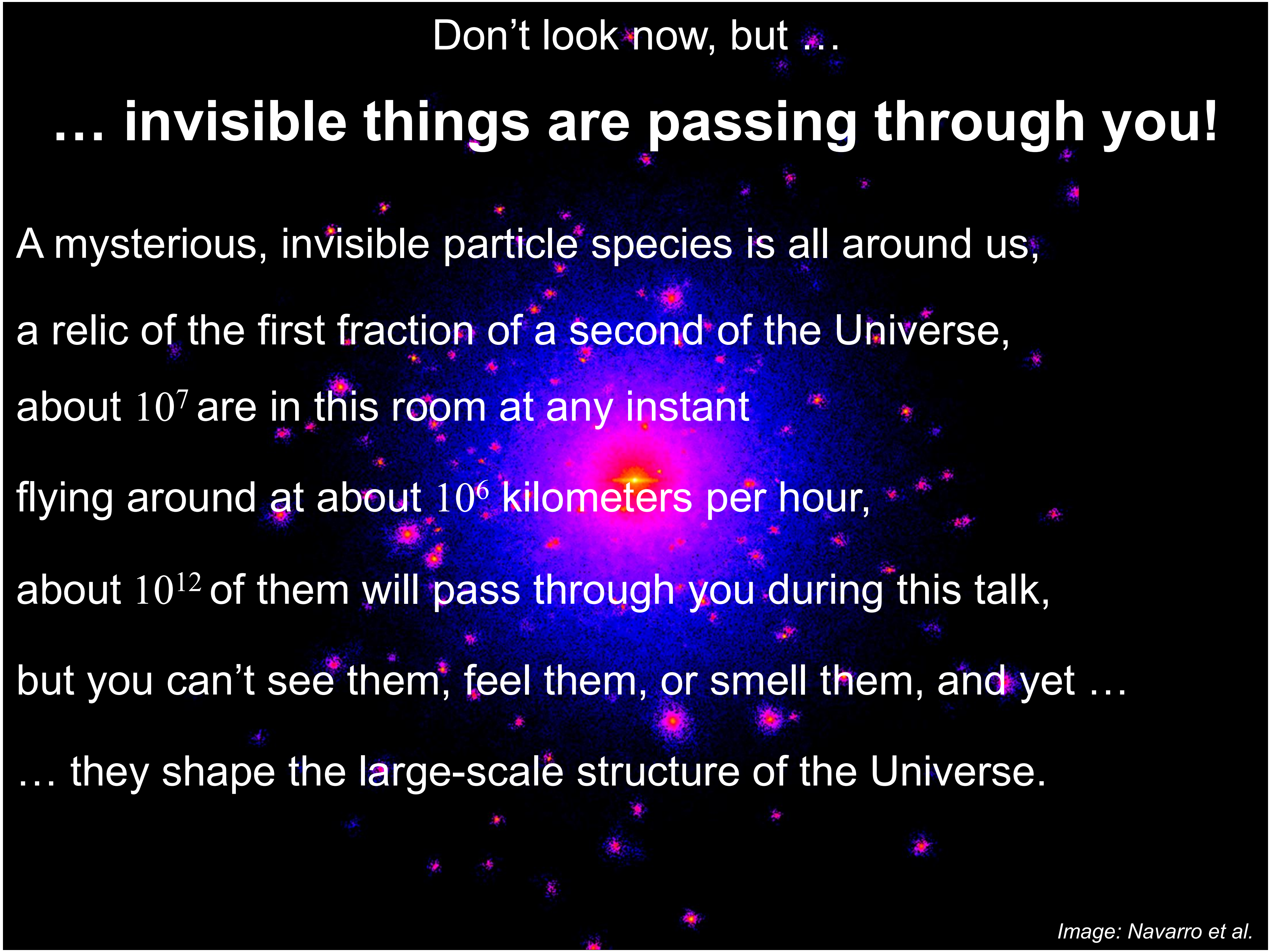


Image: Navarro et al.

Particle Dark Matter Bestiary

- sub-eV mass neutrinos (WIMPs exist!) (hot)
- sterile neutrinos, gravitini (warm)
- lightest supersymmetric particle (cold)
- lightest Kaluza-Klein particle (cold)

} thermal relics or decay of or oscillation from thermal relics

- Bose-Einstein condensates
- axions, axion clusters
- solitons (Q-balls, B-balls, …)

} from phase transitions

- supermassive wimpzillas — from inflation

} nonthermal relics

Mass

10^{-22} eV (10^{-56} g) Bose-Einstein

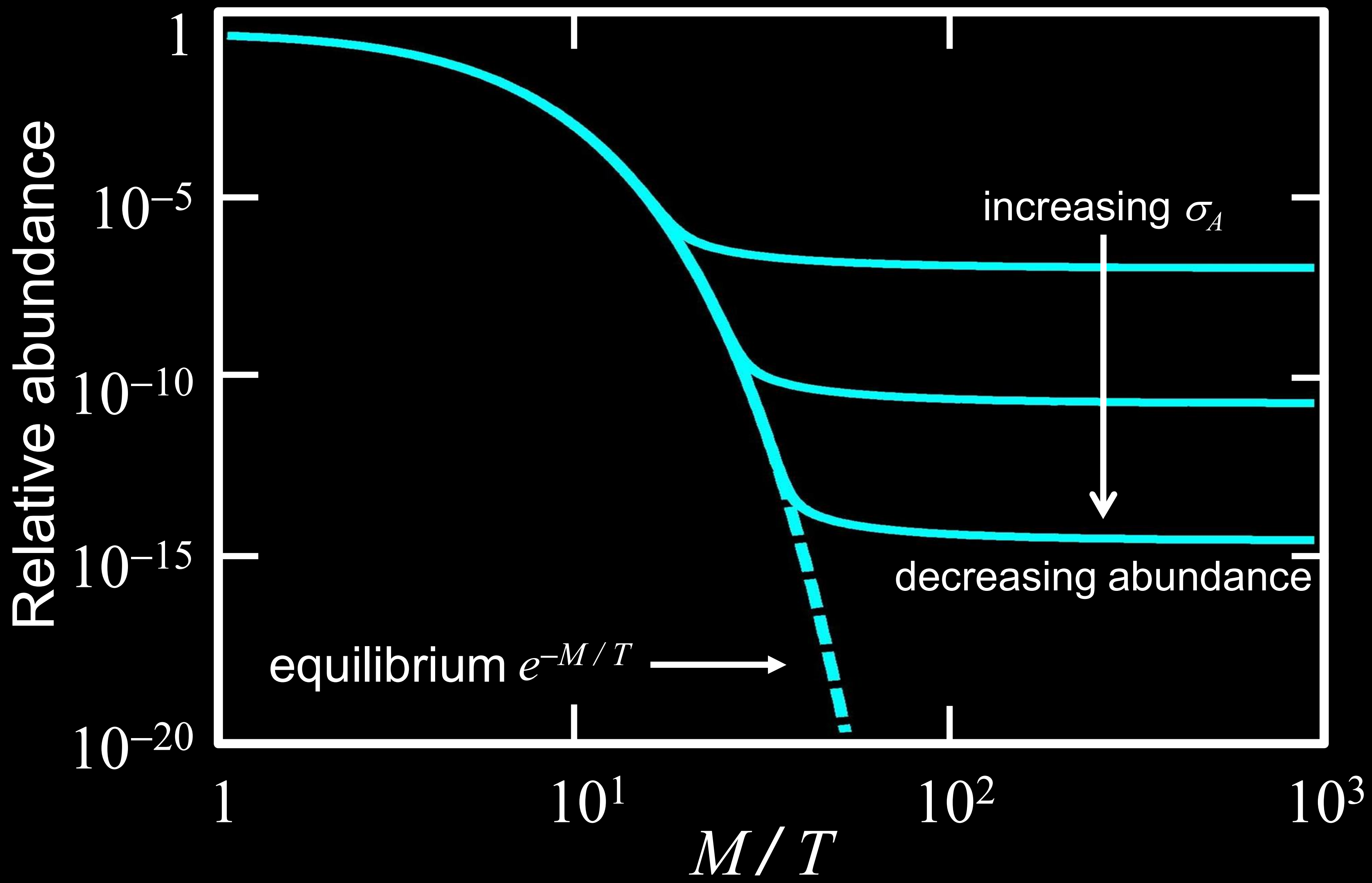
$10^{-8} M_\odot$ (10^{+25} g) axion clusters

Interaction Strength

only gravitational: wimpzillas

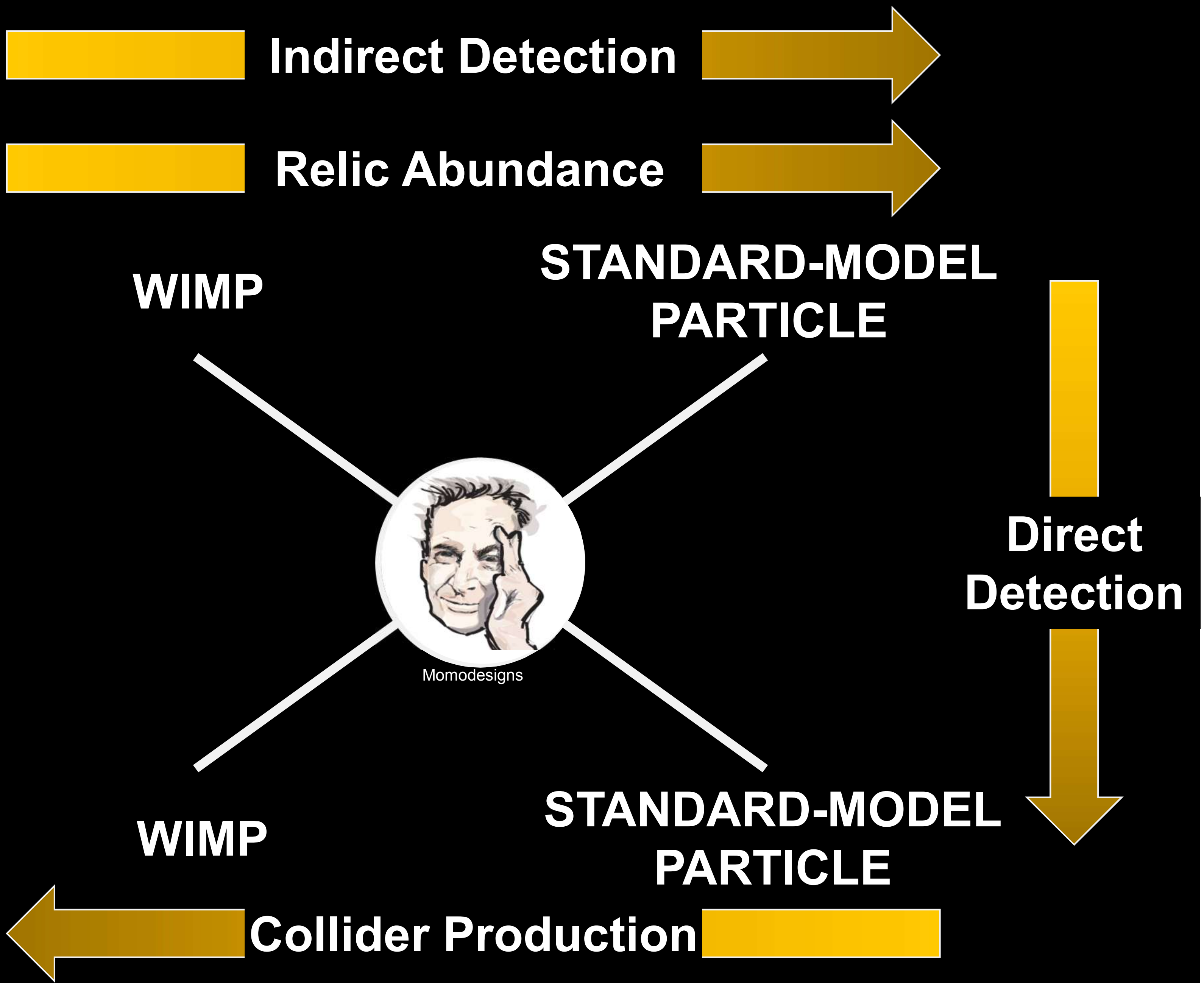
strongly interacting: B balls

Cold Thermal Relics*



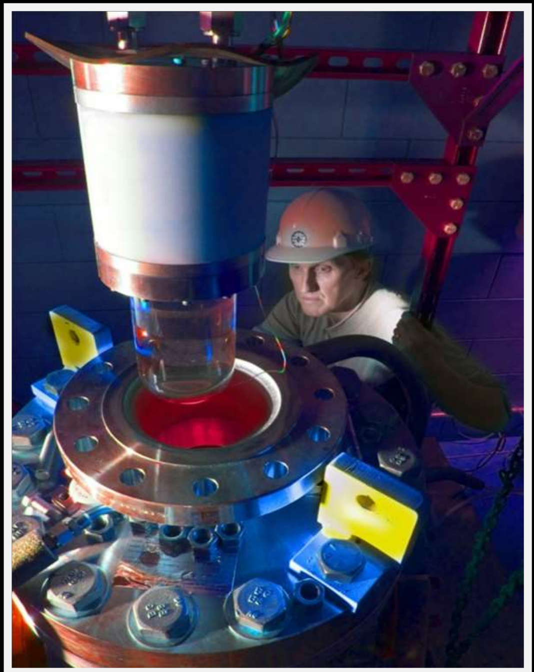
* Relic: an object of particular veneration.

Cold Thermal Relics Are WIMPs

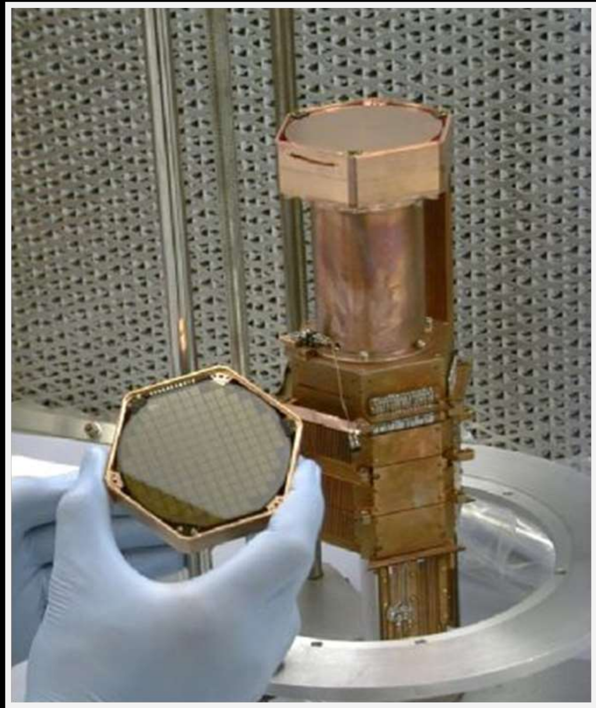


Direct Detection

COUPP



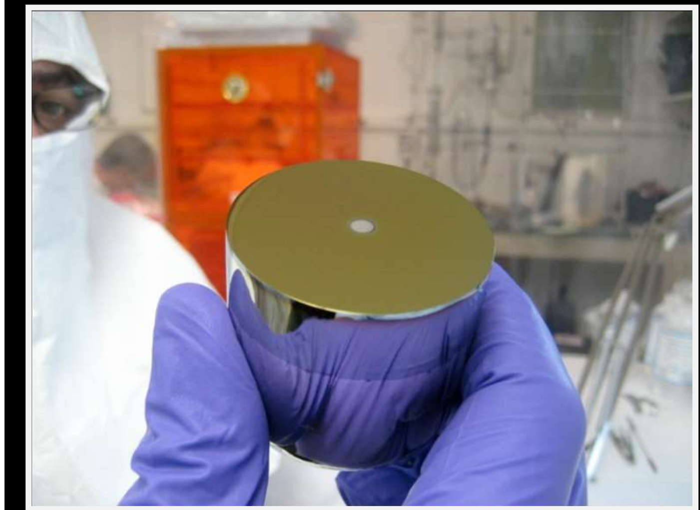
CDMS



CRESST

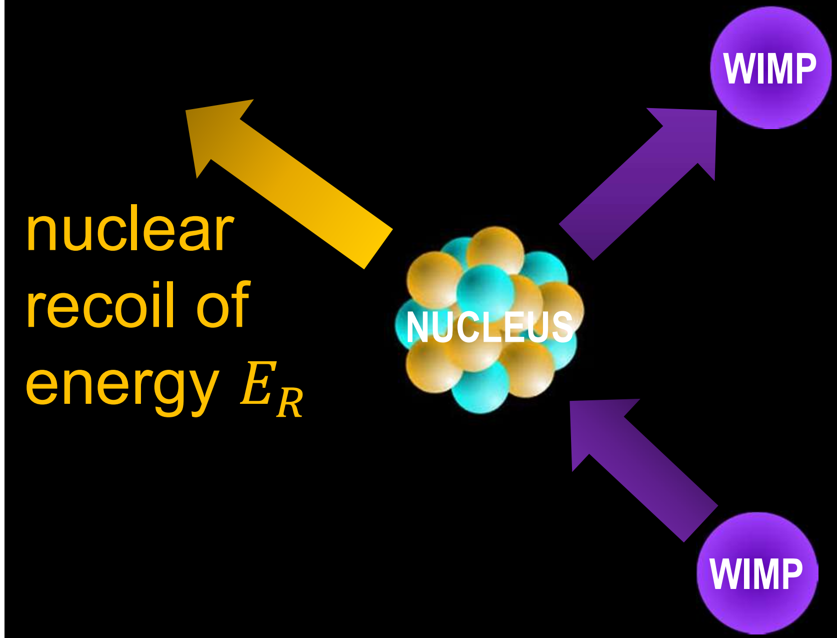
Xenon

CoGeNT



(+ EDELWEISS, DAMA, EURECA, ZEPLIN, DEAP, ArDM, WARP, LUX, SIMPLE, PICASSO, DMTPC, DRIFT, KIMS, LUX, ARDM, ANAIS, CDEX PandaX, DarkSide, DAMA/LIBRA …)

Direct Detection



$$\frac{dR}{dE_R} = N_{\text{target}} \frac{\rho_{WIMP}}{M_{\text{WIMP}}} \int_{v_{\text{MIN}}} dv\, v\, f(v) \frac{d\sigma}{dE_R}$$

Experiment: N_{target}

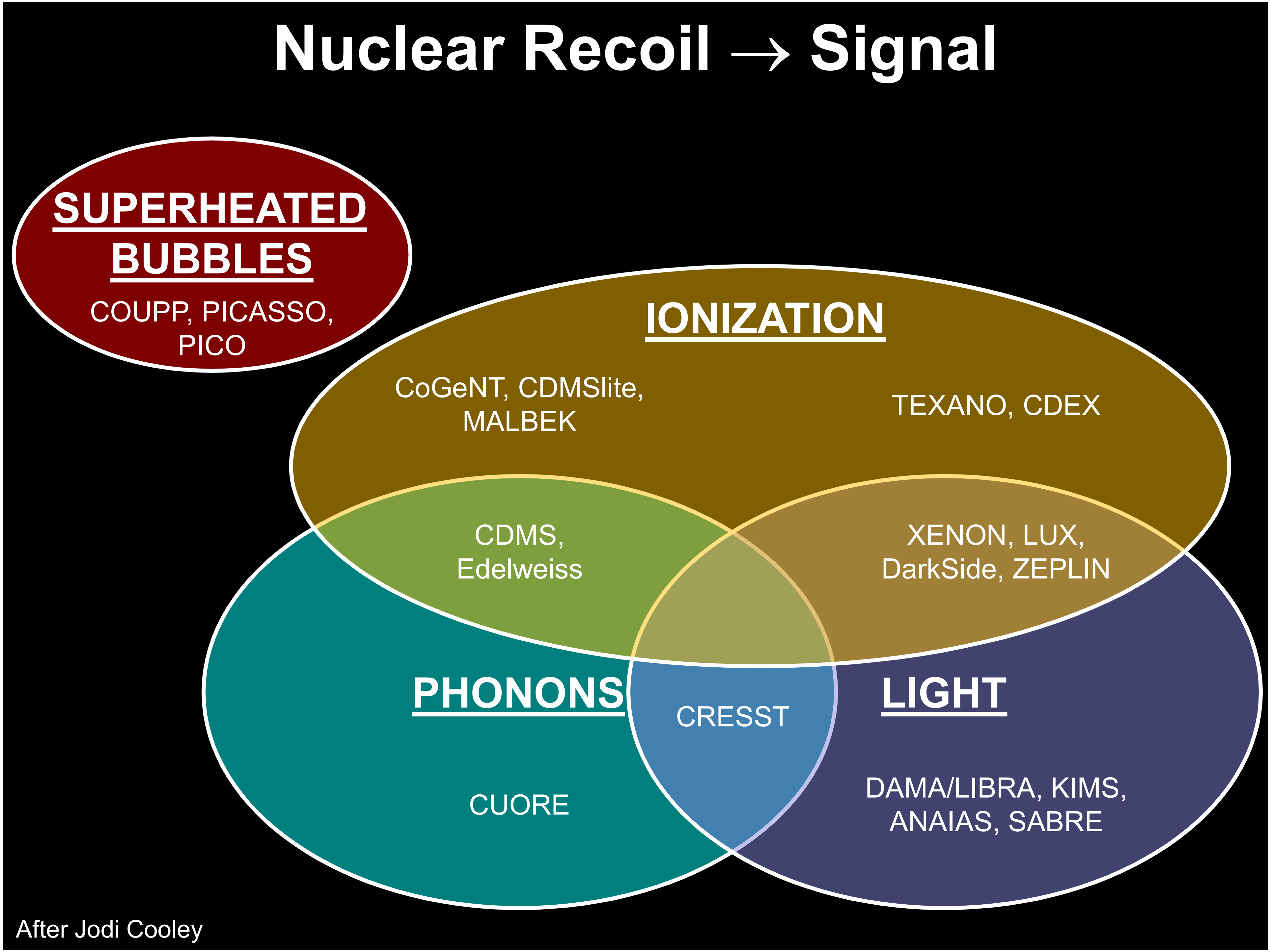
$$v_{\text{MIN}} = \sqrt{\frac{M_N E_{\text{Threshold}}}{\mu^2}}$$

$d\sigma/dE_R$

Astrophysics: ρ_{WIMP}
$f(v)$

Particle physics: M_{WIMP}
$d\sigma/dE_R$

Recoil energies few to few dozen keV


Nuclear Recoil → Signal
SUPERHEATED BUBBLES
COUPP, PICASSO, PICO
IONIZATION
CoGeNT, CDMSlite, MALBEK
TEXANO, CDEX
CDMS, Edelweiss
XENON, LUX, DarkSide, ZEPLIN
PHONONS
CRESST
LIGHT
CUORE
DAMA/LIBRA, KIMS, ANAIAS, SABRE
After Jodi Cooley

Direct Detection

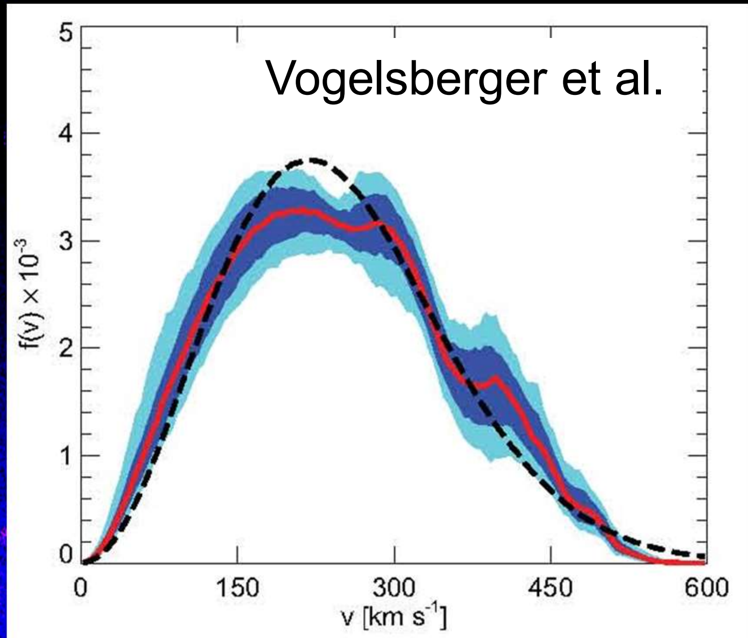
- f(v) <u>local</u> WIMP phase-space density
  - Assume: $\rho_{DM} = 0.3$ GeV cm^{-3} (subclumps, streams, cusps,…?)
  - Assume: Maxwellian velocity distribution $\langle v^2 \rangle^{1/2} = 220$ km s^{-1}
- Spin dependence (axial, tensor)?

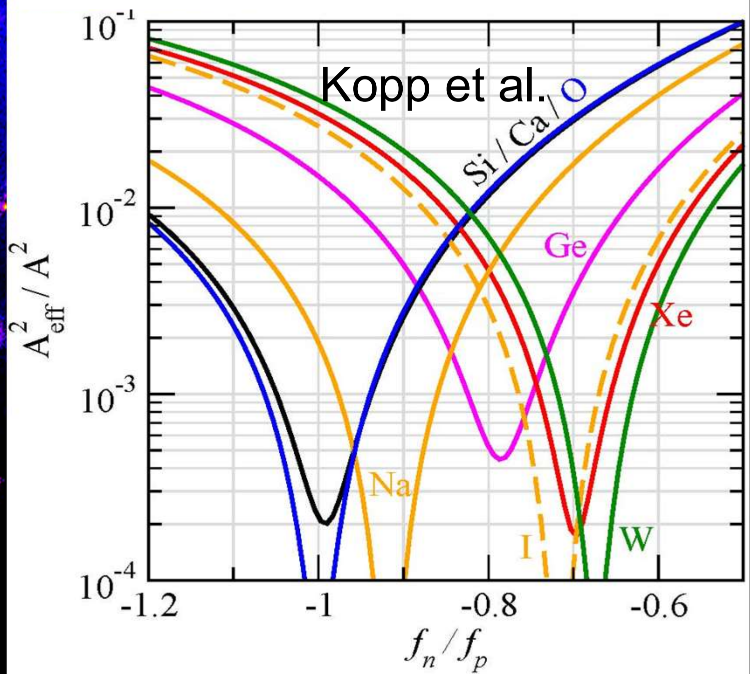
$$\sigma_{\chi N}(\text{axial}) = \frac{8}{\pi} \frac{m_\chi^2 m_N^2}{(m_\chi + m_N)^2} \Lambda^2 J(J+1)$$

- Same coupling to p and n (scalar)?

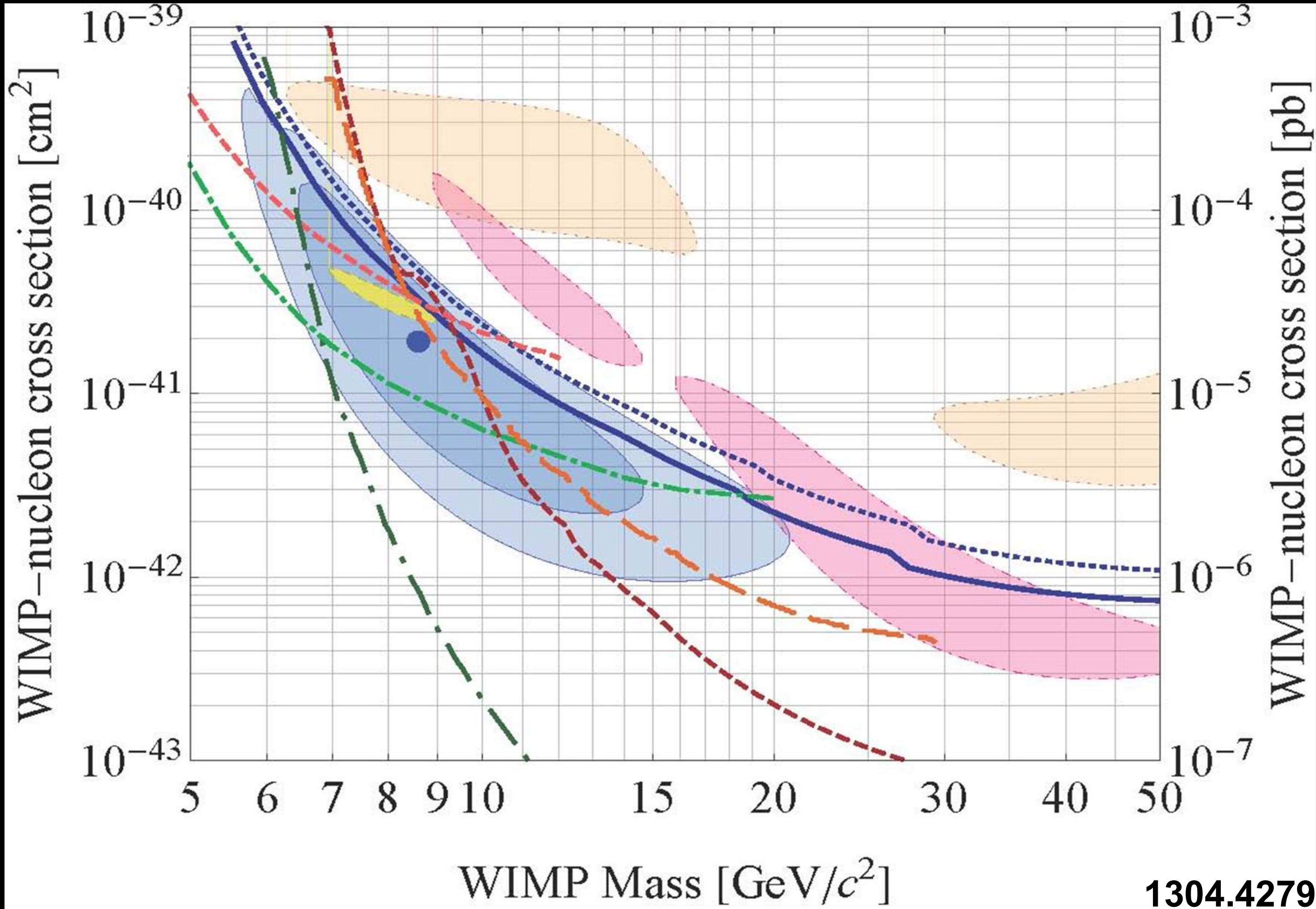
$$\sigma_{\chi N} = \frac{1}{\pi} \frac{m_\chi^2 m_N^2}{(m_\chi + m_N)^2} \left[Z f_p + (A - Z) f_n \right]^2$$

- Compare different expts. w/ caution



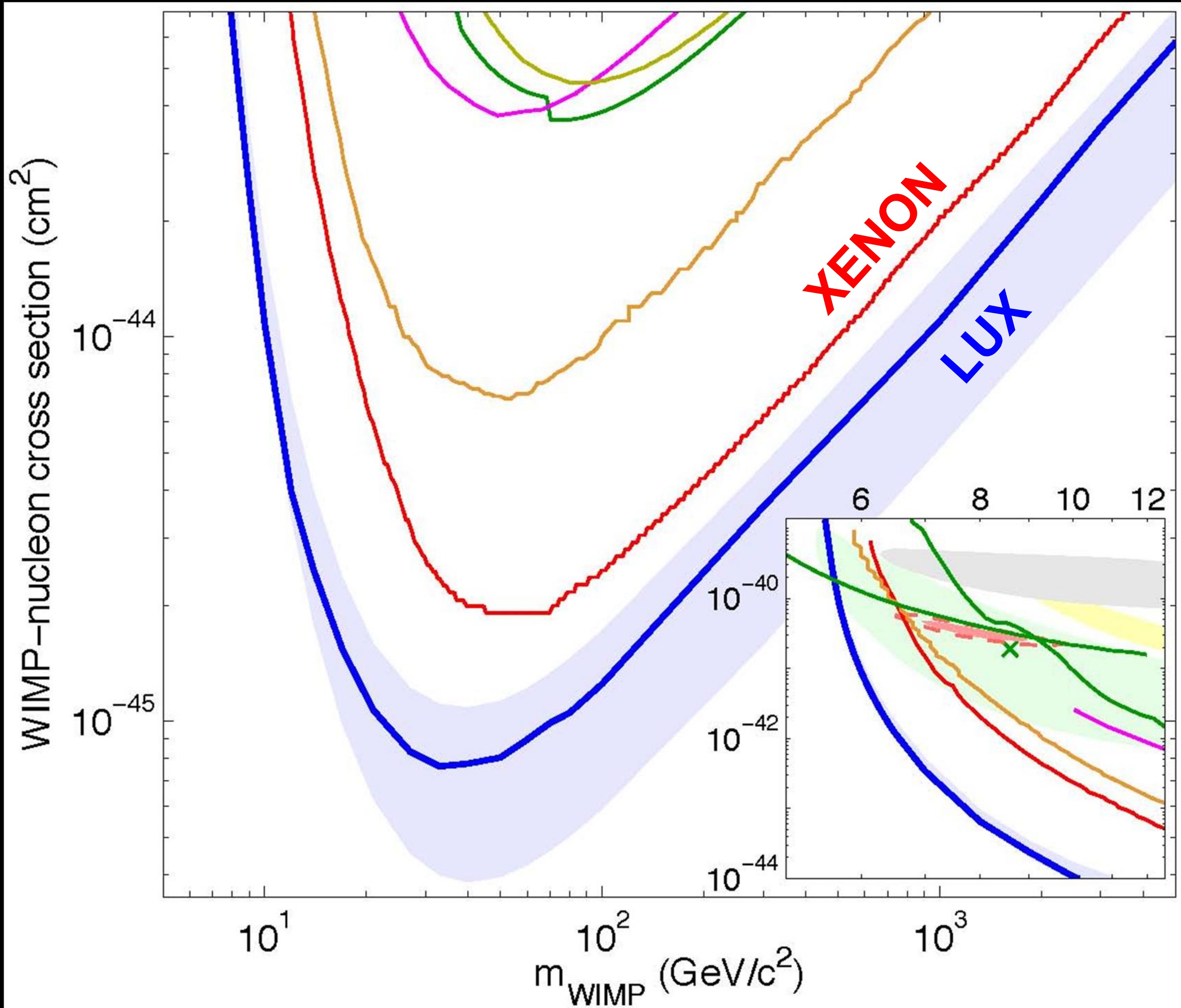


Low-Recoil-Energy (Mass) Anomalies



Limits: CDMS Si (Ge); XENON; EDELWEISS
Signal?: CSDS (Si) ; CoGeNT; DAMA/LIBRA; CRESST
Combined: Blue region 68% and 90% C.L.

LUX (arXiv:1310.8214)



Direct Detection

Low-mass region: either

1) unexplained backgrounds in DAMA, CoGeNT, CRESST-II, CDMS II/Si …

or

2) other experiments do not understand low recoil-energy calibration

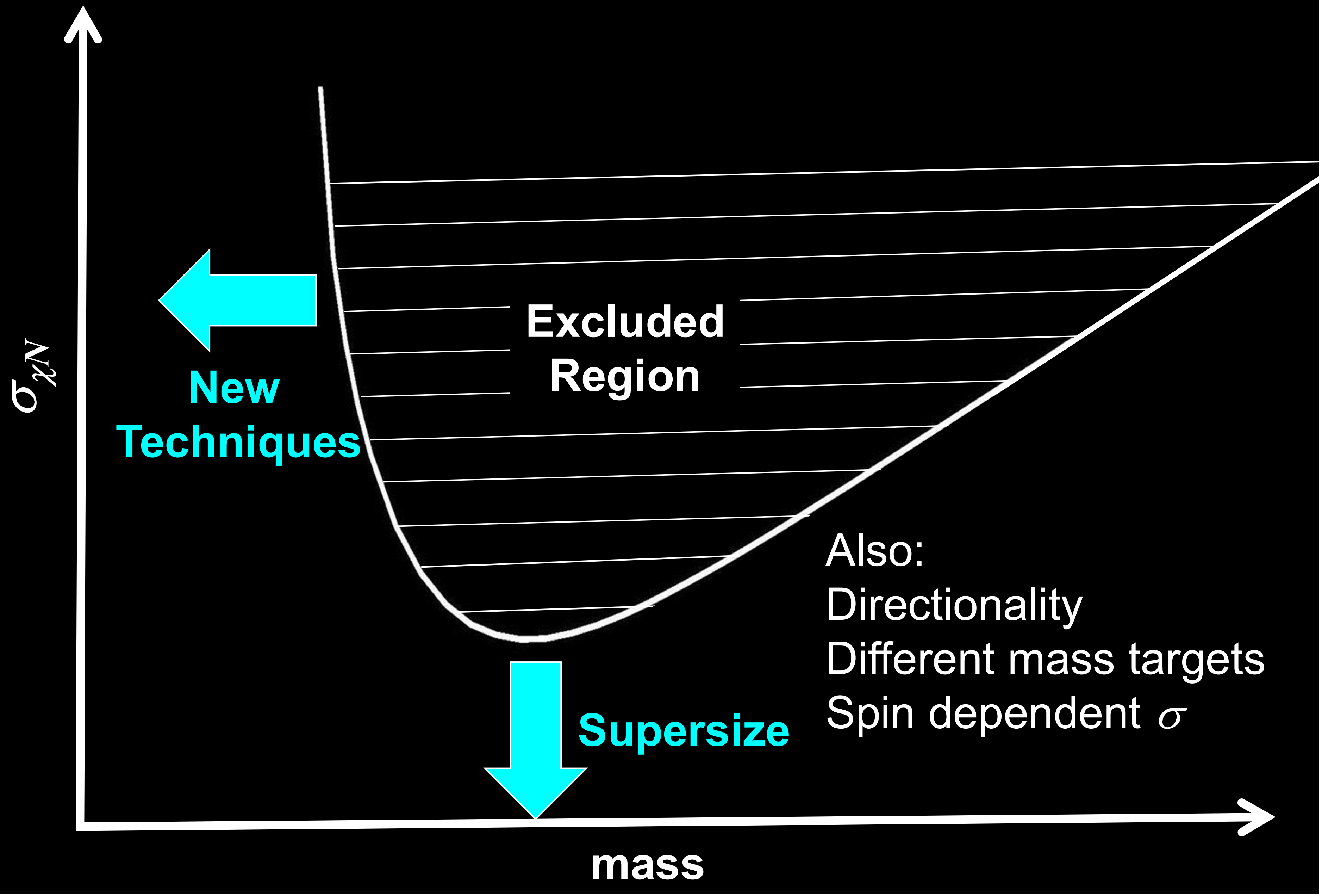
or

3) can't compare different experiments

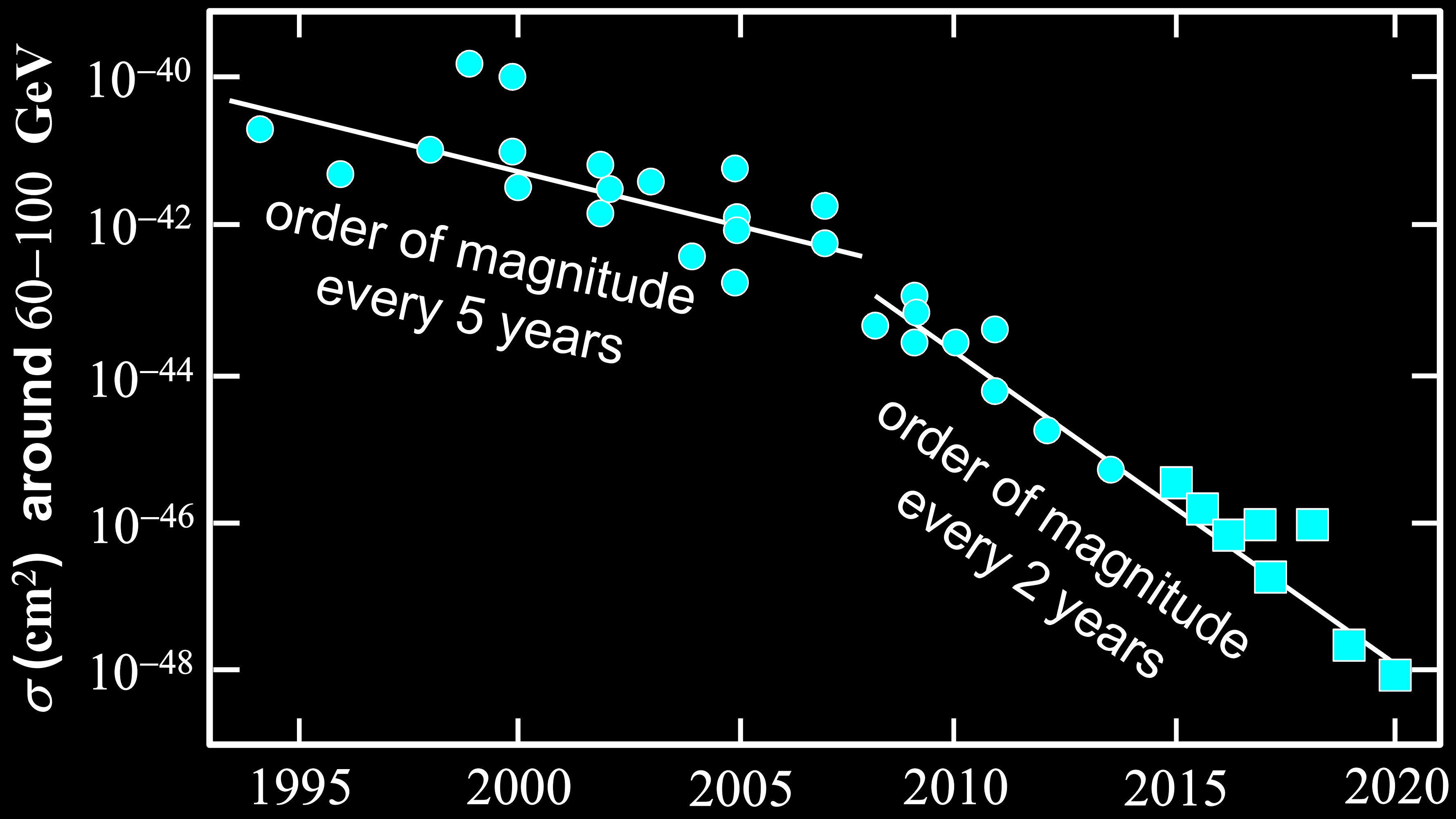
High-mass region:

Reaching sweet spot for supersymmetric WIMPs, just as LHC eats away at it!

Direct Detection

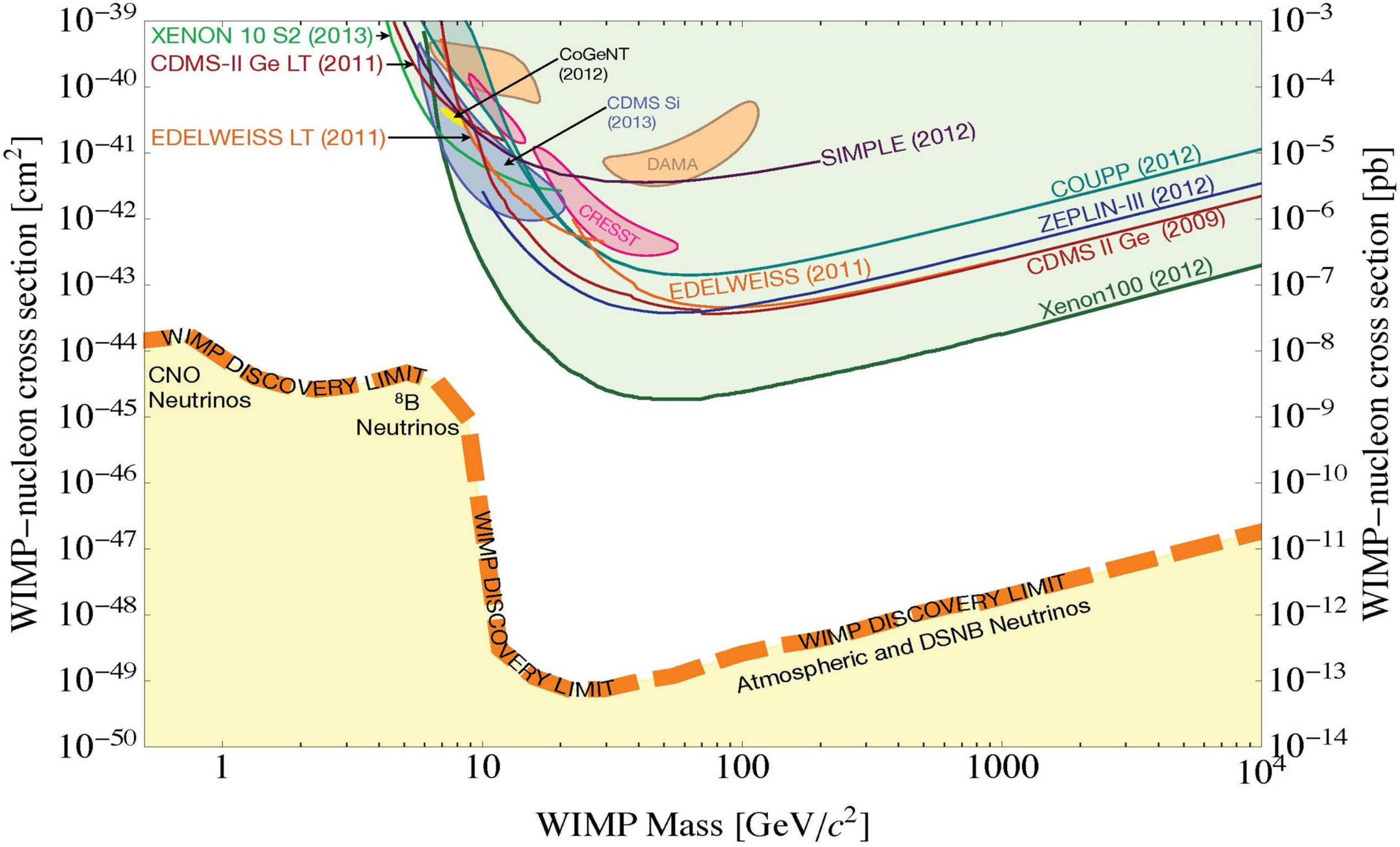


Direct Detection

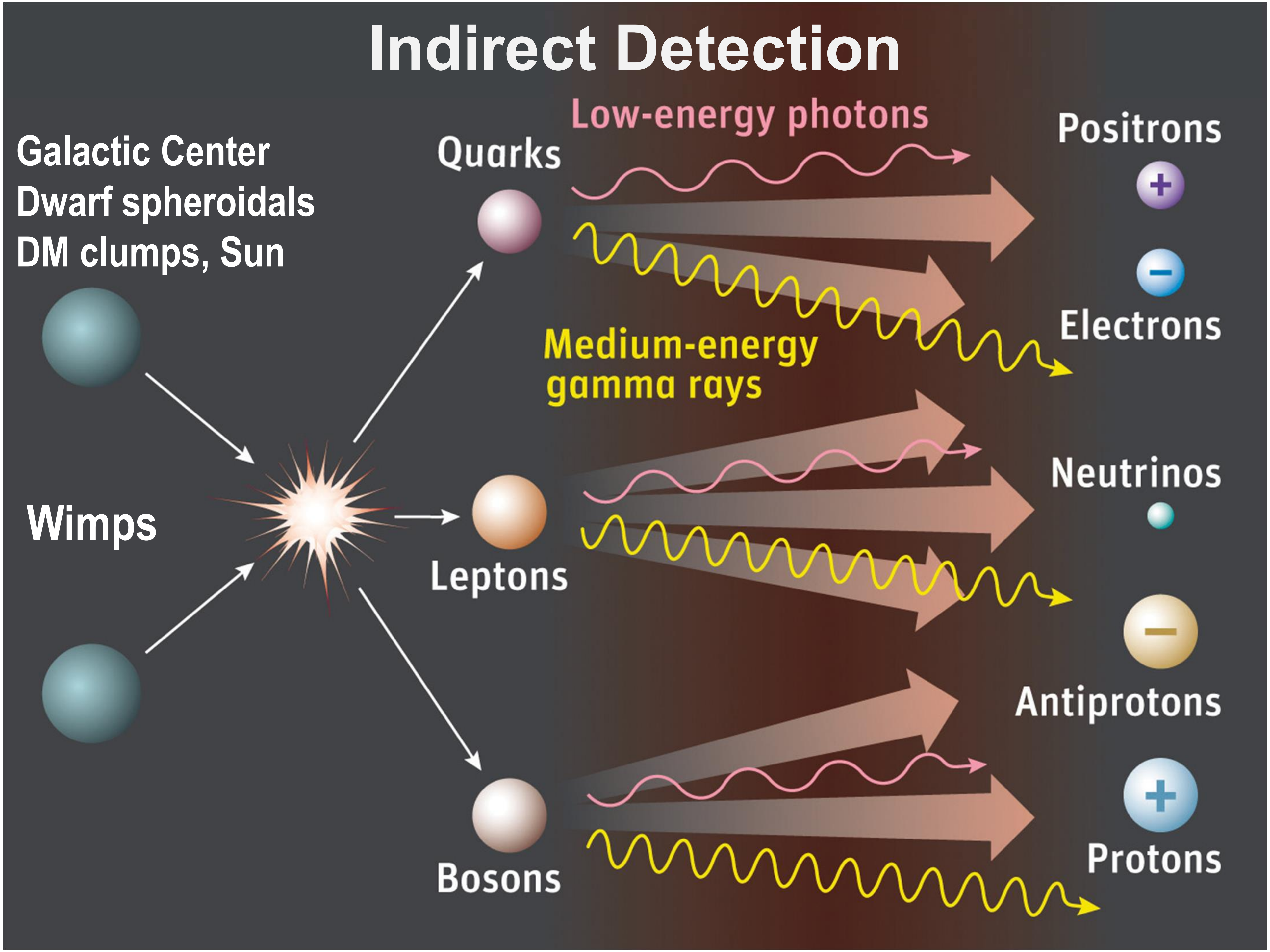


Vuk Mandic; Laura Baudis

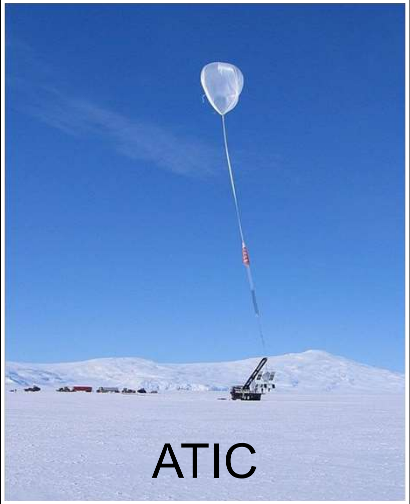
Direct Detection

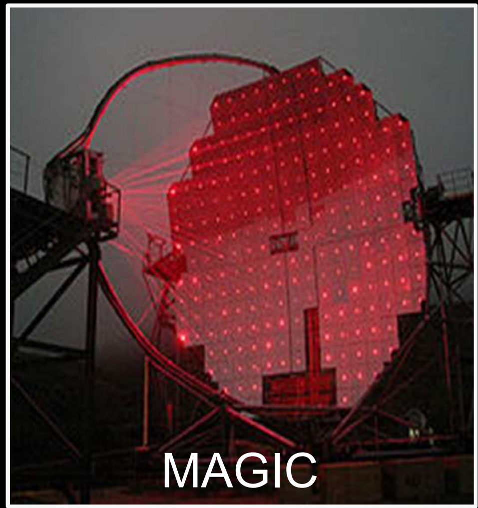


Cooley, TAUP 2013


Indirect Detection
Galactic Center
Dwarf spheroidals
DM clumps, Sun
Wimps
Quarks
Leptons
Bosons
Low-energy photons
Medium-energy gamma rays
Positrons
Electrons
Neutrinos
Antiprotons
Protons

Indirect Detection





Indirect Detection

$$R_{g,n}(y) = \frac{A_{\text{DETECTOR}}}{4p} N_{g,n} \langle s_A \text{v} \rangle \underset{\substack{\text{line of}\\ \text{sight}}}{\grave{o}} ds \frac{r^2(s,y)}{2m^2_{\text{WIMP}}}$$

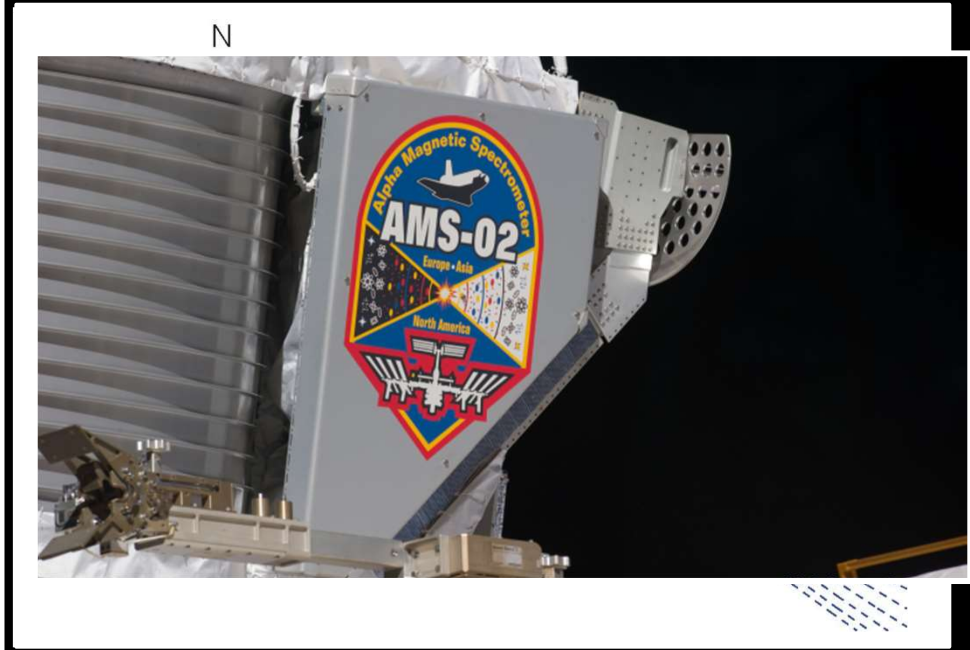
What to look for

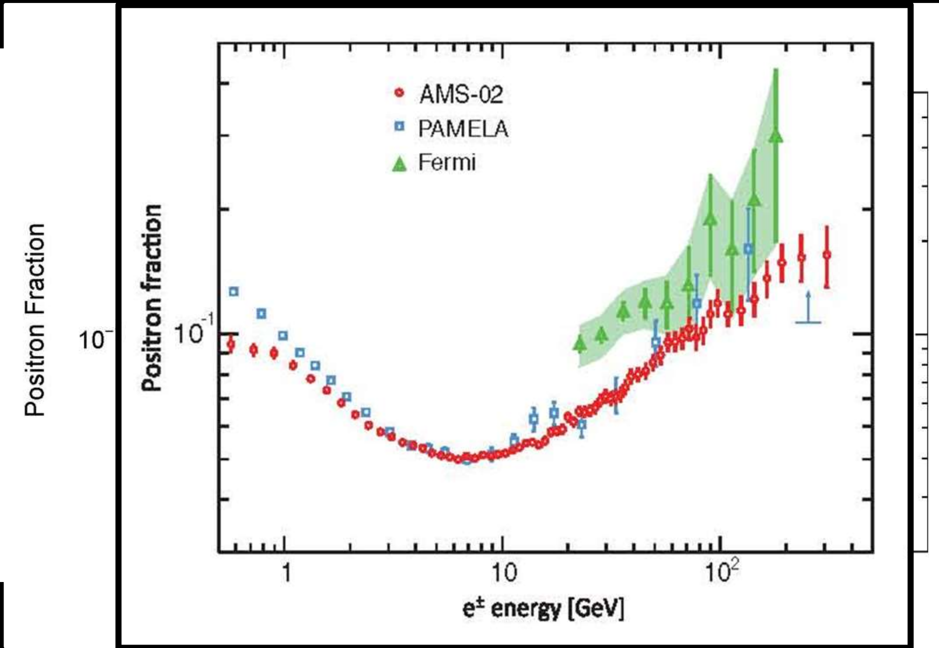
- Charged particles: $\bar{p}$, high-energy $e^- e^+$
  - astronomical backgrounds
  - easy to detect
  - bent by magnetic field
- Continuum photons, neutrinos
  - astronomical backgrounds
  - ν usually not dominant channel
  - ν hard to detect
- Monoenergetic photon line ($\bar{\chi}\chi \rightarrow \gamma\gamma$)
  - low background
  - (probably) low signal
  - “golden” detection channel

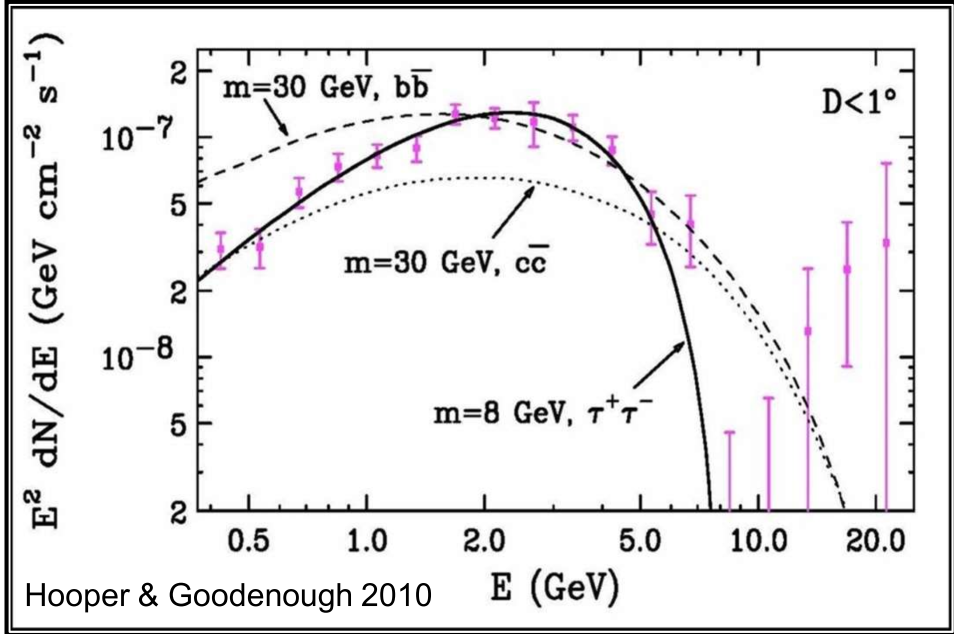
Where to look for it

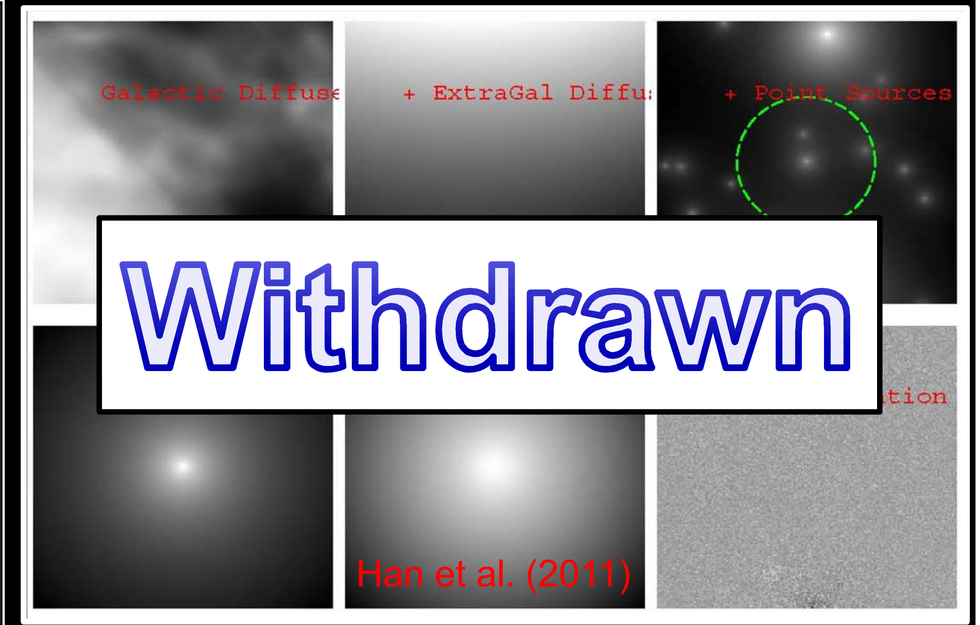
- Galactic Center
  - know where to look
  - largest signal
  - largest backgrounds
- Nearby subclumps
  - don’t know where to look
  - signal down 10^{-3}
  - clean: no baryons
- Dwarf spheroidals $(M/\Lambda)_{\square}$ > 3000
  - know where to look (about 20)
  - signal down another 10^{-3}
  - clean: few baryons

Indirect Signals Have Come (and Gone?)

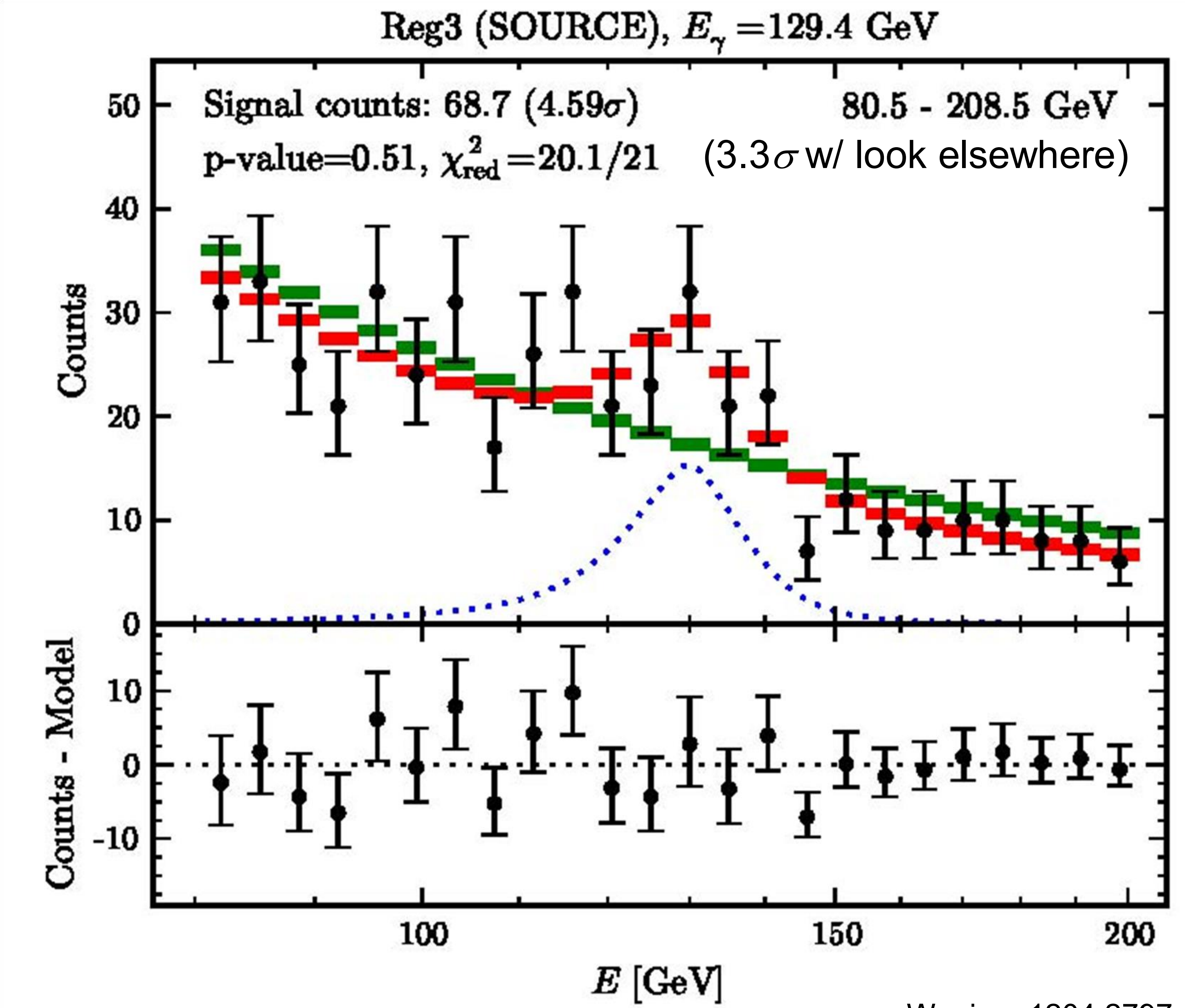








Fermi/GLAST Line



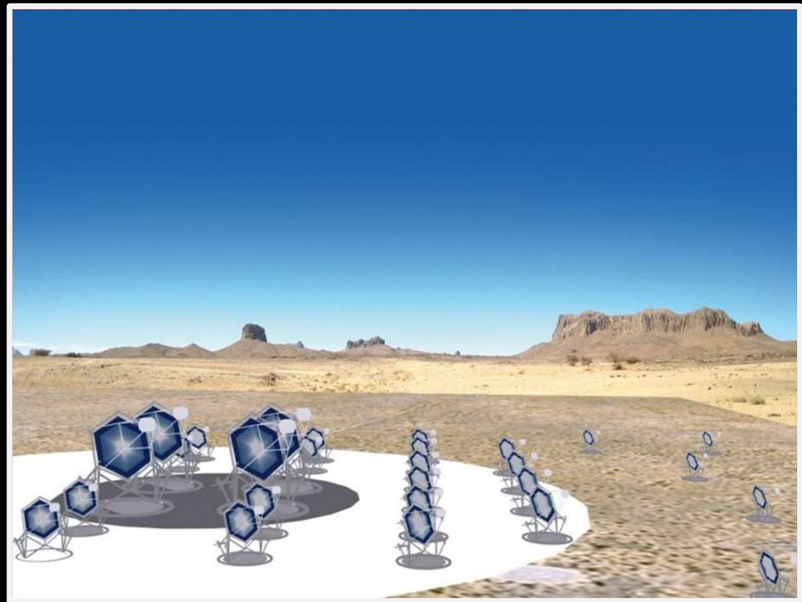
Weniger 1204.2797

Indirect Detection

Fermi/GLAST

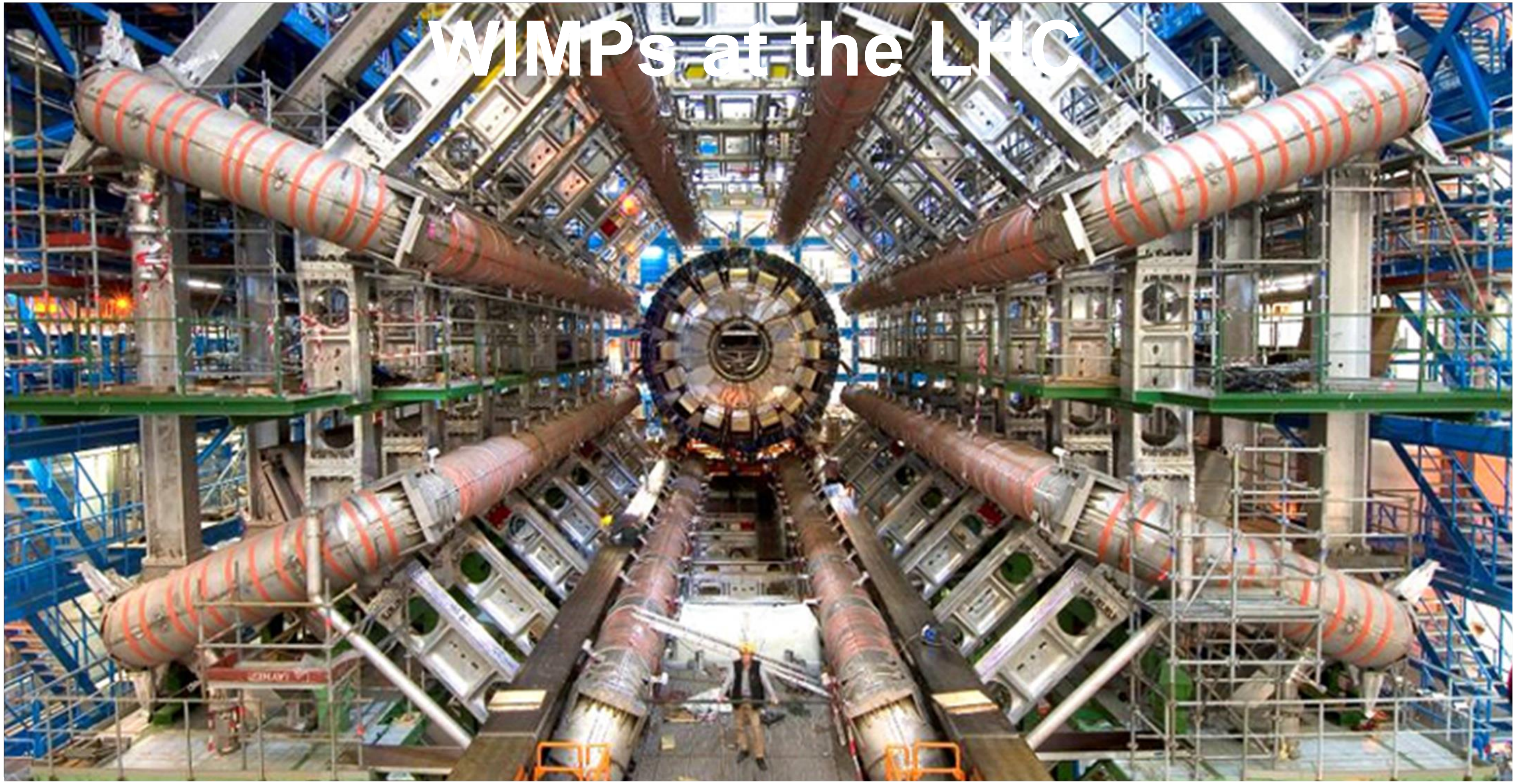
Mission	Chief scientist	Goals	Estimated launch
HXMT	Li Tipei, CAS Institute of High Energy Physics and Tsinghua University	Survey of x-ray sources; detailed observations of known objects	2014
Shijian-10	Hu Wenrui, CAS Institute of Mechanics	Study physical and biological systems in microgravity and strong radiation environment	Early 2015
KuaFu Project	William Liu, Canadian Space Agency and CAS Center for Space Science and Applied Research	Study solar influence on space weather	Mid-2015
Dark Matter Satellite	Chang Jin, CAS Purple Mountain Observatory	Search for dark matter; study cosmic ray acceleration	Late 2015
Quantum Science Satellite	Pan Jianwei, University of Science and Technology of China	Quantum key distribution for secure communication; long-distance quantum entanglement	2016

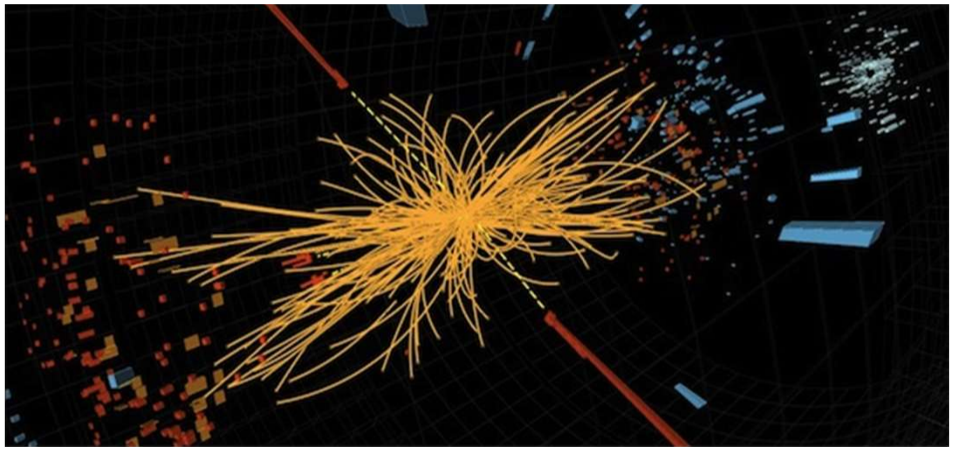
HESS-II 600 m^2



Cherenkov Telescope Array

WIMPs at the LHC





Looking for an
invisible
needle in a haystack

SUSY WIMPs at the LHC

Most popular cold thermal relic: the neutralino

neutralino:

$$\tilde{\chi}^0 = \alpha \tilde{B} + \beta \tilde{W}^3 + \gamma \tilde{H}_1^0 + \delta \tilde{H}_2^0$$

$m_{\chi 0}$ and interactions:

$100+$ SUSY parameters

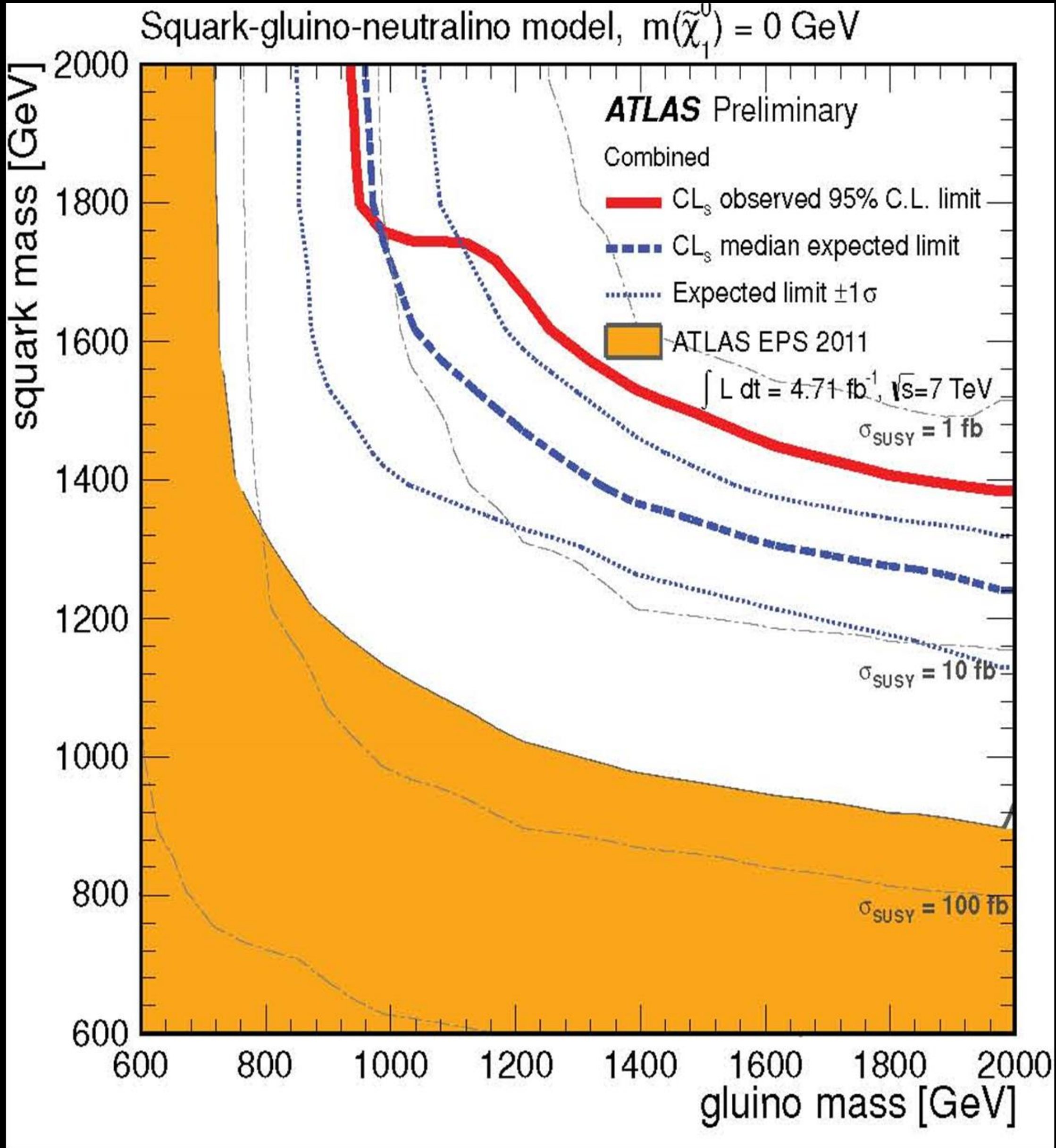
gluinos, squarks, charginos will be discovered first

analysis model dependent

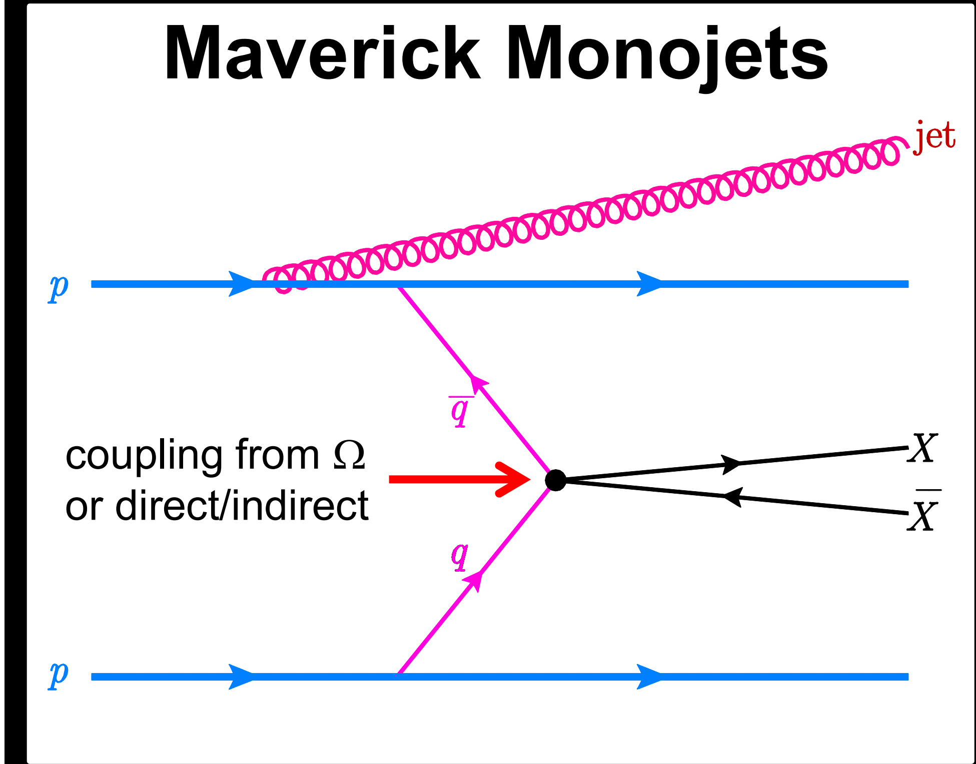
LHC chewing away allowed region

can swiggle out …
… but it is getting harder

don't throw in towelino yet



Collider Searches for Non-SUSY WIMPs



- Monojets are Nature's garbage can
- Monophotons also
- SM background extremely well modeled and understood

1. Backgrounds (neutrinos, QCD, …)
2. Only signal (other than mono-γ)
3. Largely model independent

Beltran, Hooper, Kolb, Krusberg, Tait 2009
Goodman, Ibe, Rajaraman, Shepard, Tait, Yu 2010
Rajaraman, Shepherd, Tait, Wijangco
Bai, Fox, Harnik; Fox, Harnik, Kopp, Tsai
CDF, CMS, ATLAS

The Decade of the WIMP

- Situation now is muddled
- By the end of this decade the WIMP hypothesis will have either convincing evidence or near-death experience
  - Direct detection will reach $10^{-12}\,\mathrm{pb}$ $(10^{-48}\ \mathrm{cm}^2!)$
  - Indirect detection will probe $\langle \sigma_A v \rangle \sim 10^{-28}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$
  - LHC will explore energy scales up to the TeV region
- Possibilities for discovery:
  1. Direct
  2. Indirect
  3. Colliders
- Will we have three WIMP *miracles*? (Only two needed for sainthood.)
- This is the decade of the WIMP!

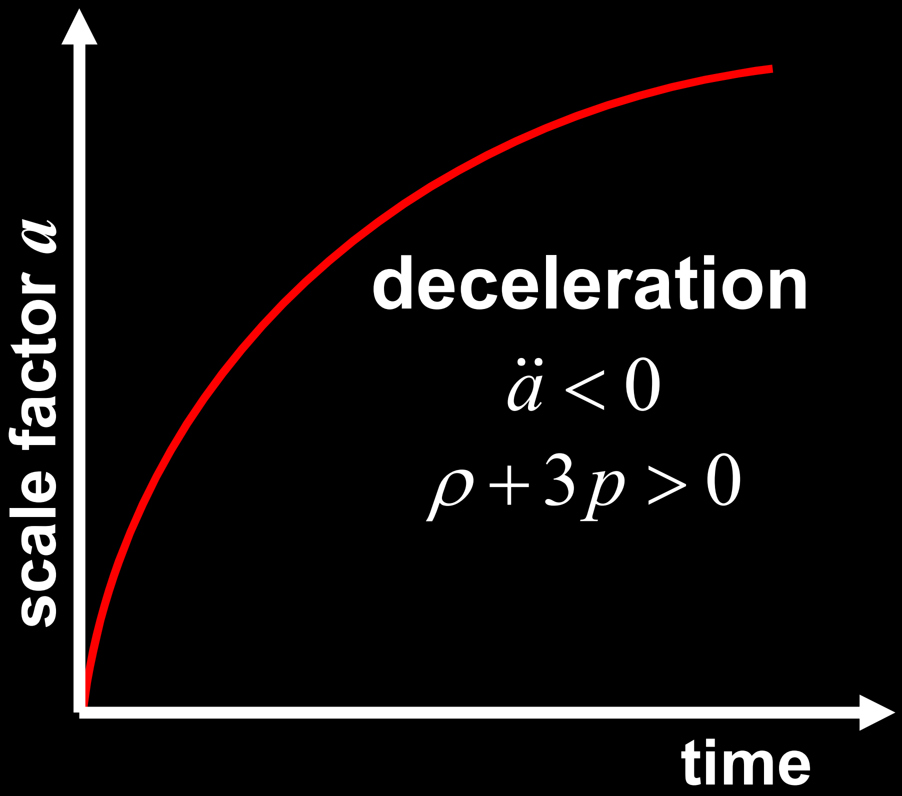
Yet More To The Dark Side

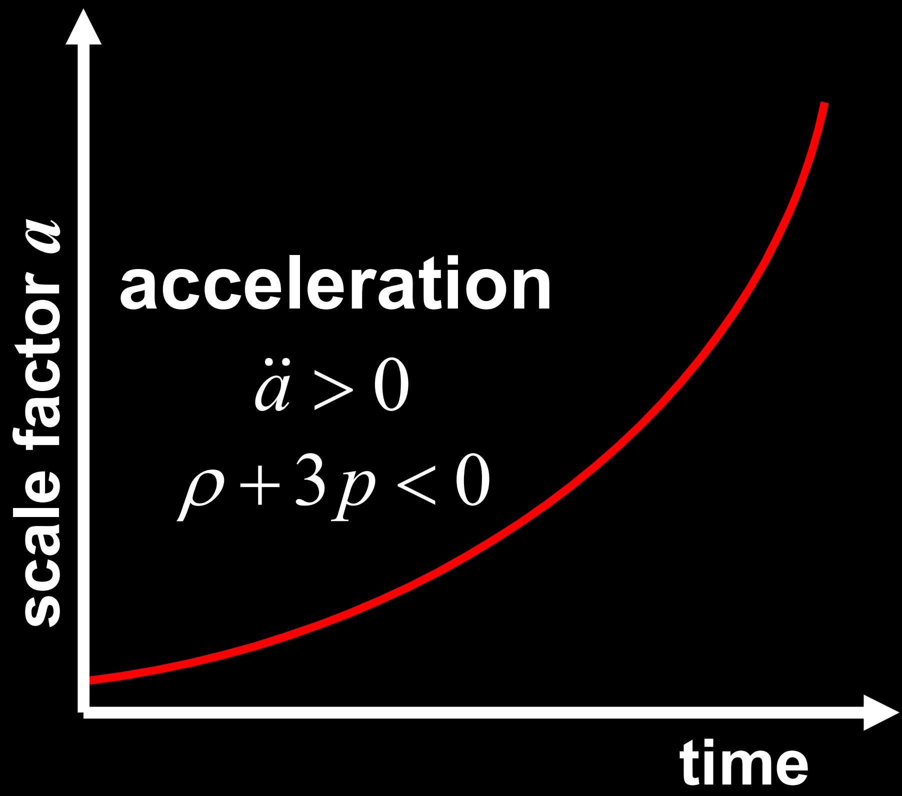
Expansion History of the Universe

distance: $a \propto D$ (a = cosmic scale factor)

velocity: $\dot{a} = Ha$ (H = Hubble parameter)

acceleration: $\ddot{a} \propto -G(\rho + 3p)\,a$





Accelerating Expansion of the Universe

The Nobel Prize in Physics 2011
Saul Perlmutter, Brian P. Schmidt, Adam G. Riess

The Nobel Prize in Physics 2011

Saul Perlmutter

Brian P. Schmidt

Adam G. Riess


Photo: Roy Kaltschmidt. Courtesy: Lawrence Berkeley National Laboratory

Saul Perlmutter


Photo: Belinda Pratten, Australian National University

Brian P. Schmidt


Photo: Homewood Photography

Adam G. Riess

The Nobel Prize in Physics 2011 was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"*.

Dark Energy

Expansion History of the Universe

Einstein's Equations: $R_{\mu\nu} - \square\, g_{\mu\nu} R - \Lambda\, g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$

Equation of State: $T_{\mu\nu} = -g_{\mu\nu} p + (\rho + p)\, U_\mu U_\nu$

If $p = -\rho$ then $T_{\mu\nu} = -g_{\mu\nu} p = g_{\mu\nu} \rho$ Identify $\Lambda \,\square\, 8\pi G \rho$

Λ acts as fluid with $\rho + 3p < 0 \Rightarrow$ acceleration!

$T_{\mu\nu} = g_{\mu\nu} \rho$ for vacuum energy (exercise for the reader)

Vacuum energy indistinguishable from cosmological constant:

Lemaitre (1934): $\Lambda \,\square\, 8\pi G \rho_\Lambda$

Just call whatever is causing acceleration "Dark Energy"

You can’t weigh it in the laboratory, but …

… completely empty space has a mass!

- Empty space has a mass density of 10^{-30} g cm^{-3},
- smaller than naïve theoretical estimates by a factor of 10^{120},
- and it dominates the universe’s present mass-energy density,
- pulling space apart,
- causing the expansion of the universe to accelerate,
- and it will determine the ultimate fate of our universe, and…
- we don’t understand it (yet)!

The Unbearable Lightness of Nothing

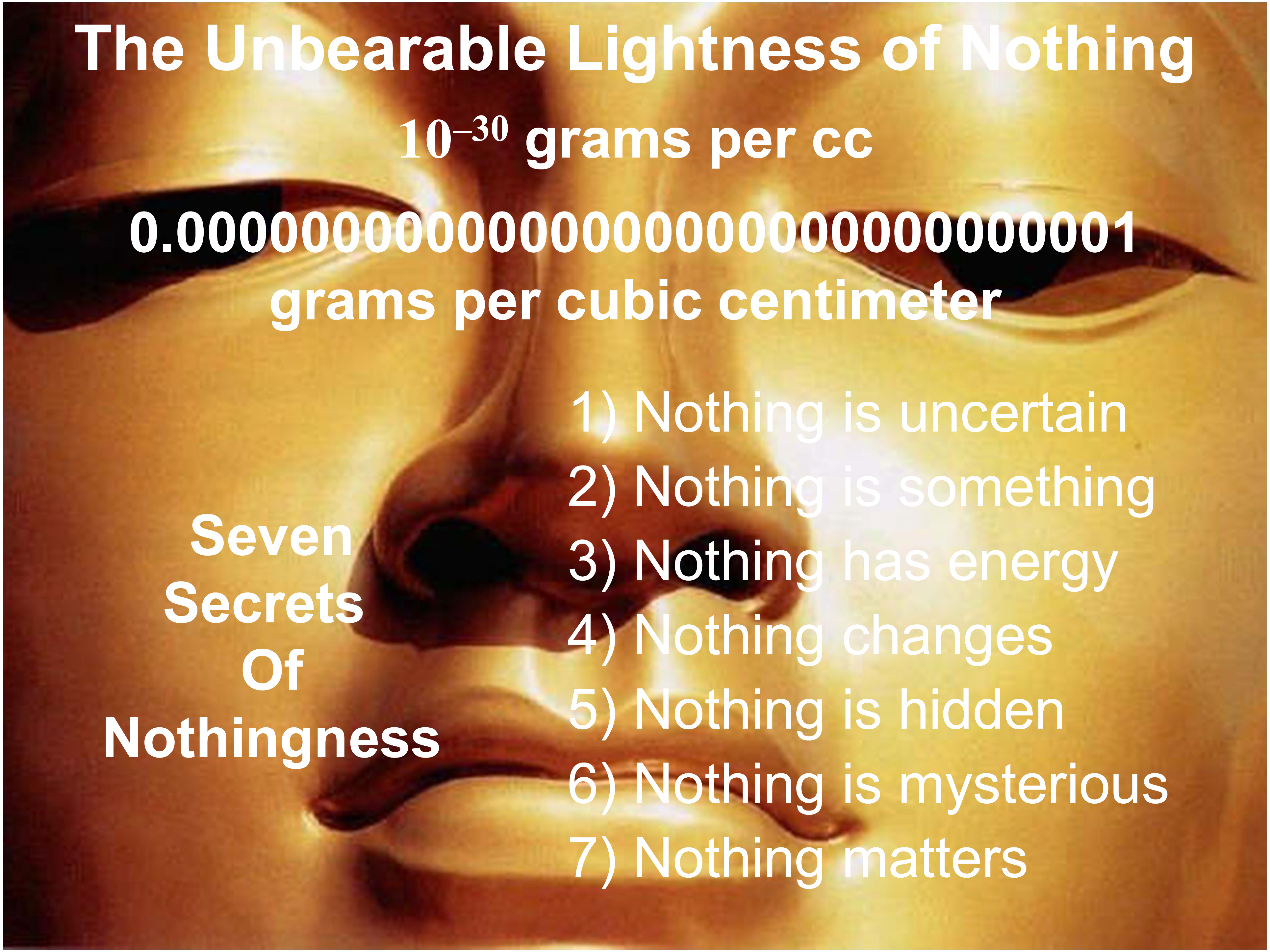
10^{-30} grams per cc

0.000000000000000000000000000001
grams per cubic centimeter

The Cosmological Constant

The Cosmoillogical Constant

So small, and yet not zero!


The Unbearable Lightness of Nothing
10^{-30} grams per cc
0.000000000000000000000000000000001
grams per cubic centimeter
Seven
Secrets
Of
Nothingness
1) Nothing is uncertain
2) Nothing is something
3) Nothing has energy
4) Nothing changes
5) Nothing is hidden
6) Nothing is mysterious
7) Nothing matters

1) Nothing Is Uncertain

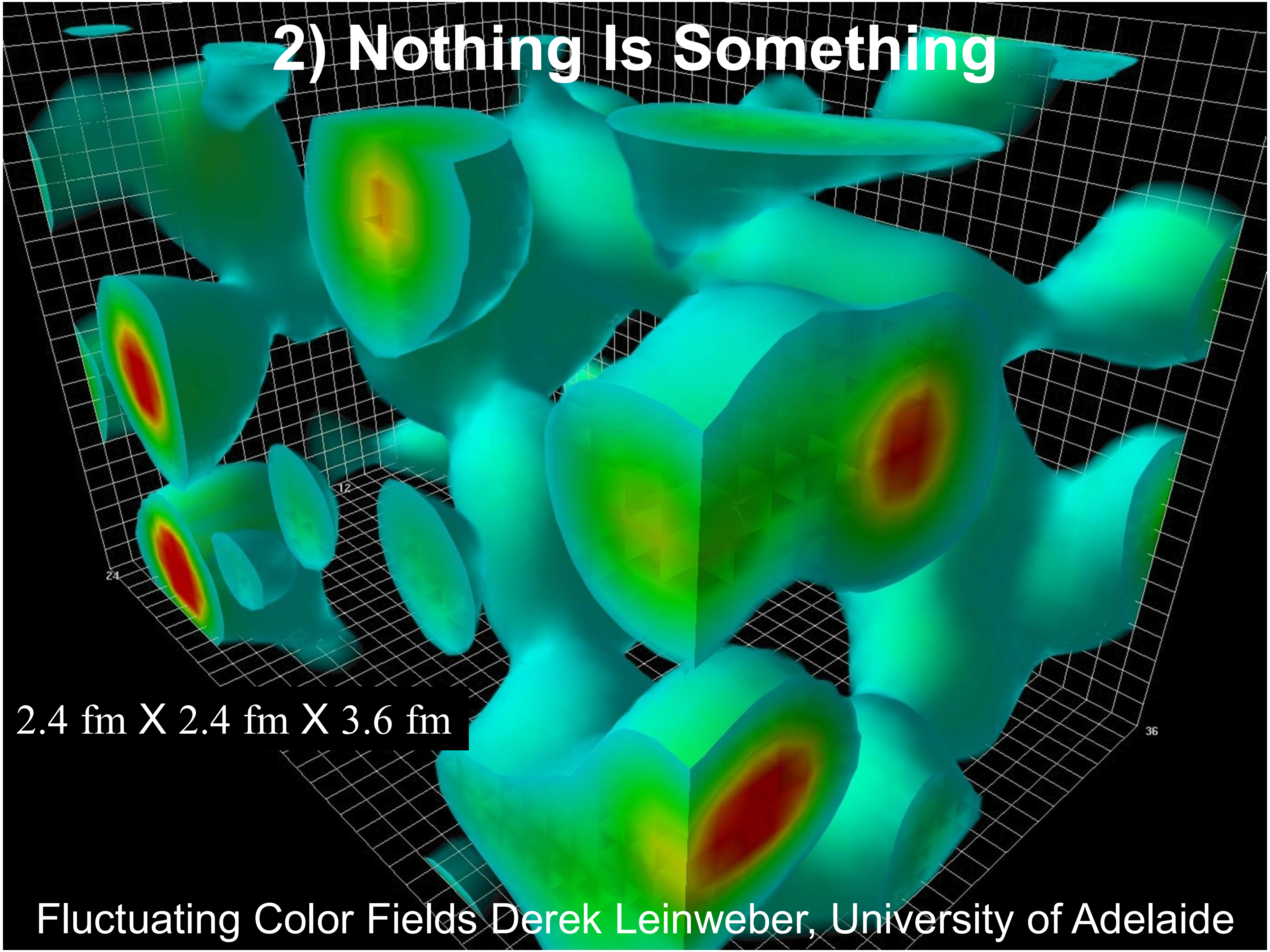
Werner Heisenberg 1901—1976

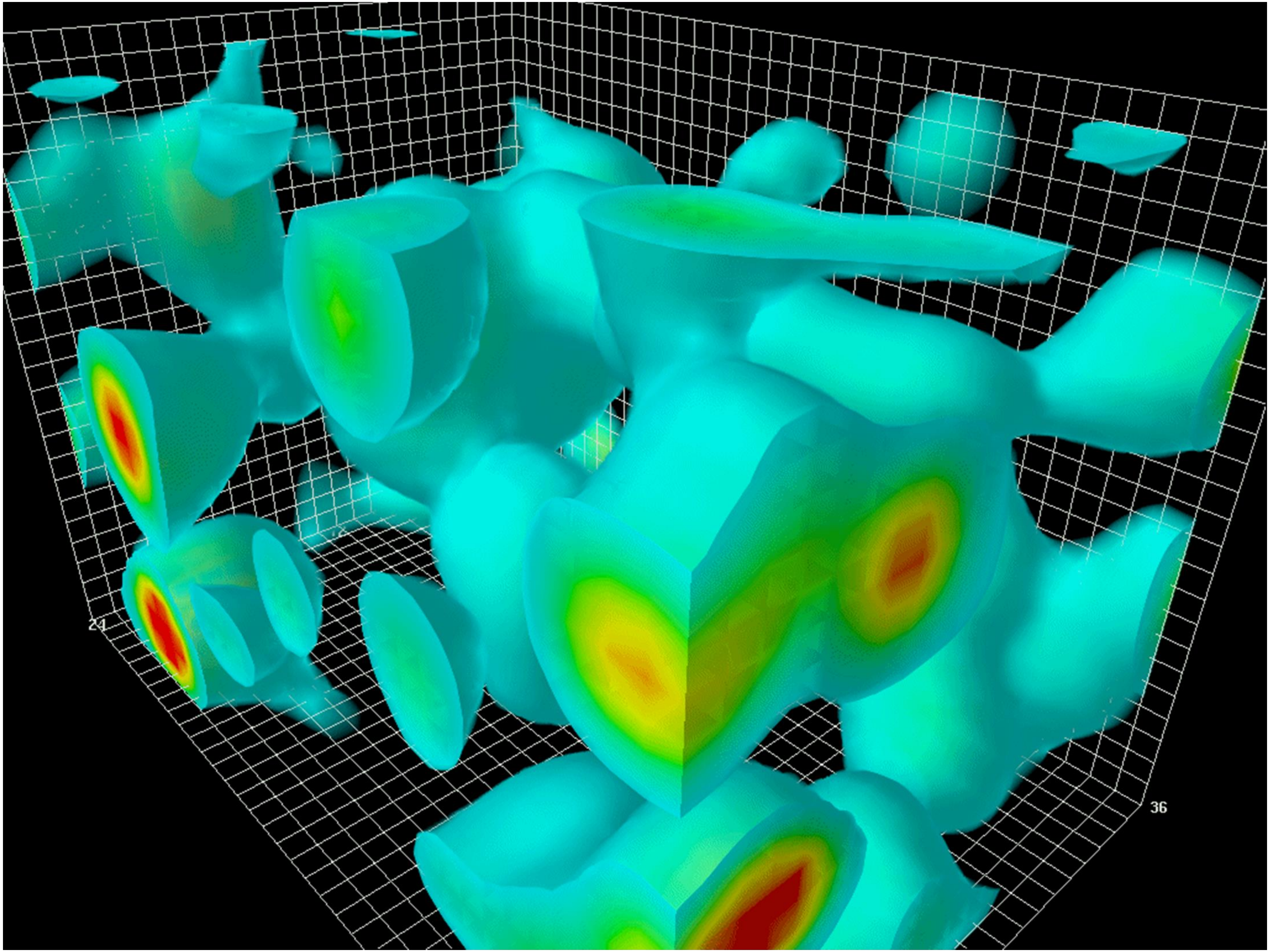
$$\Delta p \cdot \Delta q \geq \frac{1}{2}\hbar$$

$$\text{uncertainty in energy} \times \text{uncertainty in time} \geq \frac{1}{2}\text{h}$$

All quantun fields: harmonic oscillators: zero-point energy

Each momentum mode: $E = \square / 2$

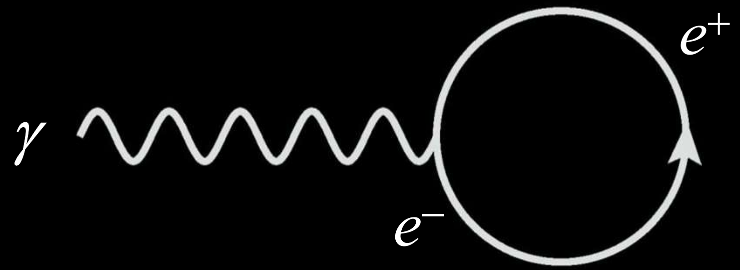

2) Nothing Is Something
12
24
36
2.4 fm X 2.4 fm X 3.6 fm
Fluctuating Color Fields Derek Leinweber, University of Adelaide


24
36

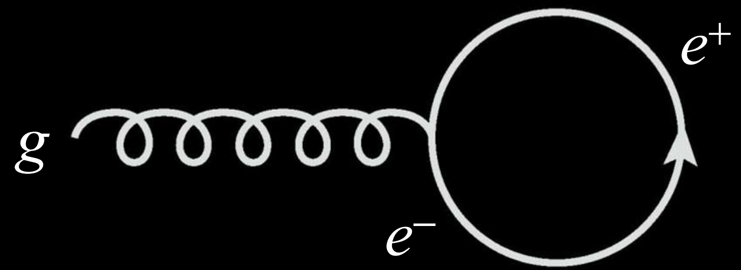
3) Nothing Has Energy

Gravity (gravitons) couple to fluctuating fields

Photons: Lamb shift



Gravitons: Vacuum energy



$$\rho = \sum_{all\ particles} \pm \int d^3k \frac{\hbar}{2}\sqrt{k^2+m^2} \sim \sum_{all\ particles} \pm \int^{\Lambda_C} dk\ k^3$$

$$\Lambda_C = \infty: \quad \rho_\Lambda = \infty^4 \quad = \text{bad prediction}$$

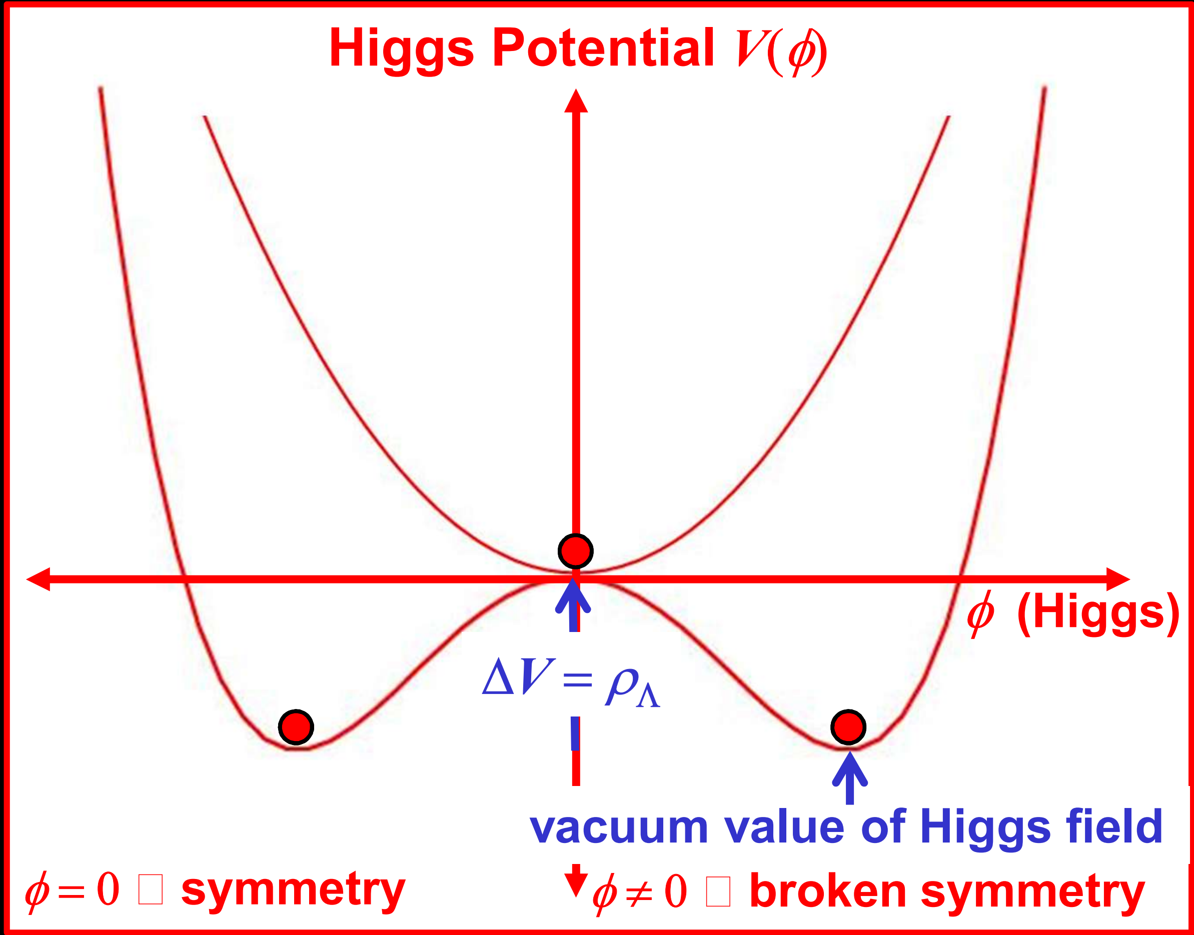
$$\Lambda_C = M_{Pl}: \quad \rho_\Lambda = M_{Pl}^4 \quad = 10^{+90}\ \text{g cm}^{-3}$$

$$\Lambda_C = M_{SUSY}: \quad \rho_\Lambda = M_{SUSY}^4 \quad = 10^{+30}\ \text{g cm}^{-3}$$

$$\Lambda_C = 10^{-4}\,\text{eV}: \quad \rho_\Lambda = \text{Observed} \quad = 10^{-30}\ \text{g cm}^{-3}$$

3) Nothing Has Energy

- "Nature weaves her tapestry from the longest threads." — Richard Feynman
- Nature seems to like symmetry, then hide it



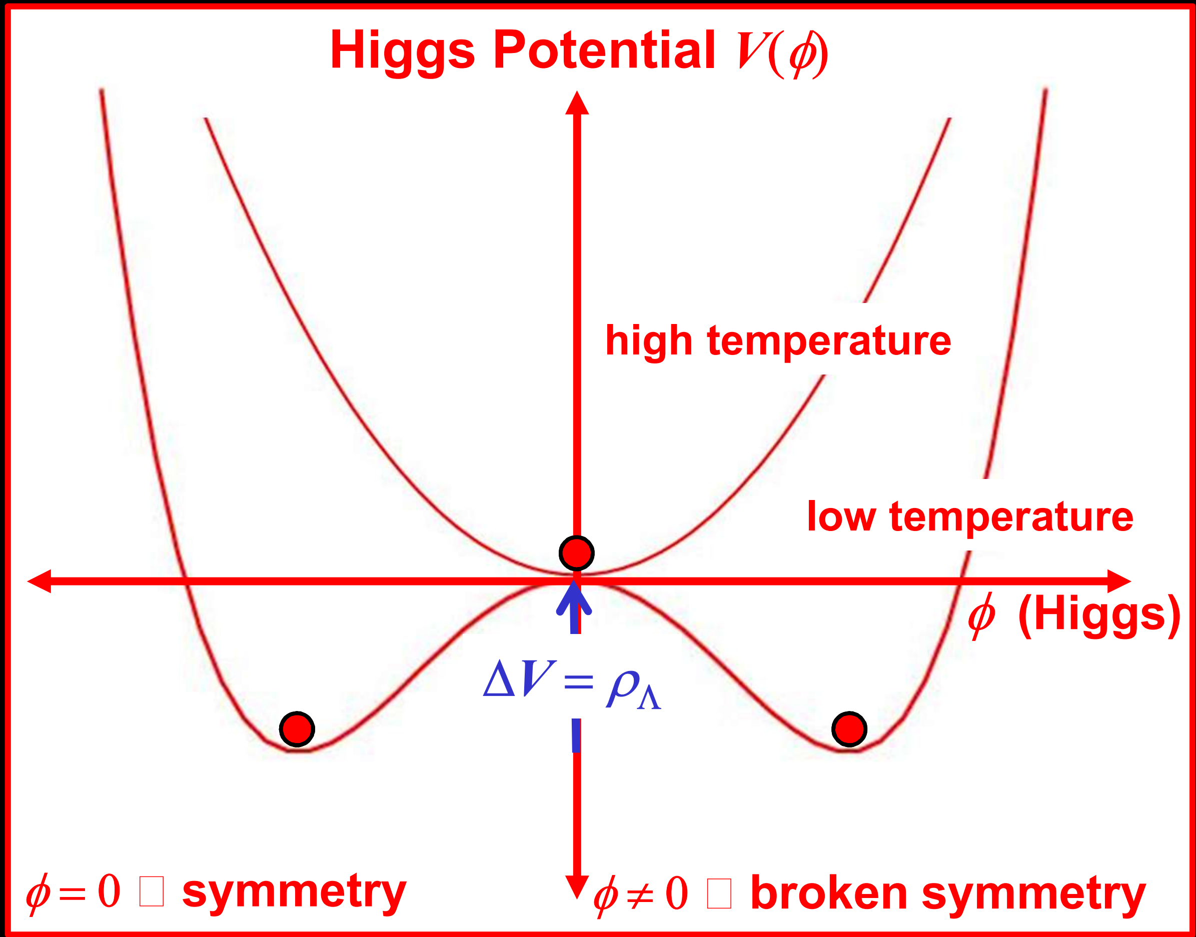
GUT: 10^{74} g cm^{-3} **SUSY:** 10^{30} g cm^{-3}

EWK: 10^{24} g cm^{-3} **CHIRAL:** 10^{13} g cm^{-3}

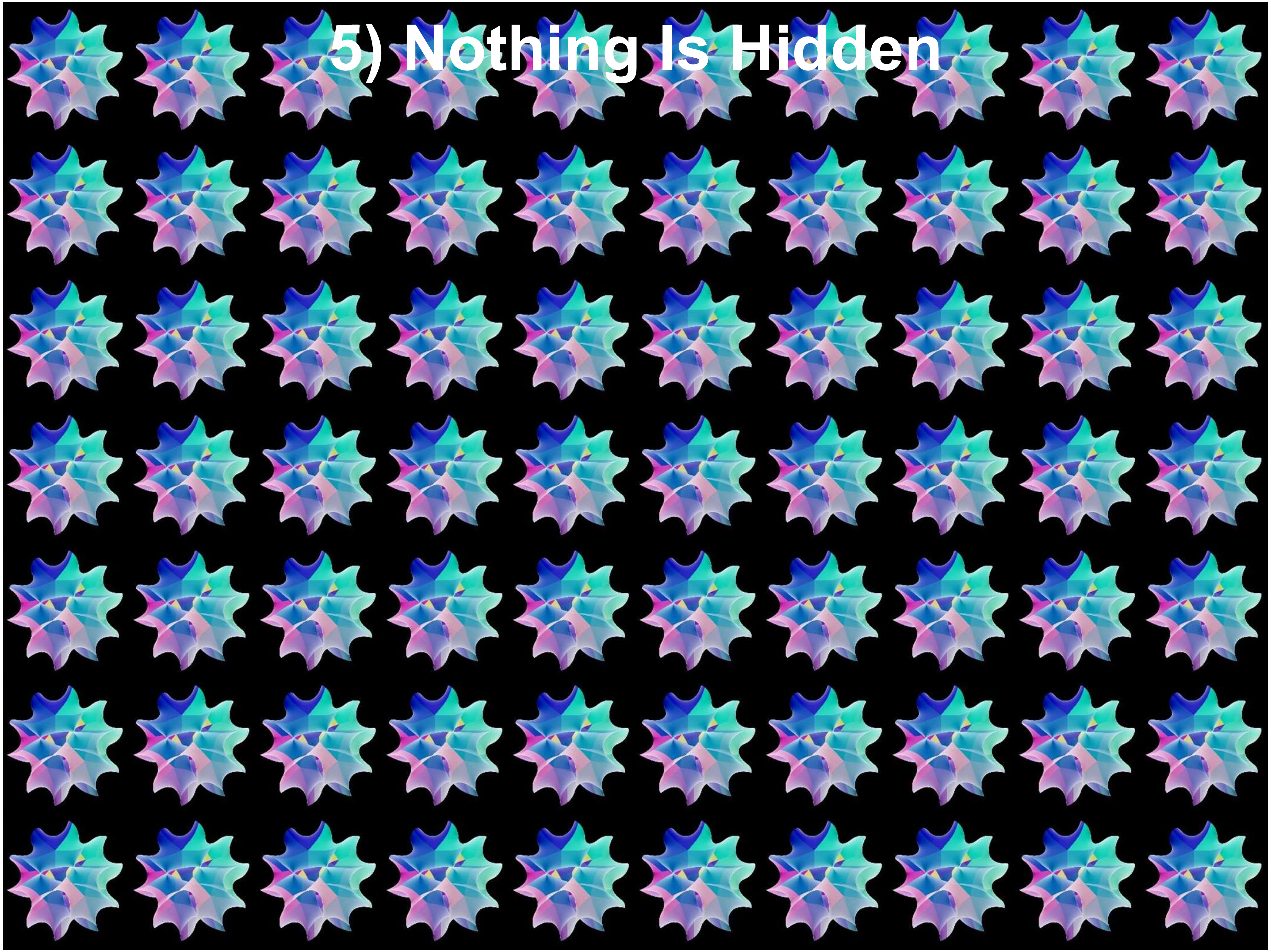
OBSERVED: 10^{-30} g cm^{-3}

4) Nothing Changes

- The Higgs potential changes with temperature



5) Nothing Is Hidden



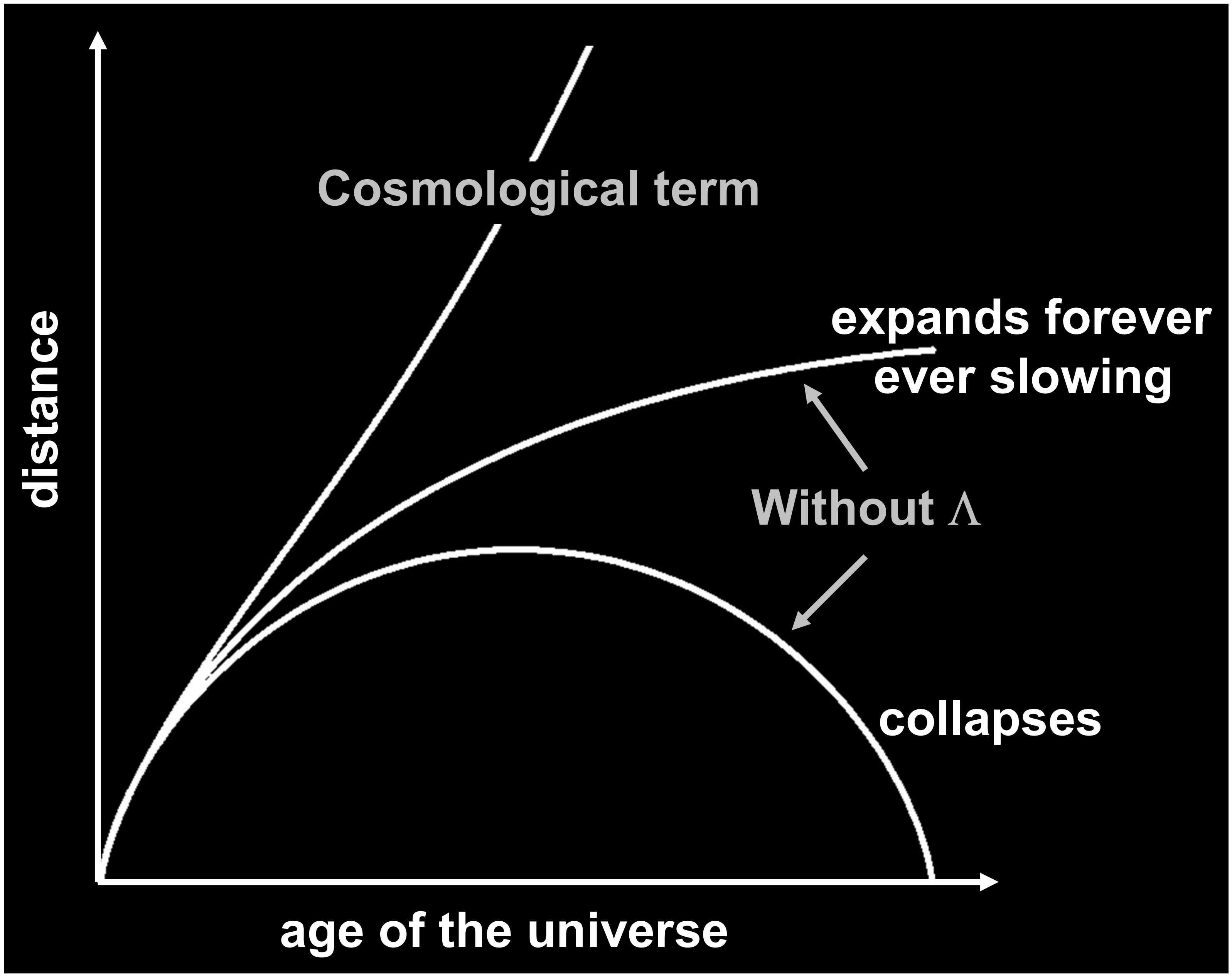
6) Nothing Is Mysterious

Illogical magnitude (what's it related to?):

Observed Dark Energy Density: 10^{-30} g cm^{-3}

Uncertainty Energy	∞^{4} g cm^{-3} 10^{90} g cm^{-3}	10^{30} g cm^{-3}
Symmetry Breaking	**GUT:** 10^{74} g cm^{-3} **EWK:** 10^{24} g cm^{-3}	**SUSY:** 10^{30} g cm^{-3} **CHIRAL:** 10^{13} g cm^{-3}
Extra Dimensions	10^{90} g cm^{-3}	

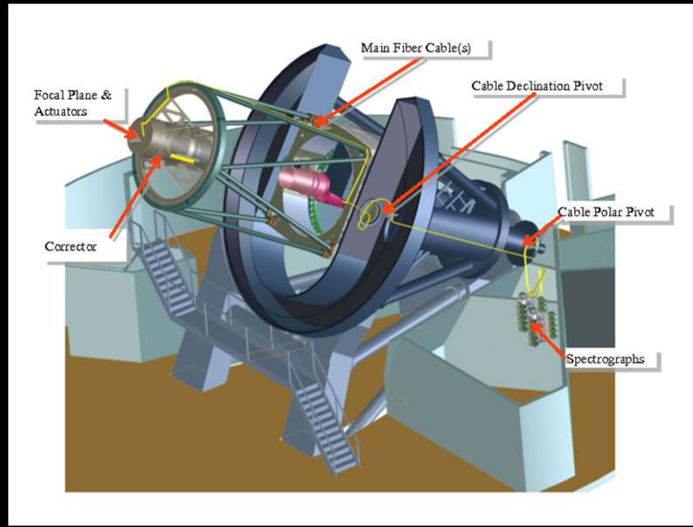
7) Nothing Matters



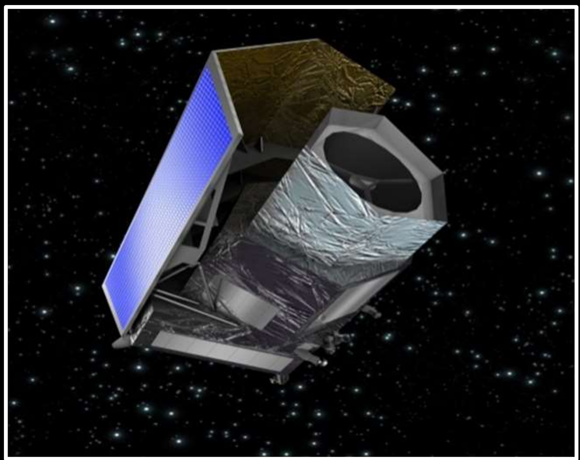
Expansion History of the Universe

BOSS

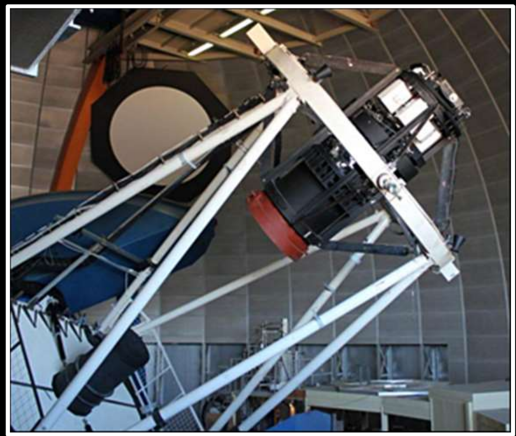
CFHT-SNLS



DESI

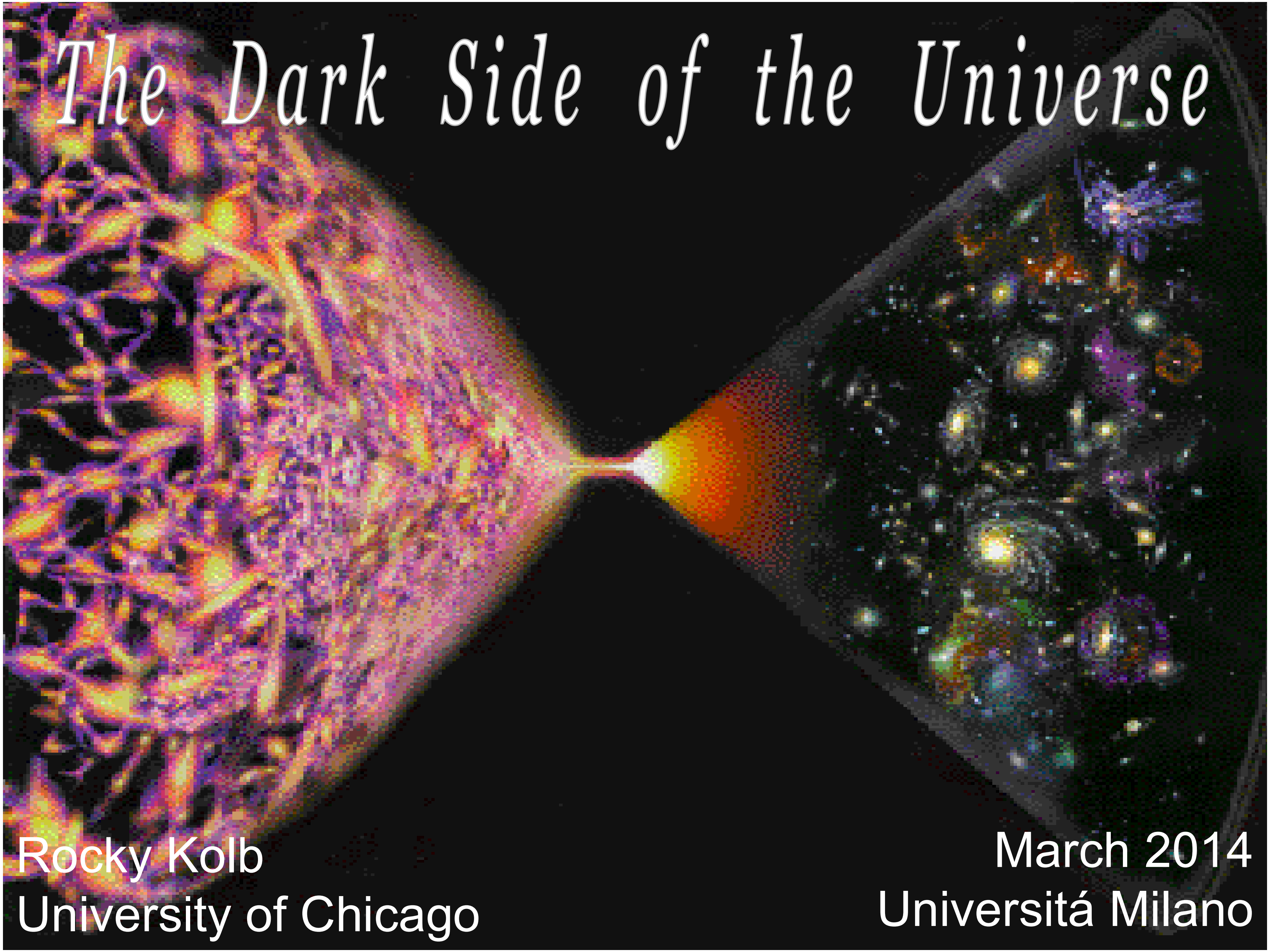


ESA-EUCLID



DES

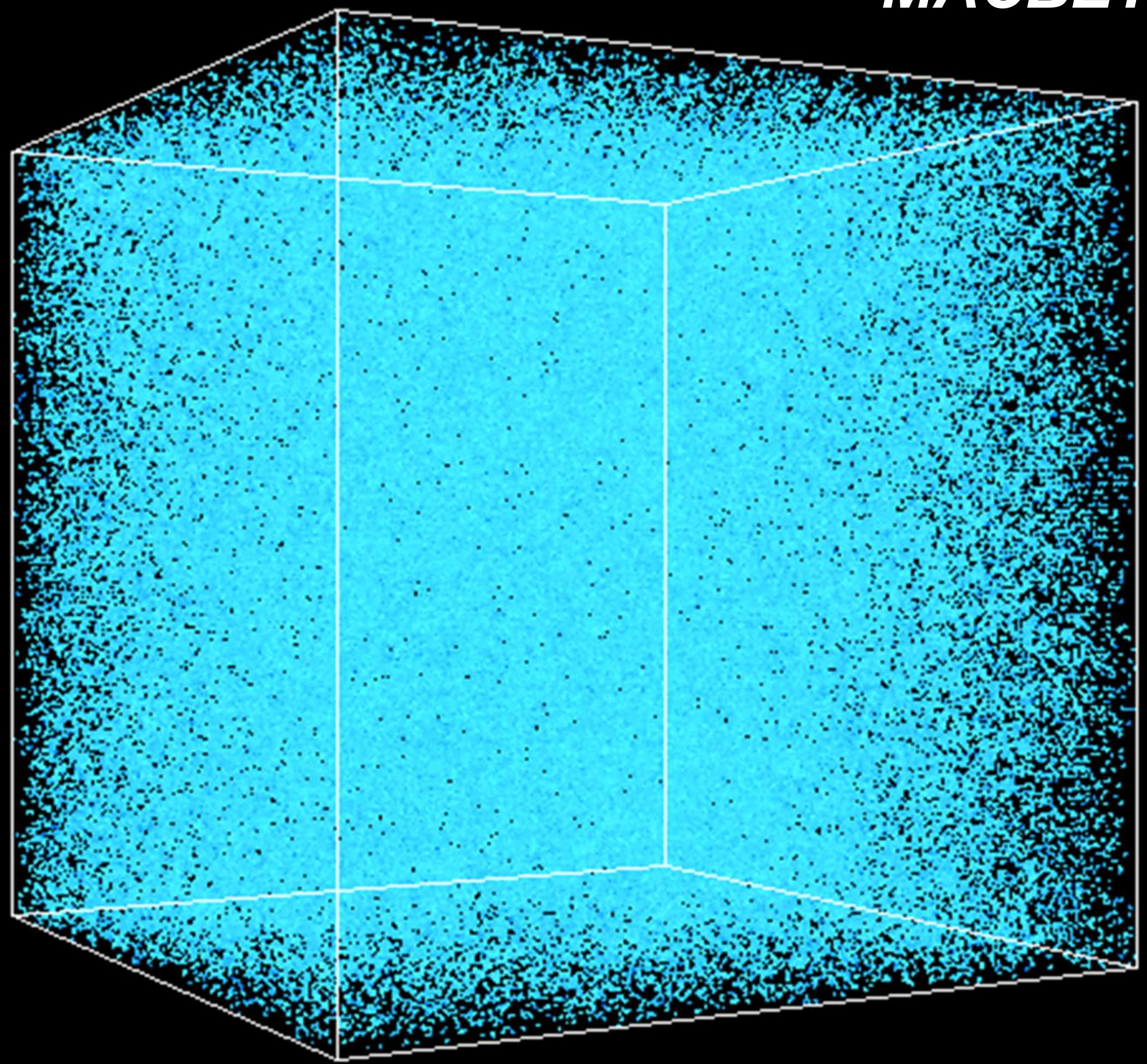
WIGGLE Z


The Dark Side of the Universe
Rocky Kolb
University of Chicago
March 2014
Universitá Milano

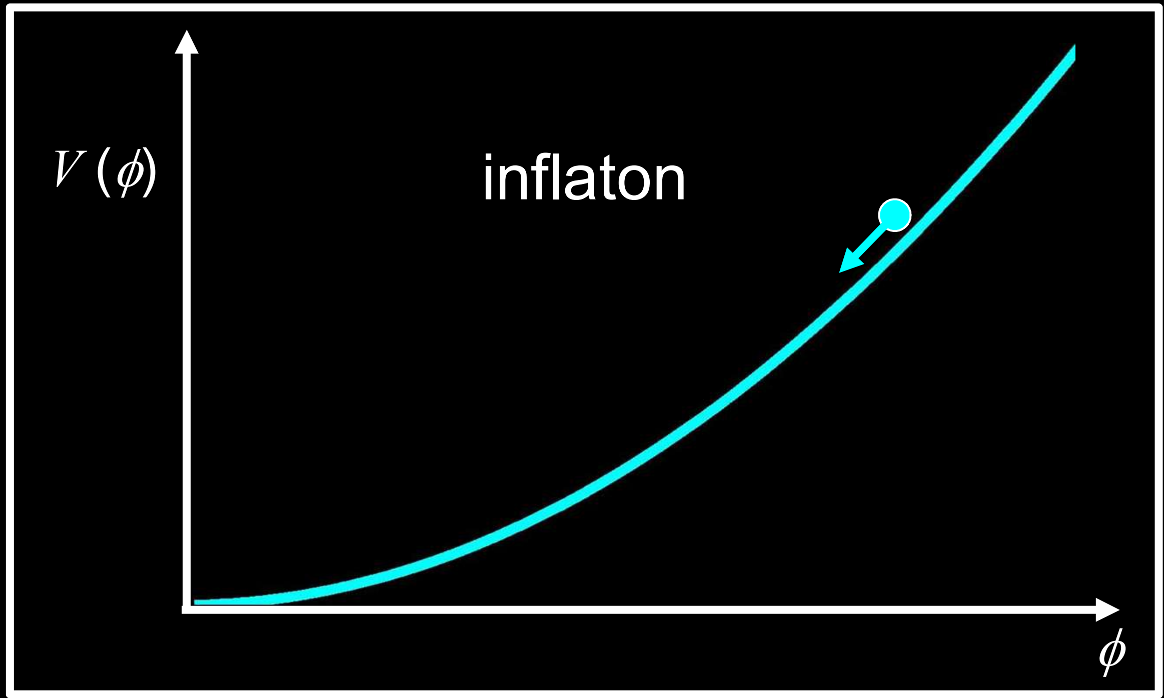
Backup slides

If you can look into the seeds of time
And say which grain will grow and which will not,
Speak then to me, who neither beg nor fear
Your favours nor your hate.

– MACBETH (Banquo)



Inflation



Classical Equations of Motion

$V(\phi) \neq 0 \longrightarrow V(\phi) = 0$

Quantum Fluctuations

$\delta\phi \longrightarrow \delta\rho \longrightarrow \delta T$

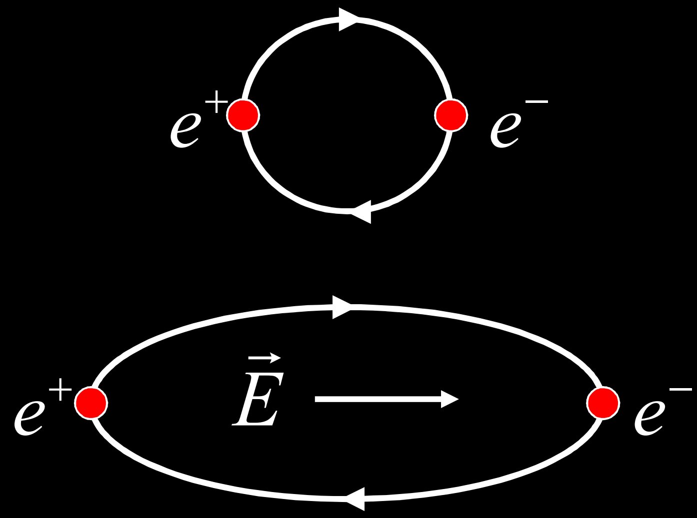
Quantum fluctuations, once microscopic, have been stretched …

… to be as large as the observable universe!

- The map of CMB $\Delta T/T$ is a map of quantum fluctuations,
- produced 10^{-35} seconds after the bang during primordial inflation,
- when the universe was dominated by vacuum energy,
- ripping particles out of the quantum vacuum,
- producing the cosmic seeds that will grow to become structure,
- and encoded in the pattern is the imprint of fundamental physics,
- and … we may be on the threshold of decoding the information!

Disturbing the Quantum Vacuum

Changing Electric field ⟶ Particle creation

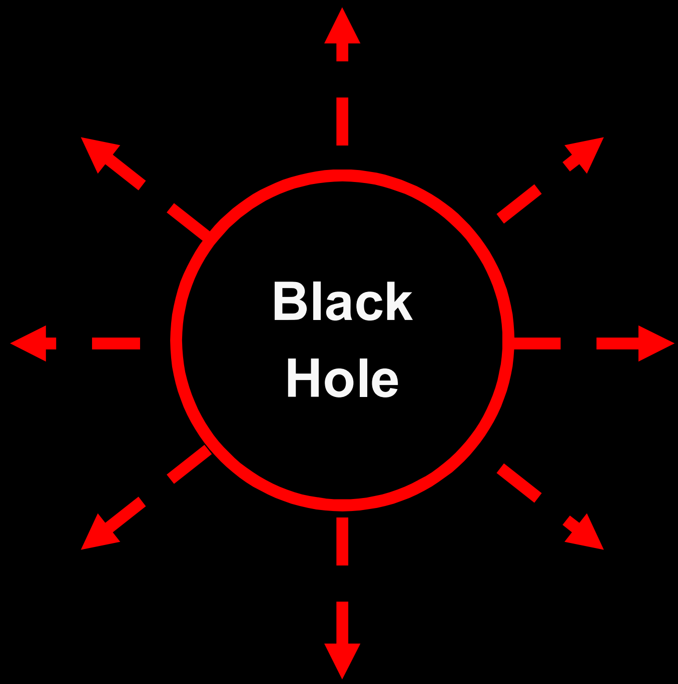


Particle creation if energy gained in acceleration from electric field over a Compton wavelength exceeds the particle's rest mass.

Schwinger (1951); Heisenberg & Euler (1935); Weisskopf (1936)

Disturbing the Quantum Vacuum

Tidal gravitational field ⟶ Particle creation

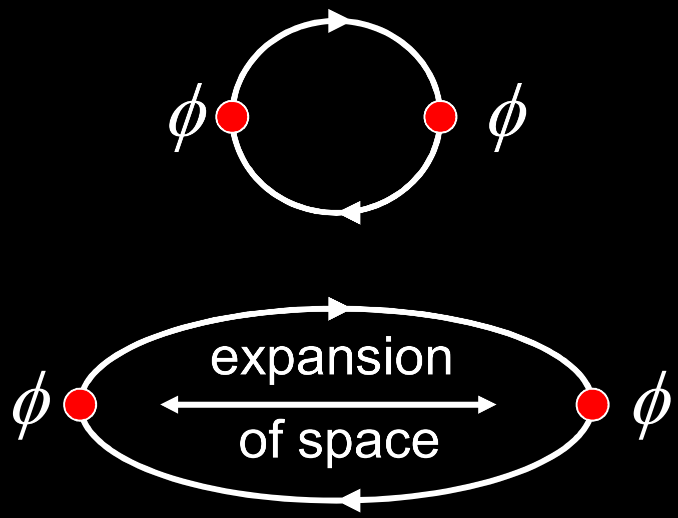


Particle creation if energy gained in acceleration from gravitational field over a Compton wavelength exceeds the particle's rest mass.

Hawking (1974); Bekenstein (1972)

Disturbing the Quantum Vacuum

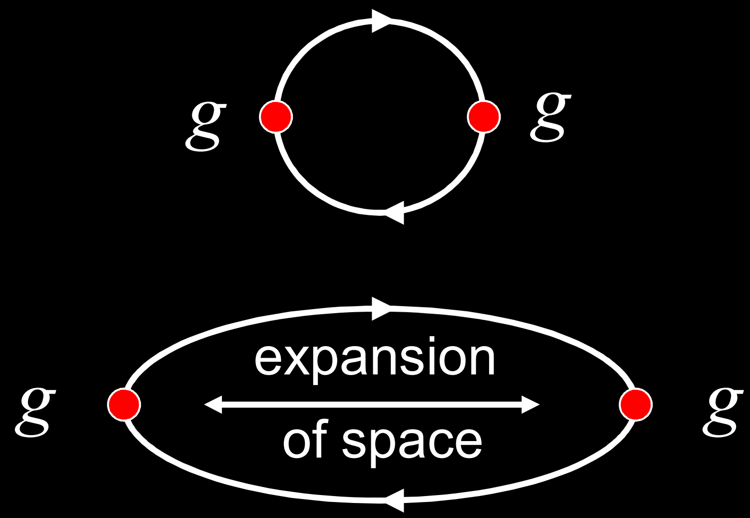
Expanding Universe ⟶ Particle creation



Particle creation if energy gained in expansion over a Compton wavelength exceeds the particle's rest mass.

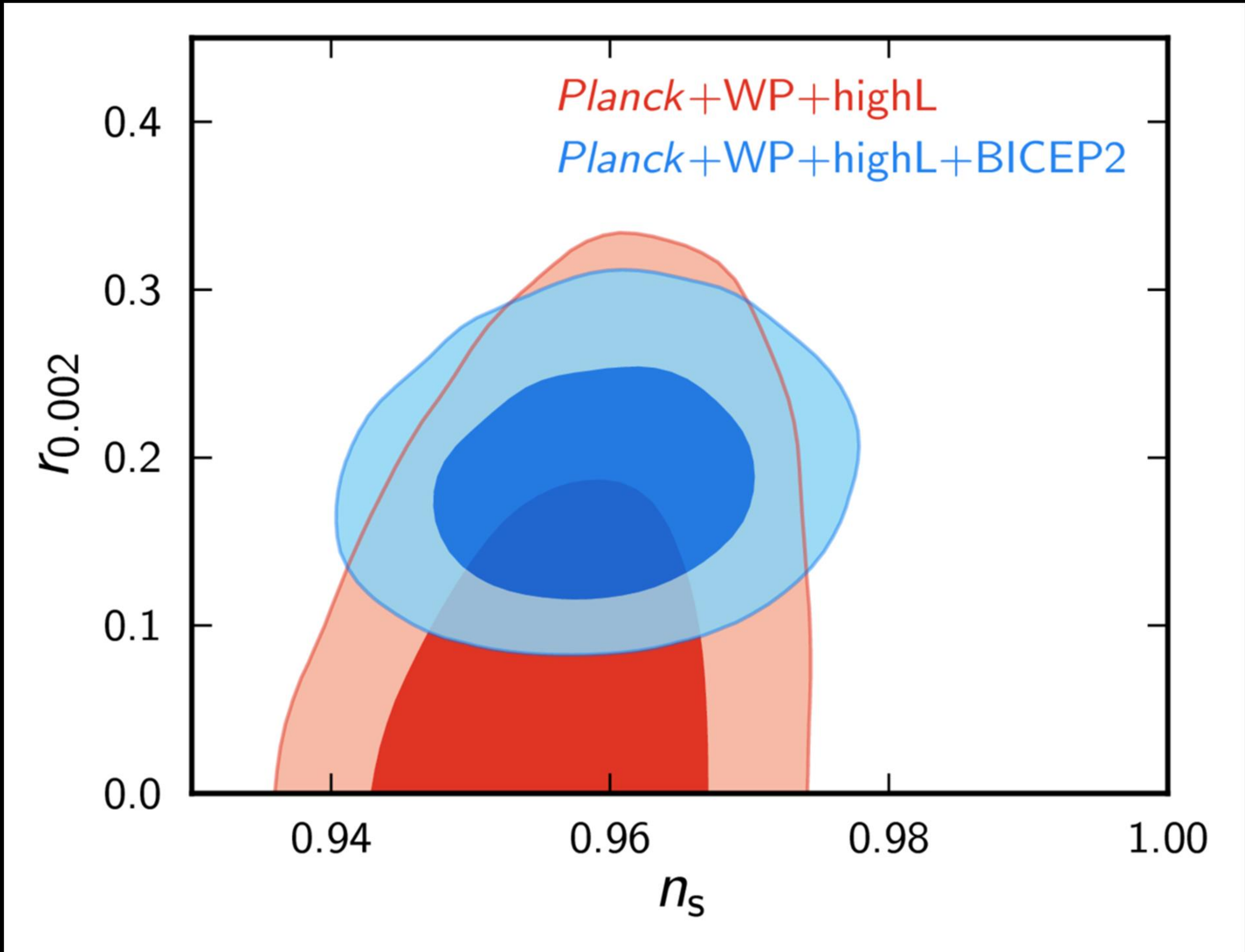
Disturbing the Quantum Vacuum

Expanding Universe → Particle creation



Particle creation if energy gained in expansion over a Compton wavelength exceeds the particle's rest mass.

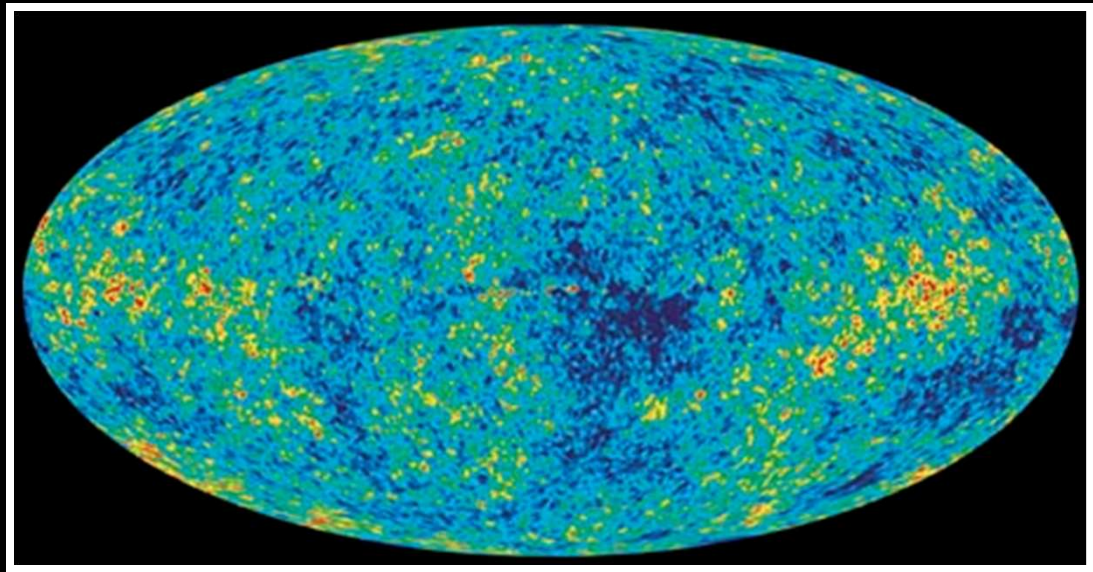
Today!



Planck+WP+highL
Planck+WP+highL+BICEP2
0.4
0.3
0.2
0.1
0.0
$r_{0.002}$
0.94
0.96
0.98
1.00
n_s

Imperfections Are Beautiful!

Tethys
90 minutes ago



The universe
13.78 billion - 380,000 years ago

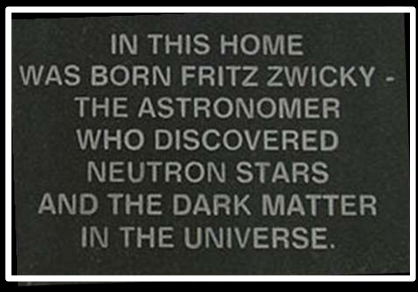
The wrinkles tell a story!

More Than Eighty Years of Dark Matter

Oort	1932	Local Neighborhood a Little Dim	$(M/\Lambda)_{\odot} \sim 2\text{–}3$
Zwicky	1937	Galaxy Clusters Really Dark	$(M/\Lambda)_{\odot} \sim 500$
Rubin & Ford	1970s	Individual Galaxy Halos Also Dark	$(M/\Lambda)_{\odot} \sim 60$
Dwarf Observers	1990s	Dwarfs Really, Really Dark	$(M/\Lambda)_{\odot} \sim 3000$

Fritz Zwicky

Varna, Bulgaria



Coma Cluster

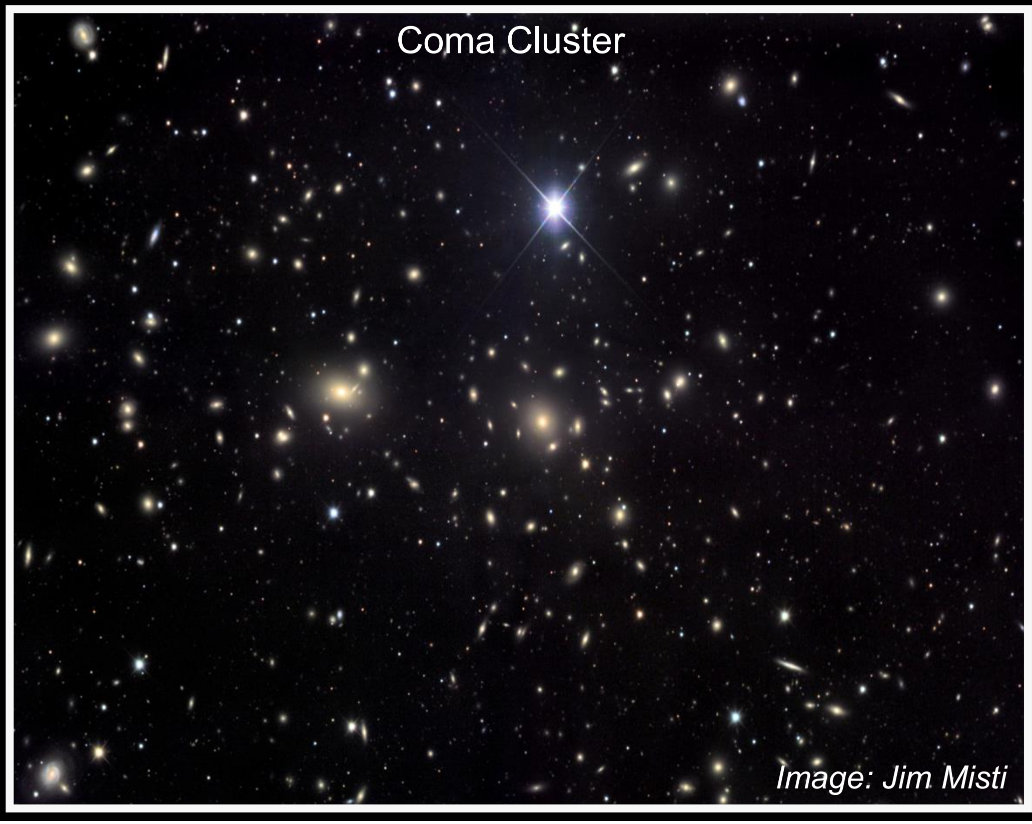


Image: Jim Misti

Vladimir Lenin 1916

Zurich, Switzerland
(Spiegelgasse 17)

Known Particle Species

?

Dark particle must be <u>stable</u> and <u>massive</u> and interact <u>weakly</u>

Dark particle must be “Beyond the Standard Model” (BSM)

Fermi National Accelerator Laboratory

FERMILAB-Pub-77/41-THY
May 1977

Cosmological Lower Bound on
Heavy Neutrino Masses

BENJAMIN W. LEE
Fermi National Accelerator Laboratory,* Batavia, Illinois 60510

AND

STEVEN WEINBERG**
Stanford University, Physics Department, Stanford, California 94305

ABSTRACT

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29}g/cm^3, the lepton mass would have to be greater than a lower bound of the order of 2 GeV.

**On leave 1976-7 from Harvard University.

*Operated by Universities Research Association Inc. under contract with the Energy Research and Development Administration

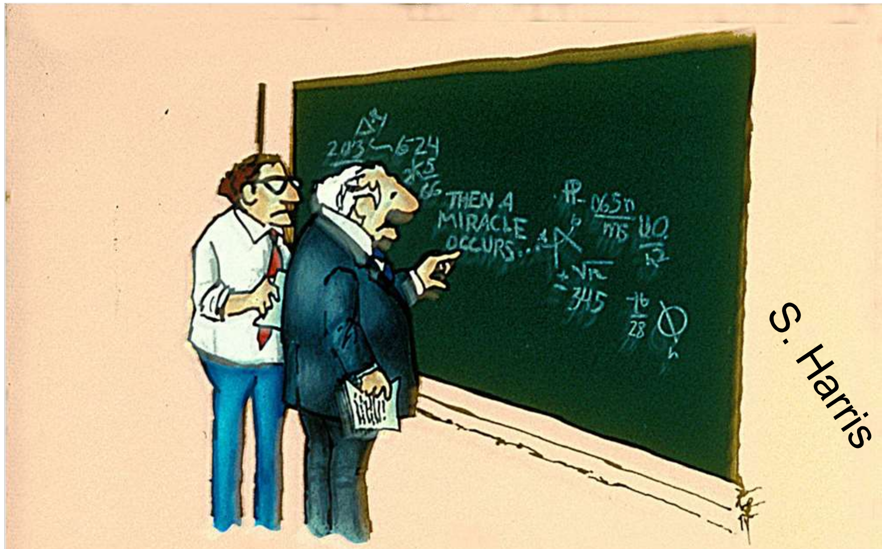
Ben Lee (1935 — June 1977)

Steve Weinberg

The WIMP "Miracle"

Merriam-Webster
Merriam-Webster OnLine

1 : an extraordinary
divine interventio



I think you should be more explicit here in step two

S. Harris

encyclopedia

. often used to give an
npression of great and
nusual value in a trivial
ontext …

WIMPs: **BSM (but not far BSM)**
Interact with Standard Model particles (weakly)

WIMPs: Social or Maverick Species?

Many Sheep Stupidly Milling (MSSM)

Noble Maverick

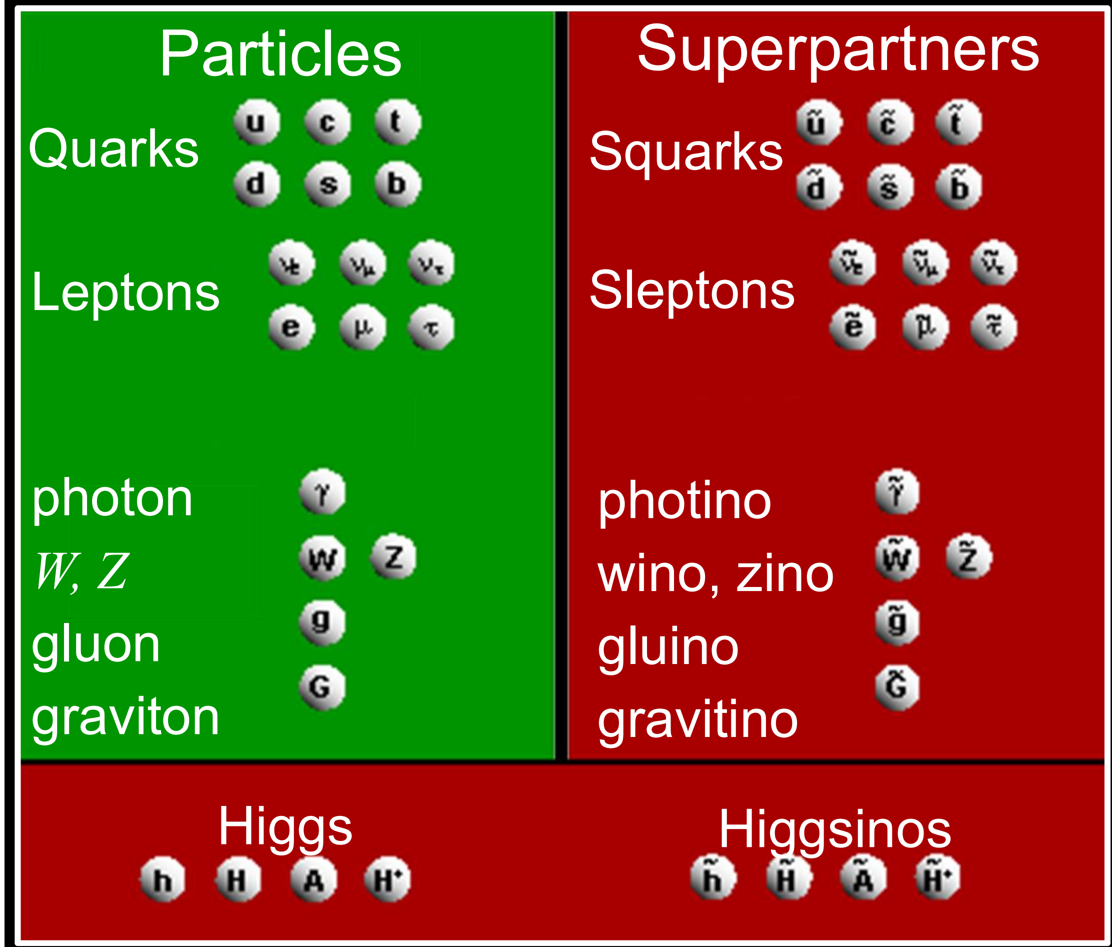
Social WIMPs:

Social WIMPs are part of a social network
Pal around with new un-WIMPy particles
Part of a larger theoretical framework
Find the WIMP by finding its friends
Example: SUSY

Maverick WIMPs:

Maverick WIMPs have no social network
Not friended by any new particles
Have no discernible reason for existing
Find the WIMP through what is not seen
Example: Neutrinos before late 1960s

Supersymmetry & Social WIMPs



Developed in the early 70's—still of great interest.

Every known particle has an undiscovered superpartner.

Superpartners are massive.

Lightest superpartner should be stable!

In many realizations, lightest superpartner is weakly interacting.

Lightest Supersymmetric Particle is a candidate WIMP.

Supersymmetry & Dark Matter: A Match

physicsmatch.com

<u>Seeking a Superpartner</u>

Super-mature, 41-year-old theory (SUSY) desperately seeks a partner for a physical manifestation.

<u>Seeking an Embedding</u>

WIMPy 35-year-old particle species seeks a theory (any theory) in which to be embedded.

Maverick WIMPs

- Assume WIMP the only non-SM particle with weak-scale mass
- Other particles are heavy compared to weak scale
- Integrate out heavy particles and form an *Effective Field Theory*

  Example: low-energy ($E \square m_Z$) neutrino physics

$$\mathcal{L} = \frac{G_F}{\sqrt{2}} \bar{n} g^m (1- g_5) n \times \bar{q} g_m \left(g_V^q - g_A^q g_5 \right) q$$

- Assume $\mathcal{L} = M_*^{-n} J_{\mathrm{DM}} \cdot J_{\mathrm{SM}}$ J_{DM} and J_{SM} are SM singlets
- J_{DM} contains scalars ϕ or fermions χ

  Examples: $J_{\mathrm{DM}} = \phi^\dagger \square^\mu \phi + h.c.$ or $J_{\mathrm{DM}} = \bar{\chi} \gamma^\mu \chi$

- J_{SM} contains SM fermions or electroweak gauge/Higgs bosons

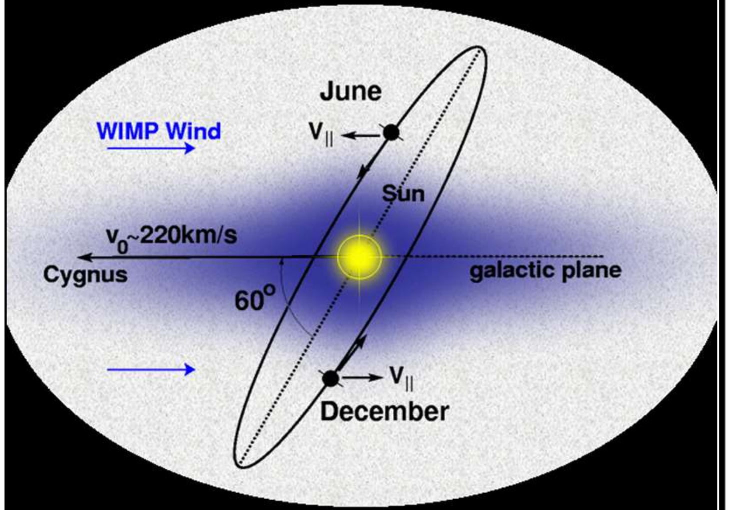
  Examples: $J_{\mathrm{SM}} = \bar{q} \gamma^\mu q$ or $J_{\mathrm{SM}} = B_{\lambda\mu} Y_H H^\dagger D^\lambda H + h.c.$

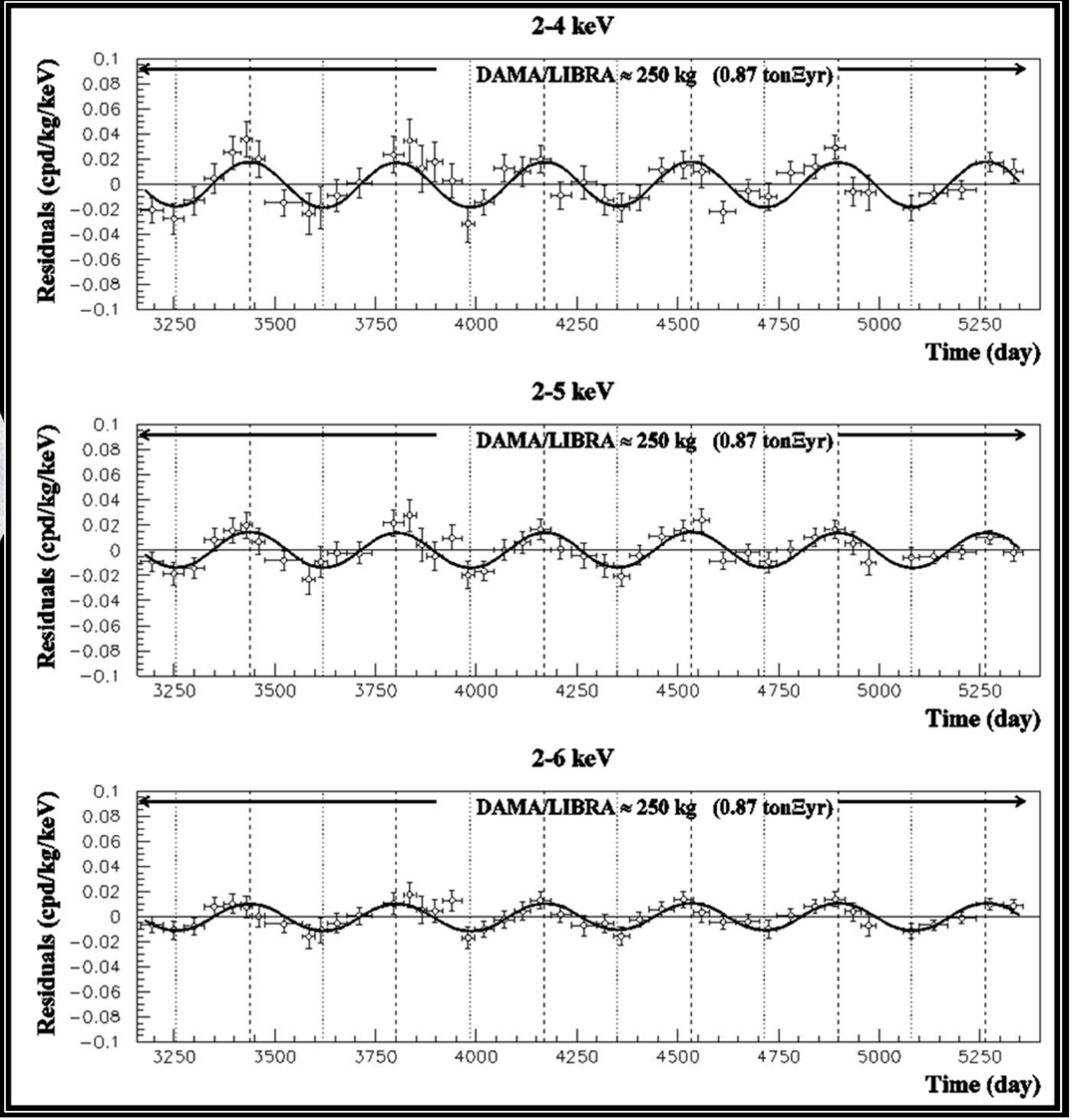
DAMA/LIBRA (NaI)

$\cos\omega(t-t_0)$

$T = 2\pi/\omega = 1$ year

$t_0 = 152.5^d$ (2 June)

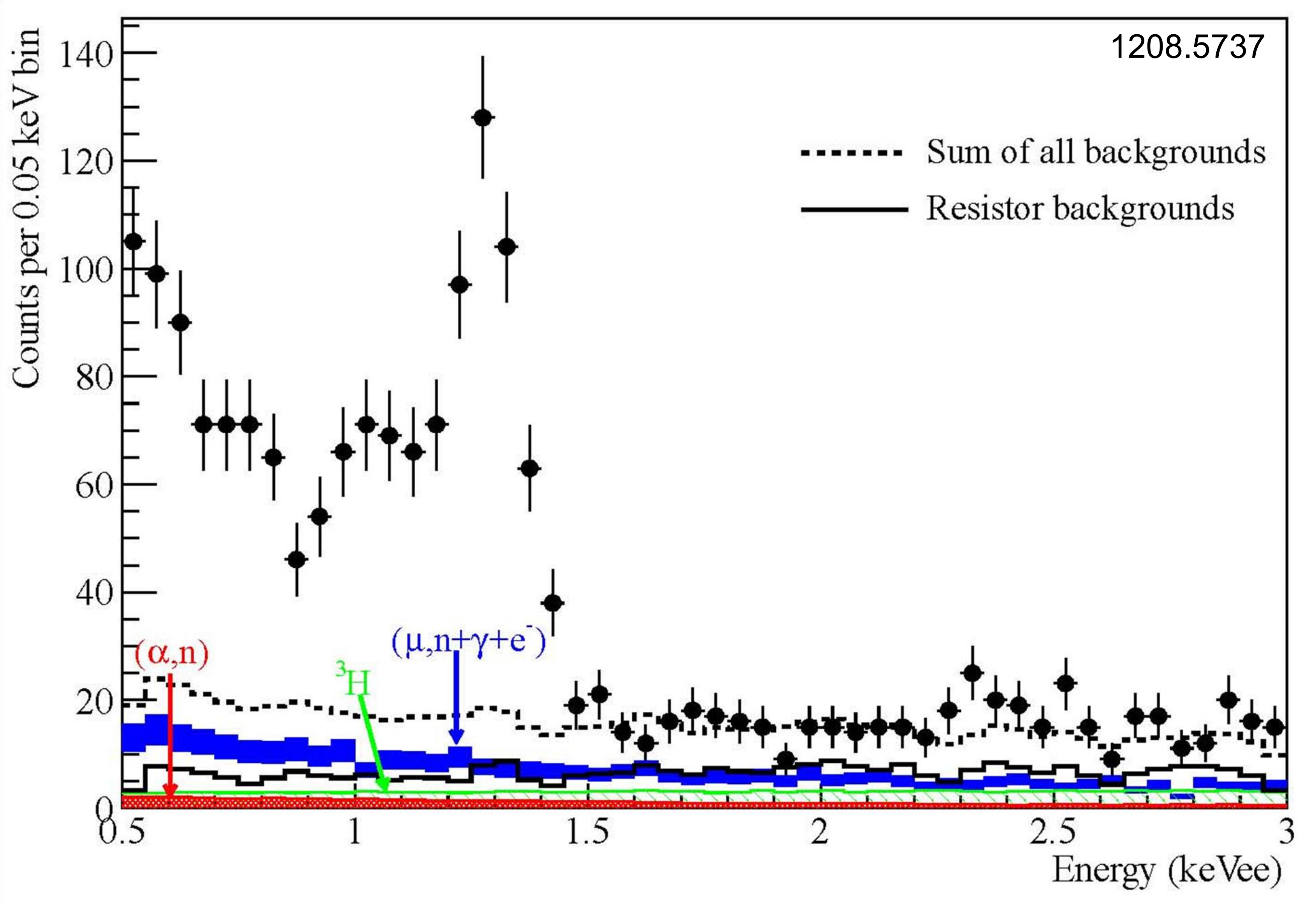




Amplitude of modulation surprisingly high

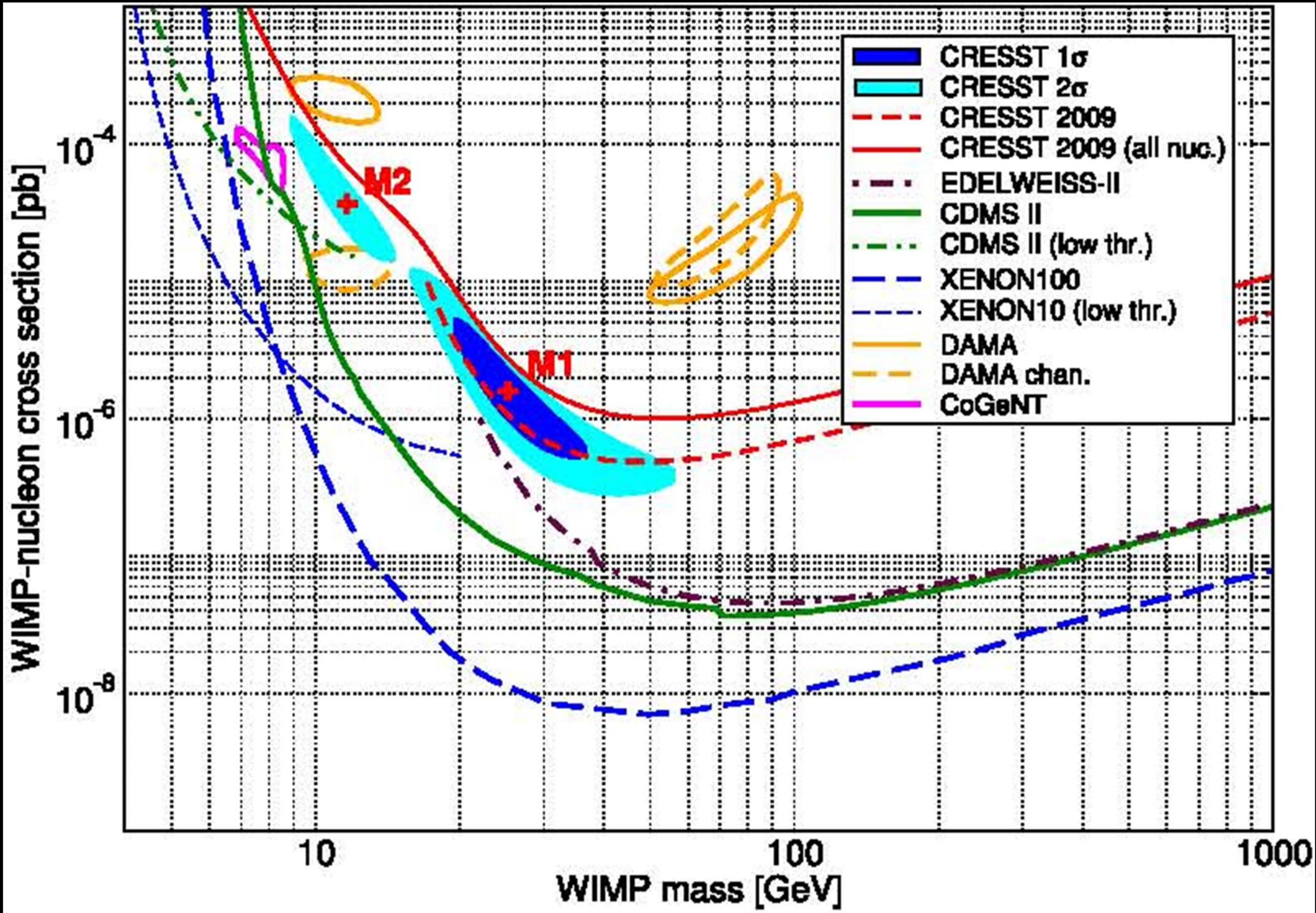
KIMS (CsI) → modulation not due to WIMP scattering on Iodine

CoGeNT (Ge)

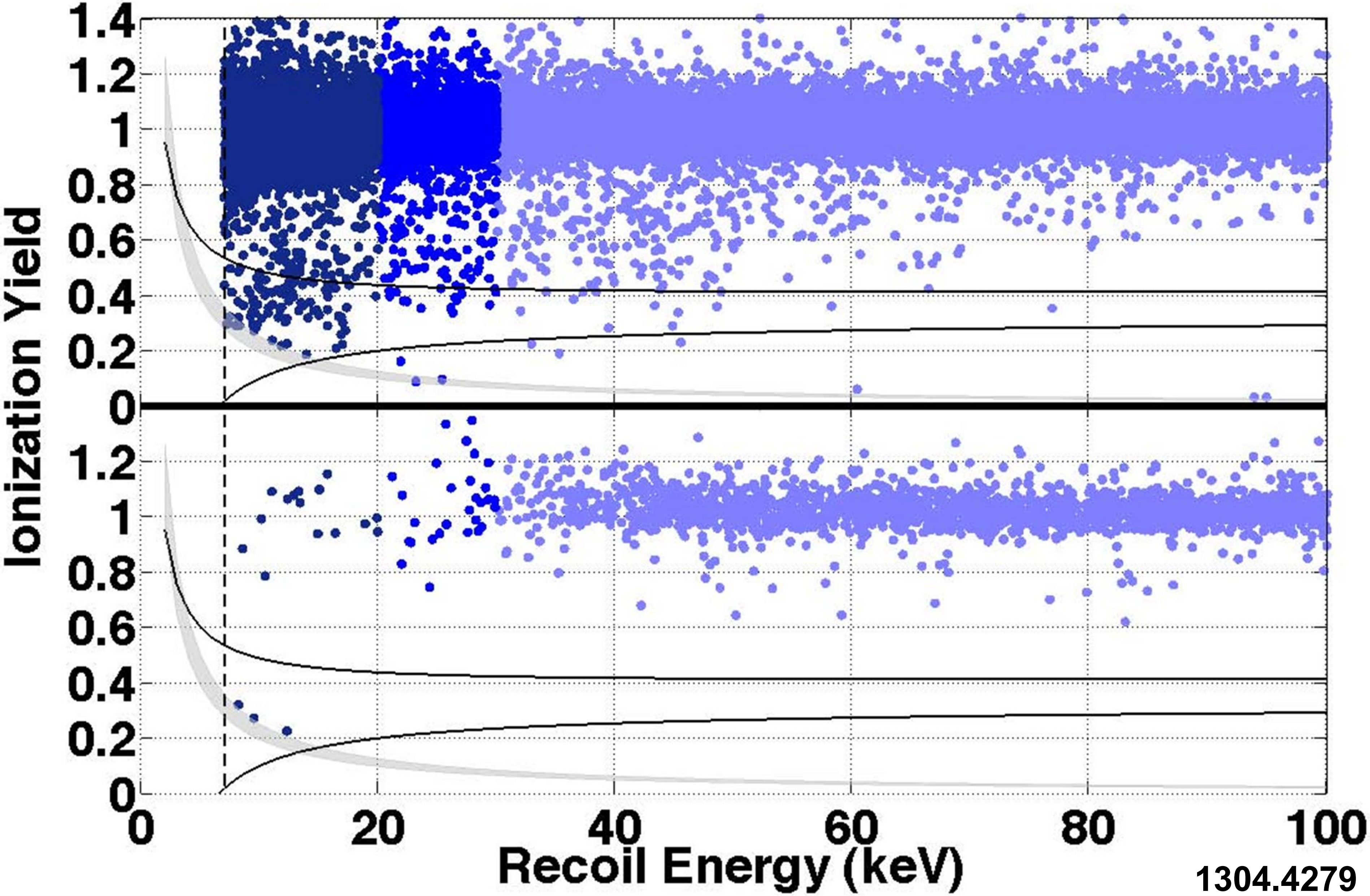


30% surface events, low-mass (10 GeV) WIMP with large cross section (10^{-4} pb)

CRESST ($CaWO_4$)



CDMS II Si Analysis April 2013



1304.4279

Direct Detection

Maverick WIMPs (for given M, choose $\Lambda \rightarrow$ relic abundance):

Vector couplings excluded in range $10\ \mathrm{GeV}$ to $2000\ \mathrm{GeV}$

Scalar couplings excluded in range $10\ \mathrm{GeV}$ to $200\ \mathrm{GeV}$

Axial & Tensor couplings spin-dependent weak or no limits

Pseudoscalar couplings velocity suppressed $\rightarrow$ no limits

SUSY WIMPs (choose 105 SUSY parameters):

Any limits very model dependent

+ LHC:

CMSSM surviving on life support

MSSM running a high fever

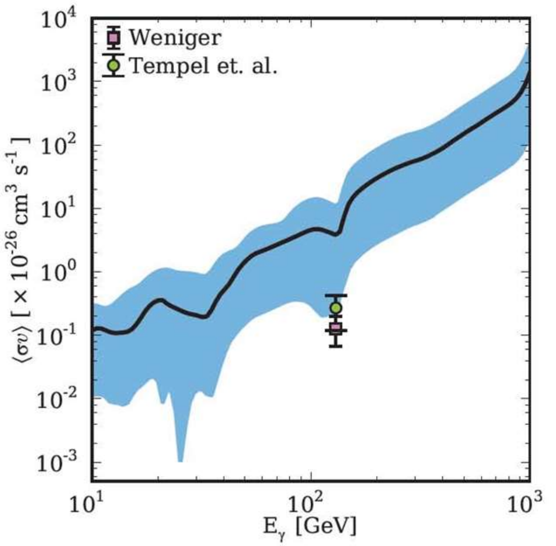
Low-energy SUSY coughing a lot

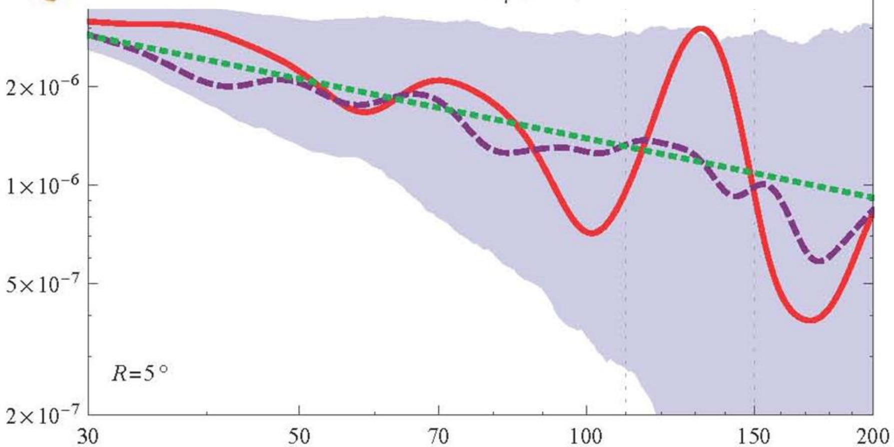
As push SUSY scale high $\rightarrow$

cross section too small for correct relic abundance,
unless ... resonant annihilation, co-annihilation, etc.

Fermi/GLAST Line(s)

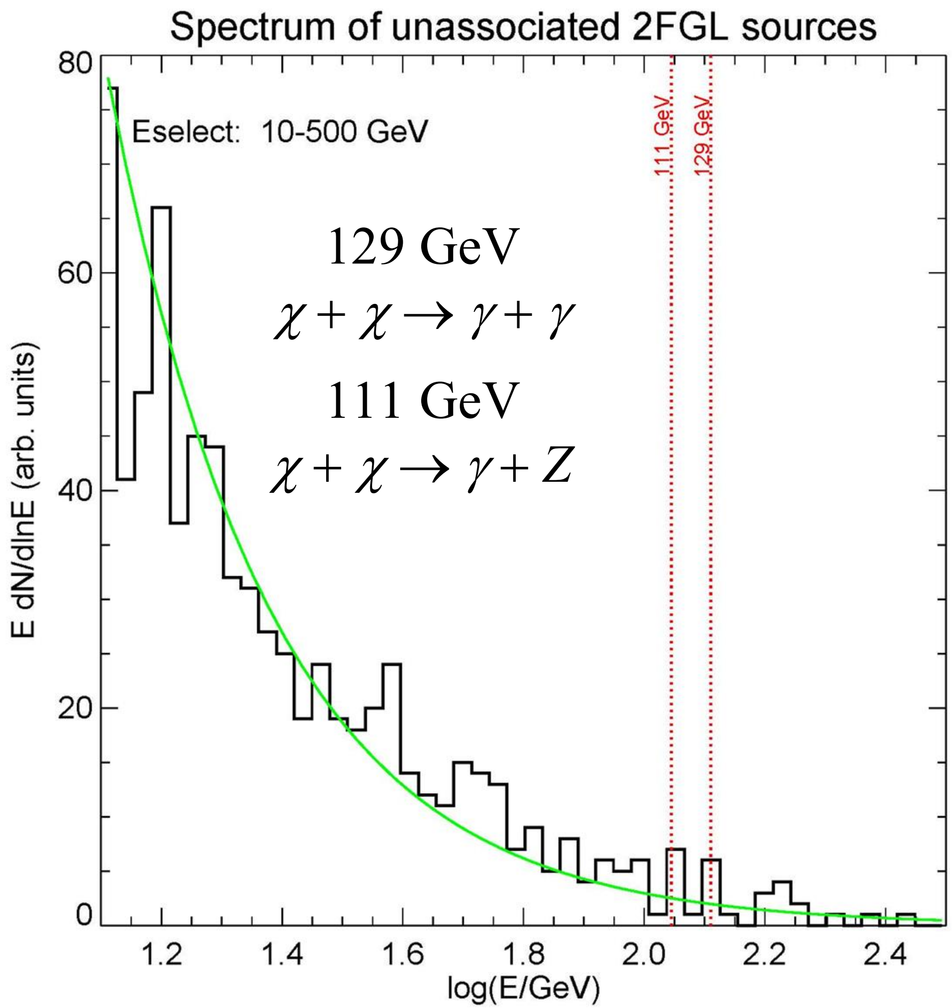
Dwarf stacking inconclusive
Geringger-Saneth, &
Koushiappas 1206.0796





Six stacked galaxy clusters: 3.2σ signal

Hektor, Raidal, Tempel 1207.4466



129 GeV
$$\chi + \chi \rightarrow \gamma + \gamma$$

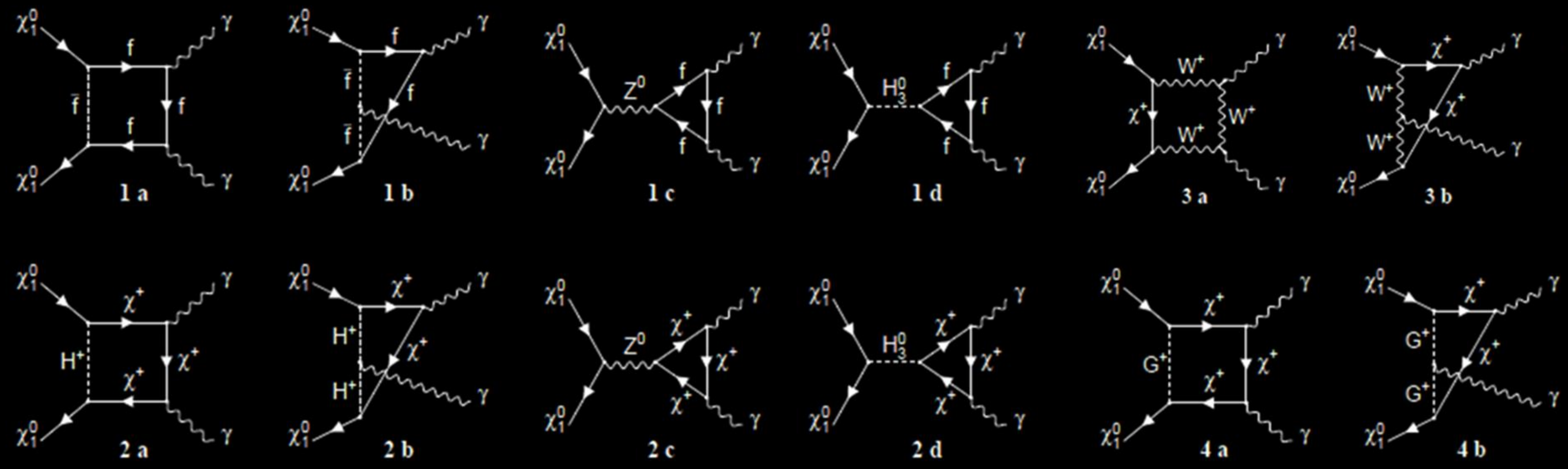
111 GeV
$$\chi + \chi \rightarrow \gamma + Z$$

$$E_1 = m_c \qquad E_2 = m_c \left(1 - m_c^2 / 4m_z^2\right)$$

About 3σ: Finkbeiner & Su 1207.7060

Fermi/GLAST Line(s)

- WIMP−charged particle coupling $\rightarrow$ annihilates to $\gamma\gamma + \gamma Z + ZZ + ...$).



Bergstrom & Ullio 97

- But also annihilates at tree-level to W's and Z's, e^+e^-, quarks, …, producing "continuum" γ-ray background. Loop smaller than tree by □($\alpha^2/4\pi$).
- Inner bremsstrahlung also produces γ's, only suppressed □(α).
- Continuum constrained by observations, BR($\gamma\gamma$) must be □(1).
- Models with no tree-level annihilation: *e.g.,* Jackson *et al*. 0912.0004

EFT: DM Couples to EWK Gauge & Higgs

(Chen, Kolb, Wang 13050021)

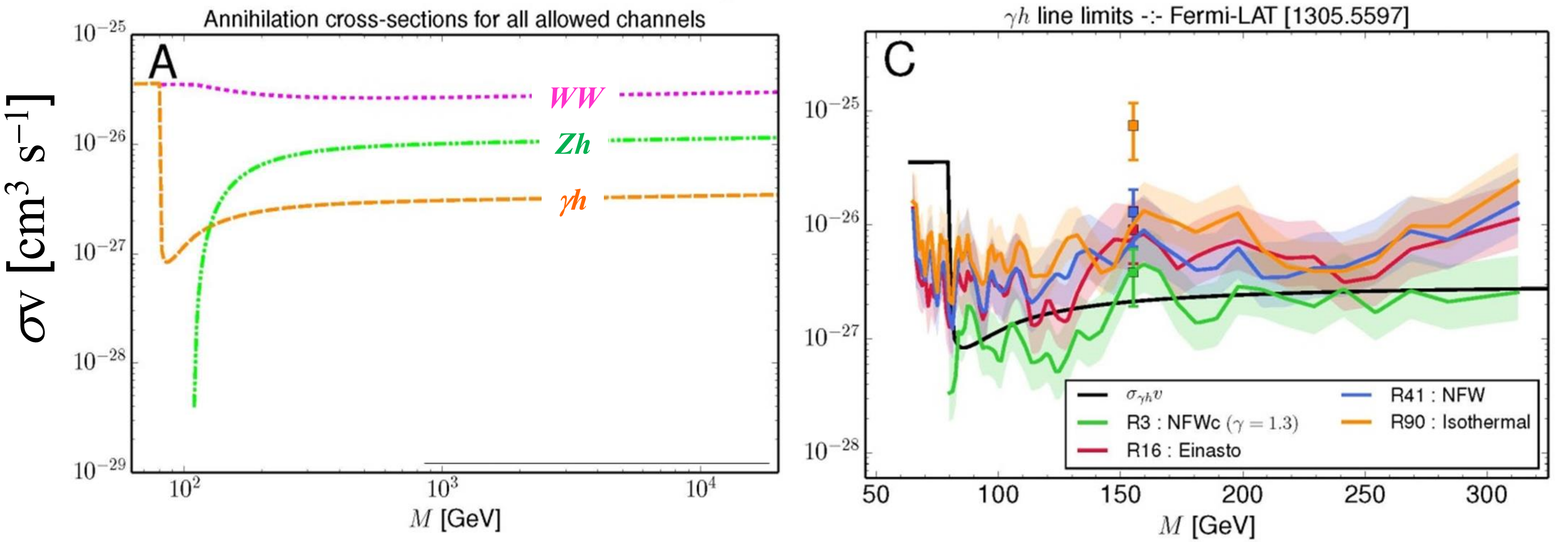
- Most analyses assume WIMPs couple to fermions, untenable if see γ lines
- Effective Field Theory analysis of gauge/Higgs di-boson couplings
- Assume $\mathcal{L}_{\text{EFT}} = J_{\text{DM}} \cdot J_{\text{SM}}$ and each J is an $\text{SU}_3 \times \text{SU}_2 \times \text{U}_1$ singlet
- 50 possible dimension-6, 7, & 8 operators
- Different final states (energy spectrum of γ-ray lines) and continuum

EFT: DM Couples to EWK Gauge & Higgs

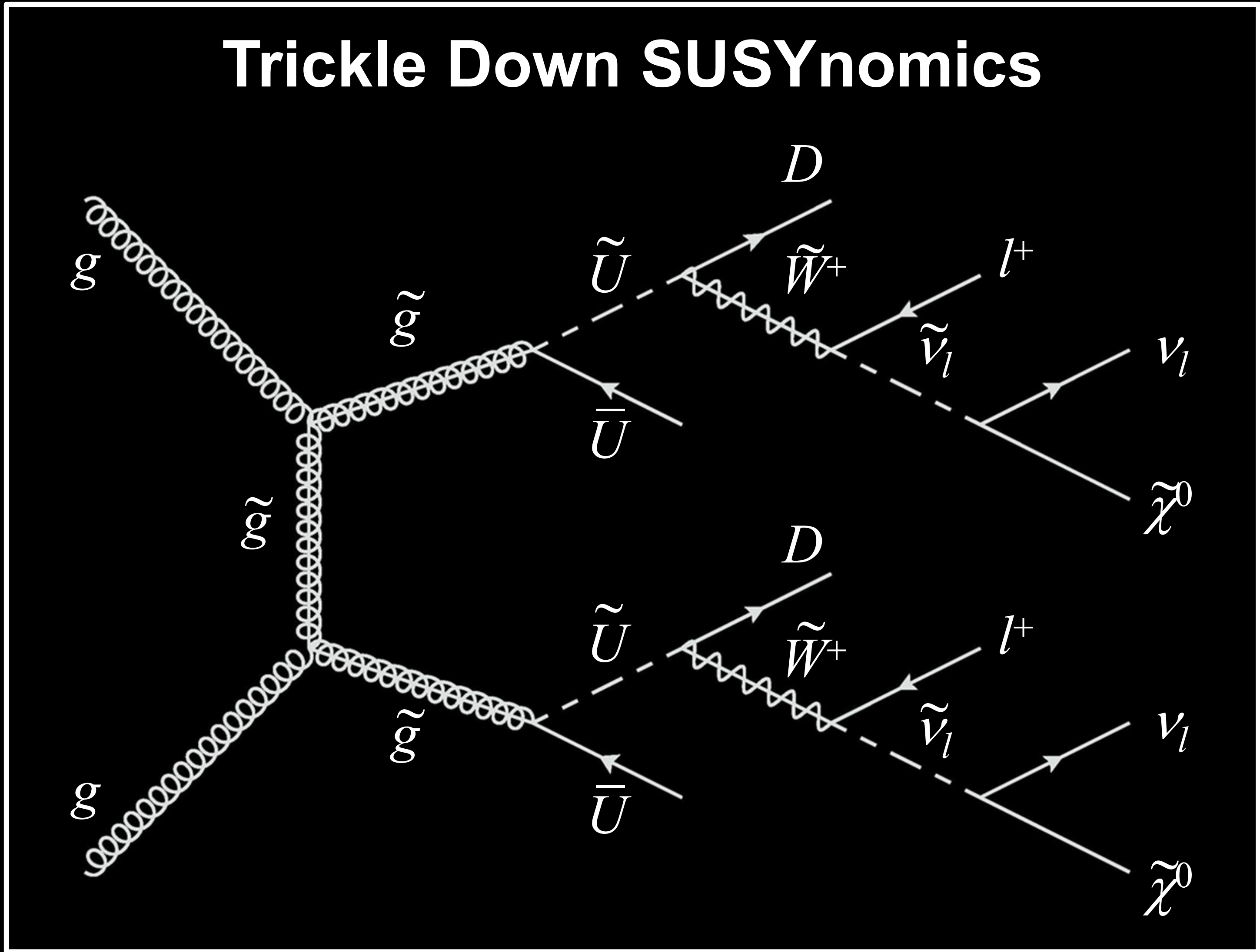
- Gamma-ray observations for this case play the role of direct detection for coupling to quarks
- Fifty operators/34 without velocity suppression
  DM+DM → *γγ, γZ, γh, W^+W^-, ZZ, Zh, hh, ff*
  For each operator calculate photon spectrum (lines+continuum)
  Compare to various constraints

} Thirteen different classes

$$\Lambda^{-4}\bar{\chi}\gamma^{\mu}\chi(\widetilde{W}^{a}_{\lambda\mu}H^{\dagger}t^{a}D^{\lambda}H + h.c.)$$



SUSY WIMPs at the LHC

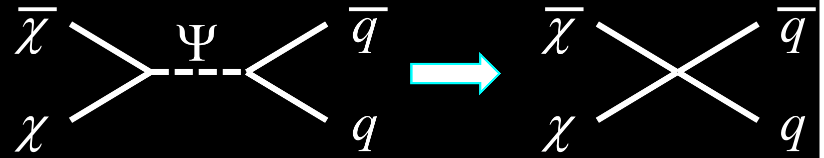


Complicated decay chain—very model dependent

Maverick WIMPs Coupling to Quarks

	operator	annih.	direct detec.
Scalar WIMPs	$\phi^\dagger \phi \; \bar{q} q$	1	SI
	$\phi^\dagger \phi \; \bar{q}\gamma^5 q$	1	v^2
	$(\phi^\dagger \partial^\mu \phi + h.c.)\bar{q}\gamma_\mu q$	0	SI
	$(\phi^\dagger \partial^\mu \phi + h.c.)\bar{q}\gamma_{\mu 5} q$		$m_q{}^2/M^2$ SD
	$i(\phi^\dagger \partial^\mu \phi - h.c.)\bar{q}\gamma_\mu q$	v^2	SI
	$i(\phi^\dagger \partial^\mu \phi - h.c.)\bar{q}\gamma_{\mu 5} q$		v^2 SD
Fermion WIMPs	$\bar{\chi}\chi \; \bar{q} q$	v^2	SI
	$\bar{\chi}\chi \; \bar{q}\gamma^5 q$	v^2	v^2
	$\bar{\chi}\gamma^5\chi \; \bar{q} q$	1	SI
	$\bar{\chi}\gamma^5\chi \; \bar{q}\gamma^5 q$	1	v^2
	~~$\bar{\chi}\gamma^\mu\chi \; \bar{q}\gamma_\mu q$~~	~~1~~	~~SI~~
	$\bar{\chi}\gamma^{\mu 5}\chi \; \bar{q}\gamma_\mu q$	v^2	SI
	~~$\bar{\chi}\gamma^\mu\chi \; \bar{q}\gamma_{\mu 5} q$~~	~~1~~	~~SD~~
	$\bar{\chi}\gamma^{\mu 5}\chi \; \bar{q}\gamma_{\mu 5} q$	$v^2, m_q{}^2/M^2$	SD
	~~$\bar{\chi}\gamma^{\mu\nu}\chi \; \bar{q}\gamma_{\mu\nu} q$~~	~~1~~	~~SD~~

- Possible WIMP—gluon couplings
- Some term vanish for Majorana fermions
- Possible "light" mediators (not a true Maverick)
- Range where effective field theory valid



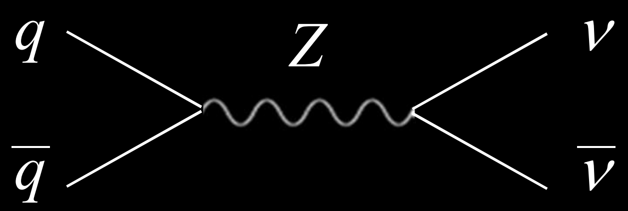
$$\frac{g_c g_q}{p^2 - M_\Psi^2} \rightarrow \frac{G}{\sqrt{2}}$$

- Could also include couplings to leptons

Neutrino Background for Mavericks

Once thought that $\nu\bar{\nu}$ background

$$q + \bar{q} \rightarrow Z \rightarrow \nu + \bar{\nu}$$

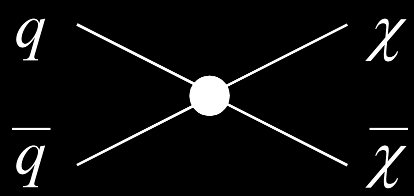


Renormalizible

$\sigma \propto s^{-1}$ (parton level)

Would swamp WIMP signal

$$q + \bar{q} \rightarrow \chi + \bar{\chi}$$

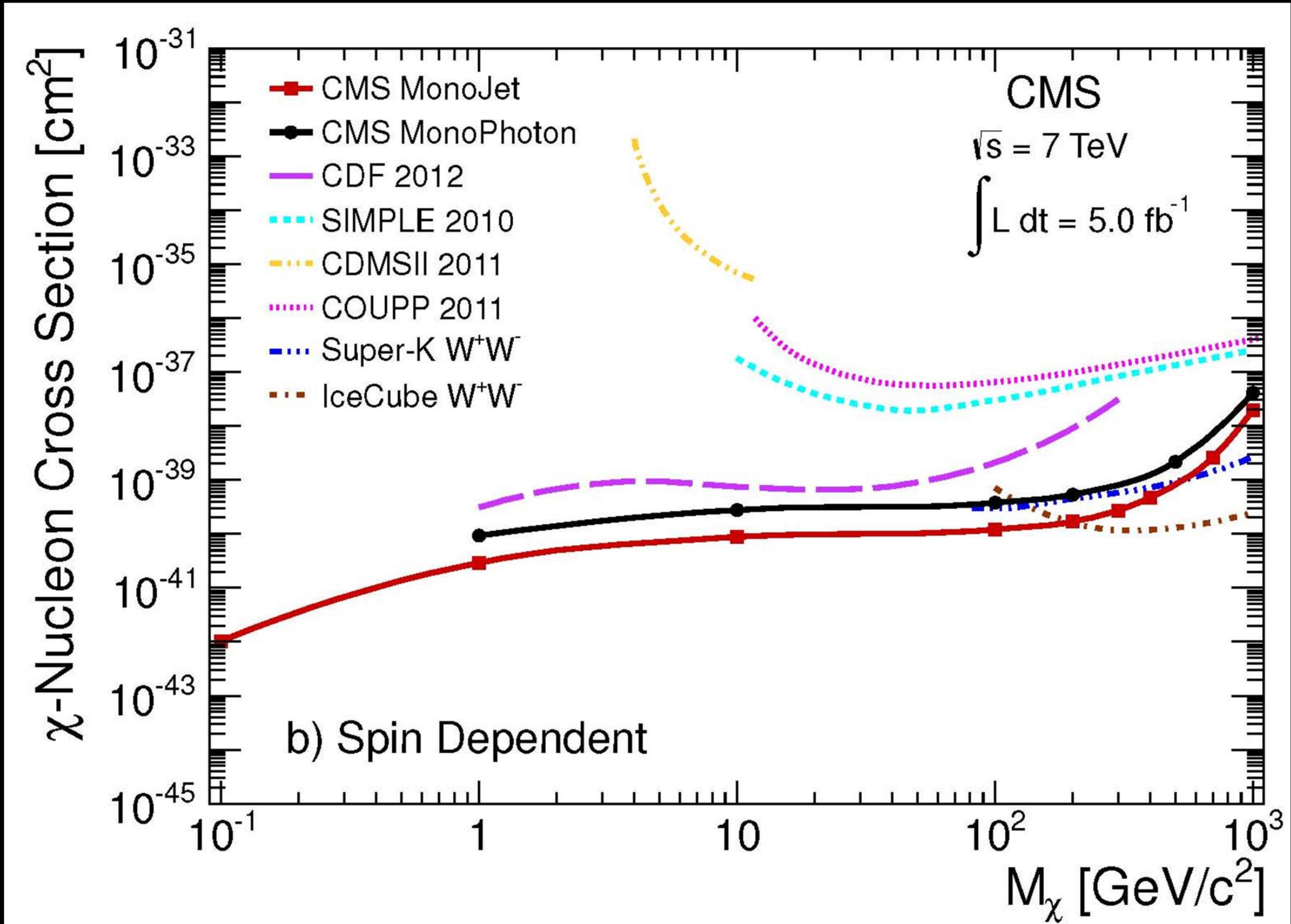


Nonrenormalizible

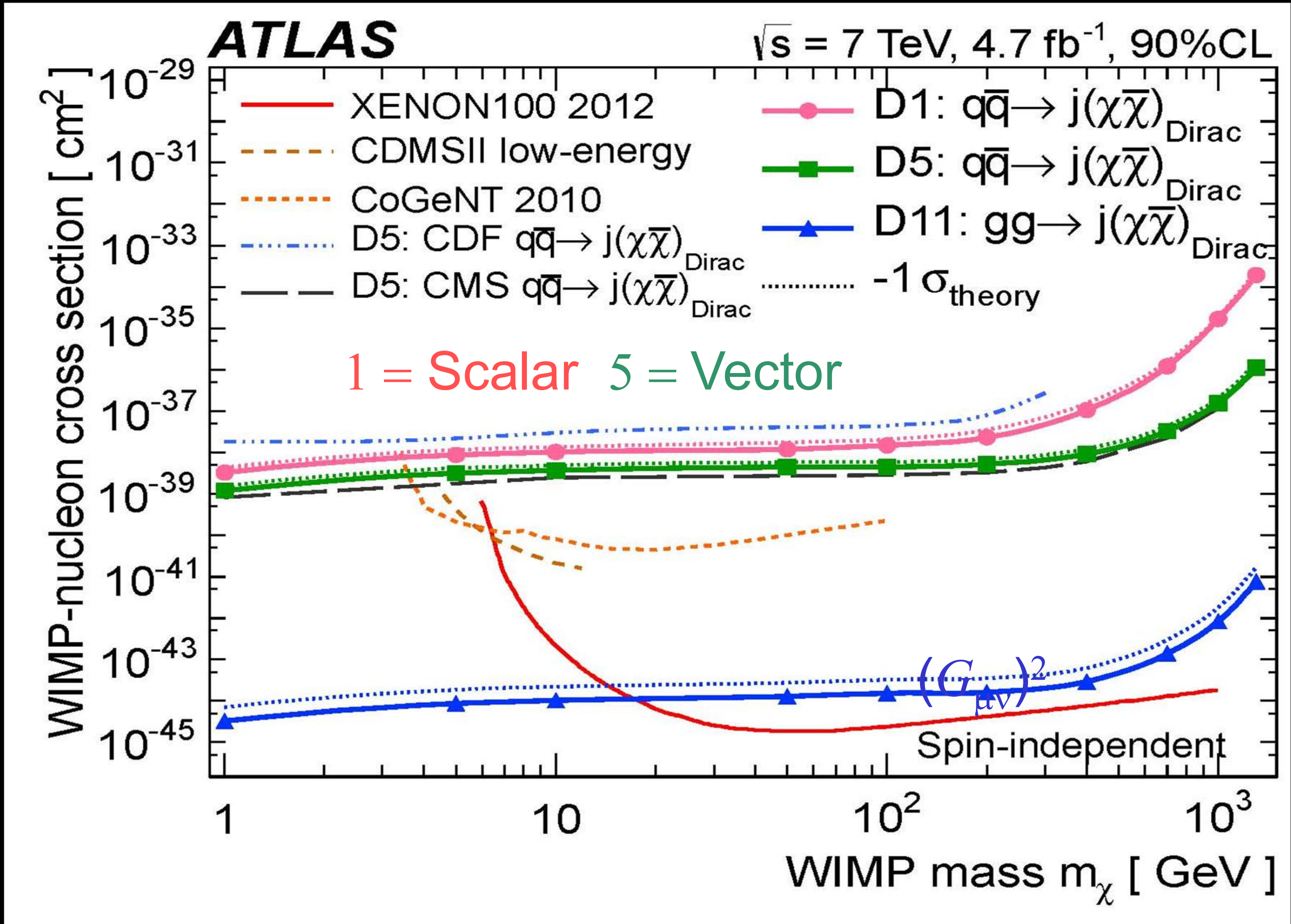
$\sigma \propto s$ (parton level)

Judicious cuts on MET can pull out signal

CMS Analysis JHEP 2012



ATLAS Analysis 1210.4491

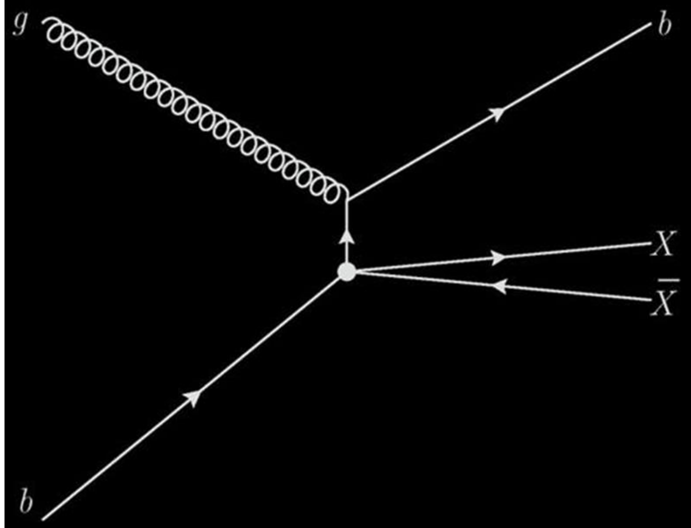


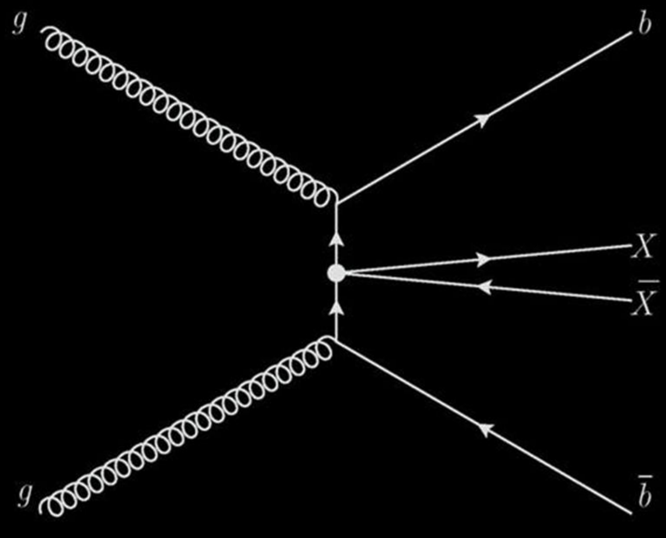
Take Advantage of Largest Yukawas

(Lin, Kolb, Wang 13036638)

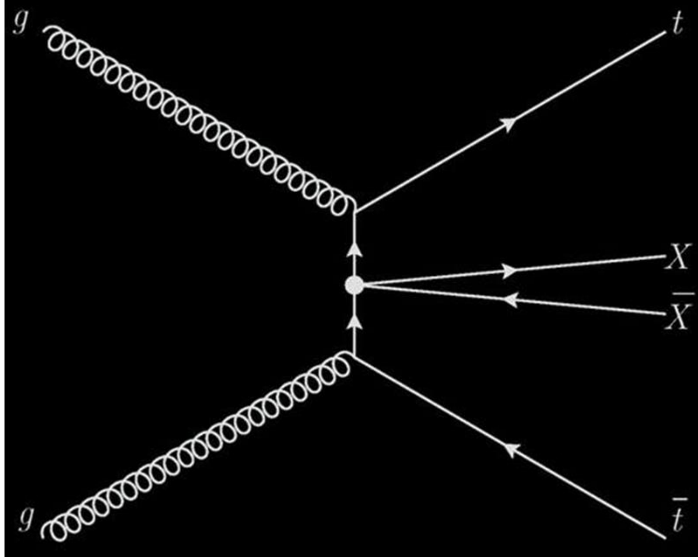
S & P couplings $\propto m_q$ (Minimal Flavor Violation) $m_c : m_b : m_t :: 1 : 3.3 : 135$

So far, analysis includes only c (b PDF smaller than c PDF) but $m_t \gg m_b \gg m_c$





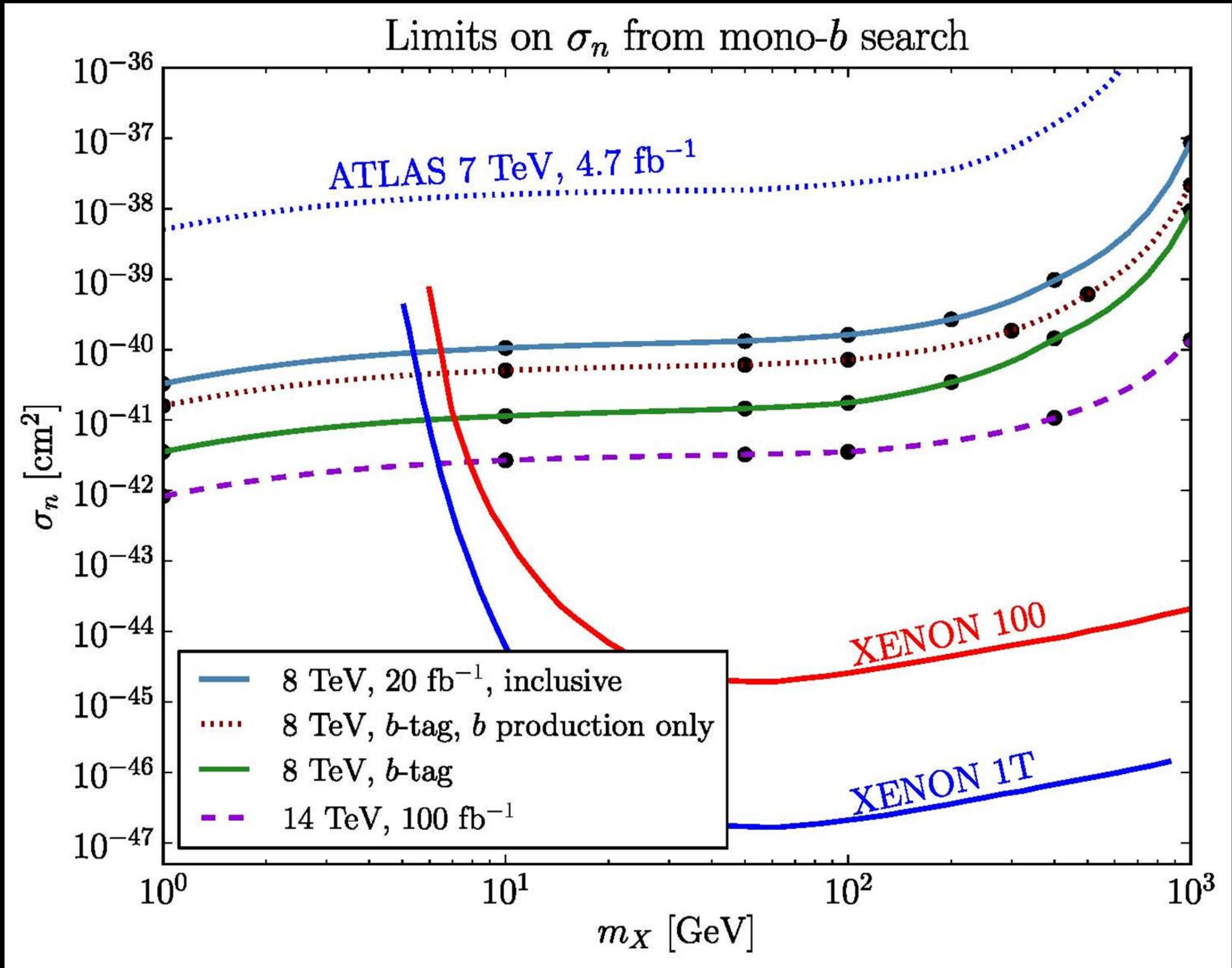
Take advantage of b tagging



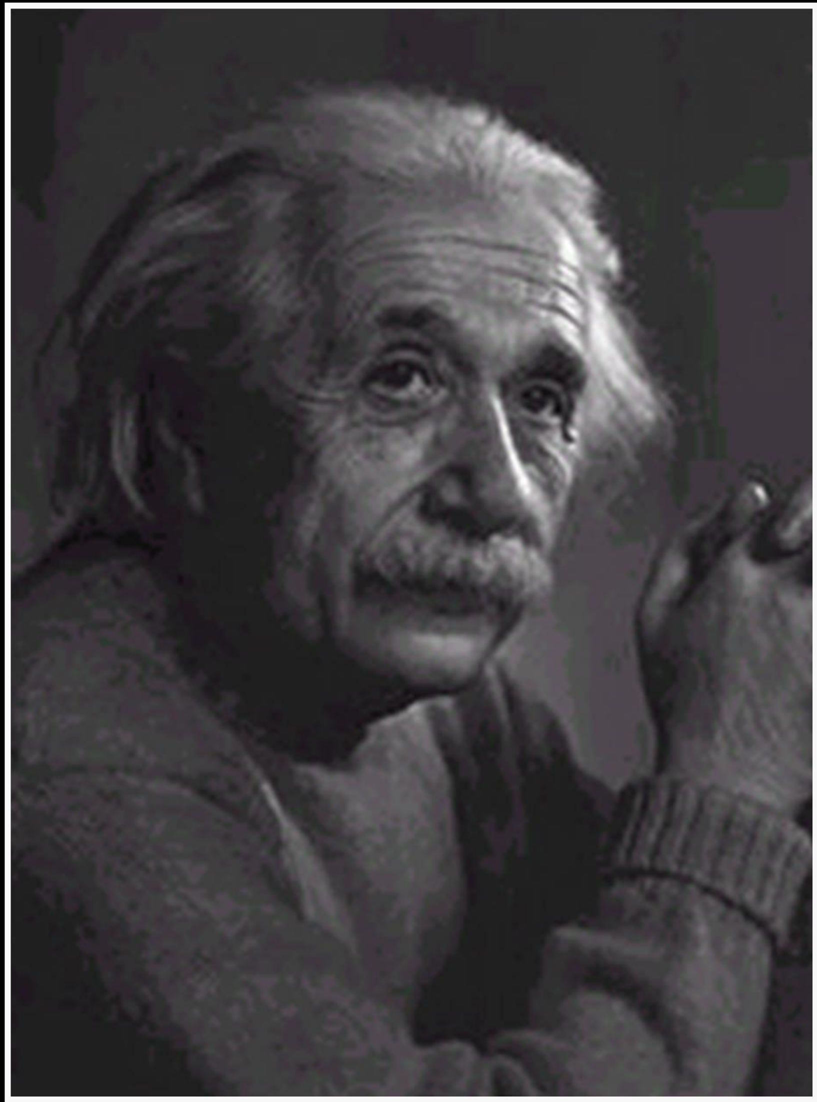
Top PDF small (& very uncertain) but m_t huge
Looks like stop signal—use stop search limits

Take Advantage of Largest Yukawas

(Lin, Kolb, Wang 13036638)



Was Einstein Right After All?



1917 Einstein proposed cosmological constant.

1929 Hubble discovered expansion of the Universe.

1934 Einstein called it "my biggest blunder."

1998 Astronomers found evidence for it.

Expansion History of the Universe $H(z)$

Einstein's Equations: $R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$

Robertson–Walker metric

$k = +1$ (^3S); -1 (^3H); 0 (^3R)

Comoving coordinates r, Ω

Scale factor $a(t)$

$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right]$$

Stress-Energy Tensor: $T_{\mu\nu} = -g_{\mu\nu} p + (\rho + p)\, U_\mu U_\nu$

Expansion rate of the Universe: $H \equiv \frac{\dot{a}}{a}$

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi}{3} G\rho$$ Friedmann Equation

$$\frac{\ddot{a}}{a} = -8\pi G(\rho + 3p)$$ Deceleration Parameter

Cosmological Constant (Dark Energy)

$$R_{\mu\nu} - \Box\, g_{\mu\nu} R = 8\pi G\, T_{\mu\nu}$$ Einstein 1915

$$R_{\mu\nu} - \Box\, g_{\mu\nu} R - \Lambda^{CC} g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$ Einstein 1917

$\Lambda^{CC} =$ **cosmological constant**

$$R_{\mu\nu} - \Box\, g_{\mu\nu} R = 8\pi G\, T_{\mu\nu}$$ Einstein 1934

$$R_{\mu\nu} - \Box\, g_{\mu\nu} R = 8\pi G\, T_{\mu\nu} + 8\pi G\, T_{\mu\nu}^{\text{vacuum}}$$ QFT+

$T_{\mu\nu}^{\text{vacuum}}$: $\rho^{\text{vacuum}} = -p^{\text{vacuum}}$ $\qquad \rho^{\text{vacuum}} + 3p^{\text{vacuum}} < 0$

$$R_{\mu\nu} - \Box\, g_{\mu\nu} R - \Lambda^{CC} g_{\mu\nu} = 8\pi G\, T_{\mu\nu} + \Lambda^{\text{vacuum}} g_{\mu\nu}$$

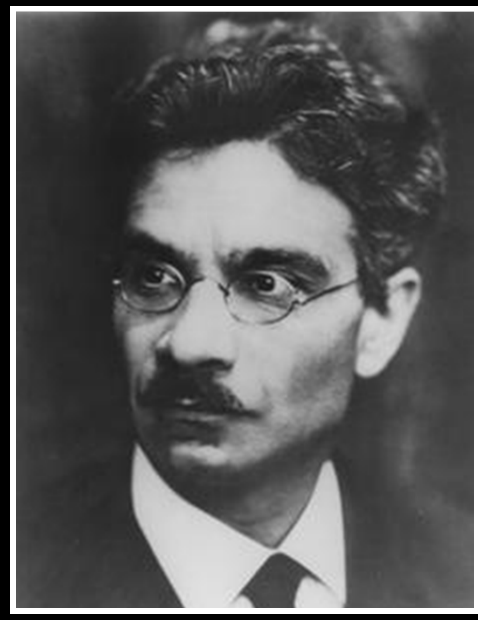
$$\Lambda^{\text{vacuum}} = 8\pi G \rho^{\text{vacuum}}$$

CC (*à la* Einstein) & ρ^{vacuum} indistinguishable

Dark Energy

"Nothing more can be done by the theorists. In this matter it is only you, the astronomers, who can perform a simply invaluable service to theoretical physics."

Einstein in August 1913 to Berlin astronomer Erwin Freundlich encouraging him to mount an expedition to measure the deflection of light by the sun.



EFT: DM Couples to EWK Gauge & Higgs

(Chen, Kolb, Wang 13050021)

SCALAR

$$\left.\begin{array}{r}\phi^\dagger\phi \\ \bar{\chi}\chi \\ \bar{\chi}i\gamma^5\chi\end{array}\right\} \times \begin{cases} H^\dagger H & \text{with final state } hh \\ B_{\mu\nu}\ B^{\mu\nu} & \text{with final states } \gamma\gamma,\ \gamma Z,\ ZZ \\ B_{\mu\nu}\ \widetilde{B}^{\mu\nu} & \text{with final states } \gamma\gamma,\ \gamma Z,\ ZZ \\ W^a_{\mu\nu}\ W^{a\,\mu\nu} & \text{with final states } \gamma\gamma,\ \gamma Z,\ ZZ,\ W^+W^- \\ W^a_{\mu\nu}\ \widetilde{W}^{a\,\mu\nu} & \text{with final states } \gamma\gamma,\ \gamma Z,\ ZZ,\ W^+W^- \end{cases}$$

TENSOR

$$\bar{\chi}\gamma^{\mu\nu}\chi \times \begin{cases} B_{\mu\nu} & \text{with final states } Zh,\ W^+W^-,\ f\bar{f} \\ \widetilde{B}_{\mu\nu} & \text{with final states } Zh,\ W^+W^-,\ f\bar{f} \\ B_{\mu\nu}Y_H\ H^\dagger H & \text{with final states } \gamma h,\ Zh,\ W^+W^-,\ f\bar{f} \\ \widetilde{B}_{\mu\nu}Y_H\ H^\dagger H & \text{with final states } \gamma h,\ Zh,\ W^+W^-,\ f\bar{f} \\ W^a_{\mu\nu}H^\dagger t^a H & \text{with final states } \gamma h,\ Zh,\ W^+W^-,\ f\bar{f} \\ \widetilde{W}^a_{\mu\nu}H^\dagger t^a H & \text{with final states } \gamma h,\ Zh,\ W^+W^-,\ f\bar{f} \end{cases}$$

EFT: DM Couples to EWK Gauge & Higgs

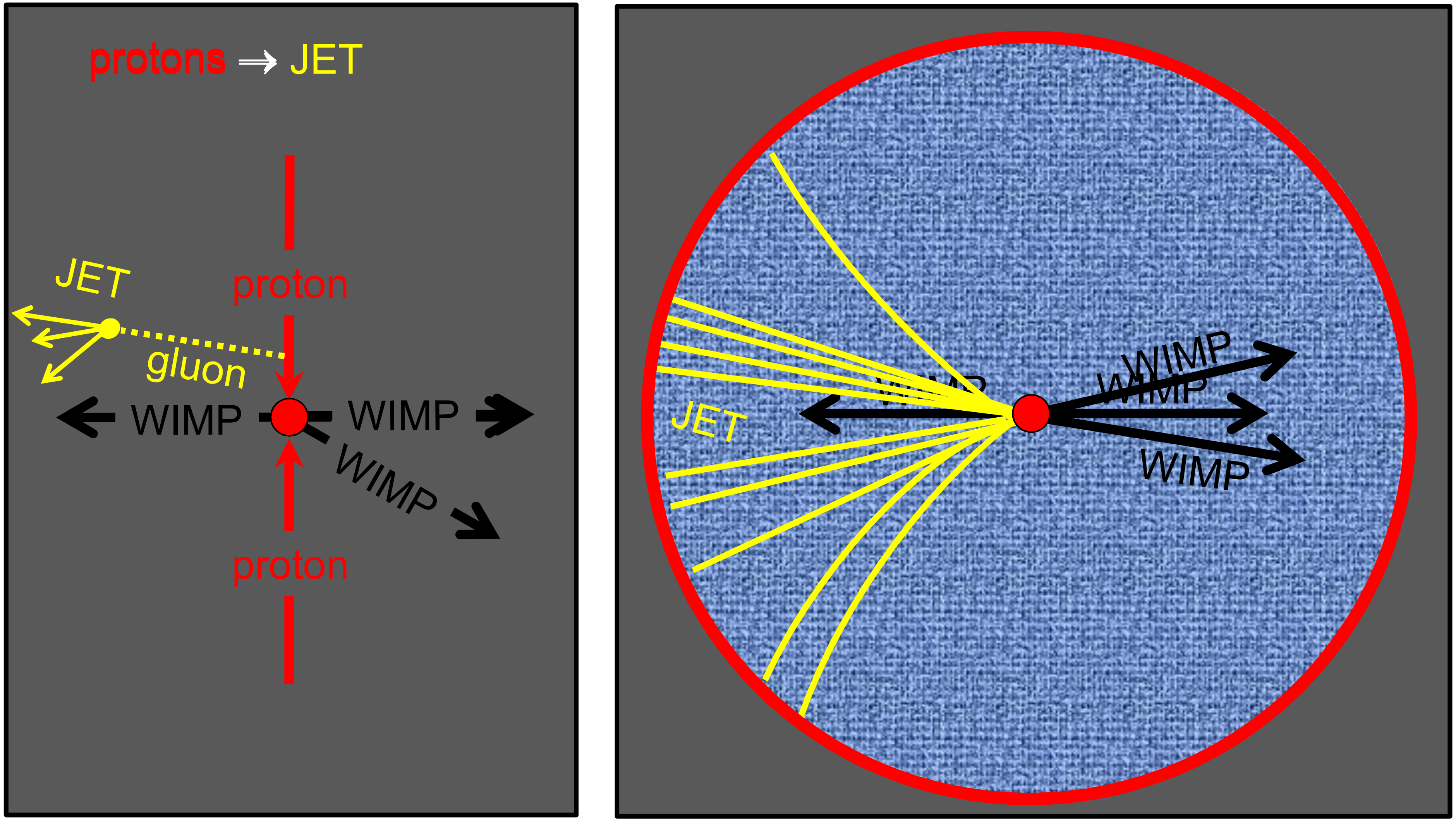
(Chen, Kolb, Wang 13050021)

V
E
C
T
O
R

$$(\phi^\dagger \partial^\mu \phi + h.c.) \times \begin{cases} \left(B_{\lambda\mu} Y_H\, H^\dagger D^\lambda H + h.c.\right) \text{ with final state } Zh \\ \left(W^a_{\ \lambda\mu}\, H^\dagger t^a D^\lambda H + h.c.\right) \text{ with final state } Zh \\ i\left(B_{\lambda\mu} Y_H\, H^\dagger D^\lambda H - h.c.\right) \text{ with final states } \gamma Z,\ ZZ \\ i\left(\widetilde{B}_{\lambda\mu} Y_H\, H^\dagger D^\lambda H - h.c.\right) \text{ with final states } \gamma Z,\ ZZ \\ i\left(W^a_{\ \lambda\mu}\, H^\dagger t^a D^\lambda H - h.c.\right) \text{ with final states } \gamma Z,\ ZZ,\ W^+W^- \\ i\left(\widetilde{W}^a_{\ \lambda\mu}\, H^\dagger t^a D^\lambda H - h.c.\right) \text{ with final states } \gamma Z,\ ZZ,\ W^+W^- \end{cases}$$

$$\left.\begin{matrix} i\left(\phi^\dagger \partial^\mu \phi - h.c.\right) \\ \bar{\chi}\gamma^\mu \chi \\ \bar{\chi}\gamma^{\mu 5} \chi \end{matrix}\right\} \times \begin{cases} \left(B_{\lambda\mu} Y_H\, H^\dagger D^\lambda H + h.c.\right) \text{ with final states } \gamma h,\ Zh \\ \left(\widetilde{B}_{\lambda\mu} Y_H\, H^\dagger D^\lambda H + h.c.\right) \text{ with final states } \gamma h,\ Zh \\ i\left(B_{\lambda\mu} Y_H\, H^\dagger D^\lambda H - h.c.\right) \text{ with final states } \gamma Z,\ ZZ \\ i\left(\widetilde{B}_{\lambda\mu} Y_H\, H^\dagger D^\lambda H - h.c.\right) \text{ with final states } \gamma Z,\ ZZ \\ \left(W^a_{\ \lambda\mu}\, H^\dagger t^a D^\lambda H + h.c.\right) \text{ with final states } \gamma h,\ Zh,\ W^+W^- \\ \left(\widetilde{W}^a_{\ \lambda\mu}\, H^\dagger t^a D^\lambda H + h.c.\right) \text{ with final states } \gamma h,\ Zh,\ W^+W^- \\ i\left(W^a_{\ \lambda\mu}\, H^\dagger t^a D^\lambda H - h.c.\right) \text{ with final states } \gamma Z,\ ZZ,\ W^+W^- \\ i\left(\widetilde{W}^a_{\ \lambda\mu}\, H^\dagger t^a D^\lambda H - h.c.\right) \text{ with final states } \gamma Z,\ ZZ,\ W^+W^- \end{cases}$$

Collider Searches for Maverick WIMPs



Discover WIMPs by searching for “monojets” (MET)

SUSY WIMPs at the LHC

- Typical SUSY models consistent w/ collider and other HEP data have too small annihilation cross section $\rightarrow$ too large Ω

- Need chicanery to increase annihilation cross section
  - s-channel resonance through light H and Z poles
  - co-annihilation with $\tilde{\tau}$ or $\tilde{t}$
  - large tanβ (s-channel annihilation via broad A resonance)
  - high values of m_0: Higgsino- like neutralino annihilates into W & Z pairs (focus point region)
  - …

- Higgs mass limit constrains SUSY models

- Squark/gluino ssearchs constrain SUSY models

- Or, unconstrained, nonminimal

WIMP Questions

- Why only <u>one</u> WIMP?

  The 4% of matter we see is pretty complex and varied.
  If social network of several WIMPs, stronger interacting ones:
    - Easier to detect
    - Smaller Ω

- Thermal Production of WIMPS?
    - Super-WIMPs
    - Asymmetric freeze out
    - Dilution after freeze out via entropy production

- Maverick WIMPs?
    - Suppose LHC only sees SM Higgs?
    - Wither SNOOZY?

- Leptophilic, Leptophobic, Flavorful, Self-Interacting, Dynamical, Inelastic, …

- Annual modulation: do we really understand DM phase space?

- Indirect detection gives indirect information