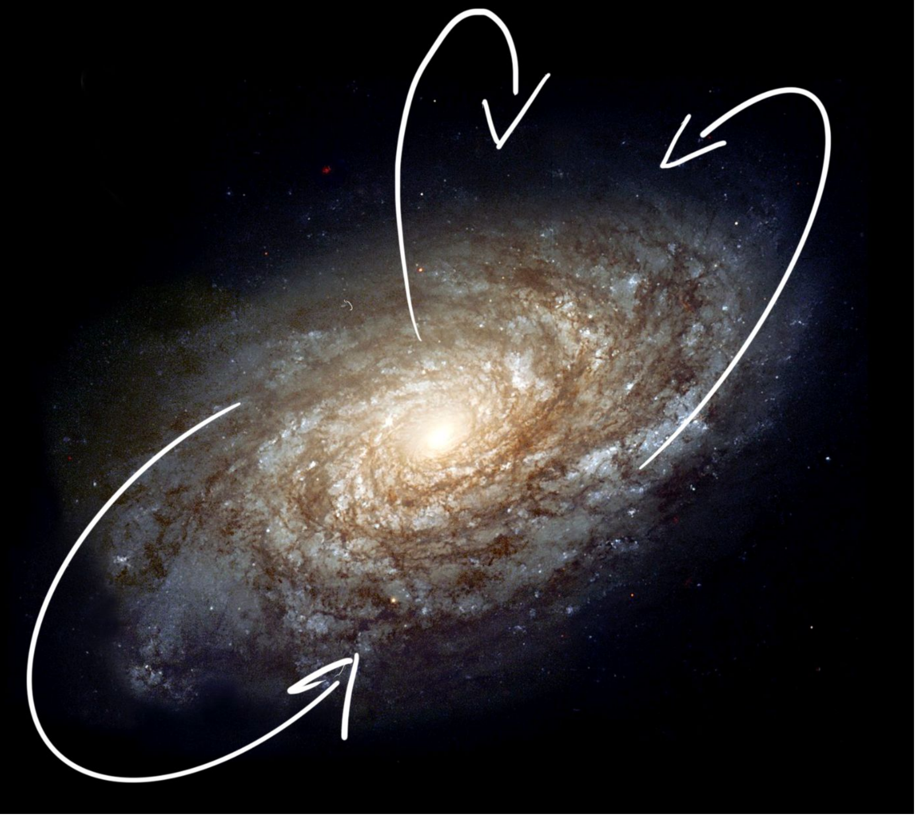


Toward a self-consistent **physical model** for star formation in galaxies

Kartheik Iyer @ NHFP Colloquium 2023
NHFP Hubble Fellow | Columbia University | 21st September 2023

Columbia University in the City of New York
NHFP
Flatiron Institute Center for Computational Astrophysics

Acknowledgements!

Columbia University
In the City of New York

Flatiron Institute
Center for Computational Astrophysics

In collaboration with:

CANDELS & CEERS - Sandy Faber, Harry Ferguson, Eric Gawiser, rachel somerville, Cami Pacifici, Casey Papovich, Steve Finkelstein, Marc Huertas-Company, Joel Primack, David Koo, Aaron Yung, Kameswara Mantha, Jeyhan Kartaltepe, Haowen Zhang, Sandro Tacchella

CANUCS - Chris Willott, Lamiya Mowla, Roberto Abraham, Marcin Sawicki, Vicente Estrada-Carpenter, Yoshihisa Asada, Gael Noirot, Victoria Strait, Ghassan Sarrouh, Gabe Brammer, Nick Martis, Guillaume Desprez, Adam Muzzin, Marusa Bradac,

CAMELS & Learning the Universe (LtU) - Francisco Villaescusa-Navarro, Greg Bryan, Chris Lovell, Viraj Pandya, Tjitske Starkenburg, Shy Genel, Lars Hernquist, Lucia Perez, Chang-hoon Hahn

& Josh Speagle, Erica Nelson, Joel Leja, Neven Caplar, John Forbes, Viviana Acquaviva, Susan Kassin, Ena Choi, Romeel Dave, Chris Hayward, Suchetha Cooray, Toby Brown, Abdurro'uf, Andrew Hearin, Danilo Marchesini, Joanna Woo, John Wu, Humna Awan, Karl Glazebrook, Colin Jacob, Themiya Nanayakkara, Vihang Mehta,

Students - Caleb Lammers, Juan Alfonzo, Eric Ludwig, Daniella Morrone, Jinoo Kim, Anika Slizewski, Eun-Jin Shin, Charlotte Olsen, Kate Gould, Obada Al Ajeh

UniverseTBD - Ioana (Jo) Ciucă, Yuan-sen Ting, Sandor Kruk, Ze-chang Sun, Josh Nguyen, Maja Jablonska, Josh Peek, Alberto Accomazzi, Alyssa Goodman …

enabled by dense-basis, george, fsps, python-fsps, synthesizer, sbi, pygam, numpy, scipy, astropy, hickle, statsmodels, matplotlib, corner, streamlit & more.

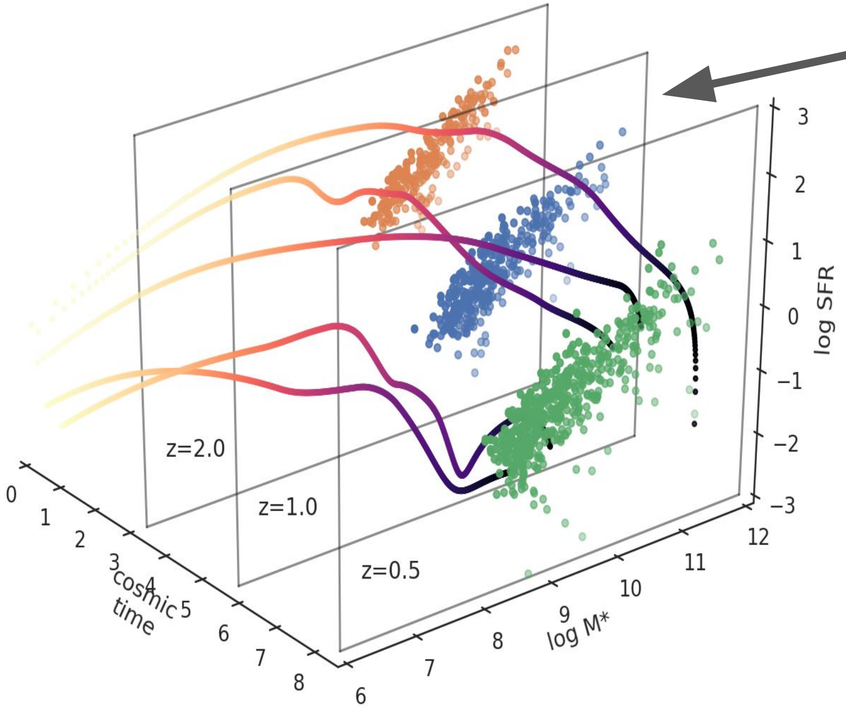
CANDELS
CEERS
CANUCS
CAMELS
arxiv-gpt
dense basis
NHFP
pan-survey SEDforum
universeTBD

Q: What makes galaxies form (and stop forming) stars?
Q: What can ensembles of noisy measurements tell us?
Q: How can we be better at communicating science?
Q: How can we be better teachers and mentors?
Q: How do we do astrophysics at scale?
Q: What will AI/ML do to astrophysics? to science?


A map of the lands spanning
galaxy evolution papers
(astro-ph.GA as on 27th June 2023)
Browse at https://kiyer-arxiv-gpt.streamlit.app/
Morphology forests
Molecular cloud bluffs
JWST valley
AGN island
Image: Kartheik Iyer & UniverseTBD
https://huggingface.co/spaces/kiyer/arxiv-gpt


A map of the lands spanning
galaxy evolution papers
(astro-ph.GA as on 27th June 2023)
Browse at https://kiyer-arxiv-gpt.streamlit.app/
Morphology forests
Molecular cloud bluffs
JWST valley
AGN island
Image: Kartheik Iyer & UniverseTBD
https://huggingface.co/spaces/kiyer/arxiv-gpt

Put simply, **what's going on?**



Adapted from Iyer et al. (2018)

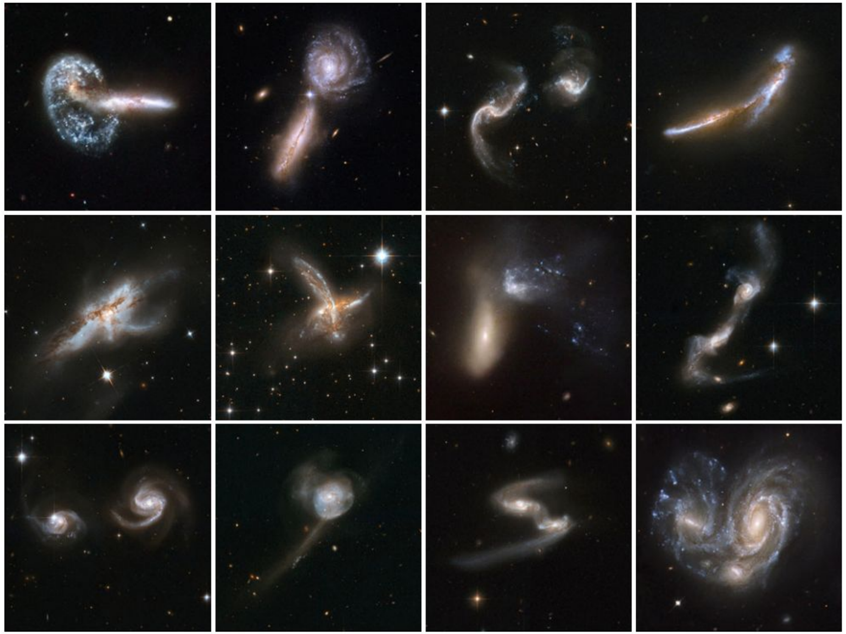
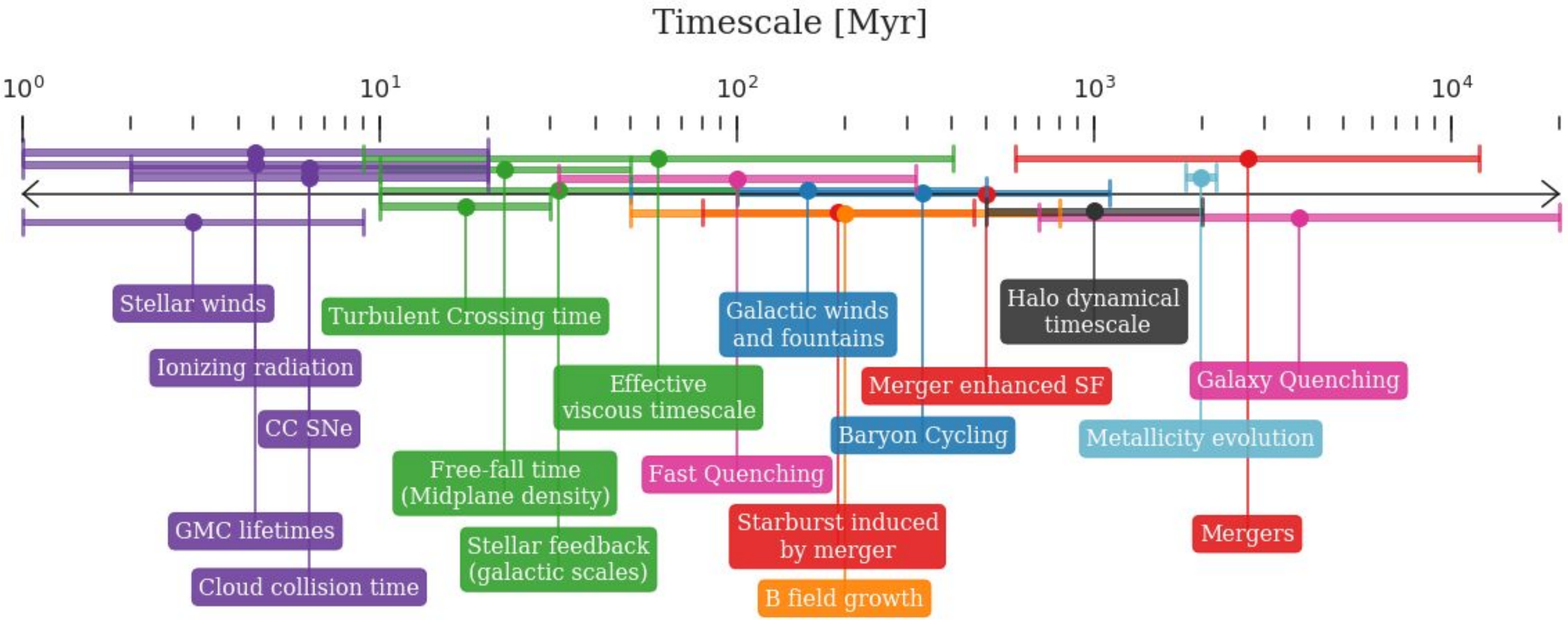


Figure 10.1 from Extragalactic Astronomy & Cosmology, P. Schneider

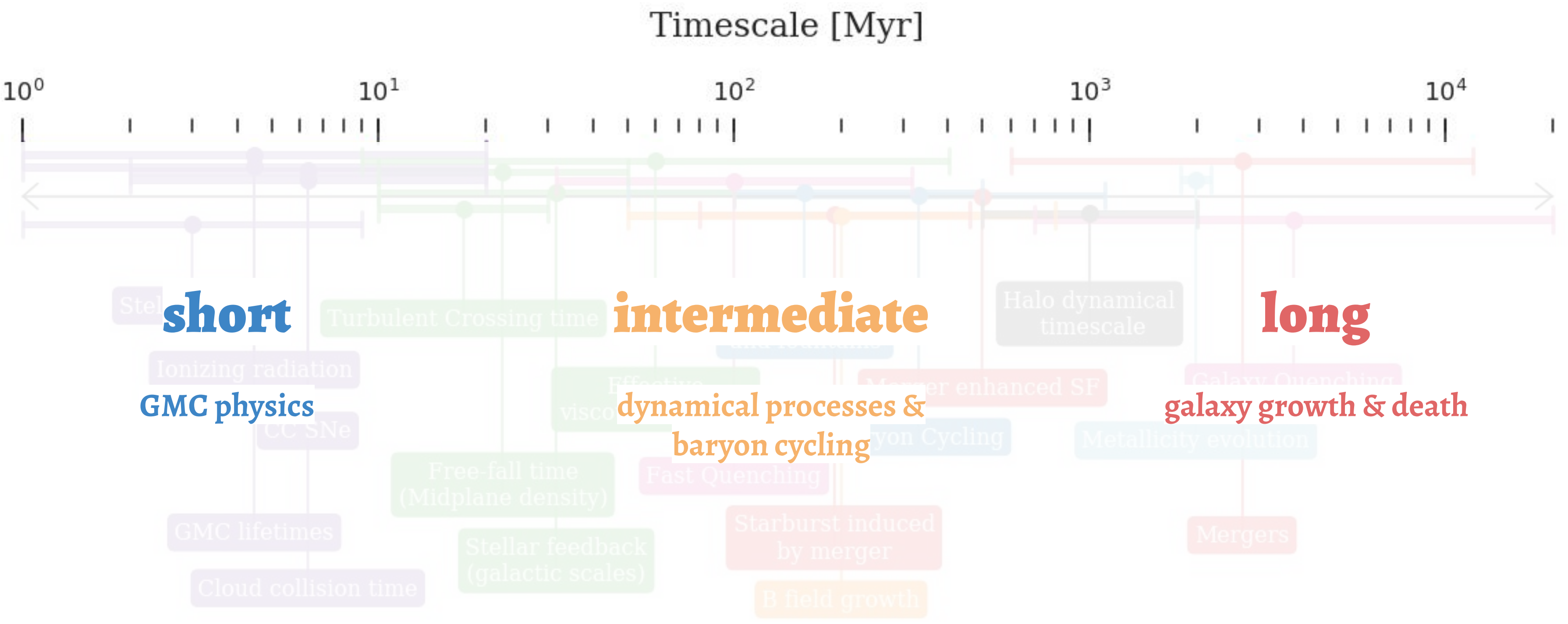
Put less simply, **how are these physical processes driving galaxy properties, their diversity and their emergent scaling relations?**



Iyer et al. (2020)

effective

Put less simply, **how are these ^ physical processes driving galaxy properties, their diversity and their emergent scaling relations?**



Iyer et al. (2020)

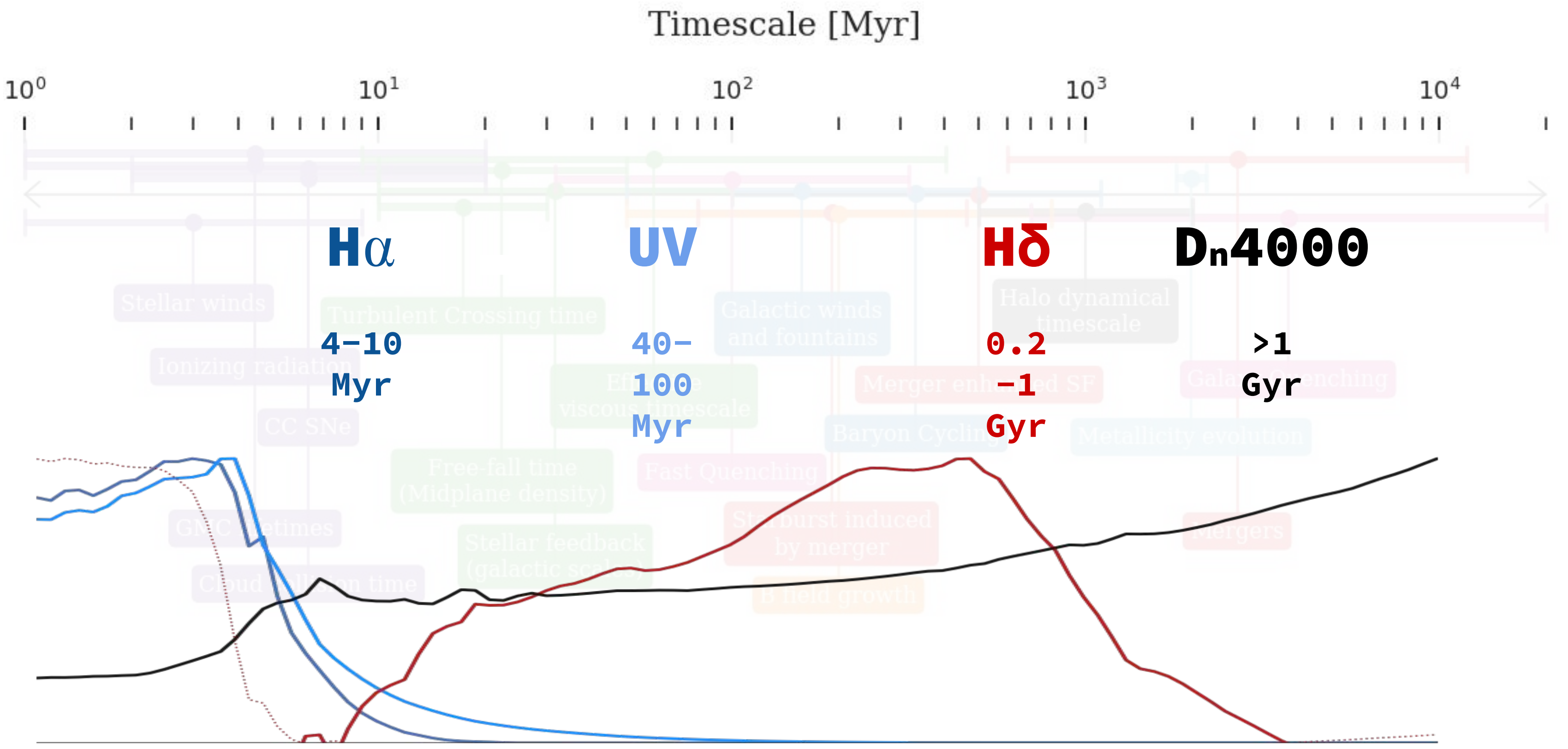
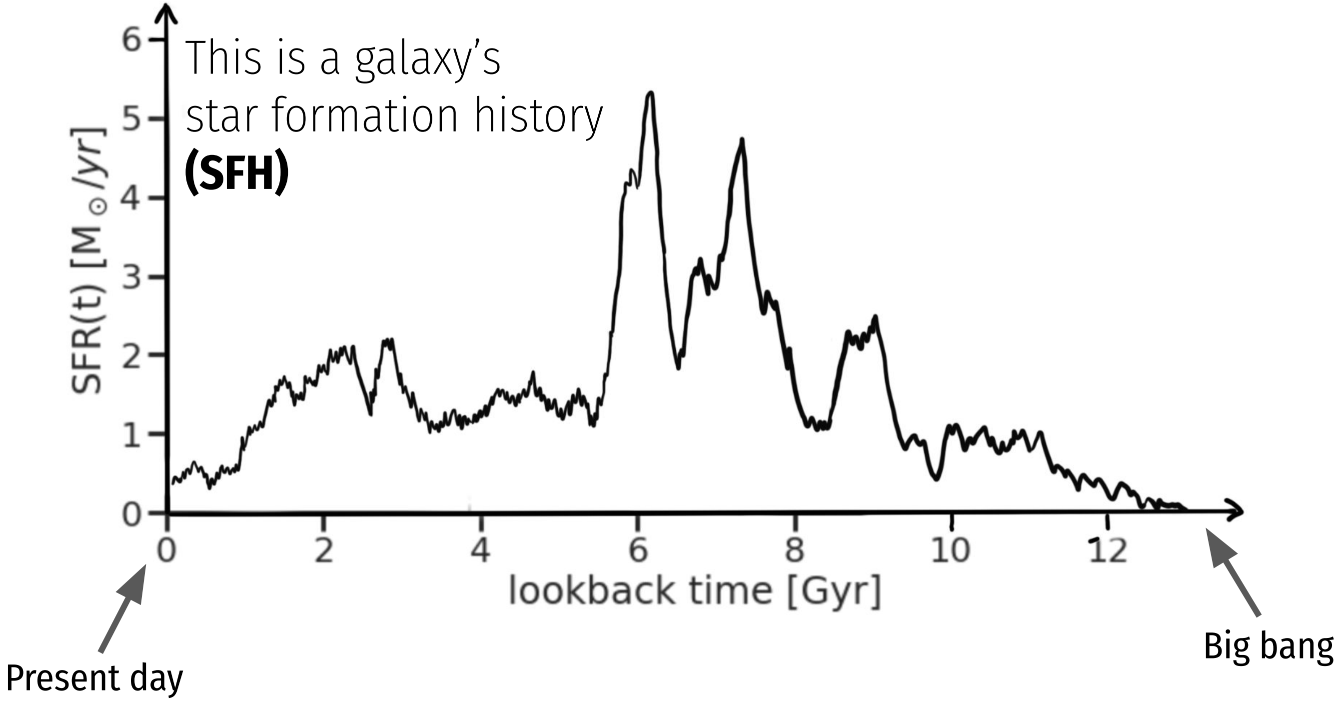
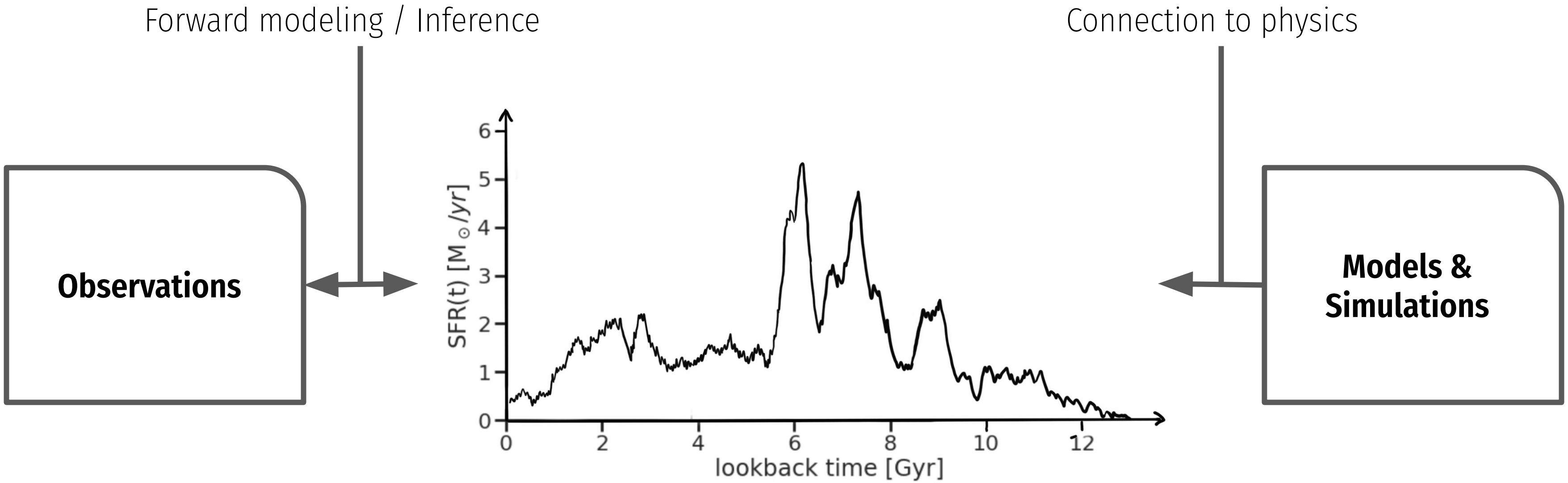


Figure: Iyer et al. 2020, arXiv:2007.07916

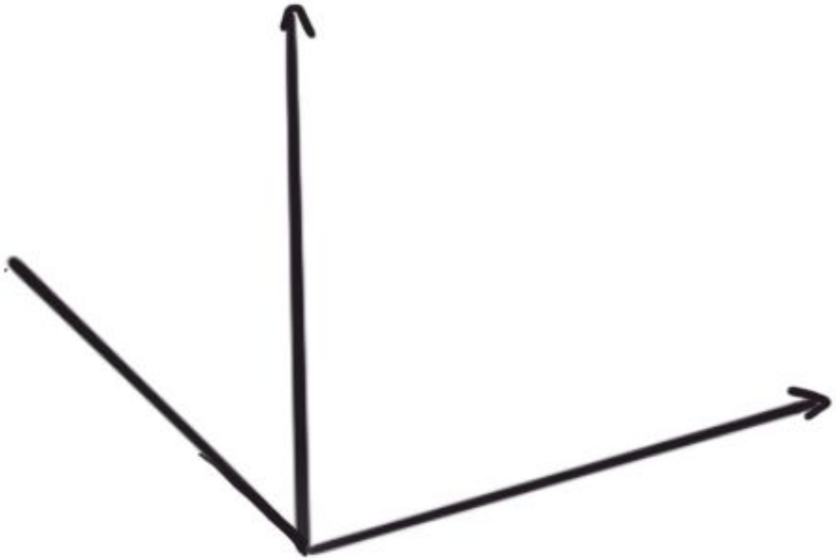

This is a galaxy's
star formation history
(SFH)
SFR(t) [M☉/yr]
6
5
4
3
2
1
0
0
2
4
6
8
10
12
lookback time [Gyr]
Present day
Big bang

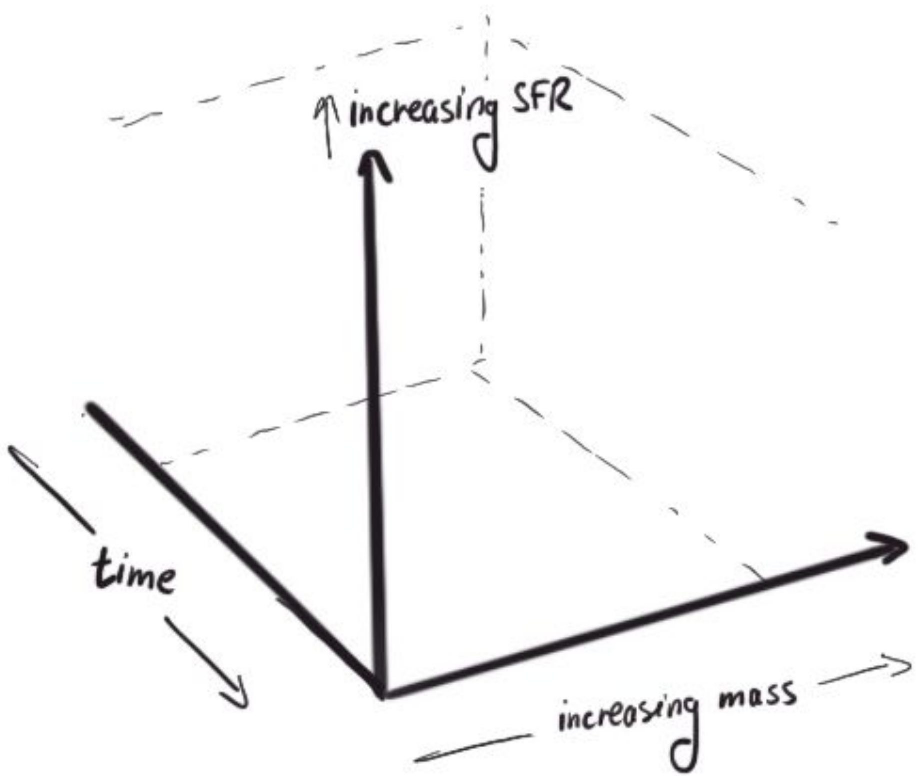


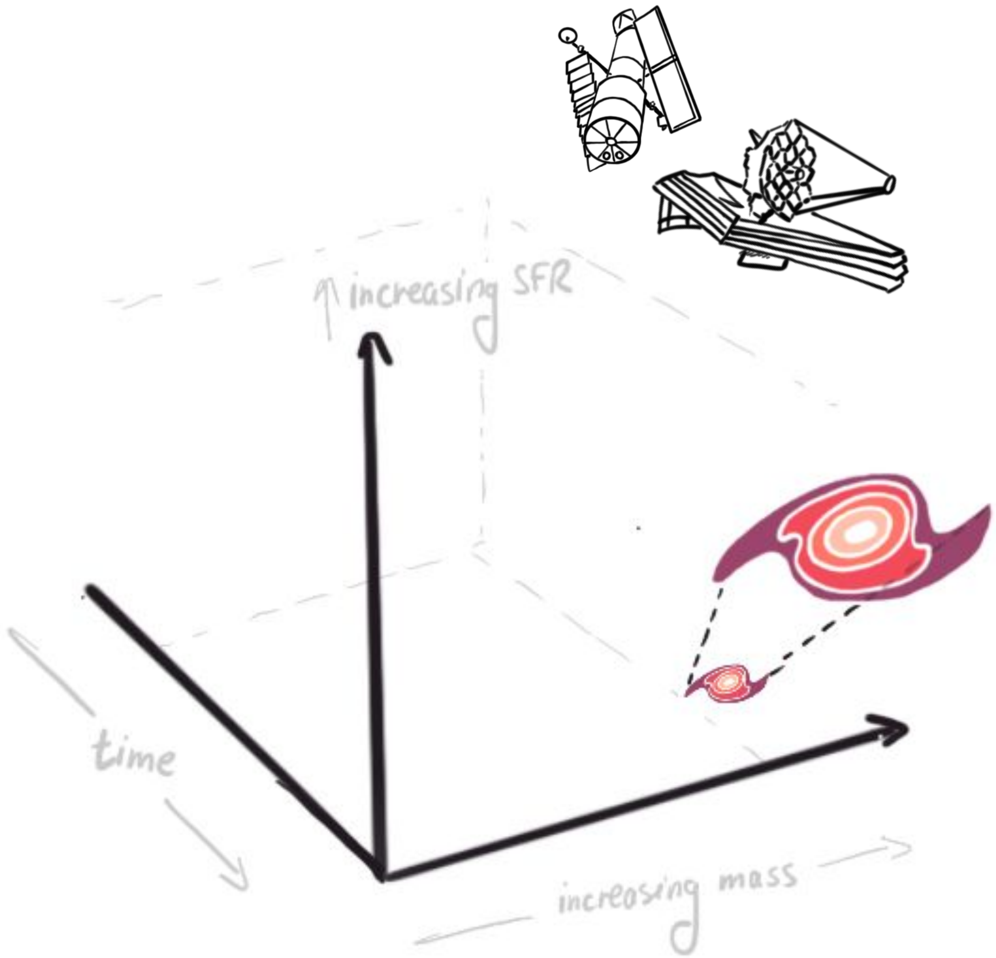
Inferring SFHs from observations

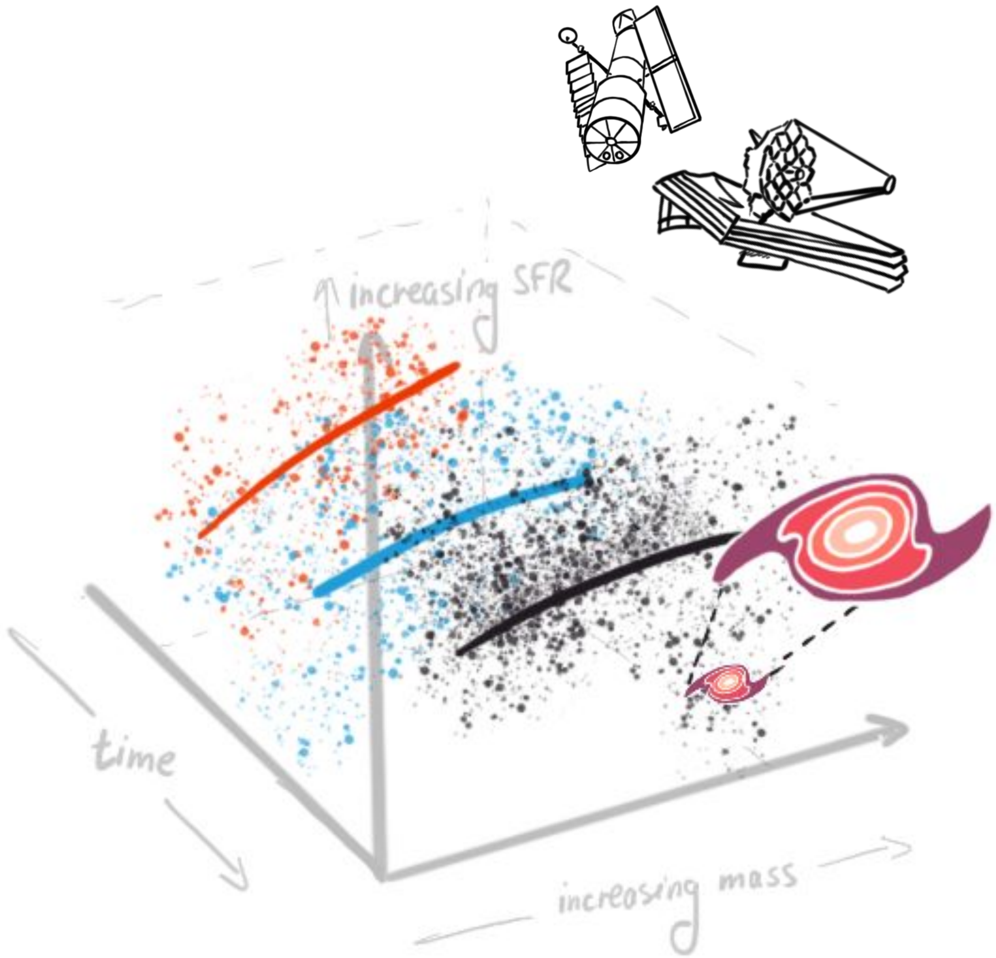
Understanding the obs-sim domain shift

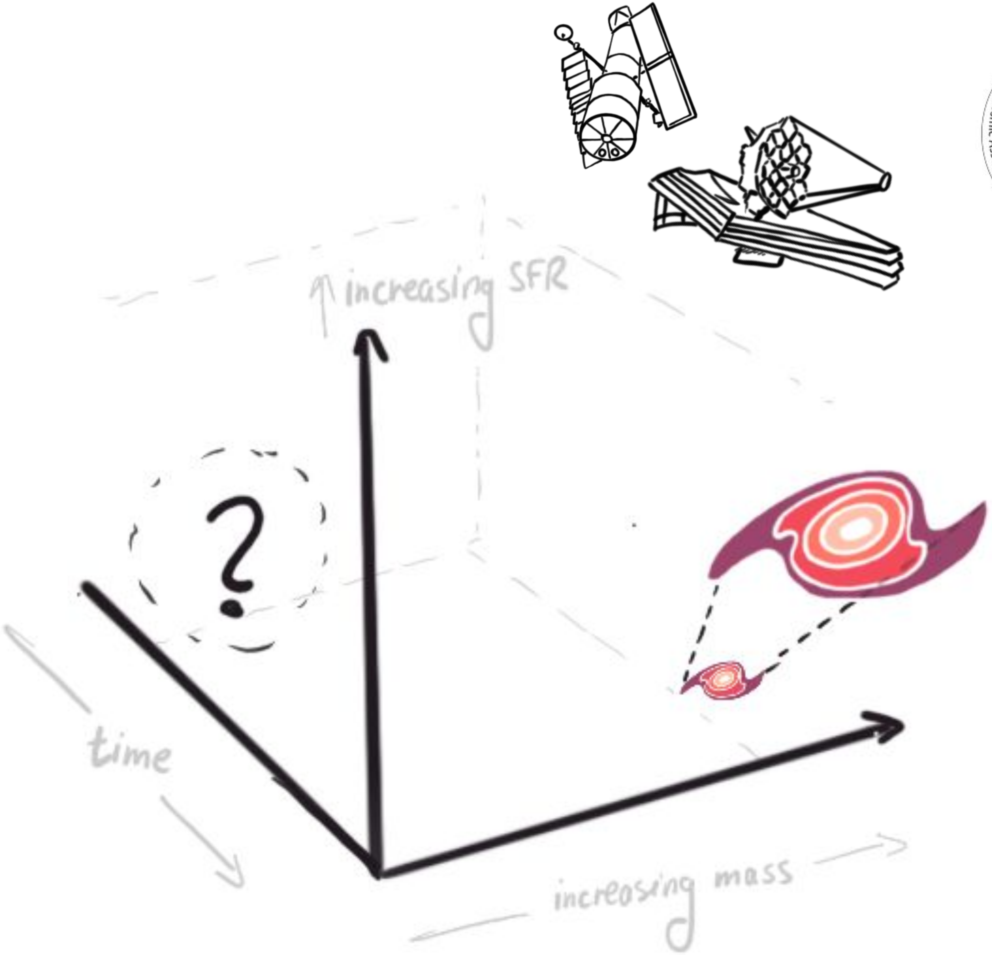
Quantifying the SFH-physics connection




increasing SFR
time
increasing mass


increasing SFR
time
increasing mass

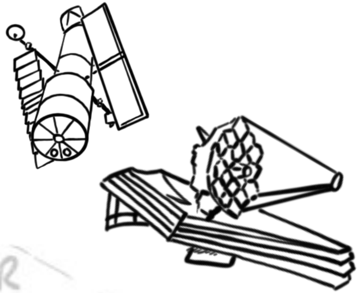

increasing SFR
time
increasing mass

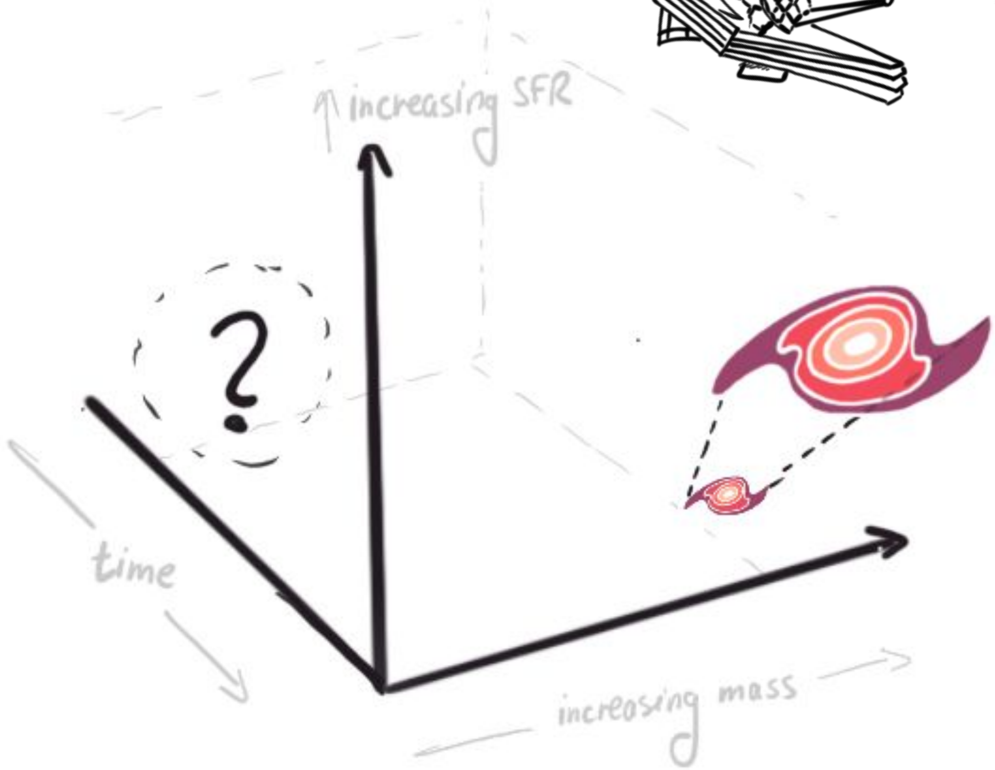


CANDELS
Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey

Cosmic Evolution Early Release Science Survey
CEERS

CANUCS





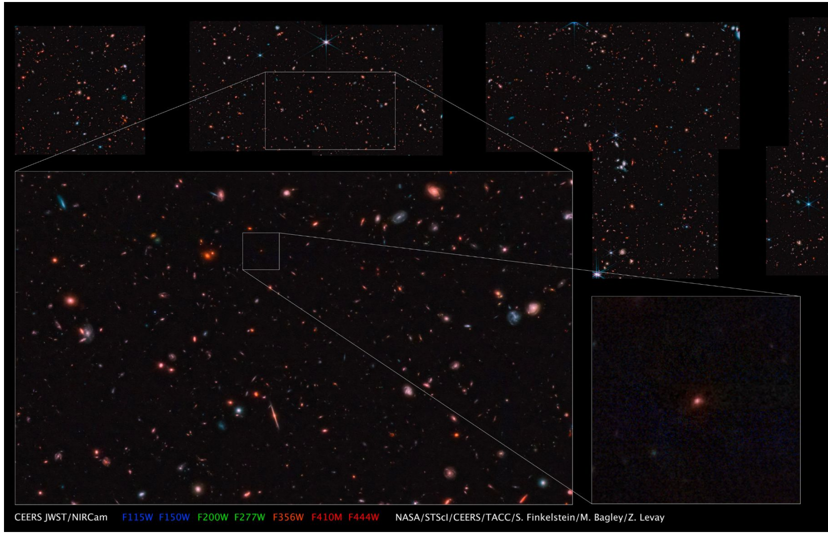
CANDELS — Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey

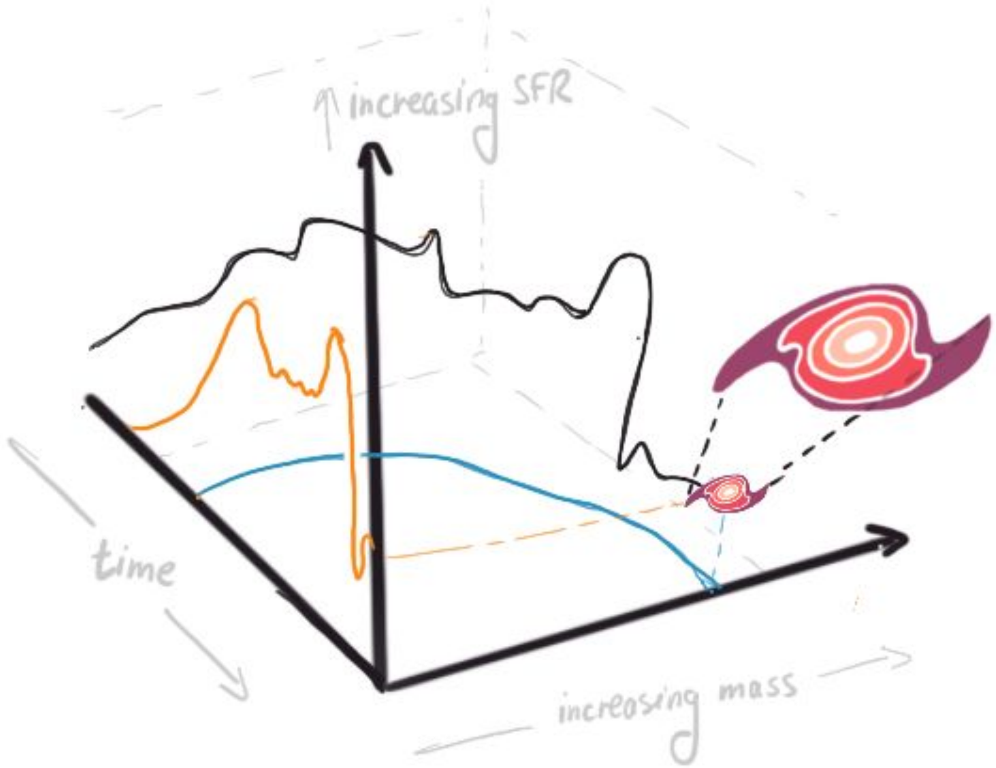
CEERS — Cosmic Evolution Early Release Science Survey

CANUCS

Maisie's galaxy at z~12 is one of the most distant galaxies to date

(Finkelstein et al. 2022 incl KI; with CEERS)

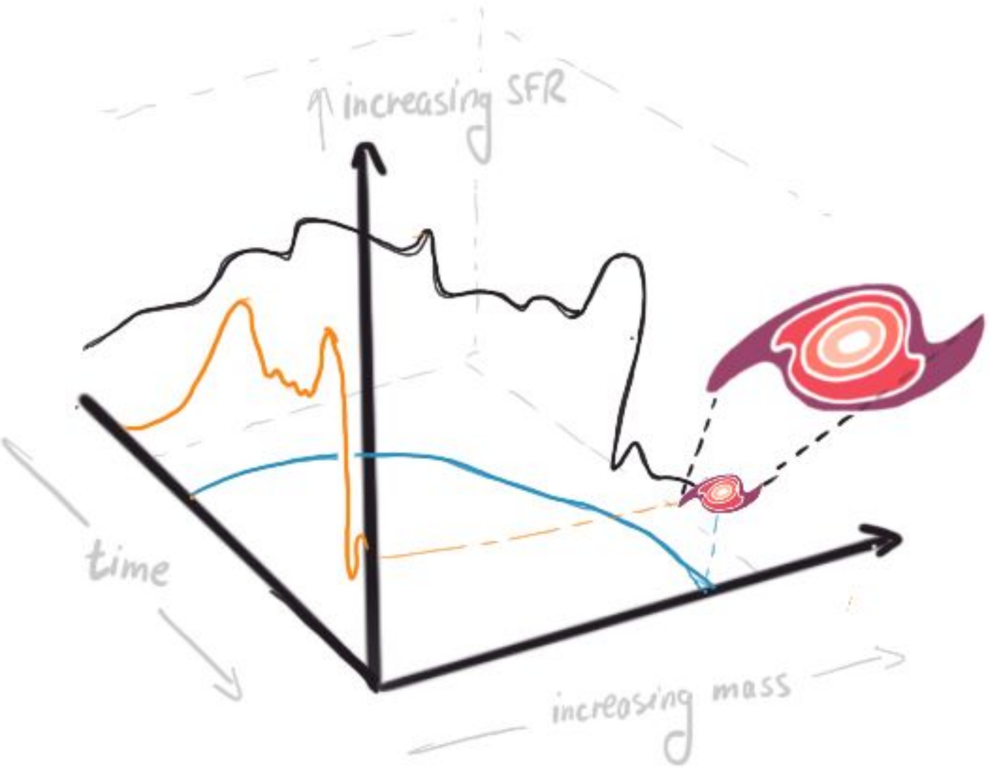


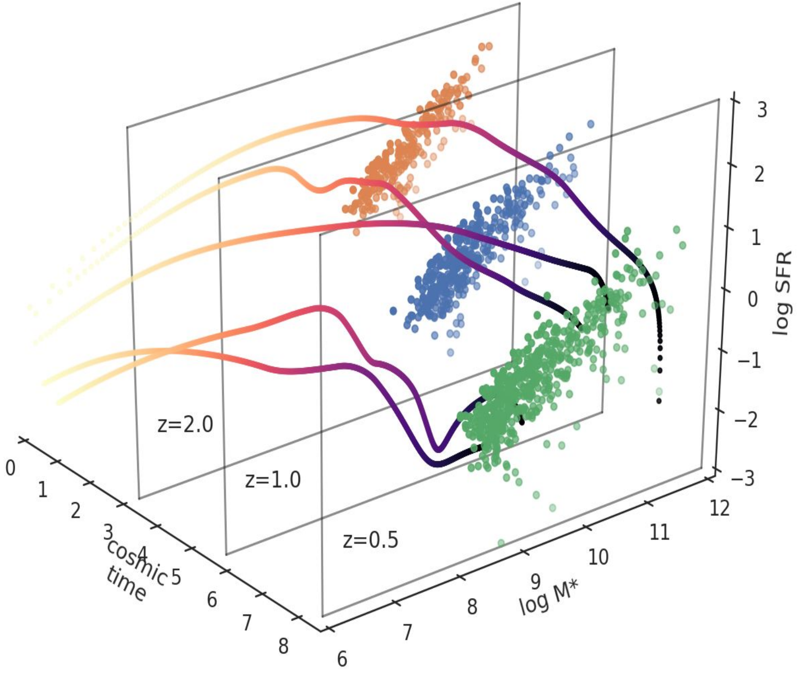

increasing SFR
time
increasing mass

Robust SFH recovery from multiwavelength observations:

The Dense Basis method

```
> pip install dense-basis
```





Iyer et al. 2018

The Sparkler: Evolved High-redshift Globular Cluster Candidates Captured by JWST

L Mowla & KG Iyer, G Desprez, V Estrada-Carpenter, NS Martis, G Noirot, ... (2022)
The Astrophysical Journal Letters 937 (2), L35

A Long Time Ago in a Galaxy Far, Far Away: A Candidate z~ 12 Galaxy in Early JWST CEERS Imaging

SL Finkelstein, MB Bagley, PA Haro, M Dickinson, HC Ferguson, ... (2022)
The Astrophysical journal letters 940 (2), L55

Star Formation at the Epoch of Reionization with CANUCS: The ages of stellar populations in MACS1149-JD1

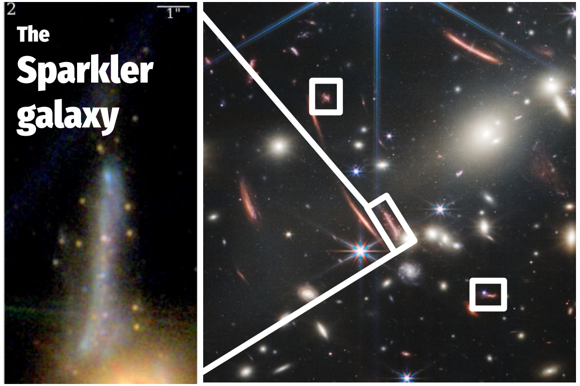
M Bradač, V Strait, L Mowla, KG Iyer, G Noirot, C Willott, G Brammer, ... (2023)
arXiv preprint arXiv:2308.13288; *Submitted to ApJL*

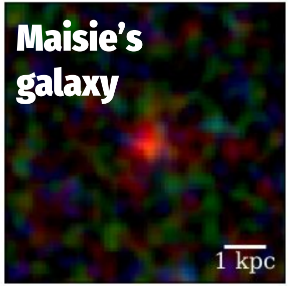
JWST reveals a Milky-way barred galaxy at z~3

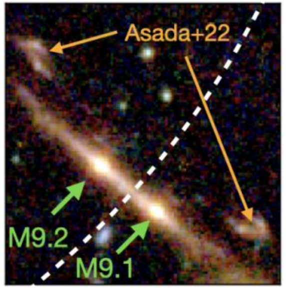
L Constantin, P Perez-Gonzalez, Y Guo, C Buttitta, S Jogee, M Bagley, ... (2023)
Accepted for publication in Nature

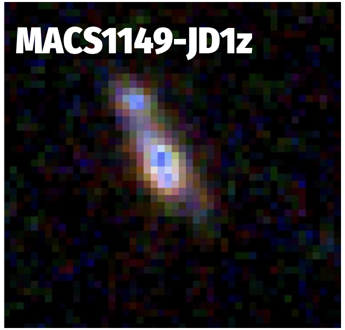
JWST catches the assembly of a z~5 ultra-low-mass galaxy

Y Asada, M Sawicki, G Desprez, R Abraham, M Bradač, G Brammer, ... (2023)
Monthly Notices of the Royal Astronomical Society: Letters 523 (1), L40-L45







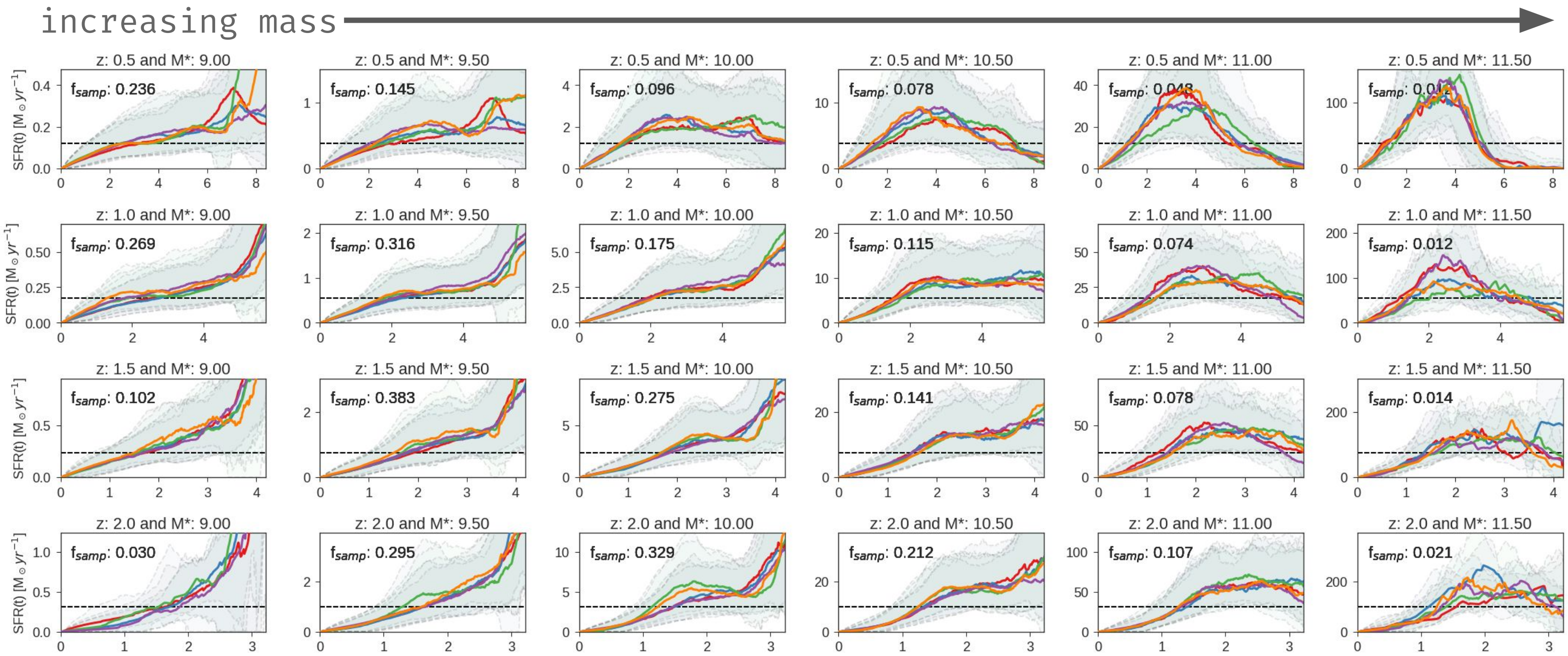


...and more!

Nonparametric Star Formation History Reconstruction with Gaussian Processes. I. Counting Major Episodes of Star Formation

KG Iyer, E Gawiser, SM Faber, HC Ferguson, J Kartaltepe, ... (2019)

The Astrophysical Journal 879 (2), 116



Nonparametric Star Formation History Reconstruction with Gaussian Processes. I. Counting Major Episodes of Star Formation

KG Iyer, E Gawiser, SM Faber, HC Ferguson, J Kartaltepe, ... (2019)
The Astrophysical Journal 879 (2), 116

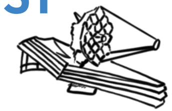
CLEAR: The Morphological Evolution of Galaxies in the Green Valley

V Estrada-Carpenter, C Papovich, I Momcheva, G Brammer, RC Simons, NJ Cleri... (2023)
The Astrophysical Journal, 951 (2), 115

Active Galactic Nuclei Feedback in SDSS-IV MaNGA: AGNs Have Suppressed Central Star Formation Rates

C Lammers, KG Iyer, H Ibarra-Medel, C Pacifici, SF Sánchez, S Tacchella, ... (2023)
The Astrophysical Journal 953 (1), 26

Galaxy Morphology from z~6 through the eyes of JWST



M Huertas-Company, KG Iyer, E Angeloudi, MB Bagley, SL Finkelstein, ...(2023)
arXiv: 2305.02478; Submitted to A&A

The Art of Measuring Physical Parameters in Galaxies: A Critical Assessment of Spectral Energy Distribution Fitting Techniques

C Pacifici, KG Iyer, B Mobasher, E da Cunha, V Acquaviva, D Burgarella, ... (2023)
The Astrophysical Journal 944 (2), 141

...and more in prep!

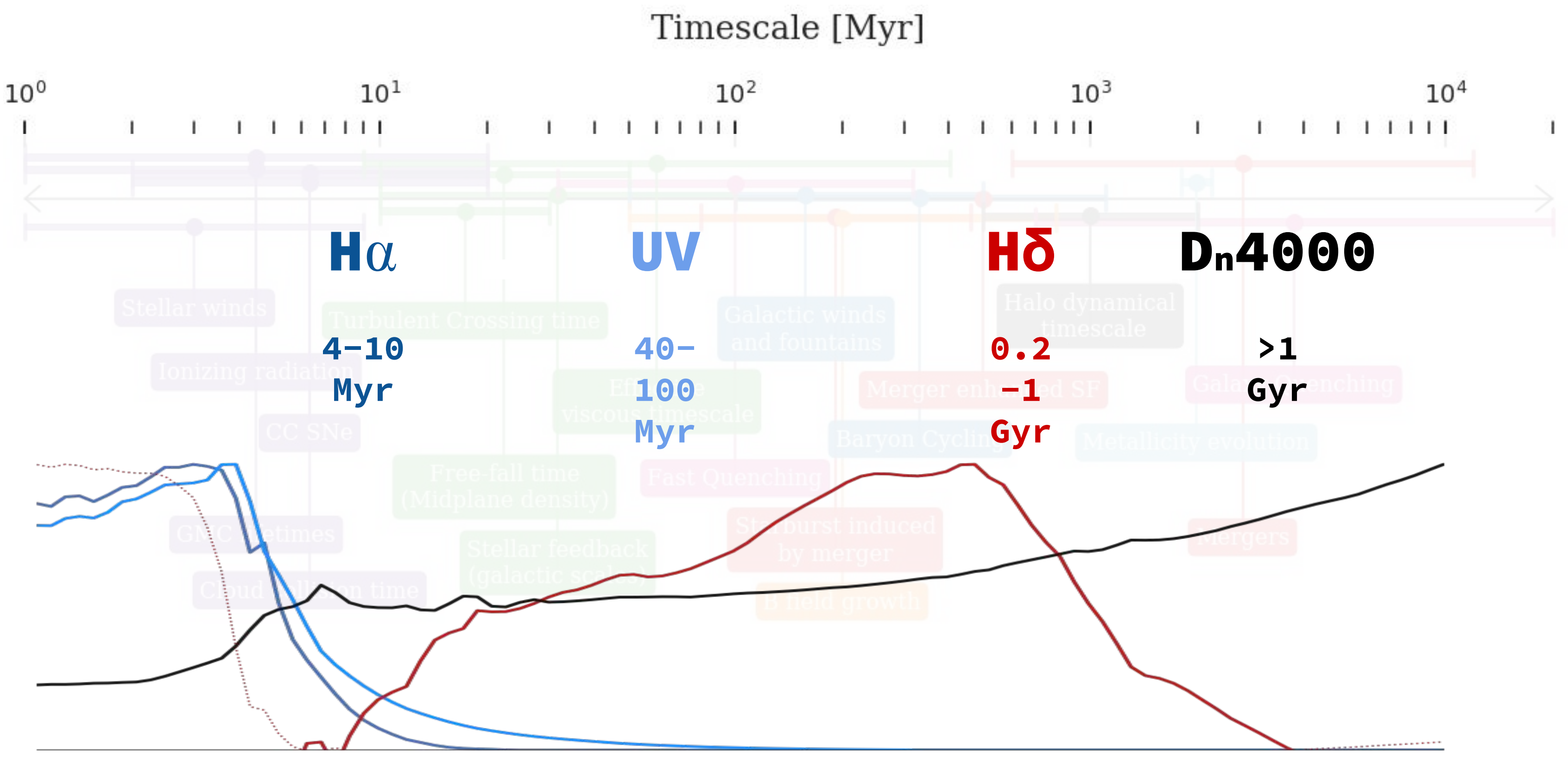


Figure: Iyer et al. 2020, arXiv:2007.07916

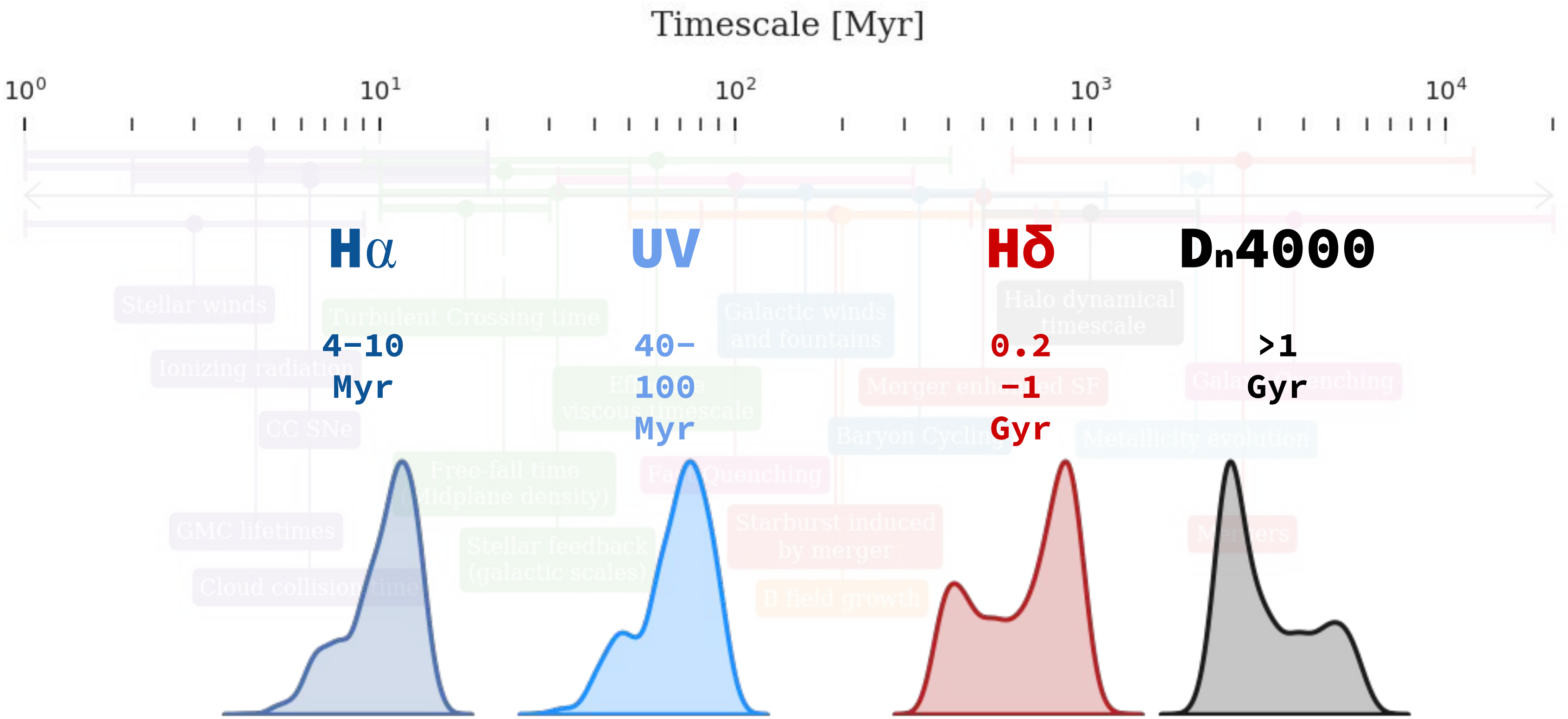
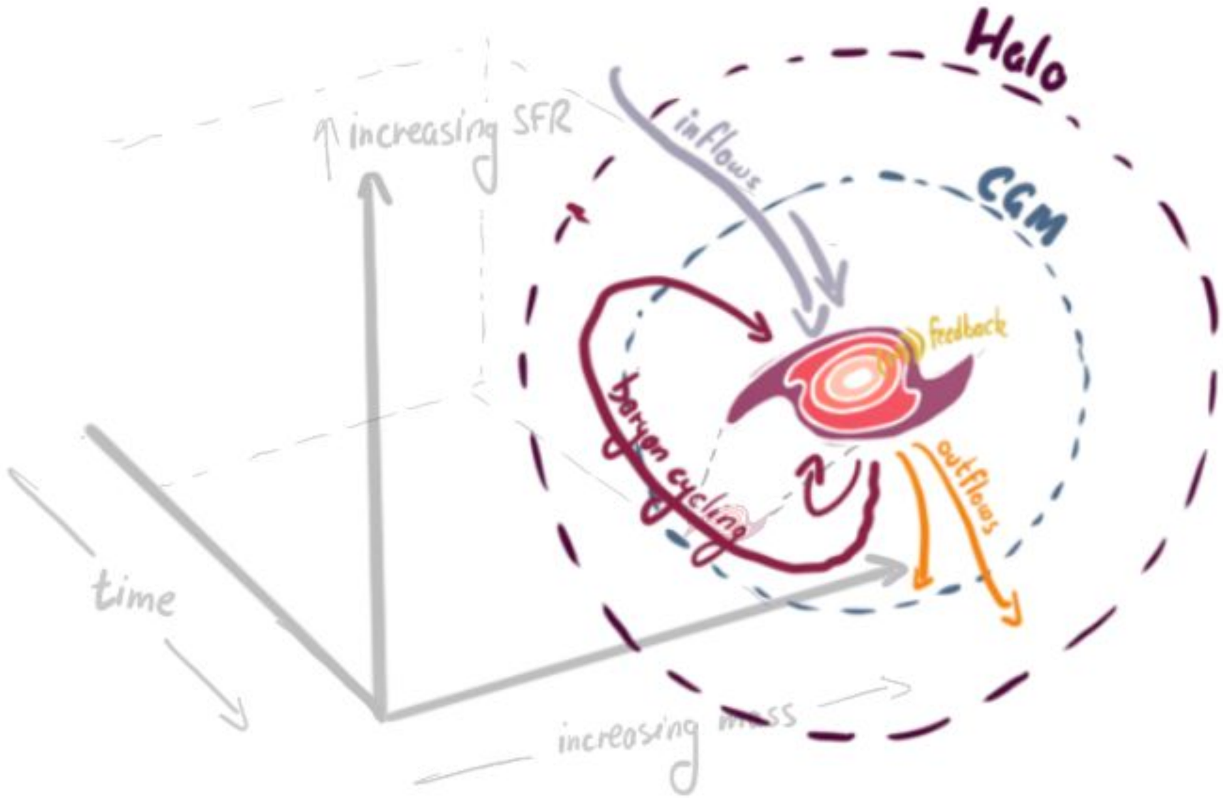
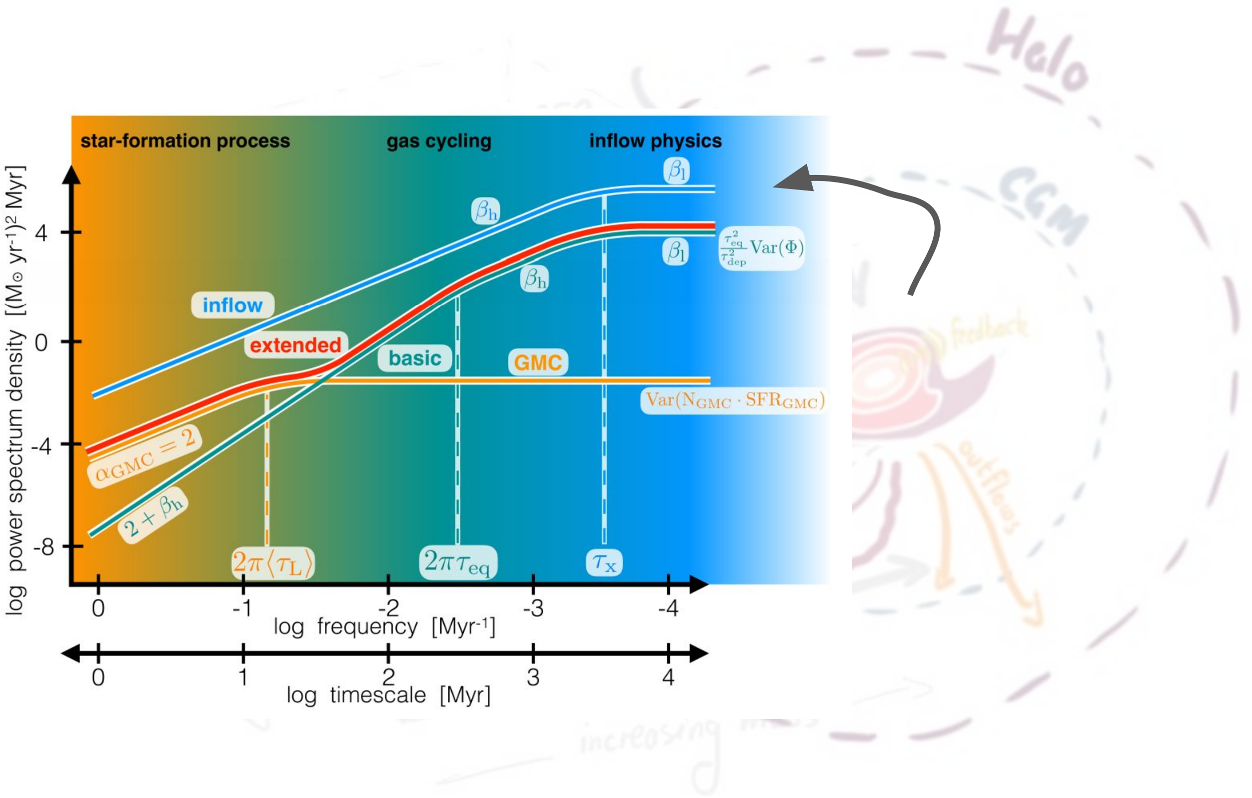


Figure: Iyer et al. 2020, arXiv:2007.07916



Halo
CGM
inflows
feedback
baryon cycling
outflows
increasing SFR
time
increasing mass

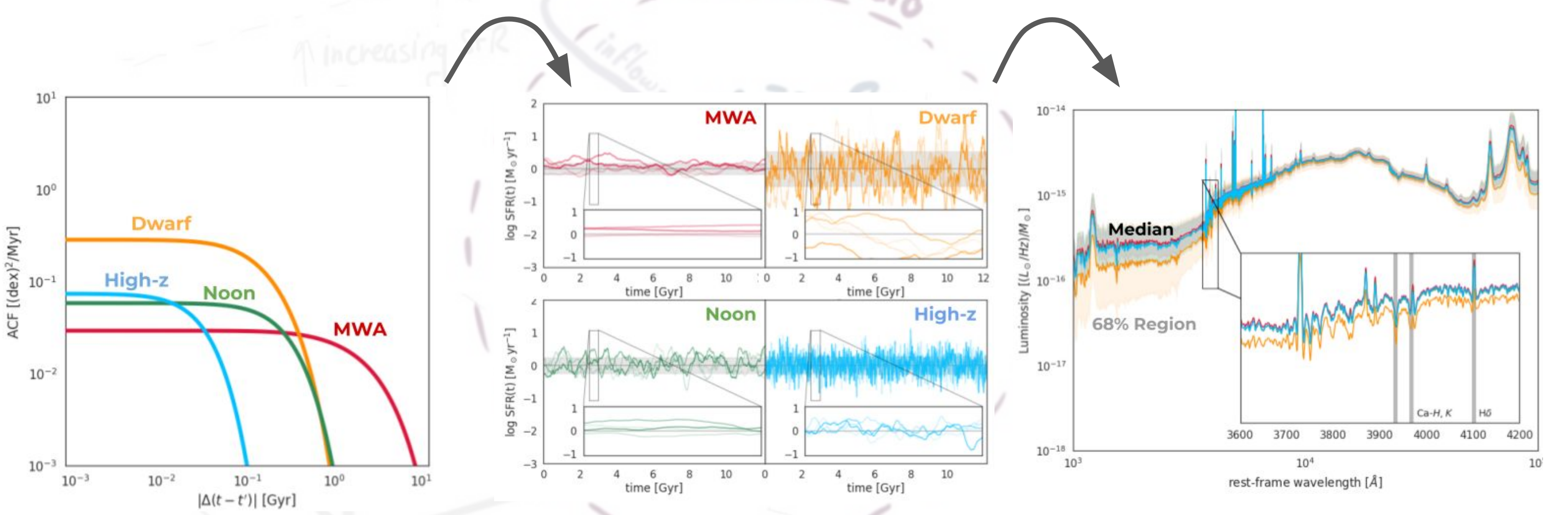


star-formation process
gas cycling
inflow physics
inflow
extended
basic
GMC
β_l
β_h
$\frac{\tau_{eq}^2}{\tau_{dep}^2}\mathrm{Var}(\Phi)$
$\mathrm{Var}(N_{GMC} \cdot SFR_{GMC})$
$\alpha_{GMC} = 2$
$2 + \beta_h$
$2\pi\langle\tau_L\rangle$
$2\pi\tau_{eq}$
τ_x
log power spectrum density [(M⊙ yr-1)2 Myr]
log frequency [Myr-1]
log timescale [Myr]
Halo
CGM
feedback
outflows

Stochastic Modelling of Star Formation Histories III. Constraints from Physically-Motivated Gaussian Processes

KG Iyer & JS Speagle, N Caplar, JC Forbes, E Gawiser, J Leja, S Tacchella (2023)

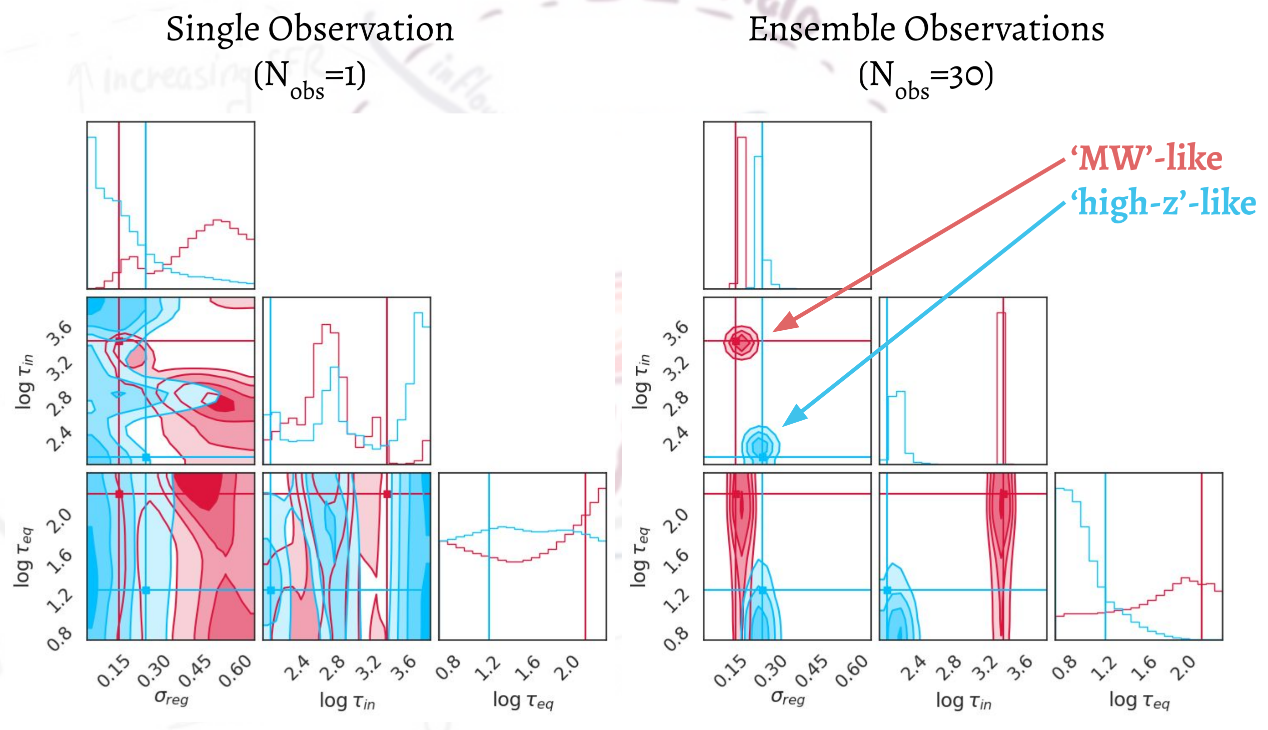
Accepted in ApJ, ArXiv: 2208.05938



Stochastic Modelling of Star Formation Histories III. Constraints from Physically-Motivated Gaussian Processes

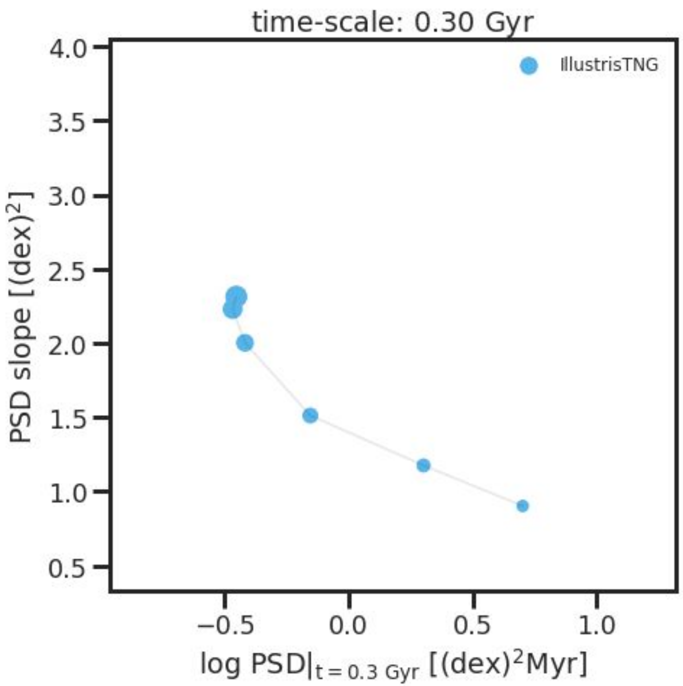
KG Iyer & JS Speagle, N Caplar, JC Forbes, E Gawiser, J Leja, S Tacchella (2023)

Accepted in ApJ, ArXiv: 2208.05938



The Diversity and Variability of Star Formation Histories in Models of Galaxy Evolution

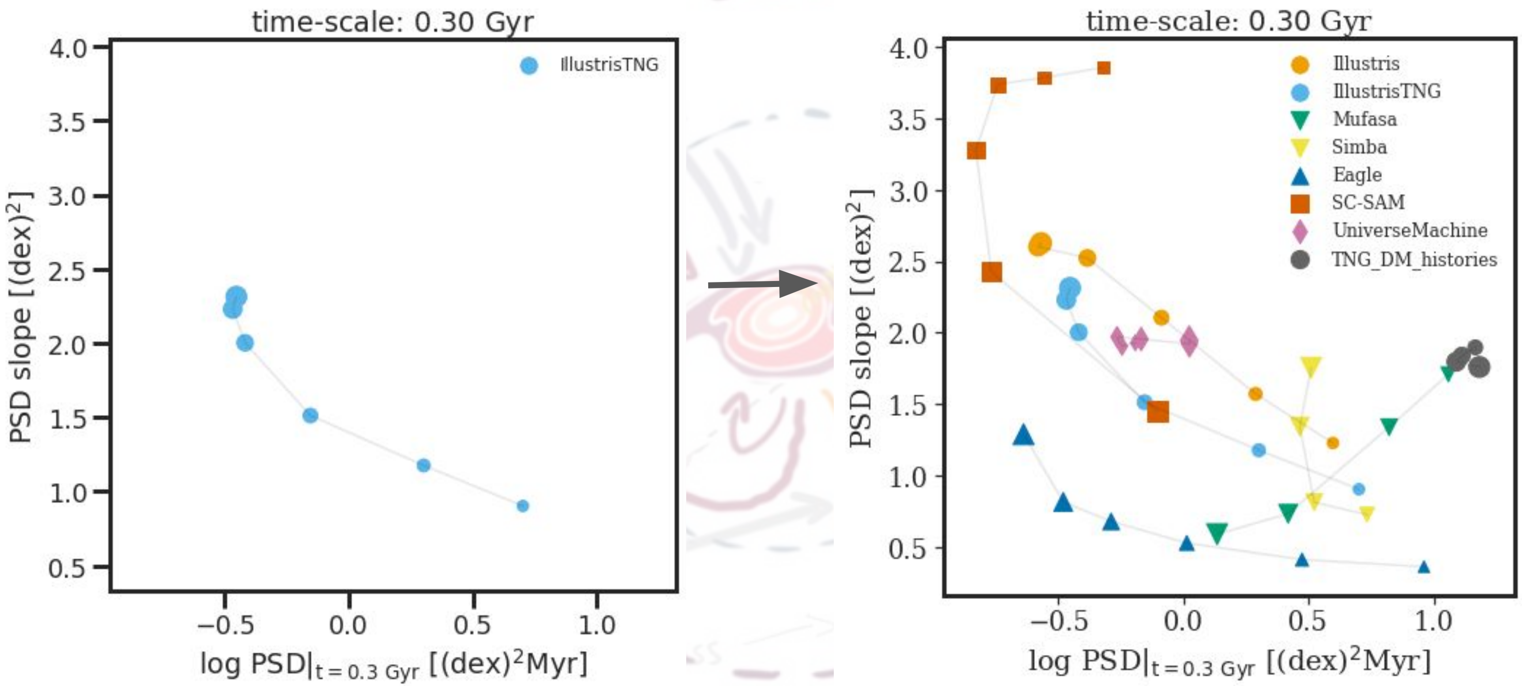
KG Iyer, S Tacchella, S Genel, CC Hayward, L Hernquist, AM Brooks, ... (2020)
Monthly Notices of the Royal Astronomical Society 498 (1), 430-463

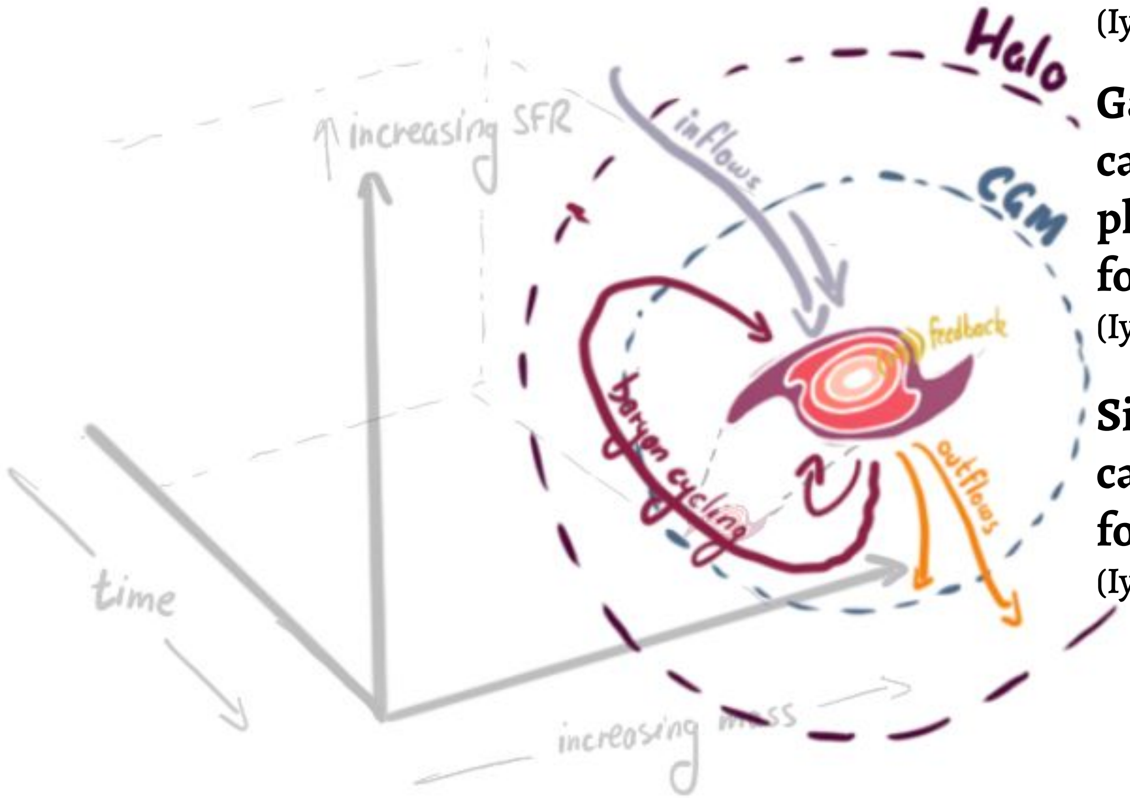


The Diversity and Variability of Star Formation Histories in Models of Galaxy Evolution

KG Iyer, S Tacchella, S Genel, CC Hayward, L Hernquist, AM Brooks, ... (2020)

Monthly Notices of the Royal Astronomical Society 498 (1), 430-463





SFHs in simulations depend sensitively on feedback & numerics
(Iyer et al. 2020)

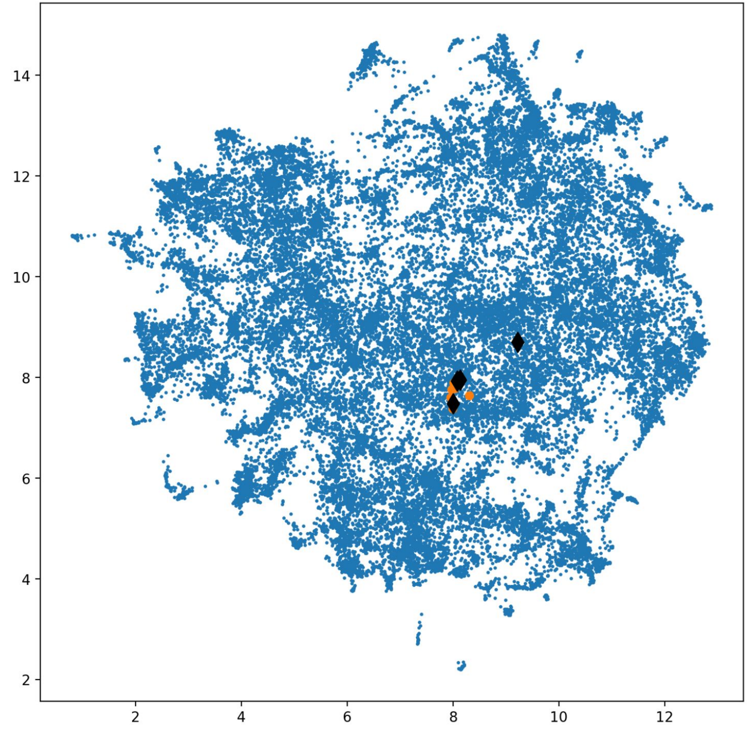
Gaussian processes (GPs) can be used to encode the physics of star formation and forward model observations
(Iyer & Speagle et al. 2023)

Simulations varying feedback can quantify their effects on star formation in galaxies
(Iyer, Starkenburg et al. in prep.)

The wilds beyond the firstlight

The wilds beyond the firstlight

[Includes astro-ph.GA papers up to 27-Jun-2023]



universeTBD

The wilds beyond the firstlight

User query: What is the sersic index of a disk galaxy?

context-based answer from sources:

```
The Sersic index of a disk galaxy can range from 0.7 to 1.1, depending on the S/N ratio and other factors.
```

Primary sources:

1. **CEERS: MIRI deciphers the spatial distribution of dust-obscured star formation in galaxies at $0.1 < z < 2.5$
   ArXiv: 2305.19331
   Authors: Benjamin Magnelli, Carlos Gómez-Guijarro, David Elbaz, Emanuele Daddi, et al.
   Summary: Rest-MIR S'ersic indices are only measured for the brightest MIRI sources ($S/N > 75$; 38 galaxies). The median rest-optical to rest-MIR size ratio of MS galaxies increases with stellar mass, from 1.1 at $10^{9.8} M_odot$ to 1.6 at $10^{11} M_odot$.

2. **Luminosity Profiles of Prominent Stellar Halos
   ArXiv: 1807.04922
   Authors: Hong Bae Ann, Hyeong Wook Park
   absts/Ann18_1807.04922.txt,

3. **The structural and size evolution of star-forming galaxies over the last 11 Gyrs
   ArXiv: 1611.05039
   Authors: Ana Paulino-Afonso, David Sobral, Fernando Buitrago, Jose Afonso

universeTBD

The wilds beyond the firstlight

User query: What is the sersic index of a disk galaxy?

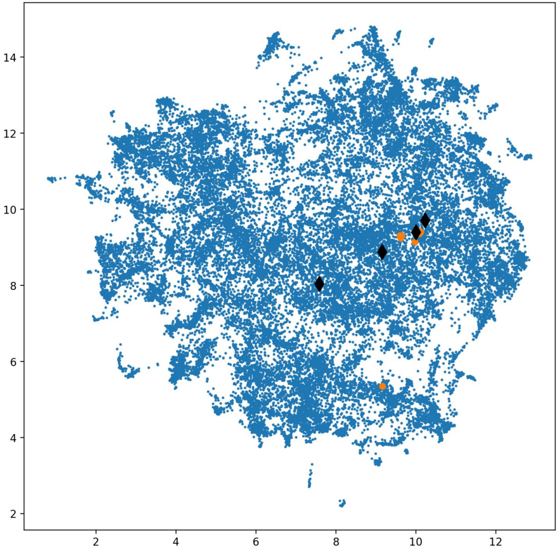
context-based answer from sources:

`The Sersic index of a disk galaxy can range from 0.7 to 1.1, depending on the S/N ratio and other fa`

`The Sersic index of a disk galaxy can range from 0.7 to 1.1, depending on the S/N ratio and other factors.`

P

1.
   $z < 2.5$
   ArXiv: 2305.19331
   Authors: Benjamin M
   Summary: Rest-MIR
   galaxies). The media
   from 1.1 at $10^{9.8} M_o$
2. **Luminosity Profile
   ArXiv: 1807.04922
   Authors: Hong Bae A
   absts/Ann18_1807.0
3. **The structural and
   ArXiv: 1611.05039
   Authors: Ana Paulinc



The wilds beyond the firstlight

User query: What are the biggest discoveries in galaxy evolution with JWST so far?

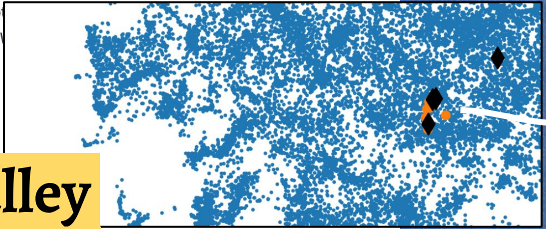
context-based answer from sources:

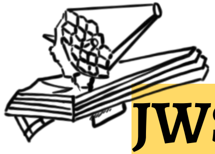
```
The biggest discoveries in galaxy evolution with JWST so far include the emergence of disk morphologies before z~2 and with candidates appearing as early as z~5, the confirmation of redshifts z > 10 for two galaxies, and the evidence for the rapid production of luminous galaxies in the very young Universe.
```

Primary sources:

1. **Identification and properties of intense star-forming galaxies at redshifts z>10
   ArXiv: 2212.04480
   Authors: B. E. Robertson, S. Tacchella, B. D. Johnson, K. Hainline, et al.
   Summary: These galaxies include the first redshift z>12 systems discovered with distances spectroscopically confirmed by JWST in a companion paper.

2. **Morpheus Reveals Distant Disk Galaxy Morphologies with JWST: The First AI/ML Analysis of JWST Images
   ArXiv: 2208.11456
   Authors: Brant E. Robertson, Sandro Tacchella, Benjamin D. Johnson, Ryan Hausen, et al.
   Summary: By cross-referencing with existing phot
   Telescope (HST) CANDELS survey, we show that J





JWST valley
(and the depths beyond)

The wilds beyond the firstlight

Try it out yourself!

- https://huggingface.co/spaces/kiyer/arxiv-gpt
- https://huggingface.co/universeTBD/astrollama
- Nguyen et al. (2023) arXiv: 2309.06126
- Ciucă et al. (2023) arXiv: 2306.11648

Thank you!

NHFP
COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK
FLATIRON INSTITUTE Center for Computational Astrophysics

- **The overall shapes of galaxy SFHs** contain information about the processes that regulate star formation
- **CAMELS + SBI** can quantify the relations between SFHs as a function of the strength of SNe and AGN feedback
- **Propagating this to observational space,** we can use distributions of SFHs from local + HST/JWST observations to constrain feedback for diff. Galaxy populations across a range of epochs coming soon!
- **UniverseTBD**: working on better literature comprehension, hypothesis generation, tools to keep up with ever increasing arxiv. .)

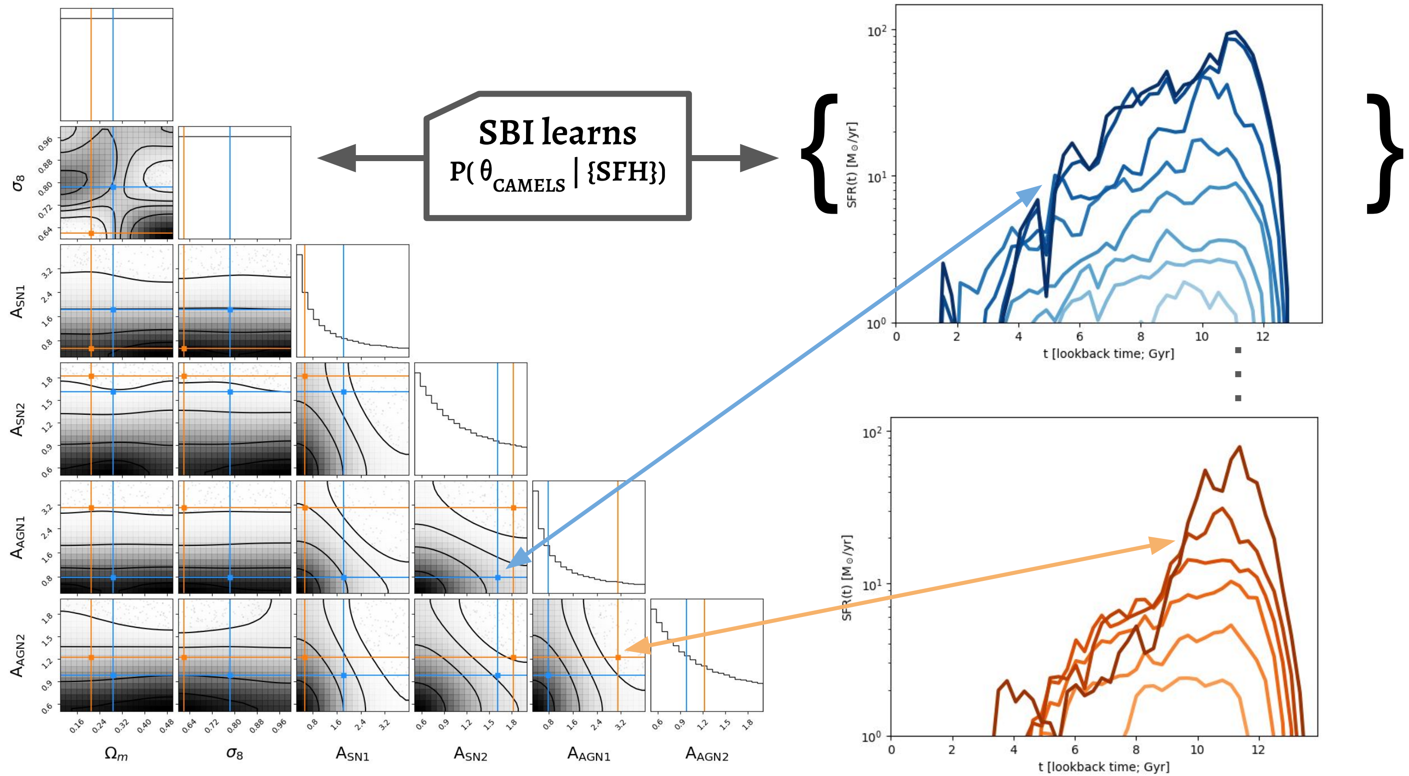
kgi2103@columbia.edu
github.com/kartheikiyer

CANDELS Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey
CEERS Cosmic Evolution Early Release Science Survey
CANUCS
CAMELS
dense basis
arxiv-gpt
pan-survey SEDforum
universeTBD

The Observable Effects of Feedback and Cosmology on Galaxy SFHs in the CAMELS Simulations

KG Iyer, TK Starkenburg, JF Wu, S Cooray, G. Bryan, RS Somerville et al. (2023)

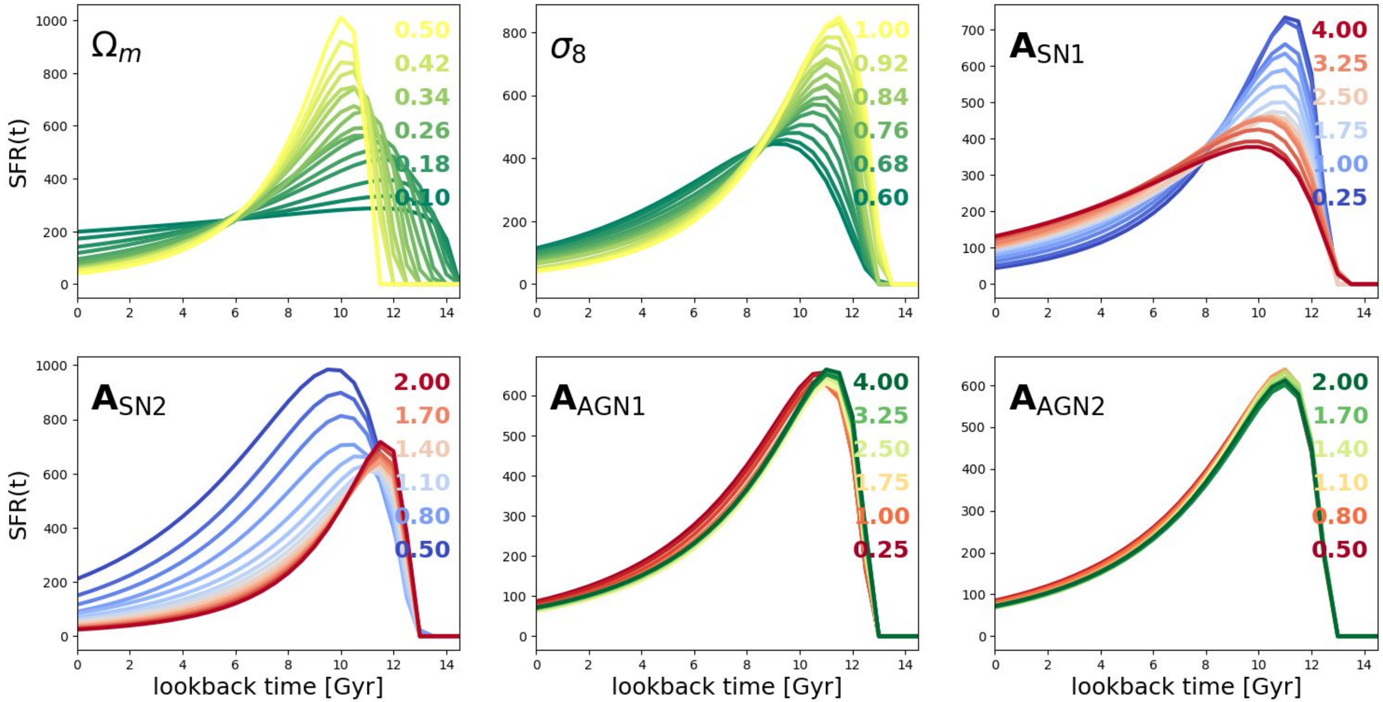
In prep. -> please don't share!



The Observable Effects of Feedback and Cosmology on Galaxy SFHs in the CAMELS Simulations

KG Iyer, TK Starkenburg, JF Wu, S Cooray, G Bryan, RS Somerville et al. (2023)

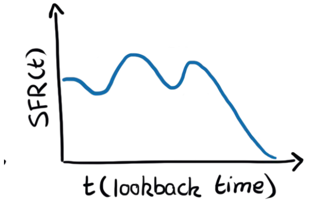
In prep. -> please don't share!



Nonparametric Star Formation History Reconstruction with Gaussian Processes. I. Counting Major Episodes of Star Formation

Iyer & Gawiser (2017); Iyer et al. (2019)

The Astrophysical Journal 838 (2), 127 & 879 (2), 116



dense-basis.readthedocs.io

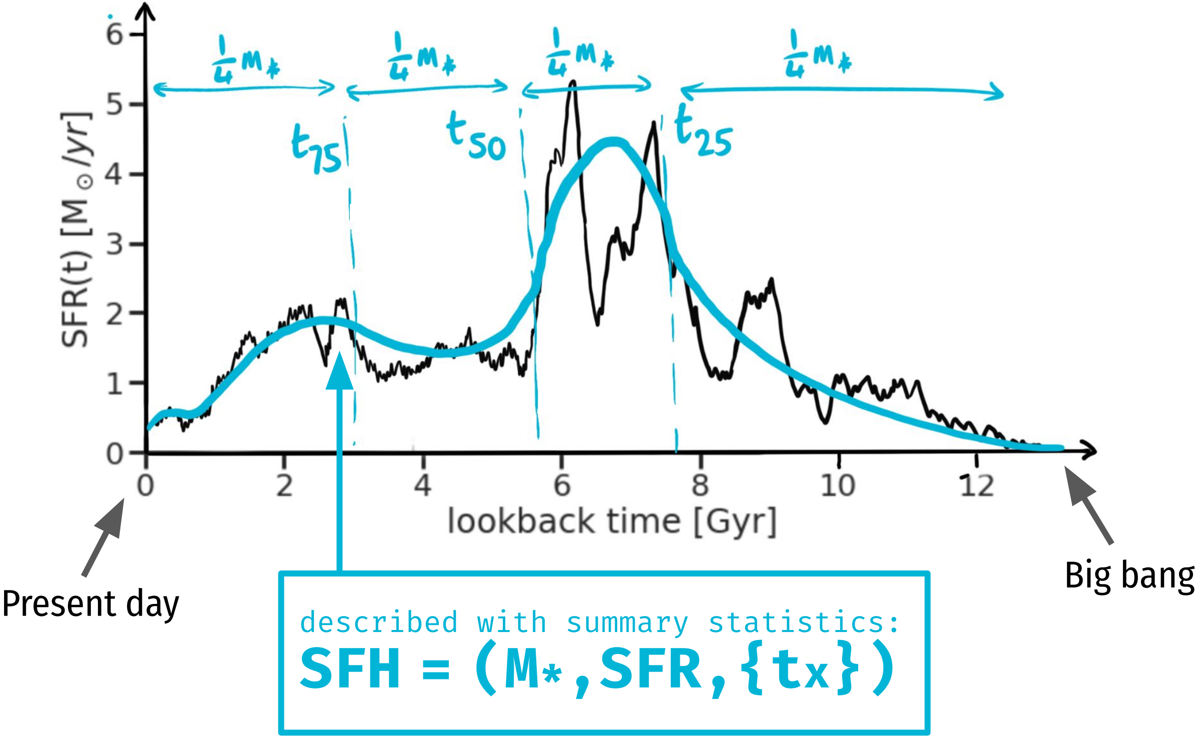
Flexible, non-parametric SFHs can be constructed using **GPs*** and an N-tuple such that

---

SFH≡SFR(t)⟷(**M_*, SFR, {tX}**)

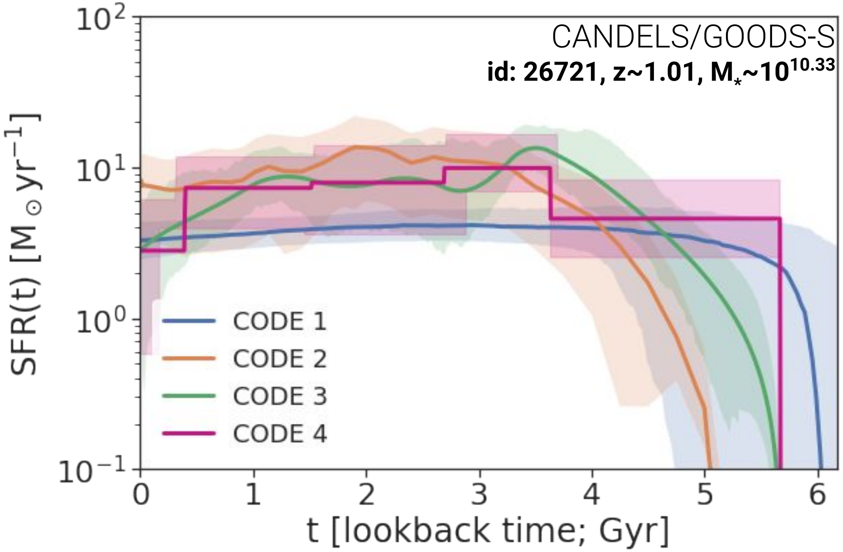
where {tX} ≡ t25, t50, t75...etc. are lookback times at which a galaxy formed X% of its total mass

---

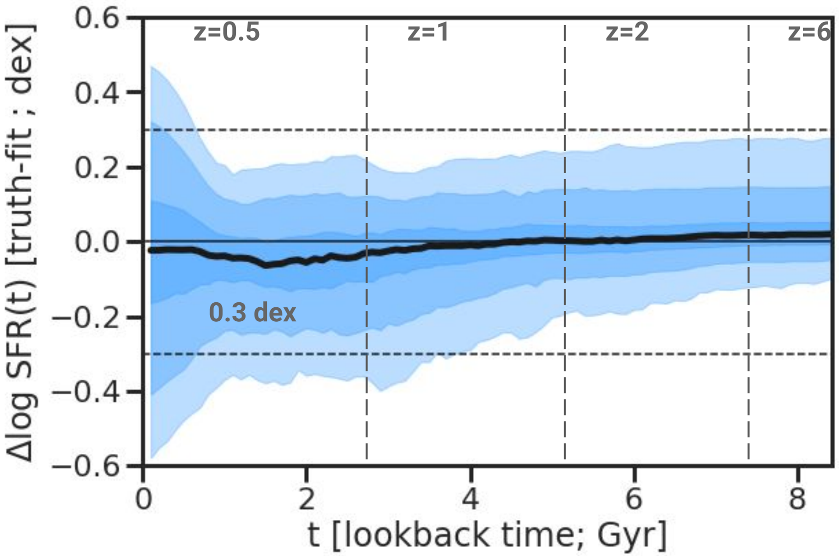


inferring SFHs from data: validation #1

(a) SFH Reconstruction of a Single Galaxy



(b) SFH Accuracy Tests Using Simulated Data



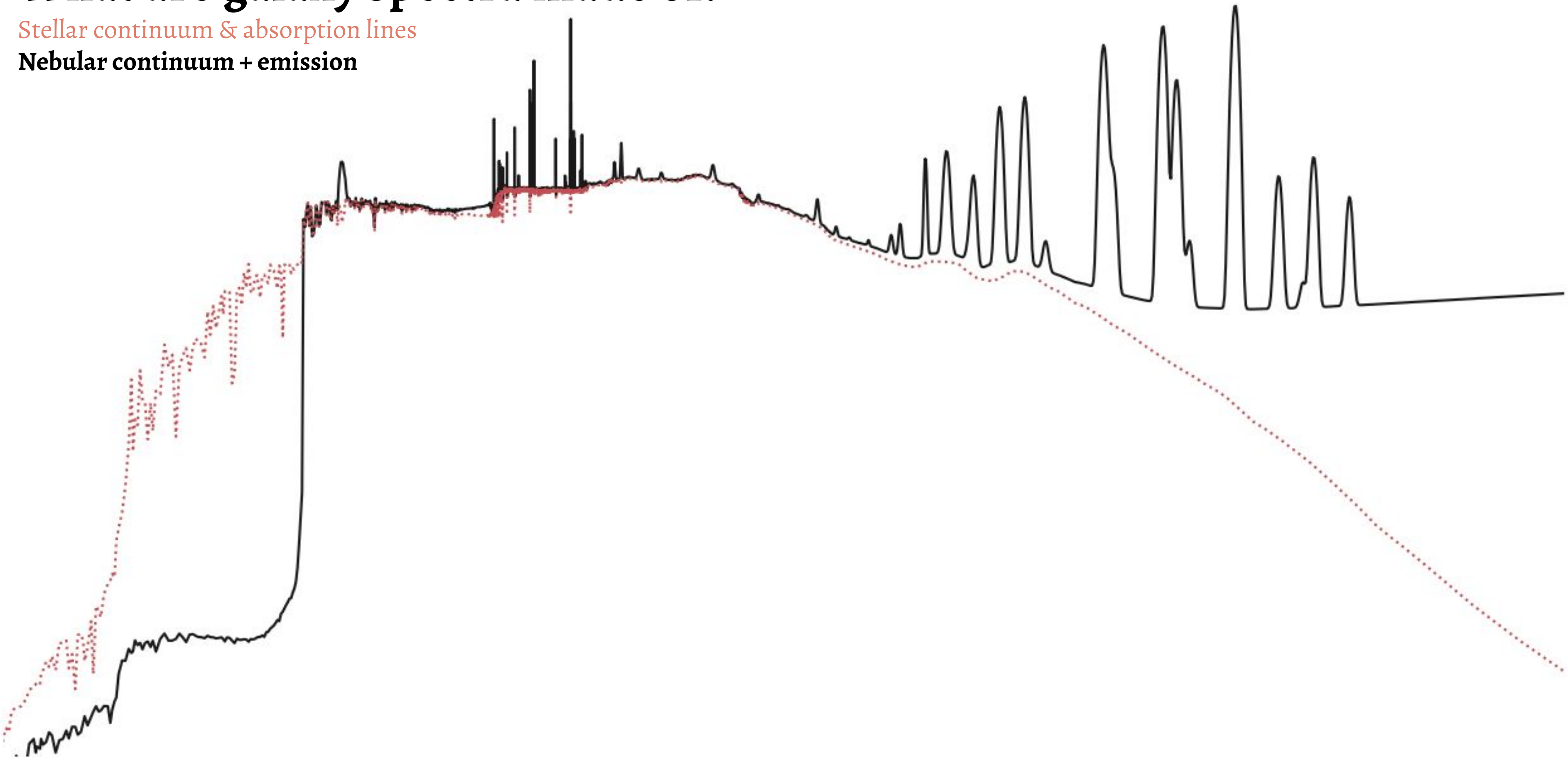
$$\mathbf{SFH(t)} = GP\left(\mu(t; M_\star, SFR, \{t_X\}),\ \Sigma(t, t'; \sigma_{cov}, \tau_{cov}) \right)$$

The what:

What are galaxy spectra made of?

Stellar continuum & absorption lines

Nebular continuum + emission



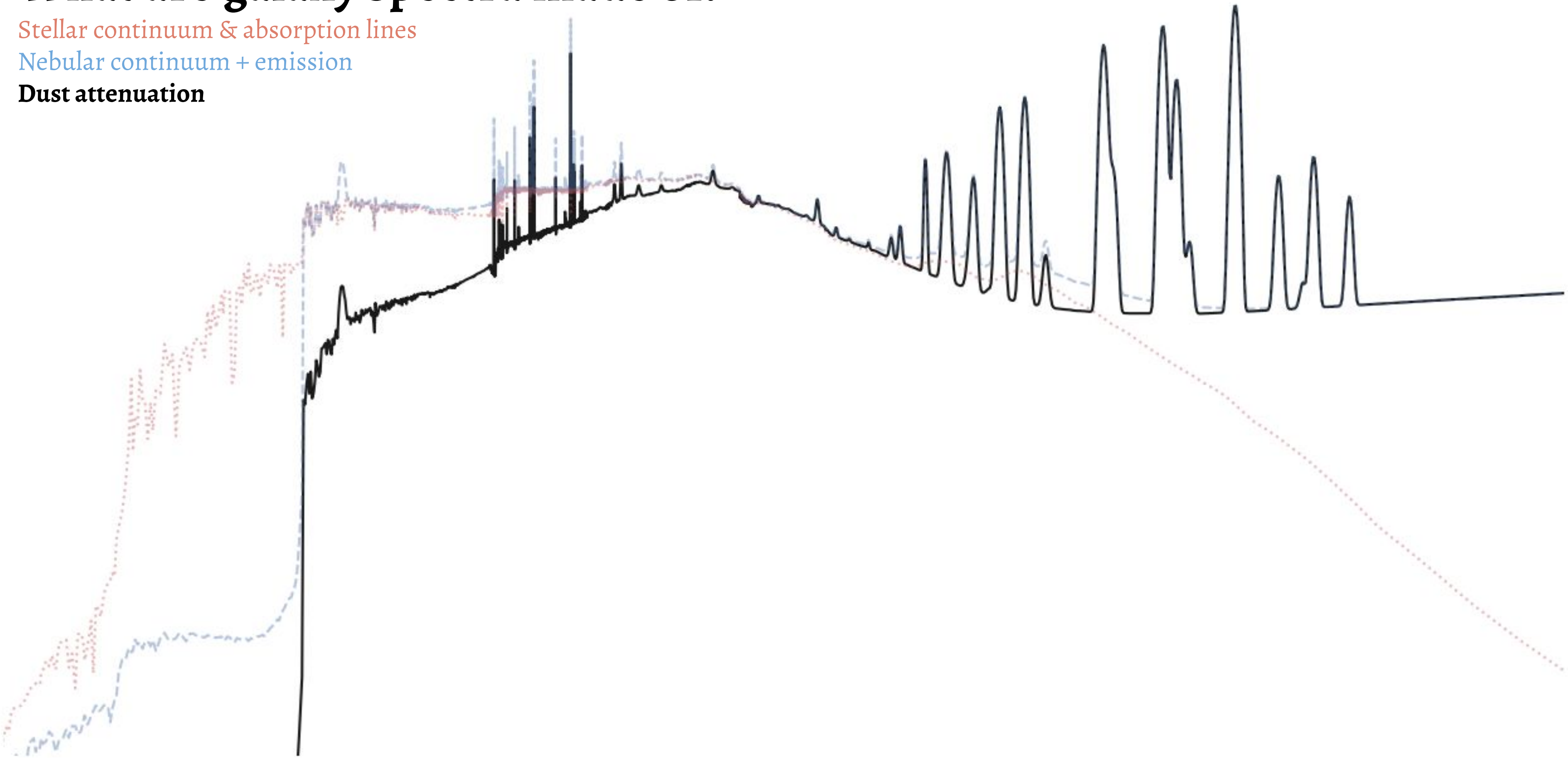
The what:

What are galaxy spectra made of?

Stellar continuum & absorption lines

Nebular continuum + emission

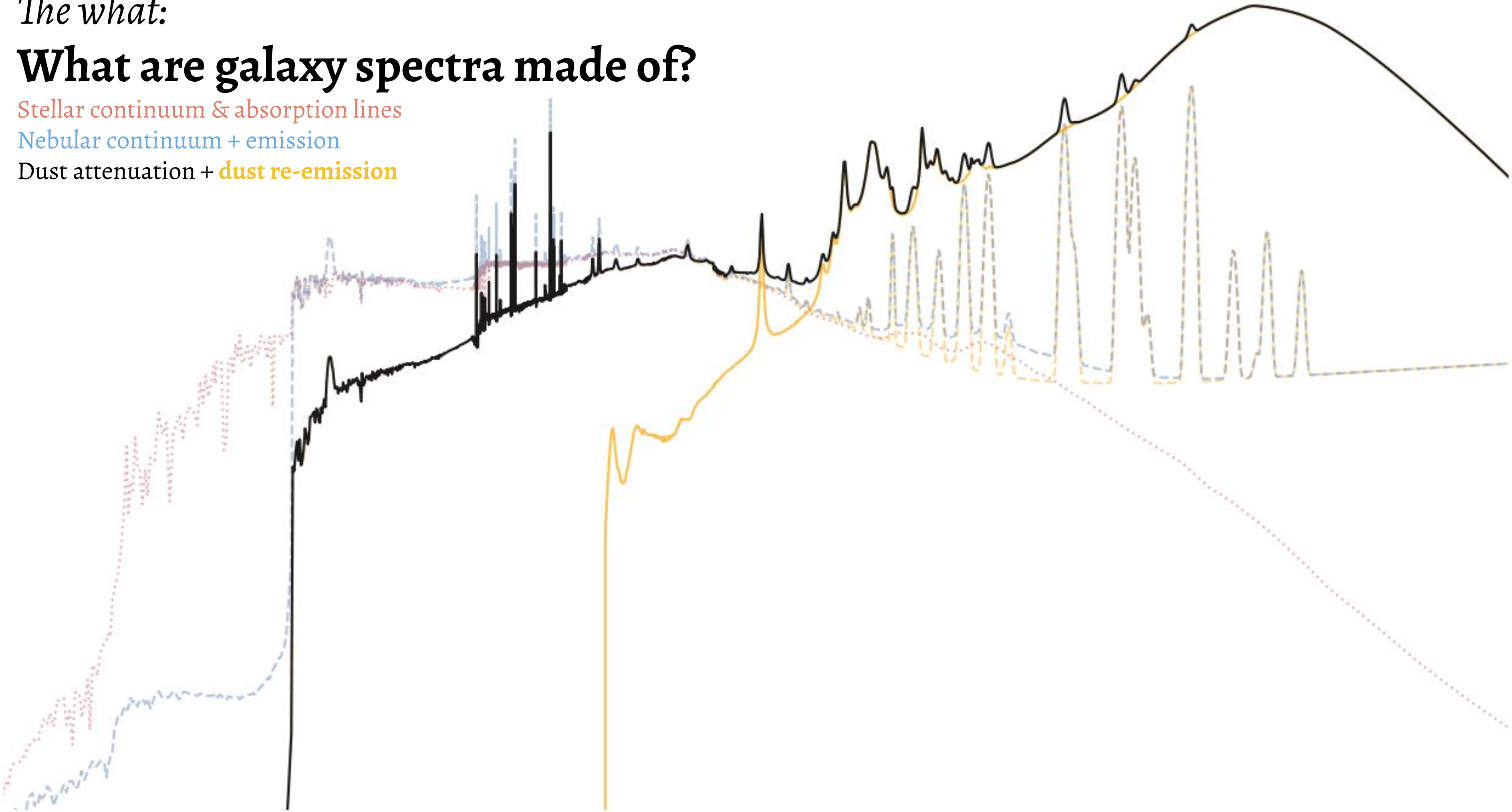
Dust attenuation



The what:

What are galaxy spectra made of?

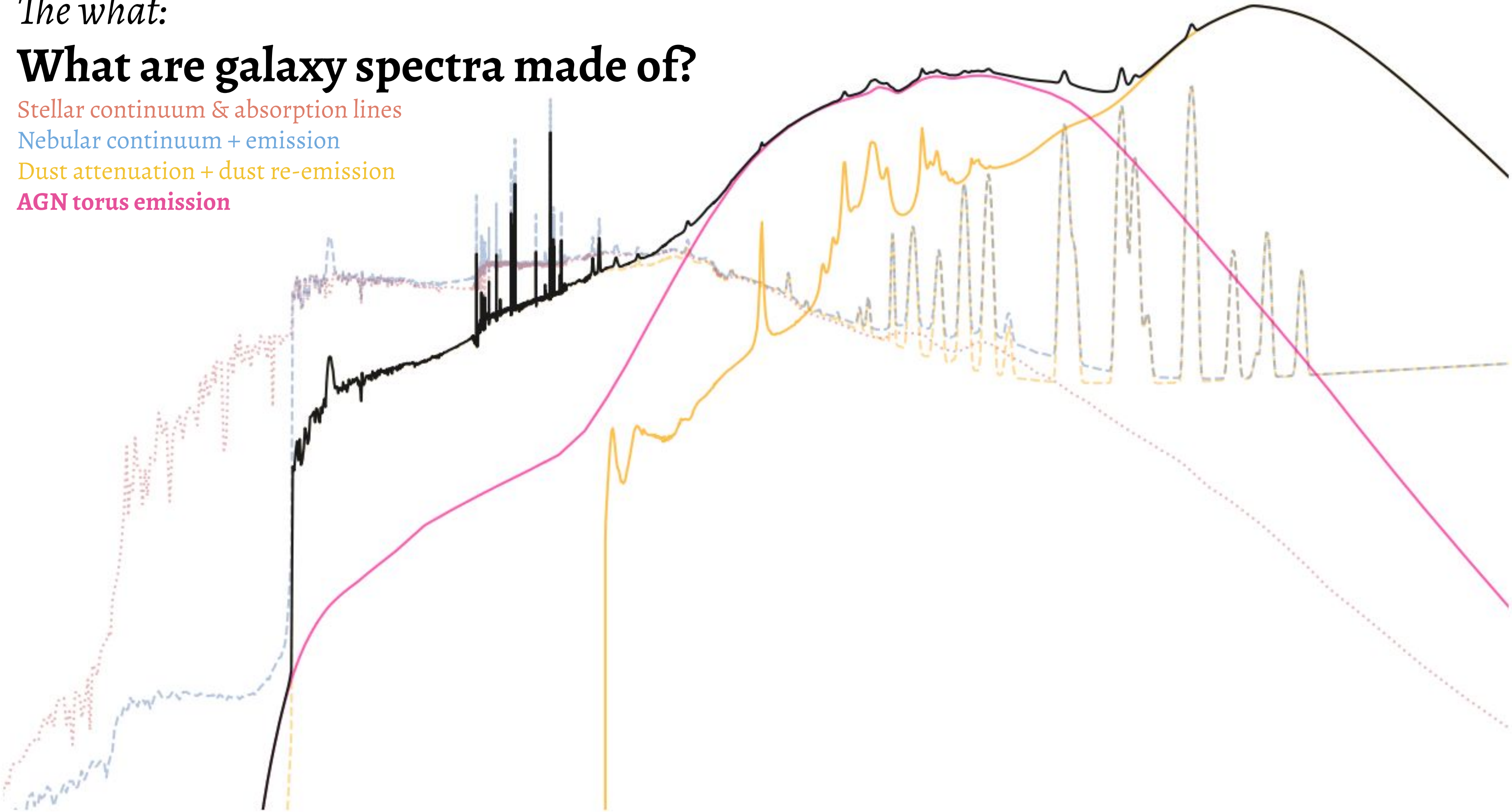
Stellar continuum & absorption lines
Nebular continuum + emission
Dust attenuation + **dust re-emission**



The what:

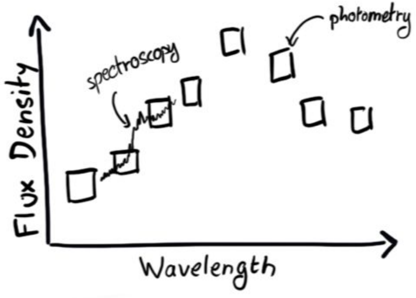
What are galaxy spectra made of?

Stellar continuum & absorption lines
Nebular continuum + emission
Dust attenuation + dust re-emission
AGN torus emission



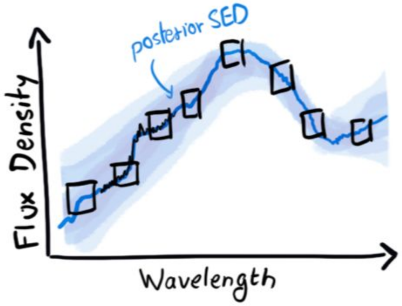
The how:

Inferring galaxy SFHs from observations



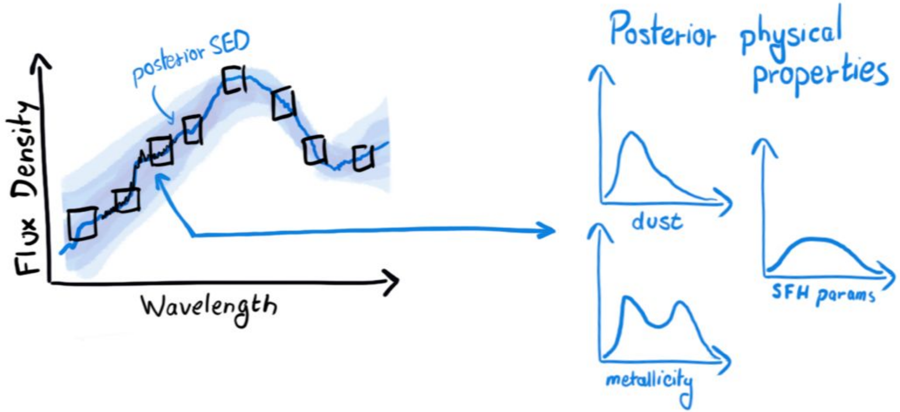
The how:

Inferring galaxy SFHs from observations



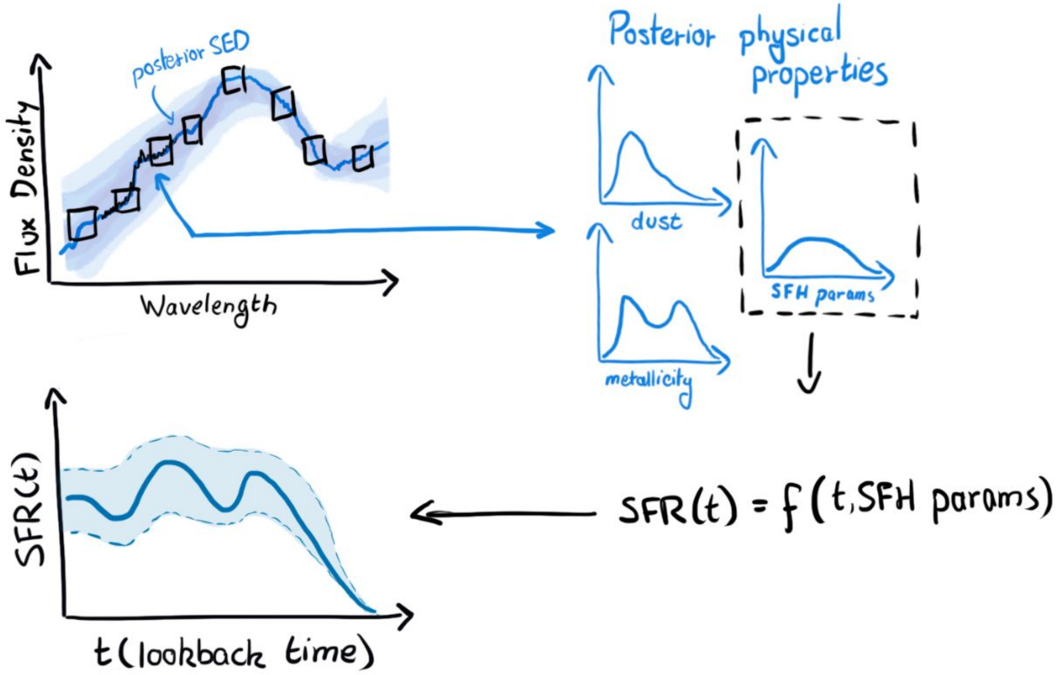
The how:

Inferring galaxy SFHs from observations



The how:

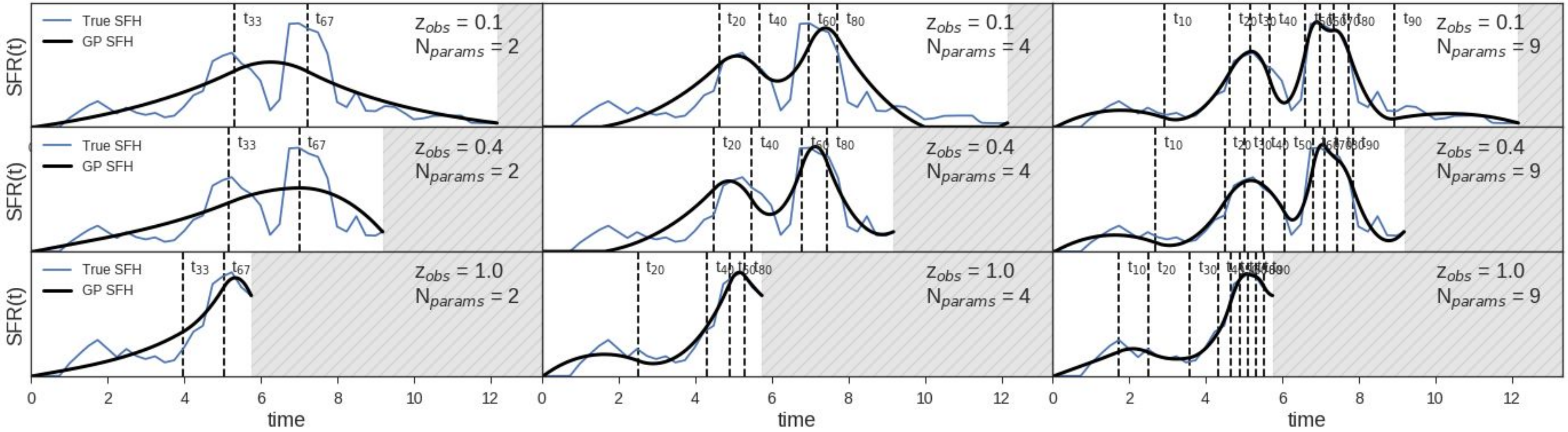
Inferring galaxy SFHs from observations



Nonparametric Star Formation History Reconstruction with Gaussian Processes. I. Counting Major Episodes of Star Formation

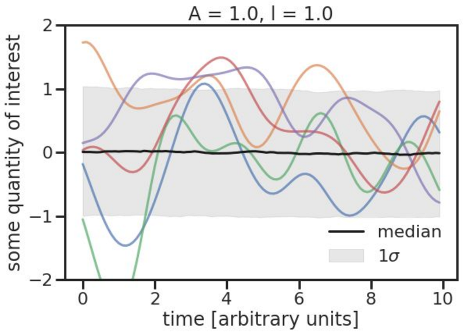
KG Iyer, E Gawiser, SM Faber, HC Ferguson, J Kartaltepe, … (2019)

The Astrophysical Journal 879 (2), 116

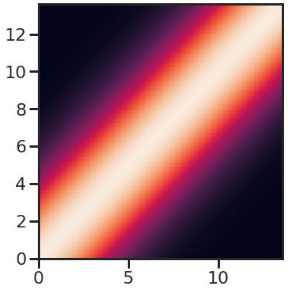


SFH(t) = *GP* (mean , covariance)

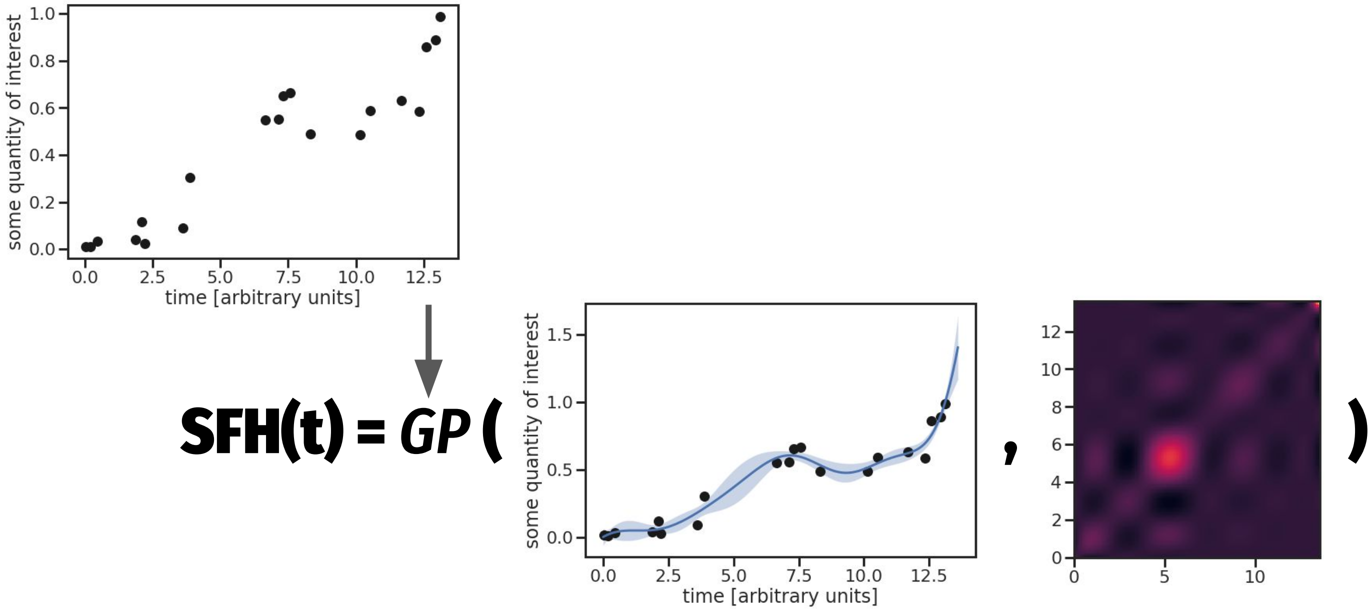
$\mathbf{SFH(t)} = GP\,($



,



$)$



some quantity of interest
1.0
0.8
0.6
0.4
0.2
0.0
0.0
2.5
5.0
7.5
10.0
12.5
time [arbitrary units]
SFH(t) = GP(,)
some quantity of interest
1.5
1.0
0.5
0.0
0.0
2.5
5.0
7.5
10.0
12.5
time [arbitrary units]
12
10
8
6
4
2
0
0
5
10

$$\mathrm{SFH}(t) = GP(\mu, \Sigma)$$

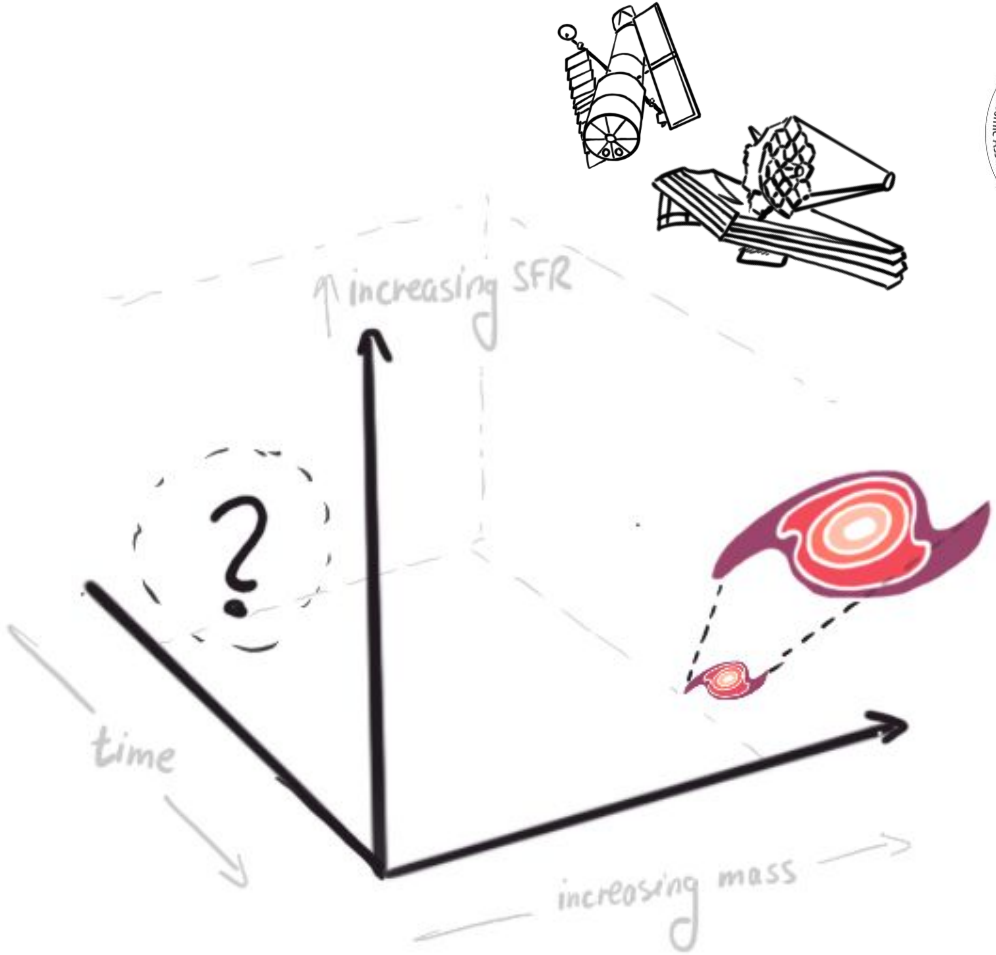


Figure from Mowla & Iyer et al. 2022

CANDELS — Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey

Cosmic Evolution Early Release Science Survey — CEERS

CANUCS

Are we seeing distant globular clusters with JWST?

(with Mowla & Iyer et al. 20223, with CANUCS)