How to use THESEUS' high-redshift GRB data to constrain the physics of

Pop-II and Pop-III progenitors

Dorottya Szécsi

Humboldt Fellow

University of Cologne, Germany

Assistant professor at Nicolaus Copernicus University, Poland

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Virtual, 24th March 2021

UNIWERSYTET MIKOŁAJA KOPERNIKA W TORUNIU

Alexander von Humboldt Stiftung/Foundation

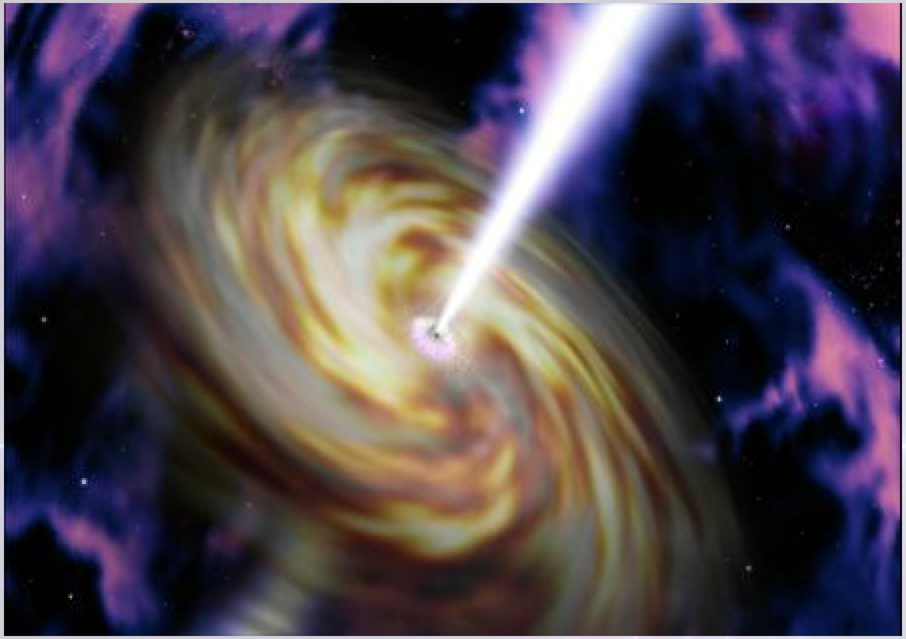
Collapsar scenario

Woosley'93, Macfadyen+99, Yoon+05, Woosley+06

Magnetar scenario

MacFadyen+01, Metzger+11, Rowlinson+13, Greiner+15

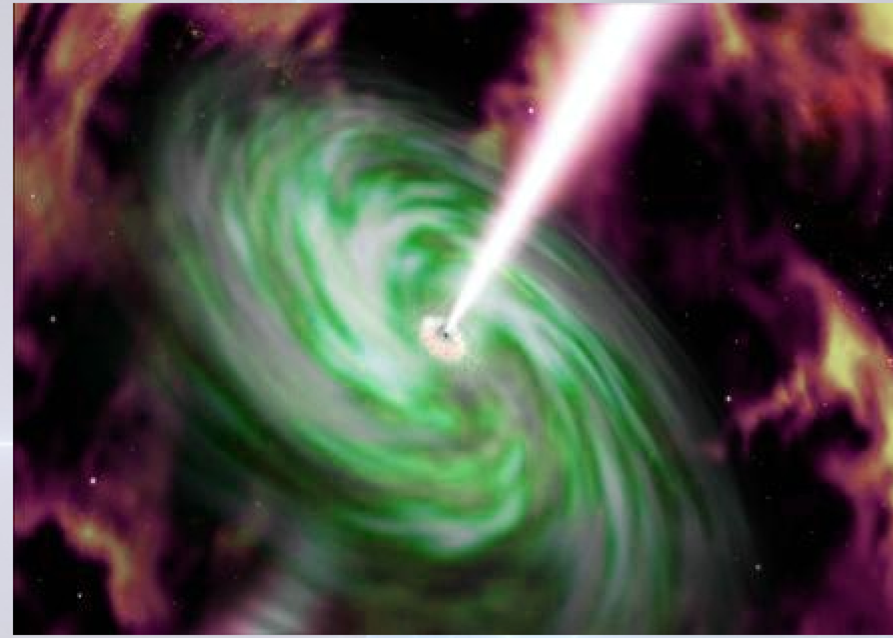
Collapsar scenario



- iron core → collapse
- supernova is weak ('failed')
  i.e. compactness parameter **ξ** is large
- material falls in → BH
- fast rotation → accretion disc
  → jet → LGRB

Woosley'93, Macfadyen+99, Yoon+05, Woosley+06

Magnetar scenario



- iron core → collapse
- supernova is successful
  i.e. compactness parameter **ξ** is small
- material expelled → NS
- fast rotating, magnetized NS
  powers the jet → LGRB

MacFadyen+01, Metzger+11, Rowlinson+13, Greiner+15

Question:

What kind of star would die this way?

…task for stellar physicists!

Question:

What kind of star would die this way?

…task for stellar physicists!

- no large envelope
  – jet should be able to penetrate through!
- fast rotation at the moment of collapse
- iron core… massive star

classical Wolf–Rayet stars?

… spin down due to strong mass loss

NO.

Chemically Homogeneous Evolution

(low metallicity)

Back in 2005/2006...

A&A 443, 643–648 (2005)
DOI: 10.1051/0004-6361:20054030

Astronomy & Astrophysics

Yoon & Langer (2005)

Evolution of rapidly rotating metal-poor massive stars towards gamma-ray bursts

S.-C. Yoon[1] and N. Langer[2]

[1] Astronomical Institute "Anton Pannekoek", University of Amsterdam, Kruislaan 403, 1098 SJ, Amsterdam, The Netherlands
e-mail: scyoon@science.uva.nl
[2] Astronomical Institute, Utrecht University, Princetonplein 5, 3584 CC, Utrecht, The Netherlands
e-mail: n.langer@astro.uu.nl

The Astrophysical Journal, 637:914–921, 2006 February 1

Woosley & Heger (2006)

THE PROGENITOR STARS OF GAMMA-RAY BURSTS

S. E. Woosley[1] and A. Heger[1,2]
Received 2005 August 6; accepted 2005 October 3

ABSTRACT

Those massive stars that give rise to gamma-ray bursts (GRBs) during their deaths must be endowed with an unusually large amount of angular momentum in their inner regions, 1–2 orders of magnitude greater than the ones that make common pulsars. Yet the inclusion of mass loss and angular momentum transport by magnetic torques during the precollapse evolution is known to sap the core of the necessary rotation. Here we explore the evolution of very rapidly rotating massive stars, including stripped-down helium cores that might result from mergers or mass transfer in a binary, and single stars that rotate unusually rapidly on the main sequence. For the highest possible rotation rates

Back in 2005/2006...

A&A 443, 643–648 (2005)
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Astronomy & Astrophysics

Yoon & Langer (2005)

Evolut... ...wards

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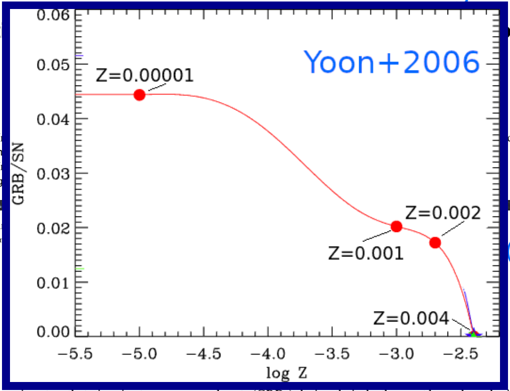
e-mail: scyoon...
[2] Astronomical I...
e-mail: n.lang...

The Astrophysical Jour...

...(2006)



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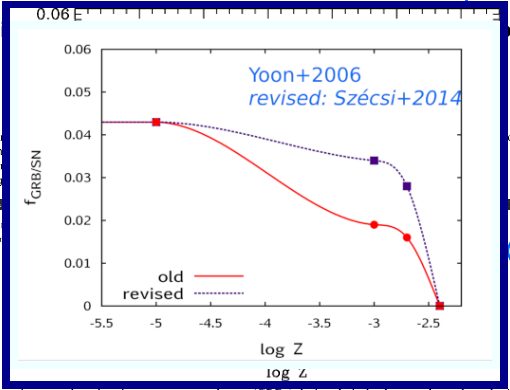

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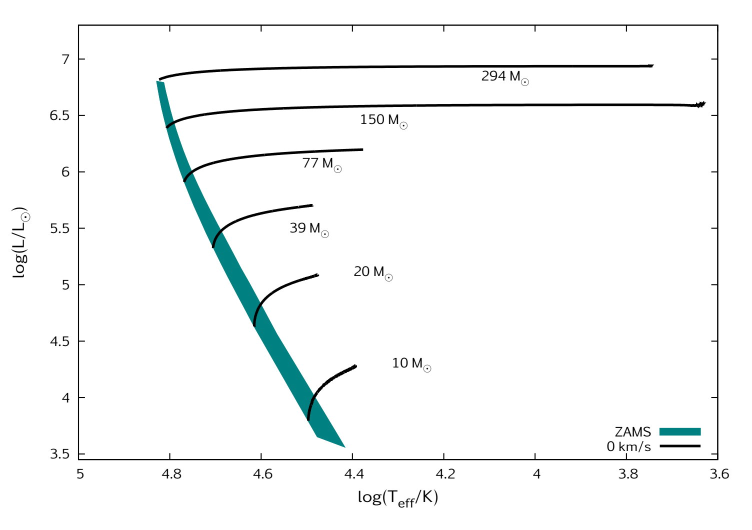
Low Metallicity Massive Stars

Szécsi et al. 2015 (Astronomy & Astrophysics, v.581, A15)



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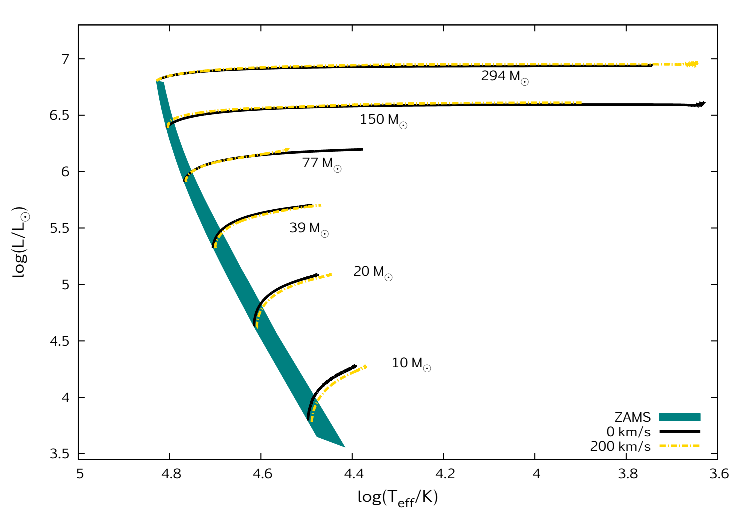

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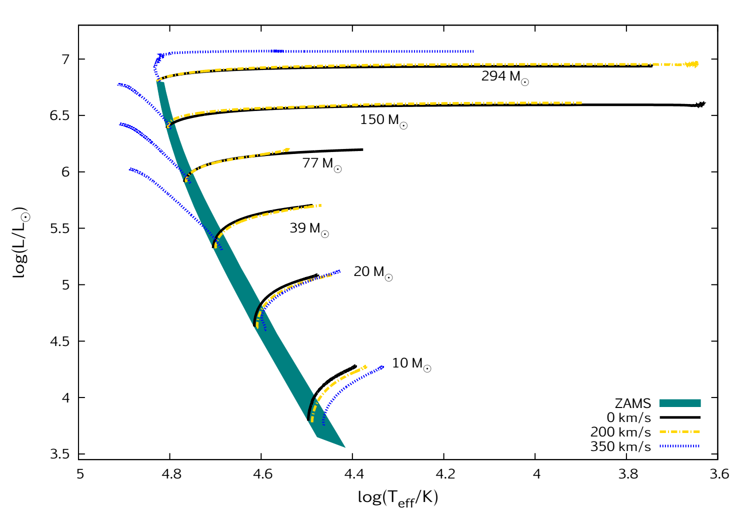

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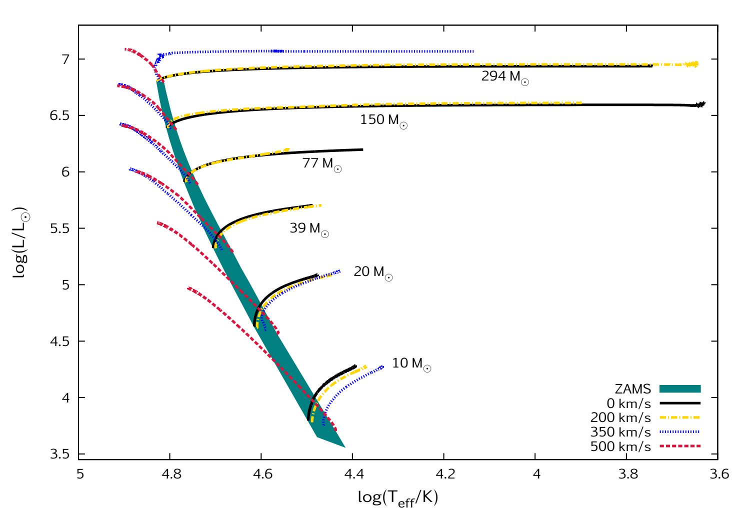

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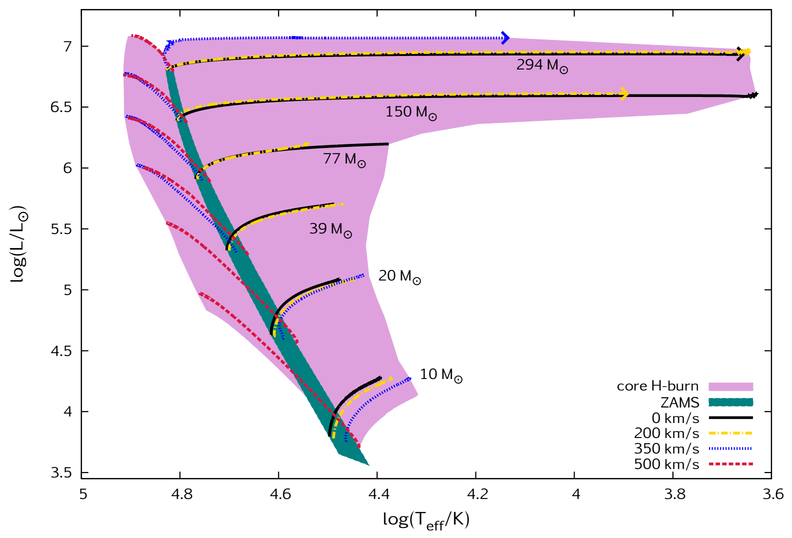

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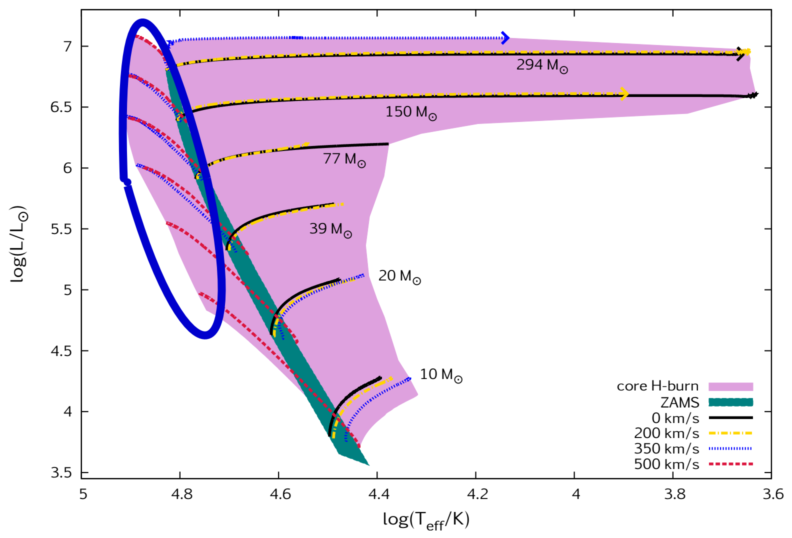

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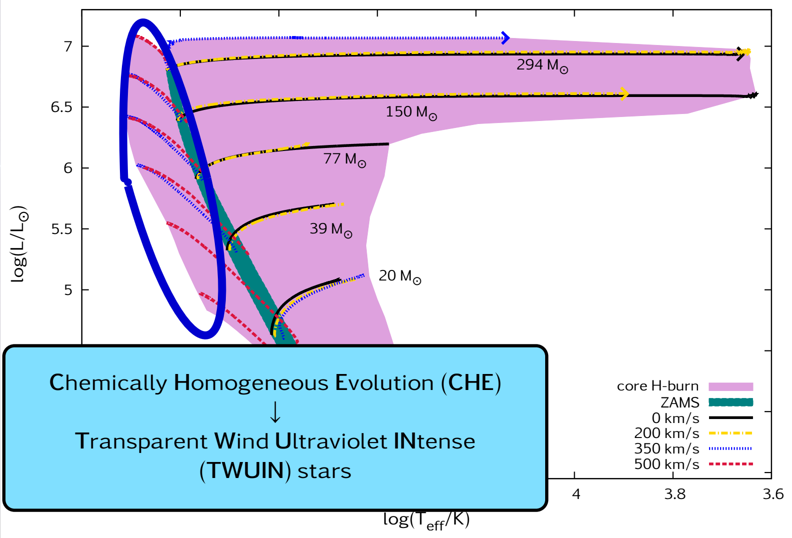
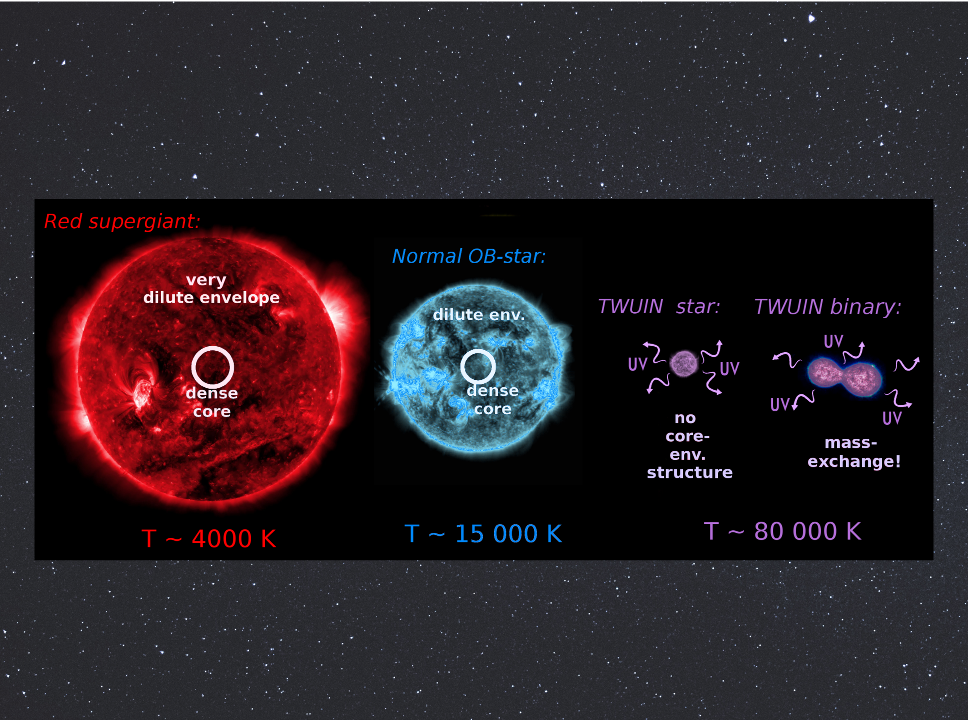


Chemically **H**omogeneous **E**volution (**CHE**)

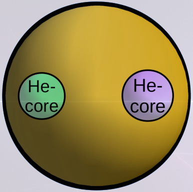
↓

Transparent **W**ind **U**ltraviolet **IN**tense (**TWUIN**) stars

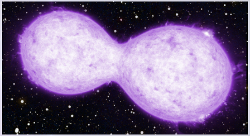


Red supergiant:
very
dilute envelope
dense
core
T ~ 4000 K
Normal OB-star:
dilute env.
dense
core
T ~ 15 000 K
TWUIN star:
UV
UV
no
core-
env.
structure
TWUIN binary:
UV
UV
UV
mass-
exchange!
T ~ 80 000 K

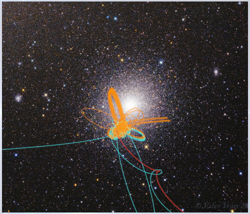
GW/SGRB progenitors: 3 theories



Common envelope
in a binary



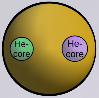
Chemically-
homogeneous
evolution
in a binary



Dynamics in
dense clusters

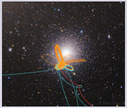
e.g. Vigna-Gómez..**Szécsi**+18; **Szécsi**'17a,b; **Szécsi**&Wünsch'18

GW/SGRB progenitors: 3 theories



Common envelope in a binary

Chemically-homogeneous evolution in a binary



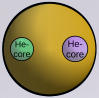
Dynamics in dense clusters

Metal-poor massive stars

e.g. Vigna-Gómez..**Szécsi**+18; **Szécsi**'17a,b; **Szécsi**&Wünsch'18; **Szécsi**'16;

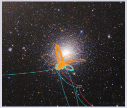
GRB progenitors

Dorottya Szécsi:
New vision
for THESEUS



Common envelope in a binary

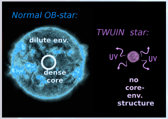
Chemically-homogeneous evolution in a binary



Dynamics in dense clusters

S-GRBs

Metal-poor massive stars



Chem.-hom. evolution as **single** star

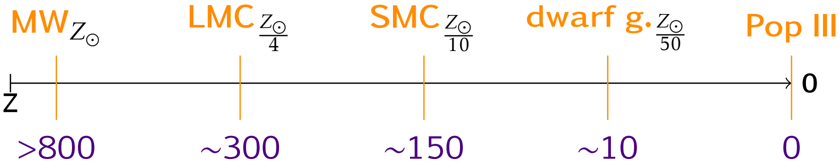
Chem.-hom. evolution in a **binary**

L-GRBs

However...

Are they observed?

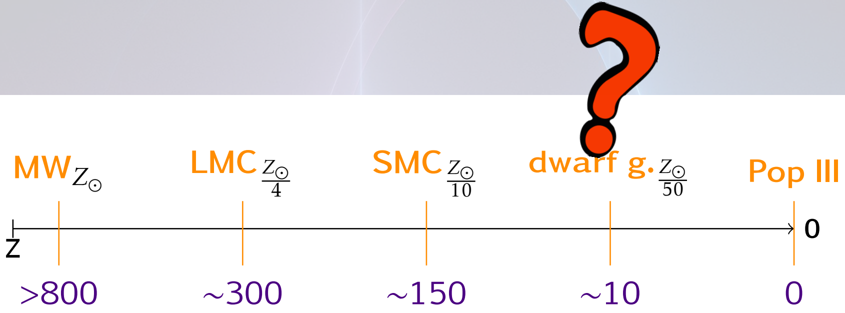
Are they observed?



spectroscopy
(i.e. direct evidence)

e.g. Castro+14,+18, Ramírez-Agudelo+17, Kubátová&**Szécsi**+18

Are they observed?



spectroscopy
(i.e. direct evidence)

GRB-progenitors theories...

e.g. Castro+14,+18, Ramírez-Agudelo+17, Kubátová&**Szécsi**+18

The literature

Theoretical models

Maeder'80,
Maeder+87,
Beech+89,
Yoon+06,
de Mink+09,
Brott+11,
Yoon+12,
Köhler+15,
Szécsi+15,
Marchant+16,
Song+16,
Marchant+17,
Aguilera-Dena+18,
Cui+18,
Schootemeijer+18,
Groh+19,

Goetberg+17,
Hainich+18,
Kubátova+19

Indirect evidence

L-GRB

- Yoon+05
- Yoon+06
- Woosley+06
- *Cantiello+07*

L-GRB & SN

- Meynet+07
- Dessart+08
- van Marle+08

ionization

- Eldridge+12
- Szécsi+15b

GW

- de Mink+16
- Mandel+16
- Marchant+16
- Eldridge+16
- Stanway+16

XRB

- Marchant+17
- Aguilera-Dena+18

GC

- Szécsi+18
- Qin+19

Observational (direct) evidence

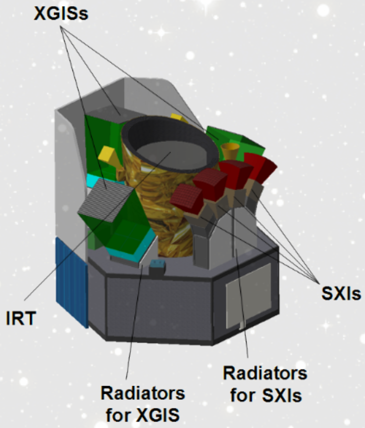
Martins+13,
Almeida+15,
Ramachandran+19

Non-observations or non-conclusive

Vink+17,
Garcia+19

Space mission THESEUS

Shortlisted by ESA → 2021



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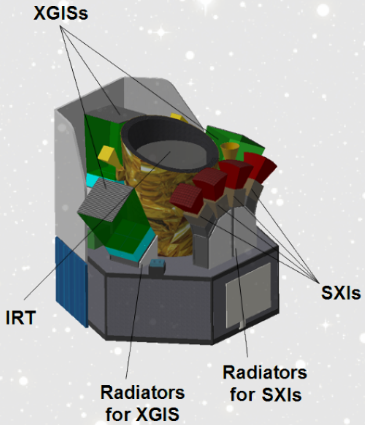
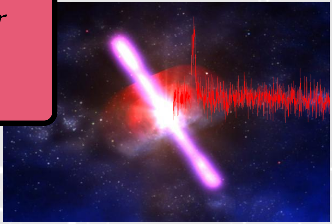
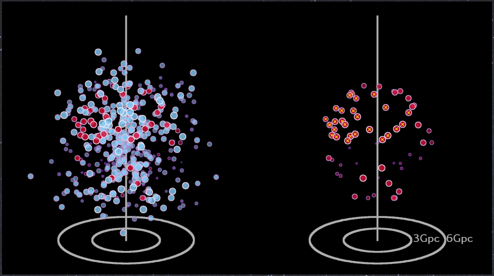


Shortlisted by ESA → 2021

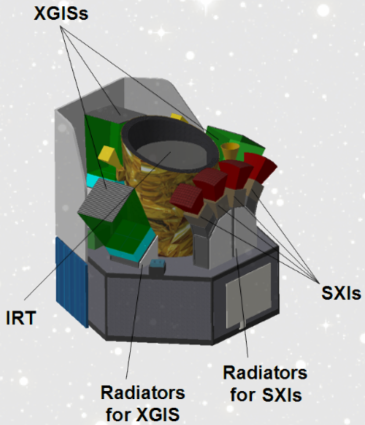
Host redshift (z)

Number of events per redshift #(GRB)/z




3Gpc
6Gpc

Space mission THESEUS



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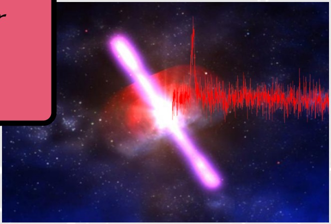

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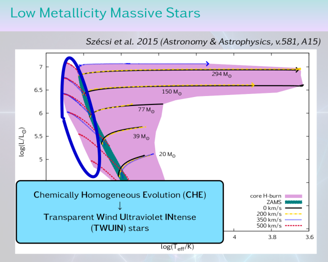

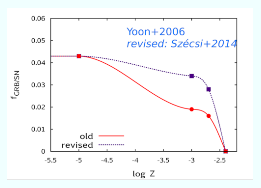

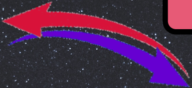

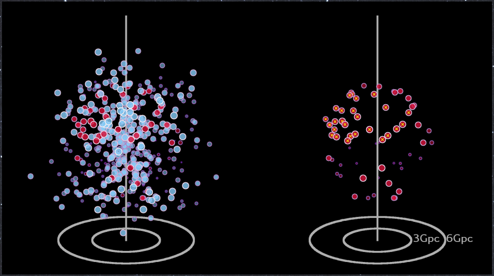

Number of events
per redshift
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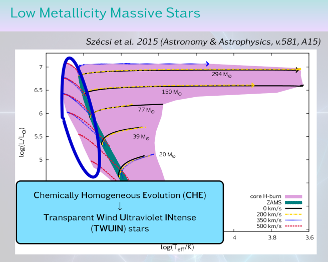
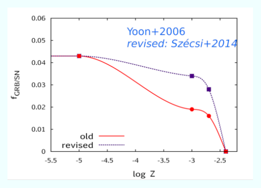
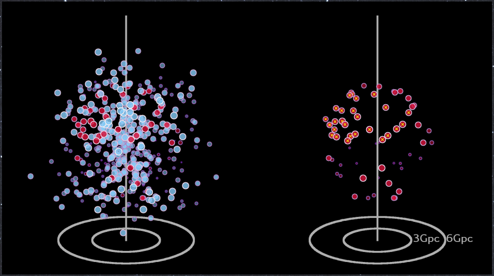
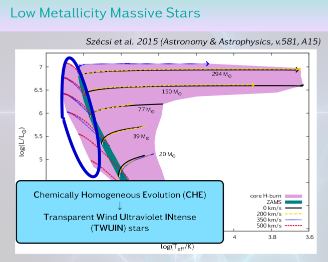






Challenges…

Get the stellar models right…
Z to z conversion…
Flexibility…
MESA…
Binaries….



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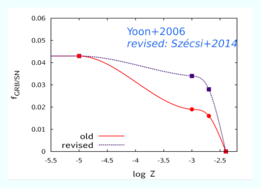

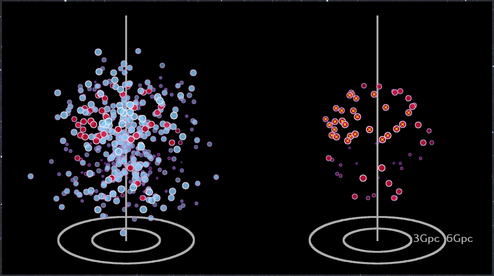

Challenges...

Get the stellar
models right...
Z to z
conversion...
Flexibility...
MESA...
Binaries....

I am applying for
an ERC Starting
group

Gamma-Ray Bursts as Probes of Cosmic Structure

I. Horvath,[1] D. Szécsi,[2,3] Á. Szabó,[4] J. Hakkila,[5] L. V. Tóth,[6] L. G. Balazs,[6] S. Pinter,[1] Z. Bagoly,[7] and I. I. Racz[1]

[1] University of Public Service Budapest, Hungary [2] I. Physikalisches Institut, Universität zu Köln, Germany [3] Institute of Astronomy, Nicolaus Copernicus University, Poland [4] Universität Hamburg, Fachbereich Mathematik, Hamburg, Germany [5] Department of Physics and Astronomy of College of Charleston, Charleston, SC, USA [6] Department of Astronomy of the Eötvös Loránd University, Budapest, Hungary [7] Department of Physics of Complex Systems the Eötvös Loránd University, Budapest, Hungary

Abstract

Because of their high luminosity, gamma-ray bursts have contributed to the identification of some of the largest structures in the Universe. We reexamine one of these, the Hercules–Corona Borealis Great Wall, from both observational and theoretical perspectives. Our statistical analysis confirms the presence of the cluster in the most reliable data set currently available. Cosmological and astrophysical explanations regarding the origin of such a structure are presented and briefly discussed. These perspectives, along with the scientific importance of using gamma-ray bursts as unique cosmological probes, emphasize the need for future missions such as the THESEUS satellite to provide us with an unprecedented, large, homogeneous sample of gamma-ray bursts having measured redshifts. Such a sample will be necessary to conclusively testing the hypothesis that the Hercules–Corona Borealis Great Wall is as it has been described here.

Introduction

The *Hercules–Corona Borealis Great Wall* ("Great Wall") is the largest structure in the Universe observed to date. It is identified from a clustering of gamma-ray bursts (GRBs) at a redshift (z) of around 2 (Horváth+, 2014, 2015; Horváth+, 2020). Here we reexamine this structure in light of recent results (Canay&Eingorn, 2020) indicating that the screening length λ above which large-scale structure formation is suppressed above screening lengths of $\lambda \approx 2.6$ *Gpc*, coinciding with the size of the Great Wall.

GRBs are uniformly distributed on the sky (Briggs+, 1996; Balázs+, 1998, 1999; Mészáros+, 2000; Magliocchetti+, 2003; Vavrek+, 2008; Řípa&Shafieloo, 2019; Andrade+, 2019), although some subsamples deviate from isotropy (Balázs+, 1998; Cline+, 1999; Mészáros+, 2000; Litvin+, 2001; Magliocchetti+, 2003; Vavrek+, 2008). Two large, anisotropic structures have been found in GRB data: the Great Wall and the *Giant GRB Ring* (Balázs+, 2015, 2018) in the redshift range of $0.78 < z < 0.86$. The Giant GRB Ring appears to be somewhat smaller (1.72 Gpc) than the Great Wall (2–3 Gpc). Studying structures like these is of high scientific importance because their existence provides a challenge to standard assumptions about universal homogeneity and isotropy (*e.g.*, the cosmological principle).

Figure 1 is an orthographic 3D representation of the 'GRB Universe', with the Great Wall marked. Establishing the viability of this cluster has required a moderately large observational database for which observational selection biases are understood. Going forward, GRB cluster analyses can be improved with the help of new, more homogeneous data sets such as the proposed THESEUS satellite mission.

As of March 2018, the redshifts of 487 GRBs have been measured (primarily detected by NASA's Swift experiment) (http://www.astro.caltech.edu/grbox/grbox.php).

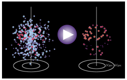

Fig. 1: *The GRB Universe.* Orthographic 3D representation of our 4D Universe as seen by GRBs in our data set. A video showing the same *GRB Universe* can be viewed at `https://www.youtube.com/watch?v=vu8ltxtt8J4`.

References

Amati, L. +. 2018, Advances in Space Research, 62, 191
Andrade, U., +. 2019, MNRAS, 490, 4481
Balázs, L. G., +. 2015, MNRAS, 452, 2236
Balázs, L. G., +. 1998, A&A, 339, 1
Balázs, L. G., +. 1999, A&AS, 138, 417
Balázs, L. G., +. 2018, MNRAS, 473, 3169
Briggs, M. S., +. 1996, ApJ, 459, 40
Canay, E. & Eingorn, M. 2020, Physics of the Dark Universe, 29, 100565
Cline, D. B., +. 1999, ApJ, 527, 827
Götz, D., +. 2018, Mem. Soc. Astron. Italiana, 89, 148
Horváth, I., +. 2015, A&A, 584, A48
Horváth, I., +. 2014, A&A, 561, L12
Horvath, I., +. 2020, MNRAS, 498, 2544
Litvin, V. F., +. 2001, Astronomy Letters, 27, 416
Magliocchetti, M., +. 2003, MNRAS, 343, 255
Mészáros, A., +. 2000, ApJ, 539, 98
Řípa, J. & Shafieloo, A. 2019, MNRAS, 486, 3027
Stratta, G., +. 2018, Advances in Space Research, 62, 662
Vavrek, R., +. 2008, MNRAS, 391, 1741

Statistical analyses with the point radius bootstrap method

We test for clustering using the *point radius bootstrap method* (Horváth+, 2014). This 2D angular test identifies the distribution of events that should lie within specified angular radii. Our sample consists of 64 GRBs in the redshift range $1.6 < z \leqslant 2.1$ that appear to cluster excessively.

After verifying that the sky exposure is independent of z, we randomly choose 64 GRB samples from the observed database and compare their sky distributions to that of the 64 GRBs with $1.6 < z \leqslant 2.1$. We compare the number of points that lie within a circle of predefined angular radius (for example, within 20°), and we repeat the process 20 000 times to generate a statistical distribution. From these 20 000 cases we select the largest number of GRBs found within the angular circle (for more details about this method see Horváth+ 2014, 2015).

This analysis is performed with both the 64 GRBs belonging to our location of interest and also with 64 randomly chosen GRB locations selected from the 487 GRBs in the sample. We repeat the experiment 10 000 times in order to understand the statistical variations of this sample. We also perform the same technique using angular circles of different radii. The frequencies obtained this way are shown in Figure 2 (black).

Table 1 shows the maximum number of GRBs in a given angular circle. The most significant deviation from isotropy appears in a circle covering 15 percent of the sky (see Fig. 2); at least 33 GRBs are contained inside this circle. The significance reaches 3σ between regions covering 11 percent and 20 percent of the sky (Fig. 2, the black horizontal line shows the 3σ limit). In these regions, between 27 and 36 GRBs are found (out of 64).

Table 1: Largest number of GRBs found within a certain area of the sky.

radius	32.9°	34.9°	36.9°	38.7°	40.5°	42.3°	43.9°
surf. area	0.08	0.09	0.10	0.11	0.12	0.13	0.14
GRBs	21	23	24	27	28	30	32

radius	45.6°	47.2°	48.7°	50.2°	51.7°	53.1°	54.5°
surf. area	0.15	0.16	0.17	0.18	0.19	0.20	0.21
GRBs	33	33	33	34	35	36	36

radius	55.9°	57.3°	58.7°	60.0°	61.3°	62.6°	63.9°
surf. area	0.22	0.23	0.24	0.25	0.26	0.27	0.28
GRBs	37	37	37	38	38	38	39

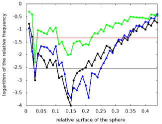

Fig. 2: Results of the Monte Carlo bootstrap point-radius test on a variety of different angular scales. The horizontal coordinate is the area of the circle in the sky relative to the whole sky (4π). The vertical coordinate is the logarithm of the relative frequency found from the 10,000 runs. The calculations were made for 64 GRBs in the $1.6 < z < 2.1$ range (black), for the 77 GRBs in the $1.6 < z < 2.3$ range (blue) and the 77 GRBs in the $1.5 < z < 2.1$ range (green). Horizontal red (black) line shows the 2σ (3σ) deviations.

To check whether the angular anisotropy spans a larger range than $1.6 < z \leqslant 2.1$, we expand the z range to smaller ($1.5 < z \leqslant 2.1$) and larger ($1.6 < z \leqslant 2.3$) redshifts. Since both volumes contain 77 GRBs, we repeat the process with 77 GRB samples selected from the observed dataset, selecting random celestial locations and determining the number of points lying within circles of predefined angular radii. Statistics are generated by repeating the process 20 000 times.

From these 20 000 Monte Carlo runs we select the largest number of GRBs found within the angular circle. We repeat the process with 77 different randomly chosen GRB positions (from the known 487 GRBs), and we repeat the experiment 10 000 times in order to understand the statistical variations of this sub-sample. We also perform the same technique using angular circles of different radii.

The results for the 77 GRBs from $1.5 < z \leqslant 2.1$ and for the 77 GRBs from $1.6 < z \leqslant 2.3$ are shown in Fig. 2. The $1.5 < z \leqslant 2.1$ sample is much more isotropic than the $1.6 < z \leqslant 2.1$ sample, and it never reaches the 3σ level (green). However, the extended z interval $1.6 < z \leqslant 2.3$ (again with 77 GRBs) shows a similar anisotropy at a comparable significance level (blue in Fig. 2).

For relative surface areas between 0.05 and 0.1, the 64 GRBs in the originally-defined z interval $1.6 < z \leqslant 2.1$ show the largest significance, but in the 0.17 - 0.27 interval, the 77 GRBs ($1.6 < z \leqslant 2.3$) exhibit the greater significance. In both cases the minimum frequency is around 0.15 (containing 33 of 64 and 37 of 77 GRBs, respectively). These results imply that *the clustering of GRBs in the Great Wall is indeed statistically significant in the most reliable database currently available.* (However, note that the as-

Observers' bias and future prospects with THESEUS

Since Swift's launch in 2004, the number of GRBs with well-determined sky position has been nearly constant (~120/year). However, the number of GRBs followed up by optical telescopes on the ground has been continuously declining since then: although it was ~44/year in 2008, it was only ~15/year in 2015 (see Fig. 3). This decline has been consistent, showing a year-to-year decrease of ~10%.

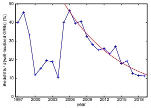

Fig. 3: Follow-up observations of the last two decades. The blue line shows the ratio of GRBs with redshift to all well-localised GRBs (i.e. localised within a few hours to days to less than 1° accuracy). The data are taken from Jochen Greiner's compilation (`http://www.mpe.mpg.de/~jcg/grbgen.html`). Since 2006, an approximately constant rate of well localised GRBs (≈ 120/year) are observed; however, the number of redshift measurements is clearly decreasing. This loss of interest in GRB redshift measurements amongst the observers can be well approximated by an exponential decay (red line). After 2006, only ≈ 90% of the previous year's redshift observations are obtained annually. If this trend continues, in 2026 we will observe less than 8 GRBs with redshift.

This measurement appears to indicate a feature resulting from human psychology: observers on the ground are less likely to dedicate resources to studying 'average' GRBs than 'interesting' ones (such as those for which the spacecraft's optical detector indicates unexpectedly large redshifts). Indeed, it seems that if early optical afterglow detection (and sub-arc minute pointing) is done with Swift's UltraViolet and Optical Telescope, this vastly increases the chance that a ground-based follow-up and measuring of the spectrum of the afterglow will happen. For instance, for redshifts $z < 1$ it enhances the chance by more than 60%.

We conclude that this loss creates a very strong argument for building optical/UV/IR telescopes on board upcoming gamma-satellites. The THESEUS mission (Amati+, 2018; Stratta+, 2018) is currently being designed to host an Infrared Telescope (Götz+, 2018). In light of the facts we report above, the importance of such a mission cannot be emphasised enough, both for motivating ground-based observers to follow-up interesting GRBs and for providing estimated redshifts for a large number of GRBs out to the epochs of the First Stars. Indeed, THESEUS will be essential for the future of studying cosmic isotropy with GRBs. We also conclude that the current sample of 487 GRBs with well-determined redshift may be observer-biased in a way that has not been previously accounted for. If so, this may mean that despite enormous efforts of several communities to detect and localise GRBs with an ever increasing precision, the current data may only allow the study of cosmic isotropy in a limited and preliminary way. Again, future space missions such as THESEUS can change this by providing large, homogeneous samples of GRB redshift measurements.

Conclusions

If the Hercules–Corona Borealis Great Wall is real (and not, for example, an observational artefact), then it is the largest structure known in the Universe. Using an up-to-date data set of all GRBs with reliable redshifts, our application of the point radius bootstrap method verifies that this GRB cluster is indeed statistically significant.

We have created a video showing the orthographic 3D representation of the 4D GRB Universe to present the community with a means to visualise the Great Wall amongst all GRBs with known redshift (https://www.youtube.com/watch?v=vu8ltxtt8J4).

We have also demonstrated, the window of opportunity created for the GRB community by Swift may be closing. Observer fatigue appears to be reducing the rate at which GRBs with known redshift are measured (see Fig. 3), thus making it harder for large-scale GRB isotropy studies to continue into the future.

We hope that this problem will be resolved because the proposed gamma-satellite mission THESEUS has been designed to continue collecting a uniform and homogeneous GRB dataset. Having an infrared telescope on-board, THESEUS can provide us with the data needed to study large-scale universal structures using GRBs, and to continue testing whether or not the Hercules–Corona Borealis Great Wall is indeed real. If it is, it may well be the largest observable structure in the Universe. We need THESEUS to decide.

Horvath, Szécsi … Szabó et al. (2020, *MRNAS*)

How to use THESEUS' high-redshift GRB data to constrain the physics of

Pop-II and Pop-III progenitors

Dorottya Szécsi

Humboldt Fellow
University of Cologne, Germany
Assistant professor at Nicolaus Copernicus University, Poland

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