PASCOS 2021

Dark sector visible signals in neutron star mergers

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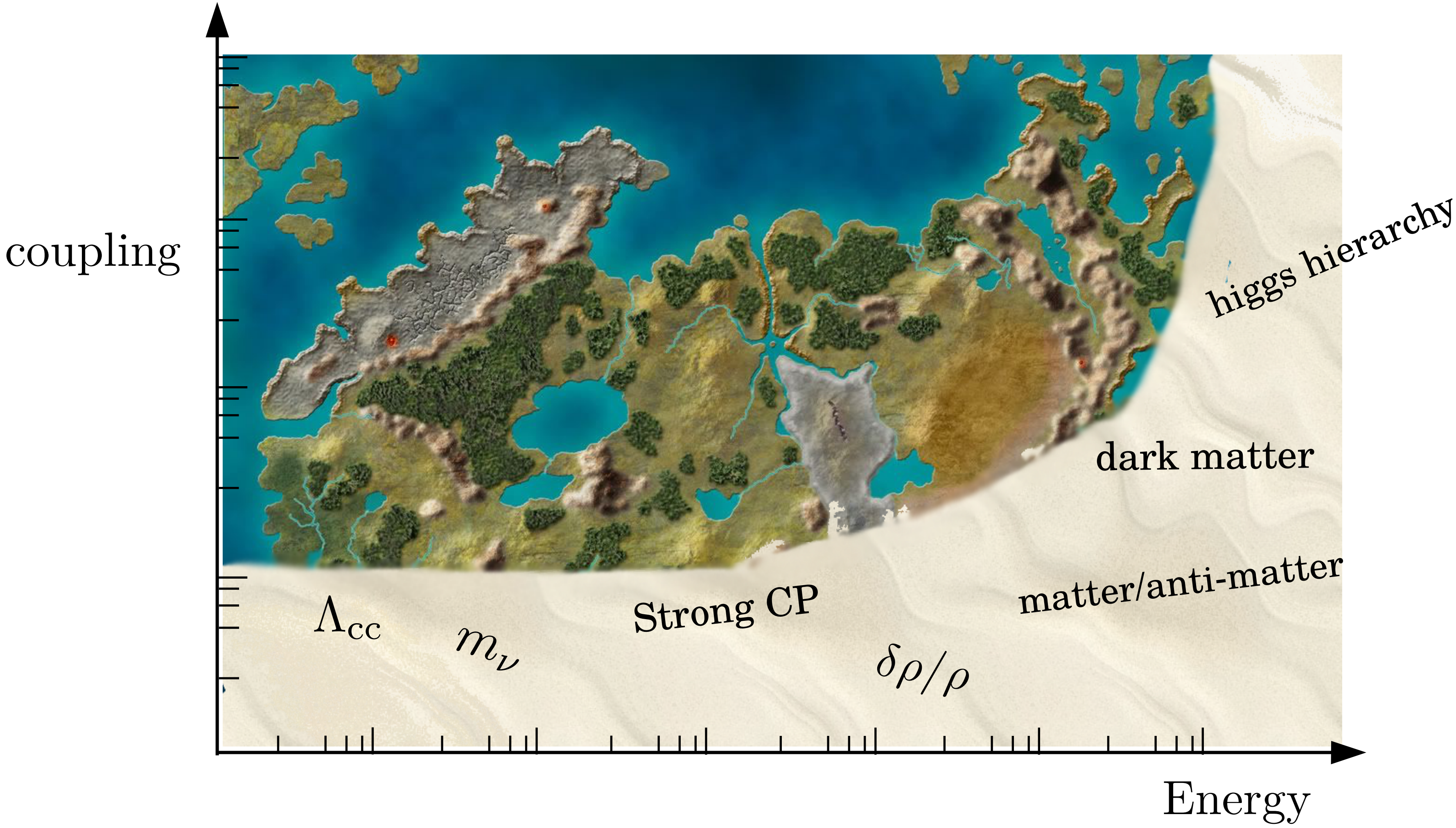
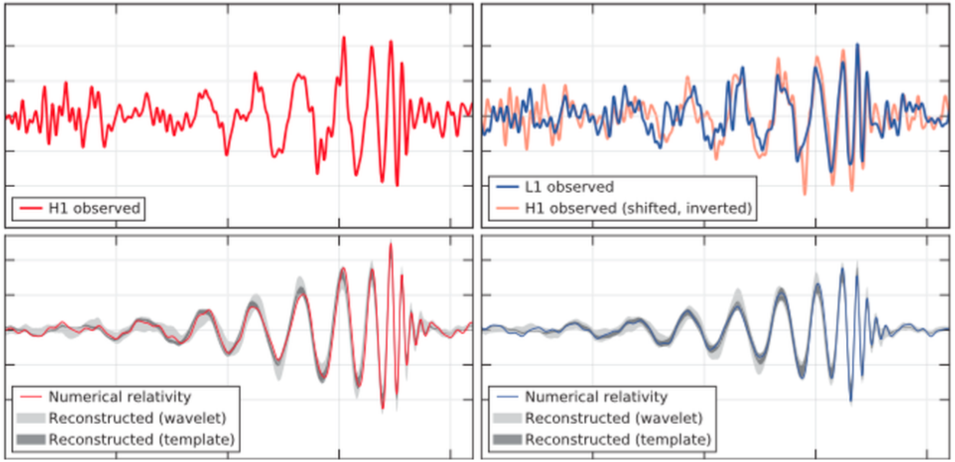
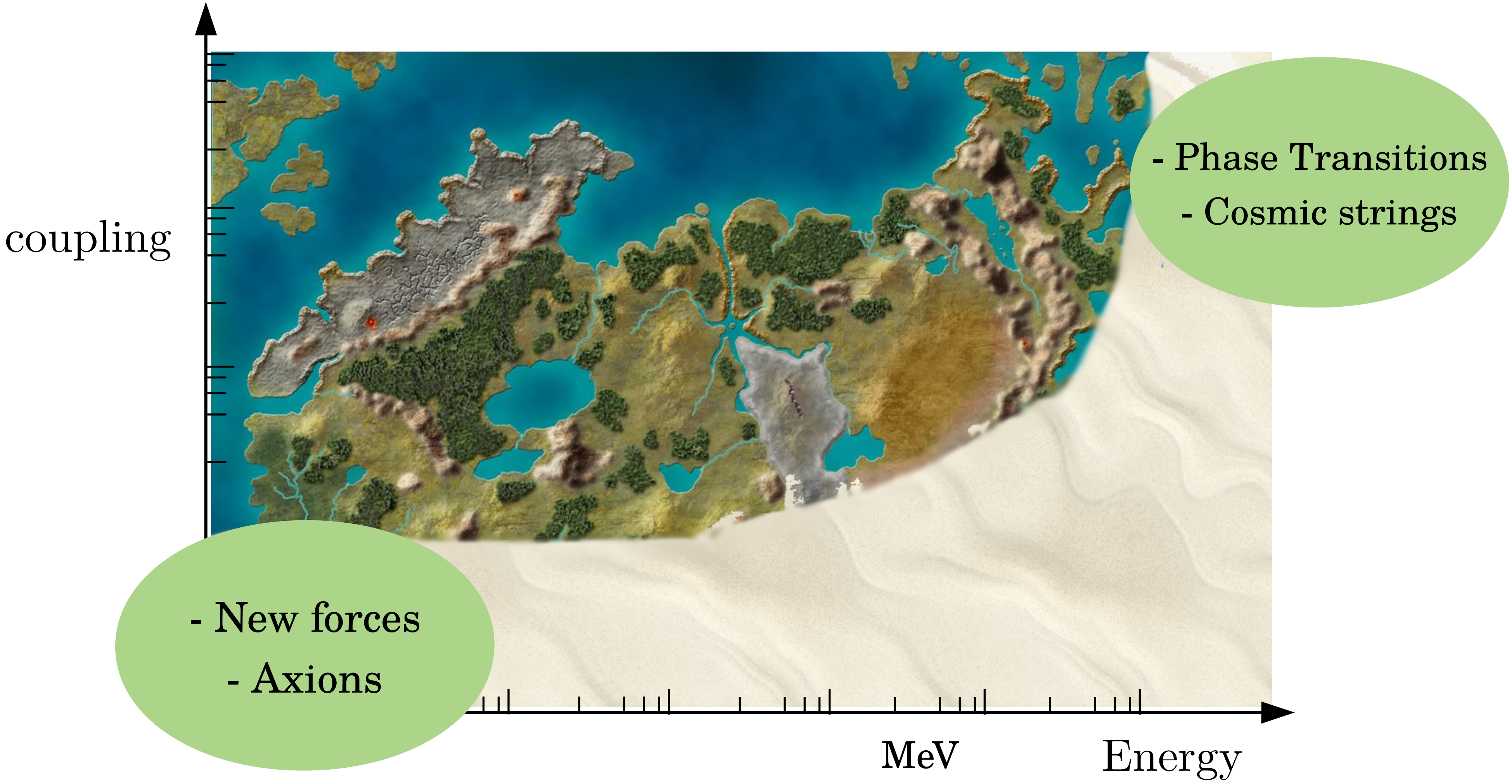
in collaboration with Melissa Diamond, arxiv:2106.03879

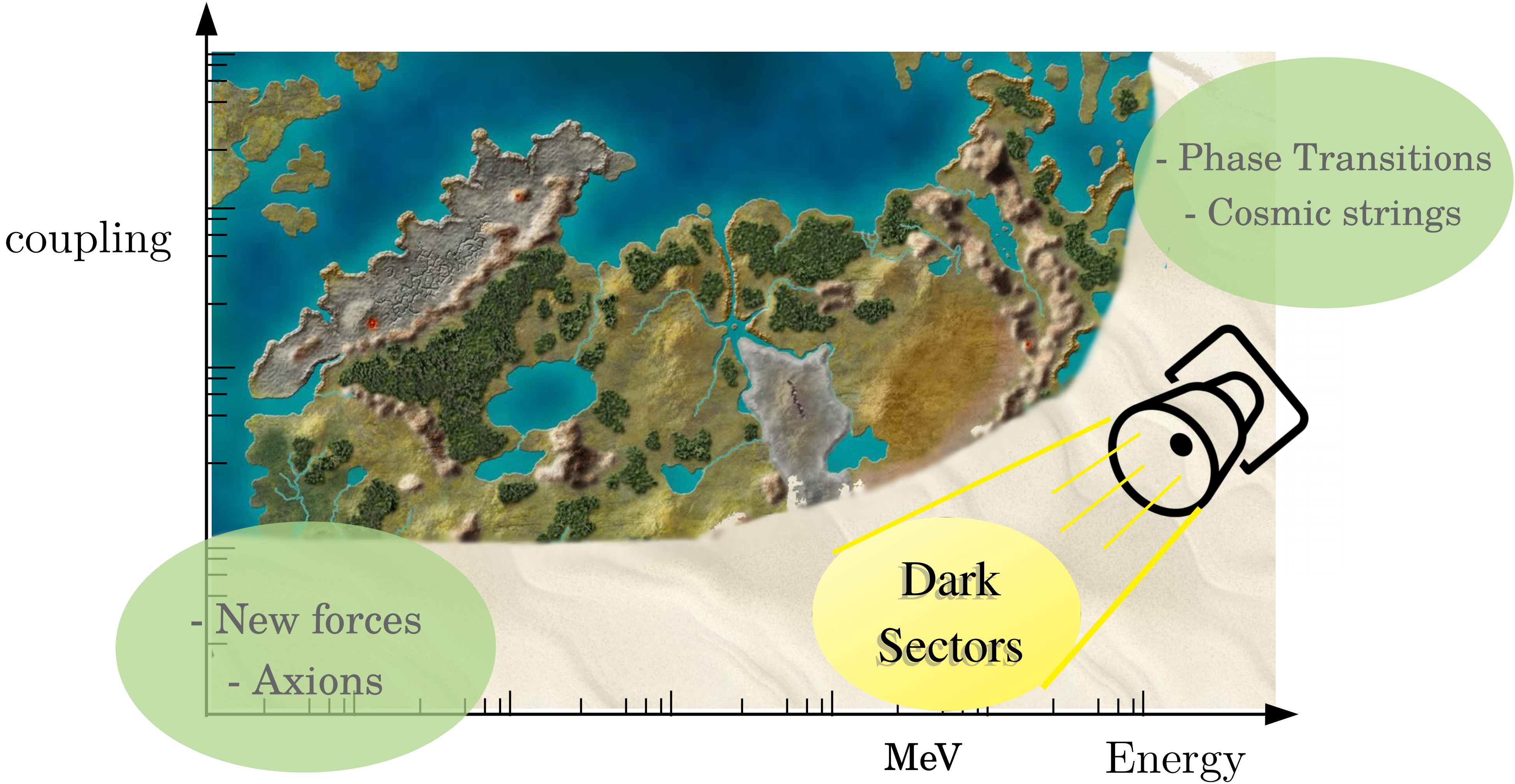

coupling
higgs hierarchy
dark matter
matter/anti-matter
Λ_{cc}
m_ν
Strong CP
$\delta\rho/\rho$
Energy

Dawn of gravitational wave era

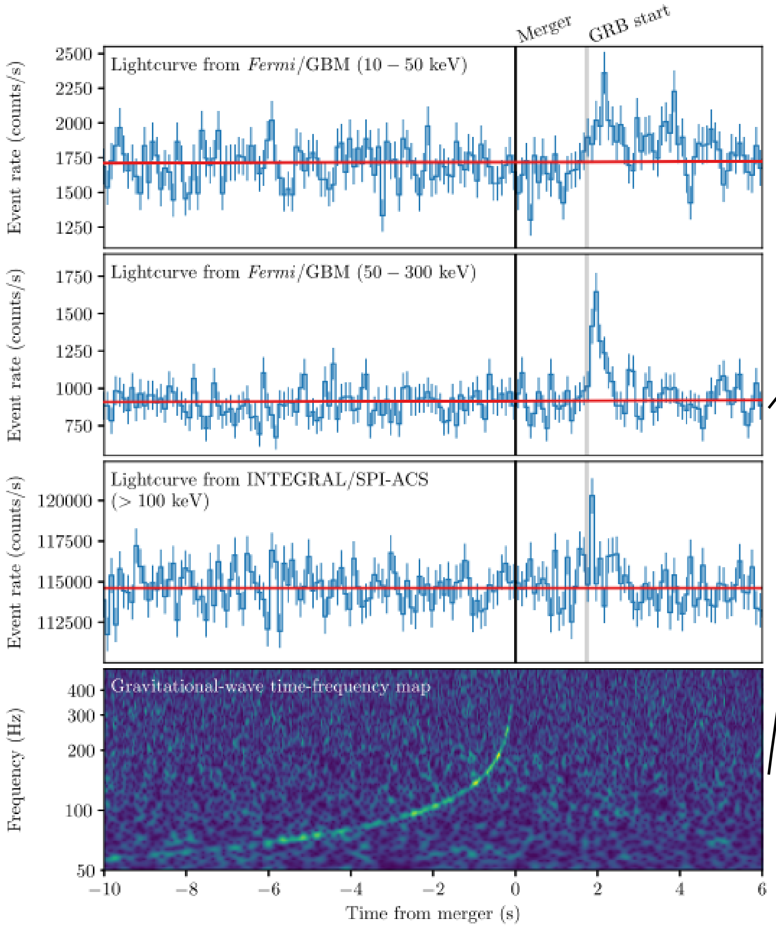


<u>A new window into the universe</u>


coupling
- Phase Transitions
- Cosmic strings
- New forces
- Axions
MeV
Energy


coupling
- Phase Transitions
- Cosmic strings
- New forces
- Axions
Dark Sectors
MeV
Energy

Multi-messenger astronomy



Gravitational Waves + Photons

A probe for new physics

- Large scale neutrino detectors + photons from SN1987a led to stringent constraints on new physics.
- What can we learn from this new probe?

Gamma-rays from dark sectors

- Neutron star mergers as factories for MeV scale dark sectors
- Unstable dark sector particles $\rightarrow$ gamma-rays
- Gravitational waves + bright gamma-ray flash as a new signal of dark sectors

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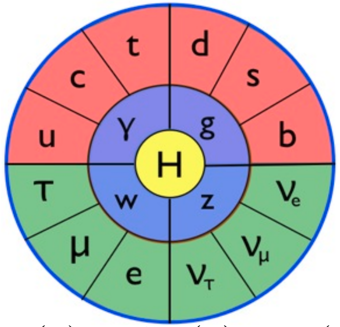
Dark sector portals

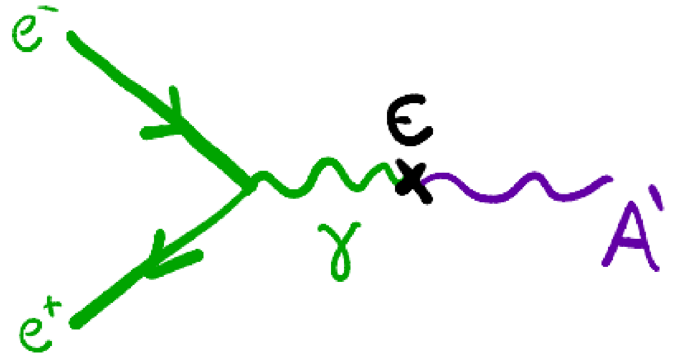


$SU(3) \times SU(2) \times U(1)$

Vector portal	$B^{\mu\nu} F_{\mu\nu}$
Scalar Portal	$\lvert H \rvert^2 \phi^{(2)}$
Fermion Portal	$(LH)\psi$

Dark Photons

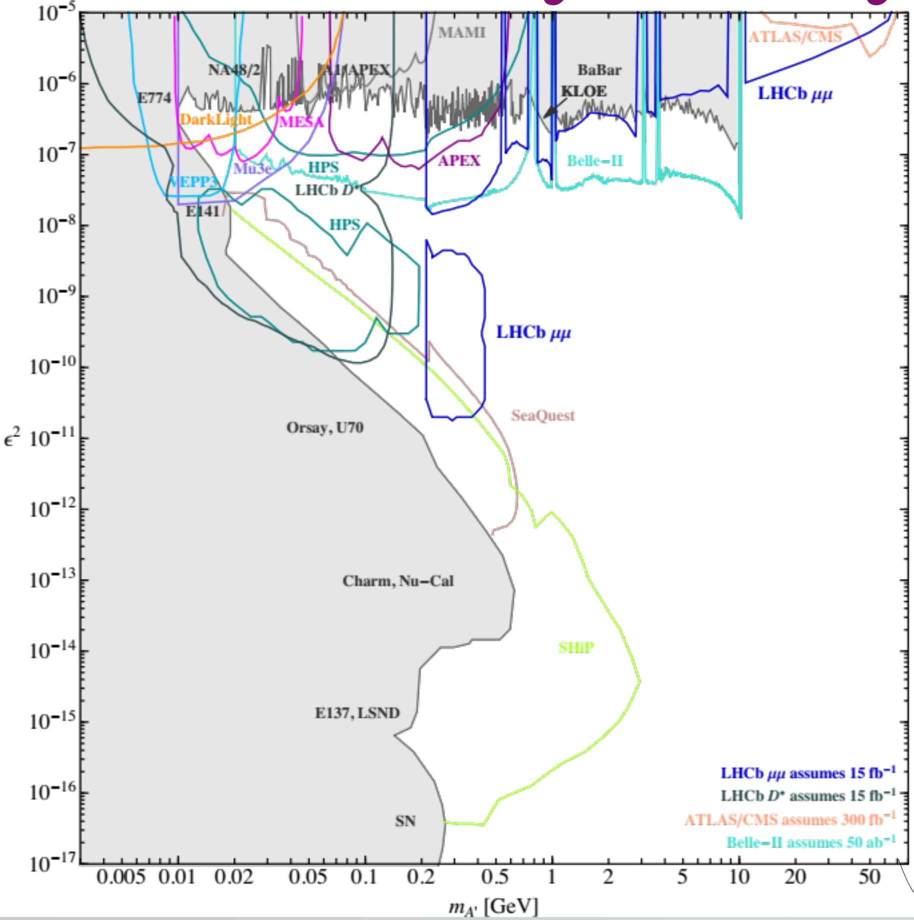
$$-\frac{1}{4}F'^2 - \frac{\epsilon}{2}FF' + \frac{m'^2}{2}A'^2$$



Focus on visibly decaying scenario

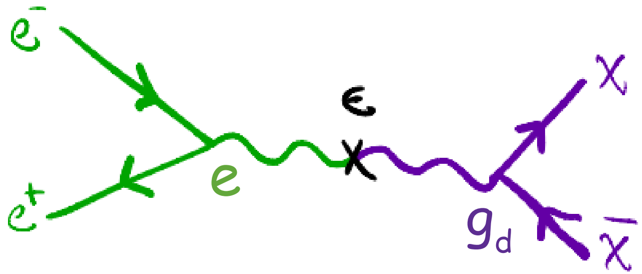
$$\mathrm{Br}(A' \to e^+e^-) \sim 1$$

Visibly decaying dark photons



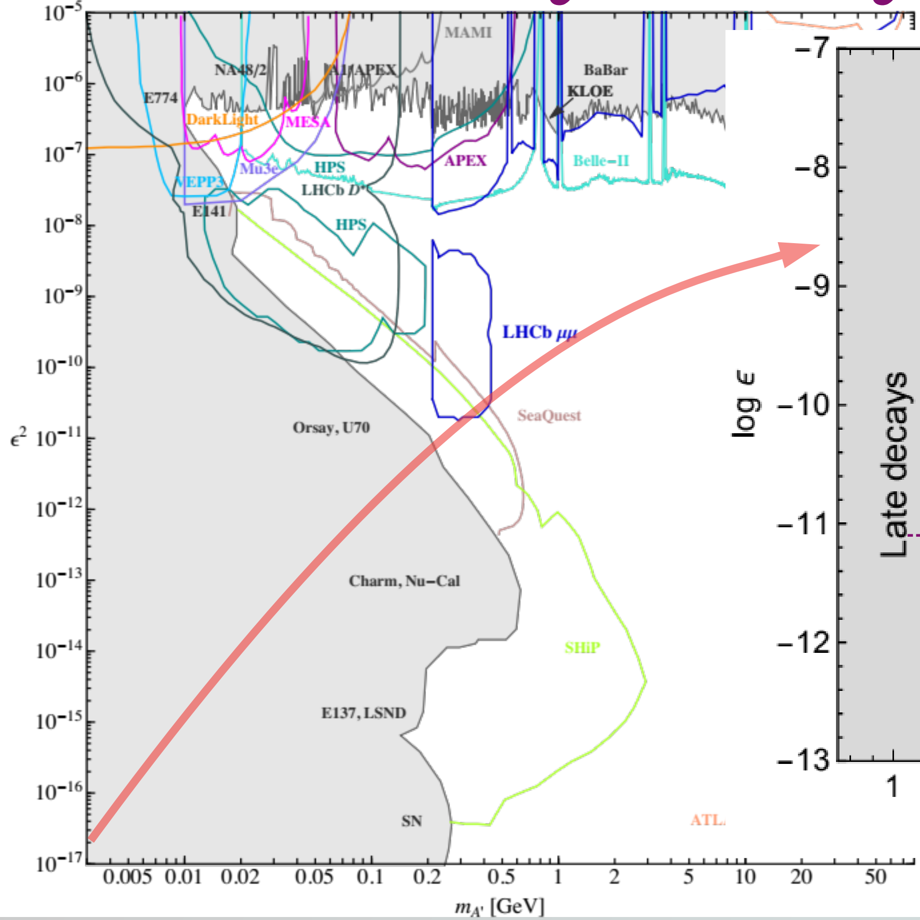
Ilten, P et. al., PRL 116, 251803

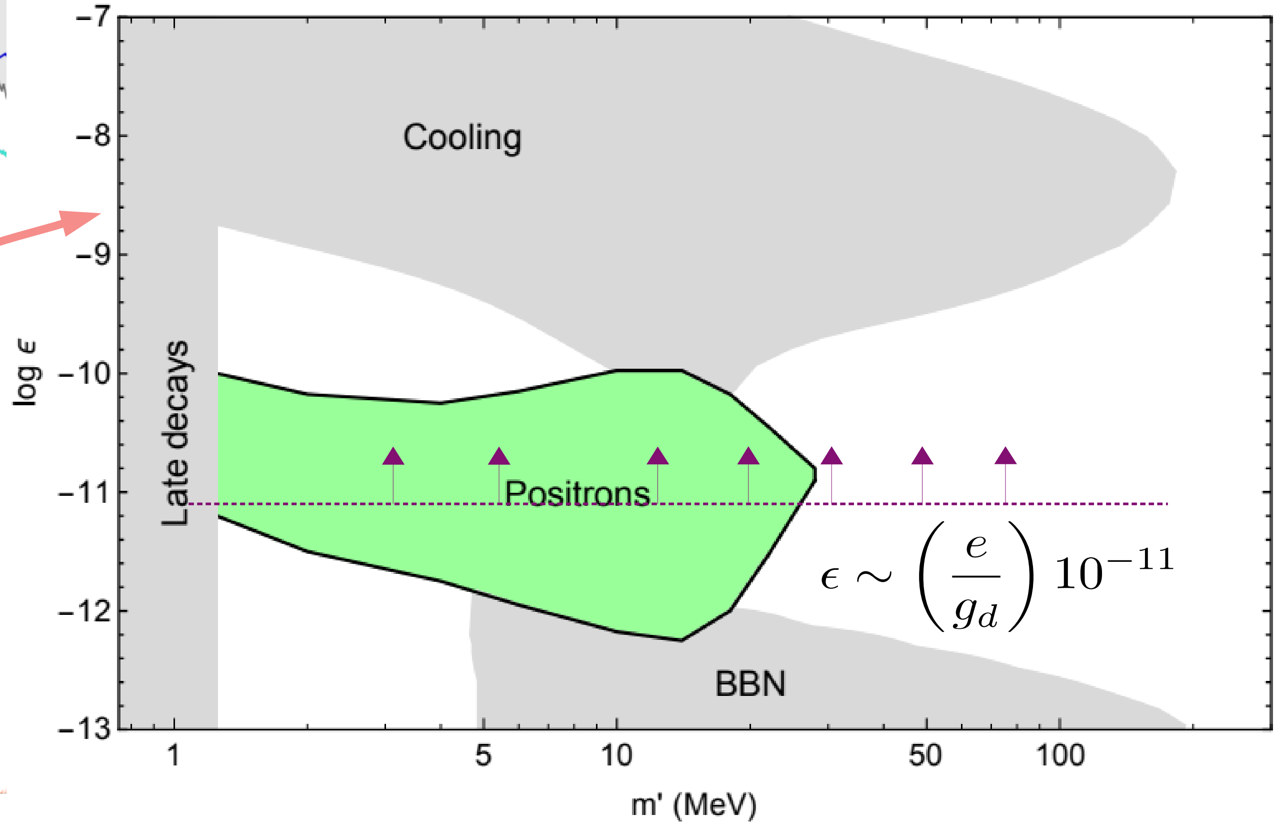
Freeze-in target



$$\epsilon \gtrsim \left(\frac{e}{g_d}\right) 10^{-11}$$

Visibly decaying dark photons





DeRocco W., GMT, et. al., JHEP 02, 171

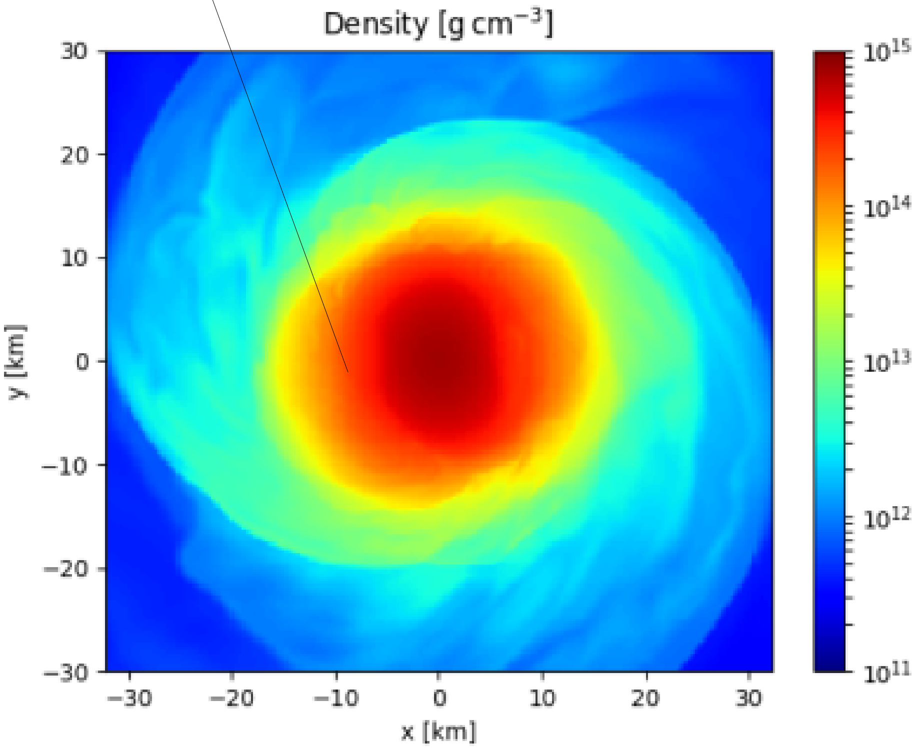
Why binary neutron star mergers

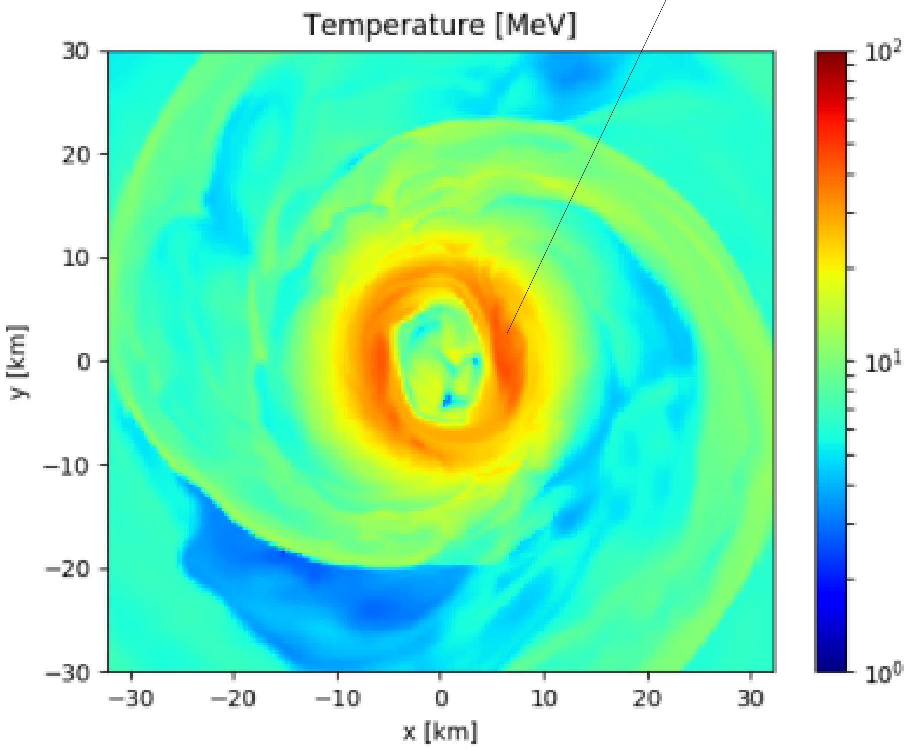
- Neutron stars about a solar mass in a radius of about 10 km: $\rho \sim (100\mathrm{MeV})^4$
- At the final state of the merger the orbital velocity is ~ 0.1c
- Tidal heating + collision lead to a remnant with $T \sim 30\mathrm{MeV}$
- Remnant can be long lived ~ 10-1000ms

Merger remnant

$\rho \gtrsim 10^{14}\mathrm{g/cm}^3$

$T \gtrsim 30\mathrm{MeV}$

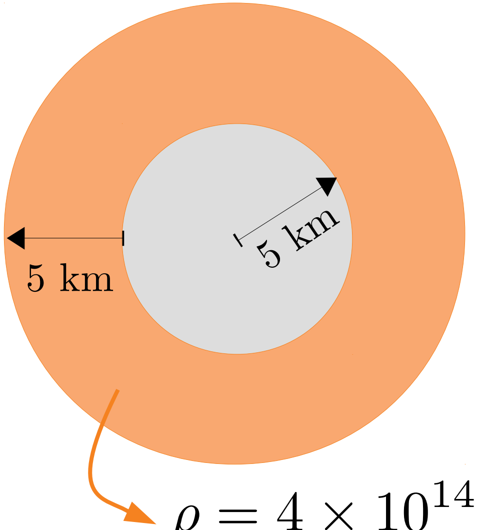




Perego, A., Bernuzzi, S., Radicce, D., Eur. Phys. J. A 55, 124

Proof of principle

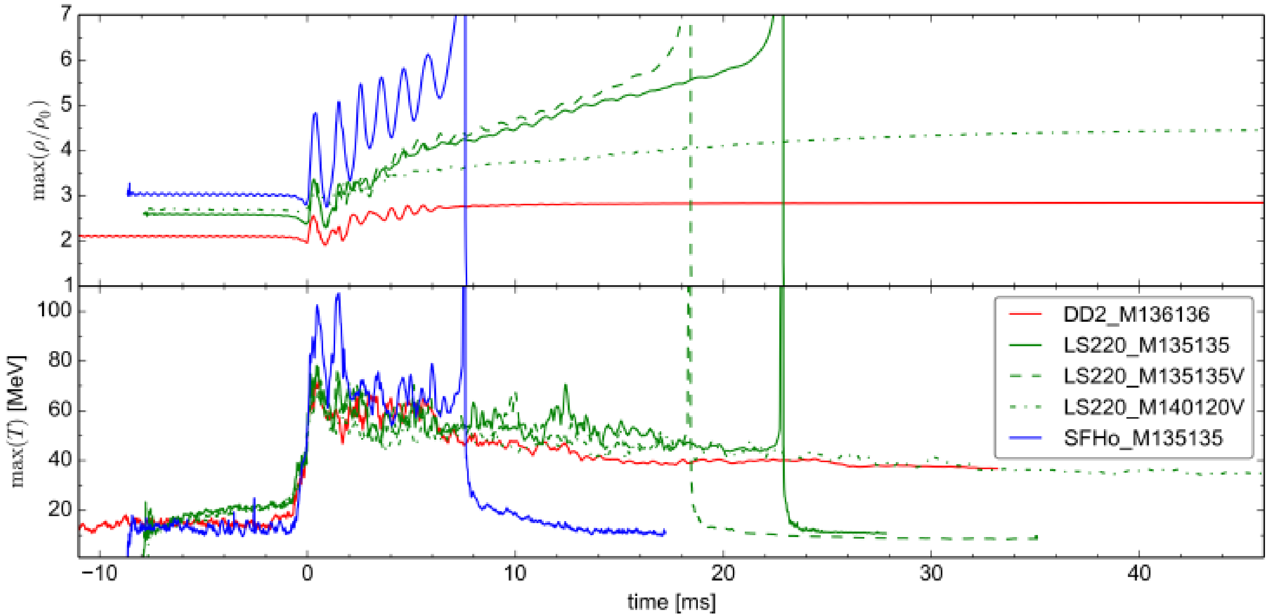
Spherical shell emission



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

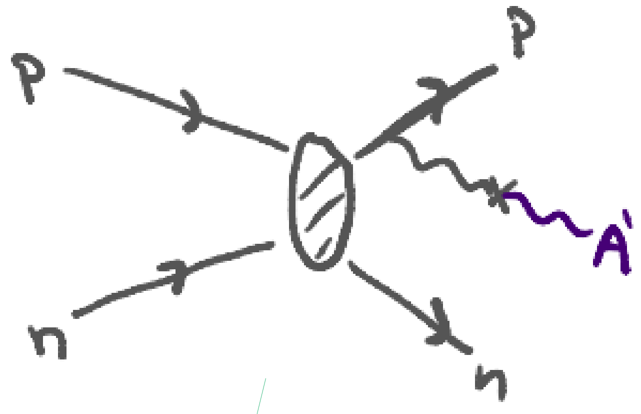
$$T = 30\,\mathrm{MeV}$$

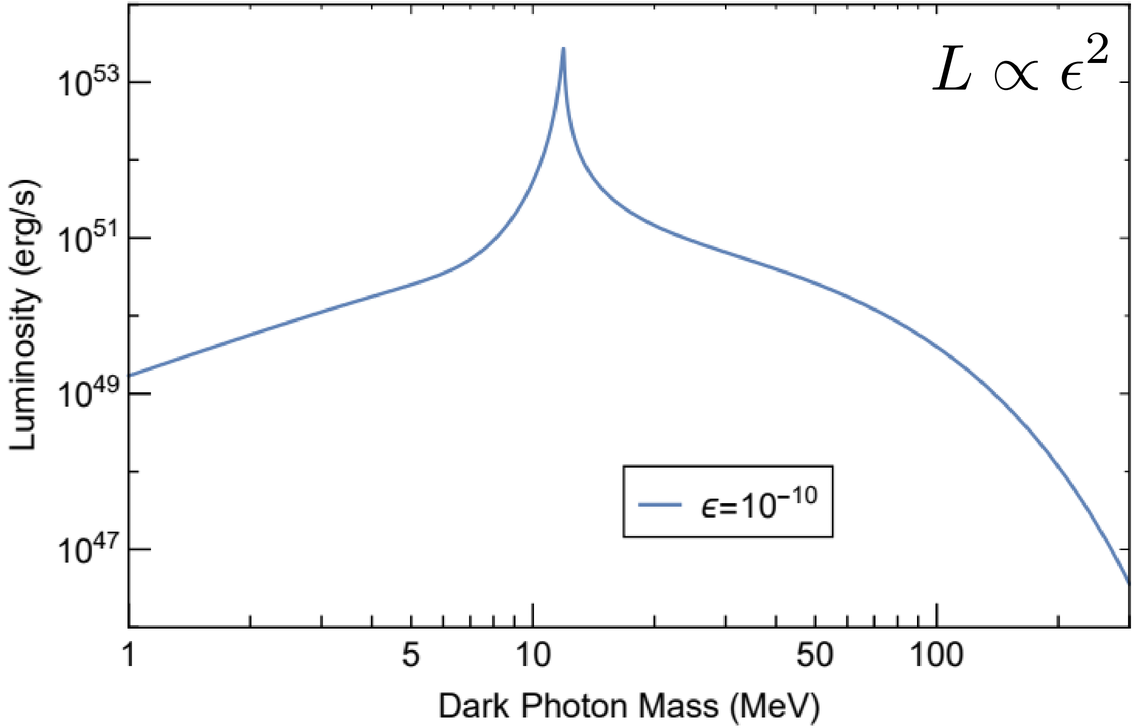
$$Y_p = 0.1$$



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

Production rate in remnant





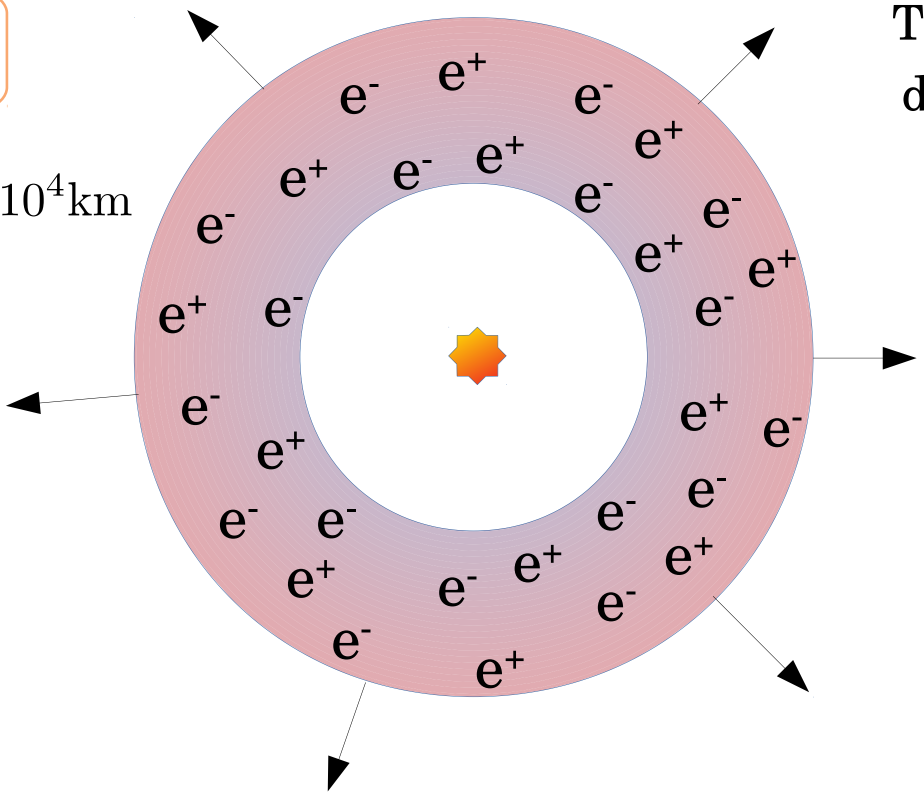
J. Chang, R. Essig, S. Mcdermott, JHEP 2017, 107

GRB170817A: 10^{47} erg/s

Dark photon visible decays

$$\boxed{A' \to e^+ e^-}$$

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



Thermodynamic properties defined in comoving frame

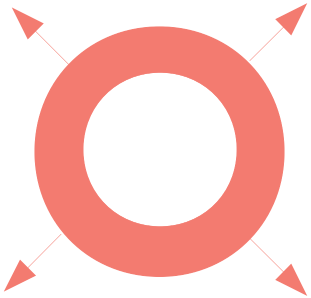
$$\boxed{T \sim m' \sim \mathrm{MeV}}$$

$$\boxed{n \sim \frac{N_{A'}}{d^3/\gamma} \ll \mathrm{MeV}^3}$$

final signal depends on evolution of this plasma

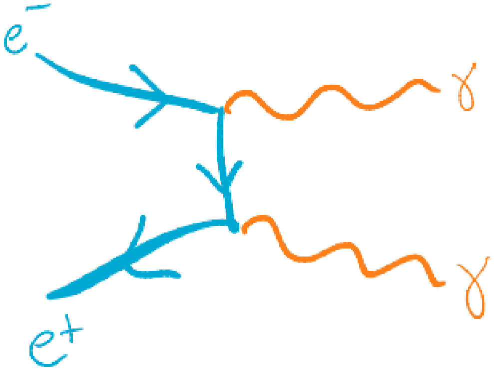
Important processes

Expansion



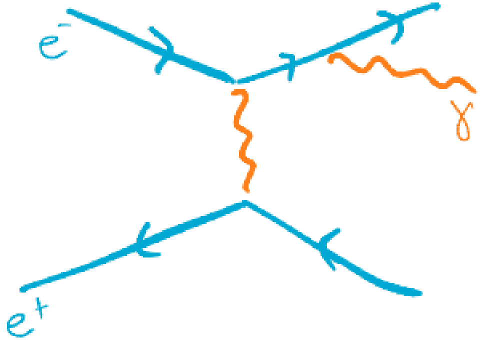
$$\rho \propto R^{-4}$$

Annihilation



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

Bremsstrahlung



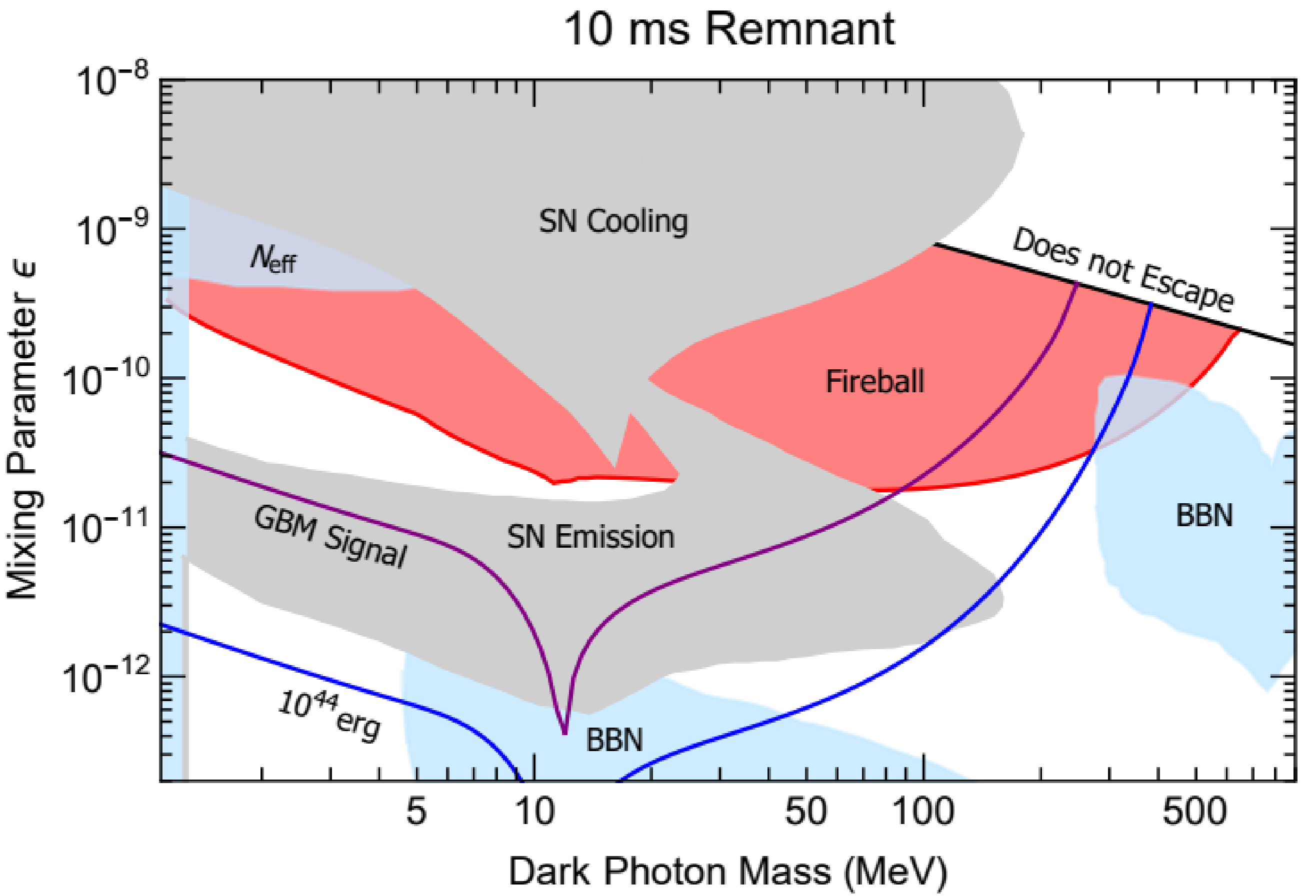
$$n_\gamma \to T^3$$

Thermal scenario

- If the annihilation and bremsstrahlung rates are faster than expansion, the temperature drops below m_e quickly
- At that point the number density of electrons becomes small and photons can escape freely: $\Gamma \propto e^{-m_e/T}$

$$\boxed{\langle E_\gamma \rangle \sim 100\,\mathrm{keV}}$$

Results



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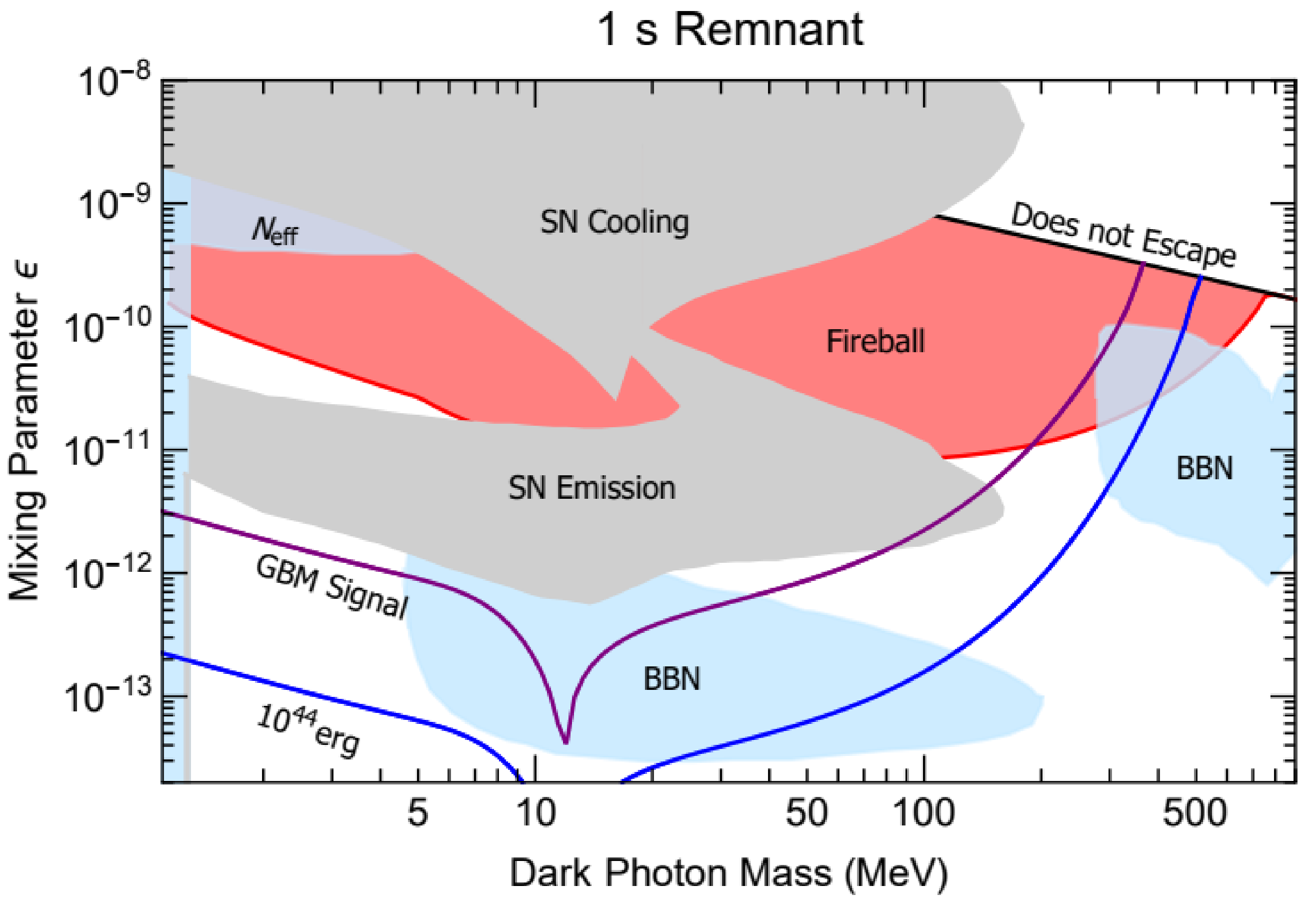
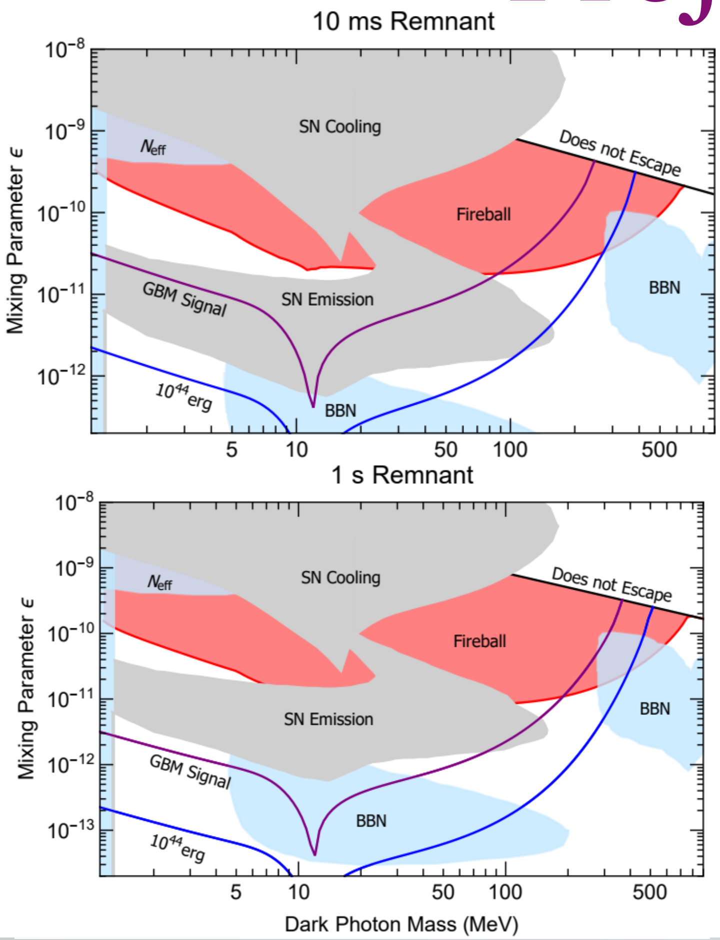
Results


1 s Remnant
Mixing Parameter ϵ
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
$N_{\rm eff}$
SN Cooling
Does not Escape
Fireball
SN Emission
BBN
GBM Signal
BBN
10^{44}erg
5
10
50
100
500
Dark Photon Mass (MeV)

Projected sensitivity



- Fireball region above purple curve should be tested with future observations
- In order to distinguish from ordinary GRB one can use thermal spectrum and near isotropy of signal
- More work needed to determine signal uncertainty due to remnant modeling

Conclusions & outlook

- Binary neutron stars are a promising environment to search for dark sectors
- Future data should probe the window for DM freeze-in through dark photons with masses 1-100 MeV
- Sensitivity can be significantly increased with mid-band GW detectors