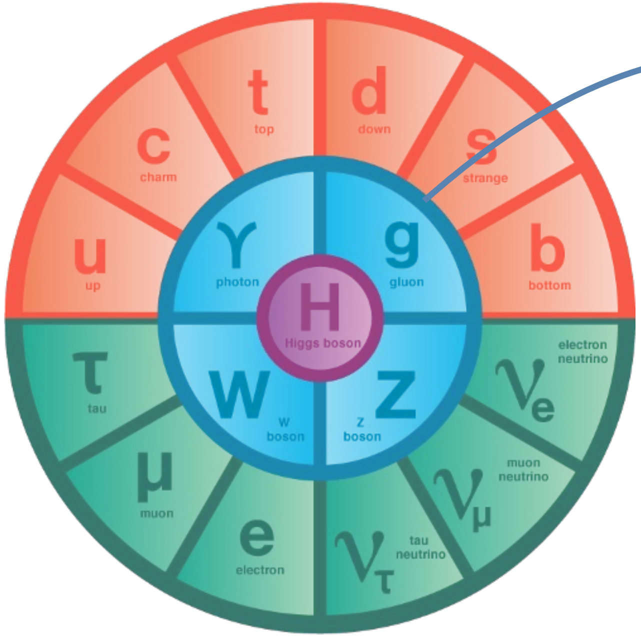
Dark sector signals from extreme astrophysical environments

Gustavo Marques-Tavares,
Maryland Center for Fundamental Physics

Standard Model



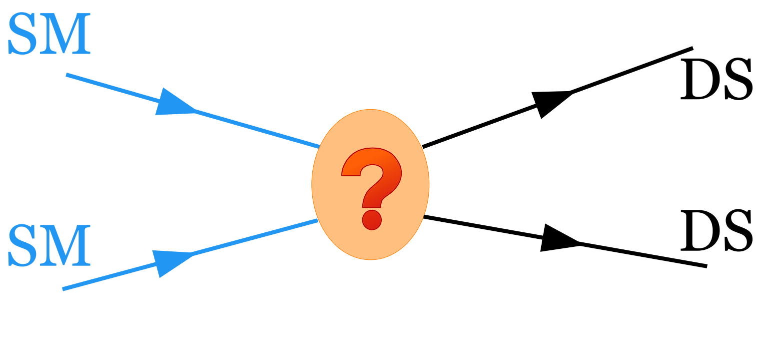
Gauge interactions were central to all discoveries (except higgs)

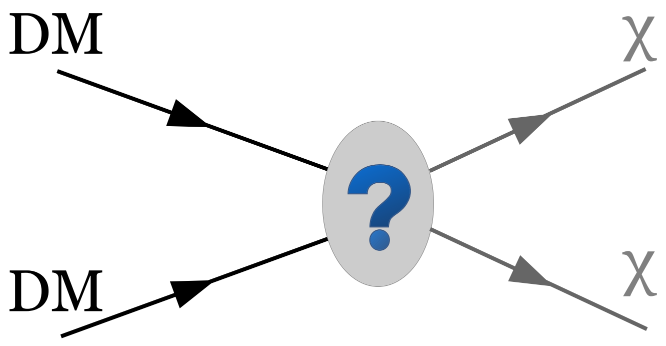
$$g \sim \mathcal{O}(1)$$

Dark Sectors

What if the BSM states at attainable energies don't have SM gauge charges?

Dark Matter from Dark Sectors

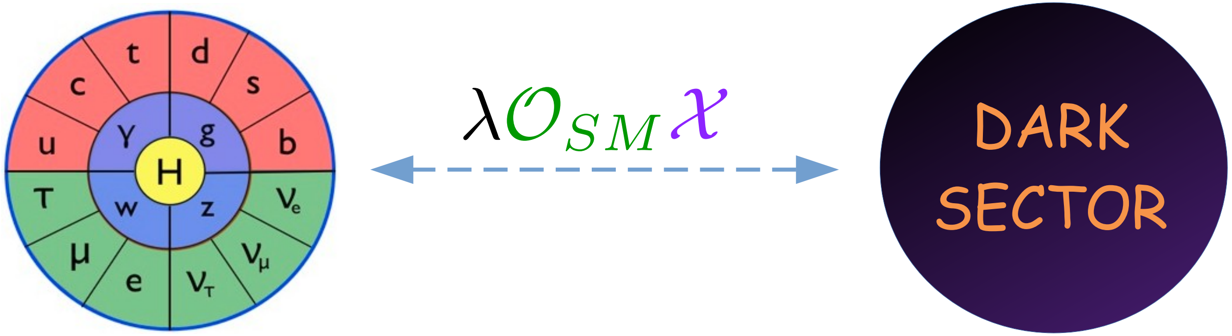




Interactions between SM and DS responsible for transferring energy to DS

Interactions in the DS can set the dark matter abundance

Dark Sector Portals

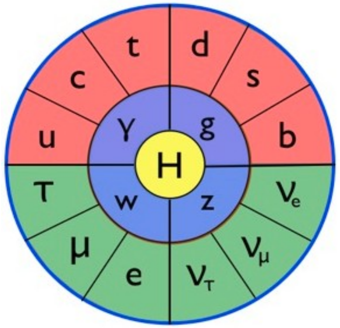


$SU(3) \times SU(2) \times U(1)$

Vector Portal:	$F^{\mu\nu} X_{\mu\nu}$
Higgs Portal:	$\|H\|^2(\phi + \phi^2)$
Neutrino Portal:	$(LH)N$
Global Symmetry:	$J^{\mu}_{SM} V_{\mu}$
Axion Portal:	$aF\tilde{F}$

- Dark Matter
- Neutral Naturalness
- Neutrino masses
- Strong CP
- ...

Dark Sector Portals

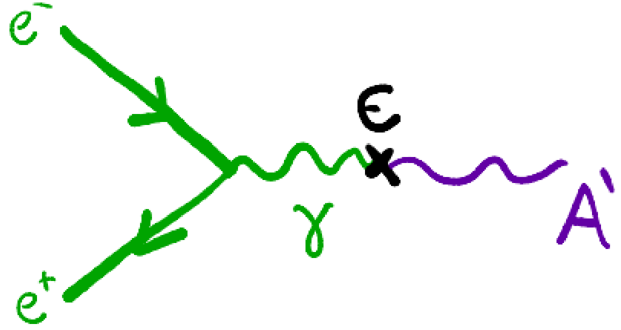


$SU(3) \times SU(2) \times U(1)$

$\lambda \mathcal{O}_{SM} \mathcal{X}$

Vector Portal:	$F^{\mu\nu} X_{\mu\nu}$
Higgs Portal:	$\lvert H \rvert^2 (\phi + \phi^2)$
Neutrino Portal:	$(LH)N$
Global Symmetry:	$J^{\mu}_{SM} V_{\mu}$
Axion Portal:	$aF\tilde{F}$

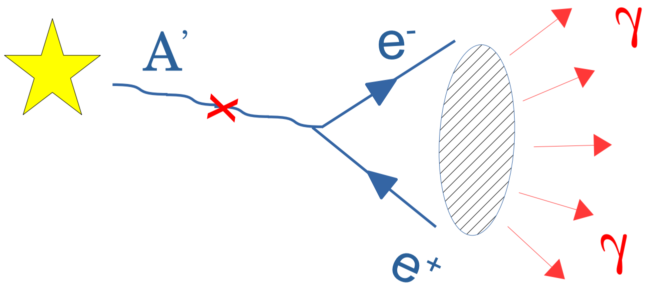
$$-\frac{1}{4} F'^2 - \frac{\epsilon}{2} F F' + \frac{m'^2}{2} A'^2$$



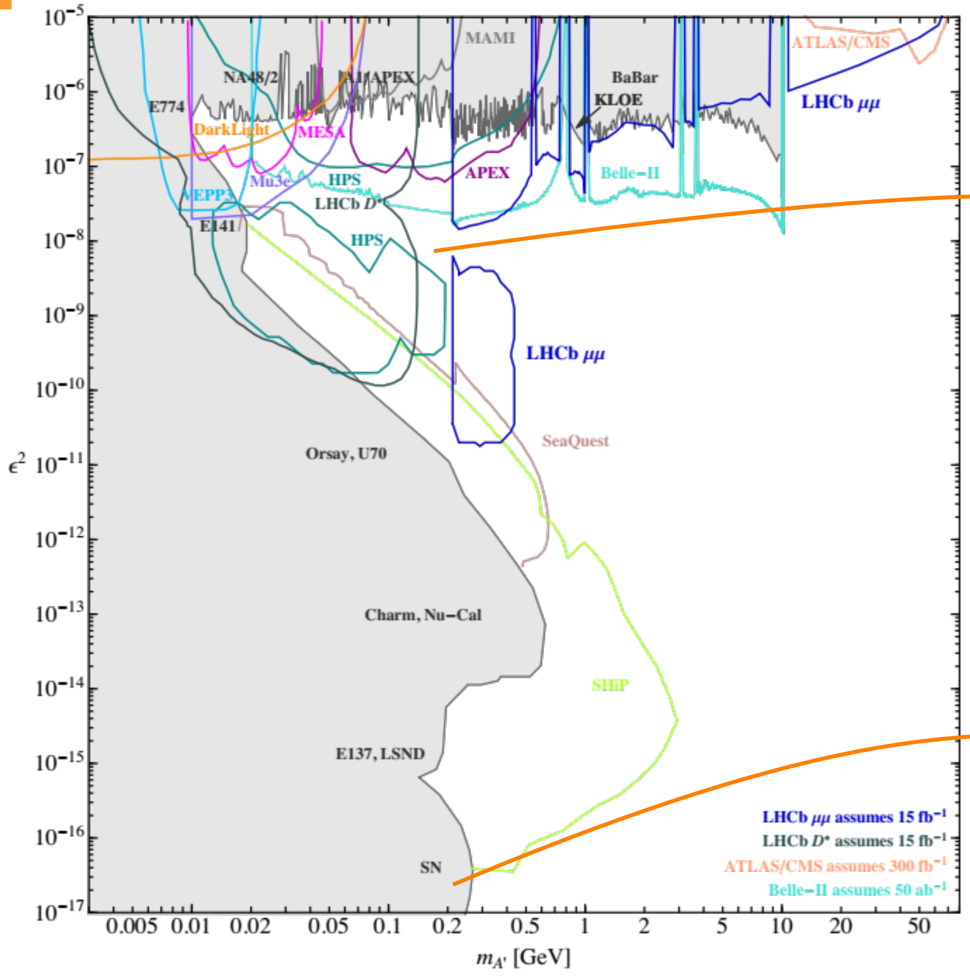
Outline

- Signals from dark photon decays in supernovae

- Transient gamma-rays from dark photons in neutron star mergers

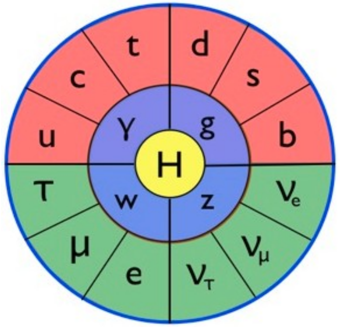


Visibly decaying dark photon



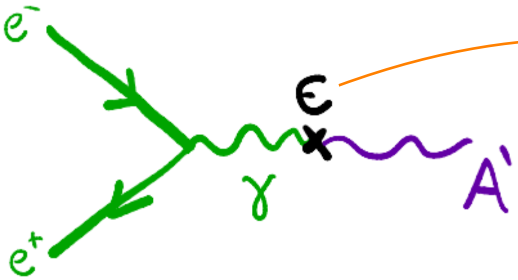
- Larger couplings prime target for accelerator probes
- At small couplings, not enough luminosity: use astrophysical sources

Look for the messenger



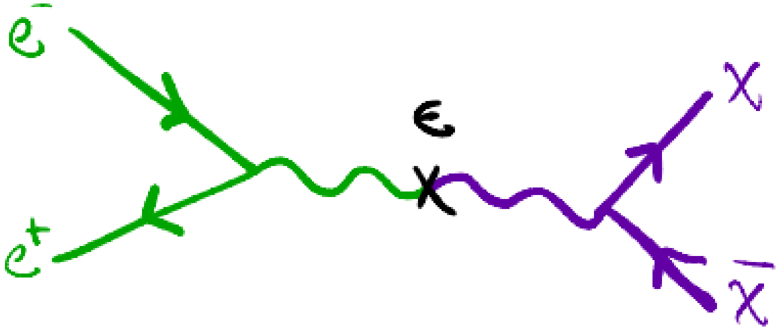
$\lambda \mathcal{O}_{SM} \chi$

- Searching for the messenger between SM and DS is a broad approach to searching for dark sectors
- Focus on dark photon searches when it is the lightest dark state



Theoretical targets for ε ?

Target: dark matter abundance



$$\langle \sigma v \rangle \sim \frac{\alpha \alpha_d \epsilon^2}{m_\chi^2}$$

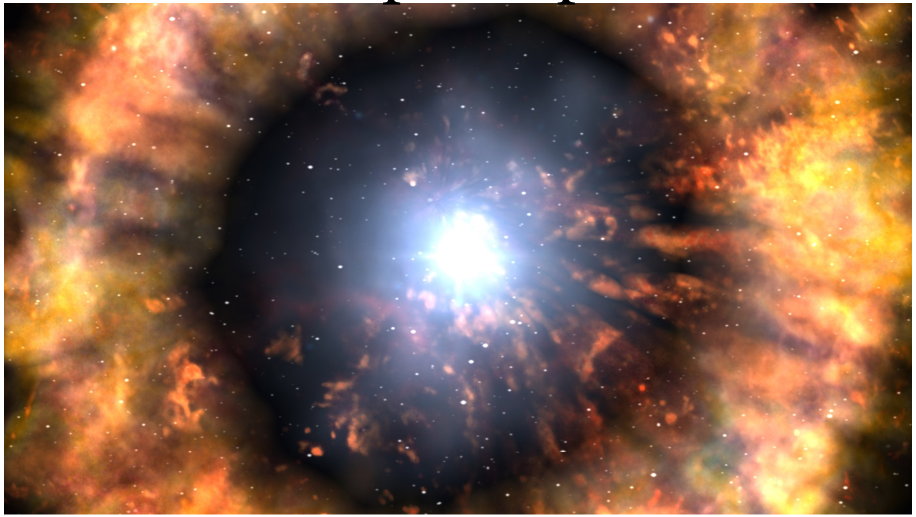
Is there enough energy transferred to dark sector?

Freeze-in

$$\epsilon \gtrsim \frac{e}{g_d} 10^{-11}$$

Extreme Astrophysical Environments

Core-collapse supernovae



Binary neutron star merger

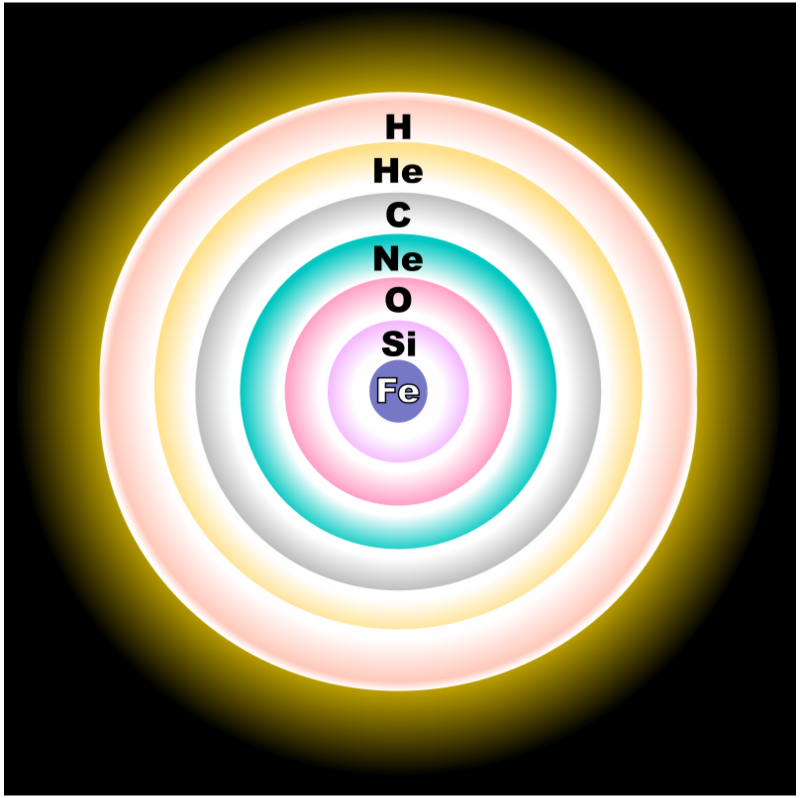
$$\rho \sim 10^{14}\,\mathrm{g/cm^3}$$
$$T \sim 50\,\mathrm{MeV}$$

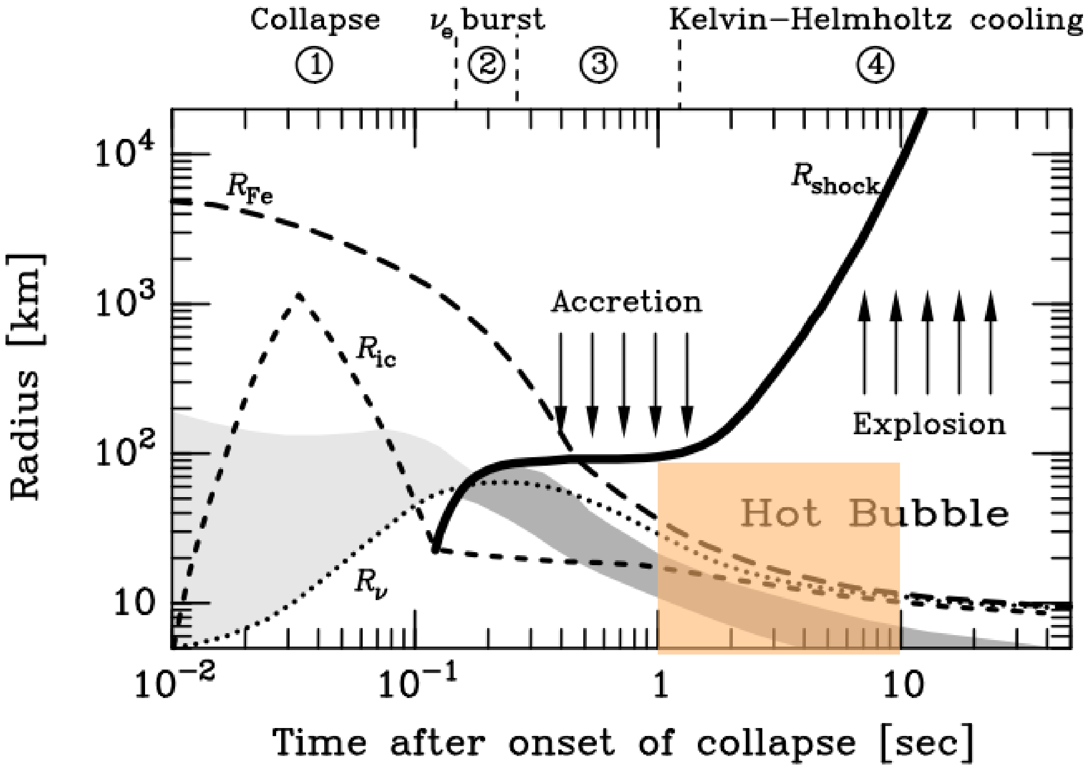
→ MeV dark sector factories

Visible signals from dark photons produced in supernovae

* DeRocco, Graham, Kasen, **GMT**, Rajendran, *JHEP (2019)*

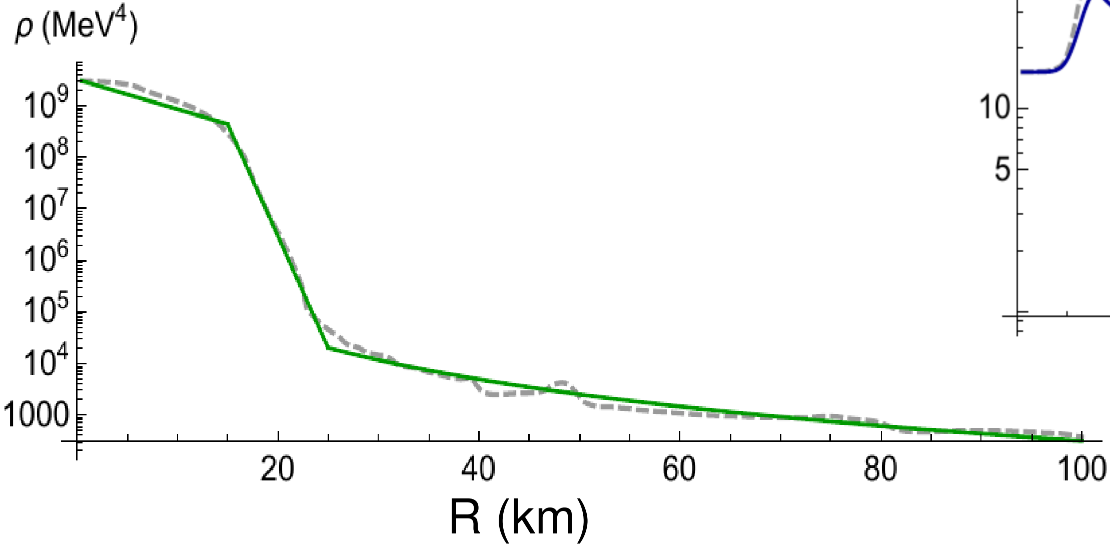
Core-collapse supernova

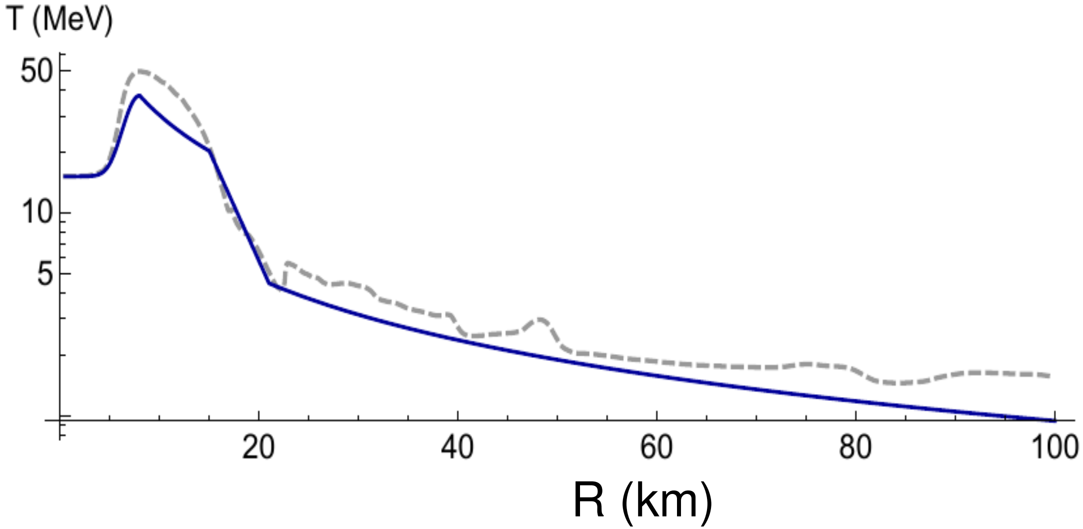




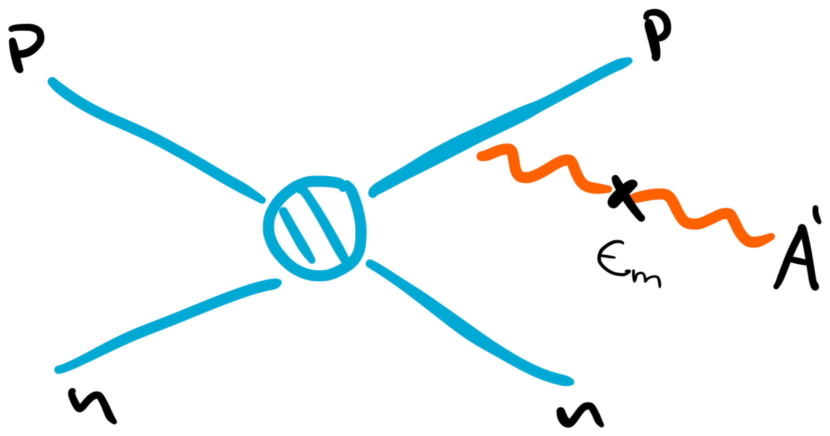
Core-collapse supernova

- When the iron-core of very massive stars collapses, infalling matter gives rise to a hot proto-neutron star (cools in ~10s)





Dark photon production



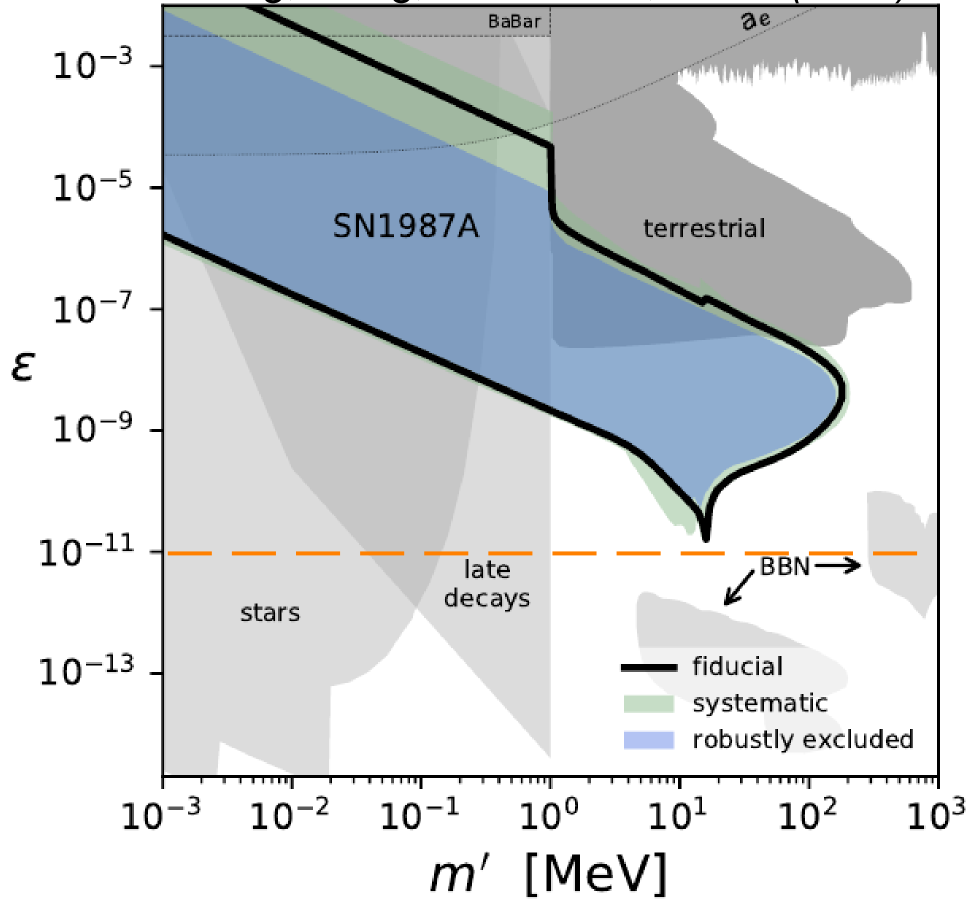
$$\epsilon_m = \frac{\epsilon^2 m^2}{\sqrt{(m^2 - \mathrm{Re}\Pi) + \mathrm{Im}\Pi}}$$

$$\frac{dN}{dt dV} = \int \frac{d\omega \omega^2 v}{2\pi^2} e^{-\omega/T} \frac{32\alpha n_{\mathrm{n}} n_{\mathrm{p}} \epsilon_m^2}{3\pi\omega^3} \left(\frac{\pi T}{m_{\mathrm{N}}}\right)^{3/2} \langle \sigma_{\mathrm{np}}^{(2)}(T) \rangle$$

* Rrapaj and Reddy, *Phys. Rev. C (2015)*

Supernova cooling constraints

Chang, Essig, McDermott, *JHEP (2017)*

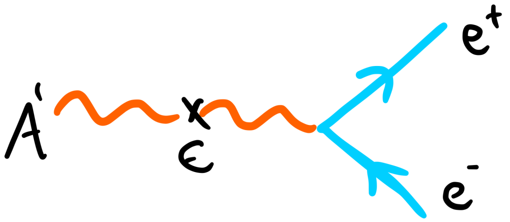


- Traditional SN constrains: dark photons cannot cool SN faster than neutrino emission:

$$L < 3 \times 10^{52}\, \mathrm{erg/s}$$

- This corresponds to incredible large luminosity. If the dark photon decays visibly, should be able to extend the constraints to much weaker couplings

Galactic positron injection



Dark photon decays → large number of positrons:

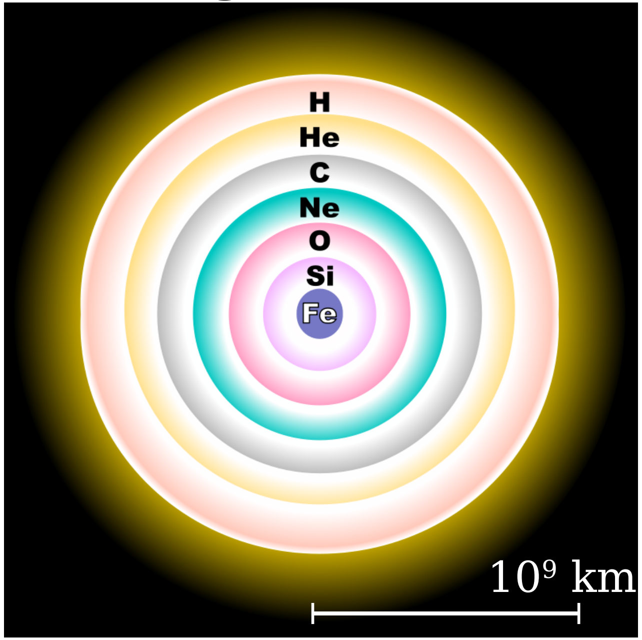
$$\sim 10^{57} \times \left(\frac{L_{A'}}{10^{52}\ \mathrm{erg/s}} \right)$$

- 511 keV line observations limit galactic positron injection:

$$\frac{dN_{e^+}}{dt} \lesssim 4 \times 10^{43} s^{-1} \longrightarrow \Delta N_{e^+}^{\mathrm{SN}} < 10^{53}$$

Long lived particle constraint

Progenitor star

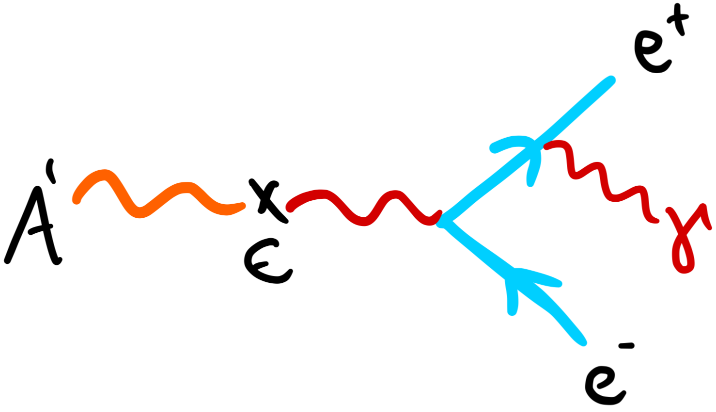


- In order to be "injected" in galaxy, positrons must be produced outside progenitor:
  - 10^9 km for typical type II SN
  - 2 x 10^7 km for type Ib/c SN (~10% of ccSN)

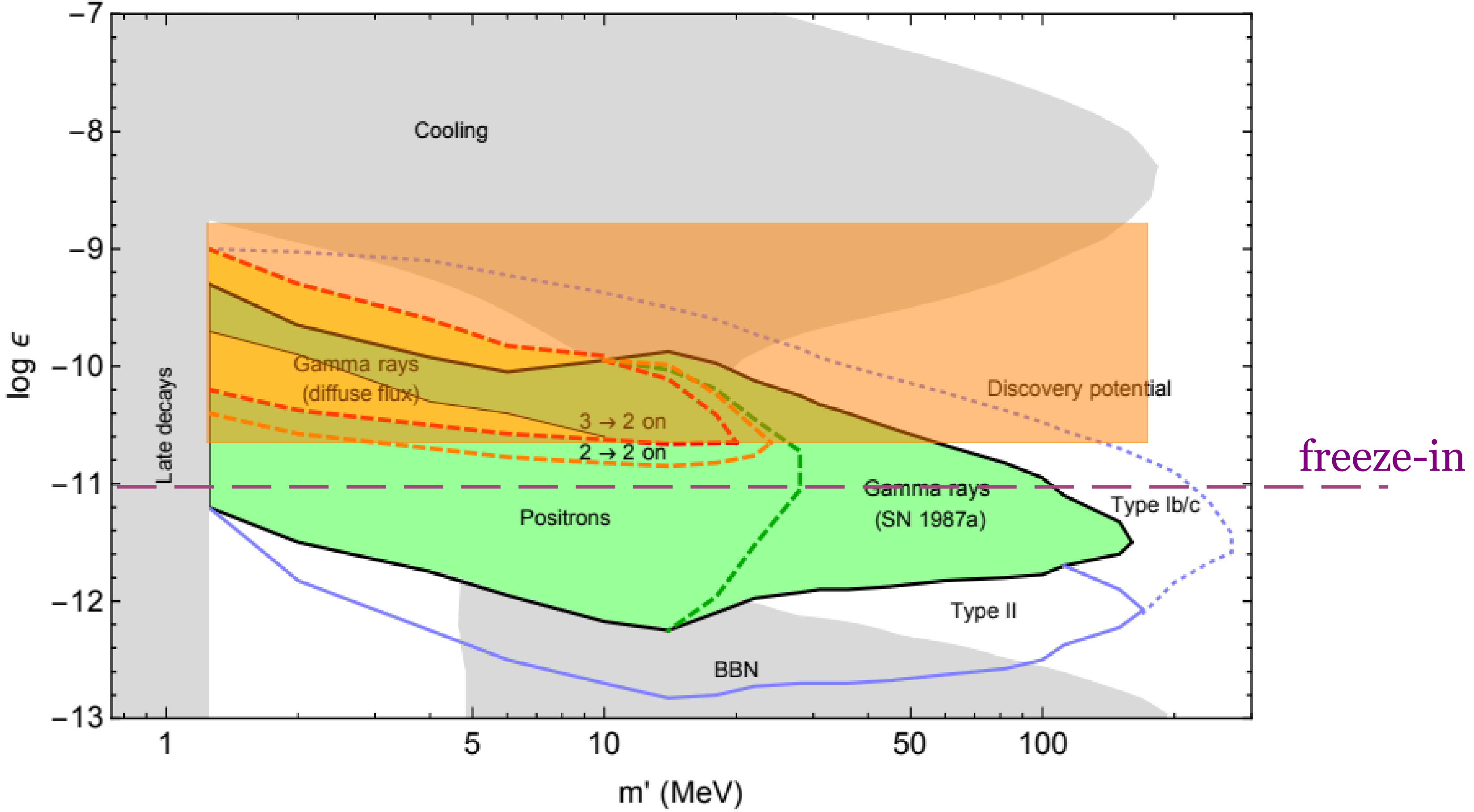
- Annihilations between $e^+ e^-$ produced by the decay can also decrease positron injection.

Gamma rays from SN1987a

- In 1987 we detected a nearby type II supernovae and had the first detection of SN neutrinos
- The Gamma Ray Spectrometer aboard SMM had sensitivity to gamma rays coming from that supernovae



Combined Constraints



A gamma-ray flash from dark photons in neutron star mergers

* Diamond, **GMT**, *PRL (2022)*

Supernova bound required long lifetime

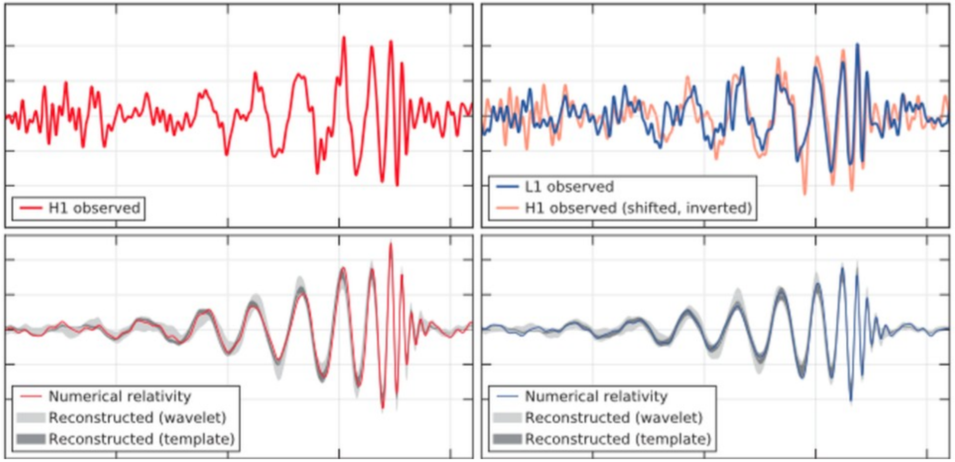
- Are there systems that get to similar temperature and density with less “shielding”?

Neutron Star Mergers

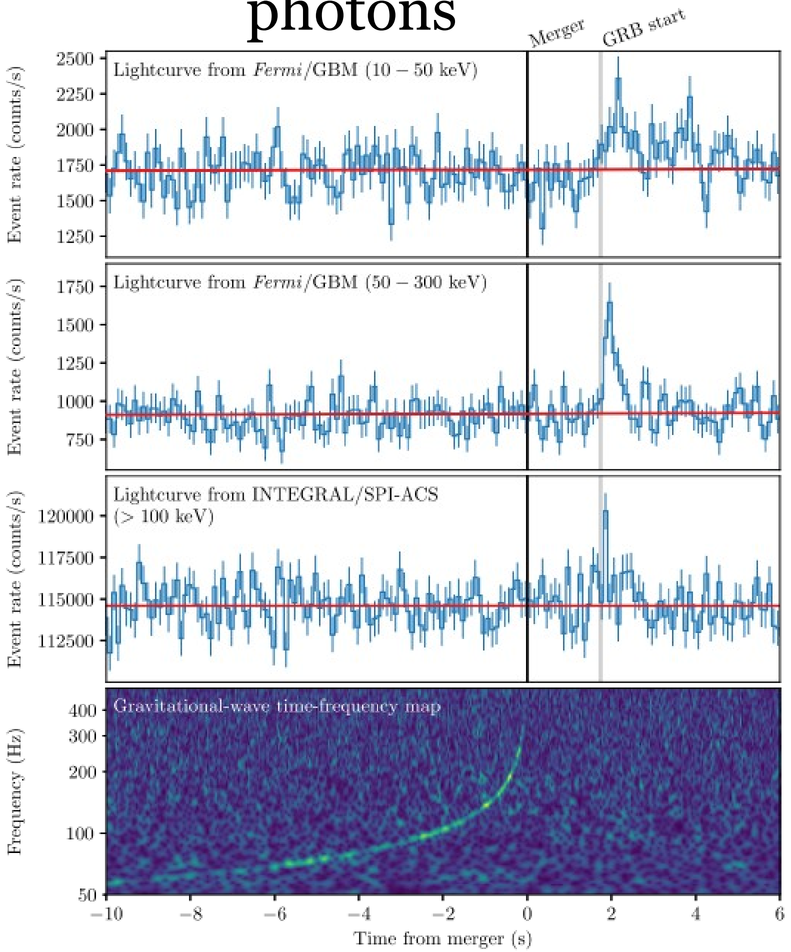
- Two neutron stars (nuclear densities) collide with orbital speeds ~ c
- Forms high density remnant with temperatures ~ 50 MeV
- Remnant life-time ~ 10 – 1000 ms
- Low density environment away from merger (1000 km)

Multi-messenger probe

gravitational waves

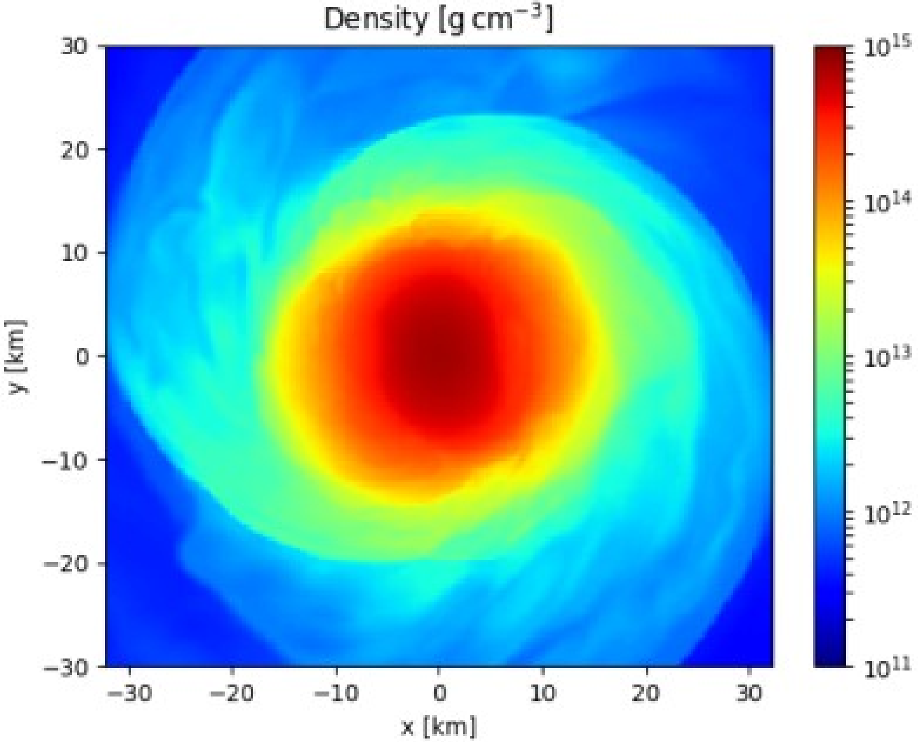


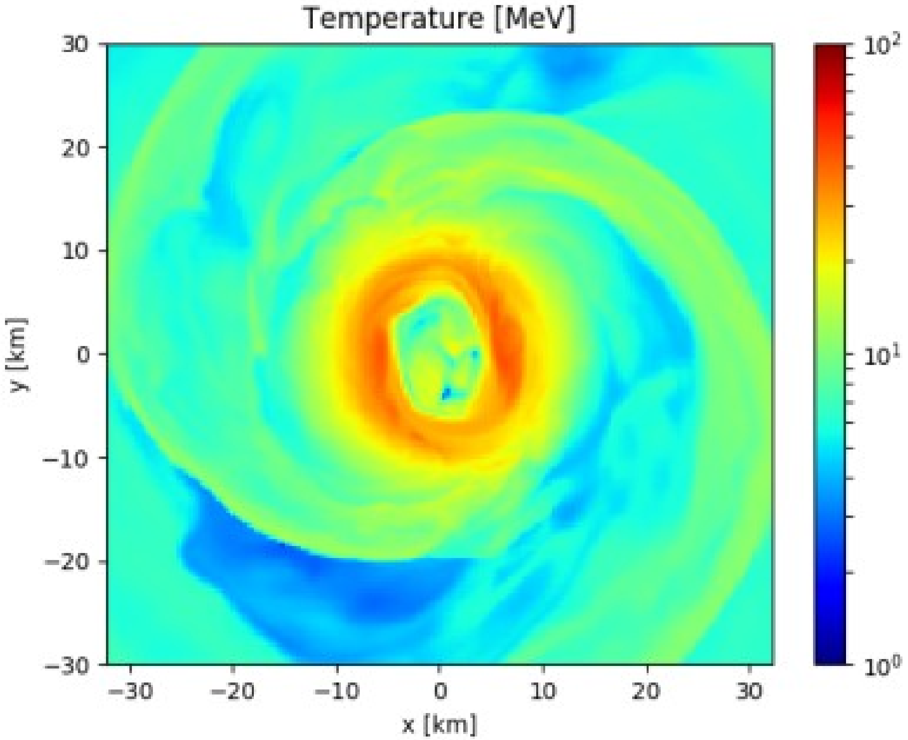
photons



Look for coincident signals:
gw as a trigger

BNS merger remnant

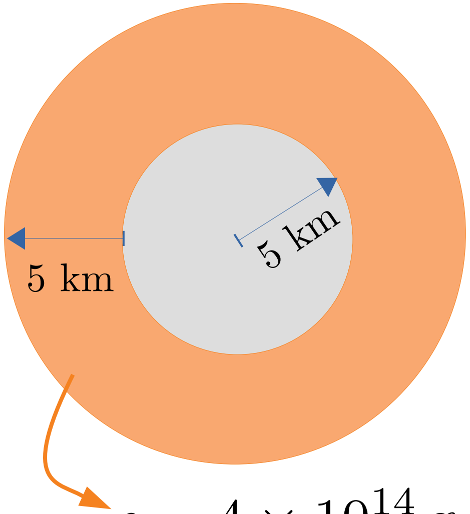




Perego, A., Bernuzzi, S., Radicce, D., Eur. Phys. J. A 55, 124

Simplified remnant profile

Spherical shell emission

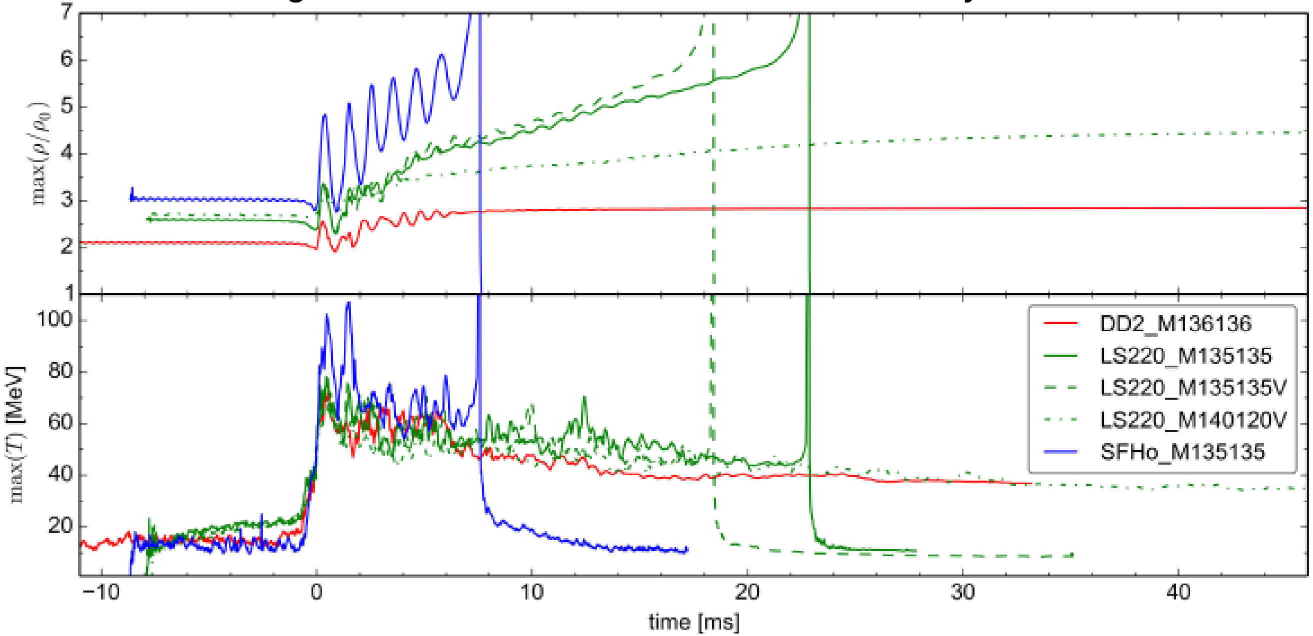


$$\rho = 4 \times 10^{14}\,\mathrm{g/cm^3}$$

$$T = 30\,\mathrm{MeV}$$

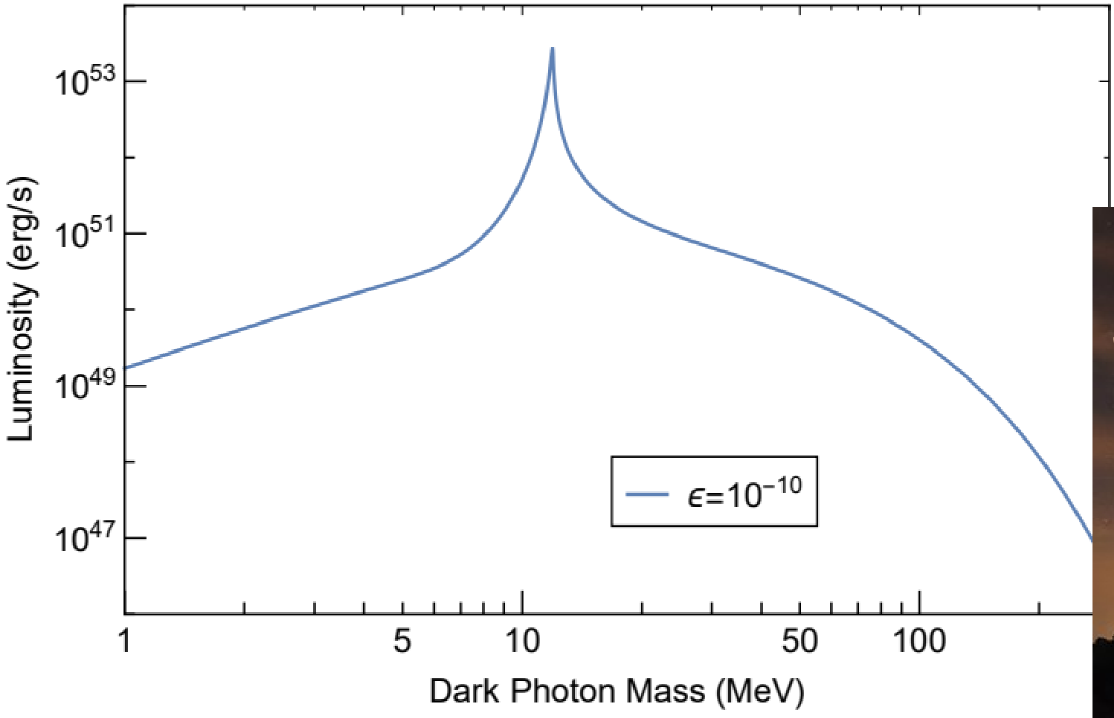
$$Y_p = 0.1$$

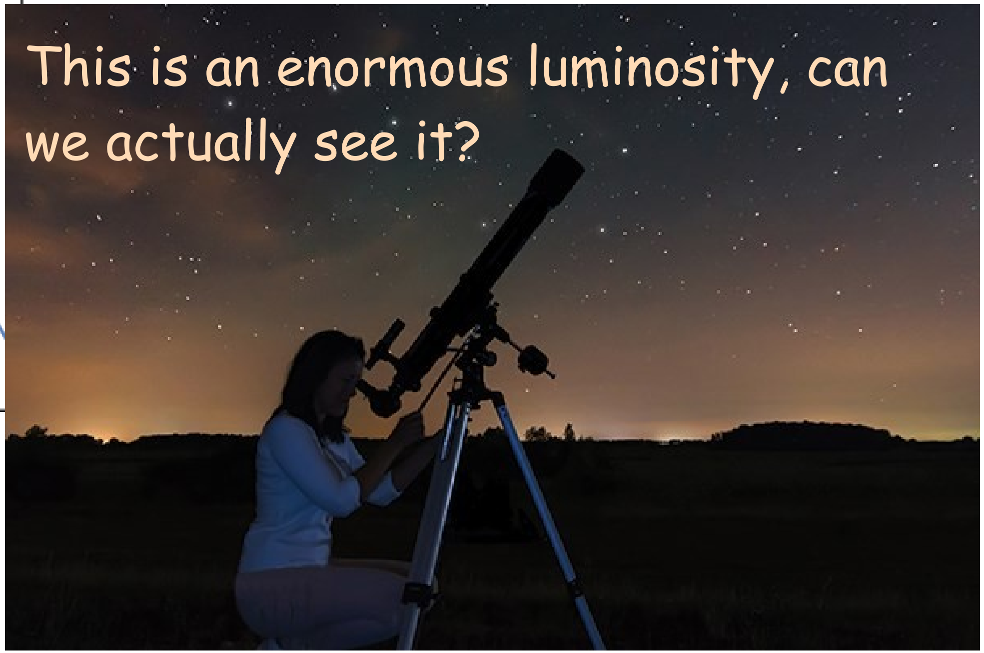
Perego, A., Bernuzzi, S., Radicce, D., Eur. Phys. J. A 55, 124



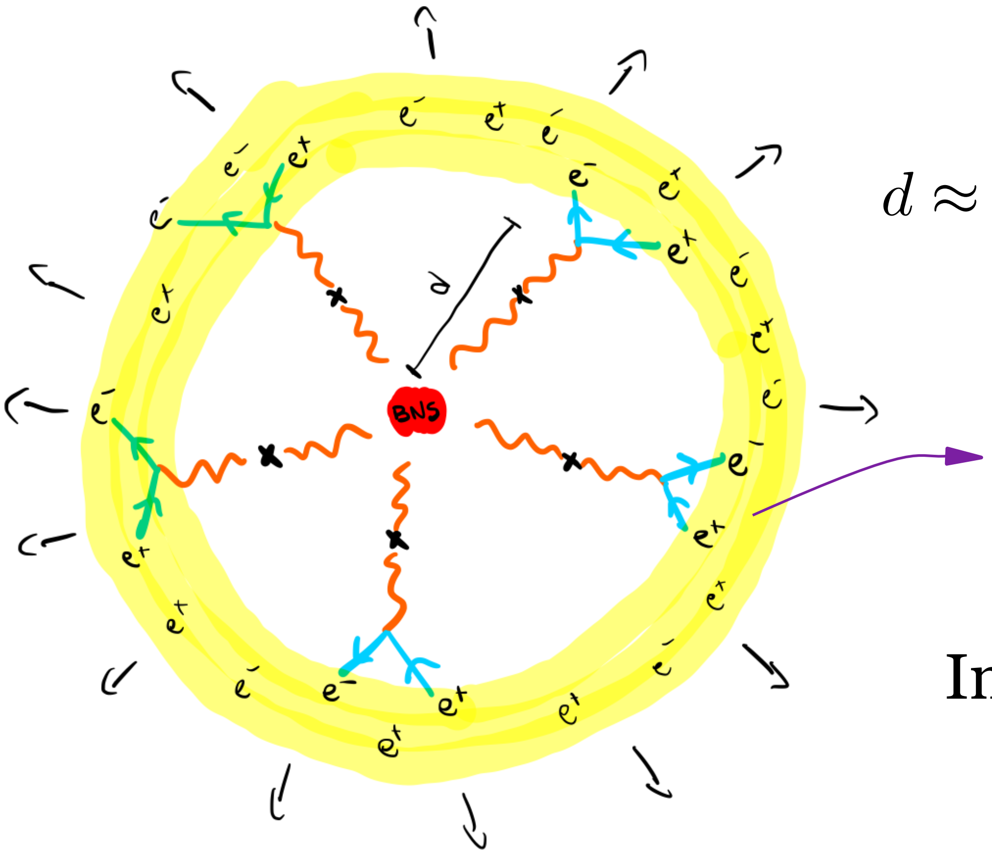
$$\delta t \approx 10 - 1000\,\mathrm{ms}$$

Dark photon luminosity





Transient photons



$$d \approx \frac{\gamma}{\Gamma} \sim \left(\frac{10^{-9}}{\epsilon}\right)^2 \left(\frac{10\,\text{MeV}}{m'}\right) 10^4\text{km}$$

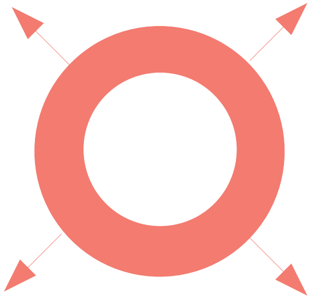
Signal duration set by shell width $\delta \approx (\gamma\Gamma)^{-1}$

Initially: $T \approx m'/6 \sim \text{MeV}$

$$n_e \ll \text{MeV}^3$$

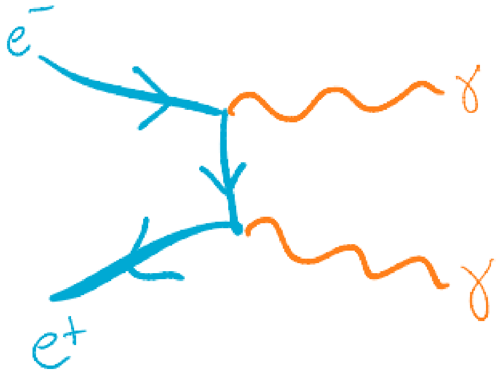
Relevant dynamics

Expansion



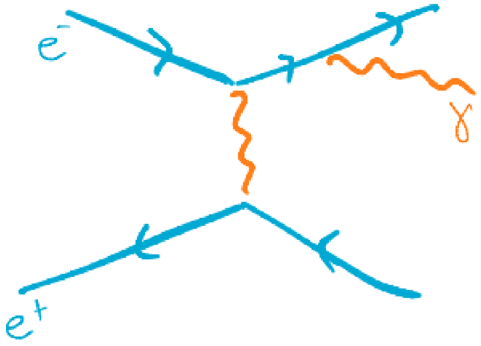
$$\rho \propto R^{-4}$$

Annihilation



$$\frac{n_e}{n_\gamma} \approx \frac{n_e^{\text{eq}}}{n_\gamma^{\text{eq}}}$$

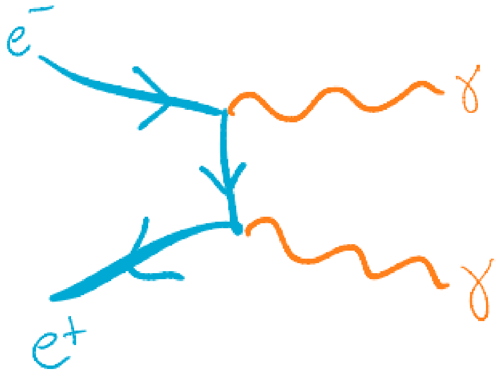
Bremsstrahlung



$$n_\gamma \to T^3$$

Thermal limit

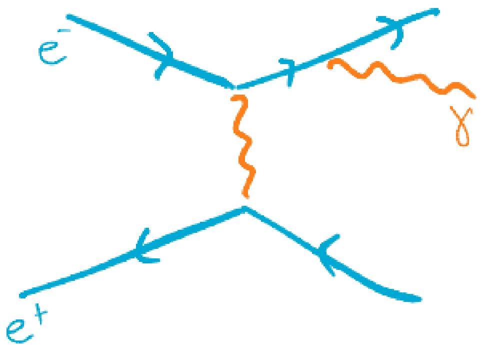
Annihilation



Detailed balance:

$$n_e \approx e^{-m_e/T} n_\gamma$$

Bremsstrahlung



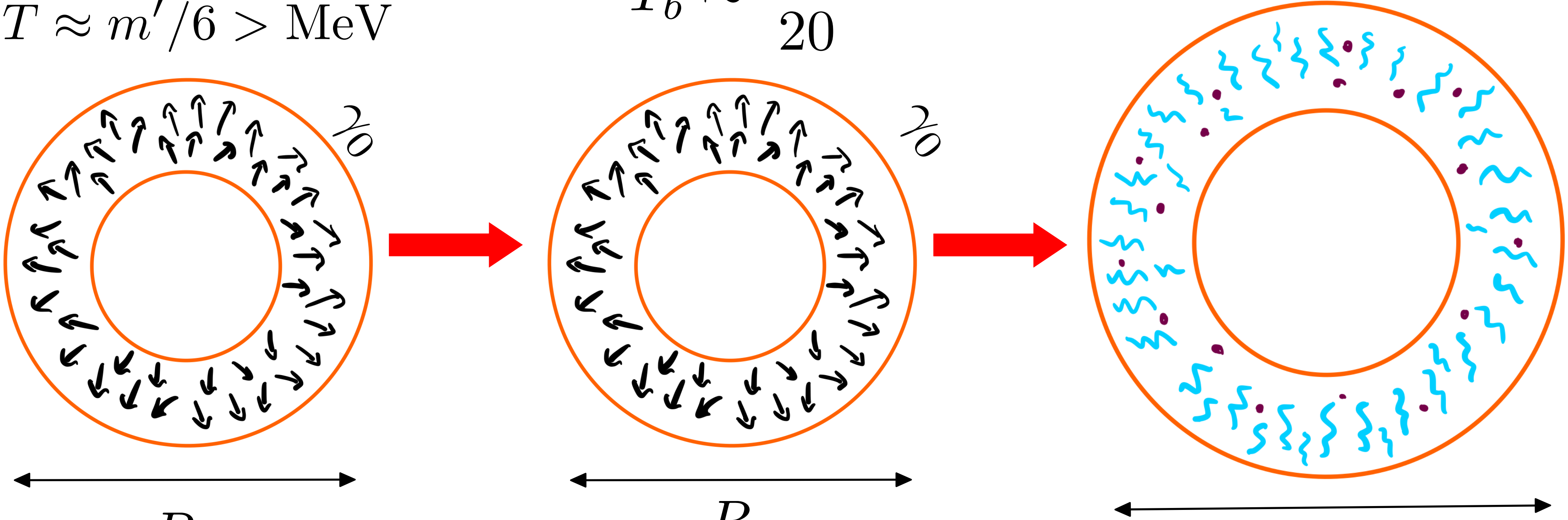
Temperature decreases

$$n_{\text{tot}} T \approx \text{const}$$

$T \approx m'/6 > \mathrm{MeV}$

$T_b \sim \dfrac{m_e}{20}$

$T_d \gamma_d = T_b \gamma_0$



R_0 | R_0 | R_d

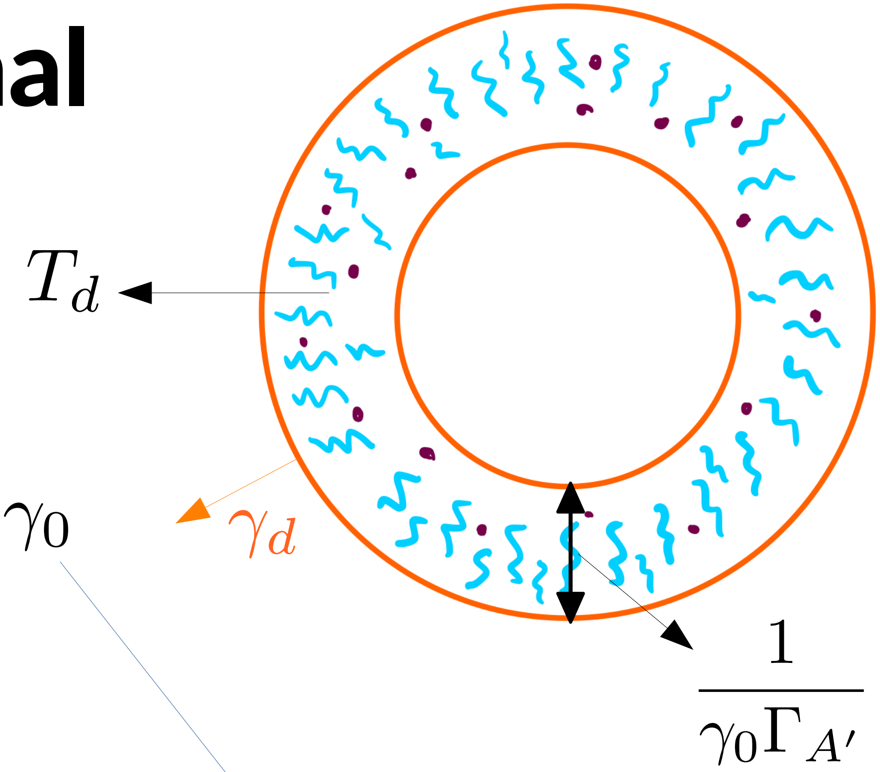
$\Gamma_{\mathrm{brem}} > \Gamma_{\mathrm{exp}}$

$\Gamma_{\mathrm{annih}} > \Gamma_{\mathrm{exp}}$

$\Gamma_{\mathrm{brem}} \sim \Gamma_{\mathrm{exp}}$

$\Gamma_{\mathrm{annih}} > \Gamma_{\mathrm{exp}}$

Signal



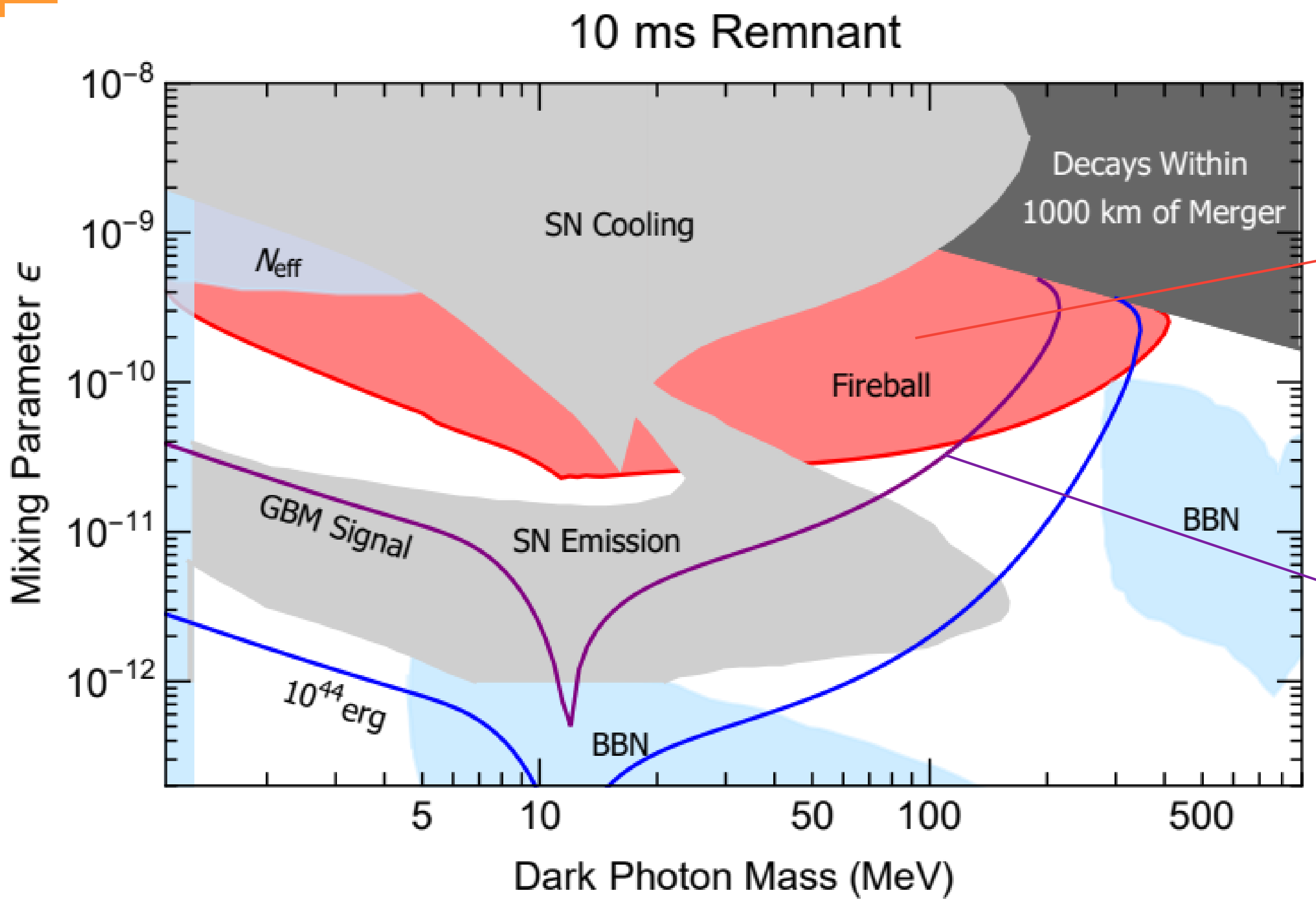
$$\omega_{\text{photon}} \approx T_d \gamma_d = T_b \gamma_0$$

$\sim m_e/20$

$\mathcal{O}(1)$

Thermal spectrum with T ~ 100 keV

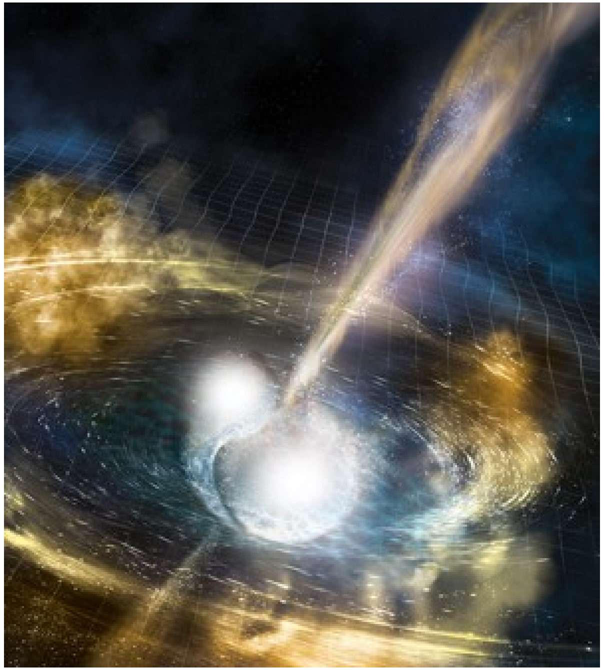
Signal region



Thermal spectrum, T ~ O(100) keV

Within Fermi-GBM sensitivity (100 kpc)

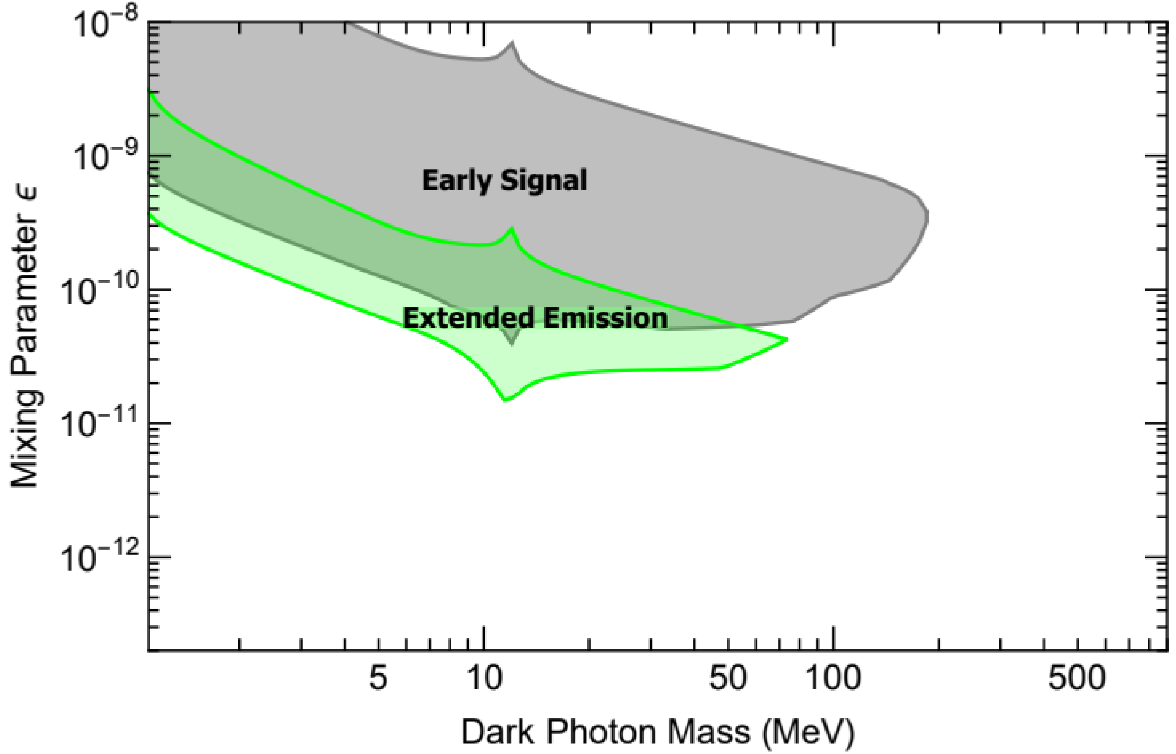
Backgrounds from sGRB



- Short Gamma Ray Burst is expected to follow a BNS merger
- Originates from relativistic jet: beamed
- In this case, for same distance, luminosity would have large variance. Statistically distinguish dark sector signal from sGRB
- One potential irreducible background would be wide angle emission. Still poorly understood.
- Timing, duration and spectrum can also be used

Tentative constraints from GW170817

Using simplified remnant model, and comparing timing and duration of signal to observed gamma ray burst:



Promising future

- Currently, prompt emissions rely on large field of view telescopes, subject to larger backgrounds
- Mid-band gravitational wave detectors would detect binary significantly before merger and improve localization
- Many proposals for new low MeV telescopes, such as AMEGO
- To use this signal for discovery will require better modeling of the expected signal from short gamma ray bursts (sGRB)

Conclusions

- Dark sectors are motivated extensions of the standard model whose experimental consequences extend over the 3 frontiers
- In models in which the interactions of dark sector particles and the standard model are very weak, extreme astrophysical systems provide one of the most promising opportunities for discovery
- Stable dark sector particles produced in supernovae could be searched for using large direct detection experiments (e.g. LZ)
- Unstable particles can produce very bright photon signals, both in supernovae and in neutron star mergers
- Many directions to explore, and significant experimental improvement expected for the future