# Deep Multi-Band Early-Phase Type Ia Supernova Survey with the ARC-Subaru-GTC Joint Observation

## Present understandings on early-phase Type Ia supernova

The progenitor system of Type Ia supernova (SN Ia) is a long-standing issue in SN Ia study. The single degenerate (SD) progenitor model indicates that the SN Ia progenitor system is composed by a white-dwarf and a main-sequence/red-giant star while the double degenerate (DD) progenitor model suggests that two merging white-dwarfs system is the real situation [1][2]. The controversy between these two scenarios has been lasted for a long time as both of them cannot perfectly interpret observational results [3]. For further testifying SN Ia progenitor models, Kasen (2010) initiatively proposed that the extra luminosity excess within a few days after the explosion should be discovered in a portion of early-phase light curves (LCs) under the SD scenario due to the collision between rapidly expanding ejecta and a companion star (hereafter **CSE**, an abbreviation of "**C**ompanion-induced **S**hock **E**mission") [4]. Searching for the CSE through **early-phase SNe Ia** (hereafter **ESNe Ia**, **"early-phase"** is defined as a period within five days after the explosion) thus becomes a promising way to tackle to the SN Ia progenitor issue.

On the other hand, photometric information of ESNe Ia also plays an important role in understanding the SN Ia explosion mechanism. Theoretical simulations by Piro et al. [5][6][7] indicated that ESN Ia LC and color behavior are very sensitive in reflecting the amount of $^{56}$Ni at the outermost regions of the progenitor star, which can be further applied as a powerful indicator for testifying various explosion mechanisms of SN Ia [8][9].

## Aims at ESN Ia! New inspirations on the origin of SN Ia

In 2015, breakthrough findings on ESNe Ia have been reported. The first statistical study on the photometric behavior of ESNe Ia has been conducted by Firth et al. (F15) [10]. By investigating LCs of several young SNe Ia (including 8 multi-epoch ESNe Ia) with the common-used power-law fitting method ($L \propto t^n$), they surprisingly found that the rising index $n$ has extremely large scatter, from $\sim 1.5$ to 3.7, which clearly contradicts with $n \sim 2$ from previous theoretical predictions [11][12]. In our further analysis, we infer that the scatter among ESN Ia LCs could be attributed to the CSE and/or the off-center explosion scenario.

Moreover, a great breakthrough on the progenitor issue has been reported by specific investigations of two local ESNe Ia as well. Cao et al. [13] and Marion et al. [14] claimed the first (iPTF14atg, subluminous type) and second (SN 2012cg, luminous "normal" type) CSE SN Ia have been confirmed, which strongly supports the SD scenario. However, new problems/insights have been proposed as both two CSE SNe Ia are not classical "normal type" SNe Ia. Hence, comprehensive investigation on the early-phase photometric behavior of various SN Ia subtypes is necessary for the further understanding of these peculiar CSE SNe Ia.

## Investigating the SN Ia progenitor and explosion mechanism with the single-band ESN Ia light curve

We found that slowly-rising ESNe Ia in F15 (PTF10accd with $n \sim 1.48$, LSQ13cpk with $n \sim 1.87$) can be well interpreted by the CSE. When fitting a power-law to a LC with extra luminosity excess at early phase, we can obtain a smaller $n$ value compared with normal LCs. *Figure* 1 presents the LC difference among F15's ESN Ia samples, SN 2011fe and simulated LCs from Kasen and Kutsuna's CSE model respectively [5][15] (*Note*: Kasen probably overestimated the strength of the CSE and Kutsuna et al. built a more conservative model). As the strength of the luminosity excess by CSE depends not only on the configuration of the progenitor system but on the direction of CSE, slowly-rising LCs could be explained by both two CSE models under specific conditions. Moreover, recent CSE SN Ia study by Marion et al. [14] suggested that because of the intrinsic inconspicuous CSE feature and viewing angle effect, large fraction of CSE SNe Ia cannot be easily discriminated by the single-band LC (e.g. SN 2012cg), which also interprets why only a small portion of ESNe Ia ($\sim 20\%$) in F15 show slowly-rising behavior. All these findings well support that SN Ia with slowly-rising early-phase LC could be attributed to the inconspicuous CSE under a SD progenitor system.

In addition to the CSE, we speculate that the scatter among ESN Ia LCs could also be triggered by specific explosion models, e.g. the off-center explosion scenario. If the initial thermonuclear spark is ignited at an offset from the centre of the white-dwarf progenitor [16], such asymmetric physical process finally results in extremely inhomogeneous radioactive element distribution near the surface of the progenitor – the opposite side to the offset direction will gain more radioactive elements near surface than the other side [17]. Under such condition, larger scatter of rising index could be realized by the viewing-angle effect [18][19].

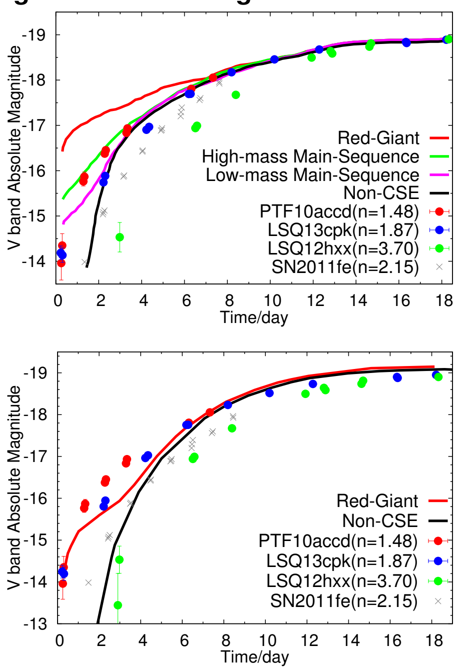


**Figure 1:** Rising-part LCs of F15 samples, SN 2011fe and CSE models by Kasen (upper panel) and Kutsuna et al. (lower panel) respectively. Solid lines correspond to different companion types under specific conditions. Well resemblance between CSE-induced LCs and two slowly-rising samples PTF10accd (red dots) and LSQ13cpk (blue dots) is displayed under both two CSE models.

In fact, F15 only showed single-band LCs with sparse and a large portion of low-quality data at early phase. In order to figure out the origin of the ESN Ia LC diversity, it is imperative to carry out more comprehensive and reliable statistical investigation via the well-organized **multi-band** ESNe Ia-targeted survey.

### Further studies with the ESN Ia color evolution

The early-phase color evolution is another powerful indicator in unveiling the nature of SNe Ia. *Figure* 2 shows early-phase color evolution of previous well-observed SNe Ia and simulated CSE SNe Ia.

**(1) "Investigating the early-phase color diversity among SN Ia subtypes"** So far, we barely know about the early color behavior of abnormal SNe Ia due to the extremely tiny sample size. However, even with such limited information, possible distinction can be found between subluminous and normal ESNe Ia. For instance, subluminous ESN Ia SN 2002es, SN 2005bl and even for CSE-induced subluminous ESN Ia iPTF14atg have much redder *B-V* color than other normal ESNe Ia. The observed *B-V* color of iPTF14atg also contradicts with the prediction by the CSE theory. One possible explanation is that subluminous SNe Ia have extremely red intrinsic color due to the deficient $^{56}$Ni and slower expansion velocity compared to normal SNe Ia at early phase. Besides, the luminous "normal" SN Ia SN 2012cg may have intrinsic bluer color at early phase due to the higher $^{56}$Ni density at the outmost region of the progenitor rather than the "inconspicuous CSE feature" [14]. Hence, by investigating the color behavior of numerous ESNe Ia we expect to not only provide the color evolution reference of non-CSE SNe Ia but infer the intrinsic differences/connections among SN Ia subtypes.

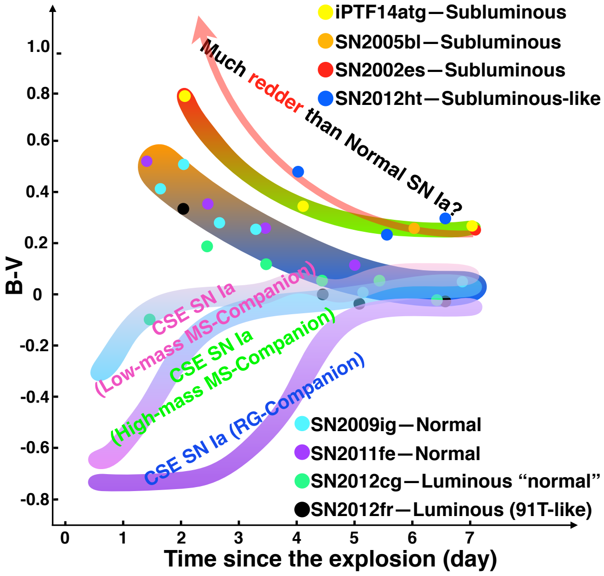


**Figure 2:** Schematic diagram showing the color evolutions of SNe Ia within one week after the explosion.

**(2) "Searching for the evidence in supporting the interaction between the supernova ejecta and a companion star"** According to Kasen's simulation, the CSE will result in the extra luminosity excess in the early-phase LC. As the strength of the excess is influenced by the configuration of the progenitor system as well as the viewing angle effect, a larger fraction of CSE SNe Ia cannot be easily distinguished only through the single-band early-phase LC. However, Kasen's simulation also implies that obvious color difference between the CSE and non-CSE ESNe Ia can be expected (*Figure* 2), as the CSE is dominant in shorter wavelength. Thus, combining both early-phase LC and color information will be an effective way to find out CSE SNe Ia.

**(3) "Providing more strict constraints on the SN Ia explosion model"** Simulations from different explosion models predict various elements configurations in the outer layer of the progenitor [20][21]. The early-phase color behavior could be a powerful indicator to discriminate them as discussed by Dessart et al [22]. Moreover, recent study by Piro & Morozova [9] pointed out that the actual early-phase color evolution of normal SNe Ia may be more complicated by taking into account the scatter of $^{56}$Ni mass distribution as well as the possible interaction between the ejecta and the circumstellar material, by combining with other observables such as the rising time, specific spectral features and absolute magnitude of SN Ia, more stringent constraints for those theoretical models will be applied.

### Observational strategy and expected results of the ARC-Subaru-GTC joint observation

The whole ESNe Ia survey program includes the Subaru survey and follow-up observations. We have continuous 2.5-nights observation with the Subaru/Hyper Suprime-Cam (HSC) from April 3, 2016 (UT), which will survey $\sim 40$ $deg^2$ in both *g*- and *r*-band. From two days after the Subaru observation (April 7), as the candidates selection will be accomplished through the HSC transient pipeline, we will conduct multi-band photometric follow-ups with the 3.5-m ARC telescope and the 10.4-m GTC telescope at specific epochs. For identifying all SN candidates and investigating their early-phase spectral characteristics, we will trigger the 10.4-m GTC telescope to take spectra of the Subaru ESN Ia candidates at $\sim 3$ days after the Subaru observation.

For profiling complete multi-band LC of each ESN Ia, we require that imaging follow-ups by the ARC and the GTC telescope should be allocated at specific epochs. In consideration of the brightness of the Subaru ESNe Ia as well as the high sky background for observations within $\pm$ 7 days from the full moon, we apply for total 5 half-nights (4 half-nights + 2 quarter-nights) ARC observation in dark/gray nights in April and May, 2016. The complete follow-up schedule is showed in *Figure* 3.

According to former well-observed ESN Ia samples and the SNe Ia rate [23], we expected that $\sim 6$ ESNe Ia can be well investigated from the early phase through the ARC-Subaru-GTC joint observation. With the new ESN Ia samples, we are able to carry out statistical investigation and put forward new evidences in addressing the long-standing issues of SN Ia. Great scientific outputs in SN Ia study can be well expected through this pioneering multi-band ESNe Ia survey program.

### References

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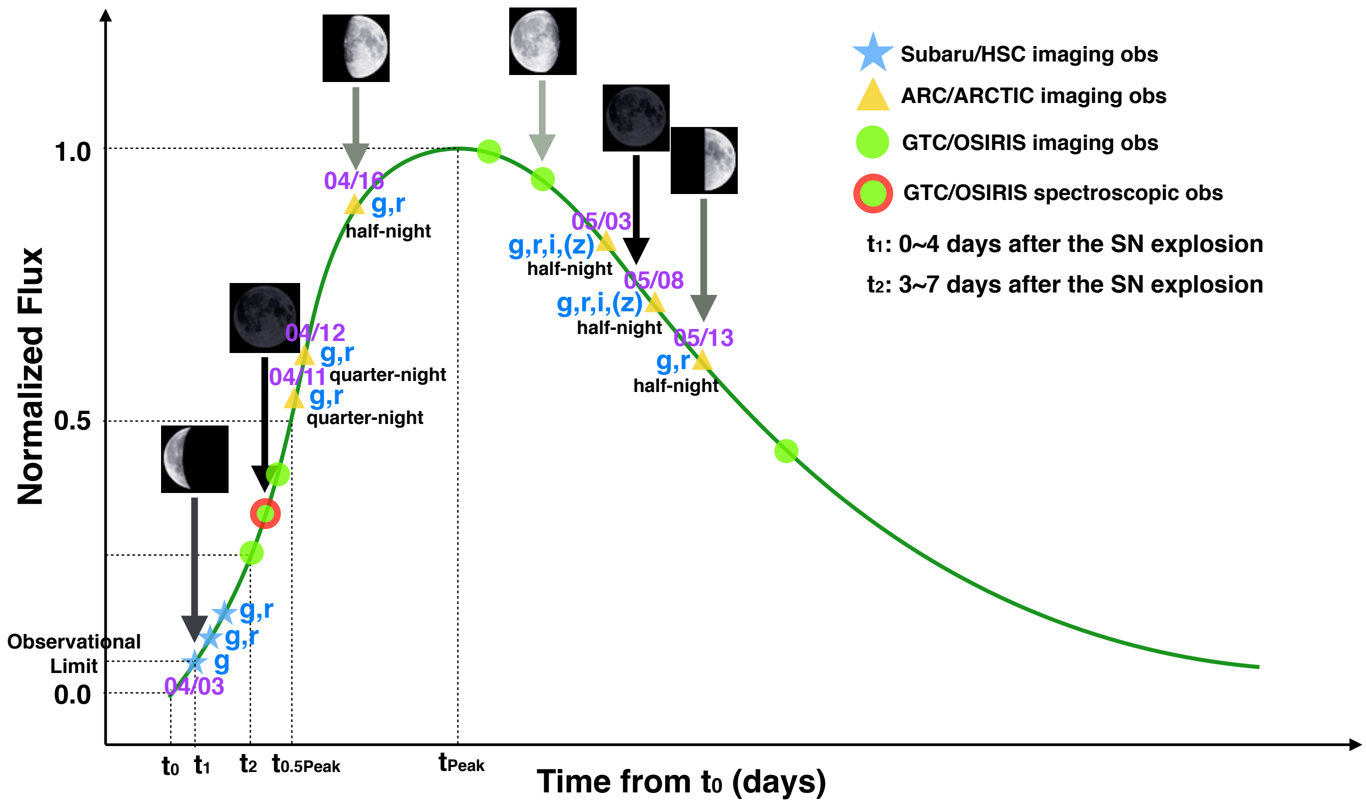


**Figure 3:** Observational plan of the ARC-Subaru-GTC joint observation. We require that the ARC imaging follow-up observations (4 half-nights + 2 quarter-nights) are arranged within $\pm$ 1 day to the date we show in this diagram. The Subaru observation will start from April 3 (UT). In consideration of the visibility of the Subaru survey region in April and May, we prefer later half-night observations in April and **require early half-night observations in May**.