# **Throwing ideas for a brainstorming Anomalies in cosmic-ray physics and more…**

1

#### Daniele Gaggero



My research activity



2. Galactic **Cosmic-ray** phenomenology <—>**WIMP searches**

#### Cosmic-ray propagation in the Galaxy to compute spectra and sky-maps of radiation emitted by CRs interactions in a huge energy Frange range the synchrotron radio waves up to the Senarch radio waves up to the Pe





$$
7 \cdot (\vec{J}_i - \vec{v}_w N_i) + \frac{\partial}{\partial p} \left[ p^2 D_{pp} \frac{\partial}{\partial p} \left( \frac{N_i}{p^2} \right) \right] - \frac{\partial}{\partial p} \left[ \dot{p} N_i - \frac{p}{3} \left( \vec{\nabla} \cdot \vec{v}_w \right) N_i \right] =
$$
  

$$
Q + \sum_{i < j} \left( c \beta n_{\text{gas}} \sigma_{j \to i} + \frac{1}{\gamma \tau_{j \to i}} \right) N_j - \left( c \beta n_{\text{gas}} \sigma_i + \frac{1}{\gamma \tau_i} \right) N_i
$$

- Evoli, **DG**, et al. JCAP 2008 (DRAGON 1)
- **DG**, Evoli, et al., PRL 2013 (DRAGON3D)<br>• Evoli, **DG**, et al., ICAR 2016 (DRAGON 2) *r, p*) is the density per total momentum *p* of the CR species *i*, *Dpp*(~
- Evoli, **DG**, et al., JCAP 2016 (DRAGON 2)
- Evoli, **DG**, et al., 2017 (DRAGON 2 xsec)

# Cosmic-ray propagation in the Galaxy



- Synchrotron emission **Seu** (leptonic CRs)
- HI **21 cm** line
- **Thermal emission** from stars



- **Pion decay** (hadronic CRs)
- **Inverse Compton scattering**, **Bremsstrahlung**  (leptonic CRs)

# **Orthodoxy**

Local Charged Cosmic Particles: The Orthodoxy

**The three pillars** [Gabici et al., 1903.11584]

- The bulk of the **CR energy is released by SN explosions** in the Galactic disk
- CRs are accelerated via **diffusive shock acceleration** at work at SNR shocks
- CRs **diffuse** within an extended, turbulent and magnetized **halo in a isotropic and homogeneous way —> A diffuse, homogeneous CR sea is present through the Galaxy**



#### However, we have anomalies!



主

 $10^{5}$ 

 $\overline{\bullet}$ 

 $10<sup>4</sup>$ 

 $E_{\gamma}$  [MeV]

 $10^{3}$ 

#### Anomalies with respect to what? describe, mainly thanks to a detailed description of the gas distribution in es with respect to what? Instead we aim at providing a description of the main physical results that

• Basic theories used as guidelines for *standard parametrizations*  • Set of "conventional models"  $\rightarrow$  anomalies "w.r.t. conventional model predictions" physical aspects is one in the election of the e $\frac{1}{2}$  $\mathcal{F}_{\text{spall/dec}}^{\text{G3}}$  or startuard parametrizations -> anomalies "w.r.t. conventional model predictions"  $\frac{\partial n_i}{\partial t}$  -  $\vec{\nabla}$  **Basic Inepries**  $\sum\limits_{p}$ *D*<sub>pp</sub> @*p*  $\mathbb{C}$  $\frac{Q}{p^2} n_i = Q_{\text{inj}} + Q_{\text{losses}} + Q_{\text{spall/dec}}$ 

![](_page_7_Figure_2.jpeg)

$$
-\frac{\partial}{\partial z} \left[ D_{\alpha}(p) \frac{\partial f_{\alpha}}{\partial z} \right] + w \frac{\partial f_{\alpha}}{\partial z} - \frac{p}{3} \frac{\partial w}{\partial z} \frac{\partial f_{\alpha}}{\partial p} + \frac{\mu v(p) \sigma_{\alpha}}{m} \delta(z) f_{\alpha} +
$$

$$
\frac{1}{p^2} \frac{\partial}{\partial p} \left[ p^2 \left( \frac{dp}{dt} \right)_{\alpha, ion} f_{\alpha} \right] =
$$

$$
= 2h_d q_{0,\alpha}(p) \delta(z) + \sum_{\alpha' > \alpha} \frac{\mu v(p) \sigma_{\alpha' \to \alpha}}{m} \delta(z) f_{\alpha'},
$$

- $\alpha$ with a *z* the Heaviside function is the galactic function. We are a position of a position of a position of a possible  $\mu$ outflow (if none is present *u* = 0). The mean Alfv´en speed ¯*v<sup>A</sup>* is the e↵ective  $\sum_{i=1}^n a_i$  superaged upon the direction of the waves: if the waves: if the waves:  $\sum_{i=1}^n a_i$  the waves:  $\sum_{i=1}^n a_i$  of the waves: • 1 source class, universal featureless source spectrum *(but sometimes breaks are introduced)*
- Isotropic, homogeneous diffusion *(is it* compatible with QLT?). Power-law in R

## How my research started…

![](_page_8_Figure_1.jpeg)

![](_page_8_Figure_2.jpeg)

0 Crosse at al. 2000 [000E 0626] D. Grasso et al. 2009 [0905.0636]

in contrast with the synthesis of light elements in the early Universe. In particular, the orange curve in the middle panel of  $\mathcal{L}$  is the estimate of  $\mathcal{L}$  (Jedam $\mathcal{L}$  ) for  $\mathcal{L}$ 

![](_page_9_Figure_0.jpeg)

# Harder CR spectrum in the inner Galaxy?

![](_page_10_Figure_1.jpeg)

A **CR hardening** in the inner Galaxy inferred by gammaray data interpreted as a progressively harder scaling of the diffusion coefficient

$$
D(\rho) = D_0 \beta^{\eta} \left(\frac{\rho}{\rho_0}\right)^{\delta(r)}
$$

$$
\delta(r)=ar+b
$$

![](_page_10_Figure_5.jpeg)

# Harder CR spectrum in the inner Galaxy?

![](_page_11_Figure_1.jpeg)

A **CR hardening** in the inner Galaxy inferred by gammaray data interpreted as a progressively harder scaling of the diffusion coefficient

$$
D(\rho) = D_0 \beta^{\eta} \, \left(\frac{\rho}{\rho_0}\right)^{\delta(r)}
$$

$$
\delta(r) = ar + b
$$

![](_page_11_Figure_5.jpeg)

#### Neutrino connections

**Base** ("pi0"/"Conventional") models VS **Gamma** ("KRAgamma") models

![](_page_12_Figure_2.jpeg)

![](_page_12_Figure_3.jpeg)

*"our model also provides a different interpretation of the full-sky neutrino spectrum measured by IceCube with respect to the standard lore, since it predicts a larger contribution of the Galactic neutrinos to the total flux, compared to conventional models. These predictions will be testable in the near future by neutrino observatories such as ANTARES, KM3NeT, and IceCube itself via dedicated analyses that are focused on the Galactic plane"*

Napoli - November 2024 13  $\frac{1}{2}$  models for two different cuts for two different cuts  $\frac{1}{2}$  values. We also different cuts  $\frac{1}{2}$  and  $\frac{1$ 

# Neutrino connections

![](_page_13_Figure_1.jpeg)

- 10 years of data
- *Cascade* events were analyzed *(lower background, better energy resolution, and lower energy threshold of cascade events compensate for their inferior angular resolution)*
- Neutrino emission from GP is **detected**. Three models tested.

### Neutrino connections + Multi-messenger

![](_page_14_Figure_1.jpeg)

- How to deal with high-energy uncertainties? Position
- •Role of unresolved sources? **New ideas needed!!**

 $\overline{10}$ <sup>6</sup>

# Part II: Black Holes and Dark Matter

#### **Black Holes phenomenology:**

- Study of Black Hole *inspirals*
- Accretion physics

![](_page_15_Picture_4.jpeg)

- Gravitational Waves
- Radio waves/ X-rays/ Gamma rays/ **Neutrinos**

#### **Dark Matter searches**

- *- Can Black holes of primordial origin be a part of the Dark Matter?*
- *- Can we learn something on the nature of the Dark Matter by*  **Multi-messenger astronomy** *studying Black Hole physics?*

#### Black Holes as Portals to new Physics

- Intermediate-Mass Black Holes may exist in the Universe.
- Dark-Matter overdensities can form around them [Gondolo&Silk 9906391, Zhao&Silk 0501625, Hannuksela+ 1906.11845]. **Dain-Matter Over**

$$
M_{IMBH} \frac{\rho_{\text{EM}}}{2} M_{\text{O}} \frac{r_{\text{sp}}}{r} \text{ m}^2
$$
\n
$$
\gamma_{\text{sp}} = 7/3 \approx 2.333
$$
\n
$$
\rho_{\text{sp}} = 200 \, M_{\odot} \, \text{pc}^{-3}
$$
\n
$$
r_{\text{sp}} = 0.5 \, \text{pc}
$$
\n
$$
\rho_{\text{DM}}(r) = \rho_{\text{sp}} \left(\frac{r_{\text{sp}}}{r}\right)^{\gamma_{\text{sp}}} \qquad \rho_{\text{sp}} = 200 \, M_{\odot} \, \text{pc}^{-3}
$$
\n
$$
\rho_{\text{sp}} = 200 \, M_{\odot} \, \text{pc}^{-3}
$$
\n
$$
r_{\text{sp}} = 0.5 \, \text{pc}
$$

 $\rho \sim 10^{24} M_{\odot} \, {\rm pc}^{-3}$ 

#### Black Holes as Portals to new Physics aLIGO ET BLACK Holes as Portals to new Physics  $\begin{picture}(180,10) \put(0,0){\line(1,0){10}} \put(1,0){\line(1,0){10}} \put(1$

Trace NS/BH Assas" or "spika 1A2 C<br>C<br>d (*m*1*, m*2*, dL*) = • Stellar-mass black holes that inspiral around IMBHs can trace the extent overdensities (DM "dresses" or "spikes") by an adiabatic compact over the compact of th • Stellar-mass black holes that uspiral around IMBHs can trace the presence of either accretion disks or Dark Matter where  $\mathbb{R}^n$  is dissipated through the slow  $\mathbb{R}^n$  is slow  $\mathbb{R}^n$ on a given circular orbit to another circular orbit to another circular orbit with a second control orbit with

![](_page_17_Figure_2.jpeg)

![](_page_17_Figure_3.jpeg)

DM particles, it loses energy via *dynamical friction* (DF)

• Dephasing of the waveform w.r.t. GR in vacuum • Physical process: Dynamical Friction d*t* JI<br>. 32*G*<sup>4</sup>*M*(*m*1*m*2)<sup>2</sup> .i. un in vacuum<br>riction

 $\left\| \left( \left( \begin{array}{cc} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{array} \right) \right) \right\|$  - - - | No DM  $\left\| \left( \begin{array}{cc} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{array} \right) \right\|$ • Kavanagh+ 2002.12811 (PRD) • Coogan+ <u>2108.04154</u> (PRD) Cole+ [2211.01362](https://arxiv.org/abs/2211.01362) (Nature Astronomy) where the constant  $\mathbb{I}$ **m**<sub>1</sub> *m m*  $\overline{\phantom{0}}$   $\overline{\phantom{0}}$  No DM  $\overline{\phantom{0}}$   $\overline{\phantom{0}}$  With DM Halo

$$
\frac{dE_{\rm DF}}{dt} = 4\pi (Gm_2)^2 \rho_{\rm DM}(r_2) \xi(v) v^{-1} \log \Lambda
$$

#### Environments Hole Environments ⇢DM(*r*)

![](_page_18_Picture_1.jpeg)

Particle Dark Matter 'Spikes' or 'Dresses' **D**ain Matte *m*<sup>2</sup> **b**<sup>2</sup>

- **we Collisionle** • **Collisionless** DM overdensity • Perturbation back-
	- **Spherical** symmetry
	- **Dynamical friction** at work
	- **Feedback** on the halo is important

$$
\frac{\mathrm{d}E}{\mathrm{d}t} = m_2 v_0 \frac{\mathrm{d}v}{\mathrm{d}t} = -\frac{4\pi (G_N m_2)^2 \rho_{\rm DM}(r)\xi(v_0)}{v_0} \log \Lambda
$$

![](_page_18_Figure_8.jpeg)

- Differentially rotating **baryonic** disk
	- $\bullet$  Digk is porturbed by  $\frac{3}{2}$ and the state of the state • Disk is perturbed by the inspiralling "wake"
	- **al friction** at work<br> **b** an the bala is inepertured torques **torques** Figure 5: An accretion disk being perturbed by an inspiral with mass ratio *q* = 10<sup>3</sup>. Streams of particles from  $u_{\rm eff}$  to downstream as they interact with the secondary object, as is further highlighted in the zoom-in panel. From [49]. • Perturbation backcts and exerts

![](_page_18_Figure_13.jpeg)

$$
T_{\rm I}=-\Sigma(r)r^4\Omega^2q^2{\cal M}^2
$$

$$
\frac{dE}{dt} = m_2 v_0 \frac{dv}{dt} = -\frac{4\pi (G_N m_2)^2 \rho_{DM}(r)\xi(v_0)}{v_0} \log \Lambda \qquad \qquad \frac{dE_{\text{torque}}}{dt} = -\frac{1}{4} m_1 T_1 \left(\frac{G_N}{r^3 M}\right)^{1/2}
$$

#### Formation of DM overdensities

![](_page_19_Figure_1.jpeg)

#### •**Formation of a supermassive**

**star:** profile is shallower compared to GS solution, because the potential of the SMS star is more extended

#### •**Direct Collapse Black Hole:** mild steepening

Orbits with  $r < 2r_S$  **captured** by the BH, as in fully relativistic computation 1305.2619 *(radius of the unstable circular orbit in the Schwarzschild geometry for a marginally bound particle*)

> Gianfranco Bertone, Renske Wierda, DG, Bradley Kavanagh, Marta Volonteri, Naoki Yoshida, *2404.08731*

IFIC - April 2024 20

# Formation of DM overdensities

•How does the nature of the DM candidate change this picture?

![](_page_20_Figure_2.jpeg)

# **Conclusions**

- •Can CR anomalies point to new physics? or interesting new astrophysics?
- •Can BH phenomenology inform us about dark matter?

## New physics searches

![](_page_22_Figure_1.jpeg)

#### Debate about a GeV excess

![](_page_23_Figure_1.jpeg)

- An extended, spherical **signal** from the **inner Galaxy**  $\mathcal{L} = \mathcal{L} = \mathcal$ (preliminary)" corresponds to Reference 13. The horizontal gray band indicates the (uniform) intensity of the Fermi bubbles (20; see  $\sim$  3.2.5), extrapolated from latitudes above 10°, which where the vertical gray band approximately delimits the region where the regio
- Outlined by a *template fitting* technique et al. (10), Daylan et al. (11),  $\alpha$  is al. (13). Because the analyses of the analyses shown in this figure are based of the analyses shown in this figure are based of the GC excess shown in this figure are based of the σαιπισα by α **ισπριαισ πιιπ**  $F11Q$ 
	- **DM interpretation**:  $M_{DM} \sim 30$  GeV;  $\sigma_{ann}$  close to thermal cross section **interpretation**: *Wem*  $\sim$  *3U* GeV:  $O_{\text{ann}}$  ( energy component of the GC excess spectrum, below ∼1 GeV, is also uncertain and covers large  $\overline{\phantom{a}}$  ologo<sup>+</sup>  $\alpha$  in space to the found of secession  $\alpha$
	- Very rich literature!  $\nu$  rich literations and high-energy component, where  $\nu$ falls below the origin of the origin of the origin of the  $\mathcal{L}$

D. Dixon et al. 1998 [arXiv:9803237]; V. Vitale et al. 2009 [arXiv:0912.3828]; L Goodenough and D. Hooper, 2009; D. Hooper and L. Goodenough, 2010 D. Hooper and T. Linden, 2011; K. N. Abazajian and M. Kaplinghat, 2012 D. Hooper and T. R. Slatyer, 2013; C. Gordon and O. Macias, 2013 T. Daylan, D. P. Finkbeiner, D. Hooper, T. Linden; S. Portillo, N. L. Rodd and T. R. Slatyer, 2014 [arXiv:1402.6703]; F. Calore, I. Cholis, C. Weniger, 2014 [arXiv:1409.0042]; F. Calore et al. 2015 [arXiv;1411.4647]  $\frac{D.1100}{V}$  and 1. Entach, 2011, it. it. *The argument* and not aad farvin adnasy) is in nime er an sona farvin ha is.  $N_{\rm eff}$  distribution. The following parameterization for a generalized  $N_{\rm eff}$  $G_{\alpha}$ Viut $1409$   $6709$  -  $F$  Colora I Cholia C Wanigar  $9$ parxiv.i+02.07 00<sub>1</sub>, r. Oaioro, r. Oriono, O. vvoriigor, 20<br>21 F. Q. Local D. Rocal D. N. Local D. D. D. D. of the GC excess, but a shallower proflem proflem proflem proflem with γ  $=1$  is also allowed. The NFW proflem  $\sim$ 

### Debate about a GeV excess

![](_page_24_Figure_1.jpeg)

- **• Is it really an excess**  (normalization issues)? Regions of the parameter space compatible with a dark matter interpretation of the Galactic center excess (contours and points with . Data from Gordon  $\mathcal{L}$  al. (10), Daylan et al. (11), Calore et al. (12), Abazajian  $\mathcal{L}$ cross section (*gray dotted line*) (56) and with the constraints from dwarf spheroidal galaxies (*solid brown line*) (54). The tan band illustrates  $\mathcal{N}$  and constraints by a factor of two (57, 58) related to the assumptions for the assumption  $\mathcal{N}$
- D. Gaggero et al. 2015 [1507.06129] E. Carlson et al. 2015 [1510.04698]  $\blacksquare$ . Carison et al. 2015 [1510.04698] reliable detections because they are less susceptible to the limitations in modeling of the IE (for a
- $\cdot$  **Is it really spherically symmetric** (morphology issues)? **guabrica promision targets for the most promising targets for the largest DM clumps in the largest DM clumps p** by cold DM *N*-body simulations of galaxy formation. As they contain stars, they are observed cesses. In addition, the determination of the *J*-factor for dwarf spheroidals is less dependent on
- spheroidal DM halo, unlike for the GC, where changes in slope can signifcantly alter the *J*-factor. R. Bartels et al. 2017 [1711.04778]
- On Mosing of all 2017 [1611 06611] O. Macias et al. 2017 [1611.06644]

#### **• DM interpretation**

tension with constraints from dwarf spheroidal galaxies? connection with other channels?

#### **• MSP interpretation**

suggested by wavelet analyses and photon statistics. **Probably:** new astrophysics found!

R. Bartels et al. 2016 [1506.05104] S. Lee et al. 2016 [1506.05124] F. Calore et al. 2021 [2102.12497]

![](_page_24_Figure_12.jpeg)

# Future prospects (LSST+Fermi, CTA)

![](_page_25_Figure_1.jpeg)