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)]
- $\mathcal{O}(1)$-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
- Long history: Cahn & Glashow (1981).
- 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)]

BBN →

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

[Cahn, Glashow (1981). Pospelov (2007). Kohri, Takayama (2007). Kaplinghat, Rajaraman (2006). Bird, Koopmans, Pospelov (2008). Kawasaki, Kohri, Moroi (2007). Jedamzik (2008). Pospelov, Pradler (2010)., etc.]

- Primordially, most X^- gets bound up as (HeX), with $\sim 10^{-4}$ in form of (pX).
  [Pospelov, Pradler, Steffen (2008). Kusakabe, Kajino, Yoshida, Mathews (2010).]

- Massive enough CHAMPs distributed ~ DM halo (do not collapse into diffuse gas structures). Present in galaxy as X^+ or (HeX)$^+$. 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)]
    - Existence of old neutron stars: Gould, Draine, Romani, Nussinov (1990). [GDRN]

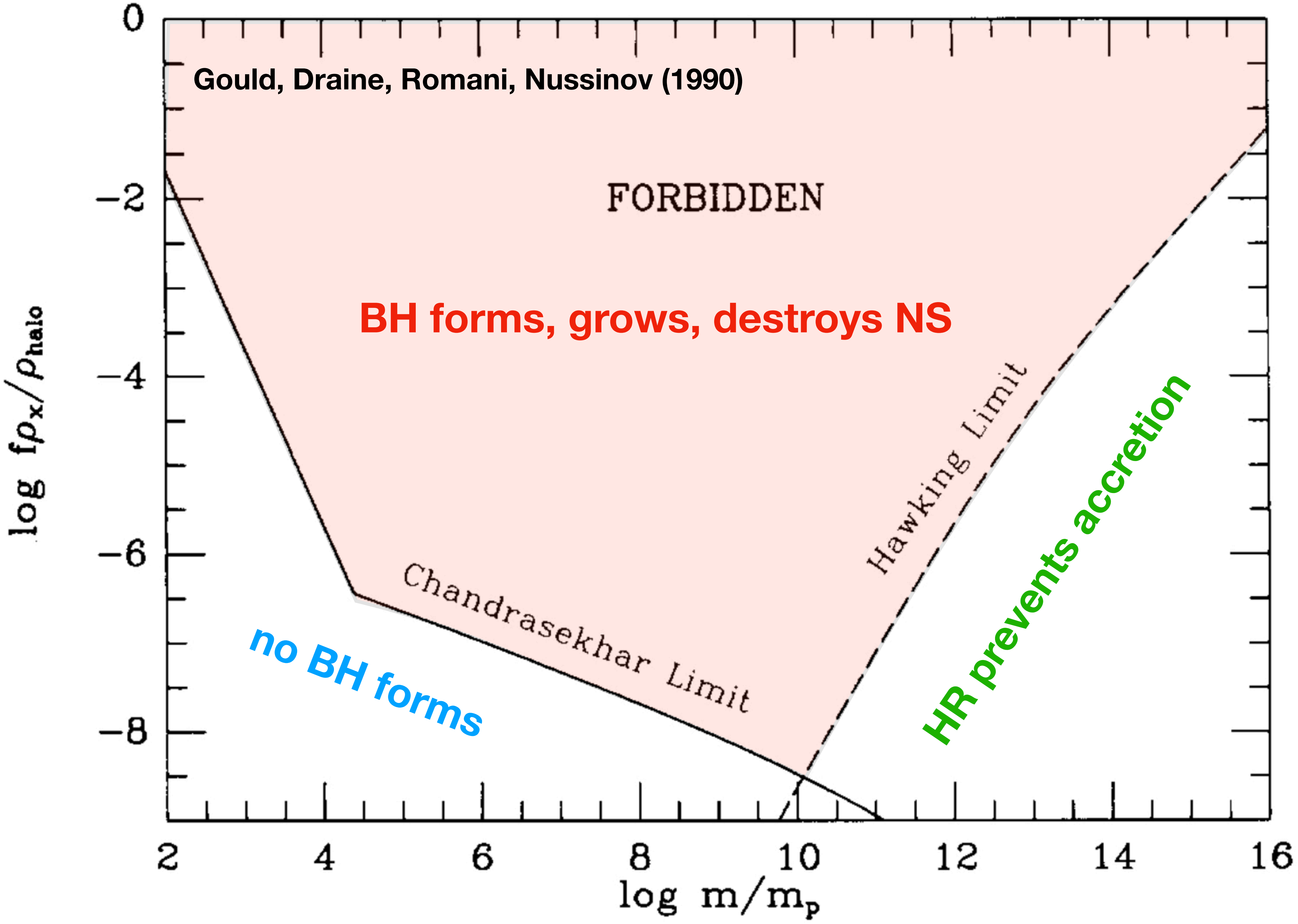
Existing Neutron Star Limits

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

- 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 $\gtrsim 10^6$ K for $\gtrsim 10^7$ 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.

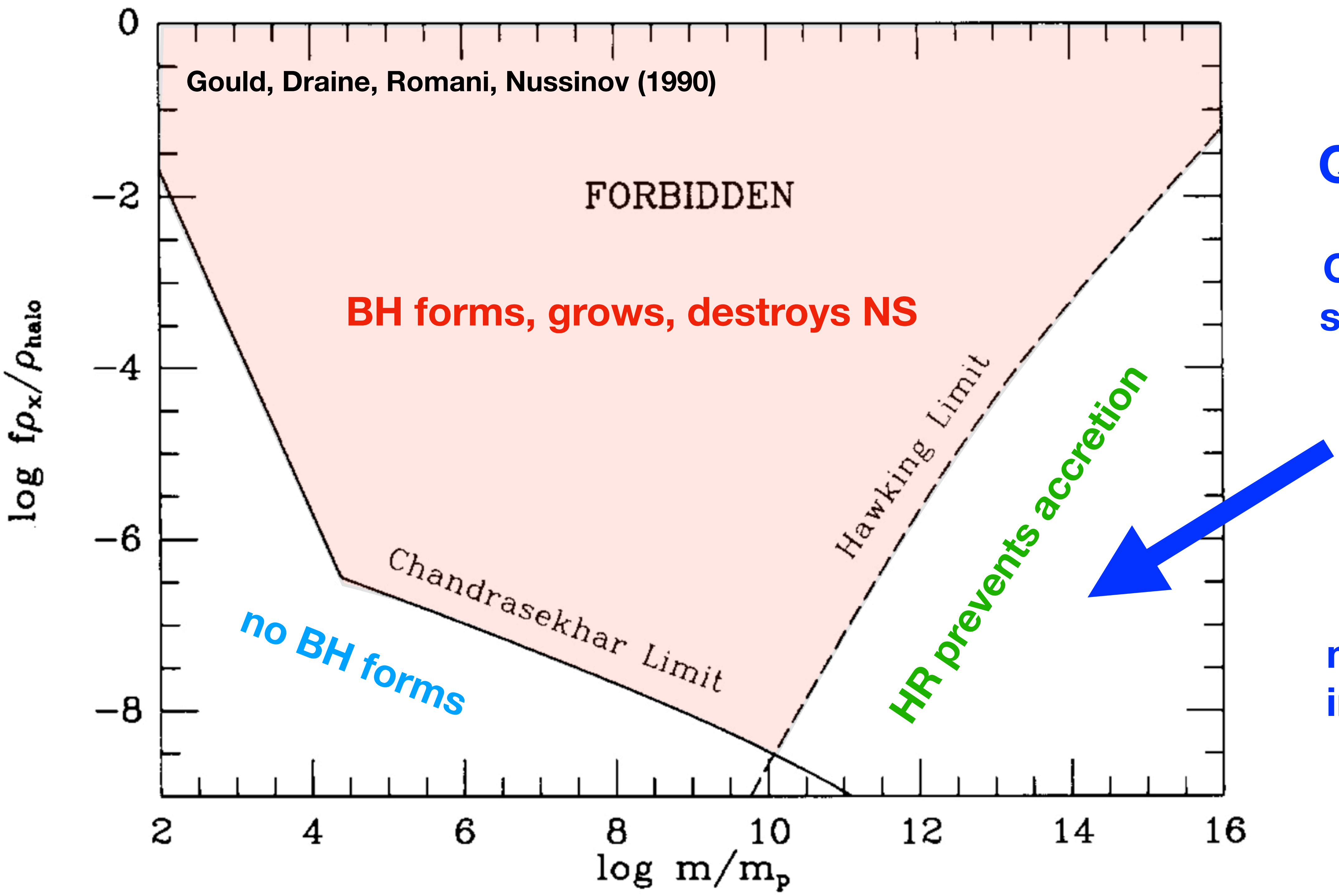
GDRN Bound

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



GDRN Bound

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



OUR QUESTION

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

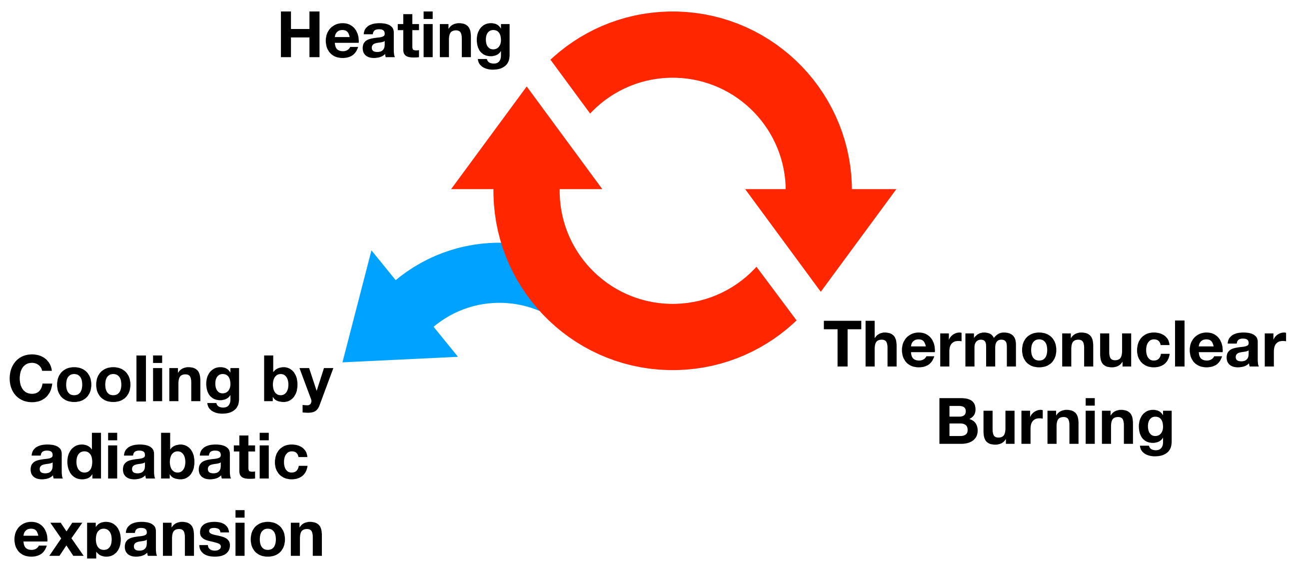
Possibly orders of magnitude of improvement to be had

White Dwarfs are High-Gain Bolometric Detectors

Timmes, Woosley (1992)
Graham, Rajendran, Varela (2015)
Bramante (2015)

Graham, Janish, Narayan,
Rajendran, Riggins (2018)
Bramante, Acevedo (2019)
Janish, Narayan, Riggins (2019)

- In an ordinary star:



Heating

Thermonuclear Burning

Cooling by adiabatic expansion

White Dwarfs are High-Gain Bolometric Detectors

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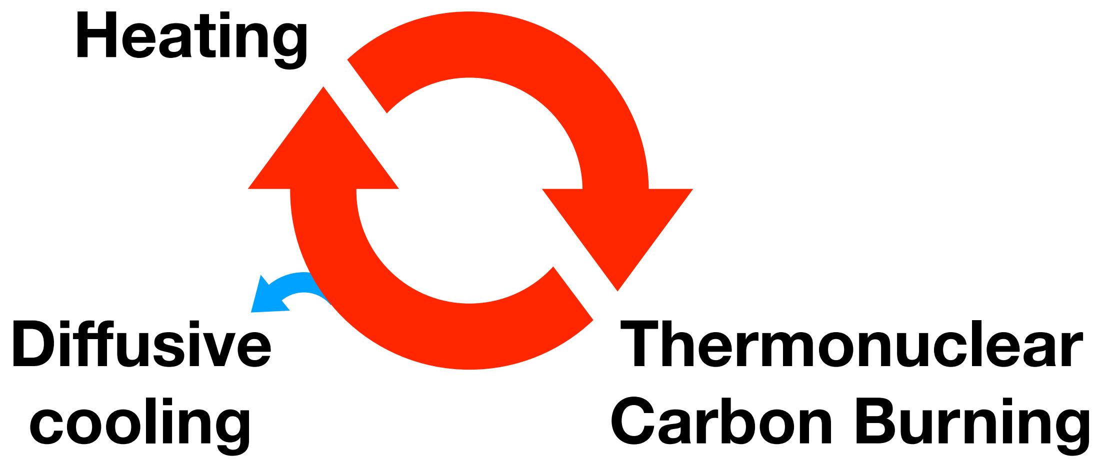
- In a white dwarf:



Heating

Thermonuclear Carbon Burning

Diffusive cooling

White Dwarfs are High-Gain Bolometric Detectors

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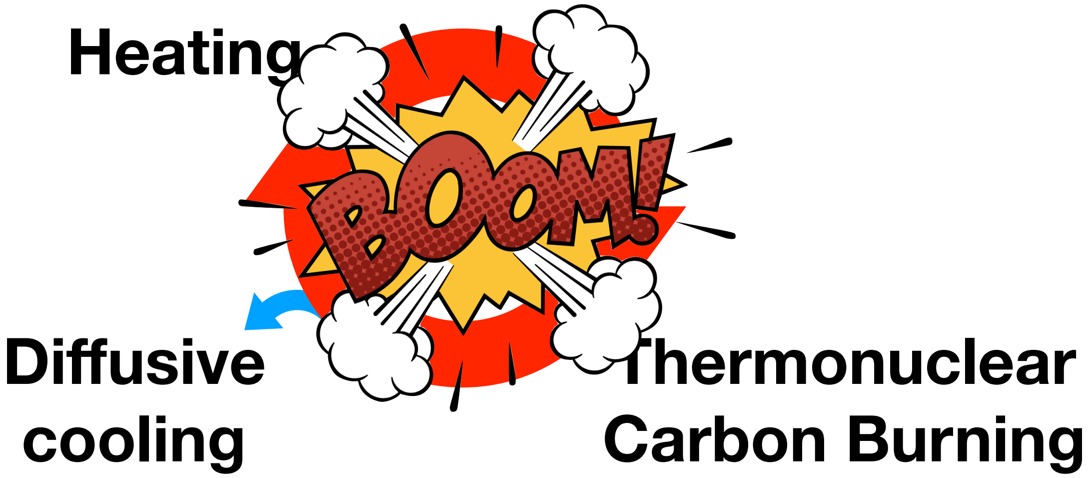

Heating

Diffusive cooling

Thermonuclear Carbon Burning

White Dwarfs are High-Gain Bolometric Detectors

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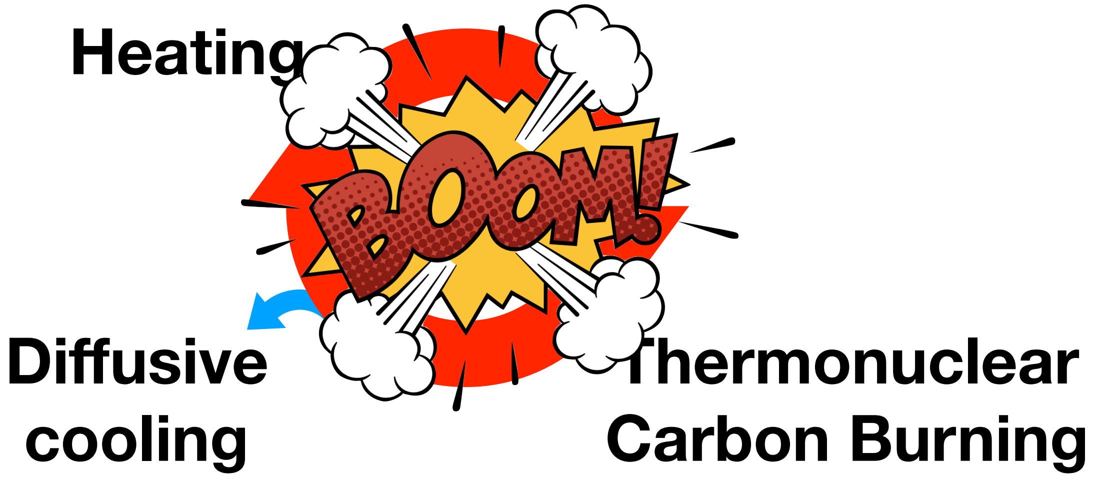


Heating

Diffusive cooling

Thermonuclear Carbon Burning

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

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

- Energy deposition required $E_T \sim 10^{17} - 10^{25}$ GeV in diffusion time $\tau_T \sim 10^{-13}$ s is **MUCH** smaller than the energy released in the supernova, $E_{\text{SN}} \sim 10^{54}$ 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 $M_{\text{WD}} \sim 1.1 M_{\odot}$ WD, once $M_{\text{BH}} \lesssim 10^{32}$ GeV, HR from BH deposits $E_T \sim 10^{21}$ GeV within τ_T.

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

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

- Timescales?

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

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

    - Dominated by time at largest mass: $\tau_{\text{evap.}} \propto \left(M^0_{\text{BH}}\right)^3$.

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

Accreting black hole in a WD

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

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

- Timescale?

  - For $M^0_{\text{BH}} \sim 10^{39}$ GeV, accretion timescale (first at Bondi rate, later Eddington-limited) is $\tau_{\text{accr.}} \sim \tau_{\text{WD}} \sim$ few × Gyr.

  - Dominated by time at lowest mass: $\tau_{\text{accr.}} \propto 1/M^0_{\text{BH}}$

- 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 $(\mathrm{He}X)$

  - Processing in nuclear burning environments (primordial) or “charge exchange” $(\mathrm{He}X) + \mathrm{C} \rightarrow (\mathrm{C}X) + \mathrm{He}$ (accreted), migrates X^- to highest-charge nuclei of significant quantity (conservative)

  - End up as $(\mathrm{C}X)$ / $(\mathrm{O}X)$ in WD/WD-progenitor core

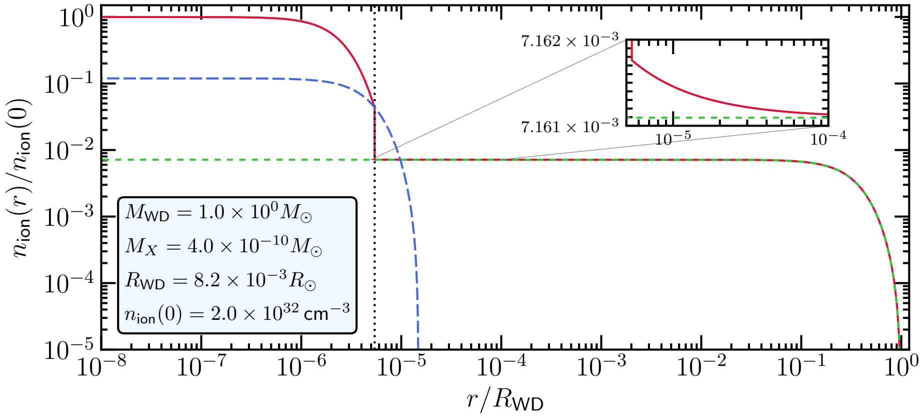
  - X^+ and $(\mathrm{C}X)$ / $(\mathrm{O}X)$ both positively charged. No significant X^+X^- annihilation (rate extremely slow… tunnelling suppressed by large reduced mass).

- X^+ and $(\mathrm{C}X)$ / $(\mathrm{O}X)$ sink diffusively in the WD.

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

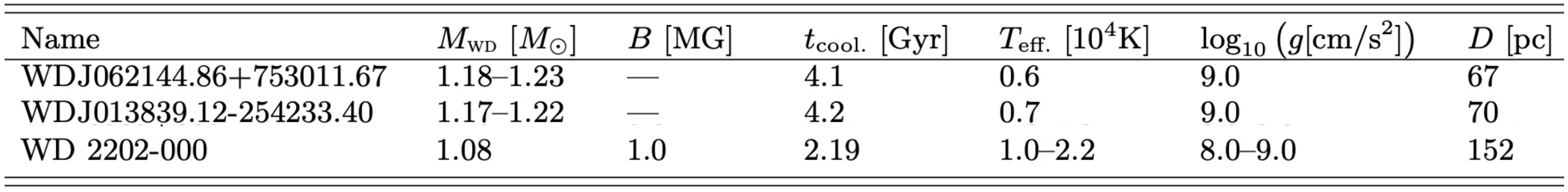
Central Structures

- CHAMPs eventually reach centre of WD
- Initially form (?) isothermal cloud: $\rho_X(r) = \rho_0 \exp[-r^2/r_*^2]$; $\qquad r_* \equiv \sqrt{\left(3TM_{\text{Pl.}}^2\right)\Big/\left(2\pi m_X \rho_{\text{WD}}\right)}$
- 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 $(\text{C}X)$ / $(\text{O}X)$ 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: $M_X^{\text{Ch.}} \sim 5.6 M_\odot \times Q_X^2 \times \left(\frac{\text{GeV}}{m_X}\right)^2$
- 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 ~ free-fall time ~ μs

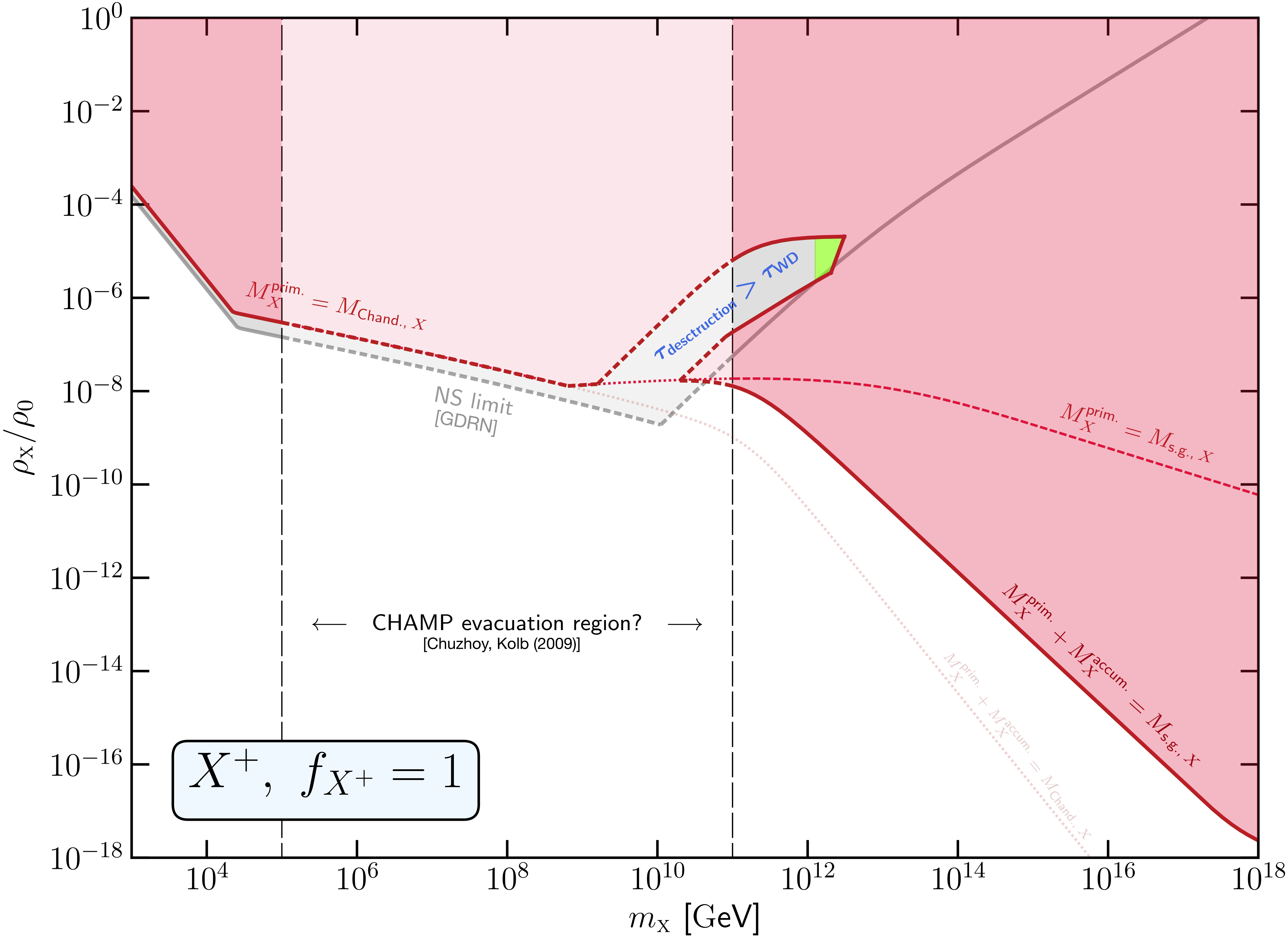


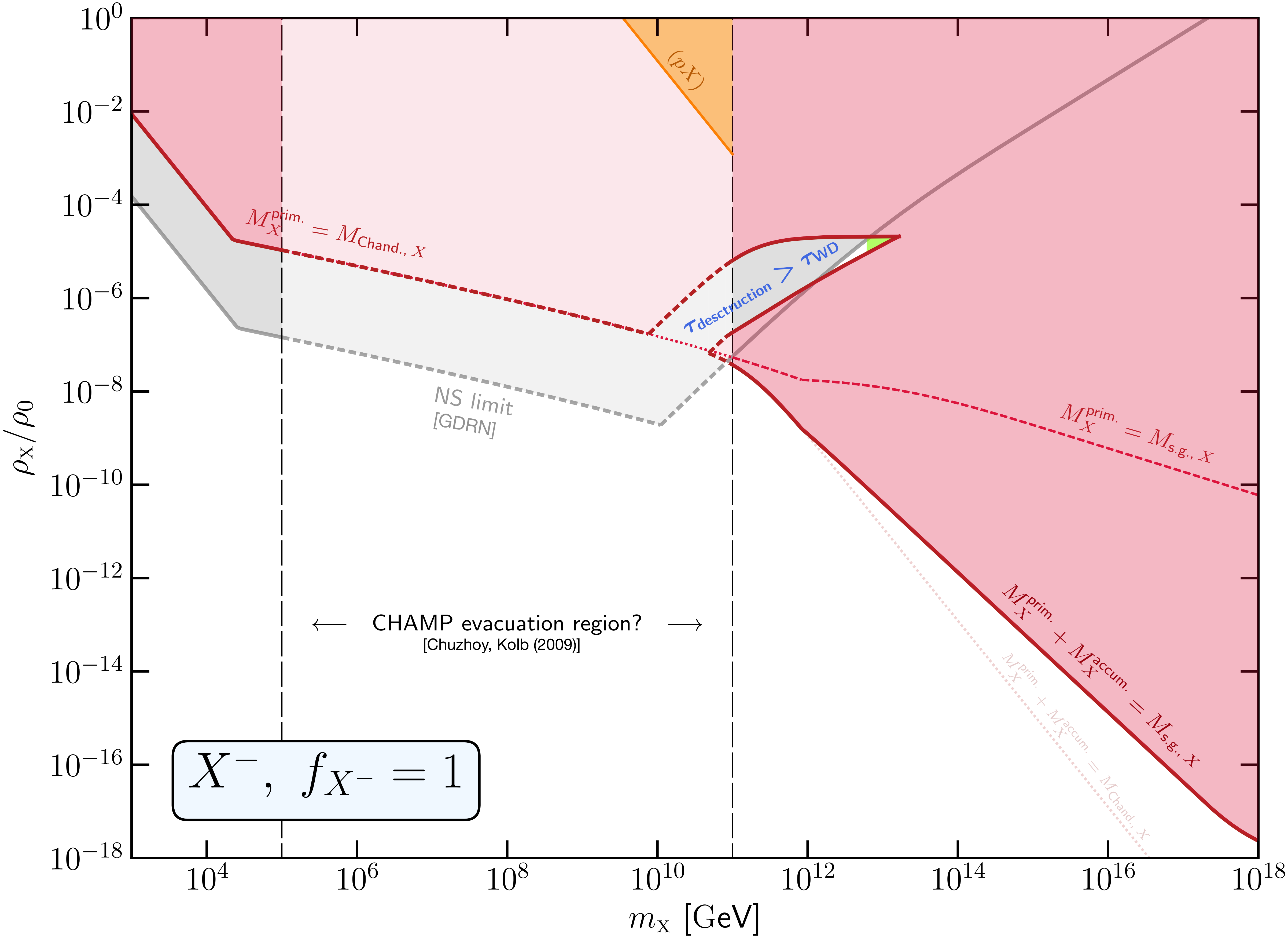
BH evolution after formation

- 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_{BH} such that $\tau_{\text{trig.}} \sim \tau_{\text{WD}} \sim$ few × Gyr.
  ∃ **untuned** parameter region where timescale too long to destroy old WD.
- Outside this region, $M_X \gtrsim \max \left[M_X^{\text{Ch.}}, M_X^{\text{s.g.}} \right]$ (conservative), implies WD destruction.
- Existence of old WD strongly constrain CHAMPs: e.g.,



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


10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
ρ_X/ρ_0
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
m_X [GeV]
$M_X^{\text{prim.}} = M_{\text{Chand.}, X}$
NS limit
[GDRN]
$\tau_{\text{desctruction}} > \tau_{\text{WD}}$
$M_X^{\text{prim.}} = M_{\text{s.g.}, X}$
$M_X^{\text{prim.}} + M_X^{\text{accum.}} = M_{\text{s.g.}, X}$
$M_X^{\text{prim.}} + M_X^{\text{accum.}} = M_{\text{Chand.}, X}$
⟵ CHAMP evacuation region? ⟶
[Chuzhoy, Kolb (2009)]
$X^+,\ f_{X^+} = 1$


10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
ρ_X/ρ_0
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
m_X [GeV]
(pX)
$M_X^{\text{prim.}} = M_{\text{Chand.}, X}$
$\tau_{\text{destruction}} > \tau_{\text{WD}}$
NS limit
[GDRN]
$M_X^{\text{prim.}} = M_{\text{s.g.}, X}$
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$M_X^{\text{prim.}} + M_X^{\text{accum.}} = M_{\text{s.g.}, X}$
$M_X^{\text{prim.}} + M_X^{\text{accum.}} = M_{\text{Chand.}, X}$
$X^-,\ f_{X^-} = 1$

Summary

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- 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?

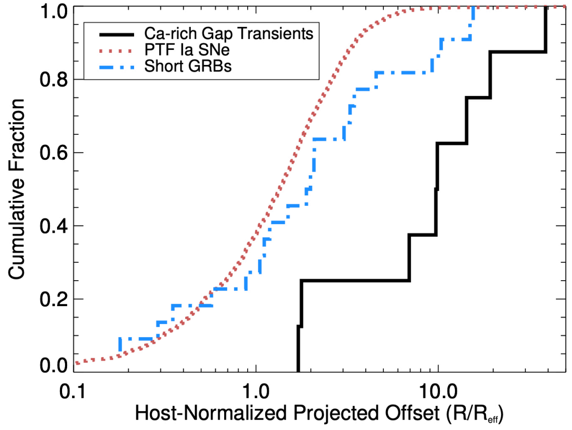
Thank You!

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 $(\mathrm{C}X)$.
- Take-home message: all other possibilities we considered lead to even earlier WD destruction.
- Lighter CHAMPs (10^5 GeV $\lesssim m_X \lesssim 10^{11}$ 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…

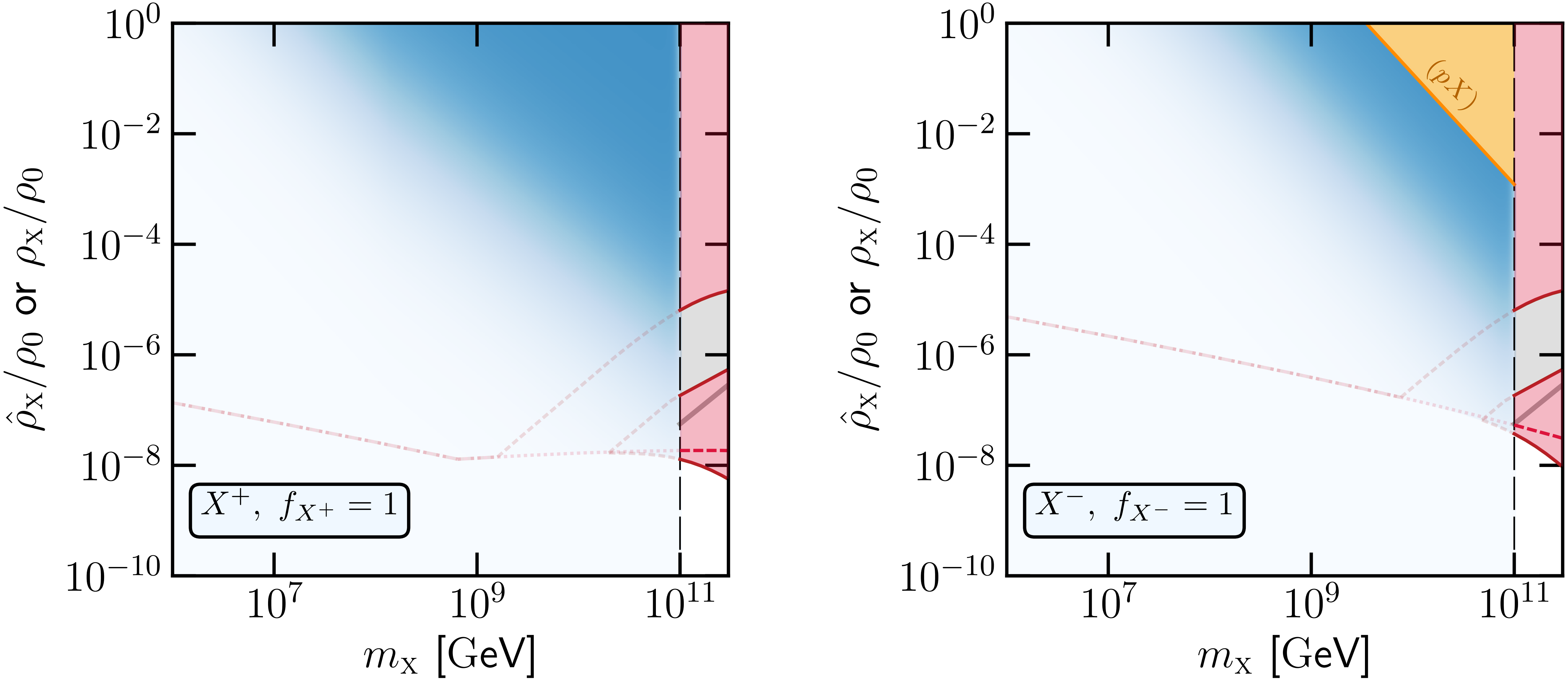
Ca-rich Gap Transients



Lunnan, et al. (2017)

- 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 GeV $\lesssim m_X \lesssim 10^{11}$ 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



Supernova shockwaves and magnetic fields

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

$$10^5 q_X^2 \lesssim \frac{m_X}{1\,\mathrm{GeV}} \lesssim 10^{11} q_X$$

- 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:

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

  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.