A Cohesive Deep Drilling Field Strategy for LSST Cosmology

Ph.Gris, H.Awan, M. Becker, H.Lin, E. Gawiser, S.Jha
and the LSST DESC Collaboration

to be submitted to ApJS (Rubin LSST Survey Strategy Optimization) (arxiv)

LSST-Fr 2024/06/11

LSST DESC Dark Energy Science Collaboration

A cohesive Deep Drilling Field Strategy for LSST Cosmology

➔ Goal: propose a set of cohesive Deep Drilling strategies fulfilling reqs from:
- cosmology measurements (photo-z, Weak Lensing, type Ia supernovae)
- the Survey Cadence Optimization Committee (SCOC) phase 2 guidelines (jan 2023)

A cohesive Deep Drilling Field Strategy for LSST Cosmology

LSST DESC
Dark Energy Science Collaboration

- **Outline**
  - Deep Drilling Fields (DDF) and LSST observing strategy
  - Design requirements
    - SCOC phase 2 recommendations
    - Requirements from cosmological measurements
  - Metrics to assess observing strategies
  - Designing a cohesive DDF strategy
  - Assessment of the proposed DESC cohesive DDF strategies
  - Conclusion

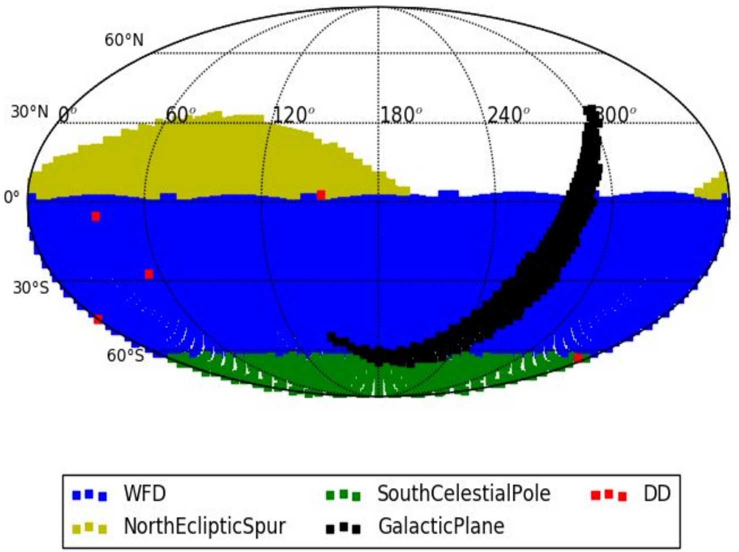
LSST Observing Strategy

2 types of surveys:

- Main survey: Wide-Fast-Deep (WFD)

- Mini-surveys:
  - Deep-Drilling Fields (DD)
  - South celestial pole
  - North Ecliptic
  - Galactic Plane

Main survey: ~ 85% of N_{visits}
DD : ~5-10% of N_{visits}



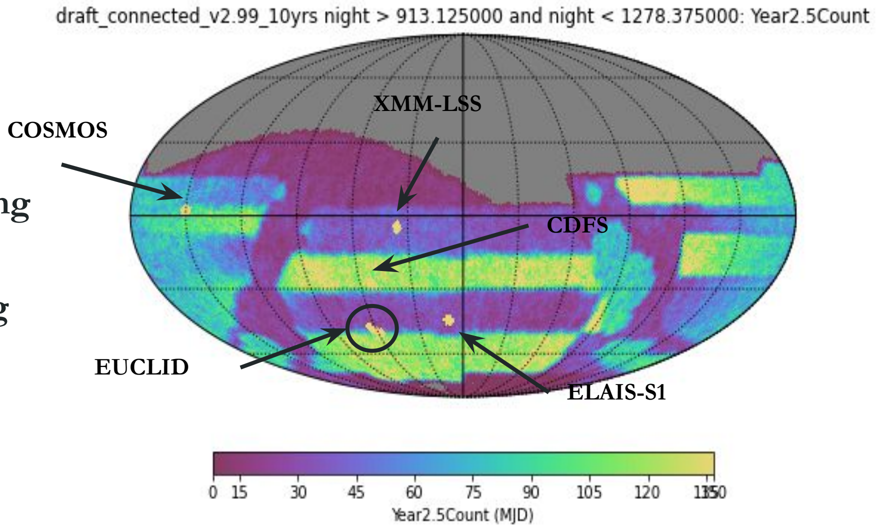
Observing Strategy status (LSST)

- Survey Cadence Optimization Committee (SCOC)
  - Final recommendations to Rubin Observatory's Director of Operations in fall 2024 (yes, this year!)
  - OS revised every year
  - DESC liaisons: R. Mandelbaum, S. Jha, S. Smart
  - Phase 2 recommendations: https://pstn-055.lsst.io (jan 2023)

- Main projects for this year:
  - N_{strips} for rolling cadence (WFD)
  - cadence for Deep Drilling Fields (DDF)
  - early science plan

SCOC phase 2 recommendations for DDFs

- 5-7% of survey time to be spent on DDFs
  - > 5% should be well justified (WFD perf.)
- 5 DDFs observed for ten years
- COSMOS prioritized with additional survey time
  - 10-year DDF depth in three years (beginning of the survey)
  - Same cadence as other fields the remaining time
- Euclid Deep Field South (EDFS) as 5th field
  - ~ twice as large as the other DDFs
  - observed at half-depth over its full area



Critical parameters tbd: cadence of observation, filter allocation

DDFs are critical for DESC: PZ, WL (calibration), SNe Ia (cosmology)

Requirements/metrics from calibration - photo-z (PZ)

- PZ estimated from SED of distant galaxies (6 bands)
- type/redshift degeneracy -> uncertainty in PZ calibration
- To break degeneracies
  - Wide-field, multi-band measurements with accurate redshift galaxies
  - Multi-band deep-fields: precise photometry (flux), reduction of sample variance, shot noise and selection effects
- Requirement
  - coadded DDFs overlap with deep spectroscopic redshift surveys (VVDS, C3R2, COSMOS2020)
  - LSST: 5-σ depth (m_5)

$$m_5^{coadded} = 1.25 log_{10} \sum_{i=1}^{N_v} 10^{0.8 m_5^i}$$

band	Y1	Y10
u	26.7	27.8
g	27.0	28.1
r	26.2	27.8
i	25.8	27.6
z	25.6	27.2
y	24.7	26.5

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Requirements (per band)

$$\Delta m_5 = m_5^{coadded} - m_5^{PZ\ req} \geq 0$$

band	Y1	Y10
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Requirements/metrics from calibration - weak lensing (WL)

- Two primary uses of DDFs:
  - calibration of weak lensing shape estimators: DDF overlapping with high-resolution space-based imaging
  - calibration of weak lensing shear estimators: reducing the loss of precision in the statistical shear measurement from 20% to 5% using the DEEP-FIELD METACALIBRATION technique (pixel noise reduction)
- Requirements (per band)

$$r = \frac{N_v^{DDF}}{N_v^{WFD}}$$

→ DDF visits

→ WFD visits

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$$r \geq 16$$

$$r = \frac{N_v^{DDF}}{N_v^{WFD}}$$

N_v^{DDF} → DDF visits

N_v^{WFD} → WFD visits

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$$r = \frac{N_v^{DDF}}{N_v^{WFD}}$$

DDF visits

WFD visits

$$r \geq 10$$

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- Requirements (per band)

band	WL requirements N_{visit} season 1	WL requirements N_{visit} season 2-10
u	48	432
g	72	648
r	184	1656
i	184	1656
z	152	1368
y	160	1440

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Metric for WL reqs.

$$r^{WL} = \frac{N_v^{OS}}{N_v^{WL\,req}} \geq 1$$

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r	184	1656
i	184	1656
z	152	1368
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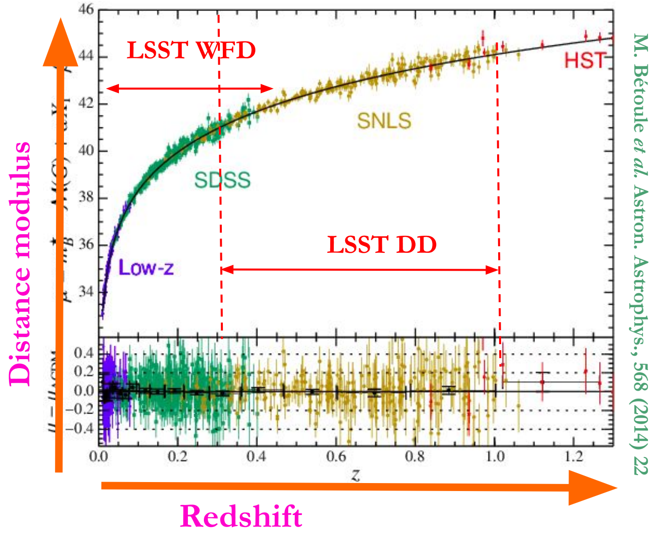
Requirements/metrics from cosmology - Type Ia Supernovae (SNe Ia)

- **SNe Ia collected by LSST** ⇨ **cosmological measurements : Hubble Diagram (HD)**



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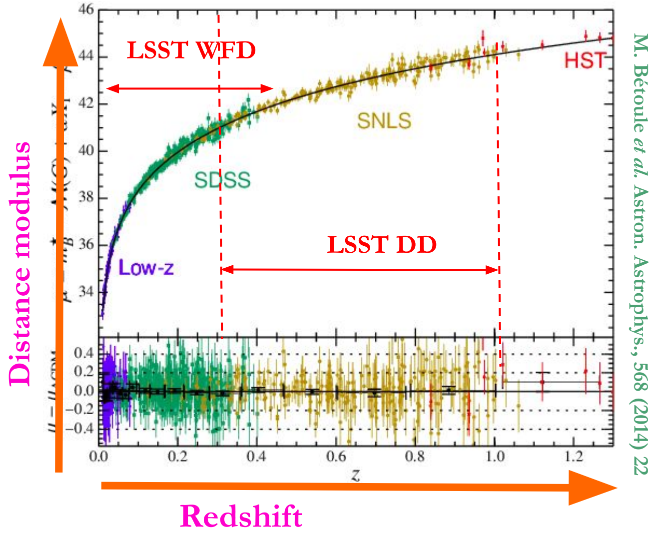

$$-ln\mathcal{L} = (\mu - \mu_{th}(z, \Omega_m, w))^T C(\mu - \mu_{th}(z, \Omega_m, w))$$

Ω_m, w : cosmological parameters

μ : distance modulus

C : Covariance matrix

$C = f(\sigma_\mu, \sigma_{int}, \sigma_{syst})$

σ_μ : μ error

σ_{int} : intrinsic SNe Ia dispersion

σ_{syst} : systematics

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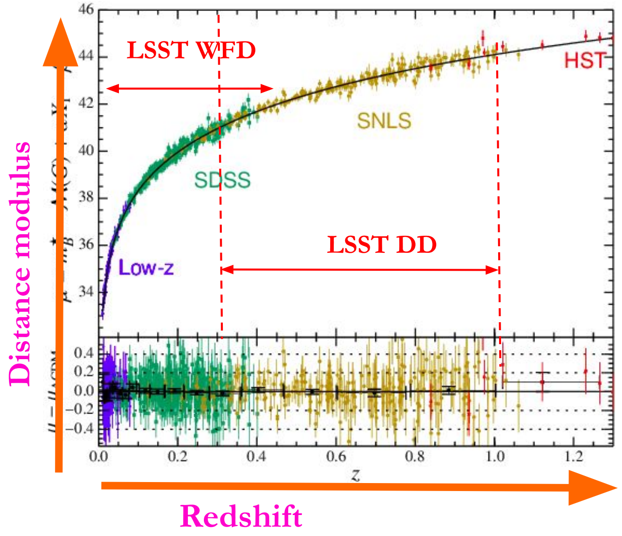

M. Bétoule *et al.* Astron. Astrophys., 568 (2014) 22

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Optimal cosmological constraints

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Minimizing uncertainties

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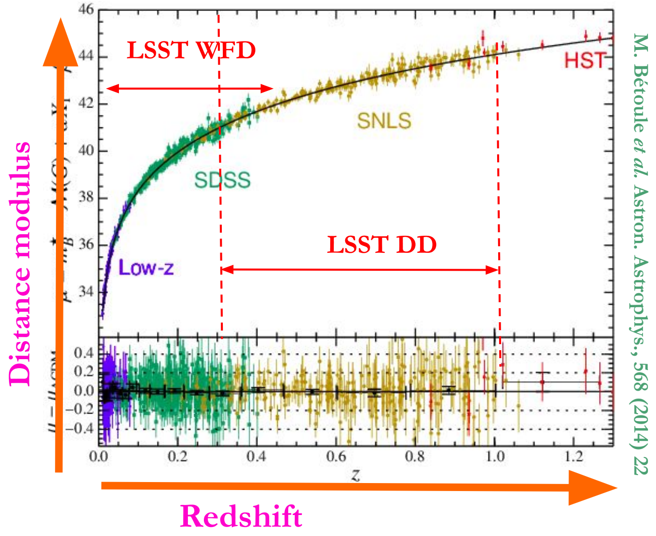

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$\sigma_\mu \leq \sigma_{int} \sim 0.12$

σ_{syst} (Malmquist bias)

σ_z

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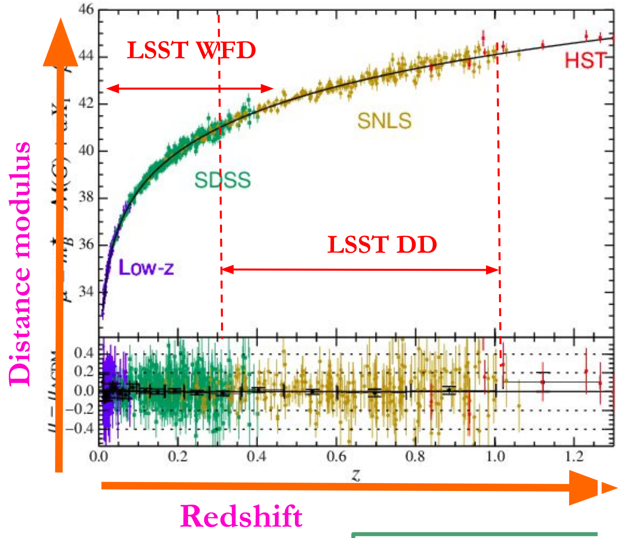

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Rubin-LSST

SNe Ia light curve parameters

Observing Strategy Constraints

- N_{visits}/band/night (LC SNR)
- cadence of observation (LC sampling+SNR)
- season length/number of seasons (N_{SN})
- number of fields (N_{SN})
- time budget

↔

SN Requirements

Observe a *large* sample of *well-measured* SNe Ia up to *high redshift completeness*

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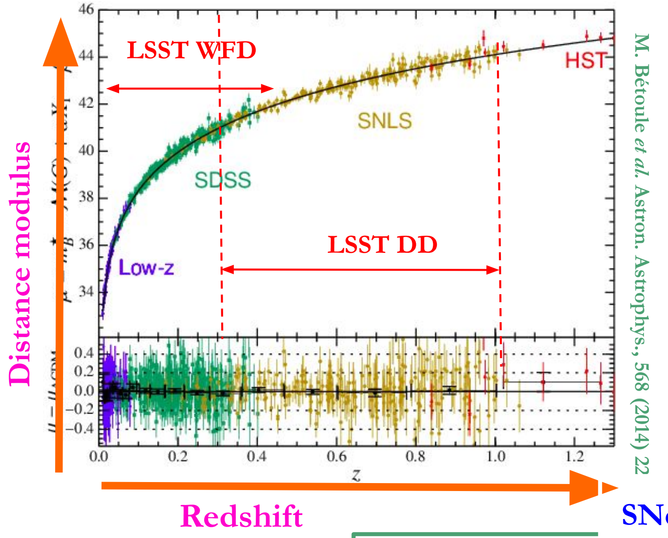

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SN Requirements

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Redshift

- Spectro — External
- Photo-z — Rubin-LSST

Requirements/metrics from cosmology - Type Ia Supernovae (SNe Ia)

- measuring (w_0, w_a) -> large SNe Ia sample at high z (necessary condition) -> **DDF!**
- requirement: SNe Ia sample with high redshift completeness (faint SNe Ia)
  - large number of visit per observing night
  - high cadence of observation (1 night)
  - optimized filter allocation

$z_{complete}$	N_{visit}/obs. night total	N_{visit}/obs. night $g/r/i/z/y$	budget per season
0.80	149	2/9/62/56/20	1.3%
0.75	108	2/9/44/38/15	0.9%
0.70	81	2/9/33/31/6	0.7%

Requirements/metrics from cosmology - Type Ia Supernovae (SNe Ia)

- **Supernovae Metric of Merit (SMoM): metric to assess OS for SN cosmology**
  - **Global metric : WFD+DDF (better than N_{SN} and $z_{complete}$ used up to now)**
  - **SMoM definition: based on the DETF FoM (see this article)**

$$SMoM = \pi/A$$
$$A = \pi\Delta\chi^2\sigma_{w_0}\sigma_{w_a}\sqrt{1-\rho^2}$$
$$\Delta\chi^2 = 6.17\ (95.4\%C.L.)$$
$$\rho = cov(w_0, w_a)/(\sigma_{w_0}\sigma_{w_a})$$
$$w = w_0 + w_a\frac{z}{1+z}(CPL)$$

$$w_0\ and\ w_a : from\ a\ Hubble\ Diagram(HD)$$
$$-\ln\mathcal{L} = \sum_{i=1}^{N_{SN}}\frac{(\mu_i-\mu_{th})^2}{\sigma_{\mu_i}^2+\sigma_{int}^2}$$

$$\sigma_{int} \sim 0.12\ (SN\ intrinsic\ dispersion)$$
$$\sigma_{\mu_i} : full\ survey\ simulation\ of\ SN\ LC$$
$$N(z)\ distribution : full\ survey\ simulation\ of\ SN\ LC$$
$$\mu_i : theory + smearing(\sigma_{\mu_i}, \sigma_{int})$$

+ **spectroscopic scenario for host galaxy redshift.**

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+ spectroscopic scenario for host galaxy redshift.

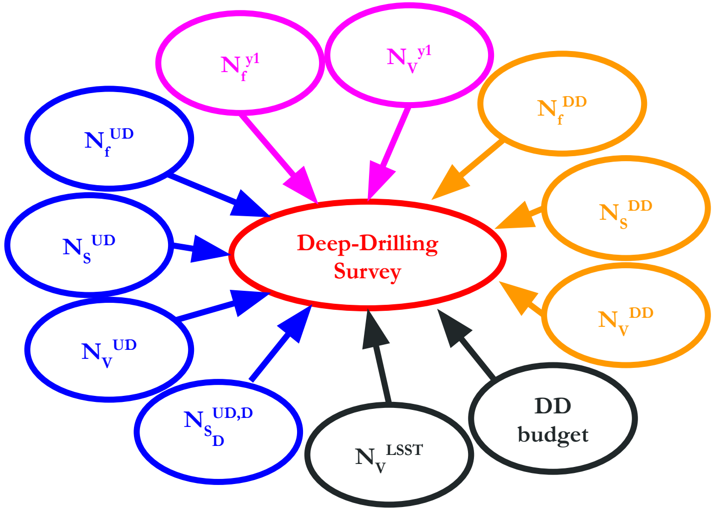
Precise cosmology with SNe Ia = highest SMoM

Designing a cohesive DESC DDF strategy

- Requirements: PZ, WL, SNe Ia + SCOC phase 2
- SNe Ia
    - High budget per season (1.3% for $z_{complete}$~0.8)
    - DDF budget for universal cadence: 1.3*50=65% !!!!
- To maximize the number of SNe Ia at higher-z: 2 types of fields
    - ultra-deep fields
        - $z_{complete}$~0.7-0.8
        - high cadence of observation/>100 visits/obs. night
        - limited number of seasons (deep fields otherwise)
    - deep fields
        - $z_{complete}$~ 0.5-0.6
        - Cadence ~ 3-4 nights/< 40 visits/obs. Night
        - 10 seasons

Deep Rolling survey

Designing a DESC cohesive DDF strategy - free parameters



N_f : Number of fields/season

N_s : number of seasons of observation/field

N_v : number of visits /season/field

$budget^{DD}$: DD budget

N_v^{LSST} : Total number of LSST visits

$$N_v^{UD} = \frac{budget^{DD} \times N_v^{LSST} - N_f^{DD,y1} \times N_v^{DD,y1} - [N_f^{UD} \times N_s^{UD,DD} + N_f^{DD} \times N_S^{DD}] N_v^{DD}}{N_f^{UD} \times N_S^{UD}}$$

$$N_v^{UD} / obs.\,night = N_v^{UD} \times sl^{UD} / cad^{UD}$$

$budget^{DD} = 5 - 7\%$ (SCOC phase 2)

$N_v^{LSST} \sim 2.1\ million$ (from simulations)

$N_f^{UD} + N_f^{DD} = 5$ (5 Deep Drilling Fields – SCOC phase 2)

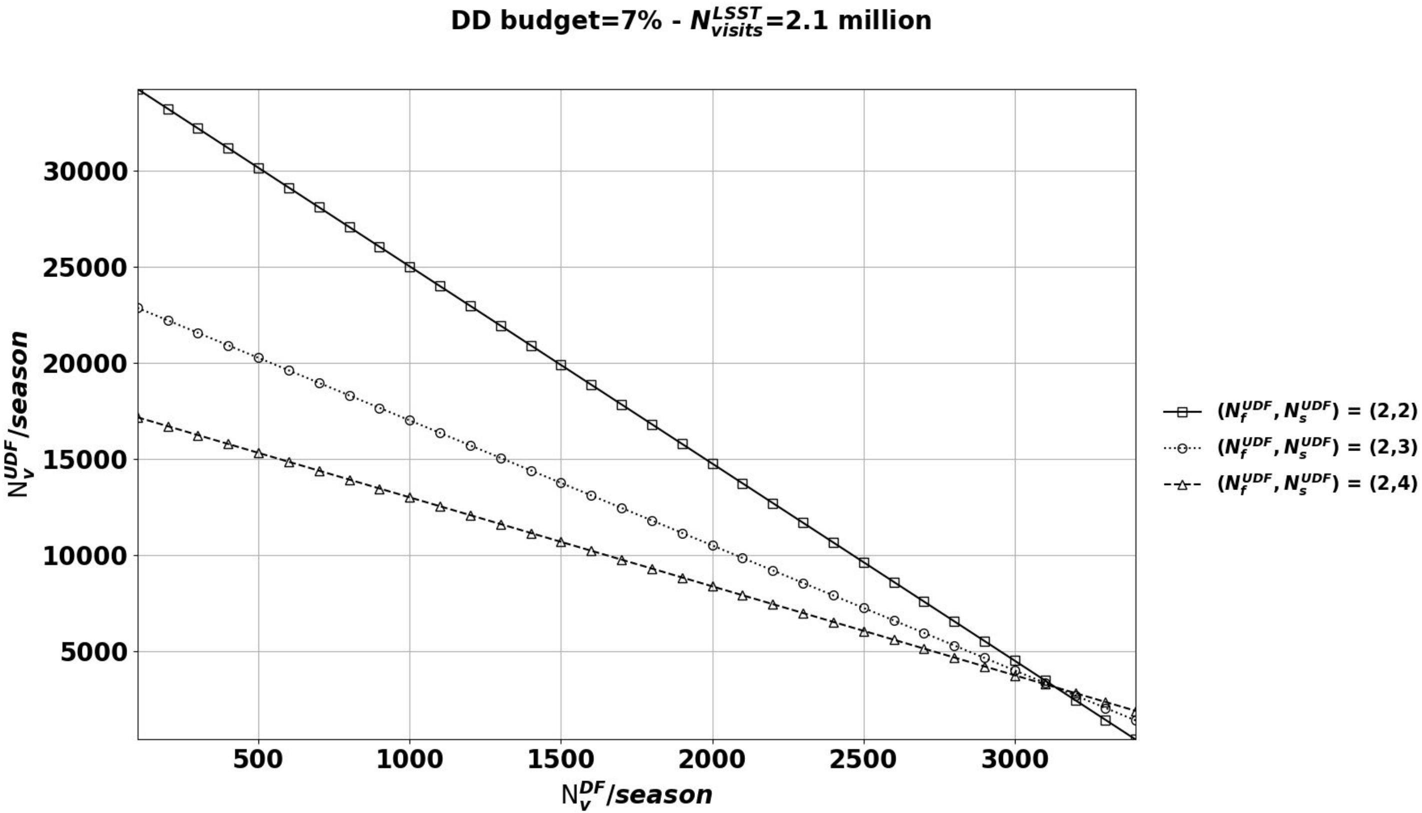
$N_s^{DD} = 10$ (SCOC phase 2)

$N_s^{UD} + N_s^{UD,DD} = 10$ (SCOC phase 2)

Free parameters

- number of UD fields
- number of UD season
- number of UD visits/obs. Night
- number of DF visits/season

Designing a DESC cohesive DDF strategy



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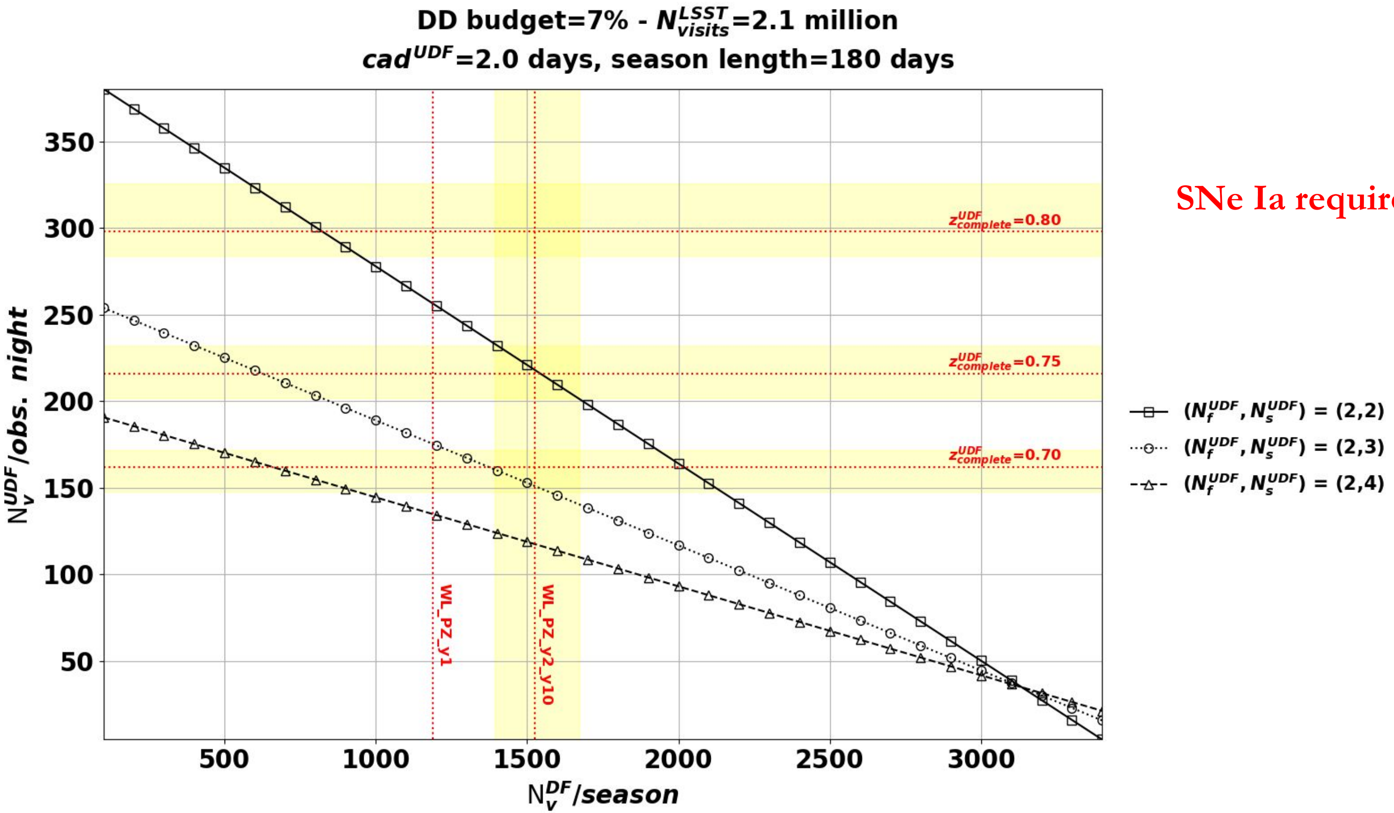
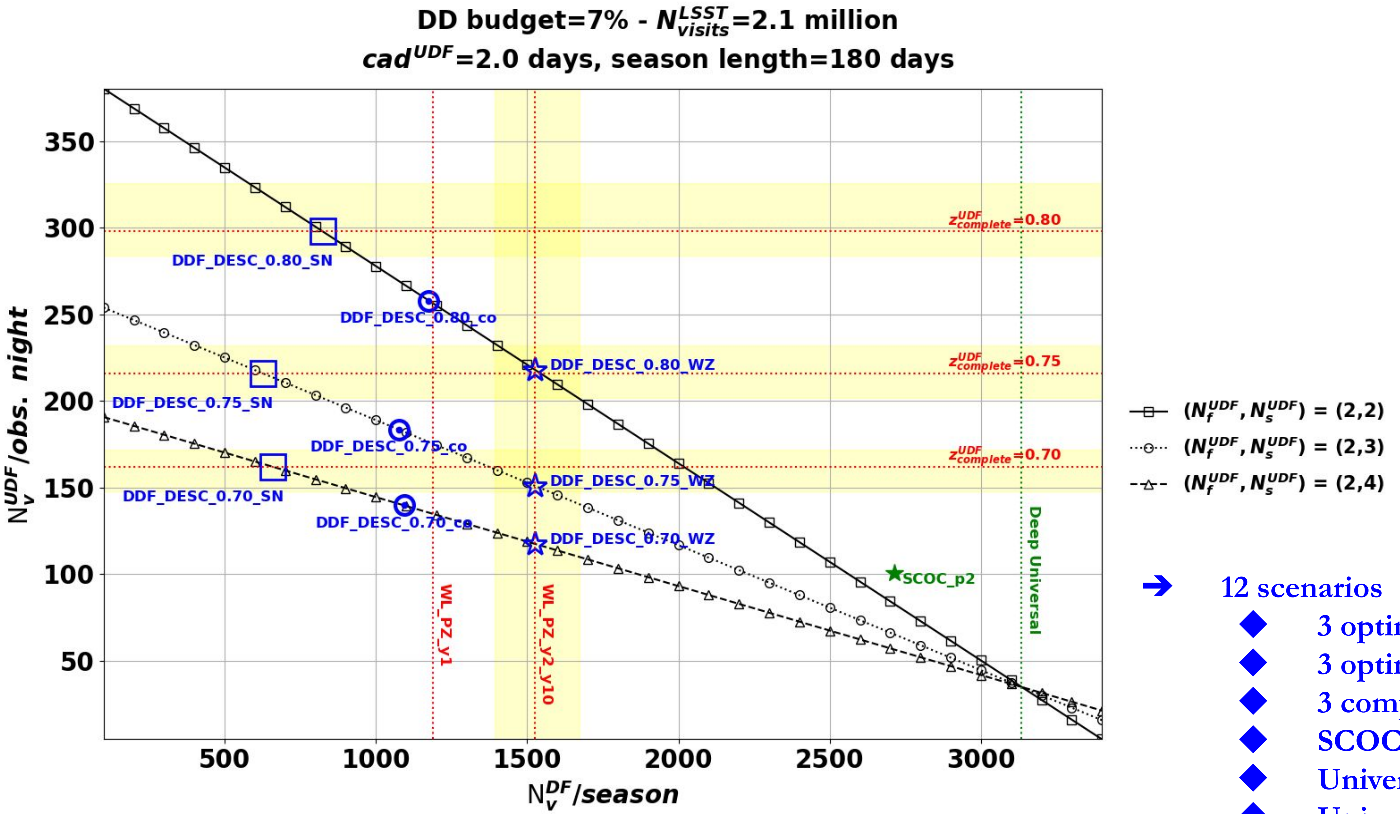


SNe Ia requirements ± 0.01

WL_PZ y2_y10 requirements ±0.05 mag

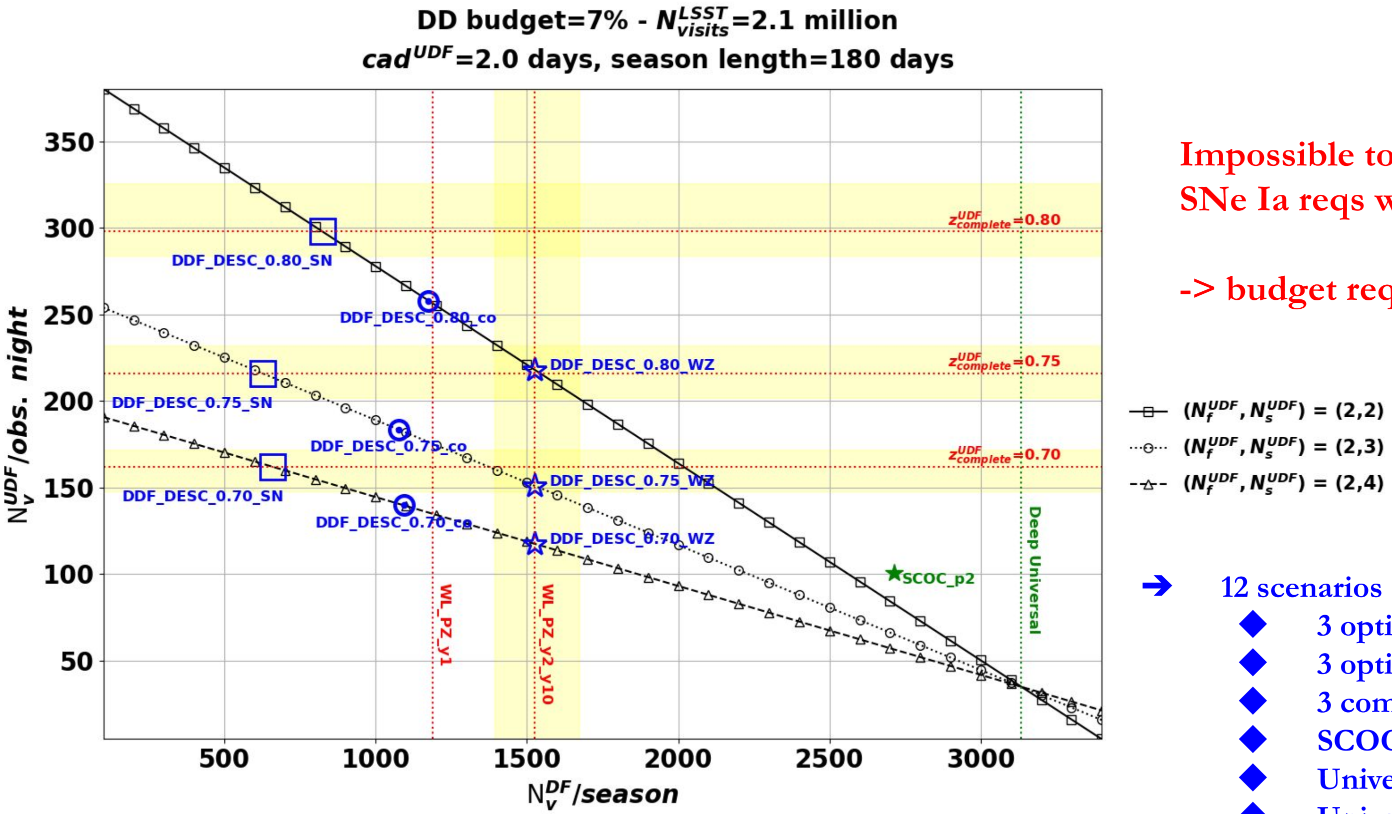
Designing a DESC cohesive DDF strategy



➔ 12 scenarios

- 3 optimal for SN (_SN)
- 3 optimal for PZ+WL (_WZ)
- 3 compromise SN-WL+PZ (_co)
- SCOC_p2
- Universal_WZ
- Universal_SN

Designing a DESC cohesive DDF strategy



Impossible to fulfill PZ, WL, and SNe Ia reqs with a budget of 7%.

-> budget required: ~ 8.5%

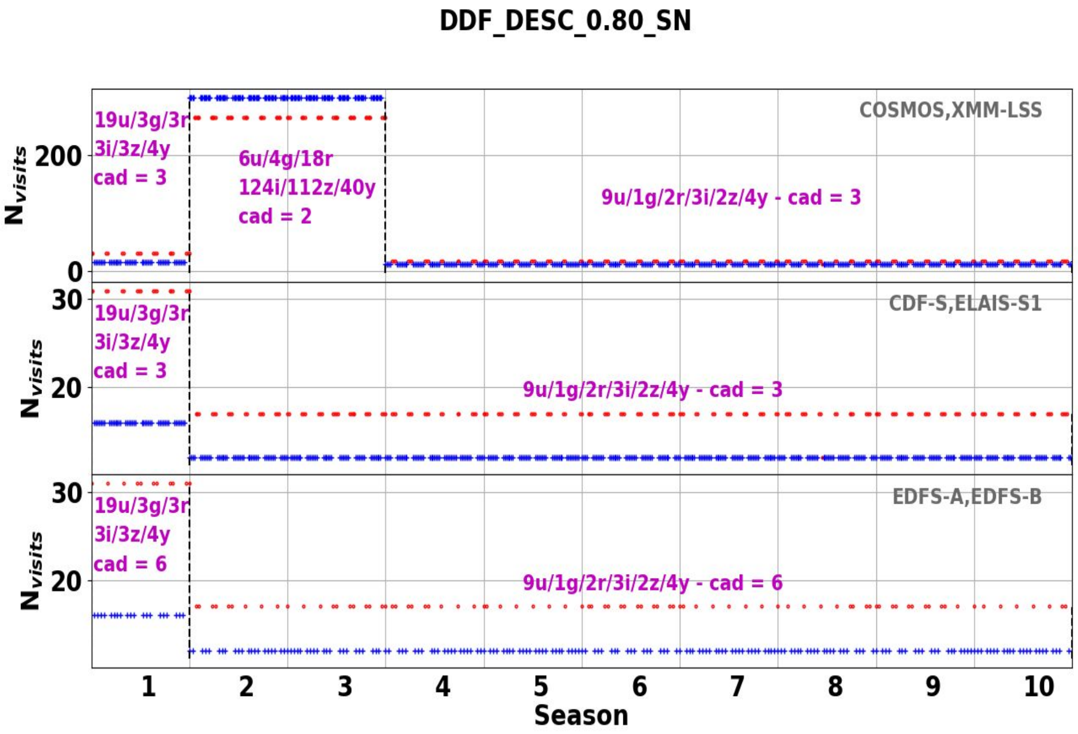
➔ 12 scenarios

- 3 optimal for SN (_SN)
- 3 optimal for PZ+WL (_WZ)
- 3 compromise SN-WL+PZ (_co)
- SCOC_p2
- Universal_WZ
- Universal_SN

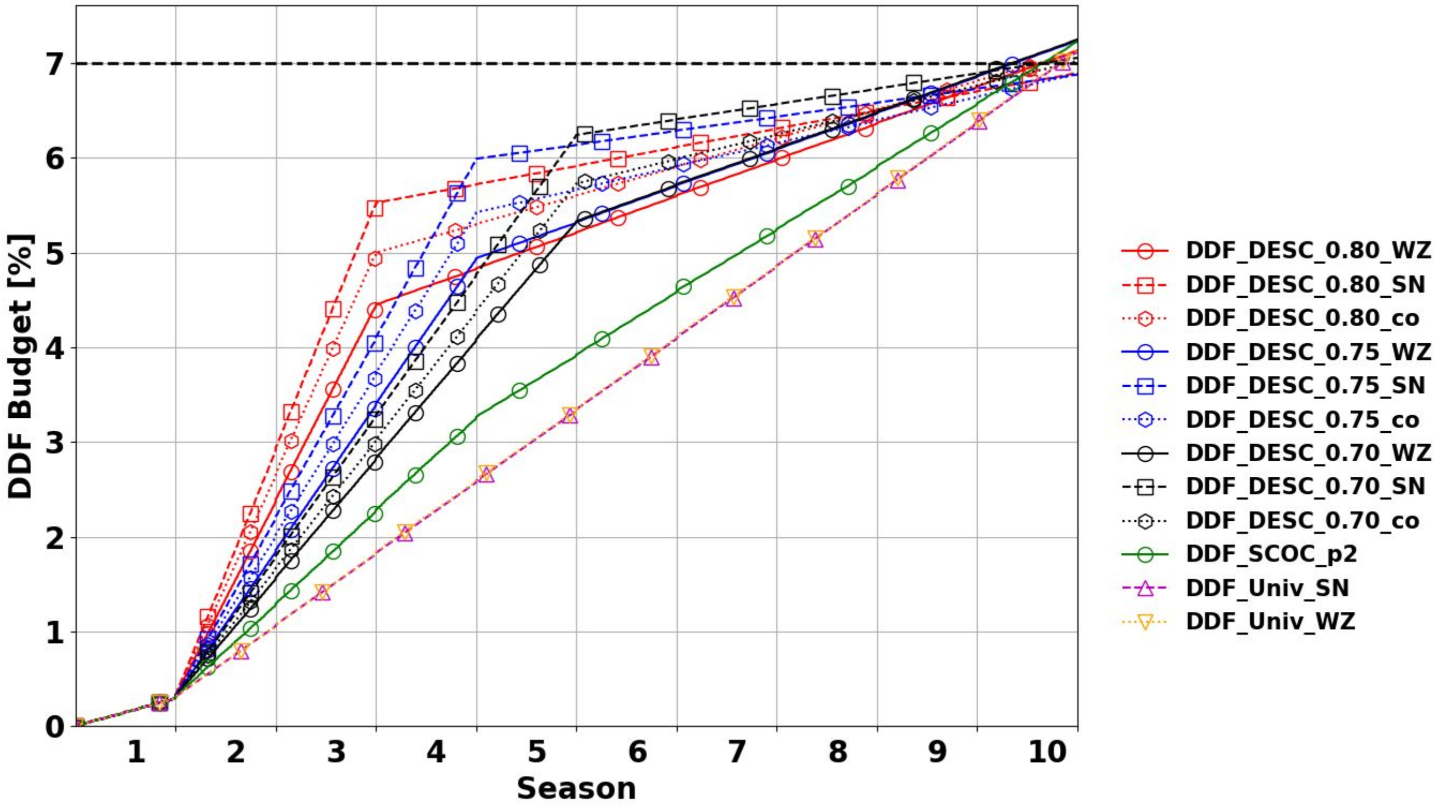
Example of a Deep Rolling strategy

- Filter allocation from SNe Ia reqs (UD fields) and from calibration reqs (PZ,WL)

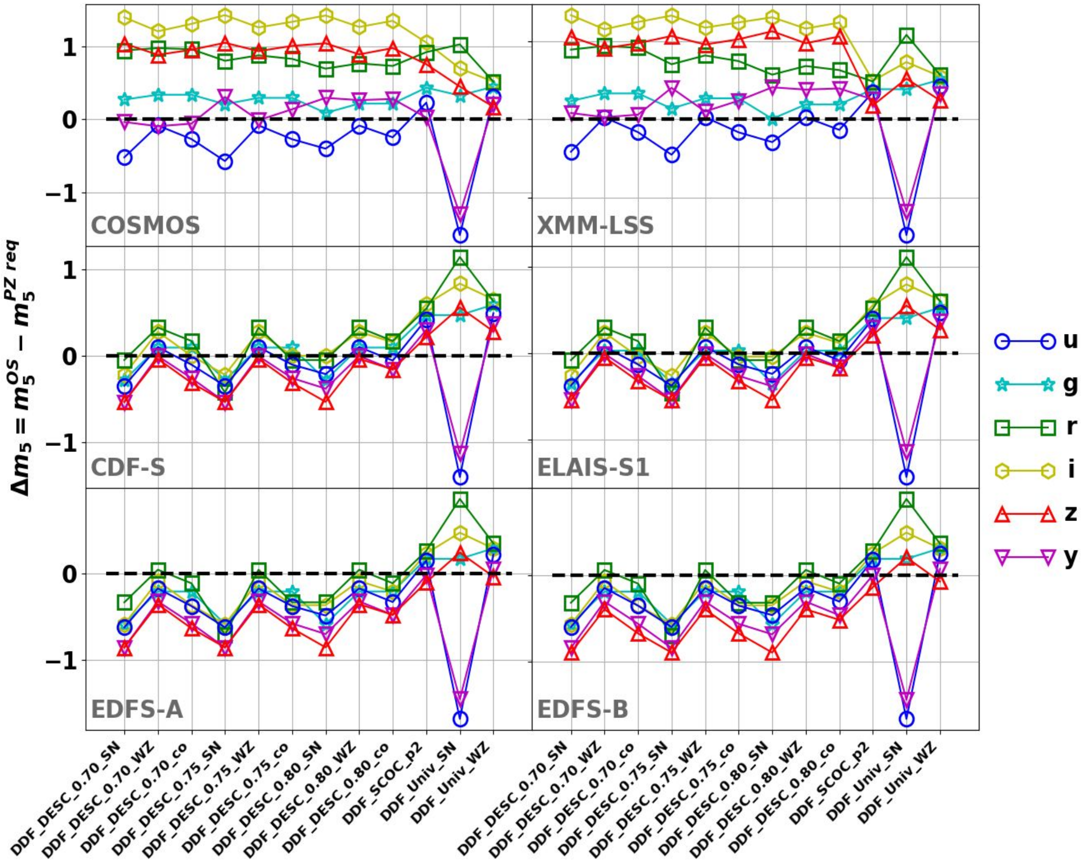
- Moon:
  - phase < 20%: u <-> y swap



DD budget vs season

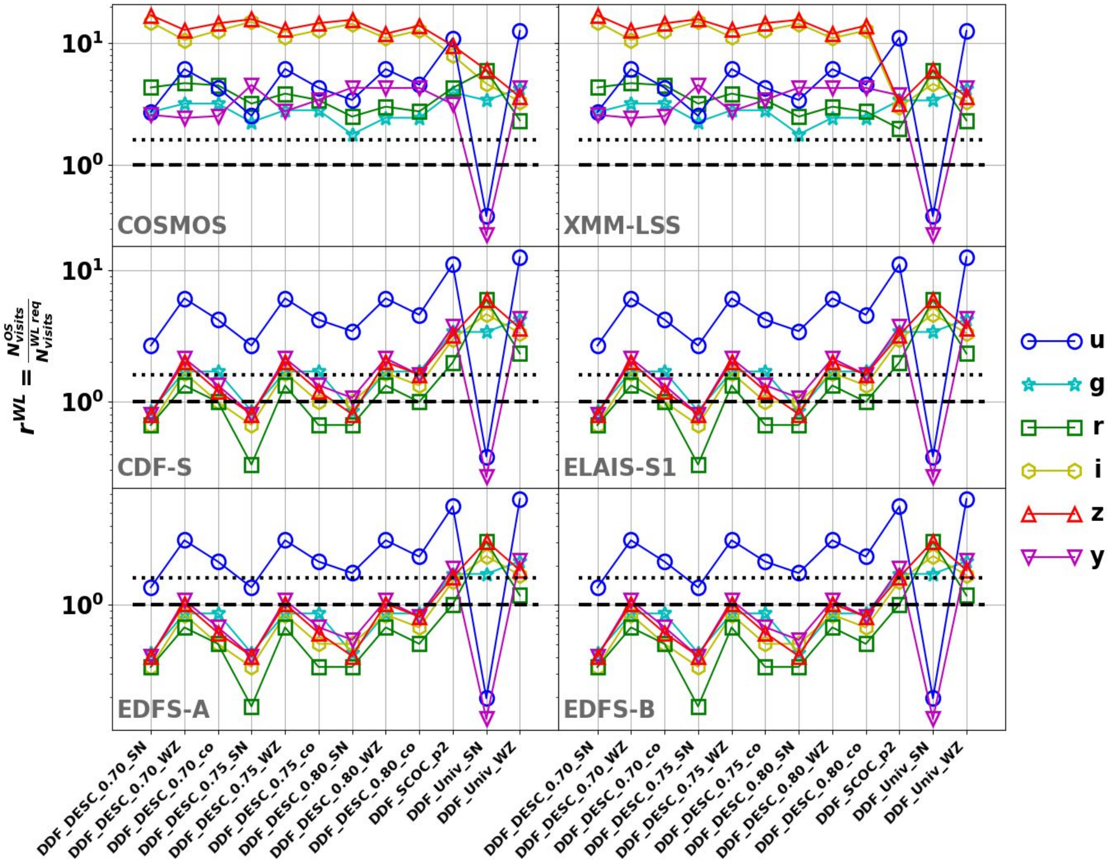


Metric: PZ



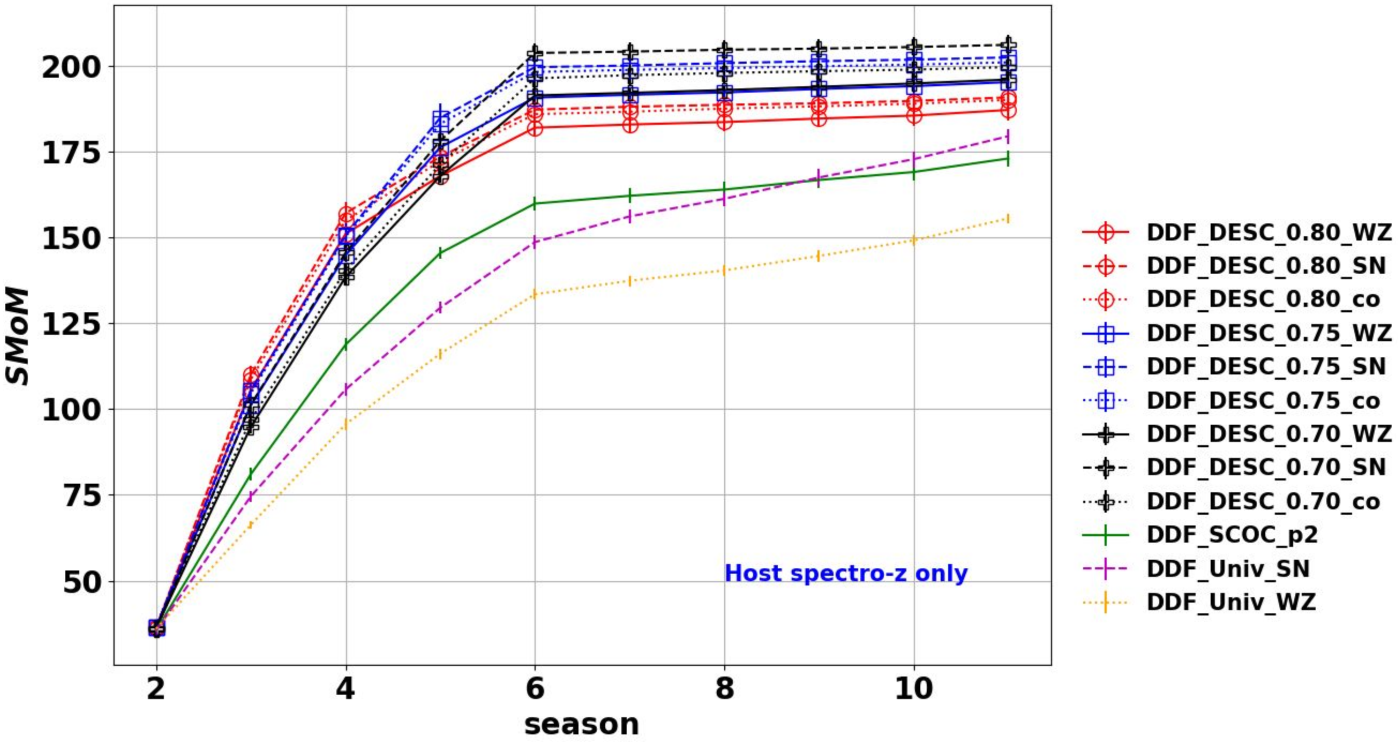
$\Delta m_5 = m_5^{OS} - m_5^{PZ\ req}$
COSMOS
XMM-LSS
CDF-S
ELAIS-S1
EDFS-A
EDFS-B
u
g
r
i
z
y
1
0
−1
DDF_DESC_0.70_SN
DDF_DESC_0.70_WZ
DDF_DESC_0.70_co
DDF_DESC_0.75_SN
DDF_DESC_0.75_WZ
DDF_DESC_0.75_co
DDF_DESC_0.80_SN
DDF_DESC_0.80_WZ
DDF_DESC_0.80_co
DDF_SCOC_p2
DDF_Univ_SN
DDF_Univ_WZ

Metric: WL

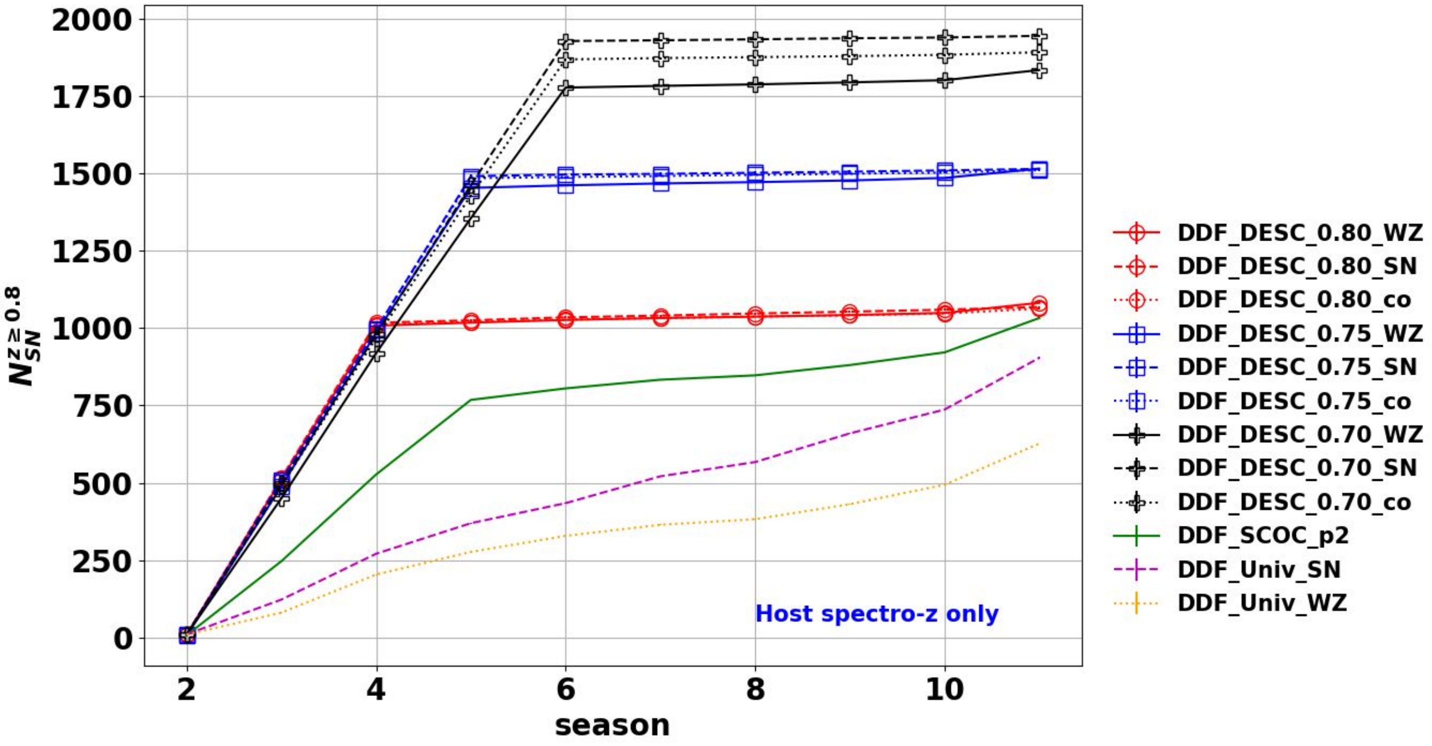


$r^{WL} = \frac{N_{visits}^{OS}}{N_{visits}^{WL\ req}}$
10^1
10^0
COSMOS
XMM-LSS
CDF-S
ELAIS-S1
EDFS-A
EDFS-B
u
g
r
i
z
y
DDF_DESC_0.70_SN
DDF_DESC_0.70_WZ
DDF_DESC_0.70_co
DDF_DESC_0.75_SN
DDF_DESC_0.75_WZ
DDF_DESC_0.75_co
DDF_DESC_0.80_SN
DDF_DESC_0.80_WZ
DDF_DESC_0.80_co
DDF_SCOC_p2
DDF_Univ_SN
DDF_Univ_WZ

Metric: SNe Ia

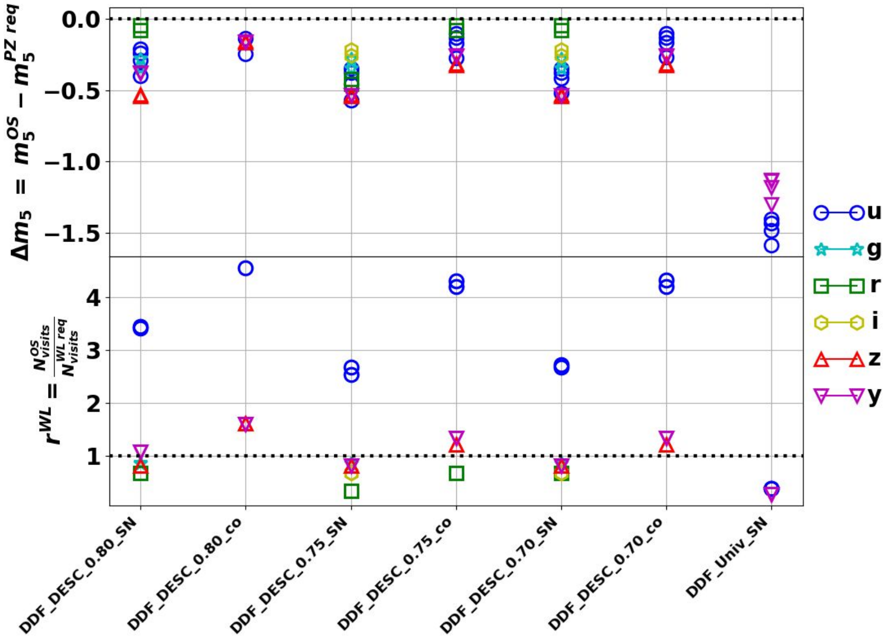


N_{SN} (z≥ 0.8)



2000
1750
1500
1250
1000
750
500
250
0
$N_{SN}^{z\geq 0.8}$
2
4
6
8
10
season
Host spectro-z only
DDF_DESC_0.80_WZ
DDF_DESC_0.80_SN
DDF_DESC_0.80_co
DDF_DESC_0.75_WZ
DDF_DESC_0.75_SN
DDF_DESC_0.75_co
DDF_DESC_0.70_WZ
DDF_DESC_0.70_SN
DDF_DESC_0.70_co
DDF_SCOC_p2
DDF_Univ_SN
DDF_Univ_WZ

Combining metric results

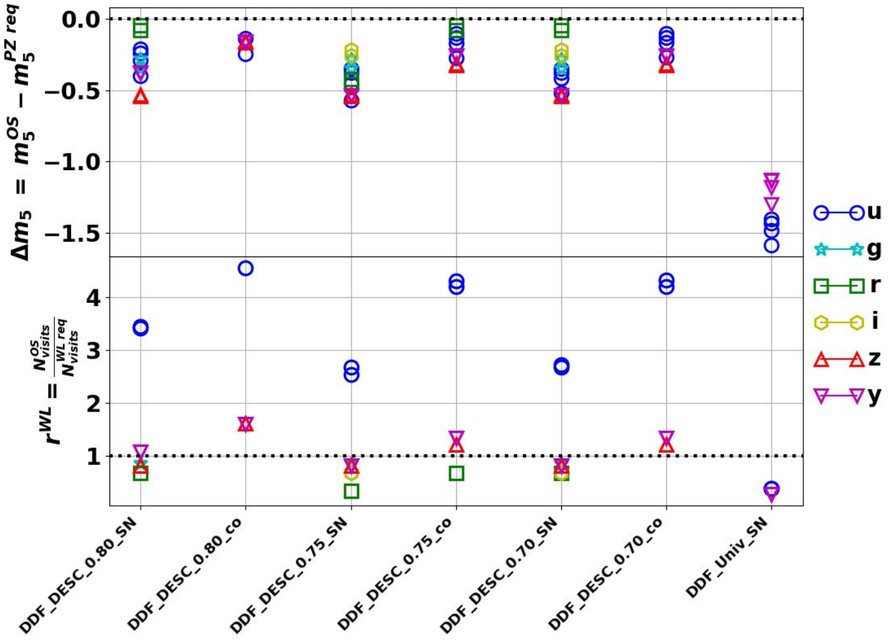


Strategies not meeting PZ or WL reqs

Observing Strategy	SMoM
DDF_Univ_WZ	155 ± 1
DDF_SCOC_p2	173 ± 2
DDF_Univ_SN	179 ± 2
DDF_DESC_0.80_WZ	187 ± 3
DDF_DESC_0.80_co	190 ± 2
DDF_DESC_0.80_SN	191 ± 3
DDF_DESC_0.75_WZ	195 ± 2
DDF_DESC_0.70_WZ	196 ± 1
DDF_DESC_0.70_co	199 ± 3
DDF_DESC_0.75_co	201 ± 2
DDF_DESC_0.75_SN	202 ± 4
DDF_DESC_0.70_SN	206 ± 3

SNe Ia SMoM

Combining metric results



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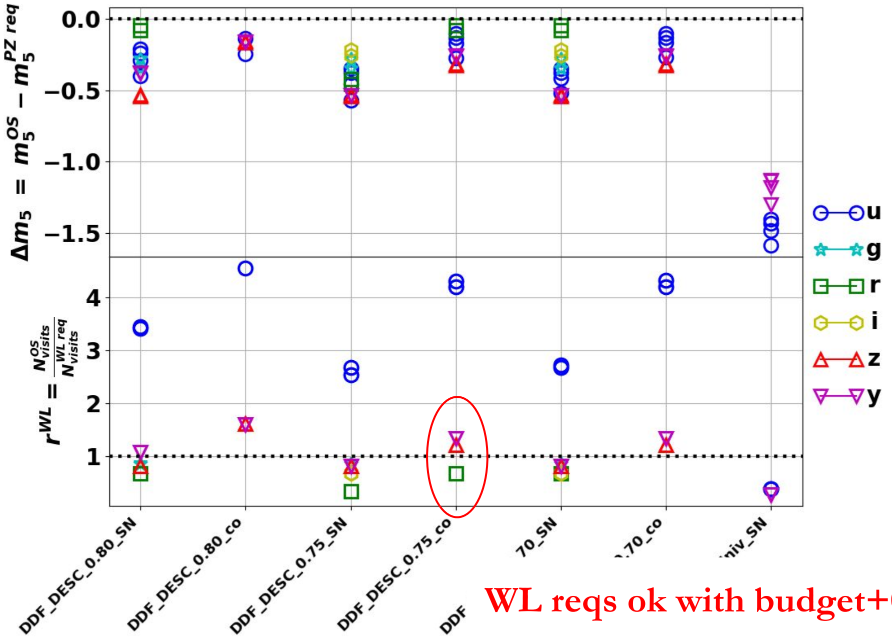
Strategies not meeting PZ or WL reqs

SNe Ia SMoM

Combining metric results



WL reqs ok with budget+0.05%

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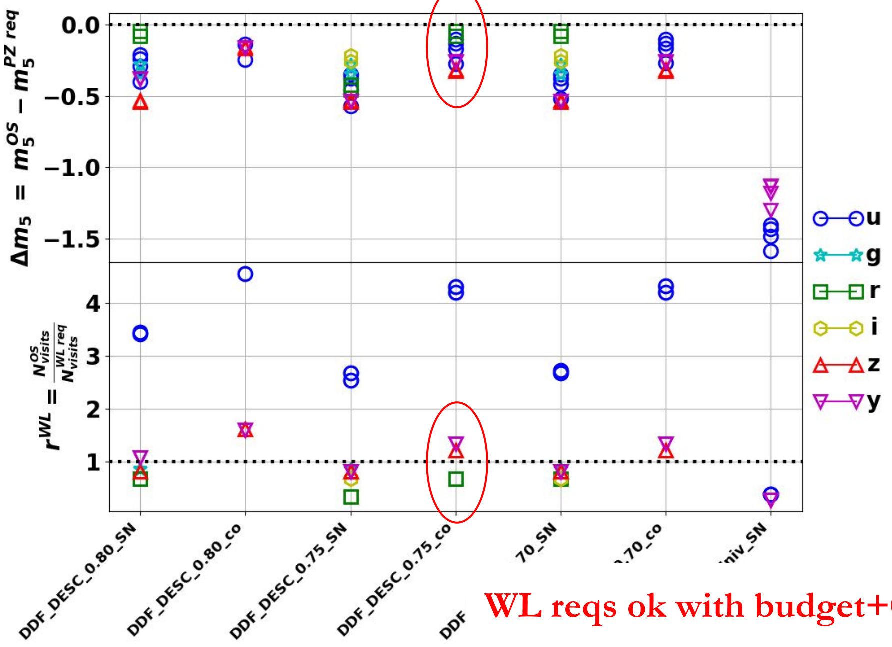
SNe Ia SMoM

Combining metric results

Δm_5 ~ -0.3-0.4 acceptable?



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SNe Ia SMoM

Conclusion

- Seems possible to design DDF strategies fulfilling PZ, WL calibration reqs, optimal for SNe Ia cosmology, and following the SCOC phase 2 recomm.
- A method used to define the strategy parameters (cadence, N_v, filter allocation) presented in this paper
- Most promising: Deep Rolling surveys
  - 2 Ultra-deep fields (high cadence, large N_v) - limited number of seasons (2-4)
  - Deep fields (lower cadence, lower N_v) for 10 seasons
- A DDF budget of ~8.5% is required for all cosmological measurement reqs. to be fulfilled
- Critical to observe SNe Ia leading to accurate distance measurements
- Results presented in this paper were achieved with a (relatively) basic simulation. A validation with realistic simulations using the LSST scheduler is required.