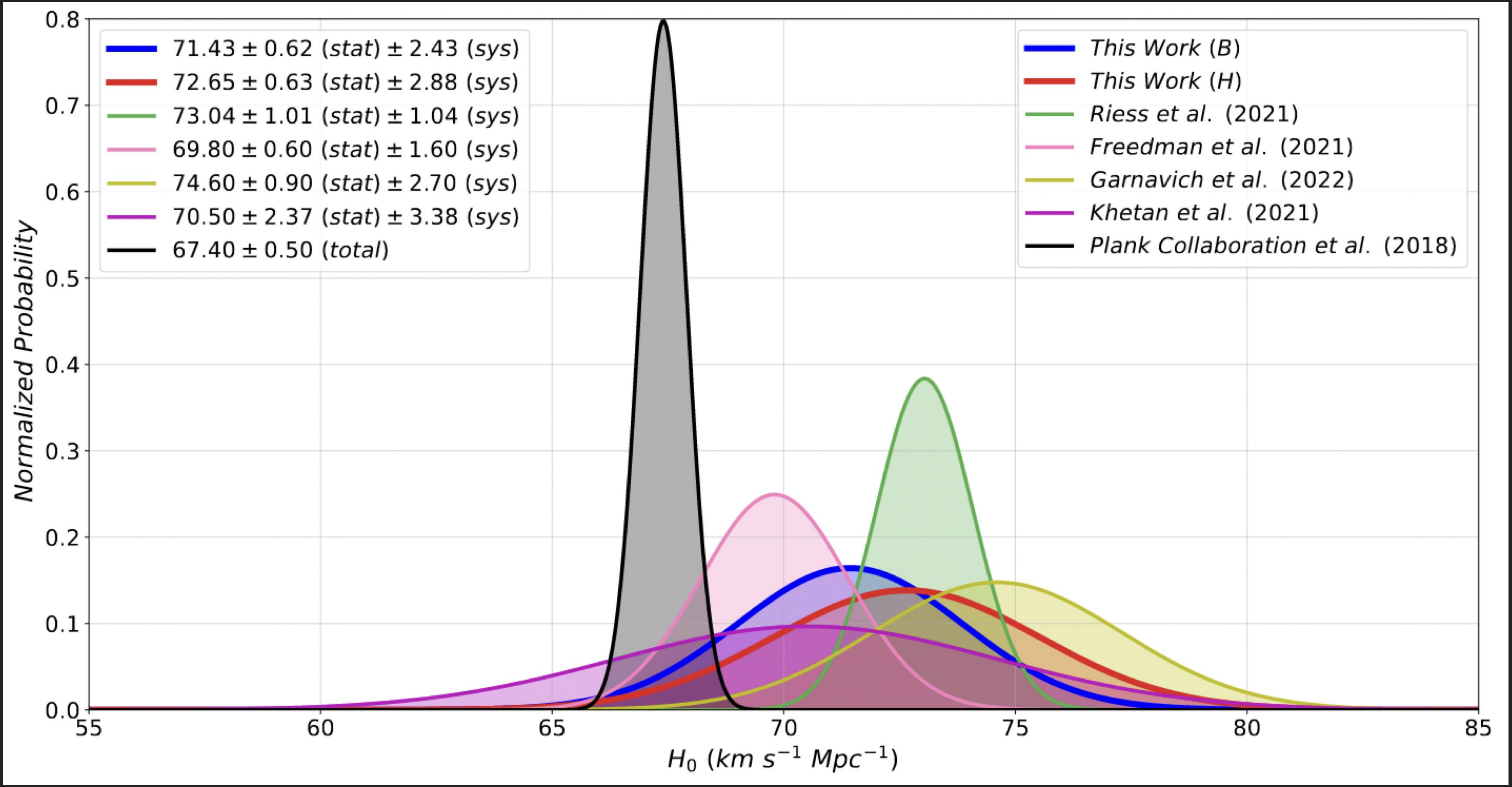
COSMIC

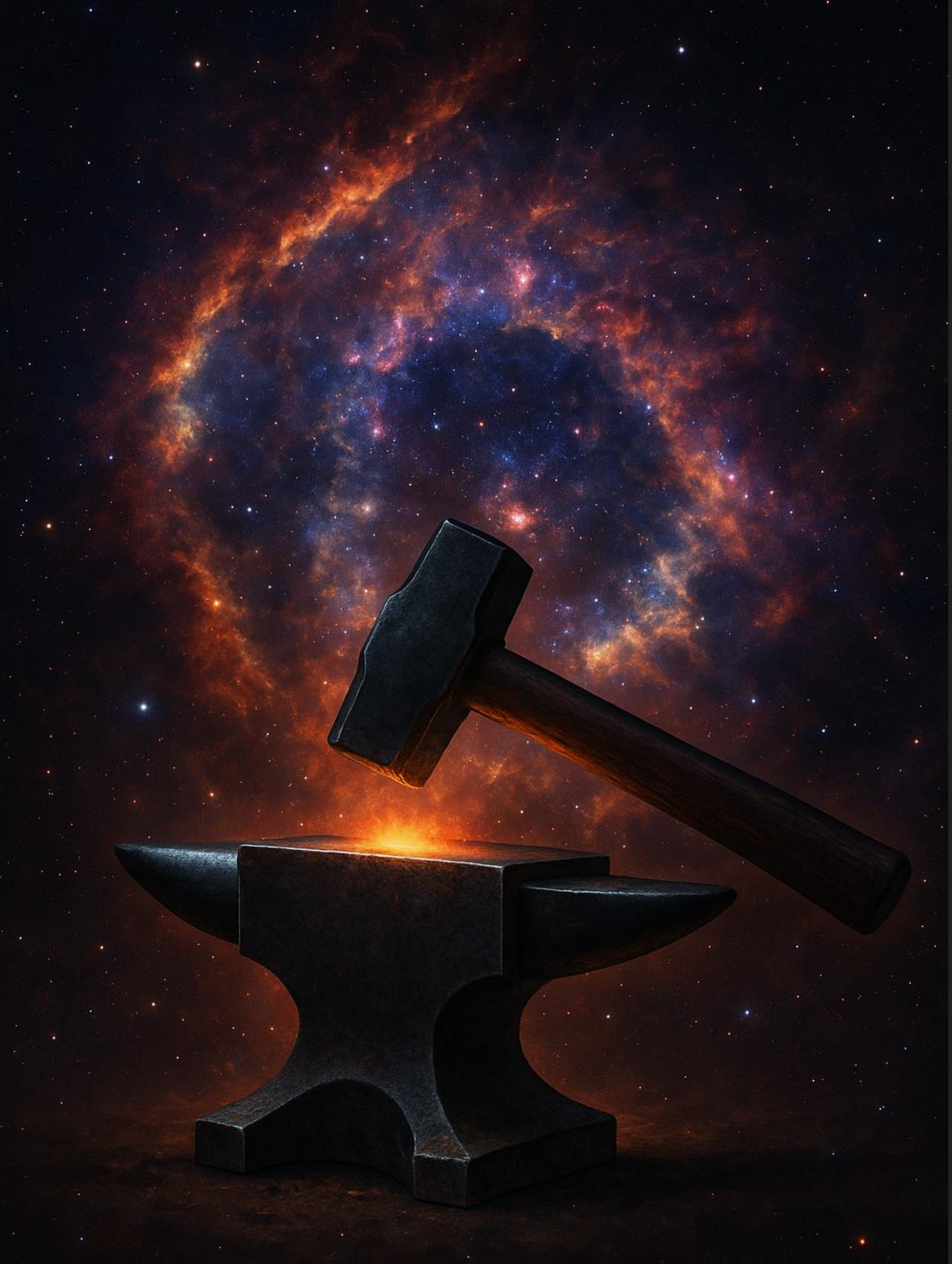
LIGHT HOUSES

see Riess+1998, Perlmutter+ 1999
Matter dominated Universe
(Ωmatter = 10.0, ΩLambda = 0.0)
Critical Universe
(Ωmatter = 1.0, ΩLambda = 0.0)
Accelerating Universe
(Ωmatter = 0.3, ΩLambda = 0.7)
Supernovae with luminosity
distance and redshift
Today
scale factor a
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
−15
−10
−5
0
5
10
15
Time relative to today [Gyr]
Thanks to M. Voit for SN data

HOWEVER...

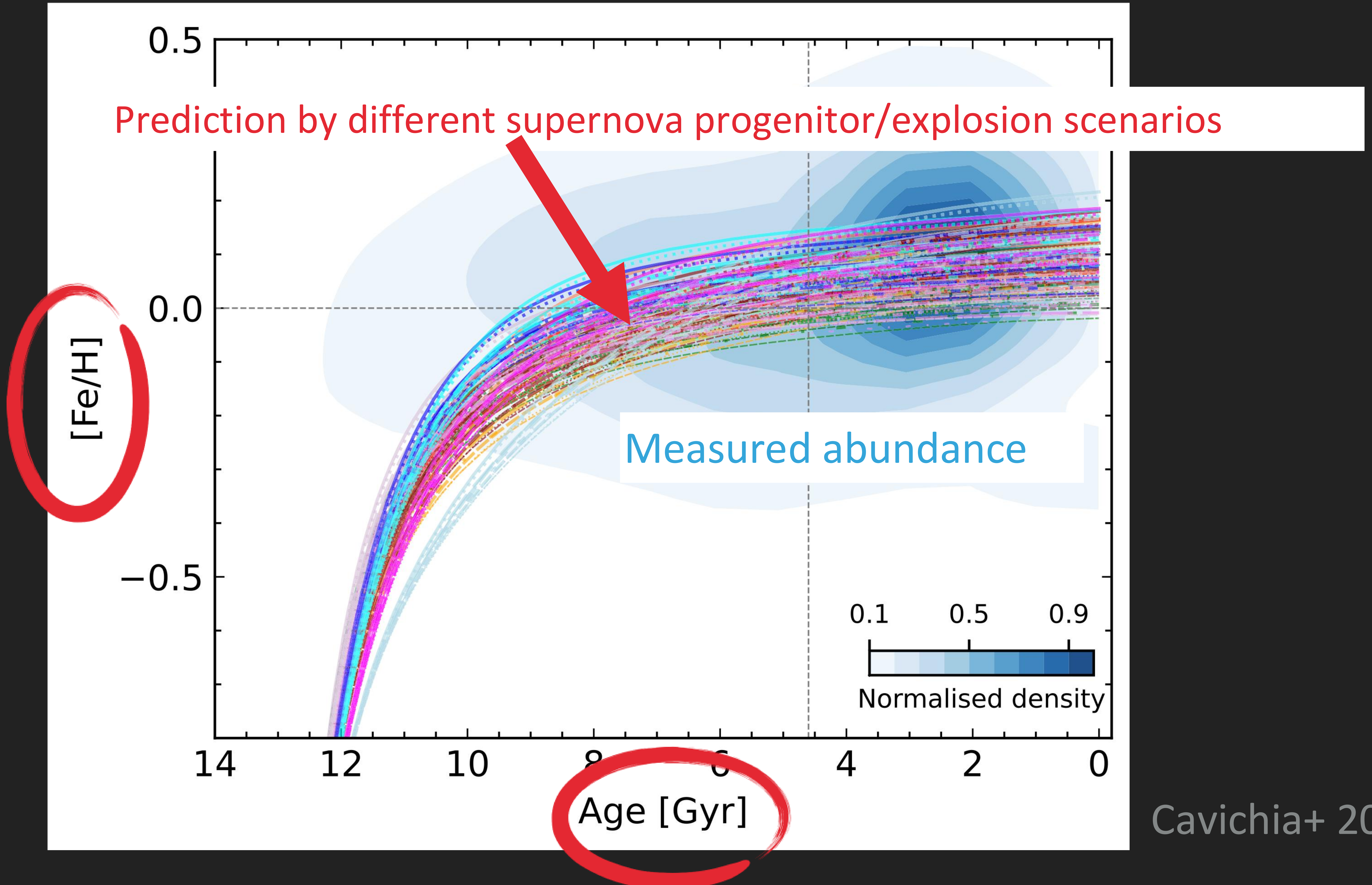


Freedman et al. 2023



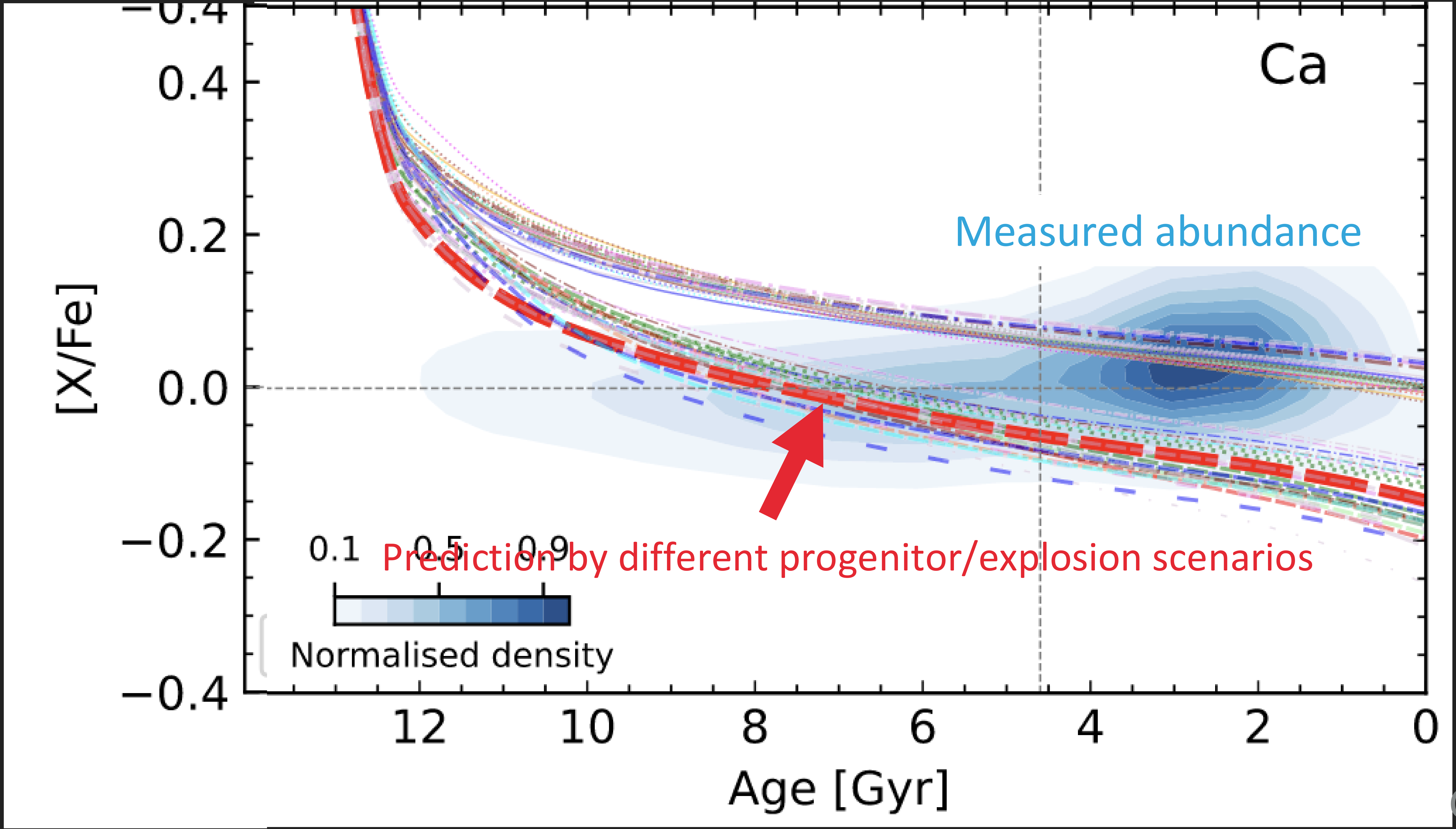
COSMIC

ELEMENTAL FORGES



Cavichia+ 2024

HOWEVER...



Cavichia+ 2024

TARDIS!
Exploring supernovae made easy

Google NUMFOCUS
OPEN CODE = BETTER SCIENCE

CALIBRATING STELLAR EXPLOSIONS AS

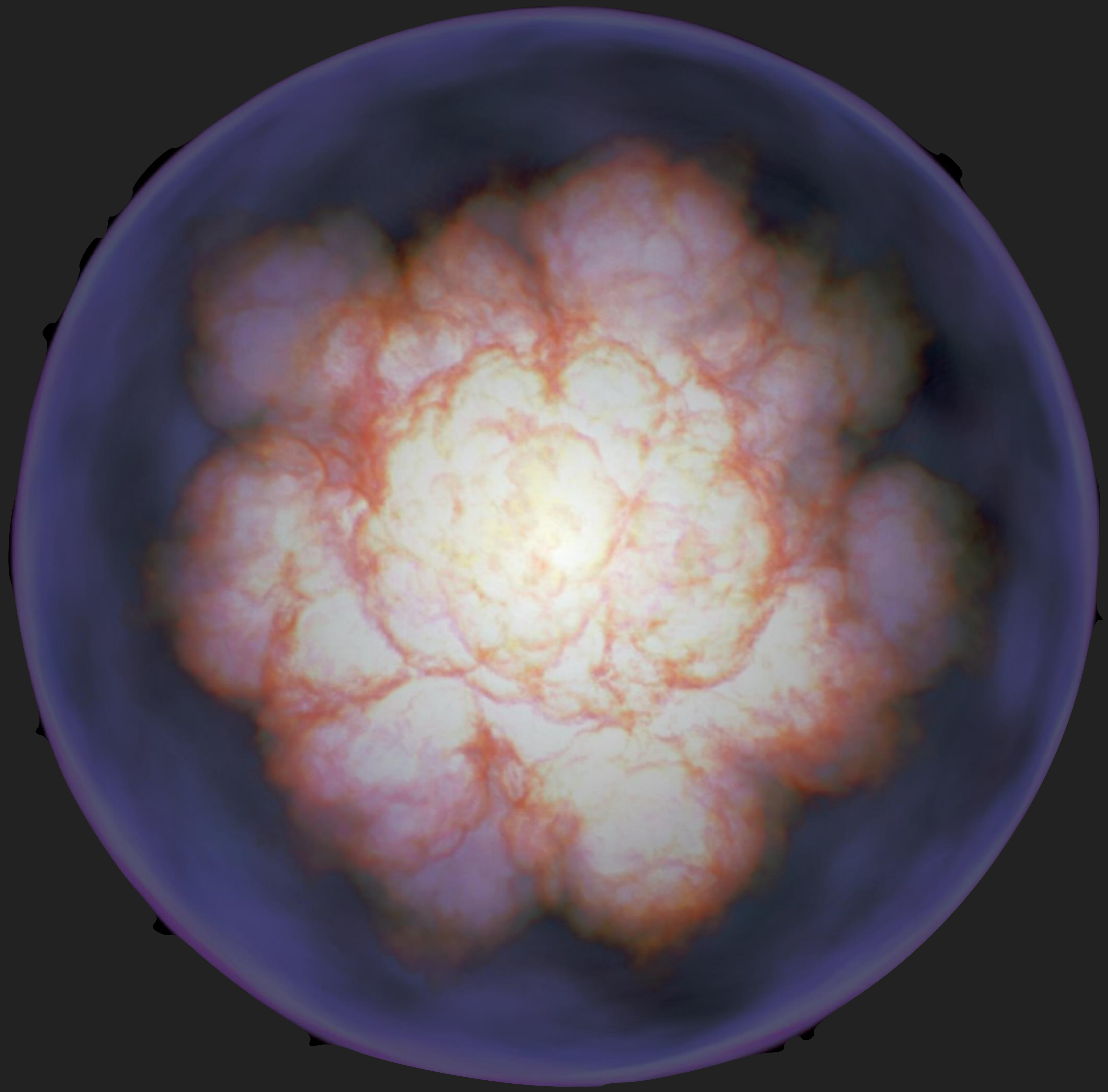
PRECISION PROBES OF THE EVOLVING

Wolfgang E. Kerzendorf

on behalf of the TARDIS/DTI collaboration

16th of July 2026

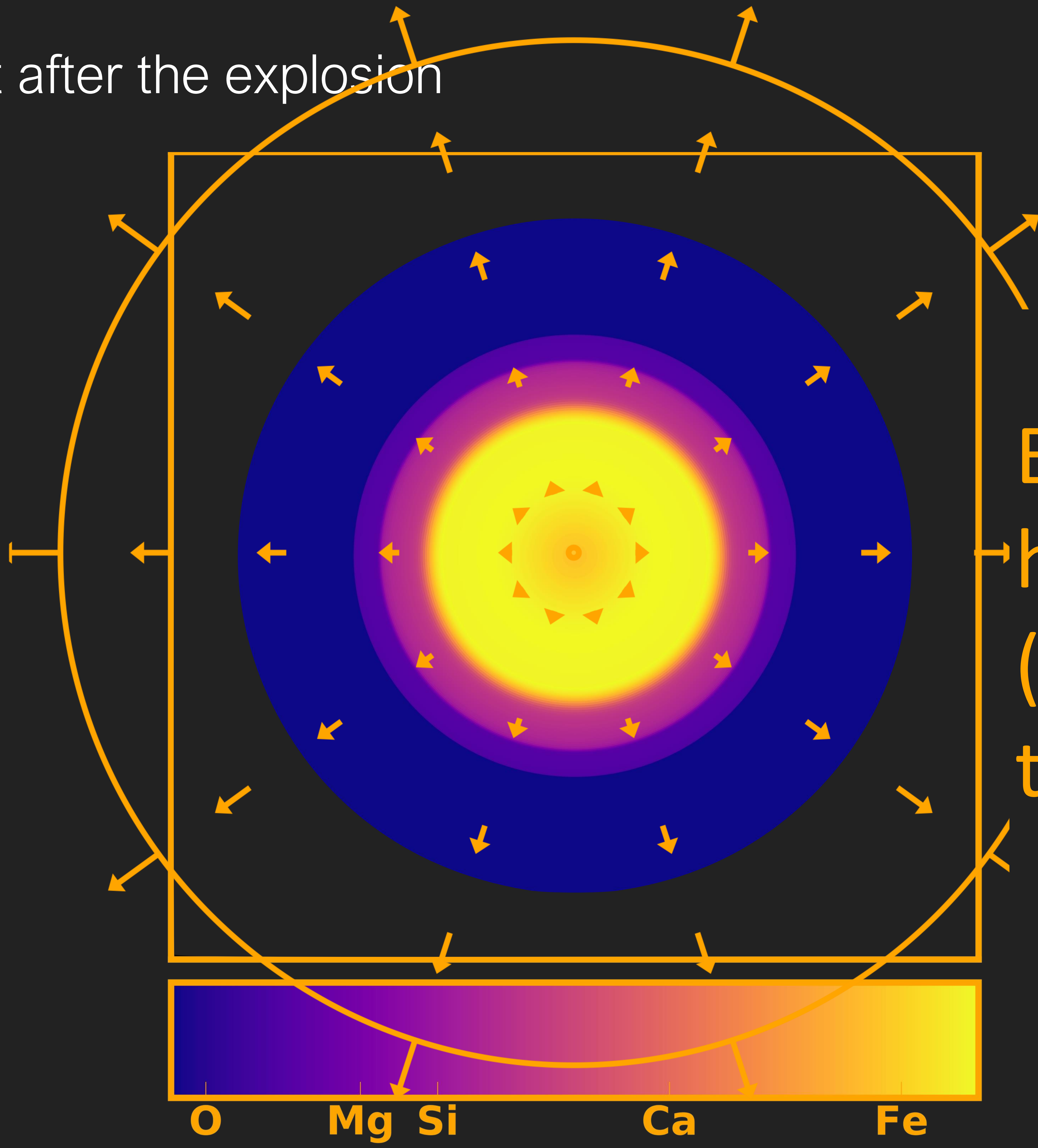
MICHIGAN STATE UNIVERSITY



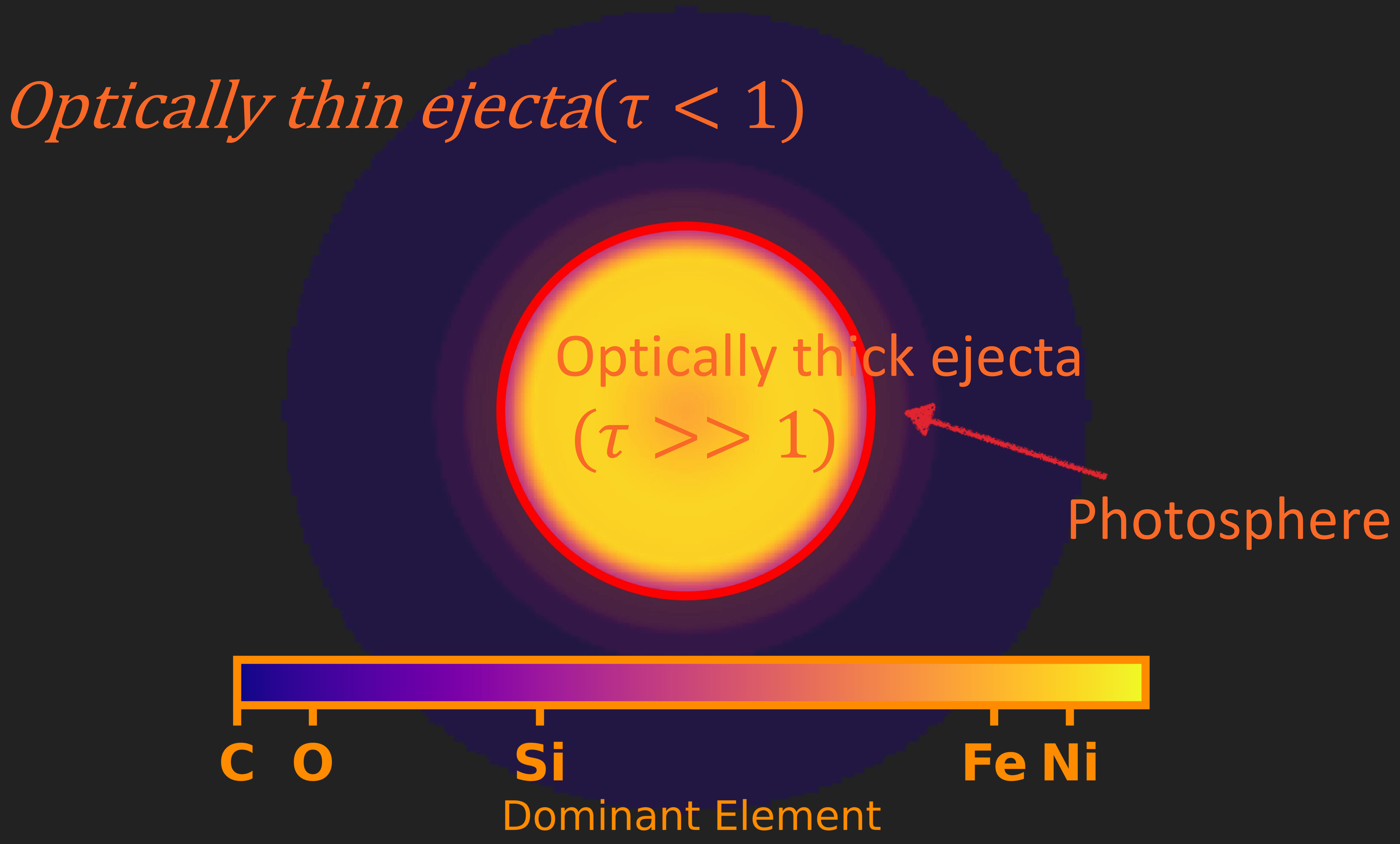
Röpke et al.

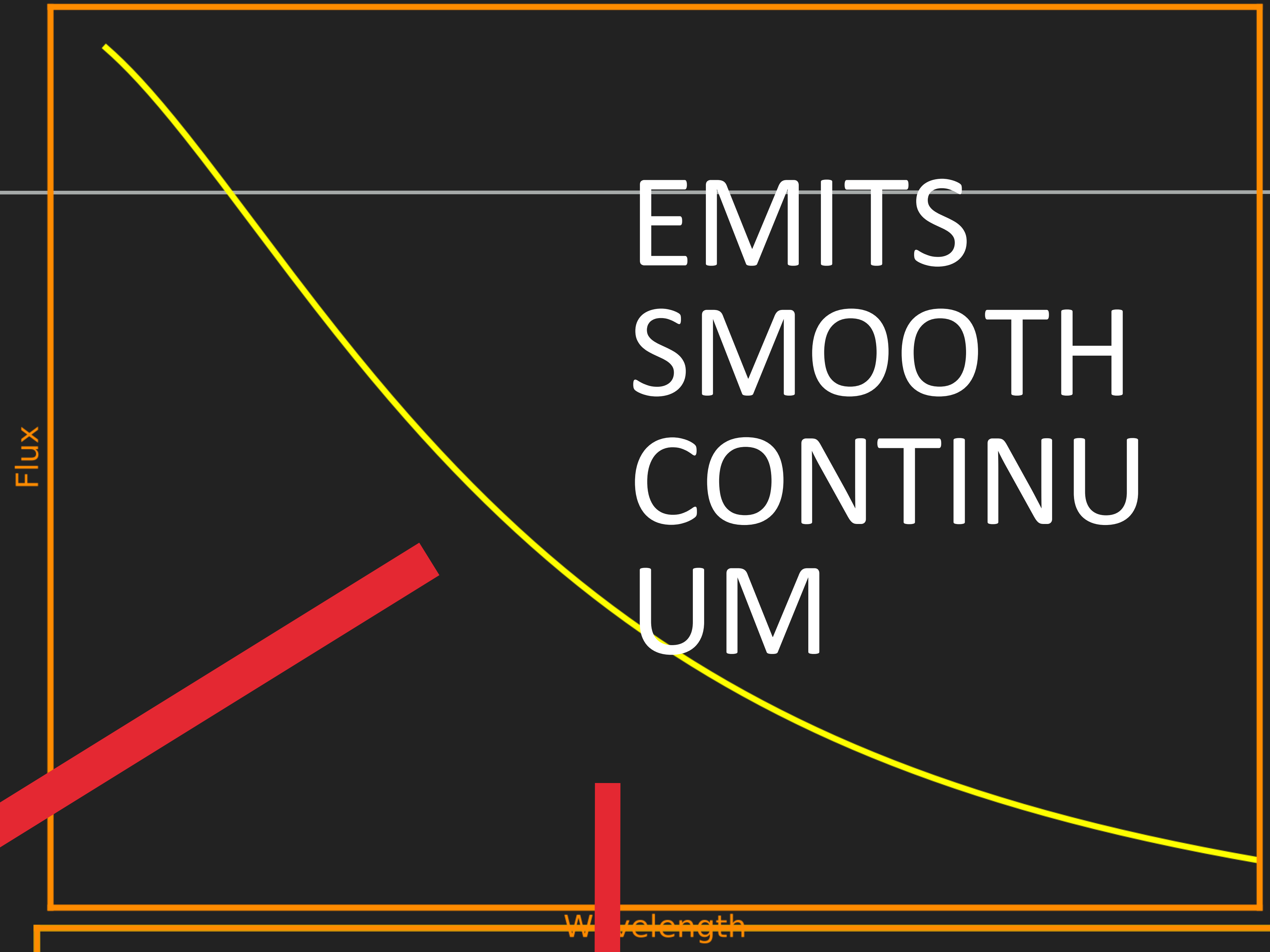
The ejecta just after the explosion

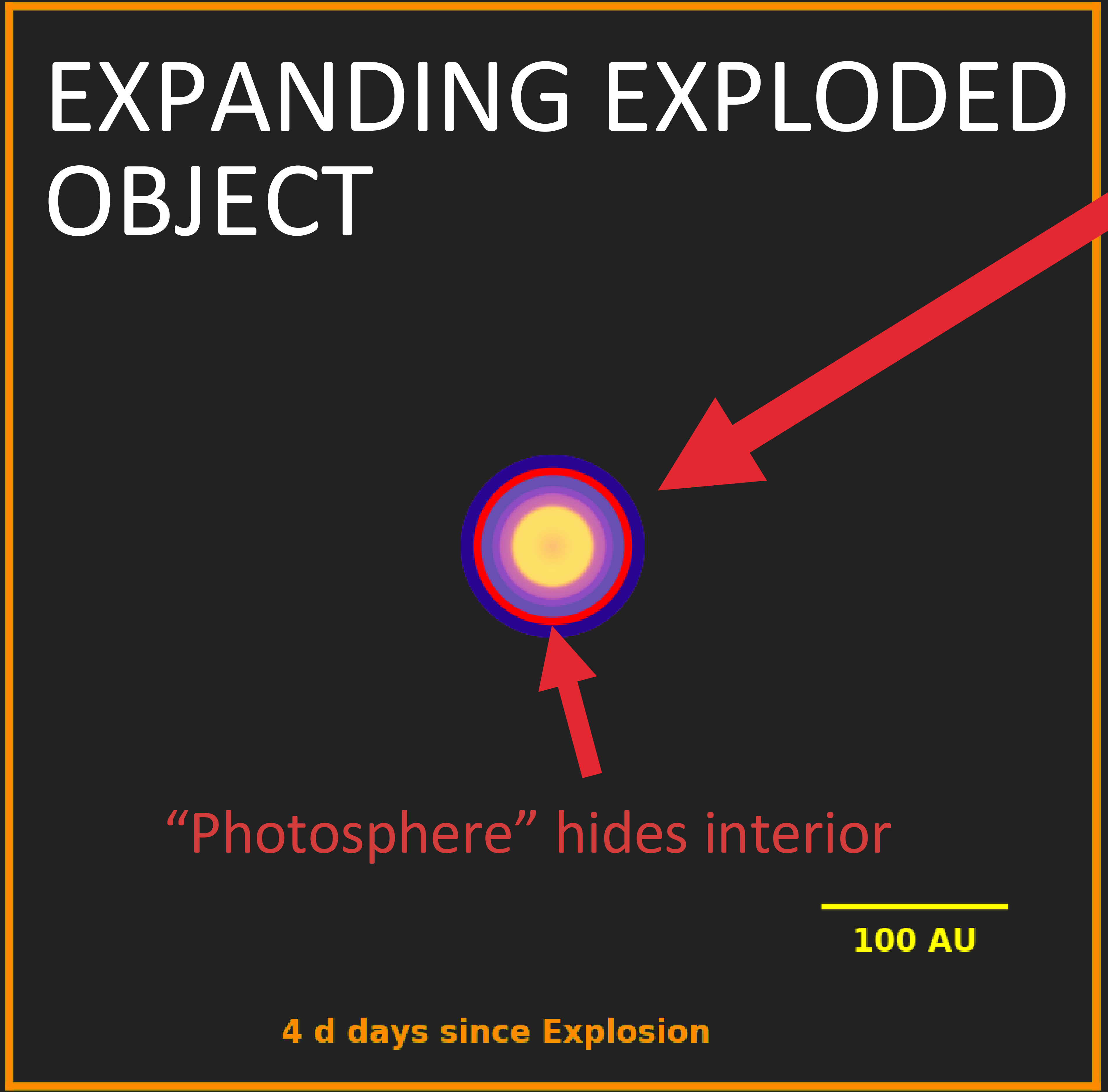
An Example:



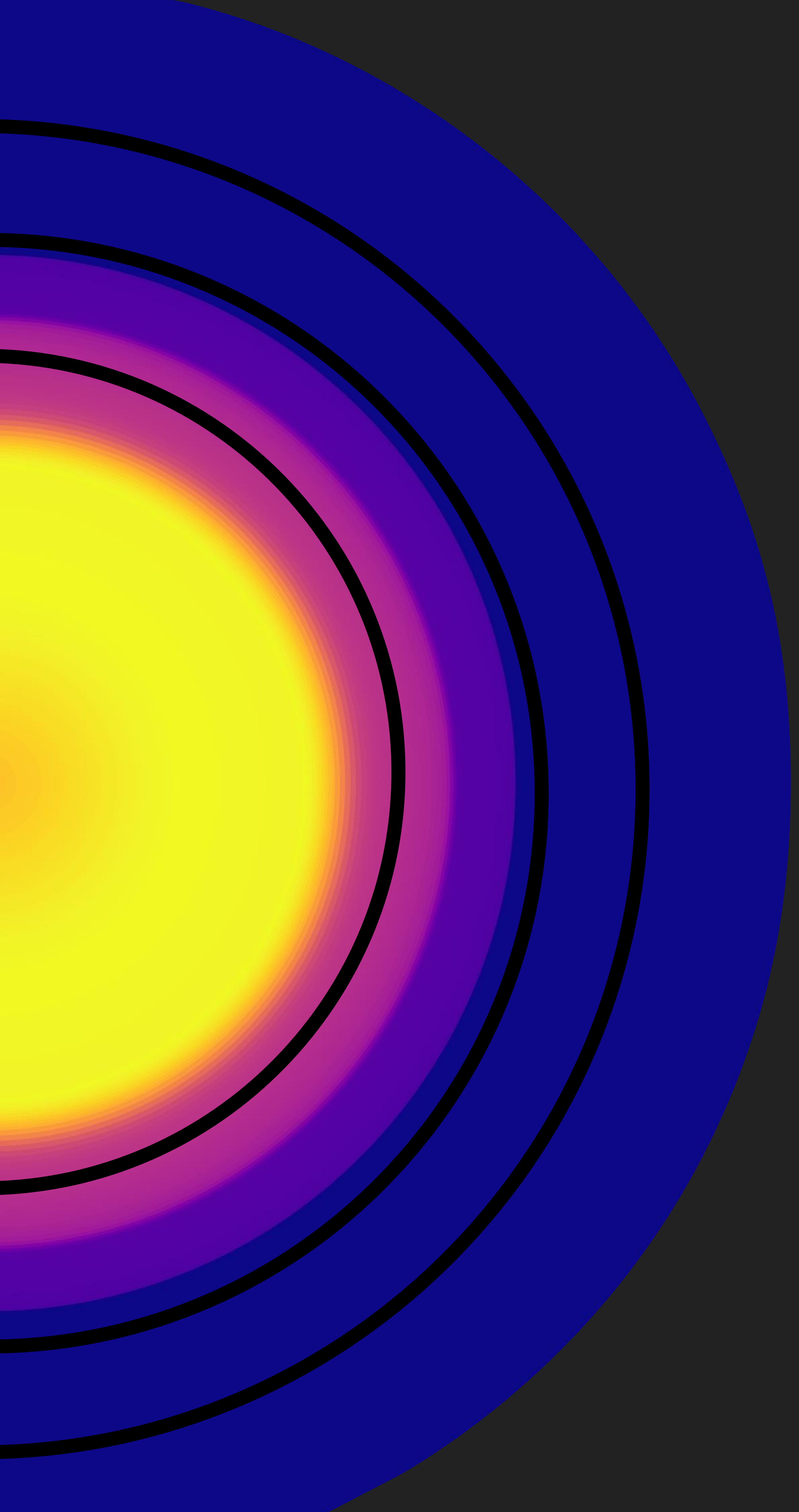
Expanding homologously (fastest layer on the outside)


Optically thin ejecta $(\tau < 1)$
Optically thick ejecta
$(\tau >> 1)$
Photosphere
C
O
Si
Fe
Ni
Dominant Element





Spectra from SN2011fe Pereira et al. 2013



RECONSTRUCTING EXPLOSIONS WITH

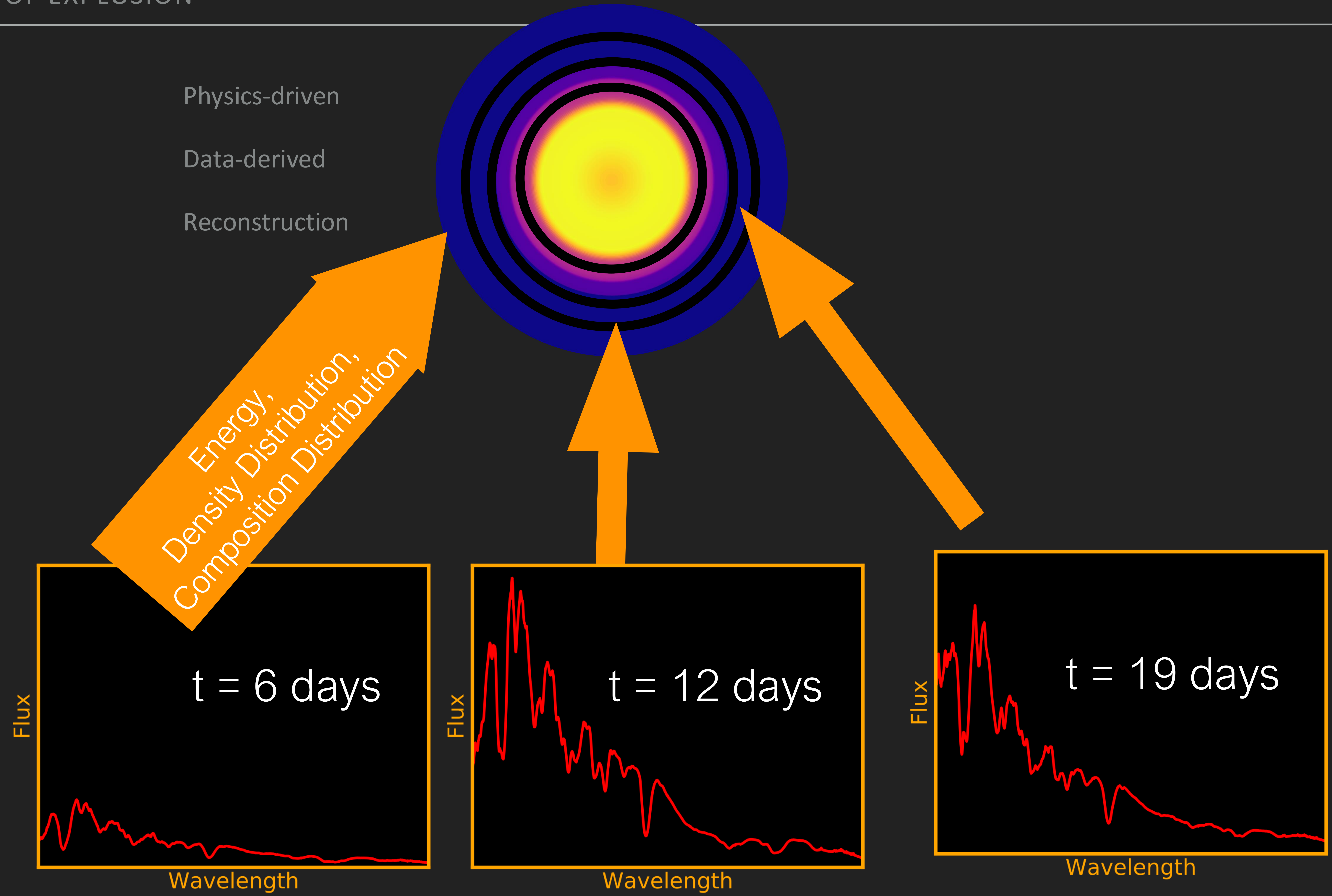
SUPERNOVA TOMOGRAPHY

INFERENCE OF EXPLOSION

Physics-driven

Data-derived

Reconstruction



$$P(Model(\vec{\theta})|data) = \frac{P(data|Model(\vec{\theta})) \times P(\vec{\theta})}{\int d\vec{\theta} P(data|Model(\vec{\theta}))}$$

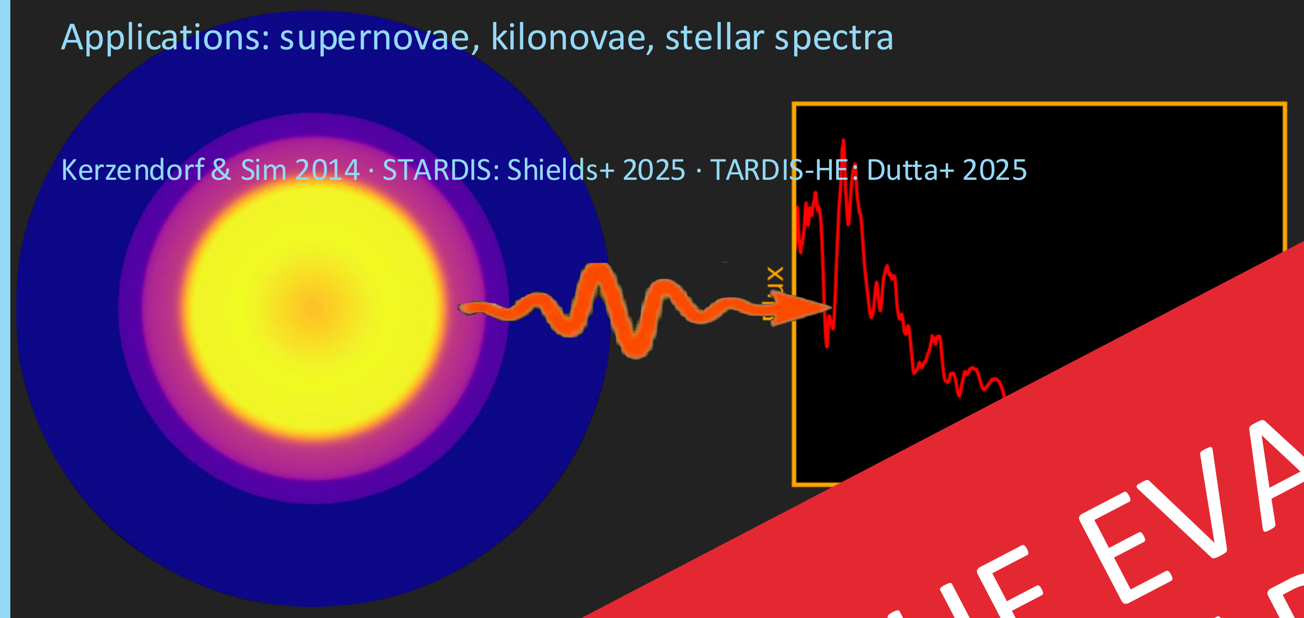
Supernova Radiative Transfer Simulator

Radiative transfer from gamma-rays to UVOIR

Plasma in full statistical equilibrium

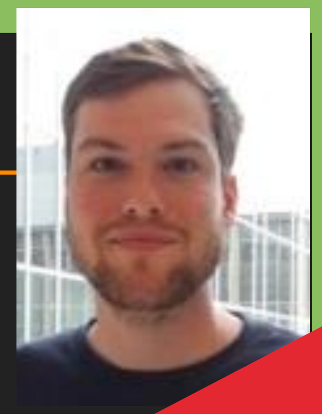
Applications: supernovae, kilonovae, stellar spectra

Kerzendorf & Sim 2014 · STARDIS: Shields+ 2025 · TARDIS-HE: Dutta+ 2025



easy

Likelihood



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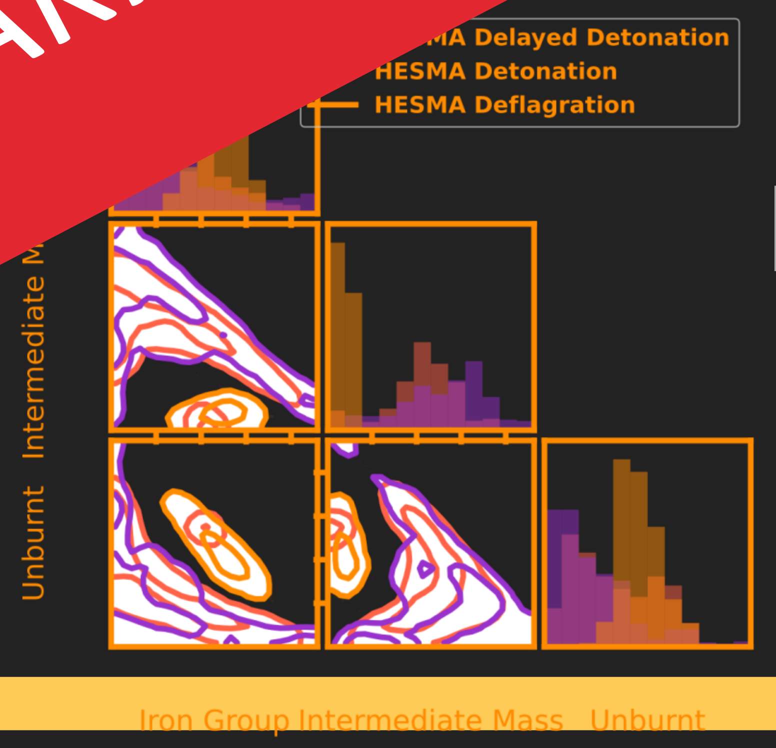


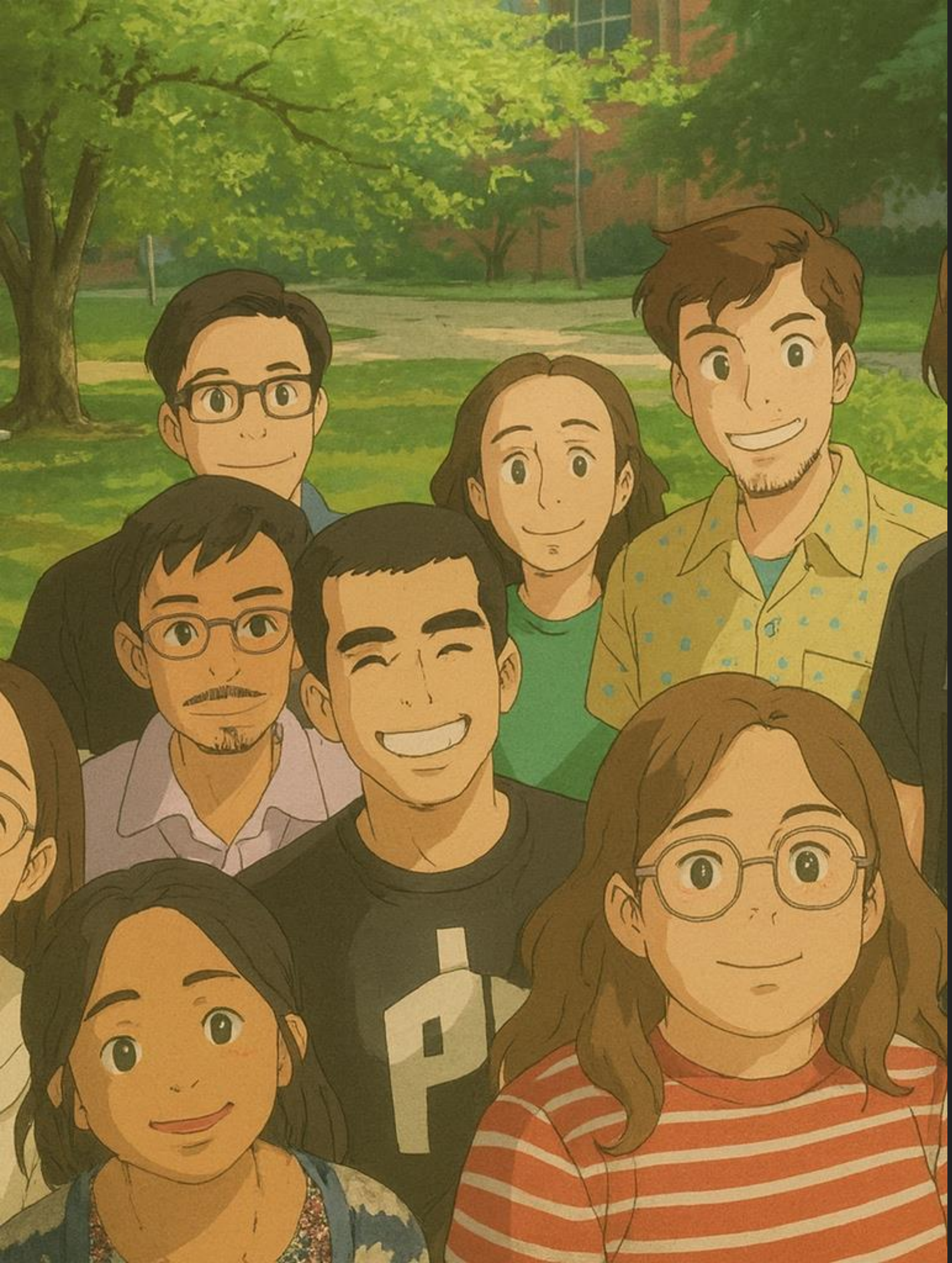
Sampler

Ultranest with additions for Emulators

J Buchner

Posterior of ity/composition distributions

REQUIRES THE EVALUATION OF 100K – 10 MIO MODELS FOR TESTING ALL THE RELEVANT PARAMETER COMBINATIONS AGAINST OBSERVATIONS RT TAKING MINUTES … WAY TOO SLOW



THE TARDIS

TEAM

NUMFOCUS
OPEN CODE = BETTER SCIENCE

TARDIS!
Exploring supernovae made easy

ASTRO/PH YSICS

JACK O'BRIEN

EXPERIMENTAL DESIGN, RT, INFERENC

SKAI FELLOW @

JING LU

EXPERIMENTAL DESIGN, RT, INFERENCE

POSTDOCTORAL FELLOW @ MSU

CHRISTIAN VOGL

EXPERIMENTAL DESIGN, RT, INFERENCE

@ZEISS

JOSH SHIELDS

EXPERIMENTAL DESIGN, RT, INFERENCE

@MSU

JOHANNES BUCHNER

STATISTICS AND INFERENCE

PATRICK VAN DER SMAGT

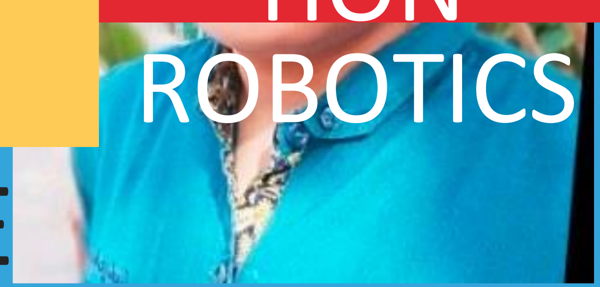
ML ARCHITECTURE

@FOUNDATION ROBOTICS

NUTAN CHEN

ML ARCHITECTURE

@FOUNDATION ROBOTICS



E

ANDREW FULLARD

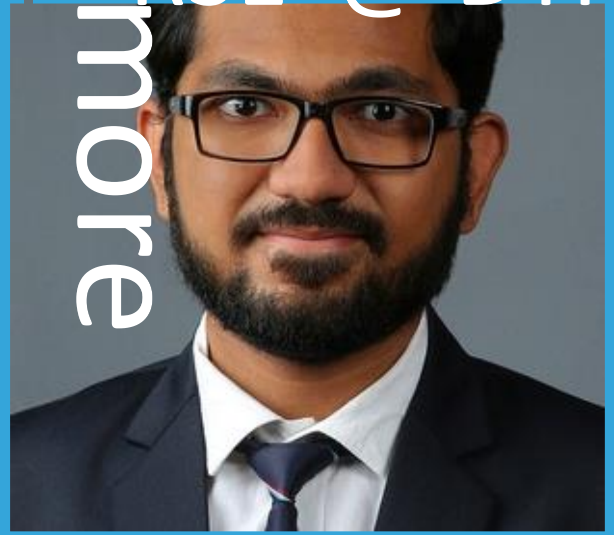
SENIOR SOFTWARE ARCHITECT

RSE @ MSU

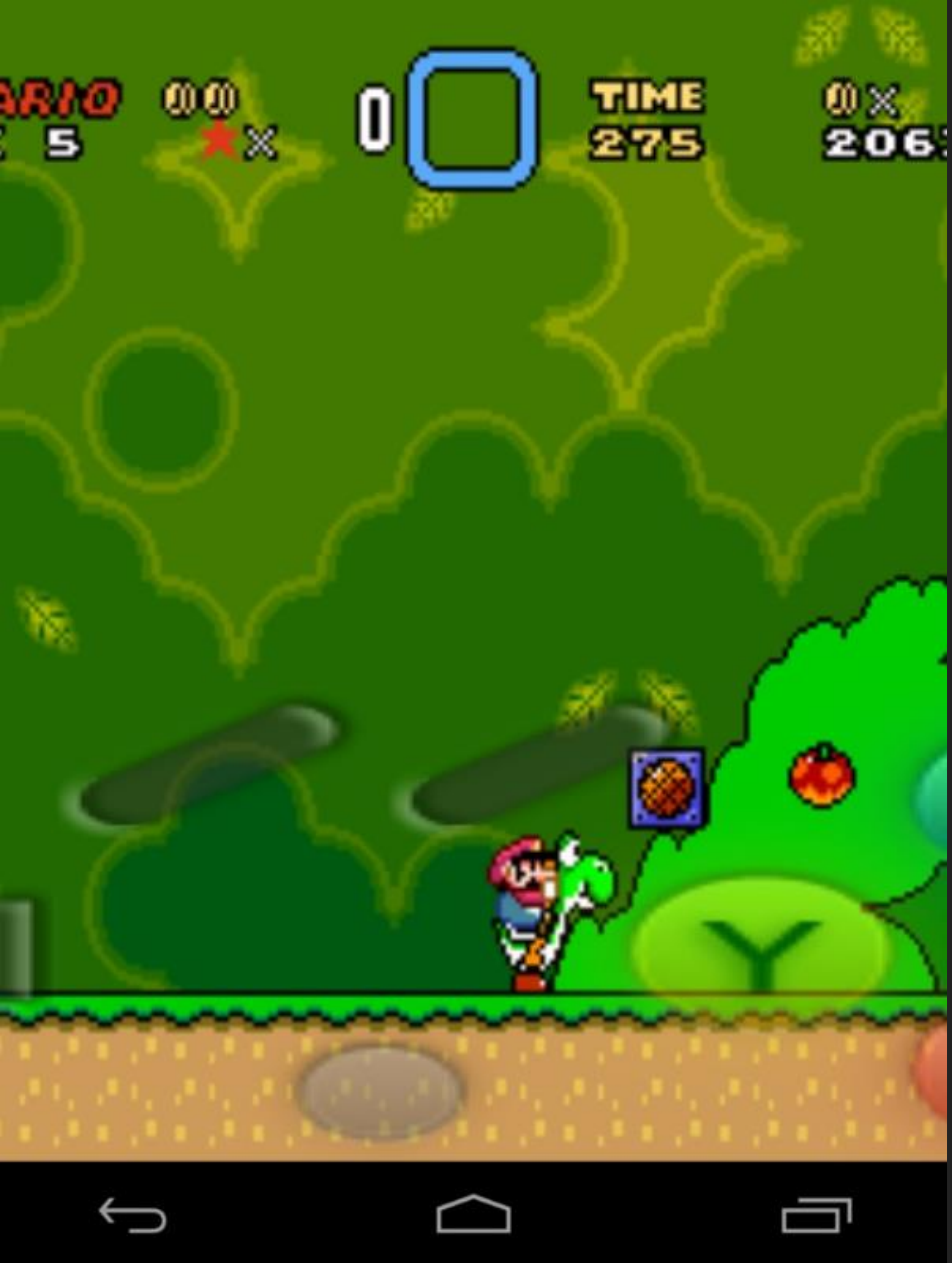
ATHARVA ARYA

DEVELOPER OPERATIONS

RSE @ DTI



more



THE DALEK

EMULA
TOR

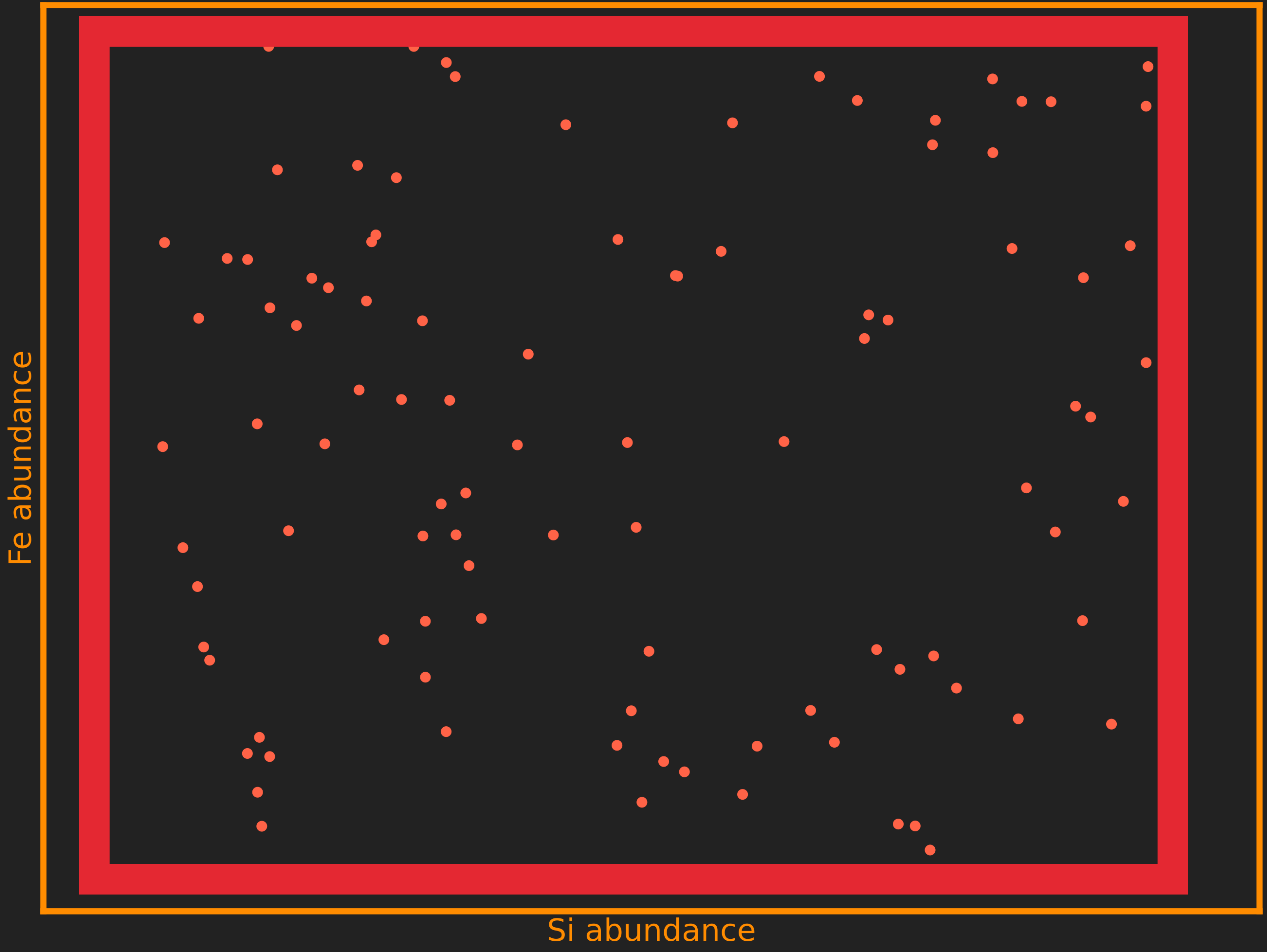
EMULATOR BUILDING

BUILDING TRAINING, VALIDATION, TEST SET

TRAINING (FITTING) THE EMULATOR

TESTING THE EMULATOR

PHYSICS!!!

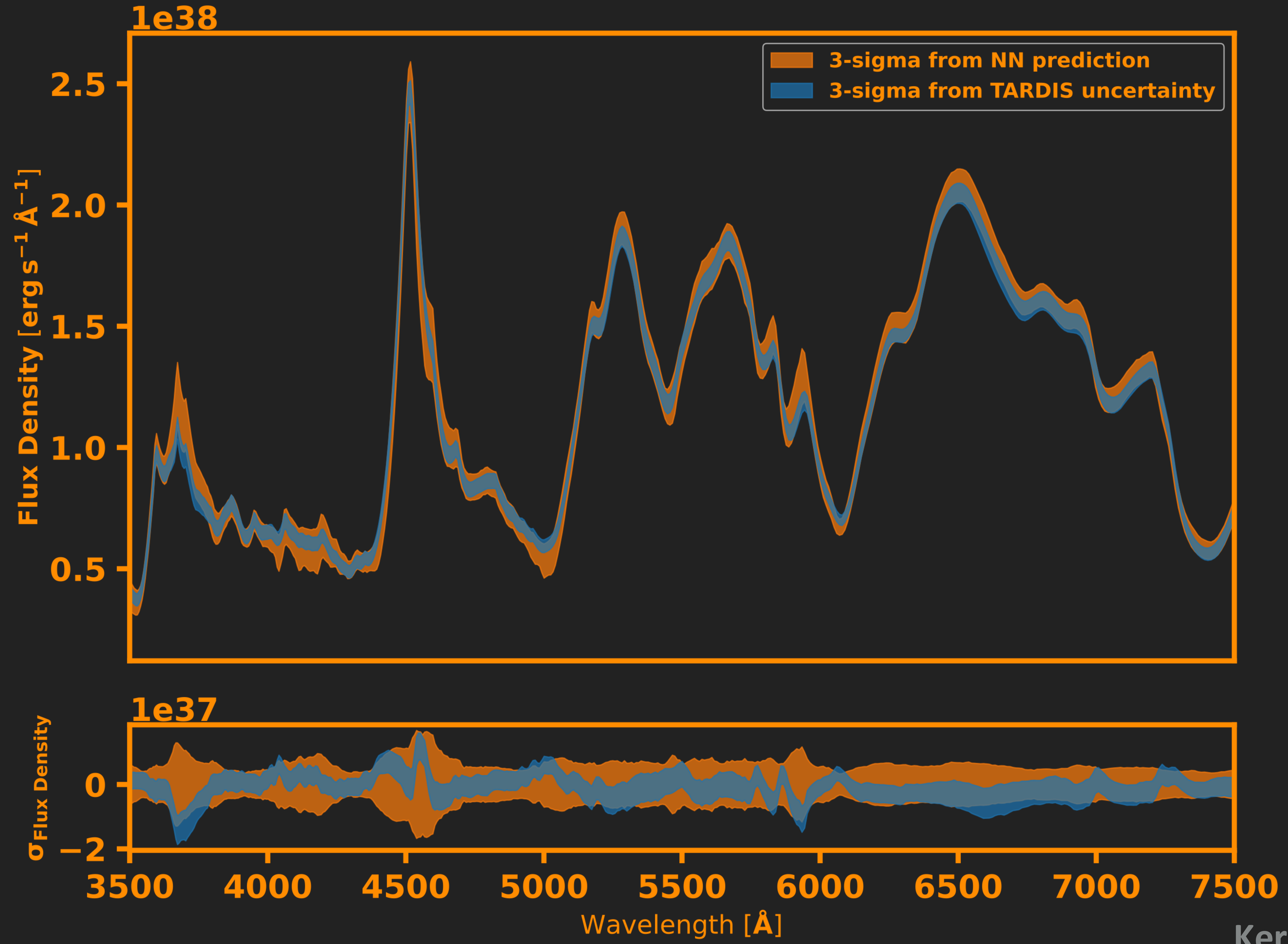


- Informed by theory (for Type Ia: HESMA models; Kromer 2018)
- We only trust predictions within the range - no extrapolation
- Custom-built for each experiment/paper

EMULATOR BUILDING

PROBABILISTIC DALEK (KERZENDORF ET AL. 2022)

- Incorporate uncertainties through (following Lakshminarayanan et al. 2017)
  - Probabilistic loss function for each individual network $\mathcal{L}(\mathbf{x}) = -\log p_\theta(\mathbf{y}|\mathbf{x}) - \beta \log p(\theta) \propto \frac{\log \sigma_\theta^2(\mathbf{x})}{2} + \frac{(\mathbf{y}-\mu_\theta(\mathbf{x}))^2}{2\sigma_\theta^2(\mathbf{x})} + \beta \parallel \theta \parallel_2 + \text{constant}$, where $\vec{\theta}$ are the weights of the network
  - Aggregated in Deep Ensembles
- Uncertainties capture the TARDIS uncertainties



Kerzendorf+ 2022

ACTIVE LEARNING

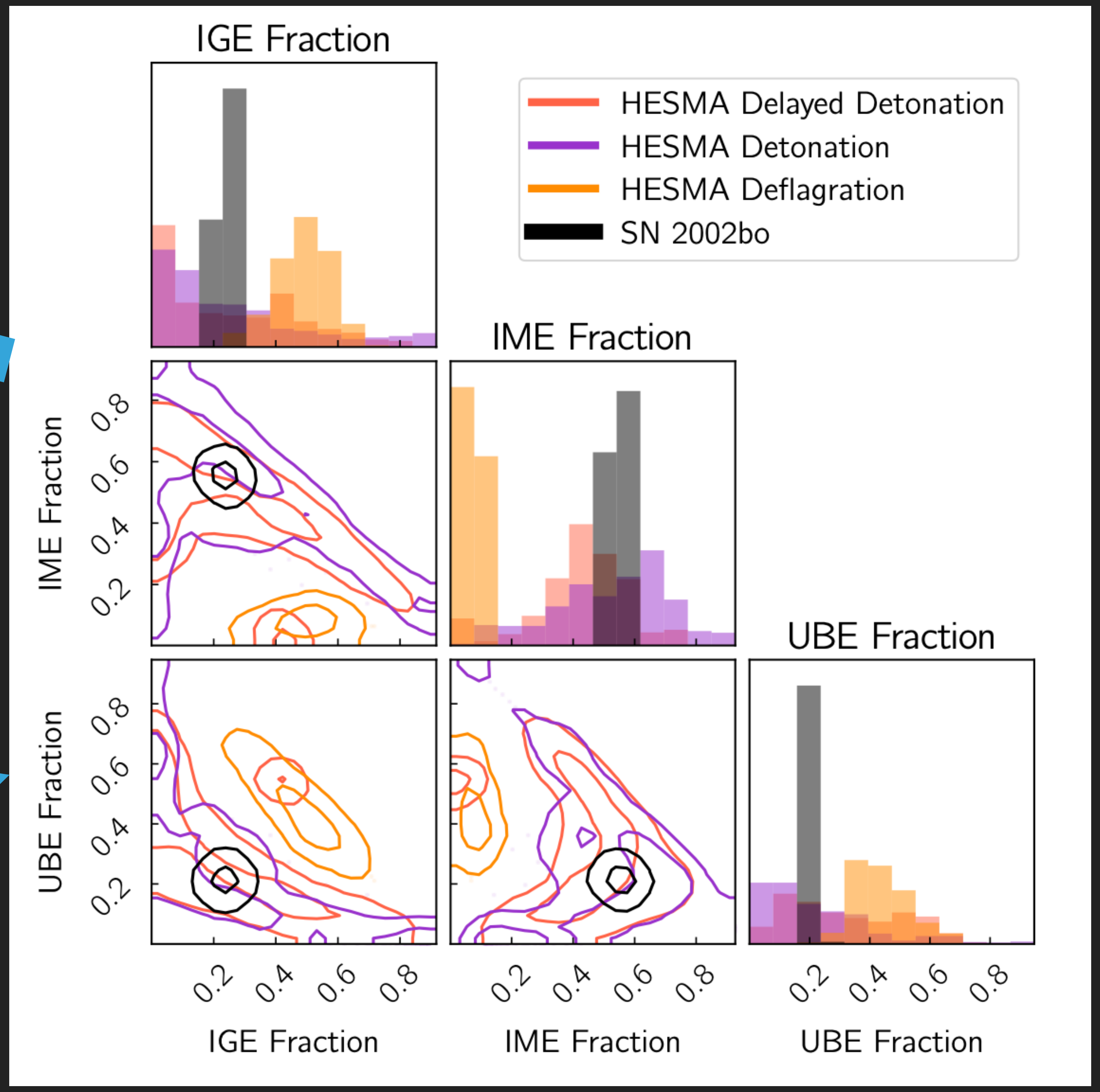
- Too large and too complex a s ertainty under 1% with classical emulator techniques
- Uncertainty quantification in e Learning (see O'Brien, WEK et al. 2024)

Adding points with high emulator uncertainty and high posterior to the training set

DEFINING TRAINING SET

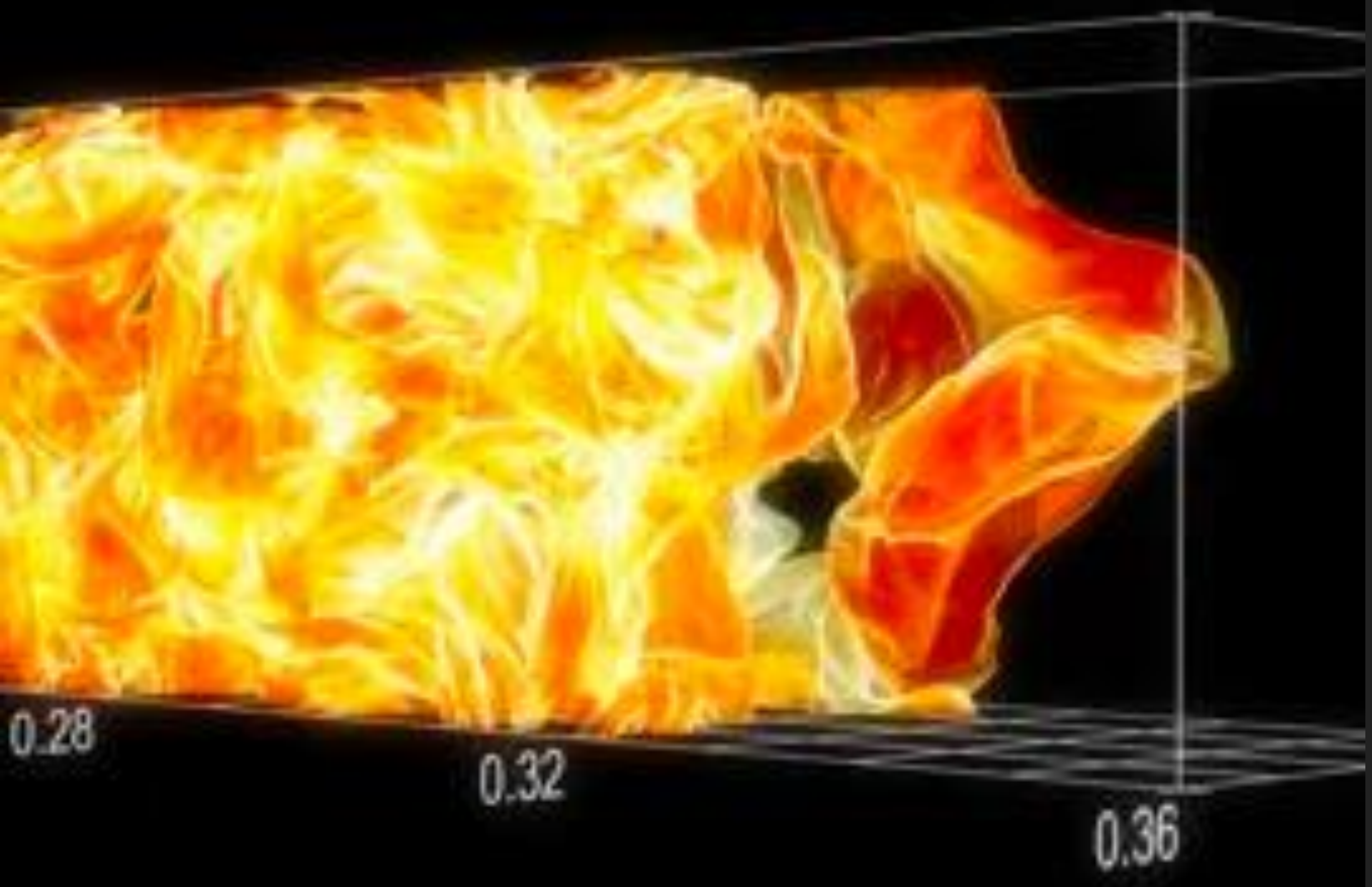
BUILDING EMULATOR

Inferring densities and composition on real spectra



APPLYING

SUPERNOVA TOMOGRAPHY



TARDIS !
Exploring supernovae made easy

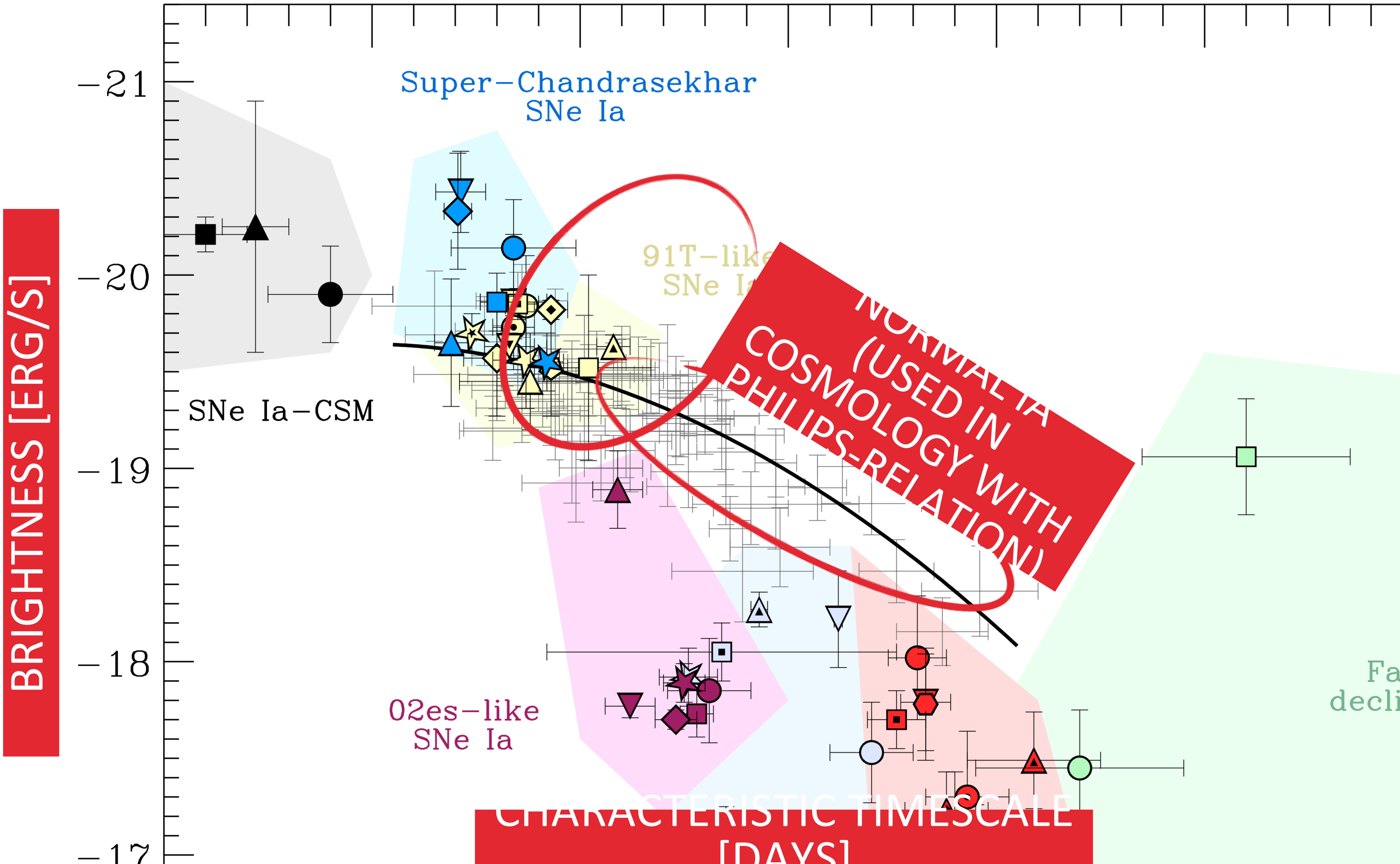
Lead: John “Jack” O’Brien

O’Brien, WEK, et al. 2022, 2024, 2025 almost submitted

DIVERSITY IN A “HOMOGENEOUS” CLASS

TYPE IA SUPERNOVAE

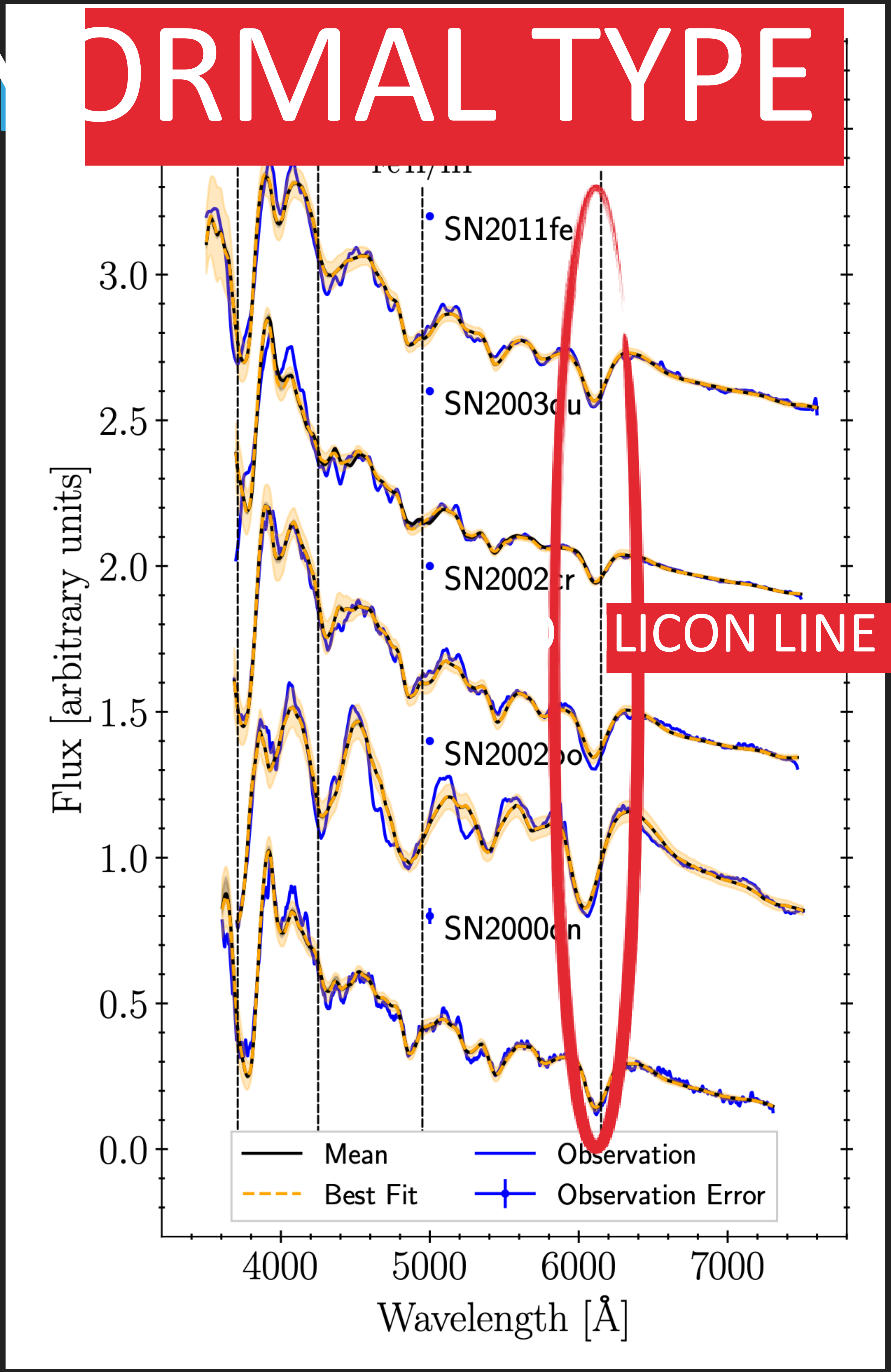
THE TYPES



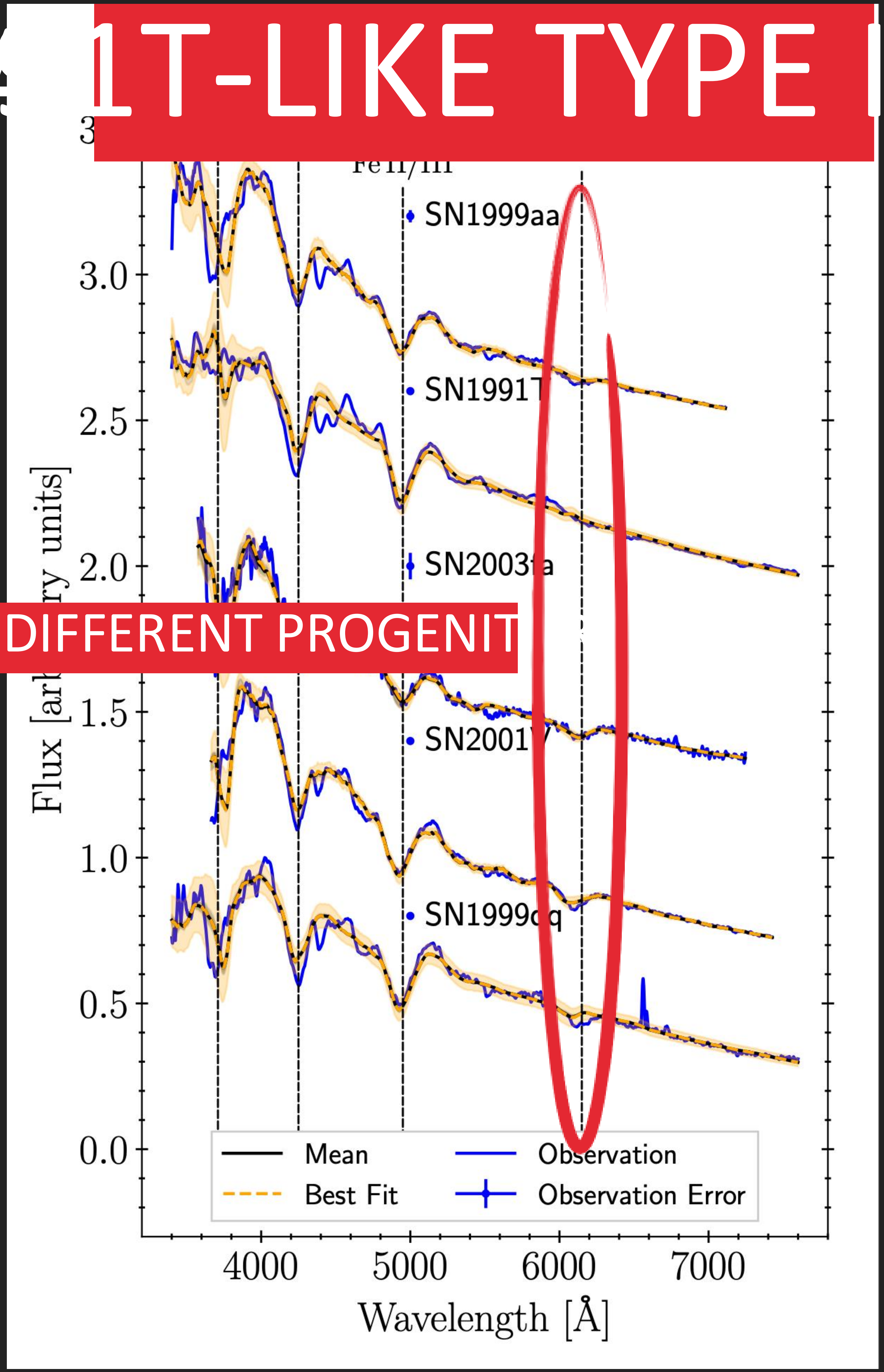
BRIGHTNESS [ERG/S]
−21
−20
−19
−18
−17
Super−Chandrasekhar
SNe Ia
SNe Ia−CSM
91T−like
02es−like
SNe Ia
(USED IN
COSMOLOGY WITH
PHILIPS-RELATION)

91T-LIKE VS NORM

NORMAL TYPE IA



91T-LIKE TYPE IA

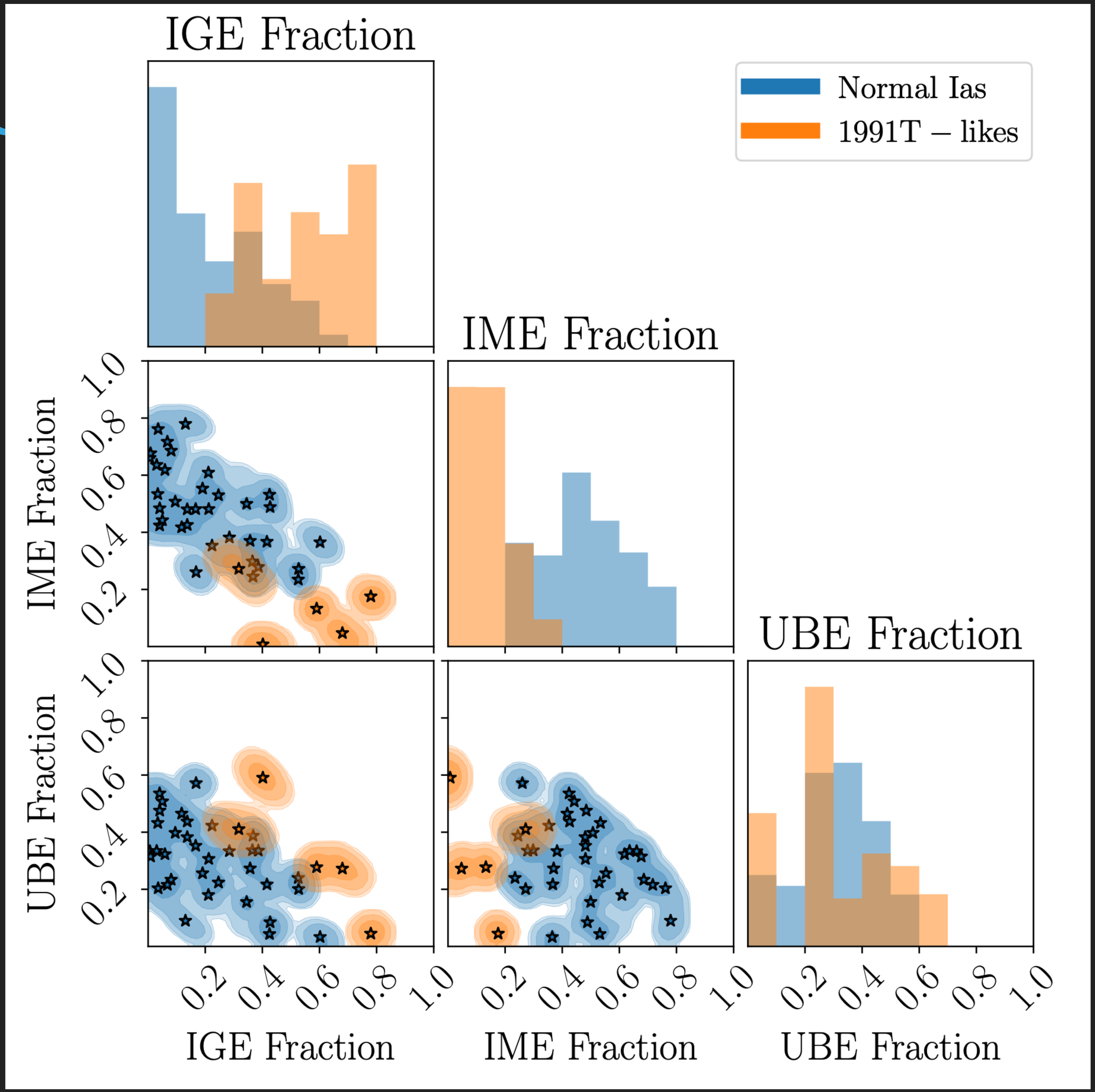


LICON LINE - DIFFERENT PROGENIT

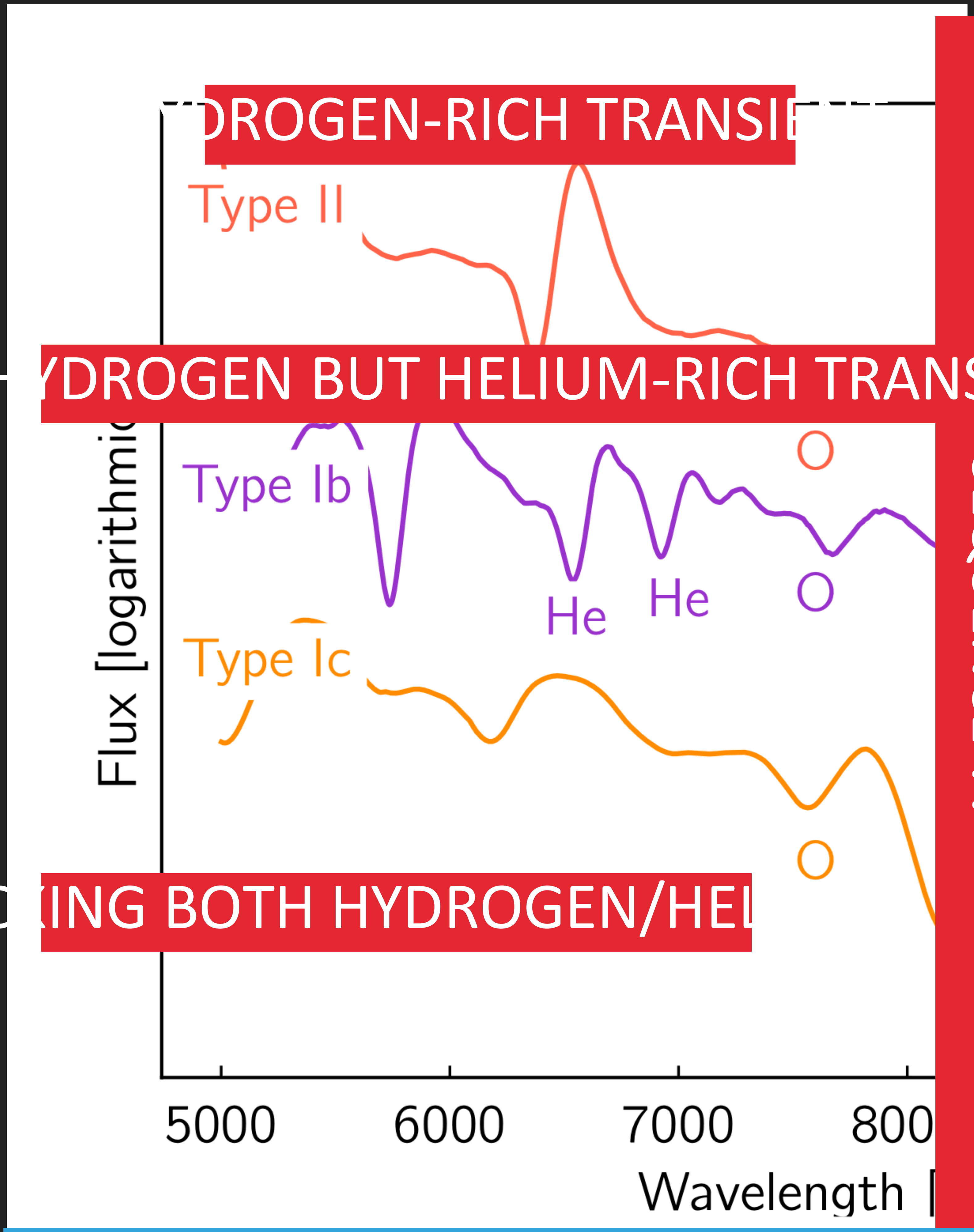
O’Brien, WEK, et al. 2024

SIMPLE ANALYSIS CAN FOOL YOU

- A decades long problem: 91T-like — a separate class from normal Type Ia?(contradictory claims: e.g. Filippenko+ 97 vs Sasdelli+ 14)
- The weak silicon line: hotter — or less silicon? (Jeffery+ 92, Ruiz-Lapuente+ 92, Sasdelli+ 14)
- Both are true — only to be seen in multiparameter inference
- In the multi-dimensional space of physical properties:
  - continuous — no two classes
- Spectroscopically dissimilar ≠ physically distinct
  - → one population, one progenitor mechanism (O'Brien, WEK et al. 2024)



CORE COLLAPSE SPECTRAL SEQUENCE



DROGEN-RICH TRANSIE

NO HYDROGEN BUT HELIUM-RICH TRANSIENT

LACKING BOTH HYDROGEN/HEL

SPECTROSCOPIC SEQUENCE == PROGENITOR SEQUENCE ??

TRANSITIONARY OBJECTS THAT SHOW HYDROGEN

TRANSITIONARY OBJECTS THAT SHOW HELIUM

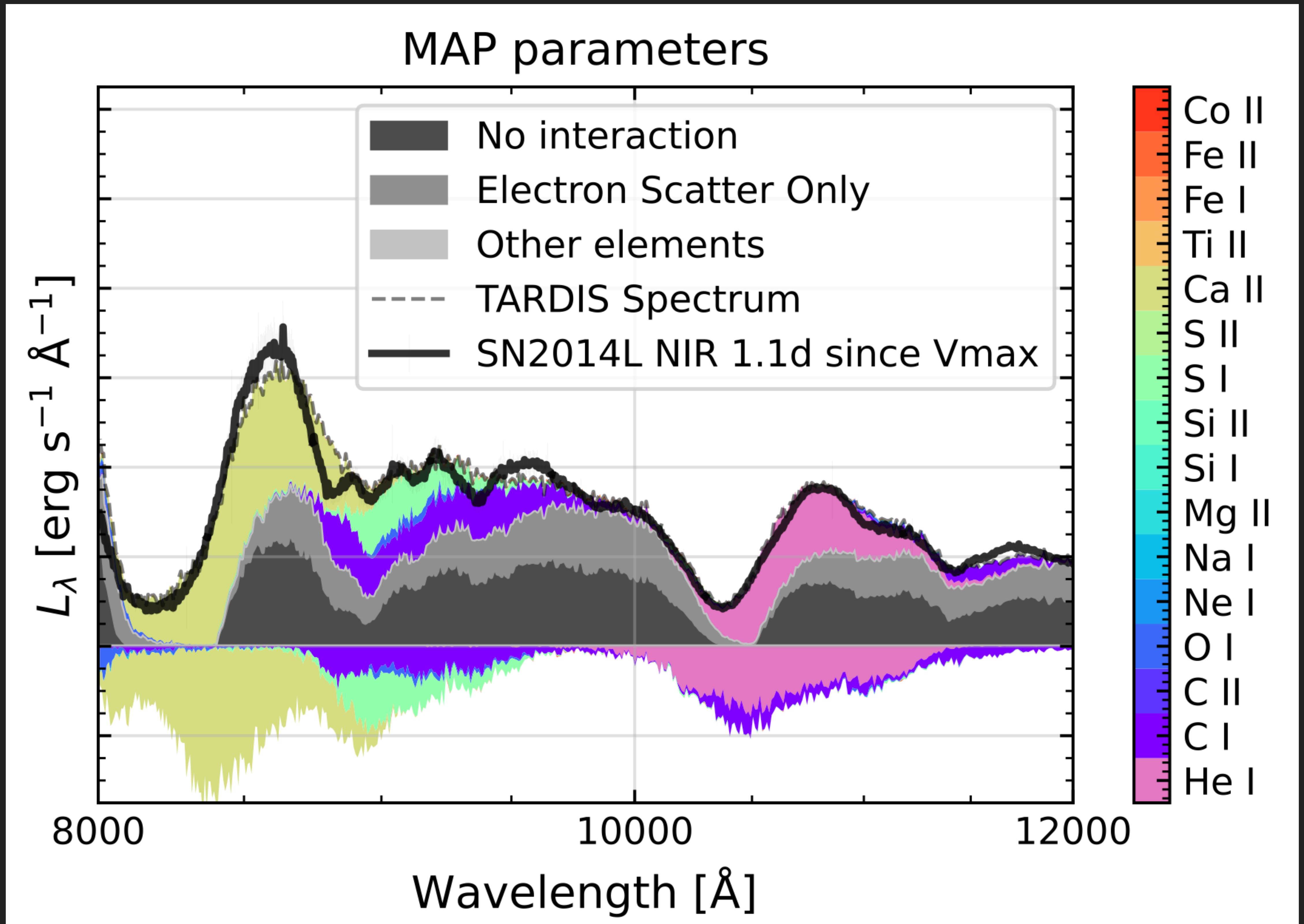
Jing Lu (MSU)

OBSERVED SPECTRAL DIVERSITY

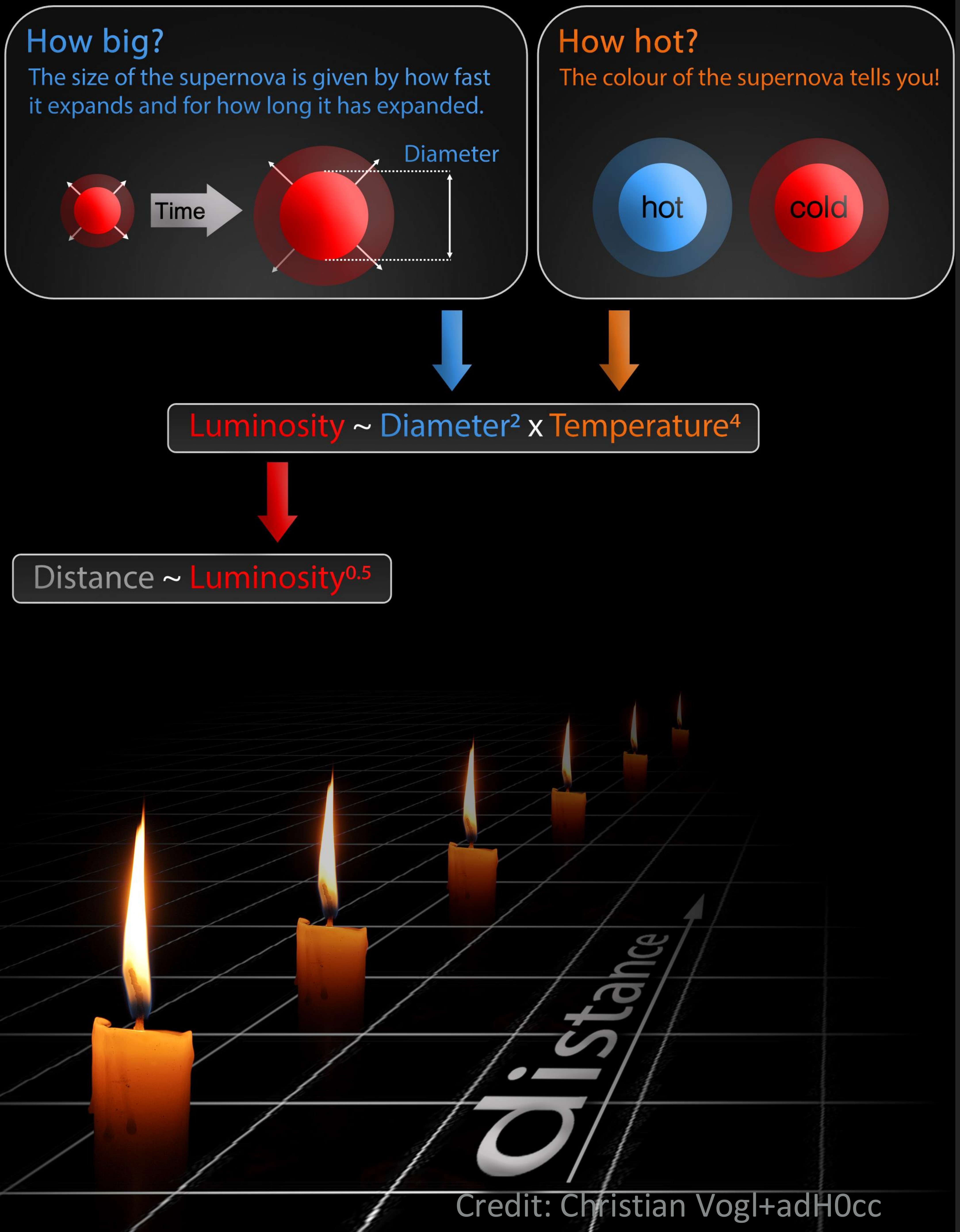
POTENTIALLY INFERRED PROGENIT

RECONSTRUCTING STRIPPED CORE COLLAPSE

- A decades long problem: Type Ic are DEFINED as helium-free - but how would a star strip away that much helium? (Wheeler+ 94, Filippenko+ 95)
- The 1 micron line flip-flops in the literature:
  - helium or a blend of other elements? (Millard+ 99, Baron+ 99, Sauer+ 06, Teffs+ 20)
- SN 2014L: the spectrum REQUIRES helium (~0.02 M⊙) - only to be seen in full-spectrum inference, with remarkable agreement from optical to infrared
- No optical helium line ≠ no helium
- → first hint of a stripping sequence, not separate classes - constraints for binary stellar evolution (Lu, WEK et al. 2026)



Lu, WEK et al. 2026



Christian Vogl (Zeiss)

ADH0CC

+

TARDIS!

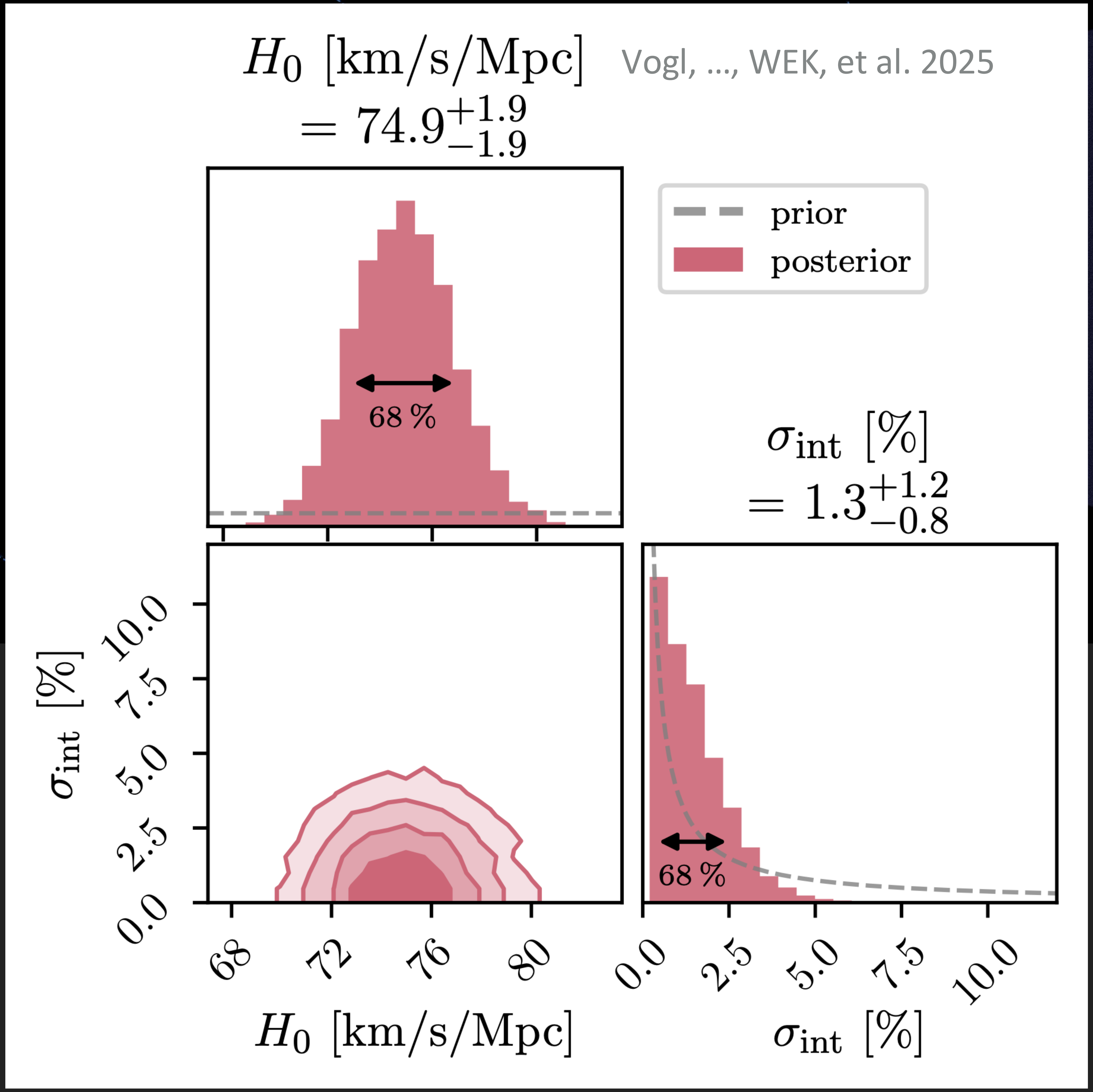
Exploring supernovae made easy

PROBABILISTIC TYPE IIP TRANSIENT TOMOGRAPHY FOR

COSMOLOGY

NO RUNGS ATTACHED: A DIRECT HUBBLE CONSTANT

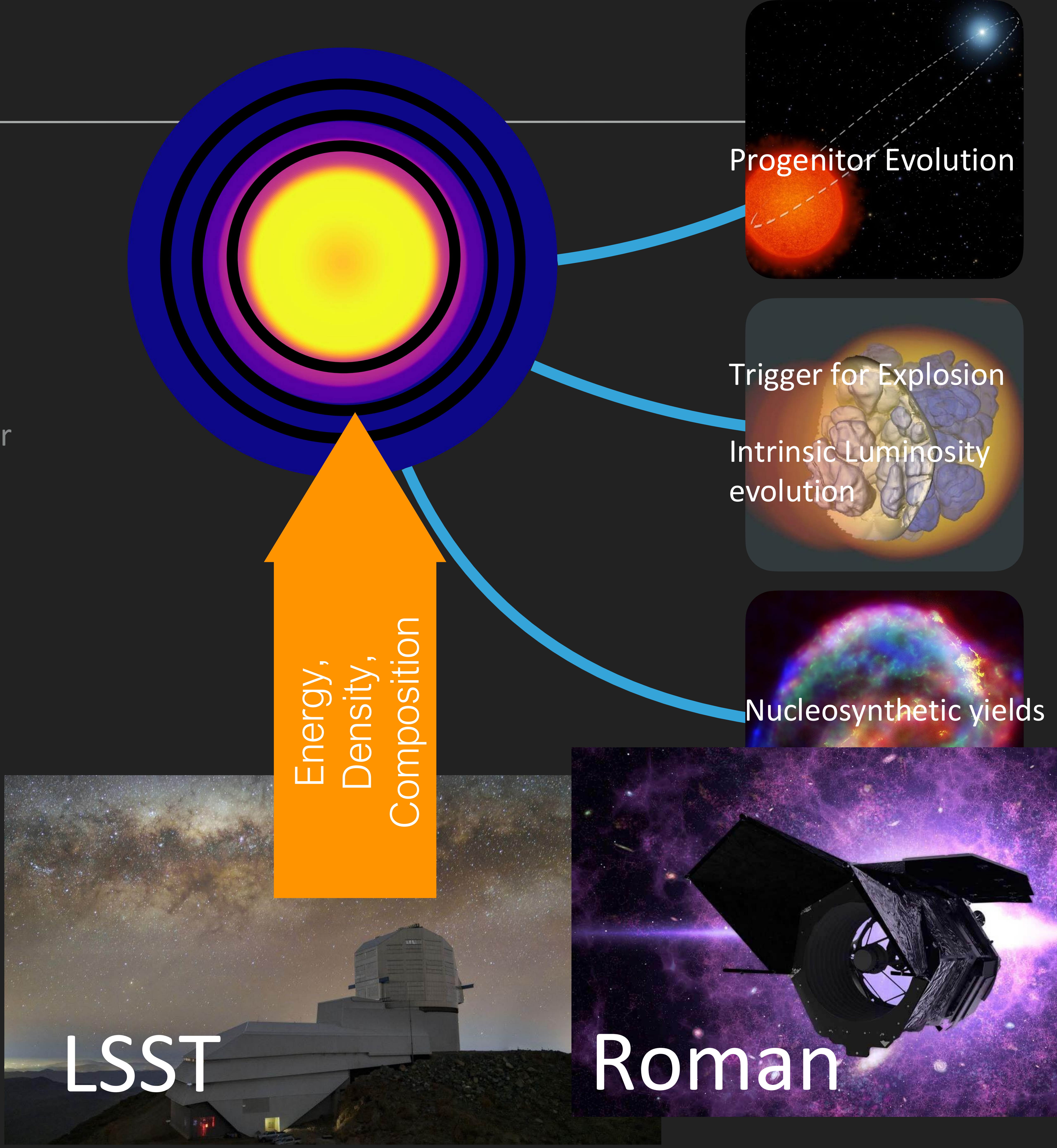
- A decades long problem: measure distances without the ladder, where every rung inherits the systematics of the rung below
- The expanding photosphere method promised distances from first principle physics, but simple spectral features alone leave uncertainties above 10 percent (e.g. Kirshner & Kwan 1974, Schmidt+ 1992, 1994)
- This needs inference with an actual radiative transfer and plasma code, made fast enough by emulators to fit full spectra
- The physics sets the absolute luminosity, no rungs needed
- H0 = 74.9 +/- 1.9 from Type IIP spectra alone (Vogl, … WEK et al. 2025)
  - More to come from Csörnyei in prep 2026



SUMMARY

WHERE ARE WE GOING?

- Open, reproducible, sustainable framework
- Synergizing simulation, machine learning, and Bayesian inference for physics knowledge
  - Important to have a experts from observations to modeling to statistical inference
- Interdisciplinary team is a given
  - BUT … integrating them in the final science case crucial
- From single spectra/objects to population-scale inference
- Next step - fusing LSST/Roman discovery streams with exascale simulations to open a new era of transients as precision probes of the evolving Universe



THANKS

ONE MORE THING …

Joe Petrecca

Benjamin Mellon

Vicente Amado

Bea Lu

SCIENCE IS NOW COMPUTATIONAL - SO IS STUDYING IT

- The DeepThought Initiative uses computational tools to study the process of science itself
- The AI entering our analysis pipelines is also entering the process of science: literature search, review, writing, code
- Reproducibility was already fragile; hosted LLMs make it harder: nondeterministic outputs, no meaningful seeding, models that drift and retire
- What does a reproducible method section even mean with a stochastic black box in the loop? We do practical research on exactly this
- Methods, reproducibility, evaluation and peer review: talk to me

Kerzendorf 2017 · Kerzendorf+ 2020 · AND: Amado Olivo, WEK+ 2025 · LLM reproducibility agents: Amado Olivo+ in prep

THANK YOU

WHERE ARE WE GOING?

- Open, reproducible, sustainable framework
- Synergizing simulation, machine learning, and Bayesian inference for physics knowledge
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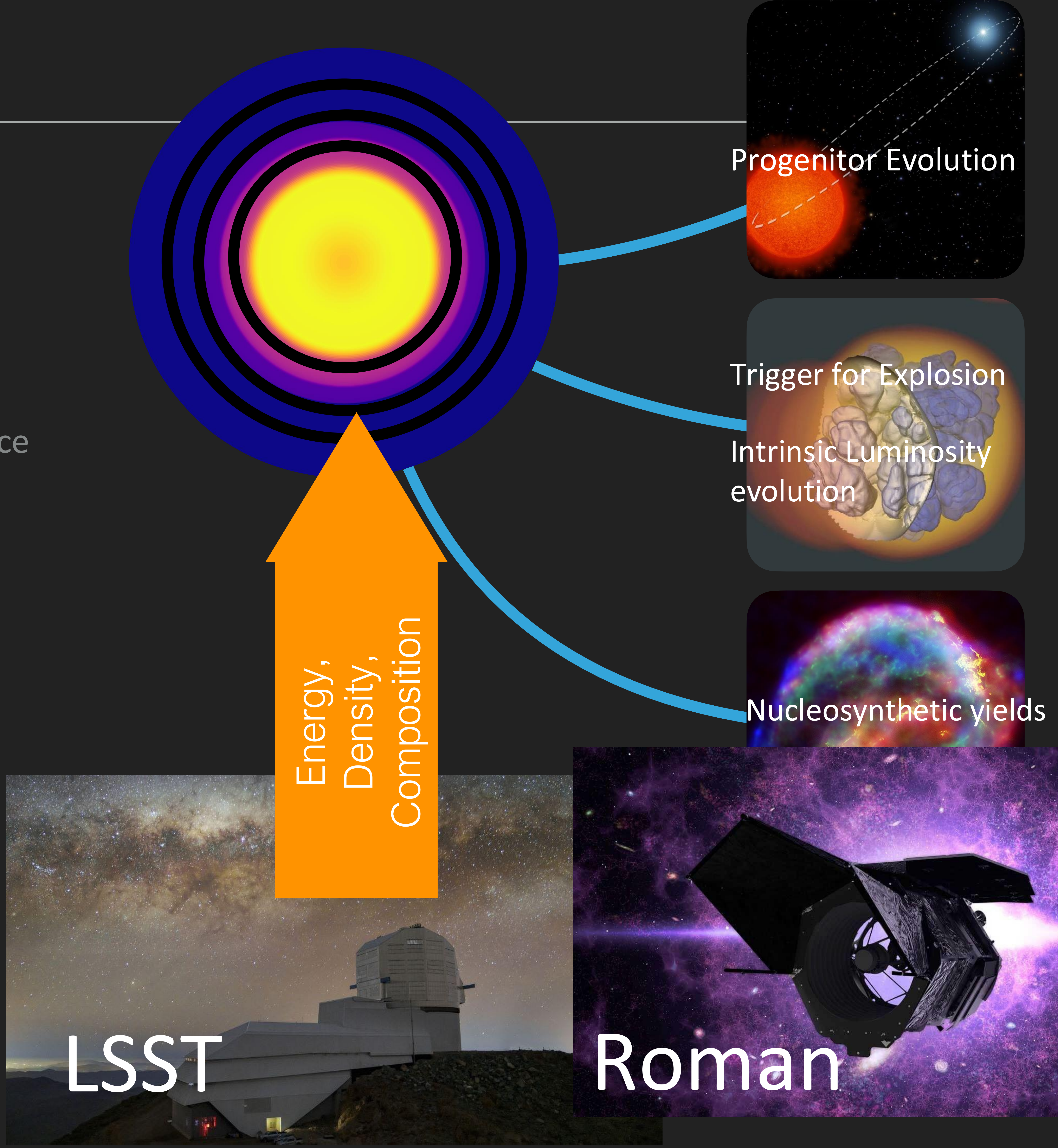

ADDITIONAL SLIDES