The missing 95%: Theory and Phenomenology of Dark Matter and Dark Energy

Joachim Kopp

DPG Spring Meeting Göttingen, March 2012

Fermilab

Outline

1. Evidence for dark matter

2. Finding dark matter
    - Direct detection
    - Indirect detection
    - Production at colliders

3. Modelling dark matter

4. Dark energy

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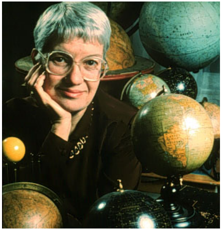
Celestial mechanics

Stellar/galactic dynamics relates:

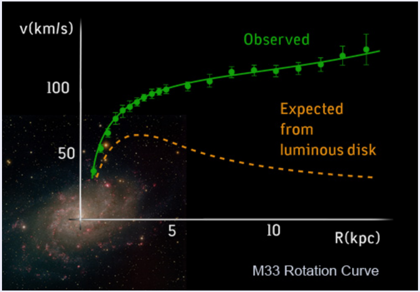
- The mass distribution
  (inferred from brightness)
- Kinetic energy
  (inferred from Doppler shifts)

Fritz Zwicky
1898–1974



Vera Rubin
1928–

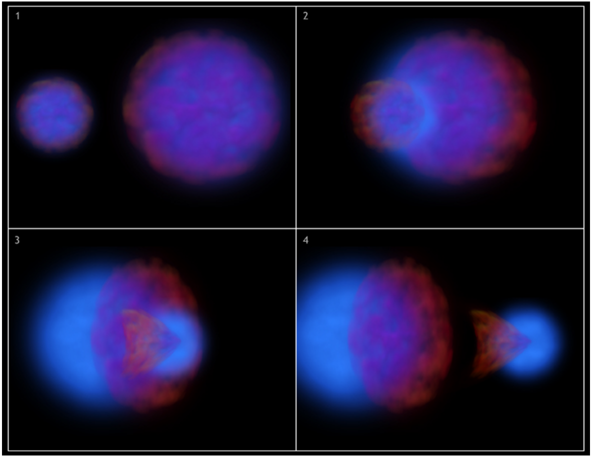
Observations of rotational velocities in galaxies show: Rubin 1975



The gravitational pull on peripheral stars is stronger than predicted from the mass of the luminous matter M

$$m\frac{v^2}{r} = G_N\frac{mM}{r^2} \qquad \text{at } r \to \infty$$

Collisions of galaxy clusters



Artist's rendering (Image: NASA)

red = gas (from x-ray observations)
blue = (dark) matter distribution (from gravitational lensing)

Collisions of galaxy clusters

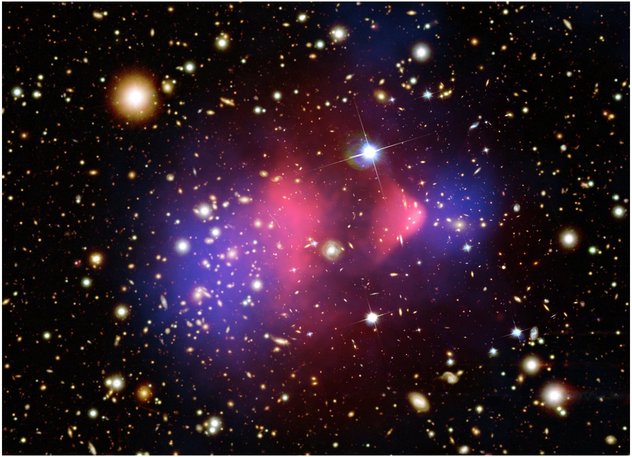


Image: NASA (Chandra [x-ray], ESO WFI [lensing], HST [optical])

red = gas (from x-ray observations)
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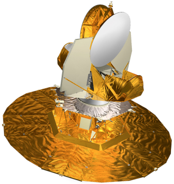
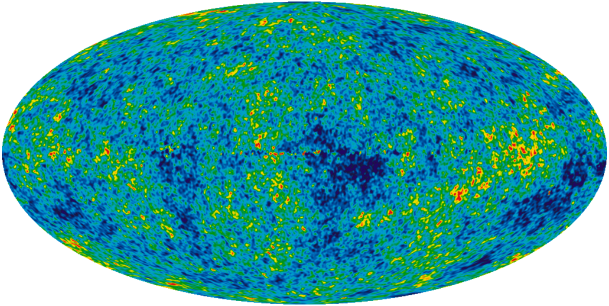
The Cosmic Microwave Background (CMB)



WMAP's observation of the CMB: A fingerprint of the universe at $t \simeq 300\,000$ yrs
(when electrons and protons first combined to form atoms).



red = overdense, hot regions ($0 \ldots +200\ \mu$K)
blue = underdense, cold regions ($-200 \ldots 0\ \mu$K)

Image credit: NASA

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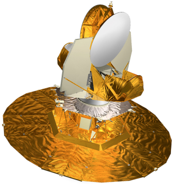

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More useful: The CMB fluctuation power spectrum

Image credit: NASA

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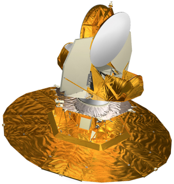

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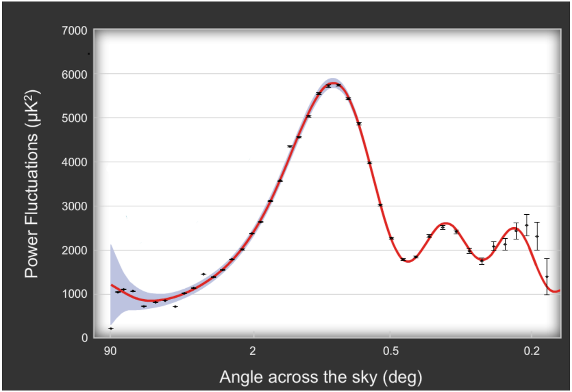

red curve = theory prediction
black points = WMAP data

Image credit: NASA

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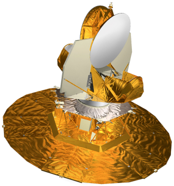

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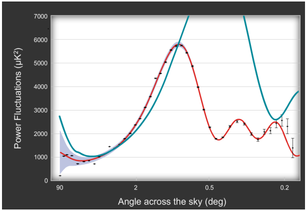
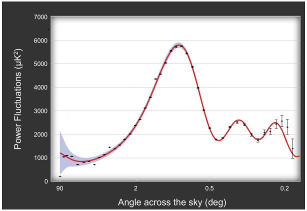
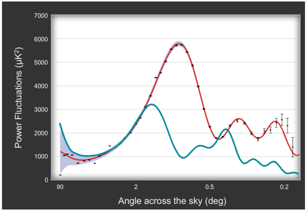


too little DM ($0.04\rho_c$)



right amount of DM ($0.22\rho_c$)



too much DM ($0.74\rho_c$)

Image credit: NASA

What is this stuff?

- Modified laws of gravity?
  - Hard to explain all observations
- MACHOs (Massive Compact Halo Objects)?
  - Planets, Brown dwarfs, neutron stars, . . .
  - Ruled out as dark matter in the mass range $0.6 \times 10^{-7} M_\odot < M < 15 M_\odot$ by searches for gravitational microlensing
  - Searches for candidate objects yield too few of them
- Hot (relativistic) Dark Matter (neutrinos or other relativistic particles)?
  - Cannot explain large scale structure of the universe (hot dark matter would smoothen the galaxy distribution)

- Cold or Warm Dark Matter
  - Axions
    - ★ Ultra-light, but non-relativistic due to non-thermal production
  - Gravitinos
    - ★ Only gravitational couplings → bad for direct/indirect/collider detection
  - WIMPs (Weakly Interacting Massive Particle)
    - ★ New, heavy, stable particles
    - ★ Should have some non-gravitational interaction with SM particles for production in the early universe

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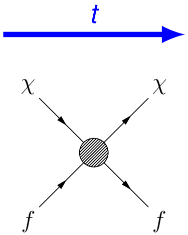
Direct Dark Matter detection

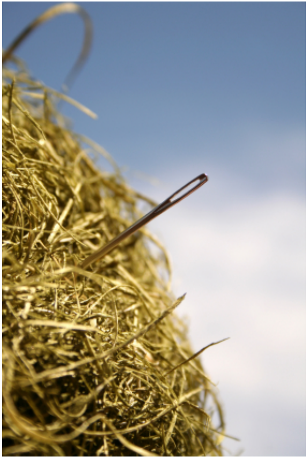
Idea: A WIMP (Weakly Interacting Massive Particle) can scatter on an atomic nucleus.



Strategy: Look for feeble nuclear recoil

Problem: Many background processes (radioactive decays, cosmic rays, . . .) can mimic the signal

Direct DM detection — The experimental challenge

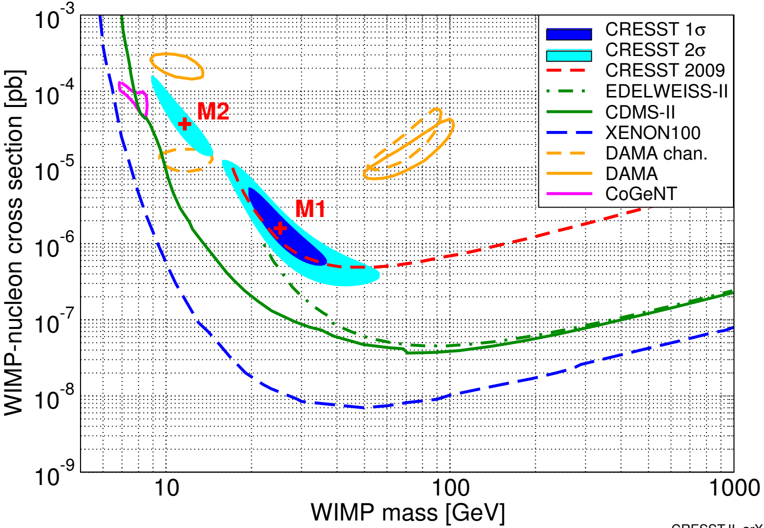


Direct DM detection — The experimental challenge


background

suppression

Direct detection results



CRESST-II, arXiv:1109.0702

Assumptions here: Elastic DM scattering $\propto$ target mass (often realized in SUSY)

Direct detection phenomenology of alternative models

- Previous slide: Elastic dark matter (χ) scattering through scalar current [$(\bar{q}q)(\bar{\chi}\chi)$] or vector current [$(\bar{q}\gamma_\mu q)(\bar{\chi}\gamma^\mu\chi)$] assumed
  $\Rightarrow$ Cross section $\propto$ target mass
- In models with different coupling structure, the relative detection efficiencies of different experimental technologies may be different

Direct detection phenomenology of alternative models

- Spin-dependent couplings
  - E.g. coupling through axial vector current [$(\bar{q}\gamma^\mu\gamma^5 q)(\bar{\chi}\gamma_\mu\gamma^5\chi)$]
  - Cross section $\propto$ target spin
  - Cannot explain DAMA, CoGeNT, CRESST results

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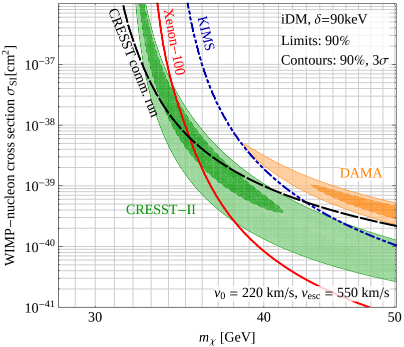
- Inelastic dark matter Tucker-Smith Weiner hep-ph/0101138
  - There may be two DM states χ and χ' with $m'_\chi = m_\chi + \delta$ ($\delta \sim 100$ keV)
  - Scattering $\chi N \to \chi' N \Rightarrow$ heavy target nuclei kinematically preferred
  - Could explain CRESST, but not DAMA JK Schwetz Zupan 1110.2721



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- …

Conclusion: Hard to explain all data simultaneously

Direct detection uncertainties

- Large uncertainty in local DM density

Direct detection uncertainties

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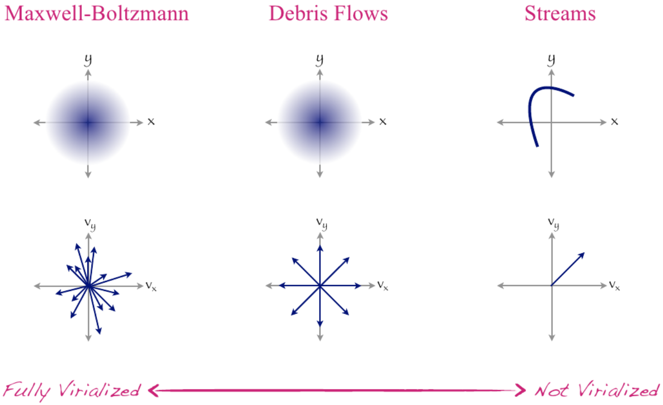
- Large uncertainties in DM velocity distribution
  - Scattering rate depends strongly on DM velocity
  - DM streams?
  - Debris flow?



Kuhlen Lisanti Spergel arXiv:1202.0007, graphics courtesy of Mariangela Lisanti

Direct detection uncertainties

- Large uncertainty in local DM density
- Large uncertainties in DM velocity distribution
  - Scattering rate depends strongly on DM velocity
  - DM streams?
  - Debris flow?
- Predicting WIMP–nucleus cross sections is difficult
  - Models predict WIMP–quark cross section
  - Need to know quark content of the nucleon
  - Especially problematic for Higgs-mediated scattering: coupling $\propto$ quark mass $\Rightarrow$ sea quarks dominate
  - Need to know nuclear form factor especially difficult for spin-dependent scattering

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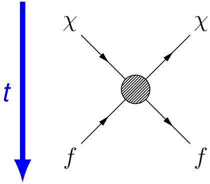
Indirect Dark Matter detection

Idea: WIMPs (Weakly Interacting Massive Particles) χ can annihilate (or decay) into Standard Model particles (f) in an astrophysical environment.



Strategy: Look for annihilation products in cosmic rays

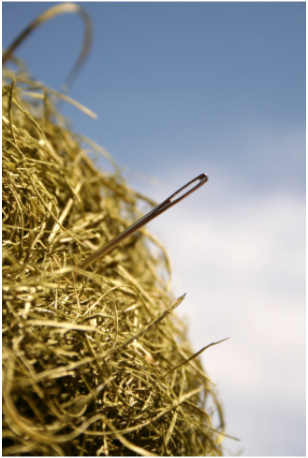
Problems:

- Many other sources of cosmic rays
- Propagation of charged particles in the galaxy poorly understood

Advantage:

- Many sources to look at

Indirect DM detection — The experimental challenge



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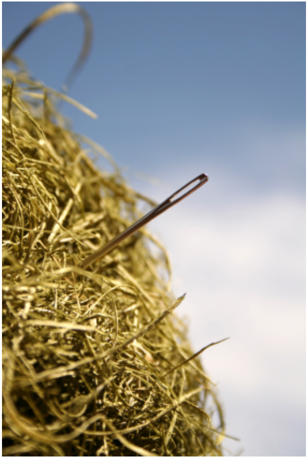

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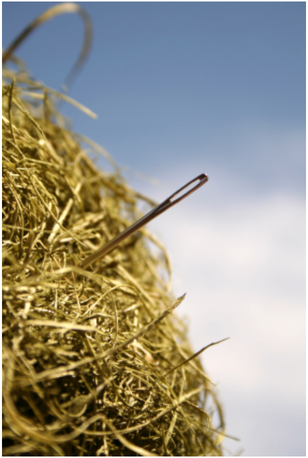

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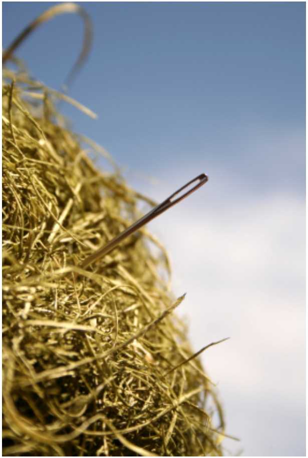

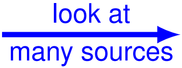
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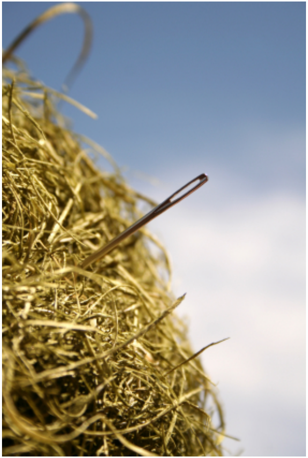

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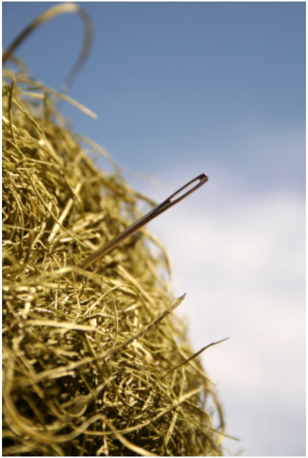

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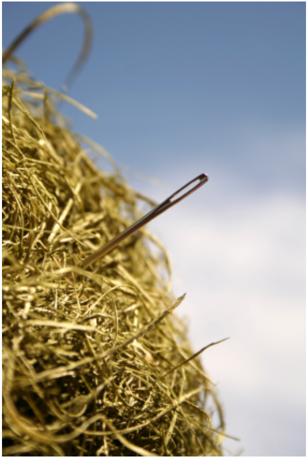

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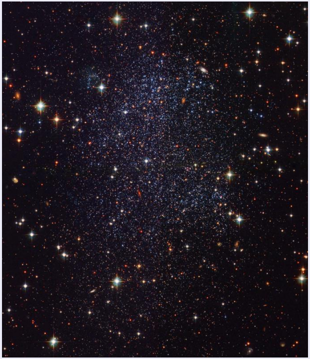
Indirect DM detection — Examples

γ-rays from dwarf galaxies



Idea:

Look for anomalous γ-ray flux

Pro:

Few stars $\Rightarrow$ few backgrounds

Con:

- Relatively low DM density
- Results model-dependent
- Large astrophysical uncertainties

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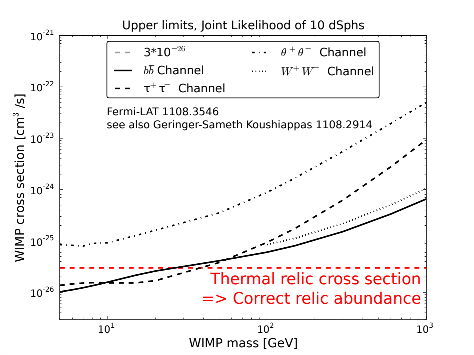

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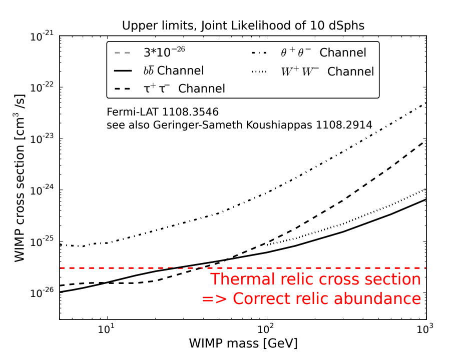

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Other indirect DM searches:

- Cosmic anti-matter (e^+, $\bar{p}$, ...) PAMELA, Fermil-LAT, ...
- γ-rays from the galactic center Hooper et al.
- High-energy neutrinos from the Sun IceCube, SuperKamiokande
- ...

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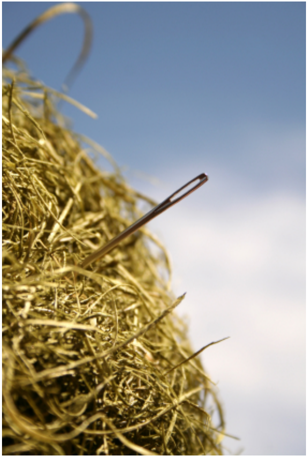
Dark matter at colliders



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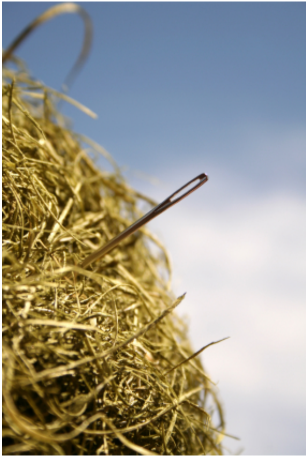


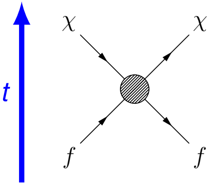
make your

own needles!

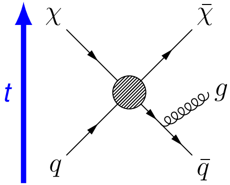
Generic collider searches for dark matter

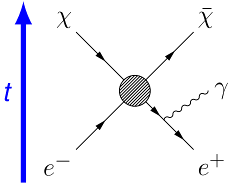
Idea:

- Produce WIMPs in collisions of Standard Model particles



- WIMPs can recoil against a jet or a photon from initial state radiation

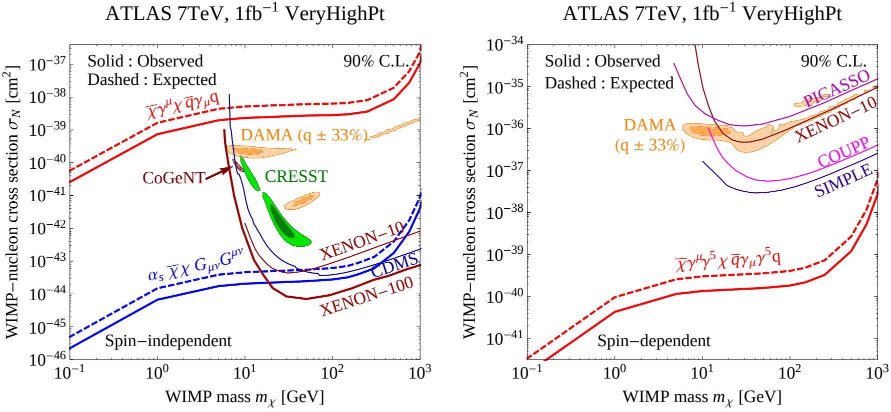




- Experimental signatures: Mono-jets + $\not{E}_T$ and mono-photons + $\not{E}$

LHC limits on DM–quark couplings

Plots from Fox Harnik JK Tsai 1109.4398
see also work by Rajaraman et al. 1108.1196

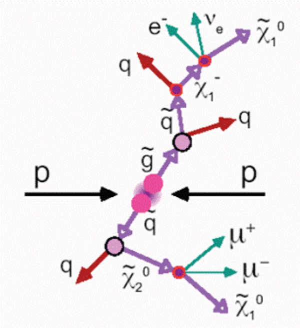


- Assumptions here:
  - Effective field theory approach valid (limits may be better or worse if EFT not valid)
  - Equal coupling to all quark flavors
- Extremely competitive limits for
  - Light dark matter (below direct detection threshold)
  - DM coupled to gluons (high gluon luminosity at the LHC)
  - Spin-dependent DM interactions (DD suffers from loss of coherence)

Model-dependent collider searches: SUSY-DM

Idea:

- In many models, DM is produced in the decay of heavy, strongly interacting particles (for instance squarks and gluinos in SUSY)
- Experimental signature: something + missing energy
- Example: $pp \to (\tilde{g} \to jZ\chi^0)(\tilde{q} \to jjW\chi^0)$



- Advantage: Very sensitive
- Problem:
  Minor modifications to the model may drastically change the phenomenology
- Problem (all collider searches):
  Collider can only find DM *candidate(s)*

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$$\langle \sigma v \rangle \simeq 3 \times 10^{-26}\ \text{cm}^3/\text{s}$$

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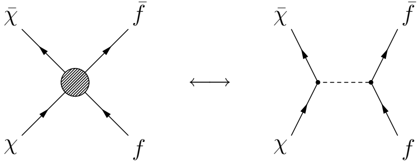
$$\langle \sigma v \rangle \simeq 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

- Consider generic DM coupling:

$$\mathcal{L} \supset \frac{g^2}{M^2}(\bar{\chi}\chi)(\bar{f}f)$$



Electroweak-scale DM? — The "WIMP Miracle"

- In the early universe, DM is in chemical equilibrium with other particles.
- As the temperature drops, DM begins to annihilate away: $\bar{\chi}\chi \to \bar{f}f$
- When the annihilation rate $\Gamma(\bar{\chi}\chi \to \bar{f}f)$ drops below the Hubble expansion rate H, annihilations cease
  $\Rightarrow$ DM abundance remains constant ("thermal freeze-out")
- From this requirement, and from the observed DM abundance today, cosmology predicts the DM annihilation cross section

$$\langle \sigma v \rangle \simeq 3 \times 10^{-26}\ \text{cm}^3/\text{s}$$

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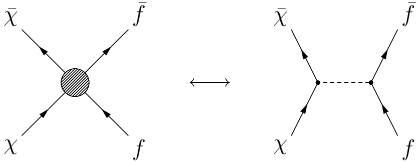

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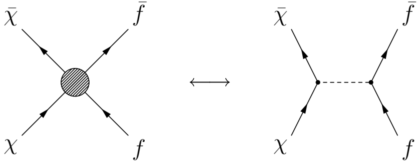

- For typical coupling $g \sim 0.1$, suppression scale $M \sim 100$ GeV, DM mass $m_\chi \sim 100$ GeV, this yields the right value for $\langle \sigma v \rangle$
- Conclusion: If dark matter originates from electroweak-scale new physics, it automatically has the right abundance

The Wimp Miracle

Relating the DM and baryon abundances

- Motivation: The DM and baryon energy densities in the universe are similar

  $$\Omega_{DM} \simeq 5\,\Omega_b$$

  (Ω = energy density as fraction of “critical density” for flat universe)

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- Baryon density Ω_b generated by yet unknown dynamics behind the particle–antiparticle asymmetry of the universe
  (not by thermal freeze-out)
- Assume dark matter (χ) density is also determined by $\bar{\chi}$–χ asymmetry
  $\Rightarrow$ Asymmetric dark matter

Models of asymmetric dark matter

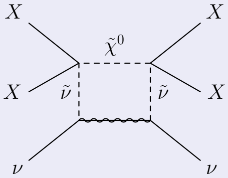
Example 1

Kaplan Luty Zurek, arXiv:0901.4117

- $B - L$ asymmetry generated at high T (e.g. via Leptogenesis)
- Effective superfield operator

$$\mathcal{L} \supset \frac{1}{M} \bar{X}^2 L H_u \qquad (*)$$

transfers $B - L \leftrightarrow 2X$, e.g. via



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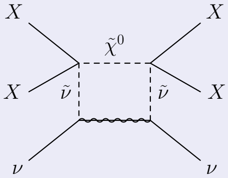

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Buckley Randall 1009.0270
Blennow et al. 1009.3159

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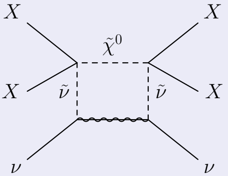

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Example 3

Davoudiasl et al. 1008.2399
Gu Lindner Sarkar Zhang 1009.2690

- New heavy particles decay partly into DM, partly into SM particles
- $B - L - X$ is conserved
- DM (X) does not participate in SM sphaleron processes
  $\Rightarrow$ Asymmetry frozen in

Outline

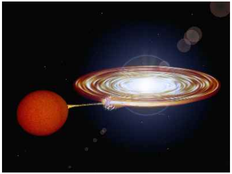
1. Evidence for dark matter

2. Finding dark matter
   - Direct detection
   - Indirect detection
   - Production at colliders

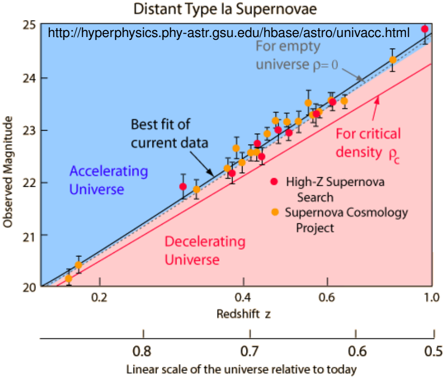
3. Modelling dark matter

4. Dark energy

Evidence for dark energy: Type Ia Supernovae



- When a white dwarf accretes matter from a companion star, it becomes unstable once it reaches $\sim 1.4 M_\odot$
  - Re-ignition of nuclear fusion
  - Thermonuclear explosion
- Since the progenitor mass is always $\sim 1.4 M_\odot$, all Type Ia Supernovae are very similar
  - Energy release precisely known
  - SN Ia are standard candles
- Measurement:
  - Apparent brightness → distance
  - Redshift → velocity
- Result:
  - Long ago (very distant SN Ia, low brightness), the universe was expanding more slowly than we thought!
  - It must be accelerating
- CMB and Large Scale Structure observations confirm this



What is accelerating the Universe?

- A cosmological constant?
  - An ad-hoc addition to the Einstein equations

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R_\alpha{}^\alpha = 8\pi G\, T_{\mu\nu} + g_{\mu\nu}\Lambda$$

  - Observations require $\Lambda \sim (10^{-12}\ \text{GeV})^4$
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  - Observations require $\Lambda \sim (10^{-12}\ \mathrm{GeV})^4$
  - Extra source of energy with negative pressure
- QFT vacuum energy?
  - A vacuum expectation value (vev) or condensate of a quantum field behaves like a cosmological constant
  - Problem: All known condensates/vevs are way too large! (We expect $\Lambda \sim M_{\mathrm{Pl}}^4 \sim (10^{19}\ \mathrm{GeV})^4$)

What is accelerating the Universe? (cont'd)

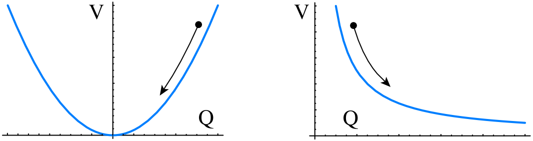
- Quintessence: A new, slowly rolling scalar field
  - Introduce new scalar field ϕ slowly rolling down its potential $V(\phi)$
  - Lagrangian:

$$\mathcal{L}_\phi = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi)$$

  - Energy and pressure:

$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi)\,, \qquad p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

  - A cosmological constant corresponds to $\rho = -p \quad \Rightarrow \quad$ require $\dot{\phi}^2 \ll V(\phi)$



for a review see Caldwell Kamionkowski 0903.0866

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- Extensions of general relativity
  - Scalar-tensor gravity: Modified Einstein-Hilbert action

$$S = \frac{1}{16\pi G}\int\sqrt{-g}\,d^4x\,R \quad\rightarrow\quad S = \frac{1}{16\pi G}\int\sqrt{-g}\,d^4x\,f(\phi)\times R$$

  - A special case: $f(R)$ gravity:

$$S = \frac{1}{16\pi G}\int\sqrt{-g}\,d^4x\,f(R)$$

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Summary

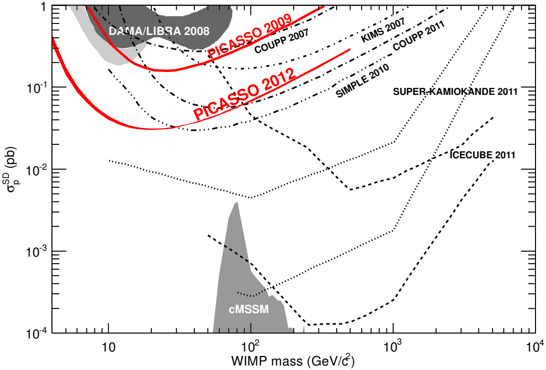
- Overwhelming evidence for dark matter
- A lot of data available
  - Direct detection
    - Difficult to reconcile possible evidence with null results
  - Indirect searches
    - Strong exclusion limits
    - Suffers from poorly understood astrophysical backgrounds
  - Collider searches
    - Generic searches (monojets + $\not{E}_T$, mono-γ + $\not{E}$) and model-specific searches (cascade decays) are underway full-steam
- Dark matter models
  - Dark matter from electroweak scale new physics:
    Correct cosmic abundance due to WIMP Miracle
  - Light (10 GeV) dark matter:
    Correct cosmic abundance if related to baryon–antibaryon asymmetry
- Dark energy
  - Accelerated expansion of the Universe well-established
  - So far, a cosmological constant is the leading explanation

Thank you!

Bonus material

Spin-dependent DM couplings?

- Previous slide: Dark matter (χ) couplings through scalar current $[(\bar{q}q)(\bar{\chi}\chi)]$ or vector current $[(\bar{q}\gamma_\mu q)(\bar{\chi}\gamma^\mu\chi)]$ assumed
  $\Rightarrow$ Cross section $\propto$ target mass
- Alternative: Axial vector $[(\bar{q}\gamma^\mu\gamma^5 q)(\bar{\chi}\gamma_\mu\gamma^5\chi)]$ interaction
  $\Rightarrow$ Cross section $\propto$ target spin



PICASSO arXiv:1202.1240

Note: CoGeNT & CRESST have very low sensitivity to spin-dependent DM scattering.

Inelastic dark matter?

Tucker-Smith Weiner hep-ph/0101138

Idea: There may be two DM states χ and χ' with

$$m_{\chi'} = m_\chi + \delta$$

Scattering proceeds via

$$\chi + N \to \chi' + N$$

- Modified kinematics compared to elastic scattering
- Affects different target nuclei differently

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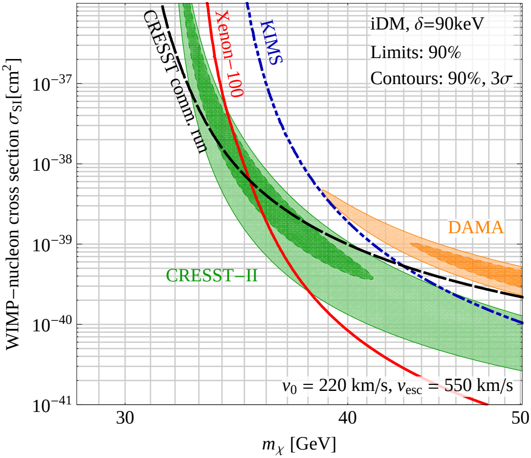


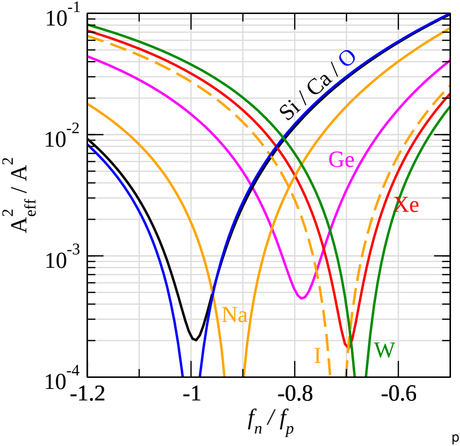
plot from JK Schwetz Zupan 1110.2721

Isospin-violating dark matter?

Feng Kumar Marfatia Sanford 1102.4331

Idea: Dark matter could couple differently to protons and neutrons

⇒ Detection efficiencies of different target materials change



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f_n, f_p: DM couplings to protons and neutrons

$A_{\rm eff}$: Effective nuclear mass for DM scattering

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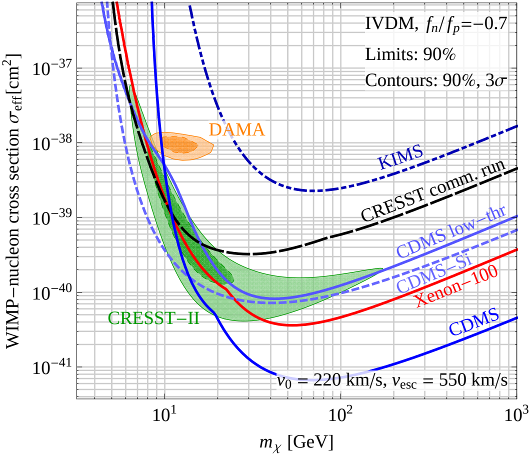

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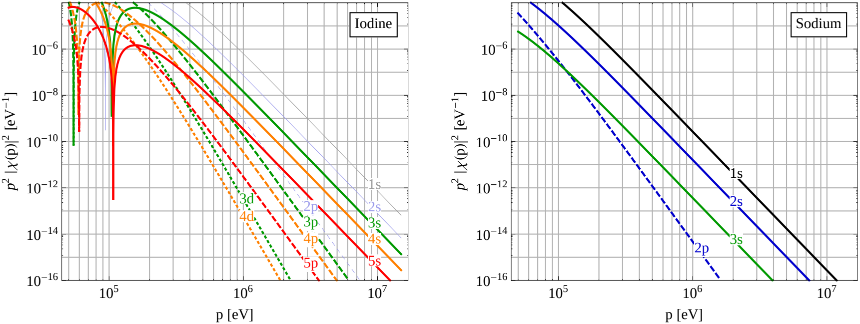
Leptophilic dark matter?

Fox Poppitz arXiv:0811.0399
JK Niro Schwetz Zupan arXiv:0907.3159

Idea: DM could couple only to leptons at tree level

- DAMA and CoGeNT do not reject electron-recoils as background
- But: Electron recoils above threshold ($\gtrsim$ 1 keV) strongly suppressed
  (electron needs large initial momentum → probe high-p tail of wave functions)



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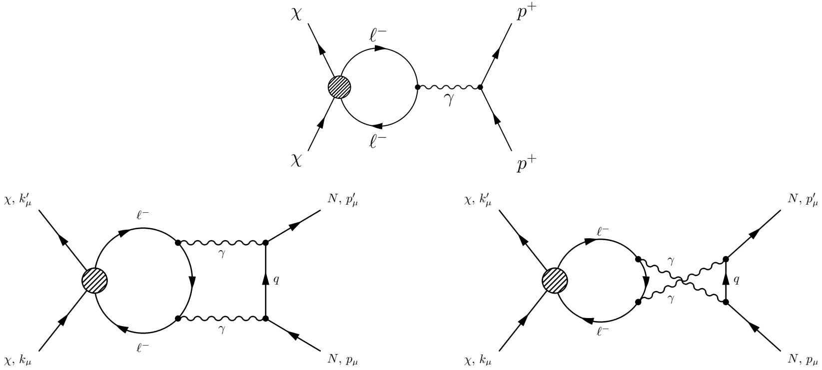

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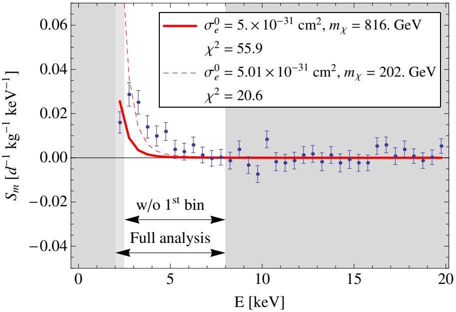
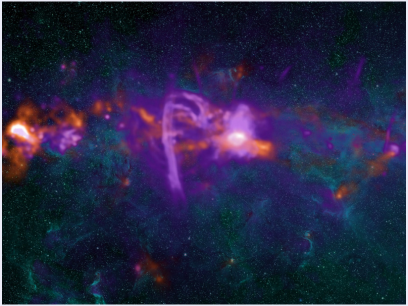
- Problems then:
  - Very large couplings needed to compensate wave function suppression
  - Poor fit to DAMA and CoGeNT energy spectra



Indirect DM detection — where to look

The Galactic Center



Pros:

- Highest DM density

Cons:

- DM distribution uncertain
- Many background sources

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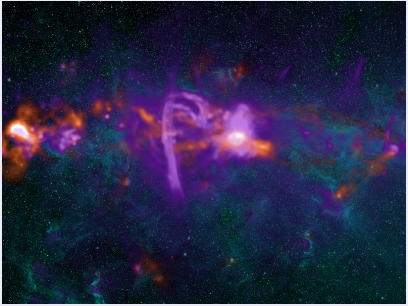

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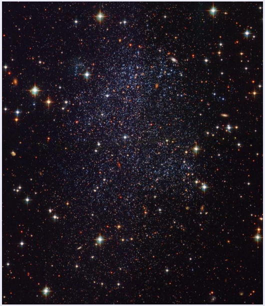

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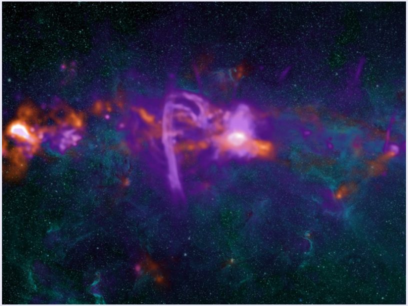

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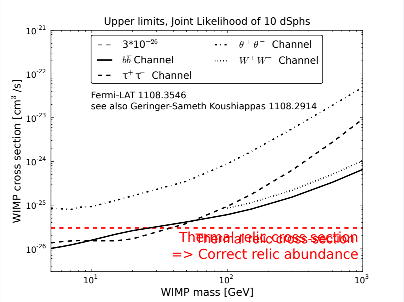

Fermi-LAT, 1108.3546
see also Geringer-Sameth Koushiappas 1108.2914

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Indirect DM detection — where to look (2)

Cosmic antimatter

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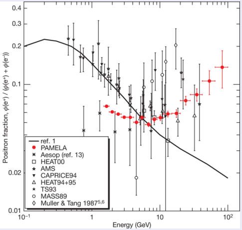

PAMELA collaboration, 0810.4995

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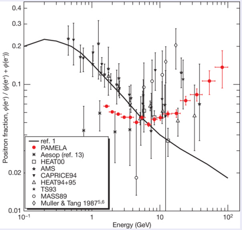

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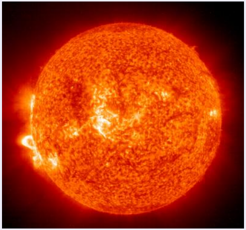

Idea:

- DM capture/annihilation in the Sun
- Flux dominated by capture rate

Pros:

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Cons:

- Low neutrino cross sections

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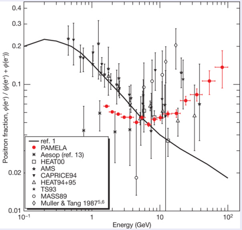

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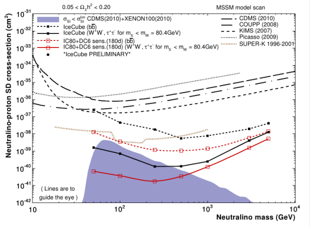

IceCube collaboration, 1111.2738

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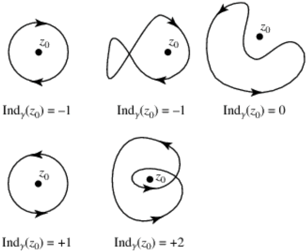
What is a sphaleron?

- $SU(2)$ gauge field vacuum configurations are classified according to their winding number (or Chern-Simons number)

$$N_{CS} = \frac{1}{16\pi^2} \int_0^t dt \int d^3x \, \mathrm{tr}\, F_{\mu\nu} \tilde{F}^{\mu\nu}$$



Configurations with different winding number cannot be continuously transformed into each other.

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- Sphalerons are processes (with $E > 0$) that change the winding number
- In the SM, a change in winding number corresponds to a change in $B + L$. In fact, considering only left-handed ($SU(2)_L$-charged) fermions:

$$j^\mu_{B+L} = \sum_{\psi=q,\ell} \frac{1}{2} \bar{\psi} \gamma^\mu (1 - \gamma^5) \psi$$

A change in $B + L$ is equivalent to a change in N_{CS}:

$$\partial_t \int d^3x \, j^0_{B+L} \equiv \int d^3x \, \frac{1}{2} \partial_\mu \bar{\psi} \gamma^\mu \gamma^5 \psi \qquad \text{(since } \partial_\mu \bar{\psi} \gamma^\mu \psi = 0\text{)}$$

$$= -\frac{1}{16\pi^2} \int d^3x \, \mathrm{tr} \, F_{\mu\nu} \tilde{F}^{\mu\nu} \qquad \text{(chiral anomaly)}$$

$$= -\partial_t N_{CS}$$