Dark Gamma Ray Burst

(based on Phys.Rev. D95 (2017) 055031 [arXiv:1607.04278])
collaborated with Vedran Brdar and Joachim Kopp

Jia Liu

MITP, Johannes Gutenberg University Mainz

July, TAUP 2017

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

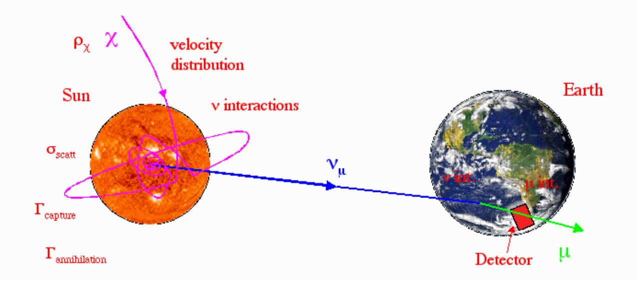
Cluster of Excellence PRISMA
Precision Physics, Fundamental Interactions and Structure of Matter

DM Indirect Detection: *p*-wave challenge

- Direct detection
  - nuclear recoils from DM scattering
- Collider searches
  - typical signal: missing energy + mono object
- Indirect detection (our focus)
  - classified by annihilation product: γ, ν, e^+...

- *p*-wave annihilation is generally harder to detect than *s*-wave
  - $\langle \sigma v \rangle = \sigma_0 v^2$
  - at freeze out $\langle \sigma v \rangle = \sigma_0 v_{fr}^2 \sim 10^{-26} cm^3/s$, $v_{fr}^2 \sim 0.26$
  - today $v \sim 10^{-3}$ for DM in galaxy, suppressed by $v^2 \sim 10^{-6}$
  - generally very weak constraint from indirect detection
- can *p*-wave annihilation has stronger signal than *s*-wave?
  - Yes, dark gamma ray burst!

DM Indirect detection from Sun



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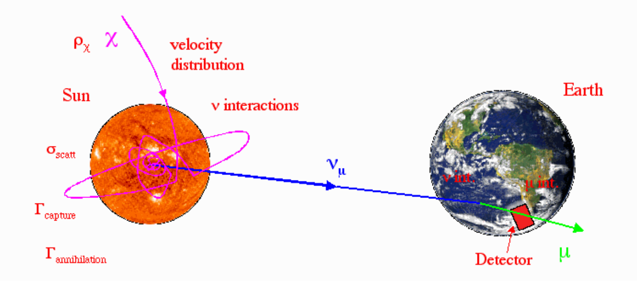

1. ν from Sun: IceCube, ANTARES and Super-K

history back to 1985, Silk *et al*, Krauss *et al*...

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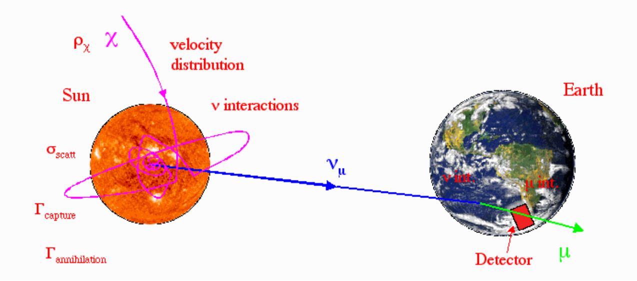


1. ν from Sun: IceCube, ANTARES and Super-K

   history back to 1985, Silk *et al*, Krauss *et al*...

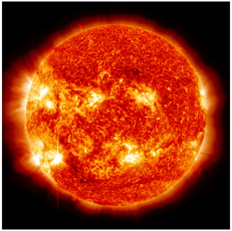
2. metastable mediator from Sun: e.g. A'

   (Schuster *et al*x2, Bell *et al*, Meade *et al*, Batell *et al*, Feng *et al*)

DM annihilation from the Sun

Capture and Annihilation $(dN/dt = C_{cap} - C_{ann} N^2)$

1. Conditions:
   - $C_{ann}^{\text{Sun}} \equiv \frac{1}{N^2} \int d^3r \, \langle \sigma v_{\text{rel}} \rangle \, n_{\text{DM}}^2(r) \sim 10^{-53} s^{-1}$
   - $C_{cap} = \sum_i \int_0^{R_{\text{star}}} dr \, 4\pi r^2 \, \frac{dC_i(r)}{dV} \sim 10^{22} s^{-1}$
   - parameters: $m_{DM} = 100\,GeV$, $\sigma_{SD}^{H} = 10^{-40} cm^2$ and $\langle \sigma v_{\text{rel}} \rangle = 3 \times 10^{-26} cm^3 s^{-1}$



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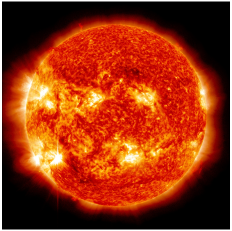
2. Results:
   - $N(t) = \sqrt{\frac{C_{cap}}{C_{ann}}} \tanh \frac{t}{t_{eq}} \to \sqrt{\frac{C_{cap}}{C_{ann}}} \sim 10^{37}$
   - $t_{eq} \equiv 1/\sqrt{C_{cap} C_{ann}} \sim 10^{15} s$, $t_{Sun} = 10^{17} s$
   - $C_{ann} N^2 = C_{cap} = 10^{22} s^{-1}$



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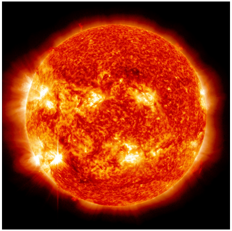
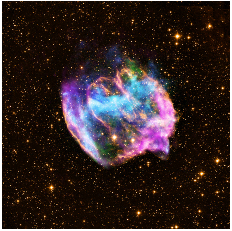
3. Conclution: **Capture and Annihilation is in Equilibrium!**
4. If in equilibrium, no difference between s-wave and p-wave annihilation



DM annihilation from Supernova

Tracing DM accumulation in a massive star

1. Same as Sun
   - $dN/dt = C_{cap} - C_{ann} N^2 + C_{self} N$



DM annihilation from Supernova

Tracing DM accumulation in a massive star

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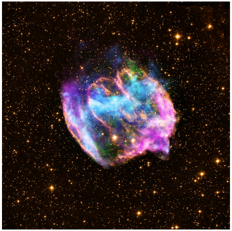
   - $dN/dt = C_{cap} - C_{ann} N^2 + C_{self} N$
2. Different from Sun
   - $\mathcal{O}(10^8)$ further than Sun, $\sim 1kpc$
   - much heavier than Sun, $\gtrsim 8 M_{Sun}$
   - $\mathcal{O}(10^{-2})$ shorter lifetime $\sim 10^{15} s$
   - density, temperature and chemical composition changes with time much faster
   - End up with a core collapse Supernova
   - Peak annihilation rate (dark gamma ray burst coincident with the supernova) $\mathcal{O}(10^{12})$ larger than the Sun!
   - Capture and Annihilation is *Not* in Equilibrium!



DM annihilation from Supernova: preparation

1. Assumptions
    - Quasi-instantaneous thermalization
    - fermionic DM annihilates to $\mathcal{O}(1)$GeV light mediator: dark photon (s-wave) or dark scalar (p-wave)

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2. Parameters
   - $\rho_i(r, t)$ and $T(r, t)$ from Herger *et al*
   - $m_{DM} \in [10, 10^3]$GeV, $\sigma_n^{SD} = 10^{-40} cm^2$, $\sigma_n^{SI} = 10^{-46} cm^2$
   - $\langle \sigma v_{\rm rel} \rangle$ fixed by relic abundance, Sommerfeld enhancement considered
   - Galactic DM density ρ_{DM}^{gal}: Einasto profile

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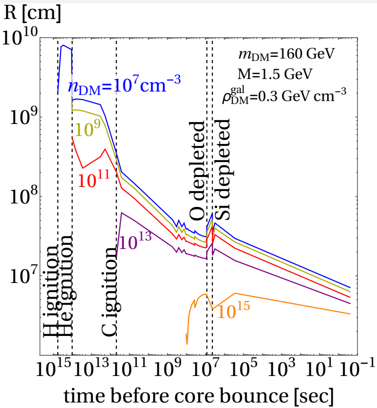
3. DM evolution

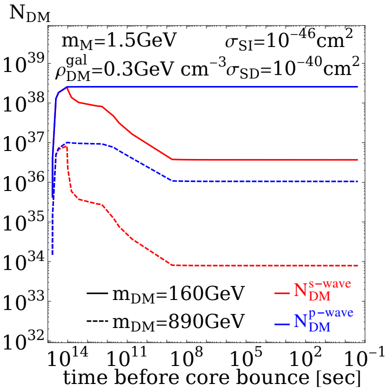
$$\dot{N}_{\rm DM}(t) = C_{\rm cap}(t) - C_{\rm ann}(t) N_{\rm DM}(t)^2 + C_{\rm self}(t) N_{\rm DM}(t)$$

- $C_{\rm cap} = \sum_i \int_0^{R_{\rm star}} dr\, 4\pi r^2 \, \frac{dC_i(r)}{dV}$
- $C_{\rm ann} N_{\rm DM}^2 \equiv \int d^3r \, \langle \sigma v_{\rm rel} \rangle \, n_{\rm DM}^2(r)$

$$n_{\rm DM}(r) = n_0 \, \exp[-m_{\rm DM}\phi(r)/T_{\rm DM}]$$

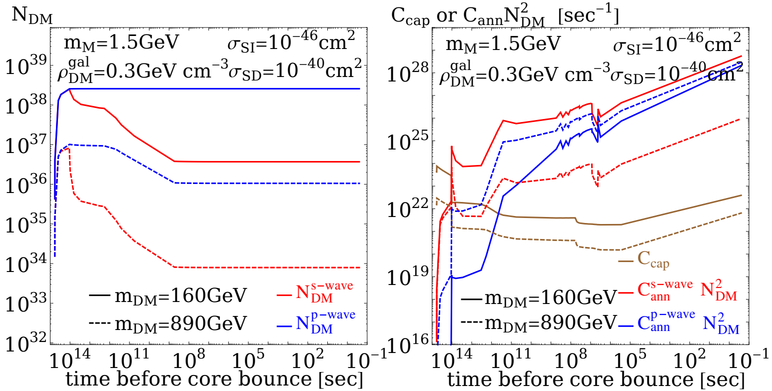
DM Distribution in the Star





- DM concentrated in the star as expected
  - $n_{DM}(r) = n_0 \exp[-m_{DM}\phi(r)/T_{DM}]$
- p-wave DM has higher N_{DM} than s-wave!
  - $\dot{N}_{DM}(t) = C_{cap}(t) - C_{ann}(t) N_{DM}(t)^2$

DM Evolution in the Star



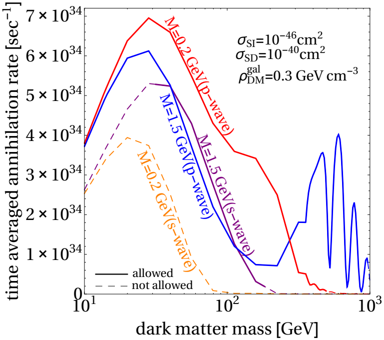
1. Capture and Annihilation is *Not* in Equilibrium!
   - after $t < 10^9 s$, N_{DM} does not change due to too short time
   - lighter DM has larger N_{DM} due to larger C_{cap} and smaller C_{ann}

DM Annihilation Burst during Supernova

- Assumption
  - Iron core collapse to proto-neutron star (size $\sim 30km$)
  - $\rho_{SN} \sim 10^{14} g/cm^3$ reaches nuclear density
  - Conservatively taking DM particles within $R_{core} \sim 30km$
  - DM gets thermalized within $10^{-7} \sim 10^{-6}$ seconds
  - high DM density leads to dark gamma ray burst

DM Annihilation Burst during Supernova

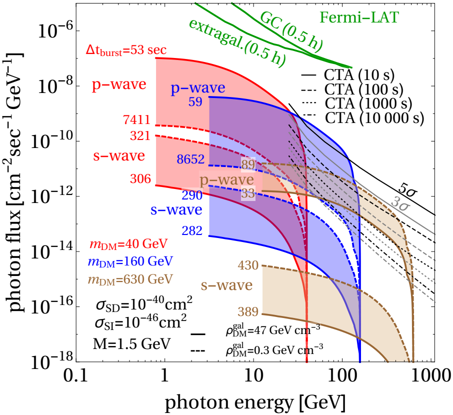
- dark Gamma ray burst, last $10 \sim 10^3$ seconds
  - $\dot{N}_{\rm DM}(t) = \not{C}_{\rm cap}(t) - C_{\rm ann}(t) N_{\rm DM}(t)^2$
  - $N_{\rm DM}(t) = \frac{N_0}{1+t\, C_{\rm ann}^{SN} N_0}$, $\Delta t_{dur} \sim (C_{\rm ann}^{SN} N_0)^{-1}$
  - $C_{\rm ann}^{SN} = \langle \sigma v_{\rm rel} \rangle \left(\frac{G_N m_{\rm DM} \rho_{\rm SN}}{3 T_{\rm SN}} \right)^{3/2}$, $\Delta N \sim (C_{\rm ann}^{SN} N_0^2) \Delta t_{dur} \propto N_0$



Dark Gamma Ray Burst

Properties

- The mediator decay gives dN_γ/dE_γ
- An observable gamma ray signal after ν arrival
- $\Delta t_{burst} = (C_{ann}^{SN} N_0)^{-1}$ related to sensitivity
- Benchmark locations: $0.1 kpc$ and $7 kpc$ from GC
- Heavier mediator m_M provides more photons generally
- $\Delta t_{dur} \in [\mathcal{O}(10), \mathcal{O}(10^3)]$ sec for p-wave, $\mathcal{O}(10^2)$ sec for s-wave



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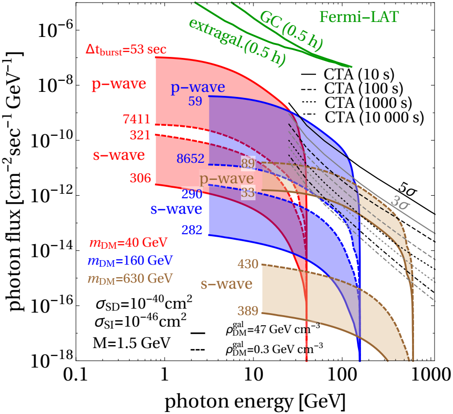


Results

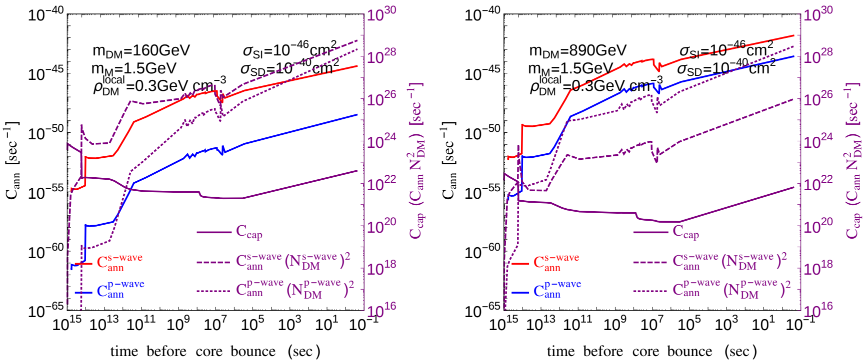
- *p*-wave has larger photon flux than *s*-wave!
- The best signal is around $m_{DM} \sim \mathcal{O}(100)$ GeV
- CTA duty cycle is 10%

Summary for Dark Gamma Ray Burst

- We have computed the evolution of the DM core in massive star until core collapse
- General process: $N_{DM} \uparrow$ C_{cap} dominates, $N_{DM} \downarrow$ C_{ann} dominates especially for s-wave, N_{DM} unchanged due to too short time
- p-wave DM accumulates more N^0_{DM} than s-wave
- Total emission $\Delta N \sim N^0_{DM}$, more photons from p-wave annihilation
- Such dark gamma ray burst can be detected by CTA for p-wave DM
- The best signal is around $m_{DM} \sim 100$ GeV
- A unique example: p-wave DM better in indirect detection than s-wave
- We need luck to see dark gamma ray burst signal

Thanks for your attention!

Backup slides



- larger C_{cap} due to more DM particles, more efficient
- smaller ratio between s-wave and p-wave in C_{ann} because of Sommerfeld enhancement