EAS 2022 Valencia - June 29

Pulsar population synthesis with multi-modal machine learning

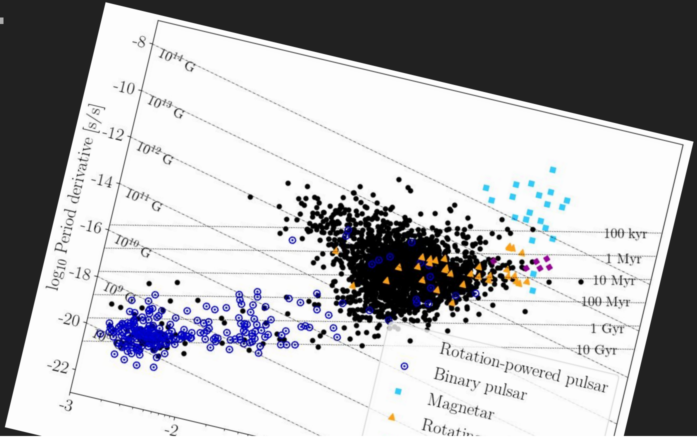
Dr. Vanessa Graber (graber@ice.csic.es)

in collaboration with Michele Ronchi, Celsa Pardo Araujo, Nanda Rea & José Pons

Background

- We have detected **~3,000 pulsars**, with ~2,000 being isolated. They have diverse characteristics, visible in different parts of electromagnetic spectrum ➡ **neutron star zoo**.

- **Galactic core-collapse supernova rate** is insufficient for independent formation of these classes (Keane & Kramer 2008) ➡ **evolutionary links** (e.g., Viganò et al. 2013)**?**



$\beta_{\rm PSR}$, $n_{\rm e}$	PSRs	RRATs	XDINSs	Magnetars	Total	CCSN rate
FK06, NE2001	2.8 ± 0.5	$5.6^{+4.3}_{-3.3}$	2.1 ± 1.0	$0.3^{+1.2}_{-0.2}$	$10.8^{+7.0}_{-5.0}$	1.9 ± 1.1
L+06, NE2001	1.4 ± 0.2	$2.8^{+1.6}_{-1.6}$	2.1 ± 1.0	$0.3^{+1.2}_{-0.2}$	$6.6^{+4.0}_{-3.0}$	1.9 ± 1.1
L+06, TC93	1.1 ± 0.2	$2.2^{+1.7}_{-1.3}$	2.1 ± 1.0	$0.3^{+1.2}_{-0.2}$	$5.7^{+4.1}_{-2.7}$	1.9 ± 1.1
V+04, NE2001	1.6 ± 0.3	$3.2^{+2.5}_{-1.9}$	2.1 ± 1.0	$0.3^{+1.2}_{-0.2}$	$7.2^{+5.0}_{-3.4}$	1.9 ± 1.1
V+04, TC93	1.1 ± 0.2	$2.2^{+1.7}_{-1.3}$	2.1 ± 1.0	$0.3^{+1.2}_{-0.2}$	$5.7^{+4.1}_{-2.7}$	1.9 ± 1.1

NS birth vs. Galactic CCSN rates (Keane & Manchester 2008).

Background

- We have detected **~3,000 pulsars**, with ~2,000 being isolated. They have diverse characteristics, visible in different parts of electromagnetic spectrum ➡ **neutron star zoo**.

- **Galactic core-collapse supernova rate** is insufficient for independent formation of these classes (Keane & Kramer 2008) ➡ **evolutionary links** (e.g., Viganò et al. 2013)**?**

NS birth vs. Galactic CCSN rates (Keane & Manchester 2008).

Pulsar Population Synthesis

- We only **observe** a very **small fraction** of the **~10^9 neutron stars** expected in the Milky Way. Instead of looking at individual pulsars, population synthesis focuses on the **entire population** (e.g. Faucher-Giguère & Kaspi 2006, Lorimer et al. 2006, Gullón et al. 2014, Cieślar et al. 2020):

model **birth properties** with Monte-Carlo approach → **evolve parameters** forward in time → **apply filters** to mimic observational biases/limits → **compare** mock samples **to observations** to constrain input

- Method provides e.g. **birth rates** and **initial v / P / B distributions.**

→ focus on **Deep Learning (DL) for** the **comparison**

DL Proof-of-concept Study - Ronchi et al. (2021)

- Focus on **positional & velocity evolution** and follow earlier works using an updated spiral-arm (Yao et al. 2017) and Galactic model (Marchetti et al. 2019) plus rigid Galaxy rotation.

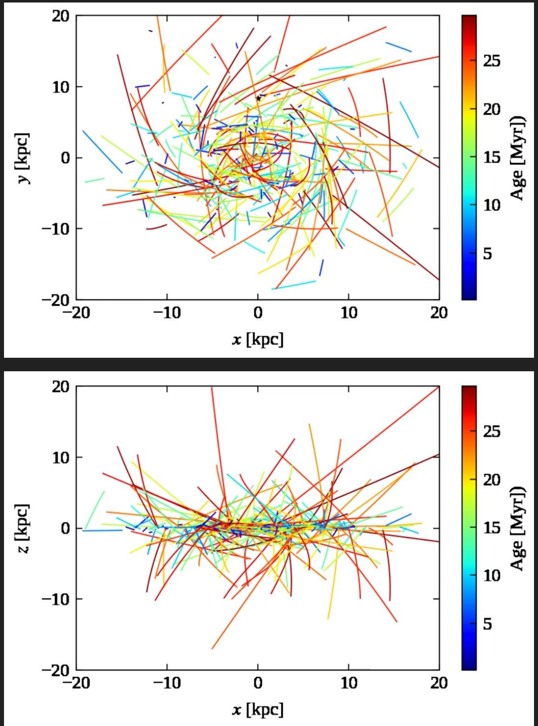
- Evolve **10^5 stars** for (up to) **10^7 yr** varying

exponential **scale height h_c** for birth distance from plane

+

dispersion σ_k of Maxwell distribution for kick velocities

to obtain 16,384 **mock populations**. Extract images (labelled by h_c,σ_k) as **training data** for a **convolutional neural network (CNN)**.



Galactic evolution tracks for h_c = 0.18 kpc, σ_k = 265 km/s.

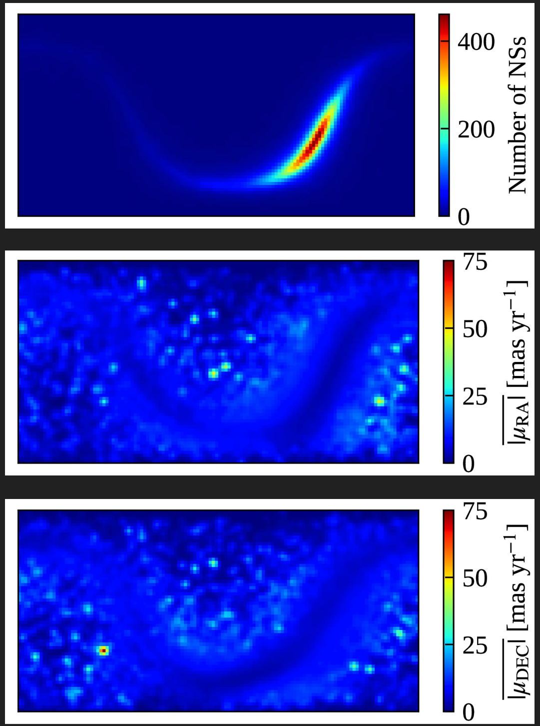
DL Proof-of-concept Study - Ronchi et al. (2021)

- Focus on **positional & velocity evolution** and follow earlier works using an updated spiral-arm (Yao et al. 2017) and Galactic model (Marchetti et al. 2019) plus rigid Galaxy rotation.

- Evolve **10^5 stars** for (up to) **10^7 yr** varying

exponential **scale height h_c** for birth distance from plane **+** **dispersion σ_k** of Maxwell distribution for kick velocities

to obtain 16,384 **mock populations**. Extract images (labelled by h_c,σ_k) as **training data** for a **convolutional neural network (CNN)**.



Stellar density and velocities in ICRS coordinates.

graber@ice.csic.es

DL Proof-of-concept Study - Ronchi et al. (2021)

- Focus on **positional & velocity evolution** and follow earlier works using an updated spiral-arm (Yao et al. 2017) and Galactic model (Marchetti et al. 2019) plus rigid Galaxy rotation.

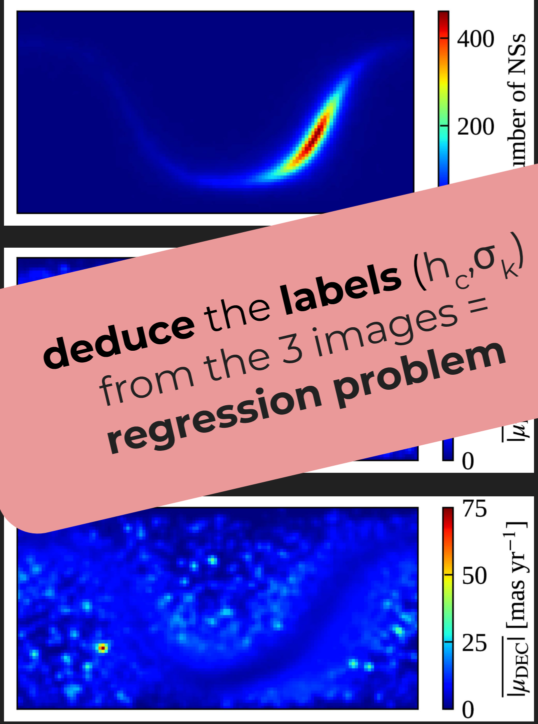
- Evolve $\mathbf{10^5}$ **stars** for (up to) $\mathbf{10^7}$ **yr** varying

exponential **scale height h_c** for birth distance from plane

+

dispersion σ_k of Maxwell distribution for kick velocities

to obtain 16,384 **mock populations**. Extract images (labelled by h_c,σ_k) as **training data** for a **convolutional neural network (CNN)**.

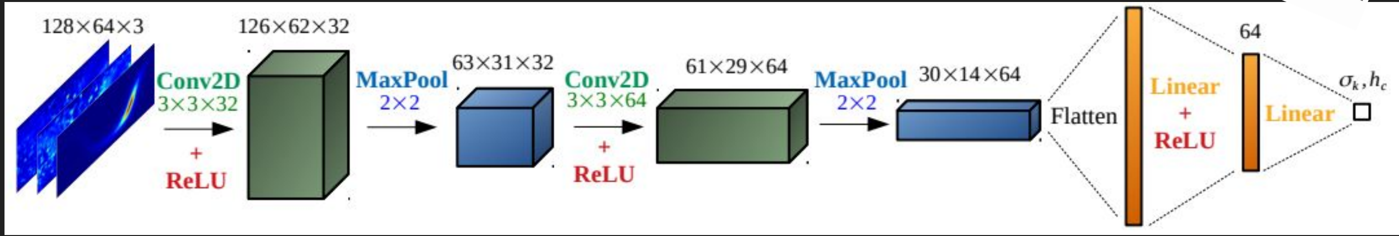


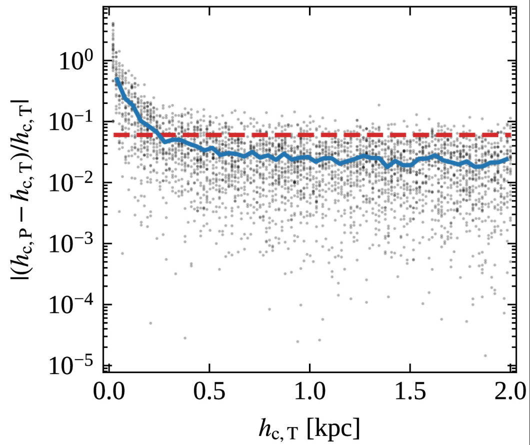
deduce the **labels** (h_c,σ_k) from the 3 images = **regression problem**

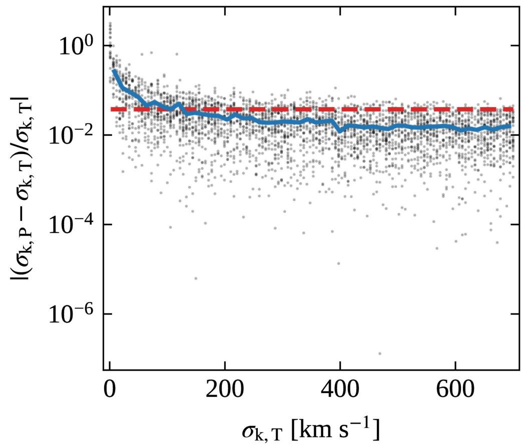
Stellar density and velocities in ICRS coordinates.

DL Proof-of-concept Study: Results

CNN architecture and results from Ronchi et al. (2021).



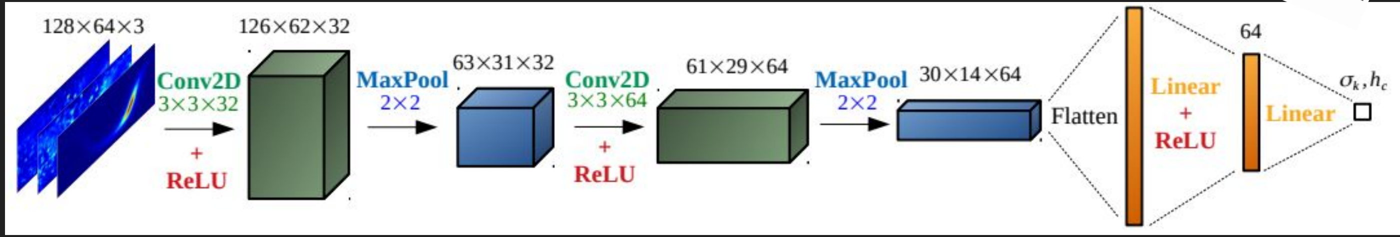


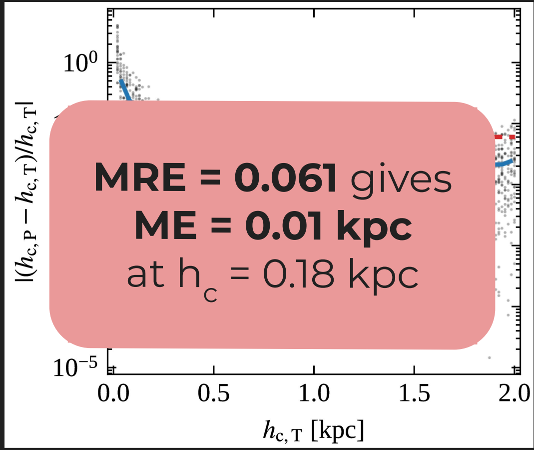


- We use **RMSE** as loss function & validation metric, **Kaiming initialisation**, **Adam** for gradient-descent optimisation, and **80 / 20%** for the training / validation process.

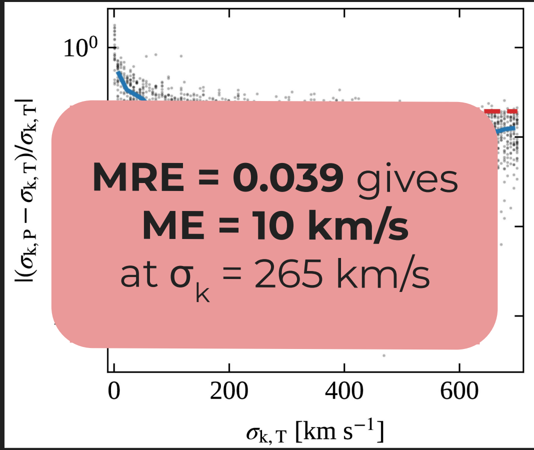
DL Proof-of-concept Study: Results

CNN architecture and results from Ronchi et al. (2021).





MRE = 0.061 gives **ME = 0.01 kpc** at h_c = 0.18 kpc

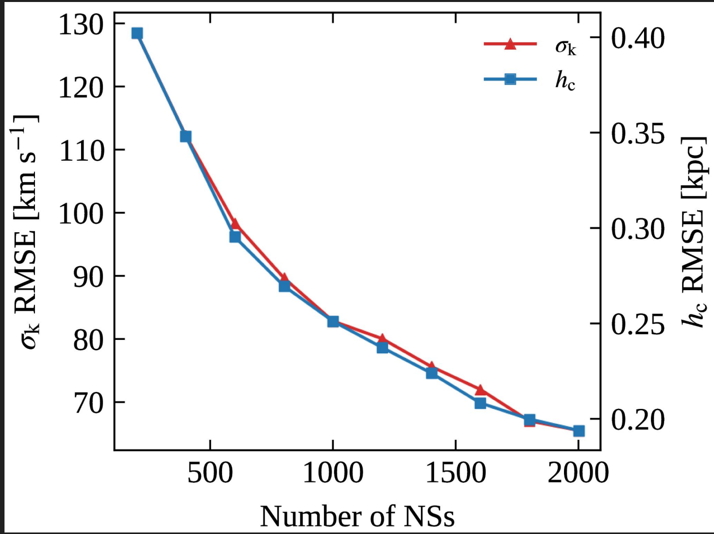


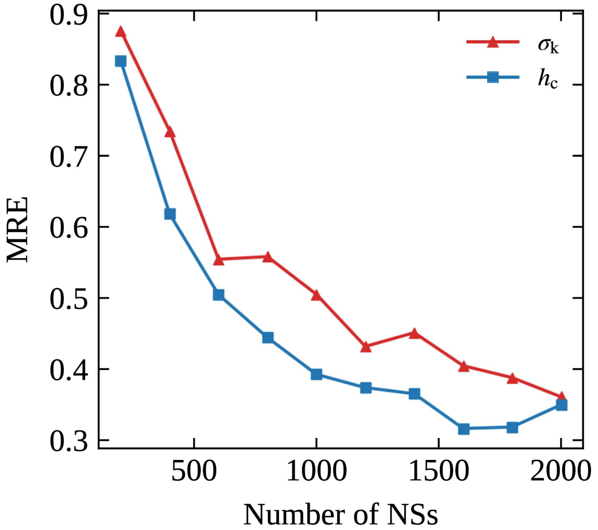
MRE = 0.039 gives **ME = 10 km/s** at σ_k = 265 km/s

- We use **RMSE** as loss function & validation metric, **Kaiming initialisation**, **Adam** for gradient-descent optimisation, and **80 / 20%** for the training / validation process.

DL Proof-of-concept Study: Selection Biases

- Analyse the **CNN's predictive power** as a function of available data points (i.e. NSs) by resampling our fiducial simulation to **incorporate selection biases** from NSs with **proper-motion measurements**.

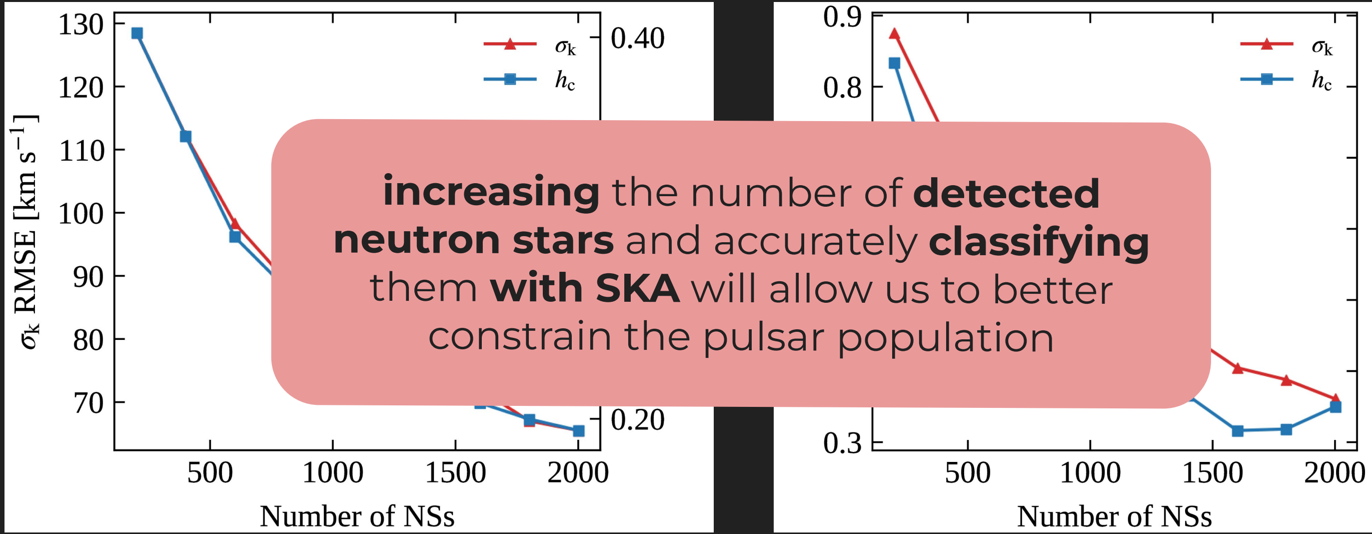




eas 2022 Valencia
CSIC
Consejo Superior de Investigaciones Científicas
IEEC

DL Proof-of-concept Study: Selection Biases

- Analyse the **CNN's predictive power** as a function of available data points (i.e. NSs) by resampling our fiducial simulation to **incorporate selection biases** from NSs with **proper-motion measurements**.

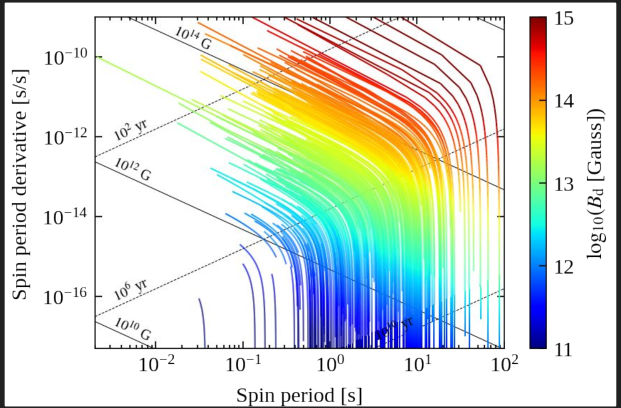


increasing the number of **detected neutron stars** and accurately **classifying** them **with SKA** will allow us to better constrain the pulsar population

Magneto-rotational Evolution & Emission

- Model **additional information** to constrain population properties further:

predict P and **$\dot{P}$** by modelling **magneto-rotational evolution** → solve **ODEs for B, P, χ** (Aguilera et al. 2008, Philippov et al. 2014)



Evolution tracks in P$\dot{P}$-plane. Objects are born on top left.

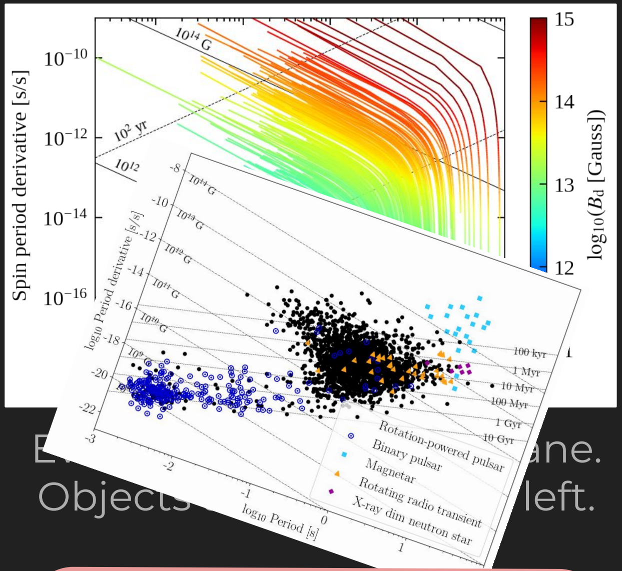
- Combine with an **emission model** and **survey detectability limits** to determine observability. This produces mock **P$\dot{P}$ populations**, which we compare to the observed pulsar sample with CNNs.

Magneto-rotational Evolution & Emission

- Model **additional information** to constrain population properties further:

predict P and **$\dot{P}$** by modelling **magneto-rotational evolution** → solve **ODEs for B**, **P**, **χ** (Aguilera et al. 2008, Philippov et al. 2014)

- Combine with an **emission model** and **survey detectability limits** to determine observability. This produces mock **$P\dot{P}$ populations**, which we compare to the observed pulsar sample with CNNs.



E ane.
Objects left.

infer information about the **initial P & B distributions** and magnetic **field evolution**

Multi-modal DL

- Different **parts of the pulsar population** are observed in **different wavebands**: observations provide **complementary information** about the same underlying neutron star population.

different neural networks are suitable to analyse **different types of observations**

- In computer science, this concept is known as **multi-modal learning**.

"Batman raises the stakes in his war on crime. With the help of Lt. Jim Gordon and District Attorney Harvey Dent, Batman sets out to dismantle the remaining criminal organizations that plague the streets. The partnership proves to be effective, but they soon find themselves prey to a reign of chaos unleashed by a rising criminal mastermind known to the terrified citizens of Gotham as the Joker." -TMDB

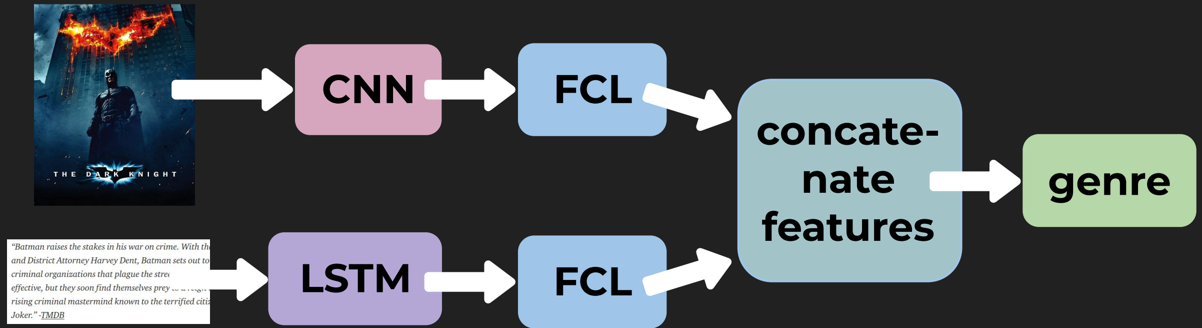
Multi-modal DL

- Different **parts of the pulsar population** are observed in **different wavebands**: observations provide **complementary information** about the same underlying neutron star population.

different neural networks are suitable to analyse **different types of observations**

- In computer science, this concept is known as **multi-modal learning**.

Multi-modal learning architecture combining information from movie poster plus description (credit: TMDB) to predict the genre of a movie.



Conclusions

pulsar **population synthesis constrains birth rates** of different neutron star classes **and birth properties** of the entire population

Deep Learning with CNNs is a promising tool to **infer birth properties** from the current population

complementary information from different wavelengths can be **combined in** a **multi-modal network**

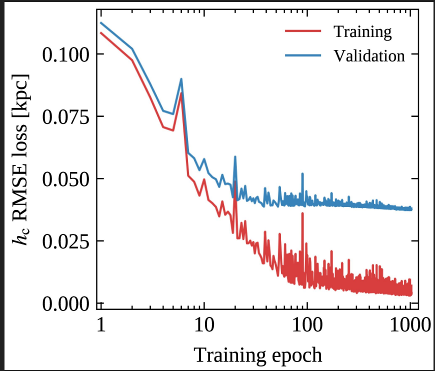
STAY TUNED FOR **UPDATES** AND/OR **COME AND TALK TO US!!**

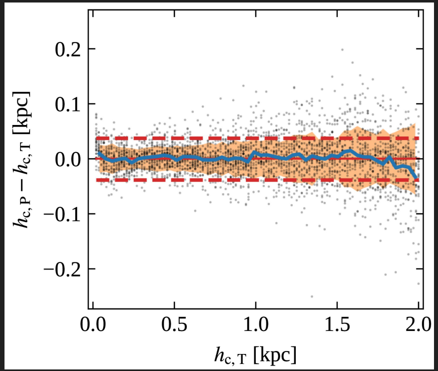
Back-up Slides

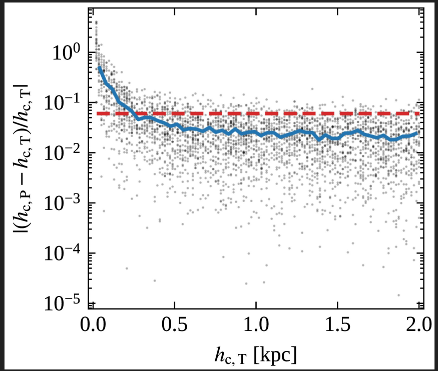
graber@ice.csic.es

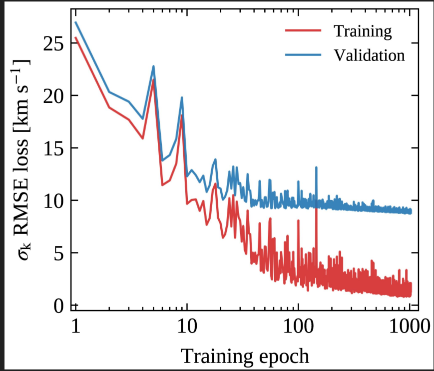
Ronchi et al. (2021) - Training Results

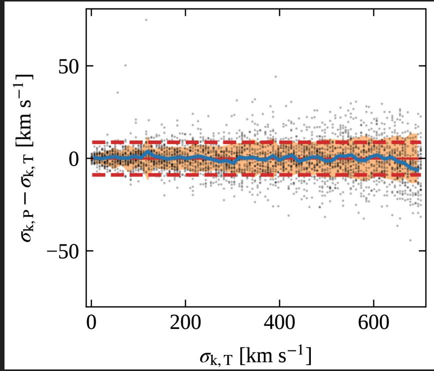
CNN validation results for h_c:
RMSE = 0.038 kpc & MRE = 0.061.

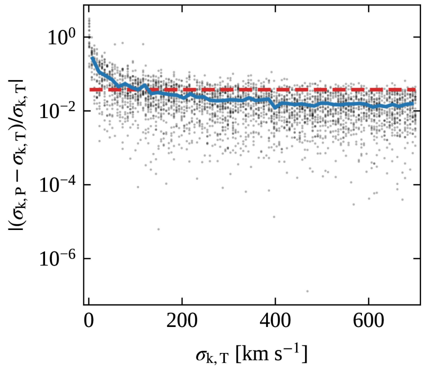










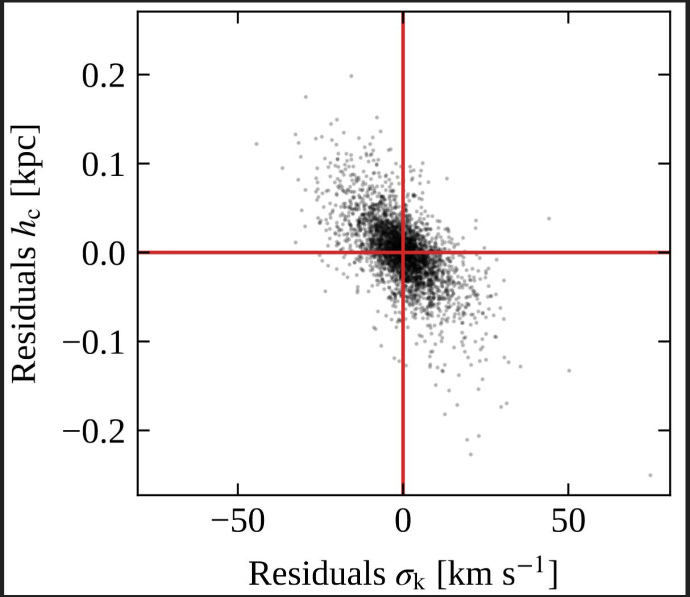


CNN validation results for σ_k:
RMSE = 8.8 km/s & MRE = 0.039.

Ronchi et al. (2021) - Degeneracy

- Histogramming **distances from the Galactic plane** for current mock pulsar populations, we note a **degeneracy between h_c and σ_k**: large scale heights combined with small velocity dispersions lead to same outcomes as small scale heights with large velocity dispersions.

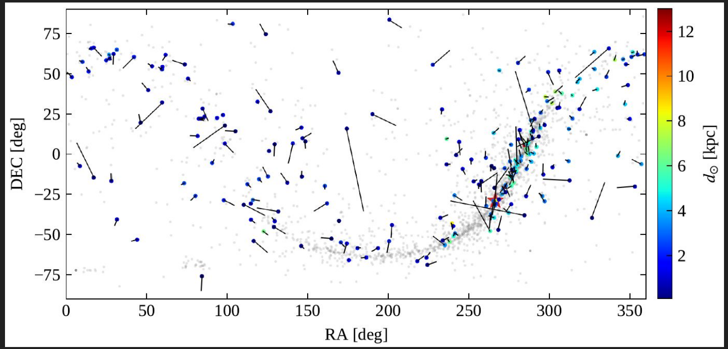
- **CNN recovers the degeneracy!**



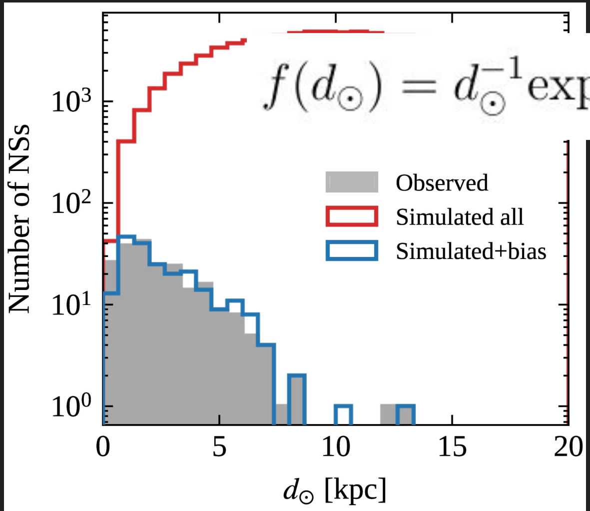
We find an anticorrelation between the residuals in h_c and σ_k.

Ronchi et al. (2021) - Selection Function

- To incorporate selection effects & observational biases, we use a **phenomenological approach** to reanalyse the CNN performance.



216 isolated NSs with proper motions.



$$f(d_\odot) = d_\odot^{-1} \exp(-d_\odot/2)$$

- Use proper motion and distance estimates for 216 isolated pulsars to deduce **empirical selection function** $f(d_\odot)$ and **resample population** with h_c = 0.18 kpc and σ_k = 265 km/s.