Dark Gamma Ray Burst

(based on arXiv:1607.04278)

collaborated with Vedran Brdar and Joachim Kopp

Jia Liu

MITP, Johannes Gutenberg University Mainz

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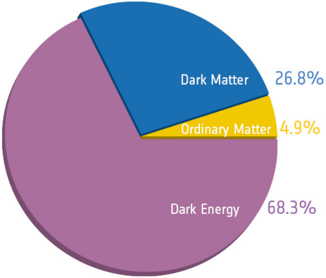
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

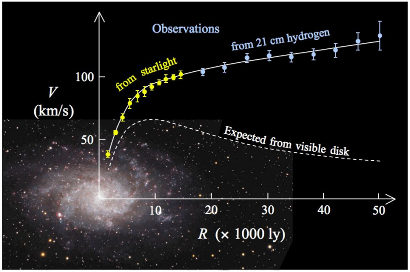
Cluster of Excellence PRISMA

Precision Physics, Fundamental Interactions and Structure of Matter

Dark matter: the mystery of this century



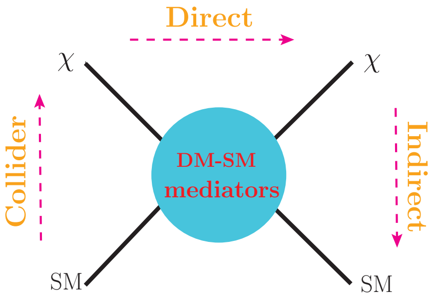
(Credit: ESA/Planck)



(Credit: Stefania)

- Property
  - No electric and color charge
  - weakly interacting with normal matter
  - stable or long lived
  - not in SM particle list

Dark Matter Searches

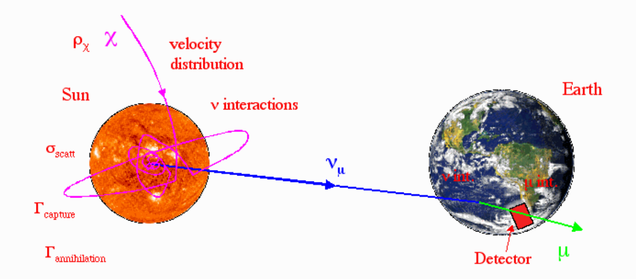


- Direct detection
  - nuclear recoils from DM scattering
- Collider searches
  - typical signal: missing energy + mono object
- Indirect detection (our focus)
  - classified by annihilation product: γ, ν, e^+...

DM Indirect Detection: *p*-wave challenge

- *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
- how to test *p*-wave annihilation?
  - can *p*-wave annihilation has stronger signal than *s*-wave?
  - Yes, dark gamma ray burst!

DM Indirect detection from Sun



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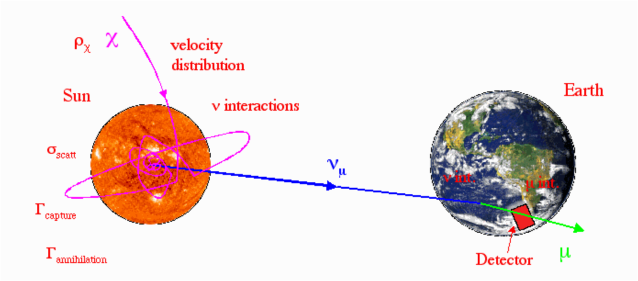

1. ν from Sun: IceCube, ANTARES and Super-K

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

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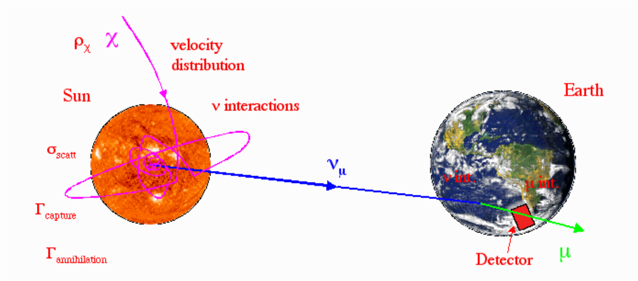


1. ν from Sun: IceCube, ANTARES and Super-K

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

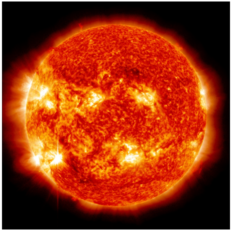
2. metastable mediator from Sun: e.g. A'

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



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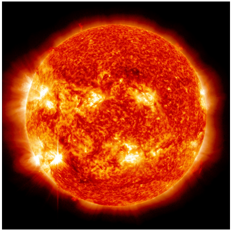
2. Results:
   - $N(t) = \sqrt{\frac{C_{cap}}{C_{ann}}} \tanh \frac{t}{t_{eq}} \to \sqrt{\frac{C_{cap}}{C_{ann}}} \sim 10^{37}$
   - $t_{eq} \equiv 1/\sqrt{C_{cap} C_{ann}} \sim 10^{15} s$, $t_{Sun} = 10^{17} s$
   - $C_{ann} N^2 = C_{cap} = 10^{22} s^{-1}$



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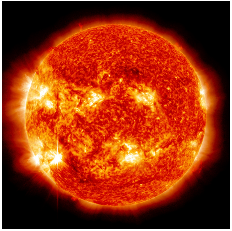
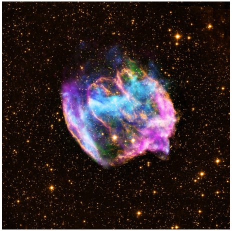
3. Conclution: **Capture and Annihilation is in Equilibrium!**
4. If in equilibrium, no difference between s-wave and p-wave annihilation



DM annihilation from Supernova

Tracing DM accumulation in a massive star

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



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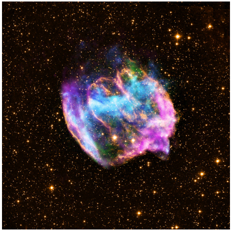
   - $dN/dt = C_{cap} - C_{ann} N^2 + C_{self} N$
2. Different from Sun
   - $\mathcal{O}(10^8)$ further than Sun, $\sim 1kpc$
   - much heavier than Sun, $\gtrsim 8 M_{Sun}$
   - $\mathcal{O}(10^{-2})$ shorter lifetime $\sim 10^{15}s$
   - density, temperature and chemical composition changes with time 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
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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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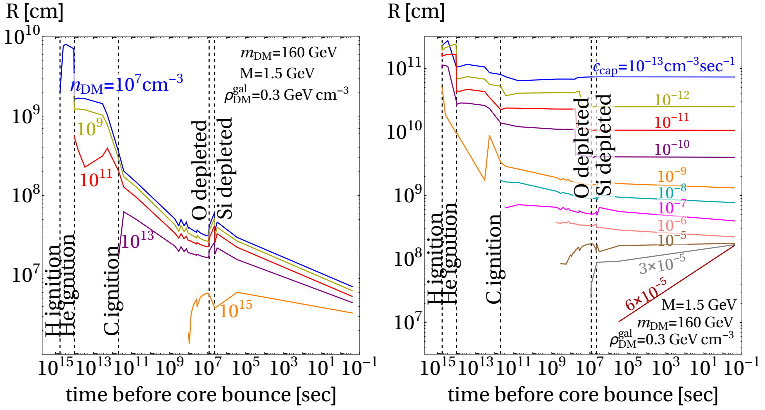
3. DM evolution

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

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

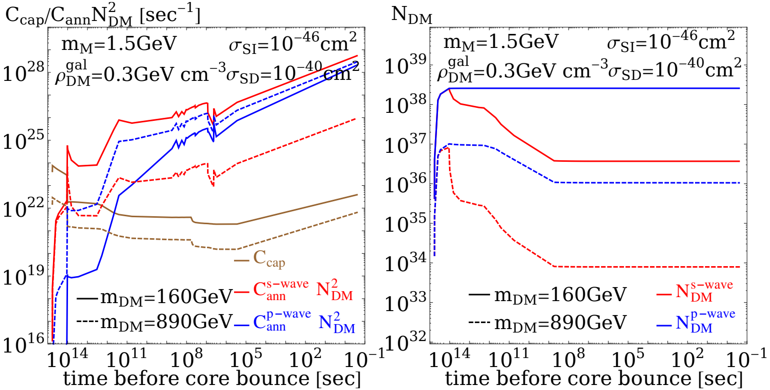
$$n_{\rm DM}(r) = n_0 \exp[-m_{\rm DM}\phi(r)/T_{\rm DM}]$$

DM Distribution in the Star



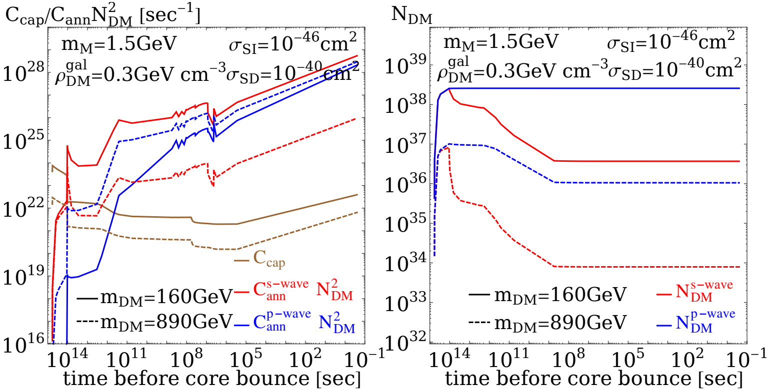
- DM concentrated in the star as expected
  - $n_{DM}(r) = n_0 \exp[-m_{DM}\phi(r)/T_{DM}]$
  - Large C_{cap} at early time due to large σ_{SD} on H
  - C_{cap} at later time dominated by H in the outer layers and ^{14}N

DM Evolution in the Star



1. p-wave DM has higher N_{DM} than s-wave!
   - $\dot{N}_{\mathrm{DM}}(t) = C_{\mathrm{cap}}(t) - C_{\mathrm{ann}}(t) N_{\mathrm{DM}}(t)^2$
   - 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 Evolution in the Star



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   - lighter DM has larger N_{DM} due to larger C_{cap} and smaller C_{ann}
2. Capture and Annihilation is *Not* in Equilibrium!

DM Annihilation Burst during Supernova

1. Assumption
   - $\rho_{SN} \sim 10^{14} g/cm^3$ reaches nuclear density from a larger iron core
   - DM particles within $R_{core} \sim 30km$ (size of proto-neutron star)
   - DM gets thermalized within $\sim 10^{-6}$ seconds

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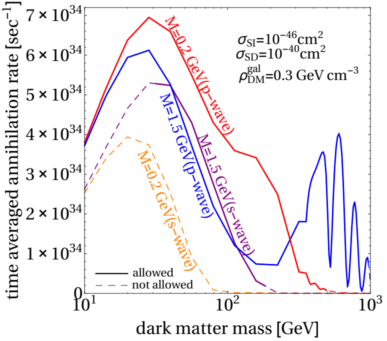
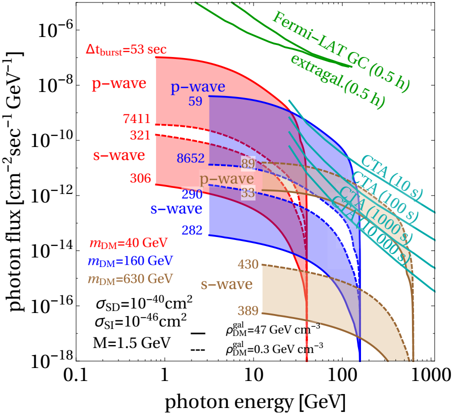
   - DM gets thermalized within $\sim 10^{-6}$ seconds
2. Result
   - $N_{\rm DM}(t) = \frac{N_0}{1+t\, C_{\rm ann}^{SN} N_0}$, $\Delta t_{dur} \sim (C_{\rm ann}^{SN} N_0)^{-1}$
   - $C_{\rm ann}^{SN} = \langle \sigma v_{\rm rel} \rangle \left(\frac{G_N m_{\rm DM} \rho_{\rm SN}}{3 T_{\rm SN}} \right)^{3/2}$, $\Delta N \sim (C_{\rm ann}^{SN} N_0^2) \Delta t_{dur} \propto N_0$



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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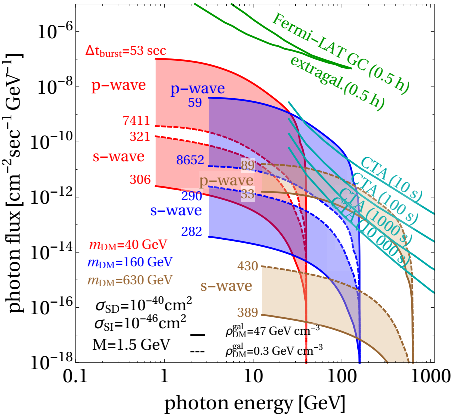


Results

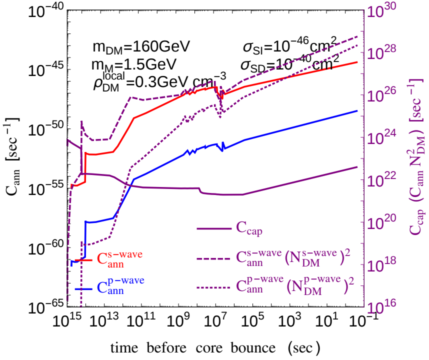
- *p*-wave has larger photon flux than *s*-wave!
- The best signal is around $m_{DM} \sim \mathcal{O}(100)$ GeV

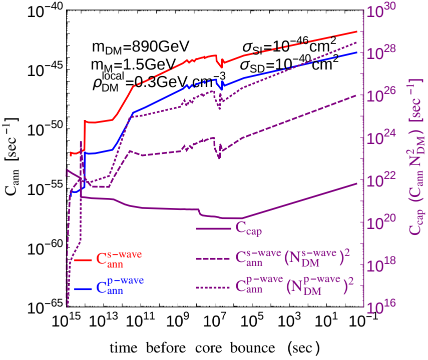
Summary for Dark Gamma Ray Burst

- 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

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