White Dwarf Bounds on CHAMPs

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Outline

❖ CHAMPs: general introduction and background

❖ Existing constraints
  ‣ Old neutron stars

❖ White dwarfs as high-gain particle physics detectors

❖ CHAMPs can trigger the WD supernova instability

❖ Dramatically improved galactic CHAMP abundance bounds
CHAMPs

- **CHArged Massive Particles** [AKA charged Stable Massive Particles (cSMP)]

- $\Omega(1)$-charged non-thermal relics of the early universe: $X^{\pm 1}$.
  - Agnostic as to production: charge-symmetric or -asymmetric
  - Mainly concerned with $m_X \gtrsim 10^{11}$ GeV in this talk; lighter CHAMPs more complicated [Dimopoulos, Eichler, Esmailzadeh, Starkman (1990). Chuzhoy, Kolb (2009). Dunsky, Hall, Harigaya (2019).]

- Candidates: charged (N)LSP, charged lightest KK-odd state in U.E.D., composite state of millicharged particles


- Proposed as DM candidate ($\sigma/m_X \ll$ SM): De Rujula, Glashow, Sarid (1990); Dimopoulos, Eichler, Esmailzadeh, Starkman (1990).

- Extremely rich phenomenology!
CHAMP Chemistry, Distribution

- $X^+$ is effectively heavy hydrogen

- $X^-$ form tightly bound states ($NX$) with nuclei:
  [Cahn, Glashow (1981)]

<table>
<thead>
<tr>
<th>$N$</th>
<th>$E_B$ [MeV]</th>
<th>$\langle r \rangle$ [fm]</th>
<th>$R$ [fm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>0.025</td>
<td>43</td>
<td>—</td>
</tr>
<tr>
<td>$^4$He</td>
<td>0.35</td>
<td>6.1</td>
<td>1.9</td>
</tr>
<tr>
<td>$^8$Be</td>
<td>1.6</td>
<td>2.6</td>
<td>2.4</td>
</tr>
<tr>
<td>$^{12}$C</td>
<td>2.9</td>
<td>2.1</td>
<td>2.8</td>
</tr>
<tr>
<td>$^{16}$O</td>
<td>4.1</td>
<td>1.8</td>
<td>3.1</td>
</tr>
<tr>
<td>$^{24}$Mg</td>
<td>6.1</td>
<td>1.7</td>
<td>3.5</td>
</tr>
<tr>
<td>$^{56}$Fe</td>
<td>10.0</td>
<td>4.1</td>
<td>4.7</td>
</tr>
</tbody>
</table>

- Primordially, most $X^-$ gets bound up as $(\text{He}X)$, with $\sim 10^{-4}$ in form of $(pX)$.

- Massive enough CHAMPs distributed $\sim$ DM halo (do not collapse into diffuse gas structures). Present in galaxy as $X^+$ or $(\text{He}X)^+$. Coulomb barrier to $X^+X^-$ annihilation!
Existing Bounds

- Bullet Cluster. Not strongly constraining if $\lesssim 1\%$ of DM abundance.

- Direct searches (MACRO, etc). But CHAMPs slow in the atmosphere…

- Terrestrial “heavy element” searches.
  - Subject to some uncertainty as to whether:
    - CHAMPs get to Earth?
    - Are they in the material sample?

- Astrophysical bounds
  - CHAMP cosmic rays [Dunsky, Hall, Harigaya (2019)]
CHAMPs don’t collapse into diffuse gas clouds, but do get captured in collapsing protostellar clouds

$M \sim 10 - 30 M_\odot$ stars are contaminated by CHAMPs

Bake at $\gtrsim 10^6 \text{K}$ for $\gtrsim 10^7 \text{yrs}$

Star runs out of fuel, collapses to a neutron star. Still contaminated by CHAMPs.

CHAMPs sink to centre of NS

If sufficient total CHAMP mass in the NS, CHAMPs undergo gravothermal collapse and form a mini black hole inside the NS.

If BH accretes, eats NS very rapidly, destroying it. Existence of old NS constrains.

If BH is too small, Hawking radiation beats accretion. BH evaporates. Nothing interesting happens to NS.
GDRN Bound

[Gould, Draine, Nussinov, Romani (1990)]

The graph illustrates the GDRN bound, indicating regions where black holes (BHs) can or cannot form. The shaded region labeled 'FORBIDDEN' indicates conditions under which a black hole forms, grows, and destroys a neutron star (NS). The boundaries are marked by the Chandrasekhar Limit, the Hawking Limit, and the HR prevents accretion line. Points outside the forbidden region, such as the no BH forms area, indicate conditions where no black hole forms.

Gould, Draine, Romani, Nussinov (1990)
GDRN Bound

[Gould, Draine, Nussinov, Romani (1990)]

**OUR QUESTION**

Can we find a system where this region **CAN** be bounded?

Possibly orders of magnitude of improvement to be had

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**Diagram Details**

- **FORBIDDEN** region
  - BH forms, grows, destroys NS
  - HR prevents accretion
  - Gould, Draine, Romani, Nussinov (1990)

- **Limits**
  - Chandrasekhar Limit
  - Hawking Limit
  - no BH forms
  - $f_{p_x}/\rho_{\text{halo}}$
  - $\log m/m_p$
White Dwarfs are High-Gain Bolometric Detectors

❖ In an ordinary star:

Heating

Cooling by adiabatic expansion

Thermonuclear Burning

Timmes, Woosley (1992)
Graham, Rajendran, Varela (2015)
Bramante (2015)
Graham, Janish, Narayan, Rajendran, Riggins (2018)
Bramante, Acevedo (2019)
Janish, Narayan, Riggins (2019)

Therm

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Burning

Heating

Cooling by adiabatic expansion
White Dwarfs are High-Gain Bolometric Detectors

❖ In a white dwarf:

![Diagram showing the cycle of heating, diffusive cooling, thermonuclear carbon burning, and cooling by adiabatic expansion.]

- Timmes, Woosley (1992)
- Graham, Rajendran, Varela (2015)
- Bramante (2015)
- Graham, Janish, Narayan, Rajendran, Riggins (2018)
- Bramante, Acevedo (2019)
- Janish, Narayan, Riggins (2019)
White Dwarfs are High-Gain Bolometric Detectors

- In a white dwarf:

  - Heating
  - Carbon Burning
  - Thermonuclear
  - Diffusive cooling

Timmes, Woosley (1992)
Graham, Rajendran, Varela (2015)
Bramante (2015)
Graham, Janish, Narayan, Rajendran, Riggins (2018)
Bramante, Acevedo (2019)
Janish, Narayan, Riggins (2019)
White Dwarfs are High-Gain Bolometric Detectors

❖ In a white dwarf:

Supernova instability: heat a volume $V_T \sim \lambda_T^3$ to temperature $T_T \sim 0.5 \text{ MeV}$, then Type-Ia-like supernova is inevitably triggered

$\lambda_T \sim \sqrt{3T/\rho \dot{S}_{\text{nucl}}} \sim 10^{-1} - 10^{-4} \text{ cm } \left( M_{\text{WD}} \sim 0.8 - 1.35 M_\odot \right)$

Energy deposition required $E_T \sim 10^{17} - 10^{25} \text{ GeV}$ in diffusion time $\tau_T \sim 10^{-13} \text{ s}$ is **MUCH** smaller than the energy released in the supernova, $E_{SN} \sim 10^{54} \text{ GeV}$

Deposit sufficient energy to heat the WD locally, get a supernova signal visible at cosmological distances.
Evaporating black hole in a WD

- Hawking Radiation (HR) from a BH evaporating away inside a WD can satisfy the trigger criteria for a supernova [Bramante, Acevedo (2019); Janish, Narayan, Riggins (2019)]

- For a $M_{WD} \sim 1.1M_\odot$ WD, once $M_{BH} \lesssim 10^{32}\text{GeV}$, HR from BH deposits $E_T \sim 10^{21}\text{GeV}$ within $\tau_T$.

- If $M_{BH} \lesssim 10^{28}\text{GeV}$, then (remaining) BH lifetime $\tau_{BH} < \tau_T$.

- Requirement for trigger: initial BH mass $M_{BH}^0 \gtrsim E_T$.

- Timescales?

  - Very roughly, BH with $M_{BH}^0 \lesssim 10^{38}\text{GeV}$ would (in free space) evaporate within $\tau_{evap} \sim \tau_{WD} \sim \text{few } \times \text{ Gyr}$.

  - Similar timescales in WD once/if HR dominates all types of accretion (WD material, CHAMPs): $\dot{M}_{BH}^{\text{Hawking}} \propto M_{BH}^{-2}$ vs. $\dot{M}_{BH}^{\text{Bondi}} \propto M_{BH}^{+2}$.

  - Dominated by time at largest mass: $\tau_{evap} \propto (M_{BH}^0)^3$.

- HR dominates accretion of WD material for $M_{BH} \lesssim 10^{38}\text{GeV}$. Coincidence. (With CHAMPs, many additional complications... see paper)
Accreting black hole in a WD

- What if more massive BH? $M_{\text{BH}} \gtrsim 10^{38} \text{GeV}$ (roughly; more complicated with CHAMPS)

- Conservative outcome: similar to GDRN, could just accrete the whole WD.

- Timescale?
  - For $M_{\text{BH}}^0 \sim 10^{39} \text{GeV}$, accretion timescale (first at Bondi rate, later Eddington-limited) is $\tau_{\text{accr.}} \sim \tau_{\text{WD}} \sim \text{few} \times \text{Gyr}$.
  - Dominated by time at lowest mass: $\tau_{\text{accr.}} \propto 1 / M_{\text{BH}}^0$

- Alternative [Janish, Narayan, Riggins (2019)]: heating of in-falling carbon ions around the sonic horizon for Bondi accretion could heat and trigger supernova.
  - Not clear this works (already Eddington limited when sonic horizon exceed trigger length?).
  - Needs more modelling.
**Implications for CHAMPs**

- We have the necessary ingredients to dramatically improve the CHAMP bounds at large $m_X$ as compared to GDRN:

  **Use a WD instead of a NS**

- If total mass of CHAMPs in a WD is large enough, a mini BH can form in the WD

- **and if** the timescale for BH to form is sufficiently short

- **and if** the timescale for BH evolution to the conditions required to destroy the WD is sufficiently short

- **Then** old WD are destroyed, no matter whether the BH evaporates or accretes
Getting CHAMPs into a WD

- Primordial protostellar cloud gets contaminated by halo CHAMPs [GDRN]
  - Assume [GDRN] WD / CO core of WD-progenitor star gets ~uniform contamination by CHAMPs at mass-fraction of CHAMPs in the star (conservative)

- CHAMPs accrete onto the WD directly over the first ~Gyr of the WD lifetime (before crystallization)
  - Magnetic fields in some old WD of correct mass range are small enough not to deflect accreting charged massive CHAMPs

- Accretion over lifetime gives larger CHAMP contamination than primordial for $m_X \gtrsim 10^{11}$ GeV
Behaviour of CHAMPs in a WD

- $X^+$ do nothing particularly special, whether primordially present or accreted.

- $X^-$ are more interesting:
  
  - $X^-$ enter star mostly as $(\text{He}X)$
  
  - Processing in nuclear burning environments (primordial) or “charge exchange” $(\text{He}X) + \text{C} \rightarrow (\text{CX}) + \text{He (accreted)}$, migrates $X^-$ to highest-charge nuclei of significant quantity (conservative)

  - End up as $(\text{CX}) / (\text{OX})$ in WD/WD-progenitor core

  - $X^+$ and $(\text{CX}) / (\text{OX})$ both positively charged. No significant $X^+X^-$ annihilation (rate extremely slow... tunnelling suppressed by large reduced mass).

- $X^+$ and $(\text{CX}) / (\text{OX})$ sink diffusively in the WD.

$$ \tau_{\text{sink}} \sim 4 \times 10^6 \text{yr} \times \left( \frac{10^5 \text{GeV}}{m_X} \right) $$
Central Structures

- CHAMPs eventually reach centre of WD

- Initially form (?) isothermal cloud: \( \rho_X(r) = \rho_0 \exp[-r^2/r_*^2]; \quad r_* \equiv \sqrt{\frac{3TM^2_{\text{Pl.}}}{2\pi m_X \rho_{\text{WD}}}} \)

- If \( \rho_X(r = 0) > \rho_{\text{WD}}(r = 0) \) or \( M_X > M_X^{\text{s.g.}} \), then self-gravitating collapse ensues on timescales \( \tau \sim 10^5 \text{yrs} \times (10^5 \text{GeV}/m_X) \).

- Collapse stopped? \( X^+ \) and \( X^+ \) and \((CX)/(OX)\) both supported by pressure of (highly) degenerate moderately relativistic electrons, communicated by electrostatic forces (also serve to maintain charge-neutrality).

- Implies existence of CHAMP Chandrasekhar mass: \( M_X^{\text{Ch.}} \sim 5.6M_\odot \times Q_X^2 \times \left( \frac{\text{GeV}}{m_X} \right)^2 \)

- If \( M_X^{\text{s.g.}} < M_X < M_X^{\text{Chand.}} \), then form stratified core: “mini-WD” inside the WD… can later grow.

- If \( M_X^{\text{Ch.}} < M_X^{\text{s.g.}} < M_X \), then will collapse to BH.

- Timescale collapse to BH \( \sim \) free-fall time \( \sim \mu \text{s} \)
BH evolution after formation

- Three dynamical contributions:
  - Hawking Radiation
  - Accretion of WD material (Bondi, later Eddington-limited)
  - CHAMP accretion (quite complicated: multiple regimes over time; see paper)

- Coincidence: $\dot{M}_{\text{BH}}^{\text{Hawking}} \sim \dot{M}_{\text{BH}}^{\text{Bondi}}$ at $M_{\text{BH}}$ such that $\tau_{\text{trig.}} \sim \tau_{\text{WD}} \sim \text{few } \times \text{ Gyr}$. 

  - Existence of old WD strongly constrain CHAMPs: e.g.,
    $M_{\text{s.g.}}^{\text{Ch.}} \approx M_{\text{WD}} \sim \text{few } \times \text{ Gyr}$
    $\exists$ untuned parameter region where timescale too long to destroy old WD.

- Outside this region, $M_{X} \gtrsim \text{max } \left[ M_{X}^{\text{Ch.}}, M_{X}^{\text{s.g.}} \right]$ (conservative), implies WD destruction.

### Table: BH evolution after formation

<table>
<thead>
<tr>
<th>Name</th>
<th>$M_{\text{WD}}$ [$M_{\odot}$]</th>
<th>$B$ [MG]</th>
<th>$t_{\text{cool.}}$ [Gyr]</th>
<th>$T_{\text{eff.}}$ [$10^{4}$K]</th>
<th>$\log_{10} (g[\text{cm/s}^{2}])$</th>
<th>$D$ [pc]</th>
</tr>
</thead>
<tbody>
<tr>
<td>WDJ062144.86+753011.67</td>
<td>1.18–1.23</td>
<td>—</td>
<td>4.1</td>
<td>0.6</td>
<td>9.0</td>
<td>67</td>
</tr>
<tr>
<td>WDJ013839.12-254233.40</td>
<td>1.17–1.22</td>
<td>—</td>
<td>4.2</td>
<td>0.7</td>
<td>9.0</td>
<td>70</td>
</tr>
<tr>
<td>WD 2202-000</td>
<td>1.08</td>
<td>1.0</td>
<td>2.19</td>
<td>1.0–2.2</td>
<td>8.0–9.0</td>
<td>152</td>
</tr>
</tbody>
</table>
$\rho_x / \rho_0$ vs $m_x [\text{GeV}]$

- $M_{X}^{\text{prim.}} = M_{\text{Chand.}, X}$
- $M_{X}^{\text{prim.}} = M_{\text{s.g.}, X}$
- $M_{X}^{\text{prim.}} + M_{X}^{\text{accum.}} = M_{\text{s.g.}, X}$
- CHAMP evacuation region?

$X^+, f_{X^+} = 1$

[Chuzhoy, Kolb (2009)]
\[ m_x \] \[ \mathcal{G} \text{eV} \]
Charged massive particles (CHAMPs) contaminate white dwarfs

If sufficient total CHAMP mass in the WD (larger of Chandrasekhar and self-gravitating masses), form mini black hole inside the WD

BH either accretes up in mass, or Hawking radiates down in mass. Either way destroys WD, except if it takes too long.

- Other supernova trigger mechanisms discussed in the paper

Dramatic, orders of magnitude improvement of GDRN galactic abundance bounds on high-$m_X$ CHAMPs

Speculation: trigger for Ca-Rich Gap Transients? Correct spatial morphology?

Thank You!
BACKUP
Other considerations

- Only discussed one trigger mechanism here (BH). Couple of others in the paper:
  - energy released during various collapse phases
  - pycnonuclear (density-enhanced) fusion of C ions drawn into dense core as $(\text{C}X)$.

- Take-home message: all other possibilities we considered lead to even earlier WD destruction.

- Lighter CHAMPs ($10^5 \text{ GeV} \lesssim m_X \lesssim 10^{11} \text{ GeV}$) more complicated: might be evacuated from galaxy [Dimopoulos, Eichler, Esmailzadeh, Starkman (1990); Kolb, Chuzhoy (2009)], or at least significantly impacted by baryonic physics [Dunsky, Hall, Harigaya (2019)], and bounds are suspect.

- But…
Ca-rich Gap Transients

- Recently discovered class of sub-luminous, Ca-rich supernova.
- Preferentially occur far away from the centres of galaxies [Perets, et al. (2010); Kasliwal, et al. (2012); Lunnan, et al. (2017), Shen et al. (2019)]
- Progenitors still a mystery
- Sub-Chandrasekhar supernova would look somewhat like these events in terms of spectrum, light-curves, brightness [Polin, Nugent, Kasen (2019)]
- We have a way to trigger these events with CHAMPs!
- Spatial morphology? For $10^5 \text{GeV} \lesssim m_X \lesssim 10^{11} \text{GeV}$, CHAMPs evacuated from inner galaxy, but can still be present in outer, baryon-poor regions of the galaxy
- Might naturally explain the events: low-mass WD born closer to centre of galaxy, wanders/ ejected into region of high CHAMP density, accretes, and then goes supernova
- Rate of events may be challenging [Frohmaier, Sullivan, Maguire, Nugent (2018)]

**NB:** This is (a lot of) speculation, but some parameter space seems open in principle…
Speculative CaRGT regions

\[ \rho_{x}/\rho_0 \text{ or } \rho_{\bar{x}}/\rho_0 \]

\[ m_x \text{ [GeV]} \]

\[ X^+, f_{x^+} = 1 \]

\[ X^-, f_{x^-} = 1 \]
Supernova shockwaves and magnetic fields

- Kolb and Chuzhoy (2009) call into question terrestrial and (MW) galactic bounds on CHAMPs in mass range

\[ 10^5 q_X^2 \lesssim \frac{m_X}{1 \text{ GeV}} \lesssim 10^{11} q_X \]

- **Lower bound**: supernova shockwaves in disk accelerate CHAMPs by Fermi mechanism; if too massive, cannot efficiently dissipate energy. Accelerated above disk escape speed.

- **Upper bound**: In-plane disk magnetic fields confine charged particles within gyroradius:

\[ R \sim 10^{-9} \text{ pc} \frac{m_X}{m_p} q_X^{-1} \frac{v_X}{300 \text{ km/s}} \frac{1 \mu G}{B_{\text{disk}}} \]

Lighter particles have gyroradii < disk thickness. If accelerated out, confined from reentry / halo cannot repopulate.

- Quite simplified view of dynamics; some disagreement about whether this result accurately reflects real galaxy dynamics... See Dunsky, Hall, Harigaya (2019).

- **Our view**: at least puts into question bounds in this mass range. Can plausibly think about signals in naïvely bounded regions.