Pulsational pair-instability supernovae – Dr David Hendriks

Lecture Slides and Descriptions

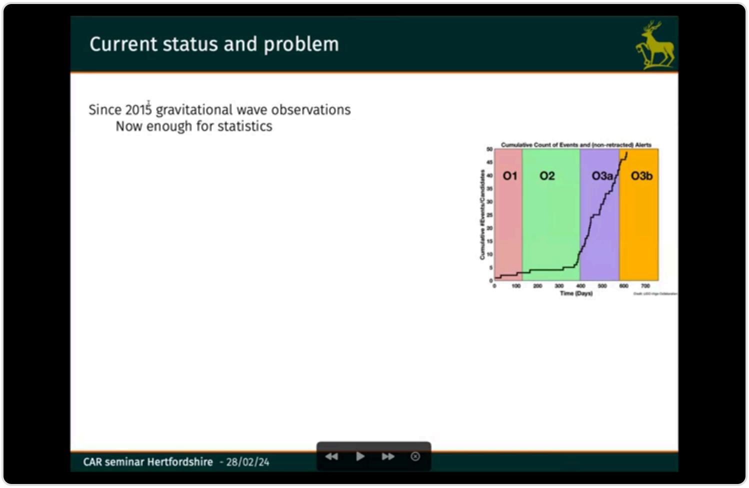
Youtube Link

Summary:
Dr. David Hendriks of the University of Surrey delivered a lecture on the role of pulsational pair-instability supernovae in electromagnetic and gravitational-wave transients. The lecture delved into the statistical properties of black hole mergers, particularly focusing on the unexpected mass distribution of these objects, and explored the potential for pair-instability supernovae as a significant contributor to the observed population.

Firstly, the speaker presented a compelling argument for the emergence of a new era in gravitational-wave astronomy. With the increasing number of detections since 2015, gravitational-wave observatories have acquired sufficient data for statistical analysis. This allows for the construction of distributions, like the distribution of black hole masses, which offer invaluable insights into the processes that generate these compact objects.

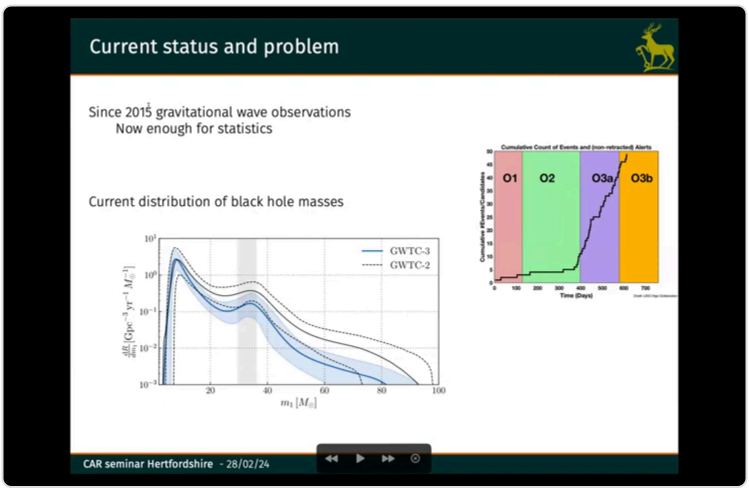
The lecture then highlighted a peculiar feature of the observed black hole mass distribution – a bump centered around 35 solar masses. Hendriks proposed that pulsational pair-instability supernovae, a type of stellar explosion characterized by intense pulsations and pair production, could account for this bump. He explained that these supernovae occur when a massive star reaches a critical stage in its evolution, leading to a catastrophic ejection of its outer layers and leaving behind a black hole. The unique physics of pair-instability supernovae, which involve a delicate balance between energy production and radiation pressure, results in the creation of black holes with masses clustered around 35 solar masses.

Finally, the lecture discussed the broader implications of this research. Hendriks argued that, if pulsational pair-instability supernovae are indeed a major contributor to the black hole population, it could have significant implications for our understanding of stellar evolution, galaxy formation, and the evolution of binary systems. Further investigations into the role of pair-instability supernovae, he concluded, are crucial to unravel the mysteries surrounding the origin and evolution of black hole mergers and their implications for the cosmic landscape.



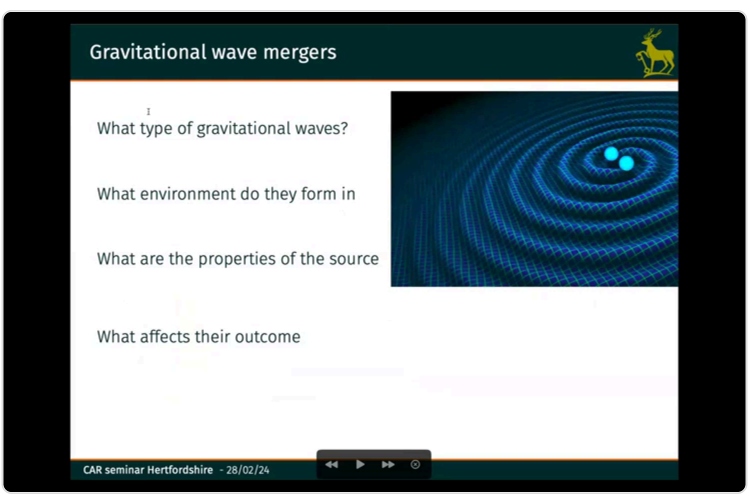
Slide 1

The slide is titled 'Current status and problem'. It includes a plot showing the cumulative number of gravitational wave events detected by the LIGO and Virgo interferometers over time, with different colors for each observing run. The speaker explains that since 2015 there has been a significant increase in the number of gravitational wave events detected, allowing for statistical analysis of their properties. These statistics reveal interesting features in the distribution of the masses of black holes.



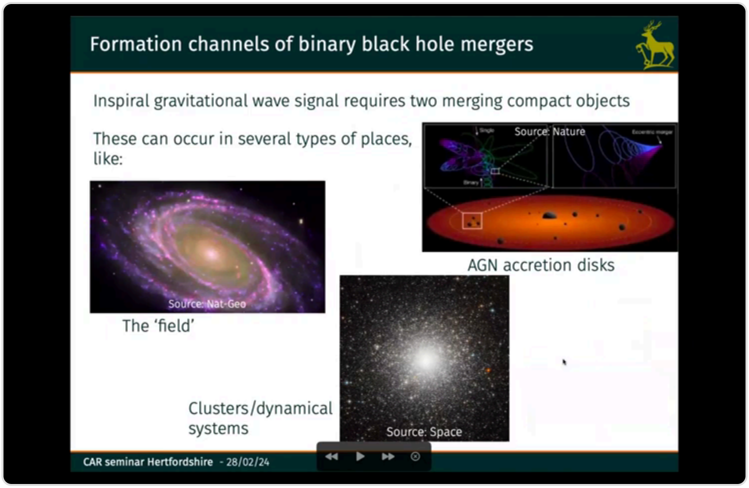
Slide 2

The slide is titled 'Current status and problem' and includes a plot showing the distribution of black hole masses for two different observing runs of the LIGO and Virgo interferometers. The black hole mass distribution for the more recent observing run, GTC-3, shows a peak or 'bump' around $40 M_{\\odot}$. The speaker discusses whether or not the 'bump' in the distribution is statistically significant, and how these observations could potentially be related to pulsational pair-instability supernovae.



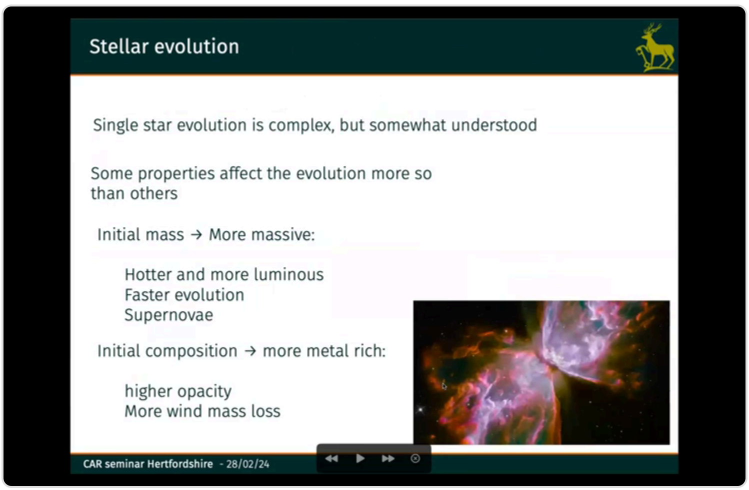
Slide 3

The slide is titled 'Gravitational wave mergers'. It shows a 3D rendering of two black holes merging, generating ripples in the spacetime fabric. The speaker raises questions about the types of gravitational waves, their formation environments, and the properties of the sources. The speaker highlights how the initial properties of the merging black holes impact the gravitational wave signal and the final remnant.



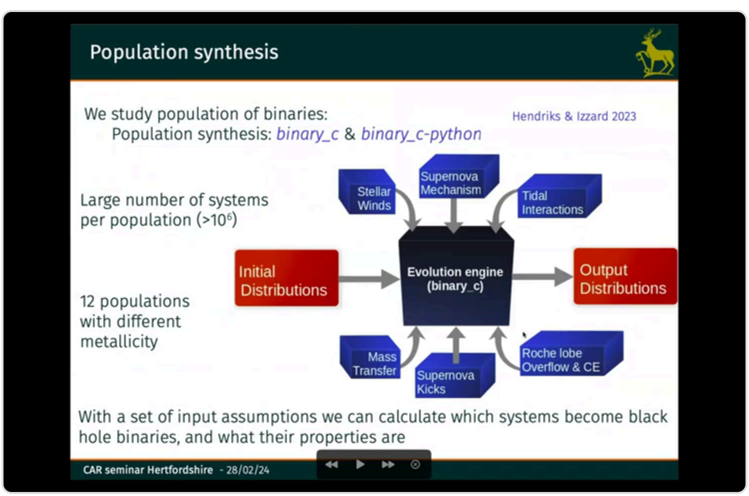
Slide 4

The slide is titled 'Formation channels of binary black hole mergers'. It shows three images: a galaxy, an accretion disk, and a globular cluster. The speaker discusses how binary black hole mergers can be formed through a variety of channels. This includes the 'field' (isolated binaries), AGN accretion disks, and dense star clusters, each with its own unique dynamics and processes that influence the final merger product.



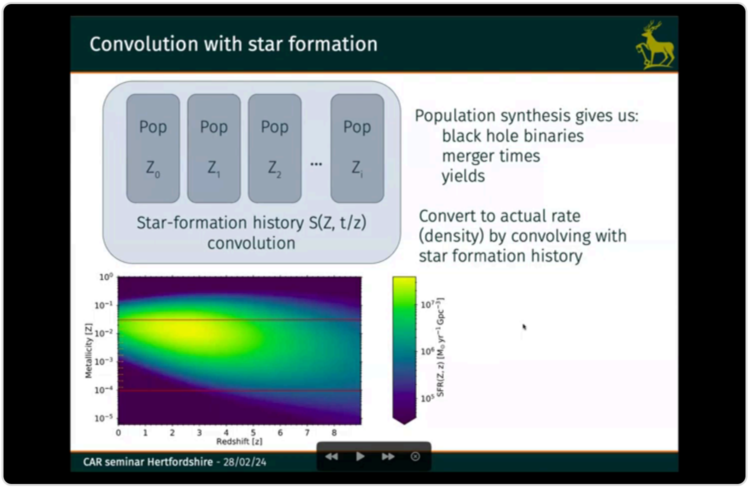
Slide 5

The slide is titled 'Stellar evolution'. It shows an image of a nebula and text highlighting two important factors in stellar evolution: initial mass and initial composition. The speaker explains that more massive stars are hotter, more luminous, evolve faster, and are more likely to undergo supernovae. Additionally, stars with higher metallicity have greater opacity and lose more mass through stellar winds. These factors significantly influence the evolution and final fate of stars.



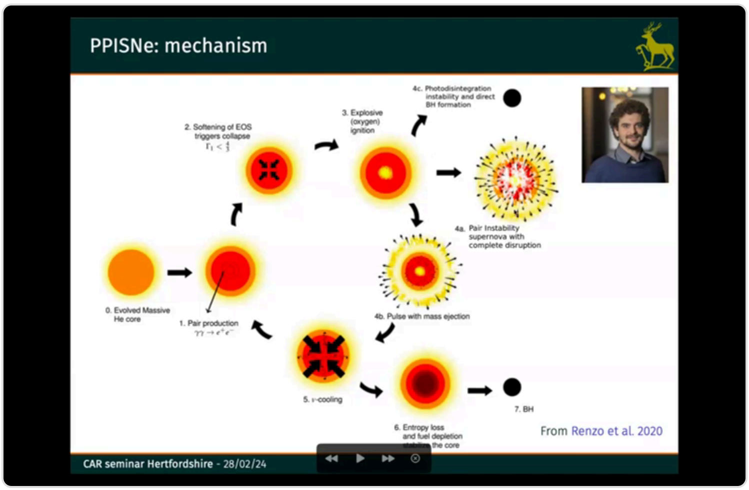
Slide 6

The slide shows a flowchart of a population synthesis model for binary stars that begins with initial distributions of binary parameters, evolves those systems using a binary_c engine that includes mass transfer, supernova kicks, and tidal interactions, and then provides final output distributions. The speaker explains that this model allows them to study the evolution of a large number of binary systems (greater than 10^9) and provides details about the use of the binary_c engine, including 12 different populations with varying metallicity, Roche lobe overflow and common envelope evolution, and supernova kicks.



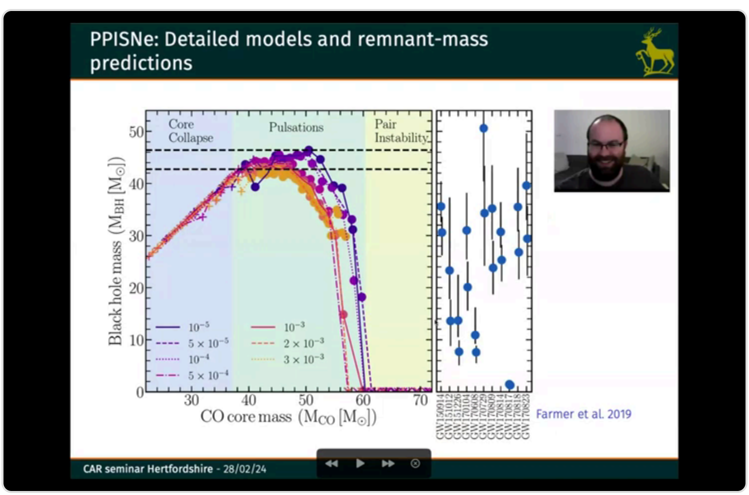
Slide 7

The slide shows a diagram of multiple populations of binary stars with varying metallicity. The speaker explains that each population can be convolved with the star formation history to provide an actual rate of black hole binary mergers. This convolution is performed by integrating the merger times over the star formation history, taking into account the dependence on metallicity and time.



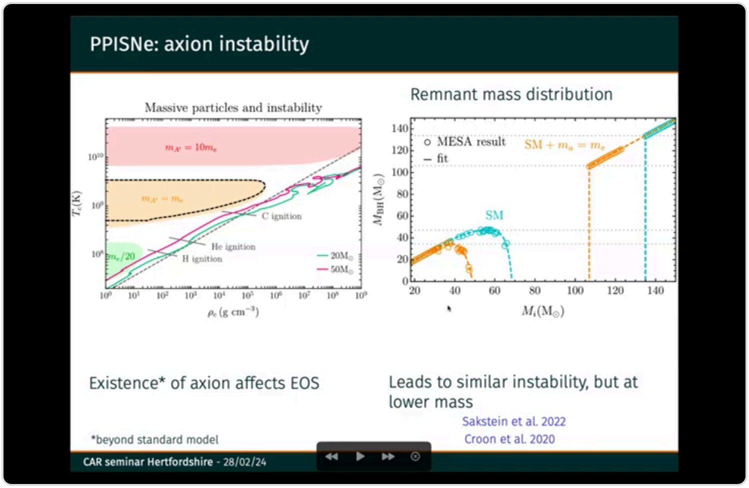
Slide 8

The slide shows a flowchart detailing the mechanism of a pulsational pair-instability supernova (PPISNe). Starting with an evolved core of helium, the star experiences a series of steps: 1) pair production, 2) softening of the equation of state triggers core collapse, 3) explosive oxygen ignition, 4) pair-instability supernova with complete disruption, 5) cooling, 6) entropy loss and fuel depletion in the core, and 7) black hole formation. The speaker emphasizes the importance of this mechanism in the evolution of massive stars, especially in the context of gravitational waves.



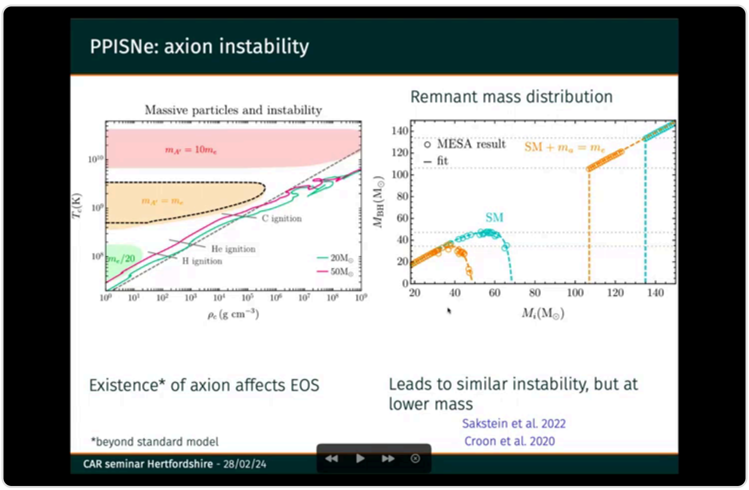
Slide 9

The slide shows a plot that displays the remnant black hole mass (in solar masses) as a function of the CO core mass (in solar masses) for different initial metallicities. This plot demonstrates how the remnant black hole mass varies based on the initial metallicity and the core mass of the star at the time of collapse. The speaker emphasizes the importance of these models for accurately predicting the remnant black hole masses formed in PPISNe events.



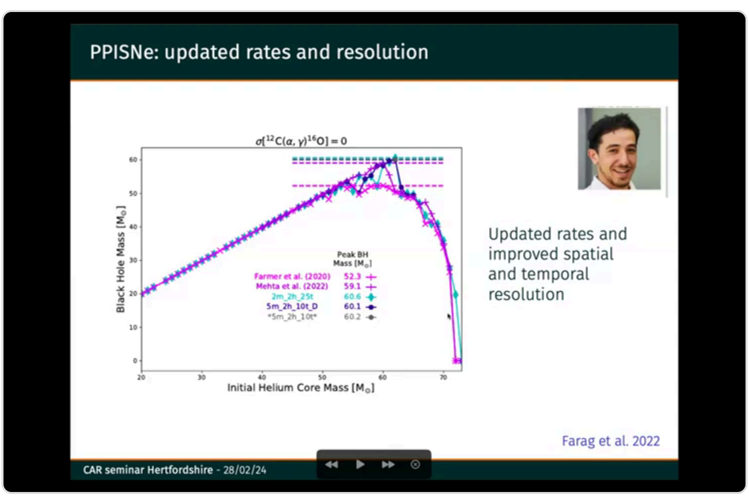
Slide 10

The slide shows a plot comparing the remnant black hole mass distribution for two models. The black line represents the fiducial model, and the blue line represents a model with axion-pair instability. The speaker is discussing how the existence of axions can affect the equation of state, leading to a similar instability as the pair-instability supernova, but occurring at lower masses.



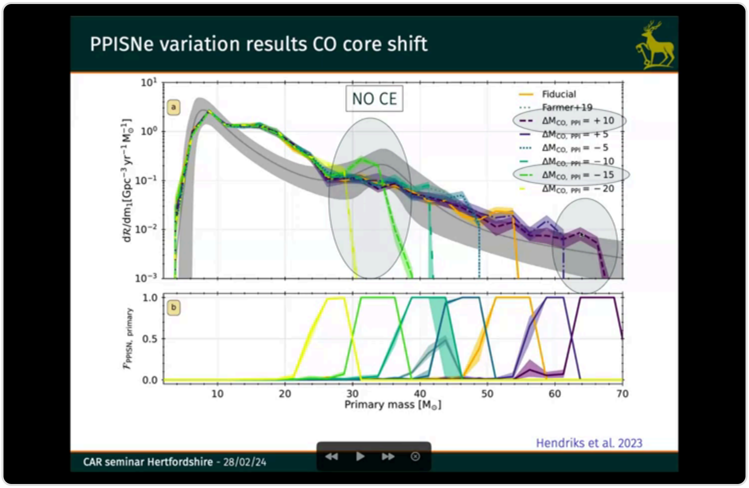
Slide 11

The slide shows a plot of temperature versus density in the core of a star, showing the onset of different nuclear burning stages, and a plot of black hole remnant mass as a function of pre-supernova mass, showing the results of MESA simulations. The speaker discusses the effect of axion particles on the equation of state (EOS) for the core of a star, which can lead to instability at lower masses than in the standard model. This instability can lead to pair-instability supernovae (PISNe).



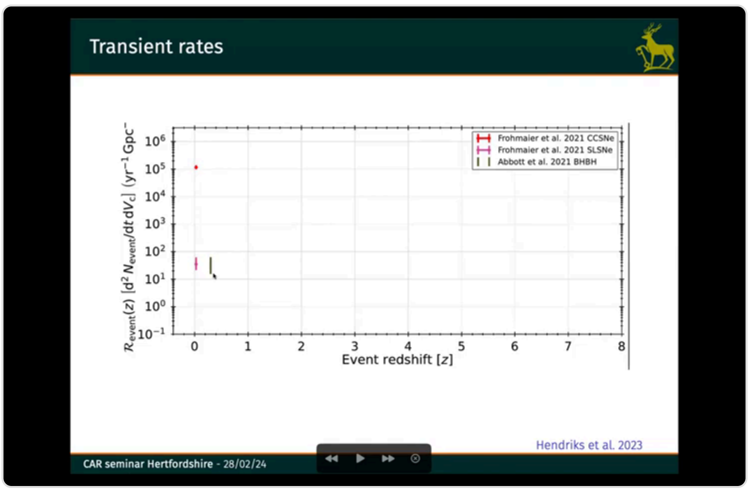
Slide 12

The slide shows a plot of black hole mass as a function of pre-supernova helium core mass. The speaker discusses the effects of updated reaction rates and improved spatial and temporal resolution on the final black hole mass in PISNe, concluding that these improvements do not significantly affect the predicted black hole masses but provide more accurate estimates for the rate of PISNe.



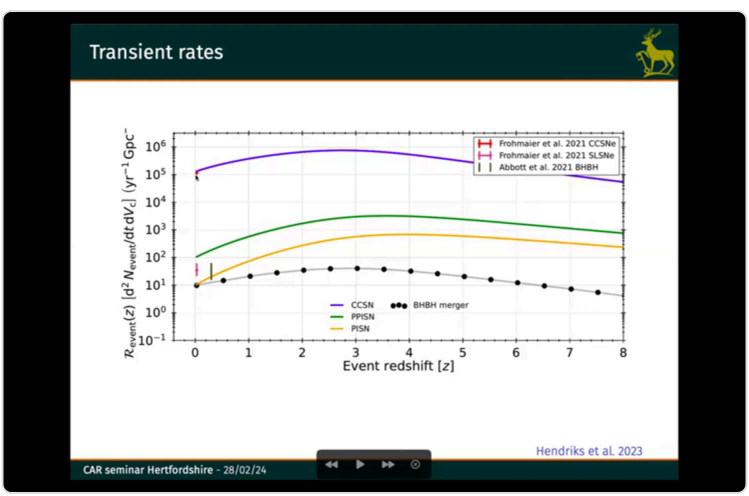
Slide 13

The slide shows a plot of black hole remnant mass as a function of CO core mass for various prescriptions of the pre-supernova evolution of a star. The speaker explains how the location of the CO core before the supernova explosion affects the final black hole remnant mass, which can be used to constrain the properties of the pre-supernova star.



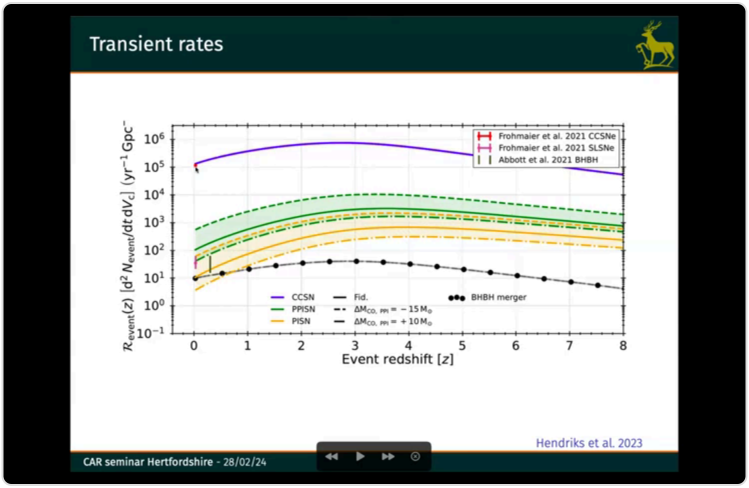
Slide 14

The slide shows a plot of the event rate per Gpc^3 as a function of redshift for a variety of transients, including core-collapse supernovae (CCSNe), superluminous supernovae (SLSNe), and binary black hole mergers (BBH). The speaker discusses the rate of these different transients, noting that the rate of PISNe is significant but still uncertain due to the lack of well-established observational constraints.



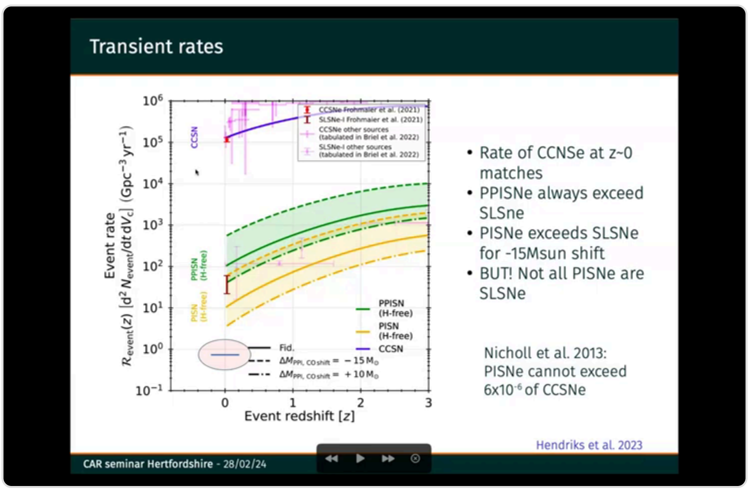
Slide 15

The slide shows a plot of event rate per Gpc^3 as a function of redshift for CCSNe, SLSNe, and PISNe. The speaker discusses how the detection of PISNe, which are expected to be less common than other transients, can help to constrain the properties of the pre-supernova star. The rate of PISNe is uncertain, but it is potentially detectable with the next generation of astronomical telescopes, particularly those capable of observing gravitational waves.



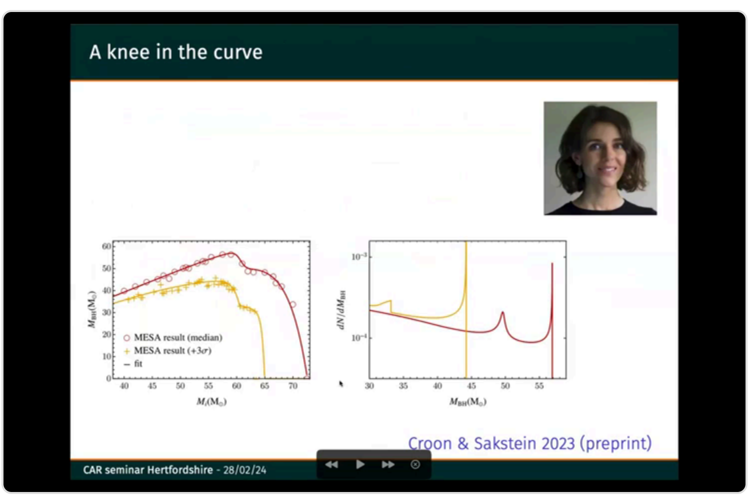
Slide 16

The slide shows a plot of event rate per Gpc^3 per year against redshift, with curves for CCSNe, SLSNe, PISNe, PPISNe, and binary black holes mergers. The speaker discusses how the rate of CCSNe at redshift 0 is consistent with observations, while the rates of SLSNe, PISNe, and PPISNe are all higher than observations. The speaker also notes that it is not necessarily the case that all PISNe are SLSNe.



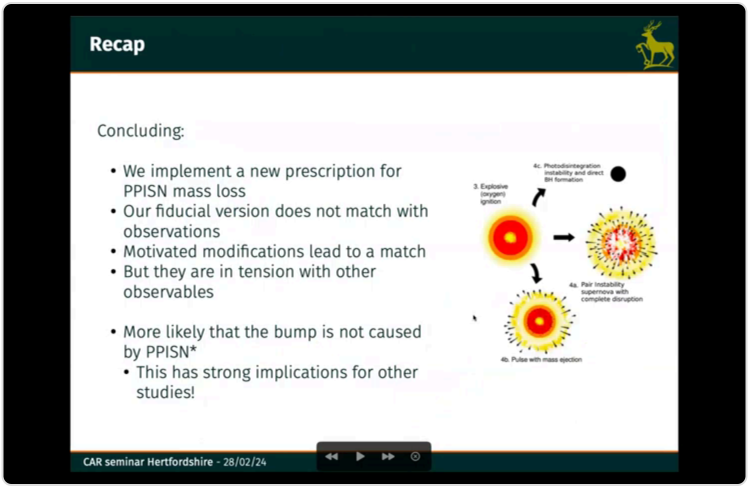
Slide 17

The slide shows a similar plot as the previous one with curves for CCr, PISNe, and SLSNe. The speaker further discusses the relation between the rates of different types of supernovae, emphasizing that the rate of PISNe always exceeds the rate of SLSNe at all redshifts. However, the speaker points out that not all PISNe are SLSNe and there is a theoretical constraint that the rate of PISNe cannot exceed 6 x 10^-6 times the rate of CCSNe.



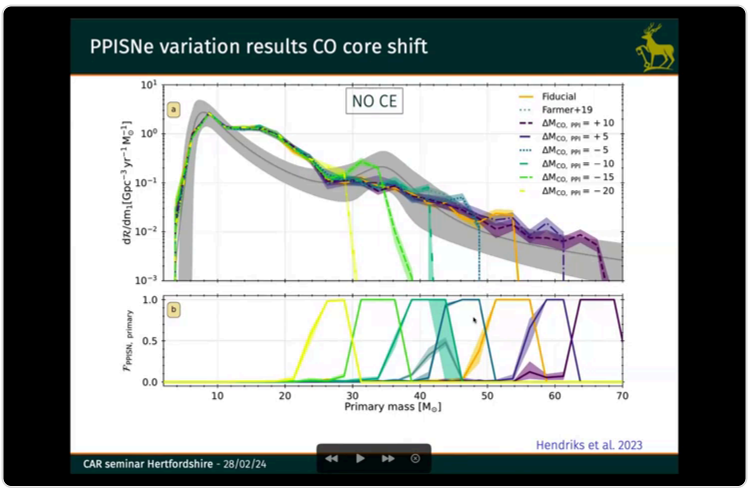
Slide 18

The slide shows two plots showing the dependence of the progenitor mass of a supernova on its remnant mass. The speaker describes how the MESA simulations show a ``knee" in the distribution of remnant masses, with fewer massive remnants formed for progenitors with masses above a certain value. This behavior is not consistent with the observed distribution of remnant masses, which are more evenly distributed.



Slide 19

The slide lists a series of points summarizing the conclusion of the research on PPISNe. The speaker mentions that they have implemented a new prescription for mass loss from PPISNe, but this prescription does not match observations. Motivated modifications to the model can lead to a better match, but these modifications are in tension with other observables. The speaker concludes that the bump in the distribution of remnant masses is not likely caused by PPISNe, and this has significant implications for other studies.



Slide 20

The slide shows the results of the variation of PPISNe rates, with different assumptions about the core shift, common-envelope evolution, and progenitor mass. The speaker discusses how different assumptions lead to different predictions for the rate of PPISNe, emphasizing that the fiducial model does not match observations. The speaker then briefly discusses the challenges in modelling the evolution of the PPISN progenitors, highlighting the need for a better understanding of the core shift, common-envelope evolution, and mass loss.