Detecting Dark Matter with Far-Forward Emulsion and Liquid Argon Detectors at the LHC

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B. Batell, J.L. Feng, ST, Phys.Rev.D 103 (2021) 7, 075023
B. Batell, J.L. Feng, A. Ismail, F. Kling, R.M. Abraham, ST, In preparation

ASTROCENT

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Light thermal relic dark matter

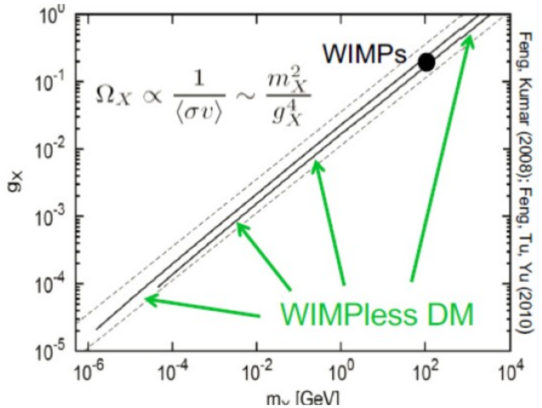
- Light BSM sector can naturally contain a DM candidate χ

C. Boehm, P. Fayet, hep-ph/0305261
M. Pospelov, A. Ritz, M. B. Voloshin, hep-ph/0711.4866
J. L. Feng and J. Kumar, hep-ph/0803.41960803.4196

- Correct thermal light DM relic density (“WIMPless” miracle)

- Efficient DM annihilation in the early Universe

+ various experimental probes



Talks:
Knut Moraa
Joseph Bramante
Natalia Toro
...

DM direct & indirect probes,
cosmology

collider, beam dumps **DM self interactions**

(e.g. long-lived mediators → SM, missing energy/momentum)

THIS STUDY
collider
DM direct detection

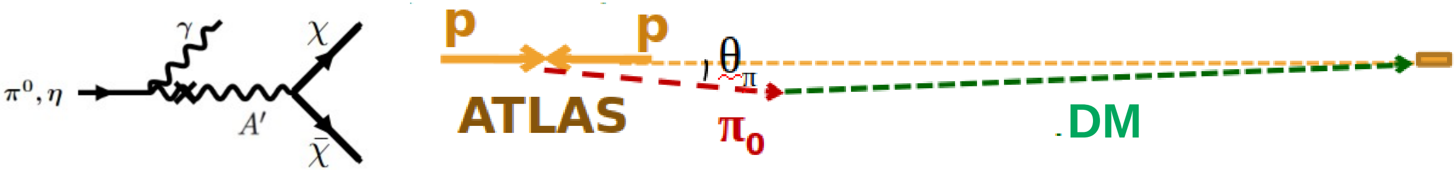
Light DM at the LHC

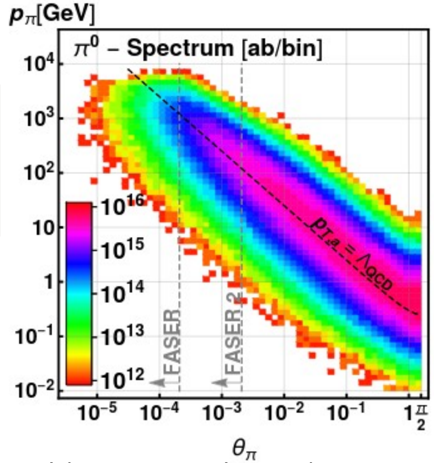
- LHC can be a very efficient light DM (LDM) factory

- LDM direct detection requires suppressing SM backgrounds – difficult in typical LHC experiments

- ...but many LDM particles will go down the beam pipe (especially high energy ones)

Example: DM production in rare decays of light mesons





other prod. modes include i.a. proton-proton bremsstrahlung

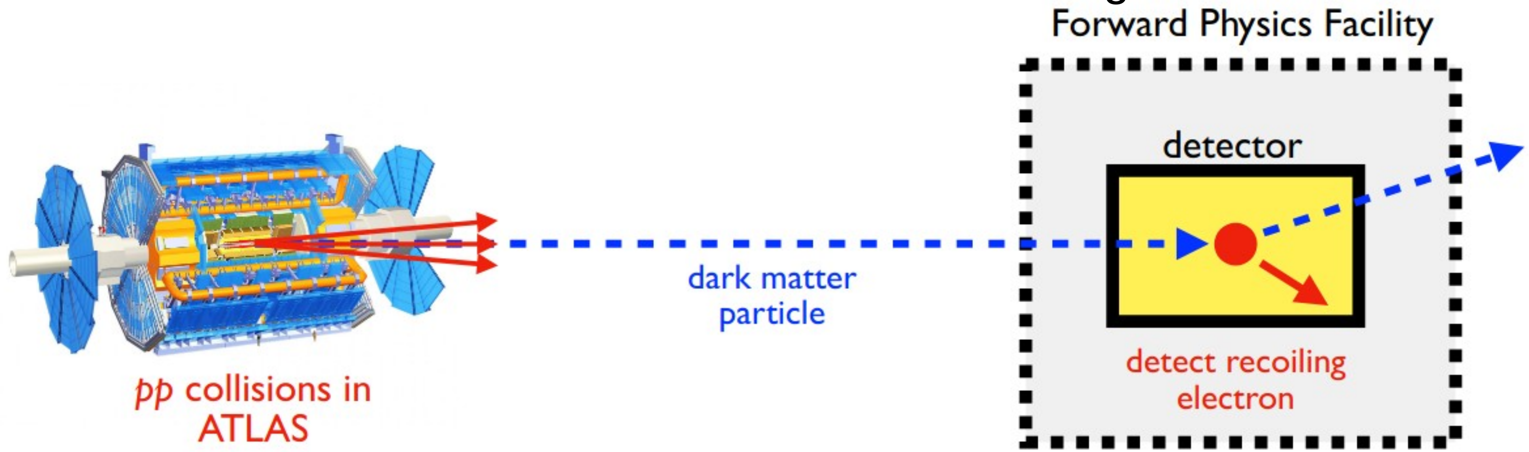
pp → pp(A' → χχ)

FASER Collaboration, hep-ph/1811.12522, hep-ex/1908.02310

- Far-forward search for light long-lived particles and studies of high-energy neutrino interactions to be initiated during Run 3 with FASER and FASERν detectors

Direct light DM detection at the LHC

- We focus on LDM particles produced in the far-forward region of the LHC & their scattering in a distance detector



credit B. Batell

- This search is highly complementary to the traditional DM direct detection searches:
  – probe of relativistic interaction rates of LDM (DM energy ~ a few hundred GeV) [collider-boosted DM]
  – the search is not sensitive to the precise abundance of χ DM component (possible variations in cosmological scenario) [collider-produced DM]

Example signature:
DM scattering off electrons

- Signature: recoiled electron (recoil energy E_e, recoil angle θ_e wrt to the beam collision axis)

- Light mediator favors low energy electron recoil

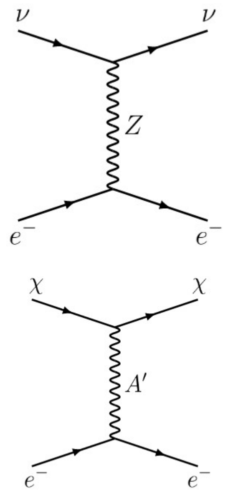
Neutrino scattering example

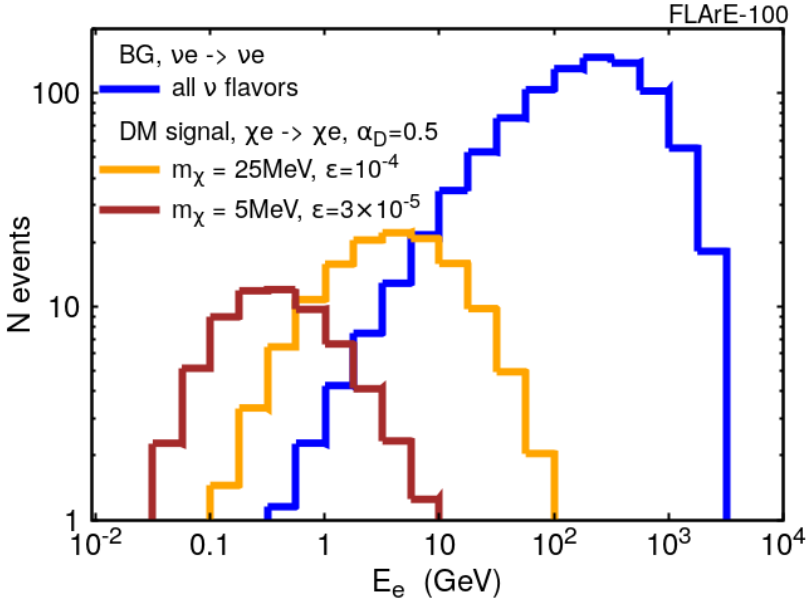
$$\frac{d\sigma(\nu_l e \to \nu_l e)}{dy} = \frac{2 m_e G_F^2 E_\nu}{\pi} \frac{1}{(1 + 2 m_e E_\nu y / M_Z^2)^2} \left(g_L^2 + g_R^2 (1-y)^2\right),$$

$y = E_e/(E_x,E_v)$

DM scattering (dark photon mediator)

$$\frac{d\sigma}{dy} \approx \frac{8\pi \epsilon^2 \alpha \alpha_D m_e E_\nu}{m_{A'}^4 (1 + 2 m_e E_\chi y / m_{A'}^2)^2}$$





$m_{A'} << M_Z$ ⇨ low y, soft recoils favored

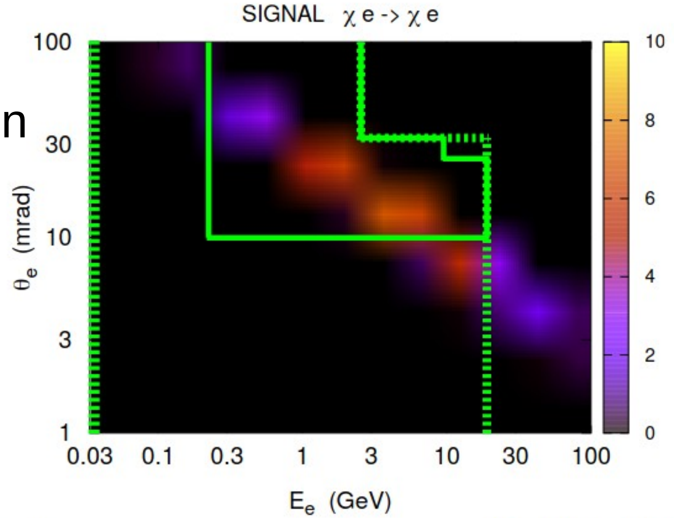
Aditional cuts

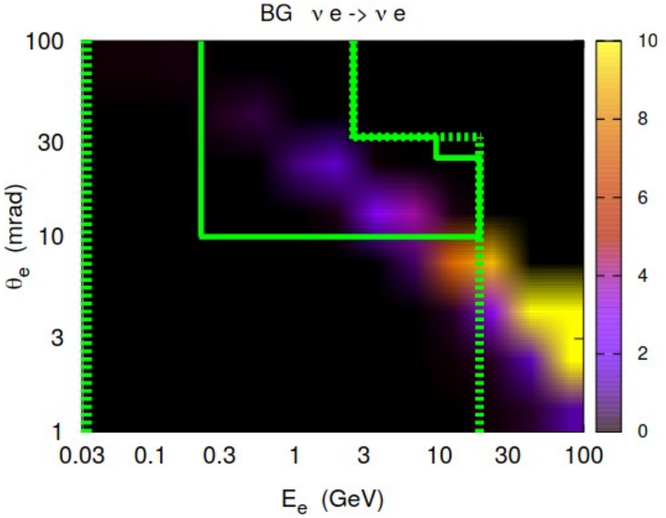
- angular cuts can further improve discrimination between DM and ν-induced backgrounds

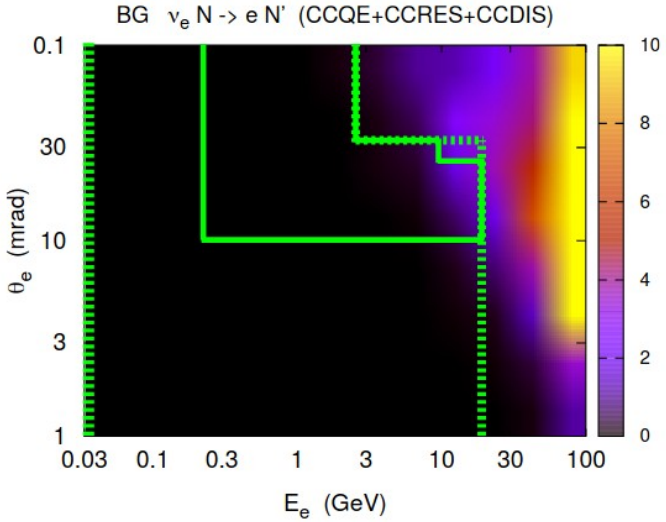
- such backgrounds can be reduced to
~10 events for the 10-tonne detector
~100 events for the 100-tonne detector
for the entire future High-Luminosity LHC era

- this depends on the detector type and geometry

- angular info also used to identify events associated with pp collisions at the distant Interaction Point







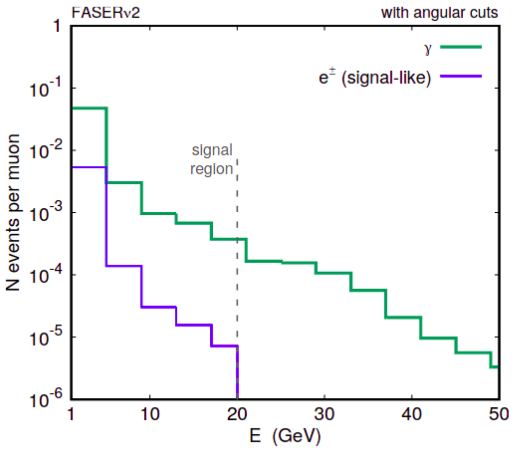
Muon-induced backgrounds

• The LHC is also the muon factory

• Most of muons are deflected by the LHC magnets so that they never reach far-forward detectors...

• ...but the remaining number of expected through-going muons is huge
$N_\mu \sim 10^{11}$ for HL-LHC and the far-forward detector with radius~1m (on axis)

• they can be further def $h_B \approx \frac{ecd}{E_\mu} B\ell = 60\ \mathrm{cm} \left[\frac{100\ \mathrm{GeV}}{E_\mu}\right] \left[\frac{d}{200\ \mathrm{m}}\right] \left[\frac{B \cdot \ell}{\mathrm{T} \cdot \mathrm{m}}\right]$



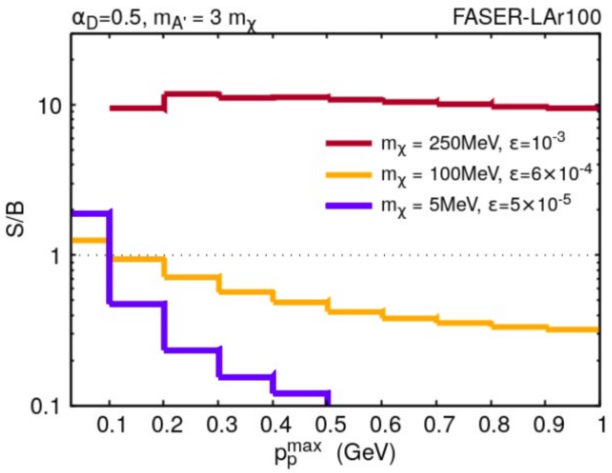
• the most energetic muons can avoid deflection and be source of backgrounds

$\mu N \rightarrow \mu N \gamma$ (photon brem.) + $\gamma N \rightarrow e^+ e^- N$ (pair prod.)

Example signature 2: Elastic DM scatterings of protons

- elastic scatterings off protons $\chi p \rightarrow \chi p$ can lead to DM detection via observation of a single proton track
- again DM with light vector mediator favors low proton recoils

SIGNAL / BG ratio as a function of the max proton momentum cut (min cut >30 MeV)



BG can be suppressed to few tens of events for 10-tonne detectors up to few-hundred for 100-tonne detector

- both for DM signal and ν-induced BG important impact of final-state interactions (FSI) of the proton before it leaves the nucleus
- further signatures: DM DIS events, resonant pion production

Detectors for HL-LHC

• Convenient location: Forward Physics Facility (FPF) – tunnel to host several far-forward experiments

Parallel talk on Tue: Felix Kling

• Considered detector types:

FASER Collaboration,

– emulsion detector FASERν2 (50cm x 50cm x 200 cm)
Similar detection strategies to be tested during Run 3: FASERν (1908.02310, 2001.03073), SND@LHC (2002.08722)
Consists of layers of emulsion films interleaved with tungsten plates + electronic tracker layers for timing
Requirements: good soft track reconstruction and readout in presence of numerous muon tracks

– **F**orward **L**iquid **Ar**gon **E**xperiment (FLArE-10 tonne: 1m x 1m x 7m, FLArE-100 tonne: 1.6m x 1.6m x 30m)
Similar to MicroBooNE, ...
Liquid-Argon time projection chamber (TPC) + PMTs to collect scintillation light
Dynamical time information
Requirements: larger space, well-shielded place → FPF

• Sample results for two benchmark models: dark photon mediator & Majorana or (inelastic) complex scalar DM

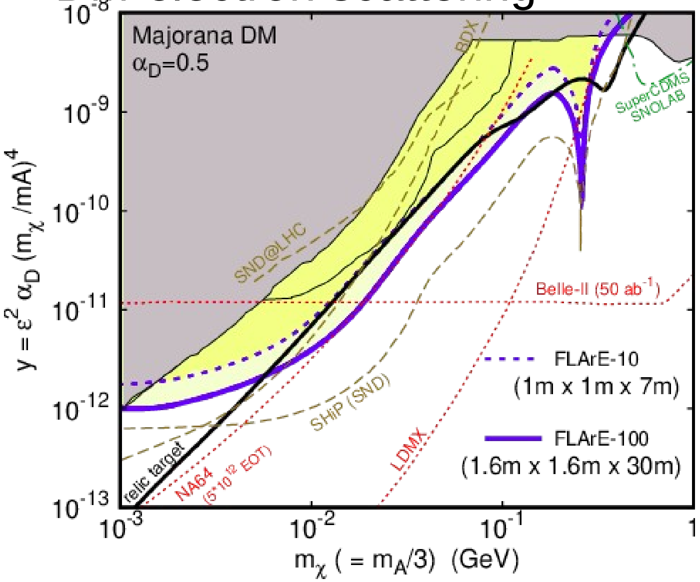
$$\mathcal{L} \supset A'_\mu (\epsilon\, e\, J^\mu_{EM} + g_D\, J^\mu_D)$$

$$\mathcal{L} \supset \begin{cases} |\partial_\mu \chi|^2 - m_\chi^2 |\chi|^2 & \text{(complex scalar DM)} \\ \frac{1}{2}\overline{\chi} i \gamma^\mu \partial_\mu \chi - \frac{1}{2} m_\chi \overline{\chi}\chi & \text{(Majorana fermion DM)} \end{cases}$$

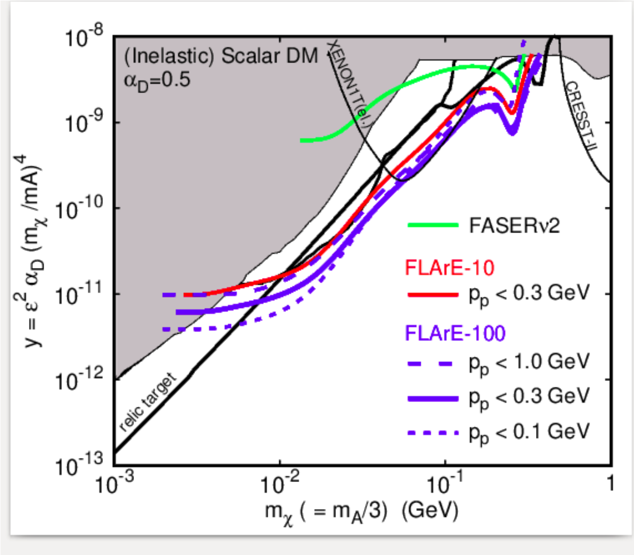
$$J^\mu_D = \begin{cases} i\chi^* \overleftrightarrow{\partial_\mu} \chi & \text{(complex scalar DM)} \\ \frac{1}{2}\overline{\chi}\gamma^\mu\gamma^5\chi & \text{(Majorana fermion DM)}\ . \end{cases}$$

Sensitivity reach for FLArE

DM-electron scattering



DM-proton elastic scattering

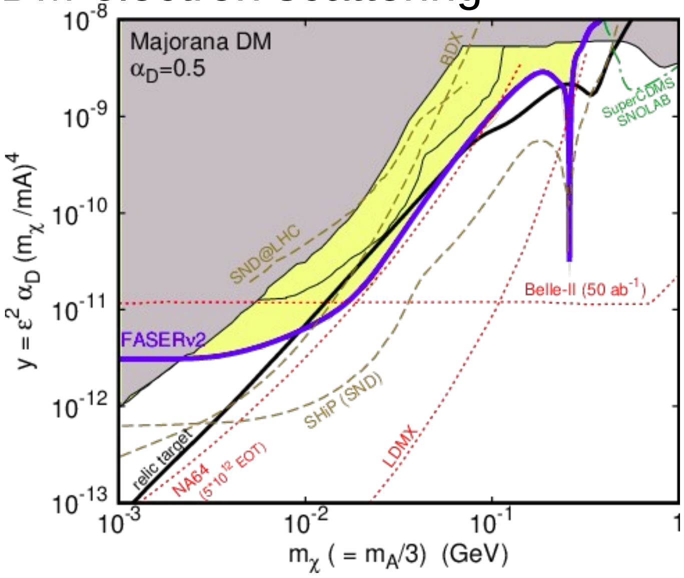


Preliminary

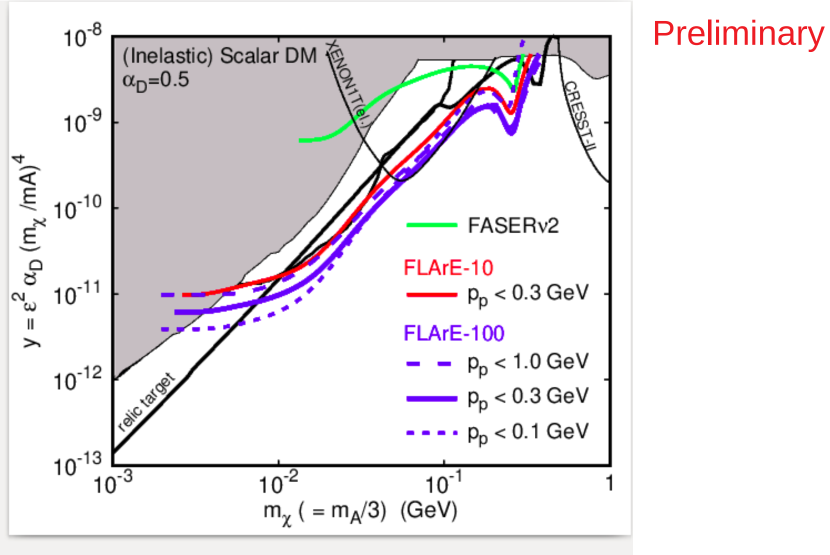
- both for Majorana and Scalar DM relic target can be probed during HL-LHC already by the 10-tonne detector FLArE-10
- complementary search strategies based on leptonic and hadronic DM couplings
- possibility to directly detect DM interactions

Sensitivity reach for FASERv2

DM-electron scattering



DM-proton elastic scattering



- DM-electron scattering search with similar prospects to FLArE-10 (provided than μ-induced BG is rejected)

- DM-proton scattering suffers from larger background and smaller signal rates: impact of larger energy threshold and possible misreconstruction of ν-induced BG events

Concluding remarks

- LHC can be a light DM factory, most of high-energy such dark species will go down the beam pipe and avoid detection

- DM direct detection in the far-forward LHC liquid-argon or emulsion detectors can probe important relic targets via scatterings off electron or nuclei during HL-LHC (Majorana, Inelastic scalar)

- Direct detection based on relativistic DM interactions complementary to traditional searches

- Backgrounds from neutrino and muon interactions (dynamical vetoing + cuts to disentangle from DM signal)

- Rich neutrino physics program is also envisioned

- Scattterings can also lead to good detection strategies for some very long-lived new particles, see e.g. such study for HNL with dark vector portal K. Jodłowski, ST, 2011.04751 (JHEP)

(VERY) SCHEMATIC FAR-FORWARD DETECTOR CAPABILITIES