LIGHT DARK SECTORS ◦ THEORY

Susanne Westhoff
Heidelberg University

questions? - westhoff@thphys.uni-heidelberg.de

Belle II Academy • March 22-26, 2021 • your living room

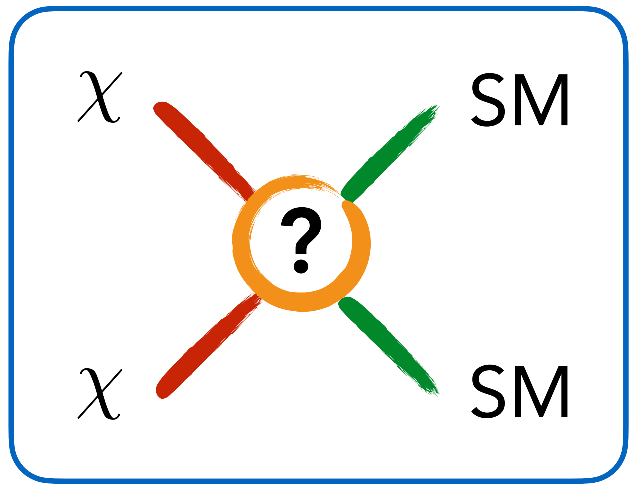
What's a dark sector?

from the particle Duden:

sector - *some set of particles that share a common feature*
dark - *anything we haven't seen or don't understand yet*

Let's make a dark sector!

dark sector

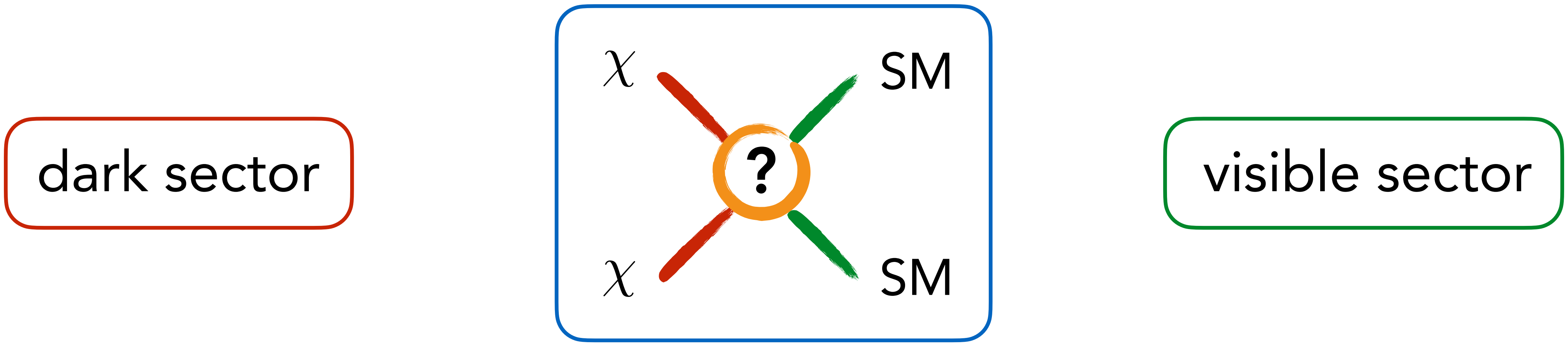


visible sector

We need:

- new dark particles
- a mediator particle
- interaction rules

Let’s make a dark sector!



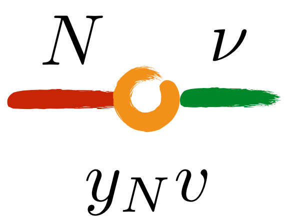
We need:

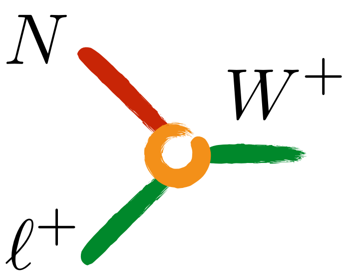
- new dark particles - no (or little) charge under SM forces
- a mediator particle - carrier of a new force
- interaction rules - quantum field theory

Portals

portal - *new interaction that leaves SM forces untouched*

Neutrino portal: $\mathcal{L} = y_N(\overline{L}H)N + h.c.$





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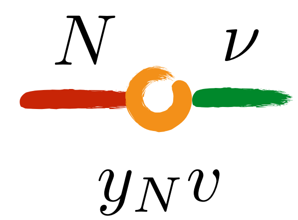
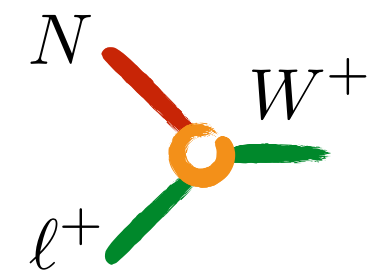
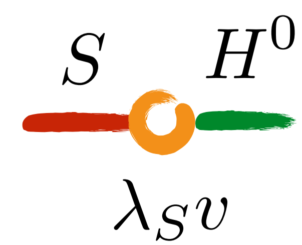
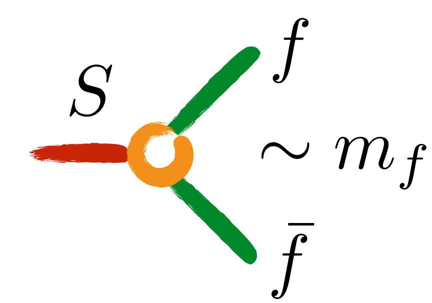




Higgs portal: $\mathcal{L} = \lambda_S(H^\dagger H)S$





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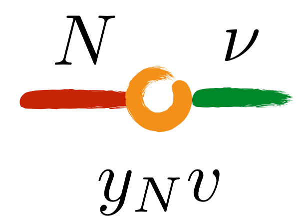

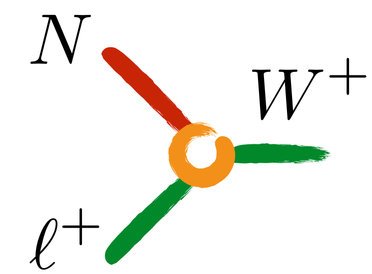

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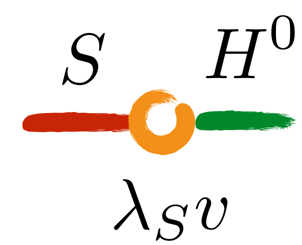
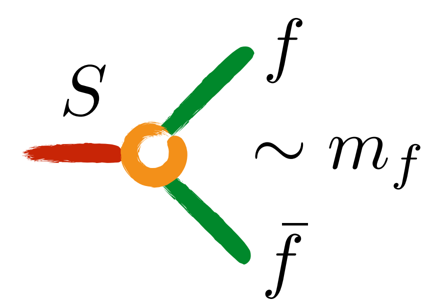
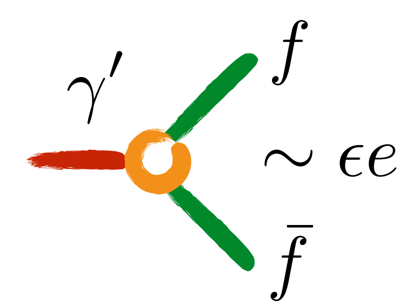




Vector portal: $\mathcal{L} = \epsilon\, F^{\mu\nu} F'_{\mu\nu}$



Portals

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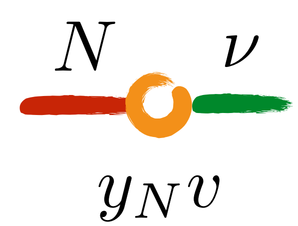

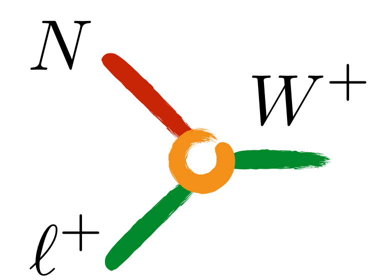

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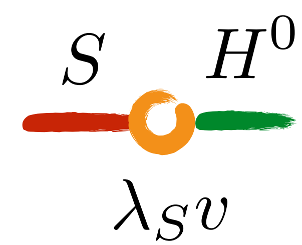

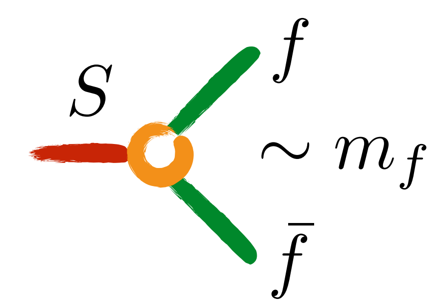

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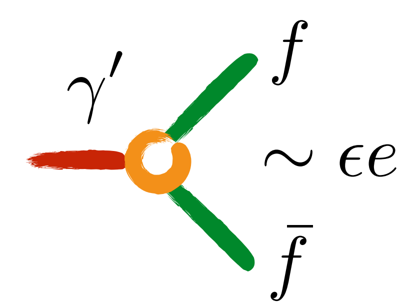
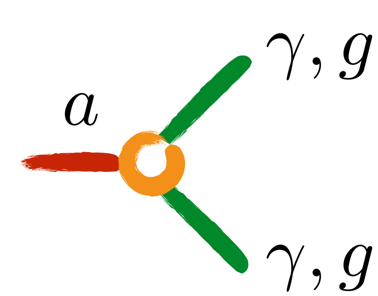
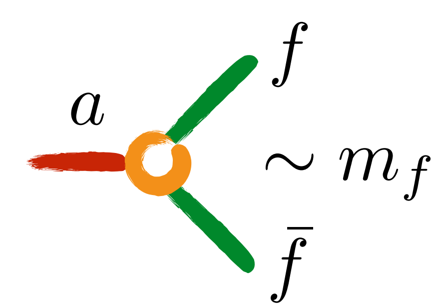


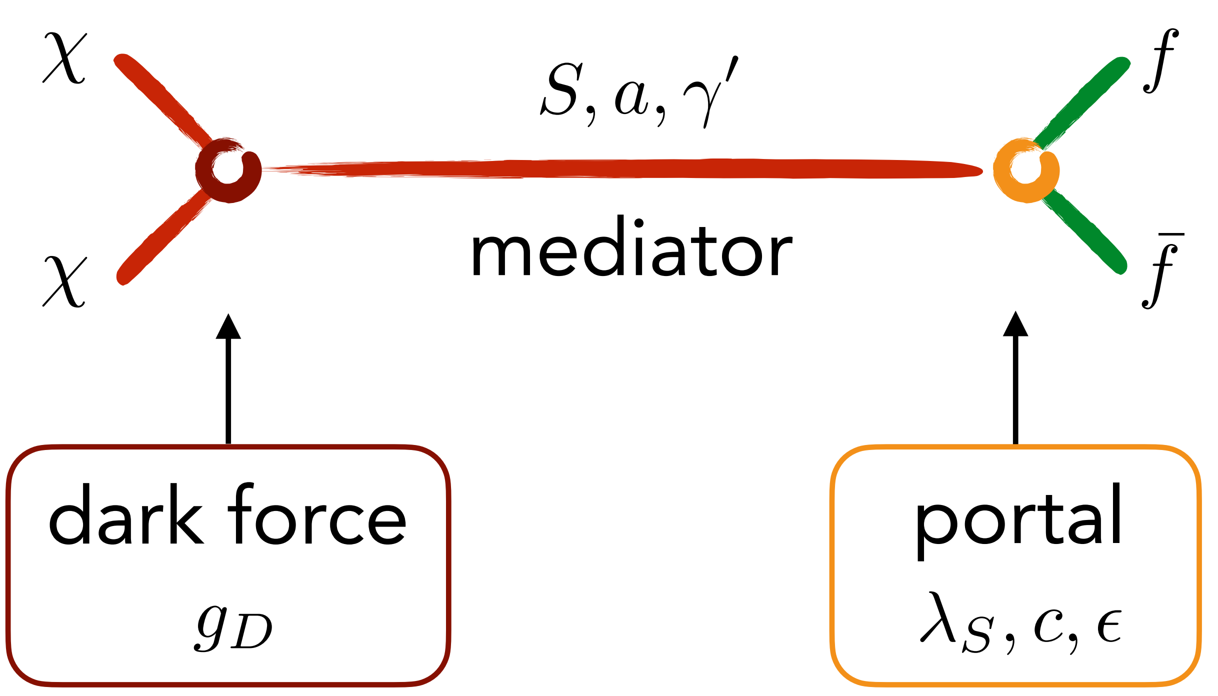
ALP: $\mathcal{L}_{\text{eff}} = c_V \, \frac{a}{\Lambda} V_{\mu\nu} \widetilde{V}^{\mu\nu} + c_f \, \frac{\partial_\mu a}{\Lambda} (\bar{f} \gamma^\mu \gamma_5 f)$





Dark and visible matter

Probe the dark sector through a portal:

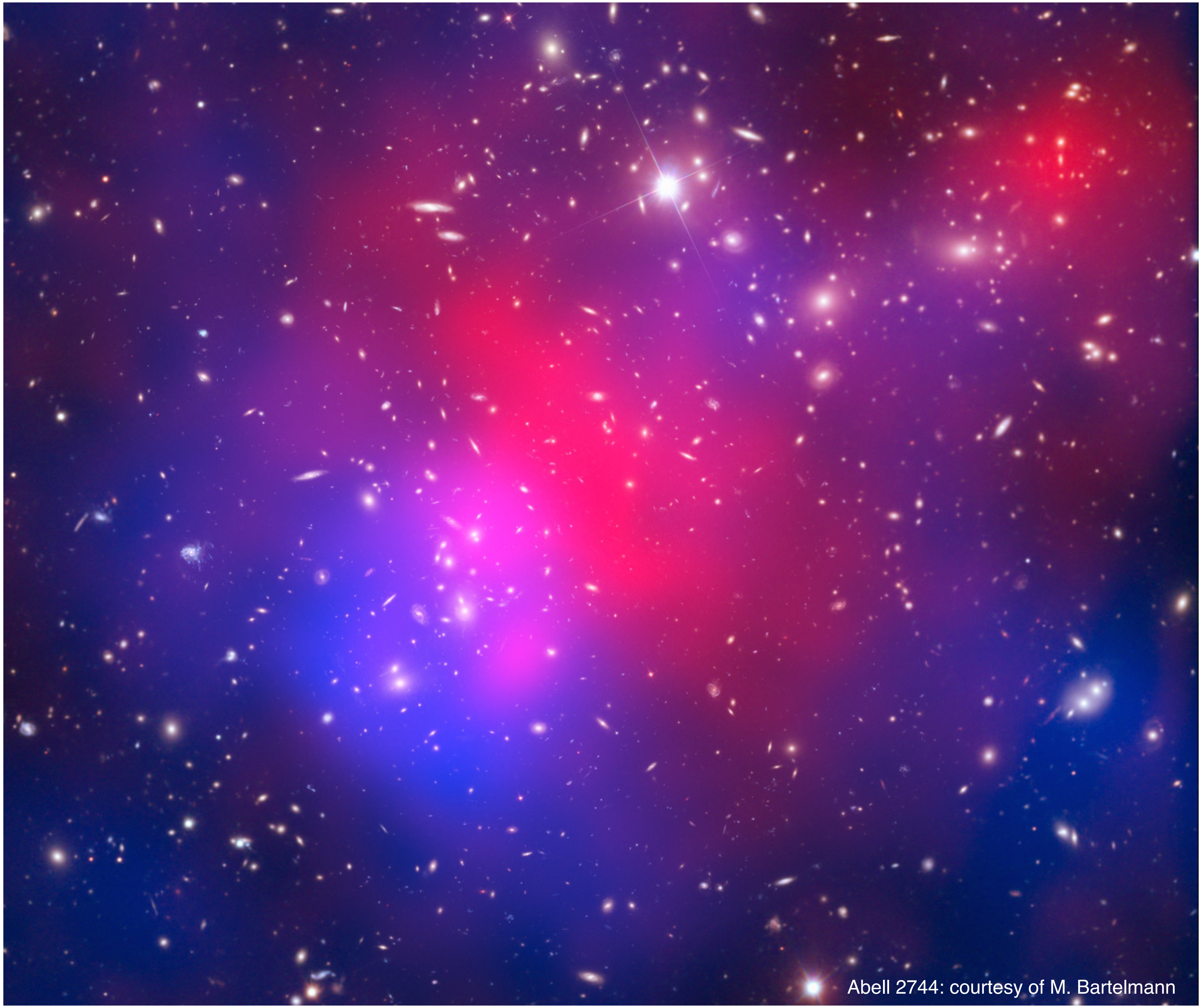


could be strong

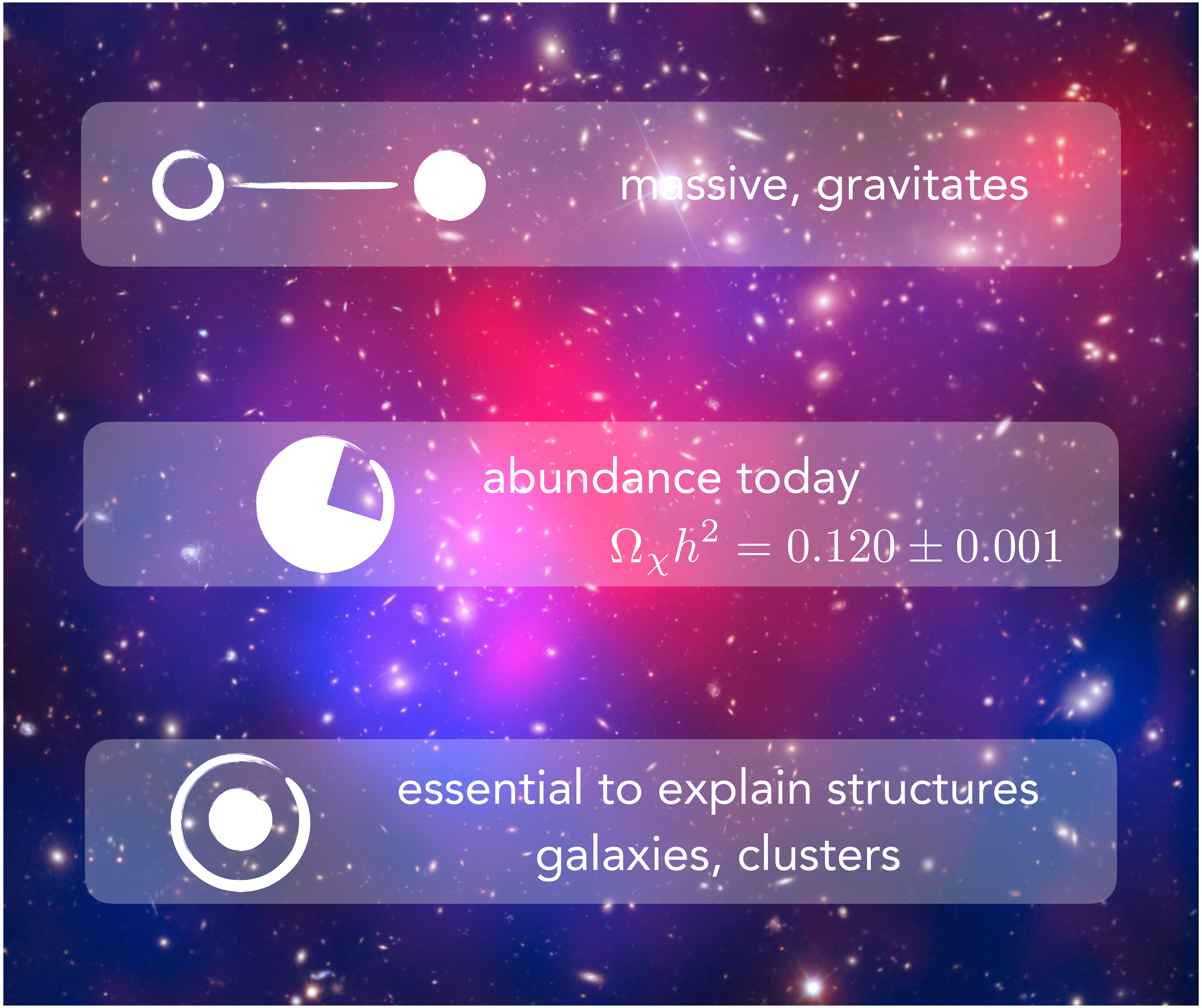
should be weak

Pospelov, Ritz, Voloshin 0711.4866

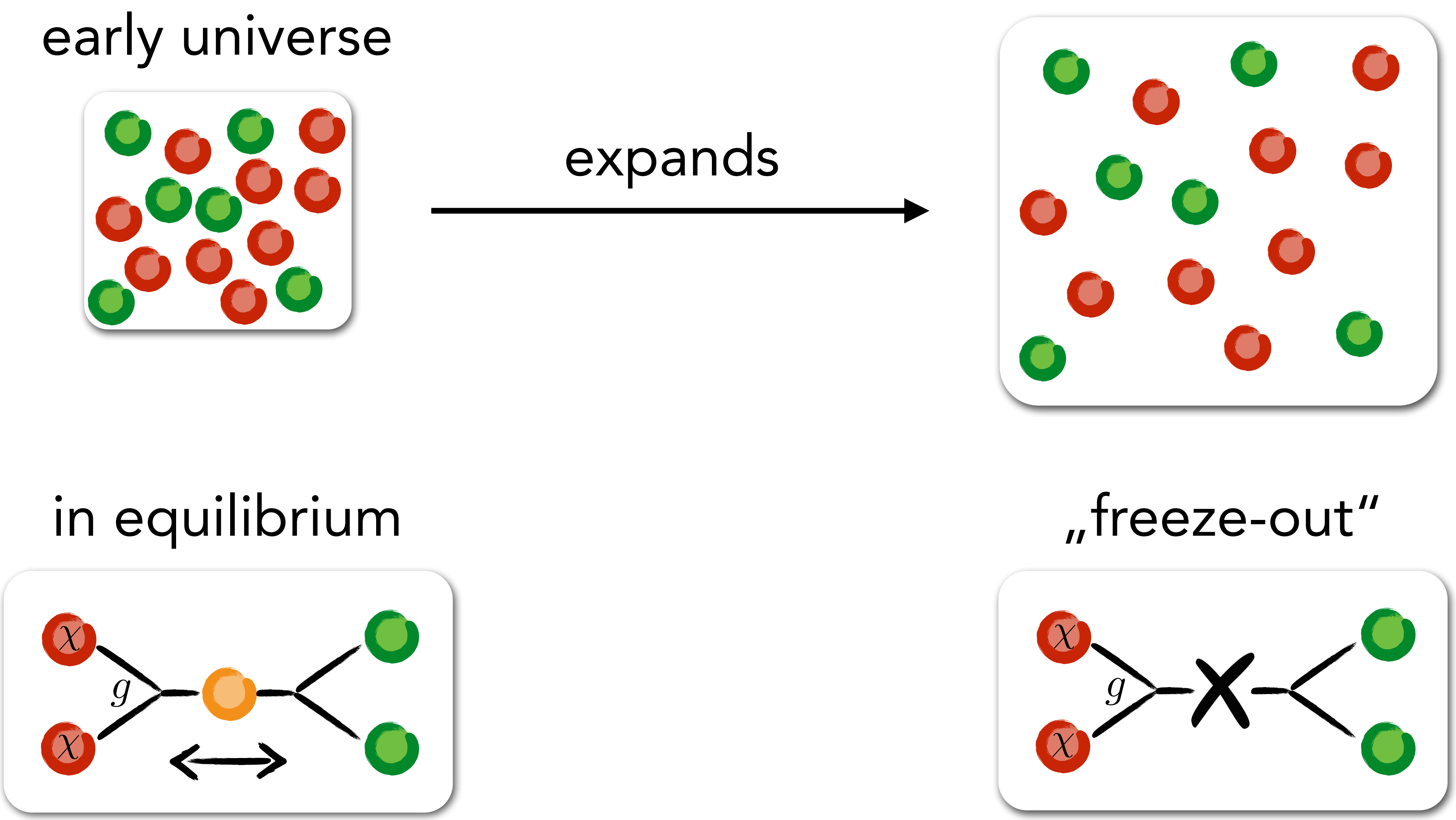
Dark matter is real!



Macro picture



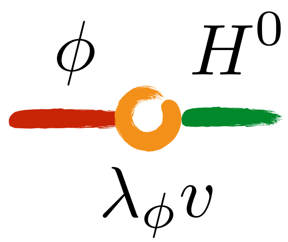
Micro picture?



Need new interaction beyond gravity.

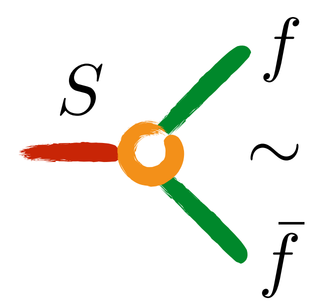
A concrete model of dark matter

Higgs portal to dark fermions: $\mathcal{L} = \lambda_\phi (H^\dagger H)\phi + y_\phi \overline{\chi}\chi\phi$



scalar mixing: $S = \sin\theta\, h + \cos\theta\, \phi \qquad \theta \sim \lambda_\phi$

Higgs-like couplings:



$\sim y_f \sin\theta$

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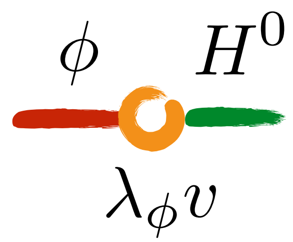

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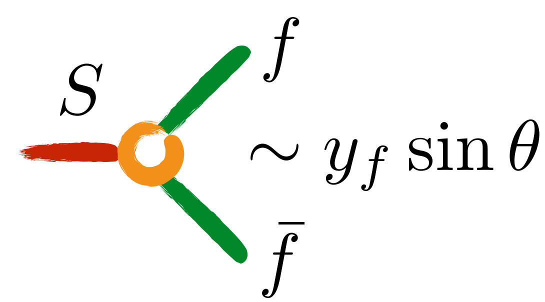
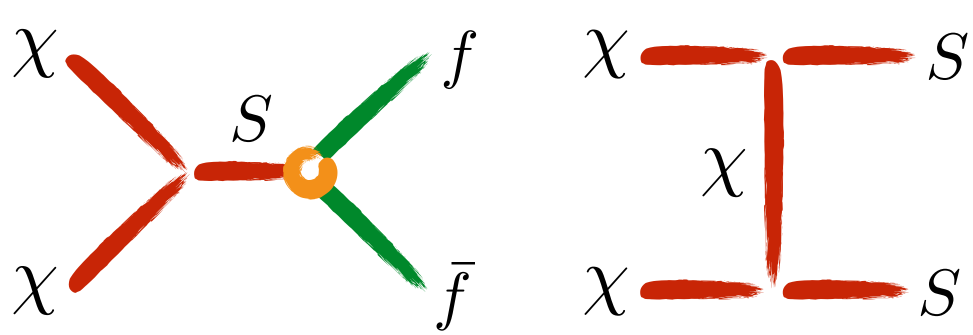


freeze-out: $10^{-7} < \theta < 10^{-2}$



χ in thermal equilibrium

Gondolo, Gelmini 1991

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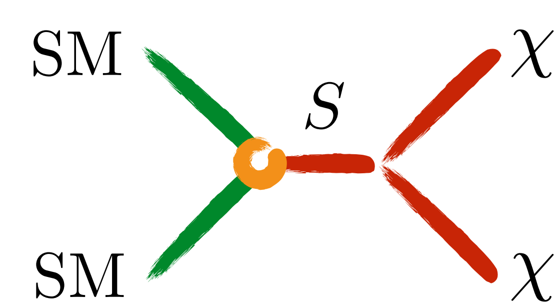
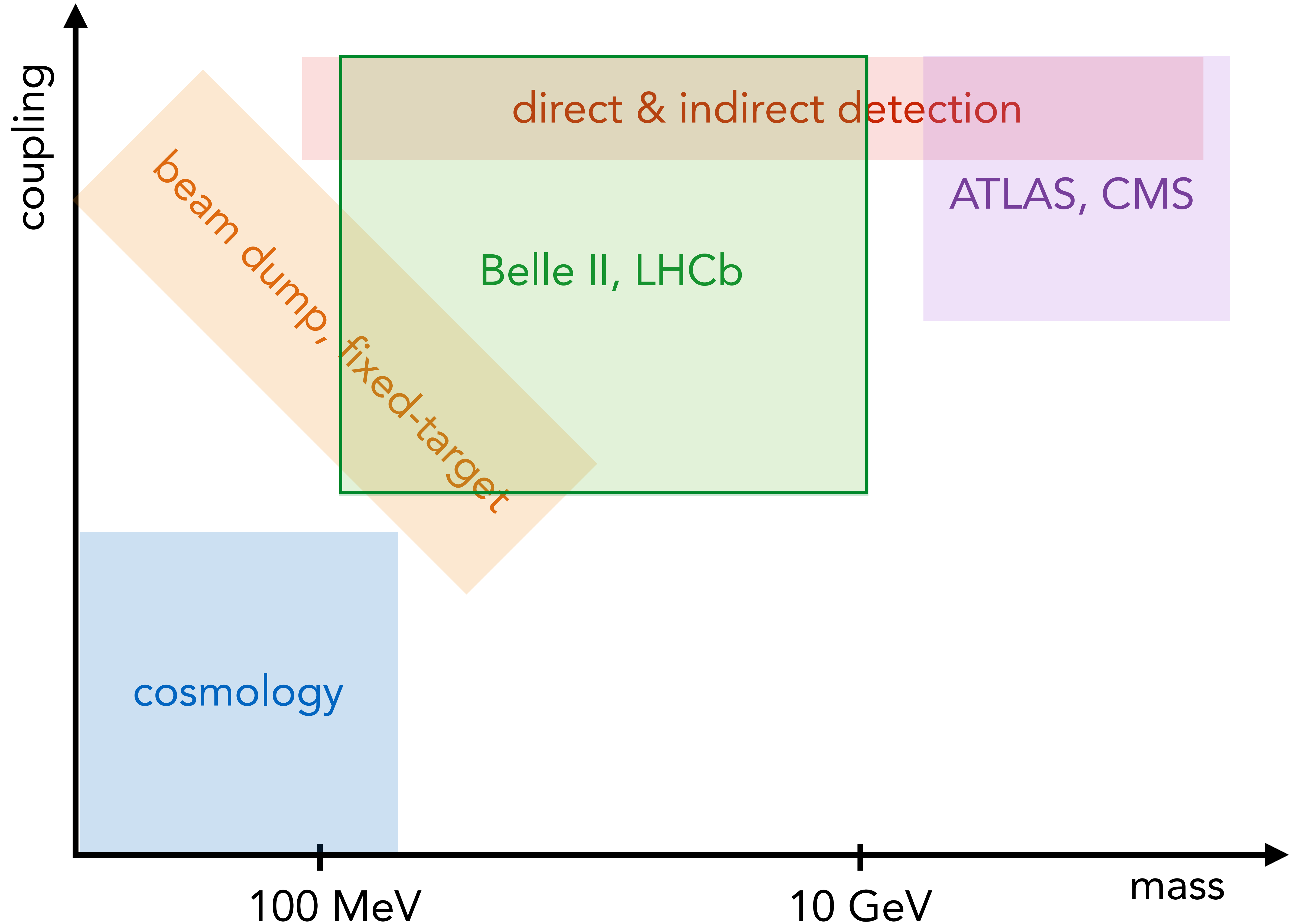


χ out of equilibrium

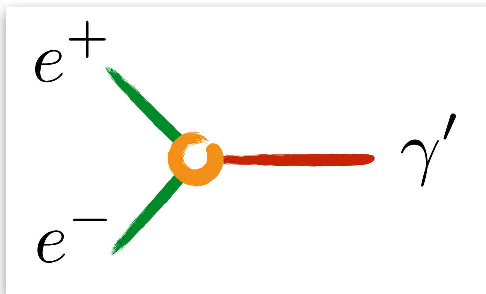
Hall et al. 0911.1120

Enter Belle II

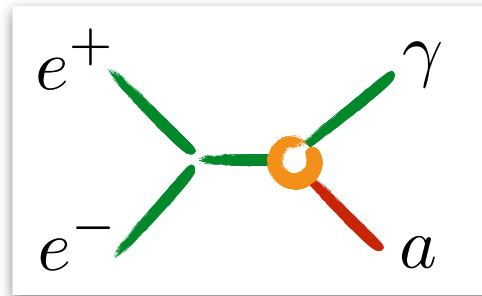


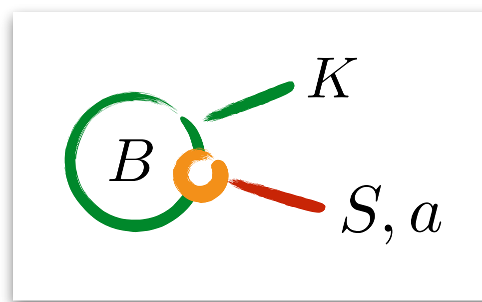
Probing the portals

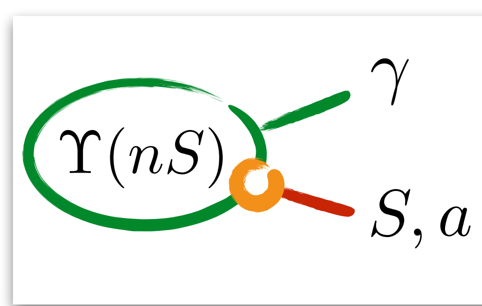
dark photon



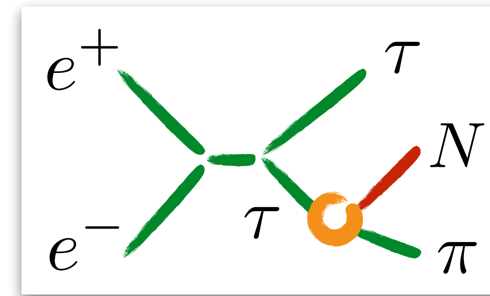
dark scalar, ALP







heavy neutral lepton



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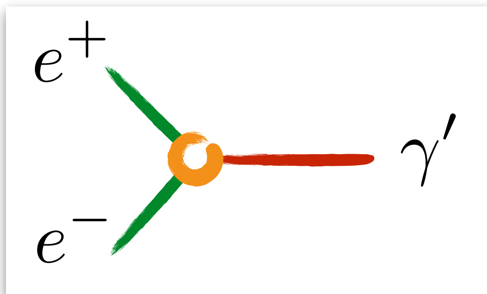

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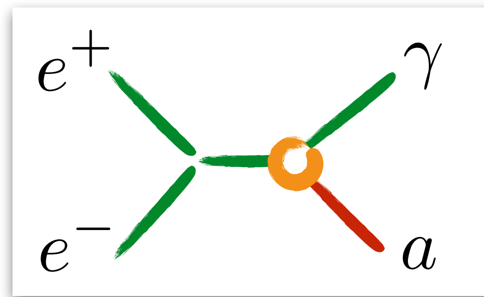

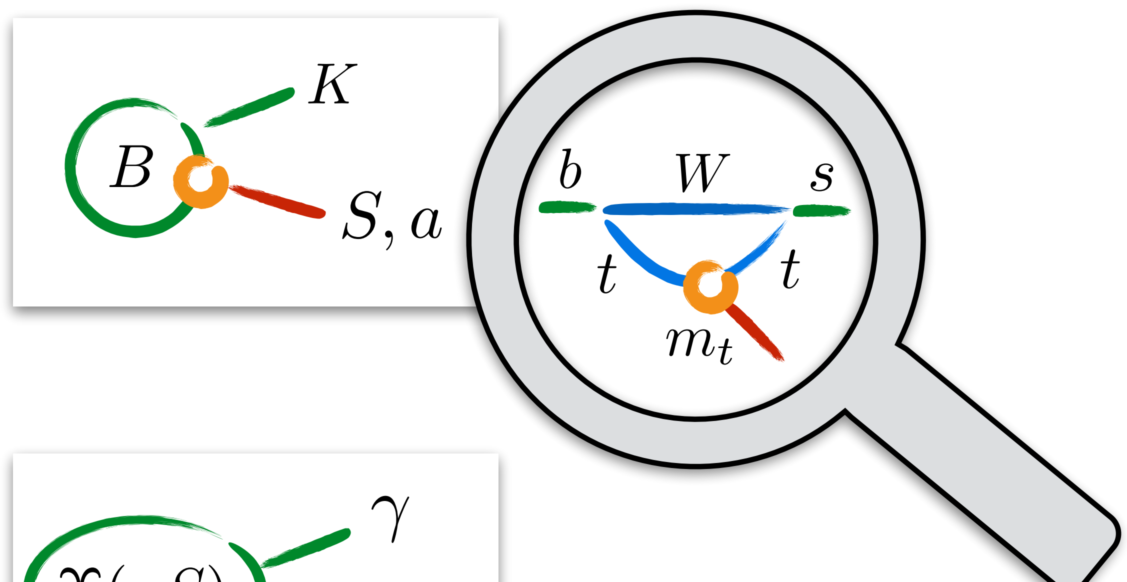

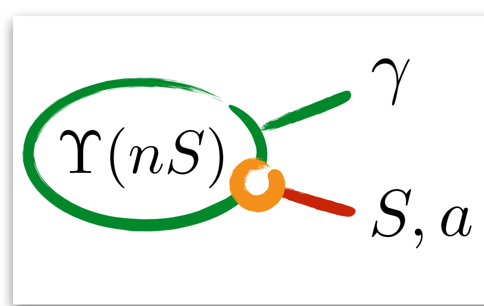

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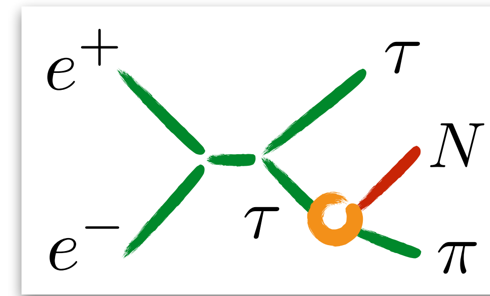
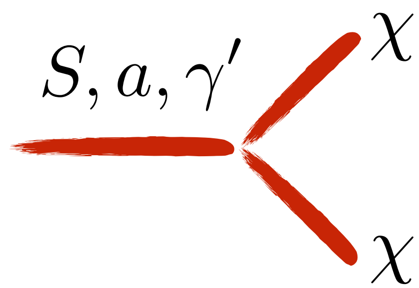


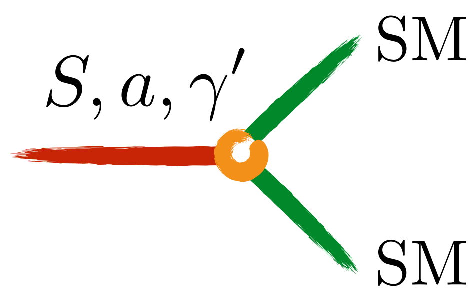
Mediator decays

dark:



$m_S > 2m_\chi$

visible:



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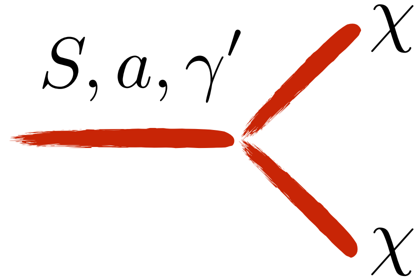

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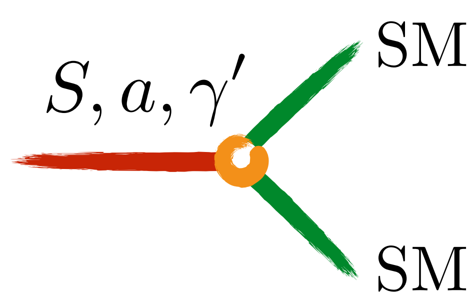

$m_S < 2m_\chi$

small portal - long lifetime:

lifetime

$$\tau = \frac{1}{\Gamma} \sim \frac{1}{\epsilon^2}$$

Long-lived particles

decay probability (lab): $P(t) = 1 - \exp\left(\frac{-t}{\gamma\tau}\right)$

decay length: $d = \beta\gamma c\tau$

B meson: $c\tau \sim 1\,\mathrm{mm}$

Belle II: $\gamma = \frac{5\,\mathrm{GeV}}{m_B} = 1,\ \beta \approx 0 \quad \longrightarrow \quad d \approx 0\,\mathrm{cm}$

LHC: $\gamma = \frac{500\,\mathrm{GeV}}{m_B} = 100,\ \beta \approx 1 \quad \longrightarrow \quad d \approx 10\,\mathrm{cm}$

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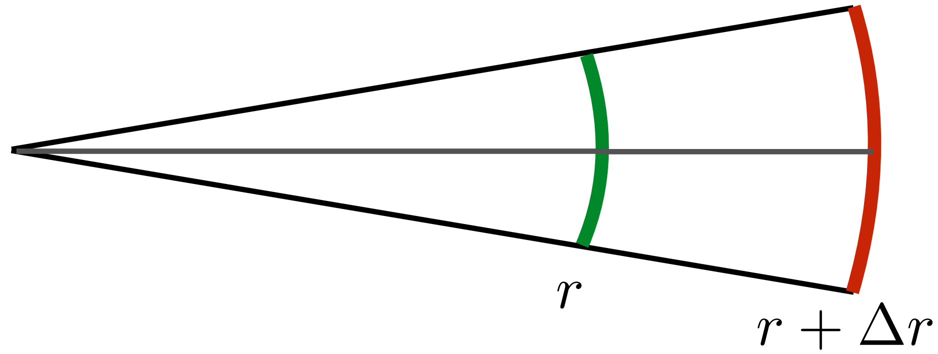
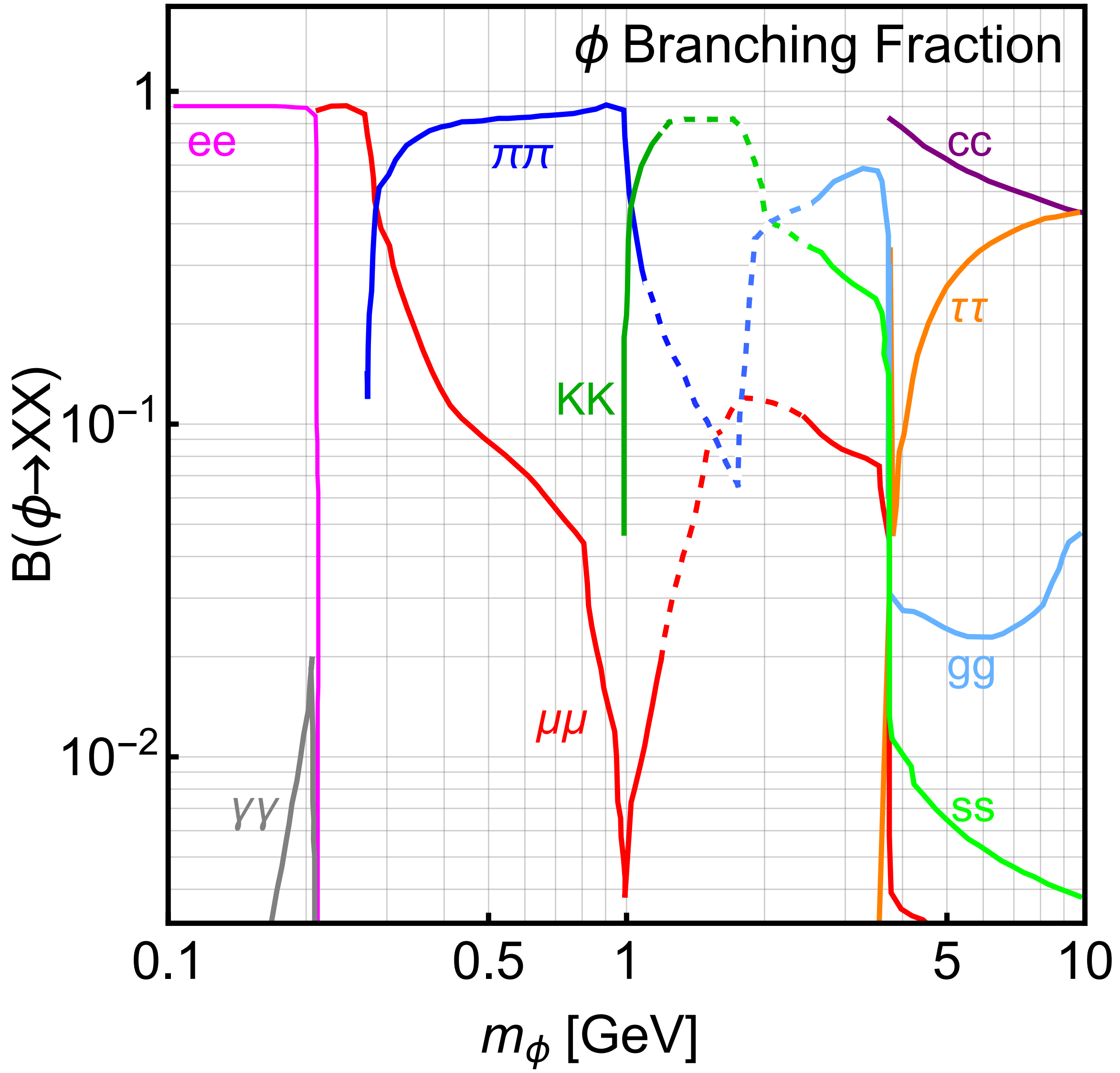
decays within detector volume:



$$N(\Delta V) = N_0 \frac{\Delta\Omega}{4\pi}\left[\exp\left(-\frac{r}{d}\right) - \exp\left(-\frac{r+\Delta r}{d}\right)\right]$$

Long-lived scalars * similar for ALPs

$$c\tau_S = \frac{c}{\Gamma_S} \sim \frac{1}{m_S}\frac{1}{\theta^2}\frac{v^2}{m_f^2}$$



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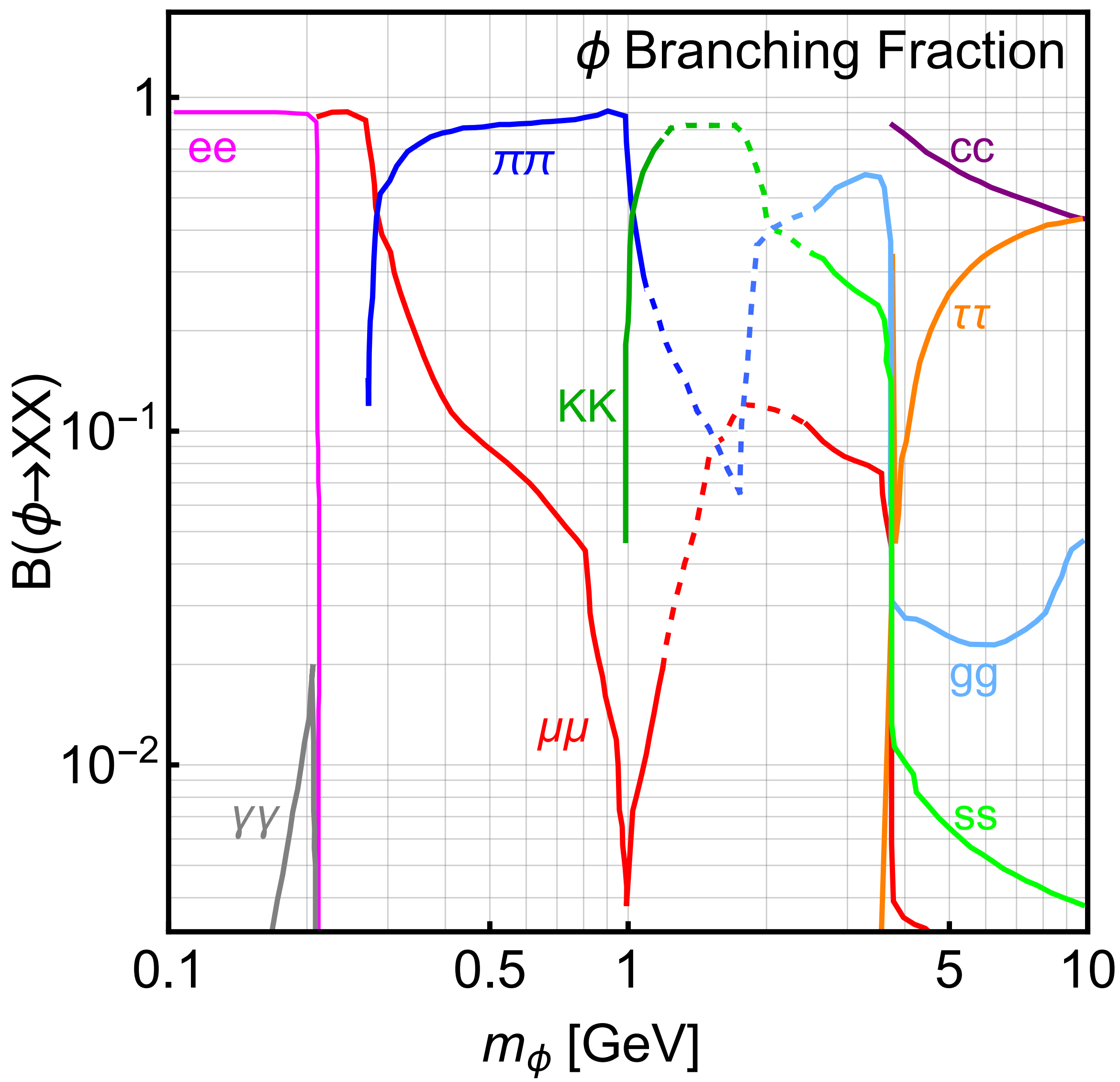
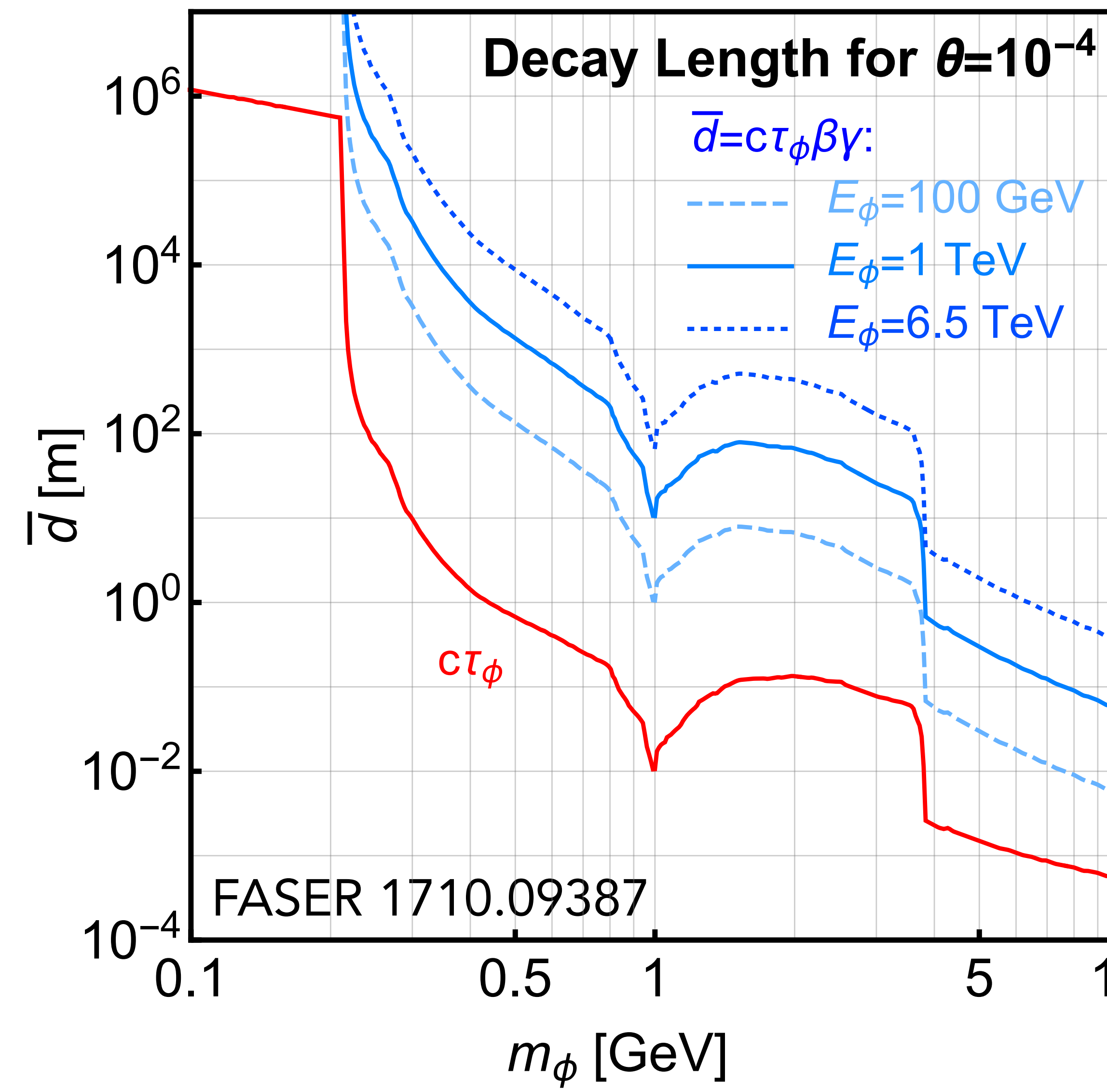
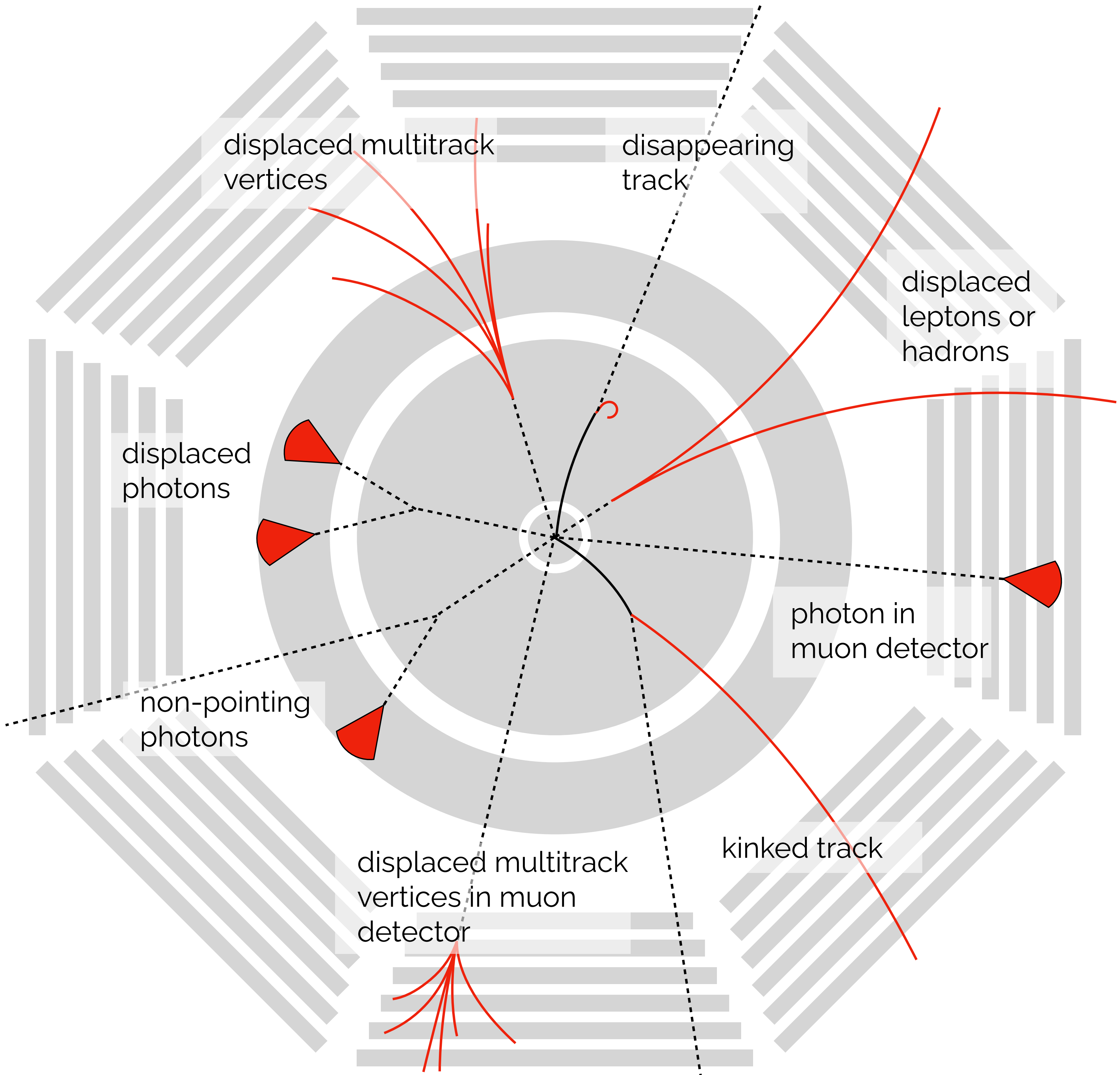




Belle II: invisible displaced prompt

What can Belle II see?



picture: Torben Ferber

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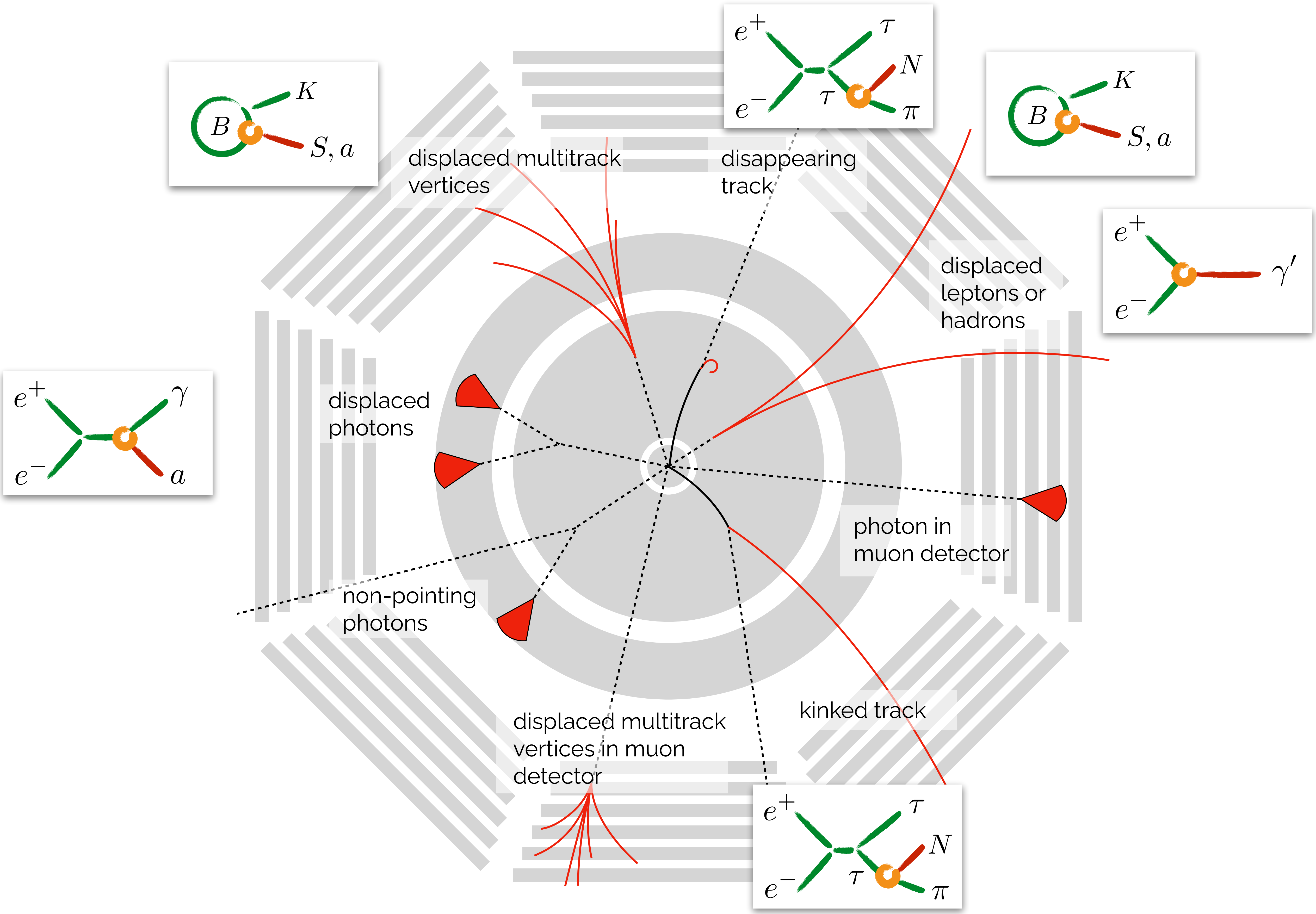
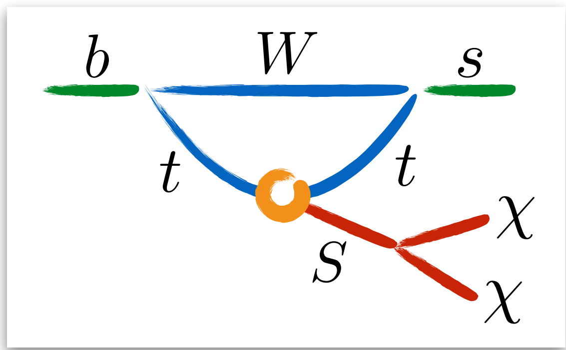


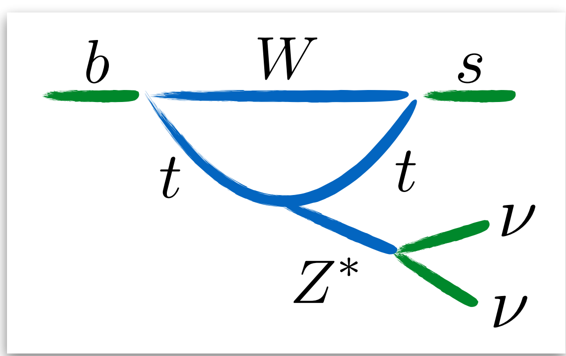
Invisible decays

signal: meson + missing energy



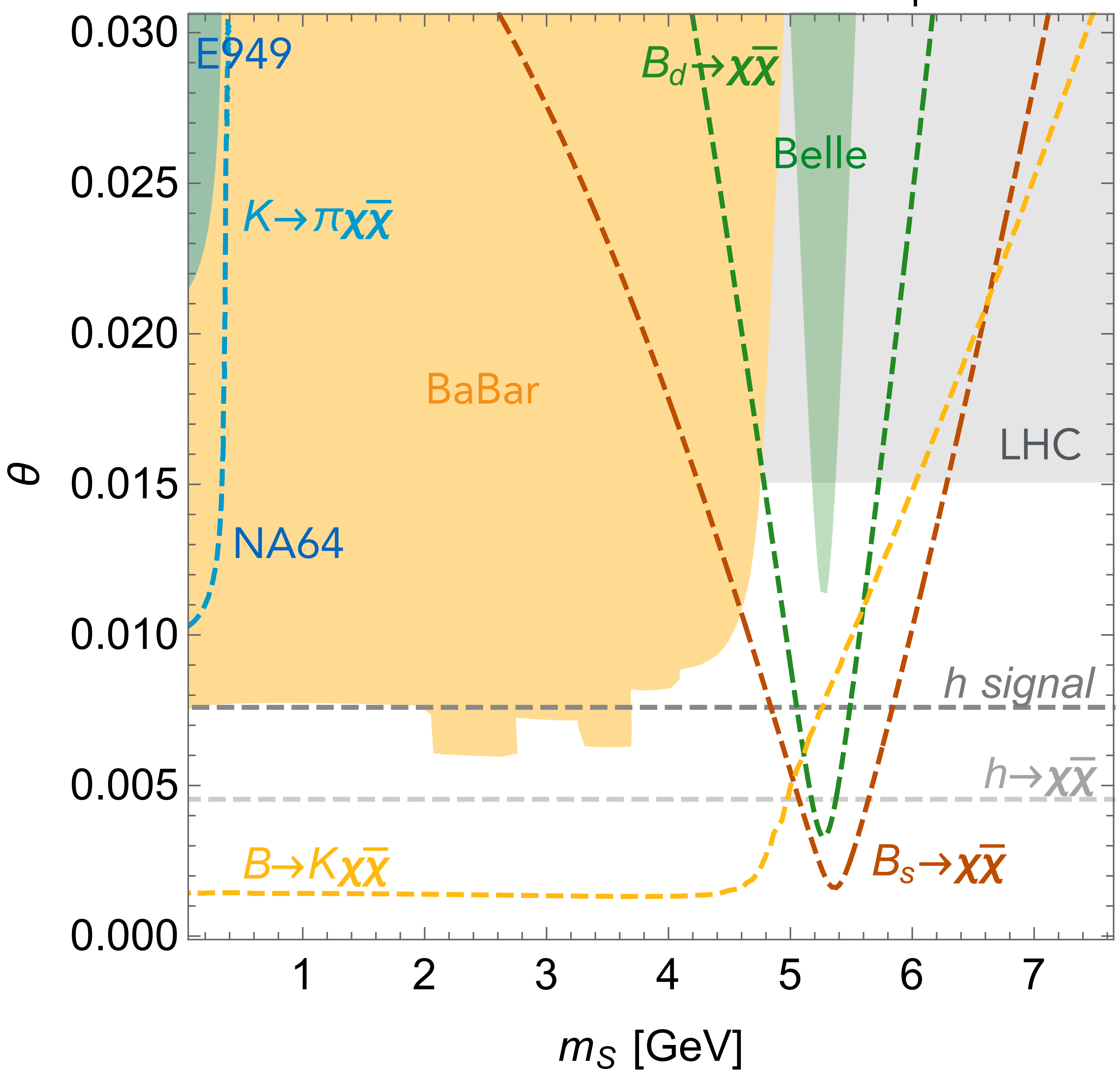
2-body decay

background



3-body decay

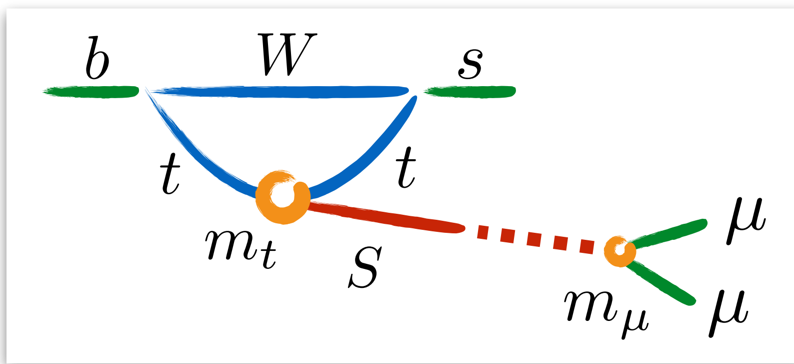
dashed: Belle II prediction



Filimonova, Schaefer, Westhoff 1911.03490

Displaced decays

signal: Kaon + displaced vertex



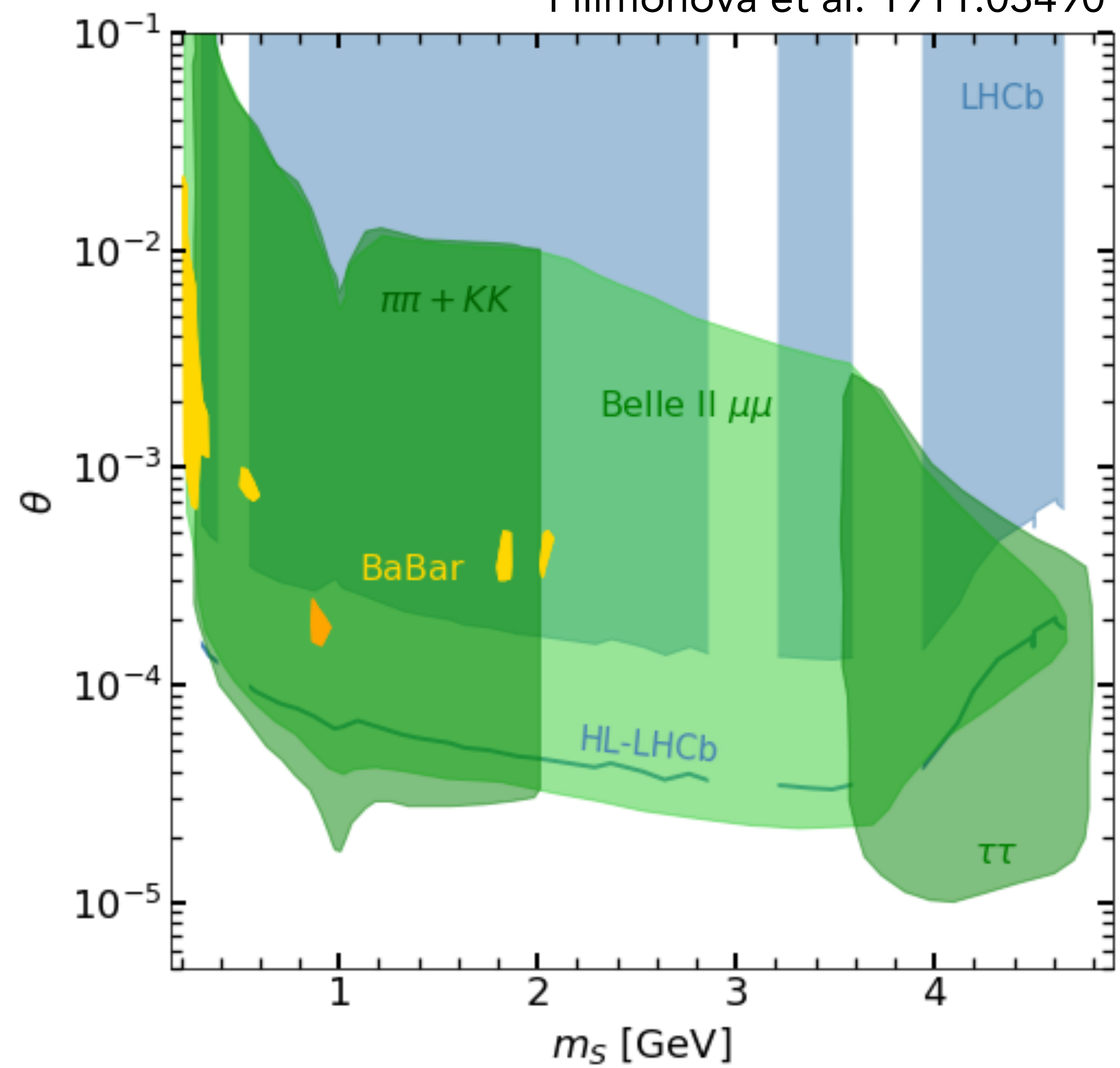
$$m(\mu, \mu) = m_S$$

BaBar: inclusive search

LHCb: high boost

Belle II: low boost, taus!

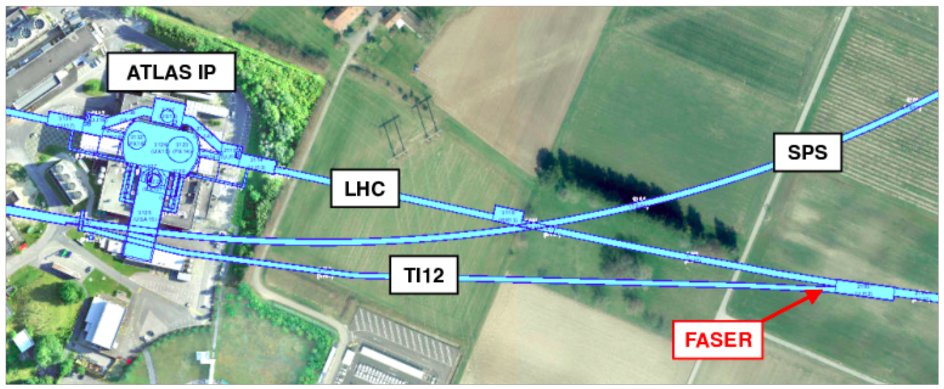
Filimonova et al. 1911.03490



see also Kachanovich, Nierste, Nisandzic 2003.01788

Displaced or invisible?

FASER

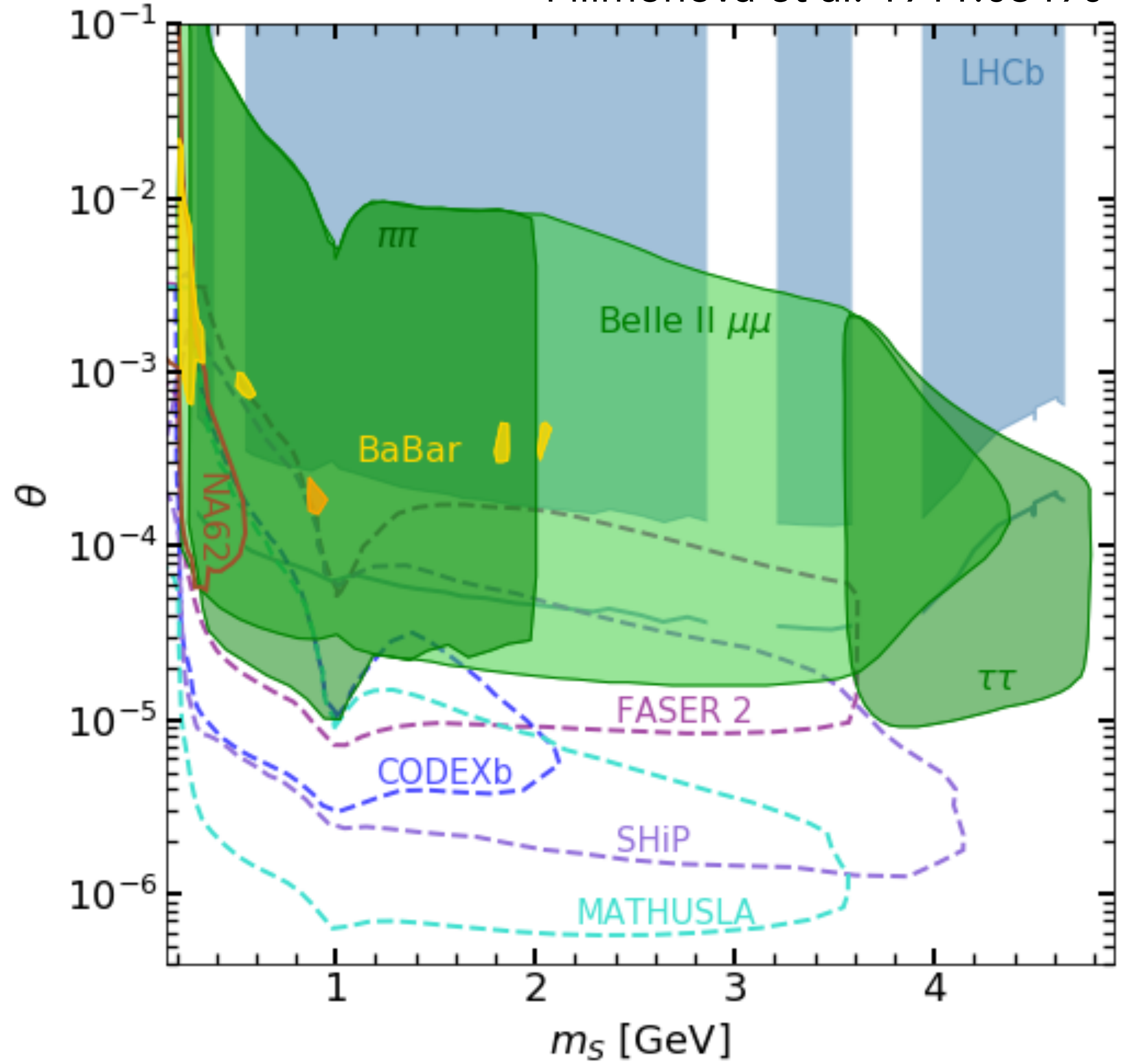


$$r = 500\,\mathrm{m}$$

$$\beta\gamma \sim 100 - 1000$$

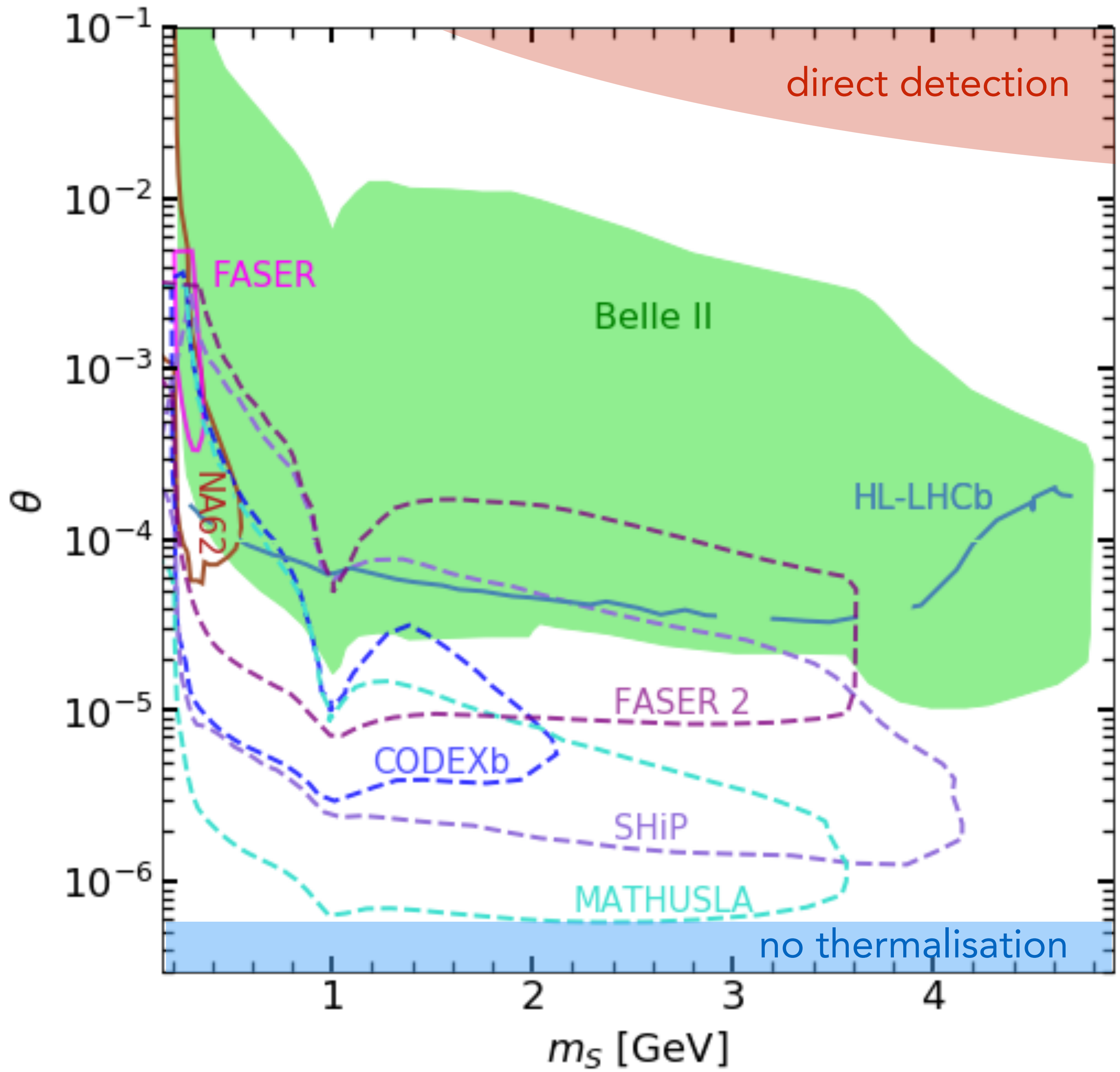
$$d \sim \frac{\beta\gamma}{\theta^2}$$

Filimonova et al. 1911.03490

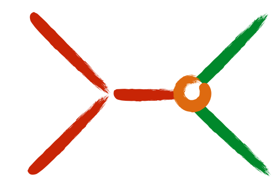


FASER's displaced vertex is Belle II's missing energy.

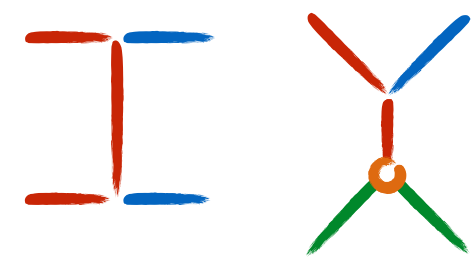
The new WIMP



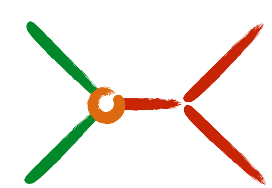
annihilation



scattering, decays
resonance, seclusion



freeze in



Belle II can probe feeble dark matter interactions.

Take-homes / keep-homes

Belle II is very sensitive to dark sectors.

- directly: long-lived particles
- indirectly: missing energy

Belle II can explore dark matter beyond the WIMP.

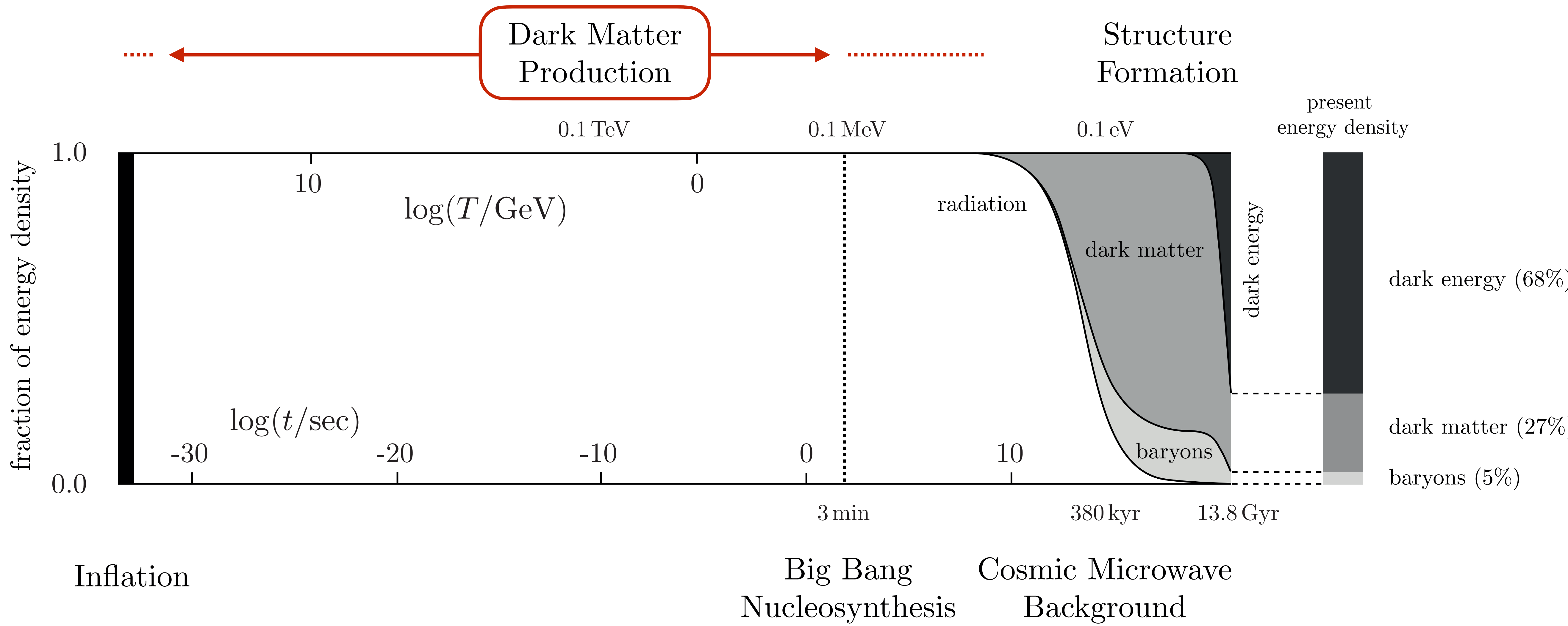
- long-baseline experiments, direct detection, astrophysics

Belle II can do much better on long-lived particles.

- very long lifetimes: calorimeter? muon detector?
- soft decay products / small rates: dedicated triggers?
- displaced photons, taus, hadrons
- your thesis here!

BACKUP

Hints from the early universe



freeze in

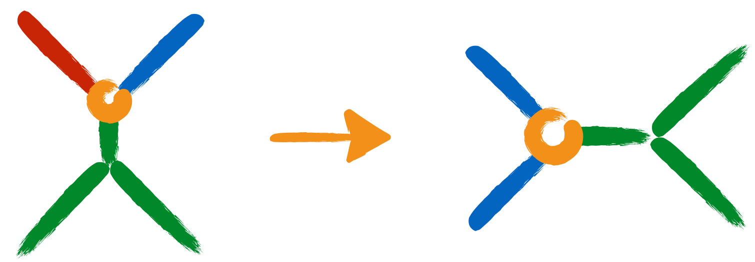
freeze out

colliders?

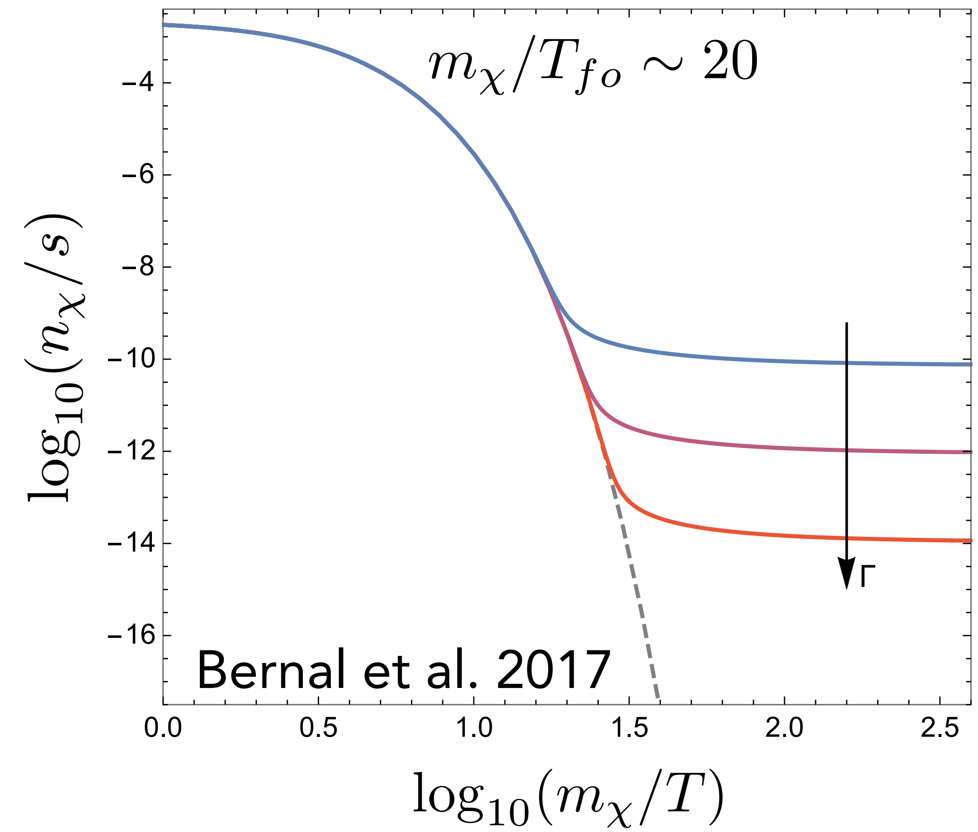
picture: D. Baumann's lecture notes

Relic abundance: freeze out

co-scattering / mediator annihilation

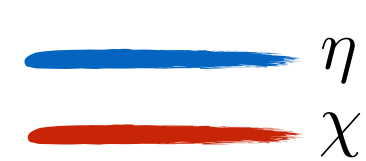


$$\Omega_\chi h^2 \sim \frac{m_\chi}{T_{fo}} \frac{\mathrm{GeV}^{-1}}{M_P \langle \sigma v \rangle}$$



- number densities in dark sector → compressed spectrum

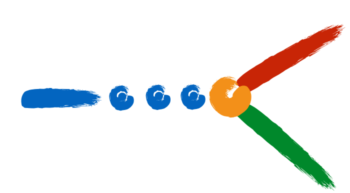
$$\frac{n_\eta}{n_\chi} \sim e^{-\frac{\Delta m}{T}} \sim 1$$



$$\frac{\Delta m}{m} \ll 1$$

- observed abundance for → long-lived mediators

$$g_\chi^2 \sim e^{-\frac{m_\chi}{T}} g_{\mathrm{WIMP}}^2 \ll 1$$

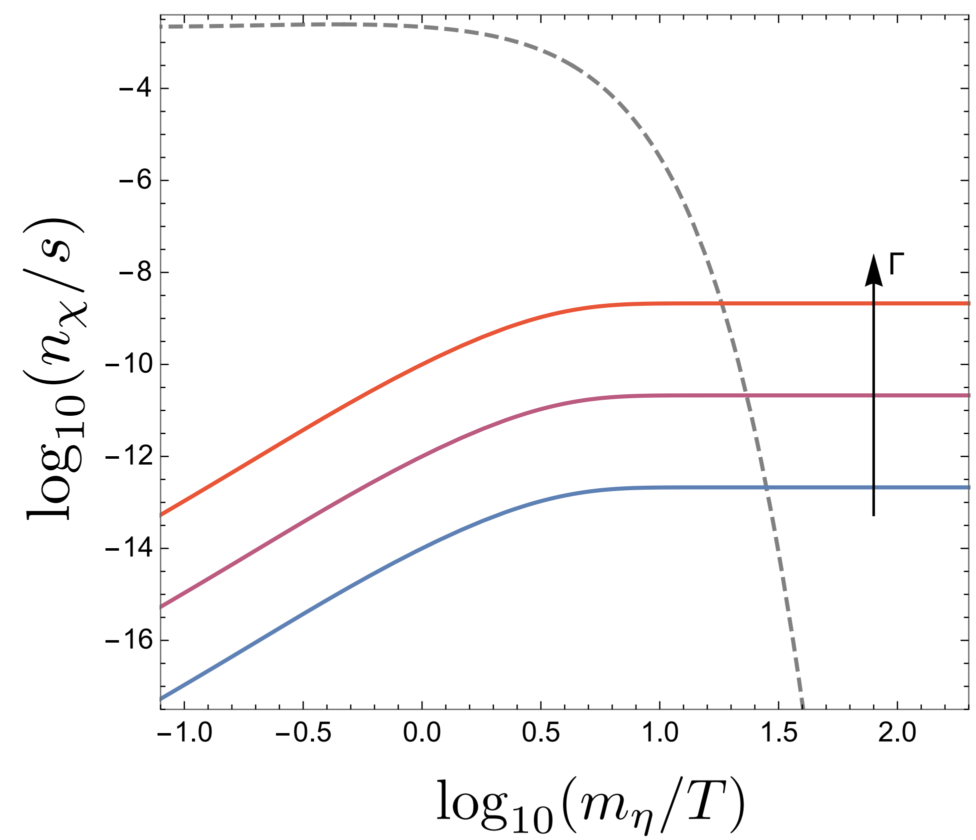


$$c\tau_\eta \sim \frac{1}{g_\chi^2 m_\eta} \left(\frac{m}{\Delta m} \right)^n$$

Relic abundance: freeze in

mediator decay / scattering

$$\Omega_\chi h^2 \sim \frac{m_\chi}{\text{GeV}} \frac{M_P \Gamma_\eta}{T_{fi}^2}$$



- mediator sets freeze-in time

$$T_{fi} \approx m_\eta/3$$

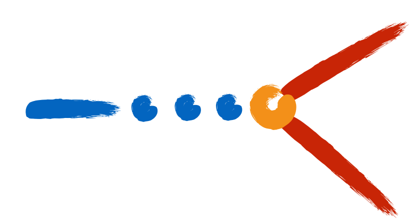
→ split spectrum

$$\frac{m_\eta^2}{m_\chi} \sim 10^9 \text{ GeV}$$

- dark matter out of equilibrium

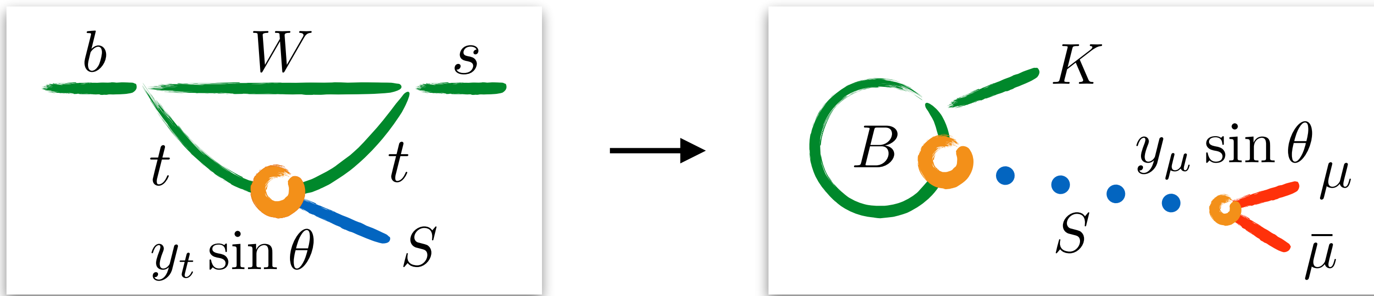
$$g_\chi \lesssim 10^{-7}$$

→ long-lived mediators



$$c\tau_\eta \sim \frac{m_\chi}{m_\eta^2}$$

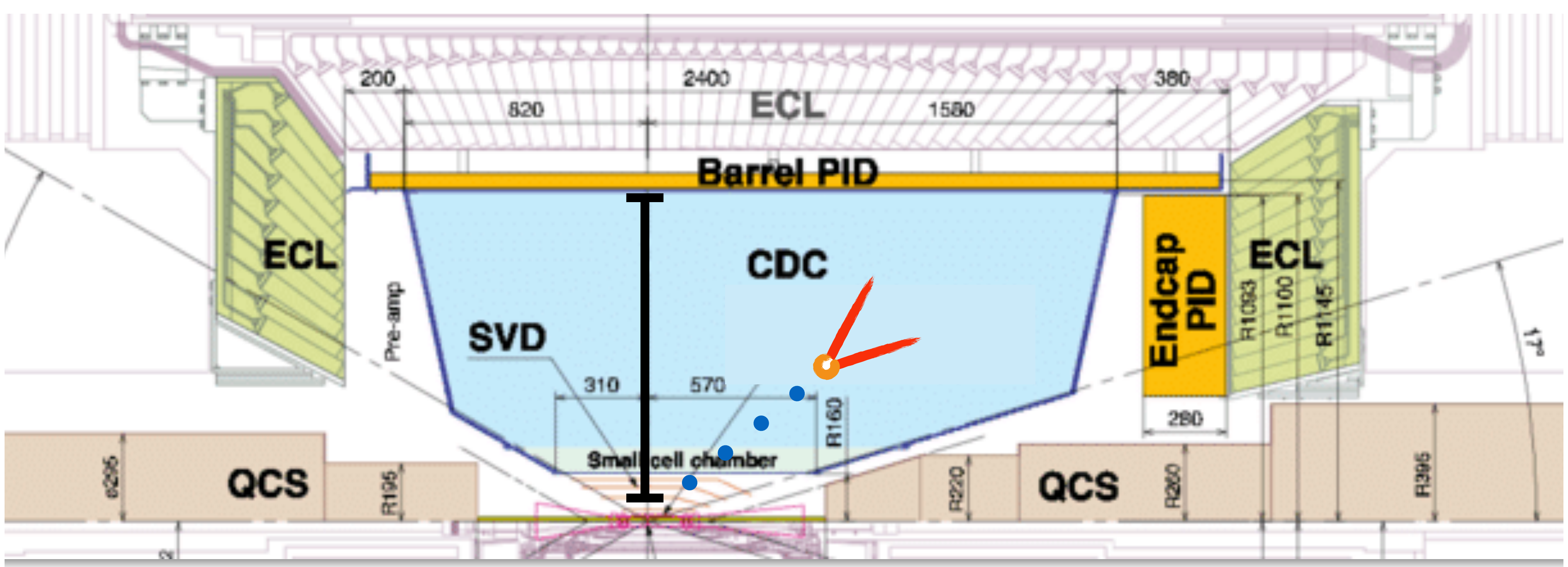
Dark scalars in meson decays



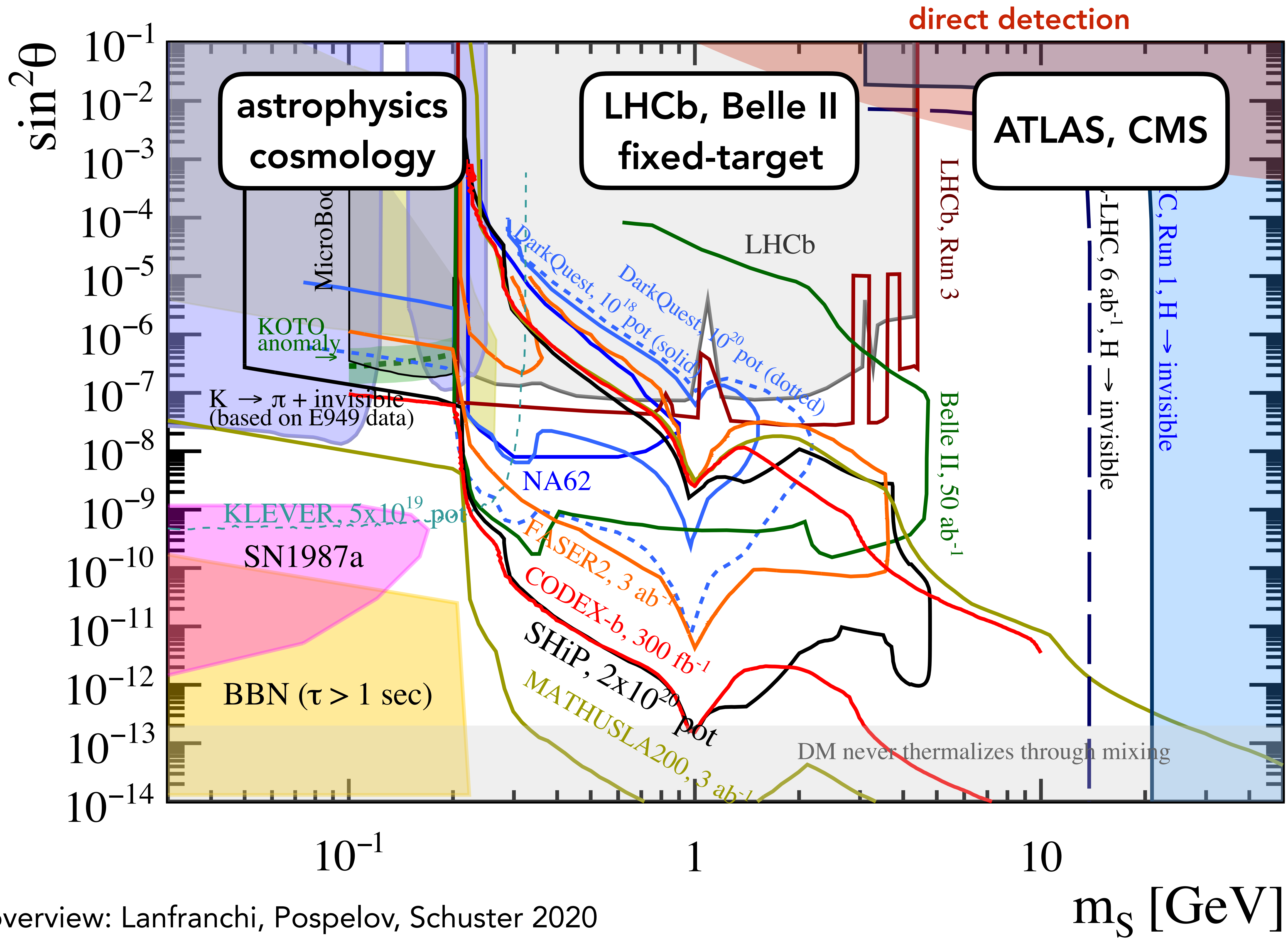
Example:

$$\sin\theta \approx 2 \cdot 10^{-5} \quad \longleftrightarrow \quad \tau_S \approx 50\,\text{ns} : \text{lifetime } K_L \text{ meson}$$

Search for dark scalars at Belle II:



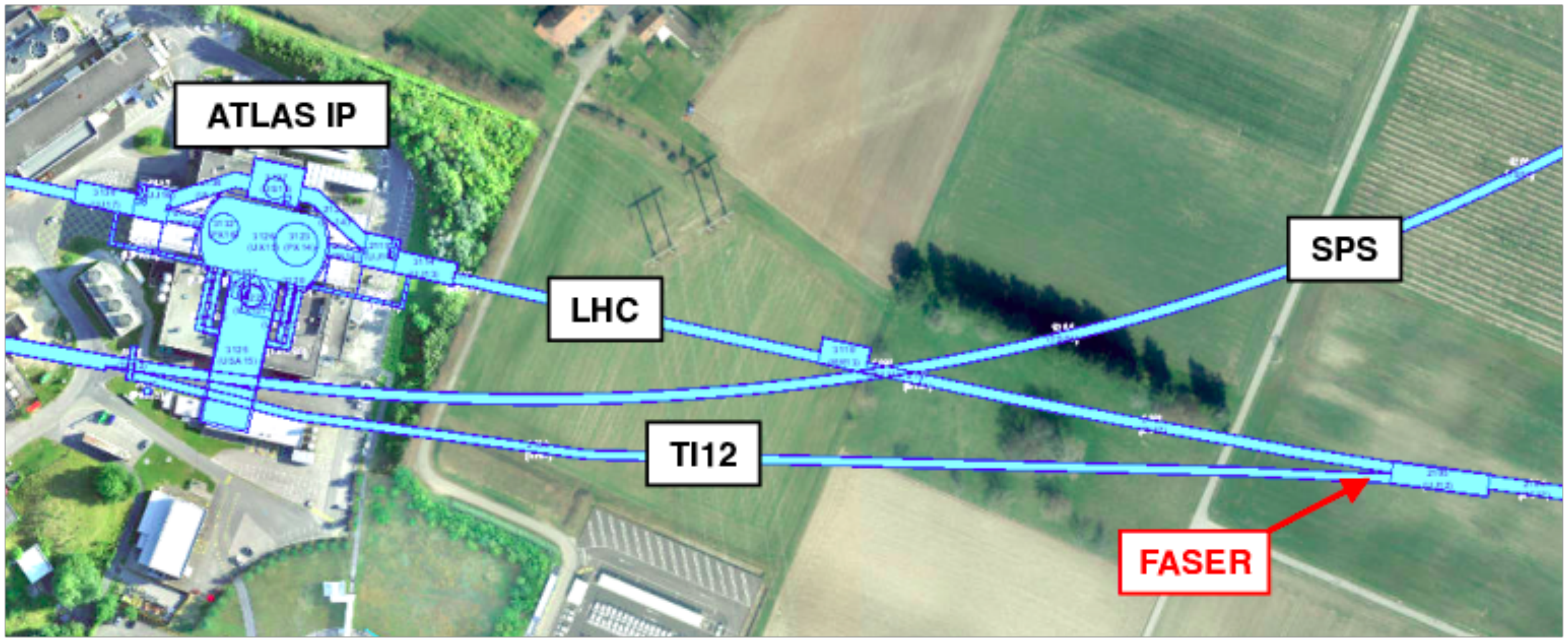
Long-lived scalars and dark matter



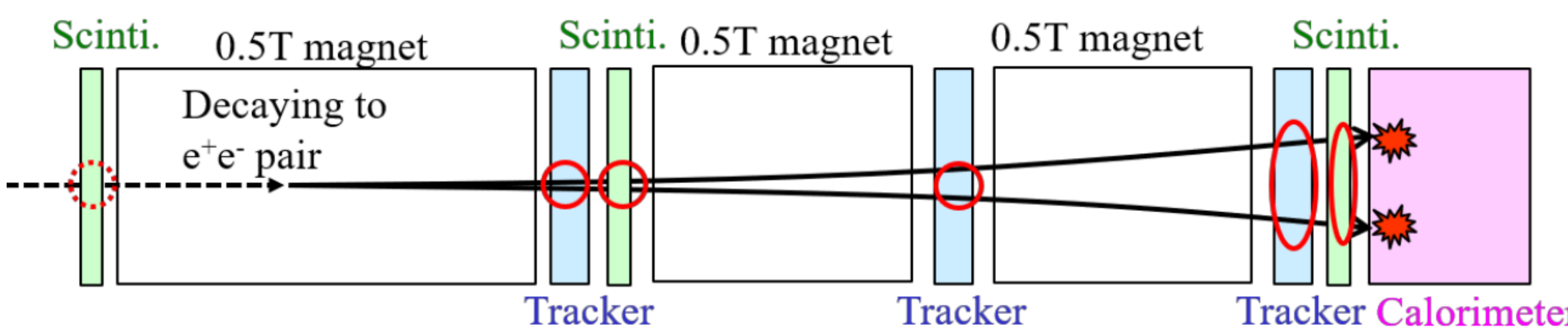
overview: Lanfranchi, Pospelov, Schuster 2020

FASER

new detector 500m away from ATLAS interaction point

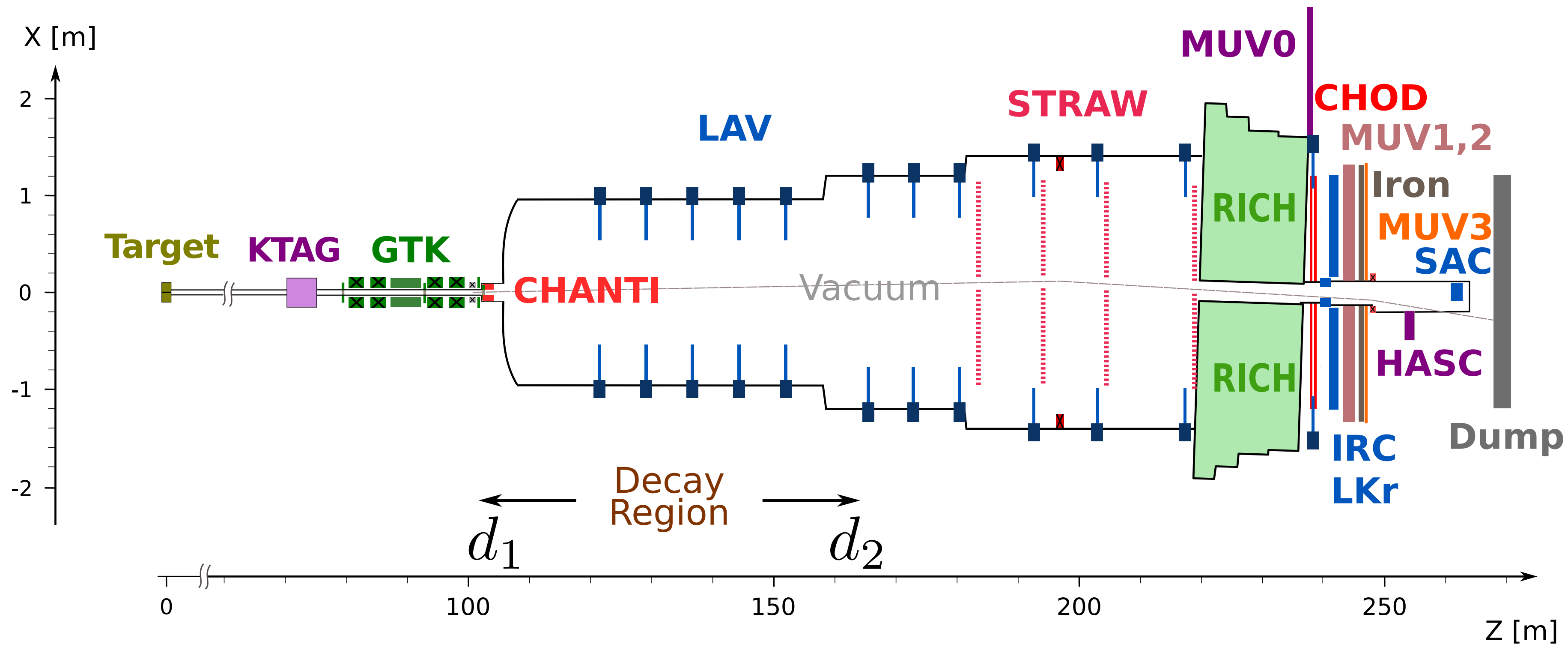


detector geometry:



images: FASER collaboration

Beam dump experiments



NA62 at CERN:

- kaons are absorbed in Be target and decay via K > Pi S
- scalar S decays within „decay region“

Probability to find decay products in detector:

$$\mathcal{P}_\phi = \int_{d_1}^{d_2} \mathrm{d}z \, \frac{\eta_{\rm geom}\, \eta_{\rm rec}\, m_\phi\, \Gamma_\phi}{p_\phi} \, e^{-m_\phi \Gamma_\phi z / p_\phi}$$

see Winkler 1809.01876