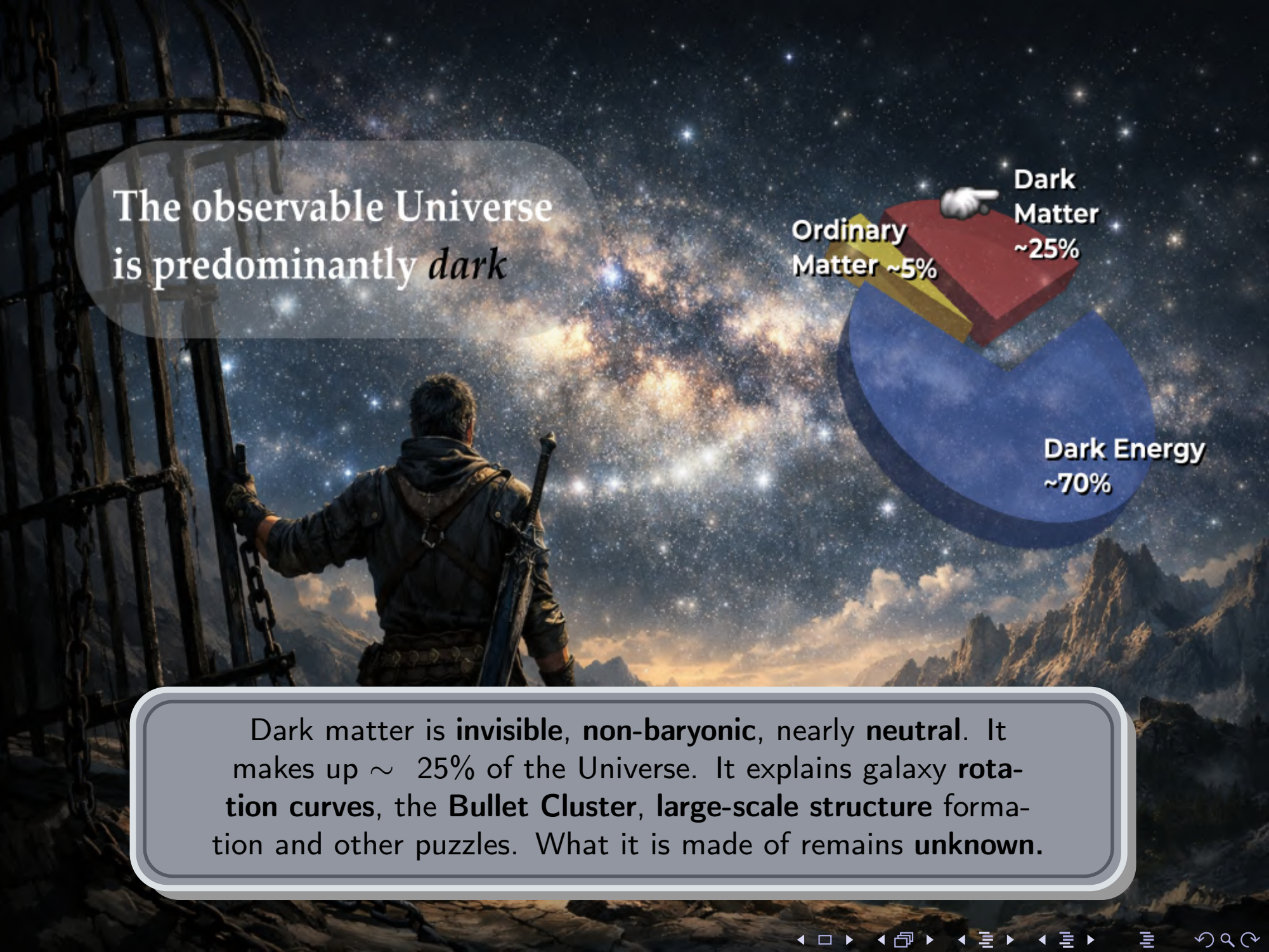
FOCUS WEEK
"AGN as Dark Sector Laboratories"

BLAZAR-BOOSTED DARK MATTER

Alessandro Granelli
Post-doc at IFIC, Valencia U.

Talk based on A. G. De Marchi, AG, J. Nava, F. Sala 2507.12278
J.-W. Wang, AG, P. Ullio 2111.13644



Dark matter is **invisible**, **non-baryonic**, nearly **neutral**. It makes up $\sim$ 25% of the Universe. It explains galaxy **rotation curves**, the **Bullet Cluster**, **large-scale structure** formation and other puzzles. What it is made of remains **unknown.**

DARK MATTER

• • • Needs confirmation • • •

PROPERTIES

$I(J^{PC})$	$?(?^{??})$
MASS	$? \pm ?$
WIDTH	$? \pm ?$
DECAY MODES	STABLE ?
PRODUCTION	$\sigma(?? \to ??) = ?$

Table of DM properties readapted from
M. Cirelli, A. Strumia, J. Zupan (2406.01705).

Dark Matter Candidates

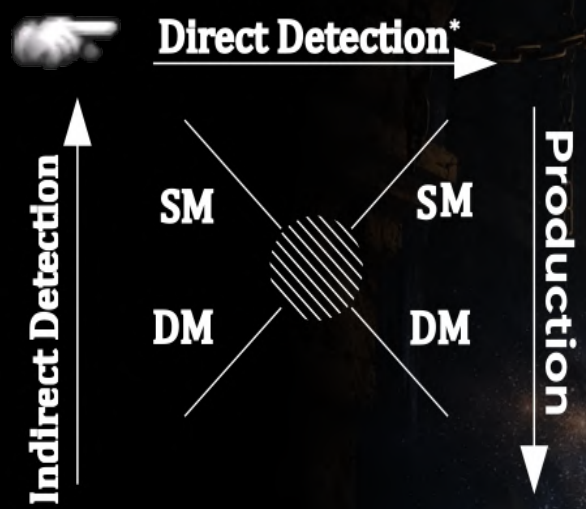
- **Theory**: (rich) dark sectors

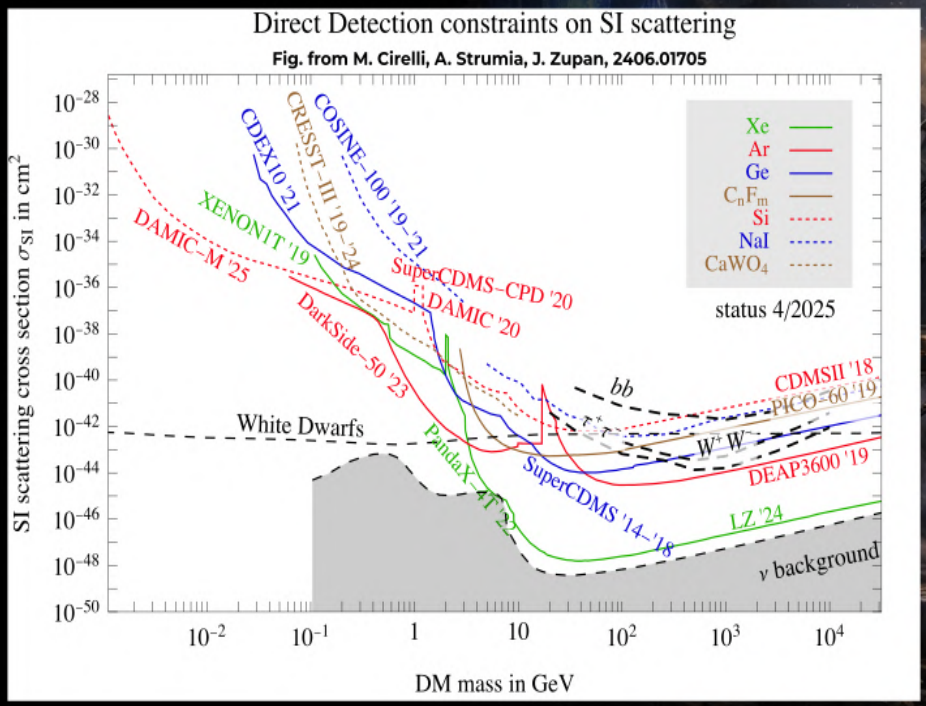
  see e.g. A. Abdullahi et al. [2505.05663]
- **Cosmology**: e.g. thermal freeze-out, freeze-in, asymmetric DM;
- **Astrophysics**: indirect hints
  - GWs at PTAs
  - 511 keV line

    e.g. P. De la Torre Luque, S. Balaji, M. Fairbairn, F. Sala, J. Silk [2410.16379]
  - 20 MeV excess at SK-Gd

    see AG, S. Pascoli, S. Rosauro-Alcaraz [2605.20162])
  - Neutrinos from AGNs?

    see A. G. De Marchi, AG, J. Nava, F. Sala [2412.07861, 2506.06416]
- **Experiments**: accessible to direct detection techniques!


Direct Detection*
Indirect Detection
Production
SM
SM
DM
DM


Direct Detection constraints on SI scattering
Fig. from M. Cirelli, A. Strumia, J. Zupan, 2406.01705
SI scattering cross section σ_{SI} in cm^2
DM mass in GeV
Xe
Ar
Ge
C_nF_m
Si
NaI
$CaWO_4$
status 4/2025
COSINE-100 '19-'21
CDEX10 '21
CRESST-III '19-'24
XENON1T '19
DAMIC-M '25
SuperCDMS-CPD '20
DAMIC '20
DarkSide-50 '23
PandaX-4T '24
SuperCDMS '14-'18
CDMSII '18
PICO-60 '19
DEAP3600 '19
LZ '24
bb
$\tau^+\tau^-$
W^+W^-
White Dwarfs
ν background


DM
DM
EXPERIMENTAL CHALLENGE
$E_{NR} \lesssim$ 0.2 KeV $(m_{DM}/0.5\ GeV)^2\ (16\ GeV/m_N)$

Experimental side

- Use lighter targets
  - NEWS-G (SciPost Phys. Proc. 12 (2023) 024)
- Lower the threshold
  - Phonons (1907.10635, 2205.02250, CRESST-III, ...)
  - Migdal effect and bremsstrahlung (1607.01789, 1707.7258, 2302.09115, SuperCDMS, SENSEI, ...)

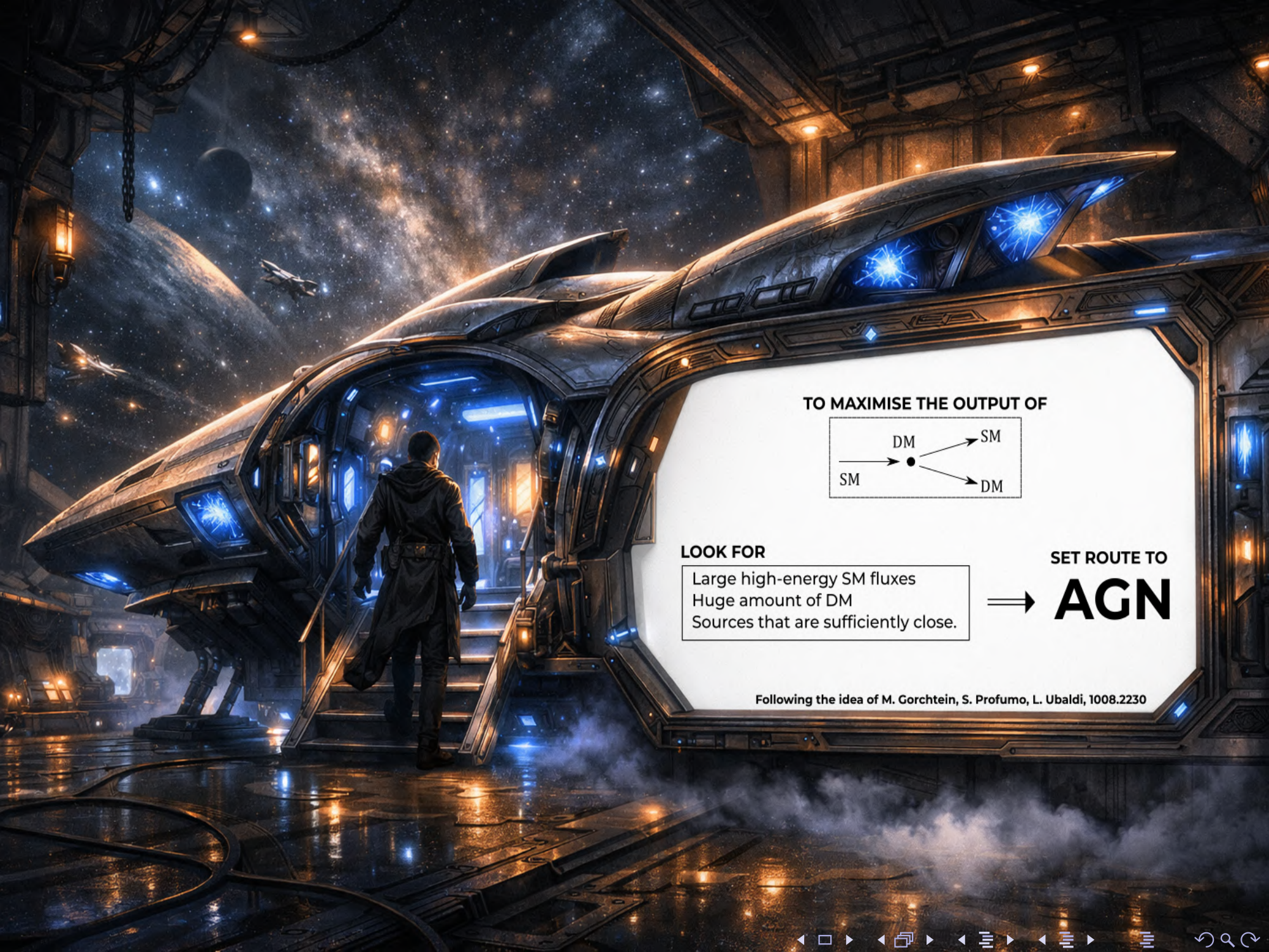
Phenomenological side

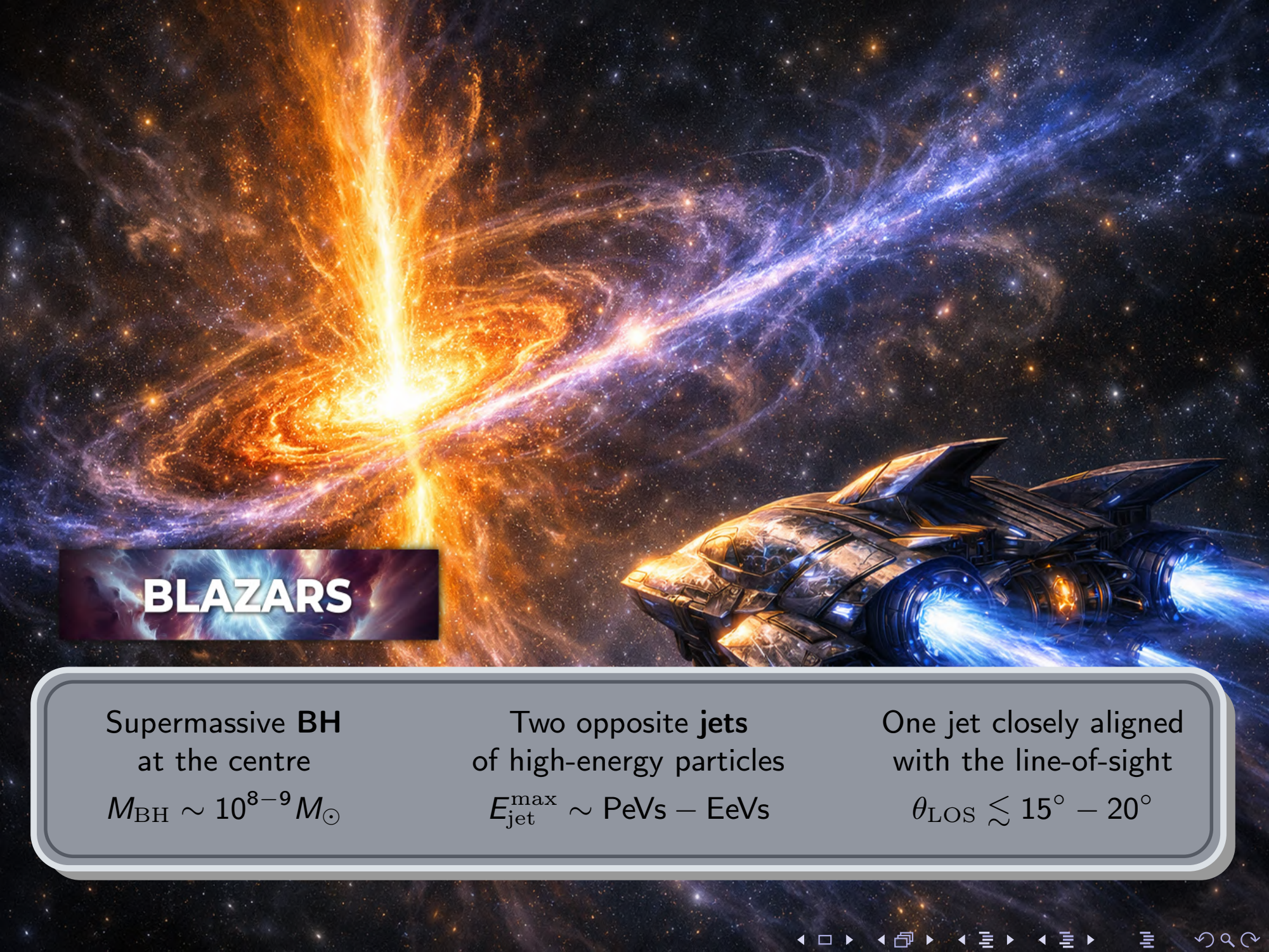
- Look for higher-speed DM particles at current direct detectors and large neutrino detectors!
  - solar up-scattering (1708.03642, 1709.06573);
  - supernovae (1905.09284);
  - evaporating primordial Black Holes (BHs) (2107.13001);
  - atmospheric dark matter (ask F. Sala, S. Pascoli, F. Xotta);
  - up-scatterings by cosmic and supernovae neutrinos (2101.11262, 2104.00027);
  - **up-scattering by Cosmic Rays** (CRs) (1810.10543, 1811.00520, 2011.01939, ...);

  - **up-scattering by blazars** (AG, J.-W. Wang, P. Ullio [2111.13644], then series of works..., A. G. de Marchi, AG, J. Nava, F. Sala [2507.12278] topic of this talk!)

* A change of reference frame

Term quoted by C. V. Cappiello, K. C. Y. Ng, J. F. Beacom in 1810.07705


TO MAXIMISE THE OUTPUT OF
DM
SM
SM
DM
LOOK FOR
Large high-energy SM fluxes
Huge amount of DM
Sources that are sufficiently close.
SET ROUTE TO
AGN
Following the idea of M. Gorchtein, S. Profumo, L. Ubaldi, 1008.2230



Supermassive **BH** at the centre

$M_{\rm BH} \sim 10^{8-9} M_\odot$

Two opposite **jets** of high-energy particles

$E_{\rm jet}^{\rm max} \sim$ PeVs $-$ EeVs

One jet closely aligned with the line-of-sight

$\theta_{\rm LOS} \lesssim 15^\circ - 20^\circ$

MAP OF THE KNOWN BLAZARS

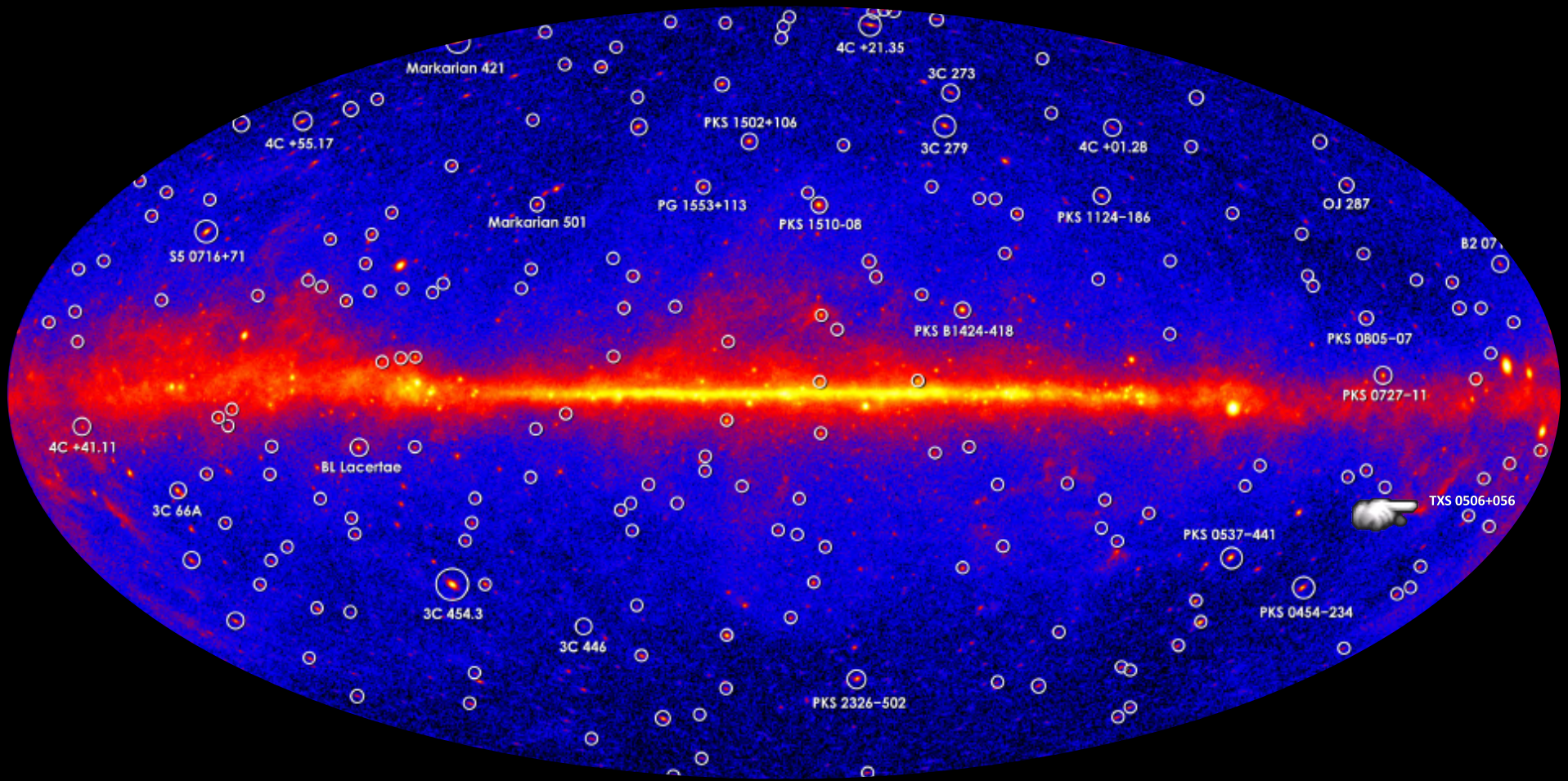
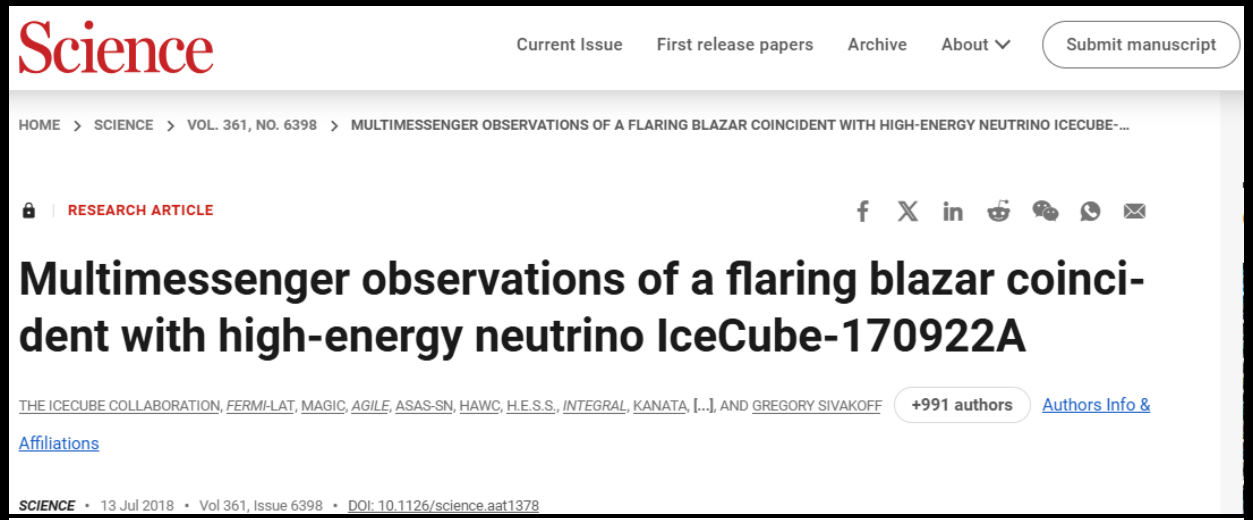


Image Credits: NASA/DOE/Fermi LAT Collaboration



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RESEARCH ARTICLE

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

THE ICECUBE COLLABORATION, *FERMI*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, KANATA, [...], AND GREGORY SIVAKOFF +991 authors Authors Info & Affiliations

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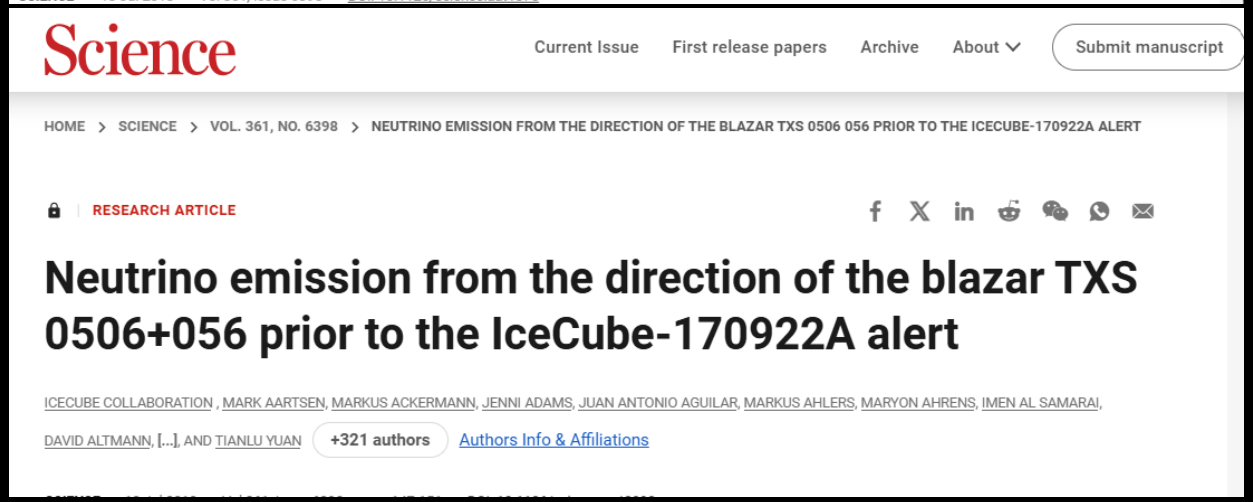

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RESEARCH ARTICLE

Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

ICECUBE COLLABORATION , MARK AARTSEN, MARKUS ACKERMANN, JENNI ADAMS, JUAN ANTONIO AGUILAR, MARKUS AHLERS, MARYON AHRENS, IMEN AL SAMARAI, DAVID ALTMANN, [...], AND TIANLU YUAN +321 authors Authors Info & Affiliations

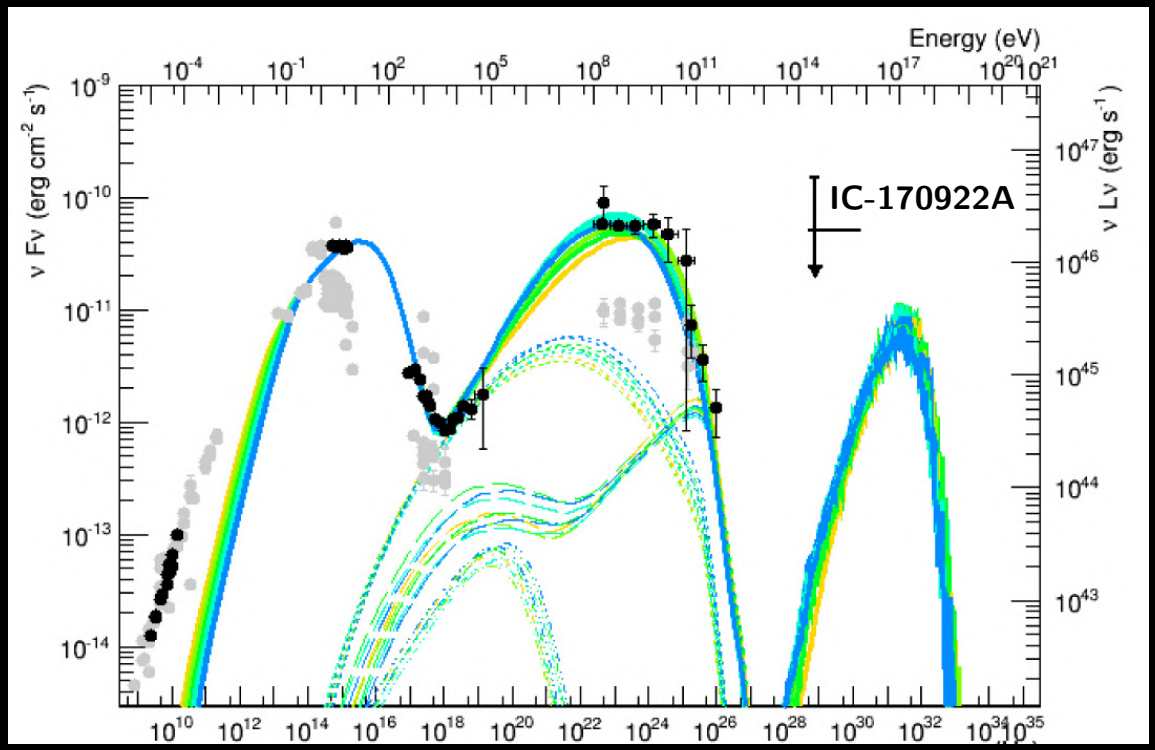
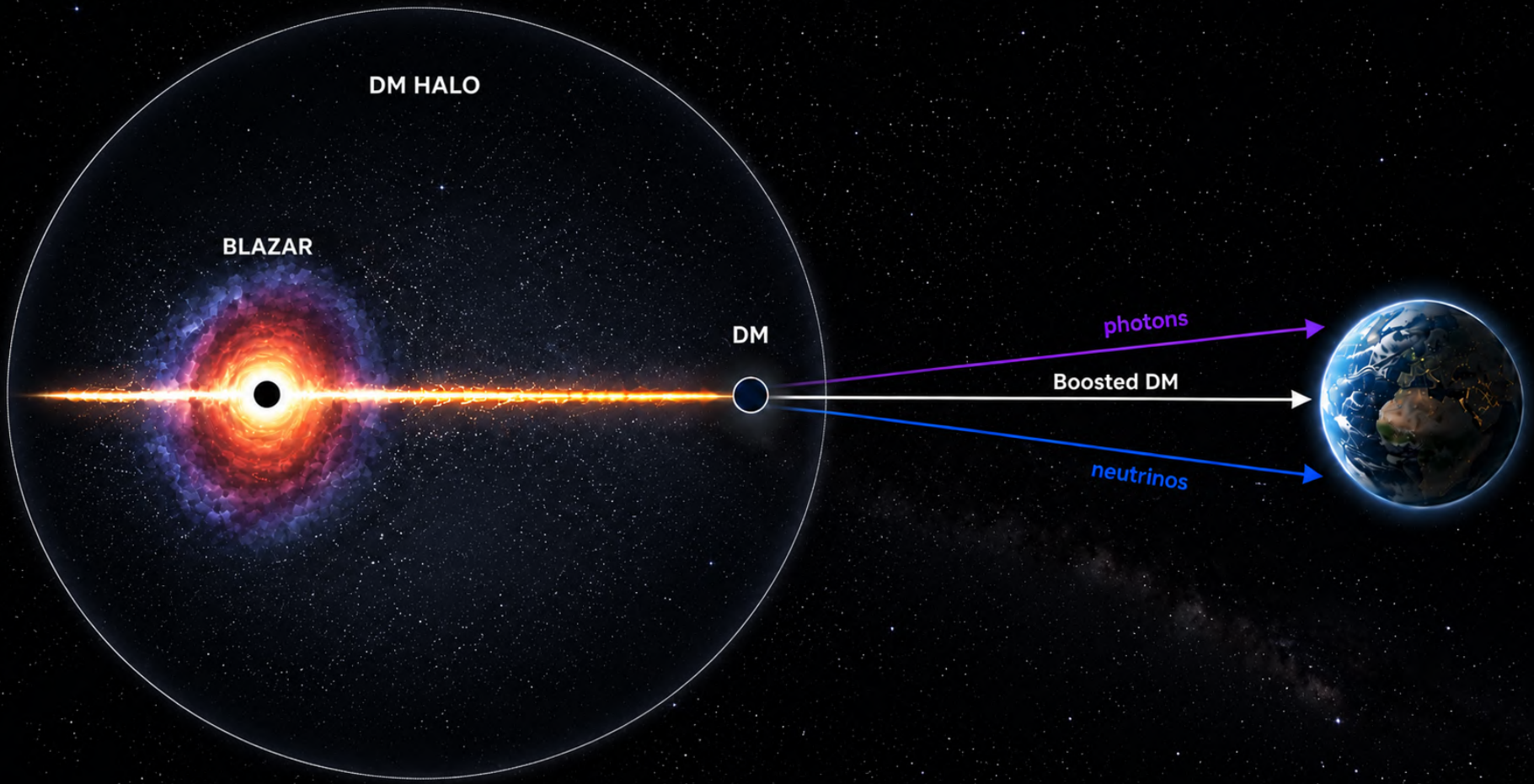


Image from M. Cerruti et al. 1807.04335

- Neutrinos from blazars are a signature of relativistic hadrons in their jets!
- See other talks by Matteo, Xavier, Kohta for many more details on blazars!

Blazars are ideal DM boosters



Blazar-Boosted DM flux

$$\frac{d\Phi_\chi}{dT_\chi} \simeq \frac{\Sigma_{\rm DM}^{\rm tot}}{m_\chi\, d_{\rm L}^2} \sum_{j=e,p} \int d\Omega \int_{T_j^{\rm min}(T_\chi)}^{T_j^{\rm max}} \frac{dT_j}{T_\chi^{\rm max}(T_j)} \frac{d^2\Gamma_j}{dT_j\, d\Omega} \frac{d^2\sigma_{\chi j}}{dT_\chi\, d\Omega}$$

DM SPIKE

Line-of-sight integral of the DM density profile $\rho_{\rm DM}$

$$\Sigma_{\rm DM}^{\rm tot} = \int_{r_{\rm min}}^{r_{\rm max}} \rho_{\rm DM}(r')\, dr'$$

where $r_{\rm min}$ ($r_{\rm max}$) is the radius where the jet starts (ends).

JET SPECTRUM

Spectrum of particles in the jet per unit of kinetic energy T_j and direction Ω.

$$\frac{d^2\Gamma_j}{dT_j\, d\Omega} = \frac{c_j}{4\pi} \left(\frac{E_j'}{m_j}\right)^{-\alpha_j}$$

with $j = e, p$ (power-law in the blob frame).

CROSS SECTION

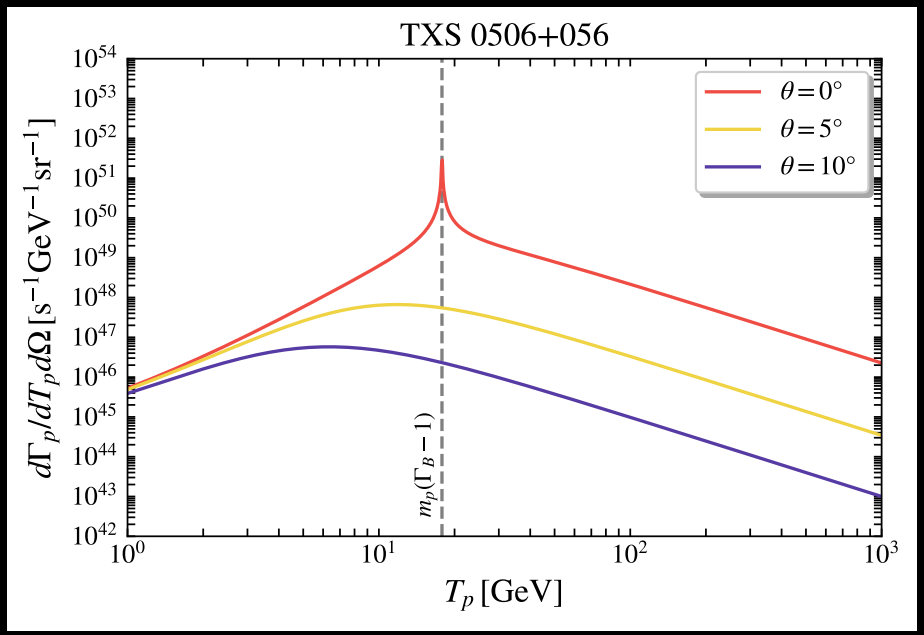
Differential cross section for DM–particle scattering (DM rest frame).

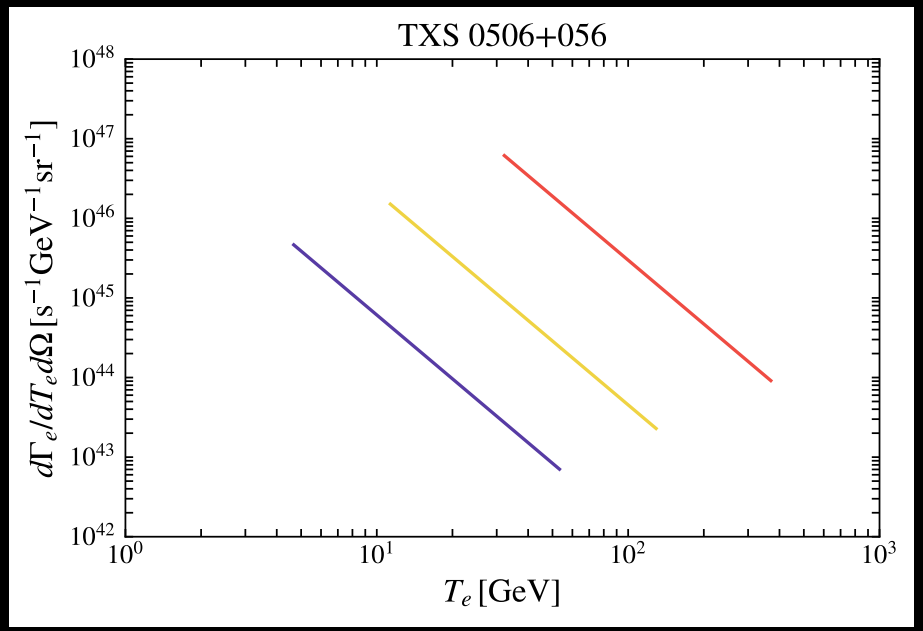
$$\frac{d^2\sigma_{\chi j}}{dT_\chi\, d\Omega}$$

DM interaction model.

Jet Spectrum - Lorentz boost to the DM rest frame

$$\frac{d^2\Gamma_j}{dT_j d\Omega} = \frac{c_j}{4\pi}\left(1+\frac{T_j}{m_j}\right)^{-\alpha_j} \frac{\beta_j(1-\beta_j\beta_B\mu)^{-\alpha_j}\Gamma_B^{-\alpha_j}}{\sqrt{(1-\beta_j\beta_B\mu)^2-(1-\beta_j^2)(1-\beta_B^2)}}$$





- $T_p \gg m_p$, $d\Gamma_p/(dT_p d\Omega) \propto T_p^{-\alpha_p}$
- $T_p \ll m_p$, $d\Gamma_p/(dT_p d\Omega) \approx c_p \Gamma_B^{-\alpha_p}(4\pi\beta_B)^{-1}\sqrt{2T_p/m_p}$.

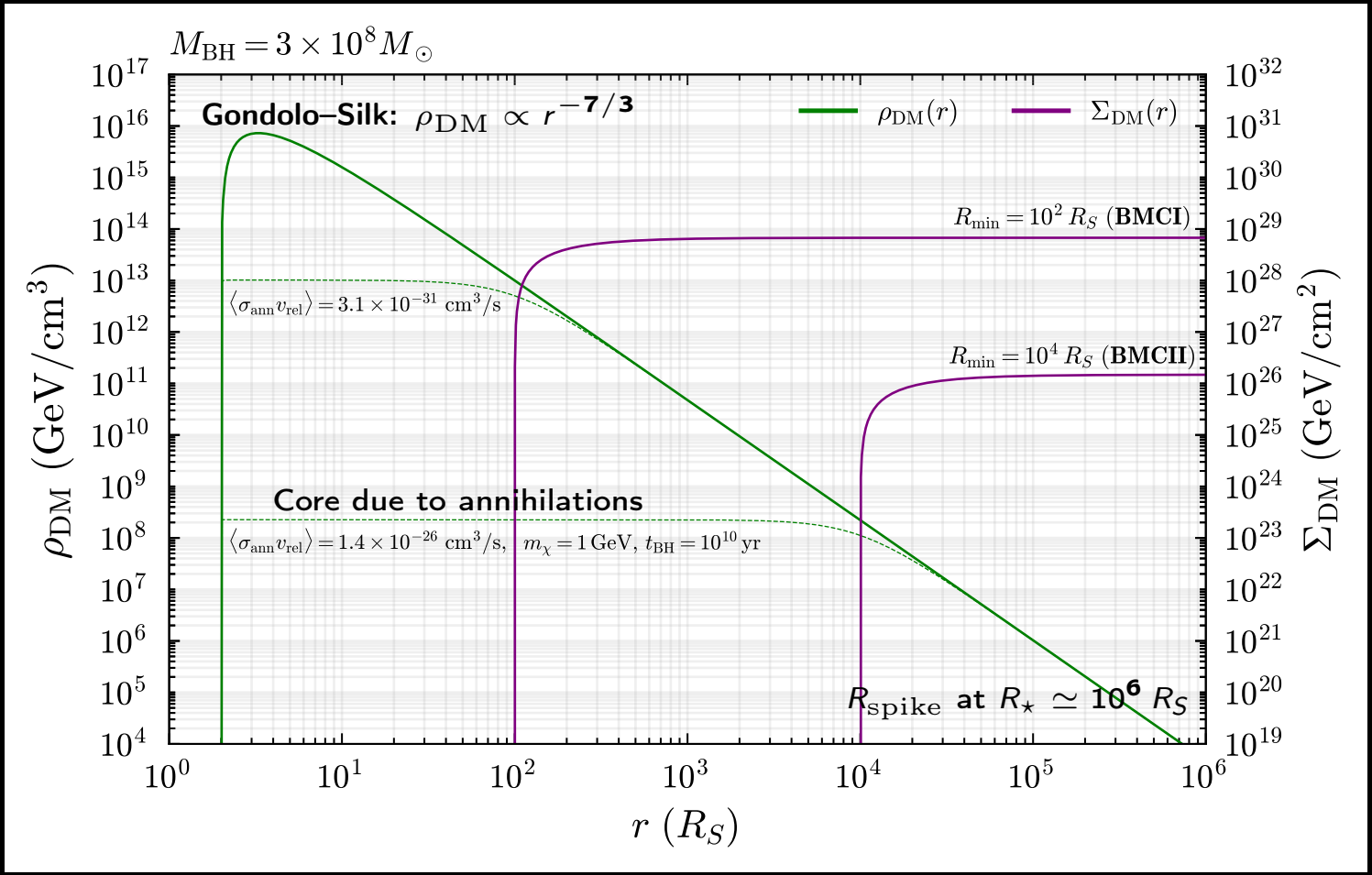
(Lepto-)Hadronic Model Parameters

Parameter (unit)	TXS 0506+056	BL Lacertae
z	0.337	0.069
d_L (Mpc)	1835.4	322.7
$M_{\rm BH}$ ($M_\odot$)	3.09×10^8	8.65×10^7
$\mathcal{D}$	$40^\star$	15
Γ_B	20	15
$\theta_{\rm LOS}$ ($^\circ$)	0	3.82
α_p	2.0	2.4
α_e	2.0	3.5
$\gamma'_{{\rm min},\,p}$	1.0	1.0
$\gamma'_{{\rm max},\,p}$	$5.5 \times 10^{7\star}$	1.9×10^9
$\gamma'_{{\rm min},\,e}$	500	700
$\gamma'_{{\rm max},\,e}$	$1.3 \times 10^{4\star}$	1.5×10^4
L_p (erg/s)	$2.55 \times 10^{48\star}$	9.8×10^{48}
L_e (erg/s)	$1.32 \times 10^{44\star}$	8.7×10^{42}
c_p ($\rm s^{-1}sr^{-1}GeV^{-1}$)	2.54×10^{47}	1.24×10^{49}
c_e ($\rm s^{-1}sr^{-1}GeV^{-1}$)	2.42×10^{50}	2.59×10^{54}

TXS 0506+056 data from 1807.04335, BL Lacertae data from 1304.0605.

$'$ In the blob frame. * Mean values.

DM spikes around blazars

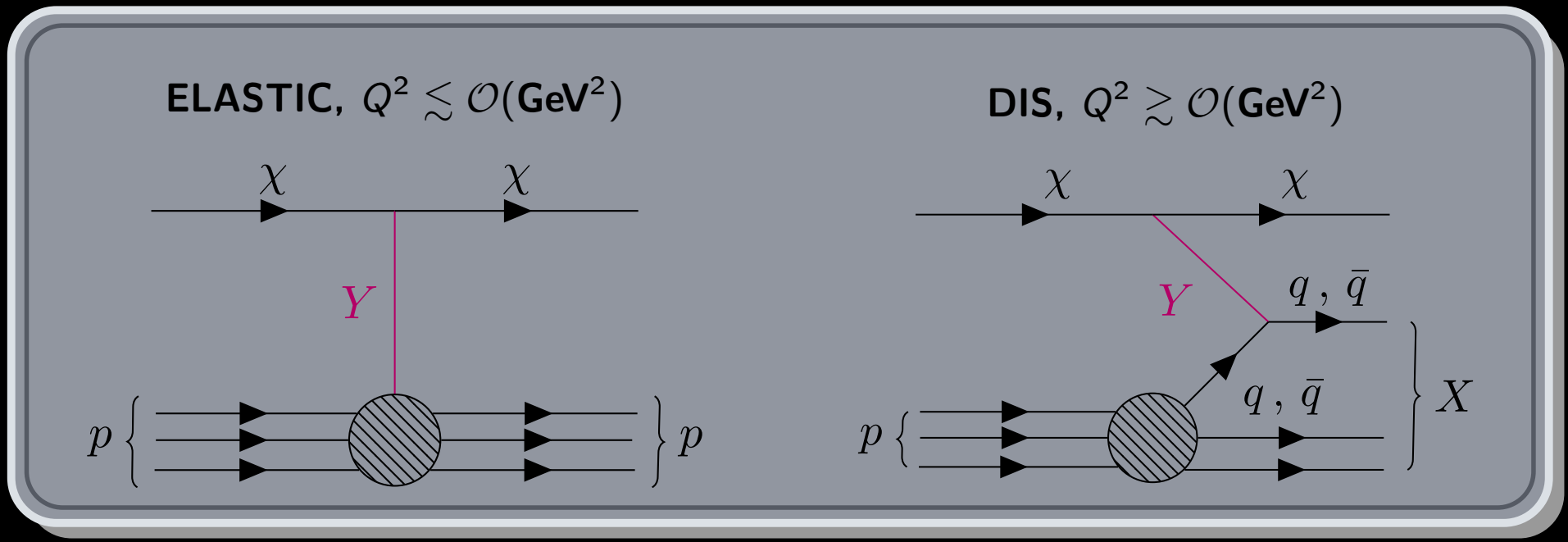


Looking forward to the talks on Wednesday!

Modelling the DM-proton interaction

Specify a model and the mediator Y, e.g., vector mediator $Y = V$

$$\mathcal{L}_{\chi qV} = g_{\chi V}\bar{\chi}\gamma^{\mu}\chi V_{\mu} + g_{qV}\bar{q}\gamma^{\mu}qV_{\mu}$$

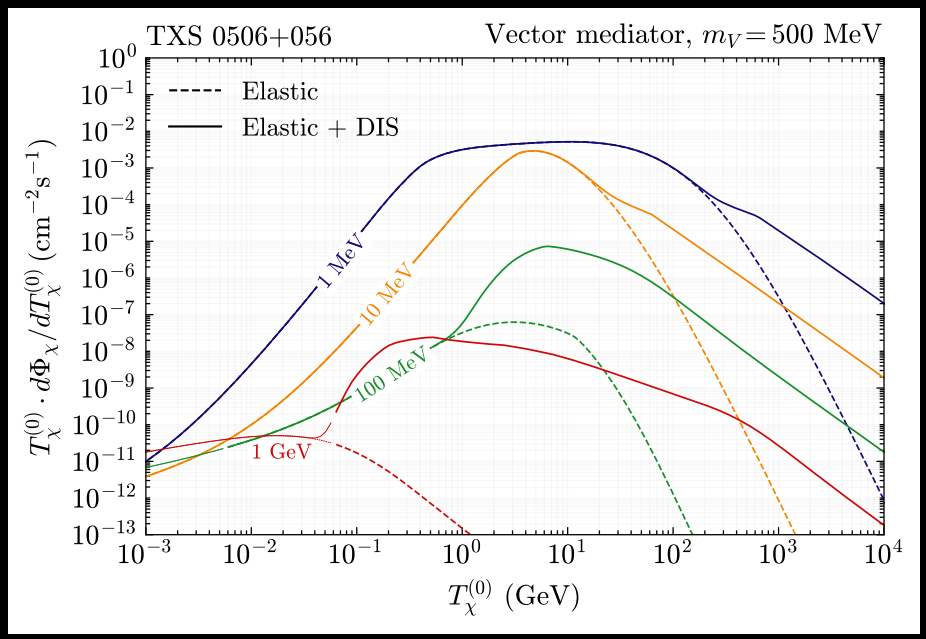


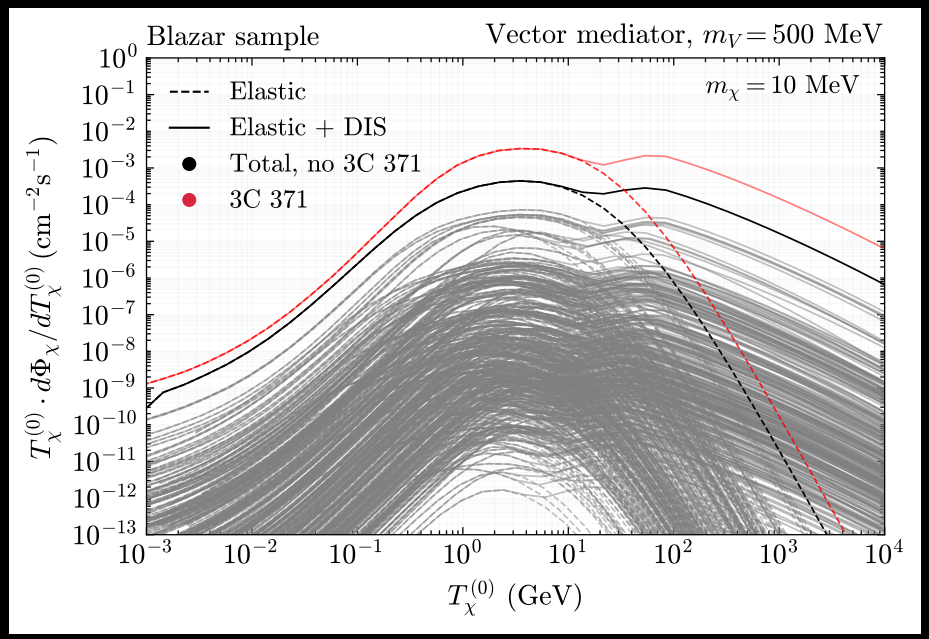
- The flux depends slightly on the type of mediator, more prominently on its mass.
- **RESONANCES?**
- The DIS can boost DM, but also disintegrate the proton and leads to neutrinos and photons (see Andrea's talk)!

EXAMPLE: vector mediator

Results from A. G. De Marchi, AG, J. Nava, F. Sala, 2507.12278

$$\frac{d\Phi_\chi}{dT_\chi^{(0)}} = \frac{dT_\chi}{dT_\chi^{(0)}} \frac{\Sigma_{\rm DM}^{\rm tot}}{m_\chi d_L^2} \sum_{j=e,\,p} \int d\Omega \int_{T_j^{\rm min}(T_\chi)}^{T_j^{\rm max}} \frac{dT_j}{T_\chi^{\rm max}(T_j)} \frac{d^2\Gamma_j}{dT_j d\Omega} \frac{d^2\sigma_{\chi j}}{dT_\chi d\Omega}$$

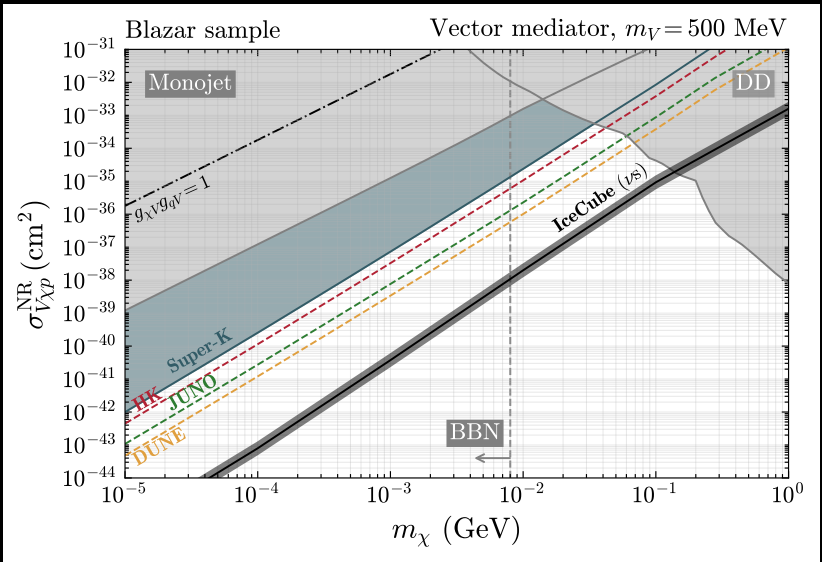


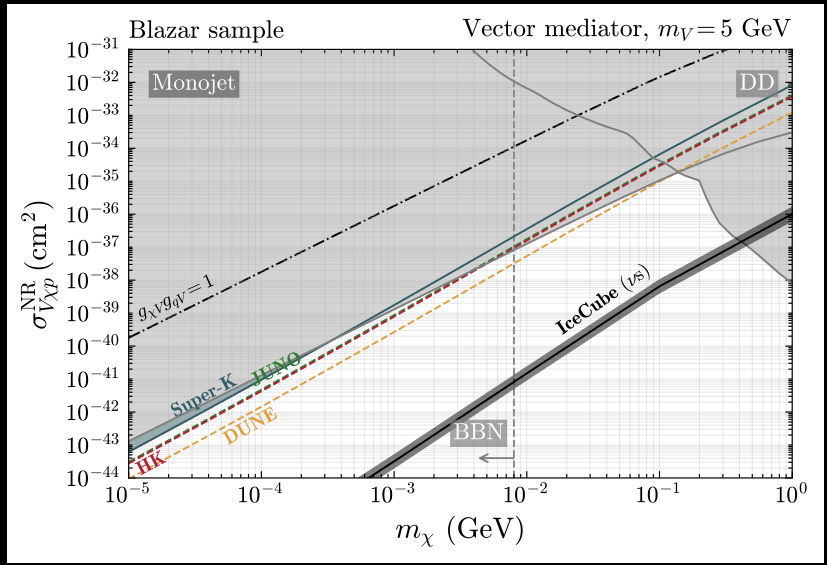


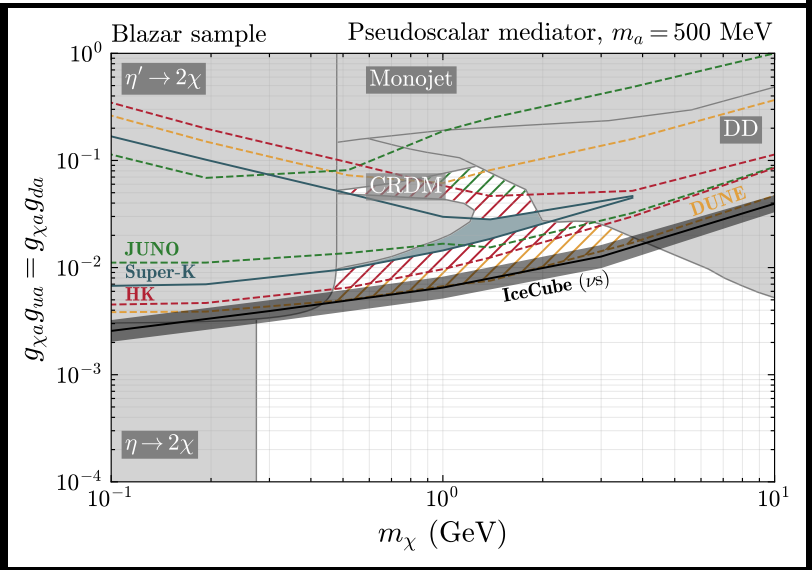
Fit from A. Keivani+ 1807.04537 for TXS, fit from X. Rodrigues+ 2307.13024 for 324 blazars

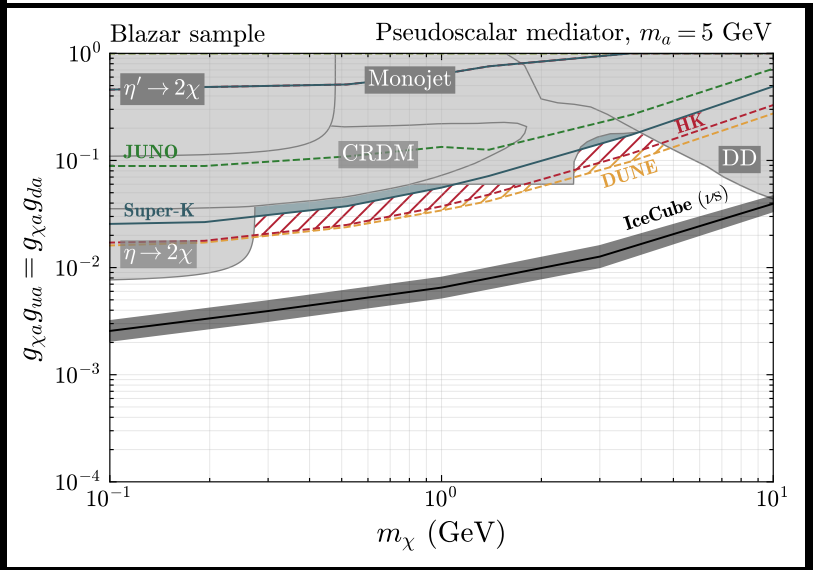
Large neutrino detectors can detect this flux!

Limits and sensitivities of large neutrino detectors

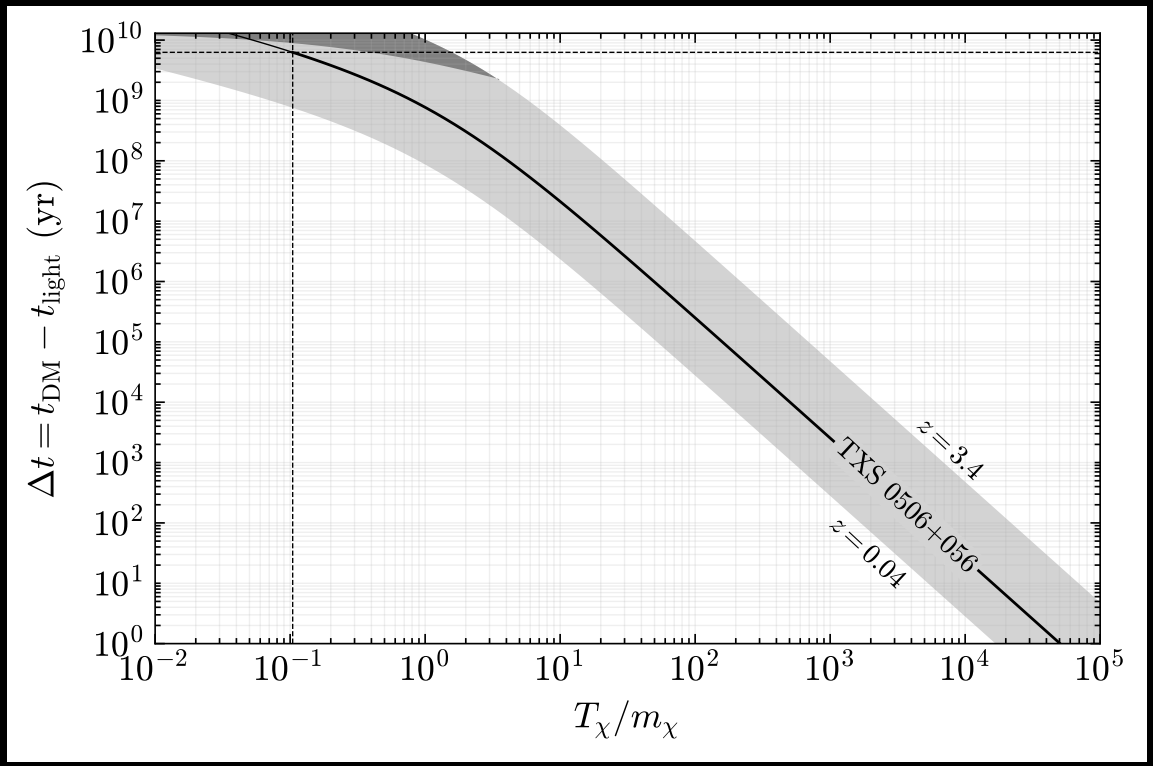






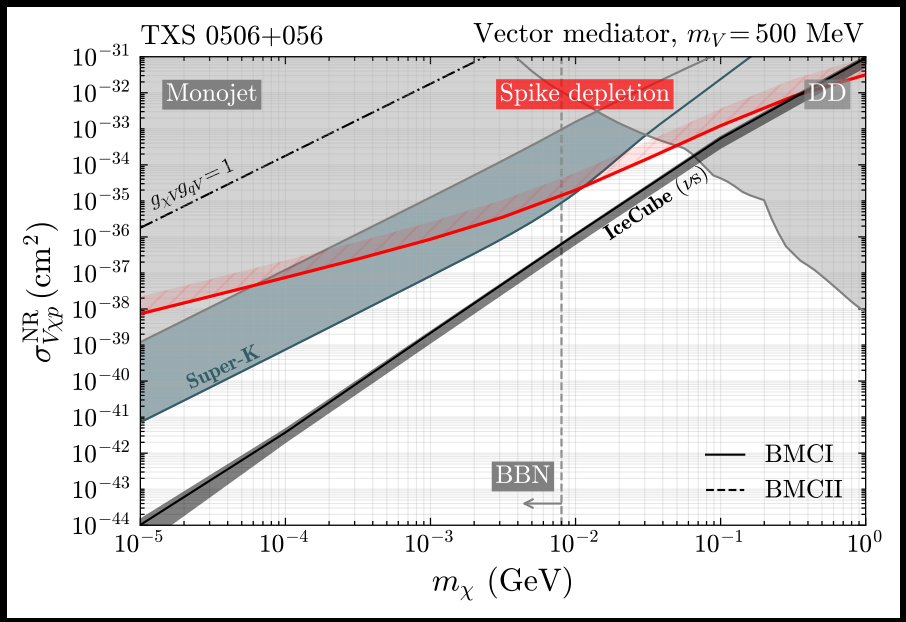


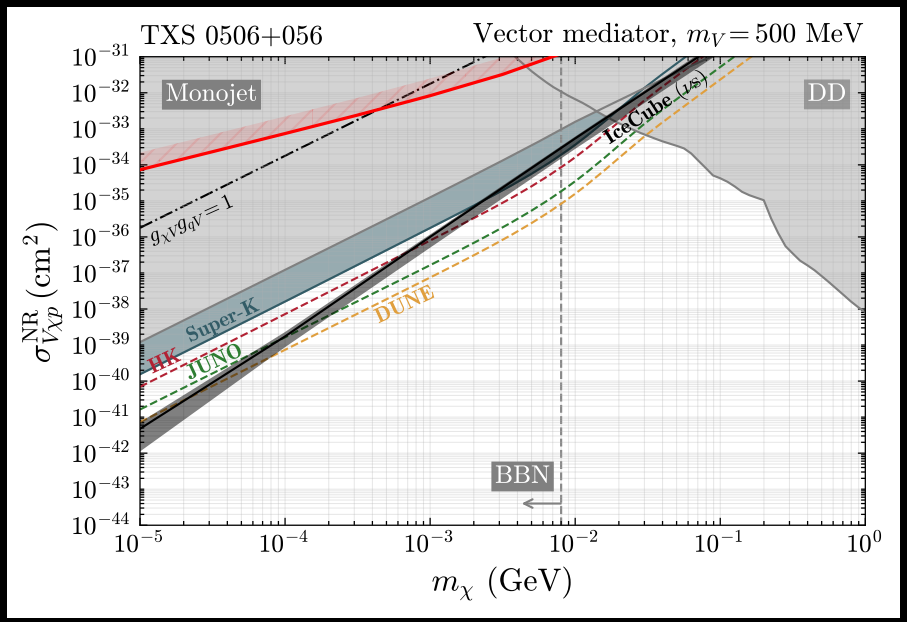
WARNING: DM arrives with a delay w.r.t photons! $\Delta t \simeq t_\gamma / 2\gamma_\chi^2$



- the DM spectrum seen at detector is a time-integred of the history of the blazar activity.
- flaring activity is aggressive $\rightarrow$ steady-state blazar activity more reliable at the cost of lowering L_p

WARNING: DM-proton collisions can deplete the spike over the time scale of spike accretion





- The blazar sample considered and BMCII (right panel) are safe from spike depletion

Outlook

Take-home messages

- **Blazars are ideal dark matter accelerators.**
- **Blazar-boosted dark matter** can be searched for **at large neutrino detectors.**
- **Blazars are multi-messenger sources**, we include dark matter to the picture.
- **Blazar-DM signals are affected by intrinsic limitations** (propagation delays w.r.t to photons and the spike depletion), other neutrino signals from DM around blazar do not.
- **Astrophysical uncertainties** dominate the predictions.


TALK OVER
THANKS FOR YOUR ATTENTION
CONTINUE?